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Review article

State-of-the-art hybrid lubrication (Cryo-MQL) supply systems, performance evaluation, and optimization studies in various machining processes

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ABSTRACT

Despite offering significant advantages in machining, cutting fluids have contributed to substantial environmental concerns. Dry machining, although considered a more environmentally friendly option, falls short in providing effective solutions for processing difficult-to-cut materials. Consequently, extensive research is underway to explore alternative greener machining solutions such as Minimum Quantity Lubrication (MQL), cryogenics, vegetable-based fluids, and hybrid strategies like Cryo-MQL. Among them, Cryo-MQL lubrication combines two sustainable machining techniques that have been widely adopted to improve the machinability of difficult-to-cut materials. This paper reviews published articles over the last six years to provide a comprehensive analysis of the current literature related to Cryo-MQL techniques, its supply systems, machinability evaluation, and optimization studies compared to other cooling and lubrication methods. Results, summarized based on reviewed articles, suggest that Cryo-MQL is an effective technique for improving the machinability of many difficult-to-cut materials in comparison to other cooling/lubrication environments. A comprehensive discussion on different supply systems; external, internal, and hybrid, for delivering Cryo-MQL mediums has also been presented in this review. It was found that hybrid technique offers favorable lubrication and cooling conditions, and advantageous in reducing the machining heat and enormous temperature. Therefore, its application can enhance the metal cutting process and benefit the manufacturing sector. Lastly, the parametric optimizations of cryogenic and MQL agents in hybrid technology can substantially improve lubrication and cooling effectiveness, leading to better surface finish, tool life, reduced cutting forces, and lower machining temperatures.

1. Introduction

Machining is the most broadly utilized manufacturing process to produce numerous mechanical components for automotive, aircraft, defense, and tool manufacturing industries. This process inevitably involves tremendous heat due to friction and plastic deformation, thus requiring the involvements of lubricants. As excessive heat is undesirable, because it can impact the functionality of both tool and workpiece material [1]. To combat this problem, liquid lubricants including water-based and oil-based, were employed in manufacturing industries to lubricate the tool and workpiece mating surfaces to remove or minimize friction and plastic deformation heat. These include vegetable oil, animal oil, and mineral oil as a derivative of petroleum with additives such as sulphur, phosphorus, and nitrogen [2]. However, the benefits of utilizing these cutting fluids come with adverse ecological, economic, and social damage [3]. In fact, the nature of these cutting fluids provides a conducive environment for the development of fungi and bacteria. Therefore, adding different kinds of bactericides, humectants, and germicides, as well as biocides in cutting fluids is necessary to control the growth of bacteria and maintain the functionality of a

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particular cutting fluid [4]. These hazardous substances cause serious health issues in the shop floor environment and cause severe allergies, body ailments, and skin problems [5]. In addition, these cutting fluids are non-biodegradable, and their chemical dissolution after disposal can exacerbate the environment. Therefore, under restricted environmental regulations, these cutting fluids need expensive treatments before their disposal. Thus, the associated cost of utilizing cutting fluids, encompassing the cost of purchasing, preparing, maintaining, and disposal, becomes much higher than its machining benefits [6].

Currently, the concept of green or sustainable manufacturing is gaining attraction and has emerged as a significant focus in manufacturing engineering. The primary goal of sustainable machining is to offer cost-effective production methods by using natural resources and minimizing the negative impact of cutting fluids [7]. In this regard, sustainable manufacturing aims to explore safe, energy-efficient, eco--friendly, and cost-effective alternatives [8]. Dry cutting, minimum quantity lubrication (MQL), and cryogenic cooling (Cryo) are recognized as sustainable machining techniques that are alternatives to the food environment [9]. Active research has been conducted on these alternatives to enhance their efficiency for controlling accelerated tool wear and improving the surface quality of machined materials during the metal-cutting process. A recent trend proposed that simultaneous application of cryogenic and MQL is advantageous rather than individual cooling and lubrication techniques [10]. Many studies confirmed the effectiveness of Cryo + MQL configuration in attaining superior surface integrity and extended tool life, particularly in machining [11,12].

Hybrid lubrication (Cryo-MQL) has shown encouraging success in improving the cutting performance of various commercially essential materials in terms of extending tool life, surface integrity, cutting temperature, chip morphology, and increasing productivity [13]. In their study, Zhang et al. [12] developed a tool wear forecast model and optimized the machining parameters using a general algorithm under Cryo + MQL conditions. The study results concluded that the Cryo-MQL lubrication mode was superior for reducing tool adhesion, oxidation, and diffusion wear relative to dry conditions. This is as a results of high heat generation at the primary deformation zone in the absence of any coolant or lubricant in dry cutting [14]. In a study by Seid and Ryon [15], which involved the use of coated carbide end-mill tools for milling Ti6Al4V alloy, the Cryo + MQL lubrication mode significantly reduced tool wear, cutting force, and surface roughness by 33%, 18%, and 43%, respectively, when compared to MQL machining. Similar results of reduced effectiveness of MQL have also been reported by Ross et al. [16] in machining C276 Hastelloy. They stated that at high cutting speed, micro-lubricant oil evaporates, thus reducing its effectiveness. Furthermore, the hybrid regime demonstrated improved surface topography results by reducing the cutting temperature by up to 23% compared to the MQL condition. It was suggested that simultaneous application of supercritical carbon dioxide and MQL can prolong tool life. Results of the study confirmed that tool life was 2.6 and 8 times better than flood and $ScCO_2$ cooling conditions, respectively [17]. Sirin and Sirin [18] conducted milling of AISI 316 L stainless steel alloy with LN_2, MQL, and LN_2+MQL cooling/lubricating environment. They noticed the lowest surface roughness value, R_a 0.237 μm at 132.4 °C cutting temperature with LN_2+MQL cutting conditions. Similarly, Liu et al. [19] in their research optimized the machining parameters for tool wear and surface roughness under diverse lubrication environment using a fruit optimization algorithm (FOA) and performed an experimental study to validate their results. It was stated that the surface roughness value with CMQL condition was decreased by 0.178 μm and 0.272 μm relative to MQL and dry cutting respectively. Numerous studies confirms that this hybrid approach is very effective in improving the overall machining performance for hard-to-cut materials by considering and evaluating the major machining outcomes, which are the cutting force required, material removal rate (MRR), tool life, and the surface roughness [20,21]. Pereira et al. [22] after performing a life cycle assessment of different cooling environments affirmed that the combination of cryogenic and MQL is best to achieve environmental and technological benefits in metal cutting processes.

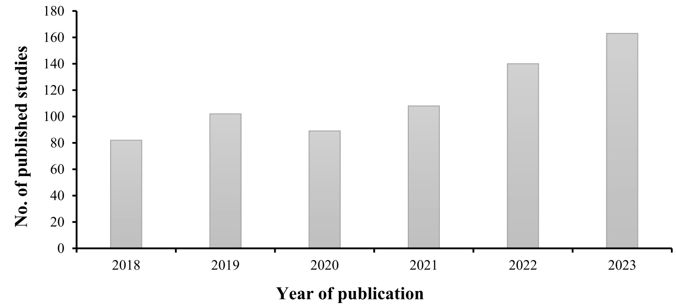

Fig. 1. Published studies in Science Direct and Scopus relevant to hybrid machining from year 2018–2023.

Besides offering numerous prominent improvements in machining of hard-to-cut materials and an increasing trend in published articles relevant to hybrid Cryo + MQL, as evident in Fig. 1, few studies focused solely on machinability aspects have been carried out since 2018. Furthermore, no thorough review of the supply systems and optimization studies of hybrid lubrication has been found. Therefore, this study presents state-of-the-art Cryo-MQL approach with respect to its supply mechanism and machinability performance compared to other cooling/lubricating techniques. The novelty of this review lies in the representation of delivery systems for Cryo-MQL, identified and categorized based on reviewed articles. Moreover, the addition of summarized discussion on optimization studies and machinability results related to various Cryo-MQL techniques adds significant value to this work.

For this study, a bibliographic analysis was conducted to select relevant literature published from 2018 to 2023 in Scopus and Science Direct databases. It is anticipated that this review contributes state-of-the-art knowledge to this rapidly advancing research domain, enabling researchers and industrialists to conduct research on newly developed advanced materials in a sustainable manner. This research also highlights the top contributors in this domain, as shown in Fig. 2. Based on the statistics of last six years, it can be seen that China, India, and the United States are the top three contributors among the top 10 countries publishing studies on hybrid techniques over the last six years.

The structure of this paper is subdivided into the following sections. Section 2 describes the adopted methodology for this research. Section 3 briefly introduces the Cryo-MQL approach, and section 4 focuses on its supply mechanism in different machining processes. Afterward, section 5 provides insight into the machinability performance and optimization studies related to Cryo + MQL. Finally, section 6 concludes with future directions.

2. Methodology

For this study, an extensive literature survey of the pertinent research articles concerning the Cryo + MQL approach from ScienceDirect and Scopus was carried out systematically using bibliographic analysis. Only recently published articles from 2018 to 2023 have been considered to discuss the recent progress on hybrid technology in this review. For this purpose, an initial search was done to select relevant articles by entering keywords like hybrid lubrication, cryogenic minimum quantity lubrication, CMQL, CAMQL, Cryo + MQL, CAMQL, LN_2+MQL, and CO_2+MQL in Scopus and Science Direct databases. An initial collection of a total of 205 research articles was made after filtering out similar studies. As the number of articles was enormous, an additional search was done on hybrid lubrication collection to remove the articles irrelevant to hybrid lubrication or employed nanofluid, ionic liquids, or solid lubricants under the hybrid technique. Finally, the bibliographic analysis was carried out by examining the abstract, and 90 articles specific to machining hard-to-machine materials were selected

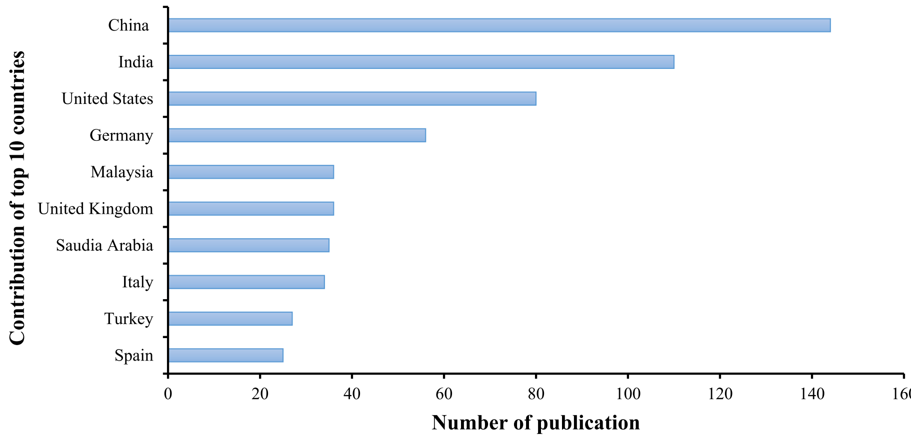

Fig. 2. Top 10 countries contributed to published studies relevant to hybrid machining from 2018 to 2023.

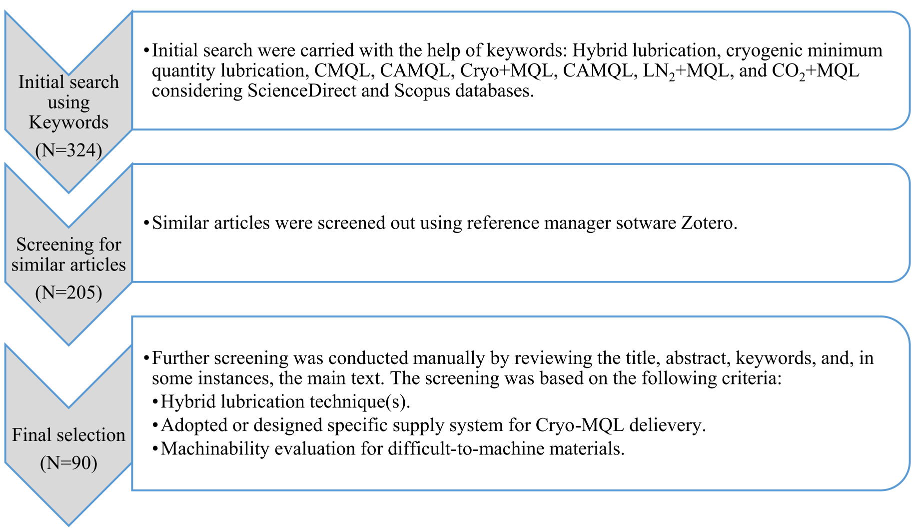

Fig. 3. Research methodology.

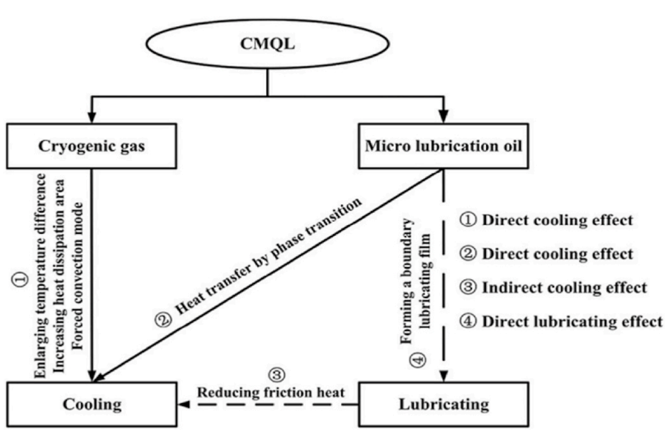

Fig. 4. Schematic of lubrication and cooling mechanisms in a hybrid lubrication environment [24].

for this study. The articles section criteria involves to select those articles, which adopted/designed the novel supply system for hybrid lubrication or those comprehensively evaluated the machinability study of advanced materials in comparison to other cooling/lubrication techniques. Fig. 3.

