

## Article

# Comparison of Machining Performance of Ti-6Al-4V under Dry and Cryogenic Techniques Based on Tool Wear, Surface Roughness, and Power Consumption

Dhvanil Chauhan <sup>1</sup>, Mayur A. Makhesana <sup>2</sup>, Rizwan Abdul Rahman Rashid <sup>3,\*</sup>, Vivek Joshi <sup>4</sup> and Navneet Khanna <sup>1</sup>

<sup>1</sup> Advanced Manufacturing Laboratory, Institute of Infrastructure Technology Research and Management (IITRAM), Ahmedabad 380026, India; dhvanil.chauhan.21mm@iitram.ac.in (D.C.); navneetkhanna@iitram.ac.in (N.K.)

<sup>2</sup> Mechanical Engineering Department, Institute of Technology, Nirma University, Ahmedabad 382481, India; mayur.makhesana@nirmauni.ac.in

<sup>3</sup> School of Engineering, Swinburne University of Technology, Hawthorn, VIC 3122, Australia

<sup>4</sup> Sr. Manufacturing Controls Engineer, Tesla Giga, Austin, TX 78725, USA; viveknjoshi@gmail.com

\* Correspondence: rrahmanrashid@swin.edu.au

**Abstract:** The machining of Ti-6Al-4V alloys is challenging due to their high strength, poor thermal conductivity, and high chemical reactivity. When used in traditional machining, cryogenic coolants can reduce tool wear, thus extending tool life, improving surface finish, and requiring less power with reduced environmental effects. In this context, this study aimed to perform a machinability analysis of the surface roughness, power consumption, tool wear, and specific energy consumption of a Ti-6Al-4V titanium alloy and to comprehend the performance of dry and cryogenic machining in turning operations. A comprehensive analysis of tool wear and specific cutting energy (SCE) under dry and cryogenic machining was conducted. It was found that the machining time under a cryogenic environment was increased by 83% and 39% at 80 and 90 m/min compared to a cutting speed at 100 m/min. The higher cutting speed (100 m/min) in cryogenic environments produced an improved surface finish. Compared to dry machining, the cooling effect of liquid CO<sub>2</sub> helped dissipate heat and reduce thermal damage, improving surface finish. The findings revealed that in dry conditions, approximately 5.55%, 26.45%, and 27.61% less power was consumed than in cryogenic conditions at 80, 90, and 100 m/min cutting speeds, respectively. Based on the outcomes of the work, the application of cryogenic cooling can be considered an alternative to dry and flood cooling for improving the machinability of Ti-6Al-4V alloys.

**Keywords:** machining; cryogenic cooling; tool wear; surface roughness; power consumption



**Citation:** Chauhan, D.; Makhesana, M.A.; Rahman Rashid, R.A.; Joshi, V.; Khanna, N. Comparison of Machining Performance of Ti-6Al-4V under Dry and Cryogenic Techniques Based on Tool Wear, Surface Roughness, and Power Consumption. *Lubricants* **2023**, *11*, 493. <https://doi.org/10.3390/lubricants11110493>

Received: 20 September 2023

Revised: 12 October 2023

Accepted: 9 November 2023

Published: 15 November 2023



**Copyright:** © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

## 1. Introduction

Titanium (Ti) alloys are applied in many sectors, but the primary requirements are in the industrial and aerospace sectors, which are 40% of the Ti market. It is frequently used for structural components, including fasteners, landing gear, and engine and airframe parts. The alloy is suitable for decreasing weight and increasing fuel efficiency in aircraft because of its excellent strength-to-weight ratio. The Ti-6Al-4V alloy is also suitable for medical implants due to its biocompatibility and resistance to corrosion under body fluid environments. It is commonly used in bone plates, dental implants, and implants for orthopaedics such as hip and knee replacements. In load-bearing applications, its great strength ensures stability and longevity, and its corrosion resistance reduces the possibility of implant failure. Titanium alloys are considered difficult-to-machine materials with the most desirable characteristics, such as improved strength and high resistance to corrosion and oxidation. A typical aircraft material is the Ti-6Al-4V alloy, renowned for its excellent

strength-to-weight ratio, corrosion resistance, and high-temperature capabilities [1]. Ti alloys' low thermal conductivity produces comparatively high cutting temperatures during machining. The high strength of this alloy causes excessive cutting forces. Its low elasticity and chemical reactivity make it challenging to process using conventional machining operations [2]. In particular, the machining of titanium and its alloys invariably results in rapid tool wear. As a result, the cutting tool's life is shortened during metal cutting due to mechanical, thermal, and chemical load factors. Another problem encountered while machining titanium alloys is the high friction coefficient, and excessive heat generation is reported in the literature [3]. Sustainability has gained importance today as we deal with climate change, biodiversity loss, resource depletion, and social injustice. Reducing energy consumption, carbon emissions, and the effect of lubricants on human health are necessary during machining [4]. It consists in adopting sustainable practices, encouraging innovation and entrepreneurship in green industries, and promoting responsible consumption and production patterns [5]. Sustainability concepts have been incorporated into policies, plans, and practices across various industries, including the metal-cutting industries. It necessitates the implementation of such practices during the machining of various difficult-to-cut materials.

It has been shown that employing cutting fluids when working with Ti alloys increases the quality of the machined components and the cutting tool's life. However, when considering their costs, adverse effects on human health, and widespread use, conventional cutting fluids—which still make up a significant share of the market—do not adhere to the concept of a green economy [6]. Because of this, it is essential that metal-cutting industry operations employ environment-friendly cutting fluids and practices. When taking into account their impacts, the majority of previously published studies stated that cryogenic coolants such as liquid nitrogen ( $\text{LN}_2$ ) and liquid carbon dioxide ( $\text{LCO}_2$ ) are sustainable and work as an alternative to conventional cutting fluids [7]. Cryogenic machining refers to using extremely low temperatures in the machining process to improve cutting performance and tool life. One standard cryogenic setup involves using carbon dioxide ( $\text{CO}_2$ ) as a cooling agent. Liquid  $\text{CO}_2$  cryogenic machining setups typically involve directing a stream of liquid or gaseous  $\text{CO}_2$  onto the machining zone during cutting. The  $\text{CO}_2$  rapidly absorbs heat from the cutting zone, lowering the temperature and the thermal stresses on the tool and workpiece. Many works have been reported recently on developing environmentally friendly machining processes for difficult-to-cut materials.

Khanna et al. [8] published a detailed review on cryogenic machining, which has emerged as a sustainable and environmentally friendly alternative, offering superior performance to traditional coolants and lubricants. It also provided an economical and sustainable perspective on state-of-the-art technology, aiming to promote the widespread adoption of cryogenic and hybrid machining techniques in the global manufacturing industry by highlighting their advantages. The paper presented an overview of in-house-developed cryogenic and hybrid machining techniques while discussing these methods' challenges and future requirements. The cryogenic machining of Ti-6Al-4V was investigated by Venugopal et al. [9], and the outcomes were compared with those obtained using traditional machining methods. They reported more extended tool lives when using cryogenic turning at lower  $v_c$  than conventional turning. However, the authors did not examine the power consumed during the process. In a review paper, Khanna et al. [10] argued that developing machining techniques that are resource- and energy-efficient was essential for developing sustainable production in the manufacturing sector. The outcomes showed that reduced cutting speed and feed rates led to a higher environmental impact for all axial depths of cut and under the same cutting technique. By comparing several cutting fluid approaches using their normalized impact scores, they determined that  $\text{LN}_2$  machining in a cryogenic environment with increased cutting speed and feed rates was the most cost-effective and environmentally friendly method. Jerold et al. [11] examined the effectiveness and effects of cryogenic coolants, specifically liquid nitrogen and carbon dioxide ( $\text{CO}_2$ ), on various machining parameters in an experimental study compared to wet machining.

