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RESEARCH ARTICLE

Machining performance of SS304 steel with hybrid nano-cutting fluids using Taguchi-based grey relational analysis

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ABSTRACT - Traditional cutting fluids are often insufficient in managing the heat, friction generated during machining and environmental issues. Using hybrid nano-cutting fluids contributes to green manufacturing by reducing the need for excessive coolant flow and minimizing environmental impact. This study investigates the machining performance of SS304 steel using hybrid nano-cutting fluids and evaluates the results through Taguchi-based Grey Relational Analysis (GRA). The hybrid nanocutting fluids were formulated by dispersing a combination of nanoparticles into a conventional cutting fluid. A series of turning experiments were conducted using the Taguchi L27 design experiment. The results demonstrated that the neem oil with 1.5% alumina and graphene inclusion observed significantly improved the machining efficiency of SS304 steel, offering reduced tool temperature, cutting forces, tool vibrations and surface roughness. A notable reduction of cutting temperature, cutting force, tool vibration, and surface roughness by 35%, 18%, 27%, and 34% respectively, are observed. From GRA, outstanding results are obtained at a cutting speed of 900 rpm, a feed rate of 40 mm/min, a depth of cut of 0.6 mm, and a 1.5 vol % concentration of hybrid nanofluid. The optimal cutting condition helps reduce the cutting temperature, tool vibrations, and cutting forces and improves surface roughness.

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1. INTRODUCTION

Cutting fluids play an important part in machining by lubricating and cooling the workpiece and the tool and facilitating the removal of chips from the cutting area [1]. Various cooling methods, such as flood, dry, and air, are used to enhance machining performance. Excessive cutting fluid consumption pollutes the environment and creates operator health issues. Dry machining leads to some materials' tool wear and poor surface quality [2]. Air cooling may not be effective for heavy-duty machining. Researchers have proposed the Minimum Quantity Lubrication (MQL) method as an effective substitute. MQL involves a small quantity of high-pressure cutting fluid in the cutting area, enhancing the chip-tool interface [3]. Scientific consensus suggests that MQL reduces cutting forces, improves surface finish, and extends tool life. Altaf et al. [4] reported the various benefits of the MQL and nanofluid-based MQL technique compared with conventional cooling methods. Manikanta et al. [5] extensively reviewed hybrid cutting fluid through nanomaterials. They reported substantial improvement in heat dissipation, tool life, surface roughness, and reduced temperature and cutting forces at the cutting zone. This study has explored various nanoparticle combinations for cutting fluid improvement. Jadhav and Sahai [6] investigated surface roughness during face milling of EN19 using neem oil with graphene nanoparticle coolant. The experiments revealed that this eco-friendly coolant offers a sustainable solution, addressing health and environmental concerns. The findings indicated that the cutting fluid was the most significant factor influencing surface roughness, with speed and depth of cut also playing important roles. Virdi et al. [7] investigated the grinding of Inconel-718 alloy using Nano Fluid MQL (NFMQL) with biodegradable oils as the base. The experimental results indicated that the nanofluid MQL significantly improved the surface roughness (0.5 μm) compared to flood cooling conditions.

Sateesh et al. [8] used a mixture of nano-boric acid and canola oil in MQL to turn EN19 steel. The results reported that cutting force, tool temperature, and surface roughness decreased with increasing percentage of boric acid nanoparticles. Zareie et al. [9] developed a hybrid nanofluid by mixing MgO and Multi-walled Nano Carbon Nanotube (MWCNT) in equal proportions in water and ethylene glycol, reporting changes in dynamic viscosity with volume fractions and temperature. According to Singh et al. [10], cutting force and surface quality are improved for Al_2O_3–graphene hybrid nanofluid. Zhang et al. [11] synthesized Al_2O_3, SiC, and Al_2O_3–SiC hybrid nanofluids, demonstrating superior performance in grinding to pure Al_2O_3 and SiC nanofluids. Jamil et al. [12] examined the effectiveness of oil-based hybrid nanofluid in machining Ti–6Al–4V, achieving reductions in cutting force and surface roughness compared to CO_2 cryogenic coolant. Ahammed et al. [13] reported significant improvements in heat transfer and temperature

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reduction by utilising Al_2O_3/graphene hybrid nanocutting fluid. Zhang et al. [14] investigated the effect of MoS_2-CNT nanofluid in grinding. The study revealed that good surface quality is achieved compared to individual use of MoS_2 and CNT. Song et al. [15] achieved a significantly elevated enhancement in conductivity by incorporating a multi-walled carbon nanotube into the cutting fluid. Sidik et al. [16] investigated diamond nanoparticles with MQL metal-cutting processes, claiming significant improvement. While extensive research has been conducted using cutting fluids enhanced with mono-type nanoparticles for machining, relatively few studies have explored hybrid nanofluids.

Tiwari et al. [17] studied the influence of varying concentrations of nano-Al_2O_3 with coconut oil with the MQL system. stigated during the turning of AISI-1040 steel. The finding showed that tool wear and cutting temperature are reduced by 53% and 55% compared with conventional methods. Das et al. [18] reported enhanced machining performance with reduced cutting forces using diverse nanofluids in steel machining. Additionally, investigations into the thermo-physical attributes of hybrid nano-cutting fluids indicated advancements in the base fluid's thermo-physical and tribological aspects. Ondin et al. [19] investigated the influence of cutting fluid and multi-walled carbon nanotubes into vegetable-based cutting fluid on PH 13-8 Mo stainless steel machining. The key finding revealed that 5% and 12% lower surface roughness was achieved with pure-MQL and nanofluid-MQL, respectively. Zhujani et al. [20] used grey relational analysis to optimize the parameters for turning Inconel 718. They used Analysis of Variance (ANOVA) to determine the optimal input parameters and their percentage contributions. Kamble et al. [20] evaluated the machining performance using Taguchi and GRA in turning AISI 4340 steel. Minimum tool wear (0.0401 mm) is observed when the MQL system is employed. Researchers [22-24] determined optimum cutting parameters with multi-performance characteristics using GRA. In some experiments, it was clearly expressed that nanotechnology helps in machining processes with the MQL method to achieve good machining performance and reduce cutting fluid wastage. Singh et al. [25] conducted turning operations utilizing a cutting fluid enriched with graphite-talc hybrid nanoparticles, demonstrating notable improvements in cutting performance compared to the base fluid. The previous studies extensively explored single-type nanoparticle-based cutting fluids; the utilization of hybrid nanofluids in machining remains relatively unexplored. The literature underscores the gap in research on hybrid nanoparticle cutting fluids, particularly in turning processes, a crucial aspect in the manufacturing sector. This study strategically focuses on exploring the use of hybrid nanofluid in turning processes to contribute to the existing knowledge base. The machining performance with neem oil-based hybrid nano-cutting fluids is investigated.