3. Hybrid lubrication (Cryo-MQL)

Cryo-MQL lubrication, as the name suggests, is a well-defined combination of the two sustainable machining lubrication/cooling techniques: cryogenic cooling and minimum quantity lubrication. As per the literature, this technique is one of the best lubrication strategies for hard-to-cut materials [23]. Cryo-MQL lubrication reduces the cutting zone temperature and supports the functional characteristics of the tool by providing an adequate lubricating film between the tool-work and tool-chip interfaces. This results in improved surface finish and reduced tool wear [24]. Zou et al. [24] have explained the resulting combined effect of both cooling and lubrication at the same time by this technique, which is shown in Fig. 4. They support the idea that the inclusion of the cryogenic gas in Cryo-MQL (CMQL) induces direct cooling which reduces the machining temperature via forced convection. Additionally, the micro-lubricating oil enhances lubrication and cooling efficiencies, which is attributed to the following ways. Firstly, it provides direct cooling through phase transformation and heat transfer by convection. In addition, there is indirect cooling when the frictional heat is reduced. Then, a lubricating boundary film is formed at the friction interfaces, which is considered direct lubrication [24]. Based on reviewed articles, it was discovered that different cryogens can be utilized with MQL under the hybrid lubrication technique, including liquid nitrogen paired with MQL (LN_2+MQL) [25], liquid carbon dioxide with MQL (LCO_2+ MQL) [26], carbon dioxide in supercritical and dry ice form with MQL as

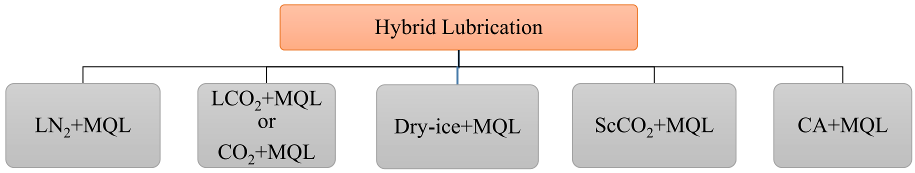

Fig. 5. Hybrid lubrication approaches characterized as per different cryogenic environments.

(SCO_2+ MQL) [17], (Dry ice + MQL) [27], and lastly Cryogenic air with MQL as CA + MQL [28]. Illustration of hybrid lubrication techniques is represented in Fig. 5.

Cryogens such as nitrogen and carbon dioxide in liquid form are widely utilized for hybrid lubrication [29–31]. Both cryogens offer substantial cooling effects on the cutting zone, but their refrigeration mechanisms differ remarkably. The temperature in cryogenic (LN_2) machining can be as low as −196 °C, whereas in CO_2, it can reach approximately −78 °C. The storage and transportation requirements for LN_2 and CO_2 are also entirely different. CO_2 is delivered to the machining zone through pressurized pipes. It is stored at a pressure of 5.73 MPa to keep it in a liquid state [32]. In comparison, the LN_2 storage requirement is entirely different. LN_2 is stored in an incubator since it absorbs heat from ambient pressure and boils at −196 °C [33]. Furthermore, when LCO_2 evaporates at −78 °C, it releases 280 kJ/kg of latent heat, whereas LN_2 evaporates at −196 °C, releases 200 kJ/kg of latent heat [34], and it is important to maintain a constant cryogenic phase delivery to the cutting zone in order to avoid thermal shock [35].

Two other carbon dioxide forms, supercritical carbon dioxide ($ScCO_2$) and dry ice blasting, have been used as cryogenic coolants in MQL environments. Because of the greater solubility of $ScCO_2$, it dissolves the lubricating oil more effectively than CO_2 and easily forms a complex and effective mixture of $ScCO_2$-based MQL [36]. Furthermore, as CO_2 can transform into the supercritical form at 31.1 °C and 73.8 bar [37], and Sc CO_2 follows the rapid expansion principle immediately after getting ejected from the supply nozzles, it, therefore, offers a lower temperature as compared to CO_2, which goes till up to −80 °C [38]. The storage requirements of $ScCO_2$ and liquid CO_2 are the same, with additional pressurization and heating setups required to convert the CO_2 into $ScCO_2$ form [39]. Another type of hybrid lubrication is dry ice blasting combined with MQL. Dry ice is solid CO_2 with a temperature of roughly 78.5 °C [40]. A blasting equipment is typically required to produce the complex mixture of dry ice-based MQL. A blasting chamber was employed by Jamil et al. [41] to form the hybrid dry ice-MQL and was assessed in the machining AISI 52100 tool steel. Their blasting equipment is mainly constructed with a pipe for flowing the liquid CO_2, connected by an expansion nozzle, followed by the expansion chamber. The cryogenic supply process is accomplished by creating pressure drops to let the liquid CO_2 expand, followed by its conversion into solid and gaseous particles. Next, the solid particles of the dry ice further break into smaller grains, which are pushed into the machining zone for penetration with the help of airflow and momentum. The MQL supply provided the required lubrication to assist these grains in penetrating deeply into the interfaces [42].

Another approach to creating a hybrid lubrication setup is to combine cryogenic air (CA) with MQL. This approach is typically made by mixing a pre-cooled compressed air of −10 °C to −60 °C with a lubricating oil under controlled pressure and flow rate conditions in a closed chamber. This results in a two-phase gas liquid that flows to the machining zone [43]. A vortex tube containing pressure-regulating valves and air filters is attached to the MQL setup to obtain the required sub-zero air [44].

4. Supply systems in Cryo-MQL lubrication

The primary supply mechanism in the Cryo-MQL approach can be external [45,46] or internal [47]. However, a third category hybrid mode has been adopted recently [48]. Thus, delivery systems for Cryo-MQL can be categorized into three main domains: external, internal, and hybrid supply modes. Fig. 6 represents the main categories and their sub-classifications related to Cryo-MQL supply systems based on reviewed research articles published annually from 2018 to 2023.

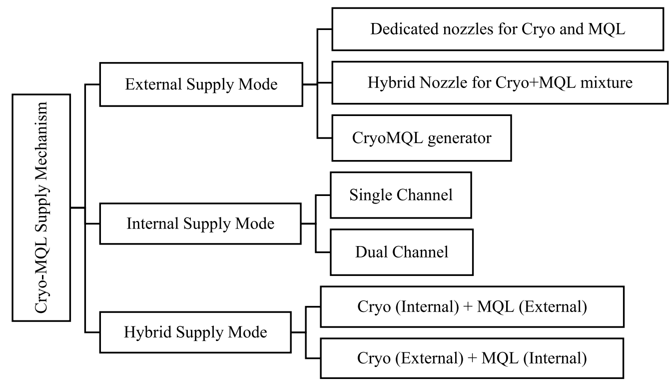

Fig. 6. Classifications of hybrid lubrication supply mechanism.

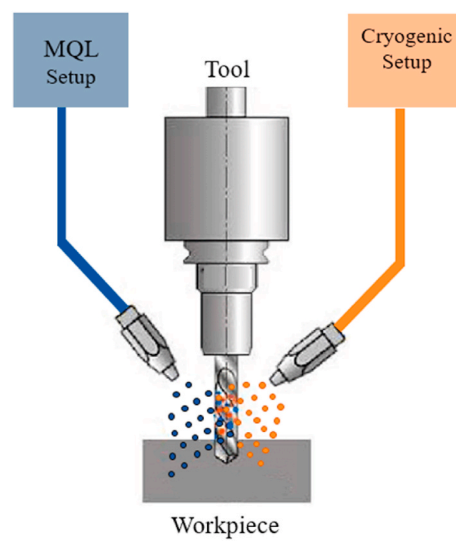

Fig. 7. Schematics of dedicated nozzles for cryogenic and MQL delivery to the machining zone in external supply mode.

4.1. Modes of supply

4.1.1. External supply mode

The external supply system supplies coolant and lubricant to the machining zone externally. This mode involves three possible methods for providing a Cryo-MQL lubrication medium.

- Dedicated nozzles: This method separately supplies cryogenic coolant and MQL aerosol from their respective storage systems to the cutting zone, as illustrated in Fig. 7.

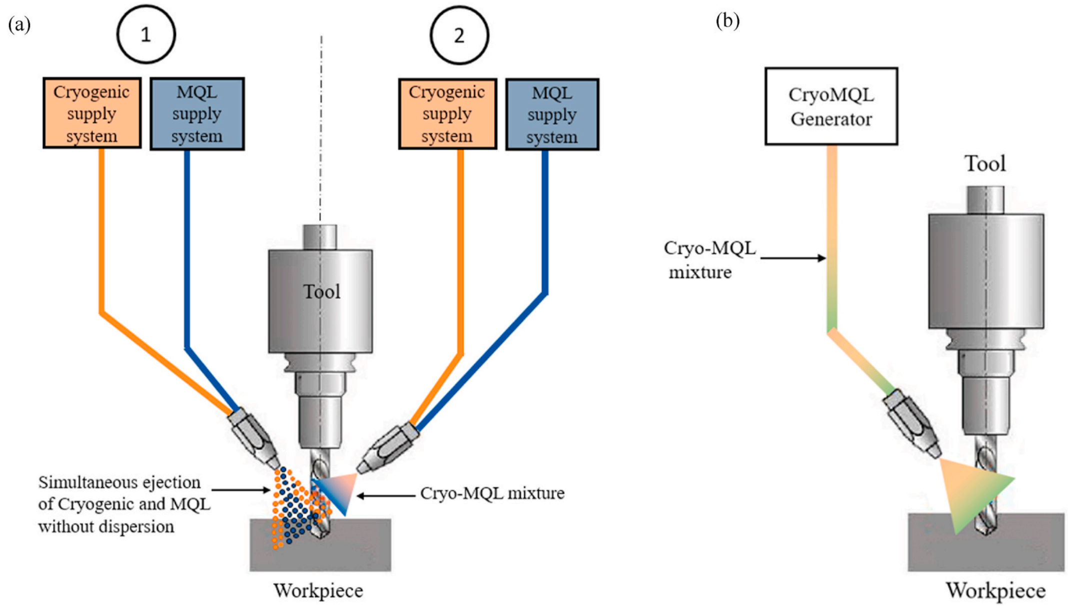

Fig. 8. Schematic representation of (a) hybrid nozzle function as types 1 and 2; *(Type 1) directing the cryogenic coolant and MQL aerosol simultaneously, (Type 2) delivering the mixture of Cryo-MQL*, and (b) CryoMQL generator.

- Hybrid nozzle: This method supplies cryogenic agent and MQL aerosol individually to a specialized nozzle called the hybrid nozzle, which functions as type 1 and type 2. A schematic of the hybrid nozzle is shown in Fig. 8a.
  - o Type 1, the designed nozzle permits the simultaneous ejection of Cryo-MQL media from the nozzle outlet without dispersion.
  - o Type 2 produces a complex mixture of Cryo-MQL by allowing both coolant and lubricant to be mixed in the nozzle cavity.
- CryoMQL generator: In this method, a complex mixture of Cryo-MQL is formed in the mixing unit of a specially designed device called a CryoMQL generator. The Cryo-MQL mixture is then transferred to the nozzle for ejection, as shown schematically in Fig. 8b.

The external supply mechanism is commonly employed as it eliminates the need for modifications to tool and tool-holder geometries. The Cryo-MQL technique using an LN_2 cryogen is generally suitable for delivery via dedicated nozzles because of LN_2 characteristics and processing properties. LN_2 remains insoluble in MQL oil at low temperatures (−196 °C boiling temperature of LN_2) [49]. In addition, LN_2 requires a lengthy start-up time owing to its drainage requirements when released from the storage system [9]. Therefore, its supply separately from the MQL aerosol is feasible. On the other hand, CO_2 cryogen can be conveniently supplied independently [50] and in a mixture form with MQL [51]. CO_2 in its liquid and supercritical forms can demonstrate improved solubility in MQL. Meier et al. utilized a mixture of different bio-based oils with CO_2 to improve the machining of X2CrNiMo17-12-2 and 100Cr6 steel materials [52]. Finally, CA + MQL is usually administered in a mixture form and is mainly applied externally [53].

The conventional setup of Cryo-MQL is based on dedicated nozzles comprising two supply systems with separate nozzles [54,55]. However, multi-nozzle arrangements can also be possible, for instance, more than one nozzle each for supplying Cryo and MQL mediums. The positions of nozzles carrying coolant/lubricant can be directed to the tool rake or flank faces. A study performed by Airao et al. [56] utilized dedicated nozzles for Cryo-MQL delivery. They directed coolant/lubricant alternately to both faces of the tool. The CO_2 (flank) + MQL (rake) approach revealed the highest flank wear and maximum surface roughness. However, a similar investigation by Khanna et al. [57] exhibited entirely different results. According to them, the CO_2 (flank) + MQL (rake) arrangement is better for abridging tool flank wear and produces a desirable surface quality than the CO_2 (rake) + MQL (flank) setup. Interestingly, the same workpiece material, Inconel 718, was experimented with similar machining input parameters in both studies using a PVD/TiAlN coated carbide tool by configuring MQL at 9 ml/h at 6 bar pressure. There was only one difference: one utilized ultrasonic vibration during turning [57], while the other was performed on conventional turning [56]. Thus, it is imperative to study the nozzle arrangements carrying cryogen and MQL for different machining operations. Besides this, the effectiveness of the coolant and lubricant is critically dependent on the nozzle angular position, its diameter, and standoff distance relative to the tool's cutting edge. Thus, these parameters must be adjusted to ensure efficient cooling and lubrication in the machining zone [58,59].

Cryo-MQL medium can also be delivered through an exclusively designed hybrid nozzle and CryoMQL generator. Both systems transfer Cryo-MQL medium externally and thus are categorized under external supply mode. There are two possible methods for supplying coolant and lubricant to the machining zone using a hybrid nozzle (Fig. 8a). Type 1: Cryo-MQL media can be simultaneously ejected from the nozzle outlet without dispersion, thus following their stream [60]. Type 2: Cryo-MQL can be ejected from the nozzle outlet as a mixture. Mixing of both media occurred in the nozzle cavity before ejection [36]. Fig. 8a illustrates a schematic representation of the hybrid nozzle serving two ways to transfer the Cryo-MQL medium to the machining zone. In contrast, the CryoMQL generator shown schematically in Fig. 8b is special equipment used to produce a mixture of coolant and lubricant in a mixing chamber. The lubricant mixture is then transferred to the nozzle for ejection. Many studies utilized the CryoMQL generator to form the hybrid lubrication during the machining of various materials. Table 1 briefly elaborates on references for the hybrid nozzle and CryoMQL generator employed in some research studies.

4.1.2. Internal supply mode

The internal supply mode transfers coolant and lubricant through the spindle, thus making it a tool application. Transferring the coolant and lubricant internally is complex because it requires significant modifications to the machine tool, tool holder, and spindle structure. The respective coolant/lubricant channel(s) are embedded with the tool cutter geometry to ensure accurate Cryo-MQL delivery to the machining

Table 1
References for the hybrid nozzle and CryoMQL generator in the external supply system.

