Available on https://www.gyanvihar.org/researchjournals/ctm_journals.php
SGVU International Journal of Convergence of Technology and Management
E-ISSN: 2455-7528
Vol.10 Issue 2 Page No 120-128

Nanofluid-Enhanced Machining: A State-of-the-Art Review of MQL and NMQL Techniques

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Abstract— MQL and NMQL are emerging as eco-friendly alternatives to traditional flood cooling methods in machining. These techniques drastically reduce the use of cutting fluids while improving machining outcomes. Adding nanoparticles to cutting fluids enhances their heat transfer, lubricating, and cooling properties. NMQL stands out particularly when working with challenging materials like nickel-based alloys, titanium alloys, and carbon fibre-reinforced plastics. Numerous studies provide evidence that these techniques lead to lower cutting forces, decreased tool wear, and lower temperatures in the cutting region. Additionally, they contribute to better surface finish quality and boost overall machining productivity. Despite the promising results, the study identifies areas requiring further research, especially in optimising nanofluid compositions for specific materials and machining conditions. The challenge of tailoring nanofluids to meet diverse application requirements underscores the need for continued investigation. The study also explores how MQL and NMQL contribute to environmental protection and cost savings, aligning with the increasing focus on sustainable manufacturing. These techniques balance effective machining and environmental stewardship, potentially transforming industrial methods. MQL and NMQL represent a significant step towards more sustainable manufacturing practices by offering both performance improvements and ecological benefits. MQL and NMQL mark major progress in high-precision machining, addressing persistent issues in this area. These methods are anticipated to be key in developing more sustainable and efficient manufacturing as research continues. They show promise for enhancing results across many industries, potentially reshaping the landscape of manufacturing technology. By combining improved performance with environmental benefits, MQL and NMQL are positioned to drive innovation in sustainable production methods across diverse industrial applications.

Keywords— MQL, NMQL, Precision Machining, Nanofluid Cutting and Sustainable Manufacturing.

I. INTRODUCTION

Expanding the heat dissipation area is crucial in cutting processes as it greatly improves cutting tool longevity, lowers energy consumption, and boosts production rates. Traditionally, methods to improve heat dissipation for different industrial uses have focused on increasing the heat exchange surface area. Nevertheless, this approach frequently results in the thermal management system becoming larger [1]. Traditionally used cutting fluids have been important in streamlining machining operations, especially when dealing with difficult-to-work materials. They have been effective in reducing surface roughness, increasing tool life, and enhancing overall machinability. However, the widespread utilization of cutting fluids having mineral bases has created serious environmental issues, jeopardized the overall quality of the soil and water, and brought up a host of health and ecological issues. The scale of this problem is significant. In 2016, the world consumed 13,726 million tonnes of non-biodegradable, mineral-based cutting lubricants. This consumption is growing at a rate of 1% annually, indicating a worrying trend. This need is particularly pressing for improving machining performance on materials that are difficult to cut, where the benefits of traditional cutting fluids have been most pronounced [2-4]. Researchers have developed various eco-friendly lubrication methods to address environmental concerns in machining. These include MQL, cryogenic cooling, and dry cutting. Dry cutting eliminates cutting fluids, but it comes with drawbacks such as faster

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tool wear and poorer surface finish. MQL offers a more balanced approach. It produces a fine mist that is delivered effectively to the cutting region using an accurate quantity of cutting fluid, atomized and blended with compressed air. This method significantly reduces fluid consumption while still providing lubrication and cooling benefits. The cryogenic technique takes a different approach, using extremely cold substances like liquid nitrogen (LN2) at temperatures below -153°C (120 K). It offers an innovative way to manage heat generation during the cutting process. Each of these methods aims to provide environmentally friendly alternatives to traditional flood cooling while maintaining or improving machining performance [5-7].

