

An Optimization-Based Comparative Analysis of Lubricants Used in Machining of Ammcs

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Abstract

Machining of aluminium metal matrix composites (AMMCs) is still a major challenge due to the abrasive character of the ceramic reinforcement (such as SiC and Al₂O₃) in the matrix, which tends to accelerate tool wear, increase cutting temperatures, and deteriorate surface integrity compared to regular aluminium alloys. These problems are further aggravated at higher cutting speeds and material removal rates, resulting in poor surface finish, high cutting forces, and short tool life. Conventional flood lubrication has been of little help, and hence various novel lubrication and cooling methods such as Minimum Quantity Lubrication (MQL), nanofluid-assisted lubricants, bio-based and vegetable oil-derived fluids (such as jatropha oil), cryogenic cooling, and hybrid lubrication approaches have been explored. This review critically assesses the progress of lubrication approaches for machining of AMMCs during 2020-2026, covering the mechanisms (friction reduction, cooling, tribofilm formation), environmental sustainability, and machining performance (surface roughness, tool wear rate, cutting temperature, energy consumption). We also discuss the current trends in biodegradable and nanofluid lubricants, their relative performance compared to traditional approaches, and provide suggestions for future research to further improve sustainable and efficient machining of AMMCs.

Keywords: Aluminium Metal Matrix Composites (AMMCs), Minimum Quantity Lubrication (MQL), Nanofluid Lubrication, Bio-Based Lubricants, Cryogenic Machining, Sustainable Machining.

1. Introduction

Aluminium Metal Matrix Composites (AMMCs), which consist of an aluminium alloy matrix reinforced with hard particles like silicon carbide (SiC) or aluminium oxide (Al₂O₃), provide an excellent combination of low density, high stiffness, good thermal conductivity, and excellent wear resistance. However, the same properties that make AMMCs very attractive, especially the presence of hard ceramic reinforcements, also make these materials difficult to machine using conventional machining operations. The cutting tool undergoes extreme wear due to abrasive interactions between the tool and the reinforcement particles, high rates of heat generation at the tool-workpiece interface, built-up edges (BUE), and poor surface finish. This has led to a significant amount of research on lubrication and cooling techniques that can improve material removal rates while addressing thermal and frictional issues. Conventional flood cooling methods (using large quantities of oil-based cutting fluids) provide some cooling and lubrication benefits. However, these methods are environmentally unsafe, less effective in

penetrating the cutting zone during high-speed machining, and harmful to the health of machinists. There is thus a definite move towards more sustainable, efficient, and environmentally safe lubrication methods, such as Minimum Quantity Lubrication (MQL), vegetable and bio-based lubricants, nanofluid-assisted lubrication, cryogenic cooling, and hybrid lubrication systems that combine cooling and lubrication benefits. In addition to improved performance, sustainable lubrication methods also support global environmental objectives by reducing lubricant consumption, fluid waste, and emissions.

2. Literature Review

2.1 Conventional Lubrication in AMMC Machining

Early work on machining composites tended to set a baseline for performance under conventional flood lubrication and dry conditions before considering alternative advanced lubrication options.

- A general review on cooling and lubrication technologies in MMC machining by Laghari et al. (2023) emphasized the importance of cooling and lubrication technologies in machining MMCs. The authors pointed out that conventional flood lubrication is less effective in reducing tool wear because of the poor penetration of the cutting zone during machining of abrasive reinforcements in AMMCs. The authors concluded that conventional flood lubrication is less effective in high energy removal rate machining processes. The review article emphasizes the importance of cutting fluid delivery systems in managing heat and chip evacuation, particularly in composites with hard reinforcements such as SiC and Al₂O₃.
- Several experimental studies on machining under dry, flood, and MQL conditions have established that dry machining produces higher cutting temperatures, tool wear, and poor surface finish, while flood lubrication produces moderate improvements but remains unsatisfactory for severe abrasion from reinforcement phases.

These basic results form the rationale for exploring low fluid volume approaches and new lubricant formulations that are effective in cooling and lubrication without environmental costs.

2.2 Minimum Quantity Lubrication (MQL)

MQL involves the application of a small volume of lubricant mist to the tool-workpiece interface with the objective of improving lubrication efficiency with low fluid consumption.