System	Ref.	Schematic representation	Description
Hybrid Nozzle (Type 1)	[60]	Fig. 9	Fig. 9 shows the schematic of hybrid nozzle functions as type 1. The supply system is designed based on the Conda effect to deliver CO_2 and MQL to the machining zone without dispersion in this configuration. Once CO_2 entered from inlet 2, it followed a path along the airfoil, dividing into two streams. One stream facilitated cooling for the MQL aerosol, while another portion of CO_2 directed its flow towards outlet 2, functioning as an air curtain to contain the MQL spray. Additional air curtains were integrated into the design to minimize the dispersion of oil and CO_2 during nozzle sprays.
Hybrid Nozzle (Type 2)	[54, 55]	Fig. 10	The following units were used to form a complex mixture of LCO_2+MQL in Fig. 10: a) dedicated oil- and water-based cutting fluid storage system, b) air compressor unit, c) two mixing chambers for forming MQL or oil-on-water MQL aerosol, d) a separate cryogenic reservoir, which is further divided into two streams, and e) two individual atomizing nozzles to form the LCO_2+MQL mixture. LCO_2 and MQL from their respective reservoirs entered the nozzle to be delivered simultaneously to the machining zone.
CryoMQL Generator (CA + MQL)	[63]	Fig. 11	In Fig. 11, a CA + MQL mixture was produced using a CryoMQL generator. The system comprised three units: a) an air supply unit, b) a coolant supply unit that stores and supplies emulsion flow, and c) a mixture flow unit. Low-temperature air from the vortex tube and emulsion micro droplets from the coolant container were mixed in a mixing tube and then transferred to the spray nozzle.
CryoMQL Generator (Sc CO_2+MQL)	[39]	Fig. 12	Fig. 12 shows a schematic of the CryoMQL generator encompassing different components to produce a $ScCO_2$+MQL mixture. A booster pump pressurizes LCO_2 and transforms it into a $ScCO_2$ state after processing from the heater. It is then transferred to the atomizer, wherein the lubricating fluid from the oil reservoir and compressed air from the air compressor are mixed to form a $ScCO_2$+MQL mixture. This CryoMQL generator also produces different cooling environments, such as $ScCO_2$, $ScCO_2$+MQL, and $ScCO_2$+OoW (oil-on-water), by controlling the opening and closing valves of different lubricants.

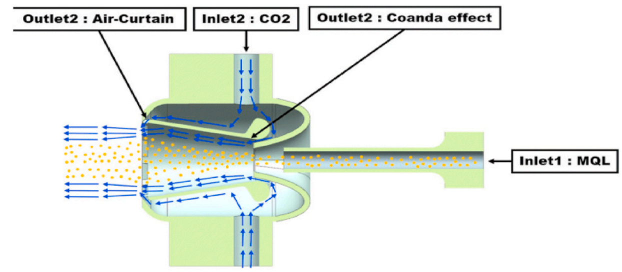

Fig. 9. Structure of the hybrid nozzle [60].

zone. Hence, this supply mode facilitates favorable cooling and lubrication, producing better machining performance. The internal cooling channel can be further categorized into two types based on the mixing mode.

- Single cooling structure: It facilitates the pre-mixing of coolant and lubricant, followed by subsequent atomization. [64],
- Double-cooling structures: It involves transmitting coolant and lubricant separately through internal channels embedded in the tool and tool holder geometry [65,66].

Developing an internal cooling structure is challenging and has limitations because it can reduce lubrication effectiveness. For instance, the transportation of CO_2 requires special pressure regulation to maintain it in liquid form; under a slight pressure drop, it can form a dry ice layer, especially at the nozzle outlet, which may cause blockage. Therefore, its integration with MQL requires special arrangements for pressure and flow rate control [49]. Grguraš et al. [67] designed a novel single-channel LCO_2+MQL supply system using an anthropomorphic robot with spindle adoption for thorough tool supply. The designed system was implemented and tested for various MQL and cryogenic flow rates during the drilling of Ti6Al4V alloy. As illustrated in Fig. 13, the tool holder is assembled into the spindle using a unique clamping system and the LCO_2+MQL mixture is supplied through the tool.

Similarly, Hanenkamp et al. [68] developed an internal cooling channel for a drilling setup by modifying the tool, tool holder, and spindle structure to process 50CrMo4 steel material. In their design, the interface between the tool holder and the spindle was sealed and covered with an additional handover part to prevent the parts of the system from unexpected cooling in case of CO_2 leakage. A sectional view of this system, illustrating its major parts, is presented in Fig. 14. In another study, a single-channel LCO_2+MQL system was designed to transport Cryo-lubricant internally through the milling cutter. Regardless of its state, this system was efficient enough to dissolve liquid- CO_2 or $ScCO_2$ in any lubricating oil. Under controlled boundaries, a complex mixture of LCO_2 and MQL was ejected in two distinct directions following a single-phase flow under specific pressure regulation and amplification (Fig. 15) [69]. In addition to single channels, CO_2 and MQL may also be transmitted internally via an embedded individual supply channel. Augspurger et al. [65] employed a dual-channel structure for LCO_2 and MQL transmissions in milling Ti6Al4V titanium alloy. Nozzle design considerations were made to ensure carbon dioxide expansion after ejection from the nozzle. Nozzle exit directions for coolant and lubricant were also incorporated into the design to avoid interdependencies between LCO_2 and MQL jets and to realize efficient coolant/lubricant delivery in the targeted area. A representation of separate cryogenic and MQL jets from the milling cutter is presented in Fig. 16.

4.1.3. Hybrid supply mode

Hybrid supply modes have been employed in several studies in addition to internal and external applications. In this mode, one medium, either MQL or cryogen, is supplied internally through a modified

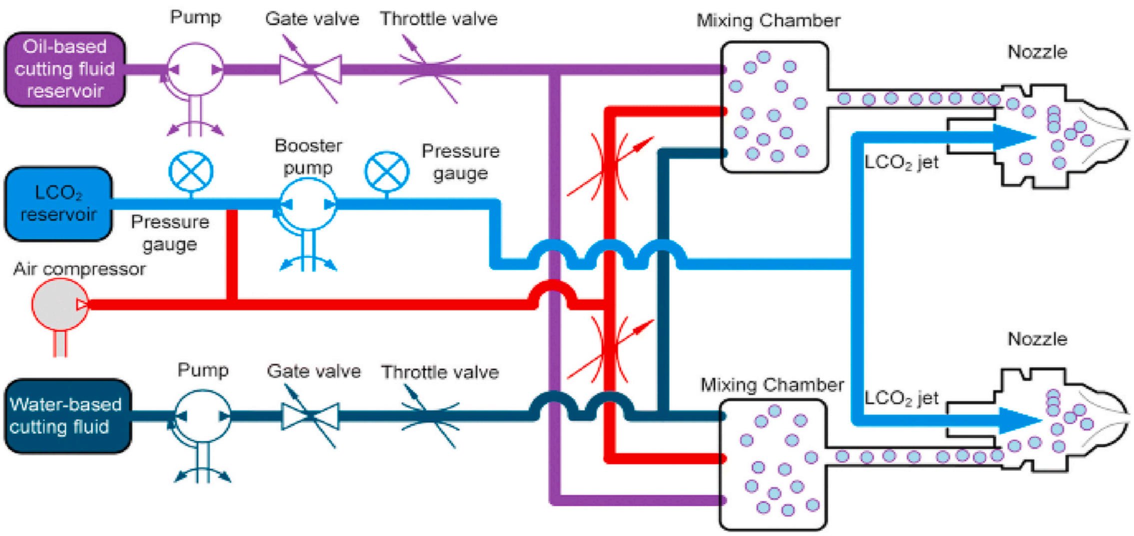

Fig. 10. Schematics of different components used to form LCO_2+MQL mixture through hybrid nozzle [62].

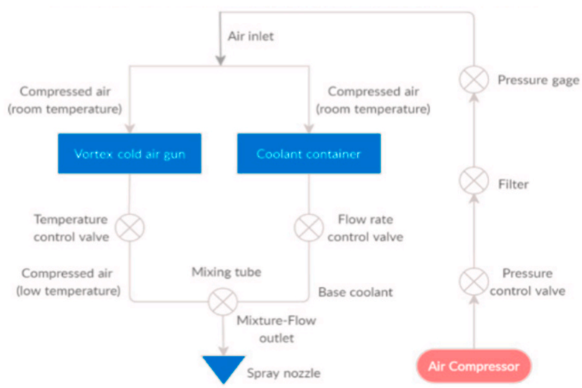

Fig. 11. Schematic of CryoMQL generator based on CA + MQL [63].

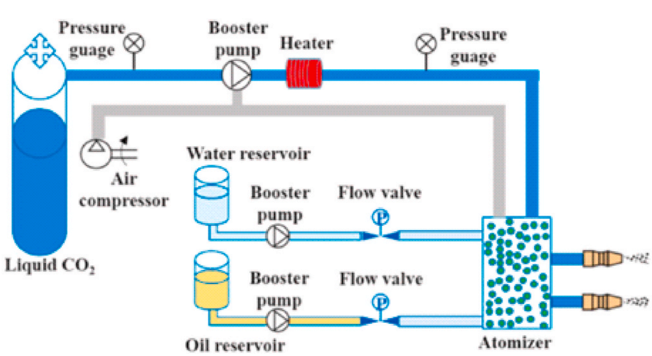

Fig. 12. Schematic of CryoMQL generator based on the $ScCO_2$+MQL [39].

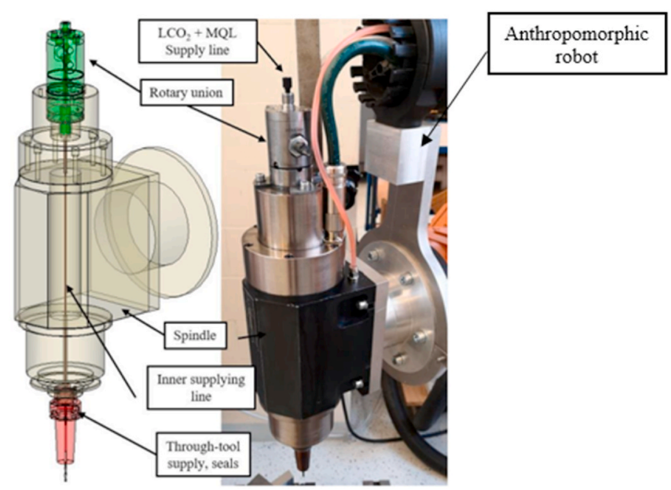

Fig. 13. Modified spindle and tool structure for internal lubrication (LCO_2+MQL) [67].

tool-holder structure, and the other is transmitted externally through a dedicated nozzle. With this arrangement, the desired cooling or lubrication effects can be accurately achieved at the friction interface. Çetindağ et al. [70] adopted a hybrid supply mode in turning AISI 52100 steel. MQL was transmitted internally through the tool holder in the hybrid supply mode, and cryogenic LN_2 was transferred externally via a dedicated nozzle. The tool holder structure was made to facilitate lubricant spray from three nozzle openings, one on the flank face and the other two on the rake face. González et al. [71] introduced LCO_2 internally through the tool from the BeCold system and lubricating oil externally from the separate nozzle in milling Ti6Al4V titanium alloy. The internal channel was designed and embedded with the spindle and tool geometry for coolant ejection. LCO_2 in this setup was supplied at 14 bar pressure to prevent the formation of dry ice inside the channel structure.

Similarly, Rakesh & Chakradhar [72] designed and fabricated a tool-holder structure for internal LN_2 transmission in turning Inconel 625 super alloy. As shown in Fig. 17a, LN_2 was directed to the tool's major and minor flank faces from notches 1 and 2, respectively. Fig. 17b shows the MQL nozzle supplying oil aerosols externally through the tool rake face. Furthermore, CA was supplied externally in an internal cylindrical grinding process, and MQL was transmitted centrifugally through internal channels built in the grinding arbor to facilitate favorable cooling and lubrication [73].

4.2. Analyzing the trends concerning supply methods and machining operations for Cryo-MQL

To analyze the trend of different Cryo-MQL environment in different machining process, selected research articles published annually from 2018 to 2023 related to Cryo-MQL approaches were thoroughly studied to analyze the following: a) the most widely adopted supply system, b)

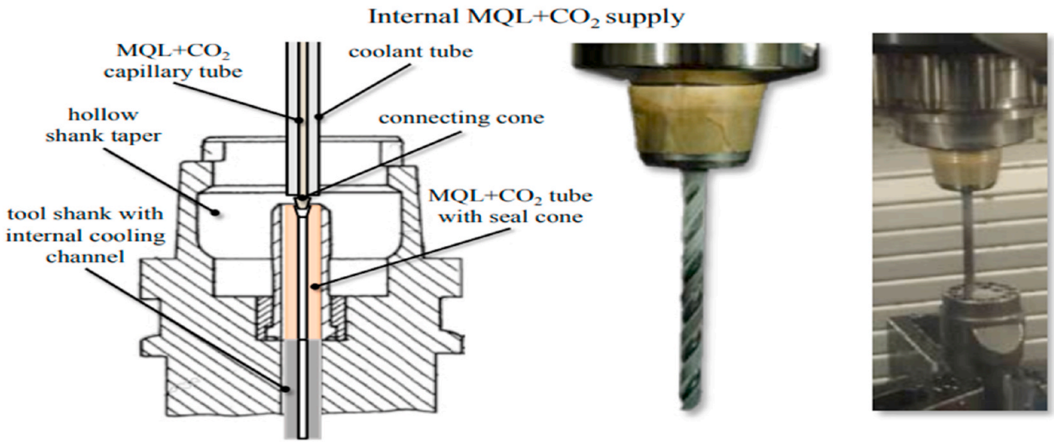

Fig. 14. Schematic of internal drilling channel for hybrid lubrication (CO_2+MQL) [68].

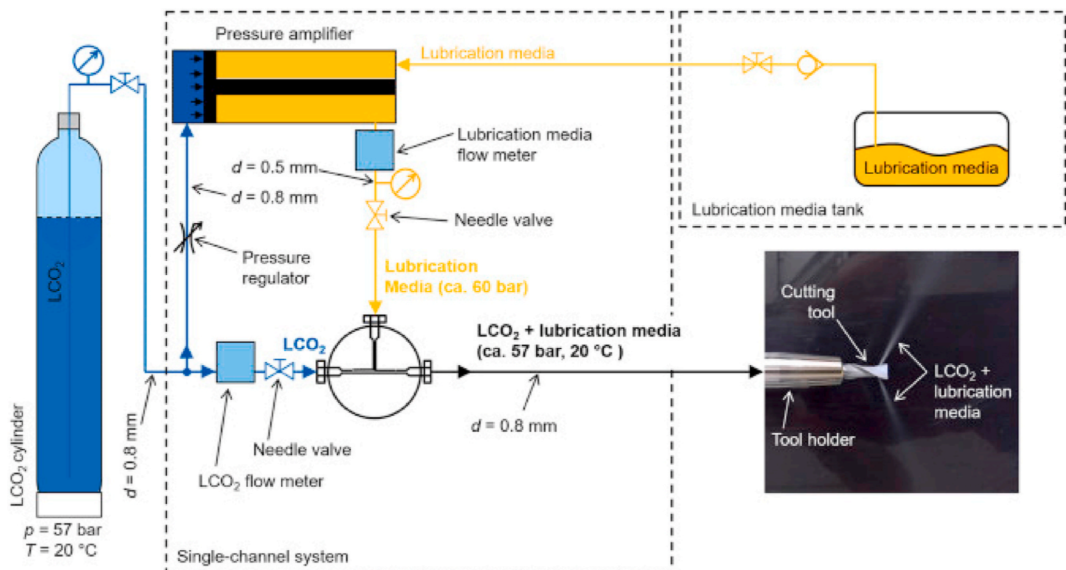

Fig. 15. Schematic of the internal Cryo-lubricant system in milling Ti6Al4V alloy [69].