Researchers have put considerable effort into improving and assessing cutting performance to create more sustainable machining processes that extend tool life and enhance machinability. Cutting fluids are essential to working with machining because they make tools last longer and process data more effectively. Cutting fluids' main purpose is to lower the temperature of the workpiece and the cutting instrument. They achieve this by decreasing friction between the chips produced during cutting and the tool itself. Studies have been conducted to examine how different materials, tools, and cutting parameters affect the machining process. One notable example involved experiments on turning AISI 1045 steel. These investigations revealed a significant advantage of using cutting fluids over dry cutting methods [8]. Researchers are beginning to recognize MQL as an environmentally acceptable cutting method. This procedure involves spraying the cutting zone utilizing compressed air and a tiny quantity of lubricant. This method seeks to improve surface quality and prolong tool life by reducing warmth and friction where the tool touches the chip. However, MQL's effectiveness has been questioned in high-heat scenarios. As metal cutting processes strive for greater efficiency, they often generate significant heat. In these situations, while the rate of metal removal increases quickly, so does tool wear, due to the intense heat and friction in the cutting area. This limitation of standard MQL has led researchers to conclude that an improved version is needed. Such an enhanced MQL system would need to offer superior cooling and lubrication capabilities to effectively manage the challenges posed by high-efficiency, high-heat cutting processes [9-11].

According to recent studies, when compared to conventional fluids, nano-fluids offer considerable reductions in heat and friction. For instance, Hegab et al. achieved better results than traditional MQL procedures when they machined Inconel 718 using MWCNTs nanofluid. Similar to this, MoS2 MQL-nanofluid was employed to grind 45 Steel, and due to the increased lubrication efficiency, the surface quality was enhanced. The effectiveness of several cooling and lubricating methods, including dry cutting, cryogenic cooling, MQL, nanofluid application, and MQL-nanofluid, was examined in a recent study with a focus on waste management, energy consumption, sustainability, and ecological implications. [12-14]. Researchers have worked to enhance the MQL approach's cooling capacities, even with its obvious benefits in machining. Minimum Quantity Cooling Lubrication (MQCL), which combines MQL mist with cooled air that has been compressed, is one such improvement. MQCL has shown to be a trustworthy and effective way to lubricate and cool, making it a competitive option to more conventional MQL methods. According to research findings, MQCL and MQL methods, as opposed to dry machining and conventional synthetic coolants, enhance tool longevity and surface roughness. However, “the thermal conductivity of cooled air alone” does not considerably improve “MQL's cooling and lubricating properties” [15]. Integrating nanoparticles within the main cutting fluid resulting in a nano-cutting fluid can efficiently disperse heat created during machining, as opposed to depending on cooled compressed air to improve MQL performance. Nanoparticles have considerably superior properties, like an elevated heat convection coefficient as well as thermal conductivity, than the standard cutting fluid. [16]. The focus of the research has been on controlling the friction behaviour that results from the workpiece's contact with the abrasive grains during the grinding procedure. This behaviour affects machining quality variables such as produced forces and tool wear. Al2O3 and CuO nanoparticles have been added at varying volume concentrations to the base fluid, which was water. The MQL method was used to grind the Ti-6Al-4V alloy with as well as without nano-cutting fluid. Investigations into the wheel shape, the surface integrity of the ground surface, grinding forces, and the coefficient of friction, including chip formation revealed that the MQL-nano-fluid approach reduced the coefficient of friction more efficiently than regular MQL. Additionally, an analysis of the chip's morphology produced encouraging findings, suggesting that the nano-mist had important lubricating and heat-transfer capabilities [17]. It must be mentioned that the MQL-nano-fluid approach is an effective interactive way to lubricate and cool, especially while cutting difficult materials. As previous studies have shown, interactive design concepts generally include the usage or integration of many methodologies and methods to deliver a dependable solution for certain industrial difficulties [18,19].

II. REVIEW METHOD

Steps adopted for conducting a review of the collected literature on MQL:

- creation of the query, which establishes the review process's main objective.
- Gathering as much as possible literature in area of interest.
- Identifying the advantages and drawbacks of MQL technology.
- Finally, the knowledge gathered is utilized in conclusion.

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III. Literature Review

According to Boswell et al., MQL is a sustainable and efficient cooling method that may someday take the place of traditional flood cooling. Given that MQL uses a significant amount less cutting fluid than standard cooling techniques, it has the potential to reduce the dangers that come with typical flood cooling, both to human health and the environment.