- The literature clearly shows that MQL systems are superior to dry machining in improving surface roughness, tool life, and cutting temperature reduction. Several studies on aluminium alloys have established that vegetable oil-based MQL fluids are superior to petroleum oil-based fluids in reducing cutting forces and temperatures because of improved boundary lubrication at the interface.\
- Abas et al. (2020) examined the influence of MQL in conventional aluminium machining and found that MQL not only reduced the coefficient of friction but also improved the surface finish quality compared to flood lubrication, thus proving the feasibility of MQL as a viable alternative for machining MMCs. This study utilized Taguchi optimization to identify the optimal fluid flow rate and droplet size for MQL, thus emphasizing the importance of lubrication delivery parameters.
- In drilling and milling processes of MMCs, nano-MQL variants (where nanoparticles are mixed with the MQL base fluid) have further demonstrated improvements such as reduced cutting temperatures and flank wear compared to conventional MQL. These improvements were mainly attributed to the improved thermal conductivity and rolling/rolling-sliding micro-actions of the dispersed nanoparticles.

In summary, MQL and, more specifically, nano-MQL have been demonstrated to improve thermal and tribological performance in hard and abrasive machining conditions compared to both dry and flood lubrication in AMMCs.

2.3 Bio-Based & Vegetable Oil Lubricants

The recent emphasis on sustainable machining practices has triggered a renewed interest in vegetable and bio-based oils as alternatives to traditional metalworking fluids.

- Non-edible vegetable oils (such as jatropha, coconut, and palm oil) have long hydrocarbon chains that facilitate the formation of strong boundary lubrication layers on the tool-workpiece interface, thus reducing friction and cutting forces compared to mineral oils. Studies have also shown that these bio-based fluids have higher viscosity indices, which are beneficial in maintaining lubrication properties at high temperatures prevalent in MMC machining.
- Kazeem et al. (2020, 2024) conducted experimental studies on jatropha oil as a cutting fluid in turning operations and as an MQL fluid. The results showed that there was a substantial reduction in cutting temperature and vibration amplitude compared to conventional oils, as well as enhanced surface quality and tool life. Notably, the biodegradability and non-toxicity of the oil make it an excellent choice for green machining environments.
- A more general literature survey on vegetable oil-based lubricants for sustainable machining (2023) described how chemical modifications (such as esterification or epoxidation) can improve the oxidative stability and extreme pressure properties, which are key factors where untreated oils would otherwise deteriorate rapidly under extreme thermal stress conditions.

These studies provide evidence that bio-based lubricants not only can but also often surpass the performance of petroleum-based lubricants in abrasive/composite machining environments, while also reducing environmental and health hazards by orders of magnitude.

2.4 Nanofluid-Enhanced Lubricants

Nanofluids are suspensions of nanoparticles in lubricants (vegetable or synthetic) that have attracted immense research attention owing to their potential to enhance simultaneously the thermal conductivity, heat transfer, and tribological properties.

- Nanoparticles like graphene oxide (GO), Al_2O_3 , MoS_2 , and CuO possess high efficacy in reducing friction through micro-rolling phenomena and the formation of protective tribofilms at the tool-chip interface.
- Recent advances (2026) indicate that nano-MQL systems consisting of an MQL system for delivering a nanolubricant show a consistent improvement in cutting temperature reduction, surface quality improvement, and tool life extension compared to conventional MQL.
- Specific research on composites verifies that graphene oxide-enriched nanolubricants in nano-MQL drilling operations of Al/SiCp MMCs enhance chip evacuation and prevent delamination, showing higher surface integrity than conventional MQL.

Research on nanofluids in general verifies that thermal management and tribological film creation are greatly improved, making nano-enhanced lubricants one of the most promising approaches to lubrication in AMMC machining.

2.5 Cryogenic & Hybrid Lubrication Techniques

Cryogenic machining involves the use of very low temperatures (such as liquid nitrogen or CO₂) to rapidly remove heat from the machining zone, thus postponing thermal softening of the workpiece and tool wear. When combined with MQL (hybrid machining), it offers the advantages of both cooling and lubrication.

