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Performance of Liquid Lubricants Using Nano-Additvies in Minimum Quantity Lubrication in Machining Process

***Sunil K. Bangar, Dr. Neeraj Kumar**

Suresh Gyan Vihar University, Jaipur, Rajasthan.

**Corresponding Author Email: sunilbangar77@gmail.com*

Abstract: *The performance of liquid lubricants employing nano-additives in minimum quantity lubrication (MQL) during the machining process has garnered significant attention in recent years. Nano-additives, due to their unique properties and characteristics, have demonstrated potential in enhancing the lubricating properties of conventional fluids used in MQL. These additives, typically ranging from nanoparticles to nanofluids, offer improved lubricity, reduced friction, and enhanced heat dissipation, thereby leading to better machining performance, extended tool life, and improved surface quality of machined components. By reducing the amount of lubricant used while maintaining or even enhancing performance, MQL with nano-additives not only addresses environmental concerns associated with excessive fluid usage but also contributes to cost savings and increased productivity in machining operations. However, challenges such as dispersion stability, compatibility with base fluids, and cost-effectiveness need to be carefully addressed to fully realize the potential benefits of incorporating nano-additives into MQL lubricants for machining applications. Ongoing research and development efforts in this field aim to further optimize the formulation and application of these advanced lubricants to meet the ever-evolving demands of modern manufacturing processes.*

Keywords: *Liquid Lubricants, Ionic Liquid Lubricants, Solid Lubricants and Minimum Quantity Lubrication*

1. INTRODUCTION

Liquid lubricants play a vital role in minimizing friction and reducing wear between moving parts in various machine settings. These lubricants, typically oils or greases, are composed of base oils supplemented with additives to enhance their performance. They form a thin film between contacting surfaces, providing a barrier that prevents direct metal-to-metal contact, thereby minimizing friction and heat generation. Additionally, liquid lubricants help dissipate heat away from the friction zone, prolonging the lifespan of the machinery. They also contribute to sealing mechanisms, preventing the ingress of contaminants and maintaining equipment integrity. With proper selection and application, liquid lubricants can optimize the efficiency, reliability, and longevity of mechanical systems across a wide range of industries, from automotive and manufacturing to aerospace and marine applications. The prevalent liquid lubricants, derived from mineral oils, encompass a range of products sourced from crude petroleum found in different regions. These mineral oils are derived from oil-based crude and exhibit a wide spectrum of molecular structures and chain lengths, resulting in varying sizes. Consequently, they offer diverse viscosity levels. Ionic liquid lubricants, harnessing the unique properties of ionic liquids, offer a promising avenue for advanced lubrication technology. The duration of effective lubrication for However, after a certain distance of sliding, the separation voltages diminished to zero, leading to a gradual rise in the friction coefficient over time, culminating in a high-friction seizure-like state. Typically, the friction coefficient was higher at the stroke edges compared to the centre. Conversely, with thicker film thickness and extended lubrication lifetime, there was a reversal in the friction coefficient behaviour between the edge and the centre after a specific sliding distance, ultimately resulting in a seizure-like high-friction state. These lubricants, entirely composed of ions, demonstrate exceptional thermal stability, resisting breakdown even under high temperatures, and exhibit low volatility, addressing concerns regarding evaporation and environmental impact. Their chemical inertness ensures longevity and reliability, as they are resistant to oxidation and degradation. Moreover, the customizable nature of ionic liquids enables tailored adjustments to meet specific lubrication needs, optimizing viscosity, solubility, and lubricating properties. Despite their notable benefits in minimizing friction and wear between moving components, challenges like production expenses and compatibility with specific materials persist,

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leading to continuous research efforts aimed at fully unleashing their potential across various industrial sectors. Solid lubricants, unlike liquid counterparts that flow between surfaces, are materials that remain in a solid state while reducing friction between surfaces in relative motion. They adhere to surfaces, forming a protective layer that diminishes direct contact and friction. Common solid lubricants encompass graphite, molybdenum disulphide (MoS2), polytetrafluoroethylene (PTFE), and various metal oxides. These substances offer advantages such as remarkable temperature stability, resistance to oxidation, and minimal contamination. Solid lubricants find application in scenarios where liquid lubricants are impracticable or ineffective, such as extreme temperature environments, vacuum conditions, or situations necessitating stringent cleanliness standards.