The impacts on cutting temperature, cutting force, tool wear, surface finish, and chip morphology were examined with an emphasis on machining AISI 1045 steel. The findings showed that using cryogenic coolants significantly lowered the cutting temperature, which enhanced the surface finish and minimized tool wear. Compared to CO<sub>2</sub> coolant, cryogenic LN<sub>2</sub> coolant caused a 3–17% drop in cutting temperature. Acharya et al. [12] optimized surface roughness and material removal rate in wet and minimum quantity lubrication (MQL) systems; that study examined the effects of turning process parameters on hard EN 31 materials. In the presence of wet and MQL systems, the study considered five adjustable input variables: cutting speed, feed rate, depth of cut, nozzle distance, and insert nose radius. Ahsan Ali Khan et al. [13] described how altering the tool to allow direct injection of liquid nitrogen as a coolant during milling significantly increased tool life. Cryogenic cooling was more effective at faster cutting speeds and greater feed rates than deeper cuts. These results highlighted the capability of cryogenic cooling to improve machining performance, produce high material removal rates, achieve higher work surface qualities, and decrease tool wear. Dhar et al. [14] emphasized the significant advantages of cryogenic cooling in machining operations. Liquid nitrogen effectively lowered cutting temperatures, improving tool life, surface finish, and dimensional error. Contrarily, using soluble oil coolant during machining had few benefits and even worsened surface smoothness. Since the turning process is frequently the first stage in mass production, it is vital to concentrate on enhancing surface smoothness while reducing time and cost.

The work carried out by Trabelsi et al. [15] found that employing liquid nitrogen as a coolant during cryogenic cooling showed promise in extending tool life, reducing tool wear and cutting forces when turning Ti17 titanium alloy. The decrease in machine temperature attained through cryogenic cooling was a factor in the desired enhancements in tool wear characteristics. In a study, during the machining of the Ti-6Al-4V alloy, cryogenic cooling was beneficial in extending tool life and decreasing tool wear. Venugopal et al. [16] highlighted the potential of cryogenic cooling as a successful way to regulate the cutting zone's temperature and enhance machining performance in titanium alloy applications. They also offered insightful information about the mechanisms underlying tool wear. Wang et al. [17] utilized tools that were cooled by liquid nitrogen (LN<sub>2</sub>), such as polycrystalline cubic boron nitride (PCBN) for ceramics and cemented carbide for other materials. That study introduced a technique for milling advanced ceramics, titanium alloys, Inconel alloys, and tantalum. LN<sub>2</sub> cooling reduced the cutting zone's temperature while retaining the tool's strength and hardness. As a result, temperature-dependent tool wear was significantly decreased under all machining circumstances. Additionally, even after the same cutting length, it was found that the surface roughness of the machined materials with LN<sub>2</sub> cooling was superior to that without LN<sub>2</sub> cooling. Waqas Khaliq et al. [18] analyzed the combined lubrication and cooling effects of minimum quantity lubrication (MQL) in the micromilling of additively produced Ti-6Al-4V. The study investigated how different cutting speeds and feed rates affected how well the machining process worked. Investigating the effects of lubrication cooling can provide helpful information for improving micromachining and resolving issues with titanium alloy machining. Dhananchezian et al. [19] showed that using liquid nitrogen through a customized cutting tool insert provided significant advantages over traditional machining. Cutting temperatures were lowered, surface roughness was improved, cutting forces were reduced, and flank wear was minimized because of cryogenic cooling. These data demonstrate the effectiveness of cryogenic cooling in increasing machining operations and maximizing productivity while working with titanium alloys. Varadarajan et al. [20] delivered cutting fluid at an extremely low rate of 2 mL/min as a high-velocity, narrow, pulsed jet directly to the cutting zone. A specialized fluid application system was designed for this purpose during the turning of hardened steel. In dry and rainy situations, the performance of HTMF was evaluated and contrasted to that of traditional hard turning. Balaji et al. [21] thoroughly examined the processes and outcomes of cryogenic machining. Several academics have conducted experimental studies using cryogenic coolants in turning and milling operations using diverse materials.

That work has provided insightful information about the developments and difficulties in producing Ti-6Al-4V utilizing various AM methods. The information gleaned from this study provides a basis for understanding the connection between processing variables, microstructures, and mechanical properties, which aids in creating better AM techniques for Ti6Al4V components [22,23]. Agrawal et al. [24,25] focused on variables that had received little attention in previous work, including tool wear (flank and crater wear), power consumption, surface roughness, total machining cost, and carbon emissions. According to the findings, wet turning caused more crater wear than cryogenic turning at most cutting speeds. However, at higher cutting rates (100 and 110 m/min), cryogenic turning greatly extended tool life (up to 125%). Across all cutting speeds, cryogenic turning exhibited a lower power consumption (up to 23.4%) and surface roughness (up to 22.1%) than wet turning. Additionally, cryogenic turning outperformed wet turning in cost-effectiveness (up to 27% reduced machining cost), especially at faster cutting speeds.

Bordin et al. [26] used a coated tungsten carbide insert during the semifinishing turn-ing of EBM Ti6Al4V under dry and cryogenic circumstances. The cutting speed and feed rate of the insert were varied. According to the results, by removing the workpiece material from the insert using chemical etching, the width of the adherent layer could be quantified, allowing for the assessment of adhesive wear compared to abrasive wear. Cryogenic cooling, however, was found to lessen the workpiece material's adhesive wear on the cutting surfaces. Salvi et al. [27] compared wire arc Additively manufactured Inconel 625 to its wrought equivalent and thoroughly investigated both materials. The examination considered machinability, environmental, and economic factors. The results showed that the two procedures differed regarding power usage, carbon emissions, tool life, and fabrication and machining costs. Similar works were reported in previous studies focusing on analyzing tool wear and other machining responses under cryogenic machining of various steels and alloys [28–32]. In recent reported work, experimental investigations were performed while drilling a Ti-6Al-4V titanium alloy under a cryogenic liquid nitrogen (LN<sub>2</sub>) environment, and the results were compared with dry drilling. The application of cryogenic-LN<sub>2</sub> was reported to have prolonged tool life three times and a noticeable improvement in surface finish. Due to less adhesion and thermal damage, the cryogenic condition resulted in favourable chip forms [33].

Recent work investigated the impact of combining cryogenic and ultrasonic-assisted machining of Ti-6Al-4v by considering cutting temperature, forces, and tool wear. Conventional turning, cryogenic turning, and ultrasonic-assisted turning were all compared to the combined technique. Compared to conventional turning, the cutting forces in combined turning were reduced by almost 22%. The new combined cutting process was proven to reduce tool wear caused by adhesion [34]. Inconel 718 and Ti-47.5Al-2.5V-1.0Cr alloys were machined under cryogenic conditions to analyze their chip morphology and geometric characteristics. It was reported that the cryogenic cooling noticeably changed the chip formation, and due to the combined action of periodic brittle fracture on the chip-free surface and ductile-brittle fracture near the cutting edge, serrated chips were produced with Ti-47.5Al-2.5V-1.0Cr [35]. The comparative analysis of dry and cryogenic machining was presented during the milling of AISI H13 steel. The influence of the cutting-nose radius was studied by keeping constant cutting parameters. Under cryogenic machining conditions, the tool with a cutting-edge radius of  $R_n = 0.03$  mm improved cutting tool performance and life by almost 55% [36]. In another study, the tantalum–tungsten alloy was machined under LCO<sub>2</sub> and MQL conditions, and the effect on tool wear and chip morphology was studied. The cryogenic cooling resulted in an almost 50% improvement in tool life by controlling abrasive and adhesive wear [37].