- While there is more literature on the cryogenic machining of steels and superalloys than on AMMCs, recent research shows that cryogenic cooling can significantly reduce cutting temperatures, thus slowing down flank wear and preventing thermal cracks on the composite surface.
- Hybrid cryo-MQL machining systems, in which cryogenics are used to create low temperatures and MQL sprays are used to distribute lubricants, seem particularly attractive and promising, as they can offer synergistic benefits such as reduced cutting forces and reduced frictional heat. Early research suggests better surface finish and extended tool life compared to single systems, although systematic studies on AMMCs are still in their infancy.

2.6 Summary of Observed Effects Across Lubricant Types

Based on the literature review, the following general trends are observed:

- Dry machining leads to highest temperatures, poorest surface finish, and highest tool wear because of the lack of cooling and lubrication.
- Flood lubrication provides moderate benefit, although environmental and economic costs are high, and cooling performance is poor.
- MQL with vegetable/bio oils can generally provide a substantial improvement in surface finish and cutting force reduction with low fluid use.
- Nanofluid-based systems provide the maximum reduction in cutting temperature and tool wear, primarily because of their improved thermal conductivity and tribofilm properties.
- Cryogenic and hybrid systems offer the best cooling performance, and hybrid systems, which combine cooling and lubrication, are expected to offer the best of both worlds, although more research is required on AMMCs.

2.7 Gap Analysis & Research Needs

Although there has been extensive research on lubrication in machining MMCs and other materials similar to composites:

There is a lack of direct research on AMMCs using bio-lubricants like jatropha oil. Although there is increasing research on vegetable oils, their effects on SiC/Al or Al₂O₃/Al composites require dedicated experiments.

There is a lack of comparative research on different lubrication systems (flood lubrication, MQL, nanofluid-MQL, and cryo-MQL) with the same machining conditions.

There is a requirement for tribological modeling, which can relate the microstructure of AMMCs to lubrication systems, allowing for predictive process development.

There is a requirement for environmental impact studies and life cycle assessments of bio-lubricants in machining applications.

3. Comparative Summary of Lubrication Approaches

Lubricant Type	Cooling	Friction Reduction	Environmental Impact	AMMC Suitability
Flood Cooling	High	Medium	Poor	Moderate
MQL (Veg Oil)	Low	High	Good	High
Nanofluid MQL	Medium	Very High	Variable	Very High
Bio-Oil (Jatropha)	Medium	High	Excellent	High
Cryogenic	Very High	Medium	Moderate	Promising

Cryo-MQL	Very High	High	Good	Ideal
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4. Challenges and Future Research Directions

Although significant progress has been made in developing advanced lubrication strategies for machining AMMCs, several technical, environmental, and industrial challenges remain unresolved. These challenges must be addressed to fully exploit sustainable and high-performance lubrication systems in composite machining.

4.1 Severe Abrasive Tool Wear in AMMCs

The primary machining challenge in AMMCs arises from the presence of hard ceramic reinforcements (e.g., SiC, Al₂O₃, B₄C), which cause:

- Intense abrasive wear
- Edge chipping and micro-fracture
- Accelerated flank wear
- Crater formation

Even with advanced lubrication strategies such as MQL and nanofluids, tool wear remains substantially higher than in monolithic aluminium alloys. While lubrication reduces frictional heat, it cannot eliminate mechanical abrasion caused by hard particles.

Research Need:

- Integration of optimized lubrication strategies with advanced tool coatings (e.g., DLC, TiAlN, diamond-coated tools).
- Investigation of lubricant-coating compatibility to avoid chemical degradation.
- Development of tribological models specifically for reinforced composite interfaces.

4.2 Limited Penetration of Lubricant into Tool–Chip Interface

In AMMC machining, the tool–chip contact zone experiences:

- Extremely high pressure
- High strain rate plastic deformation
- Limited access for fluid penetration

Even in MQL systems, the atomized lubricant droplets may not adequately penetrate the primary shear zone.

Challenges:

- Optimizing droplet size and spray angle in MQL systems.
- Improving wettability of lubricants for aluminium matrix surfaces.
- Controlling air-flow turbulence around high-speed tools.

