Journal of Engineering and Applied Research (JEAR)
National University of Skills
Summer & Autumn 2025, Vol. 2, No. 2, p. 121- 146
Journal Homepage: https://jear.tvu.ac.ir
:10.48301/JEAR.2024.474745.1100

Experimental Investigation of Nozzle Properties on Thrust force and Torque in Drilling with Hybrid Nanofluid MQL

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ARTICLE INFO

Article Type:
Original Research

Received: 03.07.2025
Revised: 05.18.2025
Accepted: 11.04.2025

Keyword:
Drilling
Thrust force
Torque
MQL
Hybrid nanofluid lubrication
Friction coefficient

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ABSTRACT

Minimum quantity lubrication (MQL) is a promising solution as an alternative to conventional flood cooling and dry machining. This study investigates the enhancement of drilling performance through the application of hybrid (Al_2O_3/CuO) and unitary (Al_2O_3) nanofluids in the MQL system, focusing on thrust force, torque, friction coefficient, and the final surface quality. A full factorial design of experiments was employed to evaluate the effects of lubrication type, nozzle configuration (number, geometry, and outlet diameter), and their interactions under identical conditions. Results demonstrated that hybrid nanofluids outperformed unitary nanofluids, achieving reductions of 51% in thrust force, 56% in torque, and 42% in friction coefficient compared to dry machining when using four rectangular nozzles with a 1.5 mm outlet. Increasing the number of nozzles from one to four enhanced lubricant distribution, reducing thrust force, torque, and friction by 22%, 23%, and 38%, respectively. Rectangular nozzles with a 1.5 mm outlet proved effective due to superior spray coverage, while ANOVA identified number of nozzles and nozzle geometry as the most influential parameters. Surface quality improvements, including reduced burrs and cracks, were observed with hybrid nanofluids, enhancing precision and fatigue life. Multi-criteria optimization via TOPSIS confirmed the hybrid nanofluid MQL system with four rectangular nozzles (1.5 mm) as the most effective configuration. These findings underscore the potential of advanced MQL strategies to improve machining efficiency, tool life, and surface integrity in green manufacturing.

E-ISSN: 3060-6357

Introduction

In recent years, the manufacturing industry has faced increasing pressure to adopt sustainable practices that align with the principles of green engineering and sustainable production. One of the critical areas of focus is machining processes, which are integral to manufacturing but often involve significant energy consumption, heat generation, and environmental impact [1]. Among these processes, drilling, particularly of lightweight materials such as aluminum alloys, plays a vital role in various industries, including aerospace, automotive, and electronics [2]. During machining operations, a significant rise in temperature occurs due to the interaction between the workpiece and the cutting tool. This temperature increase is primarily caused by the plastic deformation of the workpiece, which generates substantial heat and stresses in the cutting zone [3]. The elevated temperatures during machining have a direct impact on the surface properties of the material, often leading to undesirable effects such as reduced surface quality, tool wear, and dimensional inaccuracies [4; 5]. To address these challenges, extensive research has been conducted to develop methods and techniques aimed at minimizing the temperature in the cutting zone, thereby improving machining efficiency and workpiece quality. However, traditional machining methods often rely on flood cooling and lubrication systems, which not only consume large quantities of cutting fluids but also pose environmental and health hazards [6]. Consequently, alternative cooling methods that are more sustainable and environmentally friendly are increasingly being utilized in manufacturing processes.

MQL has been regarded as an efficient, economical, and eco-friendly technique in which a very low amount of cutting fluid (10-100 ml/h) is carried by compressed air and is also very effective in overcoming the problems of dry machining [1; 7; 8]. In the MQL technique, the lubricant is precisely delivered to the tool-chip interface, ensuring optimal lubrication during the machining process. Simultaneously, compressed air actively flushes the chips away from the cutting zone. Beyond chip removal, the compressed air facilitates the transport of lubricant particles, enhances cooling, and improves overall machining efficiency. The high-pressure jet of cutting fluid, composed of finely atomized oil droplets, effectively minimizes friction between the chip and the rake face, contributing to smoother operations and extended tool life [9]. The advantages of MQL include decreased cutting fluid consumption, cost-effectiveness, enhanced cutting operation performance, and improved surface quality [10-14]. To improve the efficiency of the MQL technique, it is essential to ensure that the lubricant effectively envelops critical contact areas such as tooltips and tool interfaces [15]. Additionally, the stability of the lubricant in thermal and chemical conditions, along with the wettability of the tool material, can impact the cutting performance [16; 17]. Using the MQL method for drilling can result in enhanced surface morphologies and reducing drill wear [18; 19]. Li and Wu [20] evaluated the process of drilling under dry and MQL techniques. They found that MQL can considerably reduce cutting loads and tool wear, as well as decreased thrust force and torque. Xu et al. [21] investigated the performance of MQL technique in the drilling process of Ti6Al4V. The findings revealed that MQL offers benefits such as enhancing the quality of the hole's surface, decreasing drill wear, and lowering drilling pressure. Pal et al. [22] compared the usage of different vegetable oils during the drilling of stainless steel using MQL technology. The results showed that in drilling under MQL conditions, particularly when using sunflower oil, enhanced lubrication, and superior drilling performance were attained compared to dry and flood conditions and demonstrated the best performance in reducing surface roughness, torque, thrust force, and friction coefficient. Khunt et al. [23] also mentioned that using vegetable-based MQL effectively reduced thrust force and torque at high speeds by improving cooling and lubrication at the tool-work interface. Dry drilling resulted in the highest thrust force and torque, followed by flood cooling, while MQL showed the lowest surface roughness due to decreased friction coefficient and smoother chip flow.

Nanofluids are created by dispersing nanoparticles (smaller than 100 nm) in a base fluid such as oil or water [24]. Nanoparticles like aluminum oxide (Al_2O_3), boron nitride (BN), carbon nanotubes, molybdenum disulfide (MoS_2), CuO, graphite nanoplatelets, and diamond are known for their exceptional tribological and thermal characteristics, and they enhance the thermal conductivity, viscosity, and lubricating properties of the MQL method [25]. One of the key features of nanomaterials is their high surface-to-volume ratio, which provides unique capabilities [26]. The concentration of nanoparticles has a significant impact on lubrication properties. Higher concentrations can enhance thermal conductivity and improve heat dissipation capabilities. However, they may also increase the fluid's viscosity, potentially leading to flow restrictions [27]. The use of hybrid nanofluids can enhance heat transfer properties compared to unitary nanofluids [28]. Hybrid nanofluids have been shown to reduce the tool wear rate, cutting force, and cutting zone temperature [29]. Hybrid nanofluids can offer synergistic effects, enhancing lubrication and cooling performance. By carefully adjusting both the concentration of these hybrid nanoparticles and the flow rate of the nanofluid, manufacturers can tailor the lubrication properties to meet specific machining requirements, ultimately improving tool life and surface finish quality [29-31].

