

A review on effects of process parameters in milling challenging materials under nanofluid-based MQL conditions

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Abstract

Purpose – The purpose of this paper is to analyze the literature that is currently available and take a glance at minimum quantity lubrication (MQL) with nanofluids (NFs) as viable candidates to improve the efficiency of various milling operations on challenging materials.

Design/methodology/approach – The extensive literature review is carried through the existing literature, which shows the effect of various process parameters in the milling operation of challenging materials under NF-MQL conditions. The manuscript also deals with identifying the inferences and research gaps from the literature review. The role and potential of NF-MQL in milling challenging materials are identified in this work.

Findings – The conclusion has also derived some recommendations for future study from the prior research, which will be helpful for any further research in this area.

Research limitations/implications – This research work is limited to milling operations in challenging materials.

Practical implications – NF-MQL applications in milling operations are comparatively underexplored and merit considerable research. The amount of effort industry practitioners put into sustainable manufacturing will surely be greatly reduced by thorough research on the milling of challenging materials under NF-MQL settings.

Social implications – MQL system has a great potential to perform well in the experimental endeavor. Despite that fact, majority of the small and medium scale manufacturing industries are still using the conventional flood system for the machining of the workpieces because of the unaffordable initial cost and requirement of expertise involved as compared to the flooded lubrication. This issue might be solved when more works will be accomplished in industries for small as well as medium scale production.

Originality/value – These are novel study approaches because there are so many variables that affect cutting efficiency; therefore, more research is required to assess and provide direction for the advancement of hard milling technology.

Peer review – The peer review history for this article is available at: <https://publons.com/publon/10.1108/ILT-01-2023-0010/>

Keywords Challenging materials, Milling, Process parameters, Cutting fluid, Minimum quantity lubrication, Nanofluid

Paper type Literature review

Notations

V_c	= Cutting speed (m/min);
V_s	= Spindle speed (rpm);
f	= Feed (mm/rev);
a_p	= Depth of cut (mm);
R_a	= Surface roughness (μm);
F_r	= Cutting force (Newton);
T_L	= Tool life;
T_{WR}	= Tool wear (μm);
V_B	= Tool flank wear (μm);
MQL	= Minimum quantity lubrication;
MQCL	= Minimum quantity cooling lubrication;
NF	= Nanofluid;

MCDM	= Multi-criteria decision making;
RSM	= Response surface methodology;
GRA	= Gray relational analysis;
AHP	= Analytical hierarchical process;
TOPSIS	= The technique for order of preference by similarity to ideal solution;
Al_2O_3	= Aluminum oxide;
MoS_2	= Molybdenum sulphide;
TiO_2	= Titanium dioxide;
SiO_2	= Silicon dioxide;
CuO	= Copper oxide; and
MWCNT	= Multiwall carbon nanotube.

1. Introduction

In the industrial sector, machining is crucial for producing the appropriate size, shape and surface quality by removing unwanted material in the form of tiny chips. Products made by

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the manufacturing industry come in diverse shapes, dimensions and materials. By removing a layer in the form of chips from the parent workpiece, cutting operations such as turning, drilling, milling and so on create a finished surface with the desired shape.

Any machining process carried out in an industrial setting aims to reduce machining costs by enhancing quality and productivity, as depicted in [Figure 1](#). This is achievable if machining is done at the best cutting parameters used while obtaining increased tool life (T_L). Numerous factors, including the cutting fluid (CF), the cutting and machine tool, the work specimen and the machining parameters, all have an impact on the cutting performance, particularly in milling. As a result, it is feasible to perform minimum quantity lubrication (MQL) milling with less expense and less coolant while yet achieving improved conditions for lubricity, tool life, cutting temperature and surface quality. The results of previous investigations demonstrate that MQL with nanofluid (NF) can replace flood lubrication for superior surface quality ([Singh and Sultan, 2019](#)).

2. Challenges in milling hard-to-cut materials under nanofluid-minimum quantity lubrication conditions

2.1 Challenging materials

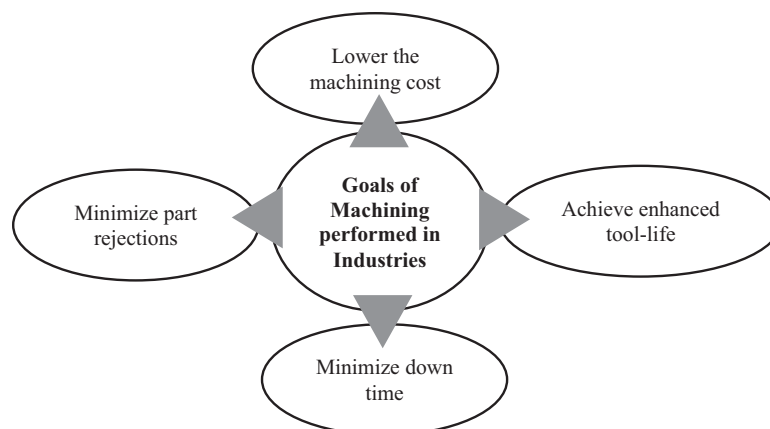
Processing hard materials require a lot of money and labor effort. Additionally, owing to their outstanding qualities, such as high hardness, stiffness, corrosion and fatigue resistance, heat capacity and so on, hard materials may not always respond well to manufacturing techniques that are simple to use for a variety of engineering materials. For the aforementioned reasons, these materials are referred to as “hard-to-machine”, “difficult-to-cut” or “challenging materials”. Cutting tools quickly deteriorate in modern materials like superalloys and steels, posing several difficulties for component quality and process effectiveness. This rapid deformation is brought on by the heat and pressure created by the procession. The corrosive nature of these materials presents a problem to the machining industry in terms of rapid tool wear ([Ahmed et al., 2021](#)). The

review cited several studies that concentrated on machining these challenging materials.