2. MATERIAL AND METHODS

In this work, a workpiece made of SS304 steel is used. The cylindrical bars of 60 mm diameter, *D* and 450 mm cutting length, *L* is selected as per ISO 3685 standards [22]. The chemical composition of the work material is 18-20% Cr, 8-10% Ni, 1% Si, 2% Mn, 0.045% P, 0.03% S, and 0.08% C. The mechanical and thermal properties are reported in Table 1. The base ingredients for the hybrid non-cutting fluid are neem oil, alumina nanoparticles ranging in size from 30 to 50 nm, and graphene nanoparticles ranging from 5 to 10 nm. In neem oil, alumina and graphene nanoparticles were mixed in a 50:50 volumetric ratio to form the hybrid nanocutting fluid. The base fluid was subjected to concentrations of the combined powdered particles of 0.5%, 1%, and 1.5%. The 50:50 volumetric ratio was selected based on maintaining equal proportions of alumina and graphene nanoparticles in the mixture. The fabrication process involved using a magnetic stirrer and ultrasonicator, each employed for 3 hours. This resulted in a homogenous and stable suspension. Combining alumina and graphene nanoparticles in neem oil at varying concentrations offers versatility for different applications. The meticulous preparation ensures the uniform distribution of nanoparticles in the base fluid, enhancing the effectiveness of the resulting nano-cutting fluid in various cutting applications. Alumina nanoparticles improve wear resistance and thermal stability in high-speed machining. Graphene offers unmatched friction reduction, thermal conductivity, and eco-friendliness, making it an excellent advanced material for cutting fluids and lubricants. Neem oil provides a biodegradable, natural option with anti-corrosive and antibacterial properties for environmentally conscious applications, especially in low to moderate load-bearing operations.

Table 1. Mechanical properties of SS304

Property	Value
Comprehensive Strength	210 MPa
Tensile Strength	520 - 720 MPa
Density	8000 kg/m^3
Modulus of Elasticity	193 GPa
Poissons ratio	0.27

The experimental configuration intended for turning operations on a centre lathe machine is schematically diagrammed in Figure 1. Nanoparticle concentration (NPC), depth of cut (DOC), feed rate, and cutting speed are the four main control elements that can be adjusted at three different levels each. The primary objective is to investigate the machining characteristics, including cutting temperature, cutting force, tool vibration, and surface roughness. By systematically altering these control factors, the study aims to discern their impact on the overall machining process. This comprehensive exploration provides valuable insights into the interactions between the chosen factors and the resulting machining outcomes. The varying levels of each parameter contribute to a thorough analysis of the experimental conditions, enabling a nuanced understanding of different factors that influence the performance of the turning operation. The chosen values for the control factors at each level are shown in Table 2. These levels are established using experience and rigorous adherence to the minimum and maximum parameters advised by the manufacturer. The experiments were carried out at least three times, and the averages of the results were taken.

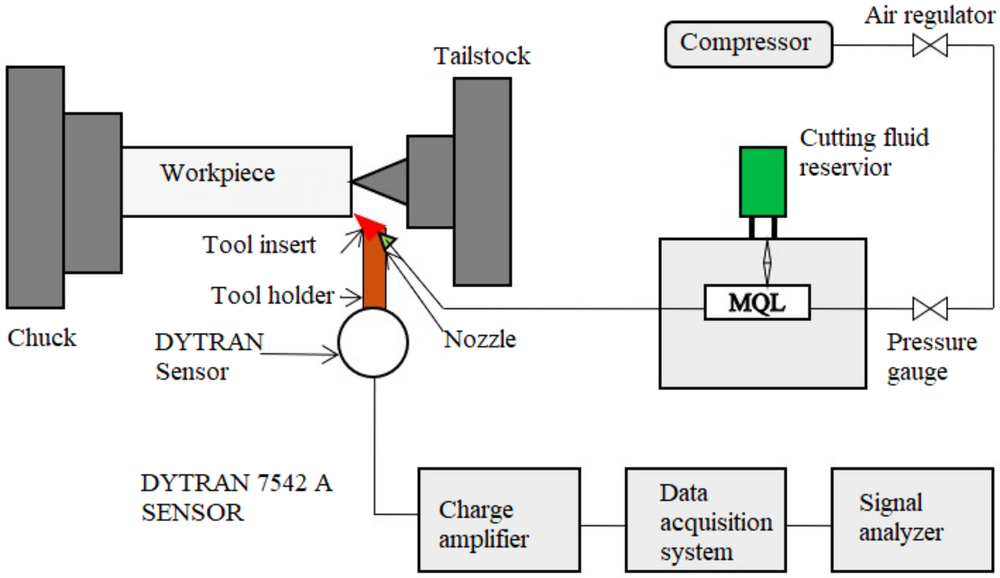


Figure 1. Experimental methodology

Table 2. Parameters and levels

Parameter	Levels		
	L1	L2	L3
Cutting speed, *S* (rpm)	700	800	900
Feed, *F* (mm/min)	20	40	60
Depth of cut (mm)	0.2	0.4	0.6
Concentration of nanoparticles (% volume)	0.5	1.0	1.5

