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Cooling Techniques Focusing on Minimum Quantity Lubrication (MQL) and Solid Lubricant (SL) Methods to Enhance the Machinability and Sustainability of Magnesium Alloys: A Comprehensive Review

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Abstract
This literature review explores the well-recognized role of cutting fluids in machining operations, highlighting their importance for effective cooling and lubrication. While mineral-based cutting fluids are commonly used in industry, they are not environmentally friendly or healthy. Therefore, there is a pressing need to implement sustainable cooling and lubrication systems that are beneficial to the environment and enhance machinability. This review presents various sustainable alternatives to traditional flood cooling applications, including minimum quantity lubrication (MQL), nanofluids-MQL, and cryogenic-MQL. Research indicates that advancements in MQL offer several advantages over conventional dry and flooded cooling methods. MQL can provide clear guidelines for incorporating solid lubricants, often in nanoparticle form, to improve heat transfer, lubrication, tool life, material disposal, and sustainability. Continued research and development are essential to address existing challenges and unlock the full potential of these innovative cooling and lubrication techniques.
Keywords: *Cooling Techniques, MQL machining, Solid Lubricant (SL), Surface Integrity.*

1. Introduction
In the metal cutting industry, processes such as turning, milling, grinding, and drilling continue to be popular due to their effectiveness in producing products with various geometries. Nowadays, the trend is shifting towards lower costs, higher quality, and greater flexibility and sustainability. Typically, metal cutting production processes require large quantities of coolants and lubricants. In the manufacturing sector, advancements in cutting tool technology have increased productivity and highlighted the crucial role of cutting and cooling fluids in managing heat at the cutting zone during machining [1]. The traditional method of supplying cutting fluids often involves using large quantities of liquids with harmful chemical content, which fail to effectively penetrate the chip-tool interface, thus not removing heat efficiently. Conversely, applying a high-pressure jet of soluble oil directly at the chip-tool interface can significantly reduce cutting temperatures and extend tool life [2]. However, the benefits of using cutting fluids have been increasingly questioned due to several negative impacts caused by their improper handling. In recent years, excessive production activities coupled with thoughtless consumption of natural resources have led to increased environmental pollution and threats to employee health [3]. Several studies have highlighted the adverse impacts caused by cutting fluids, noting that most conventional cutting fluids are toxic and non-biodegradable [4]. Workers who are frequently exposed to these fluids face various health risks, such as skin irritation, exposure to hazardous aerosols, and potential ingestion. When mishandled, cutting fluids can harm soil and water

resources, leading to significant environmental damage. As a result, the handling and disposal of cutting fluids must adhere to strict environmental protection regulations [5]. The costs associated with procuring, storing, and disposing of coolants and lubricants significantly raise the overall production costs. Additionally, the costs associated with the installation and maintenance of fluid supply systems are also significant [2]. According to Khunt et al. (2021) [6], the cost of using cutting fluids is approximately 17% of the total manufacturing cost and about 8% of the tooling cost [7]. Klocke F et al. (1997) [7] found that the costs associated with cutting fluids represent a significant portion of total machining expenses. All reflections of these processes related to efficiency, quality, cost, environmental aspects, and human health concern the companies, engineers, machining operators, and all other collaborators associated with the manufacturing sector. A review of the literature indicates that these costs are often higher than those related to cutting tools. It is essential to balance these factors to ensure clean and highly efficient production processes in machining operations. Therefore, eliminating the use of cutting fluids, where possible, can provide a substantial economic benefit. The high costs associated with cutting fluids, combined with projected increases due to stricter environmental regulations, have prompted the search for alternatives to minimize or even eliminate their use in machining operations. To deal with all above issues, sustainable production due to economic, environmental, and health-friendly approaches is inevitable [8]. Sustainability encompasses more than just environmental concerns; it also involves economic and social impacts, all of which significantly affect actual production and the industry as a whole [9, 10]. The issues mentioned are contrary to the fundamental goals of machining technology. According to Krolczyk et al. (2019) [3], the purpose of this technology is to produce products at the lowest possible cost while ensuring the highest level of dimensional accuracy and being eco-friendly, clean, and sustainable. Additionally, Sankaranarayanan et al. (2021) [5], emphasize that manufacturing industries are key stakeholders that significantly impact the environment, placing them in a crucial position for achieving sustainability. Manufacturing industries are actively seeking techniques that minimize the use of lubricants in the metal-cutting process due to financial and ecological concerns [11]. Figure 1 illustrates the main alternatives include dry machining, minimum quantity lubrication (MQL), solid lubrication, cryogenic cooling, gaseous cooling, sustainable cutting fluids, and nanofluids [12]. Dry machining has gained acceptance as a sustainable alternative, offering economic advantages. However, it can lead to a decrease in the quality of the machined surface, increased work piece hardening, and greater tool wear [13]. In this context, MQL systems represent a viable alternative from operational, economic, and environmental perspectives. The primary objective of lubrication systems is to reduce heat generation by enhancing the heat dissipation rate at the machining zone. They achieve this by creating a thin protective layer between the cutting tool and metal chips, which helps improve surface finish and reduce tool wear [14,15]. Minimal quantity lubrication (MQL) refers to cutting fluids into very small amounts, typically with a flow rate of 50 to 500 ml per hour. In an MQL system, a mixture of a very small quantity of oil and compressed air is delivered to the cutting area. This oil mist is typically supplied to the cutting zone through an external nozzle [16]. Silva et al. (2013) [17] found that the MQL system offers characteristics very similar to those of conventional cooling methods. This makes it applicable in industrial settings, enabling machining processes while significantly reducing fluid disposal expenses and contributing to environmentally friendly manufacturing [17]. It has been highlighted that using a solid lubricant in machining operations is one of the most effective strategies for enhancing the efficiency of sustainable machining systems [18]. As noted by Padmini et al. (2014) [19], combining vegetable oils with nano solid lubricant suspensions using the Minimum Quantity Lubrication (MQL) technique is one of the best formulations for lubricants in machining. This approach not only improves machining performance and reduces manufacturing costs but is also environmentally

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friendly. For instance, Padmini et al. (2014) [19] reported that using MQL with SL (in micro and nano forms) significantly reduced cutting temperatures and tool wear while improving surface quality under specific cutting conditions. Similarly. By highlighting the advantages and potential challenges of integrating MQL systems with solid lubricants, this study provides valuable insights for manufacturers seeking to achieve sustainable, productive, and environmentally friendly machining processes. Through empirical research and analysis, this review aims to contribute to the on-going dialogue about the future of machining technology in a world increasingly focused on sustainability and efficiency.

2. Cooling Methods

2.1. Dry cutting

Dry cutting is a method that eliminates the use of harmful chemicals as a coolant, thereby reducing production costs by removing the need for cutting fluid and its associated processes such as supply, usage, and disposal. It also safeguards both worker health and environmental hazards [20]. However, dry cutting often results in higher friction and temperatures compared to processes that utilize cooling or lubrication. Additionally, it is important to note that dry cutting is not entirely free from the release of toxic components, which can lead to issues such as increased cutting tool wear and surface roughness. As a result, while dry machining reduces costs associated with coolant and lubrication, it can increase other costs, particularly those related to cutting tools. It's essential to recognize that these outcomes may not apply universally to all materials [21, 22]. The cutting forces during the dry cutting of Mg alloys are approximately half of Al alloys, which allows for lower cutting temperatures, short-chipping chips, and longer tool life under high cutting speeds [22]. Hou et al. [23] reported that thin chips occur at high cutting conditions in dry milling of Mg alloy. Such chips are highly prone to ignition owing to their lower heat capacity and higher thermal expansion. Ignition of chips at high cutting speeds is dangerous to the environment and worker health at the time of machining. This problem can be solved by the use of a coolant.