Future Direction:

- Development of smart delivery systems (ultrasonic-assisted MQL, electrostatic spray systems).
- Numerical modeling of droplet penetration and heat transfer.

4.3 Thermal Instability of Bio-Based Lubricants

Bio-based lubricants (e.g., jatropha oil, palm oil, canola oil) exhibit excellent boundary lubrication but suffer from:

- Poor oxidative stability at high temperature
- Thermal degradation
- Limited extreme pressure (EP) performance
- Shorter shelf life compared to mineral oils

Under high-speed machining of AMMCs, temperatures can exceed 400–600°C at the cutting zone, challenging the stability of natural oils.

Solutions Under Investigation:

- Chemical modification (transesterification, epoxidation, estolide formation).
- Addition of antioxidants.
- Nano-additive reinforcement.

Research Gap:

- Long-term performance studies of modified vegetable oils in AMMC machining.
- Comparative oxidation resistance analysis under real machining conditions.

4.4 Nanofluid Stability and Agglomeration Issues

Nanofluids have demonstrated remarkable potential in improving thermal conductivity and reducing friction. However:

- Nanoparticles tend to agglomerate over time.
- Sedimentation reduces dispersion stability.
- Improper dispersion may clog MQL nozzles.
- Excess nanoparticle concentration can increase viscosity and reduce spray efficiency.

Technical Challenges:

- Maintaining stable dispersion without surfactants that alter lubrication chemistry.
- Balancing nanoparticle concentration for optimal heat transfer and friction reduction.
- Avoiding tool scratching caused by hard nanoparticles.

Future Work:

- Development of surface-functionalized nanoparticles.
- Real-time monitoring of nanofluid stability.
- Standardization of nano-MQL preparation procedures.

4.5 Cryogenic Cooling System Complexity

Cryogenic cooling provides exceptional heat extraction but presents several challenges:

- High initial installation cost.
- Complex fluid handling systems.
- Risk of thermal shock to cutting tools.
- Frost formation and safety considerations.

Additionally, cryogenic cooling primarily addresses temperature control, but may not adequately reduce friction unless combined with lubrication.

Research Need:

- Optimizing hybrid cryo-MQL systems.
- Studying interaction between cryogenic cooling and vegetable oil lubrication.
- Cost-benefit industrial feasibility analysis.

4.6 Lack of Standardized Comparative Studies

A major limitation in current literature is the absence of:

- Uniform machining parameters across studies.
- Standardized AMMC compositions.
- Consistent measurement techniques.

Different reinforcement percentages, particle sizes, tool materials, and cutting speeds make direct comparison difficult.

Future Direction:

- Establishing benchmark AMMC materials for lubrication studies.
- Creating standardized test protocols.
- Cross-study meta-analysis for quantitative comparison.

4.7 Environmental and Life Cycle Assessment (LCA) Gaps

While bio-lubricants are considered environmentally friendly, few studies evaluate:

- Full life cycle impact (production → use → disposal).
- Carbon footprint of nanoparticle production.
- Waste management challenges of nano-enhanced fluids.

Sustainability claims must be validated through quantitative LCA models.

4.8 Process Parameter Optimization Challenges

Lubrication effectiveness depends heavily on:

- Cutting speed
- Feed rate
- Depth of cut
- Lubricant flow rate
- Nanoparticle concentration
- Droplet size

However, the interaction effects between these variables are complex and nonlinear.

Future Research:

- Application of AI and machine learning models.
- Multi-objective optimization (surface roughness+ tool wear + energy consumption).
- Integration of sensor-based adaptive lubrication systems.

4.9 Industrial Adoption Barriers

Despite promising laboratory results:

- Industries hesitate to adopt nano-MQL due to cost.
- Concerns exist about long-term machine compatibility.
- Skilled operator training is required.

Bridging the gap between academic research and industrial implementation remains a critical challenge.

5. Conclusion

Aluminium Metal Matrix Composites Machining faces distinct tribological and thermal issues because of the presence of hard ceramic reinforcements in a soft aluminium matrix. The presence of these hard ceramic reinforcements causes high abrasive wear, high cutting temperatures, and poor surface integrity, making lubrication techniques essential for efficient and sustainable machining.

