Hybrid Nanofluid-Assisted Minimum Quantity Lubrication for Machining of Ti-6Al-4V: Research Framework and Hypothesis Development

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Abstract: **The conventional fluids have been in use for a very long period in the manufacturing industry for cooling and lubrication of various machines involved in the machining processes. However, in the recent past, the focus on enhancing productivity and sustainability has been growing and therefore there is a demand for more innovative lubrication processes. The soluble machine oils are often utilized for cooling purpose but the focus nowadays lies on alternative lubrication techniques. This paper deals with the use of alternative lubrication processes with the objective of guiding future research related to sustainable machining. Nanofluids along with minimum quantity lubrication (MQL) technique are being in trend and their use is discussed in this paper. In addition, the review of the work done by other researchers with regard to machining of difficult-to-machine super alloys with the same technique is presented and along with-it research framework and hypotheses are proposed.**

Index Terms: **Hybrid Nano-Fluid (HNF), Minimum Quantity Lubrication (MQL), Hard-to-cut alloys, Difficult to cut material, Ti-6Al-4V machining, Nano-Fluid**

I. INTRODUCTION

Focusing on reducing the environmental effect and maximizing efficiency, various technological advancements are being brought out currently in the field of machining and manufacturing. In machining operations, conventional fluids have been used for a long time as they provide advantages for cooling and lubricating. For greater sustainability, traditional lubrication techniques are being reassessed as the need for productivity and creative solutions. Some of the conventional cutting fluids including emulsions and mineral oils are used for cooling and lubricating machining process. Researches are looking at alternate lubrication techniques. Although the fluids offer sufficient heat dissipation and lubrication, worries about the effects on environment, machining efficiency and health hazards are leading researchers to look for alternatives.

One intriguing approach is using nanofluids, which are essentially basic fluids along with nanoparticles scattered throughout. They have special thermal and lubricating characteristics. In machining operations, nanoparticles have the ability to greatly improve heat transmission and lubrication efficiency. Decreased tool wear, increased lubrication efficiency and machining performance can all result from the use of nanoparticles into basic fluids.

Further development of this idea can include Hybrid nanofluids, which is a blend of many kinds of nanoparticles or include nanoparticles with several additives. They seek to provide customized solutions for particular machining problems, like high pressures or high temperatures by combining the beneficial qualities of several kinds of nanoparticles.

In aerospace and medical sector, the use of Minimum Quantity Lubrication has become more popular in the machining of titanium alloy (Ti-6Al-4V). In the form

of an aerosol, MQL uses a little quantity of cutting fluid, when compared with flood lubrication techniques. It lowers waste production, fluid consumption and environmental effect [12]. Although, the boundary lubrication capabilities, lubricant's thermal conductivity and compatibility with the alloy's special features all play an important role in how well MQL works in titanium alloy machining.

In this study, the possibility of hybrid nanofluids as substitutes for conventional fluids in MQL for TI-6AL-4V machining is investigated. The goal is to shed light on the efficacy and viability of these innovative lubricants in decreasing tool wear, increasing machining efficiency and promoting surface integrity in titanium alloy machining operations by examining their lubricating and thermal characteristics [13].

II. LITERATURE REVIW

Aydın, A., Sağdıç, Ö.F., Yücel, M. *et al.* (2026) [14] commented that from the beginning of sustainable machining, the cooling process has gradually evolved from conventional flood cooling, minimum quantity lubrication (MQL), and nanofluid MQL to the latest hybrid nanofluid MQL. The transition to such machining processes has been very significant especially for materials that are hard to machine like Ti-6Al-4V since it has very poor thermal conductivity and chemical affinity with the cutting tool leading to high cutting temperature and adhesion. While the conventional minimum quantity lubrication technique saves lubricant quantity, it cannot be sufficient under hard titanium machining. Thus, the use of nanoparticles and hybrid nanoparticles becomes significant for heat transfer and tribology improvement. Their research on mono and hybrid-nanofluids in MQL during the milling of Ti-6Al-4V was done using hBN/ MWCNT hybrid nanofluid. This research is very important because it looked at machining performance, surface integrity, and sustainability at the same time. In comparison to dry machining, the HNMQL process showed a reduction in cutting force of 63.5%, feed force of 87%, cutting temperature of 65.8%, and surface roughness of 65.8%. It also decreased work hardening, improved tool condition, reduced carbon emissions, and reduced cost. Therefore, the assessment of HNMQL should not be limited to machining responses but include surface integrity and sustainability as well. On the basis of the recent studies on this subject, the use of hybrid nanofluid MQL has shown great promise in enhancing the machinability of Ti-6Al-4V. Nevertheless, there are significant gaps that need to be filled. The choice of the type and ratio of the nanoparticles, their concentration, and the base fluid is still not standardized. Also, different machining conditions are considered in different studies. Therefore, a need arises for a more detailed study of the interaction of the composition of the hybrid nanofluids, their thermal and tribological properties, MQL spraying parameters, and machining characteristics (cutting force, temperature, tool wear, etc.)

