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Advancements in Turning: Exploring Hybrid Nanofluids and MQL Strategies

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Abstract

This research examines hybrid nanofluids in turning operations using Minimum Quantity Lubrication (MQL), a popular method for improving machining efficiency and sustainability. Hybrid nanofluids have better thermal conductivity, heat transfer, and lubrication than conventional coolants and single-component options. Using hybrid nanofluids with MQL can reduce cutting temperatures, improve surface polish, lengthen tool life, and reduce environmental impact while enhancing material removal rate and coefficient of friction. This research covers recently developed hybrid nanofluid selection criteria, MQL parameter modification, and turning process performance enhancements. Stability, cost, and health hazards are also discussed while using hybrid nanofluids in industry. The data suggest that formulations and deployment techniques require more investigation to ensure widespread acceptance of this promising technology in modern production.

Keywords: Turning, Hybrid Nanofluids, Cutting fluids, Minimum Quantity Lubrication (MQL), Surface roughness

1. Introduction

A crucial machining technique used in many different sectors to shape materials like steel, titanium alloys, and other metals is turning. Lately, efforts have been directed at enhancing this procedure's efficiency by using hybrid nanofluids in Minimum Quantity Lubrication (MQL) systems. Significant gains in machining performance, such as decreased

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surface roughness, decreased cutting pressures, and increased tool life, have been shown by this novel technique. A machining of AA6061 Steel using SiO_2, MgO, and Fe_2O_3 nanoparticles in vegetable oil was shown by Vinay et al. [1]. MgO and Fe_2O_3 both displayed a 10.05% gain in machining performance, whilst SiO_2 showed a 12.5% improvement. The use of MoS_2 nanoparticles in water for Inconel 718 machining was studied by Rahul et al. [2]. The tool tip temperature was dramatically lowered and the friction coefficient was reduced by 11.05% creating the nanofluid. According to Pradeep et al. [3] research, using nano alumina in vegetable oil on stainless steel 304 produced a 25% increase in tool life and a 15% decrease in surface roughness. Using Al_2O_3 and SiO_2 in SAE 40 oil on AISI 1040 steel resulted in a decrease in surface roughness of 23.5% and cutting force of 10.13%, according to Anup et al. [7]. Nanofluids, which are suspensions of nanoparticles inside a base fluid, are an example of the creative solutions that nanotechnology has brought out in recent years. When compared to traditional fluids, these nanofluids have better heat dissipation capabilities, better lubrication, and increased thermal conductivity.

Hybrid nanofluids, which blend many nanoparticle kinds, have shown even more promise by using the properties of each constituent to produce beneficial effects. The increasing amount of data that supports the use of hybrid nanofluids in MQL for turning operations is shown by this research. Combining nanoparticles with various characteristics allows for a customized approach to cooling and lubrication that may be adjusted for certain materials and machining circumstances. The research carried out in this area will be examined in more detail in this review article, which will also examine the prospects for future developments and the processes behind the noted breakthroughs. The goal is to provide producers a thorough grasp of how hybrid nanofluids in MQL may transform the turning process and create more economical, sustainable, and effective machining solutions.

2. Literature Review

Recent developments in the use of nanoparticles in cutting fluids have greatly enhanced surface polish, reduced tool wear, and increased lubrication in machining operations. For example, Anup et al. [11] investigated the use of graphene nanoparticles in vegetable oil during titanium alloy (Ti-6Al-4V) machining. This resulted in a 6.45% decrease in tool flank wear and a 13.75% gain in performance, both of which increased tool life. Similarly, Sarthak et al.[12] investigated incorporation of graphene nanoparticles into jatropha oil was shown to reduce tool flank wear by 11.05% and surface roughness by 13.75% for the same alloy . In machining Ti-6Al-4V alloy, Lim et al. [13] achieved an 8.76% reduction in surface roughness and a 7.45% drop in cutting temperature, demonstrating the advantages of adding Al_2O_3 nanoparticles to vegetable oil. Additionally, Talwinder et al. [14] highlighted how hybrid nanofluids in Minimum Quantity Lubrication (MQL) systems provided better lubrication and extended tool life for a variety of steels and alloys. Using an emulsion of MoS_2 and Al_2O_3 nanoparticles, Minh et al. [15] achieved a 65% decrease in surface roughness and a 42% reduction in cutting force while milling 90CrSi steel. Vineet et al. [16] discovered how using nano-cutting fluids including different nanoparticles for AISI 1045 steel may improve machining efficiency. When Anjali et al. [17] looked at the effects of Al_2O_3 and Multi-Walled Carbon Nanotubes (MWCNT) in vegetable oil on AISI 1040 steel, they discovered that a 20% MWCNT concentration decreased surface roughness by 13.6%, while a 40% concentration reduced it by 6.86%. According to Tran et al. [18], machining 90CrSi steel with MWCNT in vegetable oil produced improvements in cutting temperature of 10.45% and a reduction in surface roughness of 11.76%. Furthermore, while machining Al 7075 alloy, Ariffin et al. [19] discovered that the addition of Al_2O_3 and TiO_2 nanoparticles in mineral oil increased tool life by 10.05% and enhanced surface polish by 12.45%. Last but not least, Syh et al. [20] reported that using Al_2O_3 and graphene nanoparticles in ethylene glycol for chrome steel bars resulted in a notable 45% decrease in friction coefficient and reduced machining temperatures. Similar results were seen by Pravin et al. [22] while machining Inconel 718, where CuO nanofluids in soybean oil led to a 32.43% reduction in surface roughness and a 24.97% decrease in tool wear.