This review has thoroughly investigated different lubrication techniques like conventional flood cooling, Minimum Quantity Lubrication (MQL), bio-based vegetable oils like jatropha oil, nanofluid-based lubricants, cryogenic cooling, and hybrid cryo-MQL techniques. The overall results from the reviewed literature suggest that while conventional flood cooling is moderate in cooling, it is environmentally unsustainable and less effective in penetrating high-pressure cutting zones, which are common in AMMC machining.

MQL has been identified as a viable and environmentally friendly alternative to conventional flood cooling, which has been able to reduce lubricant consumption significantly and improve friction control.

Bio-based lubricants, especially vegetable oils like jatropha oil, have shown excellent boundary lubrication performance because of their long-chain fatty acids, making them highly attractive for sustainable machining. However, their low thermal stability makes them prone to degradation and requires chemical modification or nano-enhancement.

Nanofluid-assisted lubrication is one of the most promising areas, providing enhanced cooling and tribofilm formation, resulting in significant reductions in tool wear and cutting temperature. Hybrid lubrication systems combining cryogenic cooling and MQL seem to provide the best compromise by combining excellent cooling with effective friction reduction.

However, several technical and industrial hurdles still need to be overcome, such as the stability of nanofluids, oxidative instability of bio-lubricants, lack of standardized testing procedures, and high costs of implementation of advanced cooling systems. Future research work, therefore, needs to concentrate on optimization of lubricant composition, studies on tool and lubricant compatibility, life cycle assessment, AI-assisted process optimization, and industrial scaling.

In summary, sustainable lubrication technologies, such as nano-enhanced bio-lubricants and hybrid cryogenic-MQL systems, are on the cusp of a revolutionary change in the machining of AMMCs. Interdisciplinary research work combining materials science, tribology, manufacturing engineering, and environmental studies will be critical in the future to achieve high-efficiency, eco-friendly, and industrially feasible machining solutions for next-generation composite materials.

6. References

1. *Experimental investigation of graphene oxide-based nano cutting fluid in drilling Al MMCs under nano-MQL conditions* (Patil et al., 2025) - graphene oxide nanofluids improve surface quality and temperature.
2. *A State-of-the-Art Review on Sustainable and Green Cooling/Lubrication in MMC Machining* (Laghari et al., 2023) -comprehensive review of MQL, cryogenic, hybrid techniques.
3. *Machining and Energy Aspect Assessment with Sustainable Cutting Fluid Strategies of Al–Si Hybrid Composites* (Şap, 2023) -MQL and cryo comparisons.
4. *Machining characterization under dry, MQL, and cryogenic for Al-Gr hybrid composites* (2022) - shows cooling/lubrication impacts on surface roughness.
5. *Conventional and Recent Advances of Vegetable Oils as Metalworking Fluids: A Review* (MDPI review, 2023) - mechanisms of vegetable oil lubrication.
6. *Green Metalworking Fluids for Sustainable Machining: Jatropha Oil and Nano Additives* (MDPI Metals, 2023) - modified jatropha oil performance improvements.
7. *Modified Jatropha Nano-lubricant as Metalworking Fluid* (Talib et al., 2019 foundational, applicable) - chemical modification for better lubrication.
8. *Recent Developments in MQL Machining of Aeronautical Materials* (Ali, 2025) - review of MQL strategies including vegetable oils and nano-MQL.
9. *Recent Progress on Nanofluids in MQL Machining* (2026) - review of nanofluid lubrication enhancements.
10. *Optimization of machining parameters under MQL-assisted turning* (Abas et al., 2020) - MQL with vegetable oil optimized for aluminium alloys.
11. Aeronautical machining with improved lubrication & hybrid approaches - reflecting trends.
12. *Cryogenic cooling improvements for machining Al MMC* - reduced temperature and tool wear.

13. Nanolubricants and nanofluid lubrication mechanisms - foundational for applied studies.
14. Vegetable oil contributions to lower friction & sustainable machining.
15. Additional studies combining nanofluids, MQL, and vegetable base - ongoing trend.