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ENHANCING MACHINING PERFORMANCE AND SUSTAINABILITY BY USING COCONUT OIL-BASED MOLYBDENUM DISULFIDE NANOFLUID IN THE MINIMUM QUANTITY LUBRICATION METHOD: OPTIMIZATION OF TURNING PARAMETERS FOR THE AISI4340 STEEL

Summary

In manufacturing, cutting fluids are a significant expense, comprising about 20% of total production costs, and pose health and environmental risks. To address these challenges, there is a need for more sustainable practices, including the optimization of turning parameters using eco-friendly cooling technologies. Grey relational analysis is crucial for such optimization. In this study, a nanofluid lubricant with coconut oil was developed as the base fluid with varying weights of molybdenum disulfide nanoparticles. The thermal and tribological properties are analysed, showing improved performance over standard minimum quantity lubrication methods. The aim was to optimize the turning parameters for AISI 4340 steel using grey relational analysis in a molybdenum disulfide-based nanofluid minimum quantity lubrication setup, highlighting the potential of coconut oil nanofluids for sustainable machining.

Key words: *Minimum quantity lubrication (MQL), Nanofluids, Molybdenum disulfide (MoS2), Taguchi design of experiments, Grey relational analysis (GRA)*

1. Introduction

The AISI 4340 steel, a high-strength alloy known for its excellent mechanical properties, is extensively utilized in critical applications in the automotive, aerospace, and industrial sectors. Components, such as axles, gears, and shafts, made of AISI 4340 steel, require exceptional surface quality to ensure optimal performance and longevity. However, machining this material presents significant challenges due to its low heat capacity and tendency to strain harden, which lead to high cutting forces, elevated temperatures at the cutting tool, poor surface finish, and the formation of built-up edges [1], [2]. These challenges necessitate the use of effective cooling and lubrication strategies during machining processes to maintain tool life and surface integrity. The use of metalworking fluids or cutting fluids is crucial in machining operations as they serve multiple purposes: cooling, lubricating, preventing rust, and removing chips from the cutting zone. Despite their benefits, traditional cutting fluids pose environmental and health risks due to their chemical compositions [3]. Consequently, there is a growing interest in developing sustainable and environmentally friendly alternatives.

One such alternative is minimum quantity lubrication (MQL), which involves spraying a minimal amount of cutting fluid directly into the cutting region, thereby reducing fluid consumption and waste [1], [4]. Among the various types of cutting fluids, vegetable oils have gained popularity due to their superior lubricity, biodegradability, and environmental sustainability compared to mineral oil-based fluids. These oils have shown promise in reducing cutting forces and temperatures during machining [5], [6], [7]. However, they also have drawbacks, such as poor oxidative stability, lower lubricity, and higher cost, which require careful consideration and optimization for specific industrial applications.

Nanofluids, a recent advancement in machining fluids, significantly enhance various properties, such as thermal conductivity, lubrication, wear resistance, and stability, by incorporating nanoparticles into vegetable oils [8]. These enhancements reduce the need for frequent fluid changes and improve overall machining efficiency. The high surface area-to-volume ratio of nanoparticles facilitates superior heat dissipation, which lowers cutting temperatures and, consequently, improves product quality. Additionally, nanoparticles act as solid lubricants, reducing friction between the cutting tool and workpiece, thereby extending tool life and enhancing the stability of the cutting fluid [9], [10]. This innovative approach presents a more sustainable and environmentally friendly alternative to traditional mineral oil-based fluids. However, further research is necessary to fully comprehend the effects and potential risks associated with nanofluids [11].

Ekin Nisa et al. used nanofluids with silicon dioxide (SiO_2) nanoparticles in sunflower oil for machining the AISI 304 stainless steel. They found that the feed rate had the most significant impact on surface roughness (76%), while the cooling method affected the temperature in the cutting zone (80%) and the tool wear (50.5%). The 0.5% nano-MQL method performed best [12]. Wei et al. showed that adding graphene and aluminium oxide (Al_2O_3) nanoparticles to oleic acid-based nanofluids used for nano-MQL improved the grinding efficiency for tough materials. These nanofluids reduced specific grinding energy, friction coefficients, and temperature increases during friction tests. Workpieces made of zirconium dioxide (ZrO_2) and the Ti-6Al-4V titanium alloy achieved optimal surface quality with nano-additive concentrations of 2% and 3%, respectively, leading to substantial decreases in surface roughness compared to dry cutting [13].

Perera et al. enhanced a biodegradable metalworking fluid based on coconut oil (COCOTP) by adding nano engineered fluids ((NEFs - 0.3% Al_2O_3 and 0.3% graphite). They achieved a significant reduction in surface roughness during the turning of AISI 304 and 400 stainless steels. NEFs showed better performance with the stainless steel 400 at lower speeds due to higher thermal conductivity, reducing residual heat in the cutting fluid [14]. Nimel Sworna Ross et al. found that adding 1 wt.% carbon nanodots to rice bran oil decreased the contact angle, increased thermal conductivity, and increased viscosity. These nanodots, when used in MQL, reduced surface roughness by 60-63%, 40-43%, and 22-25% compared to dry, flood, and conventional MQL conditions, respectively, impacting the tool wear and enhancing the machinability of the 316 stainless steel [15].

