

Recent Trends and Developments in Minimum Quantity of Lubrication (MQL) Machining: A Review

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Abstract -MQL machining is a fresh, sustainable and greener substitute of the traditional flood cooling in the current manufacturing process. The growing issues on the disposal of coolants, the health of workers and the ecological footprint have led to a fast shift to the near dry machining technologies. MQL works by supplying a specific and low volume of lubricant in an atomized state to the cutting edge, lowering friction, as well as enhancing tribological characteristics without using large quantities of fluids. As opposed to traditional cooling techniques that focus on the bulk heat transfer, MQL aims at reducing the heat production by means of effective boundary lubrication and enhanced chip evacuation. Recent studies indicate important qualitative gains of machining performance under MQL conditions such as increased tool life, increased surface integrity, and decreased friction and improvement in chip morphology. Introduction of biodegradable vegetable-based lubricants has increased the environmental friendliness of the process, and nanofluid enhanced MQL systems have shown better lubrication properties because of the enhanced thermal conductivity and anti-wear properties. MQL Hybrid methods with auxiliary cooling also have an increased application to hard to machine materials. Although there are some operational constraints in harsh machining conditions, MQL is an urgent development in the sphere of sustainable production. The ongoing research in smart control systems and new lubricant compositions is supposed to make the performance and reliability even more efficient. In general, MQL machining is a moderate solution in terms of productivity, environmental responsibility, and economic performance.

Keywords- Minimum quantity lubrication; Near dry machining; Nano MQL; Sustainable manufacturing; tool wear; tool cutting temperature; green machining.

1. INTRODUCTION

The manufacturing sector across the world is in the midst of a revolutionary transition because of sustainability requirements, economic factors, occupational health regulations, and the need for productivity while ensuring minimal environmental damage [1-3]. Among all manufacturing operations, machining has been identified as an energy-intensive and resource-consuming process because of the substantial amount of cutting fluids required for cooling and lubrication. In machining operations, a substantial amount of metalworking fluids, often in the range of hundreds of litres per hour is required for cooling purposes in order to remove heat generated through plastic deformation in the primary shear zone and friction in the tool-chip and tool-workpiece

interfaces [4]. Even though the use of flood cooling in machining operations has been found to be effective in reducing the temperature of the workpiece, it has been identified as a process that faces substantial challenges in terms of the cost of purchasing the coolants, maintenance of the coolants, and their treatment and disposal [5]. The environmental impact of cutting fluids have been identified as a major problem in machining operations. A number of studies over the last few decades have identified that the cost of coolants in machining operations could be as high as 7-17% of the total machining cost and sometimes could be even higher than the cost of tools [6-10]. Dry machining was developed as an early approach to completely avoid cutting fluids, but it frequently leads to increased cutting temperatures, accelerated tool wear, poor surface integrity, dimensional inaccuracies, and unstable chip formation, especially when machining high-speed and hard-to-machine materials like titanium alloys, nickel-based superalloys, and hardened steels. Thus, the concept of Minimum Quantity Lubrication (MQL), also known as near-dry machining, was developed as a balanced approach that lies midway between dry and wet machining, with particular attention given not to cooling but to reducing friction by supplying a small quantity of cutting fluid in atomized form directly to the cutting zone [11]. The fundamental philosophy of MQL is centred around tribological optimization, where instead of reducing cutting temperatures by cooling the cutting zone after they are generated, MQL attempts to reduce cutting temperatures by reducing their generation at their source by developing a thin boundary lubricating film at the tool-chip interface, which reduces the coefficient of friction, prevents adhesion wear and built-up edge formation, and stabilizes chip formation, thereby indirectly reducing cutting forces and temperatures [12].