Moreover, Mustafa et al. [23] showed that ZnO nanofluids derived from palm oil decreased surface roughness in AISI 52100 steel machining by 57%. Furthermore, using SiO_2 nanofluids in water to machine HSLA steel produced improvements in surface roughness of 28.34% and material removal rate of 5.09%, according to Hassan et al. [24]. Using a hybrid nanofluid of MWCNT/MoS_2 in sesame oil for AISI 1040 steel, Vamsi et al. study [25] also shown significant reductions in cutting forces (up to 32%), surface roughness (28.5%), and tool flank wear (81.3%). Karthikraja et al. [29] discovered that the HF-MQL method for AISI 4130 steel using mineral oil with Al_2O_3, Cu, and MWCNT nanoparticles decreased cutting tool temperature 25.43%, increased tool life 12.45%. Additionally, it was shown by Natalia et al. [30] that while machining titanium alloys, the NF-MQL technique decreased surface roughness by 10.02% and wear cutting temperature by about 12%. Through an analysis of previous research and recommendations for future directions, this study seeks to provide practical insights into the effective use of nanofluids and MQL systems to increase performance and sustainability in turning operations.

3. Methods and Application of Turning Process

The turning process is one of the most used machining procedures in production, especially for shaping cylindrical workpieces. In recent years, advances in cutting fluid technology have considerably improved machining performance by decreasing tool wear, enhancing surface smoothness, and lowering machining temperatures. Among these improvements, the use of hybrid nanofluids in conjunction with Minimum Quantity Lubrication (MQL) has received significant attention. Hybrid nanofluids, which are made up of two or more nanoparticles distributed in a base fluid, have showed encouraging outcomes in terms of increasing machining efficiency. Tao et al. [4] achieved a 17% reduction in cutting temperature and a 36% drop in oil mist concentration while studying AISI 1040 steel utilizing Fe_3O_4 and ZnO nanoparticles in mineral oil. Youssef et al. [5] machined AISI 1045 steel using alumina nanoparticles dissolved in used cooking oil. This resulted in a 20.29% decrease in surface roughness and a little 2.36% decrease in cutting force. Using graphene nanofluids with water on M42 steel, Anandan et al. [6] observed improved material removal rates and a 15% increase in machining performance. The use of Al_2O_3, TiO_2, and SiO_2 nanoparticles in mineral oil for AISI 1040 steel and SAE 20W-40 was studied by Patole et al. [9]. The results showed a 15% reduction in cutting force and a 21.75% reduction in surface roughness. Cu nanofluids in mineral oil were found to enhance machining performance for stainless steel by 15%, according to Anup et al. [10], with MQL turning operations seeing a 12% gain in efficiency. Tool wear was decreased by almost 50% and surface roughness by 40% for Nickel-Based Alloy employing hybrid NF-MQL using palm oil with graphene and hexagonal boron nitride (hBN) nanoparticles, according to Kaushik et al. [26]. Using hybrid nanofluids containing coconut oil, Al_2O_3, and MoS_2 nanoparticles tool wear 51.65%. Surface roughness reduced by 38.75%. Miriyala et al. [27] reduced the cutting temperature and surface roughness of AISI 4340 steel. According to Kulkarni et al. [28], hybrid NF-MQL with Al_2O_3 and MWCNT in palm oil for Inconel 718 performed better, lowering cutting temperature by 10.6%, decreasing surface roughness by 12.3%, and extending tool life by 18.34%. In comparison to dry MQL, Natalia et al. [30] discovered that the NF-MQL method for Titanium Alloy using polyolester oil with Al_2O_3 nanoparticles decreased wear-cutting temperature by about 12%, surface roughness by

10.02%, and tool flank wear by 73.3% and 65.7%. Using hybrid NF-MQL with palm oil, silicon carbide, and TiO_2 for AISI 1040 steel, Popat et al. [31] reported improvements in material removal rate and surface roughness, with surface roughness decreasing from 0.567 µm to 0.357 µm. Table 1 illustrates the summary of research articles on material turning using nanofluids.