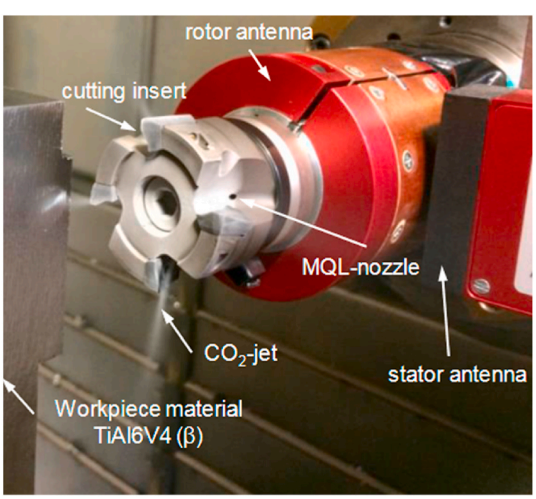

Fig. 16. Horizontal CNC milling cutter illustrating CO_2 and MQL jets through inbuilt internal cooling channels [65].

type of hybrid lubrication frequently utilized in turning, milling, drilling, and grinding operations, and c) novel supply methods configured for hybrid lubrication.

The data projected in Fig. 18a illustrates that in most of the studies, Cryo-MQL was transported externally (71%), followed by the internal supply mode (18%) and hybrid supply mode (11%). Thus, it can be inferred that the external supply mode is the conventional method for transmitting Cryo-MQL medium under hybrid lubrication. Interestingly, research articles about internal supply mode utilized carbon dioxide-based cryogenic medium with MQL for milling and drilling. As the projected data in Fig. 18b shows, milling is the most frequently adopted machining operation, followed by drilling in an internal application. Since the machine structure of milling and drilling allows tool adoption, CO_2 in its liquid and supercritical forms tends to form a stable mixture with MQL [61,74,75].

Researchers have also analyzed the focus of research concerning different hybrid lubrication approaches in turning, milling, drilling, and grinding operations. In this regard, pre-selected research papers were categorized based on different machining operations. Subsequently, several research papers about distinct hybrid lubrication were identified and recorded. Finally, the recorded data is represented in a pie chart to illustrate pre-dominant hybrid lubrication type(s) in the machining operation. The bar chart corresponding to each pie (Fig. 19) reveals the number of published research articles concerning hybrid approaches.

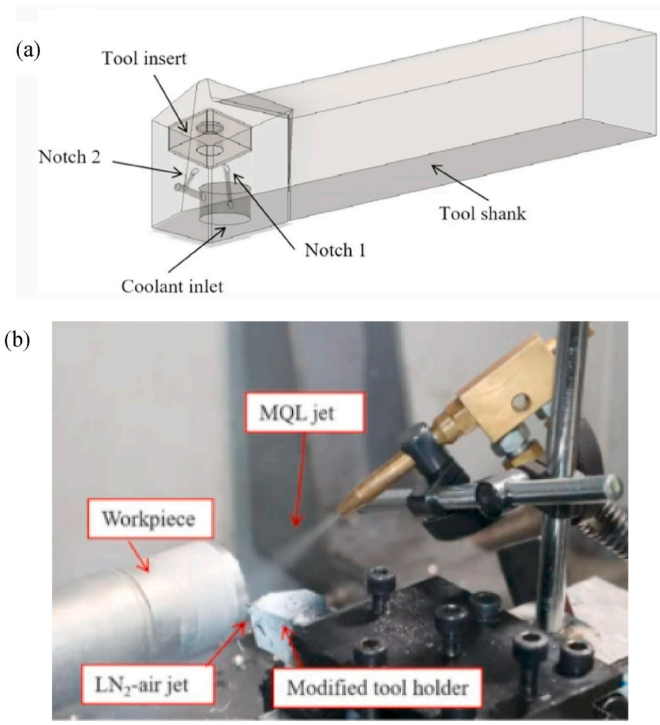

Fig. 17. (a) Modified tool holder for LN_2 supply through notch 1 and notch 2 (b) Machining setup for LN_2 (internal) + MQL (external) [72].

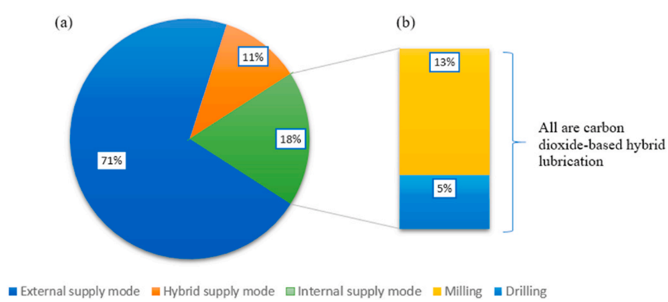

Fig. 18. Literature projecting adopted the supply mode for hybrid lubrication: (a) external, internal, and hybrid (b) internal supply mode employed for different machining processes.

After analyzing data as depicted in Fig. 19, it can be inferred that the carbon dioxide-based hybrid lubrication techniques were more dominant in milling and drilling operations, with the cumulative percentage of publications 73% and 71%, respectively (Fig. 19a–(d)). However, the liquid nitrogen-based hybrid approach was primarily utilized in turning and drilling operations with 60% and 29% of publications, respectively (Fig. 19b–(d)). Finally, cryogenic air-based hybrid lubrication was frequently adopted in grinding operations with the highest number of publications (75%) (Fig. 19c). This analysis provides a basis for researchers to highlight the gap in the literature regarding limited studies being explored in different machining operations with a particular hybrid technique. Table 2 references novel Cryo-MQL system systems already discussed in sub-section 4.1.

5. Performance analysis and optimization studies on Cryo-MQL approaches

5.1. Machinability performance

This section briefly reviews the machinability performance of different Cryo + MQL approaches in the machining processes. Das et al. [95] conducted a study incorporating hybrid cryogenic cooling to assess the tribological performance of lead-free brass while being utilized in high-speed machining. Three different cooling techniques were configured: cryogenic cooling (LN_2), cutting oil based MQL lubrication, and a hybrid cryogenic cooling technique (LN_2 + MQL). The Cryo + MQL technique was achieved with a simultaneous MQL and liquid nitrogen flow. The results showed a significantly lower value for average surface roughness as well as burr formation on the finished surface when machined with the hybrid cryogenic as compared to being machined with MQL and LN_2 separately. The flank wear on the tool-chip interface was also reduced because of the better lubrication, irrespective of the cutting speed. Das et al. [95] also declared the LN_2+MQL cooling as the most economical and eco-friendly option compared to the other two mediums used in the study due to the lesser amount of cutting fluid used, tool wear, and cost associated with the development and management of waste. They suggest that Cryo + MQL cooling brings negligible carbon emissions and eliminates the hazardous particles produced while machining with vegetable oil [95]. The hybrid cryogenic cooling was also compared with MQL by Ahmed et al. [89] when they machined the TiAl64V. With the help of CFD modeling for the flow characteristics of the MQL and LN_2, they analyzed the machining in terms of flood, high pressure, cryogenic cooling, tool wear, and surface roughness. The results confirmed the Cryo + MQL method as having superior performance among other methods [89]. To evaluate the new concept of a hybrid cryogenic- LN_2 and MQL, referred to as 'CryoMQL', two sets of experiments were performed by Khan et al. [96]. Their research supported the idea that the LN_2+MQL approach increases productivity by improving product quality and reduces production costs by lowering power consumption and cycle time. Also, the CryoMQL approach produced a cheaper product at higher machining conditions, leading it to be declared as economically sustainable only and not an environmentally friendly solution [96]. This is further confirmed by Korkmaz et al. [97] that hybrid lubrication is a sustainable machining alternative as it efficiently reduces the specific cutting energy (SCE) during the metal cutting process. The lowest value of SCE for hybrid lubrication was 82.75 J/mm^3, which was 2.7% less than dry environment.

Bagherzadeh et al. [29] studied the feasibility of adopting cryogenics and the Cryo-MQL technique while slot-milling the titanium alloy. They examined the machining performance of titanium alloy workpieces with various green lubricating/cooling methods, including MQL, LN_2, and CO_2, and combined MQL with CO_2 and LN_2. The results were compared for output variables like temperature, tool wear, surface roughness, and cutting forces. The results showed that Cryo + MQL brings improved results even at higher speeds. Also, the simultaneous spray of MQL and cryogenic coolant improved the machinability of the titanium alloy when compared to only cryogenics. The Cryo + MQL methods also reduced the volume of coolant used, thus being a sustainable and greener solution. They further suggested that the CO_2+MQL is a balanced approach for machine productivity and environment. Their hybrid method improved the tool's life and reduced costs while supporting the environment [29]. Bagherzadeh et al. [50], in an earlier study, presented an alternative & modified cooling method for using cryogenic coolant during high-speed machining (turning) of Ti6Al4V and Inconel 718. They worked with four methods for cooling: CO_2 (rake) + MQL (flank), CMQL (rake), CO_2-rake, and improved CO_2 nozzle. The results show the CO_2+MQL technique as a greener cooling technique that provided low cooling rate consumption and improved productivity. Modifying the cryogenic nozzle improved the cooling condition compared to the conventional nozzle. Hybrid CO_2+MQL supply reduced the tool wear and surface roughness while compared to the other strategies. The CMQL method with fixed lubricant and cooling rate improved the tool life by 60% for Ti6Al4V and by 30% for Inconel 718 in comparison to other lubrication method, as evident from the maximum tool wear graph in Fig. 20. The trend of wear progress in CMQL lubrication is comparatively than other lubrication environment

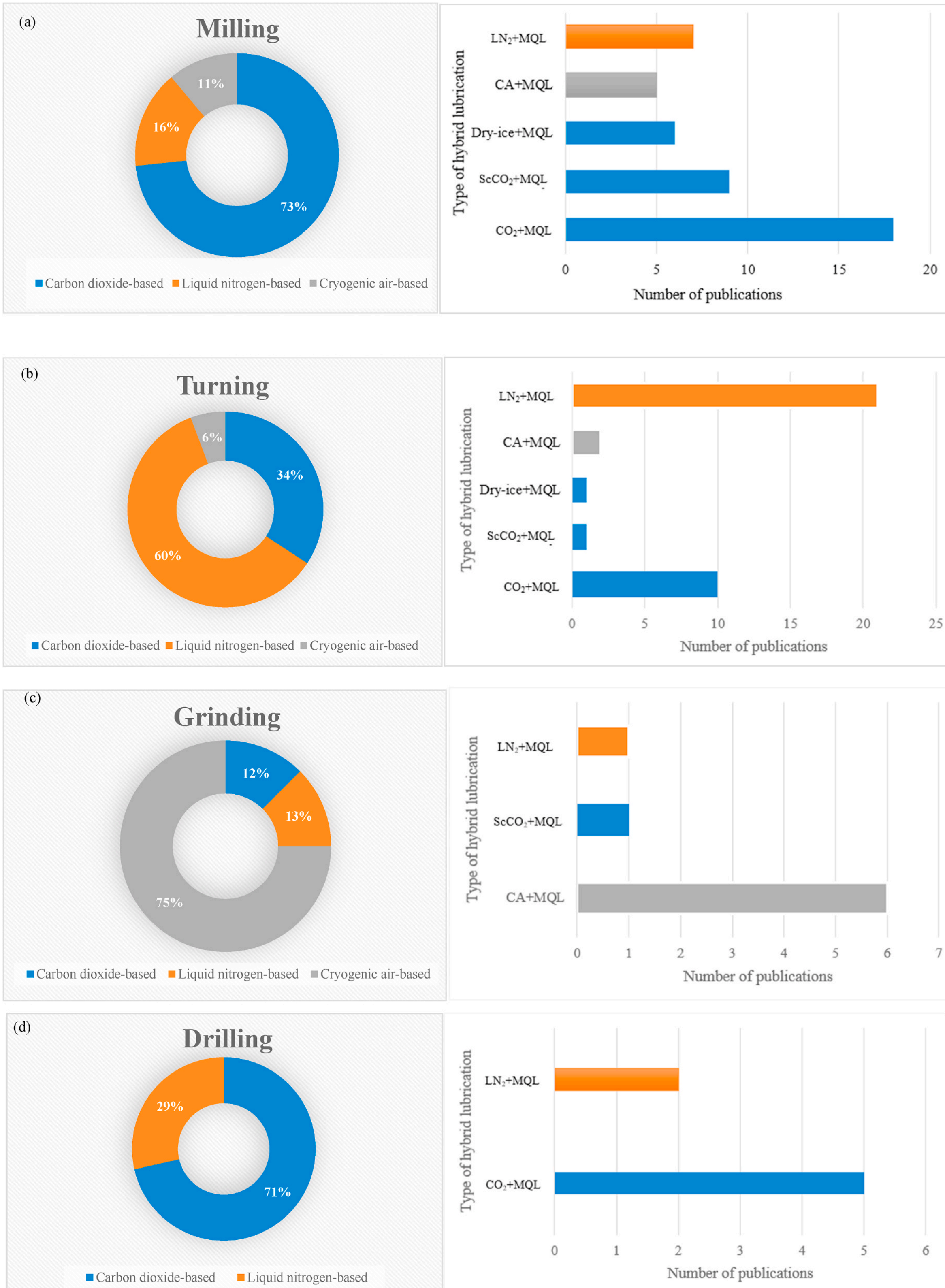

Fig. 19. Categorization of hybrid lubrication approaches in (a) milling, (b) turning, (c) grinding, and (d) drilling operations.

exhibiting longer tool life. The microstructure formed showed that CO_2+MQL offered the most reduction in the tool-chip contact length compared to the other methods. The CO_2+MQL technique also resulted in higher heat removal efficiency when compared to the CO_2.

Wang et al. [94] used the turning process on tantalum-tungsten alloy Ta-2.5W under cryogenic cooling. They observed the effects of liquid nitrogen cooling and CO_2+MQL cooling on the mechanism of cutting tool wear and the formation of chips during the process. They also studied the Rehbinder effect offered by the CO_2+MQL system. The results show an improved cutting tool life by 50%. The chips formed

Table 2
References for novel Cryo-MQL supply systems.