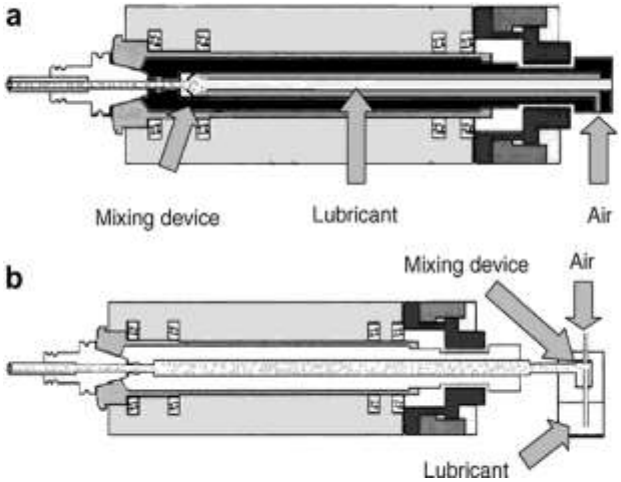

Fig. 1 . MQL-feed systems (a) internal (b) external nozzles

Additionally, because MQL uses less oil and produces clean chips that are good for reselling, using it has financial advantages [20]. Nouzilet et al. (2023) found that high cutting forces and temperatures were produced when Ti-6Al-4V was machined without lubrication under certain circumstances. But cutting force and temperature was greatly decreased when nano minimum quantity lubricating fluid (rapeseed oil with Al2O3 nanoparticles) was used [21]. Ahmed et al. (2022) examined the hard turning of AISI D3 steel under specific machining parameters. They found that there was a considerable increase in cutting force, surface roughness, and flank wear when using rice bran oil as the minimal quantity lubricant. Introducing ZnO nanoparticles into the rice bran oil markedly lowered these metrics, including cutting temperature. The study concluded that the ZnO nanoparticle-enhanced fluid outperformed pure oil by reducing cutting force, decreasing tool wear, and enhancing surface roughness [22]. Cui et al. (2022) documented considerable enhancements with Carbon group nano-enhancers in a minimum quantity lubrication system. They observed a significant improvement in tool life along with an apparent decrease in cutting force, coefficient of friction, tool flank wear, and surface roughness [23]. According to Salman Pervaiz et al. (2022), of all the lubrication methods investigated, sustainable vegetable-oil-based MCQL produced the lowest cutting force when used to machine aeronautic titanium alloy (Ti6Al4V) with TiAlN-PVD covered cutting additions. Surface roughness showed minimal variation across methods, with slightly lower values seen with MQCL. Flood cooling demonstrated superior tool life, with MQCL performing as the second-best option in the study's specific conditions [24].

Tao Lv et al. (2022) found that under a magnetic field, Fe3O4 nanofluid showed reduced contact angle, with slight increases in surface tension and dynamic viscosity. This improved the flow and spreading of Fe3O4 nanofluid on heat transfer surfaces, increasing evaporation heat transfer efficiency and enhancing its cooling effectiveness in Fe3O4 nanofluid-MQL. Fe3O4 nanofluid-MQL showed better processing performance than conventional vegetable oil MQL by lowering cutting temperature, cutting force, and tool wear. These improvements were ascribed to better heat transmission and less frictional generation of heat [25]. Bai et al. (2023) observed that adding aluminium oxide (Al2O3) nanoparticles to castor oil influenced surface roughness, noting the highest roughness at a 2wt% nanoparticle concentration compared to pure castor oil, under specific energy conditions [26]. Wafiy Amli et al. (2023) found that, while cutting at a certain parameter, minimum quantity lubrication produced a rougher surface than flood cooling did under the same cutting circumstances [27]. In comparison to conventional approaches, Raj et al. (2022) observed that incorporating nanoparticles into minimum quantity lubrication resulted in reduced cutting temperatures and increased surface roughness [28]. Wenhao Xu et al. (2022) found that adding nanoparticles to rapeseed oil for minimum quantity lubrication decreased friction compared to using rapeseed oil alone. When grinding AISI 1045, biolubricant minimum quantity lubrication exhibited greater surface roughness than nano-biolubricant minimum quantity lubrication [29]. Mohammad et al. (2021) observed that with ultrasonic nozzles–minimum quantity lubrication, the surface roughness was 2.5 µm, compared to 1.6 µm without lubrication [30]. Sagil et al. (2023) observed that adding minimum quantity lubrication, especially with 0.5% Al2O3 nanofluid, substantially improved surface finish compared to pure MQL, with a notable 63% enhancement. They evaluated surface roughness (Ra values) across different lubrication methods and temperatures, revealing varied performance influenced by the concentration of Al2O3 nanoparticles [31].