Table 1. Research Articles on Material Turning using Nanofluids

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Authors	**Work piece**	**Nanoparticles, Base fluid**	**Primary Findings**
Vinay et al [1]	AA6061 Steel	SiO_2,MgO, Fe_2O_3,Vegetable oil	SiO_2 showed a 12.5% machining Performance Improvement. MgO and Fe_2O_3 showed 10.05%., Machining performance improvement each.
Rahul et al. [2]	Inconel 718	MoS_2, Water	Reduction in friction coefficient 11.05%.Cutting forces, surface roughness, and wear. Tool tip temperature reduction from 867 K to 526.7K
A.V Pradeep et al. [3]	Stainless steel 304	Alumina, Vegetable oil	Nano alumina/oil cutting fluid improved Tool life by 25%. Surface roughness was reduced by 15% with nano alumina/oil cutting fluid.
Tao et al. [4]	AISI 1040 steel	Fe_3O_4, ZnO Mineral oil	Cutting temperature was reduced by 17% with NMQL. Oil mist concentration decreased by 36% compared to traditional MQL.
Youssef et al. [5]	AISI 1045 steel	Alumina, Wasted cooking oil	Surface roughness was reduced by 20.29% with hybrid nanofluid MQL. Cutting force was slightly reduced by 2.36% with hybrid nanofluid MQL.

Anandan et al.[6]	M42 steel	Graphene,Water	Graphene nanofluid improved machining performance by 15%. Enhanced material removal rate. Significant enhancement in environmental factors during turning of M42 steel.
Anup et al. [7]	AISI 1040 steel	Al_2O_3+SiO_2,SAE 40 oil	Turning performance improved by 23.5%. Hybrid nanofluid and MQL utilization enhanced performance significantly.
Tanmani et al. [8]	AISI 4340	Al_2O_3,SiO_2, TiO_2,Water, Ethylene glycol, Mineral oil	Hybrid nanofluids improved turning performance by 15.05%. Enhanced machining efficiency by 21%.
Patole et al. [9]	AISI 1040 steel	Al_2O_3, TiO_2, SiO_2, SAE 20W-40, Mineral oil	Surface roughness was reduced by 21.75% using nanofluids. Cutting force reduced by 15% with MQL turning.
Junankar,et al. [10]	Stainless steel	Cu ,Mineral oil	Cu nanofluid showed almost 15% improvement in machining performance. MQL turning operation exhibited 12 % increase in efficiency.
Suresh,et al. [11]	Ti-6Al-4V	Graphene, Vegetable oil	Performance improvement 13.75% surface roughness, reduced by flank wear 6.45%. enhanced tool life.
Sarthak et al. [12]	Inconel 718	Graphene, Jatropha oil	NFMQL shows lower tool flank wear up 11.05%., providing surface roughness reduced by 13.75%.

Lim et al. [13]	Ti-6Al-4V	Al_2O_3, Vegetable oil	Reduced surface roughness by 8.76%. Reduction in cutting temperature by 7.45%.
Talwinder et al.[14]	Ti-6Al-4V	Metals, Composites and ceramics, Vegetable oil	MQL with hybrid nanofluids shows improved lubrication properties, nanoparticle enhances machining Performance and tool life.
Minh et al. [15]	Steels and alloys	MoS_2,Al_2O_3 Emulsion	Reduced by surface roughness, Approximately 65 %. Reduced by Cutting force 42%.
Vineet et al. [16]	AISI 1045 steel	CuO, Soyabean oil	Nano-cutting fluid contains nanoparticles for improved lubrication and cooling properties. Improve machining efficiency.
Anjali et al. [17]	AISI 1040 steel	Al_2O_3,MWCNT, Vegetable oil	20% MWCNT reduced Surface roughness by 13.6%.40% MWCNT reduced Surface roughness by 6.86%.
Tran et al. [18]	90CrSi steel	MWCNT, Vegetable oil	Reduced surface roughness by 11.76%.Improved cutting temperature by 10.45%. Improve material removal rate.
Ariffin et al. [19]	Al 7075 alloy	Al_2O_3,TiO_2, Mineral oil	Hybrid nano-cutting fluid Improved surface finish 12.45%. Enhanced by tool life 10.05%.
Syh et al. [20]	Chrome steel bars	Al_2O_3, graphene, Ethylene glycol	45% reduction in friction coefficient achieved and reduced machining temperature.