Namlu, Lotfi, and Kılıç (2024) [15] examined the combined use of multi-axial ultrasonic vibration-assisted machining with hybrid nanofluid minimum quantity lubrication in Ti-6Al-4V. The hybrid nanofluid consisting of Al_2O_3 and CuO nanomaterials outperformed their respective mono-nanofluids. Their work demonstrated that the joint process of multi-axial UVAM and HNMQL lowered cutting forces up to 37.6% and surface roughness up to 37.4%. This study exemplifies one of the significant trends in the modern research where hybrid nanofluid lubricants are used in conjunction with machining processes to achieve improved performance of both. Another trend is the employment of HNMQL in conjunction with hybrid machining methods or assisted machining techniques. As shown by the researchers, the efficiency of HNMQL can be increased further if it is utilized along with multi-axial ultrasonic vibration-assisted machining. This implies that sustainable machining processes in the future do not necessarily have to rely solely on one type of technology. Instead, the process that utilizes the intelligent movement of tools, lubrication process, and specialized nanofluids could be the preferred process in machining Ti-6Al-4V.

Lotfi, Namlu, and Kılıç (2023) [16] studied further the performance of Al2O3–CuO hybrid nanofluid MQL on the milling of Ti-6Al-4V. This research made a comparison between pure MQL, conventional cutting fluid, dry machining, mono-nanofluid MQL, and hybrid nanofluid MQL with different nanoparticle concentrations. Apart from cutting forces and surface roughness, other variables tested

were the surface topography, surface finish, subsurface microhardness, and sustainability of the processes. What makes this research significant is that it validates the concept of designing hybrid nanofluids based on the thermal and tribological functionalities of nanoparticles.

Aydın, A., Sağdıç, Ö.F., Yücel, M. et al. (2026) [17] observed the trend in the recent literature thus reflects a move from the conventional approach of evaluating machining operations to the holistic evaluation of hybrid nanofluids MQL. In the past, the parameters used for evaluation were cutting forces, temperature, wear rate of the tool, and surface finish, while in the more recent literature, there is an increasing trend toward the evaluation of parameters such as surface topography, hardness, microstructure, burr formation, energy consumption, carbon footprint, and costs of machining. In the case of Ti-6Al-4V, this development has great significance due to the material's applications in aerospace and other high-performance industries in which the functionality of the finished surface has equal importance to productivity.

Pil-Ho Lee, Taek Soo Nam, Chengjun Li, Sang Won Lee. (2010) [1] examined the usage of nano-fluid minimum quantity lubrication (MQL) in mechanical machining, which focuses on reduction of environment contamination and increases in efficiency. In their study, nano-fluid minimum quantity lubrication involved the use of nano-scale particles which were the combination of nano-fluids. The examples of such nano-scale particles include nano-diamonds and base fluids, paraffin oil, which is renowned for its excellent cooling effect and high lubrication ability. They found out that the usage of nano-fluid MQL greatly improves the surface quality of meso-scale grinding process after some experiments. In comparison to dry grinding, the results indicated that 4% of 30nm nano-diamond particles reduced tangential grinding and normal forces by 30.3% and 33.2% correspondingly. When creating smoother grounder surfaces, this helped to decrease surface roughness by 64%. The improvement in the lubrication ability and heat transfer property of the nano-fluids was credited as the reason behind this improvement. Some of the suggested future studies included the examination of other types of nanoparticles such as AI203 to better understand the effect of heat on machining performance. Thermal modelling was another recommended research direction. According to the study conducted by Liu, Fucai & Wu, Xizhuan & Xia, Yu & Lv, Tao & Zhang, Ruochong & Hu, Xiaodong & Xu, Xuefeng [2], the use of nano-fluid MQL could help improve the grinding performance while minimizing the environmental effects created by the usage of traditional machining fluids.

