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Research Paper

Evaluation of Minimum Quantity Lubrication with Four Nozzles Using Nanofluid and Analysis of Nozzle Geometry and Position Effects on Drilling Process by TOPSIS Method

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ABSTRACT

This study investigates the effect of various lubrication strategies, particularly minimum quantity lubrication (MQL), on temperature rise and surface roughness during the drilling process of CK45, aiming to enhance MQL parameters for improved machining performance. The study evaluates dry, flood, and MQL conditions using different lubricants, including Al_2O_3 nanofluid, CuO nanofluid, and palm oil. The MQL parameters such as nozzle geometry (circular, square, rectangular cross-sections), nozzle droplet size, nozzle angle, and nozzle distance were evaluated. Surface quality was also analyzed using scanning electron microscopy (SEM). The interaction of nozzle properties was assessed using ANOVA. Additionally, the optimal experimental conditions and alternatives were determined using the TOPSIS method. Experimental results revealed that Al_2O_3 nanofluid MQL reduced temperature and surface roughness by 42% and 48%, respectively, compared to flood lubrication, and by 56% and 54% compared to dry conditions. Rectangular nozzles outperformed circular and square ones, reducing temperature by 30%-38% and improving surface roughness by 31%-36%. The best conditions were identified as a 35-degree nozzle angle and 40 mm distance. SEM analysis confirmed that Al_2O_3 nanofluid minimized fine cracks and improved surface finish. This study highlights the importance of proper nozzle configuration, particularly in systems utilizing four nozzles, to increase lubrication efficiency.

Keywords: MQL; Temperature rise; Surface roughness; Nanofluid; Drilling process.

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1 INTRODUCTION

MACHINING, a fundamental manufacturing process, involves removing material from a workpiece using cutting tools to achieve precise shapes and dimensions [1, 2]. Common Operations include turning, milling, drilling, and shaping, with drilling being one of the most widely used techniques [3]. The specific energy required for chip formation during the drilling process is considerable when compared to other machining operations. This energy is dissipated as heat during drilling, which elevates the temperature at the tool-workpiece interface [4]. This significant temperature rise negatively impacts dimensional accuracy, as thermal expansion of the workpiece and tool can lead to deviations from the desired tolerances. Additionally, the elevated temperatures increase machining forces due to changes in material properties, such as reduced hardness and strength. Furthermore, excessive heat contributes to poor surface finish by causing material smearing, oxidation, or thermal damage to the machined surface [5-8]. Traditionally, metalworking fluids (MWFs) have been employed to mitigate this heat. Various cutting fluid techniques have been explored for drilling processes, including flood cooling, minimum quantity lubrication (MQL), and cryogenic coolants like liquid nitrogen and carbon dioxide. These methods generally reduce friction, minimize temperature rise, and decrease tool wear [9]. Among them, flood cooling is the conventional approach, relying on a large amount of coolant to dissipate heat during machining [10, 11]. However, excessive use of coolants presents serious environmental and health concerns, such as contamination of water bodies and soil, along with potential hazards to workers. Moreover, the disposal of used coolants further exacerbates environmental degradation [12-14].

In response to these concerns, the manufacturing industry is increasingly adopting more sustainable and environmentally friendly cooling methods. MQL has emerged as a promising alternative to flood cooling, offering significant advantages in terms of environmental impact, cost-effectiveness, and operational efficiency [15, 16]. MQL utilizes a minimal volume of lubricant, typically atomized within a pressurized airflow directed towards the machining zone [17-20]. With a flow rate as low as 10-100 ml/hour, this method drastically reduces the coolant consumption compared to flood cooling, while maintaining effective heat dissipation [21]. The efficiency of MQL depends on its high injection pressure, typically ranging from 2 to 8 bar, which ensures effective penetration of the cutting zone. This pressure enables the coolant to cool the cutting tool, evacuate chips, and protect the workpiece surface from damage [22-24]. Additionally, the resulting lubricating film reduces friction at the tool-workpiece and tool-chip interfaces, thereby minimizing temperature rise and improving cutting efficiency [25, 26].

To further enhance the cooling and lubrication capabilities of MQL, researchers have explored the integration of nanoparticles. Nanofluids, composed of nanoparticles suspended in a cutting fluid, leverage the exceptional thermophysical properties of nanoparticles to improve heat transfer and convection [27, 28]. Their large specific surface area contributes to enhanced cooling efficiency, making them a promising addition to MQL systems [29]. Integrating nanoparticles into MQL technique decreases the machining temperature, force, and improves surface quality comparing to other lubricants [30]. Nanofluid Minimum Quantity Lubrication (NFMQL) utilizes nanofluids, which are engineered suspensions of nanoparticles in a base fluid, to enhance both cooling and lubrication capabilities during machining. The presence of nanoparticles in the lubricant significantly impacts machining performance by improving heat dissipation and enhancing lubrication properties [31]. Jadam et al. [32] investigated the use of carbon nanotubes in rice bran oil during the machining of Ti6Al4V using NFMQL. Their findings indicated that NFMQL resulted in a 62.7% reduction in temperature increase and a 12.8% enhancement in surface roughness compared to dry machining. Furthermore, NFMQL led to a reduction of flank wear and cutting force by 42% and 8.69%, respectively. Ngoc et al. [33] found that employing NFMQL resulted in reduced tool wear, improved surface roughness, and extended tool life, showcasing its benefits in cooling and lubrication during hard turning operations. Tiwari et al. [34] assessed the efficacy of Al_2O_3 nanofluid MQL in the machining of AISI-1040 steel. Their results revealed that NFMQL significantly lowered tool wear, vibration, and cutting temperatures, while enhancing tool longevity and surface finish quality. Chaleshtari et al. [35] demonstrated that using CuO nanofluid in grinding Inconel 718 reduced surface roughness by 7% compared to MQL and 35% compared to dry grinding. Eltaggaz et al. [2] observed that NFMQL improved average surface roughness, cutting forces, and chip morphology when compared to pure MQL. In addition to traditional oil-based lubricants, water-based nanofluids (WBNFs) have emerged as an eco-friendly alternative for machining processes. WBNFs provide high lubrication and cooling rates, thereby reducing wear and enhancing edge integrity, contributing to a more sustainable machining environment [36].

Several factors, including nozzle properties, lubricant characteristics, and application parameters, can affect the performance of MQL technique. An optimal nozzle configuration ensures effective penetration of the lubricant [37]. The type and properties of the lubricant also play a significant role; factors such as viscosity, thermal stability, and biodegradability impact its ability to reduce wear and dissipate heat [38]. Additionally, the flow rate and droplet size of the lubricant affect its distribution and performance during machining [39, 40]. Proper integration of these factors is essential for maximizing MQL performance and achieving sustainable machining outcomes. Zaman and Dhar [41] 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. Rana et al. [42] analyzed nozzle angles (30°, 45°, 60°) and distances (20 mm, 40 mm, 60 mm) to optimize lubrication performance in the milling of AISI 52,100 alloy steel. Their findings identified the combination of a 45° angle and a 40 mm distance as the most optimal position, significantly reducing both temperature and surface roughness. Zhu et al. [43] 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 micro-lubrication techniques such as NFMQL. This study aims to investigate the application of palm oil and two nanofluids, Al_2O_3 and CuO, each at a 4 wt% concentration in water, as lubricants during the drilling of CK45 using the MQL technique. The primarily objective is to enhance lubrication performance by improving nozzle geometry, droplet size, and nozzle positioning to the workpiece. A key aspect of this research is the evaluation of nozzle parameters, particularly when a four-nozzle system is used in MQL to enhance lubrication efficiency. Four MQL nozzles were positioned in four directions of the tool to assess the effects of rectangular, circular, and square cross-sections geometry and droplet sizes. The effect of the nozzle angle and nozzle distance was also examined on temperature rise, surface roughness, and surface finish. Experimental results from MQL and NFMQL were compared against dry and flood conditions, with statistical analysis conducted using ANOVA. TOPSIS approach was used to determine the best MQL conditions and its alternatives. Temperature rise parameter was given special attention, as it significantly affects surface roughness and overall machining performance.

