

Review

Application of Cryogenic Minimum Quantity Lubrication Technology in Different Machining Processing for Titanium Alloys: A Review

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Abstract

Titanium alloys face challenges such as high temperatures, high forces, and tool wear during turning, milling, drilling, and grinding operations. Cryogenic minimum quantity lubrication (CMQL) technology, which combines cryogenic cooling with micro-lubrication, offers an effective solution to these challenges through its synergistic mechanism of heat suppression via cooling and friction reduction via lubrication. This paper first elucidates the cooling and lubrication principles of various CMQL technologies and their adaptability process. It then reviews CMQL applications across four titanium alloy machining processes, systematically analyzing their effects on cutting forces, temperatures, tool wear, surface integrity, and chip morphology. Research indicates that CMQL technology demonstrates universal advantages over minimum quantity lubrication (MQL) across diverse titanium alloy machining processes. Furthermore, incorporating nanofluids or integrating ultrasonic vibration to form enhanced composite processes can further improve medium permeability, reduce machining loads, and enhance surface quality. Future developments in this field will advance toward intelligent and sustainable directions, providing critical technological support for high-performance green manufacturing of titanium alloys.

Keywords: cryogenic minimum quantity lubrication; clean cutting; titanium alloy; cutting performance; machining processes

1. Introduction

Modern manufacturing serves as the strategic cornerstone of the national economy and national defense security, with its development level directly impacting national competitiveness. In high-end manufacturing sectors such as aerospace, breakthroughs in product performance increasingly depend on the application of new materials. Titanium alloys have become core materials in aerospace, biomedical, and high-end equipment manufacturing due to their exceptional specific strength, outstanding corrosion resistance, and excellent biocompatibility [1–4]. However, their inherent low thermal conductivity, high chemical reactivity, and high strength also make them widely recognized as notoriously difficult-to-machine materials [5]. During conventional machining processes, intense friction and plastic deformation generate highly concentrated cutting heat. Since heat cannot be rapidly dissipated through the workpiece and chips, it primarily accumulates in the minute contact areas between the rake face and the chip, as well as between the flank face and the machined surface, causing cutting temperatures to surge dramatically [6]. This



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high-temperature environment accelerates diffusion wear and oxidation wear of the tool, significantly shortening its service life. It induces phase transformations in the surface layer material of the workpiece or generates residual tensile stresses, compromising the part's fatigue properties and service reliability. Simultaneously, the high temperatures cause titanium chips to adhere readily to the tool edge, forming built-up edges that compromise machining accuracy and surface integrity [7].

To address this challenge, traditional metalworking has widely adopted bulk cutting fluids for cooling and lubrication. However, for titanium alloy machining, this conventional approach faces increasingly severe questions regarding its effectiveness and sustainability [8]. First, bulk cutting fluids struggle to effectively penetrate and reach the enclosed, high-pressure tool-workpiece interface during titanium alloy machining, significantly reducing cooling efficiency. Second, oil mist generated by cutting fluids at high temperatures poses health risks to workers. Their use, handling, and disposal also incur substantial environmental and economic costs, running counter to the global manufacturing industry's mainstream trend toward green and sustainable development [9]. Therefore, exploring a new processing auxiliary technology that offers efficient cooling, precise lubrication, and environmental friendliness has become an urgent bottleneck requiring breakthroughs in the titanium alloy machining industry.

Against this backdrop, Minimum Quantity Lubrication (MQL) technology emerged. By mixing minute quantities of lubricant with compressed air to form a two-phase oil-air flow and precisely spraying it onto the cutting zone, it achieves significant friction reduction with extremely low lubricant consumption [10,11]. However, for the core challenge of heat generation in titanium alloy machining, the cooling capacity of ambient-temperature MQL remains insufficient. Thus, cryogenic minimum quantity lubrication (CMQL) technology, which combines the dual advantages of efficient cooling and precise lubrication, integrates low-temperature media with micro-quantity lubricants [12]. This enables active, precise control over the thermal-mechanical coupling field in the cutting zone, offering a highly promising solution for overcoming the challenges of titanium alloy machining [13].

Despite the immense potential demonstrated by CMQL technology in titanium alloy machining, significant gaps remain in current review studies. A substantial body of literature focuses on the equipment applications, machining principles, and research into the use of various CMQL techniques on different difficult-to-machine materials. However, there is a lack of comparative analysis and cutting performance evaluation across turning, milling, drilling, and grinding processes specifically for titanium alloy materials. This review aims to systematically organize and evaluate the current state of research on the application of CMQL technology in the turning, milling, drilling, and grinding of titanium alloys. The article will first elucidate the cooling and lubrication principles of various CMQL technologies and their process adaptability. The core section will comprehensively analyze the influence patterns and mechanisms of CMQL on cutting/grinding forces, cutting heat, tool wear, surface integrity, and chip morphology during titanium alloy machining for each of the four processing methods. Finally, this paper will identify limitations in existing research and outline future development directions, including technology integration, intelligent control, and sustainability evaluation based on the full life cycle. This aims to provide theoretical references and practical guidelines for advancing the scientific application and in-depth development of this technology in titanium alloy machining. This initiative aims to promote the in-depth application and sustainable development of green manufacturing technologies in the field of titanium alloy processing.

2. CMQL Technology

As the key branch of green machining, cryogenic cutting technology has seen the emergence of various forms, such as cold air, cryogenic liquid nitrogen, liquid carbon dioxide, and supercritical CO₂ [14]. CMQL technology combines low-temperature media with MQL technology, emerging as a common solution for the green and sustainable machining of titanium alloys [15]. This technology achieves dual cooling and lubrication effects by injecting a mixture of cryogenic air, liquid nitrogen, or other cooling media with micro-lubricant mist particles into the cutting zone [16]. On one hand, the cryogenic environment suppresses cutting temperature rise and prevents lubricant degradation due to heat. On the other hand, the penetrating ability of oil mist particles reduces friction between the tool, workpiece, and chips [17,18].

2.1. Cold Air MQL

Cold air minimum quantity lubrication (CA-MQL) Technology combines cold air (−10 °C to −60 °C) with MQL. The minimal quantity lubricant is atomized into micro-sized particles, which are propelled by high-pressure, low-temperature gas and sprayed at high velocity toward the cutting zone [19]. The temperature difference between the cold air and the cutting zone enhances heat transfer. The high-velocity gas flow removes heat and chips from the cutting zone. The atomized particles exhibit excellent penetration and lubricity, reducing cutting forces, minimizing tool wear, and improving workpiece surface quality [20]. CA-MQL devices can be categorized based on their cold air generation methods, including vortex tube refrigeration [21], semiconductor refrigeration [22], compressor refrigeration [23], and composite refrigeration systems [24] that utilize semiconductor refrigeration as the core with compressor refrigeration as auxiliary support. Currently, vortex tube refrigeration is the most common method. This technique utilizes the vortex cooling principle to generate swirling airflow within the tube, separating it into cold and hot streams. The cold air is then directed through the nozzle outlet to achieve cooling effects. The greatest advantage of CA-MQL technology lies in its precise control of medium temperature to accommodate the machining of various ductile metals [25].

Based on this, Table 1 lists the primary findings from researchers applying CA-MQL to various machining processes involving different difficult-to-machine materials, achieving satisfactory cooling and lubrication effects. Interestingly, Zhang et al. [26] addressed the challenge of suboptimal cooling performance in titanium alloy machining caused by high cutting temperatures and limited cold air temperatures. By combining cold air with minimal quantity lubrication using nanofluids, they achieved effective cooling, broadened the cooling range, and improved surface finish. This combination also offers a novel approach for cryogenic machining of difficult-to-cut materials.

Table 1. Application of CA-MQL in Different Difficult-to-Machine Materials and Processes.

References	Materials	Machining Process	Main Works
Zou [27]	3Cr2NiMo steel	Turning	CA-MQL demonstrates significant advantages in enhancing the durability of diamond tools and improving machined surface quality.
Jozic [28]	42CrMo4	Milling	Through grey relational analysis, the optimal combination achieving maximum material removal volume, minimum surface roughness, minimal flank wear, and lowest cutting force component under CA-MQL conditions is determined as: cutting speed 100 m/min, feed per tooth 0.05 mm/tooth, radial depth of cut 2 mm, engagement time of inserts 10 min.

Table 1. *Cont.*

References	Materials	Machining Process	Main Works
Zhang [29]	Zirconia ceramics	Grinding	CA-MQL significantly improves surface quality; the optimized surface roughness achieved through pre-stressing combined with CA-MQL grinding reached 17.12%.
Tasdelen [30]	Precipitation-hardened steel	Drilling	Compared to drilling with emulsion, using MQL plus compressed cold air results in less wear on both the center and peripheral drill bits.

