EVALUATION OF THE MILLING PROCESS USING AL_2O_3 AND FE_3O_4 NANOFLUIDS IN AN MQL SYSTEM ON MACHINING POWER AND SURFACE ROUGHNESS

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ABSTRACT: This study investigated the effect of nanofluid-based Minimum Quantity Lubrication (MQL) cooling strategy and machining parameters on machining power and surface roughness in milling process. Two nanofluids, Al_2O_3 and Fe_3O_4, were evaluated under identical cutting conditions. The results showed that the machining power using Al_2O_3 nanofluid was slightly lower than Fe_3O_4 (1%). However, it produced higher surface roughness (14.27%) than Fe_3O_4. Furthermore, machining parameters significantly affected the performance. Increasing cutting speed (v_c = 3.23%), feed rate (f_z = 0.93%), and depth of cut (a_x = 0.33%) led to higher machining power due to increased material removal rate and cutting force. Surface roughness was mainly influenced by f_z = 8.49% and a_x = 6.16%, with feed rate identified as the dominant factor. Taguchi analysis and ANOVA revealed that depth of cut contributed most to machining power, while feed rate dominated surface roughness. The optimal machining power was achieved at v_c = 22.5 m/min, f_z = 0.028 mm/tooth, and a_x = 0.5 mm, with values of 1.336 kW (Al_2O_3) and 1.341 kW (Fe_3O_4). Meanwhile, the best surface roughness was obtained at v_c = 40.8 m/min, f_z = 0.028 mm/tooth, and a_x = 0.5 mm, with values of 0.596 µm (Al_2O_3) and 0.494 µm (Fe_3O_4).

KEY WORDS: Machining power, surface roughness, optimization, nanofluid Al_2O_3 & Fe_3O_4

1. INTRODUCTION

Machining processes continue to play a critical role in modern manufacturing, particularly in producing components with high dimensional accuracy and superior surface integrity. Among these processes, milling is widely applied due to its versatility and efficiency in material removal. However, the milling operation inherently involves complex thermo-mechanical interactions at the tool–workpiece interface, leading to high cutting temperatures, significant friction, and elevated energy consumption. These phenomena directly affect key performance indicators such as machining power and surface roughness, which are crucial for product quality and process sustainability. Consequently, the use of cutting fluids has become essential to reduce friction, control temperature, and improve machining performance [1, 2, 3].

However, the conventional flood cooling method presents several critical drawbacks, including environmental pollution, health hazards to machine operators, and high operational and disposal costs. In response to these issues, Minimum Quantity Lubrication (MQL) has emerged as a sustainable alternative, utilizing a minimal amount of lubricant delivered directly to the cutting zone. MQL has demonstrated effectiveness in reducing friction and improving tool life while significantly decreasing fluid consumption. Nevertheless, under demanding machining conditions, conventional MQL systems still exhibit limitations in cooling capacity and lubrication efficiency, which can adversely affect machining performance [4, 5].

To address these limitations, recent research has focused on the application of nanofluids in MQL systems. Nanofluids are formed by dispersing nanoparticles into base fluids, enhancing their thermal conductivity and lubrication properties. Among various nanoparticles, aluminum oxide (Al_2O_3) has been widely investigated due to its high thermal stability and ability to reduce friction and wear. Studies have reported that Al_2O_3-based nanofluids can significantly decrease surface roughness and cutting forces, thereby improving overall machining efficiency [1,2,6]. In addition, iron oxide (Fe_3O_4) nanoparticles have attracted attention due to their thermal conductivity and magnetic characteristics, which may enhance lubrication stability and heat dissipation performance [7].

Various studies have been conducted regarding the use of nanofluids in machining processes, most of which still focus on one type of nanoparticle, such as Al_2O_3, and few have conducted comprehensive evaluations of the performance comparison between different types of nanoparticles on key parameters, especially machining power and surface roughness in the milling process. Therefore, the priority of this study lies in the testing and comparison of two types of nanofluids, namely Al_2O_3 and Fe_3O_4, in the MQL system in the milling process, as well as analyzing the effect of each nanofluid on machining performance simultaneously. Based on this, this study aims to analyze the effect of the use of Al_2O_3 and Fe_3O_4 nanofluids on machining power and surface roughness, while determining the optimal machining parameters to obtain the best performance, so that it can contribute to the development of more efficient, environmentally friendly, and sustainable machining technology. The input parameters in this study consist of cutting speed, feed rate per tooth, and depth of cut. Al_2O_3 and Fe_3O_4 nanofluids, each suspended in coconut oil cutting fluid. Selection of machining data variations and optimization analysis using the Taguchi method with orthogonal array $L_9(3^3)$.