2 EXPERIMENTAL METHOD AND MATERIALS

2.1. MQL System Setup

This study examined the efficiency of MQL and NFMQL in the drilling process of the CK45 workpiece. The AL3000 FRL model, made in China, was utilized to deliver a precisely regulated mist of lubricant to the cutting zone, as shown in Figure 1. The system included a high-pressure air compressor, a cutting fluid reservoir, an atomizing chamber, and custom-engineered nozzle mounting fixtures. The lubricant was transported from the upper chamber of the FRL unit to the nozzles through a pump connected by a small-diameter air hose. Furthermore, a four-channel system was employed to distribute the lubricant in the four directions of the tool. The atomization process in the MQL system involved high-velocity airflow breaking the cutting fluid into fine droplets. The droplet size and distribution were influenced by air pressure and the cutting fluid flow rate. The lubricant flow rate could be adjusted by modifying the output power. 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 MQL system settings used in this study are outlined in Table 1.

To optimize lubrication efficiency, nozzle configurations were systematically varied. Three distinct cross-sectional shapes (circular, square, and rectangular) with different outlet sizes (0.5 mm, 1 mm, and 1.5 mm) were investigated, as shown in Figure 2, which depicts the design of the nozzles. For each configuration, four nozzles were positioned at 90-degree angles to the workpiece to ensure optimal fluid application. Figure 3 illustrates the various nozzle positions examined in this study. The effectiveness of each configuration was evaluated based on its impact on workpiece temperature, surface roughness, and overall drilling performance.

Table 1
Specifications of the MQL system

Parameter	Value
Number of nozzles	4
Fluid flow rate	120 ml/h
Applied location of the lubrication	Surface of tool
Wind pressure	8 bar
Fluid spraying method	External

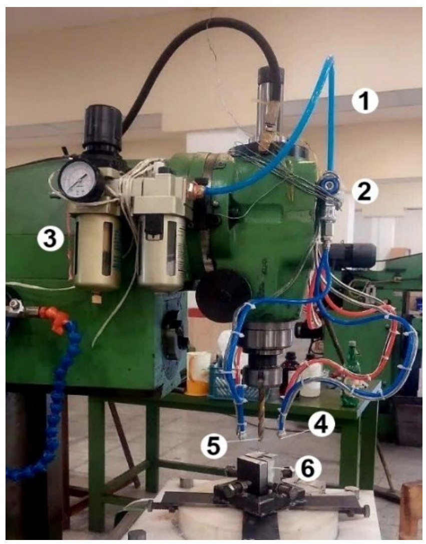


Fig. 1
MQL equipment setup on the milling machine (1- Air and fluid transmission hose, 2- Four-channel conversion of fluid and air transfer, 3- Minimum lubrication care unit, 4- Fluid transfer nozzles, 5- Tool, 6-CK45 workpiece).

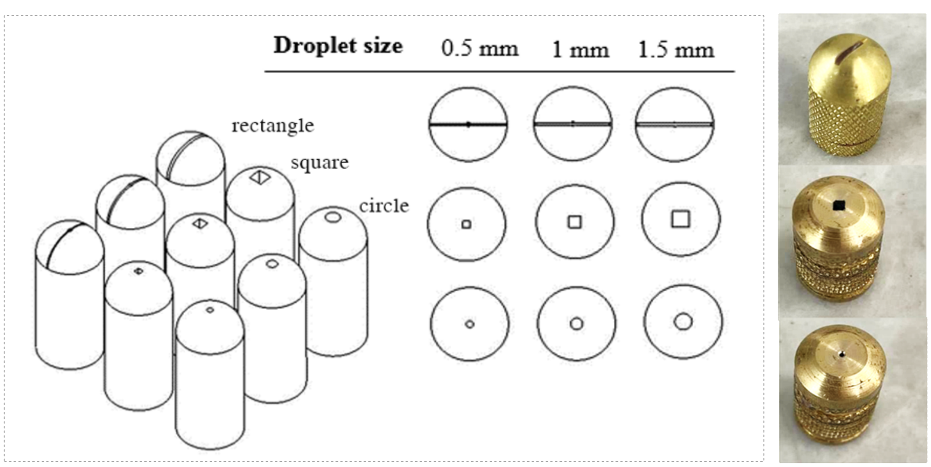


Fig. 2
The schematic of different nozzle geometries and the sample of designed nozzles.

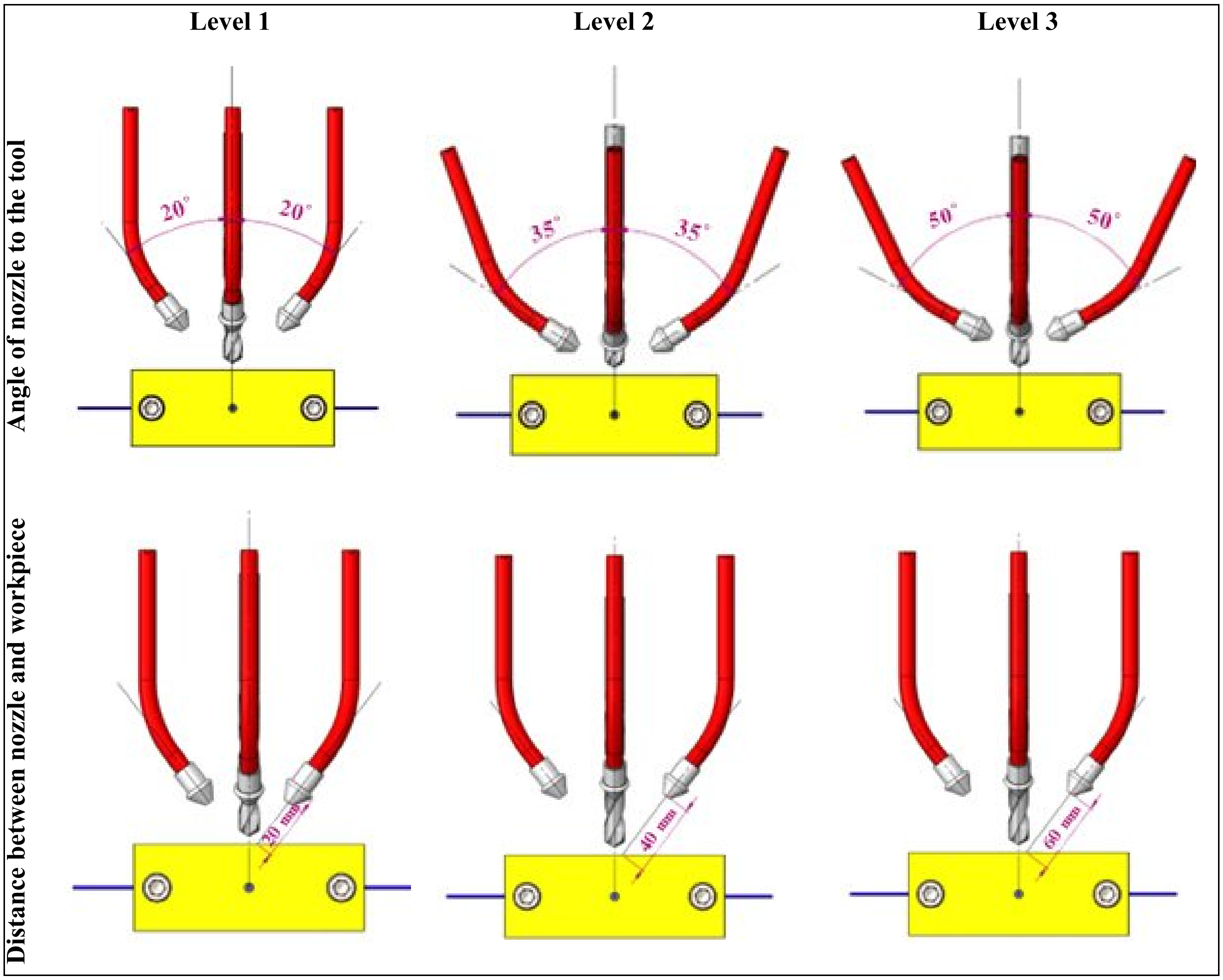


Fig. 3
The schematic of the nozzle positions into the workpiece.