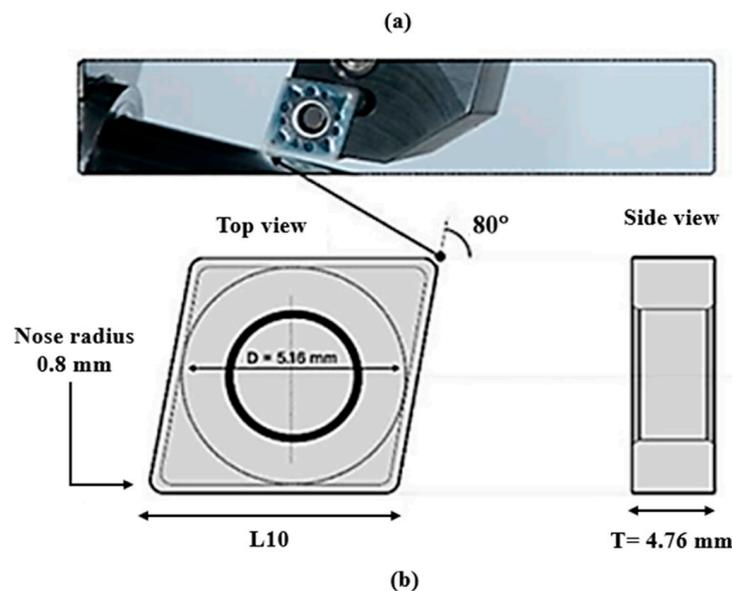
The literature study reveals that studies have been conducted to investigate the impact of various cooling/lubrication techniques on machinability indicators of Ti alloys. It is observed that fewer studies have been found to contribute to an in-depth analysis of the effect of varying machining parameters (cutting speed) during turning Ti-6Al-4V alloys under a cryogenic environment. Also, limited work is available investigating tool wear and

specific energy consumption under dry and cryogenic environments. Therefore, this work aimed to perform a machinability analysis (surface roughness, power consumption and tool wear) of hard-to-cut alloys. It also aimed to present a comparative study of cutting strategies, namely, dry and cryogenic cooling techniques with LCO<sub>2</sub> as a coolant for the machinability improvement of Ti-6Al-4V.

## 2. Material and Processes

### 2.1. Materials

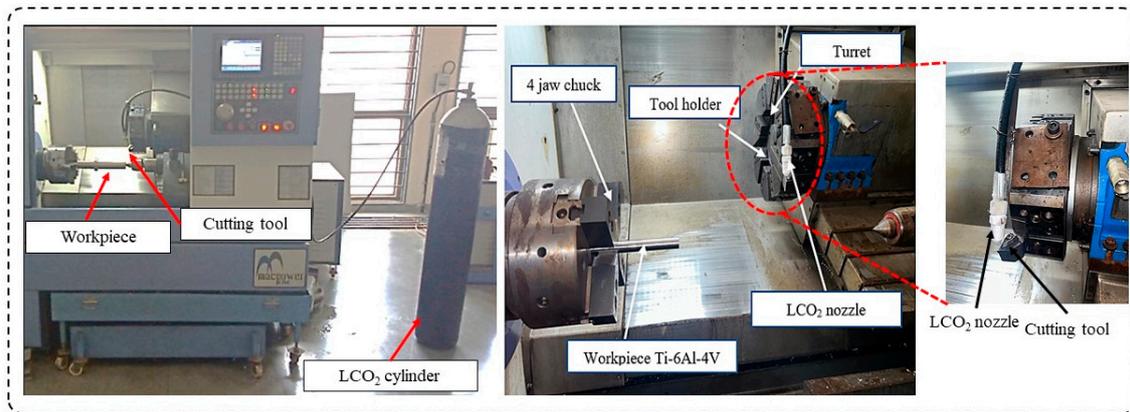
The turning experiments were performed on Ti-6Al-4V cylindrical bars with a diameter of 50 mm and a length of 200 mm. The material had an average hardness of 40 HRC and an ultimate tensile strength of 970 MPa. The cutting tool for the turning operation was a Kyocera-coated carbide insert with PVD Mega-Nanocoat CNMG120408MS PR1535 with an 80° rhombic form, 0.8 mm nose radius, 4.76 mm tool thickness, and four possible cutting sides. This insert has a nanothickness multilayer coating of TiAlN. It has a PVD coating for difficult-to-cut materials like titanium alloy. Compared to CVD, the low processing temperature increases bending strength, reduces coating breakdown, and improves tool life with consistent machining. Additionally, the high hardness, enhanced oxidation resistance, and increased stability provided by thin film coating technology prevent wear and fracture. In this study, the MVJNL2525M16 tool holder was used. Figure 1 presents the geometry of the cutting tool insert in detail.



**Figure 1.** (a) Photo of tool insert; (b) schematic view of tool geometry.

### 2.2. Experimental Method

The turning experiments were conducted on a Macpower (VX200) CNC turning centre under selected cutting conditions. Three different cutting speeds were selected to quantify the effect on machining performance by keeping a constant feed and depth of cut. In comparison to the feed and depth of cut, the cutting speed has a more significant impact on tool wear, according to the literature [38]. Hence, the experiments were performed with cutting speeds of 80, 90, and 100 m/min and by keeping a constant feed of 0.1 mm/rev and depth of cut of 0.5 mm during dry and cryogenic experiments. The cutting parameter values were selected according to the recommendations of the cutting tool manufacturer and preliminary experiments. Each experiment was repeated thrice, and an average value was considered for the analysis to avoid any experimental error. The utilized experimental setup is presented in Figure 2.



**Figure 2.** Experimental setup with LCO<sub>2</sub> supply.

Dry machining can be considered the least expensive and cleanest approach without any cutting fluid. However, because of its poor surface finish and high tool wear, it is not very productive. A higher temperature is produced due to the lack of any media that cool and/or lubricate the cutting zone, which limits the process parameters and productivity. Based on progressive tool wear and other machinability indicators, the performance of dry machining was thoroughly compared with cryogenic cooling in this study. Cryogenic fluid (LCO<sub>2</sub>) rapidly absorbs the heat produced at the cutting area during cryogenic machining by evaporating and/or expanding. Regarding tool wear and the surface finish of machined parts, it has been discovered to be more effective for machining superalloys, Ti-based alloys, steel alloys, Mg-based alloys, and composites [39]. Concerning this, the work evaluated and compared dry machining versus cryogenic machining using LCO<sub>2</sub> based on machining responses. A nozzle with a 2 mm diameter was used to apply LCO<sub>2</sub> to the machining zone. Through a nozzle, the LCO<sub>2</sub> was enabled to go through the thermoplastic hose pipe and enter the cutting area. A pressure regulator was connected to a CO<sub>2</sub> cylinder. The regulator used for this purpose had two dial indicators, one of which showed the supply pressure and the other, the pressure in the cylinder. A carbon dioxide flow meter was attached to the regulator to monitor the carbon dioxide coolant's flow rate. The considered experimental parameters are shown in Table 1.

**Table 1.** Experimental parameters.

Parameters	Information
Workpiece material	Titanium alloy (Ti-6Al-4V), grade 5, Ø50 × 100 mm
Cutting tool insert	PVD coated carbide insert with megacoat nano—PR1535 CNMG 120408
Cutting velocity, (m/min)	80, 90, 100 m/min
Feed rate (mm/rev)	0.1 mm/rev
Depth of cut (mm)	0.5 mm
Machining condition	Dry, cryogenic cooling with LCO <sub>2</sub>
Machining length	150 mm

### 2.3. Measurement of Machining Responses

A Fluke 435 (Series II) 3-phase power analyser was used to measure power consumption during machining. This device was connected to a three-phase distribution system. It has a maximum measurement range of 6000 MW with a resolution of 0.1 W to 1 MW and an accuracy of  $\pm 1\% \pm 10$  counts. During the experiment, four readings per second of power consumption were recorded. Surface roughness is one of the most important factors influencing the tribological behaviour of surfaces. Among the roughness metrics, the average surface roughness ( $R_a$  in  $\mu\text{m}$ ) is often selected to denote the degree of surface roughness [40]. With these considerations,  $R_a$  was calculated using a surface roughness