2. MATERIALS AND METHOD

2.1. Material

Machining tests using AISI 1045 material, which has mechanical properties of tensile strength of 565 N/mm^2 and hardness of 163 HB. The main chemical composition includes elements C (carbon) 0.42–0.48%, Mn (manganese) 0.60–0.90%, Si (silicon) 0.15–0.35%, and additional elements Ni (nickel) $\leq$ 0.200%, S (sulfur) $\leq$ 0.035%, P (phosphorus) $\leq$ 0.030%. AISI 1045 steel has the advantages of high strength and hardness, good wear resistance, easy to improve its properties through heat treatment, has good machinability, and offers a balance between strength and ductility. The test workpiece measures 10 × 100 × 200 mm and the length of each machining is 100 mm, with the machining operation being down milling.

2.2. Machining Process

A conventional vertical milling machine from "Dahlih DL-U2" (China) was used to machine AISI 1045 workpieces. The spindle power was 5 hp, and the table drive was 2 hp. The table had a discrete feed rate of 13-700 mm/min, and a spindle rotation speed of 70-1300 rpm. A K2 EMC 54100 coated carbide tool (brand YG-1, South Korea) with a diameter of 10 mm, four flutes, a helix angle of 60°, and a tip radius of 0.4 mm was used. To maintain machining stability and minimize vibration (chatter), the tool was mounted in a 30 mm tool holder.

2.3. Nanofluids Preparation

The cutting fluid in this study used vegetable oil, namely coconut oil which is commonly sold in the market (Barco). Coconut oil has the following specifications: absolute viscosity of 1.84 cP (40°C), density of 925.8 kg/m^3 (15°C), and flash point of 286°C [8]. Nanolfluid was made by suspending each of Al2O3 and Fe3O4 nanoparticles into coconut oil with the desired concentration of 1%. In order for the nanoparticles to be evenly dispersed in the coconut oil solution, the solution was stirred for one hour using an ultrasonic sonicator.

2.4. Measuring Systems

Machining power data was obtained from real-time measurements of machining current and voltage during each running test. Voltage (V) measurements were made using an ammeter. Current (I) measurements were detected using a sensor (SCT-013) that flows through a single-conductor cable, which represents the input current for machining. This cable is located in the electrical substation of the machine tool. The machining current readings were regulated by a controller (Arduino Mega 2560).