2.2. Conventional flood cooling

One of the most critical functions of cutting fluids is to remove heat generated in the machining area through conduction. Therefore, the fluids, namely mineral, semi-synthetic, and synthetic lubricants—should ideally have high thermal conductivity and specific heat [20]. Additionally, the function of cutting fluids during machining is to lubricate the work piece as it is being cut. They help to cool the material and flush away waste chips from the cutting area [5]. Although water is an environmentally friendly and economical option that meets these requirements, it cannot be used due to issues related to corrosion and its inadequate lubricating properties [20]. To address these concerns and enhance the lubrication properties of water-based coolants, various additives, such as soluble oil and synthetic or semi-synthetic fluids, have been blended with water [24]. However, in conventional cooling-assisted cutting, heat is only partially removed from the cutting zone, making this method not sufficiently effective [25]. Additionally, some chemical additives found in traditional cutting fluids can cause environmental damage and health issues, including skin irritation and respiratory problems for machine operators [26]. Using flood coolants has several disadvantages, including high operational costs related to coolant pumps, maintenance of coolant systems, and the need to clean the machine tool's work area. Additionally, it requires storing, treating, and disposing of large volumes of fluid. In this context, MQL has gained significance in metal-cutting operations and has been established in various fields as an alternative to traditional cooling methods [27]. Tomac et al. [28] conducted a study examining the impact of cutting fluids on flank build-up during the machining of magnesium alloys. They found that using water-based cutting fluid largely eliminated the flank build-up issue. However, cooling at low and medium cutting speeds resulted in poor surface roughness (Ra) and significant tool wear. In a related study, Spicer et al. [29] explored the machining of magnesium alloys with water-based coolants. Their findings indicate that magnesium alloys can be machined safely and economically with water-based emulsions. The risk of fire during machining was significantly lower compared to dry machining. Furthermore, using these coolants improved tool life, increased productivity, and facilitated better cleaning. However, the use of any water-based coolant should be avoided because the material reacts with water to form hydrogen gas which is hazardous for the environment and application of oil-based lubricant is also not feasible because dangerous gases can be formed [30,31].

2.3. High-Pressure Cooling (HPC)

High-Pressure Cooling (HPC) is a cooling method used to remove heat from the cutting zone more efficiently than conventional cooling techniques. In this process, coolant is delivered to various parts of the cutting insert that are in contact with the chip and work piece through specially designed nozzles that create a powerful fluid jet. The liquid pressure ranges from 5.5 to 35 MPa, and its velocity can reach up to 500 km/h. This pressurized liquid not only provides superior cooling characteristics for the tool, work piece, and chip regions but also acts as a chip breaker, thereby enhancing tool life and surface quality. It's important to note that while the use of high-pressure jets for coolant application significantly improves performance, the intensive consumption of coolant can lead to serious environmental and health issues [32]. Applying a high-pressure jet of soluble oil directly at the chip-tool interface can significantly reduce cutting temperatures and extend tool life [2].

2.4. Cryogenic Cooling

Cryogenic cooling is an environmentally friendly method used to mitigate the negative effects of heat generation and high temperatures that occur in the cutting zone during machining. This technique utilizes various cryogenic liquids, such as nitrogen and carbon dioxide, at very low temperatures (approximately -2000 C). These low-temperature coolants absorb heat from the machining area and create a barrier between the cutting tool and the work piece. In the chip removal process, the cryogenic coolant is transferred from a storage tank to the machine tool through specialized cryogenic hoses. It is then injected into the machining zone either from inside or outside the cutting tool. Numerous studies have investigated the effectiveness of cryogenic cooling for various materials [33]. Mohd Danisha et.al [34] studied the turning of AZ31C magnesium alloy under cryogenic and dry conditions and reported cryogenic machining has induced beneficial surface integrity and quality improvement in the surface finish and increase the micro hardness in comparison to dry turning. Grain refinement layer was observed on the turned samples, and it was found to be thinner for the cryogenic turned samples. Danish et al. [35] investigated the impact of cryogenic and dry machining environments on the temperature and surface roughness of AZ31 Mg alloy. Their findings indicated that cryogenic machining resulted in approximately a 56% improvement in surface quality compared to dry cutting. Muthuraman and Arunkumar [36] conducted an experimental study on machining Al7075 alloy using cryogenic liquid nitrogen, achieving reductions of up to 29% in temperature and 20% in cutting force. Pu et al. [37] machined AZ31B Mg discs using both dry and cryogenic cooling environments. They reported that cryogenic cooling, when combined with a large edge radius tool, positively influenced the surface condition of the AZ31B alloy. Pu. et.al. [37] studied the cryogenic machining of MZ31B Mg alloy and found that the application of cryogenic cooling enhances the surface integrity of the machined part, which provides potential performance improvement of critical components in various applications.

2.5. Minimum Quantity Lubrication (MQL)

2.5.1. Pure-MQL

Minimum Quantity Lubrication (MQL) also referred to as near-dry machining (NDM), has emerged as a viable alternative to traditional cooling methods that rely on large volumes of fluids. In MQL machining, a small amount of lubrication is delivered along with compressed air, creating an MQL mist at the machining zone [38]. The oil flow rate in MQL typically ranges from 50 to 500 mL/h, which is significantly lower than that of conventional cooling methods. A flow rate of less than 1 mL/h is classified as micro-liter lubrication (µLL). A notable discrepancy has been observed in the flow rate limits defining Minimum Quantity Lubrication (MQL). For instance, Sivaiah et al. (2023) [38] set the range at

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50–450 mL/h, Dhar et al. (2006) [39] at 50–500 mL/h, and Lubis et al. (2020) [40] at 10–100 mL/h. According to Dhar et al. (2006) [39], the system must operate at high pressure, and the fluid should be directed at high speed through the nozzle into the cutting zone. A schematic representation of a MQL setup is provided in Figure 2. MQL utilizes a minimal amount of lubricant to reduce friction and heat generation during machining [17]. Silva et al. (2013) [17] confirmed that the MQL system delivers characteristics very similar to those of conventional cooling methods. In MQL applications, most of the lubricant evaporates from the work piece and equipment, resulting in chips that are almost dry and suitable for recycling [21]. To enhance the sustainability benefits of the MQL technique in machining, various modifications like MQL with solid lubricants, with hybrid lubricants, with vegetable base oil and cryogenic have been developed and investigated. MQL (Minimum Quantity Lubrication) technology can mitigate environmental impacts by utilizing vegetable-oil-based cutting fluids and implementing oil mist control. In terms of environmental and employee health sensitivity, small amounts of vegetable-based oils in Minimum Quantity Lubrication (MQL) systems are preferred because they are more biodegradable than petroleum-based oils [40]. MQL using vegetable oil-based lubricants provides an excellent alternative to address the environmental issues posed by mineral oil-based lubricants [41]. For instance, Viswanathan et al. [42] conducted turning operations on magnesium alloy (AZ91D) using uncoated carbide tools under dry and MQL cooling regimes. They reported that the temperature during machining decreased under MQL conditions, resulting in increased tool life. Bhowmick and Alpas [43] studied the drilling of magnesium alloy (AZ91) with coated high-speed steel (HSS) drills, concluding that MQL reduced drill flank wear and coating degradation. A similar study by Bhowmick et al. [43] found that using MQL increased tool life by minimizing material adhesion and built-up edge (BUE) formation compared to dry drilling. Fratila and Caizar [45] investigated the effects of various cooling and lubrication methods—dry, MQL, and conventional fluids—on forces, surface topography, and surface temperature during the face milling of AlMg3. They observed that the MQL environment significantly reduced forces and rough surface compared to both dry and fluid-based face milling.
R. Viswanathan et.al. [46] found that the best surface finish was obtained with highest cutting speed and lowest feed rate under MQL in turning of Mg alloy. The study also focused on the temperature at cutting zone is reduced under MQL condition which leads to the increase the cutting tool life. The MQL system provides better results compared to dry turning of Mg alloy. Sarıkaya et al. (2021) [47] and Çamlı et al. (2022) [48] demonstrated that utilizing Minimum Quantity Lubrication (MQL) cooling technology with coated carbide inserts can reduce surface roughness by 24% and 34%, respectively, compared to dry machining conditions when working with ER7 steel in rail wheel applications. The concept of Minimum Quantity Lubrication (MQL) was developed to reduce health and environmental risks while simultaneously enhancing cutting performance. Initially, traditional lubricants, such as mineral and synthetic-based oils, were mixed with compressed air and delivered to the machining zone. Recently, there has been a significant shift towards using environmentally friendly, biodegradable vegetable-based lubricants and nanofluids within MQL systems. Despite the advantages of MQL over dry and wet cooling methods, researchers continue to invest considerable effort in its development and enhancement.