2.2. Liquid Nitrogen MQL

Liquid nitrogen minimum quantity lubrication (LN₂-MQL) technology combines liquid nitrogen (LN₂) at −196 °C with micro-lubrication techniques, synergistically leveraging the cooling effects of liquid nitrogen and the advantages of micro-lubrication. The endothermic phase transition of liquid nitrogen substantially reduces cutting zone temperatures, thereby enhancing tool cutting capacity [31] and effectively suppressing tool diffusion wear and adhesive wear [32]. The minimal quantity of oil-based/water-based lubricants supplied by the MQL system is atomized by liquid nitrogen and transported to the tool-chip and tool-workpiece interfaces under nitrogen atmosphere and cryogenic conditions. This forms a stable lubricating film that significantly reduces friction and adhesion while delaying thermal crack propagation. Given the remarkable cooling performance of LN₂, further enhancing the cooling and lubrication capabilities of LN₂-MQL can be achieved by incorporating nanoparticle cutting fluids to improve LN₂'s lubricating properties [33]. For instance, Sen et al. [34] investigated the combined effects of cryogenic LN₂ and nano-MQL on the machinability of difficult-to-cut high-temperature alloys. Compared to dry cutting, under cryogenic LN₂ and nano-MQL conditions, cutting force, cutting temperature, and surface roughness decreased by 25.49%, 29.84%, and 42.50%, respectively, while tool wear was reduced by 44.55%.

When liquid nitrogen serves as a cooling medium, its reliable transport and precise regulation are critical prerequisites for achieving efficient machining. This requires maintaining liquid nitrogen in a pure liquid state or as a low-gas-content bubble flow during transport while ensuring stable parameters such as flow rate, pressure, and temperature [35]. However, liquid nitrogen's extremely low saturation temperature and small latent heat of vaporization make it susceptible to vaporization due to environmental heat during pipeline transport, severely affecting flow state and parameter stability [36]. Furthermore, the relatively high costs associated with its preparation and storage also constrain its large-scale application to some extent. Therefore, LN₂-MQL technology remains in various experimental research stages, such as its application to different difficult-to-machine materials and process combinations, and the exploration of its synergistic mechanisms and application effectiveness, as detailed in Table 2.

Table 2. Application of LN₂-MQL in Different Difficult-to-Machine Materials and Processes.

References	Materials	Machining Process	Main Works
Gupta [37]	Ti-6Al-4V	Turning	Under LN ₂ + MQL machining conditions, smooth surface quality was achieved, tool wear was reduced, and both specific cutting power and surface hardness were minimized.
Wu [38]	P20 mold steel	Milling	Tool life is maximized and surface quality is optimized in an LN ₂ + MQL environment.

Table 2. Cont.

References	Materials	Machining Process	Main Works
Kishore [39]	Inconel 625	Grinding	Under LN ₂ + MQL conditions, the ground surface exhibits lower skewness and kurtosis parameters, a higher load-bearing area ratio (78.84%), and no grinding burn or redeposition layer formation. Grinding force and temperature remain low, with minimal variation in microhardness.
Sirin [40]	Nickel-based Hastelloy X alloy	Drilling	The cooling capacity of LN ₂ and the lubricating effect of MQL significantly reduced surface roughness, force, torque and tool wear, thus extending tool life.

2.3. Liquid CO₂ MQL

Liquid carbon dioxide minimum quantity lubrication (LCO₂-MQL) technology combines liquid CO₂ with trace lubricants to form a composite jet that delivers both highly efficient cooling and lubrication [41]. Its core advantages include: the latent heat of sublimation of liquid CO₂ (approximately 571.1 kJ/kg) is about three times that of liquid nitrogen vaporization. Micron-sized dry ice particles formed by nozzle expansion absorb heat more intensely during sublimation and can penetrate the tool–chip interface for direct cooling. Additionally, lubricants exhibit excellent solubility in liquid CO₂, facilitating uniform composite mixing and spray delivery [42]. Currently, mixing liquid CO₂ with lubricants predominantly employs external mixing methods. Some studies have developed internal mixing [43] or single-channel internal injection systems [44] by customizing spindles, internally cooled tool holders, and rotary joints. However, the engineering application of this technology faces significant challenges: on one hand, liquid CO₂ must be maintained at pressures exceeding 6 MPa to remain stable during liquid transport, imposing extremely high demands on pipeline sealing and pressure resistance [45]; on the other hand, its preparation, storage, and transportation costs are relatively high, and conventional components are prone to failure under the combined effects of high pressure and low temperature [46]. Therefore, achieving stable and reliable delivery relies on specialized high-pressure insulated piping and sealing devices. The limitations do not diminish the unique potential of LCO₂-MQL in machining difficult-to-cut materials. Table 3 summarizes the exploratory research and findings from relevant scholars who have applied LCO₂-MQL technology across various materials and machining processes.

Table 3. Application of LCO₂-MQL in Different Difficult-to-Machine Materials and Processes.

References	Materials	Machining Process	Main Works
Khanna [47]	Inconel 718	Turning	When LCO ₂ is flown on the rake, whereas EMQL on the flank face, the tool wear, roughness, and energy consumption are significantly reduced compared to other strategies. LCO ₂ -EMQL is the best strategy for creating a balance between both technical and environmental parameters.
Sivalingam [48]	Aluminum hybrid composite material	Milling	LCO ₂ -MQL resulted in the highest overall equipment effectiveness as 95.63% and very low carbon emission of 0.6 kg-CO ₂ under higher cutting speed of 120 m/min and feed rate of 0.1 mm/rev at 1 mm depth of cut.

Table 3. Cont.

References	Materials	Machining Process	Main Works
Santhosh [49]	AISI 4140 Steel	Grinding	LCO ₂ -MQL proved effective in preventing the tempering (softening) of the work material under all the grinding conditions tested.
Grguras [43]	Ti-6Al-4V	Drilling	LCO ₂ -MQL assisted drilling improves chip breakability and reduces the workpiece-material adhesion through combination of lower temperatures and lubrication barrier.

2.4. Supercritical CO₂ MQL

Supercritical CO₂ minimum quantity lubrication (scCO₂-MQL) technology fully leverages the unique physical properties exhibited by supercritical CO₂ (scCO₂) above its critical point: it possesses both the high diffusion coefficient and low viscosity like gases while also featuring the density close to liquids and excellent solubility [50]. This enables scCO₂ to serve as an efficient carrier, forming a uniform and stable mixed medium with lubricating oil. It represents a significant advancement in MQL technology, demonstrating remarkable potential, particularly when machining materials like titanium alloys that pose challenges for conventional MQL systems [51]. To achieve its efficiency-enhancing effect, CO₂ must be maintained above its critical point in terms of temperature and pressure throughout the delivery process, ensuring it remains in a supercritical state and achieves uniform mixing with the lubricating oil [52]. When this mixed medium is ejected from the nozzle into the cutting zone, the sudden pressure drop causes it to rapidly expand, forming a three-phase jet composed of gaseous CO₂, lubricant mist particles, and fine dry ice particles, as shown in Figure 1. This configuration enables synergistic cooling and lubrication functions [53].

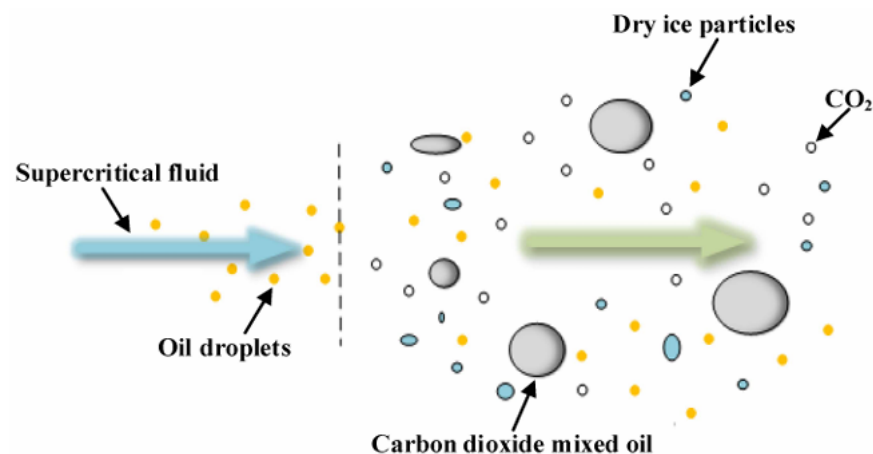


Figure 1. Schematic Diagram of scCO₂-MQL Spray [54].

