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Review

Effect of Various Lubricating Strategies on Machining of Titanium Alloys: A State-of-the-Art Review

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Abstract: In recent years, researchers have proposed a variety of sustainable ways of achieving maximal lubricant efficacy with the least amount of lubricant. As an alternative to traditional lubricating procedures, these planned solutions have been highly embraced by scientific groups. This paper provides a comprehensive review of modern cooling/lubrication technologies and their influence on titanium alloy milling, grinding, and turning. Selected studies on recent advances in the lubrication system, such as power consumption, cutting forces, surface finish, and so on, are examined. The effect of various cutting fluids on the machining of titanium alloys has also been investigated. According to the prior state of the art, lubricating techniques and lubrication types have a considerable influence on the machining efficiency of titanium alloys.

Keywords: titanium alloy; MQL; wet machining; cryogenic machining; hybrid machining; cutting fluid

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1. Introduction

Titanium alloys offer a variety of unique qualities, including high strength, resistance to chemical deterioration, and excellent corrosion resistance, particularly stress corrosion. These alloys are utilized in aircraft, power plants, heat exchangers, water heaters, pressure vessels, and orthopedic implants because of their characteristics [1]. The ability of this alloy to maintain these qualities at elevated temperatures severely hinders machinability during machining, and hence, this alloy is classified as difficult to cut. The increased temperature at the point of contact between the tool and the workpiece promotes quick tool wear and, as a result, a poor surface finish [2,3]. To address this issue, coolant/lubricant oils and liquids are delivered to the cutting zone.

The use of these fluids in machining operations produces aerosols and mists that can endanger the environment and have an impact on worker health [4]. Furthermore, the cost of these coolants is 7–17% of the entire machining cost, which is greater than the cost of tooling (i.e., 7%) [5,6]. As a result, reducing the use of these fluids is essential here [7]. Dry machining is used for economic and environmental reasons, but it has some limitations in that it is not suitable for sticky and difficult-to-cut materials such as titanium alloys because it causes the material to stick to the tool face, produces a poor surface finish, requires a high cutting force, and has a high wear rate [8]. Titanium alloy machining is confined to lower cutting speed operations, resulting in a reduced production rate [9]. Minimum quantity lubrication (MQL) is one method in which just a small amount of fluid is required during machining operations [10]. Cooling in a deformation zone is critical, hence a fluid with high thermal conductivity must be used [11]. Given the aforementioned limitations, unique cutting fluid and long-term cooling methods are critical for achieving high-performance cooling.

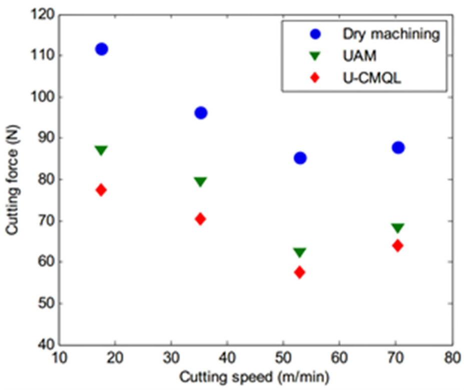
Coolants/lubricants are crucial in machining and cannot be overlooked when evaluating machining performance. If coolants/lubricants are not used during machining, high tool wear, high energy consumption, and shorter tool life will be the results, besides other machining outcomes. It is also critical to select a cutting fluid (CF) composition that does not hurt the environment or emit high levels of emissions. To address these environmental issues, various eco-friendly cutting fluids are now available. The following characteristics are used to select cutting fluids: heat transmission, lubrication, flushing action, fluid mist formation, and corrosion inhibition. Aside from that, the expense of the cutting fluid should be kept to a minimum. The fluid should provide high machining performance while also being environmentally friendly. As a result, because cutting fluids have a bigger impact on the company's sustainability, cutting fluids should be chosen properly to be profitable while emitting as little as possible.

This article discusses the impact of lubricants on titanium alloy machining in terms of their lubricating cooling influence on power consumption, cutting forces, and surface finish. Using fluids with a high ability to cool and lubricate the contact area of the tool and workpiece is one approach to improving the MQL technique. Fluid thermophysical qualities such as dynamic viscosity, wettability, surface tension, and thermal conductivity can all have an impact on machining performance [12]. Viscosity is an essential index attribute that is used to calculate the internal friction and flow resistance of a fluid. The higher the viscosity of the fluid, the better the lubricating effect. Surface tension has a significant impact on the boiling process, wetting activities, and spray properties. The capacity to penetrate may be examined using viscosity and surface tension; the lower the viscosity and surface tension, the greater the penetration [13–16]. The higher the viscosity, the better the lubrication. Wettability, according to Sillman [17], is the ability of a fluid to spread out, penetrate, and cover the tool as well as the workpiece. When the contact angle is minimal, the wettability improves. Lower cutting forces will result from improved penetration. Fluid thermal conductivity is regarded as an essential measure for assessing heat transfer performance. Along with the lubricant impact, it details which lubrication strategy and circumstances are employed, as well as their influence on machining titanium alloys under varied settings by various researchers throughout the world.

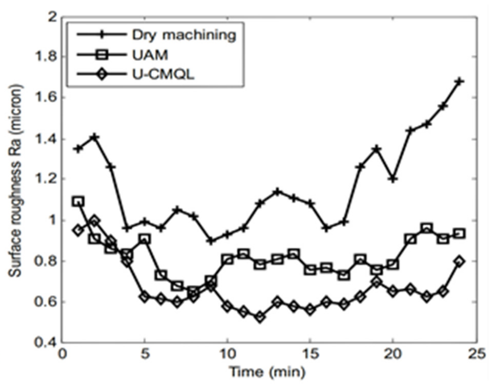
2. Minimum Quantity Lubrication (MQL) Machining Strategy

Yan et al. [18] investigated the performance of dry machining, micro lubrication in ultrasonic-assisted machining (UAM), and continuous MQL with ultrasonic vibration (U-CMQL) on turning Ti-6Al-4V. Tool wear, surface roughness, chip morphology, and cutting force were the parameters that were analyzed. When MQL with ultrasonic vibration was used, the tool rake face and workpiece contact were intermittent, due to which lubricant accessed the cutting interface. The cutting force was reduced by UAM, but due to the better lubrication in U-CMQL, the lowest cutting force was registered by U-CMQL at different cutting speeds (Figure 1). Moreover, tool wear was reduced by U-CMQL, and thus better surface roughness and favorable chip morphology were obtained (Figure 1).

Pervaiz [19] et al. perform the minimum quantity lubrication (MQL) method that offers a feasible substitute to the MWF-based conventional flood cooling method. In this study, a vegetable oil-based MQL system was mixed with sub-zero temperature air to design a new minimum quantity cooling lubrication (MQCL) system. The machinability of Ti-6Al-4V using an MQCL system under various oil flow rates and compared its machining performance with both dry cutting and conventional flood cooling, the surface roughness, flank wear, and associated wear mechanisms. The viscous nature was increased, and the penetration was decreased on adding low temperature (−4 °C) It was found that in the MQCL system (60–70 mL/h), oil supply rates provided reliable machining performance at higher feed levels. Rao et al. [20] experimented by setting cutting inserts in two different designs and comparing relative criteria further. They observed that as the cutting velocity increases, cutting temperature and flank wear increase, respectively, under all the machining environments. In this experiment of surface roughness and cutting vibration, a decreasing trend was observed as cutting velocity increased. The cutting vibration while doing machining operations was reduced by 35% and 20% when compared to normal and Design 1 cutting insert machining. The maximum tool flank wear reductions observed in Design 2 modified inserts were 62% and 40%, respectively, over normal and Design 1 cutting insert machining. Kishawy et al. [21] carried out a turning operation on Ti-6Al-4V and assessed sustainability by employing MQL and MQL-nanofluid. The fluid used in MQL and MQL-nanofluid was ECOLUBRIC E200 (flow rate of 40 mL/h, air pressure 0.5 Mpa). In this they have chosen three-level parameters cutting speed (120, 170, 220 m/min), feed (0.1, 0.15, 0.2 mm/rev) and nanoparticle concentration (Al_2O_3 wt.%-0, 2, 4). Overall, the best results based on machinability and sustainability were obtained at a cutting speed of 170 m/min, a feed rate of 0.1 mm/rev, and an Al_2O_3 concentration of 2 wt.%. There was a decrease in the induced friction on increasing nanoparticle concentration as they act as a spacer between tool and workpiece. This significantly affects power consumption. Singh et al. [22] investigated the tool wear behavior during turning Ti-6Al-4V under dry, MQL, and NMQL conditions, and the fluid used in that was canola oil. In MQL, additional lubrication is provided at the chip-tool contact area due to the high viscosity of oil, and thus heat is generated in the machining zone, and the coefficient of friction is reduced. At a lower cutting speed of 80 m/min, lubrication was good at the rake-face compared to higher speeds due to the tool life deteriorating at higher speeds. NMQL graphene has high thermal conductivity, easy-to-shear property, and high durability. It also helps in reducing friction and improving wettability; thus, it gives better tool life and a lower rate of tool wear, even at the higher cutting speed of 180 m/min. The lower Ra value was obtained in NMQL, followed by MQL and the dry environment.



(a)



(b)

Figure 1. Effect of different cutting environments on (**a**) cutting force versus cutting speed and (**b**) surface roughness [18].

Li et al. [23] carried out a turning operation on Ti-6Al-4V under a conventional cooling environment. The base fluid used was ROCOL Ultracut Clear. Moreover, in this 0.1% and 0.5% weight percentage, a graphene nanosheet was added to the base fluid. The lubrication effect was analyzed by considering friction force and friction coefficient at the tool-chip and tool-workpiece interface. The cooling and lubrication effects were analyzed by examining the wired tool surface area. It was found that the temperature at the tool/chip interface was reduced significantly on adding graphene oxide nanosheet. The friction force and friction coefficient were reduced at the flank face. It was observed that there was an improvement in the lubrication ability and cooling effect by using graphene oxide sheet in the cutting fluid, which was shown by the reduced flank wear and crater. Figure 2 shows the measured values of cutting forces at each level of cutting speed. From Figure 2a,b it was identified that the main cutting force decreases with the increase in the concentration of graphene oxide Nanosheets in a fluid. From Figure 2c,d it was observed that there was no significant effect of the increase in pressure and concentration of graphene nanosheets on feed force. Moura et al. [24] investigated the effect of solid lubricant on Ti-6Al-4V by out carrying turning operation, and the parameters that are taken into consideration in this investigation are surface roughness, tool life, cutting force, and temperature rise. The base oil used in MQL is synthetic oil, and graphite mesh 625, graphite mesh 325, and molybdenum disulfide (MoS_2) solid particles were added to the base oil. There was a reduction in surface roughness by implementing solid lubricant even at high temperatures. Satisfactory cooling and lubrication were obtained at the chip/tool interface, which increased tool life (Figure 3). There was a reduction in friction at the tool/workpiece interface due to solid lubricants, which resulted in a cutting force reduction. It was observed that the lowest machining temperature is attained when MoS_2 is used. Hegab et al. [25] researched to see the influence of dispersed MWCNTs on vegetable oil by using it with the MQL technique during the turning of Ti-6Al-4V. The whole experiment lies in enhancing the MQL heat capacity using different concentrations of nanofluid to improve Ti-6Al-4V machinability. In this, the study parameters were power consumption and flank wear. The incrementation of adding nanoparticles to the lubricant showed a significant positive effect. When MWCNT was added, there was an improvement in rank and flank regions, wetting, and lubricating properties, which resulted in smooth cutting. Anand et al. [26] investigated the effect of MQCL with Al_2O_3 nanofluid, hBN nanofluid, and soluble oil on machining Ti-6Al-4V at constant cutting parameters. It was observed that when MQCL with soluble oil was carried out, it showed better cutting force, tool wear, and adhesion of material over the rake face. MQCL with Al_2O_3 nanofluid and hBN nanofluid had not given acceptable performance in machining. Thus, MQCL with soluble oil is a better alternative to flood cooling.