2.5.2. Nano fluid-Based MQL

Solid micro- and millimeter-sized particles have been added to cutting fluids to enhance their thermal conductivity. However, issues such as easy precipitation and clogging were observed. To address these problems, researchers began developing nanoscale particles [49]. Nanoparticles, which are tiny metallic particles suspended in industrial fluids like water, ethylene glycol, or motor oil, create a new class of engineering fluids known as nanofluids, an innovative fluid created by dispersing non-metallic or metallic nanoparticles, which range in size from 1 nm to 100 nm, into a primary fluid. This dispersion enhances heat transfer in the machining zone through both convection and conduction [50,51].The use of solid lubricants improves the oil film thickness between the cutting tool and the workpiece, thereby enhancing lubrication performance and the tribological properties of the coolant in MQL [51].Common types of nanofluids include those based on aluminum oxide (Al2O3), molybdenum disulfide (MoS2), diamond, silicon dioxide (SiO2), carbon nanotubes (CNT), and grapheme, differing in shape and size, are used in the formulation of nanofluids. Based on the literature survey, several key observations can be made. First, the most used nanoparticle format is "spherical," followed by "layered structure," "lamellar," and "sheets." Second, various materials are utilized, with a particular emphasis on graphite, copper, and Al2O3. It is also noteworthy that these particles are primarily on a nanometric scale. Additionally, combinations of different nanomaterials are employed to create composite or hybrid nanofluids. Compared to conventional lubricants, nanofluids exhibit several superior properties, which include [52]:

- **Enhanced Heat Transfer:** Nanofluids have higher thermal conductivity and heat capacity, leading to more efficient heat transfer from the cutting zone.
- **Advanced Lubrication Mechanisms:** These mechanisms include: -
- **Mending Effect:** Fills and repairs surface grooves (Figure. 3(a)).
- **Protective Film Effect:** Forms a protective layer on the surface (Figure. 3(b)).
- **Third-Body Effect:** Provides load-bearing support (Figure. 3(c)).
- **Rolling-Sliding Effect:** Reduces friction and wear (Figure. 3(d)).
- **Polishing Effect:** Removes debris from the machined surface (Figure. 3(e)).
- **Improved Tribological Characteristics:** Nanofluids can significantly reduce friction and wear, enhancing the overall performance of lubricants.

According to the study of various authors the use of nanofluids led to a decrease in surface roughness and an increase in tool life compared to both traditional cutting fluids and dry machining. Rahmati et al. [53] focused on evaluating the surface quality and morphology, while Rahman et al. [54] examined the effectiveness of nano fluids by considering various parameters. This included three different types of nanoparticles (Al2O3, MoS2, and TiO2), two types of vegetable lubricants (canola and extra virgin olive oil), and three different concentrations (0.5%, 2%, and 4% by volume). The authors noted that the canola-based nanofluid containing 0.5% Al2O3 resulted in excellent surface quality. Additionally, the canola nanofluid with 0.5% MoS2 contributed to lowering the temperature and increasing the chip thickness ratio. Furthermore, the use of nanofluids was effective in preventing the formation of built-up edge (BUE). Overall, it was observed that adding nanoparticles to minimum quantity lubrication (MQL) at an appropriate ratio significantly enhanced the machining performance of lightweight alloys and contributed to more environmentally friendly machining practices. Şirin, Sarıkaya, et al. (2021) [55] conducted a study to compare the machining performance in the drilling of Hastelloy X using different cutting fluid settings in Minimum Quantity Lubrication (MQL). They evaluated base fluids and nanofluids with hexagonal boron nitride (hBN), which has a spherical morphology, against nanofluids with grapheme nanoplatelets (GNP), which have a layered structure. Their findings showed that the thermal conductivity of the hBN nanofluid (0.1897 W/mK) was greater than that of the GNP nanofluid (0.1864 W/mK). In addition to contact angle, Elsheikh et al. (2021) [56] identified thermal conductivity, dynamic viscosity, and surface tension as crucial properties of nanofluids that impact cutting performance. They evaluated these attributes for Al_2O_3 and CuO nanofluids. The Al_2O_3 nanofluid exhibited lower thermal conductivity compared to the CuO nanofluid, while its viscosity was higher than that of CuO nanofluid. Viscosity, which indicates internal flow resistance, has an inverse relationship with the temperature of the nanofluid. In terms of contact angle and surface tension. The Al_2O_3 nanofluid showed higher values than the CuO nanofluid, indicating lower wettability and spreadability. Notably, the CuO nanofluid, which has

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a lower contact angle, enhances heat transfer by increasing the contact area compared to the Al_2O_3 nanofluid, leading to greater heat transfer efficiency. The introduction of nanoparticles into cutting fluids has shown great potential for significantly enhancing both thermal and lubrication properties. This review presents opportunities to improve efficiency and quality in machining processes. However, it is essential to carefully consider factors such as the size, shape, and composition of the nanoparticles, as well as their impact on fluid properties and performance during cutting. With further research and ongoing development, nanofluids could become a valuable tool in the pursuit of more efficient, precise, and sustainable machining processes. Effects of MQL with Solid Lubricants (SL) on cutting forces the impact of cutting forces on the machining process is significant, as they affect tool life, the geometry of the machined part, and surface roughness [57]. These factors make cutting forces important criteria for monitoring and optimizing machining operations [58]. Therefore, estimating cutting forces is a critical area of research aimed at preventing failures and reducing the number of rejected parts, as well as increasing tool life and ensuring process stability [59]. Numerous studies have been conducted on cutting forces and the influence of various lubrication methods on this variable. Anand et al. (2019) [60] investigated the impact of different machining environments on cutting forces—specifically, the feed force (PX), radial thrust force (PY), and main cutting force (PZ)—during the turning of Ti-6Al-4V alloy. They compared three cooling methods: flood cooling, minimum quantity lubrication (MQL) with soluble oil (diluted at a ratio of 1:20 oil to water), and MQL with nanofluids containing alumina (Al2O3 with particle sizes under 100 nm) and hexagonal boron nitride (hBN, with particles sized between 70-80 nm). The findings revealed that MQL, with soluble oil performed the best by significantly reducing the cutting forces. In contrast, flood cooling was less effective because it did not penetrate well at the chip-tool interface, leading to higher cutting forces. Additionally, the nanoparticles used in the MQL with nanofluids provided inferior lubrication at elevated temperatures, making them less effective than the MQL with soluble oil. Khan, Sisodia, et al. (2019) [61] examined the effect of incorporating nanofluids into coconut oil cutting fluid on cutting forces. They used copper (Cu) nanoparticles with sizes ranging from 20 to 30 nm, and silver nanoparticles with sizes between 10 to 20 nm, at concentrations of 0.1%, 0.25%, 0.5%, and 1%. The cutting force and friction coefficient were assessed through turning tests. It was found that the addition of Cu and Ag nanoparticles resulted in a lower friction coefficient compared to the base oil. Additionally, the concentration that yielded the lowest shear forces for both Cu and Ag nanoparticles was 0.25%. Cu nanoparticles consistently showed superior results across all analyses conducted at various concentrations. Li et al. (2019) [62] highlighted the importance of optimizing minimum quantity lubrication (MQL) parameters for effective milling of TC4 alloy, considering milling force, temperature, surface microhardness, and surface roughness. They employed MQL with graphene-dispersed vegetable-oil-based cutting fluids, utilizing graphene particles with a thickness of less than 5 nm and a diameter of around 10 nm. In evaluating milling force, the concentration of cutting fluid (W) was identified as the most significant parameter, followed by gas pressure (P), while the cutting fluid flow rate (Q) was the least influential. Optimal results were achieved at a cutting fluid concentration of 0.1 wt. %, a flow rate of 60 mL/h, and a gas pressure of 0.6 MPa. Deviating from these parameters could lead to inadequate lubrication or blockages in the cut zone caused by the graphene additives, which hinder oil film formation. Padmini et al. (2019) [63] investigated the effects of graphene nanoparticles (nG) on the performance of coconut oil (CCO) and canola oil (CNL) in the minimal quantity lubrication (MQL) technique while turning AISI 1040 steel. The study included dry tests using only coconut and canola oil, with a particle concentration of 0.3% by weight. The authors observed that CCO combined with nG resulted in lower main cutting force values compared to CNL combined with nG. This difference was primarily attributed to the superior thermal properties of CCO, specifically its thermal conductivity and heat transfer