In research conducted by Mosleh et al. [32] on the impact of MQL application with MoS_2 and hBN nanoparticles on drilling processes, it was found that MQL with nanofluids yielded lower surface temperatures and less variation in frictional torques. Jamil et al. [33] demonstrated the potential of hybrid nanofluids to enhance machining performance. They investigated the use of a hybrid nanofluid containing both Al_2O_3 and MWCNTs to improve surface quality, lower energy consumption, and increase the material removal rate. They observed a significant reduction in surface roughness, which was attributed to the formation of a protective tribo-film at the tool-workpiece interface, facilitated by the ball-bearing and rolling effects of the nanoparticles. Thakur et al. [34] conducted turning operations on titanium-based alloys using hybrid nanofluids (Al_2O_3 and CuO). Significant improvements were observed in output parameters, including surface roughness, tool wear, cutting temperature, and cutting forces. In another study conducted by Sharma et al. [35], the effect of alumina nanoparticles dispersed in water on MQL in turning operations was investigated. The study found that adding Al_2O_3 nanofluid resulted in a significant decrease in cutting forces, tool wear, and surface roughness compared to traditional MQL methods, thereby improving the lubrication properties of nanofluids. Pal et al. [36] conducted research on using MQL with Al_2O_3-mixed vegetable-oil-based cutting fluid during the drilling process of AISI 321 stainless steel. The results indicated that the optimal MQL could decrease the thrust force, torque, and tool wear. Tiwari et al. [37] investigated the effectiveness of coconut oil enriched with Al_2O_3 nanoparticles in MQL-assisted machining of AISI-1040 steel. Their findings revealed that using nanofluid significantly decreased cutting temperature, tool wear, and tool vibration, while increasing tool life and resulting in improved surface finish quality.

From previous research, it was found that the design and positioning of nozzles are critical factors in MQL performance. Several factors, including nozzle properties, lubricant characteristics, and application parameters, can affect the performance of the MQL technique. The improved nozzle configuration ensures effective penetration of the lubricant [38]. The type and properties of the lubricant also play a significant role; factors such as viscosity, thermal stability, and biodegradability affect its ability to reduce wear and dissipate heat [39]. Additionally, the flow rate and droplet size of the lubricant affect its distribution and performance during machining [40; 41]. The nozzle geometry is a critical factor in the efficiency of the MQL system. It determines the size, distribution, and spray pattern of the cutting fluid droplets, which directly impact lubrication, cooling, chip removal, and overall machining performance. An optimized nozzle design ensures the system operates at peak efficiency, reducing tool wear, energy consumption, and operational costs [42]. Rana et al. [6] investigated the effect of nozzle parameters in the milling process of AISI 52,100 alloy steel using multi response optimization and found a better nozzle position for the MQL technique. They concluded that the optimization of nozzle MQL parameters can reduce surface roughness and temperature. Proper integration of these factors is essential for maximizing MQL performance and achieving sustainable machining outcomes. Zaman and Dhar [43] investigated the optimization of nozzle parameters in the MQL system, particularly when using two nozzles. Their findings showed that nozzle angle had the greatest influence on temperature reduction, while nozzle diameter significantly decreased surface roughness. Zhu et al. [44] also studied the effect of nozzle distance in the milling process and found that a short distance of 25 mm resulted in poor lubrication, leading to higher cutting forces and increased surface roughness.

In contrast, at a high spindle speed of 6000 rpm, positioning the nozzle at an optimal distance of 75 mm significantly improved performance, reducing cutting forces and surface roughness by 20% and 16%, respectively. Optimizing machining processes is essential for maximizing economic efficiency and ensuring high-quality production in manufacturing industries. Enhancements in the NFMQL technique are vital for remaining competitive and environmentally sustainable. A review of the existing literature reveals that there have been few studies focused on the design and optimization of the lubrication techniques such as NFMQL.

This study aims to investigate the effect of two types of nanofluids in the MQL technique including unitary nanofluid (Al_2O_3) and hybrid nanofluid (Al_2O_3 and CuO), at a 1 wt% concentration in water, during the drilling process of aluminum alloy 6061-T6. The objective is to enhance lubrication performance by finding the better number of nozzles, nozzle geometry (nozzle cross-sections and nozzle outlet diameter). The thrust force, torque, and friction coefficient were measured, comparing the results with dry modes. The experiments were conducted using a full factorial design, with constant fluid flow and feed rate. The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method was utilized to identify the best experimental condition. This research contributes to the development of more efficient and environmentally friendly drilling practices, ultimately benefiting manufacturing industries focused on quality enhancement and sustainability. The overview of experimental stages of this study is outlined in Figure 1.

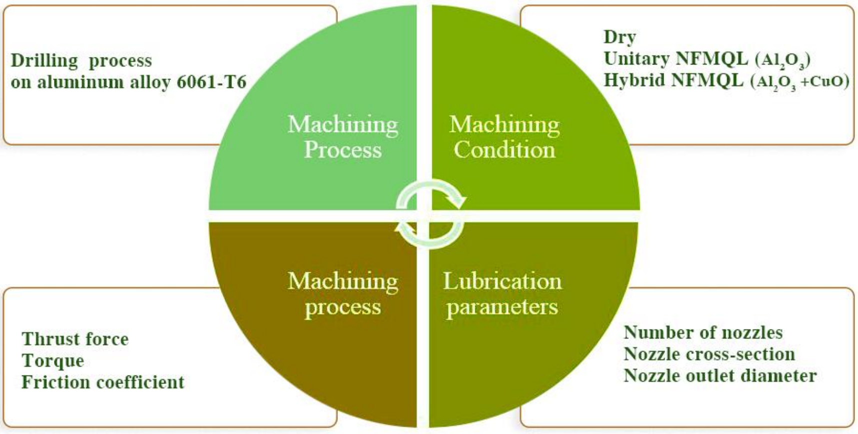


Figure 1. The overview of each stage for this study

Experimental method

The drilling process involved a high-speed steel drill (HSS) with a 10 mm diameter, a 118°point angle, a 37° helix angle, and a cobalt coating. The drill was used to create holes in aluminum alloy 6061-T6 parts measuring 30 × 100 × 30 mm. This alloy has good resistance to corrosion and for this reason, it is used in the aviation industry. The structural composition of aluminum alloy 6061-T6 and its physicochemical characteristics are detailed in Table 1. The drilling experiments were done at the spindle speed of up to 4000 rev/min.

