A study of the Minimum Quantity Lubrication (MQL) Method in Machining Applications

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Abstract: The Minimum Quantity Lubrication (MQL) method has become increasingly popular as a sustainable alternative to conventional flood cooling in machining applications. MQL significantly reduces lubricant consumption by delivering small amounts of lubricant directly to the cutting interface, thereby minimizing environmental impact and improving operational efficiency. This paper provides a comprehensive review of MQL principles, benefits, applications, challenges, and recent technological advancements. A detailed analysis of key factors influencing MQL performance, including lubricant types, nozzle design, and machining parameters, is presented. The review also explores the role of MQL in high-performance applications, such as machining hard-to-cut materials, and identifies future research directions and industrial adoption trends.

Keywords: Minimum quantity lubrication (MQL); machining lubrication; Microlubrication Machining efficiency with MQL; Biodegradable lubricants in MQL

1.INTRODUCTION

In the quest for sustainable manufacturing solutions, Minimum Quantity Lubrication (MQL) has gained attention as an eco-friendly alternative to traditional flood cooling, which consumes large volumes of coolant. Machining applications require effective cooling and lubrication to reduce tool wear, control heat, and achieve high-quality finishes. Conventional flood cooling methods fulfill these requirements but lead to significant costs and environmental concerns, as well as potential health risks from exposure to coolants [1]. MQL, by contrast, uses only 10–100 ml of lubricant per hour, reducing waste and energy consumption. The goal of this review is to examine MQL as a viable solution for sustainable and efficient machining [2]. By discussing the working principles, applications, benefits, limitations, and recent developments in MQL, this paper aims to provide a valuable resource for researchers and industry practitioners exploring alternative cooling and lubrication methods in machining.

2. PRINCIPLES AND MECHANISM OF MQL

MQL systems deliver a precisely controlled mist or aerosol of compressed air and lubricant directly to the cutting zone. This lubricant forms a thin layer between the tool and workpiece, reducing friction and cooling through evaporation rather than sheer coolant volume [3]. The system's efficiency largely depends on proper nozzle positioning and atomization quality to ensure that the lubricant reaches the high-contact areas [4]. MQL systems often use vegetable oils or synthetic esters as lubricants, which offer high lubricity, biodegradability, and lower health risks compared to conventional metalworking fluids [5]. Additionally, proper selection of air pressure and flow rate allows for an optimal balance of cooling and lubrication, contributing to prolonged tool life and improved surface finish [6].

3. BENEFITS OF MQL IN MACHINING APPLICATIONS

3.1 Environmental and Health Benefits

The use of minimal lubricant in MQL systems significantly reduces the volume of hazardous waste generated in machining operations, leading to lower disposal and recycling costs. This makes MQL a greener alternative aligned with environmental regulations and corporate sustainability goals. Moreover, MQL systems reduce aerosol and mist exposure, creating safer working conditions for operators.

3.2 Economic Advantages

MQL not only lowers lubricant costs but also minimizes the expenses associated with coolant management, such as storage, handling, and disposal. The reduction in tool wear further decreases operational costs by extending tool life, which is particularly advantageous in high-speed, high-volume production settings [7].

3.3 Performance Enhancements

Studies have demonstrated that MQL can enhance tool performance by reducing friction and controlling heat buildup, which are critical factors in achieving high surface quality and dimensional accuracy. For instance, MQL has shown promising results in machining hard materials like titanium alloys and hardened steels, commonly used in aerospace and automotive applications. Research indicates that MQL can reduce tool wear and improve surface finish, making it suitable for precision machining applications.

4. CHALLENGES IN IMPLEMENTING MQL

4.1 Lubricant Selection and Delivery

The choice of lubricant plays a crucial role in the success of MQL. Lubricants such as vegetable oils and synthetic esters offer distinct advantages in terms of lubricity and biodegradability but require careful optimization of flow rates and nozzle positioning for effective performance. Inappropriate selection or delivery can lead to insufficient lubrication, resulting in tool wear and surface defects.