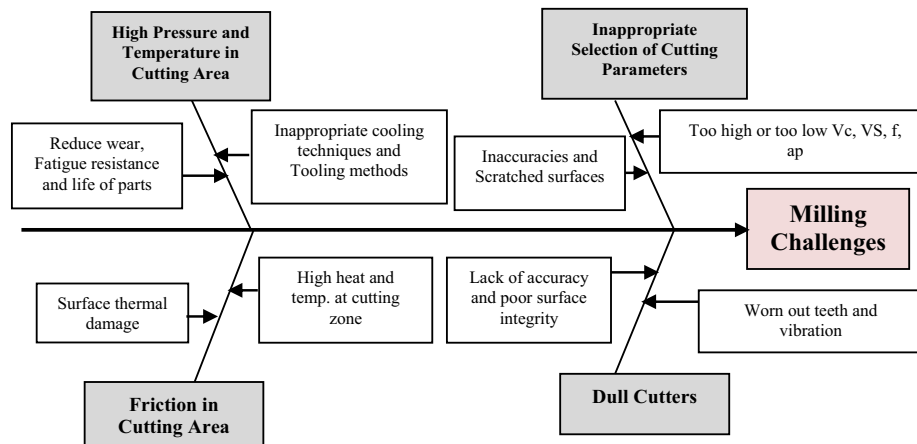
One of the most popular methods for cutting metal is milling, which involves removing excess material to create complicated, curved or flat surfaces. The effectiveness of milling is greatly influenced by the surface’s quality. Consequently, adequate lubrication and cooling, as well as the necessity to optimize cutting settings to generate a good surface quality, are crucial in the milling field. When milling challenging materials, the main problems include vibration, pressure force, accuracy, increased heat, chip formation, tool materials, machining time and tool life ([Figure 2](#)). Machining hard materials require pricey and challenging-to-come-by tool material. Hard materials will demand a lot of time to machine, which will slow down production. Due to chips rubbing against the final part surface, inadequate chip management can result in a poor surface finish. Because the tool would wear out more quickly, its life would be significantly shortened. To achieve an effective and steady machining process with hard milling, choosing the tool material grade is one of the most difficult tasks. One issue that could occur when using the milling method is that the produced object might not meet the requirements of the product design. During the milling, friction between the cutting zones occurs, creating heat and increasing the energy needed for the operation.

The life of the tool, the surface quality, tool wear and other factors are impacted by friction, heat and high energy. The effectiveness of milling is greatly influenced by the surface quality because a well-milled surface increases fatigue strength, corrosion resistance and creep life ([Ojolo et al., 2015](#)). When huge amounts of cast iron are machined, a significant temperature increase takes place in and around the cutting zone. Dimensional errors and shortened tool lifespan are brought on by these temperatures, which need to implement CFs in machining operations effectively ([Bülent and Alaattin, 2020](#)). However, because challenging materials such as Inconel and stainless steel demonstrate poor machinability, the negative impacts of dry machining are considerably more pronounced in the milling process when they are involved ([Singh et al., 2019](#); [Singh and Sultan, 2019](#)).

Figure 1 Goals of machining performed in Industries



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Figure 2 Challenges faced in milling hard-to-cut materials: causes and effects

Source: Created by author

2.2 Cutting fluid and lubrication methods

CFs are liquids and gases that are applied to the tool and workpiece to aid in the cutting operations and are referred to as lubricants or coolants. The primary concerns of the CF are to cool the tool-workpiece, lubricate and reduce friction, increase surface quality, protect the finished surface from corrosion, break up chips into smaller pieces, wash the swarf away from the tool, etc. (Duc and Long, 2020). The workpiece is physically contacted by the cutting tool during traditional machining processes for better swarf removal. Before leaving the cutting zone, this chipping flows along the rake surface of the device. High contact pressure and the relative velocity between the rake-tool surface and the streaming chips cause excessive rubbing and heat production. Numerous negative consequences on the cutting tool and the task are caused by excessive cutting heat or temperature. There are numerous ways to introduce CF into the cutting area. Every method of delivery has advantages and disadvantages of its own. Two popular fluid delivery methods that can be used with most machining processes are flood cooling and MQL. Flood cooling is the process of submerging the whole cutting zone by allowing the CF fluid to jet out of a nozzle in a liquid state. For the entire cutting zone to be fully submerged, a significant amount of CF is needed. Consequently, there is a high flow rate of the fluid. It can take in more heat from the cutting zone (Duc and Long, 2020; Javid, 2021).