Table 1. Chemical composition and mechanical properties of the workpiece

Aluminum alloy 6061-T6 chemical composition										
Elements	**Al**	**Mg**	**Si**	**Cu**	**Fe**	**Cr**	**Mn**	**Zn**	**Ti**	**Others**
Percentage	97	1.1	0.62	0.29	0.22	0.18	0.07	0.01	0.01	<0.5

Aluminum alloy 6061-T6 physical characteristics				
Density (g/cm^3)	**Hardness (HB/HRB/HRC)**	**Ultimate tensile strength (MPa)**	**Yield strength (MPa)**	**Elastic Modulus (GPa)**
2.7	95 (HB)	310	275	69
Ductility (%)	**Specific heat (J/kg·K)**	**Thermal coefficient of expansion (mm x $10^{-6/m}$)**	**Thermal conductivity (w/m.K)**	**Thermal diffusivity (10^{-5} m^2 /s)**
12 – 14	978.6	23.2	167	6.37

Figure 2 illustrates a sample of the drilled workpiece, which used as a holder for securing copper busbars used in medium-voltage power transmission.

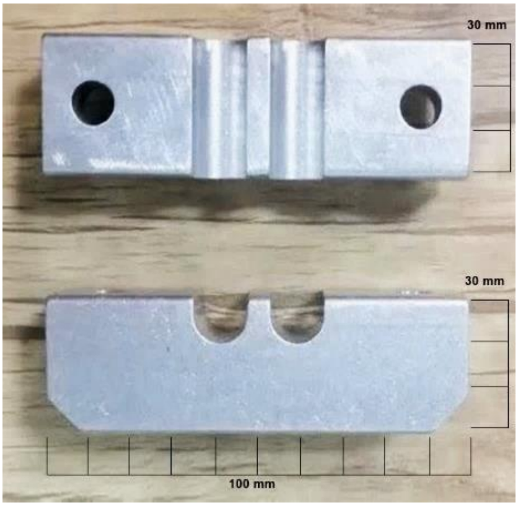


Figure 2. A sample of manufactured aluminum alloy 6061-T6 part

This study investigated the effectiveness of NFMQL in the drilling process of the aluminum alloy 6061-T6 workpieces. The FRL machine model AL3000 MQL system, manufactured in China, was utilized to atomize the cutting fluid and mix it with compressed air. The system includes a high-pressure air compressor, a cutting fluid reservoir, an atomizing chamber, and four-channel conversion system to transfer the cutting fluid to the nozzles. The nozzles were positioned at 30º angle to the tool, with the distance of 55 mm from the workpiece. To accurately position the nozzles at the desired distances, sheet metal holders were designed in SolidWorks and manufactured. The different components of the MQL system are illustrated in Figure 3.

The lubricant was transported from the upper chamber of the FRL unit to the nozzles via a pump connected by a small-diameter air hose. Additionally, a four-channel system was employed to distribute the lubricant evenly in four directions around the tool. The atomization process in the MQL system involved high-velocity airflow that broke down the cutting fluid into fine droplets. The droplet size and distribution were influenced by the air pressure and the flow rate. The flow rate could be adjusted by modifying the output power. Both air and lubricant entered the atomizing chamber separately, with the airflow rate being significantly higher than the lubricant flow rate. This ensured that the lubricant droplets were transformed into fine particles and propelled by the carrier gas as they exited the nozzles. The specific MQL system settings used in this study are outlined in Table 2.

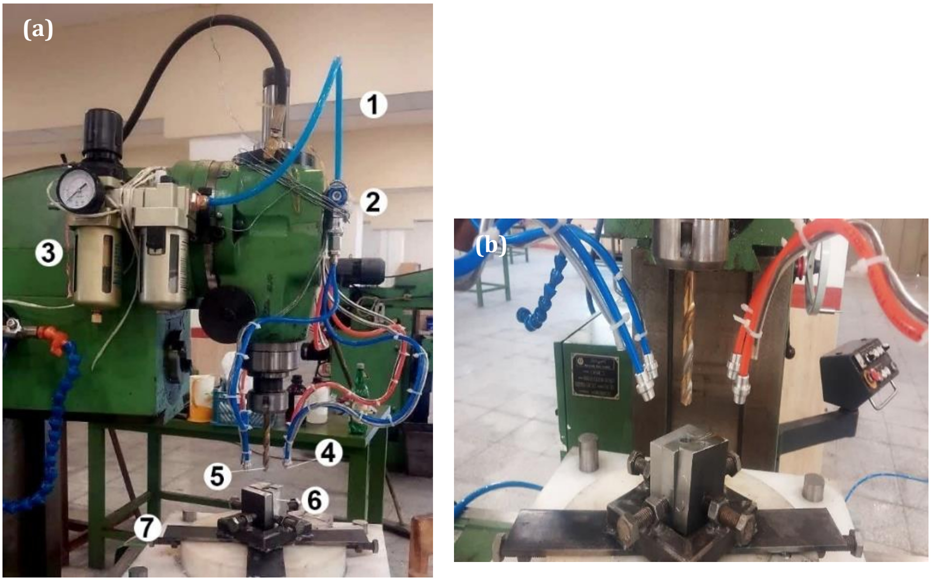


Figure 3. (a) The MQL setup on the milling machine (1. Air and fluid transmission hose, 2. Four-channel conversion of fluid and air transfer, 3. Minimum lubrication care unit, 4. Fluid transfer nozzles, 5. Tool, 6. CK45 workpiece, 7. Dynamometer), (b) The position of nozzles to the workpiece

Table 2. Specifications of the MQL system

Parameter	Value
Wind pressure	8 bars
Fluid flow rate	120 ml/h
Nozzle-tool angle	30º
Nozzle-workpiece distance	55 mm
Applied location of the lubricant	Surface of tool
Fluid spraying method	External

The main objective of this study was to enhance the performance of the MQL system by increasing the number of nozzles, determining the effective nozzle geometry, and utilizing the appropriate nanofluids. The MQL parameter investigated in this study are detailed in Table 3. To improve lubrication efficiency, three distinct cross-sectional shapes (circular, square, and rectangular) with different outlet diameters (0.5 mm, 1 mm, and 1.5 mm) were investigated, as shown in Figure 4, which depicts the design of the nozzles. Figure 5 illustrates the various number of nozzles examined in this study. Prior to the experiment, the FRL system was activated, and the nozzle tips were placed into a laboratory beaker. The fluid output was measured after one minute. This step verified the proper operation of the FRL and ensured the accuracy of the flow rate. The effectiveness of each configuration was evaluated based on its impact on thrust force, torque, and friction coefficient.