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coefficient. Furthermore, the study noted the difference in fatty acid chain lengths: CCO has medium-length chains (8–12 carbons) while CNL has long chains (14–22 carbons). Consequently, CCO combined with nG is more effective at forming and maintaining a cutting fluid film during machining, which helps to reduce the main cutting force. Yi et al. (2020) [64] conducted a study on the turning of Ti-6A-4 V using a new graphene-based cutting fluid. They experimented with three different concentrations of graphene oxide nanofluids: 0.1%, 0.3%, and 0.5% by weight. The average particle size of the nanoparticles was 50 nm. For comparison, they used a conventional coolant made by mixing mineral oil and saponified natural oil as the base fluid. The results showed that adding nanoparticles significantly reduced cutting forces compared to those experienced with conventional coolant. Specifically, the cutting force decreased with increasing particle concentration: there was a reduction of 29.95% at a concentration of 0.1% by weight, 40.09% by weight, 0.3% by weight, and 42.03% at 0.5% by weight. The study also found that when the nanofluids penetrated the chip-tool interface, they formed a tribological film that enhanced lubrication. Gaurav et al. (2020) [65] evaluated the performance of jojoba oil, a vegetable oil, both with and without molybdenum disulfide nanoparticles (nMoS2), in turning operations on Ti–6Al–4V alloy using minimum quantity lubrication (MQL). The results were compared with those obtained using a commercially available mineral oil (LRT 30), with the experimental conditions. The use of nano MQL (MQL jojoba plus nMoS2 at a concentration of 0.1 wt %, with particles ranging from 80 to 100 nm in diameter) yielded the lowest main cutting force, attributed to reduced friction between the workpiece and the rake face. A small concentration of nMoS2 (0.1%) in jojoba oil decreased cutting forces, while higher concentrations led to nanoparticle agglomeration, which increased cutting forces. Overall, jojoba oil outperformed mineral oil in reducing the main cutting force under all tested conditions. Consequently, the authors proposed that jojoba oil could serve as an effective substitute for commercial LRT oil, with the addition of 0.1% nMoS2 nanoparticles further enhancing machining performance in terms of cutting force. Sarıkaya et al. (2021) [47] evaluated several milling environments for nickel alloy X-750, including dry cutting, base fluid minimum quantity lubrication (BF-MQL) without nanoparticles, and hexagonal boron nitride (hBN) dispersed in nanofluid minimum quantity lubrication (NF-MQL). The hBN nanoparticles, sized between 65–75 nm, were dispersed at a concentration of 0.5 vol% in vegetable-based oil. The NF-MQL method demonstrated a 6% reduction in cutting force compared to dry cutting, resulting in a 0.3% decrease in overall force. In MQL, a thin layer of oil forms at the chip-tool interface, which reduces friction. This effect is notably enhanced by the crystalline structure of hBN nanoparticles, which creates strong covalent bonds between boron and nitrogen atoms, preventing direct contact between the tool and the workpiece. The lattice structure characterized by stacked hexagonal rings allows for easier movement parallel to the planes, due to weak van der Waals interactions. This design helps to minimize friction and wear, ultimately leading to a reduction in cutting forces. Rao et al. (2021) [66] analyzed the effect of nanofluid applied through Minimum Quantity Lubrication (MQL) during the turning of EN-36 steel. They used alumina nanoparticles (Al2O3), with an average size of 80 nm, incorporated into a base vegetable fluid at concentrations of 6% and 8% by volume. The lowest cutting force was recorded with 8% concentration (280 N), while the highest force was observed during dry cutting (400 N). With a concentration of 6% Al2O3 particles, the cutting force was measured at 320 N. The authors noted that because Al2O3 particles are hard and brittle, they enhance the extreme pressure of the tribo-film and create a nano ball bearing effect during the milling process. This results in improved lubrication, reduced friction, and consequently, a decrease in cutting force. Pal et al. (2020) [67] evaluated the performance of the drilling process on AISI 321 stainless steel using vegetable oil-based cutting fluid under various minimum quantity lubrication (MQL) strategies, both with and without nanoparticles. Sunflower oil served as the base fluid, while

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graphene particles with an average size of 5 to 10 nm were incorporated. The concentrations analyzed were 0.5%, 1.0%, and 1.5% by weight. The study found that the highest thrust force and torque values occurred with pure MQL. This is attributed to the lower stability of the tribo-film protective layer formed by the oil droplets, which is a result of inadequate heat dissipation in the machining zone. The addition of graphene enhanced stability due to its high thermal conductivity, thus improving cooling performance. Furthermore, it was observed that increasing the concentration of nanoparticles significantly reduced the analyzed forces. The lowest values were recorded with a concentration of 1.5% by weight. According to the authors, a higher particle concentration enhances the development of the protective oil film on the surfaces, which in turn increases the heat transfer coefficient. The reviewed studies offer valuable insights into how lubrication parameters, nanoparticle characteristics, and fluid compositions affect cutting forces. They emphasize the importance of optimizing these factors for improved machining efficiency. By implementing innovative lubrication strategies and understanding their effects on cutting forces, manufacturers can enhance tool life, part quality, and process stability.

Effects of MQL with Solid Lubricants (SL) on Cutting Temperature Yıldırım et al. (2019) [44] emphasized the crucial role of cutting temperature in machinability, which affects surface integrity, accuracy, tool life, and wear. The authors study on the impact of hBN (hexagonal boron nitride) nanofluids on the cutting temperature during the turning of Inconel 625 revealed that the highest temperatures occurred during dry cutting, while using a 1 vol% nanofluid resulted in the lowest temperatures. This reduction in temperature was attributed to hBN's high heat absorption capacity, which facilitated rapid dissipation of heat along with the fluid or chip. In comparison to dry cutting, methods using pure MQL, nano-MQL (0.5 vol%), and nano-MQL (1 vol%) showed improvements in cutting temperature of 12.45%, 16.91%, and 30.25%, respectively. Haq et al. (2021) [68] illustrated, as shown in Figure 4, the effectiveness of nanoparticle mist over oils in creating a stable lubricating layer through the formation of a tribo-film. The combination of high-pressure air and mist helped dissipate shear heat, while the evaporation of fluid also contributed to the reduction in temperature.