In conventional MQL methods, a lubricant flow rate of 10-100 mL/h reduces coolant consumption by more than 95% as opposed to flood cooling. The compressed air with 4-6 bars pressure breaks down the oil into droplets with diameters ranging from 5-50 microns. The lubricant is thus supplied effectively [13]. Experiments have demonstrated that a large percentage of heat generated during machining processes, as high as 60-80%, is carried away by chips. Therefore, cutting friction reduction keeps temperature under control without any convection. Thermal imaging has further supported this theory by revealing 15-40% lower temperature with MQL as opposed to dry machining [14]. In addition to temperature reduction, MQL has further enhanced machining performance with

improved surface roughness by 20-45%, reduced tool wear by 20-50%, lower cutting forces by 10-25%, and longer tool life by 25-60% [15]. The development of MQL has taken many generations. The first generation demonstrated its feasibility on mild steel turning. The second generation further refined its application by optimizing the position of nozzles, droplet size, and oil used. The third generation used biodegradable vegetable oils with high polarity and high adsorption [16]. The latest generation has introduced nano-enhanced MQL. In this system, nanoparticles such as aluminium oxide, molybdenum disulphide, silicon dioxide, copper oxide, carbon nanotubes, and graphene are suspended in base oil. The friction coefficient drops from 0.6-0.7 as opposed to dry machining to as low as 0.3-0.4 [17]. Tool life is further enhanced by 70-80%, especially while machining titanium and hardened steel. In addition to these nano-based MQL methods, hybrid methods that combine MQL with cryogenic fluids such as liquid nitrogen or CO₂ are being used for extreme temperature machining. These methods reduce temperature by a further 10-20% while maintaining the lubrication-based tribological performance [18]. By situating MQL within the broader global agenda of green manufacturing and resource efficiency, the introduction establishes the foundation for a detailed critical review of recent trends, technological advancements, performance evaluations, and future prospects ultimately positioning Minimum Quantity Lubrication as a transformative and strategically significant lubrication paradigm for next-generation precision and sustainable machining systems. Additionally, the inclusion of smart sensors and adaptive control in MQL is also in alignment with Industry 4.0. This is because it allows for the adjustment of the lubricant flow rate, approximately between 30-80 mL/h, in real-time in accordance with the results of the measurements of the temperatures, vibration, acoustic emission, and wear of the cutting tool.

2. MINIMUM QUANTITY LUBRICATION: PRINCIPLES, MECHANISMS AND TECHNOLOGICAL DEVELOPMENTS

Over the past three decades, the concept of MQL, starting from the notion of an alternative to flood cooling, has developed into a full-fledged, cross-disciplinary field encompassing the disciplines of tribology, heat transfer, materials engineering, nanotechnology, sustainability, and intelligent manufacturing, among others [19-21]. Research in the field has led to the realization that MQL is not just an exercise in reducing the volume of the lubricant used; it is a philosophy in lubrication that seeks to address the problem of heat generated in the process, not by carrying it away, but by reducing it to the minimum. The near-dry machining studies that formed the foundation of the work in MQL had already shown that most of the heat generated in the process, about 60-80%, is carried away by the chips formed in the process [6-11]. This knowledge led to the design and conduct of experiments in turning, milling, drilling, and grinding operations in MQL, where the lubricant flow rate is in the order of 10-100 mL/h, and compressed air at 4-6 bar is used to atomize the lubricant to droplet sizes in the range of 5-50 microns. The seminal studies in the field reported reductions in cutting temperatures by 15-40% compared to dry machining, reductions in cutting forces by 10-25%, and reductions in flank wear by 20-50%, resulting in increases in tool life by 25-60% depending on the work material and the conditions used in the process [22-25]. Tribology studies reported reductions in the coefficient of friction from 0.6-0.8 in dry machining to 0.4-0.5 in MQL, while studies in surface integrity reported improvements in surface roughness by 20-45%, reduction in tensile stresses, and stabilization of micro-hardness near the machined surfaces. Figure 1 shows the working principal and components of the MQL[7-11].