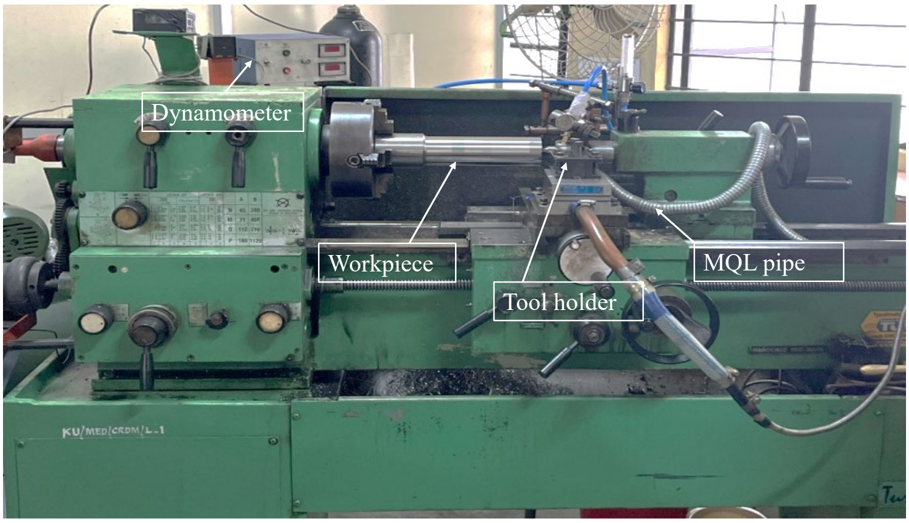
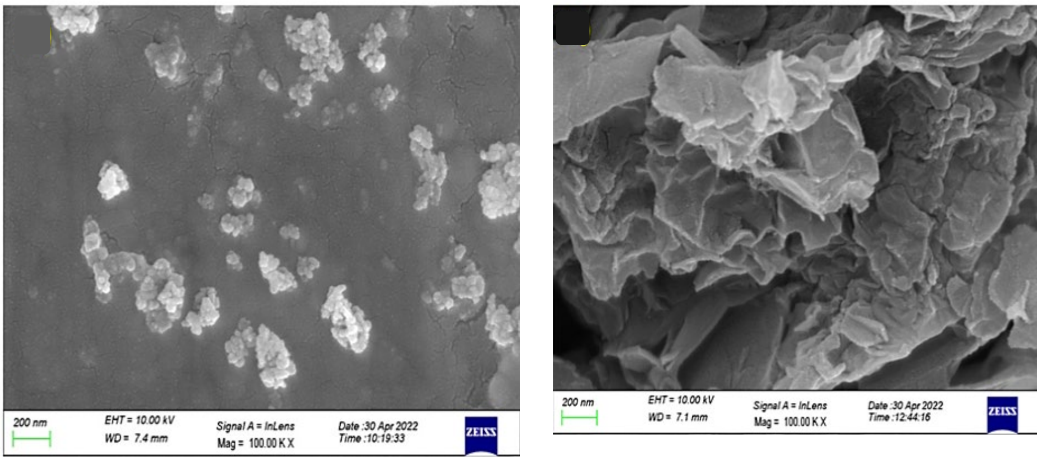


Figure 2. Lathe machine experiment setup

The experiment setup is shown in Figure 2. The experimental measurements encompassed various parameters. The cutting temperature was measured using an infrared thermometer (IRX-66), while the cutting force was gauged with a Kistler dynamometer (Type 9257 B). Vibration data was captured using a tool fitted with a vibration sensor linked to a 7543A-type PC-based triaxial accelerometer. R_a, a surface roughness instrument (Mitutoyo SJ-201 P), was employed to evaluate the workpiece's average surface roughness. Data collection occurred systematically during each turning operation, encompassing diverse machining conditions. These measurements comprehensively understand the thermal, mechanical, and surface characteristics encountered during the turning process. The utilization of advanced instruments ensures precision and accuracy in capturing critical data points related to temperature, force, vibration, and surface quality.

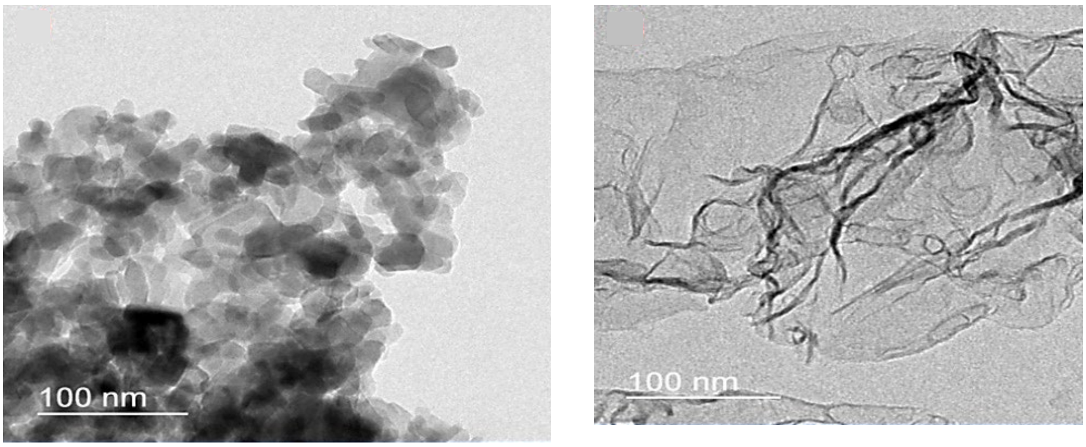
This systematic data collection contributes to a thorough analysis of the impact of varying machining conditions on the observed parameters, enhancing the overall comprehension of the turning operation.

Turning stainless steel was performed on a lathe machine (Kirloskar, turn master 35, centre lathe) using an MQL system by applying hybrid nano-cutting fluids at various concentrations. Figure 3 and Figure 4 depict the Scanning Electron Microscope (SEM) and Transmission electron microscope (TEM) images of nanoparticles. The carbide tool (SNMG 120408) was securely clamped onto a sturdy tool holder (PSBNR 2525M12). In addition, a]MQL system, comprising a nozzle, compressor and flow control unit, was employed for lubrication at the machining zone. The MQL system could sustain an air supply pressure of 5 bar and a nanocutting fluid flow rate of 50 ml/min. The strategically positioned spray nozzle, located 4 cm above the tool rake face, facilitated the precise delivery of nano-cutting fluid onto the tool surface. This arrangement ensured effective impingement of the developed nanocutting fluid into the cutting zone, optimizing the lubrication process during machining operations. The integration of the MQL system and the specific placement of the spray nozzle contribute to an efficient and targeted application of nanocutting fluid, enhancing the overall performance of the cutting process.



(a) (b)

Figure 3. SEM image of (a) Alumina and (b) Graphene



(a) (b)

Figure 4. TEM image of (a) Alumina and (b) Graphene

2.1 Design of Experiments

Experiments are designed to plan, conduct, and analyze experiments efficiently to produce accurate and dependable results. This helps to reduce the cost and effort of experimentation. In this work, the Taguchi L_{27} method of experimental matrix is employed. The Taguchi L_{27} orthogonal array is a popular method for designing experiments using the Taguchi approach. It helps study the influence of multiple variables on a response in a structured and efficient way. Taguchi's method uses the S/N ratio to quantify the quality of outcomes. Different S/N ratios are chosen depending on the goal: larger-the-better, smaller-the-better and nominal-the-best. This study aims to minimize cutting temperature, cutting force, tool vibration, and surface roughness in machining processes. Analysis of Means (ANOM) is used to assess the impact of factors listed in Table 3 on cutting temperature, *CT* (°C), cutting force, *CF* (N), tool vibration, *TV* (mm), surface roughness, and *SR* (μm). By giving each factor a rank, ANOM addresses the input factors with the greatest and least effects in descending order. Table 3 shows the experimental output for the L_{27} method.