Sarıkaya et al. (2021) [47] emphasize the importance of temperature control in machining. They note that managing temperature serves two purposes: it softens materials for easier cutting, while excessive heat can negatively affect tool life and surface integrity. Their study examined various cooling methods to assess their impact on maximum cutting temperature when turning Haynes 25 super alloy. They tested dry cutting alongside three nanofluids—hBN, MoS2, and graphite. The results showed that dry cutting produced the highest temperatures, which were significantly reduced when using cooling or lubrication methods. Incorporating solid lubricants into Minimum Quantity Lubrication (MQL) further decreased temperatures by enhancing thermal conductivity and heat dissipation. Among the nanofluids, MoS2 demonstrated the greatest temperature reduction at 34.95%, followed by graphene at 29.32% and hBN at 27.18%. These reductions were attributed to the lubricity and thermal conductivity of the nanofluids. Similarly, Junankar et al. (2021) [69] compared the effects of two nanofluids containing different nanoparticles—CuO and ZnO—on temperature during the turning process of bearing steel. Their findings revealed that the CuO nanofluid provided the best performance, leading to a greater reduction in temperature compared to the ZnO nanofluid. Singh et al. (2018) [70] found that using higher concentrations of graphene nanoparticles (0.2, 0.6, and 1.0 wt.%) during machining, combined with increased cutting speeds and feed rates, enhances the performance of the machining process. This approach effectively reduces the minimum cutting temperature during the turning operation of AISI 304 stainless steel. Anandan et al. (2021) [71] demonstrated that during the turning of M42 steel, grapheme nanofluids significantly decrease the temperature: by 82% during dry machining and by 57% when using oil applied through Minimum Quantity Lubrication (MQL). Rao et al. (2021) [66] also evaluated the impact of nanoparticles in cutting fluids on temperature during the turning of EN-36 steel. Their findings indicated that nanofluids led to lower temperatures compared to dry cutting. However, the different concentrations tested (6% and 8% volume concentration of nanoparticles) did not show significant differences in temperature reduction. Studies by Yıldırım et al. (2019) [44] demonstrated significant reductions in temperature when using hBN nanofluids, particularly when compared to dry cutting. Similarly, Sarıkaya et al. (2021) [47] emphasized the importance of temperature control, highlighting the effectiveness of various cooling methods, including nanofluids with additives such as MoS2, graphene, and hBN. Junankar et al. (2021) [69] reported that CuO nanofluids were particularly effective in reducing temperature response parameters during steel turning. Additionally, research conducted by Singh et al. (2018) [70] and Anandan et al. (2012) [71] illustrated the role of grapheme nanofluids in lowering cutting temperatures under different machining conditions. Lastly, Rao et al. (2021) [66] emphasized the effectiveness of nanofluids in reducing temperatures compared to dry cutting, regardless of the nanoparticle concentration. Collectively, these findings highlight the potential of nanofluids to mitigate cutting temperatures during machining operations. Effects of MQL with Solid Lubricants (SL) on Tool Wear Minimum Quantity Lubrication (MQL) has been shown to effectively reduce tool wear in various machining processes. According to Nguyen et al. (2015) [72], the effectiveness of MQL when using solid lubricants depends on factors such as the type and concentration of the additive, as well as its morphology. Specifically, the use of xGnP at a concentration of 1 wt% significantly reduced flank wear during the milling of titanium alloys. This improvement is attributed to enhanced penetration at the tool interfaces and better heat evacuation from the cutting zone, which is facilitated by the high thermal conductivity of nano solid lubricants. Yıldırım et al. (2019) [44] also noted that these factors contribute to prolonged tool life and improved surface quality. In the context of turning Ni-based Inconel 625, it was found that a 0.5% volume of hBN nanoparticles outperformed both pure MQL and dry cooling methods. This superior performance is due to the nanoparticles' increased capacity for heat absorption and their ability to delay the immediate release of cutting oil from the cutting zone. Additionally, Vasu and Kumar (2011) [73] reported that incorporating Al2O3 nanoparticles into cutting fluids enhances the thermal conductivity and heat transfer coefficient of emulsified nanofluids compared to standard emulsifiers. Darshan et al. (2019) [74] discovered that the use of nanofluids, specifically a mixture of MoS2 and canola oil mist applied through minimum quantity lubrication (MQL), significantly reduced flank and crater wear compared to tests without MQL. The application of nanofluid in mist form enhanced the interaction between the tool and workpiece, which helped to partially eliminate adhesion wear and reduce flank wear. Yücel et al. (2021) [75] investigated the effect of MoS2-based MQL nanofluids on tool wear while turning aluminium alloy AA 2024 T3. They observed a substantial reduction in built-up edge (BUE) formation compared to dry cutting. Additionally, machining under these conditions caused less damage to the cutting edge than both dry cutting and traditional MQL environments. To determine the optimal distribution rate of Al2O3 nanoparticles that would enhance properties and machining parameters, Günan et al. (2020) [76] investigated tool wear during the milling of Hastelloy alloy C276. They incorporated Al2O3 nanoparticles into a vegetable-based cutting fluid at various volumetric concentrations of 0.5%, 1.0%, and 1.5%. The study examined three cutting speeds (60, 75, and 90 m/min) and three different feed rates (0.10, 0.15, and 0.20 mm/rev). The authors concluded that tool life improved as the concentration of nanoparticles increased from 0.5% to 1% by volume. This enhancement was attributed to the greater thermal conductivity of the fluid with higher particle concentrations. Maruda et al. (2023) [77] conducted a study on tool wear during the turning of Ti6Al4V using the Minimum Quantity Lubrication (MQL) technique with copper nanoparticles (CuNPs) of varying sizes: 22 nm, 35 nm, 65 nm, and 80 nm. The study found that the lowest flank wear (Vb) after 30 minutes of machining occurred when using the nanofluid containing the smallest copper nanoparticles (22 nm). The application of 22 nm CuNPs resulted in a 22% reduction in flank wear compared to 80 nm CuNPs and a 20% reduction compared to the 65 nm CuNPs after the same amount of operation time. According to the authors, smaller nanoparticles, when introduced into the machining fluid at the same mass concentration, increase the surface-to-volume ratio, which enhances the wetting angle. This improvement in wettability leads to more effective action of the active medium in the machining zone, thereby reducing tool wear. Additionally, the use of 22 nm nanoparticles achieved a 38% reduction in the width of crater wear (Kb). The authors attribute this result to better droplet penetration, which facilitates the formation of a tribo-film that reduces friction at the tool rake face–chip interface. Tiwari et al. (2023) [78] evaluated the impact of Al2O3/coconut oil-based nanofluids on the turning of AISI-1040 steel. The machining tests were conducted under four different cooling environments: dry cutting, flood cooling, minimum quantity lubrication (MQL) with coconut oil, and nanoparticle-enhanced minimum quantity lubrication (NFMQL). When examining flank wear, the highest level of wear was observed in the dry cutting environment, primarily due to increased frictional heat in the absence of coolants or lubricants. In contrast, the use of NFMQL led to more stable tool wear and significantly less flank wear compared to the other cutting environments. Severe crater wear and adhesive wear were prominent on the rake surface of the tool inserts during dry cutting. Notably, significant crater wear was also seen in flood cooling environments, attributed to the insufficient penetration of mineral-based cutting fluids between the chip and tool interfaces. However, when MQL was used, a remarkable reduction in crater depth and wear area was noted, likely due to effective chip removal facilitated by pressurized air from the tool's rake surface. Furthermore, the application of nanofluids resulted in a decrease in crater wear depth of 36%, 30%, and 16% in comparison to the dry, flood cooling, and MQL environments, respectively. Tiwari et al. (2023) [78] emphasizes the importance of Al2O3 particles in reducing wear during the machining process. These particles exhibit synergistic anti-wear and anti-friction properties at the interfaces of the workpiece, tool, and chip. The use of a multilayer structure combined with coconut oil enhances the ability of the lubricating oil to fill the grooves on the surface of the part. This results in increased surface smoothness and improves overall lubrication performance. Aluminum oxide also provides superior lubricating capabilities due to its lower intermolecular forces compared to other materials. Its layered molecular structure resists deformation under the high loads typically encountered during machining. This ensures effective lubrication and promotes smooth sliding between the layers. Cui et al. (2022) [79] identified two primary mechanisms by which nanofluids reduce wear. The first mechanism involves increasing the distance between the tool and the workpiece with the assistance of nanofluids, which helps to prevent direct contact between the two surfaces, thereby reducing friction. The second mechanism pertains to the creation of a larger, continuous space facilitated by the nano fluid, allowing the nano lubricant to infiltrate the interface between the tool and the workpiece more effectively. This process leads to the formation of a continuous lubricating film, which enhances the lubricating properties. Effects of MQL with Solid Lubricants on the Roughness of Machined Surfaces Minimum Quantity Lubrication (MQL) has been extensively studied for its potential to enhance surface finish in various machining processes. Several investigations have focused on using MQL with different lubricants, including vegetable oils and synthetic ester fluids [80]. Additionally, microalgae oils have been explored as promising base oils for MQL operations due to their sustainability and eco-friendliness [81]. Research indicates that applying MQL with nanofluids can significantly improve machining conditions compared to traditional cutting fluids. Notable improvements include a 28% reduction in surface roughness, along with enhanced chip morphology [82]. These findings highlight the positive impact of MQL and its various lubricants on surface finish in machining operations. Furthermore, studies have shown that incorporating solid lubricants, such as graphite and molybdenum disulfide (MoS_2), in MQL can further reduce surface roughness, prolong tool life, and lower the temperature at the chip-tool interface [83]. In the case of machining Inconel 718, Paturi et al. (2016) [84] reported a 35% improvement in surface quality when using WS_2 solid lubricant-assisted MQL compared to MQL alone. The effectiveness of WS_2 solid lubricant in this context is attributed to the presence of transition-metal dichalcogenide WS_2 and its anisotropic layered structure, which reduces friction and heat generation during cutting. Machining with minimal quantity lubrication (MQL) and additives, such as Al_2O_3 nanoparticles, improves lubrication and cooling during hard milling. This enhancement leads to better surface quality [85]. Additionally, the use of SiO_2 nanofluid under MQL conditions has been shown to minimize surface roughness in milling hardened alloy steel. Optimal results can be achieved by carefully selecting specific cutting speeds, depths of cut, and feed rates [86]. Sharma, A. Ket.al. [87] presents a review regarding the MQL-based application of mineral oils, vegetable oils and nano fluid-based cutting fluids for different machining processes, such as, drilling, turning, milling and grinding, etc. Authors conclude that the MQL technique has proved to be a viable alternative to the flood lubrication under similar performance parameters and suggested focusing further investigations on the application of MQL with nano fluids in machining of different metals and alloys.