Mayurkumar et al. (2021) reported that 1% nMQSL (palm oil + nano-molybdenum disulfide) resulted in surface roughness (Ra) of 1.4µm, lateral wear (VBmax) of 0.3 mm, and chip morphology at 440 HV at micro-roughness per 0.6 mm depth beneath the surface. In comparison, the dry process yielded a surface roughness (Ra) of 2.4µm, lateral wear (VBmax) of 0.6 mm, and chip morphology at 512 HV in micro-roughness per 0.6 mm depth beneath the surface [32]. Tao He et al. (2023) noted that minimum quantity lubrication (MQL) yielded narrower flank wear dimensions compared to cryogenic nitrogen CO2 coolant without lubrication [33]. Sadhana et al. (2022) found that during dry machining, tool flank wear (VB) was markedly higher than when using Nanofluid Minimum Quantity Lubrication. Furthermore, they saw significant drops in tool-tip temperatures using NFMQL at

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various cutting speeds in comparison to dry machining [34]. Sujith et al. (2022) discovered that employing coconut oil with Al2O3 nanoparticles in minimum quantity lubrication led to superior machining results compared to dry machining. This included achieving lower surface roughness (Ra), decreased flank wear (VBmax), and enhanced chip morphology beneath the surface [35]. Aref Azami et al. (2023) found that CuO nanoparticles, valued for their high thermal conductivity, lowered the minimum normal grinding force to 272.103 N when blended with 4% CuO in soybean base oil. likewise, by producing an oxide layer, MoS2 nanoparticles improved friction resistance at high temperatures. At 2% saturation within soybean base oil, this resulted in a minimal tangential grinding force of 74.9 N. Furthermore, integrating 2% CuO nanoparticles in colza base oil significantly improved workpiece surface roughness by enhancing the grinding wheel's cutting efficiency, achieving a minimum surface roughness of 0.049 μm, marking a substantial 70% reduction. [36]. According to Ben Wang et al. (2023), variable scratch speeds (vc) throughout the vegetable oil process led to different angles (α), surface elevation heights (Rh), scratch depths (h), and power (Pc). In contrast, scratching with a dry procedure under comparable circumstances revealed greater values for the following parameters: angle, surface elevation height, power, depth, and scratching force [37]. Ibrahim Nouzil et al. (2022) claim that by lowering cutting forces and enhancing surface smoothness, MoS2 and WS2 nanoparticles enhance machining performance. They pose less of a risk as well. MoS2 is better in terms of surface polish and toxicity. The toxicity of hBN nanoparticles varies with length; shorter lengths are less hazardous. In general, AL2O3 nanoparticles are not very harmful. Since ZnO is extremely toxic, it should be avoided [38].

IV. MINIMUM QUANTITY LUBRICATION IN DRILLING PROCESS

Metalworking fluids (MWF) have played a crucial role in mechanical manufacturing by providing cooling and lubrication benefits. Nevertheless, there are now health and environmental problems related to their widespread use. Research has concentrated on minimizing the use of MWF to address these problems, and nanofluid MQL has emerged as a viable remedy. [39]. Highly compressed air as well as a fluid are combined via a nozzle to add nanoparticles including diamond, carbon nanotubes (CNT), C60, TiO2, Al2O3, and MoS2. Next, the fluid is applied in nanofluid MQL as a mist. Through the creation of rolling or ball-bearing action, these nanoparticles enhance wear characteristics by offering tribological advantages and significantly raising the heat conductivity of the base fluid. As a result, nanofluids find applications in diverse fields such as microelectronics, fuel cells, pharmaceuticals, and hybrid engines [40-41]. The efficient functioning of MQL with emulsion, compressed air cooling, and flood cooling in drilling gear wheel steel has been evaluated through comparative research. The findings demonstrate that MQL and air cooling greatly reduce tool wear when compared to flood conditions with emulsion; however, air cooling exhibits slightly higher wear rates than MQL. MQL also demonstrates superior surface roughness and lower cutting forces than air cooling, underscoring its effective lubricating properties, while air cooling excels in efficiently cooling during machining operations [42].