Table 3. Experimental matrix and corresponding responses

Run	*S*	*F*	DOC	NPC	*CT* (°C)	*CF* (N)	*TV* (mm/sec^2)	*SR* (µm)
1	700	20	0.2	0.5	56.8	146.4	0.0180	1.50
2	700	20	0.4	1.0	58.0	142.4	0.0177	1.42
3	700	20	0.6	1.5	53.0	140.9	0.0168	1.45
4	700	40	0.2	0.5	57.4	138.7	0.0156	1.32
5	700	40	0.4	1.0	52.9	128.1	0.0152	1.37
6	700	40	0.6	1.5	50.2	130.1	0.0160	1.14
7	700	60	0.2	0.5	52.4	135.5	0.0161	1.32
8	700	60	0.4	1.0	52.5	127.3	0.0149	1.31
9	700	60	0.6	1.5	50.5	130.5	0.0158	1.10
10	800	20	0.2	1.0	45.4	151.3	0.0174	1.02
11	800	20	0.4	1.5	44.0	135.1	0.0165	0.98
12	800	20	0.6	0.5	46.9	144.5	0.0155	1.01
13	800	40	0.2	1.0	46.7	143.5	0.0139	0.91
14	800	40	0.4	1.5	48.5	135.8	0.0130	0.92
15	800	40	0.6	0.5	43.5	143.7	0.0142	1.18
16	800	60	0.2	1.0	44.8	142.7	0.0156	1.07
17	800	60	0.4	1.5	40.3	125.1	0.0139	0.99
18	800	60	0.6	0.5	44.8	139.9	0.0140	0.96
19	900	20	0.2	1.5	45.1	132.9	0.0142	1.05
20	900	20	0.4	0.5	43.5	129.5	0.0137	1.06
21	900	20	0.6	0.1	46.7	134.7	0.0140	1.08
22	900	40	0.2	1.5	39.4	120.6	0.0131	0.99
23	900	40	0.4	0.5	38.7	114.8	0.0135	1.11
24	900	40	0.6	1.0	36.7	120.0	0.0131	0.98
25	900	60	0.2	1.5	36.2	112.5	0.0126	0.90
26	900	60	0.4	0.5	39.3	113.8	0.0127	0.96
27	900	60	0.6	1.0	37.2	123.6	0.0130	0.98

3. RESULTS AND DISCUSSION

3.1 Thermo Physical Properties of Nanocutting Fluids

This study mainly focused on the effect of nanoparticle concentration on fundamental properties such as thermal conductivity and viscosity. Figure 5 shows the equipment used to measure the thermal conductivity and viscosity. A KD 2 pro thermal analyzer was used to measure thermal conductivity. Figure 6 depicts the effect of varying concentrations of alumina/graphene hybrid nanofluids on the thermal conductivity. It can be seen that there is an increasing trend in thermal conductivity as the percentage of hybrid nanofluids increases. Neem oil-based hybrid nano-cutting fluid shows low thermal conductivity.

(a) (b)

Figure 5. (a) KD 2 pro thermal analyser and (b) Redwood viscometer

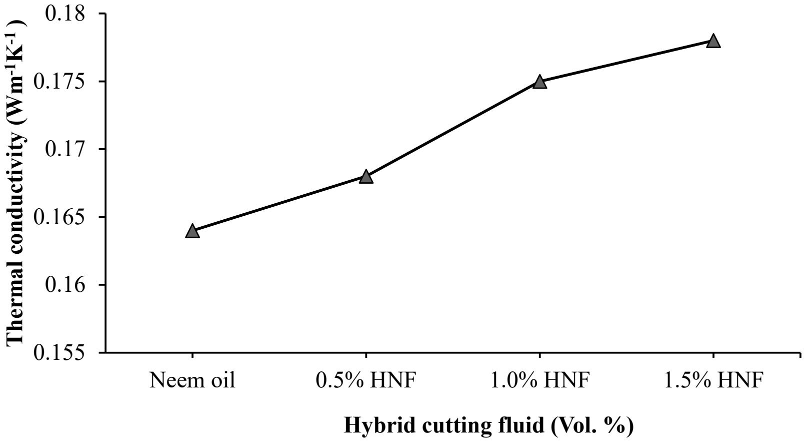


Figure 6. The variation in thermal conductivity with various nanofluids

The highest value, with 1.5% hybrid nanoparticles, was discovered and denotes the highest thermal conductivity of all fluids. The thermal conductivity of hybrid nano-cutting fluids has been improved, helping to dissipate more heat effectively from the cutting zone in turning operation, which leads to good machining performance. Figure 7 depicts the effect of the concentration of alumina/graphene hybrid nanofluids on the viscosity. It can be revealed that viscosity is increased with increased hybrid nanoparticles over base oil with particle concentrations of 0.5-1.5% by volume. The alumina/graphene hybrid nanofluid becomes more viscous due to the increased particle concentration in the fluid. As a result of the improved intermolecular force of attraction between the particles at higher concentrations, viscosity becomes greater. Nanoparticles have a high surface area-to-volume ratio, which enhances heat transfer between the fluid and the solid particles. The random motion of nanoparticles suspended in the fluid leads to increased energy transfer and better thermal conduction.