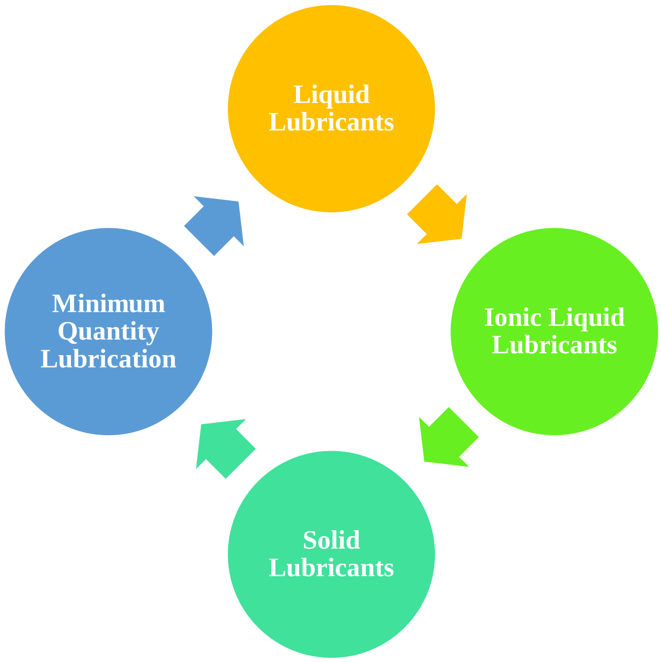

FIGURE 1. Performance of Liquid Lubricants

Minimum Quantity Lubrication (MQL) represents a contemporary strategy for lubricating machining operations, striving to mitigate environmental repercussions, prolong tool longevity, and enhance machining efficacy. Diverging from conventional flood or mist lubrication techniques, MQL administers a precisely regulated quantity of lubricant directly to the cutting area, typically in the form of a fine mist or aerosol. This minimal application of lubricant not only curtails lubricant consumption but also diminishes the production of waste fluids and airborne particles.

2. LIQUID LUBRICATION

Research on self-lubrication in liquid-solid systems focuses on assessing thermal spray coatings for their lubricating properties and resistance to wear. These coatings, produced through flame spraying, consist of a Nylon-11 matrix filled with synthetic oil, such as polyalphaolefin (PAO). Various parameters like spraying distance, powder feeding settings, and post-treatment techniques are investigated. The study also compares two types of capsules with different liquid contents. Evaluations involve using a reciprocating tribometer to measure under different loads and velocities in dry conditions [1]. In internal combustion (IC) engines, friction and wear are significant factors leading to component failure. Lubrication conditions in IC engines can be categorized into boundary, mixed, hydrodynamic, or elastohydrodynamic lubrication. Improving fuel efficiency relies on effectively lubricating surfaces in contact. Common lubricants typically consist of 95% base oil, derived from natural, petroleum, or synthetic sources, and 5% additives tailored for specific applications. These lubricants aim to reduce surface contact by forming a thin film, although some contact is still permitted, especially under boundary lubrication conditions [2]. liquid lubricants ranging from 1 μm to 165 μm in thickness were utilized. Increasing the thickness of the lubricant extended the lubrication life, resulting in significant outcomes. Initially, during the experiment, the coefficient of friction remained constant, particularly at the edges and during reciprocating motion, while it was lower at the center. However, with the progression of the test and sliding distance, breakdown voltages decreased to zero, and the friction coefficient gradually increased over time, eventually surging to exceedingly high levels. rim and the center, leading to seizure-like high friction levels. This might be attributed to increased viscosity in the surroundings due to an inadequate supply of lubricant. Furthermore, the authors suggested the possibility of polymerization under conditions of high vacuum and oxidation on new surfaces. [3]. The expanding global production and consequent rise in cutting fluids usage have spurred intensive research into The cutting zone and cooling systems' socioeconomic and environmental implications. Because of this, numerous cooling and lubricating methods have been created to encourage environmentally friendly production by lowering or doing away with the requirement for cutting fluids. At the moment, the methods that are most frequently used and have the least detrimental effects on the environment and human health are high-pressure coolant (the High Court), minimum quantity lubrication (MQL), freezer cooling, dry slicing, and the use of biodegradable oils as cooling and lubricating fluids. These emerging technologies not only offer economic and environmental benefits but also demonstrate enhanced efficiency compared to traditional flood cooling methods. Significant enhancements have been noted in surface quality, tool lifespan, productivity, and overall costs [4]. One method for improving the lubrication and cooling process in cryogenic machining is to use oil and liquid gaseous carbon dioxide (LCO2) in minimal quantity lubrication (MQL). Current advanced cryogenic machining setups employ a dual-channel delivery system for these fluids. This approach outperforms dry or MQL-only methods by enhancing machinability. However, challenges arise due to potential issues arising from the interaction between the two fluids (CO2 and MQL). These include complications stemming from LCO2 expansion and disparities in pressure and velocity between the fluids, resulting in inadequate cooling and lubrication and consequently shorter tool lifespan compared to flood lubrication. Furthermore, implementing the dual-channel approach necessitates custom tool designs, with multiple internal channels (nozzles) carefully positioned to facilitate separate fluid delivery. This becomes particularly demanding for tools with smaller diameters [5].