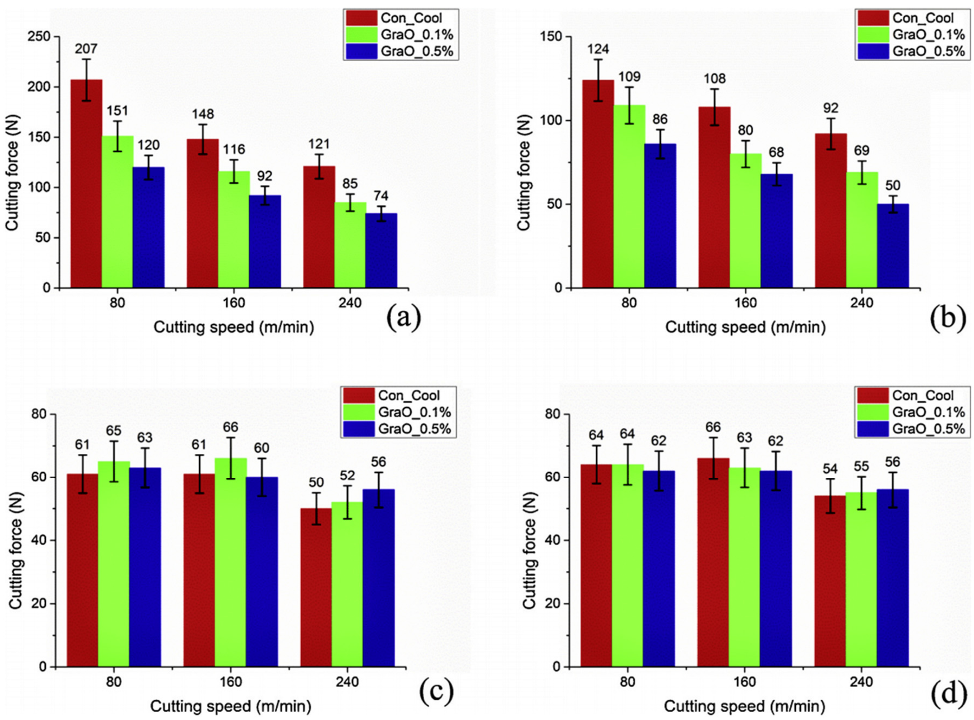


Figure 2. Measurement of cutting forces at different cutting levels (**a**,**b**) main cutting forces under 1 bar and 10 bar coolant pressure, respectively, (**c**,**d**) feed forces under 1 bar and 10 bar coolant pressure, respectively [23].

The experiment performed by Srikant et al. [27] used sustainable lubricants in turning Ti-6Al-4V. Soybean oil-based lubricants were used with/without the addition of micro-graphite particles in a minimum quantity of lubrication at a rate of 40 mL/h. The PVD-coated carbide tools were used for machining under different cutting conditions. Among the considered combinations, it was found that a cutting speed of 90 m/min, a feed of 0.3 mm/rev, and a depth of cut of 0.5 mm were optimal for overall machining performance. By using a different type of coolant, it was observed that the cutting conditions under those situations Tool wear is significantly affected by the type of coolant used (Figure 4).

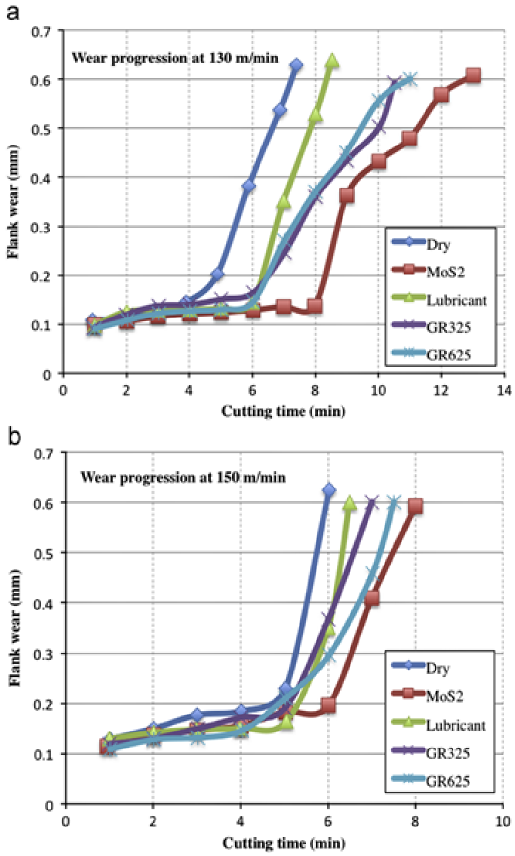


Figure 3. Tool wear as time progress: (**a**) at 130 m/min and (**b**) 150 m/min [24].

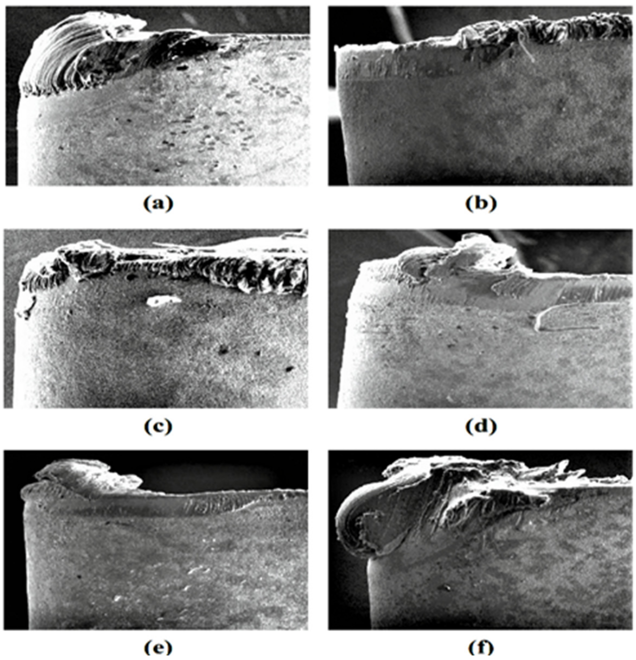
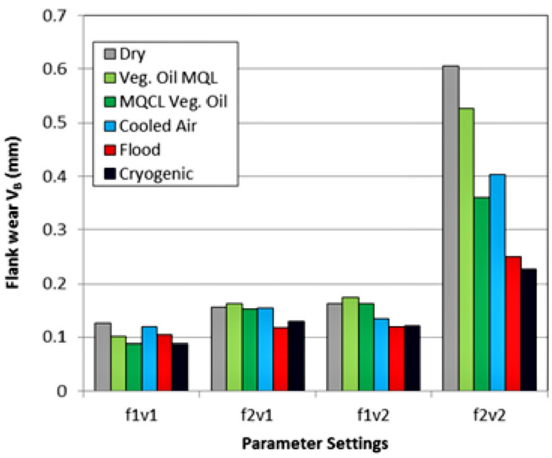
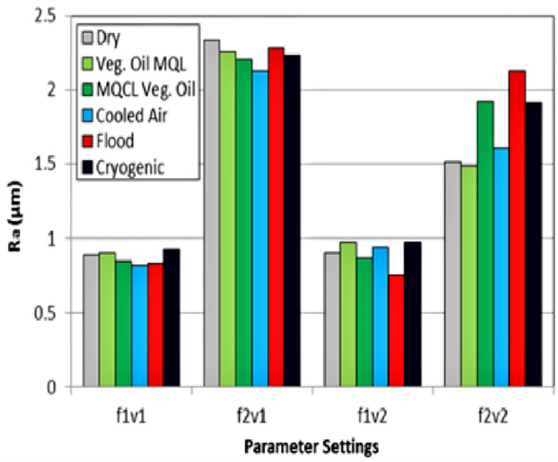


Figure 4. SEM image of tool wear (**a**) dry, (**b**) cutting fluid, (**c**) cutting fluid with graphite, (**d**) oil, (**e**) oil with graphite, and (**f**) dry in run 6 [27].

Under all the cutting conditions, dry machining showed the highest tool wear. Cutting fluids give the least tool wear due to effective cooling. However, under severe conditions, oil + powder gave better results due to the combined lubricating effect of oil and graphite. While machining at high feeds and speeds, oil with graphite inclusions gave about 85% less tool wear compared to dry machining and about 20% less tool wear compared to cutting fluid. Raza et al. [28] have used six different strategies that include dry, cooled air, flood, cryogenic, MQL, and MQCL and investigated flank tools during the turning of Ti-6Al-4V. The tool used was uncoated carbide. Rapeseed vegetable oil was used in MQL and MQCL. The cutting parameters were a depth of cut of 0.8 mm, a cutting speed of 90, 120 m/min, and a feed rate of 0.1, 0.2 mm/rev. It was observed that MQL and MQCL could be the alternatives to dry machining at low feed and a speed of 0.1 mm/rev and 90 m/min, respectively, as they had given lower flank wear compared to dry. For higher feed and cutting speed, cryogenic was giving lower flank wear. At lower speeds, feed surface roughness was close to each other under all lubricating conditions. At higher feed, the surface roughness is higher. At a feed of 0.2 mm/rev and a speed of 90 m/min, the surface roughness is high; thus, at a higher feed high, the cutting speed gives better surface roughness values (Figure 5).



(**a**)

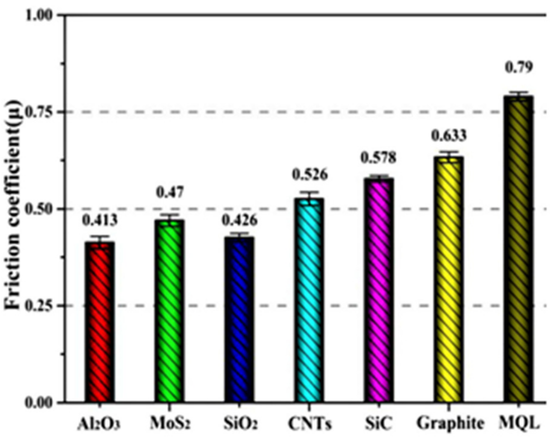


(**b**)

Figure 5. Effect of different lubrication techniques on (**a**) flank wear and (**b**) surface roughness [28].