The typical system comprises three independent reservoirs containing liquid carbon dioxide, vegetable oil, and deionized water, with an air compressor providing the power for atomization. Supercritical carbon dioxide is obtained through a series of processes, including pressurization, heating, and atomization, maintaining minimum pressure and temperature values of 72.8 atm and 31.2 °C, respectively [55]. The vegetable oil and deionized water lubricating media are transported through separate channels to a mixing vessel. Under compressed air pressure, they undergo atomization before combining with scCO₂ at the nozzle. This forms a cryogenic micro-lubrication medium at approximately −78 °C, which is then sprayed onto the machining area [56]. On one hand, the micro-lubricant in scCO₂-MQL reduces tool–chip friction, lowers cutting forces, and delays tool wear [57]. On the other hand, the supercritical carbon dioxide medium in scCO₂-MQL

enhances convective heat transfer effects, significantly reducing cutting temperatures. The scCO₂-MQL technology offers a novel solution for the efficient machining of difficult-to-cut materials [58]. Scholars have conducted extensive research and applied it to various difficult-to-machine materials and different machining processes, as shown in Table 4.

Table 4. Applications and Works of scCO₂-MQL in Different Machining Processes.

References	Materials	Machining Process	Main Works
Huang [59]	Ti-6Al-4V	Turning	In comparison with dry cutting, scCO ₂ , and scCO ₂ -MQL, the cutting temperature drops of supercritical CO ₂ mixed with nanofluid MQL are more than 25%, 15%, and 12%, respectively. The use of scCO ₂ mixed with nanofluid MQL cooling conditions provides lower cutting force and a superior surface finish.
Zhang [60]	Silicon carbide particle-reinforced aluminum matrix	Milling	Under the condition of scCO ₂ -MQL ultrasonic vibration, proper control of milling parameters can significantly reduce tool wear, extend tool service life, improve machining quality, and effectively reduce blade breakage and spalling damage to the tool, reduce abrasive wear and adhesive wear, and thus significantly improve the durability of the tool.
Arafat [61]	100Cr6	Grinding	Grinding forces were lower when using scCO ₂ -MQL compared to emulsion. The impact of grinding wheel porosity on process performance can be balanced by utilizing the scCO ₂ -MQL customization tool.
Guo [62]	CFRP/Ti6Al4V stacks	Drilling	The scCO ₂ cooling strategy can effectively reduce the drilling temperature of the CFRP, interface, and Ti6Al4V by 15%, 72%, and 33%, respectively, compared with the internal air-cooling strategy.

In summary, the four distinct CMQL technologies, CA-MQL, LN₂-MQL, LCO₂-MQL, and scCO₂-MQL, have been applied in various machining processes for different difficult-to-machine materials. The core differences among various CMQL technologies primarily stem from the distinct physical states and phase transition characteristics of different cryogenic media, which result in varying cooling efficiencies. Researchers primarily employed various optimization methods to refine process parameters while conducting comparative evaluations of machining results based on factors such as cutting forces, cutting heat, surface quality, and tool wear. Drawing upon the research of Liu [51] and Jawahir [63], this paper conducts a comparative analysis of CA-MQL, LN₂-MQL, LCO₂-MQL, and CMQL green cutting processes across six dimensions: cooling performance, lubrication performance, surface quality enhancement capability, tool wear reduction capability, economic viability, and sustainability. Performance levels are rated numerically from 1 to 5, where 1 represents the weakest and 5 represents the strongest. The comparison results are presented in Table 5.

Table 5. Performance Comparison Under Different Cooling and Lubrication Conditions.

	CA-MQL	LN ₂ -MQL	LCO ₂ -MQL	scCO ₂ -MQL
Cooling	3	5	4	5
Lubrication	3	2	4	5
Surface quality enhancement	3	4	4	5
Tool wear reduction	3	4	4	5
Economic viability	4	2	3	3
Sustainability	4	3	4	5

3. Application of CMQL Technology in Different Processing Techniques for Titanium Alloys

3.1. Turning

As the most fundamental and typical material removal process for titanium alloys, this section systematically reviews the effectiveness of different CMQL strategies in titanium alloy turning [64]. In the aerospace sector, numerous critical components fabricated from titanium alloys require turning to achieve superior surface integrity. CMQL offers a highly promising new pathway for high-performance and environmentally sustainable titanium alloy turning. The analysis focuses on three critical aspects: cutting forces/heat, tool wear, and surface integrity [65]. Under continuous cutting conditions, the study examines how the synergistic effects of low temperatures and lubrication influence cutting force and heat generation, suppress built-up edge formation, reduce tool diffusion and adhesion wear, and ultimately achieve exceptional surface integrity.

3.1.1. Cutting Force/Heat

In titanium alloy machining, cutting forces directly reflect the energy expenditure for material removal and serve as a key indicator influencing system deformation, vibration, and machining accuracy [66]. Simultaneously, the low thermal conductivity of titanium alloys readily leads to heat accumulation and rapid temperature rise in the cutting zone, subsequently causing tool wear and thermal damage to the workpiece [67]. Cooling and lubrication conditions directly regulate the evolution of cutting forces and heat by altering the friction behavior at the tool-chip/tool-workpiece interface and the material deformation mechanisms.

Gajrani et al. [68] combined MQL with liquid nitrogen (LN₂) in turning operations, achieving a 31% reduction in feed force and a 27% reduction in cutting force at 80 m/min compared to dry cutting, demonstrating synergistic gains from cooling and lubrication. Chen et al. [69] further indicated that cutting edge geometry exerts a more significant influence on force components than cooling methods: When the cutting-edge radius increased from 5 µm to 50 µm, the thrust force F_t rose sharply from approximately 138 N to 504 N, and F_t/F_c increased from 0.37 to 1.1. This indicates that cutting-edge geometry primarily influences cutting forces by altering the degree of plastic deformation in the material. The CMQL strategy for rake faces proposed by Bagherzadeh et al. [70] leverages the phase-change heat absorption and lubrication maintenance of cryogenic oil films to achieve superior temperature reduction compared to pure CO₂ (rake) and the CO₂ (rake) + MQL (flank) hybrid systems. It reduced cutting-zone temperatures by 49% and 18%, respectively, while demonstrating superior control over feed rates and radial forces. Pervaiz et al. [71] found that the impact of plant oil-based CA-MQL on cutting forces is significantly regulated by matching feed rates with oil flow rates. At low feeds, lubrication dominates, substantially reducing cutting forces. However, at higher feed rates, insufficient cooling may cause cutting forces to exceed those of dry cutting. This indicates that CA-MQL's effectiveness stems from a dynamic equilibrium between cooling hardening and lubrication-induced friction reduction, requiring parameter optimization to achieve synergistic effects. Naik [72] employed pulse-assisted cryogenic LN₂-MQL to further reduce cutting forces by 35.19% compared to dry cutting, demonstrating synergistic effects of pulse-enhanced penetration and cryogenic lubrication.

3.1.2. Tool Wear

In titanium alloy turning, tool wear is a critical factor affecting machining economy, efficiency, and stability [73]. The high chemical reactivity and strength of titanium alloys readily lead to various severe failure modes, such as adhesion, diffusion, and crescent

wear [74]. Research indicates that cryogenic micro-lubrication technology can effectively suppress tool wear through the synergistic effects of cooling and lubrication, with its efficacy jointly regulated by cooling strategies, tool geometry, and process parameters.

Hybrid cooling strategies represented by LN_2 combined with MQL exhibit significant advantages. Gupta et al. [37] demonstrated that LN_2 -MQL reduced average tool rear face wear by 36.4% compared to dry cutting and nearly eliminated front face pitting wear. This mechanism stems from liquid nitrogen's intense cooling, suppressing high-temperature diffusion and adhesion, while the MQL oil film reduces interfacial friction. Zhang et al. [75] also confirmed that CA-MQL significantly reduces tool rake face wear and material adhesion, as shown in Figure 2, attributed to the synergistic effects of intense cooling from the cryogenic gas flow and lubrication provided by the oil film. Meanwhile, micro-texture design on tool surfaces can further enhance wear resistance. Su et al. [76] demonstrated that PCD tools with micro-texture exhibit superior anti-adhesion wear performance under CA-MQL conditions. Micro-groove structures can store lubricants, prevent sustained tool-chip contact, and promote chip breaking. They significantly reduce titanium alloy adhesion, particularly at high speeds (175.84 m/min).

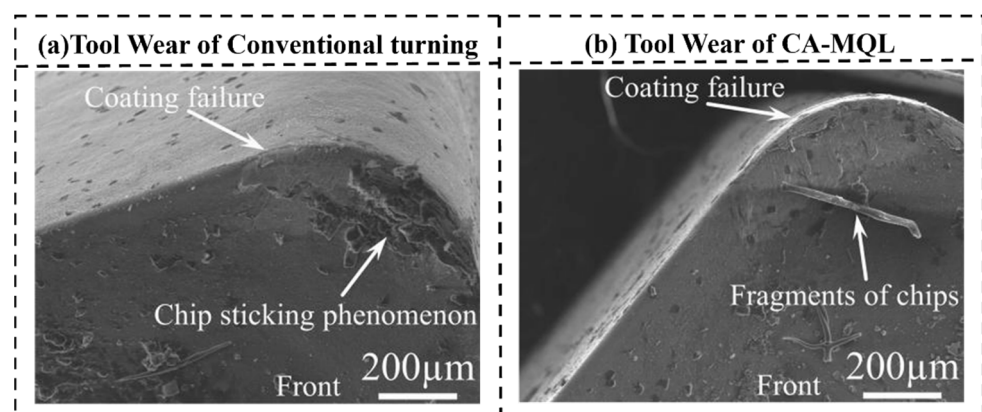


Figure 2. Tool wear of (a) conventional turning and (b) CA-MQL conditions [75].