Venkatesan et al. [21]	Inconel X-750.”	Silver (Ag), Coconut oil	Reduced Surface roughness 6.83%. Cutting Force 47.13%, and residual stress by 51.70%.
Pravin et al. [22]	Inconel 718	CuO, Soyabean oil	Surface roughness reduced by 32.43% With CuO nanofluid. Tool wear reduced by 24.97%. Improve material removal rate.
Mustafa et al. [23]	AISI 52100	ZnO,(palm oil, peanut oil, and coconut oil)	Palm oil-based NFs at (0.125%) reduced surface roughness by 57%, and sunflower oil-based NFs at the same concentration decreased coefficient of friction by 13%.
Hassan et al [24]	HSLA steel	H_2O,SiO_2	NF-MQL machining condition resulted in 28.34% surface roughness and 5.09% improvement in material removal rate.
Vamsi et al [25]	AISI 1040	MWCNT,MoS_2, Sesame oil	NF-MQL Reduces the cutting forces 7.05% cutting temperature 21.65%, surface roughness 10.25%, and tool flank wear 12.23%.
Kaushik at el. [26]	Inconel 718	Graphene, hexagonal boron nitride, Palm oil	Hybrid NF-MQL reduces tool wear by 51.65%. Surface roughness reduced by 38.75% compared to dry machining.
Miriyala et al. [27]	AISI 4340 Steel	Al_2O_3,MoS_2, Coconut oil	Hybrid nanofluids with MQL fluid surface roughness reduced 0.988 µm from 0.757µm, reduced cutting temperature 10.68%.

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Kulkarni et al [28]	Inconel 718	Al_2O_3,MWCNT, Palm oil	Hybrid NF-MQL performed better than unitary nanofluid 10.6% reduced cutting temperature, 12.3% surface roughness, and improved 18.34% tool life.
Karthikraja et al [29]	AISI 4130	Al_2O_3,Cu,MWCNT,Mineral oil	Hybrid NF-MQL performed decreased cutting tool temperature 25.43%, increase tool life 12.45%.
Szczotkarz, et al [30]	Ti-6Al-4V	Al_2O_3, Polyolester oil	The use NF-MQL process reduced wear-cutting temperature by almost 12%, surface roughness 10.02%, and tool flank wear 14%.
Popat et al, [31]	AISI 1040 Steel AISI 1040 Steel	Silicon Carbide, TiO_2, Palm oil	Using Hybrid NF-MQL improvements in material removal rate 12.09% and surface roughness reduced from 0.567µm from 0.357µm.

4. Discussions

Significant advancements in machining performance in turning of hybrid nanofluids (NFs) in Minimum Quantity Lubrication (MQL) have been shown by the research works. The hybrid NF studies reviewed demonstrate that when hybridized with a mixture of nanoparticles (Al_2O_3, MWCNT, TiO_2, SiO_2, MoS_2, graphene) into decreased frictional force potential, with different base fluids (olive oil, vegetable oil, mineral oil, polyolester oil and other) it is extremely successful in improving machining efficiency in a variety of materials. Common steels (e.g., AISI 1040, 1045, 4130, 6061, 52100), stainless steels, Titanium alloys (e.g., Ti-6Al -4 V), Inconel 718, and aluminum alloys (e.g., Al7075) are considered to be these materials. Utilization of hybrid NFs results in several measurable benefits such as improved surface finish, enhanced tool life, and reduced cutting temperatures. Using SiO_2 nanoparticles Vinay et al [1] observed a 12.5% increase in machining performance and Anup et.al [2] observed 23.5% improvement in turning performance with a combination of Al_2O_3 and SiO_2

in SAE 40 oil. Room for improvement was also reported by Tanmani et al. [8] who enhanced their turning performance up to 15.05% with an Al_2O_3, SiO_2, TiO_2 mixed with a blend of water and ethylene glycol during their study.