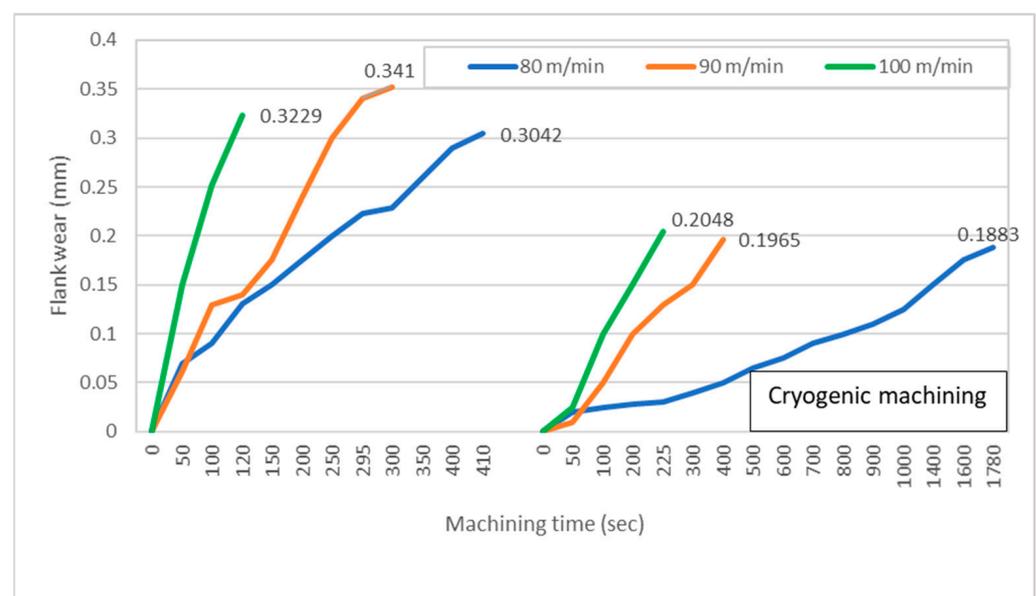
device. A Taylor Hobson Surtronic (S128) surface roughness tester with a measurement range of up to 400  $\mu\text{m}$  and resolution of 50 nm was utilized to analyse the surface roughness produced on the machined part. According to ISO 4287 [41], the cutoff, sampling, and evaluation lengths were chosen as 0.8 mm, 0.8 mm, and 4.0 mm. The measurements were obtained from three points of the machined surface by rotating the workpiece along its axis and the mean value was considered as a comparison. The flank surface of the tool gradually wore out because of the friction and heat generated when the tool's cutting edge seemed to come into contact with the workpiece during turning. The cutting parameters, tool material, workpiece material, and cutting fluid can all impact this wear. This study used the Mitutoyo-TM series toolmaker microscope to measure the tool wear resulting from the machining trials. The flank wear resulting on the tool insert was evaluated using ISO 3685:1993 criteria [42].

### 3. Results and Discussions

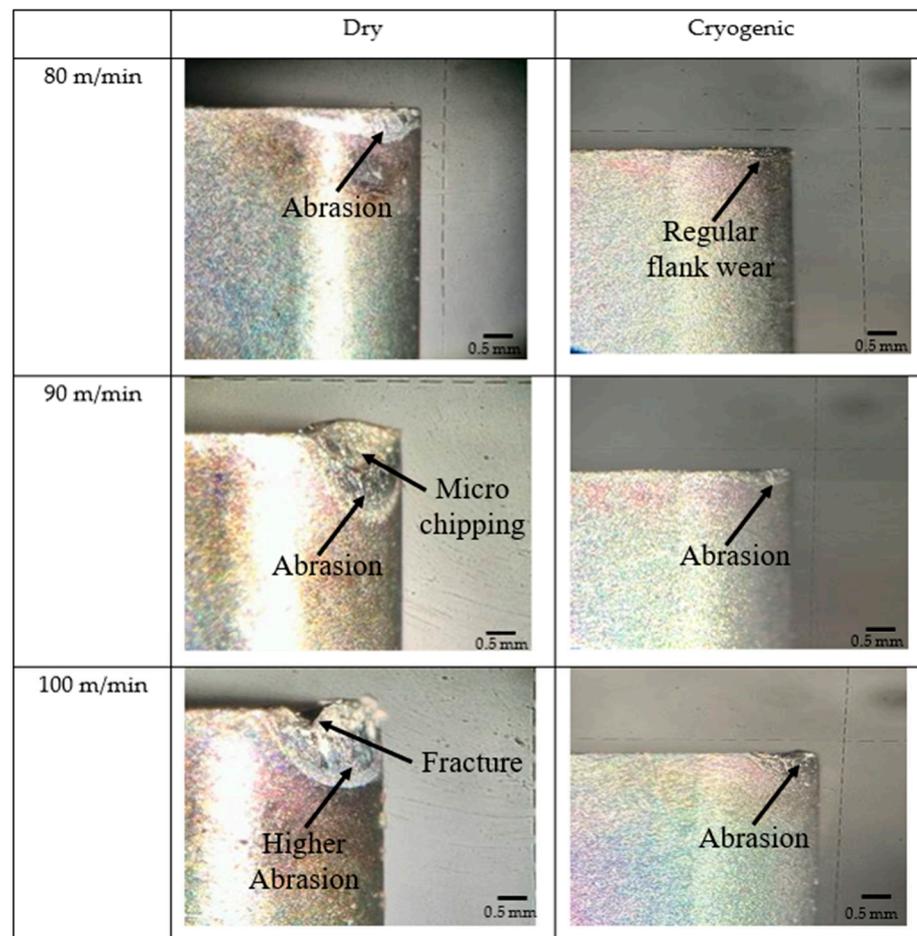
This study performed turning experiments on Ti-6Al-4V to analyse machinability in terms of (i) tool wear, (ii) surface roughness and (iii) power consumption under dry and cryogenic machining environments under three cutting speeds.

#### 3.1. Analysis of Tool Wear

Any material's ability to be machined is significantly impacted by flank wear. Each material has a unique method for causing flank wear. Catastrophic cracking, chipping, and notching are the leading causes of failure during the machining of titanium alloys [13]. Manufacturing techniques of that result in high-quality components are more valuable. The flank wear of the cutting inserts used in turning Ti-6Al-4V at various speeds in dry and cryogenic cutting settings was investigated to better understand the tool failure behaviour. The experiments were performed with a constant machining time and the same material removal rate for each cut, and all data and graphs were produced at 5 s for each cut. Cutting conditions and tooling, among other factors, impact how quickly flank wear develops over time. Different machining techniques, such as dry turning and cryogenic machining, can have varying effects on the progression of flank wear. The evolution of tool wear at 80, 90, and 100 m/min cutting speeds under a dry machining environment is shown in Figure 3. As shown in Figure 4, the machining time reduced as the cutting speed increased.



**Figure 3.** Progression of flank wear under dry and cryogenic machining.



**Figure 4.** Tool wear mechanism under dry and cryogenic machining.

Experimental findings show that the flank wear rate increases rapidly as  $v_c$  increases in cryogenic and dry environments. It is due to the abrasive action of the workpiece with the tool surface, which removes the coating on the insert [25]. When cutting without using a coolant or lubricant, it is referred to as “dry turning”. The cutting temperature can rise rapidly without any cooling effect, increasing thermal stress and tool wear. Initial stage: There will be some initial wear as the cutting procedure starts. However, because dry turning does not utilize cooling, the cutting temperature is typically higher, which can cause almost immediate tool wear. Midstage: As cutting progresses, the increasing temperatures may speed up the process of flank wear. Increased tool wear rates may result from a lack of coolant to remove heat, especially when performing high-speed machining or working with difficult-to-machine materials. Last stage: When dry turning is performed for an extended period, the flank wear may quickly increase, requiring tool replacement or resharpening. This is the main reason because a low cutting velocity results in a lower temperature formation between the tool and workpiece than a high velocity. A high cutting velocity results in quick tool wear compared to a low cutting velocity since higher cutting temperatures are generated that increase the tool wear. At a cutting speed of 80 m/min, the machining time increased by 28% and 70% compared to the 90 and 100 m/min cutting speeds. Compared to a cutting speed of 100 m/min, the machining time was 59% higher when compared to machining at a 90 m/min cutting speed.

The progression of tool wear under cryogenic machining is shown in Figure 4. In cryogenic turning, a cryogenic coolant, such as liquid carbon dioxide ( $\text{CO}_2$ ), is used to help the cutting process by decreasing the cutting temperature. The tool–workpiece interface temperature decreases with the cryogenic coolant, which may lead to a longer tool life. Here is how lateral wear could develop over time: Initial stage: The tool obtains some

initial wear at the start of the cutting operation because of contact with the workpiece material. Compared to dry turning, cryogenic turning's lower cutting temperature can result in lower thermal stresses and less tool wear. Midstage: Due to the mechanical and thermal effects of the machining, flank wear may gradually grow as the cutting process continues. However, the cryogenic coolant controls the heat produced and reduces flank wear. As a result, the tool wear process is typically slower than the dry turning operation. Later stage: With continued cutting, the flank wear may eventually get to a point where it becomes crucial and begins to speed up. The type of tool, cutting speed, feed rate, and workpiece material properties can all impact this. Compared to dry turning, cryogenic turning tends to increase tool life and delay the beginning of rapid flank wear.