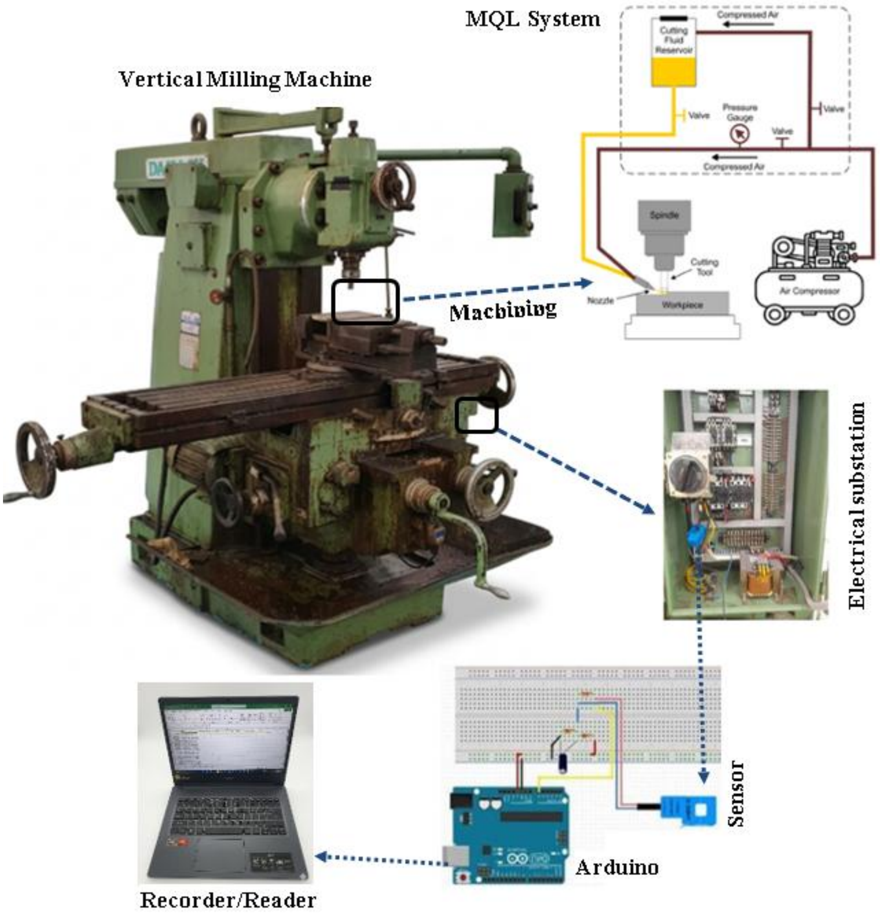

Fig. 1. Machining test procedures

The controller's output current was then read and analyzed on a PC. Before testing, the custom-built current reader was calibrated. Calibration was performed using a standard clamp-meter (Kyoritsu), and the results showed an average difference of 8 % from the readings of the custom-built tool. The electric motor in the machine tool used had a balanced three-phase load.

For a three-phase electric motor, by considering a power factor (φ) of 0.8, the machining power (P) calculation uses Eq. (1).

$$P = \sqrt{3}.V.I.\cos\varphi \tag{1}$$

To analyze the surface roughness data from the test results, measurements were performed using an Accretech Handysurf (E-35 A/E) measuring instrument. Surface roughness measurements were performed in the longitudinal direction (parallel) with a feed rate and cutting conditions of 0.8 mm and a cutting length of 4.0 mm. The schematic of the machining test implementation is presented in the Fig. 1.

2.5. Design of Experiment (DOE)

The design of experiments developed for machining parameter combinations was the Taguchi method. Three input parameters, namely cutting speed (v_c), feed/tooth (f_z), and axial depth of cut (a_x), at three value levels, were selected for this experiment (Table 1). Based on the Taguchi approach, the $L_9(3^3)$ orthogonal array was the appropriate number of experiments to accommodate the three cutting conditions and three parameter value levels. he input parameter values were selected based on the capabilities of the machine tool used. Analysis of variance (ANOVA) was then used to determine the influence of each parameter on the measured response. The type of quality characteristic used to evaluate and optimize process results (considering the average 'signal' (S) and 'noise' (N) variation or S/N ratio) based on the Taguchi method in this experiment is *Smaller is Better* (Eq. (2)):

$$S/N = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \tag{2}$$

where, n = number of data points and y_i = value of the i-th observation result.

Table 1: Variation of input parameters - $L_9(3^3)$

Test Input Parameters (factor)		**Values of each level**		
		1	**2**	**3**
1.	v_c - Cutting Speed (m/min)	11.6	22.5	40.8
2.	f_z – Feed/tooth (mm/tooth)	0.028	0.041	0.086
3.	a_x - Depth of Cut (mm)	0.5	0.75	1.25

3. RESULTS AND DISCUSSION

3.1. Effect of Cooling Strategy on Machining Power and Surface Roughness

Fig. 2 shows the machining process of two different nanofluid cutting fluids in the MQL system, namely the machining power and surface roughness for each experiment at the same cutting parameters. Machining power in this study is the sum of total cutting power and power loss. Total cutting power consists of cutting power, feed rate per tooth, and depth of cut. Meanwhile, power loss can be caused by power lost to drive machine components and friction in the transmission system. In general, the machining power values for both nanofluids tended to increase with changes in machining parameters in each experiment. On the other hand, a different trend was observed in the surface roughness results. The surface roughness values produced by the Fe_3O_4 nanofluid were consistently lower than those of Al_2O_3 in most experiments.

The experimental results showed that the use of Al_2O_3 nanofluid in the Minimum Quantity Lubrication (MQL) system resulted in slightly lower machining power consumption of approximately 1% compared to Fe_3O_4. This indicates that Al_2O_3 nanofluids provide slightly better energy efficiency during the cutting process. In contrast, the surface roughness achieved using Al_2O_3 nanofluids is significantly higher than that achieved with Fe_3O_4 nanofluids, which equates to an improvement of approximately 14.27%. This indicates that Fe_3O_4 nanofluids are more effective in improving surface quality.