Key features of the flood lubrication:

- CF is given at a much larger volume flow rate and without mixing with air.
- For uninterrupted delivery during machining, a sizable amount of CF must be kept in stock in the machine's storage chamber.
- Due to increased costs for a significant amount of expensive CF, the overall cost of machining rises.
- It can sometimes cause the machine tool to corrode more quickly; thus, it is important to insulate the essential sections properly.
- At the cutting zone, flood cooling impairs visibility.

2.3 Minimum quantity lubrication

Instead, in the MQL process, pressurized air is combined with a little amount of CF before being permitted to spray or aerosolize at a high rate of speed through a nozzle. Cutting oil continues to flow at a very low volume flow rate—one hundred times lower than flood cooling. This method of delivering CF has demonstrated potential improvements in machinability and is both economical and less harmful to the environment, making it perfect for green production. Because it is sustainable and ecologically friendly, it increases productivity and lowers expenses. The MQL system produces a droplet with cohesive particle sizes in the precision area, which lubricates the tool, specimen and swarf. It then serves this fine droplet to the tool cutting point either externally or internally. When the aerosol travels through the spinning spindle, the majority of the droplets are kept from being separated from the air by centrifugal force because of their small diameters. Depending on the type of cutting, the material being cut, and the machine setting, the amount of lubrication used is often less than 50 ml/h. In the internal feed MQL, the tool, tool holder and spindle are all lubricated with compressed air or an aerosol at the precise location where the tool meets the workpiece. The external feed MQL uses nozzles to supply the aerosol to the lubrication point from the outside. MQL is used in basic machining operations such as turning, drilling, forming and milling (Duc and Long, 2020; Singh *et al.*, 2019; Javid, 2021; Manikanta *et al.*, 2018; Wong and De Leon, 2010; Kadirgama, 2021, p. 28).

Key features of the MQL:

- CF has a relatively low volume flow rate and is provided after being mixed with compressed air.
- Good visibility is provided by the MQL distribution method. Therefore, machining processes can be halted if any issues arise.
- Work specimens and chippings no longer need to be cleaned.
- Saving money, labor, health and safety concerns related to contaminated chips and residual fluid that need to be maintained and disposed of.

Thus, MQL offers a more environmentally friendly substitute for flood lubrication systems, which could help firms advance in embracing sustainability programs and putting in place “Smart Factory” capabilities.

2.4 Nanofluids

“Nanofluid” contains nanoparticles that are suspended in a base fluid (water, ethylene glycol, oil, etc.) and combine to form a colloidal solution. Nanoparticles are typically comprised of metals, oxides, carbides or carbon nanotubes. NFs have special properties that make them potentially useful in a variety of heat transfer applications, including nanoelectronics, liquid fuels, medicines, automobiles, domestic fridges and manufacturing. In addition to thermo-physical characteristics, including specific heat, density, viscosity and thermal conductivity, NFs also possess new traits that set them apart from basic fluids. Base fluid’s thermo-physical characteristics are altered when the nanoparticles are added to it. The most significant thermo-physical characteristics of NFs are their viscosity, thermal conductivity, convective heat transfer and specific heat (Shahzad, 2020; Das *et al.*, 2006; Choi, 2009; Wong and De Leon, 2017; Kadrigama, 2020; Javid, 2021; Manikanta *et al.*, 2018; Wong and De Leon, 2010; Kadrigama, 2021).

Key features of nanofluids:

- More heat transfer surfaces between particles and fluids are provided.
- Increased stability for dispersion.
- Different particle concentrations can be used to change attributes like heat conductivity and surface wettability as per requirements.

4. Review on milling challenging materials under nanofluid-minimum quantity lubrication conditions condition

Several studies; included in the literature review concentrated on the machining of challenging materials. Because of the severe heat generation, challenges with chip formation, high material hardness and strength all contribute to low efficiency and high operation costs. According to certain earlier studies (Tables 1 and 2), NF-MQL process parameters have shown convincing effects on milling performance.

5. Findings from the existing research

- The earlier researchers discussed their work on a variety of challenging materials for various milling operations, including nickel-based, titanium-based, manganese-based superalloys and medium and hardened alloy steels (Soori and Mohammed, 2021; Okokpujie and Tartibu, 2021).
- According to studies, earlier researchers focused on MQL machining of challenging materials in milling with output parameters, including surface roughness, tool wear, tool life, cutting forces, cutting temperature and chip deformation coefficient (Soori and Mohammed, 2021).
- It has been noted that previous studies have generally regarded surface roughness as an output characteristic in all milling operations. Also, in milling operations cutting forces, cutting temperature, tool wear and tool life are the factors that receive the least attention (Ojolo *et al.*, 2015;

Safei *et al.*, 2018; Duc *et al.*, 2021; Bülent and Alaattin, 2020; Duc and Long, 2020; Günan *et al.*, 2020; Singh *et al.*, 2019; Xiufang *et al.*, 2021; Sayuti *et al.*, 2014; Rahmati *et al.*, 2013; Uysal *et al.*, 2015).

- As can be observed, relatively little research has been done on how the NF-MQL process parameters affect cutting forces and chip deformation coefficients as output parameters in the end and side milling operations (Safei *et al.*, 2018; Günan *et al.*, 2020; Muthusamy *et al.*, 2015; Uysal *et al.*, 2015).
- It has been found that applying NFs to the machining zone and adding the proper lubrication can enhance the tribological properties of a variety of challenging materials.