2.5.3. Hybrid Methods Using MQL

In recent years, hybrid nanofluids have been developed by combining multiple types of nanoparticles into a base liquid, either in the same or varying proportions [88]. Due to the presence of unbonded atomic sites, nanoparticles are inherently unstable and unsaturated, making them capable of easily binding with other atoms. For instance, a nanoparticle can associate with a polar atom in a vegetable-based lubricant, resulting in increased surface tension, which is the energy per unit area of a fluid and plays a crucial role in heat transfer [89, 90]. Sharma et al. (2020) [87] developed a hybrid nano cutting fluid by combining alumina-based cutting fluid with multiwalled carbon nanotube (MWCNT) nanoparticles. These nanoparticles have a cylindrical shape, consisting of 3 to 15 walls, with an outer diameter of 5 to 20 nm, an inner diameter of 2 to 6 nm, and lengths ranging from 1 to 10 µm. The mixture was tested at different volumetric concentrations (0.25%, 0.75%, and 1.25%) and its performance was compared with that of Al_2O_3 nanofluids (spherical shape, 45 nm diameter) under minimum quantity lubrication (MQL) conditions during the turning of AISI 304 steel. The results indicated that the hybrid cutting nanofluid resulted in lower cutting force (Fz), thrust force (Fy), and feed force (Fx). This was attributed to the hybrid fluid's lower coefficient of friction and superior thermo physical properties compared to the Al_2O_3 nanofluid. These properties also contributed to maintaining the tool's temperature within the recommended range set by the manufacturer, helping to preserve its hardness. Şirin and Kivak (2021) [91] investigated the influence of hybrid nanofluids on the milling of Inconel X-750 superalloy. These hybrid nanofluids were created by adding two types of nanoparticles in various combinations: hBN + graphite (Grpt), hBN + MoS_2, and Grpt + MoS_2. The average size of the nanoparticles was 80 nm, and the total concentration was set at 0.5, with each type of nanoparticle contributing 0.25. Vegetable oil served as the base fluid. For all cutting conditions evaluated, the hybrid cutting fluid comprised of hBN and Grpt exhibited the lowest cutting force. The combinations that included hBN nanoparticles resulted in lower forces compared to the hybrid nanofluid made from graphite and MoS_2. According to the authors, the superior performance of hBN is attributed to its lower viscosity, which facilitates better penetration at the tool-workpiece interface. In contrast, higher viscosity can increase the thickness of the lubrication film layer, hinder the penetration of the cutting fluid, and elevate friction. The study also focuses the tool wear during the milling of Inconel X-750 under three hybrid nanofluid conditions (hBN/Grpt, hBN/MoS_2, and Grpt/MoS_2) at various cutting speeds and feed rates. They found that the hBN/Grpt nanofluid demonstrated superior tool life, with 20.7% less flank wear compared to the Grpt/MoS_2 condition, which was attributed to its lower viscosity. The experimental analysis conducted by Ngoc et al. (2023) [92] demonstrates that using MoS2 nanofluid for minimum quantity lubrication (MQL) consistently results in the lowest cutting forces (Fc) during the hard turning of 90CrSi steel. This is in comparison to Al2O3 nanofluid MQL and hybrid Al2O3/MoS2 MQL, particularly at higher concentrations of MoS2 nanoparticles. The hybrid Al2O3/MoS2 MQL tends to exhibit higher cutting forces. Furthermore, adjustments to pressure and flow rates have a significant impact on the results. The optimal outcomes are achieved with balanced nanoparticle concentrations along with increased pressure and flow rates. These findings highlight the effectiveness of MoS2 nano fluid in reducing cutting forces and enhancing machining performance. Sharma et al. (2018) [93] investigated the effects of hybrid nanoparticle additives comprising alumina and graphene (GnP) in tribology and wettability tests. Their findings revealed that increasing the concentration of nanoparticles led to reductions in both wear and the friction coefficient to assess the impact of various cooling methods during the turning of Inconel-601 alloy as alternatives to conventional cooling techniques, Korkmaz et al. (2023) [94] evaluated several machining methods: dry cutting, minimum quantity lubrication (MQL), nanofluid with graphene (Nano MQL1), nanofluid with hexagonal boron nitride (hBN) (Nano MQL2), a hybrid nanofluid comprising graphene and hBN (Nano MQL3), cryogenic cooling (Cryo), and a hybrid cooling method combining cryogenic and nano MQL. The results indicated that the highest flank wear occurred during dry cutting, followed closely by the MQL-only cutting condition. Among the nanofluids tested, the hybrid nanofluid (graphene and hBN) yielded the lowest values for flank wear (Vb). The optimal results from the study were achieved using the hybrid cooling method (cryogenic combined with nano MQL), which, according to the authors, effectively maintains cutting temperatures at an acceptable level while preserving the lubricating effectiveness of the MQL. Lim et al. (2022) [95] investigated graphene-mixed aluminum oxide (G-Al2O3) hybrid nanolubricants in MQL machining, revealing a reduction in the coefficient of friction and an improvement in surface finish.

2.5.4. MQL Plus Ionic Liquids

Ionic liquids are low-melting organic salts known for their unique properties. According to research [96], these ionic fluids exhibit high viscosity and excellent lubrication, allowing them to create lubricating films with improved thickness profiles. Because of their low friction values, ionic liquids are suitable for metal forming applications. Additionally, their low volatility benefits sustainable machining practices, leading to increased studies on the use of Minimum Quantity Lubrication (MQL) in conjunction with ionic liquids. The lubricants can form layered oil and ionic liquid films that penetrate the cutting zone through physical adsorption on sliding surfaces, serving as an anti-wear protective film. This anti-wear film effectively reduces stress in adhesion, sliding, and friction zones during the chip removal process. As a result, it shortens the tool/chip contact length and improves chip control [97]. Despite the advantages of ionic liquids, there is limited research on their use in MQL, particularly regarding machining lightweight materials. Davis et al. [98] investigated the performance of ionic liquids in MQL during titanium machining and found that it significantly improved machining efficiency compared to dry machining and conventional MQL without additives. Pham et al. [99] examined the influence of ionic liquids during the micro-milling of the Al5052 alloy, reporting that ionic liquids provided better surface quality than traditional lubrication methods. A comprehensive review of the effectiveness of MQL was conducted by Boswell et al. [100]. While ionic liquids are noted to be relatively expensive and may contain toxic substances that are not environmentally friendly, there remains no clear consensus among researchers regarding their overall impact.