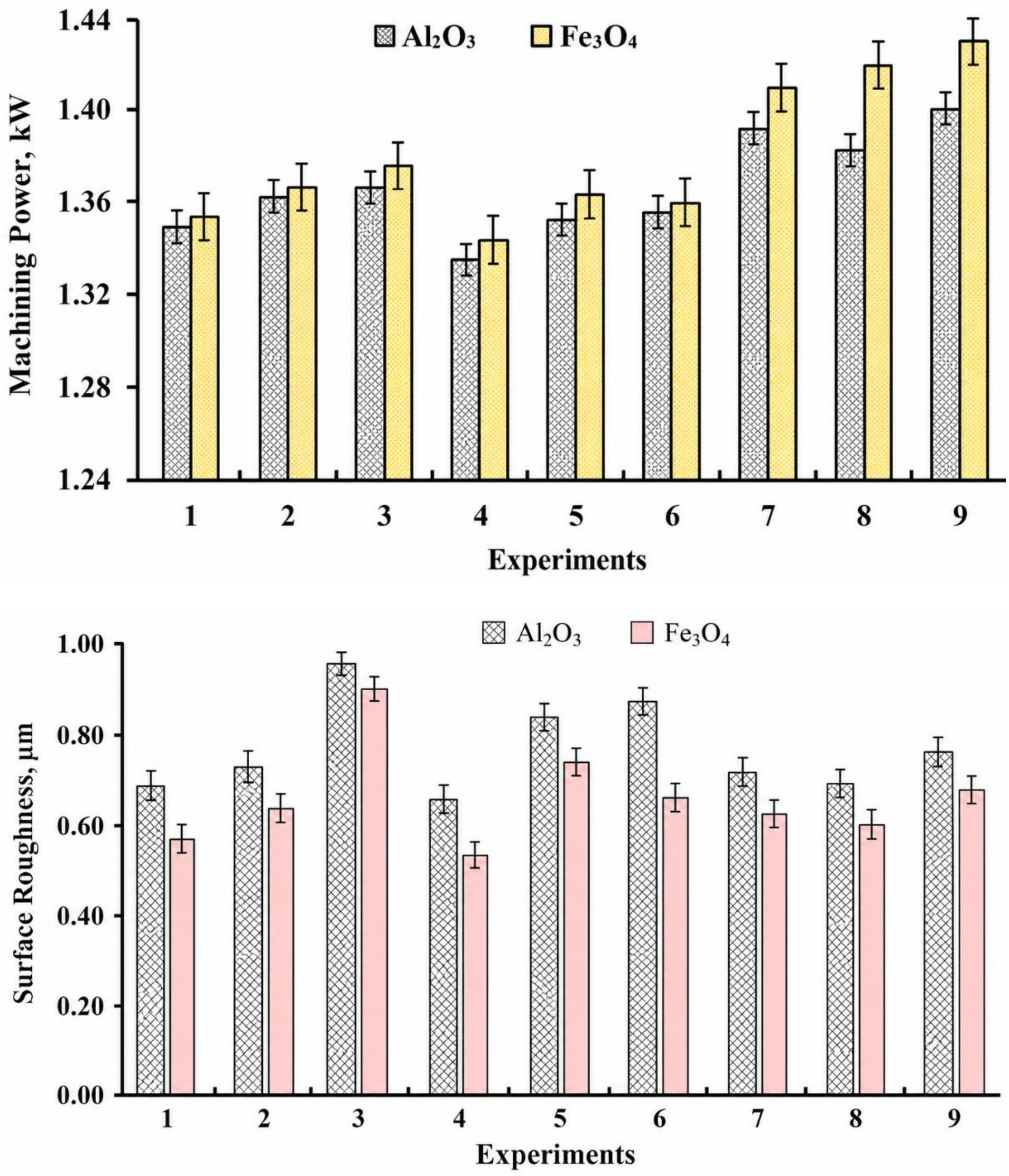

Fig. 2. Machining power and surface roughness results from all machining tests using Al_2O3 and Fe_3O_4 nanofluid cooling in an MQL system

The reduction in power consumption with Al_2O_3 nanofluids is closely related to the rolling effect mechanism and the stability of the nanoparticle dispersion. Nano-sized ceramic Al_2O_3

particles tend to form a thin lubricating layer in the tool-workpiece contact zone, thus changing the friction mechanism from sliding to rolling friction. This effect reduces the friction coefficient, cutting force, and ultimately the machining power [9]. In addition, the addition of nanoparticles generally increases the thermal conductivity of the fluid, so that cutting heat can be absorbed and dispersed more effectively, which also contributes to the reduction of machining energy [10]. However, the higher surface roughness of Al_2O_3 compared to Fe_3O_4 indicates that lubrication performance is determined not only by the reduction in cutting force but also by the characteristics of the surface interaction. Fe_3O_4 has higher magnetic properties and density, which under some conditions can promote the formation of a more stable and homogeneous tribofilm in the cutting zone. This layer acts as a micro-protection against mechanical scratches, resulting in a smoother surface. On the other hand, hard and abrasive Al_2O_3 particles can cause micro-scratches on the surface of the workpiece if the particle distribution is uneven or agglomeration occurs, thereby increasing the surface roughness value.