Type of supply system	Method adopted	Experimented Workpiece Material	Machining Operation	References
External Nozzle(s)	Hybrid Nozzle	Ti6Al4V	Milling	[60–62,76,77]
		Ti3Al2.5V	Turning	[78]
		Inconel 718	Milling	[79]
			Grinding	[53,79,80]
		AISI 304	Turning	[81]
		300 M	Milling	[82]
		Compacted graphite iron	Milling	[83]
		γ-TiAl	–	[59]
	4 Nozzles	Ti6Al4V	Milling	[84]
Modified tool holder geometry for Cryo-MQL	Single supply structure	Ti6Al4V	Milling	[64,69,85,86]
			Drilling	[67]
		TiAl6V4 and AISI1045	–	[87]
		Ti6Al4V and 42CrMo4	Milling	[88]
		42CrMo4 steel	Drilling	[26,68]
		AISI 304	Milling	[75]
	Dual supply structure	Ti6Al4V	Milling	[65]
		AISI 1045	Milling	[47]
	Hybrid supply structure	Ti6Al4V	Turning	[89]
			Milling	[71]
		Inconel 718	Milling	[48]
		Inconel 625	Turning	[72]
		AISI 52100	Turning	[70]
		100Cr6	Grinding	[73]
		CFRP composite	Drilling	[90]
New System	CryoMQL generator	Ti6Al4V	Turning	[43]
		Ti6Al4V, X5CrNi18-10 and 42CrMo4		[74]
		Ti6Al4V	Milling	[63,91]
		Inconel 718	Turning	[92]
			Milling	[39]
		GH605	Turning	[93]
		AISI 4340	Grinding	[28]
		Ta-2.5W	Turning	[94]
		X2CrNiMo17-12-2 and 100Cr6	Milling and Turning	[52]

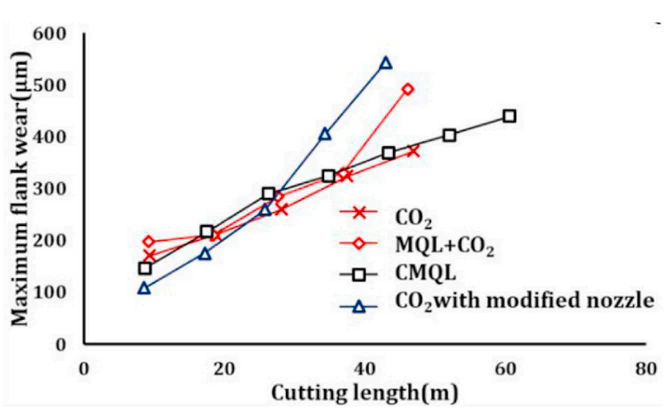

Fig. 20. Trend of tool flank wear progression in different lubrication environments [50].

during the turning process of Ta-2.5W showed a non-periodic and non-uniformed fold with a classic “pomelo-meat-shaped” morphology. Later, the Rehbinder effect turned the “pomelo-meat shaped” chips into a more “layered-rock shaped” chip. The experiment offered an effectively improved machinability of tantalum-tungsten with an increased tool life and reduced chip thickness [94]. Cheng et al. [58] studied the

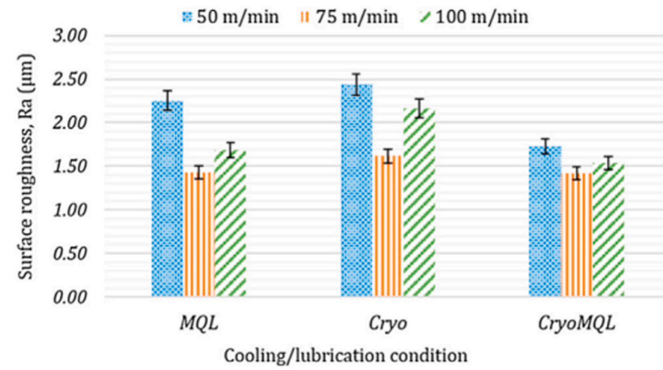

Fig. 21. Variation of surface roughness under different machining environments [98].

influence mechanism of CO_2 in CO_2+MQL based machining on tool wear in the context of oil flow and temperature. They observed the chip morphology and wear mechanism and concluded that tool wear reduces with less CO_2. The oil mist reaches effectively and in an improved manner when the temperature of the CO_2 carrier is lower. Among the options of wet cutting, dry cutting, and the cryogenic CO_2-assisted MQL, tool diffusion wear was controlled better with wet cutting, and tool adhesive and oxidation wear were better controlled by cryogenic CO_2-assisted MQL. the cryogenic CO_2-assisted MQL offers the serrated chip, and with smaller thickness, lower frequency, it is assumed to reduce the tool wear [58].

In another study by Yildirim et al. [98] nickel based super alloy was machined with various lubricating/cutting fluids, and results were analyzed on multiple factors. The study reveals that the Cryo + MQL reduced the surface roughness by 24.82% compared to regular cryogenic cooling. The trend of surface roughness in Fig. 21 under different cutting speeds and lubrication environments suggested that Cryo + MQL technique can produced outstanding surface quality. Cryo + MQL also reduced the cutting temperature to a significant figure of 24.9%. A drastic reduction of 79.60% in the tool wear was also observed by the Cryo + MQL approach [98]. Wika et al. [75] conducted a study to analyze the basic output response in milling, speed, and feed rate while machining austenitic stainless steel 304 L, majorly assessing the impact of two different cooling methods, flood coolant vs. supercritical carbon dioxide cooling with Minimum Quantity Lubrication ($ScCO_2$+MQL). The study reveals an increase in tool life by 32.4% while machining with $ScCO_2$ compared to the flood coolant.

Moreover, a 30% reduction in surface roughness was observed with the $scCO_2$ cooling system [75]. In investigating the machinability of high strength low alloy steels, Ti-6Al-4V and 40NiCrMo6 with the presence of CO_2 in the coolant, Iqbal et al. [99] found that the application of CO_2 increased the machinability of the 40NiCrMo6 alloy effectively, and titanium alloy remained least affected. They however found the application of CO_2 snow at the flank face supported the option of using micro-lubrication at the rake face and helped in the machining process [99]. Cobalt-based superalloy GH605, which has been machined with hazardous cutting fluids, was machined and investigated by Dai et al. [93] with three cooling and lubrication methods: liquid nitrogen, Flood condition, and cryogenic minimum quantity lubrication. The results showed that cryogenic MQL reduced the plasticity of GH60 but did not affect the compressive yield strength. Liquid nitrogen reduced the cutting force by 72.2%, whereas cryogenic MQL reduced the surface roughness by up to 19.7% [93].

Combining MQL with compressed carbon dioxide can assist in a sustainable and improved machining process, but the throttling high pressure of CO_2 produces fog, thereby impacting the MQL mist (having lower pressure) to reach the cutting zone. To counter this, Jamil et al. [41] suggested a low-pressure hybrid of MQL plus CO_2 for machining the AISI-52100 on milling. This low-pressure hybrid dry ice approach not

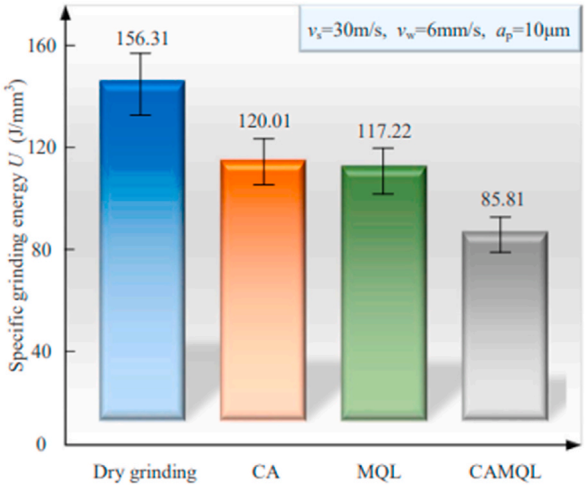

Fig. 22. Specific grinding energy in different lubrication environments [103].

only lowered the smog in the cutting zone, but the dry ice grains also supported the MQL-mist as carriers. Their study shows that this combination of MQL with low-pressure CO_2 (dry-ice + MQL) improved the cutting speed to about 200 m/min, decreased the surface roughness by 42 %, reduced the tool life to 57 %, and increased surface hardness to 9 %. Hence, the overall machinability advancement was observed in terms of easier chip removal, excellent lubrication, and dissipation of the cutting heat by the sublimation of dry ice [41]. Cryogens are excellent coolants with being green, but they are poor lubricants. Ester oils are the absolute opposite, being excellent lubricants but poor coolants. Jamil et al. [42] suggested a hybrid lubri-coolant (dry-ice + MQL) with ethanol, ester oil, and ethanol–ester oil in varying ratios and further made combinations with and without dry ice. The samples evaluated multiple aspects, including their thermophysical properties (thermal conductivity, viscosity, density & specific heat), tribological properties (friction force & its coefficient), and thermal properties (heat transfer coefficient, surface temperature, heat flux). The results show that induction of dry ice with a hybrid ethanol-easter oil combination overall increased the thermal conductivity by 15%, reduced the density by 20%, decreased viscosity by 5%, & decreased specific heat by 10%, and increased the tool life by 11.5 % [42]. Jamil et al. [100] conducted another research with a hybrid MQL-dry ice with blasting lubri-cooling technique as an eco-friendly way to investigate the machinability and sustainability in the machining of AISI-52100. The findings show that their dry-ice blasting reduced the processing time to 2.6%, specific energy consumption by 2.3%, carbon emission by 2.35%, and surface roughness by 22.5% compared to the machining done with MQL. Moreover, hybrid dry ice blasting offered a relatively small fraction of the total cost compared to MQL and with only dry ice blasting [100].

The effect of adding sub-zero air in the MQL aerosol, the hybrid MQL or minimum quantity cooling lubrication CA + MQL in milling Ti-6-Al-4-V was studied by Mark Benjamin et al. [44], and results were assessed for cutting temperatures, surface roughness and the quality of chips produced. The study shows that CA + MQL improves the lubricity of the cutting fluid and makes it easier to remove chips from the rake face when assisted by cold air. CA + MQL also supported thinner chips, having lower radii, reduced underside roughness, and lesser segmentations. Adding a sub-zero air stream in the standard MQL system also produced a lower friction coefficient at the tool-rake interface. The overall system productivity was improved with CA + MQL specifically

Table 3
Performance analysis of hybrid lubrication in machining various difficult-to-cut materials.

Reference	Workpiece/Cutting Tool	Conclusion (In decreasing order)					
		Flank wear	Cutting force	Surface Roughness	Cutting Temperature	Specific Cutting Energy	Power
[105]	AISI-52100/TiAlN Coated carbide insert		Dry ice + MQL > MQL	Dry ice + MQL > MQL			Dry ice + MQL > MQL
[47]	AISI 1045/TiAlCrN Coated carbide insert	MQL > CO_2+MQL	MQL≈ CO_2+MQL				MQL≈ CO_2+MQL
[106]	300 M Steel alloy/coated carbide insert	Dry > CA + MQL	Dry > CA + MQL				
[107]	HS6-5-2 High-speed steel/Alumina abrasive wheel	CA > MQL> CA + MQL> Flood		CA > MQL> CA + MQL> Flood			
[108]	100Cr6 Steel/Corundum grinding wheel			Flood> $ScCO_2$+MQL			Flood> $ScCO_2$+MQL
[109]	27MnCr5 Steel/Cubic boron nitride wheel			LN_2>flood> LN_2+MQL			
[103]	Ti6Al4 V Titanium alloy/Cubic boron nitride wheel		Dry > CA> MQL> CA + MQL	Dry > CA> MQL> CA + MQL	Dry > CA > MQL > CA + MQL	Dry > CA> MQL> CA + MQL	
[110]	Ti3Al2.5V Titanium alloy/Uncoated carbide	Dry > MQL> LN_2> LN_2+MQL		Dry > MQL> LN_2> LN_2+MQL	Dry > MQL> LN_2> LN_2+MQL	Dry > MQL > LN_2> LN_2+MQL	
[111]	TC4 Titanium alloy/Carborundum silicon carbide disc wheel		Flood > MQL> CO_2+MQL	Flood> MQL> CO_2+MQL			
[112]	Monel-400	Dry > MQL> CO_2> CO_2+MQL		Dry > MQL> CO_2> CO_2+MQL	Dry > MQL> CO_2> CO_2+MQL		
[113]	Carbon/epoxy (T800/X850) multidirectional CFRP laminates/ Diamond coated cemented carbide insert		$ScCO_2$>Dry> $ScCO_2$+MQL	Dry > $ScCO_2$> $ScCO_2$+MQL	Dry > $ScCO_2$> $ScCO_2$+MQL		
[114]	AZ91/5SiC Mg-based Particulate Metal Matrix Composites (PMMCs)/Uncoated carbide		LN_2> LN_2+MQL> MQL	MQL > LN_2> LN_2+MQL			
[115]	TiC/PVD coated insert	Dry > MQL > LN_2> LN_2+MQL		Dry > MQL > LN_2> LN_2+MQL			Dry > MQL > LN_2> LN_2+MQL

Table 4
Studies conducted relevant to parameter optimization of hybrid lubrication techniques.