2.5.5. MQL Plus Cryogenic Cooling

Minimum Quantity Lubrication (MQL) provides effective lubrication between the cutting tool and the workpiece, while cryogenic machining offers substantial cooling using cryogenic liquids, such as liquid nitrogen (LN2). This method is not just a standalone cooling or lubrication technique; instead, it is a hybrid approach that combines MQL with cryogenic machining. A schematic illustration of a hybrid cooling and lubrication system is provided in Figure 5. In this system, compressed dry air is supplied by an external compressor and is routed to both the MQL and refrigeration systems. The mixture of oil and air generated from the MQL system, along with the cooled air from the refrigeration system, is delivered to the cutting zone through two separate nozzles. Boswell et al. [100] conducted a comparative analysis of various combinations of the MQL method, including MQL with nanoparticles, MQL with ionic liquids, MQL with Recycled Heat Vapor Technology (RHVT), cryogenic combined with MQL, and MQL with supercritical CO2, as summarized in Table 1. Their analysis considered factors such as tool wear, tool life, surface roughness, and cutting force for each lubrication/cooling method. It was found that the nano-fluid-based MQL system outperformed the other hybrid methods in these aspects. Yıldırım (2020) [51] conducted a comparison between the performance of a nanofluid made from grapheme nano platelets and cryogenic cooling using liquid nitrogen in the hard turning process of AISI 420 steel. The use of cryogenic cooling resulted in tool-chip interface temperatures that were, on average, 31.05% lower than those achieved with the nanofluid. The author explains that liquid nitrogen effectively absorbs heat, evaporates quickly, and generates a fluid gas shield between the chip and the tool head, acting as a lubricant. Additionally, the nanofluid applied through minimum quantity lubrication (MQL) has a disadvantage due to the small quantity of coolant used, as the cutting oil evaporates in a much shorter time and loses its effectiveness. The hybrid cryogenic MQL technique has been explored to mitigate the shortcomings of MQL and low-temperature refrigerants [102]. This method allows for reduced wear due to effective cryogenic cooling of the cutting tool while providing necessary lubrication through MQL [103]. The combination of hybrid cryogenic MQL with solid lubricants enables efficient cooling and lubricant processing, significantly improving machinability [55].

3. Sustainability in the Machining

Concerns about sustainability have been rising in recent years, prompting industries to adapt their processes to meet new regulations and consumer demands. Customers are increasingly conscious and selective about the impacts of their choices [104]. Unlike past decades, when sustainability was primarily focused on environmental concerns, it now encompasses a broader perspective. This is exemplified by the concept of the Triple Bottom Line (TBL) of sustainability, which includes economic, environmental, and social dimensions [105]. Incorporating the TBL principle into traditional life cycle analysis (LCA) results in the concept known as life cycle sustainability assessment (LCSA). LCSA evaluates sustainability from three perspectives:

- **Life Cycle Assessment (LCA) -** This examines the environmental impact of a product from raw material sources to final disposal.
- **Life Cycle Costing (LCC) -** This looks at the economic implications of the product throughout its life cycle.
- **Social Life Cycle Assessment (SLCA) -** This assesses the product’s impact on employees, consumers, local communities, and society.

This holistic approach influences not only manufacturing processes but also component design and the entire product life cycle. Increased focus on analyzing and improving manufacturing processes is essential because these stages typically consume the most resources and pose the greatest risks to both the environment and employee health [106,107]. Numerous works have been conducted to understand and minimize manufacturing processes impacts from various perspectives. Machining processes remain a significant segment of the manufacturing industry, making it crucial to understand the environmental, economic, and social impacts associated with them. Researchers have explored various factors related to machining processes, including manufacturing costs, resource and energy consumption, carbon emissions, environmental hazards, and human health. Dry machining is often viewed as a favorable approach to enhance the sustainability of machining processes.

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However, it may not be suitable for all applications, as it can compromise component quality and manufacturing costs. Research by Hegab et al. [108] has shown that the choice of cooling technique is crucial to the sustainability of the machining process. Each cooling method presents its own advantages and disadvantages, impacting all dimensions of the TBL.

3.1. Economic Sustainability

The economic dimension of machining is significantly affected by the chosen cooling technique, which involves direct costs associated with coolant and lubricant, their application processes, and their influence on productivity and tool life. The costs related to lubricant usage—including purchasing, preparation, and maintenance, and disposal— account for 7–17% of the total machining costs for components [109]. Since most cutting fluids are not biodegradable, they require expensive treatment before disposal, often exceeding the initial purchase cost [20]. Moreover, different cooling techniques necessitate various application apparatuses, which have significantly different power consumption rates that directly affect operational costs [110,111]. Although dry machining may seem appealing due to the lack of expenses related to coolant usage and application, it is observed that, under the tested cutting parameters, it resulted in premature tool wear and poor surface quality [112].

3.2. Environmental Sustainability

The choice of cooling methods significantly impacts the sustainability of machining processes, influencing the use of natural resources, environmental hazards, energy consumption, and carbon emissions. Benedicto et al. [113] noted that petroleum-based mineral oils, often used with emulsifiers and special additives, are non-renewable resources. Even when these conventional fluids are replaced with vegetable-based oils, the coolant consumption is much higher when using flood cooling compared to methods like Minimum Quantity Lubrication (MQL). While substituting mineral oils with vegetable oils is a positive step for mitigating environmental hazards, alternative techniques like MQL or cryogenic cooling offer greater advantages in terms of environmental impact.

3.3. Social Sustainability

A key aspect of the social dimension in machining processes is the health and safety of employees involved in operations. Dry machining, which eliminates the use of coolants, is recognized as one of the safest machining operations in terms of human health. However, this method has several limitations, as discussed in previous sections, and its application needs to be evaluated based on the materials, tools, and machine tools being used. Research by Pereira et al [114]. indicates that the cryogenic-MQL (Minimum Quantity Lubrication) method, especially when using liquid nitrogen (LN2) presents a viable alternative to conventional cooling methods when considering both technological and ecological factors. It is important to highlight that handling cryogenic liquids during storage and transportation can be hazardous, as high-pressure cryogenic liquids pose explosion risks in extreme situations. Additionally, work areas that are exposed to cryogenic gases must be equipped with effective ventilation systems to mitigate suffocation risks. High-Performance Cutting (HPC) can achieve better surface finishing and reduce tool wear compared to traditional flood methods. However, it also introduces health hazards due to the excessive use of fluids in comparison to MQL and cryogenic cooling. The MQL technique significantly minimizes—though does not eliminate—the risks associated with contact with emulsifiers because it uses only a small quantity of fluid in the process. After analyzing the available literature through the lens of sustainability, it becomes evident that the traditional flood method does not outperform other cooling methods and often presents better alternatives. Though flood lubrication has no economic advantages and poses greater risks to both the environment and worker safety, it is one of the most used techniques as it offers versatility and easier to implement because all necessary apparatus and equipment are already integrated into standard machining tools. Therefore, the advantages and disadvantages of various coolant methods should be carefully considered during process design. The decision to adopt a particular method should be backed by feasibility and sustainability analyses that encompass all three dimensions of the Triple Bottom Line (TBL) [105]. Among various materials, alloys of aluminum, titanium, and magnesium have excellent weight-to-strength ratios and can be used individually, in combination with each other, or alongside other lightweight structural elements. Magnesium (Mg) alloys offer several advantages. Magnesium has a density that is only 66% of that of aluminum and 25% of that of steel, making it an ideal candidate for replacing these metals. It is the lightest structural alloy available, but its use is limited due to its low formability. The application of magnesium alloys across multiple industries is primarily driven by their attractive light weight, corrosion resistance, and biodegradable properties. Transport-related industries, such as aeronautics and automotive, have made reducing consumption and pollutant emissions a top priority. This shift is propelled by increasingly strict environmental regulations and a society that is more aware of the need for sustainability. Consequently, there is a trend towards replacing conventional structural materials with lightweight alternatives that meet these stringent requirements. As demand continues to rise, it is crucial to explore sustainable methods for increasing production while minimizing negative impacts on sustainability. However, this material has some drawbacks. It poses a risk of ignition at temperatures above 450°C and can be explosive in powder form. Additionally, when it reacts with water, it creates flammable and potentially explosive hydrogen atmospheres, highlighting the need to reduce the use of water-based coolants. (David Blanco et al. [12].

4. Key Findings and Future Challenges

The review article analyzes the different cooling techniques and use of MQL (Minimum Quantity Lubrication) combined with solid lubricants (SL) to enhance the performance of machining processes, machinability and sustainability aspects of cutting processes. Based on the extensive review, there are several findings and prospects.