Furthermore, differences in effective viscosity and wettability also play a role. Nanofluids with better lubrication characteristics can form a continuous lubricating film, significantly reducing direct contact between the tool and the workpiece. In this context, surface quality is strongly influenced by the stability of the lubricating film and tool wear. Surface roughness during machining is known to be highly sensitive to flank wear and mechanical scratching mechanisms in the contact zone [11]. If the lubricating film is less stable (as is possible with Al_2O_3 under certain conditions), direct contact increases, resulting in a rougher surface. Furthermore, although Al_2O_3 increases thermal conductivity and lowers cutting temperatures, this does not always result in better surface quality. Too low a material's thermal softening effect can lead to suboptimal plastic deformation during chip formation, thus increasing surface roughness. Conversely, more balanced thermal conditions can increase chip flow and improve surface quality [12].

3.2. Effect of Input Parameters on Machining Power and Surface Roughness with Different Cooling Strategies

The experimental results in Fig. 3 and Fig. 4 show that the machining input parameters, namely cutting speed, feed rate, and depth of cut, have a significant influence on the machining power and surface roughness in the milling process with the Al_2O_3 and Fe_3O_4 nanofluid-based MQL system. The values in the graphs are the results of analysis using the Taguchi method in Minitab software. The Minitab graph output was modified to clarify the readability and interpretation of the test data. The results show that the machining power increases consistently with the increase in these three parameters. This is mainly due to the increase in material removal rate (MRR) and cutting force, where the depth of cut and feed rate directly determine the volume of material cut and chip thickness. The increase in cutting speed also contributes to an increase in the temperature in the cutting zone, which increases the plastic deformation energy and friction [13].

Increasing cutting speed, feed rate, and depth of cut generally leads to an increase in machining power. This phenomenon is directly related to the increase in material removal rate (MRR) and cutting force. Fundamentally, machining power is the product of cutting force and cutting speed, so any parameter increase that increases force or speed will increase the process's energy consumption. As feed rate and depth of cut increase, chip thickness and cross-sectional area also increase, leading to greater shear forces and plastic deformation of the material. This directly increases cutting force and, ultimately, machining power [14].

On the other hand, surface roughness shows an increasing trend with increasing feed rate and depth of cut, while the effect of cutting speed is relatively smaller. This is caused by the increase in the distance between tool traces (feed marks) and the increase in cutting force that triggers vibration and plastic deformation on the workpiece surface. These results are consistent with recent research which states that feed rate is the most dominant parameter on surface roughness in the nanofluid MQL-based milling process [5]. In addition, the use of Fe_3O_4 nanofluids produces smoother surface roughness than Al_2O_3. This is due to the ability of Fe_3O_4 to increase heat dissipation and form a more effective protective layer, thereby reducing material adhesion and the formation of built-up edge (BUE). Other studies also show that nanofluids are able to suppress BUE and improve surface quality by improving lubrication and cooling mechanisms [15]. Conversely, Al_2O_3 particles with high hardness tend to cause micro-abrasion effects, thereby increasing surface roughness, especially at high feed rate conditions.

Statistical analysis using the Taguchi method and ANOVA confirmed the experimental findings. Based on the Taguchi approach with the "smaller is better" criterion, the optimal parameters for minimizing machining power and surface roughness were obtained at a combination of low feed rate and small depth of cut, as presented in Table 2. The ANOVA results showed that the largest contribution to machining power came from the depth of cut (≈45–55%), followed by feed rate (≈25–35%) and cutting speed (≈10–20%). Meanwhile, surface roughness was dominated by feed rate (≈40–50%), followed by the type of nanofluid (≈20–30%) and depth of cut (≈15–25%). This finding is in line with recent studies that reported that geometric parameters such as feed rate have a dominant influence on roughness, while cooling/lubrication strategies (nanofluids) contribute significantly to surface quality through tribological mechanisms [12].