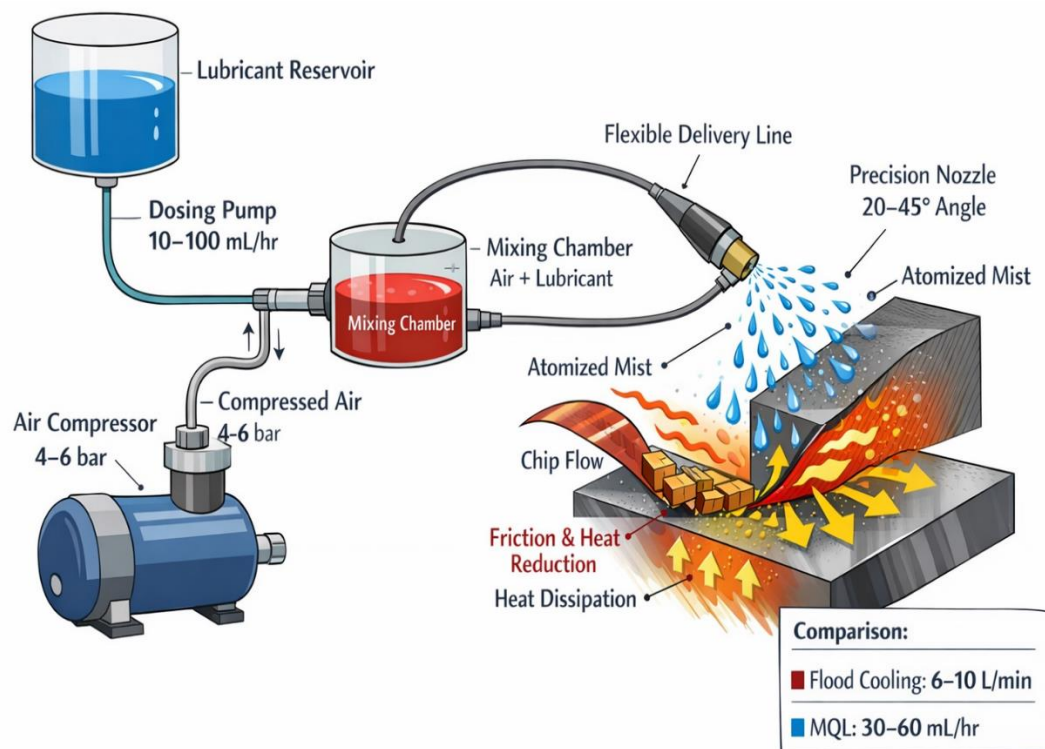


Fig. 1 Working principal and components of the MQL [7-11].

The more recent studies in the field have concentrated on the optimization of the process, including the orientation of the nozzle, generally at an angle of 20-45 degrees to the cutting zone, the distance between the nozzle and the work, generally in the range of 20-40 mm, the droplet size for penetration, and the choice between internal and external

supply methods, with the challenge of penetration in deep-hole drilling, where the depth is more than five times the diameter of the tool, leading to the optimization of the supply method in such situations [26-28]. Table 1 represents the performance of nanofluids in machining.

TABLE 1: PERFORMANCE OF NANOFLUIDS IN MACHINING (NANO-MQL STUDIES) [15-22]

Work Material	Nanoparticle	Concentration (%)	Cutting Temperature Reduction (%)	Tool Wear Reduction (%)	Surface Roughness Improvement (%)	Friction Coefficient Reduction (%)	Tool Life Increase (%)
AISI 1045 Steel	Al ₂ O ₃	1.0	20–30	35–45	25–40	25–30	40–55
AISI 304 Stainless Steel	MoS ₂	1.0	18–28	30–50	30–45	30–40	45–60
Aluminium 6061	Graphene	0.5	15–25	25–40	20–35	25–35	30–50
Ti-6Al-4V	CNT	0.5	25–35	40–60	35–50	30–45	60–80
Hardened Steel (55 HRC)	SiO ₂	1.5	20–30	30–45	20–30	20–30	35–55
Inconel 718	Hybrid (Al ₂ O ₃ + MoS ₂)	1.0	30–40	45–65	40–55	35–50	65–85