2.2. Cutting Fluids

The cutting fluid system used in this study combines a lubricant and compressed air, delivered through a compressor with specific pressure and flow rate settings. Three different types of cutting fluids were examined: palm oil lubricant, Al_2O_3 nanofluid, and CuO nanofluid. The thermal properties of these cutting fluids are summarized in Table 2. To ensure optimal dispersion of nanoparticles and prevent agglomeration, both nanofluids underwent ultrasonic agitation for 30 minutes prior to application. This process effectively disaggregates nanoparticle clusters, resulting in a stable suspension that enhances the performance of the nanofluids in the machining zone.

Table 2
The thermal characteristics of different type of lubrication [44, 45]

Cutting fluid	Density (kg/m^3)	Thermal conductivity (w/m.K)	Specific heat (kJ/kg.K)
Palm oil	890	0.15-0.25	1.67
Al_2O_3 nanofluid	3970	17.65	0.525
CuO nanofluid	6500	20	0.536

2.3. Workpiece and drilling tool

Drilling operations were conducted using a 10 mm high-speed steel (HSS) drilling tool with a point angle of 118°, a cobalt coating, and a helix angle of 37° on a CK45 workpiece with the dimension of 30 × 30 × 100 mm. CK45 is a versatile carbon steel recognized for its excellent strength, machinability, and heat treatability. Its strength and toughness make it suitable for demanding applications in the automotive, machinery, and construction sectors. The machinability of CK45 allows for efficient processing into the various components, while its heat treatability allows for the customization of hardness and strength to meet specific requirements. Figure 4 illustrates a sample of the CK45 workpiece. The structural composition and physicochemical properties of CK45 are detailed in Table 3.

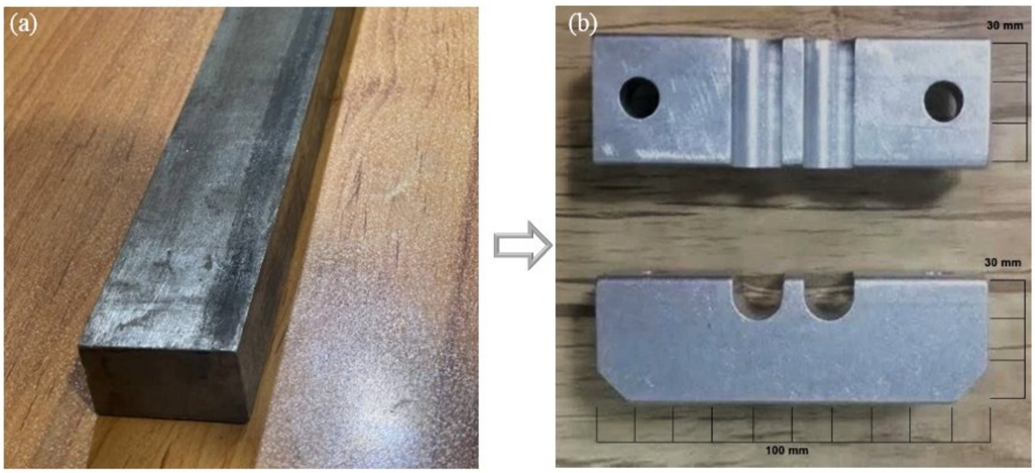


Fig. 4
The manufacturing process of CK45 parts from (a) raw material preparation to (b) final product.

Table 3
Chemical composition and thermal properties of the workpiece [46, 47]

Chemical composition of CK45							
Elements	C	Mn	Si	P	Ni	Mo	S
Content	0.467	0.657	0.309	0.014	0.039	0.0087	0.021

Thermal properties of CK45			
Tensile strength (MPa)	850	Yield strength (MPa)	510
Density (Kg/m^3)	7700	Elongation	8-25%
Melting temperature (˚C)	1450 - 1510	Thermal conductivity (w/m.K)	25
Specific heat (J/kg.K)	460		

2.4. Design of Experiments

Central Composite Design (CCD) was utilized in Design Expert software to optimize the experimental parameters and assess their interactive effects. This method enabled an efficient exploration of the response surface while minimizing the number of experimental runs. To evaluate the temperature and surface roughness of drilled CK45 workpieces, Response Surface Methodology (RSM) was employed. The RSM model analyzes variable interactions with fewer experiments and provides predictive equations and visualization tools for deeper insights. A total of 60 experiments were conducted with four input parameters: nozzle geometry, nozzle droplet size, nozzle angle to the tool, and nozzle distance with the workpiece, as detailed in Table 4. Additionally, five extra experiments were carried out with different types of lubrication for comparative analysis. Each variable was selected based on literature review. Each experiment was replicated three times to ensure data validity. After completing the experiments and measuring temperature and surface roughness, the results were analyzed using ANOVA. This analysis determined the influence of each input parameter on the drilling process. Furthermore, the quality of the surface was evaluated to assess the impact of lubrication optimization on the workpiece.

Table 4
The selected level of the input parameters

Parameters	**Level 1**	**Level 2**	**Level 3**
Nozzle geometry	circle	rectangle	square
Nozzle angle to the tool	20˚	35˚	50˚
Nozzle distance to the workpiece (mm)	20	40	60
Nozzle droplet size (mm)	0.5	1	1.5
Type of lubrication	Al_2O_3 nanofluid	CuO nanofluid	Palm oil

2.5. Experimental Measurements

To measure the temperature, an optical thermometer MS6550B manufactured by Mastech was applied to measure initial temperature. This advanced digital thermometer is designed to measure temperature through contact using a thermocouple. It utilizes a needle thermocouple with enhanced accuracy to ensure precise measurements under specific drilling conditions. Thermocouples were positioned to measure temperature radially, capturing variations along the radius for accurate temperature distribution. To measure temperature, all three thermocouples are positioned at the center of the workpiece, placed at precise distances of 5 mm, 7 mm, and 10 mm from the exact location of the hole**.** The position of thermocouples to measure temperature is shown in Figure 5. Surface roughness was measured with a Time model TR100 roughness tester, which is calibrated to ensure precision and reliability in evaluating surface characteristics. The analyzed specimens were machined via a wire-cutting process, specifically around the diameter of the holes, to create a consistent and reproducible surface for assessment. The roughness measurements were performed in accordance with the ISO 4288:1996 standards, which provide guidelines for the evaluation of surface texture. In this study, the Ra criterion was employed, as it is one of the most widely accepted parameters for quantifying surface roughness in engineering applications. In addition, the Scanning Electron Microscope (SEM) was used to meticulously analyze the surface quality of the workpieces. The SEM is a powerful analytical tool that enables high-resolution imaging of surfaces at the micro and nanoscale. By analyzing the microstructural changes caused by the drilling process, we aim to gain a better understanding of how NFMQL can improve tool longevity and machining performance.

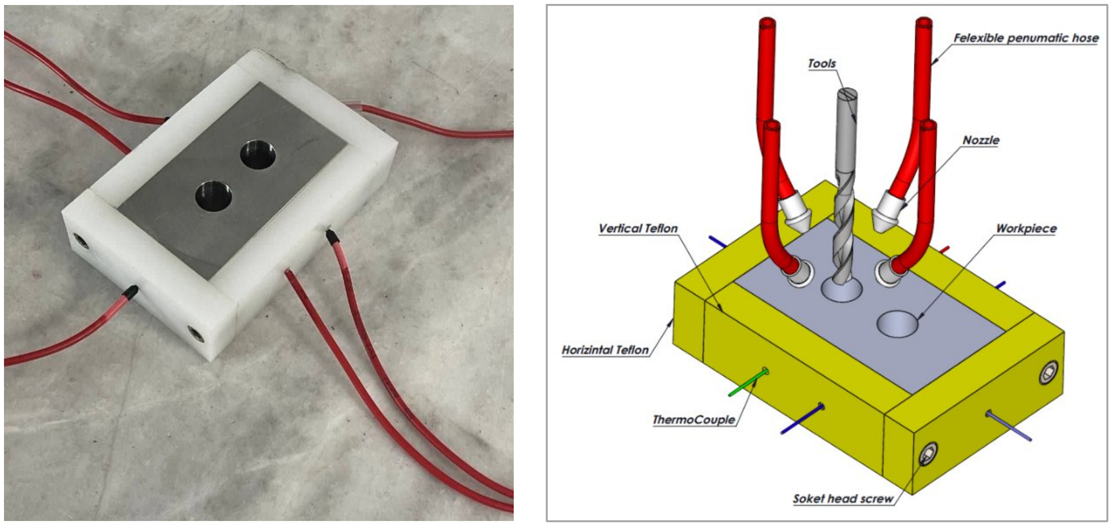


Fig. 5
The positions of the thermocouples into the workpiece.