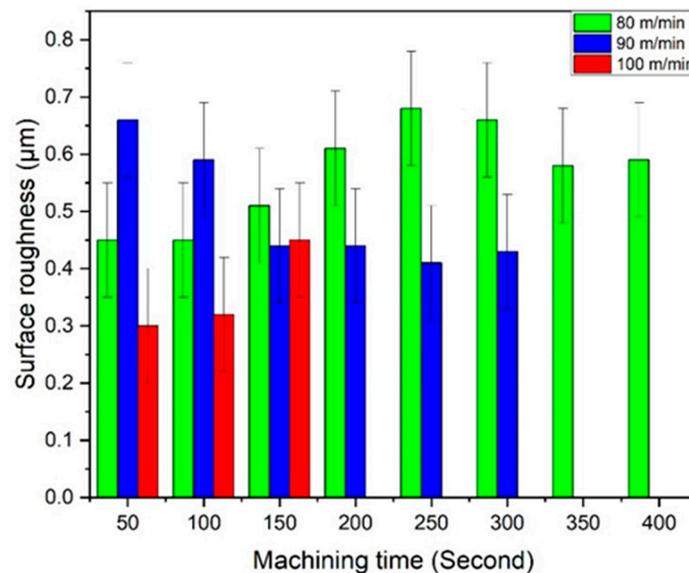
Figure 3 shows the tool wear concerning machining time at various cutting strategies in cryogenic environments. At an 80 m/min cutting speed, the machining time was higher than at the other speeds shown in the figure, and the total machining time at 80 m/min in cryogenic conditions was 29 min. Liquid CO<sub>2</sub> was applied as a cryogenic coolant as the tool and workpiece interface temperatures decreased. At a 90 m/min cutting speed, the total machining time was 7.67 min. At 80 m/min, the increase in tool life was three times that at 90 m/min. When the cutting speed was high, the flank wear increased, as can be seen in Figure 4, and at a cutting speed of 80 m/min, the machining time was increased by 73.55% compared to 90 m/min.

At 100 m/min, the flank wear rate rapidly increased compared to 80 and 90 m/min. The increasing cutting speed decreased the machining time for dry and cryogenic conditions. At that 90 m/min cutting speed, the machining time was 4.67 min. The machining time increased by 39.11% at 90 m/min and by 83.89% at 80 m/min compared to the cutting speed at 100 m/min. The result of the low cutting speed on the flank wear was more beneficial to extending tool life and the significant difference to the overall performance was larger compared to that of the high cutting speed. As shown in the figure, decreasing the cutting velocity increased the machining time in dry and cryogenic environments. The tool wear mechanism observed during dry and cryogenic machining is presented in Figure 4. The abrasive wear was seen as a common wear mechanism along with chipping and fracture at a higher cutting speed during dry machining. The increase in cutting speed caused rapid tool wear due to high frictional forces at the tool–workpiece interface and resulted in edge chipping and fracture of the cutting tool. The increased abrasive wear, chipping, and fracture observed in dry machining was attributed to the decreased material yield and ultimate tensile strength with increased ductility at higher temperatures. This promoted material flow into the notch region of the cutting tool, resulting in chipping and fracture [43]. In comparison to dry machining, the flank wear under cryogenic conditions was smooth and low. The beneficial effect of cryogenic cooling was seen in terms of regular flank wear produced due to abrasion while machining under selected cutting speeds. Previous research reported that superior cooling with cryogenic application resulted in decreased tool wear compared to alternative lubricating systems. Furthermore, creating a gaseous cushion at the cutting edge during machining could result in smooth and minimum tool wear [44,45].

### 3.2. Analysis of Surface Roughness

The cost associated with rework and rejections can be reduced by improving the quality of the machined surface. Surface roughness produced during machining is frequently considered as an important parameter to judge the quality of the surface produced. In this work, surface roughness (Ra) was analysed at different cutting speeds under dry and cryogenic machining. Higher cutting velocities in dry machining, which does not require coolant or lubricant, make the surface rougher. This is due to the possibility of increased heat and friction buildup due to the lack of lubrication, which can result in more obvious tool wear and surface failures. Surface roughness is significantly affected by increasing the cutting speed and cutting interface temperature. Thus, a relatively smooth surface finish was expected with a cutting speed of 80 m/min compared to higher cutting

rates. This slower speed reduced the possibility of vibration and work hardening while enabling a better control over cutting forces. It may consequently lead to a reduced surface roughness. As shown in the Figure 5, when the high cutting speed produced a better surface roughness than the low cutting speed and the machining time increased, the surface roughness changed, resulting in a smoother surface.

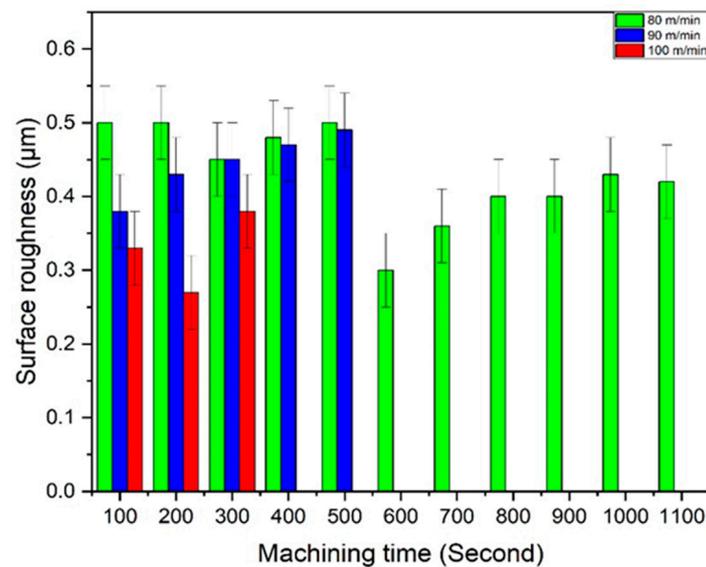


**Figure 5.** Variation in surface roughness under dry machining.

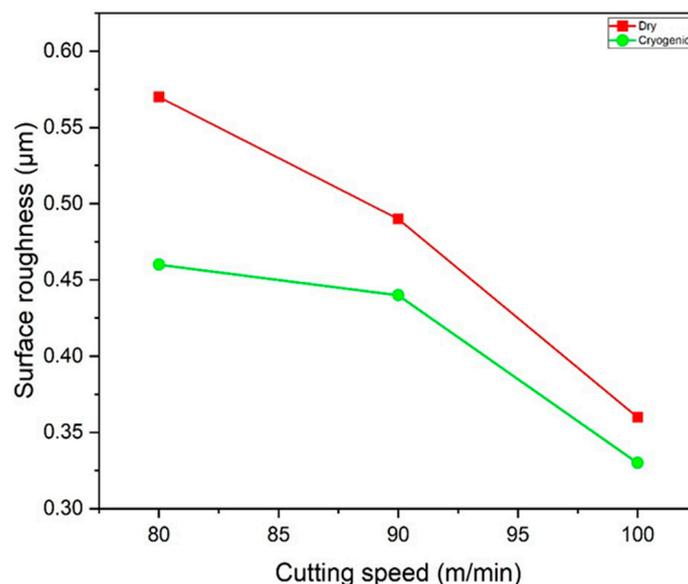
As shown in Figure 5, with an increased cutting speed, the surface roughness increased and then decreased after some machining time. The surface roughness on Ti-6Al-4V may still be acceptable when the cutting speed is increased to 90 m/min, but there may be a little increase in roughness compared to the lower cutting speed. This is due to the alloy's harder machinability potentially beginning to impact surface roughness at this rate. Surface roughness may be more significantly impacted by raising the cutting speed on Ti-6Al-4V. The higher cutting speed may impact work-hardening effects, increase cutting forces, and increase temperatures. As a result, the surface finish may be rougher than it was with the lower cutting rates. However, the high velocity has a better surface roughness than the lower velocity. In the study of this experiment, the high cutting velocity resulted in a better and smoother surface roughness.