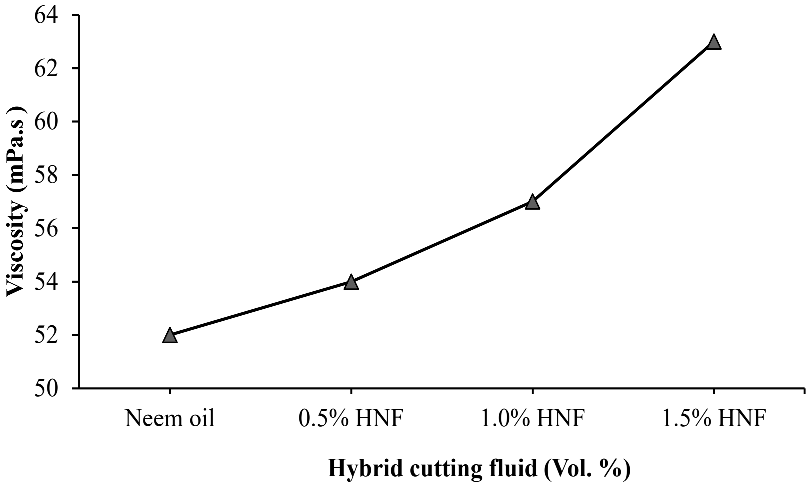


Figure 7. The variation in viscosity with various nanofluids

3.2 Cutting Temperature

Cutting temperature significantly represents the friction and heat in machining. The present work measured cutting temperatures for all considered lubrication conditions. It may be noted from Table 4 that neem oil with 1.5% alumina and graphene inclusion observed the lowest cutting temperatures. The reduction in cutting temperature with alumina and graphene di-hybrid nanofluid is primarily attributed to the enhanced thermal conductivity of the nanofluid.

Table 4. ANOM for S/N ratios of main cutting temperature

Level	Cutting speed	Feed	Depth of cut	Concentration of nanoparticles
1	-34.61	-33.73	-33.12	-33.26
2	-33.07	-33.18	-33.08	-33.47
3	-32.08	-32.84	-33.56	-33.03
Delta	2.53	0.89	0.48	0.44
Rank	1	2	3	4

Including alumina and graphene nanoparticles improve the nanofluid's ability to dissipate heat, leading to more effective cooling at the cutting zone. This increased thermal conductivity facilitates heat transfer from the cutting tool, preventing excessive temperature buildup. Additionally, the lubricating properties of graphene contribute to smoother cutting, reducing frictional heat generation. The overall effect is a lower cutting temperature, which helps mitigate thermal damage to the tool and workpiece during machining. Figure 8 shows the effects of the factors on the main cutting temperature. It may be inferred that 900 rpm speed, 60 mm/min feed rate, 0.4 mm depth of cut, and 1.5% concentration of nanoparticles are the optimum conditions for reducing cutting temperature.

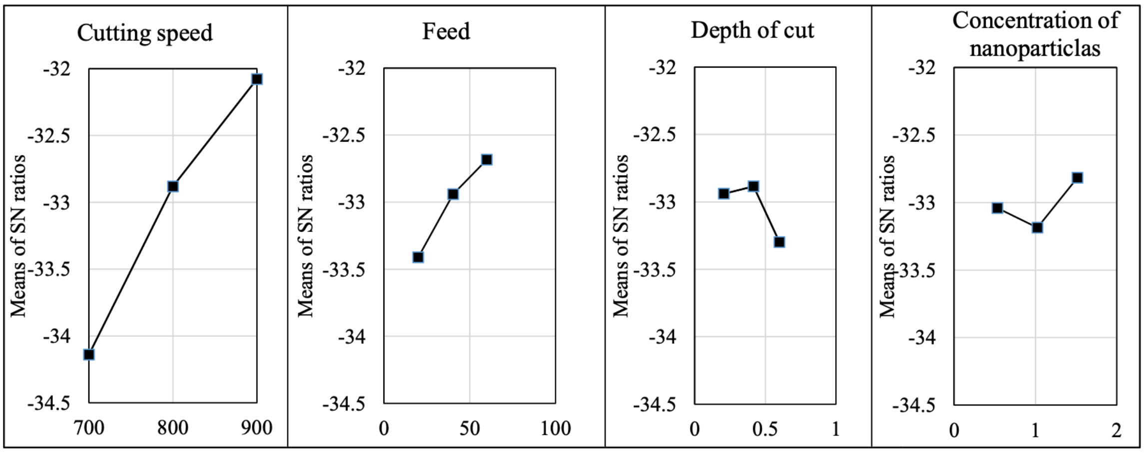


Figure 8. Factor effects for cutting temperature

3.3 Cutting Forces

Cutting forces is considered a crucial parameter for assessing the machining process's performance. Table 5 shows ANOM for S/N ratios of the main cutting force. The reduction in cutting force with alumina and graphene di-hybrid nanofluid can be attributed to enhanced thermal conductivity and lubrication properties. The nanofluid's improved cooling, favorable flow properties, and friction reduction contribute to a more efficient machining process, lowering cutting forces. Figure 9 shows ANOM for S/N ratios of the main cutting force. It may be inferred that 900 rpm speed, 60 mm/min feed rate, 0.4 mm depth of cut and 1.5% concentration of nanoparticles are the optimum conditions for reducing cutting force.

Table 5. ANOM for S/N ratios of main cutting force

Level	Cutting speed	Feed	Depth of cut	Concentration of nanoparticles
1	-42.64	-42.90	-42.42	-42.48
2	-42.94	-42.30	-42.31	-42.52
3	-41.75	-42.13	-42.59	-42.33
Delta	1.19	0.78	0.28	0.19
Rank	1	2	3	4