Ref.	Workpiece Material	Tool Material	Optimized Parameters	Effect Description
[26]	42CrMo4 steel	AlCrTiN coated solid carbide drill	LCO_2 flow rate= (0, 25, 250) g/min MQL flow rate= (0, 50, 100) ml/h Cutting speed= (30, 40, 50, 60, 70) m/min	The Kienzle equation was applied to optimize the flow rate of both media. It was demonstrated that a combination of LCO_2 flow rate of 115 g/min, MQL flow rate of 80 ml/h, and cutting speed of 70 m/min is optimal for improving the drilling efficiency, reducing the cutting temperature, and preventing chip clogging.
[86]	Ti6Al4V	CVD TiCrN + Al2O3+TiN coated tool	$ScCO_2$ flow rate = (15, 40) kg/h MQL flow rate= (1, 2) ml/min	Tool life was extended when $ScCO_2$+ MQL was combined with a $ScCO_2$ flow rate of 40 kg/h and an MQL flow rate of 1 ml/min.
[116]	Grade 2 CP-Ti pure titanium	Carbide end mill	$ScCO_2$ flow rate = (15, 35, 55) kg/h with constant MQL flow rate of 0.5 ml/h Cutting speed= (70, 85, 100, 115, 130) m/min	The surface roughness and tool life results were better at a cutting speed of 115 m/min and a $ScCO_2$ flow rate of 35 kg/h.
[74]	Ti6Al4V, X5CrNi18-10 and 42CrMo4	coated carbide tools PVD TiAlN for Ti6Al4V CVD TiCN + Al2O3+TiN for X5CrNi18-10 and 42CrMo4	CO_2 flow rate for Ti6Al4V, X5CrNi18-10= (6, 13, 19) kg/h CO_2 flow rate for 42CrMo4= (13, 22.5, 26.2) kg/h MQL flow rate= (12, 30, 48) ml/h	Preliminary tests were conducted to optimize the flow rate with respect to the cutting force. It was found that 13 kg/h and 48 ml/h had a positive impact on restraining the cutting force in all the materials.
[76]	Ti6Al4V	Ti AlN coated carbide end mill	MQL parameter: a) Nozzle type 1. Smooth jet nozzle (SJN) 2. Plastic tube (PT) b) Diameter (d) SJN 1, d = 0.2 mm; $\dot{m}CO_2$ = 4.7 kg/h SJN 2, d = 0.3 mm; $\dot{m}CO_2$ = 8.6 kg/h SJN 3 d = 0.2 mm; $\dot{m}CO_2$ = 8.0 kg/h PT, d = 0.5 mm; $\dot{m}CO_2$ = 5.8 kg/h	Temperature measurement analysis showed that the trend of the temperature curve representing the cooling effect was better with a smooth jet nozzle (SJN 3) having an orifice diameter of 0.2 mm and a CO_2 flow rate of 8 kg/h.
[114]	AZ91 SiC/PMMCs magnesium alloy metal matrix composite	Uncoated diamond-like carbon (DLC) insert	Nozzle angle = 15°, 30°, 45°, 60°, 75° Standoff distance= (30, 50, 70, 90, 110) mm MQL flow rate= (2, 5, 8, 11, 14, 17, 20) ml/h	It was stated that a nozzle angle of 75° and a standoff distance of 30 mm with a 2 ml/h MQL flow rate was better for machining AZ91 SiC/PMMC magnesium metal matrix composites.
[117]	Ti6Al4V	Uncoated tungsten carbide inserts	CA + MQL Multi nozzle angular position (N) N1 = 0°, 20°, 40° N2 = 90° (fixed) N3 = 180°, 160°, 140°	The best multijet CA + MQL nozzle position was when nozzle 1 was positioned at 20°, nozzle 2 at 90°, and nozzle 3 at 180°. This nozzle arrangement covers the maximum coverage area in the machining zone and thus demonstrates the lowest cutting force.
[58]	N 87 alloy steel	TiN/TiAlN coated tool	LCO_2 Temperature = −10C°, −30C°, −50C°, MQL flow rate= (0, 60, 40, 80) ml/h	It was revealed that the highest coolant temperature is better at reducing the tool wear mechanisms, adhesive, diffusion, and oxidation. Therefore, the tool life results were better with LCO_2 -50C° and MQL at 60 ml/h.

suited for high-temperature cutting of titanium alloys at higher speeds [44]. In another study by Gupta et al. [101], a new approach of sustainable CA + MQL, the Ranque- Hilsch Vortex tube plus MQL (RHVT + MQL), was compared with liquid nitrogen plus minimum quantity lubrication (LN_2+MQL), as well as with liquid nitrogen (LN_2) were employed for the turning of Ti6Al4V. The results were assessed based on tool wear, surface roughness, workpiece surface hardness, and specific cutting energy. The results showed that LN_2 with MQL brings up the best surface finish among the three cooling options used in the experiments. The LN_2+MQL supported the lowest specific cutting energy and produced smooth and fragmented chips thus declared as the most suitable option for a producing smoother surface in energy efficient manner. In a recent study, Korkmaz et al. [102] revealed similar results, showing improved surface quality with fewer feed marks, reduced adhesion of work material, and minimized surface damage under Cryo + MQL conditions while turning 601 alloy. Another approach of adding CA with MQL was experimented by Liu et al. [103] while grinding titanium alloy with MQL and MQL + CA. Their study reveals that CA + MQL improved the grinding effect more than MQL alone. It also amplified the cooling process during the grinding. In this combination, when compared to the dry grinding, the specific grinding energy is decreased by 45.1%, as shown in Fig. 22. Moreover, the coefficient of friction is also reduced by

19.8%, and the friction temperature is also reduced to a considerable amount of 43.9% in comparison to dry cutting. Moreover, Rsm, Ra, Rt, and Rz values decreased by 35.4%,46.3%, 61.5%, and 60.6% respectively [103]. A Comparative study was carried out by Wu et al. [63] for CA + MQL machining. The results were assessed based on cutting force, tool wear, surface quality, chip morphology, and workpiece deformation. It was proved that CA + MQL machining significantly lowered the cutting loads and deformation and it led to a reduction of cutting force by up to 31.2% and deformation by up to 44.7%. Also, up to 45.8% reduced surface roughness was achieved with CA + MQL as compared to MQL machining [56] at higher speed machining. Because MQL machining generally produces continuous chips, which accumulate on the tool rake face, causing the tool positive rake angle to become more negative. Further accumulation creates abstractions in the way of chips, which leads to increased load and results in pitting on the tool surface [104].

Based on the literature analysis, it is evident that the Cryo + MQL combination is outperformed than traditional lubrication technique as well as standalone sustainable lubrication/cooling environments. In this regard, Table 3 provides summarized additional evidence relevant to the effective machinability performance of various Cryo + MQL techniques in comparison to other environments.

5.2. Optimization studies

The effectiveness of the Cryo + MQL technique is critically dependent on the parametric considerations of coolant/lubricant, such as flow rates, lubricating oil viscosity, dissolution rate (in the case of Cryo + MQL mixture), and supply pressure. In addition, individual nozzle parameters, including position, diameter, and standoff distance, can also influence the effectiveness of the hybrid lubrication technique [59]. Table 4 summarizes the optimized parameters relevant to coolant/lubricant flow rates and nozzle parameters.

6. Conclusions and future scope

This paper extensively investigates various approaches of Cryo + MQL approaches, its supply systems, machining performance, and optimization studies from selected literature published yearly from 2018 to 2023. The comprehensive review concludes that Cryo-MQL is an effective, sustainable lubrication approach for machining difficult-to-cut materials. Moreover, it was determined that the effectiveness of Cryo + MQL has been evaluated in almost all types of conventional machining operations, such as milling, turning, drilling, and grinding, as well as in burnishing and additive manufacturing processes. Furthermore, this study also discussed the supply mechanism for cryogen and MQL applications in Cryo-MQL mode. The analysis of selected literature reveals three primary modes for delivering Cryo-MQL to the machining zone: external, internal, and hybrid modes. The external supply mode predominantly employs separate or combined nozzles and is frequently observed in turning and grinding operations using LN_2 and CA-based cryogens. On the other hand, the internal supply mode ensures precise delivery of coolant and lubricant through the tool and spindle, commonly applied in milling and drilling utilizing CO_2-based cryogens. Lastly, the hybrid mode combines the internal and external supply of one medium, either cryogenic or MQL, employed in milling, drilling, and grinding operations. The review of Cryo-MQL's machining performance indicates its effectiveness in enhancing the machinability performance of many materials but most particularly difficult-to-machine materials. However, the optimization studies relevant to the flow rate of cryogenic and MQL mediums also showed improvement in the lubrication and cooling effectiveness of the hybrid technique in terms of reducing surface roughness, tool wear, and cutting forces.

In terms of future prospects, it is recommended to investigate the efficacy of various supply modes within the same Cryo-MQL environment. Additionally, conducting additional studies focused on parameter optimization of lubricants and cryogenic mediums along with nozzle positions will be instrumental in determining the feasibility and potential enhancements of the Cryo-MQL approach. These investigations can provide valuable insights into refining and maximizing the benefits of Cryo-MQL technology for improved machining performance and sustainability.

CRediT authorship contribution statement

Maria Iruj: Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Saima Yaqoob:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Jaharah A. Ghani:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Hadi Jaber:** Writing – review & editing, Writing – original draft, Supervision, Formal analysis, Conceptualization. **Nizaroyani Saibani:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **Mohammad Alkhedher:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

This paper has included all the data.

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References

[1] A.B. Chattopadhyay, Machining and Machine Tools, second ed., Wiley, New Delhi, 2019.
[2] A.H. Abdelrazek, I.A. Choudhury, Y. Nukman, S.N. Kazi, Metal cutting lubricants and cutting tools: a review on the performance improvement and sustainability assessment, Int. J. Adv. Manuf. Technol. 106 (2020) 4221–4245, https://doi.org/10.1007/s00170-019-04890-w.
[3] S. Ravi, P. Gurusamy, V. Mohanavel, A review and assessment of effect of cutting fluids, Mater. Today: Proc. 37 (2021) 220–222, https://doi.org/10.1016/j.matpr.2020.05.054.
[4] A. Das, S.K. Patel, B.B. Biswal, N. Sahoo, A. Pradhan, Performance evaluation of various cutting fluids using MQL technique in hard turning of AISI 4340 alloy steel, Measurement 150 (2020) 107079, https://doi.org/10.1016/j.measurement.2019.107079.
[5] P.J. Liew, A. Shaaroni, N.A.C. Sidik, J. Yan, An overview of current status of cutting fluids and cooling techniques of turning hard steel, Int. J. Heat Mass Tran. 114 (2017) 380–394, https://doi.org/10.1016/j.ijheatmasstransfer.2017.06.077.
[6] M. Osama, A. Singh, R. Walvekar, M. Khalid, T.C.S.M. Gupta, W.W. Yin, Recent developments and performance review of metal working fluids, Tribol. Int. 114 (2017) 389–401, https://doi.org/10.1016/j.triboint.2017.04.050.
[7] A.A. Ahmad, J.A. Ghani, C.H.C. Haron, Green lubrication technique for sustainable machining of AISI 4340 alloy steel, J. Tribol. 28 (2021) 1–19. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85103299018&partnerID=40&md5=e34393047281dae34b7e18c12a5014b0.
[8] M.E. Korkmaz, M.K. Gupta, N.S. Ross, V. Sivalingam, Implementation of green cooling/lubrication strategies in metal cutting industries: a state of the art towards sustainable future and challenges, Sustain. Mater. Technol. 36 (2023) e00641, https://doi.org/10.1016/j.susmat.2023.e00641.
[9] I.S. Jawahir, H. Attia, D. Biermann, J. Duflou, F. Klocke, D. Meyer, S.T. Newman, F. Pusavec, M. Putz, J. Rech, V. Schulze, D. Umbrello, Cryogenic manufacturing processes, CIRP Ann. 65 (2016) 713–736, https://doi.org/10.1016/j.cirp.2016.06.007.
[10] V. Sivalingam, Q. Zhou, B. Selvam, J. Sun, K. Pandiyan, M.K. Gupta, M. E. Korkmaz, A mathematical approach of evaluating sustainability indicators in milling of aluminium hybrid composite by different eco-friendly cooling