Table 3. The MQL parameters investigated in this study

Parameter	Level 1	Level 2	Level 3	Level 4
Number of nozzles	1	2	3	4
Nozzle cross-section	circle	rectangle	square	-
Nozzle outlet diameter (mm)	0.5	1	1.5	2
Type of lubricant	Unitary nanofluid (Al_2O_3)	Hybrid nanofluid (Al_2O_3 + CuO)	-	-

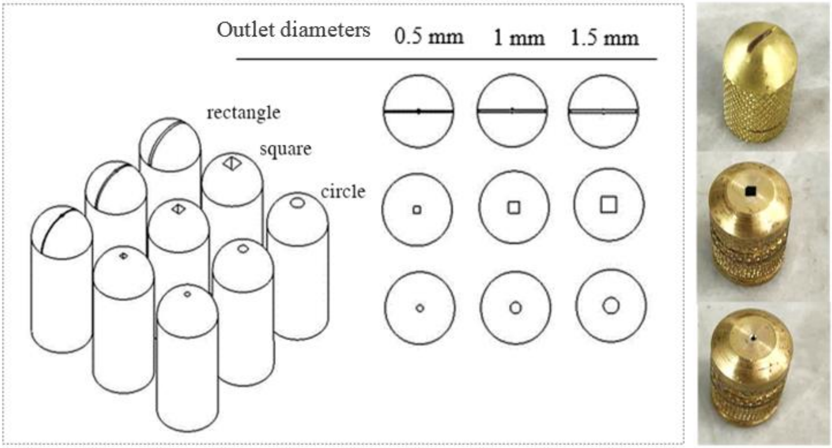


Figure 4. **The design of different nozzle geometries with different cross-sections and outlet diameter**

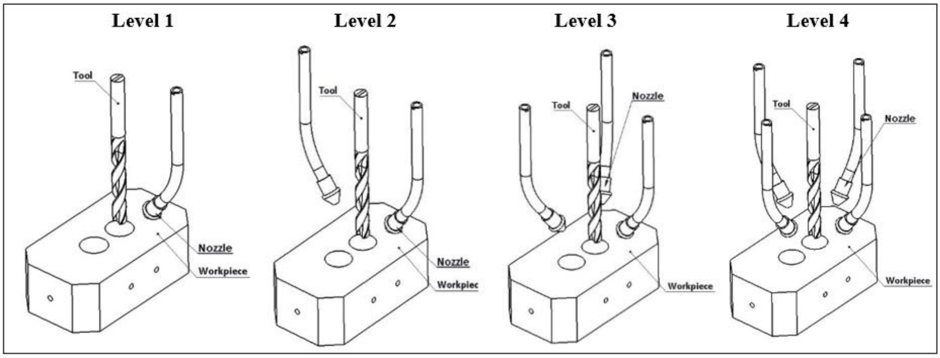


Figure 5. **The schematic of the various number and positions of the nozzles into the workpiece**

Combining different nanofluids to create hybrid nanofluids is a crucial step in enhancing lubrication performance. This process involves dispersing nanoparticles of two or more distinct materials within a base fluid. The synergistic effect of these diverse nanoparticles leads to improved thermal conductivity and heat transfer characteristics compared to single-nanofluid systems. The unique properties of each nanoparticle, such as size, shape, and material composition, contribute to enhanced thermal conductivity, reduced viscosity, and improved stability. By strategically combining these nanoparticles, hybrid nanofluids achieve a superior balance of properties, resulting in significantly enhanced heat transfer rates and overall thermal performance [45; 46].

In the present study, two-step method was utilized for the preparation of nanofluid. Nanofluids are obtained by mixing 99% pure cupric oxide (CuO) which had an average crystal size of 10-20 nm, and 99% pure aluminum oxide (Al_2O_3) nanoparticles, which had an average particle size of 10-30 nm. The high purity of the nanoparticles ensured minimal impurities that could affect the performance of the cutting fluid. It had been reported before that biodegradable hybrid nanofluids with CuO and Al_2O_3 (50:50) combination produces better properties for nanofluids and, hence, better machining performance [33]. The unitary Al_2O_3 nanofluid is obtained by mixing Al_2O_3 nanoparticles with a concentration of 1%wt and hybrid nanofluid (Al_2O_3/CuO) were suspended in base fluid in a 50:50 ratio with a 1%wt concentration. The multi-step homogenization process to ensure a well-dispersed and stable hybrid nanofluid. This process includes mechanical stirring (20 minutes), magnetic stirring (20 minutes), probe sonication (30 minutes), and a 10-minute settling period to remove air bubbles. The multi-step approach is crucial to minimize particle agglomeration and sedimentation, which can negatively impact performance. The thermal properties of the synthesized nanofluids are presented in Table 4.

Table 4. The thermal characteristics of different type of nanofluids [47; 48]

Nanofluid	Density (kg/m^3)	Thermal conductivity (w/m.K)	Specific heat (kJ/kg.K)
Al_2O_3	3970	17.65	0.525
CuO	6500	20	0.536

The response parameters including thrust force, torque, and friction coefficient were investigated with different numbers of nozzles, various nozzle cross-sections and outlet diameters, and types of lubrication, while machining environments were kept constant during the drilling process. Experimental trials were conducted using the full factorial design for the MQL (96 experiments), with additional tests carried out in dry conditions for comparative analysis. Each experiment was replicated three times to ensure data validity. After conducting the experiments, the results were analyzed using ANOVA. This analysis determined the influence of each input parameter on the drilling process.

A dynamometer was used to measure thrust force and torque during the drilling process of 200 operations. This dynamometer could measure thrust force in the X and Y axes from -20 to +20 kilonewtons and in the Z axis from -10 to +60 kilonewtons. After tightening and calibrating the dynamometer device, two values of thrust force (entered in the vertical direction) and torque (caused by thrust force) were measured simultaneously during the drilling operation. Also, a friction tester was also used to measure the friction coefficient. To examine the final quality of drilled workpiece, a scanning electron microscope (SEM) was utilized. In the last stage of research, the multi-objective optimization of lubrication parameters is expressed through the TOPSIS approach. The input parameters and output response values have been transferred to the standard formula of the TOPSIS method and the best and the worst test modes are determined.