FIGURE 2. Liquid Lubrication

This study utilizes liquid lubricants to decrease friction, employing three categories Commercial chemical lubricants include triglyceride and vegetable oil-based options, which are derived from fatty acids and glycerides, as well as polypropylene glycol-based lubricants. Additionally, diesel oil and crude oil are analyzed, taking into account their API gravity, paraffin, and asphaltene content, making them highly economical and convenient for use in oil and gas fields. However, despite their availability, they are relatively less effective compared to dedicated lubricants. Consequently, it has been determined to blend water-based drilling lubricants with crude oil/diesel oil to enhance lubrication efficiency to find the best combination that balances good lubricating properties with cost-effectiveness. A water-based lignosulfonate mud is chosen as the base drilling fluid due to its common usage and affordability. However, this system lacks the necessary strength to withstand high torque and exhibits insufficient lubricating performance. Therefore, it is considered the base mud, with various lubricants added to improve lubrication. The fundamental system comprises bentonite, lignosulfonate, CMC, NaOH, OCMA, and barite. Prior to testing, drilling fluid samples were subjected to 150°F conditions for 16 hours to mimic field/downstream conditions and reflect fluid circulation. Chemical analysis at 120°F in the flow line simulates soil temperature to observe temperature effects, with field soil temperature selected for this study. Lignosulfonate was found not to be significantly affected by drilling fluid system temperature, thus high-temperature consequences were not prioritized in this study. The OFITE LUBRICITY TESTER (LT) was employed to estimate lubricity values of the samples, providing torque values in pounds. The coefficient of friction (COF) was calibrated using a constant to compare lubricant performance as a metric. Samples consisting of

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bentonite, CMC, chromium-free lignosulfonate, NaOH, OCMA, and barite were combined with aqueous lignosulfonate to prepare basic mud. Three types of lubricants, including diesel oil and two crude oil samples with different API gravity, were used. Furthermore, lubricant performance in contaminated media was evaluated by introducing gypsum for mud contamination and NaCl. [6].