6. Review of the impact of changing process parameters on output responses

The radial linear speed that results from rotation is known as cutting speed (V_c). To provide the cutter with the desired peripheral speed, the spindle speed of a machine is chosen. In milling, the specimen moves under the cutter at a rate known as feed (f) and is expressed in terms of feed/tooth, feed/cutter revolution and feed/minute. The thickness of the material removed in one pass under the cutter is known as the depth of cut (a_p) in milling and represents the perpendicular distance between the original and finished surfaces of the specimen. Because a cutting tool must be ground and reset frequently, tool life (T_L) is a crucial component of performance. When a tool is performing satisfactorily, it is said to have surpassed the end of its useful life. A dull tool increases cutting forces increase power consumption, leads to chatter in the machining process and leaves the tool overheated. These irregularly fluctuating forces cause the arbor to vibrate torsionally, which affects cutting speed and, in turn, reduce cutter life. The surface finish may also be harmed by the varying radial and axial stresses. Any part of the machine can be excited to vibrate naturally by further cyclic variations in the force, which will supply the necessary energy. Surface roughness (R_a), which is determined by three criteria, including surface roughness, waviness and lay, is a measurement of a product’s entire surface texture. All these variables have been noted by previous researchers as input-output parameters to a large or small extent, as shown in Figure 3.

6.1 Effects of cutting parameters in milling challenging materials

The following conclusions can be derived from the findings and analysis of the earlier investigations on the influence of cutting parameters in milling challenging materials:

- According to Ojolo *et al.* (2015) in the multiple regression model, two of the parameters, namely, “ V_s ,” “ f ” and “ a_p ”; while keeping one of them constant at a time and their interactions, it is possible to predict the “ R_a ” regardless of whether it was produced in a dry or MQL environment. In addition to being ecologically friendly, they also conclude that machining with MQL reduces the “ R_a ” value more effectively than dry machining.
- According to the findings of Duc and Long (2020), “ R_a ” levels are largely dependent on geometrical printing in end milling, and input machining settings have relatively little effect on these values.

Table 1 Review of studies on the milling challenging materials under NF-MQL condition

Investigators	Material used	Machine/(Mill operation)	Tooling/Insets used	Lubrication method	Cutting parameters	NF-MQL parameters	Output parameters	Methodology used
Ojolo et al. (2015)	AL 6061	CNC/ (End)	HSS	MQL	V_s, f, a_p	–	R_a	RSM
Saffiet et al. (2018)	AA 6061-T6	CNC/ (End)	Coated Carbide	MQL	V_s, f, a_p	Air Press. No. of Nozzle, Nozzle Angle, Nozzle Distance, Flow Rate	R_a	Taguchi
Duc et al. (2021)	60Si2Mn	VMC/ (Hard)	PVD submicron Carbide	NF-MQL	V_c, f, a_p	Air Press., Flow Rate	R_{sp}, F_r	ANOVA Analysis with Minitab
Bulent and Alaattin (2020)	EN-GS1 700–02 CI	VMC/ (Climb)	Al ₂ O ₃ Coated Carbide	NF-MQL	V_c, f, a_p	Air Press., Flow Rate	R_{sp}, T_{WR}	Dunnet Statistical Test, Minitab 17
Duc and Long (2020)	SKD-11 Steel	VMC/ (Hard)	PVD submicron Carbide	MQL, MQCL	–	Air Press., Flow Rate	R_a	Factorial Expt. Design, Minitab 18
Günan et al. (2020)	Hastelloy C276	VMC/ (Side)	Coated Carbide	NF-MQL	V_s, f	Fluid flow rate, Spray angle, Spray Press., Nanoparticle Concentration	R_{sp}, T_L, T_{WR}	Taguchi
Singh et al. (2019)	Inconel 625	CNC/ (Face)	PVD Coated Carbide	NF-MQL	V_c, f, a_p	Air Press., Nozzle Angle, Nozzle Distance, Flow Rate	R_{sp}, T_{WR}	RSM
Xiufang et al. (2021)	Grade-45 Steel	CNC/ (Plain)	End Milling Cutter	NF-MQL	V_s, f, a_p	Flow Rate, Nozzle position, Nozzle angle, Air Press., Nanoparticle concentration	R_{sp}, F_s Specific Cutting Energy, Surface Micromorphology, Morphology of chip surface contact	Micro and Macro Evaluation Parameters
(Sayuti et al., 2014)	AL 6061-T6	VMC/ (End)	HSS	NF-MQL	V_c, f, a_p	Nanoparticle concentration	R_{sp}, F_r, T_{WR}	Morphological and Surface elemental mapping analysis SEM and EDX
Muthusamy et al. (2015)	AlSi 304	CNC/ (End)	TiN Coated Carbide	NF-MQL	V_c, f, a_p	Nanoparticle concentration	T_L, T_{WR}	Analysis
Rahmati et al. (2013)	AL 6061-T6	VMC/ (Slot)	Tungsten Carbide	NF-MQL	–	Nanoparticle concentration, Air Press., Nozzle Orientation	R_{sp}, F_r, T_{WR}	Taguchi
Uysal et al. (2015)	AlSi 420	CNC/ (Side)	Uncoated Tungsten Carbide	NF-MQL	V_c, f, a_p	Flow rate, Air Press., Nozzle angle, Nozzle distance, Nozzle diameter	R_{sp}, T_{WR}	Optimization
Okokpuije and Tartibu (2021)	Ti-6Al-4V-ELI Alloy	CNC/ (Face)	Carbide	NF-MQL	V_c, f, a_p	Dry, Mineral Oil, TiO ₂ conditions	F_r	Experimental Analysis
Haq et al., 2021)	IN718 Inconel 718	CNC (Face)	PVD Coated	NF-MQL	V_s, f, a_p	Flow Rate, Air Press. Nozzle angle, Nozzle distance	R_{sp}, T_{WR}	Taguchi Design
Mohanraj et al. (2022)	Inconel 625	CNC (Face)	Milling Inserts	NF	V_s, f, a_p	–	R_{sp}, T_{WR}	RSM
Source: Created by author							R_{sp}, T_{WR}	TOPSIS