2.6. TOPSIS method

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is a robust multi-criteria decision-making (MCDM) method used to rank alternatives based on their proximity to ideal solutions. It evaluates alternatives by considering their distances from the Positive Ideal Solution (PIS) and the Negative Ideal Solution (NIS) [48]. 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 [49, 50]. Applications of TOPSIS extend across diverse fields, including engineering, finance, and supply chain management [51]. This study presents the TOPSIS method, a multi-criteria decision-making technique employed to rank the different NFMQL strategies. It includes 60 experiments based on temperature and surface roughness during drilling process of CK45. Below is a detailed step-by-step procedure with equations to implement TOPSIS effectively.

Step 1: Construction of decision matrix: The average values of each output response for all experiments are organized into a decision matrix, which shows the basis for evaluating alternatives across multiple criteria in TOPSIS. The decision matrix (*D*) is shown in equation (1), where *n* represents response variables with *m* corresponding alternatives values.

$$\boldsymbol{D} = \begin{bmatrix} x_{11} & x_{12} & x_{13} & \cdots & \cdots & x_{1n} \\ x_{21} & x_{22} & x_{23} & \cdots & \cdots & x_{2n} \\ x_{31} & x_{32} & x_{33} & \cdots & \cdots & x_{3n} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ x_{m1} & x_{m2} & x_{m3} & \cdots & \cdots & x_{mn} \end{bmatrix} \tag{1}$$

Step 2: Normalization of decision matrix: To ensure comparability across criteria with varying dimensions and scales, the decision matrix is normalized using equation (2), transforming the response variables into dimensionless values.

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \quad i = 1,2,\ldots,m; j = 1,2,\ldots,n \tag{2}$$

Step 3: Calculatation of weighted normalized matrix: 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 step, the normalized response variables are multiplied by their corresponding weights, as determined by the Entropy Weighting Method (EWC). 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 MQL strategy across the different criteria [52]. The weighted normalized matrix is computed using equation (3).

$$v_{ij} = w_j * r_{ij} \quad i = 1,2,\ldots,m; j = 1,2,\ldots, \tag{3}$$

Step 4: Identification of ideal solutions and distance calculation: The PIS (V_j^+) represents the optimal values that maximize the desired response variables, whereas the NIS (V_j^-) corresponds to the values that minimize them. Then, the euclidean distance of each alternative from the PIS (d_i^+) and the NIS (d_i^-) is computed using equation (4) and (5).

$$d_i^+ = \sqrt{\sum_{j=1}^{n} \left(V_{ij} - V_j^+\right)^2} \tag{4}$$

$$d_i^- = \sqrt{\sum_{j=1}^{n} \left(V_{ij} - V_j^-\right)^2} \tag{5}$$

Step 5: Calculation of Closeness Coefficient: The relative closeness of each alternative to the positive ideal solution is determined using equation (6). This coefficient quantifies the proximity of an alternative to the optimal solution, providing a basis for ranking the alternatives.

$$C_i = \frac{d_i^-}{d_i^+ + d_i^-} \tag{6}$$

Step 6: Ranking of Alternatives: The ranking of alternatives is determined based on the values of the closeness coefficient (C_i), which ranges from 0 to 1. The higher (C_i) value indicates that the alternative is closer to the PIS and farther from the negative ideal solution NIS. Alternatives are arranged in descending order of (C_i), where the value closest to 1 is ranked first and considered the optimal choice among the multiple decision-making response variables. This approach ensures a systematic and objective selection of the best-performing alternative.

3 RESULTS AND DISCUSSION

3.1. Temperature rise

3.1.1. Effect of type of lubrication on temperature rise

One of the aims of this study is to determine the most effective lubrication type for MQL in drilling CK45 by comparing its performance against flood lubrication and dry machining methods. The results revealed that the type of lubrication significantly impacts the temperature rise during drilling. The use of Al_2O_3 nanofluid in MQL achieved the lowest mean temperature at the tool-workpiece interface, followed by CuO nanofluid and palm oil lubricant. Specifically, Al_2O_3 nanofluid resulted in a 56% reduction in temperature compared to dry machining and a 42% reduction compared to flood lubrication. Figure 6 illustrates the average temperature rise during drilling operations with different types of lubrication.

The significant thermal reduction observed with Al_2O_3 nanofluid can be attributed to two main factors, the MQL technique's efficient fluid delivery and the thermal properties of the Al_2O_3 nanoparticles. The high-pressure delivery system in MQL ensures precise transport of lubricant particles into the cutting zone, enabling effective cooling. This findings aligns with previous studies, which highlighted the advantages of MQL over conventional cooling methods in reducing heat generation during machining [53]. Moreover, the high thermal conductivity of Al_2O_3 nanoparticles plays a crucial role in reducing heat feneration in the cutting interface. Studies by Boukerma and Kadja [54] and Alosious et al. [55] demonstrated that Al_2O_3 nanoparticles facilitate faster heat transfer than CuO nanofluid, which supports the finding of this study. The slightly inferior performance of CuO nanofluid, despite its good thermal conductivity, can be attributed to its larger particle size and lower stability in the base fluid, which limit its heat transfer efficiency [56]. These observations indicate that both the concentration of the nanofluid and the thermophysical properties of the base fluid significantly influence heat dissipation [57-59]. On the other hand, palm oil-based MQL, while environmentally friendly and offering satisfactory lubrication, showed a higher temperature rise compared to Al_2O_3 and CuO nanofluids. This is primarily due to the absence of nanoparticles, which enhance the thermal conductivity of the lubricant [60-63].

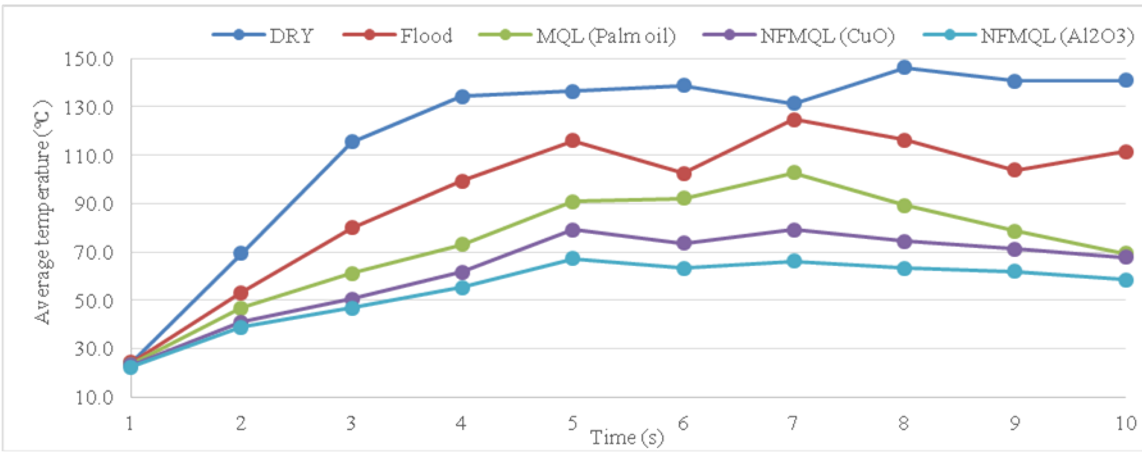


Fig. 6
Comparison of average temperature values during drilling operations with different types of lubrication.