3. IONIC LIQUID LUBRICANTS

Ionic liquids, essentially salts in liquid form, possess minimal volatility, a broad operating temperature range, non-flammability, and remarkable thermal stability, showcasing various unique characteristics. They have been explored for their performance as lubricants, as numerous studies have shown their promising lubricating properties. Moreover, in space mechanisms, their use as lubricants has been investigated, as their extremely low vapor pressure enhances pressure conditions [7]. The synthesis of three fatty acid ionic liquids (FAILs) through metathesis involved the utilization of various reagents. These included natural fatty acids—Octanoic, lauric, and Palmitic Acids—each with a purity of 98%, serving as ionic precursors. The cation precursor employed was Methyltrioctylammonium bromide, an ionic liquid with a purity of 97%, denoted as [N8881]. Toluene (purity: 99.8%), sodium hydroxide, and a 70% w/w ethanol solution were also used in the process. These chemicals were directly sourced from Sigma-Aldrich S.A and utilized without further purification. Additionally, Priolube 3970 Polyol Ester, obtained from Repsol S.A, was introduced to regulate oxidative status and viscosity. These low-viscosity lubricant compounds were integral in the formulation process [8]. Lubricants tailored for aerospace applications encompass a variety of formulations to meet demanding requirements. Silicone oils, renowned for their wide temperature range and high viscosity index, offer enhanced fluidity. However, their limitations, such as low extreme stress capacity and tendency to migrate, are addressed by perfluoropolyether (PFPE) lubricants. Originating from the 1960s development efforts of the US Air Force, PFPE lubricants were initially designed as fire-resistant hydraulic fluids and later found utility in magnetic hard drive manufacturing due to their exceptional lubricating properties. With approved low steam pressure and anti-spin-off characteristics at high rotational speeds, PFPE lubricants exhibit comparable properties to silicone oils while boasting superior oxidative stability and lower volatility. Consequently, they are widely employed in spacecraft oil formulations and greases. Nevertheless, drawbacks such as metal-catalyzed decomposition and limited load-carrying capacity persist. To address these concerns, polyalphaolefins (PAOs) and other synthetic lubricants, including polyesters, have gained traction in aviation applications. These liquid-film lubricants offer an approximate operating range spanning from 70°C to around 300°C [9]. The introduction of liquid lubrication in Triboelectric Nanogenerator (TENG) systems has shown remarkable advancements in enhancing wear resistance, signifying notable progress. By introducing lubricating oil between surfaces in TENG outputs and investigating the impact of stratification, surprising findings have emerged. It has been revealed that optimal fluid lubrication not only enhances wear resistance in TENG but also augments its power output. When compared to slide-mode TENGs, those utilizing liquid lubrication have demonstrated exceptional durability, enduring 36,000 operating cycles without visible signs of wear, thus significantly extending the service life of TENGs. Particularly noteworthy is squalane, which when used to lubricate TENGs, has been observed to amplify outputs of short-circuit power and voltage in the open circuit that are three times higher than those of unlubricated TENGs. When there is no lubrication, a stiff transfer polymer coating forms on the surface, which reduces the effectiveness of communications. By preventing the development of this film, liquid lubrication increases the effective solid-solid interaction area and removes air from the interface, ultimately resulting in higher power outputs [10]. The main objectives of this research encompass the examination of the influence of anions and cations on the performance and tribochemical interactions within a novel family of ionic liquids, primarily thiazolium-based. This entails evaluating interactions using fluorine-containing bis(trifluoromethylsulfonyl)amide and halide-free dicyanamide ions, along with examining the interaction between thiazolium and imidazolium cations. A comparative analysis will be conducted to discern differences among sliding materials, particularly in terms of wear resistance and sensitivity to corrosion, focusing on wear mechanisms and tribocorrosion processes. Through these investigations, the study aims to elucidate the performance and tribochemical interactions within the examined ionic liquids [11]. This high-performance level of lubrication is particularly well-suited for machinery where friction arises from fluid viscosity management and surface damage caused by rotation on solid surfaces, thereby controlling stress and fatigue effects. Elasto-hydrodynamic lubrication (EHL) is recognized for its ability to manage specific pressure-viscosity properties of fluids, which are essential under specific operating conditions. However, as the liquid film thickness decreases towards the surface roughness measure, a transition occurs towards mixed lubrication (ML), and ultimately to boundary lubrication (BL), where the surface, or boundary, becomes the dominant regime for lubrication. Throughout the ML to BL spectrum, the significance of tribochemical effects increases, catalyzing chemical reactions within the tribosystem and altering the properties of materials at the physics of materials level [12]. Organic PILs serve various purposes such as acting as efficient lubricants in their pure form, enhancing synthetic base oils, or functioning as additives in water to combat corrosion and serve as cutting fluids in challenging tribological conditions. They find utility in scenarios where conventional lubrication methods struggle, such as in

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sliding pairs involving ceramic-metal interfaces, light alloys against steels, or metal-to-metal contacts like copper-copper contacts, especially relevant in electric or transport applications [13]. The introduction of corrosion inhibitors in Ionic Liquids (ILs) has led to notable advancements in enhancing efficiency. For instance, the utilization of hexafluorophosphate as a benzotriazole corrosion inhibitor in ILs has been investigated, particularly in steel/Cu-Sn contacts. This addition has resulted in the formation of surface films containing copper oxide and copper-benzotriazole, thereby improving anticorrosion properties and contributing to antivirus characteristics [14].