For a variety of materials, including AISI 1045 and AISI 304 steels, aluminium 6061, hardened steels up to 55 HRC, and titanium alloys Ti-6Al-4V, consistent performance improvements have been demonstrated for minimum quantity lubrication over dry machining [29-31]. They highlight that a flood cooling approach could attain a marginally lower absolute temperature in certain high-speed machining operations because of the convective heat transfer. Nevertheless, the quantity of fluid utilized in a flood cooling approach is considerably higher than that of the MQL approach. The fluid consumption in a flood cooling approach is in the order of 6-10 L/min, whereas in an MQL approach it is in the order of 30-60 mL/h. This equates to a fluid reduction of over 95-99%. With the issue of sustainability becoming a concern in machining operations, a new direction for research was taken in the use of biodegradable vegetable-based cutting fluids derived from soybean oil, rapeseed oil, sunflower oil, canola oil, and palm oil. These cutting fluids are highly polar and adsorb strongly onto metal surfaces because of their long fatty acid chains [12]. This gives an improvement in boundary lubrication properties, viscosity index, and toxicity. Biodegradation tests revealed a level of over 90% biodegradation after 28 days. This resulted in a reduction in

environmental impacts and disposal costs. However, issues of oxidation stability and thermal degradation at elevated cutting temperatures had to be addressed through the use of additives. The current trend in cutting fluid research has progressed to the use of nano-enhanced minimum quantity lubrication cutting fluids. In this approach, cutting fluids are mixed with nanoparticles of Al₂O₃, MoS₂, SiO₂, CuO, carbon nanotubes, and graphene [14-17]. The concentration of the nanoparticles in the cutting fluids was around 0.5-2 weight percent. This resulted in an enhancement in the thermal conductivity of the cutting fluids. The thermal conductivity of cutting oils was around 0.15 W/mK. After the addition of the nanoparticles, this was increased to around 0.3-0.5 W/mK. This enhancement in the cutting fluids was found to improve the rolling action and the surface asperity filling and tribofilm formation. Experiments revealed a reduction in the friction coefficients of around 0.3-0.4 and flank wear reduction of over 50% over dry machining. Tool life was found to be increased by around 70-80%. The issue of nanoparticle stability was addressed in the research [32]. Figure 2 shows the comparative machining performance under Dry, MAL and Nano-MQL.