strategies, Sustain. Mater. Technol. 36 (2023) e00605, https://doi.org/10.1016/j.susmat.2023.e00605.
[11] A. Gupta, R. Kumar, H. Kumar, H. Garg, Sustainable machining using hybrid nanofluids under minimum quantity lubrication (MQL), in: K. Shanker, R. Shankar, R. Sindhwani (Eds.), Advances in Industrial and Production Engineering, Springer Singapore, Singapore, 2019, pp. 573–584, https://doi.org/10.1007/978-981-13-6412-9_56.
[12] M.K. Gupta, Q. Song, Z. Liu, M. Sarikaya, M. Jamil, M. Mia, N. Khanna, G. M. Krolczyk, Experimental characterisation of the performance of hybrid cryo-lubrication assisted turning of Ti–6Al–4V alloy, Tribol. Int. 153 (2021) 106582, https://doi.org/10.1016/j.triboint.2020.106582.
[13] Ç.V. Yıldırım, T. Kıvak, M. Sarıkaya, Ş. Şirin, Evaluation of tool wear, surface roughness/topography and chip morphology when machining of Ni-based alloy 625 under MQL, cryogenic cooling and CryoMQL, J. Mater. Res. Technol. 9 (2020) 2079–2092, https://doi.org/10.1016/j.jmrt.2019.12.069.
[14] S.T. Alam, A.N.M.A. Tomal, M.K. Nayeem, High-speed machining of Ti–6Al–4V: RSM-GA based optimization of surface roughness and MRR, Results Eng. 17 (2023) 100873, https://doi.org/10.1016/j.rineng.2022.100873.
[15] Y. Seid Ahmed, A. Ryon, Tribological performance of a hybrid CryoMQL system on Ti6Al4V milling, Int. J. Adv. Manuf. Technol. 120 (2022) 8185–8199, https://doi.org/10.1007/s00170-022-09249-2.
[16] N.S. Ross, N. Srinivasan, P. Amutha, M.K. Gupta, M.E. Korkmaz, Thermo-physical, tribological and machining characteristics of Hastelloy C276 under sustainable cooling/lubrication conditions, J. Manuf. Process. 80 (2022) 397–413, https://doi.org/10.1016/j.jmapro.2022.06.018.
[17] N. Tapoglou, C. Taylor, C. Makris, Milling of aerospace alloys using supercritical CO2 assisted machining, Proc. CIRP 101 (2021) 370–373, https://doi.org/10.1016/j.procir.2020.06.008.
[18] E. Şirin, Ş. Şirin, Investigation of the performance of ecological cooling/lubrication methods in the milling of AISI 316L stainless steel, Manuf. Technol. Appl. 2 (2021) 25–84.
[19] N. Liu, C. Zheng, D. Xiang, H. Huang, J. Wang, Effect of cutting parameters on tool wear under minimum quantity cooling lubrication (MQCL) conditions, Int. J. Adv. Manuf. Technol. 105 (2019) 515–529, https://doi.org/10.1007/s00170-019-04259-z.
[20] M.K. Gupta, Q. Song, Z. Liu, M. Sarikaya, M. Mia, M. Jamil, A.K. Singla, A. Bansal, D.Y. Pimenov, M. Kuntoğlu, Tribological performance based machinability investigations in cryogenic cooling assisted turning of α-β titanium Alloy, Tribol. Int. 160 (2021) 107032, https://doi.org/10.1016/j.triboint.2021.107032.
[21] S. Sartori, A. Ghiotti, S. Bruschi, Hybrid lubricating/cooling strategies to reduce the tool wear in finishing turning of difficult-to-cut alloys, Wear 376–377 (2017) 107–114, https://doi.org/10.1016/j.wear.2016.12.047.
[22] O. Pereira, A. Rodríguez, A.I. Fernández-Abia, J. Barreiro, L.N. López de Lacalle, Cryogenic and minimum quantity lubrication for an eco-efficiency turning of AISI 304, J. Clean. Prod. 139 (2016) 440–449, https://doi.org/10.1016/j.jclepro.2016.08.030.
[23] R. Mallick, R. Kumar, A. Panda, A.K. Sahoo, Current status of hard turning in manufacturing: aspects of cooling strategy and sustainability, Lubricants 11 (2023) 108, https://doi.org/10.3390/lubricants11030108.
[24] L. Zou, Y. Huang, M. Zhou, Y. Yang, Effect of cryogenic minimum quantity lubrication on machinability of diamond tool in ultraprecision turning of 3Cr2NiMo steel, Mater. Manuf. Process. 33 (2018) 943–949, https://doi.org/10.1080/10426914.2017.1376077.
[25] A.C. Okafor, P.M. Jasra, Effects of milling methods and cooling strategies on tool wear, chip morphology and surface roughness in high speed end-milling of Inconel-718, IJMMM 21 (2019) 3, https://doi.org/10.1504/IJMMM.2019.098065.
[26] L. Sterle, P. Krajnik, F. Pušavec, The effects of liquid-CO2 cooling, MQL and cutting parameters on drilling performance, CIRP Ann. 70 (2021) 79–82, https://doi.org/10.1016/j.cirp.2021.04.007.
[27] M. Jamil, N. He, M.K. Gupta, W. Zhao, A.M. Khan, Tool wear mechanisms and its influence on machining tribology of face milled titanium alloy under sustainable hybrid lubri-cooling, Tribol. Int. 170 (2022) 107497, https://doi.org/10.1016/j.triboint.2022.107497.
[28] F.S.F. Ribeiro, J.C. Lopes, M.V. Garcia, D.L. De Moraes, A.E. Da Silva, L.E. De Angelo Sanchez, P.R. De Aguiar, E.C. Bianchi, New knowledge about grinding using MQL simultaneous to cooled air and MQL combined to wheel cleaning jet technique, Int. J. Adv. Manuf. Technol. 109 (2020) 905–917, https://doi.org/10.1007/s00170-020-05721-z.
[29] A. Bagherzadeh, E. Kuram, E. Budak, Experimental evaluation of eco-friendly hybrid cooling methods in slot milling of titanium alloy, J. Clean. Prod. 289 (2021) 125817, https://doi.org/10.1016/j.jclepro.2021.125817.
[30] A. Mehta, S. Hemakumar, A. Patil, S.P. Khandke, P. Kuppan, R. Oyyaravelu, A.S. S. Balan, Influence of sustainable cutting environments on cutting forces, surface roughness and tool wear in turning of Inconel 718, Mater. Today: Proc. 5 (2018) 6746–6754, https://doi.org/10.1016/j.matpr.2017.11.333.
[31] N.S. Ross, V. Sivaraman, M.B.J. Ananth, M. Jebaraj, Multi response optimization of dual jet CO_2 +SQL in milling Inconel 718, Mater. Manuf. Process. 38 (2023) 722–734, https://doi.org/10.1080/10426914.2022.2136378.
[32] D. Gross, M. Blauhöfer, N. Hanenkamp, Milling of Ti6Al4V with carbon dioxide as carrier medium for minimum quantity lubrication with different oils, Procedia Manuf. 43 (2020) 439–446, https://doi.org/10.1016/j.promfg.2020.02.190.
[33] F. Pušavec, D. Grguraš, M. Koch, P. Krajnik, Cooling capability of liquid nitrogen and carbon dioxide in cryogenic milling, CIRP Ann. 68 (2019) 73–76, https://doi.org/10.1016/j.cirp.2019.03.016.
[34] F. Pusavec, A. Deshpande, S. Yang, R. M'Saoubi, J. Kopac, O.W. Dillon, I. S. Jawahir, Sustainable machining of high temperature Nickel alloy – inconel 718: part 1 – predictive performance models, J. Clean. Prod. 81 (2014) 255–269, https://doi.org/10.1016/j.jclepro.2014.06.040.
[35] F. Pusavec, C. Courbon, J. Rech, J. Kopac, I.S. Jawahir, An Investigation of the Effect of Nitrogen Phase on Cryogenic Machining Performance and a Case Study on Machining of Inconel 718 Alloy, in: Volume 2: Processing, American Society of Mechanical Engineers, Detroit, Michigan, USA, 2014 V002T02A055, https://doi.org/10.1115/MSEC2014-3992.
[36] T. Meier, M. Lermer, D. Gross, N. Hanenkamp, Influence of carbon dioxide temperature on sprayability and solubility in cryogenic minimum quantity lubrication with bio-based lubricants, in: H. Kohl, G. Seliger, F. Dietrich (Eds.), Manufacturing Driving Circular Economy, Springer International Publishing, Cham, 2023, pp. 202–210, https://doi.org/10.1007/978-3-031-28839-5_23.
[37] W. Xu, M. Li, Y. Li, J. Zhao, A comprehensive review of the effect of lubricant on the flow characteristics of supercritical CO2 during cooling, Int. J. Refrig. 133 (2022) 145–156, https://doi.org/10.1016/j.ijrefrig.2021.10.018.
[38] A.B. Chattopadhyay, A. Bose, A.K. Chattopdhyay, Improvements in grinding steels by cryogenic cooling, Precis. Eng. 7 (1985) 93–98, https://doi.org/10.1016/0141-6359(85)90098-4.
[39] H. Zhang, J. Dang, Q. An, W. Ming, M. Chen, J. Zhang, Investigation of machinability in milling of Inconel 718 with solid Sialon ceramic tool using supercritical carbon dioxide (scCO2)-based cooling conditions, Ceram. Int. 48 (2022) 4940–4952, https://doi.org/10.1016/j.ceramint.2021.11.032.
[40] G. Spur, E. Uhlmann, F. Elbing, Dry-ice blasting for cleaning: process, optimization and application, Wear 233–235 (1999) 402–411, https://doi.org/10.1016/S0043-1648(99)00204-5.
[41] M. Jamil, N. He, W. Zhao, A.M. Khan, H. Xiang, M.K. Gupta, A. Iqbal, A novel low-pressure hybrid dry ice blasting system for improving the tribological and machining characteristics of AISI-52100 tool steel, J. Manuf. Process. 80 (2022) 152–160, https://doi.org/10.1016/j.jmapro.2022.05.056.
[42] M. Jamil, A. Iqbal, N. He, Q. Cheok, Thermophysical properties and heat transfer performance of novel dry-ice-based sustainable hybrid lubri-coolant, Sustainability 14 (2022) 2430, https://doi.org/10.3390/su14042430.
[43] Y. Su, L. Li, G. Wang, X. Zhong, Cutting mechanism and performance of high-speed machining of a titanium alloy using a super-hard textured tool, J. Manuf. Process. 34 (2018) 706–712, https://doi.org/10.1016/j.jmapro.2018.07.004.
[44] D. Mark Benjamin, V.N. Sabarish, M.V. Hariharan, D. Samuel Raj, On the benefits of sub-zero air supplemented minimum quantity lubrication systems: an experimental and mechanistic investigation on end milling of Ti-6-Al-4-V alloy, Tribol. Int. 119 (2018) 464–473, https://doi.org/10.1016/j.triboint.2017.11.021.
[45] V.P. Allu, D.L. Raju, S. Ramakrishna, Performance analysis of cryogenically treated plus tempered carbide inserts in turning of Inconel 718 using cryogenic minimum quantity lubrication cooling technique, Proc. IME J. J. Eng. Tribol. 233 (2019) 1810–1819, https://doi.org/10.1177/1350650119845744.
[46] N.S. Ross, M. Mia, S. Anwar, M. G, M. Saleh, S. Ahmad, A hybrid approach of cooling lubrication for sustainable and optimized machining of Ni-based industrial alloy, J. Clean. Prod. 321 (2021) 128987, https://doi.org/10.1016/j.jclepro.2021.128987.
[47] N. Villarrazo, S. Caneda, O. Pereira, A. Rodríguez, L.N. López De Lacalle, The effects of lubricooling ecosustainable techniques on tool wear in carbon steel milling, Materials 16 (2023) 2936, https://doi.org/10.3390/ma16072936.
[48] O. Pereira, A. Celaya, G. Urbikaín, A. Rodríguez, A. Fernández-Valdivielso, L.N. L. de Lacalle, CO2 cryogenic milling of Inconel 718: cutting forces and tool wear, J. Mater. Res. Technol. 9 (2020) 8459–8468, https://doi.org/10.1016/j.jmrt.2020.05.118.
[49] M. Liu, C. Li, Y. Zhang, Q. An, M. Yang, T. Gao, C. Mao, B. Liu, H. Cao, X. Xu, Z. Said, S. Debnath, M. Jamil, H.M. Ali, S. Sharma, Cryogenic minimum quantity lubrication machining: from mechanism to application, Front. Mech. Eng. 16 (2021) 649–697, https://doi.org/10.1007/s11465-021-0654-2.
[50] A. Bagherzadeh, E. Budak, Investigation of machinability in turning of difficult-to-cut materials using a new cryogenic cooling approach, Tribol. Int. 119 (2018) 510–520, https://doi.org/10.1016/j.triboint.2017.11.033.
[51] L. Sterle, D. Mallipeddi, P. Krajnik, F. Pušavec, The influence of single-channel liquid CO2 and MQL delivery on surface integrity in machining of Inconel 718, Proc. CIRP 87 (2020) 164–169, https://doi.org/10.1016/j.procir.2020.02.032.
[52] T. Meier, M. Seydaack, D. Gross, N. Hanenkamp, Investigation of the influence of the additivation of a biological metalworking oil in cryogenic machining, Proc. CIRP 105 (2022) 694–699, https://doi.org/10.1016/j.procir.2022.02.116.
[53] A. Mitrofanov, K. Parsheva, V. Nosenko, Simulation of an artificial neural network for predicting temperature and cutting force during grinding using CAMQL, Mater. Today: Proc. 38 (2021) 1508–1511, https://doi.org/10.1016/j.matpr.2020.08.139.
[54] J. Caudill, J. Schoop, I.S. Jawahir, Correlation of surface integrity with processing parameters and advanced interface cooling/lubrication in burnishing of *Ti-6Al-4V* alloy, Adv. Mater. Process. Technol. 5 (2019) 53–66, https://doi.org/10.1080/2374068X.2018.1511215.
[55] G. Chen, J. Caudill, S. Chen, I.S. Jawahir, Machining-induced surface integrity in titanium alloy Ti-6Al-4V: an investigation of cutting edge radius and cooling/lubricating strategies, J. Manuf. Process. 74 (2022) 353–364, https://doi.org/10.1016/j.jmapro.2021.12.016.
[56] J. Airao, N. Khanna, C.K. Nirala, Tool wear reduction in machining Inconel 718 by using novel sustainable cryo-lubrication techniques, Tribol. Int. 175 (2022) 107813, https://doi.org/10.1016/j.triboint.2022.107813.

[57] N. Khanna, J. Airao, C.K. Nirala, G.M. Krolczyk, Novel sustainable cryo-lubrication strategies for reducing tool wear during ultrasonic-assisted turning of Inconel 718, Tribol. Int. 174 (2022) 107728, https://doi.org/10.1016/j.triboint.2022.107728.

[58] L. Cheng, T. Qiu, S. Huang, H. Xie, C. Liu, Y. Li, L. Lin, Z. Xiang, Y. Shui, F. Wang, X. Wu, L. Yan, F. Jiang, Study on tool wear mechanism under cryogenic CO2-assisted minimum quantity lubrication technology, Review (2022), https://doi.org/10.21203/rs.3.rs-1734237/v1.

[59] L. Shi, T. Wang, E. Liu, R. Wang, Lubrication mechanism of scCO2-MQL in the assisted machining of titanium alloys, Machines 11 (2023) 291, https://doi.org/10.3390/machines11020291.

[60] K.H. Song, D.W. Lim, J.Y. Park, S.J. Ha, G.S. Yoon, Investigation on influence of hybrid nozzle of CryoMQL on tool wear, cutting force, and cutting temperature in milling of titanium alloys, Int. J. Adv. Manuf. Technol. 110 (2020) 2093–2103, https://doi.org/10.1007/s00170-020-05646-7.

[61] Q. An, C. Cai, F. Zou, X. Liang, M. Chen, Tool wear and machined surface characteristics in side milling Ti6Al4V under dry and supercritical CO2 with MQL conditions, Tribol. Int. 151 (2020) 106511, https://doi.org/10.1016/j.triboint.2020.106511.

[62] C. Cai, X. Liang, Q. An, Z. Tao, W. Ming, M. Chen, Cooling/lubrication performance of dry and supercritical CO2-based minimum quantity lubrication in peripheral milling Ti-6Al-4V, Int. J. Precis. Eng. Manuf. Green Tech. 8 (2021) 405–421, https://doi.org/10.1007/s40684-020-00194-7.

[63] G. Wu, G. Li, W. Pan, I. Raja, X. Wang, S. Ding, Experimental investigation of eco-friendly cryogenic minimum quantity lubrication (CMQL) strategy in machining of Ti–6Al–4V thin-wall part, J. Clean. Prod. 357 (2022) 131993, https://doi.org/10.1016/j.jclepro.2022.131993.

[64] T. Bergs, F. Pušavec, M. Koch, D. Grguraš, B. Döbbeler, F. Klocke, Investigation of the solubility of liquid CO2 and liquid oil to realize an internal single channel supply in milling of Ti6Al4V, Procedia Manuf. 33 (2019) 200–207, https://doi.org/10.1016/j.promfg.2019.04.024.

[65] T. Augspurger, M. Koch, F. Klocke, B. Döbbeler, Investigation of transient temperature fields in the milling cutter under CO2 cooling by means of an embedded thermocouple, Proc. CIRP 79 (2019) 33–38, https://doi.org/10.1016/j.procir.2019.02.007.

[66] S. Cordes, F. Hübner, T. Schaarschmidt, Next generation high performance cutting by use of carbon dioxide as cryogenics, Proc. CIRP 14 (2014) 401–405, https://doi.org/10.1016/j.procir.2014.03.091.

[67] D. Grguraš, L. Sterle, F. Pušavec, Cutting forces and chip morphology in LCO2 + MQL assisted robotic drilling of Ti6Al4V, Proc. CIRP 102 (2021) 299–302, https://doi.org/10.1016/j.procir.2021.09.051.

[68] N. Hanenkamp, S. Amon, D. Gross, Hybrid supply system for conventional and CO2/MQL-based cryogenic cooling, Proc. CIRP 77 (2018) 219–222, https://doi.org/10.1016/j.procir.2018.08.293.

[69] D. Grguraš, L. Sterle, P. Krajnik, F. Pušavec, A novel cryogenic machining concept based on a lubricated liquid carbon dioxide, Int. J. Mach. Tool Manufact. 145 (2019) 103456, https://doi.org/10.1016/j.ijmachtools.2019.103456.

[70] H.A. Çetindağ, A. Çiçek, N. Uçak, The effects of CryoMQL conditions on tool wear and surface integrity in hard turning of AISI 52100 bearing steel, J. Manuf. Process. 56 (2020) 463–473, https://doi.org/10.1016/j.jmapro.2020.05.015.

[71] H. González, O. Pereira, L.N. López De Lacalle, A. Calleja, I. Ayesta, J. Muñoa, Flank-milling of integral blade rotors made in Ti6Al4V using cryo CO2 and minimum quantity lubrication, J. Manuf. Sci. Eng. 143 (2021) 091011, https://doi.org/10.1115/1.4050548.