The lowest surface roughness exhibited at the higher cutting speed during cryogenic machining (Figure 6) may have resulted from the relatively low tool wear brought on by the LCO<sub>2</sub> delivery at the surface contact of the tool–chip and tool–workpiece interfaces. The lower surface roughness during cryogenic machining was due to the low tool wear [46]. The rapid tool wear, which altered the tool geometry, was the reason for the increased surface roughness during dry machining. Compared to dry machining, the cooling effect of liquid CO<sub>2</sub> helped dissipate heat and reduce thermal damage, improving surface finish.

Additionally, it is essential to note that although cryogenic machining typically provides benefits over dry machining in surface finish, the precise optimal cutting velocity to achieve the desired surface roughness may vary and depend on the material, tools, and other process variables. Figure 7 shows the surface roughness at a low cutting speed in cryogenic environments was higher than that at a high cutting speed. In this case, as the cutting speed increases, a better surface roughness is obtained. At the high cutting speed of 100 m/min, to obtain a better roughness, lubrication or LCO<sub>2</sub> can be applied to get the benefits of the high cutting speed. The figure presents the calculated average surface roughness. As shown, the result of the surface roughness is that cutting speed at 100 m/min produces a better surface roughness and a smoother surface than other cutting speeds.



**Figure 6.** Variation in surface roughness under cryogenic machining.

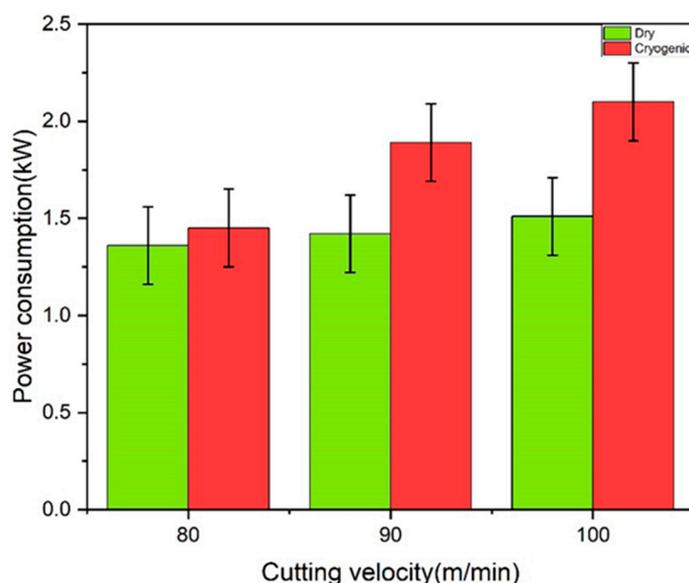


**Figure 7.** Variation in surface roughness with cutting speed.

### 3.3. Analysis of Power Consumption

The amount of power consumed during the process significantly impacts how economical the machining technique is. The industry prefers machining processes that perform better while using less power for process economy. Power consumption provides stability to the machining process and assists in determining the most efficient process variables to maximize process efficiency. In general, several variables, including the cutting condition, can affect how much power is used during a turning operation on a CNC machine. Power consumption can be impacted by the choice between dry and cryogenic machining, but it is vital to remember that several other factors can also impact it. The resultant power consumption differed at the various cutting speeds for different cutting parameters and strategies. Figure 8 depicts the power consumption at 80, 90, and 100 m/min under dry and cryogenic machining. Dry machining is the cutting technique without applying any lubricants or coolants. With this technique, the tool, the workpiece, and the surroundings all contribute to heat dissipation during cutting. For sufficient heat dissipation during dry machining, faster cutting rates and feeding are often needed. Due to the higher energy

required to operate the machine and effectively complete the cutting operation, higher cutting speeds and feeds may result in increased power consumption.



**Figure 8.** Variation in power consumption under cryogenic machining.

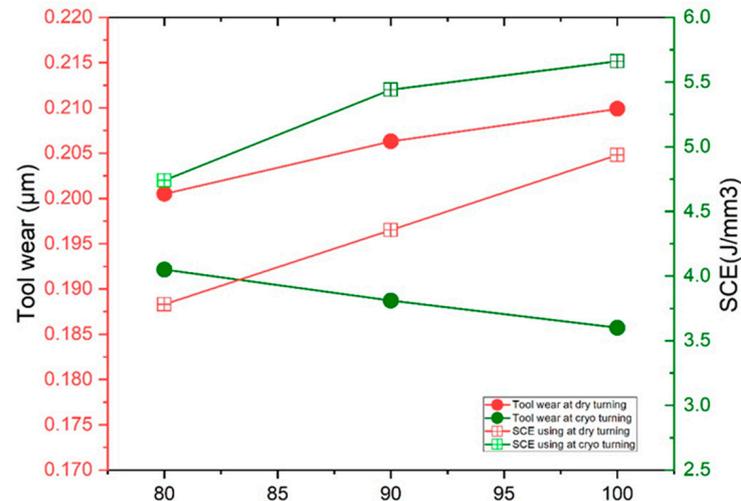
Coolants in extremely cold gases or liquid CO<sub>2</sub> are required for cryogenic machining. Applying these coolants to the cutting zone lowers the temperature and dissipates heat produced during machining. Cutting forces can be decreased, the surface finish can be improved, and tool wear can be minimized with cryogenic machining. By regulating the temperature, it would be feasible to improve the cutting conditions while achieving faster cutting rates, which might result in less power being used than with dry machining. However, the energy needs of the cooling system might also affect the power usage.

In this experiment, power consumption in cryogenic conditions was higher than in the dry environment. At the same cutting speed, the machining process continuously ran and decreased the workpiece diameter. When the workpiece diameter decreased, the RPM continuously increased, which resulted in a higher power consumption. When the cutting speed was 80 m/min, the average power consumption in dry conditions was 1.36 kW and in cryogenic conditions, it was 1.44 kW. In dry conditions, 5.55% less power was required than in cryogenic conditions. When the cutting speed was 90 m/min, the average power consumption in the dry condition was 1.39 kW and in the cryogenic condition, 1.89 kW. In the dry condition, 26.45% less power was required than in the cryogenic condition. For the 100 m/min speed, the average power consumed in a dry environment was 1.52 kW, and in cryogenic conditions, 2.10 kW. In a dry environment, less power was required than for the cryogenic environment in experimental criteria and cutting parameter conditions. At 100 m/min, in dry conditions, 27.61% less power was required than in the cryogenic condition. The resultant power consumption differed at the various cutting speeds for different cutting parameters and strategies. These experiments showed the power consumption at the cutting velocities of 80, 90, and 100 m/min. It is essential to remember that various factors, including cutting parameters, tool geometry, workpiece material, machine efficiency, and more, affect how much power is used during machining procedures.

### 3.4. Tool Wear and Specific Cutting Energy Variation in Dry and Cryogenic Conditions

In machining operations, it is essential to consider variables like tool wear and specific cutting energy (SCE). The choice of cutting conditions can strongly impact these variables, such as cutting speed and coolant type. Figure 9 presents the variation in tool wear and specific cutting energy for various cutting speeds in dry and cryogenic situations. Overall, tool wear tended to rise with increasing cutting speeds in both dry and cryogenic

environments. However, compared to cryogenic coolant conditions, dry machining resulted in higher tool wear and specific cutting energy, especially at higher cutting speeds. Because power consumption in cryogenic conditions is high compared to dry conditions, specific cutting energy also tends to be high in cryogenic conditions.



**Figure 9.** Tool wear and SCE variation in dry and cryogenic conditions at different cutting conditions.

The efficacy of cryogenic machining while machining Ti-6Al-4V was reflected in an improved surface finish and a reduced tool wear compared to dry machining. The application of LCO<sub>2</sub> removed the frictional heat from the cutting zone, reduced the tool wear, and generated fewer defects on the machined surface.