Heat flow influences the distribution of temperature during deep-hole drilling; research on thermal modelling under MQL settings has demonstrated that it peaks at the chisel edge and reduces towards the drill bit's periphery. Studies evaluating cutting temperatures during "MQL drilling and dry milling of titanium alloy" have highlighted the need for sensitive devices that accurately reflect cutting temperatures. This makes precise process control and tool performance assessment possible [43-44]. Flute and margin-side microtextures have been used in subsequent studies on microtextured tools in dry, wet, and MQL environments to lessen sliding friction, which lowers thrust forces and improves cutting efficiency. Although enhanced cooling and lubrication effects under wet and MQL conditions have improved surface quality and decreased burr formation, MQL's limited cooling efficiency, especially in hard machining, can result in roll-back type burrs that impair machining accuracy and tool longevity [45-46]. Recent advancements focus on integrating nanoparticles into MQL fluids to enhance lubrication and cooling capabilities. Compared with traditional coolant-lubrication techniques, nanofluid-based MQL eliminates thrust forces, decreases drilling torques, and greatly extends tool life. These advantages are attributed to the rolling actions of nanoparticles, which result in increased cooling efficiency and reduced friction at the point of contact face. However, challenges persist in optimising MQL for uncoated tools and machining challenging materials, driving ongoing research into alternative cooling and lubrication techniques to address these limitations and meet industry demands for efficient, high-quality machining solutions [47-48]. MQL and cryogenic methods consistently yield superior surface finishes compared to dry machining. For example, MQL applied in grinding ceramics and using hydrocracked oil has significantly enhanced surface quality compared to synthetic oils. Studies on the grinding of Inconel 718 and GH4169 revealed that MQL with castor oil produced the best surface morphology with the lowest possible roughness values, highlighting the usefulness of particular lubricants in enhancing surface finish [49-50]. Moreover, cutting temperature is a major factor in the surface finish; MQL achieves a noteworthy 50% temperature decrease during turning, which greatly improves the AISI D2 steel's surface quality. This enhancement also applies to hard steels, such as HSS and 100Cr6, where grinding tests reveal that MQL outperforms flood approaches in terms of surface quality and roughness. Furthermore, MQL efficiently lowers cutting forces when turning Inconel 718 and grinding hard steels, demonstrating how well it enhances machining conditions by using less power and better lubrication [51-52].

Tool wear remains a critical concern in machining challenging materials due to thermal softening and plastic

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deformation caused by high temperatures and compressive stresses. MQL machining emerges as advantageous in mitigating tool wear, as demonstrated in studies on cobalt-based superalloys and Inconel 718. Research indicates that MQL with vegetable-based fluids at lower speeds and higher flow rates effectively minimises notch wear, underscoring its capability to maintain tool performance over extended machining periods. Comparative studies show that MQL exhibits tool wear rates comparable to cryogenic methods during initial turning processes, affirming its effectiveness in cutting down on tool wear in contrast to dry machining [53].

V. NANO CUTTING FLUIDS

Using nanofluids as cutting fluids in conjunction with traditional MQL makes NMQL an inventive and environmentally responsible precision lubrication technique. Because of their far higher thermal conductivity than liquids, nanoparticles successfully get over the limits of conventional MQL in terms of heat transfer. When introduced to cutting fluids, these nanoparticles enhance lubrication and cooling through a number of mechanisms, including film creation, filling, polishing, and friction reduction via the ball effect [54]. The application of nanofluids (NFs) in machining procedures presents encouraging benefits in resolving the heat dissipation issues related to cutting challenging materials. When compared to base fluids, nanocutting fluids have significantly better thermal conductivity, which leads to improved heat extraction efficiency and superior cooling capabilities. Nanofluids are made by combining metallic or non-metallic nano-additives, typically smaller than 100 nm, with base fluids such as metallic, mixed metallic, non-metallic, carbon, or ceramic nanoparticles. The high specific surface area of nanofluids facilitates efficient heat transfer between fluids and additives, hence reducing power consumption and enhancing heat transfer properties. By changing the amount of nano-additive, it is possible to accurately modify the surface wettability and heat transmission qualities. Previous research has focused on using nanofluids to model, analyze, and improve heat transmission [55-56].