The anti-wear effect of cooling lubrication strategies is closely related to cutting parameters. Raza et al. [77] found that LN_2 -MQL performed optimally under low cutting parameters, reducing wear by approximately 15.4% compared to conventional cooling. Under high parameters, pure cryogenic cooling demonstrated superior wear control by more effectively suppressing high temperatures in the cutting zone. Lakshmi [78] demonstrated that CA-MQL extended tool life by 60% compared to dry cutting at moderate feed rates (120 mm/min). Naik [72] observed in Ti-3Al-2.5V turning that pulse-assisted cryogenic MQL (PCMQL) reduced tool wear by 47% compared to dry cutting, with shorter pulse duration (0.5 s) further enhancing friction reduction.

3.1.3. Surface Integrity

In titanium alloy machining, surface integrity is critical to determining the service performance of components. Titanium alloys are prone to surface damage such as work hardening, residual tensile stress, and microcracks [79]. Cryogenic micro-lubrication technology can positively influence surface roughness, microstructure, and residual stress by improving thermal-mechanical conditions in the cutting zone, thereby enhancing part reliability and service life. Research indicates that composite cooling and lubrication strategies can significantly optimize surface quality. Gajrani et al. [68] found that at cutting speeds of 80 m/min and 120 m/min, LN_2 -MQL reduced surface roughness (R_a) by 46% and 32%, respectively, compared to dry cutting while also producing shallower work-hardened layers. This indicates that cryogenic cooling suppresses thermal effects while generating

a quenching-like surface strengthening effect. Chen et al. [69] further noted that surfaces processed under LN₂-MQL exhibited the highest hardness, with residual stresses shifting from tensile to compressive. This was primarily attributed to the cryogenic environment suppressing thermally induced tensile stresses, allowing mechanical plowing effects to dominate the stress field. Similarly, Lakshmi et al. [78] observed that, at moderate speeds, CA-MQL improved surface finish by 30% compared to dry cutting and stabilized the machining process by reducing cutting vibration by 40%.

The synergistic effect of different cooling media with auxiliary processes can further enhance surface integrity. Chauhan et al. [80] noted that increasing cutting speed during liquid CO₂ (LCO₂) cooling reduces surface roughness, with its strong cooling effect becoming more pronounced at high speeds. Khan et al. [81] compared that under high-speed, high-removal-rate conditions, LN₂-MQL achieved approximately 6.61% lower surface roughness than mixed nanofluid MQL while offering superior cost-effectiveness. Gupta's [82] research demonstrated that LN₂-MQL pre-cooled using a Ranque-Hilsch vortex tube reduced surface roughness by 77% compared to dry cutting at low feed rates and high speeds. SEM images revealed smoother surfaces with less adhesion, attributed to enhanced medium penetration and heat transfer efficiency from the pre-cooling process. Additionally, auxiliary vibration can further enhance cooling and lubrication effects. Agrawal et al. [83] found that combining MQL with cryogenic ultrasonic-assisted turning (CUMQAT) significantly reduces surface roughness. The intermittent cutting induced by ultrasonic vibration enhances liquid nitrogen penetration, while minimal quantity lubrication reduces friction and adhesion. The synergistic effect of both significantly improves surface finish.

In summary, cryogenic micro-lubrication technology effectively regulates cutting forces and heat during titanium alloy machining through the synergistic effects of cooling and lubrication, thereby suppressing tool wear and enhancing surface integrity. Its comprehensive performance depends on the precise matching of process parameters, optimized design of tool surface texture, and systematic integration of auxiliary measures such as pre-cooling and vibration. Based on the literature review and compilation, the comprehensive application and effects of CMQL in titanium alloy turning processes are summarized in Table 6.

Table 6. Application and Effects of CMQL Technology in Titanium Alloy Turning.

References	CMQL Technology	Evaluation Indicators			Conclusions
		Cutting Force/Heat	Tool Wear	Surface Integrity	
Gajrani [68]	LN ₂ -MQL	✓		✓	Feed force and cutting force reduced by 31% and 27% compared to dry cutting; surface roughness reduced by 46% to 32%.
Chen [69]	LN ₂ -MQL	✓		✓	The thrust force F_t is more sensitive to the cutting-edge radius; LN ₂ -MQL induces compressive residual stresses on the surface.
Bagherzadeh [70]	LCO ₂ -MQL	✓			Lower radial forces and feed forces
Pervaiz [71]	CA-MQL	✓			Cutting forces are regulated by matching feed rates with oil flow rates.
Naik [72]	LN ₂ -MQL	✓	✓		Compared to dry cutting, cutting force is reduced by 35.19%, and tool wear is reduced by 47%.
Gupta [37]	LN ₂ -MQL		✓	✓	Tool wear is reduced by 36.4% compared to dry cutting, and surface roughness is decreased.
Zhang [75]	CA-MQL	✓	✓	✓	Effectively reduces tool wear, lowers cutting forces, and improves surface integrity.

Table 6. Cont.

References	CMQL Technology	Evaluation Indicators			Conclusions
		Cutting Force/Heat	Tool Wear	Surface Integrity	
Su [76]	CA-MQL		✓	✓	Micro-slot tools significantly reduce adhesive wear at high speeds.
Raza [77]	LN ₂ -MQL		✓		Wear is reduced by approximately 15.4% compared to traditional cooling.
Lakshmi [78]	CA-MQL		✓	✓	Tool life increased by 60% compared to dry cutting; surface finished improved by 30%.
Chauhan [80]	LCO ₂ -MQL			✓	Higher cutting speeds produce lower surface roughness.
Khan [81]	LN ₂ -MQL			✓	Surface roughness is approximately 6.61% lower than that of mixed nanofluid MQL.
Gupta [82]	LN ₂ -MQL			✓	Surface roughness reduced by 77% compared to dry cutting.
Agrawal [83]	CUMQAT			✓	Significantly reduces surface roughness.

3.2. Milling

Unlike traditional continuous cutting turning processes, milling represents a typical intermittent cutting operation. The tool periodically enters and exits the workpiece, causing dynamic and severe fluctuations in cutting zone temperature, stress, and tool loading conditions, accompanied by significant cyclic thermal shocks and high-frequency mechanical impacts [84]. This intermittent, non-steady state cutting behavior complicates the thermo-mechanical coupling dynamics during titanium alloy milling, accelerating tool wear, inducing work hardening, and degrading surface integrity [85]. CMQL technology holds promising application prospects for milling titanium alloys. This section systematically reviews the influence patterns and underlying mechanisms of various CMQL techniques on cutting forces, cutting heat, tool wear, and surface integrity during titanium alloy milling. This analysis aims to reveal the optimization pathways and performance boundaries of cooling and lubrication strategies under interrupted cutting conditions.

3.2.1. Cutting Force/Heat

During titanium alloy milling, cutting forces exhibit significant dynamic fluctuations that directly impact system stability and machining accuracy. Simultaneously, alternating thermal loads readily induce thermal fatigue and undesirable microstructural transformations [86]. Research indicates that low-temperature micro-lubrication technology can effectively synergistically regulate both cutting forces and temperature. Multiple cryogenic lubrication strategies exhibit distinct characteristics in experiments. Rauf et al. [87] found that in ultrasonic-assisted milling, cutting forces were lowest under MQL conditions, reduced by 33.49%, 16.93%, and 4.91% compared to dry cutting, water immersion, and LN₂ conditions, respectively. Shi et al. [88] indicated that combining supercritical CO₂ with oil-water-based MQL (scCO₂-OoWMQL) significantly suppressed temperature rise, reducing maximum cutting temperatures by up to 66.58% compared to dry cutting under specific parameters. This advantage stems from multiple mechanisms: high pressure and low temperature, phase-change heat absorption, and stable lubrication film. Cai et al. [89] further revealed that while pure cryogenic cooling reduces temperatures, it increases average cutting forces by approximately 49% due to material work hardening. In contrast, scCO₂-OoWMQL achieves synergistic cooling and lubrication, maintaining effective temperature reduction while lowering average cutting forces by about 28%. In the milling of thin-walled components, the penetration capability of cutting fluid is particularly critical. Research by He et al. [90] demonstrated that LCO₂ + MQL, due to its high density and low

viscosity, penetrates more effectively into the core cutting zone. This resulted in an average reduction of 32.8% in the milling combined force and a significantly lower maximum surface temperature rise (181.7 °C) compared to CA + MQL (236.1 °C), as shown in Figure 3. Park et al. [91] also confirmed that the combination of LN₂ and MQL effectively reduces cutting forces even at high speeds.