Ramana [29] investigate the effect of cutting fluid and optimization of process parameters to reduce surface roughness under dry, minimum quantity lubrication (MQL), and flooded conditions using Taguchi's robust design methodology. The fluid used in flood and MQL is sunflower-based vegetable oil. For MQL, the optimum parameters are the following: a cutting speed of 63 m/min, a feed rate of 0.206 mm/rev, and a depth of cut of 1 mm. The CVD-coated tool showed a good result as it is tough and wear-resistant. In minimizing the surface roughness, the feed rate contributes 92.01%. A better surface roughness reduction was obtained in MQL compared to dry and flood conditions. Gupta et al. [30] performed the turning of titanium (Grade-2) alloy to assess the life cycle model with MQL (commercially available cutting fluid). The results showed that the Ranque–Hilsch vortex tube-assisted minimum quantity cutting fluids (RHVT-MQCF) was less energy-hungry compared to MQCF. Besides, the higher machining temperature that was generated during the MQCF compared to the RHVT-MQCF and RHVT-MQCF resulted in a regular chip and a smoother surface, which led to the better machining performance of the RHVT-MQCF technique. Faga et al. [31] compared the effects of various cutting strategies on machinability during the turning of Ti-6Al-4V. The best tool life was achieved with Emulsion Mist Cooling/Lubrication (EMCL) compared to MQL, wet, and dry. The study divulged that the lubricant type, delivery strategy, and supplied amount are the most important parameters that control the overall process. Khan et al. [32] investigated the effects of cooling strategy and cutting speed on the machinability during the turning of titanium grade-II. The better penetration of MQL resulted in the lowest cutting temperature compared to flood and dry cutting methods. The lower cutting force was observed with MQL than in dry and flood conditions, which further confirmed the lower power consumption. The MQL with vegetable oil provided better surface smoothness in contrast with another cutting environment. Sartori and Bruschi [33] performed a turning of Ti-6Al-4V to investigate the enhancements in tool life and surface quality of the final product with MQL and minimum quantity cooling (MQC). The solid lubricant aided MQC and provided the best results in terms of both nose and crater wear. However, in contrast with the MQC, the MQL exhibited lower cooling capacity, which led to the involvement of a cratering phenomenon. Gupta et al. [34] evaluated the machining performance of grade II Ti alloy in terms of cutting force, surface roughness, and cutting performance using Al_2O_3, MoS_2, and graphite immersed nanofluid. The lower cutting temperature, cutting force, and surface roughness were observed using graphite NF compared to Al_2O_3 and MoS_2 NFs. Additionally, the scanning electron microscopic evaluation of the tool divulged that the graphite NFs can provide a better tool profile and machined surface. Limin et al. [35] compared the surface roughness and tool wear in different cooling/lubrication conditions, i.e., dry, wet, and MQL, in the turning of Ti-6Al-4V. The rake wear was not found to be improved when using MQL compared to dry and wet machining strategies. However, better surface roughness was observed using MQL compared to dry machining. Singh et al. [36] studied the effects of different cooling conditions such as dry, MQL, and NMQL on tool life, cutting force, and temperature while turning Ti-6Al-4V alloy. The thermal conductivity was significantly enhanced by mixing graphene (1 wt.%) with canola oil. The friction between chip/workpiece and tool was reduced, and NMQL provided better cooling and lower cutting force compared to vegetable-based MQL. At a cutting speed of 180 m/min, catastrophic tool failures have taken place under dry cutting. The tool life was improved by 178–190%, the cutting force was reduced by 36–40%, and the temperature was reduced by 31–42% in NMQL compared to dry cutting conditions. Singh et al. [37] carried out a turning operation on Ti-3Al-2.5V alloy and investigated the effects of the different cooling environments such as dry, compressed air assisted wet cooling, Ranque–Hilsch vortex tube (RHVT), MQL, and wet oil cooling on workers' health, surface roughness, power consumption, tool wear, and chip morphology. The large chip curl was causing poor surface roughness, while in MQL and RHVT, it had given proper cooling effect and thus improved the tool life. Moreover, in this, the chip curl diameter was small, which resulted in a better surface finish. The power consumption and carbon emissions were also less under MQL and RHVT conditions compared to other conditions. The air quality was degrading in MQL, so vortex tubes (RHVT) were found profitable as a tool-related cost, and workers' health was saved with this. Yi et al. [38] investigated the performance of graphene oxide (GO) suspended fluid under MQL turning of Ti-6AL-4V alloy. In this, they have analyzed cutting temperature and cutting forces using a finite element analysis model. With this, it was seen that GO nanofluid provides better lubrication and reduced friction compared to conventional cooling conditions. With 0.1 wt.%, 0.3 wt.% and 0.5 wt.% of GO nanoparticles, the reduction in friction was 4.01%, 5.36% and 3.37%, respectively. The cutting force was lower with 0.3 wt.% of GO nanoparticles than with 0.5 wt.% of GO nanoparticles. Yi et al. [39] investigated the effect of new graphene oxide (GO) suspended fluid on drilling Ti-6Al-4V at different cutting parameters. The parameters that were considered in the result are thrust force, surface roughness, tool wear, and chip morphology. It was observed that when the feed rate is high, the thrust force is high, and when the spindle speed is increased, the thrust force reduces. The reduction in thrust force was up to 17.21%, and the reduction in surface roughness was 15.1% in the GO fluid compared to the conventional coolant. Excellent chip morphology was obtained when feed was below 0.12 mm/rev, and spindle speed was below 1600 rpm, while in conventional coolants, a discontinuous chip was formed. The tool wear was insignificant after 32 drills under suspended coolants, while under conventional coolants, chip abrasion was observed on the tool. Nam et al. [40] evaluated the micro-drilling process on Ti-6Al-4V under NMQL conditions. The base fluid used here was palm oil in MQL, and the nanodiamond particles

(0.2 wt.%, 0.4 wt.%) were added to it in NMQL. The spherical shape of the nanoparticle could effectively penetrate the area of drilling. The machinability was enhanced in terms of torque, force, tool wear, and quality of hole at small particle size (35 mm), high concentration of nanoparticles (0.4 wt.%), and low feed rate (10 mm/min). Niketh et al. [41] analyzed the effect of micro-textures on the sliding friction in the drilling of Ti-6Al-4V. The non-textured, margin-textured, and flute-textured drills were used in experimentation. The margin-textured drill resulted in a reduction of thrust force (10.68%) and torque (12.33%) compared to the margin-textured drill. The chip evacuation force was decreased by using a flute-textured drill. Overall, the study revealed that the texturing of the tool can significantly reduce energy consumption by reducing the friction between two sliding surfaces. Li et al. [42] have carried out milling on titanium alloy TC4, in which they have used LB2000 oil as a base fluid for MQL, and they have checked the feasibility of graphene MQL. Moreover, they compared it with pure MQL, gas, and dry conditions. The cutting tool was TiAlN coated with a 6 mm diameter, four flutes, a helix angle of 45°, a rake angle of 8°, and a relief angle of 14°. In their experiment to evaluate force and tool wear, they performed slot milling by taking machining parameters N = 796 rpm, feed = 0.016 mm/tooth, and axial depth = 0.1 mm. In addition, for evaluating temperature and surface integrity, they have performed side milling by taking machining parameters of speed of 796 rpm, feed of 0.04 mm/tooth, axial depth of 0.2 mm, and radial depth of 0.2 mm. Firstly, they found the lubricating oil film showed good antiwear and load-bearing capacity, due to which milling force was smaller in pure MQL and graphene MQL. Secondly, they found that the lubricating oil film was giving a good cooling effect in MQL, especially in graphene MQL, due to which tool wear was also less in these conditions. Surface roughness with pure and graphene MQL is 0.425—0.311 µm, respectively. Yin et al. [43] performed a milling operation on Ti-6Al-4V, taking cottonseed oil as the base fluid. The milling parameters were kept the same; only nanoparticles were changed in the fluid, and their effect on milling force and surface roughness was observed. It was observed that after incorporating Al_2O_3 NMQL, the lubricating effect on the workpiece surface was improved, and the lowest force (Fx of 312 N, Fy of 96 N, and the friction coefficient of 0.413) was noted. Thus, Al_2O_3 NMQL consumes less energy and is efficient. The best surface roughness was achieved under SiO_2 NMQL conditions as it exhibits high viscosity (Figure 6).



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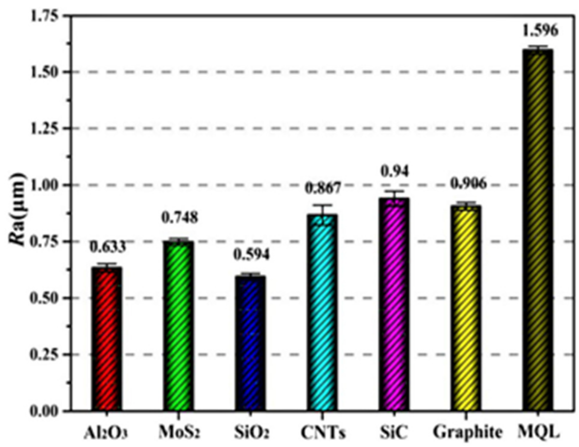

(**b**)

Figure 6. Effect of different working conditions on (**a**) friction coefficient and (**b**) surface roughness [43].

Priarone et al. [44] have used LB2000 vegetable-based oil as MQL fluid for the milling of titanium alloy Ti-48Al-2Cr-2Nb. They have compared MQL against dry and flood cooling environments. They have kept milling parameters such as axial and radial depth of cut, feed, and cutting speed equal to 0.3 mm, 0.08 mm/tooth, and 50 m/min, respectively. The tool used for milling was TiAlN coated (diameter of 8 mm), and the LB2000 vegetable-based oil was conveyed by air at 5.5 bar pressure, with a 0.3 mL/min quantity as the rate of consumption. They have obtained results in the form of tool wear and surface roughness. Moreover, better lubrication was obtained in MQL, due to which there was friction reduction, and hence tool wear was lowest in MQL, while in surface roughness, dry cutting was found to be slightly better than in MQL and flood cooling. Bartolomeis et al. [45] proposed an electrohydrodynamic atomization cooling-lubrication system for MQL (EHDA-MQL) during milling of Ti-6Al-4V. The EHDA-MQL was proficient at generating a micron-sized fine droplet. The tool life was enhanced 6 times compared to MQL and 22 times compared to flood cooling. The emergence of fine particles significantly improved the heat removal rate, ultimately resulting in a reduction in tool wear. Figure 7 exhibits the change in power consumption for tool wear under different machining conditions. It can be seen that EHDA-MQL consumed the least power up to 60 μm, and afterward, MQL exhibited the lowest power consumption compared to other machining environments.

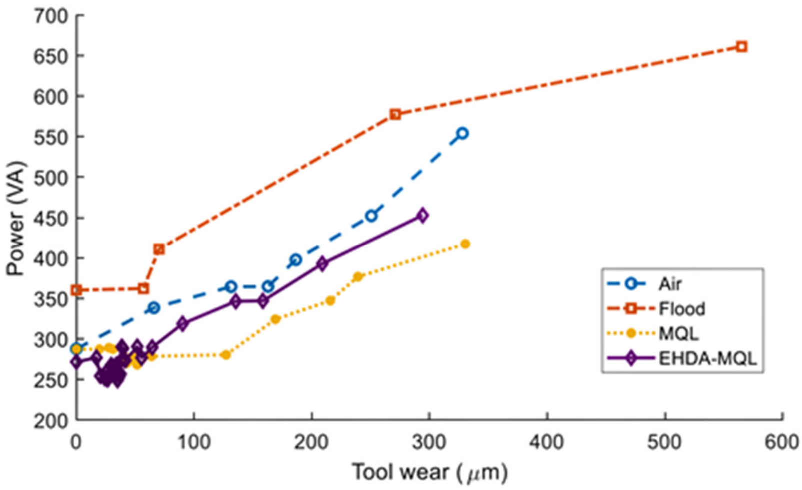

Figure 7. The variation in power consumption against tool wear under different machining conditions [45].

Dong et al. [46] studied the cooling effect of various nanoparticles in the milling of Ti-6Al-4V under the MQL strategy. The lubricant was prepared with 1.5 wt.% concentrated six different nanoparticles, i.e., Al_2O_3, MoS_2, SiO_2, CNTs, SiC, and graphite immersed in cottonseed oil. Among the compressions, it was observed that the lowest cutting temperature was obtained with SiO_2 nanofluid followed by Al_2O_3 nanofluid. The minimum surface roughness was achieved with Al_2O_3 nanofluid, followed by SiO_2 nanofluid. The overall result demonstrated that the Al_2O_3 and SiO_2 exhibited the best cooling characteristics compared to those with other nanoparticles. Cai et al. [47] analyzed the impact of different machining environments, i.e., dry, supercritical CO_2, MQL-based supercritical CO_2 with water altered cutting fluid, and supercritical CO_2 with oil on water cutting fluid, on machinability during milling of Ti-6Al-4V. The superior lubrication/cooling effect and better chip evacuation characteristic of supercritical CO_2 with oil on water cutting fluid turned in a minimum cutting force with favorable surface roughness and cutting temperature. This can be attributed to the fact of higher heat transfer capacity and vaporization capacity of CO_2 gas and the lubrication characteristics of oil. Ni et al. [48] investigated the machining performance of ultrasonic vibration-assisted milling (UVAM) of Ti-6Al-4V using MQL. The surface acoustic, separate type cutting mechanism, and cavitation execution of the vibrating workpiece enhanced the cooling/lubricating performance of UVAM compared to MQL. The cutting force characteristic was extensively affected due to the coupling effect of UVAM and the intermediate cutting mechanism of MQL and UVAM. The UVAM and MQL systems enhanced the profile fluctuation of the uniform microtextured surface. The improvement in the surface roughness of 20%–30% and 30%–50% was obtained using UVAM and MQL compared to UVAM and conventional milling. Davis et al. [49] used the ionic liquid as an additive to increase the effectiveness of MQL during the machining of titanium alloy. The 0.5 wt.% concentration of 1-butyl-3-methylimidazolium hexafluorophosphate (BMIM-PF6) in deionized water is used as a lubricant. The BMIM-PF6 improved tool wear by 15% and 60% compared to dry and water-based MQL. Furthermore, the ionic liquid additive provided better surface roughness and cutting force compared to dry and water-based MQL. Ziberov et al. [50] investigated the effect of lubricant (Coolube 2210EP) on the micro-milling of Ti-6AL-4V alloy under dry and MQL environments. Tool life and surface quality are the responses that were measured. The use of lubricant improved the surface quality, but the tool life was longer in dry-cutting conditions. The secondary face of the tool gets worn in MQL, and the tool edge radius increases in dry machining. Zou et al. [51] analyzed the output responses in belt grinding of titanium alloys. The results divulged that the use of MQL provided lower abrasive wear with an improved machined surface. Moreover, favorable fatigue strength and a compact microstructure can be achieved by the MQL-assisted belt grinding process. The CNT immersed cutting fluid MQL further enhanced the machinability and also improved the sustainability of the belt grinding process. Mishra et al. [52] used laser-textured tools to assess the machining performance of the Ti-6Al-4V alloy. Laser textured cutting tools were employed in MQL settings based on vegetable oil and nano-MQL (nMQL) settings based on alumina dispersed DI water. Under dry environments and with similar machining variables, the outcomes were evaluated by comparing them with plain and textured tools. The results revealed an enhanced lubricating mechanism when using MQL textured tools. On the other hand, nMQL textured tools were ineffective because nanoparticles penetrated the droplets and aggregated in the textured region. The summary of MQL machining strategy has been presented in Table 1.