- Mineral-based flood cooling is not a sustainable method due to its negative impacts on health, the environment, and economic factors. Moreover, disposal of petroleum oil is also a serious issue. Hence the replacement of conventional fluids by biodegradable oils such as vegetable oil needs to be investigated.
- Due to financial and ecological concerns, the industries are searching for techniques that minimize the use of cutting fluids in machining. The alternative methods include dry machining, MQL, cryogenic cooling, Nano fluids, and combination of hybrid cryogenic MQL with solid lubricants. MQL with solid lubricants (MQL+SL) is emerging and requires more exploration.
- To mitigate the drawbacks of flood cooling, dry machining appears to be a more sustainable alternative. This method improves machinability by eliminating all costs associated with coolants, including purchasing, preparation, maintenance, and disposal. However, dry cutting often results in higher friction and temperatures which can lead to issues such as increased cutting tool wear and surface roughness.
- Significant advances have been made in reducing the temperature in the cutting zone and the chip formation (chip breakability) through high-pressure machining and Cryogenic machining. However, it cannot be concluded that these methods are suitable for feasibility for application on the shop floor, environmental, social, and economic sustainability.
- Minimum quantity lubrication (MQL) machining is becoming increasingly significant in the manufacturing industry due to its ability to balance productivity, sustainability, and cost efficiency. Several alternatives to enhance MQL effects have been explored.
- Solid lubricants can be incorporated into cutting fluids to improve machining performance through MQL technology. Moreover, another emerging trend focuses on combining solid lubricants with MQL and cryogenic cooling.
- Research indicates that using MQL in combination with SL can effectively reduce

tool-chip interface temperature and results in reduction in tool wear. Therefore, employing SL alongside MQL can extend tool life, enhance productivity, and reduce material waste, contributing to more sustainable machining practices.

This review is novel in its exploration of advanced techniques and their contributions to sustainability in cutting lightweight materials, which have been overlooked in previous literature. It is important to outline the main characteristics and limitations of each cooling technique, as substituting conventional emulsion cooling—which is generally regarded as the least sustainable option—is crucial. Future studies should not only focus on efficiency but also evaluate social, environmental, and economic sustainability together. More research is needed to assess social sustainability using quantitative metrics.

Table 1 **Comparative analysis of different combinations of MQL [100].**

Types of MQL Improvement	**MQL + nanoparticles**	**MQL + ionic liquid**	**Cryogenic MQL**	**MQL + SC CO2**
Tool wear	reduced	reduced	Reduced	Reduced
Tool life	improved		improved	improved
Surface quality	improved	improved	improved	improved
Cutting forces	reduced	reduced	reduced	reduced

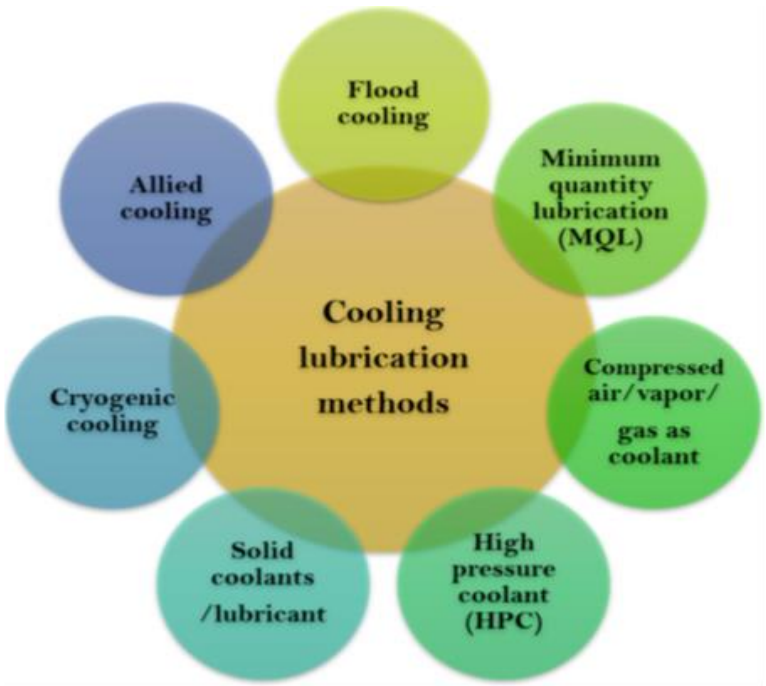

Figure 1 **A Schematic Representation of the Possible Cooling/Lubrication Strategies.**

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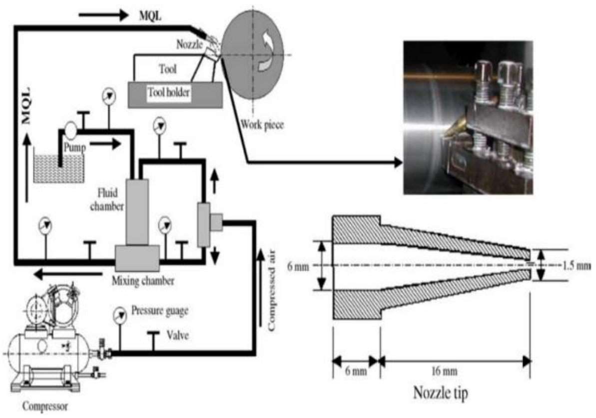

Figure 2 **Schematic View of the MQL Unit By [39].**

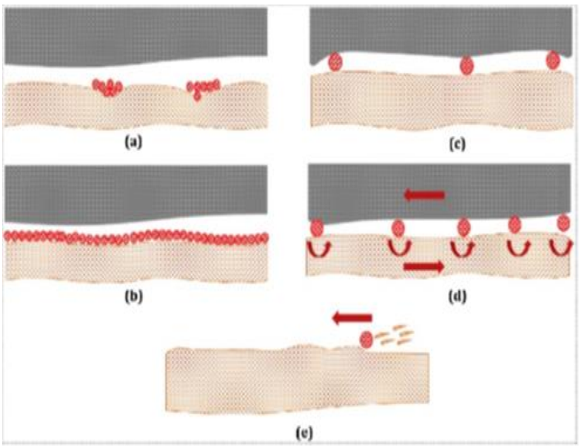

Figure 3 **Functions of nanoparticles between contacting surfaces a) mending effect b) protective film effect c) third body effect d) rolling/sliding effect e) polishing effect [47].**

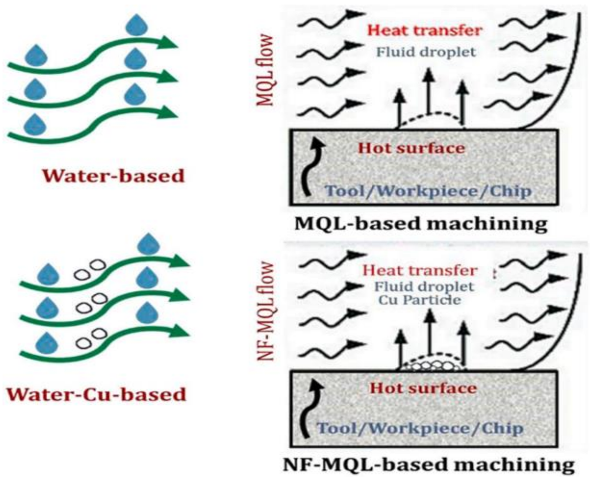

Figure 4 **Mechanism of Heat Transfer in MQL And NF-MQL Systems [68].**

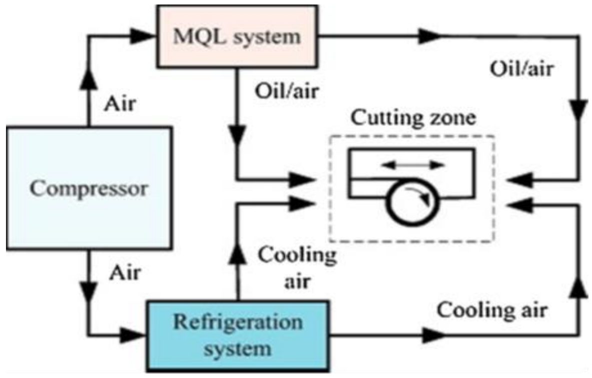

Figure 5 **Schematic view of the combination of MQL and cryogenic cooling in machining operation [101].**

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