3.1.2. Effect of the nozzle geometry on temperature rise

Research into the drilling process has revealed a significant gap in understanding the effects of nozzle geometry and its droplet size on the performance of the MQL technique. This gap becomes particularly evident when multiple nozzles are utilized in the MQL system. To investigate the influence of nozzle geometry and droplet size, four nozzles with circular, rectangular, and square cross-sections were analyzed at varying droplet sizes of 0.5 mm, 1 mm, and 1.5 mm. Figure 7 presents the average temperature variations during drilling operations. The results indicate that using rectangular cross-section nozzles with a droplet size of 1.5 mm achieved the most significant temperature reduction, lowering the temperature rise by 30% and 38%, compared to circular and square cross-section nozzles, respectively. This notable improvement can be attributed to the enhanced cooling effect and superior penetration of the nanofluid into the machining zone. The geometry of nozzles plays a crucial role in determining the spray pattern and coverage of the lubricant in the MQL system. A rectangular cross-section nozzle covers a larger surface area at the tool-workpiece interface, which improves lubrication efficiency. The increased area coverage ensures effective cooling by evenly distributing the lubricant, removing heated chips, and covering the entire contact zone between the tool and workpiece [64]. Additionally, the internal design of the nozzle significantly influences its performance. Smooth internal surfaces reduce turbulence and facilitate better flow and atomization of the lubricant. In contrast, sharp internal turns can cause turbulence, affecting droplet size, uniformity, and overall efficiency of the spray [65]. These findings align with a study by Abiyari and Abootorabi [66], which demonstrated that the rectangular cross-section of the nozzle enhanced lubricant coverage, leading to reduced temperatures and improved surface quality. Furthermore, it was observed that using an outlet size of 1.2 mm resulted in a greater reduction in temperature.

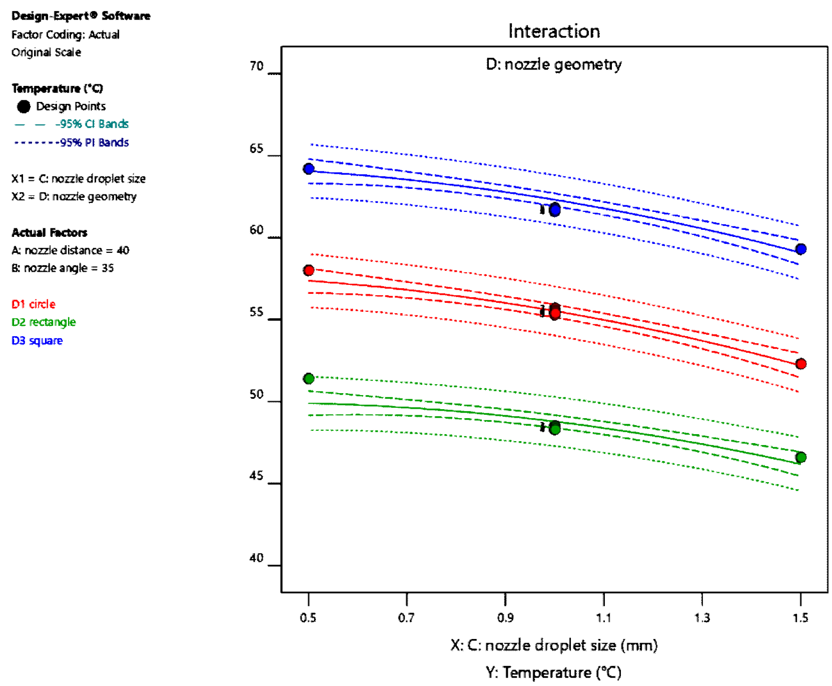
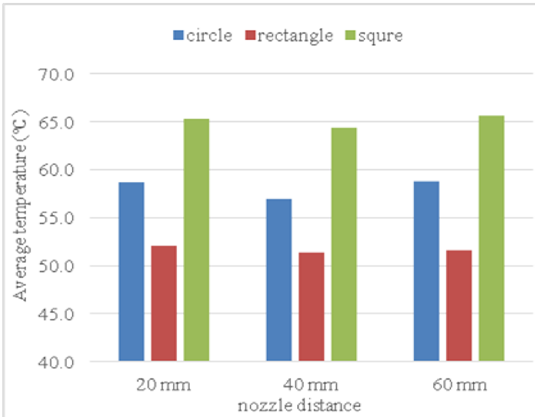


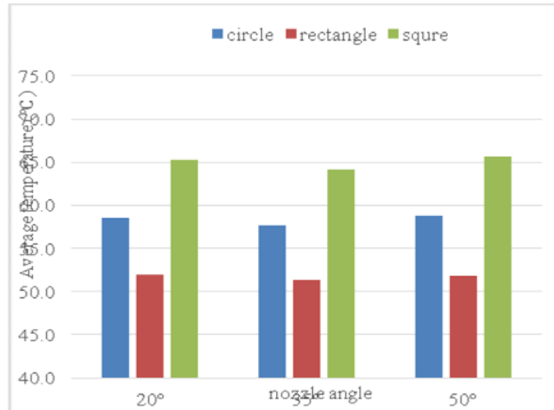
Fig. 7
Comparison of average temperature under NFMQL with different nozzle geometries.

3.1.3. Effect of nozzles position on temperature rise

Adjusting the optimal nozzle position to the tool and workpiece is a crucial parameter that can greatly impact the MQL systems. The injection angle of the coolant is essential for ensuring effective delivery of the lubricant to the cutting zone, thereby enhancing both cooling and lubrication during the drilling operation. Mean Temperature changes at different distances and angles are shown in Figure 8. Experimental results presented in Figure 9 demonstrate that adjusting the nozzle angle to 35 degrees at the distance of over 40 mm elevates the heat transfer efficiency. It was observed that keeping the droplet size and nozzle cross-sections constant, the lowest temperature rise was found for a distance of 40 mm and an angle of 35 degrees. This decrease in temperature can be attributed to improved penetration of Al_2O_3 nanofluid into the drilled hole, as well as more effective removal of chips generated during the drilling process. while the nozzle distance had less impact compared to other parameters, the aim of this study was to improve the MQL efficiency by optimizing the nozzle position to the drilling tool. Inappropriate nozzle position led to the mist may disperse before reaching the cutting zone, leading to inadequate lubrication and cooling. On the other hand, at too short a distance, continuous chips create a challenge for effectively injecting the lubricant into the machining area [67]. In another research conducted by Rana et al. [42], it was found that the angle and distance of the nozzle position significantly influence the milling process. Additionally, when the nozzle distance exceeds 40 mm, increasing the nozzle angle negatively influenced the cutting temperature.

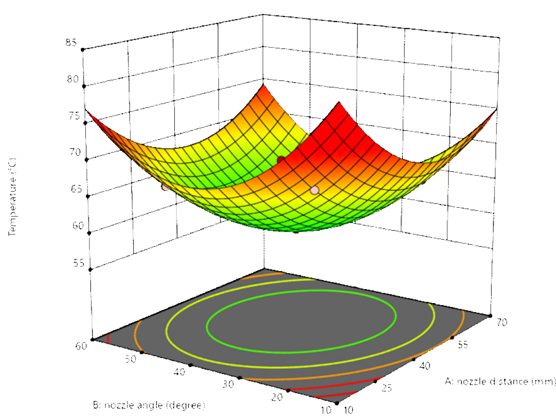


(a)



(b)

Fig. 8
Comparison of average temperature values in different (a) nozzle distances and (b) nozzle angles.



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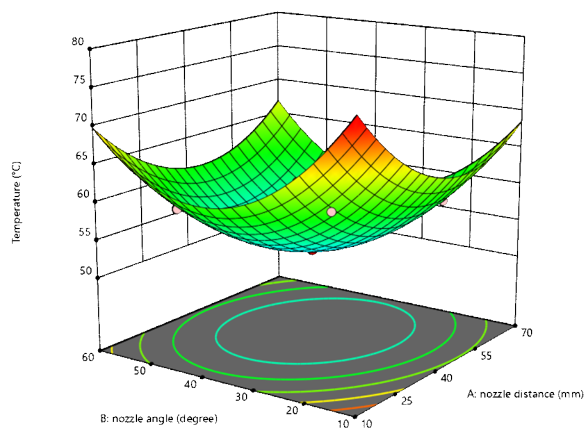

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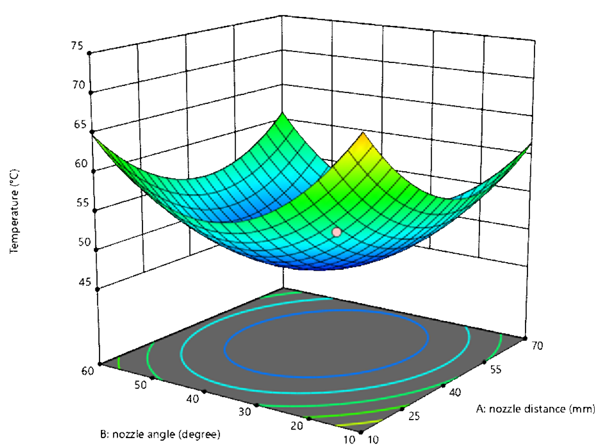


(c)

Fig. 9
Comparison of average temperature values with different nozzles positions for (a) square, (b) circular, (c) rectangular cross-sections.