Table 1. Summary of minimum quantity lubrication (MQL) machining strategy.

Ref No.	Process	Coolant/Lubricant Strategy	Coolant/Lubricant Type	Workpiece	Tool	Cutting Parameters
[18]	Turning	Dry, U-CMQL	Vegetable oil	Ti-6Al-4V	40Cr, insert-cemented carbide	Vc-17.6–70.4 m/min ap-0.75 mm f-0.15 mm/rev
[19]	Turning	MQL, MQCL	Vegetable oil-based	Ti-6Al-4V	CCMT 12 04 04 MM H 13A	Vc-90–150 m/min ap-0.8 mm f-0.1–0.3 mm/rev
[20]	Turning	MQL	Coconut oil	Ti-6Al-4V	PCD insert	Vc-100–200 m/min ap-1 mm f-0.5 mm/rev
[21]	Turning	MQL, NMQL	ECOLUBRIC E200	Ti-6Al-4V	Carbide insert	Vc-120–220 m/min ap-0.2 mm f-0.1–0.2 mm/rev
[22]	Turning	MQL, NMQL	Canola oil	Ti-6Al-4V	Uncoated carbide	Vc-80–180 m/min ap-0.2 mm f-0.15 mm/rev
[23]	Turning	NMQL	ROCOL Ultracut Clear with 0.1% and 0.5% graphene nanosheet	Ti-6Al-4V	CBN	Vc-80–240(m/min) ap-1(mm) f-0.01(mm/rev)
[24]	Turning	NMQL	Synthetic oil with graphite mesh 625, graphite mesh 325, molybdenum disulphide (MoS_2)	Ti-6Al-4V	TiAlN-coated carbide	Vc-130, 150(m/min) ap-1(mm) f-0.2(mm/rev)
[25]	Turning	NMQL	ECOLUBRIC E200 MWCNT nanoadditives (wt.%) 2%, 4%	Ti-6Al-4V	CNMG 120416MR (ISO)	Vc-200, 220 (m/min) f-0.15, 0.2 (mm/rev)
[26]	Turning	MQCL with nanofluid	Flood, MQCL (Al_2O_3 nanofluid, hBN nanofluid, soluble oil)	Ti-6Al-4V	Straight carbide (K20)	Vc-80 m/min f-0.16 mm/rev ap-1.5 mm

Table 1. *Cont.*

Ref No.	Process	Coolant/Lubricant Strategy	Coolant/Lubricant Type	Workpiece	Tool	Cutting Parameters
[27]	Turning	MQL, NMQL	Soybean oil-based lubricants 40 mL/h dry, wet	Ti6Al4V	PVD-coated carbide tools	Vc-90 m/min f-0.3 mm/rev ap-0.5 mm
[28]	Turning	Dry, cooled air, flood cooling, cryogenic, MQL, MQCL	ECOLUBRIC E200	Ti-6Al-4V	Uncoated carbide	Vc-90,120 m/min ap-0.8 mm f-0.1,0.2 mm/rev
[29]	Turning	Dry, MQL, flood cooling	Sunflower-based vegetable oil	Ti-6Al-4V	Uncoated, PVD coated carbide, CVD coated carbide	Vc-63–99 (m/min) f-0.206–0.343(mm/rev) ap-0.6–1.6 (mm)
[30]	Turning	MQL	Commercially available cutting fluid	Titanium (Grade-2) alloy	Uncoated carbide, ISO Designation: CCMT 09 T3 08, 7° relief angle	Vc-250–300 m/min ap-0.3–0.5 mm f-0.05–0.13 mm/rev
[31]	Turning	Dry, MQL, and wet	An emulsion of 7% miscible oil in (93%) water and vegetable oil; an emulsion of 5% ester-based oil in (95%) water	Ti-6Al-4V	Uncoated carbide round inserts (RCMT 12 04 M0-SM H13A)	Vc-90–150 m/min ap-0.5 mm f-0.15 mm/rev
[32]	Turning	Dry, flood and MQL	Water soluble oil (flood) and vegetable oil (MQL)	Titanium (CP-Ti) grade II	Carbide inserts	Vc-51–87 m/min ap-0.5 mm f-0.12 mm/rev
[33]	Turning	MQL and MQC	Vegetable oil enriched PTFE particles + Graphite particles	Ti-6Al-4V	TiAlN-coated tungsten carbide insert	Vc-80 m/min ap-0.25 mm f-0.2 mm/rev
[34]	Turning	NFMQL	Vegetable base oil Al_2O_3 nanofluid MoS_2 nanofluid Graphite nanofluid	Ti alloy (grade II)	CBN inserts (rhombic shape CNMG 120408)	Vc-200–300 m/min ap-1.0 mm f-0.1–0.2 mm/rev
[35]	Turning	Dry, wet, MQL	LUBROIL oil (MQL)	Ti-6Al-4V	Fine grain-coated carbide tool	Vc-40–120 m/min ap-0.5 mm f-0.1–0.2 mm/rev
[36]	Turning	Dry, MQL, NMQL	Canola oil (MQL), graphene-mixed canola oil (NMQL)	Ti-6Al-4V	Carbide tool	Vc-80–200 m/min ap-0.2 mm f-0.05–0.15 mm/rev
[37]	Turning	Dry, compressed air wet cooling, Ranque—Hilsch vortex tube (RHVT), MQL, wet oil cooling	Canola oil (MQL), soluble oil (wet oil cooling)	Ti-3Al-2.5V	AlTiN-coated carbide tool	Vc-80–130 m/min ap-0.2 mm f-0.1 mm/rev
[38]	Turning	NMQL	Graphene oxide mixed in ROCOL Ultracut Clear	Ti-6Al-4V	PCBN tool	Vc-80–240 m/min ap-0.1 mm f-0.05–0.1 mm/rev
[39]	Drilling	NMQL	ROCOL Ultracut Clear with graphene oxide suspended	Ti-6Al-4V	WC	N-800–2880 (rpm) f-0.1–0.18(mm/rev) ap-8 (mm)
[40]	Drilling	NMQL	Compressed air, Veg.-based MQL, NMQL	Ti-6Al-4V	Uncoated tungstate carbide twist drill	N-60,000 r/min f-10, 50 (mm/min) ap-0.4 mm
[41]	Drilling	Dry	Dry	Ti-6Al-4V	Textured- and non-textured-carbide drill tool	N-80–6000 rpm ap-10 mm f-0.04–0.07 mm/r
[42]	Milling	MQL, NMQL	LB2000 vegetable-based oil	Ti-6Al-4V	TiAlN-coated	N-796 rpm f-0.016, 0.04 mm/tooth ap-0.2 mm ae-0.1 mm

Table 1. *Cont.*

Ref No.	Process	Coolant/Lubricant Strategy	Coolant/Lubricant Type	Workpiece	Tool	Cutting Parameters
[43]	Milling	NMQL	Cottonseed oil with Al_2O_3, MoS_2, SiO_2, carbon nanotubes, SiC, graphite	Ti-6Al-4V	Quenched 42CrMo	N-8000 r/min f-10,000 mm/min
[44]	Milling	MQL, dry, flood cooling	LB2000 vegetable-based oil	Ti-48Al-2Cr-2Nb	TiAlN coated	Vc-50 m/min f-0.08 mm/tooth ap-0.3 mm
[45]	Milling	Flood cooling, air, MQL and EHDA-MQL	Rapeseed oil	Ti-6Al-4V	WC tool with 5 flutes and TiSiN coating	Vc-120 m/min N-3183 rpm ap-3 mm f-0.05 mm/tooth
[46]	Milling	NMQL	Cottonseed oil with 1.5 wt.% Al_2O_3, MoS_2, SiO_2, CNTs, SiC, or graphite	Ti-6Al-4V	Bap300r-c16-160-160l milling tool bar with an APMT1135PEDR blade	Vc-1200 r/min N-3183 rpm ap-0.25 mm f-500 mm/min
[47]	Milling	MQL	Supercritical carbon dioxide ($scCO_2$)	Ti-6Al-4V	A 4-edge cemented carbide end mill with CVD coating	Vc-20–60 m/min ap-0.025–0.055 mm f-0.3–0.9 mm/rev
[48]	Milling (UVAM)	MQL	Vegetable oil-based cutting fluid	TC4	-	N-600–2400 rpm ap-0.2 mm
[49]	Milling	MQL	Ionic liquid	Titanium alloy	Cubic boron nitride (CBN) inserts	Vc-120 m/min ap-0.1 mm f-0.5 mm/rev
[50]	Milling	MQL, Dry	Coolube 2210EP	Ti-6Al-4V	WC tool	N-20,000 rpm ap-10 µm f-0.1 mm/r
[51]	Grinding	MQL	Castor oil	Ti-6Al-4V	Abrasive belt	Vc-2–12 m/min f-0.5 mm/min
[52]	Turning	MQL, nano–MQL	Vegetable oil-based MQL, alumina suspended DI water-based nMQL	Ti-6Al-4V	Laser-textured cutting tools	Vc-60–12 m/min f-0.1–0.2 mm/rev dc-50 µm ap-1 mm afr-6 bar

3. Wet Machining Strategy

An et al. [53] examined the tool wear and machined surface properties of Ti-6Al-4V during the side milling operation. Four sustainable cooling environments, namely, dry, supercritical carbon dioxide ($scCO_2$), $scCO_2$ with antifreeze water-based minimum quantity lubrication ($scCO_2$-WMQL), and $scCO_2$ with oil-on-water based MQL ($scCO_2$-OoWMQL), were employed during the process. A continuous wavelet transform was used to study the comprehensive properties of the machined surface profile. The findings demonstrated that $scCO_2$-OoWMQL outperformed $scCO_2$ as a novel, sustainable and efficient cooling, and lubricating approach. Jamil et al. [54] investigated the effects of CO_2-snow and subzero MQL on Ti-6Al-4V. The machining operation was carried out under flood, CO_2-snow, and MQL conditions, and the heat transfer capabilities of CO_2-snow and subzero MQL were examined. According to the study, the order of overall greater machinability is CO_2-snow > flood cooling > subzero MQL. Furthermore, the considerably greater heat transfer behavior of CO_2-snow in machining led to less tool wear (i.e., a longer tool life) and better surface quality. In conclusion, the CO_2 snow has shown encouraging results that justify its use in the machining sector. Zheng et al. [55] used concentrated ZJ-846 fluid diluted in 1:20 proportion and three different textured YG8 (line, rhombic, and sinusoidal textured) and non-textured tools for performing the turning operation on Ti-6Al-4V. Under the same lubricating condition, the textured tool had given good results in terms of cutting force and surface roughness. By incorporating textured tools into machining, the cutting force reached up to 30.97%, and the roughness was reduced by 35.8% compared to the non-textured tool. The sinusoidal texture gave the best result compared to other tools. Gunda et al. [56] optimized the machining parameters using the electrostatically charged lubricant spray technique in the turning of Ti-6Al-4V. The cutting force and surface roughness were notably affected by the higher velocity and number of droplets of the charge lubricants. Yi et al. [57] studied the effect of graphene oxide (GO)-immersed nanofluid on machining output responses during the turning of Ti-6Al-4V. The lower cutting force was observed with GO Nanofluid compared to conventional cutting fluid. Besides, the concentration of the nanoparticles in the base fluid has a notable impact on the cutting force and tool wear. The reduction in flank wear was noted at 71.3%, 53.9%, and 44.1% with 0.5 wt.%, 0.3 wt.%, and 0.1 wt.% concentration, respectively. Additionally, a less adhered layer on the rake face and build-up edge (BUE) was formed with nano lubrication. Furthermore, the worn area and material adhesion on the rake faces were observed to be lower using GO Nanofluid compared to a conventional cutting fluid, as shown in (Figure 8).