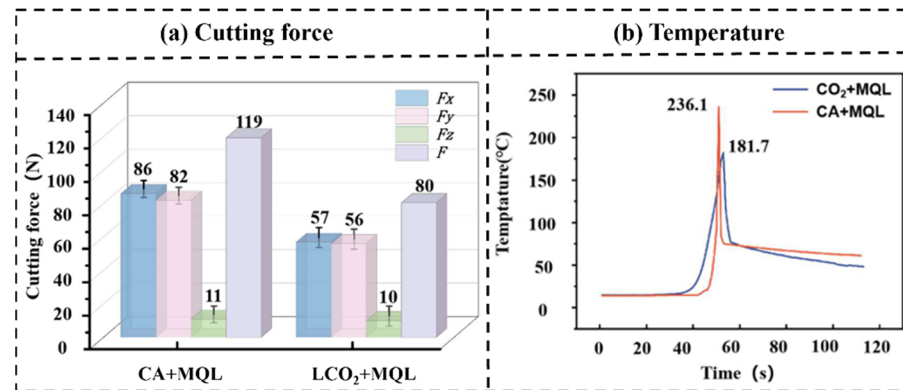


Figure 3. (a) Cutting force, (b) Temperature under two working conditions [90].

3.2.2. Tool Wear

In titanium alloy milling, tool wear is a complex result of combined mechanical, thermal, and chemical effects, often manifesting as composite forms such as front/back face wear and edge chipping [92]. Research indicates that a combined strategy of low-temperature cooling and minimal quantity lubrication can effectively suppress wear through synergistic effects, with the outcome dependent on the specific combination of technologies and matching process parameters. Research indicates that single-fluid cooling may exacerbate wear due to insufficient lubrication. AN et al. [50] found that while pure scCO₂ cooling significantly reduced temperatures in side milling, it increased tool wear by 111% compared to dry cutting. Conversely, scCO₂-OoWMQL effectively suppressed wear and stabilized cutting torque. Rauf et al. [87] further noted in ultrasonic-assisted milling that tool wear under MQL conditions decreased by 26.43%, 9.48%, and 5.17% compared to dry cutting, water immersion, and LN₂ cooling, respectively. Among these, cutting speed emerged as the parameter exerting the most significant influence on wear. The rational matching of process parameters is fundamental to achieving effective composite cooling and lubrication. Noor et al. [93] noted that nano-composite LCO₂-MQL can extend tool life by approximately 50% under optimal parameters. However, excessively high feed rates can rapidly induce severe wear, indicating that thermal loads must be controlled within the system's cooling and lubrication capacity. The penetration and synergistic mechanisms of lubricating media are crucial for wear control. Ha et al. [94] employed a dual-fluid atomizing nozzle to co-inject cryogenic CO₂ with MQL, achieving tool life three times that of pure MQL while maintaining stable wear at cutting volumes up to 28,800 mm³. Song et al. [95] integrated MQL oil mist with cryogenic CO₂ into a single fluid via a mixing nozzle, achieving 800 mm of cutting distance without failure. Their synergistic penetration effectively reduced temperatures and suppressed interfacial adhesion. Armin et al. [96] further demonstrated that the scCO₂-MQL strategy reduced tool edge wear by over 190% in precision dental machining, significantly outperforming conventional emulsion cooling.

3.2.3. Surface Integrity

In titanium alloy milling, surface integrity directly determines the final service performance of components, which are susceptible to defects such as surface waviness and residual tensile stresses caused by dynamic loads and thermal cycling [97]. CMQL technol-

ogy enables synergistic control of cutting heat and force at the source, thereby systematically improving surface quality. Multiple composite cooling lubrication strategies have demonstrated positive effects. Shokrani et al. [98] found that applying MQL and LN₂-MQL in milling significantly improved surface quality, with MQL delivering optimal and stable surface roughness. The Ra value remained around 0.2 µm even at higher speeds, attributed to its continuous lubrication, effectively suppressing adhesion and abrasive wear. Research by Shi et al. [88] indicates that employing scCO₂-OoWMQL technology significantly reduces three-dimensional surface roughness (Sa). At higher parameters, it achieves a 21.65% reduction compared to dry cutting while effectively controlling surface defects such as built-up edges and material remelting, resulting in clearer and more regular surface textures. In terms of regulating residual stresses and surface microstructure, synergistic cooling lubrication demonstrates unique advantages. Ju et al. [99] found that combining nanofluid MQL (NF-MQL) with cryogenic LN₂ significantly reduced surface residual stresses to only 22 MPa at 80 m/min. This resulted from cryogenic temperatures suppressing thermally induced tensile stresses, while nanofluid lubrication reduced mechanical shear stresses. Their synergistic effect promoted the stress field toward a stable compressive stress state. Li et al. [100] further confirmed that the scCO₂-MQL process induces favorable surface residual compressive stress during TC11 titanium alloy milling and significantly suppresses work hardening. Both surface microhardness and hardening layer depth were lower than those in dry cutting, attributed to the technology's effective reduction of thermo-mechanical coupling intensity during machining.

In titanium alloy milling, the phase change heat absorption and enhanced penetration of cryogenic media in micro-lubrication technology can significantly reduce cutting temperatures and suppress thermal damage. Combined with its lubricating and friction-reducing effects, this approach avoids the increased cutting forces caused by single-source intensive cooling, achieving dual control over force and heat [96]. Cooling suppresses heat generation while lubrication reduces interfacial adhesion. Enhanced medium penetration via dual-fluid or hybrid nozzles, coupled with optimized cutting parameters, effectively delays tool wear and substantially extends tool life. Additionally, this technology improves surface morphology and roughness, promotes residual stress transformation from tensile to compressive, and suppresses work-hardening layers, thereby comprehensively enhancing machined surface integrity. Based on the literature review and compilation, the comprehensive application and effects of CMQL in titanium alloy milling processes are summarized in Table 7.

Table 7. Application and Effects of CMQL Technology in Titanium Alloy Milling.

References	CMQL Technology	Evaluation Indicators			Conclusions
		Cutting Force/Heat	Tool Wear	Surface Integrity	
Rauf [87]	ultrasonic-assisted MQL	✓	✓		Minimum cutting force and minimum tool wear under MQL conditions.
Shi [88]	scCO ₂ -OoWMQL	✓		✓	Cutting temperature reduction reached 66.58%; Surface roughness reduction reached 21.65%.
Cai [89]	scCO ₂ -OoWMQL	✓			scCO ₂ -OoWMQL reduces cutting forces by approximately 28% and provides excellent cooling performance.
He [90]	LCO ₂ + MQL	✓			Milling force reduced by 32.8%, average temperature decreased.
Park [91]	LN ₂ -MQL	✓			Effectively reduce cutting forces at high cutting speeds.
AN [50]	scCO ₂ -OoWMQL		✓		scCO ₂ -OoWMQL can suppress tool wear.

Table 7. Cont.

References	CMQL Technology	Evaluation Indicators			Conclusions
		Cutting Force/Heat	Tool Wear	Surface Integrity	
Noo [93]	LCO ₂ -MQL		✓		Tool life increased by approximately 50% under optimal parameters.
Ha [94]	LCO ₂ -MQL		✓		Tool life is three times that of pure MQL.
Song [95]	LCO ₂ -MQL		✓		Tool wear remains stable.
Armin [96]	scCO ₂ -MQL		✓		Side wear of cutting tools reduced by over 190%.
Shokrani [98]	LN ₂ -MQL		✓	✓	MQL stabilizes surface roughness Ra at approximately 0.2 µm, cryogenic suppress thermal wear.
Ju [99]	LN ₂ +NF-MQL			✓	Surface residual stress is minimized, reduced by approximately 76.6% compared to pure cryogenic conditions.
Li [100]	scCO ₂ -MQL			✓	The surface exhibits residual compressive stress, significantly suppressing work hardening.

3.3. Drilling

As a critical structural material in aerospace applications, titanium alloys pose significant challenges during drilling operations. The material's inherent low thermal conductivity and high strength generate substantial thermal loads during machining, leading to severe fluctuations in drilling forces and torque [101]. These fluctuations directly compromise process stability and dimensional accuracy. Concurrently, the combined effects of accumulated cutting heat and high mechanical stresses dramatically accelerate tool wear mechanisms such as adhesion and diffusion, severely limiting machining efficiency and economic viability [102]. Ultimately, these dynamic thermo-mechanical processes profoundly affect hole dimensional accuracy, surface integrity, and subsurface quality, factors directly impacting component joint reliability and service life.