Result and discussion

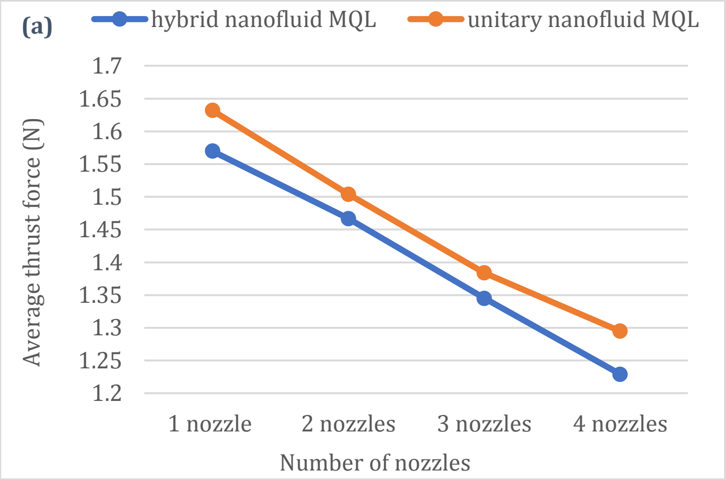
Effect of type of lubrication

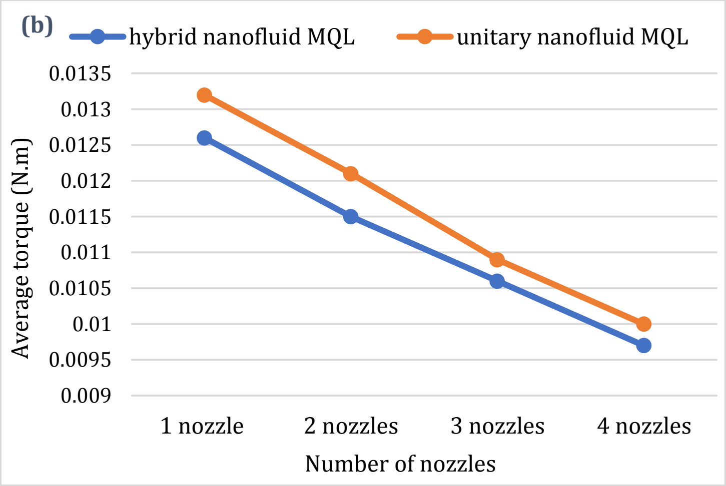
Monitoring force and torque during machining is crucial for optimizing tool life, energy efficiency, and surface quality. High forces can lead to tool wear and instability, and analyzing these parameters essential for enhancing performance [49; 50]. This study explores the effects of hybrid and unitary nanofluids under identical experimental conditions, as well as the impact of the number of nozzles and their geometry in the MQL process. The primary goal of this study is to improve the performance of the MQL system by using Al_2O_3 and CuO nanofluids while minimizing thrust force, torque, and friction coefficient during drilling. Table 5 presents the drilling performance results under dry conditions, and Figure 6 illustrates how lubricant type affects the MQL system with different nozzle configurations. Experimental results indicate that both hybrid nanofluids (Al_2O_3 + CuO) and unitary nanofluids (Al_2O_3) significantly reduce average thrust force, torque, and friction coefficient when compared to dry machining. Notably, hybrid nanofluids consistently outperform unitary nanofluids across all tested conditions.

As illustrated in Figure 6, using hybrid nanofluids in the MQL system with four nozzles resulted in reductions of 51% in thrust force, 56% in torque, and 60% in the friction coefficient compared to dry machining. The application of high-pressure air in the MQL system not only enhances lubrication but also reduces the friction coefficient on the machined surface compared to dry conditions. Furthermore, the high-pressure jet system integrated into MQL plays a crucial role in improving lubrication effectiveness and facilitating efficient chip evacuation during drilling operations [51]. In addition to the advantages of MQL over dry machining, the incorporation of nanofluids further advanced lubrication performance. CuO nanofluid exhibits superior thermal conductivity properties compared to Al_2O_3. The addition of CuO to Al_2O_3 nanoparticles was done to improve heat transfer characteristics, which is essential for enhancing machining performance. As Lotfi et al. [52] found that using hybrid nanofluids (Al_2O_3 + CuO) is the most sustainable approach to improve machining processes. They also mentioned that using hybrid nanofluid reduced cutting forces, surface roughness, microhardness by 46.5%, 61.2%, and 6.6%, respectively, while yielding better surface finish and topography. However, before using hybrid nanofluids, it is important to create a stable and well-mixed suspension, as this directly affects lubrication and heat transfer performance [53].

Table 5. **The average values during the drilling process in dry condition**

Thrust force (N)	Torque (N.m)	Friction coefficient
2.49	0.022	0.0097





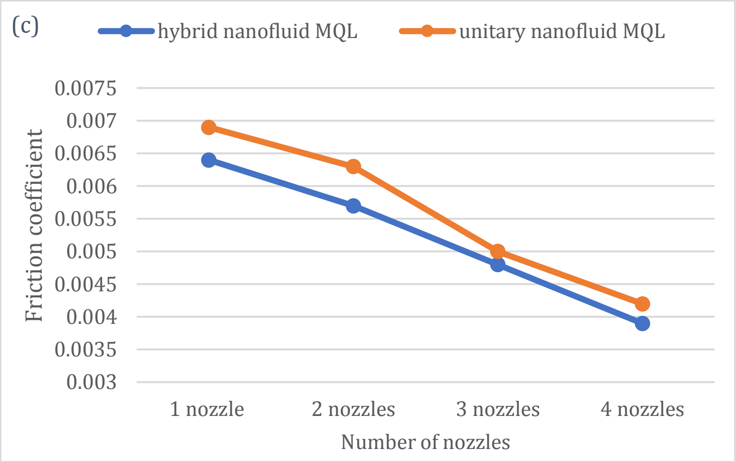


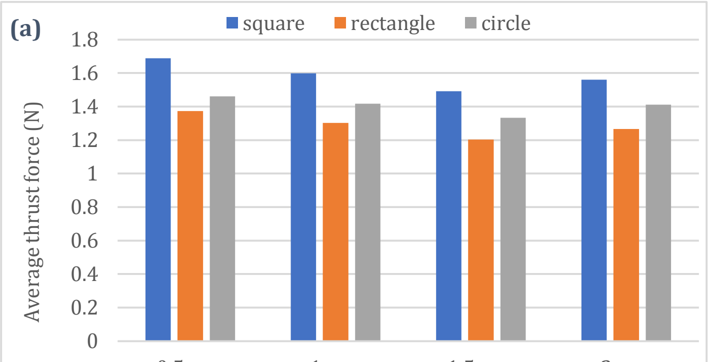
Figure 6. **Comparison of (a) average thrust force, (b) torque, and (c) friction coefficient values during drilling operations using unitary nanofluid (Al_2O_3) and hybrid nanofluid (Al_2O_3+CuO) in the MQL**