4.2 Equipment and Process Optimization

Optimizing the parameters of MQL, including air pressure, lubricant flow rate, and nozzle design, is essential for achieving desired outcomes in different machining applications. Factors like cutting speed, feed rate, and tool geometry must be adjusted in tandem with MQL parameters to avoid under-lubrication or over-saturation, which could negate the benefits of the system [8].

4.3 Material-Specific Challenges

Certain materials, such as superalloys, have high thermal resistance and low machinability, which poses additional challenges for MQL systems. Research on these materials is ongoing, and hybrid MQL systems with cryogenic cooling have been explored as potential solutions to address these issues [9].

5. APPLICATIONS OF MQL IN HIGH-PERFORMANCE MACHINING

MQL has been successfully applied in various machining processes, including turning, milling, drilling, and grinding. In each of these processes, MQL has demonstrated its potential to improve tool life, reduce surface roughness, and maintain dimensional accuracy, especially in machining materials like hardened steels and aluminum alloys [10].

5.1 MQL in Milling and Drilling

Milling and drilling are highly demanding operations, often involving elevated temperatures and high tool wear rates. Studies have shown that MQL significantly reduces cutting forces and enhances surface finish in milling and drilling operations, especially for hard-to-machine materials like titanium [11]. Additionally, MQL has been effective in reducing burr formation in drilling, which is critical for assembly applications in the aerospace and automotive industries [12]

5.2 MQL in Grinding

Grinding is another challenging process where MQL has shown positive results in terms of reducing thermal damage to the workpiece and improving wheel life. Compared to flood cooling, MQL in grinding has been shown to enhance surface integrity, making it suitable for high-precision applications [13].

6. RECENT ADVANCEMENTS IN MQL TECHNOLOGY

Advances in MQL technology focus on improving delivery systems, lubricant compositions, and hybrid cooling methods. Innovations such as adjustable nozzles, multi-channel delivery systems, and nanoparticle-enriched lubricants have shown potential to enhance MQL efficiency across various machining applications. Hybrid systems combining MQL with cryogenic cooling are gaining interest for applications involving superalloys and other heat-resistant materials, further expanding MQL's applicability.

7. FUTURE RESEARCH AND INDUSTRIAL ADOPTION

While MQL has shown promise, further research is needed to refine its application across diverse materials and complex geometries. The development of smart MQL systems, incorporating sensors and adaptive control, is a potential area for future exploration. Furthermore, as environmental regulations tighten, the adoption of MQL technology in industry is likely to grow, driven by its alignment with sustainable manufacturing goals.

8. CONCLUSION

MQL represents a valuable alternative to traditional flood cooling, offering environmental, economic, and performance benefits in various machining applications. Its ability to reduce lubricant consumption and enhance machining efficiency aligns with the growing emphasis on sustainable manufacturing practices. While challenges remain, continued research and technological advancements are expected to expand the application of MQL in high-performance machining. As industries continue to seek sustainable solutions, MQL stands out as a promising method that balances productivity, cost, and environmental responsibility.

REFERENCES

[1] Anuj Kumar Sharma , Arun Kumar Tiwari, Amit Rai Dixit, Effects of Minimum Quantity Lubrication (MQL) in machining processes using conventional and nanofluid based cutting fluids: A comprehensive review, Journal of Cleaner Production, Volume 127, 20 July 2016, Pages 1-18, https://doi.org/10.1016/j.jclepro.2016.03.146

[2] Pariniti Singh, Chinmaya Prasad Padhy, Chinmaya Prasad Padhy; Chinmaya Padhy, Is MQL an efficient and sustainable option? -A Review, International Journal of Scientific & Engineering Research, Volume 7, Issue 6, June-2016 , ISSN 2229-5518 April 2016, Conference: NCRTME 2016

[3] Yazid, M.Z.A., CheHaron, C.H., Ghani, J.A., Ibrahim, G.A., & Said, A.Y.M. (2011). Surface integrity of Inconel 718 when finish turning with PVD coated carbide tool under MQL. Procedia Engineering, 19, 396-401. https://doi.org/10.1016/j.proeng.2011.11.131.