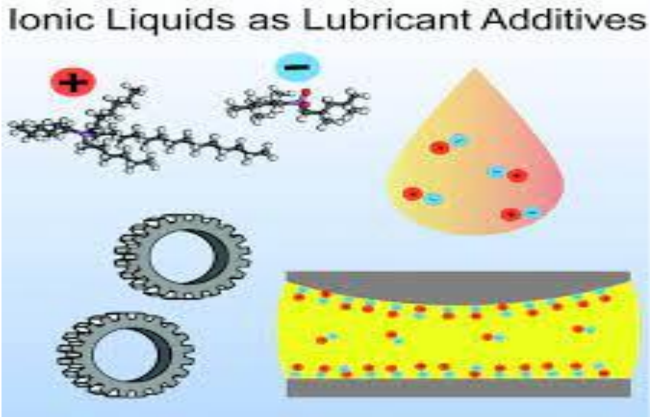

FIGURE 3. Ionic Liquid Lubricants

In the elastohydrodynamic regime, liquid lubricants offer advantages such as low engine noise, minimal wear, and easy refilling, effectively removing waste debris. They are preferred in various environmental conditions, including endurance scenarios, due to their capacity and environmental benefits. However, in high vacuum environments, the use of liquid lubricants poses challenges due to their rapid evaporation and the absence of oxide films, which can lead to mechanism failure. More recently, multialkylated Cyclopentanes (MACs) have gained popularity for aerospace lubrication due to their favorable properties. Nonetheless, under vacuum conditions, MACs, perfluoropolyethers (PFPE), and similar lubricants may initially exhibit high friction and wear, especially under boundary lubrication conditions. To address these issues and reduce friction, combinations of additives have been employed [15]. Researchers conducted a detailed investigation into the lubrication properties of dialkylimidazolium tetrafluoroborate and hexafluorophosphate ionic liquids. These liquids have demonstrated excellent capabilities in reducing friction, wear, and overload resistance performance, making them highly suitable as lubricants for sliding pairs with high tolerance. However, their practical application poses challenges, particularly regarding oxidative stability higher temperatures, attributed to the susceptibility of the aromatic ring to oxidation and ring-opening. To address this issue, modifying the cation to enhance oxidative stability is being explored to systematically advance research on ionic liquid lubricants [16]. Phosphonium-based ionic liquids have garnered increasing interest due to their commercial availability and have been investigated for various applications beyond lubrication. Some members of this family have shown superior tribological performance compared to imidazolium counterparts and conventional oils. Notably, [(C2F5)3PF3] and have been studied as neat lubricants in steel-to-steel contact, with [C2C2PO4] demonstrating superior antifriction ability, albeit with poorer wear reduction behavior and thermal stability compared to [(C2F5)3PF3]. Analysis revealed the formation of tribofilms composed mainly of iron phosphides and oxides on the worn surface with both ionic liquids [17].

4. SOLID LUBRICANTS

Solid lubrication and in-situ liquid lubricants, which are polymer-based, offer potential avenues for enhancing tribological characteristics. However, polymeric composites encounter a significant challenge due to their low thermal conductivity. For instance, phenolic resins exhibit thermal conductivity of around 0.35W/mK, which is approximately 1/50th compared to steel. This limitation hampers heat dissipation in bearings and may lead to molecular degradation and failure due to burnout. To address this issue, carbon fibers with high thermal conductivity can be incorporated into phenolic resins. By coupling with these fibers, heat dissipation problems can be mitigated to some extent. Optimization of reinforcement and fillers to achieve optimal tribological, thermal, and mechanical properties is crucial in this regard [18]. Epoxy resins possess high mechanical strength, thermal stability, excellent chemical resistance, and adhesive properties when bonded with metals. However, their inherent fragility limits their applicability across a wide range of applications. To fully leverage the advantages of epoxy, incorporating additives is crucial. MoS2, a well-known solid lubricant, enhances wear resistance in sliding wear and increases mechanical strength in polymers. At interfaces, MoS2 facilitates heat dissipation due to its unique lamellar structure and weak van der Waals forces binding its layers. The nano-sheets of MoS2 enable easier sliding