Liu, Fucai & Wu, Xizhuan & Xia, Yu & Lv, Tao & Zhang, Ruochong & Hu, Xiaodong & Xu, Xuefeng (2023) [2] explored the efficacy of a novel lubrication/cooling method termed, "cold air electrostatic minimum quantity lubrication (CAEMQL)" in the milling of titanium alloys, particularly Ti-6Al-4V. In comparison to conventional methods, such as (MQL), (EMQL) and (CAMQL). Their study systematically assessed CAEMQL. It has been found to perform much better than those benchmarks in several important domains. It exhibited improved heat flux density and heat transfer coefficient, leading to lower milling force, reduced milling temperature, enhanced surface quality, heat flux, and prolonged tool life. Connective heat exchange and reduced tool wear was improved by the superior performance of CAEMQL and was attributed to its synergistic cooling and lubrication effects. CAEMQL minimized adhesion layer formation and wear on the tool flank was revealed by optical and SEM analyses. Its cooling effect enhanced chip segmentation, resulting in smoother chip surfaces. While mitigating the environmental impacts associated with traditional flood cooling technologies, this study underscores the potential of CAEMQL to enhance milling performance.

Wafiy Amli, Mohammad Yeakub Ali, Abdul Md Mazid Seri Rahayu Ya'akub , Ramesh Singh, Zunaidi Ibrahim and Azlina Diyanah Hamid (2023) [3, 12] investigated of the effectiveness of Minimum Quantity Lubrication (MQL) versus flood cooling lubrication in lathe turning operations on a 1-inch-thick mild steel rod. By using tungsten carbide Chemical Vapor Deposition (CVD) coated cutting tools they conducted several experiments. The experiments evaluated surface roughness and chip formation at cutting speeds of 460, 750, and 1250 rpm, and feed rates of 0.2, 0.4, and 0.8 mm/rev, with a constant depth of cut of 0.125 mm, by utilizing an orthogonal array (OA) and analysis of variance (ANOVA). Their research suggested minimal impact

of lubrication on Ra by revealing that both feed rate and cutting speed significantly impact the roughness, with the flood cooling system producing a lower surface roughness value (Ra) compared to MQL. While MQL conditions produced more segmented chips, flood cooling resulted in more discontinuous chips. The results from optimizing process parameters for reducing Ra indicated that feed rate with low values and higher values of cutting speed were preferable. The feed rate showed more significant influence on the roughness of surface than cutting speed and was studied with the help of signal-to-noise ratio of Taguchi method [12].

Shazzad Hossain and Mohammad Zoynal Abedin (2021) [4, 13] have investigated the impact of Minimum Quantity Lubrication (MQL) compared to conventional cutting fluid (CCF) and dry conditions in the machining of 50HRC steel. Their research focused on challenges posed by, high temperatures in cutting zone, surface roughness, increased tool wear and dimensional deviations, when using conventional cutting fluids and non-uniform chip formation. They found that MQL significantly reduces tool wear and improves surface roughness as compared to both flood and dry conditions in their experimental work. MQL optimized extended tool life, enhanced surface finish and surface roughness. By reducing the temperature intensity in the cutting zone and controlling the deterioration of the auxiliary cutting edge, they noticed that MQL provided better surface roughness. The research concluded by summarizing that MQL offers several benefits over dry and conventional machining, making it a superior lubrication method for achieving high-quality machining outcomes in 50HRC steel [13].

Paresh Kulkarni and Satish Chinchanikar (2022) [5] reviewed the machining of nickel-based superalloys using nanofluid-based minimum quantity lubrication (NFMQL), emphasizing its benefits over traditional methods. Compared to pure MQL, dry cutting, and flood cutting, NFMQL reduces cutting force, friction, tool wear and temperature, while improving integrity and surface finish. Nanofluids with zirconium oxide (ZrO2) enhances lubrication, while with carbon nanotubes (CNTs) excel in cooling. Al2O3 nanofluids offer improved spreadability, and graphene and HBN reduces surface roughness. An effective base fluid like Palm oil was identified for its lubrication and cooling properties. Most influential MQL parameter was highlighted as Flow rate. To overcome current limitations in machining nickel alloys at higher cutting parameters, it was suggested for further exploration of hybrid nanoparticles in their study.