3.3.1. Drilling Force/Torque

In titanium alloy drilling, the effects of different cooling and lubrication strategies on cutting forces (thrust), torque, and temperature exhibit complex and sometimes contradictory characteristics [103]. Their outcomes are highly dependent on material type, specific technology combinations, and process parameters. MQL technology typically demonstrates significant advantages in reducing cutting forces during titanium alloy drilling operations. Bhowmick et al. [104] found that compared to conventional flood cooling, MQL reduced drilling torque by approximately 35% and controlled the maximum drilling temperature at 152 °C. Chen et al. [105] also observed minimal thrust forces under MQL conditions during small-hole drilling of β -type Ti-Zr-Nb alloys. Iqbal et al. [106] conducted drilling experiments under various conditions, finding that low-temperature CO₂ and MQL produced lower axial forces. Dalke [107] reduced thrust and torque by approximately 21% and 12%, respectively, through optimized MQL parameters. Xu [108] confirmed that MQL reduces torque and specific cutting power when drilling CFRP/Ti6Al4V laminated materials.

The effect of cryogenic cooling on cutting forces exhibits dual characteristics. On one hand, pure cryogenic cooling often leads to a significant increase in thrust force. Grguras [109] found that LCO₂ cooling increased thrust by 42% compared to dry cutting, with higher thrust at greater flow rates. Additionally, pure LCO₂ reduced torque by approximately 20%. Chen et al. [105] and Percin [110] also noted that cryogenic cooling can increase thrust or maximize it due to material cold hardening and poor gas permeability. Iqbal et al. [106] reported that cryogenic LN₂ cooling produced the highest axial force. Conversely, cryogenic cooling excels at reducing torque and improving chip evacuation.

Shah et al. [111] reported the lowest thrust and torque under LCO₂ conditions, reduced by 75.3% and 333%, respectively, compared to dry cutting. Chealvan et al. [112] demonstrated that high-pressure (22 bar) cryogenic cooling significantly reduces thrust, torque, and temperature by enhancing penetration.

Cryogenic MQL technology demonstrates potential for synergistic optimization. Grguras [109] found that incorporating MQL into LCO₂ further significantly reduced torque (by up to 69%), combining the advantages of cooling and lubrication. Process parameters and tool geometry exert precise control over cutting forces. Kumar et al. [113] identified an optimal MQL flow rate (6 mL/h), noting that excessively high flow rates (100 mL/h) paradoxically increase thrust due to overcooling and droplet impact. Iqbal et al. [106] highlighted that increasing cutting speed reduces axial force, whereas pecking significantly elevates it. Research by Niketh et al. [114] demonstrated that microtextured drill bits can further reduce thrust by 15–19% under MQL conditions. Modeling studies by Zhu et al. [115] revealed that dry cutting may yield the lowest measured thrust and torque due to high temperature softening of the material, but this comes at the expense of tool life and machining stability.

3.3.2. Tool Wear

In titanium alloy drilling, different cooling and lubrication strategies exhibit significant differences in their effects on tool wear mechanisms and tool life, which are closely related to material properties. For β -type Ti-Zr-Nb alloys, Chen et al. [105] found that the primary wear mechanism is adhesive wear. They indicated that the MQL method maintains the longest tool life and is the most recommended cooling method, while low-temperature cooling increases machining difficulty and is not suitable. In studies of Ti-6Al-4V alloy, different cooling methods yield varying effects. Iqbal et al. [106] found that cryogenic CO₂ cooling, with its moderate temperature (approximately $-72\text{ }^{\circ}\text{C}$), effectively conducts heat and resists adhesion, resulting in the lowest wear. Conversely, cryogenic LN₂ cooling, due to its extremely low temperature (approximately $-197\text{ }^{\circ}\text{C}$), causes thermal shock and severe adhesion, leading to the highest wear. Percin [110] indicated that cryogenic cooling maximally suppresses friction and thermal wear, resulting in minimal wear; MQL wear was intermediate; and dry cutting exhibited the most severe wear. Shah et al. [111] observed that drill wear under cryogenic cooling (LCO₂/LN₂) was uniform, with smooth hole walls, significantly outperforming dry cutting and conventional pouring cooling. Zhu et al. [115] demonstrated that compressed air cooling exhibits the lowest wear due to its efficient chip evacuation and minimal temperature rise.

MQL demonstrates stable performance. Zhang et al. [75] confirmed that CA-MQL significantly reduces drill wear while enhancing machining efficiency and surface quality. Composite cooling lubrication technology exhibits notable synergistic advantages. Grguras [109] found that LCO₂ + MQL produces shorter, more easily evacuated chips, thereby improving machining stability and extending tool life. Khanna et al. [116] also strongly supported the effectiveness of combined technologies, demonstrating that LCO₂ cryogenic cooling significantly outperformed electrostatic MQL (EMQL) in key metrics, extending tool life by approximately 416%. Furthermore, chip morphology directly correlates with machining conditions and wear, as shown in Figure 4. Studies consistently indicate [105,109,110] that dry cutting and pure cryogenic cooling tend to produce long, irregular chips prone to clogging, which exacerbates wear. Conversely, MQL, hybrid technologies, and adequate cooling promote chip fragmentation and smooth evacuation, thereby protecting tools.

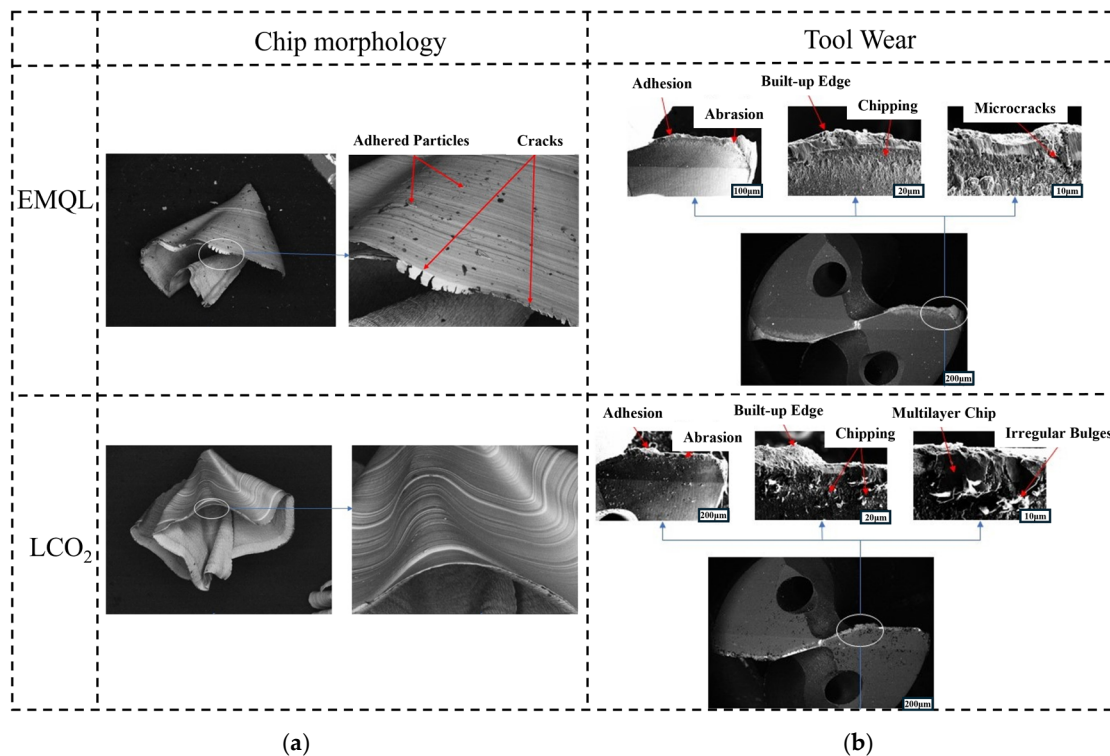


Figure 4. (a) Chip morphology, (b) Tool wear under LCO₂ and EMQL conditions [116].