#### 4. Conclusions

An effort was made to analyse the machinability of Ti-6Al-4V during dry and cryogenic turning, and a few parameters were examined, including tool wear, surface roughness, and power consumption. The following important points can be summarized:

1. Compared to dry turning, using coolant or lubricant in turning activities, such as cryogenic turning, offers advantages such as increased tool life and less tool wear. The machining time was constant for 5 s, and each cut took 5 s. Thus, when the machining time was minimal, the tool life increased, and the accuracy was more significant with more machining time.
2. In a dry environment, the effects of tool wear on variations in cutting speed (80, 90, and 100 m/min) and machining time were evaluated. It was discovered that machine time decreased as cutting speed increased. The reduced machining time resulted from a lower temperature generation between the tool and workpiece caused by the lower cutting velocity compared with higher velocities. Due to the faster rate of tool wear caused by elevated temperatures, a high cutting velocity outperforms low cutting velocities.
3. Higher cutting speeds increase flank wear, shortening the tool's life. In cryogenic circumstances, the machine took 29 min at an 80 m/min cutting speed but only 7.67 min at a 90 m/min cutting speed, a threefold increase. The machine time fell even further at 100 m/min, indicating a shorter tool life than at lower cutting rates.
4. In dry machining, faster cutting speeds typically lead to rougher surface finishes. Due to the poor machinability of the alloy in the case of Ti-6Al-4V, increasing the cutting speed to 90 m/min in cryogenic conditions may result in a slightly enhanced roughness compared to lower cutting rates. Surface roughness may be more significantly affected and even increase at 100 m/min compared to lesser cutting rates. The maximum cutting speed in cryogenic environments (100 m/min) produced the best

surface roughness in the experiment. The results show that cryogenic machining with the proper cutting speeds can give a greater surface roughness than dry machining.

5. At the same cutting speed, it was discovered in the experiment that power consumption was higher in the cryogenic condition than in the dry environment. This is due to the workpiece's diameter continuously decreasing during the machining process, which raised the RPM and in turn, power consumption.

Overall, tool wear, surface finish, and power consumption during turning operations can be considerably influenced by cutting conditions, cutting speed, and using coolant or lubrication. To maximize the effectiveness and performance of the turning process, it is crucial to consider these elements and choose the optimal cutting parameters.

## 5. Future Possibilities

Sustainability is of major importance in manufacturing. Machining experiments under flood cooling, MQL, high-pressure cooling, gas cooling, hybrid cooling, etc., can be performed for sustainability assessment. The setup can be retrofitted to control the cryogen flow from the nozzle. There is a possibility of installing an electronic flow control valve that can be commanded through an external controller to control the flow. PID and other algorithms can be utilized to achieve the set point flow to a point where it shoots out the gas just enough to compensate for the heat generated. The extra cryogen that is shot out on the workpiece goes unused into the atmosphere which can be avoided with this setup. Further, more experiments can be run with thermal cameras that would behave as a feedback device in the system and have the controller command the cryogen valve to the required workpiece temperature value. To improve this even better, artificial training models can be generated with a few trials with workpiece and cutting parameters being inputs and having the system autogenerate AI models to shoot out just enough cryogen for the entire duration of the cut.

**Author Contributions:** Conceptualization, D.C. and N.K.; methodology, D.C. and N.K.; validation D.C. and N.K.; formal analysis, D.C., M.A.M. and N.K.; investigation, D.C. and N.K.; resources, N.K.; data curation, D.C. and N.K.; writing—original draft preparation, D.C., M.A.M., N.K., R.A.R.R. and V.J.; writing—review and editing, D.C., M.A.M., N.K., R.A.R.R. and V.J.; visualization, D.C. and N.K.; supervision, N.K.; project administration, N.K. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Data Availability Statement:** Data are contained within the article.

**Acknowledgments:** The authors acknowledge the Science and Engineering Research Board (SERB), India, for their financial support granted under the Make-in-India project (ECR/2016/000735).

**Conflicts of Interest:** Author Vivek Joshi was employed by the company Tesla Giga. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## References

1. Zhang, L.C.; Chen, L.Y.; Wang, L. Surface modification of titanium and titanium alloys: Technologies, developments, and future interests. *Adv. Eng. Mater.* **2020**, *22*, 1901258. [[CrossRef](#)]
2. Cai, C.; Liang, X.; An, Q.; Tao, Z.; Ming, W.; Chen, M. Cooling/Lubrication Performance of Dry and Supercritical CO<sub>2</sub>-Based Minimum Quantity Lubrication in Peripheral Milling Ti-6Al-4V. *Int. J. Precis. Eng. Manuf. Technol.* **2020**, *8*, 405–421. [[CrossRef](#)]
3. Gupta, M.K.; Niesłony, P.; Sarikaya, M.; Korkmaz, M.E.; Kuntoğlu, M.; Królczyk, G.; Jamil, M. Tool wear patterns and their promoting mechanisms in hybrid cooling assisted machining of titanium Ti-3Al-2.5V/grade 9 alloy. *Tribol. Int.* **2022**, *174*, 107773. [[CrossRef](#)]
4. Rakesh, P.; Chakradhar, D. Machining performance comparison of Inconel 625 superalloy under sustainable machining environments. *J. Manuf. Process.* **2023**, *85*, 742–755. [[CrossRef](#)]
5. Gupta, K.; Laubscher, R.F. Sustainable machining of titanium alloys: A critical review. *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.* **2016**, *231*, 2543–2560. [[CrossRef](#)]