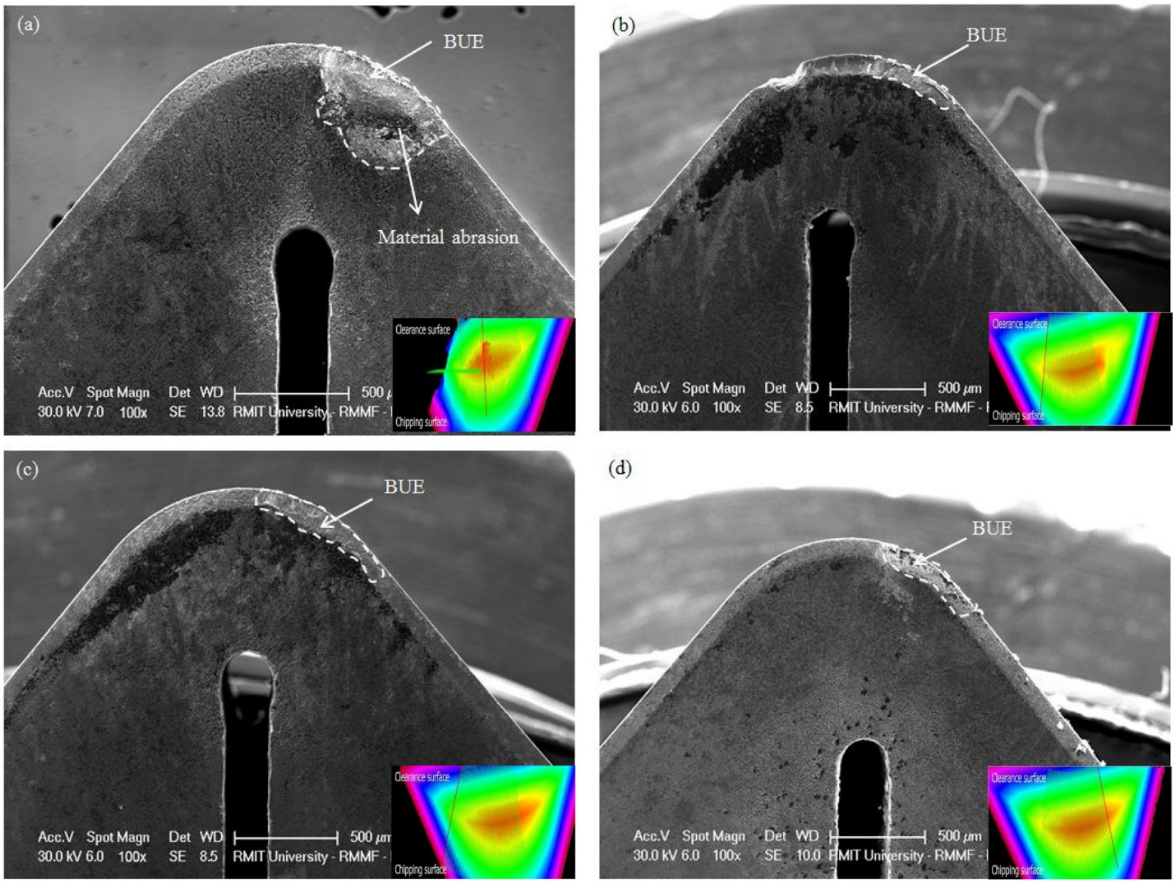

Figure 8. The rake face images of tool using (**a**) conventional cutting fluid, (**b**) 0.1 wt.% GO Nano fluid, (**c**) 0.3 wt.% GO Nano fluid, and (**d**) 0.5 wt.% GO Nano fluid [57].

Nath et al. [58] used an atomization-based cutting fluid (ACF) spraying system to evaluate the machining performance (surface roughness, cutting temperature, roundness error, and chip morphology) of Ti-6Al-4V. The ACF and flood coolant have shown similar results in terms of residual stress and surface roughness. Additionally, the highest values of tool nose wear and surface roughness were observed with compressed air conditions compared to ACF and flood conditions. The flow rate of ACF was optimized to be 1.5 mL/h to enhance the machining performance. Sahu et al. [59] evaluated the machinability of Ti-6Al-4V during turning with multi-walled carbon nanotube nanoparticles. The nanofluid reduced the tool wear by 34% and 56% compared to conventional fluid and dry machining, respectively. Furthermore, a 7% reduction in surface roughness and a 28% reduction in cutting force were obtained using nanofluid compared to the conventional machining strategy. Lu et al. [60] performed the turning of Ti-6Al-4V using high-speed ultrasonication vibration (HUVC) under high-pressure coolant (HPC) conditions. The application of HUVC with HPC at a cutting speed of 400 m/min enhanced the tool life 7.3 times compared to the conventional cutting strategy. A reduction of 55% in machining temperature was observed with A cutting speed of 300 m/min under HPC conditions. This can be attributed to the fact that the HUVC allows the high-pressure coolant to fully reach the cutting edge. Mia and Dhar [61] investigated the impact of duplex jets' high-pressure coolant on machining performance and cutting temperature when turning Ti-6Al-4V. The use of duplex HPC induces forced convection, and hence the heat transfer capability can be enhanced. The tool life was increased by 55–60% under duplex HPC compared to dry machining. Furthermore, using duplex HPC, the lower cutting force was obtained at a high cutting speed and lower feed rate. Ganguli et al. [62] analyzed the effect of an atomization-based cutting fluid (ACF) spray system in the milling of Ti-6Al-4V. The use of an ACF spray system considerably improves the tool life with lower cutting force and lower surface roughness than flood cooling. Furthermore, thinner and shorter chips were generated under the ACF spray system compared to flood cooling. Figure 9 shows the average and maximum surface roughness with different machining conditions. The surface roughness of the flood and ACF was nearly comparable within the first 6–8 min, and it has drastically deteriorated.

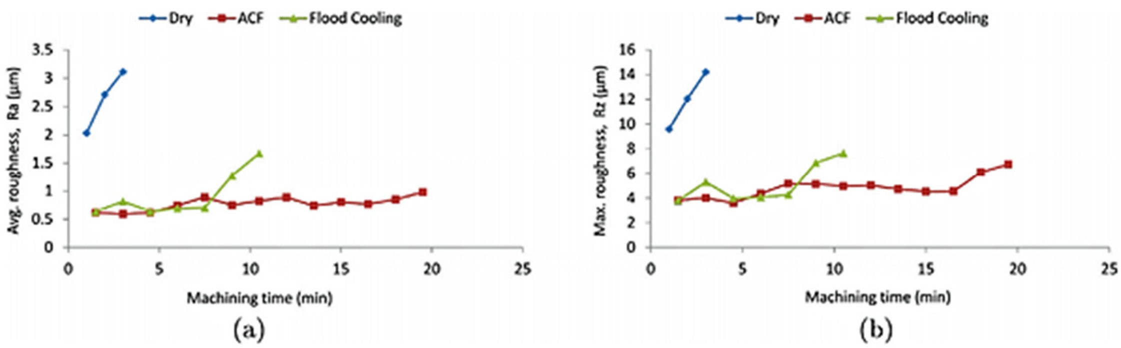

Figure 9. The values of (**a**) average and (**b**) maximum surface roughness in dry, ACF, and flood cooling strategies [62].

Su et al. [63] analyzed the impact of Nanofluid electrostatic atomization lubrication (NFEAL) and electrostatic atomization lubrication (EAL) methods on the environment and machining in the milling of Ti-6Al-4V. Among the comparison, it was divulged that the EAL and NFEAL have significantly reduced the tool wear compared to MQL, while NFEAL was more efficient than EAL to lower the tool wear. Zhou et al. [64] discussed the effects of nanofluid and micro-texture coupling effects in the milling of Ti-6Al-4V. The maximum decrement in cutting force was observed using a cutting tool with laser surface texturing and nanofluid compared (NP + NF) to those cutting tools without surface texturing and conventional cutting fluid (NT + CC). The reduction of 27.75% in surface roughness and 63.3% in tool wear were attained with NP + NF rather than that of NT + CC. Su et al. [65] studied the sustainable machining of titanium alloys using composite electrostatic spraying. The environment's friendliness and better machining performance can be obtained using electrostatic spraying. The composite electrostatic spraying can significantly reduce tool wear and the oil mist concentration. The increasing flow rate of external fluid has a remarkable influence on the oil mist concentration compared to those with internal fluid. The electrostatic spraying had improved the lubrication property of the lubricating oil and effectively reduced the cutting zone temperature. The enhanced cooling performance of trace water under composite electrostatic produced shorter chips compared to electrostatic spraying. Mittal et al. [66] analyzed the impact of lubricant on the chatter and cutting force during the micro-milling of Ti-6Al-4V. The cutting force was reduced (38%) using wet lubrication compared to dry machining. Lee et al. [67] used nanofluid air flow-assisted electrostatic lubrication (AF-ESL) in the micro-grinding of titanium alloy. The nanofluid

AF-ESL remarkably reduced the G-ratio and the grinding force compared to dry machining. Moreover, the concentration of nanodiamonds in the base fluid has a significant impact on the machining performance. The enhanced surface quality of the machined surface was obtained with nanofluid AF-ESL. Grguraš et al. [68] used carbide tools to perform robotic drilling on Ti6Al4V and studied chip morphology and cutting forces in an LCO_2 + MQL environment. The results show a significant association between LCO_2 flow rate and thrust force owing to material hardness, as well as a significant correlation between torque and MQL flow rate due to the simultaneous impacts of cutting zone lubrication and the chip evacuation process. Due to a conjunction of lower temperatures and lubrication threshold, dry drilling demonstrates significant chip adherence to the tool, whereas LCO_2 + MQL aided drilling enhances chip breakability and minimizes workpiece-material adhesion. The summary of wet machining strategy has been presented in Table 2.

Table 2. Summary of Wet machining strategy.

Ref No.	Process	Coolant/Lubricant Strategy	Coolant/Lubricant Type	Workpiece	Tool	Cutting Parameters
[53]	Milling	Dry, $scCO_2$, $scCO_2$-WMQL, $scCO_2$-OoWMQL	Antifreeze water droplets and oil-on-water droplets	Ti-6Al-4V	Cemented carbide flat end mill with diamond coating	Vc-20–60 m/min f-0.010 mm/rev ae-0.2 mm ap-3 mm
[54]	Milling	CO_2-snow and MQL	Flood cooling: Castrol Syntilo-9913 + water (10:90); Subzero-MQL: Blaser SWISSLUBE oil + refrigerated air; CO_2-snow	Ti-6Al-4V	FIRE-coated tungsten carbide end-mill EMC6210010	Vc-90–10 m/min f-0.06–0.10 mm/tooth
[55]	Turning	Wet	Concentrated ZJ-846 was diluted in 1:20 proportion	Ti-6Al-4V	YG8	Vc-22.7–90.4 (m/min) ap-0.1–0.4 (mm) f-0.2 (mm/rev)
[56]	Turning	Electrostatic-charged solid lubricant spray system (ECSL)	MoS_2 solid lubricant, water-soluble synthetic oil	Ti-6Al-4V	Coated carbide cutting tool, CNMG 120412	Vc-100 m/min ap-0.5 mm f-0.1 mm/rev
[57]	Turning	Nanofluid	Conventional coolant and 0.1–0.5 wt.%, graphene oxide-suspended fluid	Ti-6Al-4V	Polycrystalline cubic boron nitride (PCBN)	Vc-80–240 m/min ap-0.1 mm f-0.05–0.1 mm/rev
[58]	Turning	Wet (atomization-based cutting fluid (ACF))	Mixture of air and CO_2 (66:34)	Ti-6Al-4V	Uncoated micro crystalline carbide insert	Vc-100–150 m/min ap-0.06–0.1 mm f-0.04–0.06 mm/rev
[59]	Turning	Dry, Wet	Blasocut 4000, MWCNT-based nanofluid	Ti-6Al-4V	TiCN+Al2O3+TiN-coated carbide insert	Vc-90–150 m/min ap-1 mm f-0.1 mm/rev
[60]	Turning	HPC	Water soluble oil 6% in water	Ti-6Al-4V	Triangular cemented carbide inserts	Vc-200–500 m/min ap-0.05 mm f-0.005–0.015 mm/rev
[61]	Turning	Dry, HPC	Coolant at 80 bar pressure	Ti-6Al-4V	TiCN+Al2O3+TiN-coated carbide insert	Vc-78–156 m/min ap-1 mm f-0.12–0.16 mm/rev
[62]	Milling	Dry, flood, and atomization-based cutting fluid spray system	Water-soluble S-1001 at 10% dilution	Ti-6Al-4V	Uncoated carbide tool with 30° helix angle	N-1500 rpm ap-2 mm f-0.1–0.14 mm/tooth