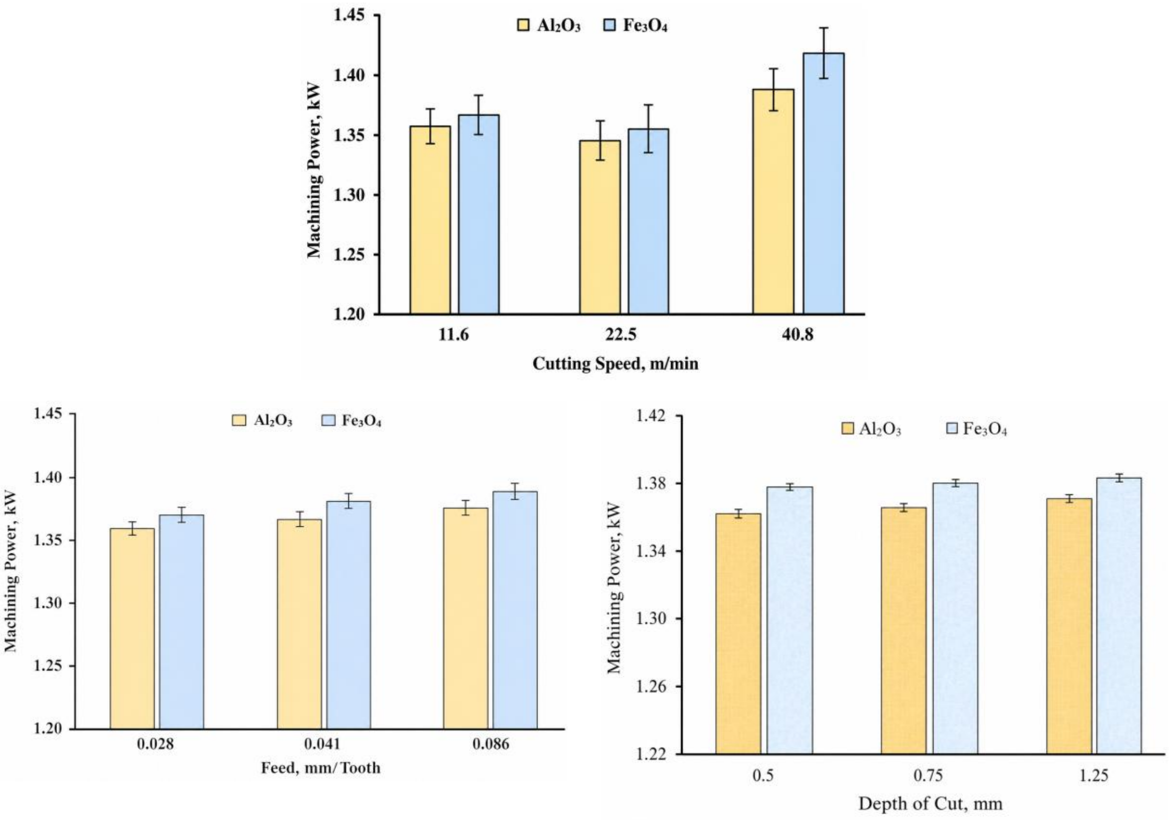

Fig. 3. Effect of cooling strategies on machining power at different cutting speeds, feed rates, and depths of cut