Table 2 Review of effects of NF-MQL process parameters in milling challenging materials

Investigators	Lubrication method	Process parameters			Key findings
		Cutting parameters	NF-MQL parameters	Optimum results obtained	
Ojolo et al. (2015)	Dry, MQL	$V_s = 700, 1,500, 2,000, 3,000, 4,000$ rpm, $f = 120, 200, 500, 1,000$ mm/min, $a_p = 0.4, 0.8, 1.0$ mm	–	(a) For dry and MQL conditions, $f = 120$ mm/min, R_a minimized with increased speed (b) R_a increase with the increase in f from $1.64 \mu\text{m}$ to $7.16 \mu\text{m}$ at $a_p = 0.4$ mm Optimum MQL parameters were obtained at 30° , 30 mm and 1.98 mL/min of nozzle angle, nozzle distance and airflow rate, respectively Ra and Fr operate more effectively at larger pressure flow rates and reduced air pressure	Combination of f, V_s have the best interaction, followed by V_s, a_p
Saffei et al. (2018)	MQL	$V_s = 2,000$ rpm, $f = 100$ m/min, $a_p = 3$ mm	Air Press. = 0.5 MPa, No. of Nozzles = 03 , Nozzle Angle = $30^\circ, 45^\circ, 60^\circ$, Nozzle Distance = 30 mm, Flow Rate = $0.66, 1.32, 1.98$ mL/min Air Press. = $5, 7$ MPa, Flow Rate = $100, 200$ l/min	The least Ra value, measured at 5 Bar pressure and 160 mL/h flow rate under MQL + 0.5% MoS ₂ spray conditions, was 0.47 m. The largest Ra value ever recorded in dry machining was 0.86 m Airflow has a small influence on R_a , whereas it is better to use a small air flow rate	Best combination of MQL parameters can help to increase overall manufacturing efficiency
Duc et al. (2021)	NF-MQL	–	–	Optimum parameters designed for T_L were V_c (60 m/min), f (0.10 mm/rev) and Al ₂ O ₃ NP at (1 Vol. %) concentration Optimum results were obtained at $V_c = 50$ m/min, $f = 0.05$ mm/tooth, $a_p = 0.20$ mm for R_a of $0.89 \mu\text{m}$ and V_B of $19.47 \mu\text{m}$ under MQL condition Specific energy gradually decreased with an increase in Al ₂ O ₃ concentration	Ideal values must be determined through additional research and analysis because air pressure and airflow rate are repeated measures By including nano MoS ₂ , tool wear was improved
Bülent and Alaattin (2020)	NF-MQL	$V_c = 300$ m/min, $f = 0.2$ mm/tooth, $a_p = 4$ mm	Air Press. = $3, 5, 7$ Bar, Flow Rate = $160, 310$ mL/h	Optimum results were obtained at $V_c = 50$ m/min, $f = 0.05$ mm/tooth, $a_p = 0.20$ mm for R_a of $0.89 \mu\text{m}$ and V_B of $19.47 \mu\text{m}$ under MQL condition Specific energy gradually decreased with an increase in Al ₂ O ₃ concentration	
Duc and Long (2020)	MQL, MQCL	–	Airflow Press. = $5, 7$ Bar, Air Flow Rate = $150, 250$ l/min	Optimum parameters designed for T_L were V_c (60 m/min), f (0.10 mm/rev) and Al ₂ O ₃ NP at (1 Vol. %) concentration Optimum results were obtained at $V_c = 50$ m/min, $f = 0.05$ mm/tooth, $a_p = 0.20$ mm for R_a of $0.89 \mu\text{m}$ and V_B of $19.47 \mu\text{m}$ under MQL condition Specific energy gradually decreased with an increase in Al ₂ O ₃ concentration	Base fluid with nanoparticles provided good results
Günan et al. (2020)	NF-MQL	$V_c = 60, 75, 90$ m/min, $f = 0.10, 0.15, 0.20$ mm/rev	Nanoparticle Concentration = $0.5, 1.0, 1.5\%$	Optimum parameters designed for T_L were V_c (60 m/min), f (0.10 mm/rev) and Al ₂ O ₃ NP at (1 Vol. %) concentration Optimum results were obtained at $V_c = 50$ m/min, $f = 0.05$ mm/tooth, $a_p = 0.20$ mm for R_a of $0.89 \mu\text{m}$ and V_B of $19.47 \mu\text{m}$ under MQL condition Specific energy gradually decreased with an increase in Al ₂ O ₃ concentration	R_a and V_c have an indirect correlation, whereas f and Ra have a direct relation NF-MQL maintains dry, clean workspaces
Singh et al. (2019)	NF-MQL	$V_c = 30, 40, 50$ m/min, $f = 0.5, 0.75, 0.1$ mm/tooth, $a_p = 0.2, 0.3, 0.4$ mm	Air Press. = 5 Bar, Nozzle Angle = 45° , Nozzle Distance = 50 mm, Flow Rate = 75 mL/h	Optimum parameters designed for T_L were V_c (60 m/min), f (0.10 mm/rev) and Al ₂ O ₃ NP at (1 Vol. %) concentration Optimum results were obtained at $V_c = 50$ m/min, $f = 0.05$ mm/tooth, $a_p = 0.20$ mm for R_a of $0.89 \mu\text{m}$ and V_B of $19.47 \mu\text{m}$ under MQL condition Specific energy gradually decreased with an increase in Al ₂ O ₃ concentration	
Xiufang et al. (2021)	NF-MQL	$V_s = 1,200$ rpm, $f = 500$ mm/min, $a_{pa} = 0.25$ mm, $a_{pr} = 10$ mm	Flow Rate = 85 mL/h, Nozzle position = 40 mm, Nozzle angle = 45° , Air Press. = 0.4 MPa, Nanoparticle concentration	Optimum parameters designed for T_L were V_c (60 m/min), f (0.10 mm/rev) and Al ₂ O ₃ NP at (1 Vol. %) concentration Optimum results were obtained at $V_c = 50$ m/min, $f = 0.05$ mm/tooth, $a_p = 0.20$ mm for R_a of $0.89 \mu\text{m}$ and V_B of $19.47 \mu\text{m}$ under MQL condition Specific energy gradually decreased with an increase in Al ₂ O ₃ concentration	The tribological performance of nanofluid is superior to that of pure plant oils and can greatly improve milling quality
Sayuti et al. (2014)	NF-MQL	$V_c = 5,000$ rpm, $f = 100$ mm/min, $a_p = 5$ mm	Nozzle Angle = 30° , Nozzle Distance = 1 mm, MQL Oil Press. = 20 MPa MQL Flow rate = 2 mL/min, Nano particle concentration = $0.2, 0.5, 1.0\%$	Optimum parameters designed for T_L were V_c (60 m/min), f (0.10 mm/rev) and Al ₂ O ₃ NP at (1 Vol. %) concentration Optimum results were obtained at $V_c = 50$ m/min, $f = 0.05$ mm/tooth, $a_p = 0.20$ mm for R_a of $0.89 \mu\text{m}$ and V_B of $19.47 \mu\text{m}$ under MQL condition Specific energy gradually decreased with an increase in Al ₂ O ₃ concentration	SiO ₂ nanoparticles would emerge as a novel-efficient flood lubrication replacement as ecological aspects