Table 2. *Cont.*

Ref No.	Process	Coolant/Lubricant Strategy	Coolant/Lubricant Type	Workpiece	Tool	Cutting Parameters
[63]	Milling	Electrostatic atomization lubrication (EAL) and nanofluid electrostatic atomization lubrication (NFEAL)	LB2000 oil (MQL and EAL) and 0.5 wt.% graphite-LB2000 oil (NFEAL)	Ti-6Al-4V	Uncoated carbide inserts	Vc-100 m/min ap-0.5 mm f-0.1 mm/rev
[64]	Milling	Wet	0.5 wt.% Fe_2O_3 in conventional cutting fluid	Ti-6Al-4V	YG6X-cemented carbide tool	N-1000–4000 rpm ap-0.6 mm f-0.06 mm/r
[65]	Milling	Electrostatic spraying, composite electrostatic spraying	LB2000 + deionized water	Titanium alloy	Uncoated carbide milling inserts (type: R390-11T308M-KM H13A)	Vc-70–130 m/min ap-0.2 mm f-0.5 mm/rev
[66]	Milling	Dry, Wet	10% Hocut 795H oil in water	Ti-6Al-4V	Uncoated tungsten carbide	N-20,000–100,000 rpm ap-20 µm f-0.5–5 µm/r
[67]	Grinding	Air flow-assisted electrospray lubrication (AF-ESL)	Dry air, AF-ESL using nanofluid (0.2–0.8 wt.% nano diamond particle)	Titanium alloy	CBN grinding tool	N-50,000 rpm f-120 mm/min ap-0.005 mm
[68]	Drilling	Dry, Wet + MQL	Liquid CO_2	Ti-6Al-4V	SumiDrill SDP0300U3HAK with AlCrTiN coating	Vc-15 m/min (N = 1592 RPM) f-0.025 mm/rev

4. Cryogenic Machining Strategy

Pereira et al. [69] studied modern cryogenic machining technologies and advocated the use of cryogenic and minimal quantity lubrication for an environmentally friendly turning operation. In a study, Pereira et al. [70] manufactured a knee prosthesis by using a Kondia HS1000 5-axis machining center to execute machining operations. Ti-6Al-4V grade 23 was utilized as the raw material for this project. In this work, a CO_2 cryogenic machining environment was proposed to manufacture the product. The benefit of this configuration is that it not only incorporates economic and environmental aspects but also suggests a clean approach, in which cutting fluid based on oil is restricted. Kaynak and Gharibi [71] used cryogenic cooling and dry machining to accomplish a high-speed cutting operation on Ti-5553. The experiments were carried out at various cutting speeds using cryogenic coolants such as carbon dioxide (CO_2) and liquid nitrogen (LN_2). Cryogenic machining increases the machining performance of the Ti-5553 alloy by significantly lowering tool wear, cutting temperature, and dimensional deviation of the machined components, according to this study. Cryogenic machining also resulted in smaller chips than dry machining. Gajrani [72] performed turning on Ti-6Al-4V in three different lubrication environments, namely, dry, MQL, and cryo-MQL. The study revealed a considerable increase in machining performance; the cryo-MQL environment reduced machining forces and workpiece surface roughness by 27% and 46%, respectively, compared to the dry environment. The morphology of the tool rake surface revealed a considerable drop in the contact length of the sliding-sticking zones. When compared to the dry and MQL settings, the elemental composition revealed a decline in workpiece material adherence on the tool rake surface. The study proposed cryo-MQL as a hybrid lubrication environment for Ti-6Al-4V machining. Rodríguez et al. [73] recommended using CO_2 cryogenic cooling during the drilling of CFRP-Ti-6Al-4V stacks. This recommendation was based on a comparative study between dry drilling and drilling using CO_2 cryogenic cooling. Implementation of liquified CO_2 brought the tooltip temperature down, leading to a reduction in damaged tool edges, thereby enhancing the tool life. Agrawal et al. [74] compared wet and cryogenic machining to analyze the surface roughness, carbon emissions, tool wear, and tool life. The cryogenic cooling was effective at reducing tool wear by reducing the machining temperature. The tool life was observed to be increased by 125% at a higher speed using cryogenic cooling. Additionally, the surface roughness and power consumption were reduced by 22.1% and 23.4%, respectively, using cryogenic cooling compared to wet machining. Figure 10 exhibits the crater and flank wear during cryogenic and wet machining.

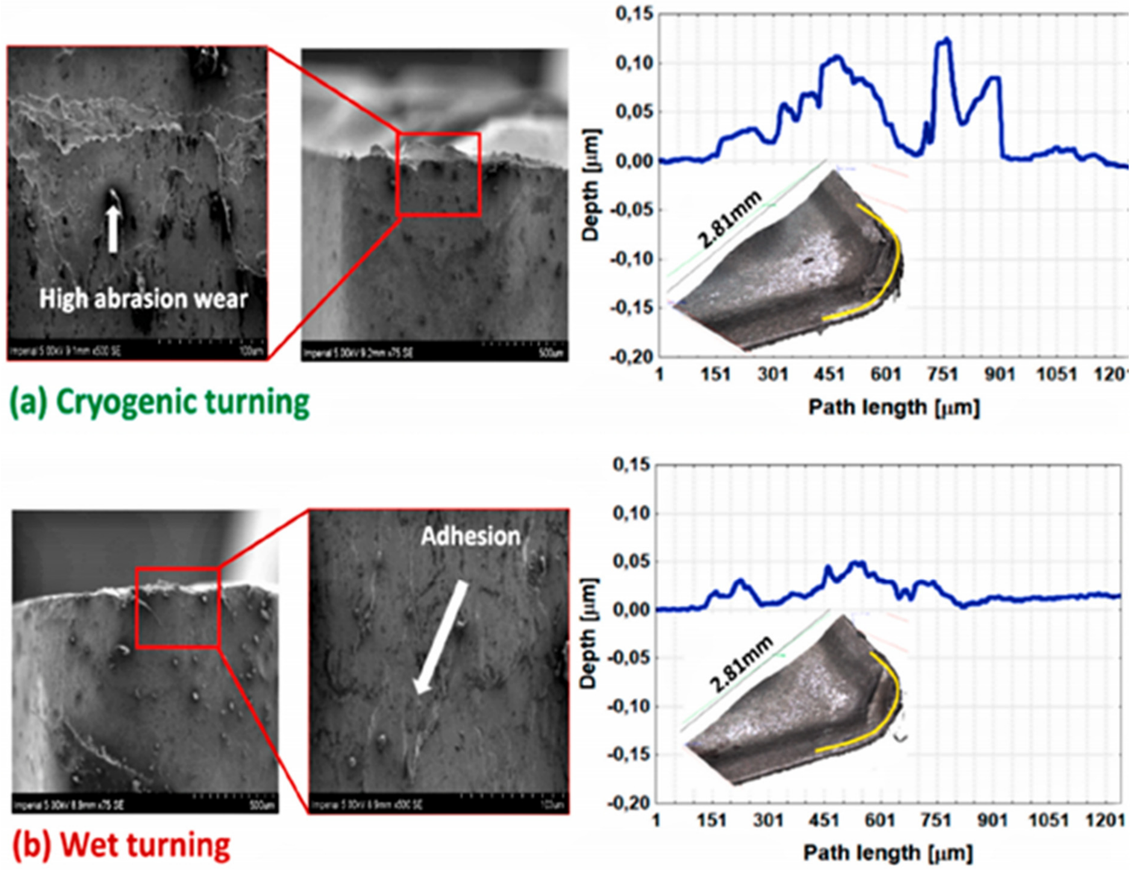

Figure 10. Crater and flank wear during (**a**) cryogenic machining and (**b**) wet machining [74].

Wet turning has less adhesion compared to cryogenic machining. Furthermore, the higher abrasion on the flank face and higher adhesion on the face resulted in quick tool wear compared to wet machining. Ayed et al. [75] investigated the influence of the supply condition of LN_2 on surface integrity and tool wear during the turning of Ti-6Al-4V. The results revealed that cryogenic cooling can improve the tool life by approximately four times compared to dry machining. The pressure and the flow rate of the coolant have a significant impact on the tool wear. The attenuation of thermal loads at a high flow rate brought an improvement in residual stresses. Perçin et al. [76] analyzed the cooling/lubrication effect of LN_2 during the micro-drilling of Ti-6Al-4V. The study revealed that cryogenic cooling has a different effect on both engagement and mean torque value. To achieve better surface quality, boron oil was recommended. The burr height can be reduced by using a higher spindle speed and a lower feed rate. Shokrani et al. [77] investigated the effect of cryogenic machining Ti-6Al-4V using liquid nitrogen (LN_2) as the coolant in an end milling operation, and the tool used was solid carbide. The cryogenic cooling was compared with dry and flood cooling. In the design of the experiment, the L_9 method was used, and the cutting parameters were cutting speed (30, 115, 200 m/min), feed rate (0.03, 0.055, 0.1 mm/tooth), and depth of cut (1, 3, 5 mm). On average, in cryogenic cooling 18% and 20% reduction in surface roughness compared to flood and dry machining. With a cutting speed of 115 m/min, feed rate of 0.03 mm/tooth, and depth of cut of 5 mm, the lowest surface roughness of 0.58 µm was obtained in cryogenic machining, which is 30% and 40% lower than flood and dry machining, respectively. Masood et al. [78] evaluated the cost and tool wear in face milling of Ti-6Al-4V with cryogenic cooling. A maximum tool life of 1065 min was observed with cryogenic cooling compared to those dry (225 min) and conventional cutting fluid (643 min). During the cost analysis, cryogenic machining was found to be cheaper than conventional and dry strategies. Chen et al. [79] investigated the impact of cutting-edge radii and various lubricant methods on the surface integrity of Ti-6Al-4V. To accomplish orthogonal cutting on Ti-6Al-4V, a variety of lubrication conditions were used, including dry, MQL, LN_2, hybrid with LN_2, and MQL with varied cutting-edge radii. Substantial changes in the size and depth of machining-induced compressive residual stress fields were also seen in machining with increased cutting-edge radii and hybrid cooling. In addition, when the cutting-edge radius rose, the surface hardness rose marginally. Because of increased deformation stress and lower fracture strain at lower temperatures, cryogenic cooling (LN_2) produces thinner deformation layers and wider deformation gradients. In another experiment, Chen et al. [80] investigated the surface integrity of Ti-6Al-4V during finish machining using dry, MQL, and cryogenic cooling techniques. According to the findings, with a minimum uncut chip thickness of 10 m, the pressures at the dry and MQL conditions caused fluctuations owing to the unsteady cutting process. This was due to frequent material buildup at the cutting edge, which implies that materials accumulated ahead of the cutting edge regularly as a result of the simultaneous impacts of sliding, ploughing, and cutting. Altogether, finish machining surface integrity, and mechanical behaviors were observed during orthogonal machining of Ti-6Al-4V alloy with cryogenic cooling and minimal uncut chip thickness. Table 3 summarizes the cryogenic machining strategy.

Table 3. Summary of cryogenic machining strategy.