In their comprehensive review, Wajiha Tasnim Urmi1, Md Mustafizur Rahman, Wahaizad Safiei, Kumaran Kadirgama, Md Abdul Maleque (2022) [6] highlights the advantages and applicability of Minimum Quantity Lubrication (MQL) in metal cutting processes. As an environmentally-friendly method, which reduces coolant usage up to 99%, the MQL allows minimizing the environmental impacts and cost of operations related to the coolant disposal and operators' health protection. As a technology that helps reducing friction, cutting forces, tool-chip interface temperature, thus improves surface quality and prolongs tool life, the MQL is highly efficient in enhancing the machining process. Special types of MQL, namely, UV-MQL and NF-MQL, help dealing with the problem of built-up edge (BUE). To further optimize tool performance, the usage of low viscosity lubricants in MQL system was recommended. Choosing MQL is a key step towards sustainable machining and environmentally-friendly cost-effective output.

Dharam Pal Kashyap, Sachit Vardhan, Manu Dogra, Rupinder Singh (2022) [7] conducted an experiment on the surface grinding of Ti-6Al-4V alloy by cubic boron nitride (CBN) grinding wheels under dry and minimum quantity lubrication (MQL) conditions. Increasing use of sustainable technologies in the process of surface grinding, especially with the help of MQL techniques, makes it possible to minimize the environmental impacts and operational cost. Comparing the grinding processes under MQL and dry conditions, MQL improves the performance of grinding process due to reduction of tangential cutting force and surface roughness. In view of high anti-oxidation mono-saturated fatty acids present in canola oil, which is applied as an MQL lubricant and helps in good lubrication and cooling of the grinding zone more than dry condition, in which the surface roughness becomes bad with an increase in grinding passes, the use of MQL with the vegetable-based cutting fluid provides very good alternatives to the traditional grinding.

Rasaq Kazeem, Tien-Chien Jen, Godwin Akande, Stephen Akinlabi, and Esther Akinlabi (2024) [8]

carried out a study on the performance of the hybrid vegetable oils as cutting fluids in MQL when turning of AISI 304 stainless steel was performed. The comparative performance of these oils with mineral-based oils concerning cutting temperature (CT) and surface roughness (SR) was studied in the research. Though the hybrid vegetable oil gave competitive performance in reducing CT under certain machining conditions, but usually the mineral oil gives low SR values. The best hybrid oil blend among the tested ones was that of palm oil kernel and yellow oleander oils. It recommended the possible use of the tested hybrid vegetable oil blend as a sustainable alternative to mineral oils. The need for optimization of its performance depending on machining parameters was emphasized in their study.

P. Sudarsana Reddy, P. Sreedevi, and Ali J. Chamkha [9] examined the features of unsteady magnetohydrodynamics heat and mass transfer of TiO2/Al2O3-Water hybrid nanofluid flow over stretching/shrinking surface along with the physical properties. By using a similarity transformation technique, the governing equations were converted into ordinary differential equations and then solved numerically via Finite Element Method. The key objective of the research was the analysis of effects of various pertinent parameters, like volume fractions of nanoparticles, suction parameter, unsteadiness parameter, and chemical reaction on the fluid velocity, temperature, and concentration. Main results revealed the increase of temperature in presence of increasing volume fractions of nanoparticles, the adverse effect of suction parameter on temperature and concentration, and the increase of temperature and concentration profiles due to increasing values of unsteadiness parameter. Also, there was discussed the change in values of Sherwood number and skin-friction coefficient depending on the value of magnetic field parameter, and the reduction of dimensionless heat transfer rates due to the increasing values of thermal radiation parameter in both stretching and shrinking flow of TiO2/Al2O3-Water hybrid nanofluid. This paper adds the knowledge about heat and mass transfer processes in nanofluids, highlighting the importance of hybrid nano fluids in thermodynamics engineering applications.