(continued)

Table 2

Investigators	Lubrication method	Process parameters			Key findings
		Cutting parameters	NF-MQL parameters	Optimum results obtained	
Muthusamy et al. (2015)	NF-MQL	$V_c = 1,500, 2,000, 2,500$ rpm, $f = 0.02, 0.03, 0.04$ mm/tooth, $a_p = 0.1, 0.2, 0.3$ mm	Nanoparticle concentration = 0.5, 1, 1.5%	f has the most dominant effect on tool life followed by a_p and V_c in end milling with MQL and NF-MQL conditions	Flank wear (V_b) chipping, cracking, fracture was the main tool failure mode
Rahmati et al. (2013)	NF-MQL	$V_c = 8,000$ m/min, $f = 2,100$ mm/min, $a_p = 5$ mm	Nanoparticle concentration = 0, 0.20, 0.50, 1%, Air Press. = 1, 2, 3, 4 Bar, Nozzle Orientation = 15°, 30°, 45°, 60°	By adding 1 Wt.% NP suspended in mineral oil with a high air stream pressure of 4 Bar and a 30° nozzle orientation, Fr can be reduced	MOS ₂ could be a novel-effective substitute flood lubricant
Uysal et al. (2015)	NF-MQL	$V_s = 995$ rpm, $f = 180$ mm/rev., $a_p = 0.5$ mm	Flow rate = 20, 40 mL/h, Air Press. = 5 Bar, Nozzle angle = 10°, Nozzle distance = 50 mm, Nozzle tip diameter = 1 mm	For MQL flow rates of 20 and 40 mL/h, respectively, the best outcomes were obtained at 9.8% and 15.5 when compared to dry milling	MOS ₂ particles led to the least amount of T_{WR} and Ra because of the lubricating properties
Okokpuje and Tartibu (2021)	NF-MQL	$V_c = 2,000, 2,500, 3,000$ rpm, $f = 150, 200, 250$ mm/min, $a_p = 0.3, 0.6, 0.9$ mm	Dry, Mineral Oil, TiO ₂ conditions	Ideal parameters were attained under the NF-MQL condition at 3,000 rpm of V_c 200 mm/min of f , and 0.3 mm of a_p	Reduction of Fr by 19% compared to conventional lubrication was achieved using a mineral oil-based TiO ₂ nanolubricant
Haq et al. (2021)	NF-MQL	$V_s = 2,000, 2,500, 3,000$ rpm $f = 30, 55, 80$ mm/min $a_p = 0.30, 0.55, 0.80$ mm	NF-MQL, Water-based Cu nanofluid Flow rate = 400, 600, 800 mL/h Air Press. = 4 Bar Nozzle angle = 45° Nozzle distance = 25 mm	Depth of cut is the most crucial process variable for lubrication environments. The reductions in surface quality, temperature, power of 20.1%, 14.7% and 13.3%, respectively, show that the NF-MQL is a superior substitute	NF-MQL outperformed MQL in terms of desirability achievement (71.3%) as opposed to MQL (70.1%)
Mohanraj et al. (2022)		$V_s = 1,500, 2,000, 2,500, 3,000$ rpm, $f = 125, 150, 175, 200$ mm, $a_p = 01.0, 0.15, 0.20, 0.25$ mm	Palm oil with 0.5, 0.25 Wt.% of CuO and TiO ₂	Best parameters for the TOPSIS multi-response optimization were 2,000 rpm, 175 mm/min feed, 0.15 mm depth and palm oil coolant with 0.25 Wt.% CuO and 0.25 Wt.% TiO ₂ nanoparticles	Ra, MRR, spindle vibration were all reduced by the TOPSIS optimization by 3.10, 6.14, 7.54 and 6.78% (Vx), and by 3.10, 6.18% (Vz), respectively