Ref No.	Process	Coolant/Lubricant Strategy	Coolant/Lubricant Type	Workpiece	Tool	Cutting Parameters
[69]	Turning	Cryogenic machining technologies	MQL oil with L CO_2	AISI 304	TiN-coated carbide DNMG 150608-MM (GC2025) with chip-break	Vc-225 m/min f-0.25 mm/rev ap-1.5 mm
[70]	Drilling	Cryogenic machining	CO_2	Ti6Al4V grade 23	TiAlN-coated carbide inserts	Vc-40 m/s f-0.03 mm/teeth ae-12, 3 mm ap-1, 0.1 mm
[71]	Turning	Cryogenic cooling	Liquid nitrogen (LN_2) and carbon dioxide (CO_2)	Ti-5553 Alloy	Uncoated 883 grade carbide inserts (CNMG120408-M1)	Vc-30 210 m/min f-0.12 mm/teeth ae-3 mm ap-0.2 mm
[72]	Turning	Dry, MQL, and cryo-MQL	MOL and liquid nitrogen (LN_2)	Ti-6Al-4V Alloy	Uncoated carbide TNMA 220,412 inserts	Vc-80–120 m/min f-0.2 mm/rev a-1 mm
[73]	Drilling	Dry, CO_2-cryogenic cooling	Liquefied CO_2	CFRP-Ti6Al4V stacks	Carbide tools coated with diamond CVD	Vc-70 and 15 m/min f-0.025 mm/teeth
[74]	Turning	Wet and cryogenic cooling	LN_2	Ti-6Al-4V	CNMG 120,408 PR1535 Megacoat Nano	Vc-70–110 m/min ap-0.5 mm f-0.3 mm/rev
[75]	Turning	Cryogenic cooling	LN_2	Ti-6Al-4V	uncoated H13A carbide inserts have been used (CCMT 12-04–08 KM)	Vc-80 m/min ap-1 mm f-0.2 mm/rev
[76]	Drilling	Dry cutting, traditional cooling (flood cooling), cryogenic cooling, and MQL	LN_2	Ti-6Al-4V	Micro-drill containing *n* 90% WC and 10% Co	N-1000–10,000 rev/min ap-3 mm f-5–70 mm/min

Table 3. *Cont.*

Ref No.	Process	Coolant/Lubricant Strategy	Coolant/Lubricant Type	Workpiece	Tool	Cutting Parameters
[77]	End Milling	Cryogenic	Liquid nitrogen (LN_2)	Ti-6Al-4V	TiN-TiAlN-coated solid carbide	Vc-30–200 (m/min) ap-1–5 (mm) f-0.03–0.1 (mm/tooth)
[78]	Milling	Dry, cryogenic cooling,	LN_2	Ti-6Al-4V	PVD-coated carbide inserts	Vc-20–50 m/min ap-0.05–0.15 mm f-0.1–0.2 mm/tooth
[79]	Turning	Dry, MQL, LN_2, Hybrid (LN_2 and MQL)	LN_2	Ti-6Al-4V	Uncoated carbide tool inserts, TPG432 k313	Vc-100 m/min Uncut chip thickness-0.06
[80]	Turning	Dry, MQL, Cryogenic	-	Ti-6Al-4V	-	-

5. Hybrid Cryogenic Machining Strategy

Furthermore, Pereira et al. [81] presented a revolutionary cryogenic nozzle design. The development and optimization of CFD (ANSYS Fluent) simulation-derived nozzle outlets for CO_2 + MQL cooling were carried out with a primary focus on nozzle diameter. The suggested models were confirmed by actual trials, and a prototype nozzle was created based on the data collected in the study (a CO_2 velocity of 325 m/s is required to allow sustainable machining). Based on these research outcomes, three nozzle diameters (0.5, 1, and 1.5 mm) were considered by the researchers for their CFD model. Along with his teammates, Pereira then assessed the comparative effectiveness of each nozzle design based on normal average velocity at a distance of 20 mm from the outlet, noticing that the CO_2 velocity was best preserved with the 1.5 mm. According to this finding, when tested, the 1.5 mm nozzle achieved the largest spray distance of 40 mm (compared to 10 mm and 18 mm for the 0.5 mm and 1.0 mm nozzles, correspondingly). Taking inspiration from the works of Pereira and his team, Gross et al. [82] performed preliminary CO_2 + MQL nozzle optimization tests on Ti-6Al-4V, accompanied by cryogenic CNC milling experiments. During the process, it was discovered that when MQL was sprayed with compressed air, there were a high number of lubricant splashes on the oil trail. When the MQL was used in combination with CO_2, no such splashing occurred. The researchers observed this as an anticipated result of the CO_2 jet's enhanced flow speed (compared to compressed air) concentrating the oil droplets. Gupta et al. [83] evaluated the machining performance of Ti-6Al-4V using hybrid lubricating strategies that consist of cryogenic cooling with MQL. The lower tool wear was obtained with N_2 + MQL compared to dry and cryogenic machining. Besides, lower surface roughness, the highest micro-hardness, and lower cutting energy were observed using N_2 + MQL compared to dry and cryogenic and Ranque–Hilsch vortex tube plus MQL (RHVT + MQL) machining. Huang et al. [84] compared the machining performance among MQL, cryogenic cooling, and cryogenic + MQL strategies during the turning of Ti-6Al-4V. The cryogenic + MQL strategy exhibited the highest cooling efficacy compared to MQL and cryogenic gas. The reduction in lubrication effect because of the higher temperature of the cryogenic gas, the cryogenic + MQL, resulted in more prominent tool wear compared to MQL. The higher surface roughness and the lowest cutting fluid consumption proved more sustainable in terms of ecological and health problems. Furthermore, the lower temperature was generated with cryogenic cooling, which lowers the yield strength of the workpiece material, and hence the main cutting was relatively smaller than with cryogenic + MQL (Figure 11).

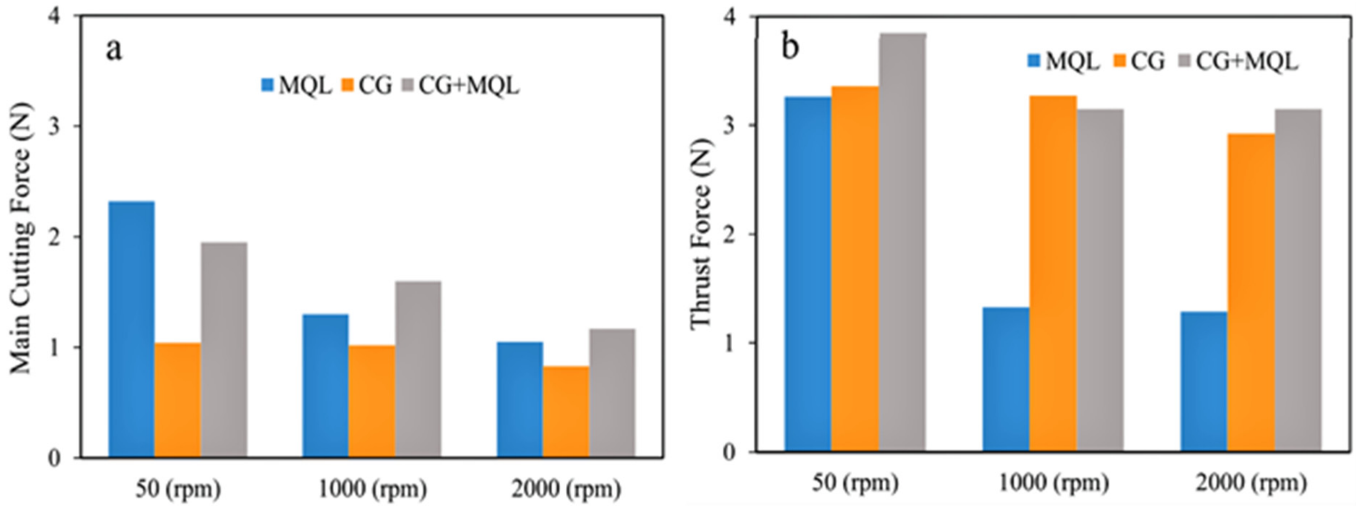

Figure 11. Measurement of (**a**) main cutting force and (**b**) thrust force during diamond turning of Ti-6Al-4V under different machining environments [84].

Lin et al. [85] proposed an internal and external oil-water lubrication method when turning Ti-6Al-4V. The proposed method was further compared with cryogenic air mixed with MQL (CAMQL). The better the lubrication property of the oil on water lubrication method has resulted in better surface roughness with a lower flank wear rate. The internal oil in water method was successfully able to make better penetration into the cutting zone and, hence, the machining performance can be enhanced. Sartori et al. [86] investigated the tool wear during the turning of Ti-6Al-4V using hybrid cooling/lubrication strategies. The use of LCO_2/MQL and LN_2/MQL solely eliminated the cratering phenomenon in flank wear. The thickness of the deformed layer was reduced by 29% and 15% with LCO_2/MQL and LN_2/MQL compared to dry machining. The nozzle has a remarkable influence on the tool wear with the LN_2/MQL strategy. However, the LCO_2/MQL strategy proved best in terms of machining performance compared to LN_2/MQL, MQL, and cryogenic machining. Wakabayashi et al. [87] investigated the effects of various near-dry machining conditions such as UE-3, CO-1 (MQL), and vegetable-based oil (hybrid mist cooling) on carrying out turning operations on Ti-6Al-4V alloy. Due to the lower viscosity of CO-1 compared to UE-3, it was able to better penetrate through the chip-tool interface. It gave superior lubrication and resulted in terms of flank wear (reduced flank wear). The hybrid mist further improved machining performance than with the CO-1 combined cooling mist. Shah et al. [88] analyzed different cooling and lubricating techniques such as dry, flood cooling, and cryogenic by drilling on VT-20 titanium alloy. The parameters that were analyzed during drilling were thrust force, torque, surface roughness, and power consumption. It was observed that there is no lubrication in dry machining and due to unfavorable chip clogging in flood cooling hinders the flow of coolant and thus thrust force increases in dry and flood cooling. The values of torque and surface roughness in cryogenic with LCO_2 were lower compared to other techniques. The lowest power consumption was found in cryogenic with LN_2 compared to dry, flood, and cryogenic with LCO_2. This result shows that cryogenic with LCO_2 and LN_2 are sustainable coolants and lubricants compared to flood coolants for reducing power consumption and tool wear (Figure 12).

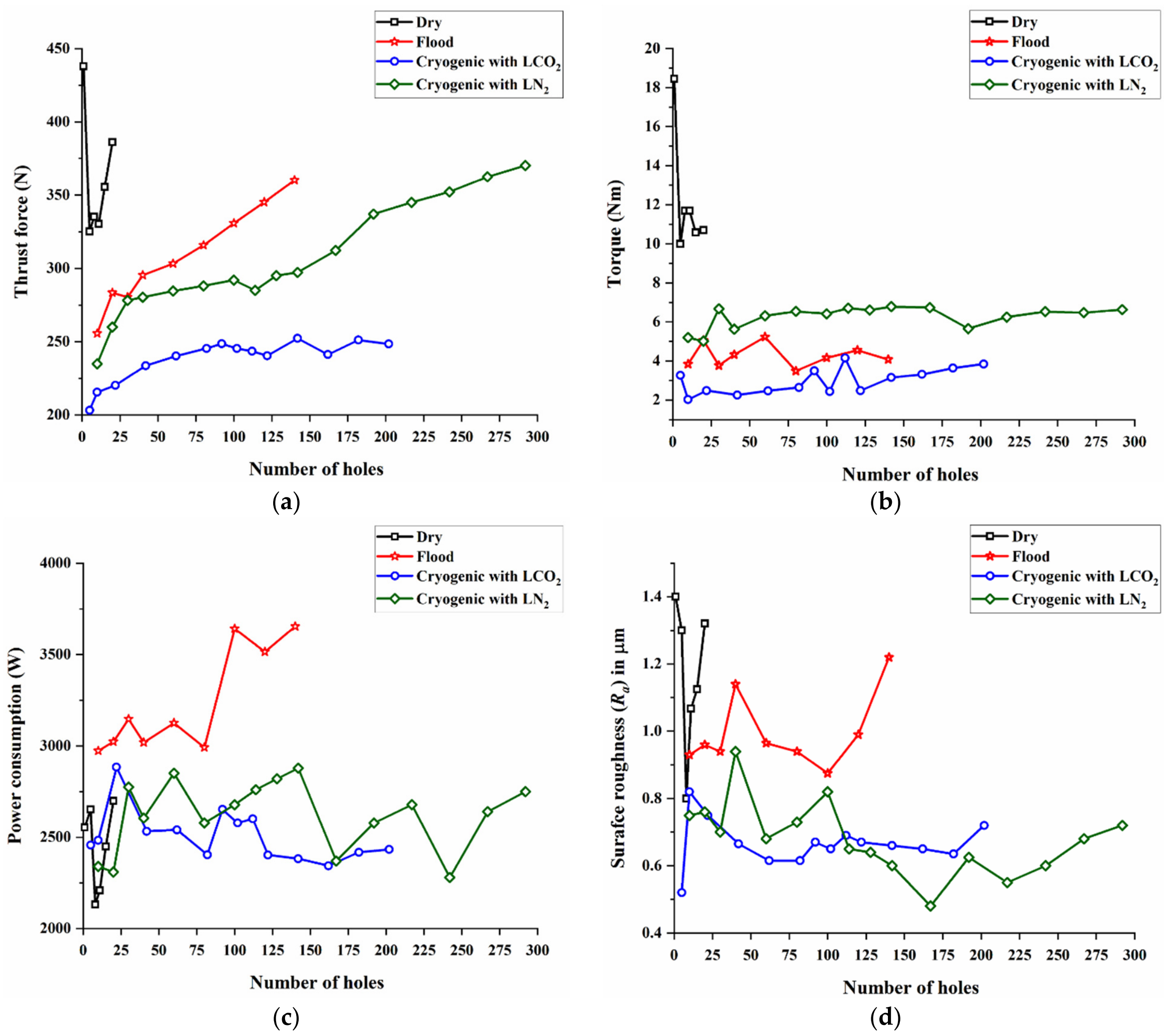

Figure 12. Comparison of (**a**) thrust force, (**b**) torque, (**c**) surface roughness, and (**d**) power consumption for different lubricant conditions with the progression of the number of holes [88].