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between surfaces, effectively reducing friction coefficients in epoxy. Studies have demonstrated that the incorporation of synthesized fullerene, such as MoS2, decreases friction and wear by 25.6% and 65.5%, respectively [19]. Solid lubricants and liquid lubricants both offer effective solutions for lubrication challenges that arise. Dry lubricants, comprised of solid materials, are widely recognized for their performance, with graphite and molybdenum disulfide (MoS2) being notable examples. However, there is ongoing debate regarding the performance of solid additives when incorporated into liquid lubricants, particularly when combined with other substances. Various factors, including the concentration and type of additives such as graphite and MoS2, as well as the test methods used to assess wear on test samples, impact their performance. Analyzing the effects of these factors at different concentrations is crucial for evaluating their effectiveness [20].

FIGURE 4. Solid Lubricants

During machining operations, researchers have explored various options for solid lubricants to enhance the machinability of materials such as AISI 1040 steel. Solid lubricants have been investigated to improve parameters such as chip thickness ratio, surface roughness, and mechanical efficiency during machining. Graphite and molybdenum disulfide (MoS2) are commonly used as solid lubricants in alloys. It was observed that MoS2-assisted machining resulted in lower surface roughness and machining force values compared to graphite. In final grinding operations on AISI 1045 steel, both graphite and molybdenum disulfide were utilized, leading to improved surface quality, reduced cutting forces, and lower specific energy consumption. Overall, the adoption of these advanced processes yielded favorable results [21]. Solid lubricants such as MoS2, CaF2, HBN, and WS2 are commonly mixed with oils by various mechanics to enhance performance. However, at elevated temperatures, vegetable oils experience a loss of oxidative stability. To address this issue, solid lubricants are added to improve the lubricating performance of oils. More recently, carbon-based 2D materials like graphene have garnered attention from researchers due to their exceptional mechanical properties and high thermal conductivity (up to 5000 W/mK). The inclusion of graphene in lubricants reduces temperatures in the shear zone promptly owing to its extremely high thermal conductivity. In light of these advancements, a critical review was conducted in this study, focusing on the utilization of different plant oils, bio-oils, solid lubricants, and carbon-based nano-solid lubricants in oil formulations [22]. Extensive research has been conducted on solid lubricant additives with layered structures, resulting in enhanced surface finish and tool life, which in turn improve machine performance overall. Numerous studies have been conducted on 13 solid additives to lubricant, including aluminium disulfide, the material graphite chromium disulphide, and boron nitride. These additives are composed of lamellar crystal structures in which successive layers are bonded by tiny van der Waals forces, while each layer exhibits strong covalent bonding. Tool wear productivity and cutting force have decreased significantly as a result of the inherent crystal structure of these materials, resulting in low shear strength. Incorporating these additives into base oils enhances their tribological properties. However, it's worth noting that the inclusion of hardened solid lubricant micron-sized particles may cause abrasion and conflict. Graphite and sulphuric acid are frequently employed as cooling fluids and are acknowledged as efficient suspending particles that significantly reduce friction between slides elements and potentially lowering shear strength [23].

5. MINIMUM QUANTITY LUBRICATION IN MACHINING PROCESS

Various micro and nano particles are incorporated into fluids in Minimum Quantity of Lubrication (MQL) systems to increase the fluids' ability to cool and to become more lubricant. Research has indicated that adding alumina and gem nanoparticles to lubricants in MQL systems can enhance their thermal conductivity. To improve lubrication and solid grease additives like graphite and MoS2 are also used. Dichalcogenides of refractory metal, such as TaS2 and WS2, show superior thermal stability compared to graphite, however, research on their impact as solid lubricants in machining operations is relatively limited. Some studies are focusing on utilizing WS2 in soft coatings, although these coatings tend to wear quickly over the tool's lifespan and may have less impact. An alternative approach involves introducing WS2 into the MQL stream throughout machining operations. For instance, WS2 dispersed in emulsifier oil-based cutting fluid was examined for its effects on Inconel 718, primarily focusing on surface roughness analysis [24]. Because of their exceptional strength as well as outstanding temperature endurance, AISI H-13 steel, a titanium alloy, Heinz twenty-five Superalloy, Inconel 718, and Al/SiC composites composed of metal matrix are used in the aerospace and automotive industries for dies and turbines. Such substances have a high degree of corrosion resistance, but because of their high durability and low temperature transfer coefficients, they are difficult to machine.. Previous attempts at mechanization have been made, including Wire Electrical Discharge Machining (EDM) processes using Al/SiC metal matrix composites and other hard materials. Additionally, EDM utilizing SPK cold work steel cylinders has been employed to achieve high tolerance and superior surface finish, but concerns arise due to significant heat production and elevated temperatures during machining. Economically cutting these materials and reducing tool wear necessitates advanced surface temperature control measures to mitigate heat-related issues [25].