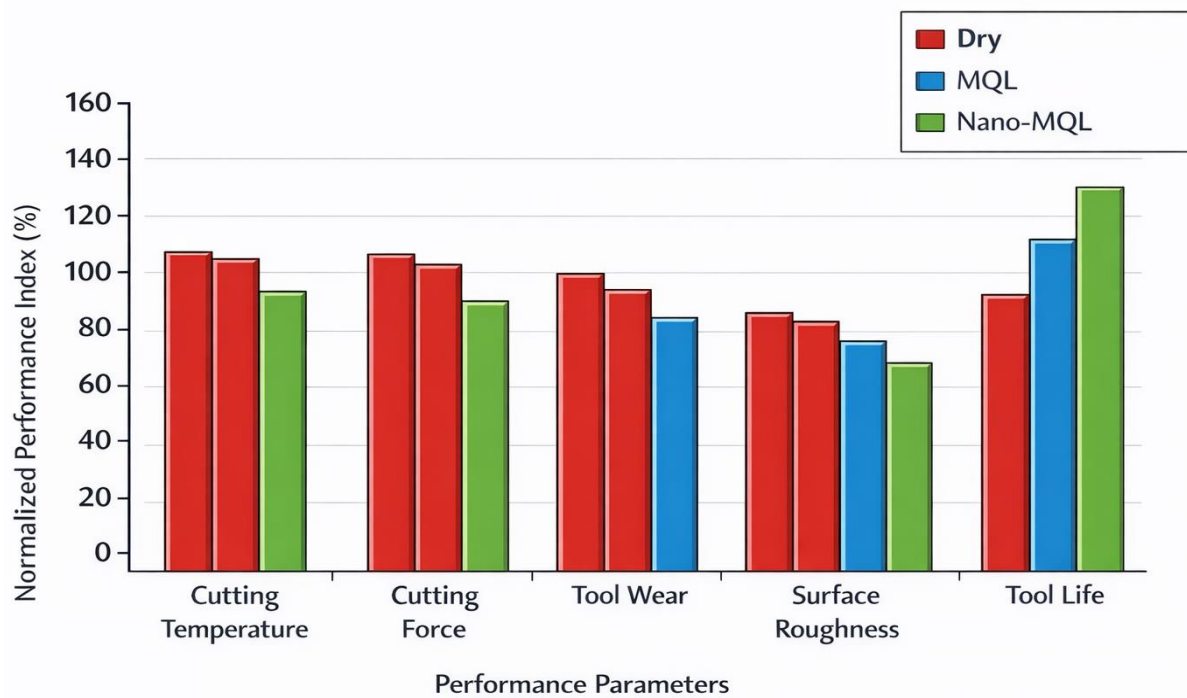


Fig. 2 Comparative machining performance under Dry, MAL and Nano-MQL [26-31]

In high-speed and aerospace machining, pure MQL was found to be limited in its cooling capabilities when cutting speeds exceeded 300 m/min or when machining nickel superalloys and titanium. To address this problem, hybrid MQL cooling was developed by mixing it with cryogenic cooling agents like liquid nitrogen or carbon dioxide. This produces two-fold cooling effects of reduced friction and suppressed heat. Studies of hybrid cryogenic MQL cooling found that it could reduce cutting temperatures by 37% compared to dry machining and could achieve 80% longer tool life when machining titanium, although with increased complexity and cost. In grinding operations, although MQL is known to be limited by variable wheel wear depending on the coolant delivery method, it is found that it could achieve comparable surface roughness to flood cooling with less fluid consumption. Moreover, economic analyses of MQL and flood cooling found that flood cooling could contribute 7 to 17 percent of total manufacturing costs, although MQL could achieve 15 to 25 percent savings in annual manufacturing costs and payback periods of 8 to 18 months depending on production volumes [33].

3. Nanofluids: Thermal Transport Mechanisms and Engineering Applications

The term nanofluids has been used to refer to the suspension of nanoparticles, between 1 to 100 nanometers in diameter, in standard base fluids such as water, ethylene glycol, oils, and refrigerants, among others. Over the past three decades, nanofluids have emerged as a new class of advanced media for the management of heat and wear, and the list of research works that demonstrate the potential of nanofluids in enhancing the efficiency of a variety of applications is growing exponentially [2-6]. The concept of nanofluids was born in the mid-1990s when it was hypothesized that by suspending high-thermal-conductivity solid nanoparticles, such as Al_2O_3 , CuO , SiO_2 , TiO_2 , ZnO , Ag , Cu , graphene, carbon nanotubes, MoS_2 , etc., in low-thermal-conductivity base fluids, it would be possible to exceed the classical Maxwell models for the effective conductivity of the suspension [12-14]. The initial experiments conducted to validate the hypothesis showed that even small amounts of these solid particles, between 0.1 to 2 volume percent, could increase the thermal conductivity by 5-40% depending on the nature of the nanoparticle, its size, and the extent to which the suspension was dispersed. More recent experiments conducted with nanofluids containing graphene and carbon nanotubes have reported increases in the conductivity of over 50-100% [34]. Table 2 represents the thermophysical properties enhancement of common nanofluids.

TABLE 2: THERMOPHYSICAL PROPERTIES ENHANCEMENT OF COMMON NANOFLUIDS [31-35]

Base Fluid	Nanoparticle Type	Particle Size (nm)	Volume Fraction (%)	Thermal Conductivity Enhancement (%)	Viscosity Increase (%)	Stability Duration
Water	Al_2O_3	20–50	0.5–2.0	10–25	5–15	2–4 weeks
Water	CuO	20–40	0.5–1.5	15–30	8–18	1–3 weeks
Water	TiO_2	25–60	0.5–2.0	8–20	6–12	3–5 weeks