Source: Created by author

Figure 3 Literature study on input–output variables

Notes: Observation: Most of the researcher has considered the " V_c ", " f " and " a_p " as a input variables and " R_a " as an output variable

Source: Created by author

- According to [Günan et al. \(2020\)](#), when " V_c ", the " T_L " significantly dropped. In other words, when " V_c " increases, the milling area temperature rises. Increased " f " in milling operations expose the cutting tool to additional load, which, in turn, causes wear because they increase " F_r " and chip removal volume. By allowing the material of the workpiece to soften as the temperature rises, the " F_r " and vibration are decreased. The combination of a high " V_c " and a moderate " f " value produces the highest surface quality.
- According to [Singh et al. \(2019\)](#), the " R_a " is greatest when the table " f " is increased. Increased " f " and " V_c " result in significant vibration and temperature in the cutting zone, which raises " R_a ". " R_a " does, however, steadily reduce as the " V_c " rises. " R_a " increases as " f " and " a_p " increase because of the high friction that forms at the tool-chip interface, as well as the increasing chip area, temperature and " F_r ".
- According to [Muthusamy et al. \(2015\)](#), " T_L " rose as " V_c ", " f " and " a_p " were reduced. As a result, the end milling process can benefit from the use of low " V_c ", low " f " value and low " a_p ".
- [Okokpujie and Tartibu \(2021\)](#) demonstrated the impact of " V_c " on " F_r " under three different lubrication conditions. For each of the three cutting circumstances, the lowest " F_r " was attained at the fastest " V_c ". When the machining condition has not affected the " f ", the " F_r " increases. " F_r " decreases as " V_c " increases while maintaining a relatively modest " f ".

6.2 Effects of minimum quantity lubrication process parameters in milling challenging materials

As illustrated in [Figure 4](#), the variables that have a significant impact on milling challenging materials have been identified by prior researchers as NF-MQL process parameters. Results and analysis of past studies on the influence of NF-MQL process parameters in milling led to the following conclusions:

- " R_a " and " F_r " were significantly influenced by air flow rate and pressure. In line with earlier findings, the results

demonstrated that using reduces the air pressure and a larger air flow rate produced better outcomes for both " R_a " and " F_r ". According to the data, using reduces the air pressure and a larger air flow rate appears to be more beneficial for getting better results ([Duc et al., 2021](#)).