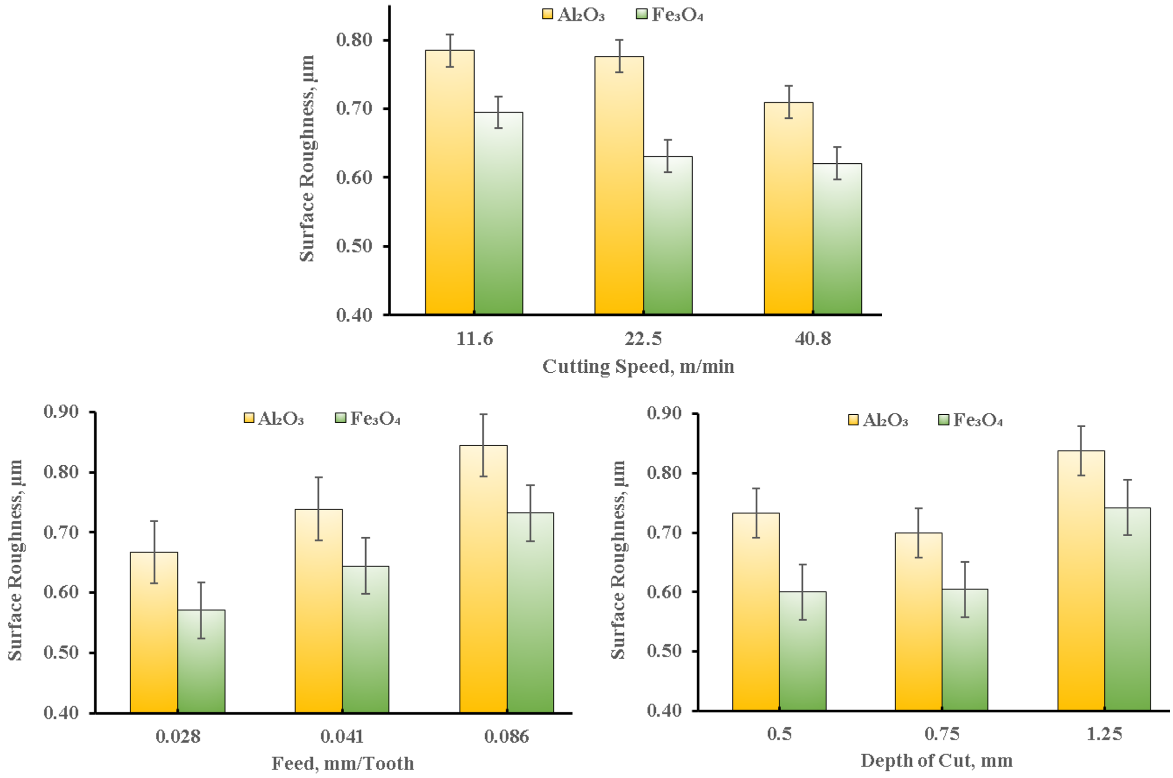

Fig. 4. Effect of cooling strategies on surface roughness at different cutting speeds, feed rates, and depths of cut

Table 2: Optimum parameters for machining using Al_2O_3 and Fe_3O_4 nanofluids

Response parameters	**input parameters**			**Nanofliuds**	
	v_c (m/min)	**f_z (mm/tooth)**	**a_x (mm)**	Al_2O_3	Fe_3O_4
Machining Power, kW	22.5	0.028	0.5	1.336	1.341
Surface Roughness, µm	40.8	0.028	0.5	0.596	0.494

Al_2O_3 nanofluids are superior in reducing machining power due to the dominance of friction reduction mechanisms, while Fe_3O_4 is more effective in improving surface quality through increased heat dissipation and lubrication film stability. The practical implication of this finding is that the selection of nanofluid types should be tailored to the process objectives: energy efficiency or surface quality. In addition, these results open up opportunities for the development of hybrid nanofluids that combine the tribological advantages of Al_2O_3 and the cooling ability of Fe_3O_4 to achieve optimal performance simultaneously.

4. CONCLUSION

The conclusion obtained from this study is that nanofluid cutting fluids, namely Al_2O_3 and Fe_3O_4, have different effects on machining power and surface roughness in the milling process with the MQL system. Al_2O_3 nanofluid consistently produces lower machining power (1%) than Fe_3O_4 under all experimental conditions, indicating better energy efficiency due to its more effective lubrication and friction reduction capabilities. In contrast, Fe_3O_4 produces lower surface roughness values (14.27%), thus providing a smoother surface quality than Al_2O_3. In addition, increasing machining parameters such as cutting speed (3.23%), feed rate (0.93%), and depth of cut (0.33%) tends to increase machining power due to increasing cutting load and volume of cut material. For surface roughness, increasing feed rate (8.49%) and depth of cut (6.16%) causes the surface to become rougher, while increasing cutting speed tends to improve the surface quality (3.73%). The optimal machining power conditions were achieved at v_c = 22.5 m/min, f_z = 0.028 mm/tooth, and a_x = 0.5 mm with values of 1,336 kW and 1,341 kW for Al_2O_3 and Fe_3O_4 nanofluids, respectively. Meanwhile, the optimal values for surface roughness were achieved at v_c = 40.8 m/min, f_z = 0.028 mm/tooth, and a_x = 0.5 mm with values of 0.596 µm and 0.494 µm for Al_2O_3 and Fe_3O_4 nanofluids, respectively. Overall, there is a trade-off between energy efficiency and surface quality, where Al_2O_3 is superior in reducing power consumption, while Fe_3O_4 is superior in producing smoother surfaces, so the selection of the type of nanofluid must be adjusted to the main objective of the machining process.