Effect of number of nozzles

One important factor in the drilling process is the method of applying cutting fluid at the workpiece-tool interface. In the study by Zaman and Dhar [43], using double nozzle in the MQL system improved its efficiency, leading to the significant reduction in cutting temperature, surface roughness, cutting force, and tool wears, compared to the dry conditions in turning operations. Similarly, another study by Cönger et al. [54] acknowledged using multiple nozzles in the NFMQL system. The findings of this study indicate that increasing the number of nozzles from one to two improved machining response and sustainability indicators. These results align with the findings of Mallick et al [55], who reported a reduction in the cutting power, cutting temperature, flank wear, and surface roughness using dual nozzles instead of single nozzle in the MQL system. According to recent literature, no studies have been conducted to investigate the effect of using four nozzles in the NFMQL system on thrust force and torque in machining. Experimental findings shown in Figure 6 reveal that thrust force, torque, and friction coefficient decreased by applying four nozzles instead of one in both types of NFMQL. Utilizing four nozzles in the NFMQL enhances the distribution of the lubricant, ensuring more effective cooling and lubrication at the cutting interface. This improved nanofluid delivery reduces friction and thermal buildup, leading to a 22%, 23%, and 38% decrease in thrust force, torque, and friction coefficient, respectively, when using hybrid nanofluids. This highlights the importance of improving MQL technique to achieve optimal results in green engineering within the manufacturing industries.

Effect of nozzle geometry and outlet diameter

Recent research into the MQL technique has highlighted a significant gap in understanding the influence of nozzle geometry and outlet size on the drilling process, particularly in multi-nozzle systems. Optimizing these parameters is crucial for enhancing lubrication efficiency, reducing forces, and improving tool life. To address this gap, the investigation was conducted on three different nozzle cross-sections (circular, rectangular, and square) while varying outlet diameters. The results, as presented in Figure 7, show that the use of rectangular nozzles with a droplet size of 1.5 mm resulted in the most significant reductions in machining forces. Compared to square nozzles, using the rectangular nozzles with the outlet diameter of 1.5 mm led to a 29% reduction in thrust force, a 39% decrease in torque, and a 43% decrease in the friction coefficient. The improved performance of rectangular nozzles is mainly attributed to their ability to create a wider spray pattern, which ensures a more uniform distribution of lubricant at the tool-workpiece interface [56]. Additionally, the internal design of the nozzle significantly impacts lubrication efficiency. Nozzles with smooth internal surfaces facilitate laminar flow, resulting in more effective atomization and delivery of the lubricant. In contrast, nozzles with sharp internal edges can create turbulence, which adversely affects the consistency of droplet size and overall spray efficiency [57]. Another important factor influencing MQL performance is the outlet diameter of the nozzle. An effective designed outlet ensures the formation of a fine lubricant mist, which enhances lubrication coverage, prevents premature evaporation of the lubricant, and maintains consistent cooling throughout the drilling process. These observations are supported by a study conducted by Abiyari and Abootorabi [58], which demonstrated that the rectangular cross-section of the nozzle enhanced lubricant coverage, leading to reduced temperatures and improved surface quality in the grinding. Furthermore, it was observed that using an outlet size of 1.2 mm resulted in a greater reduction in temperature. Increasing the nozzle outlet diameter from 1.5 mm to 2 mm can reduce MQL efficiency by lowering spray pressure, producing larger droplets with weaker penetration into the tool-workpiece interface. The larger nozzle may cause turbulence, disrupting droplet uniformity and spray consistency. In contrast, a 1.5 mm nozzle maintains a better balance of pressure, droplet size, and spray coverage, ensuring optimal lubrication performance.



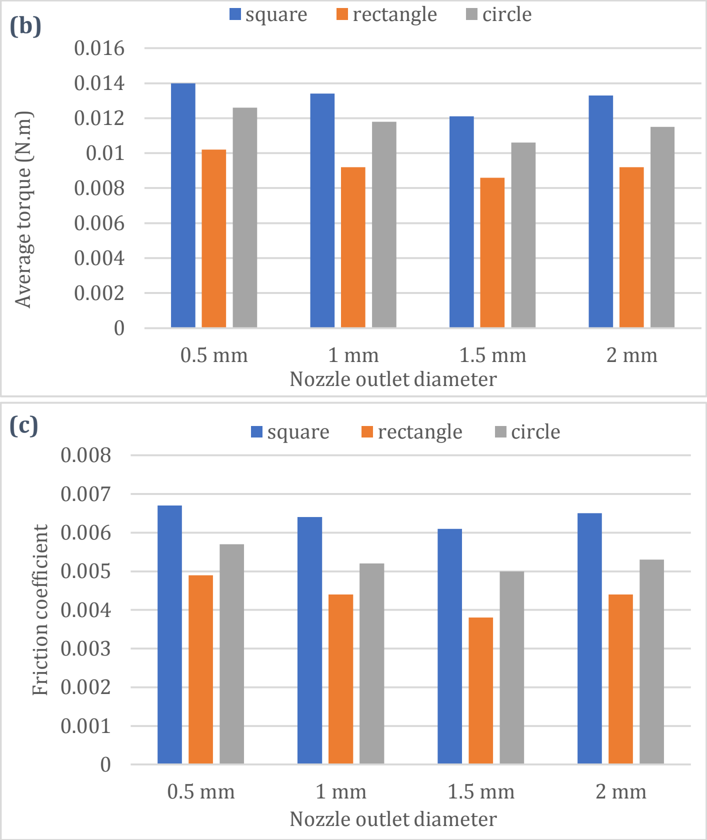


Figure 7. Comparison of (a) average thrust force, (b) torque, and (c) friction coefficient values during drilling operations with different nozzle cross-sections and outlet diameters in the MQL

Analysis of variance (ANOVA analysis)

Effect of input parameters on thrust force

According to the analysis of variance table and the sig statistic in Table 6, it is concluded that the independent variables (type of lubrication, nozzle cross-section, nozzle outlet diameter, and number of nozzles) have the significant effects on the dependent variable (thrust force). Based on the coefficients of the model, number of nozzles and nozzle outlet diameter exhibit an inverse relationship with the thrust force. This means that by increasing these variables, the thrust force decreases. Additionally, number of nozzles has the most significant effect on thrust force, based on the highest F value, as mentioned in this table.