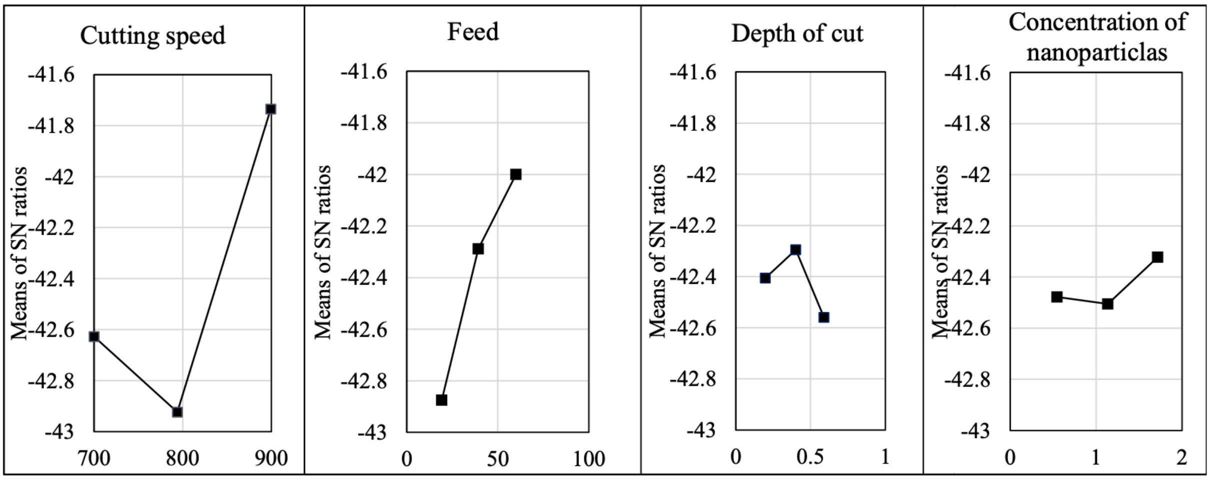


Figure 9. Factor effects for cutting force

3.4 Tool vibration

Tool vibration significantly represents the friction and disturbances in machining. Tool vibrations have been captured for all experimental runs. Table 6 shows ANOM for S/N ratios of tool vibration. Alumina and graphene di-hybrid nanofluid reduces tool vibration by enhancing thermal conductivity, mitigating thermal expansion, and reinforcing the cutting tool. The lubricating properties of graphene further minimize friction and wear, contributing to smoother machining processes and overall reduced tool vibration. Figure 10 shows the factor effects on tool vibration. It may be inferred that 900 rpm speed, 40 mm/min feed rate, 0.6 mm depth of cut, and 0.5% concentration of nanoparticles are the optimum conditions for reducing tool vibration.

Table 6. ANOM for S/N ratios of tool vibration

Level	Cutting speed	Feed	Depth of cut	Concentration of nanoparticles
1	35.80	35.96	36.49	36.76
2	36.56	36.99	36.56	36.66
3	37.51	36.92	36.83	36.45
Delta	1.71	1.02	0.34	0.31
Rank	1	2	3	4

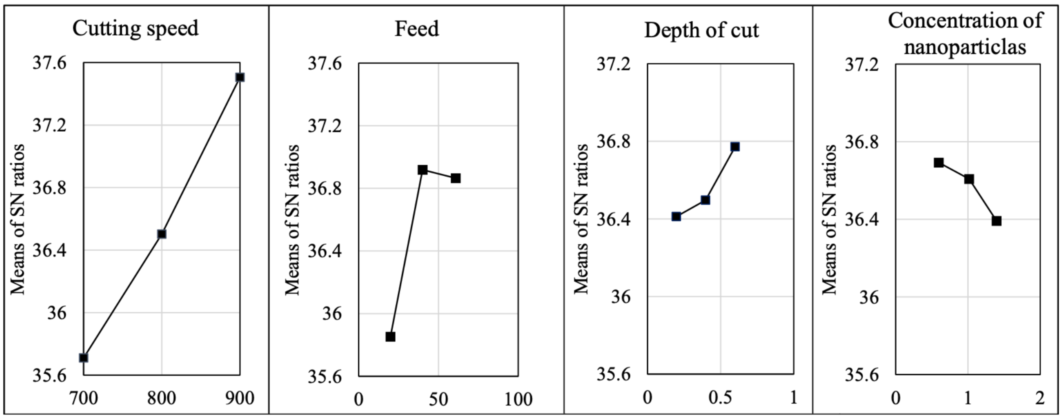


Figure 10. Factor effects for tool vibration

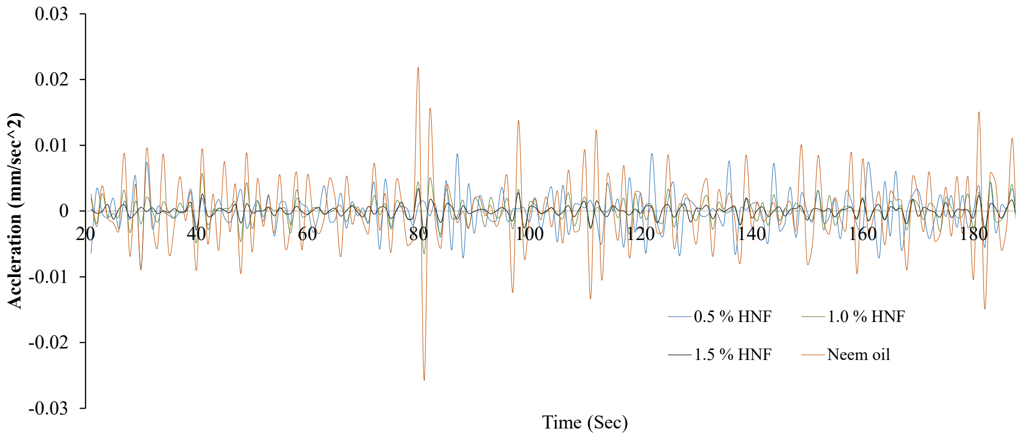


Figure 11. Vibration response of tool holder

Figure 11 shows the tool response in the time domain for the hybrid. In the time domain, vibration signals are represented as a function of time. The tool's vibration amplitude is recorded as it fluctuates with time due to various forces and cutting conditions. When the concentration of 1.5% hybrid particles is used, the vibration amplitude in the time-domain graph is likely relatively small, indicating smoother and more stable cutting conditions.

3.5 Surface Roughness

In machining, surface roughness substantially represents friction and thermal deformation. Surface roughness was measured for all experimental runs. The findings reveal that neem oil with 1.5% alumina and graphene provides the least surface roughness. Table 7 represents the set of cutting conditions for enhanced surface surface quality. Alumina and graphene di-hybrid nanofluid reduces surface roughness by enhancing thermal conductivity for efficient heat dissipation, utilizing graphene's lubricating properties to minimize friction, and employing the reinforcement effect of nanoparticles to ensure a stable cutting process, reducing tool wear and achieving a finer surface finish. The impact of factors on surface roughness is depicted in Figure 12. The best conditions for reducing surface roughness may be deduced to be 800 rpm speed, 60 mm/min feed rate, 0.4 mm depth of cut, and 1.5% concentration of nanoparticles.