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REFERENCES

[1] A. Sharma and R. Kumar, “Potential use of minimum quantity lubrication (MQL) in machining of biocompatible materials using environment friendly cutting fluids: An overview,” *Mater. Today Proc.*, vol. 45, pp. 5315–5319, 2021, doi: 10.1016/j.matpr.2021.01.904.

[2] F. Kara, “Investigation of the effect of Al_2O_3 nanoparticle-added MQL lubricant on sustainable and clean manufacturing,” *Lubricants*, vol. 12, no. 11, 2024, doi: 10.3390/lubricants12110393.

[3] D. Y. Pimenov, O. Der, G. C. Manjunath Patel, K. Giasin, and A. Ercetin, “State of the art review of energy consumption in machining operations: Challenges and trends,” *Renew. Sustain. Energy Rev.*, vol. 224, no. June, p. 116073, 2025, doi: 10.1016/j.rser.2025.116073.

[4] R. Padmini, P. Vamsi Krishna, S. Mahith, and S. Kumar, “Influence of green nanocutting fluids on machining performance using minimum quantity lubrication technique,” *Mater. Today Proc.*, vol. 18, pp. 1435–1449, 2019, doi: 10.1016/j.matpr.2019.06.612.

[5] T. M. Duc and T. T. Long, “An experimental investigation of the effects MQL using nanofluids on surface roughness of hard milling Process,” *Eng. Technol. J.*, vol. 09, no. 05, pp. 3887–3892, 2024, doi: 10.47191/etj/v9i05.03.

[6] A. R. Amin, A. Ali, and H. M. Ali, “Application of nanofluids for machining processes: A comprehensive review,” *Nanomaterials*, vol. 12, no. 23, 2022, doi: 10.3390/nano12234214.

[7] C. Zhang, L. Gao, X. Zhou, and X. Wu, “Stability and photothermal properties of Fe_3O_4-H_2O magnetic nanofluids,” *Nanomaterials*, vol. 13, no. 13, 2023, doi: 10.3390/nano13131962.

[8] M. Yanis *et al.*, “Optimization of the surface roughness of the milling process using Al_2O_3 nanoparticles in MQL coconut oil based on the Taguchi method,” *AIP Conf. Proc.*, vol. 2991, no. 1, 2024, doi: 10.1063/5.0198636.

[9] D. T. Minh, L. T. The, and N. T. Bao, “Performance of Al_2O_3 nanofluids in minimum quantity lubrication in hard milling of $60Si_2Mn$ steel using cemented carbide tools,” *Adv. Mech. Eng.*, vol. 9, no. 7, pp. 1–9, 2017, doi: 10.1177/1687814017710618.

[10] S. Haghnazari and V. Abedini, “Effects of hybrid Al_2O_3–CuO nanofluids on surface roughness and machining forces during turning AISI 4340,” *SN Appl. Sci.*, vol. 3, no. 2, 2021, doi: 10.1007/s42452-020-04088-w.

[11] T. B. Ngoc, T. M. Duc, N. M. Tuan, and T. T. Long, “Influence of Al_2O_3/MoS_2 hybrid nanofluid MQL on surface roughness, cutting force, tool wear and tool life in hard turning,” *Forces Mech.*, vol. 16, no. July, 2024, doi: 10.1016/j.finmec.2024.100285.

[12] M. D. Shah and A. Utpat, “Performance evaluation of Al_2O_3-based castor oil nanofluid in MQL-assisted turning of AISI 316L stainless steel,” *J. Mater. Sci. Mater. Eng.*, vol. 20, no. 1, 2025, doi: 10.1186/s40712-025-00341-5.

[13] S. Kalpakjian and S. R. Schmid, *Manufacturing - Engineering and Technology*, Seventh Ed. United Kingdom, 2021.

[14] N. M, P. S. T. Kumar, T. H. P. Prasada, R. Rangappa, J. C. Abbar, and S. Prabhu S, "Performance evaluation of nano cutting fluids under MQL technique in turning of duplex stainless steel-2205," *Discov. Appl. Sci.*, vol. 7, no. 11, 2025, doi: 10.1007/s42452-025-07702-x.

[15] A. Yücel *et al.*, "Influence of MoS_2 based nanofluid-MQL on tribological and machining characteristics in turning of AA 2024 T3 aluminum alloy," *J. Mater. Res. Technol.*, vol. 15, pp. 1688–1704, 2021, doi: 10.1016/j.jmrt.2021.09.007.