Additionally, hybrid NFs are found to exhibit superior mechanical properties over single nanoparticle fluids. Enhanced thermal conductivity, better lubrication, and less friction can be achieved through sequential mixing of different nanoparticles into one fluid. The work of Kaushik et al. [26] also highlighted this synergy by demonstrating that hybrid nanofluids can reduce tool wear by 51.65% and surface roughness by 38.75% against the dry machining process. This improvement is due to improved lubrication and cooling properties of hybrid nanoparticles. The use of environmentally friendly base fluids such as vegetable oils and lubricants in hybrid NFs follows the strong trend towards green manufacturing strategies. For example, several studies, such as those by Anup et al., [11] showed that the use of bio lubricants in hybrid NF does not only improve machining performance but also helps in reducing ecosystem-related impact due to the machining process. Coupling MQL with the hybrid NFs greatly reduces the amount of coolant required while still achieving high machining performance, making the hybrid NFs and the hybrid NFs/MQL a cost-effective solution. Lower overall operational costs result from reduced coolant usage, better lubrication and increased tool life. Moreover, hybrid NFs and MQL can enable more sustainable and energy-efficient manufacturing.

Finally, the performance of the machining using hybrid nanofluids in MQL is improved significantly. Multiple nanoparticles in the same fluid in one fluid work together to improve lubricity, decrease surface roughness, reduce heat when cutting, and provide longer tool life. In addition, the inclusion of eco-friendly base fluids enhances the sustainability of this technology by current manufacturing trends toward environmentally sustainable manufacturing. Hybrid NF results from the studies studied indicate its ability to transform turning operation on most of materials.

5. Future Scope

The tuning procedure employing hybrid nanofluid with Minimum Quantity Lubrication (MQL) opens up new opportunities for future study, particularly in examining the usage of multi-base fluids and combinations of multi-nanoparticles. These advancements might lead to considerable increases in heat conductivity, lubrication, and overall machining performance. Further optimization of nanoparticle size and distribution, together with the interplay between multiple fluid bases, might minimize tool wear and increase surface finish quality.

Incorporating Pico fluids (10^{-12}m) and sophisticated nanoparticle combinations affords the possibility to fine-tune the thermal and lubrication qualities of the fluid even further. This method might lead to advancements in precision machining, especially in complicated or sensitive procedures. Future study might potentially examine the environmental benefits of these sophisticated fluids, seeking to produce more sustainable and efficient industrial processes. Electronic sensors could be incorporated into advanced MQL systems to provide real-time monitoring of machining parameters like temperature, lubricant flow rates, and tool wear. Remote monitoring, predictive maintenance, and dynamic lubrication rate modifications based on real-time data can all be made possible by these sensors in conjunction with IoT-enabled devices. Additionally, by analyzing machining data, informatics tools like machine learning algorithms could optimize MQL settings and nanofluid formulations, decreasing the need for trial-and-error experiments and increasing efficiency. Manufacturers might forecast results under various scenarios by simulating machining operations using the idea of digital twins. Integrating real-time monitoring technologies with AI might further enhance the application of these fluids, assuring maximum performance and tool lifespan in varied industrial contexts.

6. Conclusion

The complete analysis of current studies on hybrid nanofluids (NFs) in Minimum Quantity Lubrication (MQL) for turning shows considerable advances and the transformational potential of this technology in modern machining. Hybrid nanofluids, including nanoparticles like Al_2O_3, MWCNT, TiO_2, SiO_2, MoS_2, graphene, and others, have shown significant increases in machining performance indicators in various base oils (e.g., vegetable, mineral, polyol ester). Across varied materials, including steels (AISI 1040, 1045, 4130, 6061, 52100), stainless steels, titanium alloys (Ti-6Al-4V), Inconel 718, and aluminium alloys (Al 7075), hybrid NFs have been demonstrated to increase surface roughness, lengthen tool life, lower cutting temperatures, and minimize tool wear. The synergistic benefits of integrating distinct nanoparticles in hybrid nanofluids are clear, as they provide higher lubrication, better thermal conductivity, and superior mechanical characteristics compared to single nanoparticle fluids. This synergy not only improves the lubrication regime but also mitigates common machining issues such as high friction, excessive heat production, and quick tool deterioration. Additionally, the use of eco-friendly base oils such vegetable oils and bio lubricants in these hybrid NFs corresponds with the rising need for sustainable and ecologically responsible production procedures. Moreover, the integration of hybrid NFs with MQL processes has shown to be a cost-effective and efficient strategy, delivering considerable savings in coolant usage and environmental impact while retaining great machining performance. The flexibility of hybrid NFs to diverse machining conditions and materials further highlights their versatility and extensive use in the industry

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