3.3.3. Hole Quality

In titanium alloy drilling, surface quality and hole integrity are significantly influenced by cooling lubrication strategies, with diverse outcomes observed across different techniques. MQL consistently demonstrates superior and stable performance in reducing surface roughness [117]. Studies by Bhowmick et al. [104], Chen et al. [105], and Iqbal et al. [106] all confirm that optimal surface finish is achieved under MQL conditions. This mechanism stems from the stable lubricating film effectively reducing friction, inhibiting material adhesion, and suppressing built-up edge formation. Kumar et al. [113] further discovered an optimal MQL flow rate (6 mL/h), with both lower and higher rates leading to deteriorated surface quality. Paulsen et al. [118] noted that combining MQL with low-frequency vibration helps generate beneficial residual compressive stresses in the subsurface layer, enhancing fatigue performance. Through parameter optimization, Dalke [107] further reduced surface roughness by 26% using MQL. Xu's [108] research demonstrated that MQL significantly improves bore wall quality and suppresses burrs when drilling CFRP/Ti6Al4V laminated materials. Zhang et al. [75] also reported that CA-MQL reduced internal bore surface roughness by 42% compared to conventional drilling. The effect of cryogenic cooling on surface quality is more complex, closely related to the type of medium, temperature, and pressure. Shah et al. [111] found that LCO₂ cryogenic cooling achieves the best surface quality, with a roughness 94.44% lower than dry cutting, while LN₂ cryogenic cooling performs better in improving hole roundness and cylindricity. However, studies by Iqbal et al. [106] and Ahmed et al. [119] indicate that LN₂ cooling often results in the worst surface roughness due to thermal shock and material adhesion while also degrading hole geometric accuracy. Percin's [110] observations also support the finding that cryogenic cooling produces relatively high surface roughness, approaching dry cutting results.

Composite technology and process optimization are effective approaches to enhancing surface integrity. Chealvan et al. [112] demonstrated that high-pressure (22 bar) cryogenic cooling significantly enhances medium penetration, thereby simultaneously im-

proving surface roughness and hole geometric accuracy during high-speed drilling while minimizing the influence of feed rate. Zhang et al. [75] similarly demonstrated the synergistic advantages of CA-MQL in enhancing surface quality and machining efficiency. Additionally, studies revealed other critical factors: Karabulut [120] proposed that the heat + MQL method reduces cutting forces but compromises surface quality due to elevated temperatures; Iqbal et al. [106] and Percin [110] both found that pecking machining often degrades surface quality; Percin [110] further emphasized that adequate cooling lubrication is crucial for preventing subsurface thermal softening and maintaining microstructural stability.

To achieve synergistic optimization of surface quality, cutting force and thermal management, tool wear control, and subsurface integrity during titanium alloy drilling, systematic consideration of matching and innovative cooling lubrication strategies is essential. MQL demonstrates robust performance in reducing cutting forces, suppressing adhesive wear, and achieving excellent surface finish due to its superior anti-friction capabilities, though its cooling capacity remains limited. Pure cryogenic cooling (especially liquid CO₂) delivers powerful temperature reduction and may improve hole form accuracy, but it often carries the risk of increased thrust forces. It is also sensitive to material properties (such as β -type alloys without cryogenic brittleness) and penetration conditions. The application of extremely cryogenic LN₂ requires even greater caution. Research indicates that effective chip control is the key process linking these performance aspects. Dry cutting and pure cryogenic cooling tend to produce long chips prone to clogging, exacerbating wear. Conversely, MQL and hybrid technologies promote chip fragmentation and smooth evacuation, thereby protecting tools. Therefore, a hybrid strategy combining cryogenic media with MQL, supplemented by high-pressure delivery to enhance penetration, optimized process parameters, and the application of textured tools, emerges as a critical development direction. This approach synergistically manages the force–heat–wear–surface trade-offs, counters high thermomechanical loads, and safeguards subsurface integrity. Based on the literature review and compilation, the comprehensive application and effects of CMQL in titanium alloy milling processes are summarized in Table 8.

Table 8. Application and Effects of CMQL Technology in Titanium Alloy Drilling.

References	CMQL Technology	Evaluation Indicators			Conclusions
		Drilling Force/Torque	Tool Wear	Hole Quality	
Bhowmick [104]	MQL	✓		✓	MQL reduces drilling torque by approximately 35%, significantly lowers maximum drilling temperatures, and achieves optimal surface roughness.
Chen [105]	MQL	✓	✓	✓	MQL minimizes cutting force, tool wear, and surface roughness.
Iqbal [106]	LCO ₂ , LN ₂ , MQL	✓	✓	✓	MQL achieves the best surface quality, while cryogenic CO ₂ cooling results in the lowest tool wear.
Dalke [107]	MQL	✓		✓	Thrust decreased by approximately 21%, torque decreased by approximately 12%, and surface roughness decreased by approximately 26%.
Xu [108]	MQL	✓		✓	MQL reduces drilling torque and improves the surface quality of CFRP hole walls.
Grguras [109]	LCO ₂ + MQL	✓	✓	✓	LCO ₂ increases thrust but may reduce torque. After adding MQL, torque decreased significantly by 69%, resulting in extended tool life.

Table 8. Cont.

References	CMQL Technology	Evaluation Indicators			Conclusions
		Drilling Force/Torque	Tool Wear	Hole Quality	
Percin [110]	cryogenic, MQL	✓	✓	✓	MQL achieves maximum initial engagement torque and minimal tool wear at cryogenic, but results in higher roughness surface.
Shah [111]	LCO ₂ , LN ₂	✓	✓	✓	Under LCO ₂ conditions, thrust and torque are minimized, with surface roughness reduced by 94.44% compared to dry cutting. Under cryogenic cooling, drill wear is uniform with no built-up edge formation.
Chealvan [112]	LN ₂	✓		✓	High-pressure LN ₂ effectively enhances coolant permeability, significantly reducing thrust, torque, and temperature. Hole quality is markedly improved.
Kumar [113]	MQL	✓		✓	Minimum thrust and optimal surface finish achieved at the MQL flow rate of 6 mL/h.
Niketh [114]	MQL	✓			Microtextured drill bits reduce thrust by 15–19% under MQL conditions.
Zhu [115]	MQL	✓	✓		Compressed air provides the most effective cooling, resulting in the lowest thrust and torque during dry drilling, and causing the least tool wear under compressed air conditions.
Khanna [116]	LCO ₂ , EMQL		✓	✓	LCO ₂ significantly outperforms EMQL across all machinability metrics: hole roughness reduced by 42% to 71%, and tool life extended by approximately 416%.
Paulsen [118]	MQL			✓	MQL effectively reduces deformation and tensile stress while generating higher compressive stress.
Ahmed [119]	LN ₂	✓		✓	Cutting temperature has decreased significantly, but cutting force has increased, roughness has deteriorated, and hole quality has declined.

3.4. Grinding

In high-end manufacturing sectors such as aerospace and medical devices, the stringent demands for dimensional accuracy and surface properties in titanium alloy components make their final machining highly dependent on grinding processes. However, the inherent low thermal conductivity, high chemical reactivity, and high strength of titanium alloys transform the grinding process into an extremely challenging thermal–mechanical coupling environment [121]. The intense fluctuations in grinding forces not only directly impact the stability of the process system and machining accuracy but also directly reflect the material's severe plastic deformation and high energy consumption. Simultaneously, the heat accumulated within the confined grinding zone, which is difficult to dissipate, causes grinding temperatures to easily exceed critical thresholds [122]. This not only leads to thermal damage such as surface burning and phase transformations on the workpiece but is also the primary source inducing harmful residual tensile stresses. Ultimately, the complex interaction between grinding forces and heat, coupled with the resulting rapid wheel wear, collectively determines the critical surface integrity of the workpiece [123]. This includes micro-topography, surface microstructure, and residual stress state, factors that directly dictate a component's fatigue strength, corrosion resistance, and long-term service reliability.

3.4.1. Grinding Force/Temperature

In titanium alloy grinding, different cooling lubrication technologies significantly influence grinding forces, temperatures, and machining efficiency, with effects varying based on specific technology combinations, process parameters, and material types. Research indicates that MQL is generally effective in reducing grinding forces. Jha et al. [124] found that pure oil MQL can significantly lower grinding forces, even below those achieved with conventional overflow cooling, making it a viable alternative. Naskar [125] further indicated that pure oil MQL effectively suppresses grinding force increases at low-to-medium speeds (≤ 40 m/s), outperforming water-based coolants. Singh [126] observed in Grade I titanium alloy grinding that MQL combined with pneumatic nozzles achieves the lowest grinding forces and force ratios (maintained at 0.24–0.34). The combined technology of low temperature and MQL demonstrates significant synergistic advantages. Liu [127] demonstrated that CA-MQL significantly reduces normal force, tangential force, specific grinding energy, and temperature, with overall performance superior to using CA or MQL alone. Zhang et al. [128] theoretically and experimentally confirmed that the comprehensive cooling and lubrication performance of CA-MQL surpasses that of cold air or MQL acting independently. Mahata [129] discovered that combining SQL (Small Quantity Lubrication) with liquid CO₂ significantly reduces grinding forces and improves the grinding ratio, outperforming liquid CO₂ alone. Singh [130] employed a hybrid system combining MQL with liquid CO₂ jets, confirming its ability to substantially reduce grinding forces through synergistic effects. The effects of pure cryogenic cooling are more complex. Research by Elanchezhian et al. [131] indicates that LN₂ cryogenic cooling can significantly reduce tangential force, normal force, and grinding temperature while improving surface quality. However, Mahata [129] also notes that using liquid CO₂ cooling alone may result in slightly higher grinding forces than dry grinding due to material cold hardening. Exploration of novel cooling and lubrication processes has also yielded positive results. The CNMQL method (cold air + nanofluid MQL) proposed by Zhang [26] minimized grinding zone temperatures by optimizing the cold air fraction (optimally set at 0.35). A novel process combining low-temperature air and bio-lubricants proposed by Liu et al. [127] significantly reduces multiple metrics including normal force, tangential force, and specific grinding energy. Zou [132] further decreased tangential force and temperature while improving grinding efficiency by applying MQL with carbon nanotube additives in belt grinding. Process parameters significantly influence grinding forces. Jha et al. [124] noted that increasing the undercut depth leads to a marked rise in both grinding force and specific grinding energy. Naskar's [125] research revealed the impact of wheel speed on MQL effectiveness, showing that pure oil MQL still increases grinding force by 20–40% at high speeds (60 m/s). Zhang [26] systematically elucidated the influence of cold air fraction on the physical properties (viscosity, contact angle) and delivery flow rate (14.4 to 29.1 m³/h) of nanofluids, which directly relates to the overall effectiveness of cooling lubrication. Elanchezhian et al. [131] further discovered that nozzle angle (optimally 45°) significantly impacts the performance of liquid nitrogen cooling.