[72] P.R. Rakesh, D. Chakradhar, Experimental investigation of hybrid cooling approach using a modified tool holder for turning of Inconel 625 superalloy, Int. J. Adv. Manuf. Technol. 125 (2023) 873–885, https://doi.org/10.1007/s00170-022-10781-4.

[73] S. Kieraś, M. Jakubowski, K. Nadolny, Simulation studies on centrifugal MQL-CCA method of applying coolant during internal cylindrical grinding process, Materials 13 (2020) 2506, https://doi.org/10.3390/ma13112506.

[74] D. Gross, M. Bigelmaier, T. Meier, S. Amon, N. Ostrowicki, N. Hanenkamp, Investigation of the influence of lubricating oils on the turning of metallic materials with cryogenic minimum quantity lubrication, Proc. CIRP 80 (2019) 95–100, https://doi.org/10.1016/j.procir.2019.01.005.

[75] K.K. Wika, P. Litwa, C. Hitchens, Impact of supercritical carbon dioxide cooling with Minimum Quantity Lubrication on tool wear and surface integrity in the milling of AISI 304L stainless steel, Wear 426–427 (2019) 1691–1701, https://doi.org/10.1016/j.wear.2019.01.103.

[76] D. Gross, M. Appis, N. Hanenkamp, Investigation on the productivity of milling TI6AL4V with cryogenic minimum quantity lubrication, MM SJ 2019 (2019) 3393–3398, https://doi.org/10.17973/MMSJ.2019_11_2019098.

[77] S.-J. Ha, D.-W. Lim, J.-H. Kim, J.-Y. Park, K.-H. Song, Economic evaluation and machining performance in Ti-6Al-4V titanium alloy milling by integrated CO2 & MQL injection system, J. Mech. Sci. Technol. 35 (2021) 4135–4142, https://doi.org/10.1007/s12206-021-0825-4.

[78] Q. An, J. Dang, Cooling effects of cold mist jet with transient heat transfer on high-speed cutting of titanium alloy, Int. J. Precis. Eng. Manuf. Green Tech. 7 (2020) 271–282, https://doi.org/10.1007/s40684-019-00076-7.

[79] X. Lei, X. Wei, Y. He, Effect of cooling and lubrication conditions on cutting performance and surface integrity of Inconel 718 superalloy in end face milling, Adv. Mech. Eng. 15 (2023) 168781322311582, https://doi.org/10.1177/16878132231158217.

[80] A.P. Mitrofanov, K.A. Parsheva, A novel approach to improving the efficiency of a minimum quantity lubrication technique in the course of grinding, J. Mach. Manuf. Reliab. 50 (2021) 66–71, https://doi.org/10.3103/S1052618821010131.

[81] N. Liu, B. Liu, H. Jiang, S. Wu, C. Yang, Y. Chen, Study on vibration and surface roughness in MQCL turning of stainless steel, J. Manuf. Process. 65 (2021) 343–353, https://doi.org/10.1016/j.jmapro.2021.03.041.

[82] H.-P. Zhang, Q.-Y. Zhang, Y. Ren, T. Shay, G.-L. Liu, Simulation and experiments on cutting forces and cutting temperature in high speed milling of 300M steel under CMQL and dry conditions, Int. J. Precis. Eng. Manuf. 19 (2018) 1245–1251, https://doi.org/10.1007/s12541-018-0147-3.

[83] L. Tu, J. Chen, Q. An, W. Ming, J. Xu, M. Chen, L. Lin, Z. Yang, Machinability improvement of compacted graphite irons in milling process with supercritical CO2-based MQL, J. Manuf. Process. 68 (2021) 154–168, https://doi.org/10.1016/j.jmapro.2021.05.044.

[84] A. Shokrani, I. Al-Samarrai, S.T. Newman, Hybrid cryogenic MQL for improving tool life in machining of Ti-6Al-4V titanium alloy, J. Manuf. Process. 43 (2019) 229–243, https://doi.org/10.1016/j.jmapro.2019.05.006.

[85] J. Khosravi, B. Azarhoushang, M. Barmouz, R. Bösinger, A. Zahedi, High-speed milling of Ti6Al4V under a supercritical CO2 + MQL hybrid cooling system, J. Manuf. Process. 82 (2022) 1–14, https://doi.org/10.1016/j.jmapro.2022.07.061.

[86] K.K. Wika, O. Gurdal, P. Litwa, C. Hitchens, Influence of supercritical CO2 cooling on tool wear and cutting forces in the milling of Ti-6Al-4V, Proc. CIRP 82 (2019) 89–94, https://doi.org/10.1016/j.procir.2019.04.169.

[87] C. Courbon, L. Sterle, M. Cici, F. Pusavec, Tribological effect of lubricated liquid carbon dioxide on TiAl6V4 and AISI1045 under extreme contact conditions, Procedia Manuf. 47 (2020) 511–516, https://doi.org/10.1016/j.promfg.2020.04.139.

[88] T. Augspurger, M. Koch, T. Lakner, A. De Bartolomeis, A. Shokrani, T. Bergs, Development of a virtual sensor for the comparison of heat partitions in milling under cryogenic cooling lubrication and high-pressure cutting fluid supply, CIRP J. Manuf. Sci. Technol. 35 (2021) 118–131, https://doi.org/10.1016/j.cirpj.2021.05.004.

[89] A. Damir, B. Shi, M.H. Attia, Flow characteristics of optimized hybrid cryogenic-minimum quantity lubrication cooling in machining of aerospace materials, CIRP Ann. 68 (2019) 77–80, https://doi.org/10.1016/j.cirp.2019.04.047.

[90] A. Nagaraj, A. Uysal, S. Gururaja, I.S. Jawahir, Analysis of surface integrity in drilling carbon fiber reinforced polymer composite material under various cooling/lubricating conditions, J. Manuf. Process. 82 (2022) 124–137, https://doi.org/10.1016/j.jmapro.2022.07.065.

[91] D. Gross, N. Hanenkamp, Energy efficiency assessment of cryogenic minimum quantity lubrication cooling for milling operations, Proc. CIRP 98 (2021) 523–528, https://doi.org/10.1016/j.procir.2021.01.145.

[92] N. Ostrowicki, A. Kaim, D. Gross, N. Hanenkamp, Effect of various cooling lubricant strategies on turning Inconel 718 with different cutting materials, Proc. CIRP 101 (2021) 350–353, https://doi.org/10.1016/j.procir.2021.02.037.

[93] Z. Dai, P. Yan, H. Chen, S. Li, M. Cheng, J. Sun, L. Jiao, X. Wang, Investigation of machining property and sustainability performance of cryogenic turning of GH605 superalloy, Int. J. Adv. Manuf. Technol. (2023), https://doi.org/10.1007/s00170-023-10816-4.

[94] R. Wang, X. Wang, P. Yan, T. Zhou, L. Jiao, L. Teng, B. Zhao, The effects of cryogenic cooling on tool wear and chip morphology in turning of tantalum-tungsten alloys Ta-2.5W, J. Manuf. Process. 86 (2023) 152–162, https://doi.org/10.1016/j.jmapro.2022.12.063.

[95] A. Das, A.R.S. Mundu, V. Bajpai, Enhancing tribological performance of lead free brass in high speed micro turning via hybrid cryogenic cooling technique, Tribol. Int. (2022) 108090, https://doi.org/10.1016/j.triboint.2022.108090.

[96] A.M. Khan, W. Zhao, L. Li, M. Alkahtani, S. Hasnain, M. Jamil, N. He, Assessment of cumulative energy demand, production cost, and CO2 emission from hybrid CryoMQL assisted machining, J. Clean. Prod. 292 (2021) 125952, https://doi.org/10.1016/j.jclepro.2021.125952.

[97] M.E. Korkmaz, M.K. Gupta, H. Yilmaz, N.S. Ross, M. Boy, V.K. Sivalingam, C. K. Chan, J. Raman, Towards specific cutting energy analysis in the machining of Inconel 601 alloy under sustainable cooling conditions, J. Mater. Res. Technol. 27 (2023) 4074–4087, https://doi.org/10.1016/j.jmrt.2023.10.192.

[98] C.V. Yildirim, T. Kivak, M. Sarikaya, S. Şirin, Evaluation of tool wear, surface roughness/topography and chip morphology when machining of Ni-based alloy 625 under MQL, cryogenic cooling and CryoMQL, J. Mater. Res. Technol. 9 (2020) 2079–2092, https://doi.org/10.1016/j.jmrt.2019.12.069.

[99] A. Iqbal, J. Zaini, M. Nauman, Machinability of alloy steel and titanium alloy under carbon dioxide snow, micro-lubrication and hybrid lubro- cooling, IOP Conf. Ser. Mater. Sci. Eng. 521 (2019) 012003, https://doi.org/10.1088/1757-899X/521/1/012003.

[100] M. Jamil, N. He, W. Zhao, H. Xiang, M.K. Gupta, A. Iqbal, A.M. Khan, Assessment of energy consumption, carbon emissions and cost metrics under hybrid MQL-Dry ice blasting system: a novel cleaner production technology for manufacturing sectors, J. Clean. Prod. 360 (2022) 132111, https://doi.org/10.1016/j.jclepro.2022.132111.

[101] N.S. Ross, C. Gopinath, S. Nagarajan, M.K. Gupta, R. Shanmugam, M.S. Kumar, M. Boy, M.E. Korkmaz, Impact of hybrid cooling approach on milling and surface morphological characteristics of Nimonic 80A alloy, J. Manuf. Process. 73 (2022) 428–439, https://doi.org/10.1016/j.jmapro.2021.11.018.

[102] M.E. Korkmaz, M.K. Gupta, M. Günay, M. Boy, N. Yaşar, R. Demirsöz, K.N.S. Ross, Y. Abbas, Comprehensive analysis of tool wear, surface roughness and chip morphology in sustainable turning of Inconel-601 alloy, J. Manuf. Process. 103 (2023) 156–167, https://doi.org/10.1016/j.jmapro.2023.08.026.

[103] M. Liu, C. Li, M. Yang, T. Gao, X. Wang, X. Cui, Y. Zhang, Z. Said, S. Sharma, Mechanism and enhanced grindability of cryogenic air combined with

biolubricant grinding titanium alloy, Tribol. Int. 187 (2023) 108704, https://doi.org/10.1016/j.triboint.2023.108704.

[104] M.S. Kasim, M.S.A. Hafiz, J.A. Ghani, R. Izamshah, M.N.A. Rahman, W.N. F. Mohamad, S.B. Mohamed, The effect of pulsating lubrication method on rake face cutting tool during end milling of inconel 718, Results Eng. 17 (2023) 100764, https://doi.org/10.1016/j.rineng.2022.100764.

[105] M. Jamil, N. He, Z. Wei, M.K. Gupta, A.M. Khan, A novel quantifiable approach of estimating energy consumption, carbon emissions and cost factors in manufacturing of bearing steel based on triple bottom-line approach, Sustain. Mater. Technol. 36 (2023) e00593, https://doi.org/10.1016/j.susmat.2023.e00593.

[106] H.-P. Zhang, Z.-S. Zhang, Z.-Y. Zheng, E.-L. Liu, Tool wear in high-speed turning ultra-high strength steel under dry and CMQL conditions, Integrated Ferroelectrics Int. J. 206 (2020) 122–131, https://doi.org/10.1080/10584587.2020.1728633.

[107] W. Stachurski, J. Sawicki, R. Wójcik, K. Nadolny, Influence of application of hybrid MQL-CCA method of applying coolant during hob cutter sharpening on cutting blade surface condition, J. Clean. Prod. 171 (2018) 892–910, https://doi.org/10.1016/j.jclepro.2017.10.059.

[108] R. Arafat, N. Madanchi, S. Thiede, C. Herrmann, S.J. Skerlos, Supercritical carbon dioxide and minimum quantity lubrication in pendular surface grinding – a feasibility study, J. Clean. Prod. 296 (2021) 126560, https://doi.org/10.1016/j.jclepro.2021.126560.

[109] A.F. Abedrabbo, Cryogenic Plunge Cylindrical Grinding Dataset, 2021, https://doi.org/10.17632/4N2NFX6CX9.1.

[110] M.K. Gupta, P. Niesłony, M.E. Korkmaz, M. Kuntoğlu, G.M. Królczyk, M. Günay, M. Sarikaya, Comparison of tool wear, surface morphology, specific cutting energy and cutting temperature in machining of titanium alloys under hybrid and green cooling strategies, Int. J. Precis. Eng. Manuf. Green Tech. (2023), https://doi.org/10.1007/s40684-023-00512-9.

[111] S. Kumar Singh, A. Kumar Jha, A. Ray, S. Dewangan, Enhancing grinding parameters of TC4 titanium superalloy by using hybrid eco-friendly cooling system, Mater. Today: Proc. 62 (2022) 1505–1509, https://doi.org/10.1016/j.matpr.2022.02.214.

[112] N.S. Ross, M. Ganesh, D. Srinivasan, M.K. Gupta, M.E. Korkmaz, J.B. Krolczyk, Role of sustainable cooling/lubrication conditions in improving the tribological and machining characteristics of Monel-400 alloy, Tribol. Int. 176 (2022) 107880, https://doi.org/10.1016/j.triboint.2022.107880.

[113] F. Zou, J. Dang, X. Wang, H. Zhang, X. Sun, Q. An, M. Chen, Performance and mechanism evaluation during milling of CFRP laminates under cryogenic-based conditions, Compos. Struct. 277 (2021) 114578, https://doi.org/10.1016/j.compstruct.2021.114578.

[114] N. Khanna, P. Shah, N.M. Suri, C. Agrawal, S.K. Khatkar, F. Pusavec, M. Sarikaya, Application of environmentally-friendly cooling/lubrication strategies for turning magnesium/SiC MMCs, Silicon 13 (2021) 2445–2459, https://doi.org/10.1007/s12633-020-00588-x.

[115] M.E. Korkmaz, M.K. Gupta, R. Demirsöz, M. Boy, N. Yaşar, M. Günay, N.S. Ross, On tribological characteristics of TiC rollers machined under hybrid lubrication/cooling conditions, Tribol. Int. 174 (2022) 107745, https://doi.org/10.1016/j.triboint.2022.107745.

[116] L. Proud, N. Tapoglou, K.K. Wika, C.M. Taylor, T. Slatter, Role of CO2 cooling strategies in managing tool wear during the shoulder milling of grade 2 commercially pure titanium, Wear 524–525 (2023) 204798, https://doi.org/10.1016/j.wear.2023.204798.

[117] P.K. G, S. P, D.S. Raj, S. Hussain, V.R. Shankar, N. Raj, Optimization of jet position and investigation of the effects of multijet MQCL during end milling of Ti-6Al-4V, J. Manuf. Process. 64 (2021) 392–408, https://doi.org/10.1016/j.jmapro.2021.01.038.