Nanofluid technology has been successfully applied in several industries, such as engine cooling, electronics cooling, welding cooling, engine transmission oil, nuclear systems cooling, and a range of cutting operations, to enhance thermal, rheological, and stability qualities. Research combining MQL with nanofluids that contain nanotubes and nanoparticles has been shown to produce better outcomes than conventional MQL techniques in terms of tool wear, power consumption, and surface roughness. Two main benefits of the MQL-nanofluid technique are that it reduces oil consumption, which contributes to sustainability, and it improves heat transfer characteristics, which improves process performance [57]. In real-world applications, NMQL has proven to be quite beneficial. For instance, using MoS2-castor oil to act as nano-cutting fluid has already been shown to significantly reduce grinding temperatures in comparison with pure oil MQL when grinding cemented carbide. This level of temperature drop is necessary to maintain the integrity of the tool and the workpiece, which enhances machining performance and lengthens tool life. Even in high-stress situations, effective and accurate grinding is ensured by the improved heat dissipation offered by nanoparticles [58]. Analogously, research on alloys based on nickel has demonstrated that NMQL raises overall machining efficiency, lowers processing temperatures, increases tool life, and improves surface quality. Nickel-based alloys, renowned for their toughness and high-temperature resistance, often present considerable challenges in machining. However, the incorporation of nanofluids in NMQL effectively gets around these issues by providing superior cooling and lubrication, which reduces tool wear and enhances the surface polish of manufactured components [59]. Titanium alloys are renowned for their exceptional hardness and low heat conductivity, and using NMQL to machine them has produced encouraging results. By increasing heat dissipation and decreasing friction at the cutting surface, nanofluids utilized in NMQL greatly improve machining performance. Better surface integrity and greater tool longevity result from this, increasing the efficiency and economy of machining [60].

Carbon fibre-reinforced plastics (CFRP) have also benefited from NMQL. In this context, nanofluids not only reduce the required volume of cutting fluid but also decrease the defect rate in finished workpieces. NMQL implementation in machining CFRP helps mitigate issues such as delamination and fibre pull-out, common in traditional machining methods. This advancement facilitates broader adoption of CFRP across industries, driven by the enhanced performance and efficiency offered by NMQL [61]. Additional research is vital to refine the selection of nanofluids for diverse materials and specific machining conditions, despite their proven efficacy in machining various materials. Comprehensive studies are indispensable to fully grasp how different processing materials interact with specific nanofluid formulations. These research endeavours are crucial for maximising the advantages of NMQL in precision machining [62]. The integration of MQL-nanofluid technology marks a notable progression in precision machining. By utilising the superior thermal and lubricating characteristics of nanofluids, this method not only tackles the heat dissipation complexities linked to machining tough materials but also promotes environmental sustainability. As ongoing research refines and customises nanofluid formulations for machining applications, the potential for wider adoption and improved performance across diverse industries becomes more apparent. Tailoring nanofluid compositions to specific applications is expected to further enhance their effectiveness, resulting in machining processes that are both more efficient and cost-effective [63].

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VI. CONCLUSIONS

It is evident from the thorough examination that there have been substantial breakthroughs in precision machining technology with the use of MQL and its more sophisticated version, NMQL. These methods successfully tackle important issues facing the machining sector, especially when working with challenging materials such as "carbon fibre-reinforced plastics, titanium alloys, and nickel-based alloys". The incorporation of nanoparticles into cutting fluids has revolutionised machining practices by enhancing thermal conductivity, improving lubrication efficiency, and offering superior cooling capabilities compared to conventional methods. This approach not only prolongs tool lifespan and enhances surface finish quality but also contributes to reduced energy consumption and environmental impact, aligning with the increasing emphasis on sustainable manufacturing practices. Studies have repeatedly demonstrated the benefits of MQL and NMQL for a variety of machining tasks, including drilling, grinding, and turning. Minimizing cutting forces, minimizing tool wear, lowering cutting temperatures, and increasing overall machining efficiency have all been shown to be significantly improved by these techniques. The versatility of nanofluid applications in diverse materials and processes underscores their potential to transform the machining industry. Nevertheless, it is important to acknowledge that nanofluid-based machining is still evolving. Despite notable advancements, there remains a necessity for further research to optimise nanofluid formulations tailored to specific materials and machining conditions. The challenge lies in adapting nanofluids to meet the distinct demands of various machining processes and materials, ensuring consistent performance across a wide range of applications. Looking forward to the future of precision machining shows promise with the ongoing advancement of MQL and NMQL technologies. As research progresses, we anticipate the development of more sophisticated nanofluid formulations, enhanced delivery systems, and a deeper understanding of the mechanisms underlying their effectiveness. These advancements are likely to result in significant improvements in machining performance, further reducing environmental impact and enhancing production efficiency. MQL and NMQL technologies represent a substantial leap forward in addressing longstanding challenges related to heat dissipation and lubrication in precision machining. Their adoption not only holds the potential for enhanced machining outcomes but also aligns with broader goals of sustainable manufacturing. As industry and academic collaboration continue to refine these technologies, we can expect to witness broader adoption and integration of MQL and NMQL across various manufacturing sectors. This evolution promises to deliver more efficient, cost-effective, and environmentally friendly machining processes in the future.

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