Table 6. Analysis variance of ANOVA of thrust force values

Model	Sum of square	df	Mean square	F	sig
Regression	77.943	8	9.743	46.941	.000
Residual	18.057	87	.208		
Total	96.000	95			

Coefficients

Model	Beta	Std. Error	F	sig
Type of lubrication	0.149	0.050	8.766	.000
Nozzle cross-section	0.559	0.046	149.755	.000
Nozzle outlet diameter	-0.262	0.050	27.737	<0.001
Number of nozzles	-0.639	0.054	139.728	.000

Effect of input parameters on torque

According to the analysis of variance table and the sig statistic in Table 7, it is concluded that the independent variables (type of lubrication, nozzle geometry, nozzle outlet diameter, and number of nozzles) have the significant effects on the dependent variable (torque). Based on the coefficients of the model, number of nozzles and nozzle outlet diameter exhibit an inverse relationship with the torque. This means that by increasing these variables, the torque decreases. Additionally, nozzle outlet has the less significant effect on torque, based on the less F value, as mentioned in this table.

Table 7. Analysis variance of ANOVA of torque values

Model	Sum of square	df	Mean square	F	sig
Regression	68.556	9	7.617	23.870	.000
Residual	27.444	86	0.319		
Total	96.000	95			

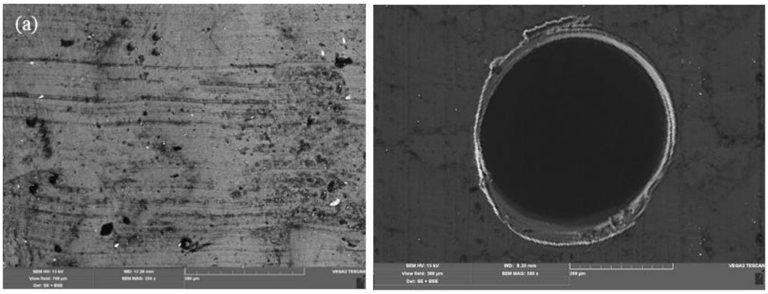
Coefficients

Model	Beta	Std. Error	F	sig
Type of lubrication	0.105	0.044	0.69	.000
Nozzle geometry	0.610	0.045	.068	.000
Nozzle outlet diameter	-0.266	0.068	0.045	0.002
Number of nozzles	-0.510	0.056	.056	.000

Quality of surface finish

The quality of drilled holes can be significantly impacted by the lubrication method used during the drilling process. During the drilling process, cutting fluid lubrication is used to cool the bit, which increases tool life, increases feeds, and speeds, aids in removing solid material chips, and also makes the surface finish improved [39]. For this application, the workpiece is dipped in lubricant or coolant after spraying mist. Further NFMQL resulted in the better surface quality of holes by eliminating burrs and chips, and tool life would be increased because of the lowest tool wear. Additionally, Compressed air in the MQL technique can result in the formation of burrs around the circumference of the hole, which can affect the overall precision and smoothness of the hole. However, there may still be some residual burrs present.

As shown in Figure 8, hybrid NFMQL has been shown to produce the highest quality drilled holes. By incorporating hybrid nanofluid (Al_2O_3+CuO), NFMQL minimizes burr formation and results in smoother and more precise holes. The circularity error of holes drilled using NFMQL was measured to be the smallest compared to dry conditions, indicating superior quality and precision. After examining the inner surface of the hole, small cracks were observed, indicating residual stress in the workpiece. These cracks were more noticeable in the dry state and less pronounced when using hybrid nanofluid in MQL. Using four nozzles in MQL hybrid nanofluid (Al_2O_3+CuO) improved the quality of the hole better, than unitary nanofluid, which also affected the fatigue life and surface roughness of the workpiece. This reduction can be associated with the comprehensive cooling effect on the tool, which helps reduce heat generation and diminish friction, leading to the less surface roughness [59], enhancing the quality of drilled holes by decreasing burrs and enhancing precision. This innovative lubrication method holds promise for achieving high-quality results in drilling applications.



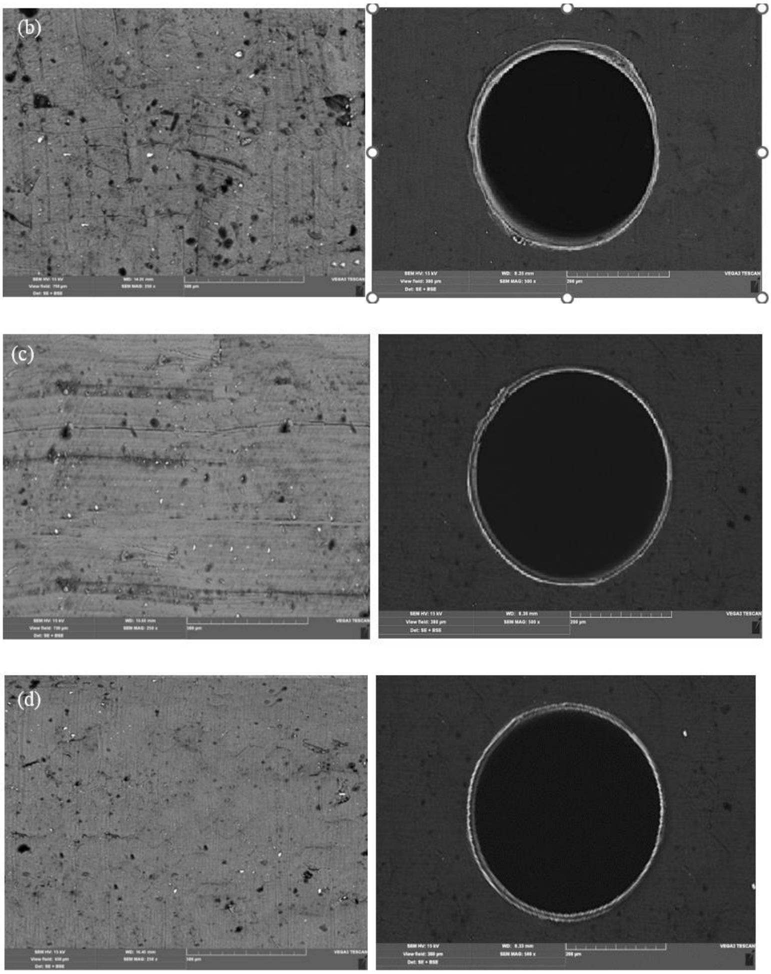


Figure 8. SEM images of inner surface quality of drilled hole in the dry (a), unitary nanofluid MQL with one nozzle(b), hybrid nanofluid MQL with 1 nozzle (c), and hybrid nanofluid MQL with 4 nozzles (d)