6. Khan, A.M.; He, N.; Li, L.; Zhao, W.; Jamil, M. Analysis of Productivity and Machining Efficiency in Sustainable Machining of Titanium Alloy. *Procedia Manuf.* **2020**, *43*, 111–118. [[CrossRef](#)]
7. Shokrani, A.; Dhokia, V.; Newman, S.T. Energy conscious cryogenic machining of Ti-6Al-4V titanium alloy. *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.* **2016**, *232*, 1690–1706. [[CrossRef](#)]
8. Khanna, N.; Zadafiya, K.; Patel, T.; Kaynak, Y.; Rashid, R.A.R.; Vafadar, A. Review on machining of additively manufactured nickel and titanium alloys. *J. Mater. Res. Technol.* **2021**, *15*, 3192–3221. [[CrossRef](#)]
9. Venugopal, K.; Paul, S.; Chattopadhyay, A. Tool wear in cryogenic turning of Ti-6Al-4V alloy. *Cryogenics* **2007**, *47*, 12–18. [[CrossRef](#)]
10. Khanna, N.; Agrawal, C.; Pimenov, D.Y.; Singla, A.K.; Machado, A.R.; da Silva, L.R.R.; Gupta, M.K.; Sarikaya, M.; Krolczyk, G.M. Review on design and development of cryogenic machining setups for heat resistant alloys and composites. *J. Manuf. Process.* **2021**, *68*, 398–422. [[CrossRef](#)]
11. Jerold, B.D.; Kumar, M.P. Experimental investigation of turning AISI 1045 steel using cryogenic carbon dioxide as the cutting fluid. *J. Manuf. Process.* **2011**, *13*, 113–119. [[CrossRef](#)]
12. Acharya, S.S.; Karwande, R.L. Experimental investigation of Turning process in Wet and MQL system on EN 31 Alloy Steel. *Int. J. Sci. Eng. Res.* **2015**, *6*, 1074–1080.
13. Khan, A.A.; Ahmed, M.I. Improving tool life using cryogenic cooling. *J. Mater. Process. Technol.* **2008**, *196*, 149–154. [[CrossRef](#)]
14. Dhar, N.; Kamruzzaman, M. Cutting temperature, tool wear, surface roughness and dimensional deviation in turning AISI-4037 steel under cryogenic condition. *Int. J. Mach. Tools Manuf.* **2007**, *47*, 754–759. [[CrossRef](#)]
15. Trabelsi, S.; Morel, A.; Germain, G.; Bouaziz, Z. Tool wear and cutting forces under cryogenic machining of titanium alloy (Ti17). *Int. J. Adv. Manuf. Technol.* **2017**, *91*, 1493–1505. [[CrossRef](#)]
16. Venugopal, K.A.; Paul, S.; Chattopadhyay, A.B. Growth of tool wear in turning of Ti-6Al-4V alloy under cryogen-ic cooling. *Wear* **2007**, *262*, 1071–1078. [[CrossRef](#)]
17. Wang, Z.; Rajurkar, K. Cryogenic machining of hard-to-cut materials. *Wear* **2000**, *239*, 168–175. [[CrossRef](#)]
18. Khaliq, W.; Zhang, C.; Jamil, M.; Khan, A.M. Tool wear, surface quality, and residual stresses analysis of micro-machined additive manufactured Ti-6Al-4V under dry and MQL conditions. *Tribol. Int.* **2020**, *151*, 106408. [[CrossRef](#)]
19. Dhananchezian, M.; Kumar, M.P. Cryogenic turning of the Ti-6Al-4V alloy with modified cut-ting tool inserts. *Cryogenics* **2011**, *51*, 34–40. [[CrossRef](#)]
20. Varadarajan, A.; Philip, P.; Ramamoorthy, B. Investigations on hard turning with minimal cutting fluid application (HTMF) and its comparison with dry and wet turning. *Int. J. Mach. Tools Manuf.* **2002**, *42*, 193–200. [[CrossRef](#)]
21. Balaji, V.; Ravi, S.; Chandran, P.N.; Damodaran, K.M. Review of the cryogenic machining in turning and milling process. *Int. J. Res. Eng. Technol.* **2015**, *4*, 38–42.
22. Liu, S.; Shin, Y.C. Additive manufacturing of Ti6Al4V alloy: A review. *Mater. Des.* **2018**, *164*, 107552. [[CrossRef](#)]
23. Hong, S.Y.; Ding, Y. Cooling approaches and cutting temperature in cryogen-ic machining of Ti-6Al-4V. *Int. J. Mach. Tools Manuf.* **2001**, *41*, 1417–1437. [[CrossRef](#)]
24. Agrawal, C.; Wadhwa, J.; Pitroda, A.; Pruncu, C.I.; Sarikaya, M.; Khanna, N. Comprehensive analysis of tool wear, tool life, surface roughness, costing and carbon emissions in turning Ti-6Al-4V titanium alloy: Cryogenic versus wet machining. *Tribol. Int.* **2021**, *153*, 106597. [[CrossRef](#)]
25. Agrawal, C.; Khanna, N.; Pruncu, C.I.; Singla, A.K.; Gupta, M.K. Tool wear progression and its effects on energy consumption and surface roughness in cryogenic assisted turning of Ti-6Al-4V. *Int. J. Adv. Manuf. Technol.* **2020**, *111*, 1319–1331. [[CrossRef](#)]
26. Bordin, A.; Bruschi, S.; Ghiotti, A.; Bariani, P.F. Analysis of tool wear in cryogenic machining of additive manufactured Ti6Al4V alloys. *Wear* **2015**, *328*, 89–99. [[CrossRef](#)]
27. Salvi, H.; Vesuwala, H.; Raval, P.; Badheka, V.; Khanna, N. Sustainability analysis of additive + subtractive manufacturing processes for Inconel 625. *Sustain. Mater. Technol.* **2023**, *35*, e00580. [[CrossRef](#)]
28. García-Martínez, E.; Miguel, V.; Martínez-Martínez, A.; Manjabacas, M.C.; Coello, J. Sustainable lubrication methods for the machining of titanium alloys: An overview. *Materials* **2019**, *12*, 3852. [[CrossRef](#)]
29. Dhar, N.R.; Paul, S.; Chattopadhyay, A.B. The influence of cryogenic cooling on tool wear, dimensional accuracy, and surface finish in turning AISI 1040 and E4340C steels. *Wear* **2002**, *249*, 932–942. [[CrossRef](#)]
30. Kumar, K.K.; Choudhury, S.K. Investigation of tool wear and cutting force in cryogenic machining using design of experiments. *J. Mater. Process. Technol.* **2008**, *203*, 95–101. [[CrossRef](#)]
31. Wang, Z.Y.; Rajurkar, K.P.; Fan, J.; Petrescu, G. Cryogenic machining of Tantalum. *J. Manuf. Process.* **2002**, *4*, 122–127. [[CrossRef](#)]
32. Dutta, S.; Kanwat, A.; Pal, S.; Sen, R. Correlation study of tool flank wear with machined surface texture in end milling. *Measurement* **2013**, *46*, 4249–4260. [[CrossRef](#)]
33. Shah, D.; Rashid, R.R.; Jamil, M.; Pervaiz, S.; Gajrani, K.K.; Rahman, M.A.; Khanna, N. Cryogenic assisted drilling of Ti-6Al-4V: An industry-supported study. In *Sustainable Materials and Manufacturing Technologies*; CRC Press: Boca Raton, FL, USA, 2023; pp. 3–15.
34. Bejjani, R.; Bachir, E.; Salame, C. Advanced Manufacturing of Titanium Alloy Ti-6Al-4V by Combining Cryogenic Machining and Ultrasonic-Assisted Turning. *J. Mater. Eng. Perform.* **2023**, 1–21. [[CrossRef](#)]
35. Qiu, W.; Pan, D.; Li, J.; Guo, P.; Qiao, Y.; Wang, X. Chip formation mechanism in cryogenic machining of high temperature alloy-Inconel 718 and Ti-47.5Al-2.5V-1.0Cr. *J. Manuf. Process.* **2023**, *97*, 35–47. [[CrossRef](#)]

36. Abu Bakar, H.; Ghani, J.; Haron, C.C.; Ghazali, M.; Kasim, M.; Al-Zubaidi, S.; Jouini, N. Wear mechanisms of solid carbide cutting tools in dry and cryogenic machining of AISI H13 steel with varying cutting-edge radius. *Wear* **2023**, *523*, 204758. [[CrossRef](#)]
37. Wang, R.; Wang, X.; Yan, P.; Zhou, T.; Jiao, L.; Teng, L.; Zhao, B. The effects of cryogenic cooling on tool wear and chip morphology in turning of tantalum-tungsten alloys Ta-2.5W. *J. Manuf. Process.* **2023**, *86*, 152–162. [[CrossRef](#)]
38. Jawaid, A.; Sharif, S.; Koksai, S. Evaluation of wear mechanisms of coated carbide tools when face milling titanium alloy. *J. Mater. Process. Technol.* **2000**, *99*, 266–274. [[CrossRef](#)]
39. Tapoglou, N.; Lopez, M.I.A.; Cook, I.; Taylor, C.M. Investigation of the Influence of CO<sub>2</sub> Cryogenic Coolant Application on Tool Wear. *Procedia CIRP* **2017**, *63*, 745–749. [[CrossRef](#)]
40. Öndin, O.; Kivak, T.; Sarıkaya, M.; Yıldırım, Ç.V. Investigation of the influence of MWCNTs mixed nanofluid on the machinability characteristics of PH 13-8 Mo stainless steel. *Tribol. Int.* **2020**, *148*, 106323. [[CrossRef](#)]
41. ISO 4287:1997; Geometrical Product Specifications (GPS). Surface Texture: Profile Method. Terms, Definitions and Surface Texture Parameters. International Organization for Standardization: Geneva, Switzerland, 1997.
42. Kaynak, Y.; Lu, T.; Jawahir, I.S. Cryogenic Machining-Induced Surface Integrity: A Review and Comparison with Dry, MQL, and Flood-Cooled Machining. *Mach. Sci. Technol.* **2014**, *18*, 149–198. [[CrossRef](#)]
43. Kaynak, Y.; Karaca, H.; Noebe, R.; Jawahir, I. Tool-wear analysis in cryogenic machining of NiTi shape memory alloys: A comparison of tool-wear performance with dry and MQL machining. *Wear* **2013**, *306*, 51–63. [[CrossRef](#)]
44. Behera, B.C.; Alemayehu, H.; Ghosh, S.; Rao, P.V. A comparative study of recent lubri-coolant strategies for turning of Ni-based superalloy. *J. Manuf. Process.* **2017**, *30*, 541–552. [[CrossRef](#)]
45. Yuan, S.M.; Yan, L.T.; Liu, W.D.; Liu, Q. Effects of cooling air temperature on cryogenic machining of Ti-6Al-4V alloy. *J. Mater. Process. Technol.* **2011**, *211*, 356–362. [[CrossRef](#)]
46. Sivaiah, P.; Chakradhar, D. Comparative evaluations of machining performance during turning of 17-4 PH stainless steel under cryogenic and wet machining conditions. *Mach. Sci. Technol.* **2017**, *22*, 147–162. [[CrossRef](#)]

**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.