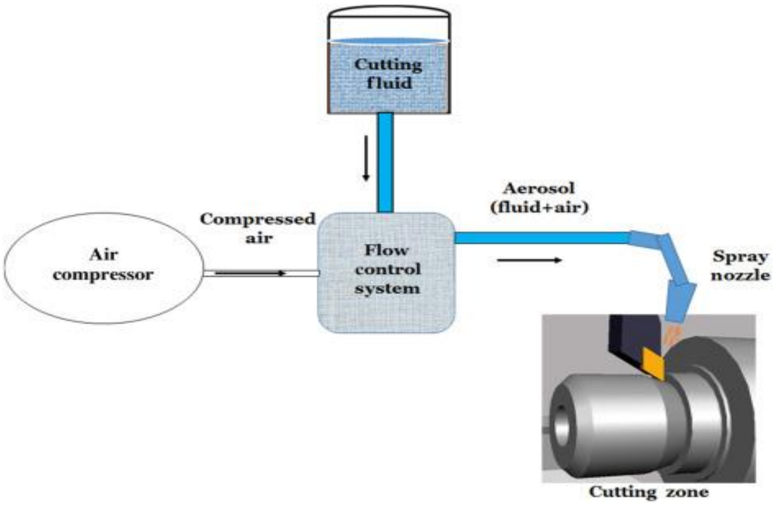

FIGURE 5. Minimum Quantity Lubrication

Minimum Quantity of Lubrication (MQL) grinding is an increasingly adopted method in which a minimal amount of lubricant, typically ranging from 30 to 200 ml/h, is supplied to the grinding zone at a specific pressure, mixed with air. This system, known as oil mist lubrication, utilizes compressed air for both lubrication and cooling purposes, thereby reducing lubricant consumption in compliance with environmental regulations while also controlling heat production in the shear zone. Studies comparing MQL with flood lubrication during grinding, particularly when utilizing a CBN wheel, have demonstrated promising results in terms of surface coating, grinding efficiency, and power consumption, with lubricant flow rates ranging from 30 ml/h to 150 ml/h [26]. Reducing oil consumption in workshops is achieved by maintaining mist concentrations in Minimum Quantity Lubrication (MQL) systems. The effectiveness of MQL in lubricating workpiece surfaces relies on desk readings. To assess deposition efficiency under various lubrication conditions, a droplet size measurement device is employed. This device, positioned 60 mm vertically from the worktop during mechanical testing, includes a nozzle, tip, and collection sheets. The horizontal distance between the nozzle and collection sheets ranges from 100 to 1500 mm (1550 mm from the side wall of the machine tool). AISI-304 stainless steel collection sheets, with an area of 16 cm^2, are utilized to collect deposited droplets. MQL/EMQL is applied at a test air pressure of 0.3 MPa and a flow rate of 20 mL/h for a specified collection duration. The weights of deposited droplets are measured using an electronic analytical balance, and the sediment weight per unit area (M/A) is calculated for comparison among different lubrication levels. Prior to testing, collection sheets are cleaned using acetone and ultrasound treatment to remove surface contaminants. All experiments are conducted in triplicate, and mean values are reported [27]. Minimum Quantity Lubrication (MQL) systems, compressed air and an atomizer are utilized to mix oil, generating aerosols that form a fog between the tool and workspace interface. Braga et al. (2002) conducted a study on the application of MQL technique in drilling A356 aluminum-silicon alloys using uncoated and diamond-coated drills. The results of the drilling tests revealed that, compared to drills used without MQL, diamond-coated drills exhibited minimal improvement when employed with MQL. However, the quality of the holes drilled using MQL was found to be equal to or superior to those drilled using flood cooling. Additionally, the study investigated the impact of MQL on tool wear and the surface hardness of the workpiece. Compared to dry and wet machining, MQL demonstrated sophisticated machining capabilities and effectively reduced surface hardness [28]. Equipment is crucial in various industries for achieving desired outcomes, including processes like machining, vehicle operation, space exploration, and manufacturing. Heat generated by friction at the tool-workpiece and tool-chip interfaces during machining can damage cutting tools, making cooling and lubrication essential to prevent tool damage and reduce power consumption. Traditional cutting fluids, typically a mixture of synthetic with water or mineral oil, are commonly used due to their superior lubricating properties and coolant capabilities compared to water alone. However, petroleum-based emulsifying fluids used at room temperature pose environmental and health risks and can be costly to maintain. In response to increasing environmental regulations and stricter laws, industries and researchers are actively seeking environmentally friendly alternatives to traditional cutting fluids to reduce the use of harmful substances in machining processes [29]. Enhancing engine performance and prolonging tool life are key objectives in metalworking operations, achieved through the efficient utilization of Metal Working Fluids (MWFs) to manage heat in the shear zone effectively. Recent attention has been directed towards the benefits of the MQL, or Minimum Quantity Lubrication, method. When comparison to flood cooling techniques, MQL uses a mist spray of liquid lubricant, which seems to be very effective. Research on turning the alloy Inconel 718 containing CBN inserts using MQL-assisted turning has demonstrated that raising the feed rate increases the material removal efficiency (MRR) and shear pressures at higher cutting temperatures. Additionally, a comparison has been made between the efficacy of MQL-assisted Inconel 718 machining and dry and flood-assisted milling techniques. revealing that MQL, along with dry conditions, results in reduced tool wear and improved engine performance. Moreover, investigations into micro-machining of Inconel 718 under various conditions using coated cutting tools have been conducted, highlighting the advantages of MQL-assisted machining in terms of engine performance and tool wear [30].