Multi-criteria optimization

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is a widely used multi-criteria decision-making (MCDM) method for ranking alternatives based on their proximity to ideal solutions. Developed by Hwang and Yoon, TOPSIS leverages the concept of ideal and negative-ideal solutions to assess the performance of each alternative relative to the best and worst possible scenarios across multiple criteria. TOPSIS identifies two hypothetical solutions: the Positive Ideal Solution (PIS) and the Negative Ideal Solution (NIS). The PIS represents the optimal outcome for each criterion, maximizing benefits and minimizing costs, while the NIS represents the worst possible outcome, maximizing costs and minimizing benefits [60]. The ranking process involves normalizing raw data to eliminate scale differences between criteria, assigning weights to each criterion based on their relative importance, and calculating Euclidean distances for each alternative from both the PIS and NIS. A similarity index is then calculated, representing how close an alternative is to the PIS compared to the NIS. Alternatives are ranked based on these similarity indices, with higher values indicating better performance. TOPSIS offers several advantages, including its simplicity, intuitive nature, and ability to consider all criteria simultaneously. It is also flexible and can be adapted to various decision-making problems [61; 62]. Applications of TOPSIS extend across diverse fields, including engineering, finance, and supply chain management [63].

This study presents the TOPSIS method, a multi-criteria decision-making technique employed to rank the different NFMQL strategies. It includes 96 experiments based on thrust force, torque, and friction coefficient values. A crucial step in effectively employing the TOPSIS method involves establishing weighted efficiency distributions for each criterion. The efficiency distribution can be assigned uniformly across all outcomes or determined by the researcher through their expertise or mathematical equations. In this study, the equations presented by Ghalme and Karolczak [64] were used to calculate the efficiency distributions. This research utilizes the entropy method to calculate these weights. Shannon entropy is a measure of uncertainty or randomness in a set of data. In this context, it is used to quantify the uncertainty associated with the performance of each NFMQL strategy across the different criteria. The distributions of the results' weighted efficiencies were determined as 0.162, 0.295, and 0.543 for thrust force, torque, and friction coefficient, respectively. Following the computation of the outcomes' weighted efficiency distributions, the TOPSIS decision-making method is applied. Table 8 displays 10 cases of the best conditions evaluated for the experiments, while Table 9 shows 10 cases of the worst situations evaluated. The results presented in Tables 8 and 9 indicate that the closer the closeness coefficient is to 1, the more optimal the test performance. Conversely, a closeness coefficient closer to 0 signifies poorer test results. The most optimal configuration was achieved with four nozzles with rectangular cross-sections and outlet diameters of 1.5 mm in the NFMQL mode with hybrid nanofluid. In contrast, the least effective test configuration occurred with one nozzle with square cross-section and outlet diameter of 0.5 mm, in NFMQL mode with unitary nanofluid.

Table 8. Ranking the most optimal lubrication parameters for the drilling process

Run.	Type of lubrication	Number of nozzles	Nozzle geometry	Nozzle outlet diameter (mm)	Closeness coefficient	Ranking
44	**hybrid NFMQL**	**4**	**rectangle**	**1.5**	**0.99979**	**1**
92	unitary NFMQL	4	rectangle	1.5	0.95136	2
91	unitary NFMQL	3	rectangle	1.5	0.93203	3
43	hybrid NFMQL	3	rectangle	1.5	0.92780	4
96	unitary NFMQL	4	rectangle	2	0.91319	5
40	hybrid NFMQL	4	rectangle	1	0.88249	6
48	hybrid NFMQL	4	rectangle	2	0.87712	7
95	unitary NFMQL	3	rectangle	2	0.87707	8
88	unitary NFMQL	4	rectangle	1	0.87083	9
84	unitary NFMQL	4	rectangle	0.5	0.86357	10

Table 9. Ranking of the worst lubrication parameters for the drilling process

Run.	Type of lubrication	Number of nozzles	Nozzle geometry	Nozzle outlet diameter (mm)	Closeness coefficient	Ranking
49	unitary NFMQL	**1**	**square**	**0.5**	**0.00012**	**1**
50	unitary NFMQL	2	square	0.5	0.07343	2
53	unitary NFMQL	1	square	1	0.10024	3
1	hybrid NFMQL	1	square	0.5	0.18451	4
2	hybrid NFMQL	2	square	0.5	0.19414	5
61	unitary NFMQL	1	square	2	0.19668	6
13	hybrid NFMQL	1	square	2	0.25946	7
5	hybrid NFMQL	1	square	1	0.26998	8
54	unitary NFMQL	2	square	1	0.27266	9
57	unitary NFMQL	1	square	1.5	0.30125	10

Conclusion

This study investigated the performance enhancement of MQL systems in drilling operations through the application of hybrid nanofluids (Al_2O_3 + CuO) and optimization of nozzle configurations. The primary objective was to minimize thrust force, torque, and friction coefficient while improving surface quality and process sustainability. Key findings and their implications are summarized as follows:

- Hybrid nanofluids consistently outperformed unitary nanofluids (Al_2O_3), achieving reductions of 51% in thrust force, 56% in torque, and 42% in friction coefficient compared to dry machining. The synergistic combination of Al_2O_3 and CuO nanoparticles enhanced thermal conductivity and lubrication efficiency, aligning with sustainable machining goals by reducing tool wear and energy consumption.

- Increasing the number of nozzles from one to four significantly improved lubricant distribution, reducing thrust force, torque, and friction coefficient by 22%, 23%, and 38%, respectively, with hybrid nanofluids. Rectangular nozzles with a 1.5 mm outlet diameter demonstrated improved performance, attributed to their wider spray pattern and laminar flow, which enhanced cooling and chip evacuation.

– ANOVA analysis confirmed the significant influence of nozzle geometry, number of nozzles, and outlet diameter on machining performance. The number of nozzles exhibited the strongest inverse correlation with thrust force (F-value = 139.728), emphasizing its critical role in MQL efficiency.

– Hybrid NFMQL produced superior surface finishes with minimal burrs, cracks, and circularity errors compared to dry machining. The integration of four nozzles further reduced residual stresses, improving fatigue life and workpiece precision.

– The TOPSIS method identified the optimal configuration as four rectangular nozzles (1.5 mm outlet) with hybrid nanofluid, highlighting the balance between lubrication efficiency and sustainability. These findings underscore the potential of hybrid nanofluids and improved MQL systems to advance green engineering practices in manufacturing.

Disclosure statement and funding

The authors declare no potential conflicts of interest. The present study received no financial support from any organization or institution.

Acknowledgment

The authors would like to thank Islamic Azad University of Yazd, Iran for supporting this research. This article is part of a PhD thesis in mechanical engineering, and the authors are grateful for the guidance and resources provided by this university.

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