[4] Tazehkandi, A.H., Shabgard, M., & Pilehvarian, F. (2015). On the feasibility of a reduction in cutting fluid consumption via spray of biodegradable vegetable oil with compressed air in machining Inconel 706. Journal of Cleaner Production, 104, 422-435. https://doi.org/10.1016/j.jclepro.2015.05.039.

[5] Sarıkaya, M., Yılmaz, V., & Güllü, A. (2016). Analysis of cutting parameters and cooling/lubrication methods for sustainable machining in turning of Haynes 25 superalloy. Journal of Cleaner Production, 133, 172-181. https://doi.org/10.1016/j.jclepro.2016.05.122.

[6] Li, B., Li, C., Zhang, Y., Wang, Y., Jia, D., & Yang, M. (2016). Grinding temperature and energy ratio coefficient in MQL grinding of high-temperature nickel-base alloy by using different vegetable oils as base oil. Chinese Journal of Aeronautics, 29(4), 1084-1095. https://doi.org/10.1016/j.cja.2015.10.012.

[7] Abukhshim, N.A., Mativenga, P.T., & Sheikh, M.A. (2006). Heat generation and temperature prediction in metal cutting: A review and implications for high speed machining. International Journal of Machine Tools and Manufacture, 46(7-8), 782-800. https://doi.org/10.1016/J.IJMACHTOOLS.2005.07.024

[8] Matthew Alberts, Kyriaki Kalaitzidou, Shreyes Melkote, An investigation of graphite nanoplatelets as lubricant in grinding, International Journal of Machine Tools and Manufacture, Volume 49, Issues 12–13, October 2009, Pages 966-970. https://doi.org/10.1016/j.ijmachtools.2009.06.005

[9] Nilanjan Banerjee, Abhay Sharma, Identification of a friction model for minimum quantity lubrication machining, Journal of Cleaner Production Volume 83, 15 November 2014, Pages 437-443, https://doi.org/10.1016/j.jclepro.2014.07.034

[10] D. Biermann, I. Iovkov, H. Blum, A. Rademacher, K. Taebi, F.T. Suttmeier, N. Klein, Thermal Aspects in Deep Hole Drilling of Aluminium Cast Alloy Using Twist Drills and MQL, Procedia CIRP, Volume 3, 2012, Pages 245-250. https://doi.org/10.1016/j.procir.2012.07.043

[11] C. Bruni, A. Forcellese, F. Gabrielli, M. Simoncini, Effect of the lubrication-cooling technique, insert technology and machine bed material on the workpart surface finish and tool wear in finish turning of AISI 420B, International Journal of Machine Tools and Manufacture Volume 46, Issues 12–13, October 2006, Pages 1547-1554, https://doi.org/10.1016/j.ijmachtools.2005.09.007

[12] Durval U Braga, Anselmo E Diniz, Gilberto W.A Miranda, Nivaldo L Coppini, Using a minimum quantity of lubricant (MQL) and a diamond coated tool in the drilling of aluminum–silicon alloys, Journal of Materials Processing Technology, Volume 122, Issue 1, 5 March 2002, Pages 127-138, https://doi.org/10.1016/S0924-0136(01)01249-3

[13] Sukanta Bhowmick [a], Michael J. Lukitsch [b], Ahmet T. Alpas, Dry and minimum quantity lubrication drilling of cast magnesium alloy (AM60), International

Journal of Machine Tools and Manufacture Volume 50, Issue 5, May 2010, Pages 444-457, https://doi.org/10.1016/j.ijmachtools.2010.02.001