Table 7. ANOM for S/N ratios of surface roughness

Level	Cutting speed	Feed	Depth of cut	Concentration of nanoparticles
1	-2.44582	-1.27786	-1.19310	-0.96492
2	-0.06429	-0.82873	-0.56905	-0.91613
3	-0.10215	-0.50568	-0.85011	-0.73122
Delta	2.38153	0.77218	0.62405	0.23370
Rank	1	2	3	4

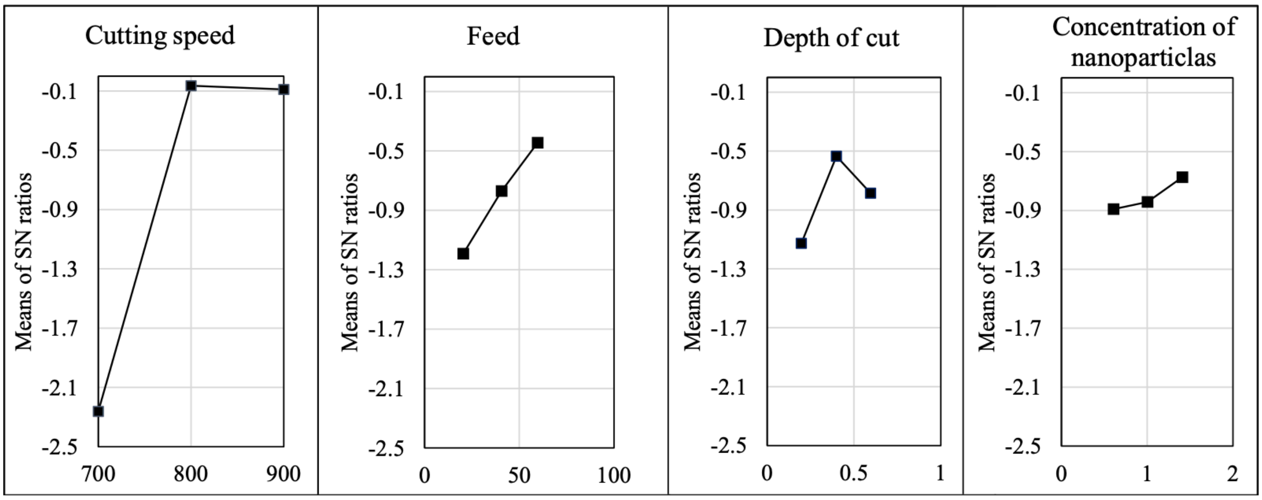


Figure 12. Factor effects for surface roughness

3.6 Grey Relational Analysis

The arrays, structured as m x n matrices, feature rows representing test numbers and columns representing input parameters. Stainless steel turning adhered to the experimental design outlined in Table 3, which succinctly organizes the experiment sequence, machining parameters, and four response parameters for various hybrid nano-cutting fluids. The first phase of the GRA is called "grey relational generating," which processes each alternative to create a comparability sequence before estimating the grey correlational coefficients. The original sequence is normalised, and strategies like "smaller/larger-the-better" are applied based on the intended value. The current study adopts the "smaller-the-better" approach, and Eq. (1) shows the employed formula.

$$y_i^*(k) = \frac{max.y_i^{(o)}(k) - y_i^{(o)}(k)}{max.y_i^{(o)}(k) - min.y_i^{(o)}(k)} \tag{1}$$

where, $y_o(k)$ and $y_i(k)$ assumed as an original sequence for comparison. Several experiments and observations are represented with'm' and'n', respectively. The regression grey relational coefficient is given by Eq. (2).

$$\gamma(y_o^*(k), y_i^*(k)) = \frac{\Delta_{min} + \zeta_{max}}{\Delta_{oi}(k) + \zeta\Delta_{max}} \tag{2}$$

$$0 < \gamma(y_o^*(k), y_i^*(k)) \leq 1 \tag{3}$$

where Δmin is the smallest value of $\Delta_{oi}(k)$ and $\zeta$is the distinguishing coefficient. The grey relational grading (GRG) is evaluated using Eq. (3),

$$\gamma(y_o^*, y_i^*) = \sum_{k=1}^{n} \beta_k \gamma(y_o^*(k), y_i^*(k)) \tag{4}$$

$$\sum_{k=1}^{n} \beta_k = 1 \tag{5}$$

GRG is estimated upon applying the processing parameters in the above-represented equations, as listed in Table 8. The 24th combination is ranked with the best position, '1' and treated as the best combination for obtaining outstanding results for *CT*, *CF*, *TV* and *SR*.

Table 8. Grey relational coefficient and grey relational grade

Run	Grey relational coefficient				GRG	Rank
	CT	*CF*	*TV*	*SR*		
1	0.411	0.287	0.316	0.300	0.503	27
2	0.383	0.368	0.406	0.346	0.539	25
3	0.296	0.492	0.542	0.324	0.500	23
4	0.398	0.341	0.376	0.374	0.581	24
5	0.545	0.602	0.663	0.380	0.615	11
6	0.576	0.729	0.804	0.378	0.612	9
7	0.570	0.535	0.589	0.372	0.495	13
8	0.561	0.622	0.685	0.478	0.604	10
9	0.481	0.807	0.889	0.396	0.673	8
10	0.408	0.298	0.329	0.321	0.398	26
11	0.447	0.513	0.565	0.398	0.492	18
12	0.373	0.513	0.565	0.359	0.468	19
13	0.378	0.436	0.481	0.419	0.474	20
14	0.344	0.431	0.475	0.393	0.489	22
15	0.462	0.703	0.774	0.589	0.527	7
16	0.425	0.506	0.558	0.464	0.486	17
17	0.410	0.480	0.529	0.542	0.547	14
18	0.425	0.542	0.598	0.525	0.520	12
19	0.417	0.387	0.427	0.397	0.475	21
20	0.463	0.566	0.624	0.382	0.518	15
21	0.377	0.542	0.598	0.484	0.489	16
22	0.545	0.612	0.675	0.756	0.653	5
23	0.694	0.643	0.709	0.594	0.609	4
24	0.890	0.862	0.950	0.856	0.668	1
25	0.826	0.678	0.747	0.900	0.763	2
26	0.656	0.622	0.685	0.599	0.653	6
27	0.830	0.843	0.929	0.661	0.599	3

Table 9. Grey relation grade responses

Parameter	GRD			Rank
	L1	L2	L3	
S	0.5691	0.4890	0.6030	1
F	0.4869	0.5809	0.5933	2
D	0.5364	0.5629	0.5618	4
NP	0.4890	0.5416	0.5479	3

The optimal configuration of parameters for the turning operation on materials like stainless steel was identified as 900 RPM, a feed rate of 40 mm/min, a depth of cut of 0.6 mm, and a 1.0 vol % concentration of hybrid nanofluid. These settings yielded the minimum values for cutting temperature, cutting force, tool vibration, and surface roughness, resulting in 36.7°C, 120N, 0.0131 mm, and 0.98 µm, respectively. Referring to Table 9, it is evident that cutting speed secured the top position among all input parameters based on grey relation grade responses, closely followed by the feed rate. This optimal parameter combination demonstrates its efficacy in achieving superior results and minimizing the adverse effects of turning on stainless steel, such as elevated temperature, excessive cutting force, tool vibration, and surface irregularities.