Ethylene Glycol	Al ₂ O ₃	30–60	1.0–3.0	15–35	10–25	3–6 weeks
Water	Graphene	10–30	0.1–1.0	25–60	5–12	2–4 weeks
Water	CNT (Carbon Nanotube)	10–20 (dia)	0.1–0.8	30–80	8–20	1–3 weeks
Vegetable Oil	MoS ₂	20–80	0.5–1.5	12–28	6–15	2–5 weeks

The enhancement in the conductivity of nanofluids is thought to be the result of the combined effects of the Brownian motion of the particles, the high surface-to-volume ratio, the layering of the fluid molecules at the solid-liquid interface, the formation of chains, and the ballistic transport in the highly conductive nanostructures, among others [35]. However, the extent to which these factors influence the enhancement in the conductivity is subject to ongoing research. In experiments conducted to validate the hypothesis, the Nusselt number has been found to increase by 10-30% compared to the base fluid, but at the expense of an increase in the viscosity of the fluid by 5-25%. According to research done on boiling heat transfer, it has been found that the

addition of nanofluids can increase the CHF by up to 50%. This is because the nanoparticles tend to settle on the surfaces, leading to the formation of porous films that alter the wettability and roughness, hence increasing the nucleation sites [36]. Figure 3 shows the tribological and thermal mechanism of nanoparticle enhanced lubrication [15-19].

However, the stability, fouling, and repeatability of nanofluids in boiling remain an important research topic. In solar collectors, nanofluids have been explored for direct absorption media because of the high absorption properties of the nanofluids, especially when carbon-based and metal particles are used. Laboratory-scale experiments have shown that the efficiency can be increased by 10-25% [37].

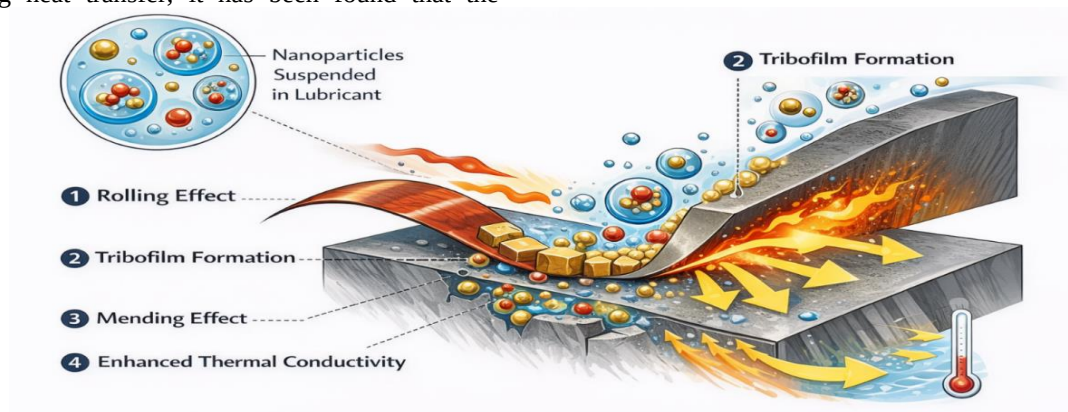


Fig. 3 Tribological and thermal mechanism of nanoparticle enhanced lubrication [15-19].

4. CONCLUSION

Minimum Quantity Lubrication machining is another significant step in the technology of sustainable manufacturing. The temperature reduction by empirical evidence of 15 to 40 percent, tool wear of up to 50 percent and the surface finish of up to 45 percent are better than dry machining. More than 95 percent of the fluid consumption is minimized as compared to flood cooling systems. Nano MQL and hybrid cryogenic assisted MQL also improve the performance especially in machining hard-to-cut materials like titanium alloys and hardened steels. In extreme thermal conditions and deeper hole operations, although there are still limitations in effect, new advances in technology such as smart delivery systems and new nano lubricants are increasing industrial usability. MQL is essentially a balance solution with increased productivity, environmental sustainability, economic viability, and higher machining performance. As innovation and optimization continue,

MQL would be a major lubrication strategy in the next generation systems of precision manufacturing.

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