3.1.4. Analysis of variance of the temperature rise

Selecting the proper experimental design is crucial for accurate data, considering objectives and feasibility. Statistical analysis, including model adequacy checks and ANOVA, helps identify significant factors and interactions after the experiment. Table 5 presented the ANOVA analysis for temperature rise values. Based on this table, the nozzle geometry and droplet size had the greatest impact on temperature reduction with highest F-values.

Table 5
Analysis of the input parameters interactions using ANOVA

Source	Sum of Squares	df	Mean Square	F-value	p-value	comment
Model	2663.83	17	156.70	303.99	< 0.0001	significant
A-nozzle distance	87.38	1	87.38	169.52	< 0.0001	
B-nozzle angle	37.63	1	37.63	73.01	< 0.0001	
C-nozzle droplet size	160.55	1	160.55	311.46	< 0.0001	
D-nozzle geometry	1830.61	2	915.31	1775.70	< 0.0001	
AB	5.42	1	5.42	10.51	0.0023	
AC	0.2817	1	0.2817	0.5464	0.4639	
AD	0.5687	2	0.2843	0.5516	0.5801	
BC	0.3267	1	0.3267	0.6337	0.4305	
BD	0.6320	2	0.3160	0.6130	0.5465	
CD	3.13	2	1.57	3.04	0.0485	
A^2	93.00	1	93.00	180.43	< 0.0001	
B^2	122.77	1	122.77	238.17	< 0.0001	
C^2	4.55	1	4.55	8.82	0.0049	
Std. Dev.	0.7180	R^2	0.9919	Predicted R^2	0.9809	
Mean	58.77	Adjusted R^2	0.9887	C.V. %	1.22	

3.2. Surface roughness

3.2.1. Effect of type of lubrication on surface roughness

The type of lubrication used during drilling significantly affects the surface roughness of the components, as demonstrated by the experimental findings. Various lubricants differ in viscosity, thermal stability, and film-forming capability, all of which directly influence the tribological interactions at the tool-workpiece interface [68]. Figure 10 illustrates the impact of each lubrication type on surface roughness. The results revealed that dry machining resulted in the highest surface roughness, due to increased friction and higher tool wear. Conversely, palm oil MQL reduced surface roughness, indicating improved tribological performance through effective heat dissipation and lubrication.

The Al_2O_3 nanofluid MQL demonstrated the best performance. Using Al_2O_3 nanofluid reduced surface roughness by 54% compared to dry conditions and by 48% compared to flood lubrication. The enhanced performance of Al_2O_3 nanofluid in improving surface roughness is primarily due to its ability to form a uniform lubricating film at the tool-workpiece interface. This reduces friction, minimizes tool wear, and ensures smoother cutting [69]. Additionally, the spherical shape and nano-scale size of Al_2O_3 particles enable them to penetrate micro-grooves and fill surface irregularities, further contributing to a smoother finish [70, 71]. Virdi et al. [7] reported that NFMQL with 1% of Al_2O_3 resulted in a lower surface roughness value. This improvement is attributed to enhanced lubrication, which facilitates easier sliding of chips over the surface. Pal et al. [72] found that using Al_2O_3 nanofluid reduced surface roughness and drill tip temperature by 56 % and 26 %, respectively, compared to flood conditions.

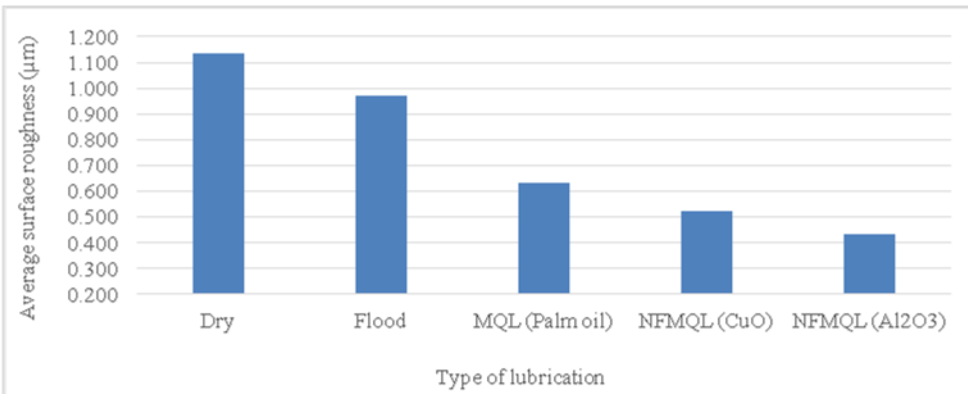
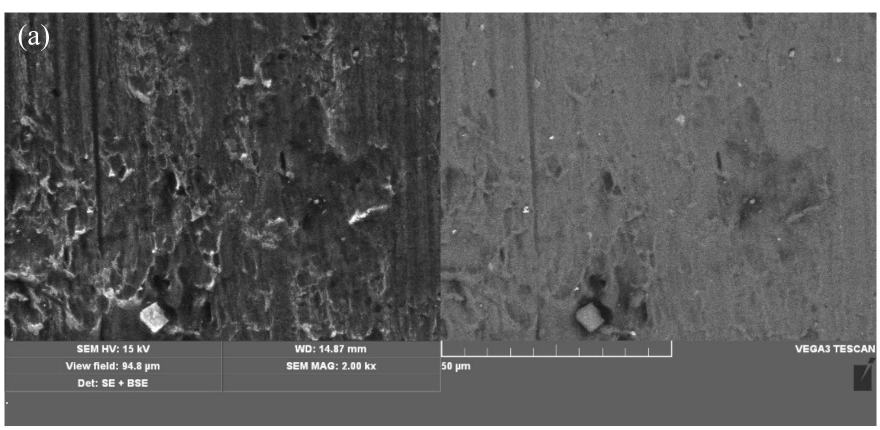


Fig. 10
Comparison of surface roughness values in drilling process with different types of lubrication.

Upon analyzing the final surface quality using SEM, minor cracks were identified, indicating residual stresses within the workpiece. These cracks were more prominent in dry conditions and less evident when utilizing NFMQL. SEM images presented in Figure 12 demonstrate that the application of Al_2O_3 nanofluid with rectangular cross-section nozzles enhanced the surface finish of the machined components. The Al_2O_3 nanofluid contributes to improved surface quality of drilled workpieces and mitigates small crack formation through enhanced thermal management, superior lubrication, and more efficient chip evacuation. Its excellent thermal conductivity facilitates effective heat dissipation, reducing temperatures at the cutting interface and minimizing thermal stress in the workpiece. Moreover, Al_2O_3 nanoparticles enhance lubrication by lowering friction and wear, resulting in smoother interactions between the cutting tool and workpiece. Reduced tool wear maintains sharper cutting edges for cleaner machining, while Al_2O_3 nanoparticles help fill microstructural defects, yielding smoother surfaces and fewer sites for crack initiation. Overall, this innovative lubrication approach demonstrates its capability to achieve high-quality outcomes in drilling operations.