Table 10. GRD ANOVA analysis

Source	DoF	Sum of Squares	Mean Square	% Contribution
S	2	0.061687	0.032195	34.36%
F	2	0.060964	0.023738	33.95%
D	2	0.004027	0.002575	2.24%
NP	3	0.010875	0.003625	6.06%
Error	17	0.041993	0.002470	23.39%

Table 10 demonstrates the impact of each parameter on test results. Figure 13 shows the main effect plot for GRG. Cutting speed exerts the most significant influence on machining responses, while the depth of cut exhibits the least effect. Subsequently, Table 11 presents the experimental confirmation results employing the optimal process variables.

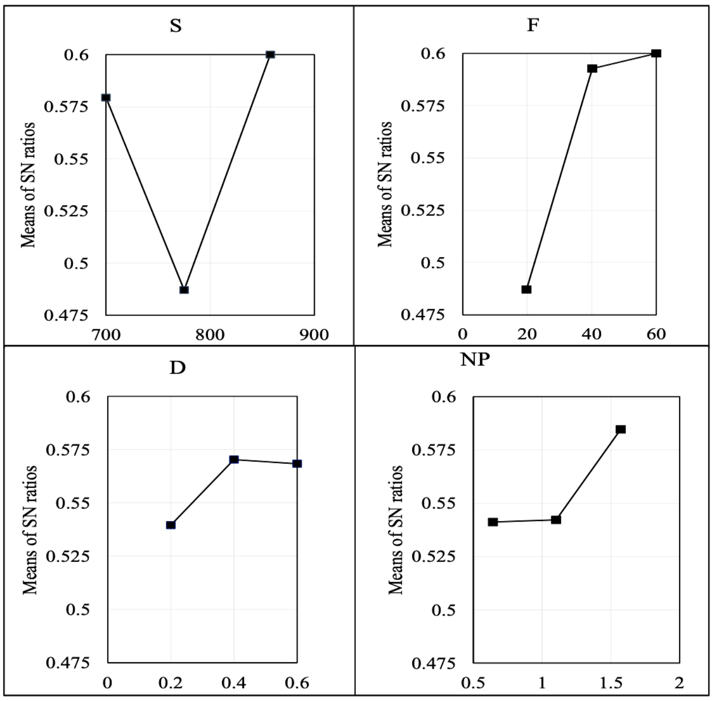


Figure 13. Main effect plot for GRG

To validate the experiment in this work, a set of arbitrary combinations of input parameters that fell inside the boundaries of the complete factorial design but outside the experimental run were chosen. The initial turning parameters were as follows: cutting speed at 700 RPM, feed rate set to 20 mm/rev, depth of cut at 0.2 mm, and nanoparticle concentration at 0.5 vol.%. The experiments were conducted thrice using the established optimal levels and randomly chosen settings for process variables. For each specimen, the cutting temperature, cutting force, tool vibration, and surface roughness were measured under alumina-graphene hybrid nano-cutting fluid conditions.

Table 11. Experimental confirmation

Level	Optimal Process variables and corresponding response values (A)				Initial Process variables and corresponding response values (B)				% Variation of A w.r.t B
	S 900 rpm	*F* 40 mm/min	*D* 0.6 mm	*NP* 1.5 vol %	*S* 700 rpm	*F* 20 mm/min	*D* 0.2 mm	*NP* 0.5 vol %	
CT (°C)	36.7				56.8				35%
CF (N)	120				146.4				18%
TV (mm)	0.0131				0.0180				27%
R_a (µm)	0.98				1.5				34%

The results reveal notable variations when comparing optimal and randomly chosen parametric settings. Specifically, a significant difference of 35%, 18%, 27%, and 34% is observed in the cutting temperature, cutting force, tool vibration, and surface roughness, respectively, under optimal process variables. This indicates a substantial impact on the machining responses. The findings affirm the effectiveness of the optimal values in contrast to randomly chosen parameters, validating the robustness of the experimental setup.

4. CONCLUSIONS

The investigation is conducted to evaluate the machining performance in turing of SS304 steel with hybrid nano-cutting fluids using Taguchi-based Grey Relational Analysis. The findings of the investigation are reported as follows:

i) The thermal conductivity of hybrid nanofluids increases proportionally with higher concentrations of alumina/graphene hybrid nano-cutting fluid compared to pure neem oil.

ii) The viscosity of hybrid nanofluids increases with increased alumina/graphene hybrid nano-cutting fluid over pure neem oil. The highest value, with 1.5 % hybrid nanoparticles, was discovered and denotes the highest thermal conductivity of all fluids.

iii) Grey relational grade analysis highlights that cutting speed substantially impacts responses more than feed rate, depth of cut and nanoparticle concentration.

iv) The optimal configuration of parameters for the turning operation on materials like stainless steel was identified as 900 RPM, a feed rate of 40 mm/min, a depth of cut of 0.6 mm, and a 1.5 vol % concentration of hybrid nanofluid.

v) Optimal parameter settings result in a notable reduction of cutting temperature, cutting force, tool vibration, and surface roughness by 35%, 18%, 27%, and 34%, respectively, compared to the initial factor settings.

Future studies on neem oil-based hybrid nano-cutting fluids can explore other eco-friendly oils, optimize nanoparticle types and concentrations, and assess long-term stability for industrial application. It is essential to investigate their impact on tool wear, heat reduction, and surface finish across various machining processes and their suitability in advanced techniques like CNC machining. Environmental and health impacts should be evaluated, including lifecycle assessments and safety concerns related to nanoparticle exposure. Integrating AI-based optimization techniques with Taguchi methods offers the potential for multi-objective optimization. Industrial-scale trials, economic analyses, and collaborations with nanoparticle manufacturers are recommended to validate lab results. Broader testing on different materials and the standardization of these fluids will ensure compliance with environmental regulations, enhancing market viability and sustainability in machining.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

AUTHORS CONTRIBUTION

J. E. Manikanta (Writing - original draft; Conceptualization; Formal analysis; Visualisation)

N. Ambhore (Writing - original draft, Conceptualization; Methodology; Data curation; Resources)

C. Nikhare (Writing - original draft, Conceptualization, Methodology; Data curation; Resources)

N. K. Gurajala (Conceptualization; Methodology; Data curation; Resources, Supervision)

AVAILABILITY OF DATA AND MATERIALS

The data supporting this study's findings are available on request from the corresponding author.

ETHICS STATEMENT

Not applicable

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