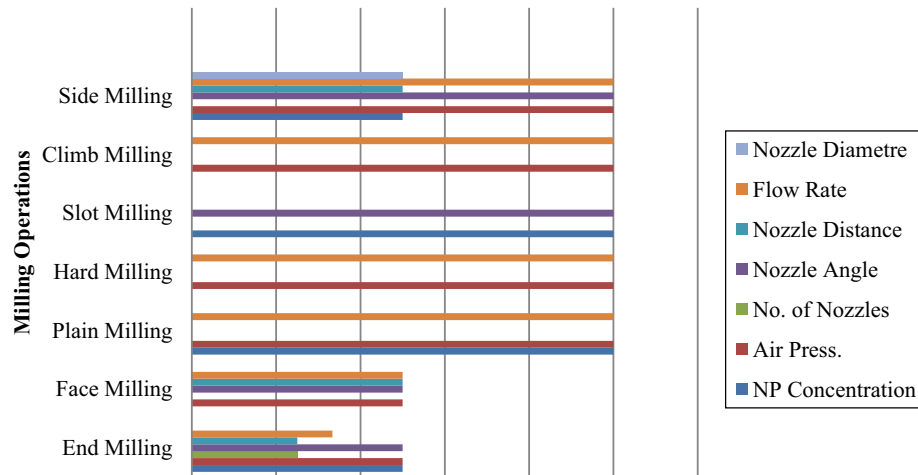
- As the flow rate increased, the " R_a " value grew. Dunnet's repeated comparison test findings showed that the flow rate was successful on " R_a " ([Bülent and Alaattin, 2020](#)).
- Nozzle orientation is a key factor in high-speed machining. The optimal cutting temperature was found at a 30° nozzle angle to efficiently removed heat from the workpieces surface ([Rahmati et al., 2013](#)).
- " R_a " was significantly lower for the selected flow rates when comparing the MQL method to dry milling. Additionally, it was found that nano MQL milling resulted in a better reduction in surface roughness than dry milling ([Uysal et al., 2015](#)).
- Because the nano-CF could reach the point where the cutting tool and workpiece made contact, the MQL approach reduced " T_{WR} ". As a result, increasing the amount of nano-CF was able to reduce " T_{WR} " ([Uysal et al., 2015](#)).

6.3 Effects of nanoparticles in milling challenging materials

Results and analysis of past studies on the use of nanoparticles in the milling of challenging materials are summarized and led to the following conclusions:

- Significant " R_a " and " F_r " effects are caused by MoS₂ and Al₂O₃ nanoparticles. Given the differences in nanoparticle morphology and characteristics, Al₂O₃ nanoparticles performed better in terms of " R_a " and " F_r ". Due to their almost spherical form, Al₂O₃ nanoparticles have exceptional lubricating properties, making the rolling mechanism the primary source of lubrication ([Duc et al., 2021](#)).
- " T_{WR} " decreased as a result of the nano-MoS₂ addition. There were traces of the wear mechanisms caused by diffusion, adhesion and abrasion ([Bülent and Alaattin, 2020](#)).

Figure 4 Literature study of NF-MQL parameters



Notes: Observation: Almost all the researcher has focused on Nozzel diameter, Flow rate, Nozzel angle, Air Presuure as NF-MQL Process Parameters

Source: Created by author

- Presence of MoS_2 nanoparticles improves the based fluid's viscosity and thermal conductivity, which enhances the fluid's cooling and lubricating effects, making it superior to a pure fluid (Duc and Long, 2020).
- " T_L " appears to have enhanced because of the increased nanoparticle ratio. This is explained by the fact that the thermal conductivity of the CF rises as the ratio of Al_2O_3 nanoparticles in the base CF increases (Günan *et al.*, 2020).
- According to earlier experimental findings, NF-MQL has a low " T_L " and a high " R_a " at a weight concentration of 0.05%. However, machining performance improves as the weight concentration of nanoparticles in the base oil rises, and minimal " V_B " and " R_a " were found at 1% weight concentration (Singh *et al.*, 2019).
- Due to the rapid heat transfer rate of the NF, it has been observed that using it as a CF minimizes the penetration of high temperatures into the cutting tool (Muthusamy *et al.*, 2015).
- Due to the nano MoS_2 particles' lubricating function, using them in reinforced CF for MQL milling resulted in the least amount of " T_{WR} " and " R_a " (Uysal *et al.*, 2015).

7. Future works

There has been a demand in recent years to lower the use of CFs when cutting materials that are challenging to machine. NF-MQL is novel study approaches because there are so many variables that affect cutting efficiency; therefore, more research is required to assess and provide direction for the advancement of hard milling technology. MQL characteristics, such as nozzle diameter and air pressure, can be investigated for further research and recommendations. Additionally, other machining responses like cutting temperature and cutting force can be assessed. Also, more research should be done on the usage of

hybrid nano-CF (such as $\text{Al}_2\text{O}_3/\text{MoS}_2$ and $\text{MoS}_2/\text{SiO}_2$) for MQL hard, side, climb, slot and plain milling operations.

8. Conclusions

- The need for high quality in milling draws attention to the roughness of the machined surface because of its impact on product performance. In general, the machining of Al6061-T6, AISI 304 and AISI 5160 will experience various issues during milling, and this is fairly prevalent in the industry.
- Surface finishing has a significant impact on milling productivity because a well-milled surface boosts wear corrosion resistance as well as creep life. So, to produce a high-quality surface, process parameters must be carefully managed.
- NF-MQL milling of hardened steels, particularly useful in automobile applications, had not received much attention in prior studies. In various milling processes, particularly end, side and high-speed milling, the MQL approach may be used instead of flood cooling, according to the research that has been conducted.
- The literature study reveals that there are currently few investigations on the use of NF-MQL in machining using multi-criteria decision-making methods like Response surface methodology. It would be possible to analyze the performance parameters through MCDM techniques such as Gray Relational Analysis, Analytical Hierarchical Process and TOPSIS.

Thus, NF-MQL applications in millings are comparatively underexplored and merit considerable research. The amount of effort industry practitioners put into sustainable manufacturing will surely be greatly reduced by thorough research on the milling of challenging materials under NF-MQL settings.

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