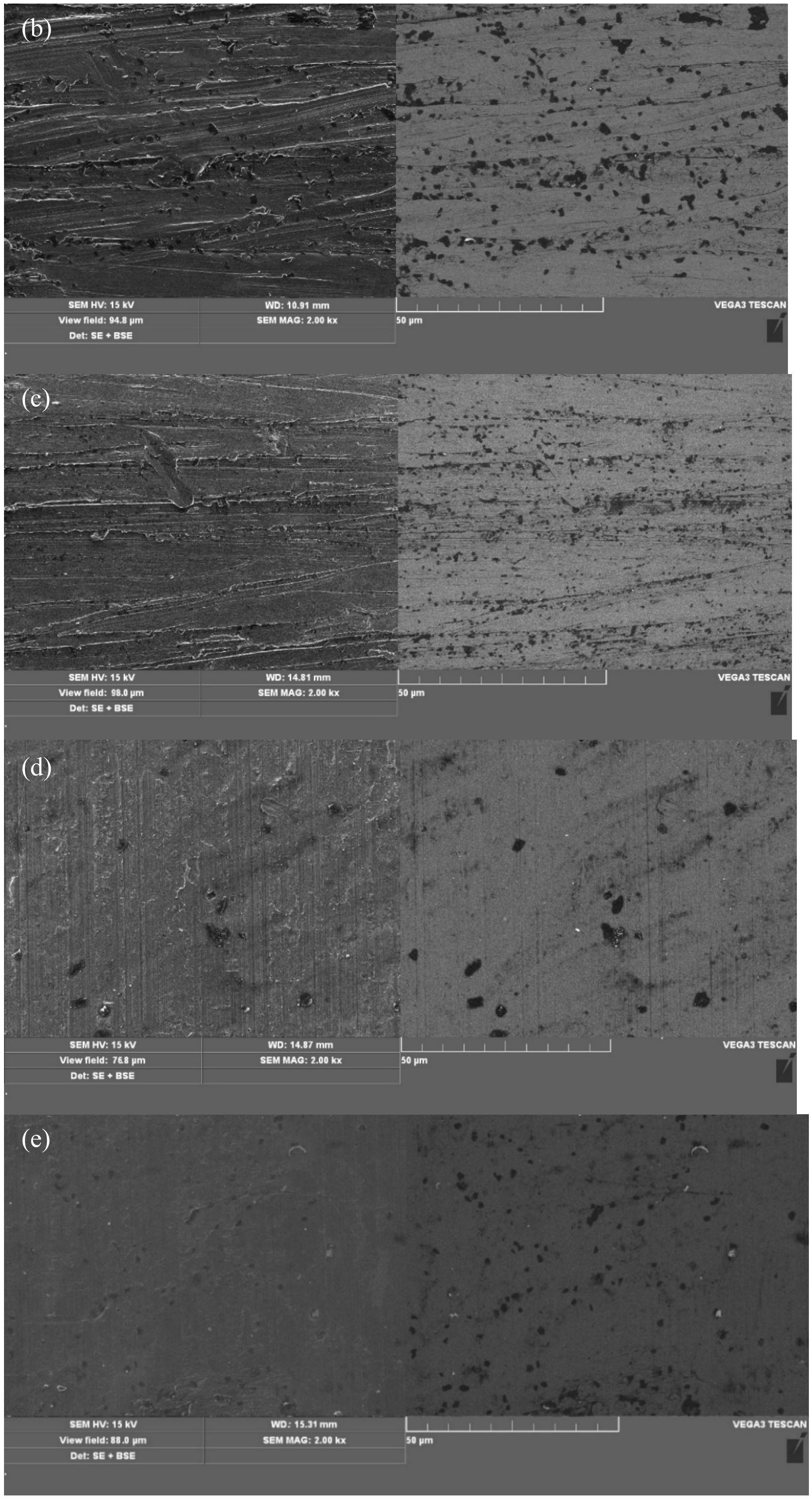


Fig. 11
SEM images of final surface quality in the dry condition (a), flood lubrication (b), Palm oil MQL (c), CuO nanofluid MQL (d), and Al_2O_3 nanofluid MQL (e).

3.2.2. Effect of the nozzle geometry on surface roughness

One objective of this study was to evaluate the impact of different nozzle droplet sizes and cross-sections on the surface roughness of CK45 specimens. It was discovered that using NFMQL with rectangular cross-section nozzles with a droplet size of 1.5 mm significantly improved surface roughness by 36% and 31% compared to nozzles with circular and square cross-sections. The rectangular nozzle provides wider and more uniform mist coverage over the cutting zone. This ensures that the lubricant consistently reaches the machining area, reducing friction and preventing tool adhesion. Reduced friction minimizes surface irregularities caused by tool wear or material build-up, leading to improved surface finish. Additionally, larger droplets from the rectangular nozzle (with a 1.5 mm droplet) have higher thermal capacity and penetrate deeper into the cutting zone.

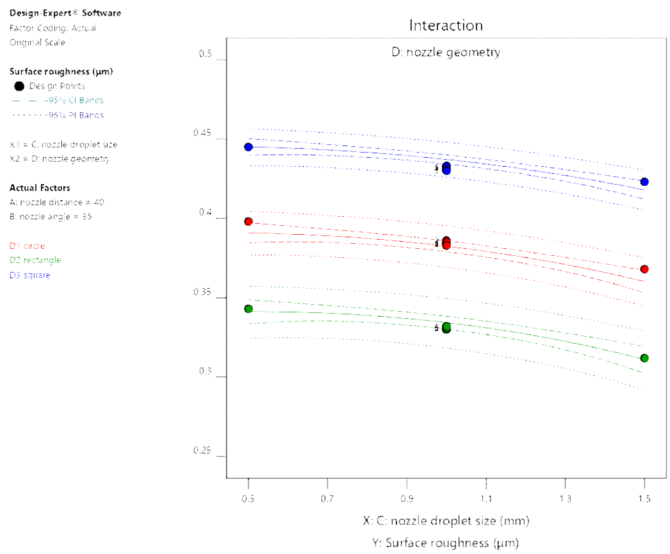


Fig. 12
Comparison of surface roughness values with different nozzle geometries.

3.2.3. Effect of nozzle position on surface roughness

Improving the position of four nozzles with various angles to the tool can improve fluid coverage and penetration, reducing rebound and enhancing the retention of nanoparticles on the surface. This promotes better filling of surface asperities, reducing friction and wear. Moreover, an optimal nozzle distance ensures uniform distribution of the nanofluid; being too close leads to uneven coverage, while being too far dilutes its effectiveness [43, 73]. Experimental results show that proper nozzle positioning can significantly enhance lubrication efficiency. Adjusting the nozzle angle to 35 and the nozzle distance to 40 mm reduced surface roughness. Mean Surface roughness changes at different distances and angles are shown in Figure 13 and Figure 14 presents the surface roughness values measured for different nozzle positions.

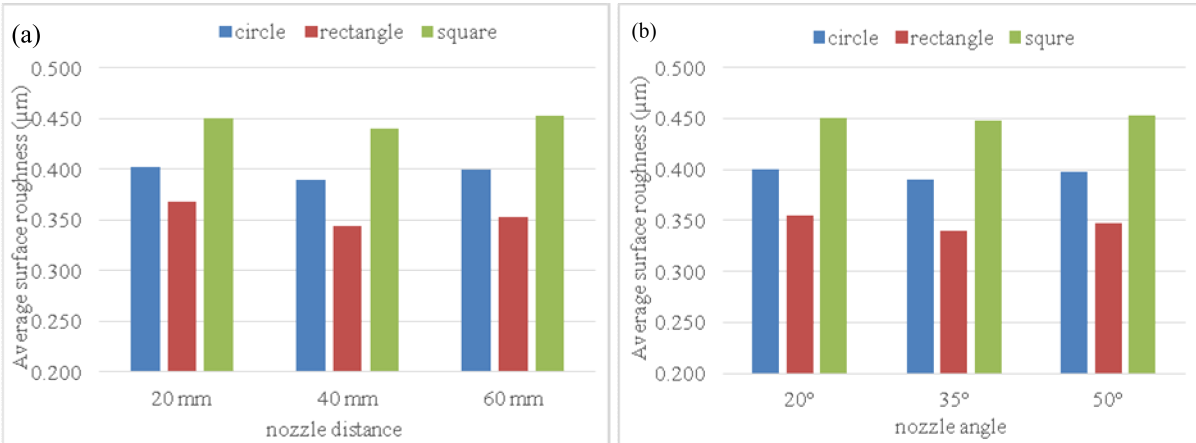


Fig. 13
Comparison of average surface roughness in different (a) nozzle distances and (b) nozzle angles.