6. CONCLUSION

Liquid lubricants play a vital role in minimizing friction and reducing wear between moving parts in various machine settings. These lubricants, typically oils or greases, are composed of base oils supplemented with additives to enhance their performance. They form a thin film between contacting surfaces, providing a barrier that prevents direct metal-to-metal contact, thereby minimizing friction and heat generation. Additionally, liquid lubricants help dissipate heat away from the friction zone, prolonging the lifespan of the machinery. Research on self-lubrication in liquid-solid systems focuses on assessing thermal spray coatings for their lubricating properties and resistance to wear. These coatings, produced through flame spraying, consist of a Nylon-11 matrix filled with synthetic oil, such as polyalphaolefin (PAO). Various parameters like spraying distance, powder feeding settings, and post-treatment techniques are investigated. The study also compares two types of capsules with different liquid contents. Ionic liquids, essentially salts in liquid form, possess minimal volatility, a broad operating temperature range, non-flammability, and remarkable thermal stability, showcasing various unique characteristics. They have been explored for their performance as lubricants, as numerous studies have shown their promising lubricating properties. Solid lubricants and liquid lubricants both offer effective solutions for lubrication challenges that arise. Dry lubricants, comprised of solid materials, are widely recognized for their performance, with graphite and molybdenum disulfide (MoS2) being notable examples. However, there is ongoing debate regarding the performance of solid additives when incorporated into liquid lubricants, particularly when combined with other substances. Various factors, including the concentration and type of additives such as graphite and MoS2, as well as the test methods used to assess wear on test samples, impact their performance. Analyzing the effects of these factors at different concentrations is crucial for evaluating their effectiveness. Various micro and nano particles are incorporated into fluids in Minimum Quantity of Lubrication (MQL) systems to increase the fluids' ability to cool and to become more lubricant. Research has indicated that adding alumina and gem nanoparticles to lubricants in MQL systems can enhance their thermal conductivity. To improve lubrication and solid grease additives like graphite and MoS2 are also used. Dichalcogenides of refractory metal, such as TaS2 and WS2, show superior thermal stability compared to graphite, however, research on their impact as solid lubricants in machining operations is relatively limited.

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