3.4.2. Surface Integrity

In titanium alloy grinding, surface quality (including roughness, morphology, residual stress, and microstructure) is significantly influenced by cooling lubrication strategies. Multiple studies indicate that MQL delivers stable performance in achieving good surface finish [133]. Jha et al. [124] found that surface roughness under MQL approached and was only marginally inferior to that of optimal overflow cooling ($R_a \approx 0.4$ μm), with reduced redeposition. Ronoh [134] demonstrated through optimization experiments that MQL (particularly sunflower oil-based) outperforms wet cooling in achieving high surface

hardness and optimal morphology. Further studies by Singh [126] and Zou [132] confirmed that MQL, especially when combined with pneumatic nozzles or applied in belt grinding, achieves the lowest surface roughness parameters and promotes smoother, more complete surfaces. Zou [132] additionally observed that MQL-assisted grinding formed a fine, uniform dual-phase microstructure, contributing to enhanced fatigue strength.

The combined technology of MQL and cryogenic media demonstrates synergistic advantages in enhancing surface quality. Singh [130] found that a hybrid system integrating MQL with liquid CO₂ jets achieved the lowest Ra value (approximately 0.32 µm) with surfaces free of cracks and pits. Mahata [129] observed that combining SQL or soapy water MQL with liquid CO₂ significantly reduces surface roughness while achieving optimal surface quality and chip morphology. The process proposed by Liu et al. [127], utilizing cryogenic air combined with bio lubricants, also markedly improves multiple metrics, including surface roughness. Notably, specific cryogenic cooling techniques also demonstrate potential for improving surface quality. Research by Elanchezhian et al. [131] confirmed that liquid nitrogen (LN₂) cryogenic cooling can significantly reduce surface roughness (by up to 38%), with optimal results achieved at a 45° nozzle angle. However, the effectiveness of these techniques is influenced by process parameters and comparative benchmarks. Naskar [125] noted that pure oil MQL effectively controls surface redeposition and residual stresses at low-to-medium speeds, ensuring surface integrity, but its efficacy diminishes with increasing speed. Kuo et al. [135] emphasized that grinding speed is the most significant factor affecting surface quality. Concurrently, other studies observed that under certain conditions, MQL effectiveness may diminish [124], or dry grinding may achieve lower roughness due to a polishing effect caused by wheel blunting [129].

In summary, during titanium alloy grinding, MQL serves as a reliable strategy for reducing grinding forces and enhancing machining stability due to its exceptional anti-friction capabilities. It also represents an effective choice for achieving superior surface quality (often surpassing traditional wet cooling). To achieve synergistic optimization of grinding forces, temperature, and surface integrity, combining MQL with cryogenic media (such as CO₂, cold air, or LN₂) represents a key technological direction. This strategy leverages the synergistic effects of cooling and lubrication to further improve surface roughness and morphology while enabling superior integrated force–heat control. However, while pure cryogenic cooling (LN₂) proves effective under specific conditions, its potential to induce material hardening effects warrants careful consideration. Based on the literature review and compilation, the comprehensive application and effects of CMQL in titanium alloy milling processes are summarized in Table 9.

Table 9. Application and Effects of CMQL Technology in Titanium Alloy Grinding.

References	CMQL Technology	Evaluation Indicators		Conclusions
		Grinding Force/ Temperature	Surface Integrity	
Jha [124]	MQL	✓	✓	Significantly reduces grinding force, with roughness approaching that of overflow cooling. Residual stress conditions are dominated by thermal effects.
Naskar [125]	MQL	✓	✓	Pure oil MQL effectively suppresses grinding force increase and grinding wheel wear, with minimal surface resurfacing on workpieces.
Singh [126]	MQL	✓	✓	Achieved the lowest grinding force and force ratio, resulting in the best surface roughness.
Liu [127]	CA-MQL	✓	✓	Compared to dry grinding, the normal force, tangential force, specific grinding energy, and temperature are significantly reduced.

Table 9. Cont.

References	CMQL Technology	Evaluation Indicators		Conclusions
		Grinding Force/ Temperature	Surface Integrity	
Zhang [128]	CA-NFMQL	✓		The maximum temperature in the grinding zone varies with the fraction of cold air.
Mahata [129]	LCO ₂ + MQL	✓	✓	Compared to dry grinding and single-fluid CO ₂ , it significantly reduces grinding force, optimizes chip morphology, and improves workpiece surface quality.
Singh [130]	LCO ₂ -MQL	✓	✓	Significantly reduces grinding force and achieves the lowest surface roughness Ra value (approximately 0.32 µm).
Elanchezhian [131]	LN ₂	✓	✓	Compared to conventional wet grinding, tangential force is reduced by 8% to 27%, normal force is reduced by 3% to 12%, grinding zone temperature is lowered by approximately 55%, and surface roughness is reduced by 38%.
Zhang [26]	CA-MQL	✓		CA-MQL exhibits synergistic reinforcement effects, minimizing both tangential and normal grinding forces.
Zou [132]	MQL	✓	✓	MQL effectively controls grinding temperature and reduces grinding forces, stabilizing surface roughness at approximately Ra 0.4 µm.
Ronoh [134]	MQL		✓	Cooling technology is the most significant factor affecting surface hardness, with MQL outperforming wet cooling.
Kuo [135]	MQL	✓	✓	Grinding speed is the most significant factor affecting material removal rate and surface quality.

4. Conclusions

This paper systematically reviews the cooling lubrication mechanisms and machining adaptability of four distinct CMQL technologies, CA-MQL, LN₂-MQL, LCO₂-MQL, and CMQL, and conducts a comparative analysis of these technologies based on green sustainable machining performance metrics. The paper then reviews the application of CMQL technology in titanium alloy machining, highlighting its universal advantages across various processes by suppressing thermal damage through cooling and reducing interface friction via lubrication. In turning operations, CMQL enables continuous and stable control of heat accumulation and interface friction. Its synergistic effects are further enhanced by optimizing cool delivery positions and methods, integrating them with advanced tooling technologies, and refining machining parameters. For milling processes, CMQL excels in countering transient thermal shocks and improving coolant penetration during intermittent cutting through high-pressure, supercritical fluids, and specialized nozzle designs. In drilling, CMQL achieves stable machining through a systematic approach that leverages lubrication for chip breaking, provides cryogenic intensive cooling, and aids chip evacuation. During grinding, CMQL penetrates the grinding vapor barrier layer via jets while cryogenic lubrication synergistically controls thermal loads. This enables intensive cooling and effective lubrication in the grinding zone, ensuring surface integrity. Maximizing the effectiveness of CMQL in titanium alloy machining is a systematic endeavor that requires integrated matching and optimization of cutting tools (geometry, texture, etc.), process parameters (speed, feed rate, etc.), medium characteristics (type, pressure, flow rate, etc.), and delivery strategies (pulse, position, etc.).

Current research demonstrates the tremendous potential of CMQL in enhancing machining performance. Future developments in this field will follow two major trends: First, intelligent and adaptive processes will leverage machine learning and artificial

intelligence to achieve dynamic optimization and real-time control of process parameters. This will establish intelligent decision-making systems to maximize CMQL's effectiveness across diverse process environments. Second, the pursuit of sustainable and refined technologies. This involves continuous development of eco-friendly nanofluids and bio-lubricants, precise control over the physical parameters of lubricants (such as particle size and concentration), and in-depth investigation of synergistic effects with tool microstructure and coatings. Ultimately, by advancing cooling lubrication technology toward greater intelligence, precision, and sustainability, a robust foundation will be established for high-performance, green manufacturing of challenging materials like titanium alloys.

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