Shokrani et al. [89] studied a hybrid cryogenic technique by performing end milling on Ti-6Al-4V and compared it with the flood, cryogenic cooling, and MQL. The investigation parameters were tool life, tool wear, and surface roughness. In flood cooling, the water-based emulsion was used at 8% concentration in MQL rapeseed oil, and in cryogenic LN_2 was used as coolant/lubricant. With MQL and hybrid cryogenic, 30% tool life is increased compared to flood cooling. Of these, hybrid is superior for achieving the highest tool life due to effective cooling and lubrication. In cryogenic cooling, friction was increased due to insufficient lubricity and increased plastic deformation of cutting edges. Due to the good lubricity in MQL conditions, the lowest surface roughness was noted at 0.2 µm, even at the higher cutting speed. Suhaimi et al. [90] carried out the end-milling operation on Ti-6Al-4V and investigated the effects of different cooling and lubrication techniques such as flood coolants, MQL with nanoparticles, external cryogenic, internal cryogenic, Nano-MQL + internal cryogenic, Nano-MQL + indirect cryogenic by considering force and tool wear. It was observed that compared to flood coolant, Nano-MQL + indirect cryogenic reduced the cutting force to 54% and reduced the tool wear to 90%. The workpiece hardening that was found due to the excessive use of LN_2 external and internal spray methods is prevented by the novel idea of indirect cryogenic cooling. Park et al. [91] analyzed the result that a combination of MQL with added hBN nanoparticle with custom-designed internal cryogenic cooling performs better than conventional flood cooling in terms of cutting force and tool life. This combination of cooling and lubrication strategy improves tool life by up to 32% compared to the conventional flood cooling condition in the deep axial depth-of-cut machining of Ti-6AL-4V. Kim et al. [92] experimented, and the objective of this research is to experimentally characterize the micro end milling process of (Ti-6Al-4V) using both nanofluid minimum quantity lubrication and chilly gas CO_2. At some point, the higher weightage (1.0 wt.%) concentration of Nanodiamond partials increases the cutting forces and coefficient of friction in comparison to the lower weightage concentration (0.1 wt.%), which is more effective in the micro-end-milling process. Iqbal et al. [93] investigated the effects of milling orientation and different cryogenics on tool damage, cutting force, production cost, and surface roughness of Ti-6Al-4V. The use of MQL was found to be more sustainable in production cost, surface roughness, energy consumption, and tool wear compared to the cryogenic cooling strategy. The specific cutting energy can be reduced by a higher helix angle and higher cutting speed, providing lower specific cutting energy consumption and surface roughness. Iqbal et al. [94] investigated the effect of CO_2 in cryogenics and the location of its application area. Moreover, the hybrid cooling strategy was analyzed. This grooving was carried out on Ti-10V-2Fe-3Al, and the coolant used was CO_2 snow, vegetable-based MQL, and hybrid (MQL + cryogenic). In this response, measured were tool displacement area, energy per groove, and the average width of flank wear. The application of CO_2 snow was found to be better than flood cooling. When CO_2 snow on the flank face and MQL on the rake face were used as hybrid cooling, they outperformed all other cooling strategies for tool deflection. From the statistical analysis, it was observed that the dominant reasons for tool wear were adhesion and progressive wear. Khanna et al. [95] performed Ti-6Al-4V machining and compared conventional flood coolant with MQL and liquid CO_2 as a cryogenic coolant. The comparison was based on machining performance and life cycle assessment (LCA). The outcomes of the study articulate that MQL machining is environmentally friendly; however, it badly affects the tool life as compared to flood and cryogenic machining. The flood machining has some problems of impacts generated for most of the ReCiPe 2016 (H) midpoint categories, hence found to be ineffective in terms of sustainability. The study recommends cryogenic machining based on environmental concerns and machining performance. González et al. [96] machined integral blade rotors (IBRs) made up of Ti-6Al-4V. Cryo CO_2 and Minimum Quantity Lubrication were employed on polycrystalline diamond (PCD) tools during the process. Cryogenics simplified the usage of PCD tools by means of eliminating the reactivity problems of such tools with Ti-6Al-4V. To avoid the formation of dry ice and clogging of both nozzles and pipes a novel device was proposed in this study. Hybrid cryogenic machining strategy has been summarized in Table 4.

Table 4. Summary of hybrid cryogenic machining strategy.

Ref No.	Process	Coolant/Lubricant Strategy	Coolant/Lubricant Type	Workpiece	Tool	Cutting Parameters
[81]	Milling	MQL and cryogenic gas (CryoMQL)	MQL oil microdroplets with liquefied CO_2 gas	Inconel 718	TiN-coated carbide inserts	Vc-120 m /min f-0.12 mm/teeth ae-3 mm ap-0.2 mm
[82]	Milling	Cryogenic MQL	CO_2	Ti-6Al-4V	Four-edged carbide end mill	Vc-70; 130 m/min fz-0,04 mm ap-2 mm ae-2 mm
[83]	Turning	Cryogenic + MQL	LN_2 + vegetable oil	Ti-6Al-4V	Rhombic shape CNMG 120408	Vc-100–150 m/min ap-0.5 mm f-0.05–0.15 mm/rev
[83]	Turning	Cryogenic + MQL	LN_2 + vegetable oil	Ti-6Al-4V	Rhombic shape CNMG 120408	Vc-100–150 m/min ap-0.5 mm f-0.05–0.15 mm/rev
[85]	Turning	Oil in water (OoW), Hybrid, wet, dry	Fatty alcohol, synthetic ester	Ti-6Al-4V	Coated carbide tool	Vc-70–110 m/min ap-1 mm f-0.25 mm/rev

Table 4. *Cont.*

Ref No.	Process	Coolant/Lubricant Strategy	Coolant/Lubricant Type	Workpiece	Tool	Cutting Parameters
[86]	Turning	Dry, wet, MQL, Cryogenic, Hybrid	Semi synthetic oil (wet), Bechem Berecut MQL A20, LN_2,LCO_2 (cryogenic)	Ti-6Al-4V	WC insert with TiAlN-coated tool	Vc-80 m/min ap-0.25 mm f-0.2 mm/rev
[87]	Turning	Dry, MQL, hybrid mist cooling (HMC)	UE-3, CO-1 (MQL), vegetable-based oil (HMC)	Ti-6Al-4V	JIS K10-cemented carbide tool	Vc-80 m/min ap-0.5 mm f-0.15 mm/rev
[88]	Drilling	Dry, flood cooling, cryogenic	Dry, flood, cryogenic (LCO_2 and LN_2)	VT-20	Solid carbide (coating KC05)	Vc-80 m/min f-100 mm/min
[89]	End Milling	Hybrid cryogenic, flood, cryogenic, MQL	Flood cooling-water based, MQL-rapeseed oil, cryogenic-LN_2, hybrid combination of MQL and Cryogenic	Ti-6Al-4V	TiSiN coated	Vc-90–180 (m/min)
[90]	End Milling	Flood cooling, hybrid cryogenic	Flood coolants, MQL with nanoparticles, external cryogenic, internal cryogenic, Nano-MQL + internal cryogenic and Nano-MQL + indirect cryogenic	Ti-6Al-4V	AlCrN	Vc-86 m/min ap-24.5 mm f-1026 mm/min width of cut-1.2 mm
[91]	Milling	Hybrid, flood cooling	MQL + hBN nanoparticle + cryogenic, flood	Ti-6Al-4V	AlCrN-coated tool	Vc-72–86 m/min f-0.1 mm/rev ap-24.5 mm ae-1.2 mm
[92]	Micro-end-milling process	Hybrid	Nanodiamond fluid MQL, gas CO_2	Ti-6Al-4V	WC	N-45,000 rpm ap-100 µm
[93]	Milling	Cryo-MQL	(LN_2/CO_2/MQL)	Ti-6Al-4V	-	Vc-100–175 m/min ap-0.5 mm f-0.3 mm/rev
[94]	Grooving	Hybrid cryogenic	CO_2 snow, vegetable-based MQL, hybrid	Ti-10V-2Fe-3Al	Carbide coated	Vc-50,100 m/min f-0.1 mm/min
[95]	Turning	Conventional flood coolant with MQL, Cryogenic coolant	Canola-based vegetable oil, liquid CO_2	Ti-6Al-4V	TiAlN-coated carbide inserts (VNMG110404 FN)	Vc-75 m/min ap-1 mm f-0.3 mm/rev
[96]	Milling	CryoMQL	CO_2	Ti6Al4V	Polycrystalline diamond (PCD) tools	-

6. Conclusions

In machining titanium alloy (Ti-6Al-4V), dry machining is very difficult due to the high strength and poor thermal conductivity of Ti-6Al-4V. Thus, MQL and MQCL are the alternatives to dry machining at low feed rate and cutting speed, and at higher feed rate and cutting speed, cryogenic can be the alternative to dry cutting conditions as lower flank wear is achievable with this. In the case of reducing friction and improving surface quality, NMQL is preferable over MQL; under cutting conditions, nanoparticles help in the decapitation of heat, ease the shearing of Ti-6Al-4V, and also improve the wettability of the lubricant; thus, it lowers the rate of tool wear even at higher cutting speeds. The thrust force increases due to hindrance caused by the chip to the flow of coolant in flood cooling conditions, so reducing power consumption and endowing better surface quality is possible with cryogenic cooling, which is an efficient and sustainable mode of cooling in machining. There is the requirement for alternative cryogenic cooling, which is more economically beneficial in terms of manufacturing cost compared to other cooling strategies. While MQL provides sufficient lubrication along with those cooling strategies such as hybrid cryogenic (MQL + cryogenic cooling), the machining of titanium alloy still requires to be analyzed under different conditions. As nanoparticles improve the heat transfer property of the fluid, there is a need to explore the potential of nano-enhanced cutting fluid.

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Nomenclature

MQL—Minimum quantity lubrication
CF—Cutting fluid
UAM—Ultrasonic-assisted machining
MQCL—Minimum quantity cooling lubrication
MWF—Metal working fluid
NMQL—Nanofluid minimum quantity lubrication
MoS_2—Molybdenum disulphide
GO—Graphene oxide
MWCNT—Multi-walled carbon nanotube
HBN—Hexagonal boron nitride
PVD—Physical vapor deposition
TiAlN—Titanium aluminum nitride
CVD—Carbon vapor deposition
RHVT-MQCF—Ranque–Hilsch vortex tube
MQCF—Minimum quantity cutting fluids
EMCL—Emulsion mist cooling/lubrication
EHDA—Electrohydrodynamic atomization
UVAM—Ultrasonic vibration-assisted milling
CNT—Carbon nanotube
BMIM—PF6-1-butyl-3-methylimidazolium hexafluorophosphate
ACF—Atomization-based cutting fluid
NFEAL—Nanofluid electrostatic atomization lubrication
AF-ESL—Air flow-assisted electrostatic lubrication
HPC—High-pressure coolant
LN2—Liquid nitrogen
LCO_2—Liquid carbon dioxide
CAMQL—Cryogenic air mixed with MQL
CBN—Cubic Boron Nitride
WC—Tungsten Carbide
PCBN—Polycrystalline cubic boron nitride

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