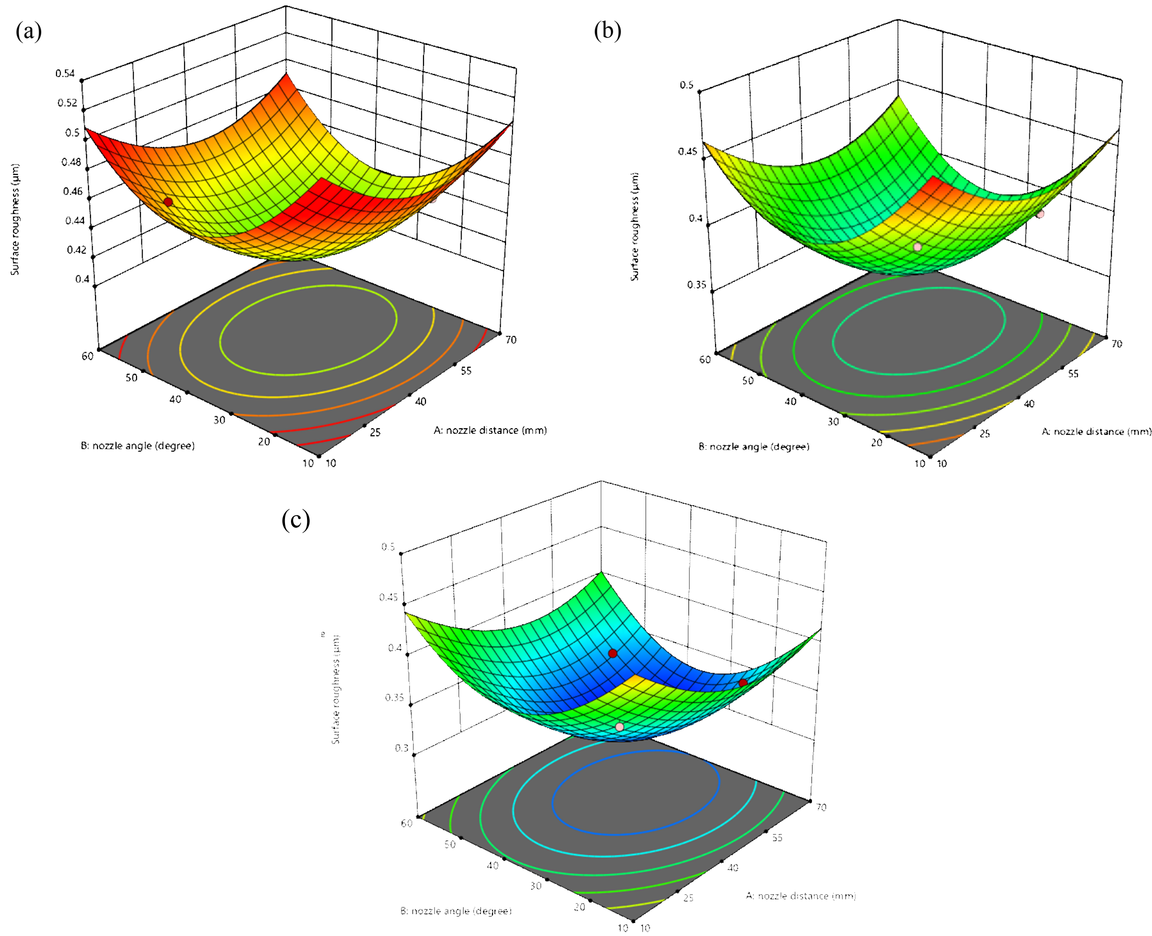


Fig. 14
Comparison of surface roughness values during drilling under NFMQL with different nozzles positions for (a) square, (b) circular, (c) rectangular cross-sections.

3.2.4. Analysis of variance of the surface roughness values

Table 6 presented the ANOVA analysis for surface roughness values. Based on this, nozzle geometry has the most significant impact on the surface roughness.

Table 6
Analysis of the impact input parameters on surface roughness using ANOVA

Source	Sum of Squares	df	Mean Square	F-value	p-value	comment
Model	0.0623	17	0.0037	217.46	< 0.0001	significant
A-nozzle distance	0.0027	1	0.0027	158.81	< 0.0001	
B-nozzle angle	0.0007	1	0.0007	39.20	< 0.0001	
C-nozzle droplet size	0.0027	1	0.0027	157.92	< 0.0001	
D-nozzle geometry	0.0469	2	0.0235	1392.51	< 0.0001	
AB	0.0000	1	0.0000	1.09	0.3031	
AC	4.003E-06	1	4.003E-06	0.2376	0.6285	
AD	0.0001	2	0.0001	3.45	0.0409	
BC	0.0000	1	0.0000	0.9661	0.3313	
BD	0.0001	2	0.0000	2.00	0.1485	
CD	0.0000	2	0.0000	0.9138	0.4088	
A^2	0.0013	1	0.0013	77.69	< 0.0001	
B^2	0.0026	1	0.0026	154.45	< 0.0001	
C^2	0.0001	1	0.0001	8.58	0.0055	
Std. Dev.	0.0041	R^2	0.9888	Predicted R^2	0.9761	
Mean	0.1251	Adjusted R^2	0.9842	C.V. %	3.28	

3.3. Multi-criteria optimization

The distributions of the results' weighted efficiencies were determined as 0.495 and 0504 for temperature and surface roughness, respectively. Following the computation of the outcomes' weighted efficiency distributions, the TOPSIS decision-making method is applied. Table 7 displays the alternatives of the most optimal conditions evaluated for the experiments. The results 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 improved configuration was achieved with a nozzle distance of 40 mm, nozzle angle of 35 using rectangular cross-secton with the outlet size of 1.5 mm.

Table 7
Ranking the most optimal lubrication parameters for the drilling process

Run.	Nozzle geometry	Nozzle droplet size	Nozzle distance (mm)	Nozzle angle (mm)	Closeness coefficient	Ranking
78	rectangle	1.5	40	35	0.99902	1
77	rectangle	1	40	35	0.95403	2
81	rectangle	1	60	35	0.91194	3
80	rectangle	1.5	60	50	0.89399	4
75	rectangle	0.5	40	35	0.86468	5
76	rectangle	1	40	50	0.84593	6
79	rectangle	1	60	20	0.83730	7
73	circle	1.5	40	35	0.83705	8
69	rectangle	0.5	60	50	0.76620	9
72	rectangle	1.5	20	50	0.76617	10

4 CONCLUSION

This study conducted an experimental analysis to assess the effects of dry, flood, MQL, and NFMQL modes on temperature and surface roughness during the drilling of CK45. The MQL trials investigated variations in critical parameters, including nozzle geometry, nozzle angle, nozzle distance, and droplet size. The key findings of this investigation are summarized as follows:

- The average temperature measured during MQL is lower compared to flood lubrication, which is lower than dry conditions. Using Al_2O_3 nanofluid results in the lowest temperature, whereas palm oil lubricant leads to the highest temperature.
- In NFMQL with Al_2O_3, both the average temperature and surface roughness significantly decreased, showing reductions of 42% and 56% for temperature, and 48% and 54% for surface roughness, compared to the flood and dry modes, respectively.
- Nozzle geometry is the most influential lubrication parameter in improving drilling process. Using rectangular cross-section nozzle with a droplet size of 1.5 achieved a temperature reduction of 30% and 38%,

and a surface roughness reduction of 31% and 36%, compared to circular and square cross-section nozzles, respectively.

- The optimal conditions for nozzle angle and distance were identified to enhance temperature control and surface roughness. A nozzle angle of 35 degrees was found to be ideal, as it allows better penetration of nanofluid particles into machining point, effectively lowering the temperature and surface roughness. Additionally, inappropriate nozzle distances led to the accumulation of continuous chips on the nozzle, which disrupted proper lubrication. To overcome this, a nozzle distance of 40 mm was determined to be optimal, ensuring consistent and efficient lubrication.
- SEM results also showed that higher temperatures in dry mode significantly contribute to less favorable surface quality. It also indicated a lower presence of fine cracks was achieved when using Al_2O_3 nanofluid with rectangular cross-section nozzles.
- The optimal setup for enhancing lubrication in the MQL system involves using four rectangular cross-section nozzles positioned 40 mm from the workpiece, angled at 35 degrees to the tool, and delivering droplets sized at 1.5 mm.

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