Patil Amit S., Ingle Sushil V., More Yogesh S., and Nathe Manik S. (2015) [10] reviewed the issues of machining Titanium alloy (Ti-6Al-4V) Grade 5 that is vital for aerospace, automotive and biomedical purposes. According to them, even though there are some advantages, the machining of Ti-6Al-4V faces difficulties in metallurgy, chip formation, wear of tools and lubrication. The review covered many studies, offering the following solutions, among others:

- Tooling: Coated carbide tools with high-pressure lubrication achieve optimal material removal rates, reducing wear.
- Clamping: Rigid setups counter low modulus, minimizing chatter for better surface quality.
- Lubrication: Cryogenic methods with high-pressure delivery enhance chip control, heat dissipation, and surface finish.
- Machining: Ideal conditions—shallow cuts, high RPM, low speeds in wet setups—optimize surface finish. Dry machining compromises tool life and finish.

The review suggests future research for advancing Ti-6Al-4V machining, aiming to enhance the efficiency in critical industries.

From the review of recent research works, it is clear that there is a great potential of hybrid nanofluids MQL to enhance the performance of Ti-6Al-4V material machining. But in spite of all these promising findings, systematic information about the choice of hybrid nanoparticles, their amount and mixture ratio for the case of Ti-6Al-4V milling is scarce. Also, there is a lack of integration between machining performance, tool behaviour, surface integrity and sustainability in the current literature. Hence, this research study is designed to explore the below mentioned aspects, but is not limited to and is expected to contribute to further research:

1. Evaluation of tool wear and surface roughness under HN-MQL in the milling of Ti-6Al- 4V.
2. Investigating the properties of different nanoparticles to be used in the hybrid nanofluid and analysing its impact on lubrication and cooling during milling operation.
3. Identifying and addressing practical challenges and limitations in adopting HN-MQL in real-world manufacturing processes, including scalability and compatibility with existing machinery.

4. Optimizing the cutting parameters, such as nanofluid concentration and flow rate, to achieve the best performance in terms of surface finish, tool wear and cutting forces.
5. Assessing long-term sustainability and energy efficiency, including a Life Cycle Assessment of the machining processes, cost analysis and environmental impacts.

III. HYPOTHESES

The elaborate exposure to various studies and the extant literature has led the authors to arrive at the following hypotheses for the proposed validation.

1. The quaternary hybrid nanofluid will provide improved Ra, Rz, Rt and cutting-force performance comparatively, due to collaborative multi-mechanism lubrication from the four nanoparticles.
2. Feed rate will exert the most statistically significant influence on surface roughness, consistent with prior Taguchi-based Ti-6Al-4V milling studies.
3. DOC will exert the most statistically significant influence on Cutting Forces, consistent with prior Taguchi-based Ti-6Al-4V milling studies.
4. The quaternary hybrid nanofluid will reduce cumulative flank wear and suppress dominant adhesion mechanism relative to dry and base-oil MQL conditions.

The proposed research framework is given below in Fig. 1.

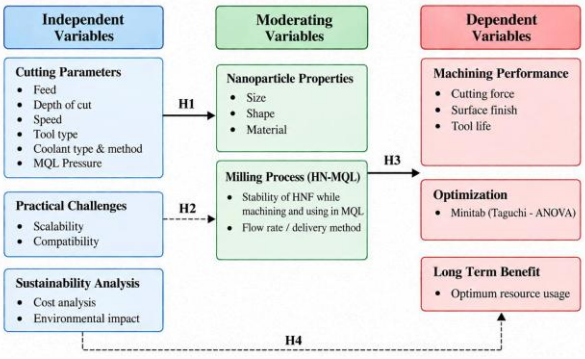


Figure 1 Proposed Research Framework

IV. CONCLUSION

From multiple studies analyzed, it has been observed that the nanofluid minimum quantity lubrication (NFMQL) improves the surface quality with reduction in cutting forces. It also helps in reducing the environmental impacts and improves milling performance, when applied on titanium alloys. MQL offers many benefits over conventional machining, which makes it a superior lubrication method for achieving high quality outcomes. It is also found that the sustainable alternative to conventional lubrication method for machining difficult-to-cut alloys is NFMQL. It helps in reducing the cutting forces, friction, tool wear and temperature with improved surface finish and tool life. Despite the benefits, machining Ti-6Al-4V presents challenges like chip formation, tool wear and lubrication. Future research could focus on improving machinability of Ti-6Al-4V using hybrid nanofluid MQL.

V. DECLARATION

AI technology was used only to rephrase a few statements identified during the similarity index check. All authors declare that they have no conflicts of interest.

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