Gaurav Sharma and colleagues studied the turning of AISI 304 steel using nanofluids containing Al-GrP and graphene mixed with sunflower oil. Hybrid nanofluids showed lower contact angles than graphene at the same concentrations and led to a 10% improvement in surface finishing and a 7.25% reduction in the cutting force compared to graphene-based nanofluids [16]. Mayur et al. investigated the machinability of Inconel 625 using MQL with a blend of vegetable oil, graphite, and molybdenum disulfide nanoparticles. Using nano MQL with molybdenum disulfide in sunflower oil enhanced surface quality by 56% compared to dry conditions, with slower tool wear progression and lower cutting temperatures, suggesting the improved machinability of Inconel 625 [17].

Maruda et al. studied the effect of copper nanoparticle size and concentration in nanofluids on tool vibrations and machined surface topography during the turning of 316L stainless steel under MQL conditions. Nanofluids with smaller copper nanoparticle sizes (22 nm) and a concentration of 0.5% showed the highest stability and improved surface quality, highlighting the importance of nanoparticle characteristics in optimizing the MQL performance [18]. Jing Ni et al. investigated eco-friendly cutting fluids derived from sesame oil and copper (II) oxide (CuO) nanofluids in the broaching process. Sesame oil showed superior characteristics among five vegetable oils studied. Introducing nanofluids of copper (II) oxide nanoparticles and sesame oil enhanced the cutting fluid efficacy. The optimal copper (II) oxide nanofluid concentration was 0.54 wt.%, reducing the peak and trough loads by 62.7% and 68.6%, respectively, compared to pure sesame oil [8].

Kedong Zhang et al. introduced a ferric oxide and carbon nanotubes (Fe_3O_4@CNTs) nanofluid for enhancing the titanium carbide (TiC) ceramic tool cutting efficiency. Combined with micro-texturing and a magnetic field, the nanofluid reduced cutting forces and tool wear. At a 1200 Gs magnetic field strength, it achieved a 36.9% decrease in cutting force and a 28.15% reduction in surface roughness [19]. Shruti Raut et al. used nanofluids as lubricants in turning, reducing the tool tip and workpiece temperatures by 25% to 33% and improving surface finish by 11.26% to 17.26% across different spindle speeds [20].

In their study, Saurabh Tiwari et al. investigated the effect of coconut oil enriched with nano aluminium oxide on machining the AISI 1040 steel. They found that nano aluminium oxide reduced the contact angle by up to 70%, indicating improved wettability. Additionally, the nanofluid showed enhanced dynamic viscosity and thermal conductivity. Nanofluid minimum quantity lubrication (NFMQL) outperformed dry, flood, and minimum quantity lubrication with pure coconut oil (MQL-CO), significantly reducing tool wear and surface roughness. These findings highlight NFMQL as an effective approach to improve the machinability of AISI 1040 steel [21].

K. Venkatesan et al. explored the machinability of Inconel 800H, a high-temperature nickel-iron-chromium alloy known for its resistance to oxidation and high-temperature corrosion. They focused on optimizing cutting parameters for machining by using 0.25% aluminium oxide nanofluid in coconut oil. Through CNC experiments and the Taguchi design, they found out that a nanofluid concentration of 0.25%, combined with a cutting speed of 100 m/min and a feed rate of 0.14 mm/rev, minimized cutting forces, surface roughness, and tool wear effectively [22]. Mayur A. Makhesana et al. studied the machinability of Inconel 625 using NFMQL with sunflower oil blended with molybdenum disulfide and graphite nanoparticles. They found NFMQL significantly improved surface quality by 56% compared to dry turning and reduced cutting temperatures by 35% compared to standard MQL. Graphite and molybdenum disulfide nanoparticles also slowed tool wear progression. The study highlighted the effectiveness of NFMQL in enhancing machining performance and its potential sustainability benefits [23].

Coconut oil, known for its superior lubricity and biodegradability, is emerging as a promising base for environmentally friendly cutting fluids that is easily available. However, its potential drawbacks, such as poor oxidative stability, necessitate careful consideration. Recent advancements in nanofluid-based minimum quantity lubrication (MQL) offer a sustainable alternative, enhancing the performance of vegetable oils like coconut oil. However, there is a lack of comprehensive research on the optimization of process parameters for the machining of AISI 4340 steel using the molybdenum disulfide nanofluid-based MQL with coconut oil as the base fluid. Additionally, integrating these optimized processes into actual industrial applications remains unexplored.

This study aims to bridge these gaps by investigating the effects of various process parameters on critical output characteristics, such as surface roughness, cutting force, and cutting temperature, using the Taguchi design and grey relational analysis (GRA) for multi-objective optimization. The ultimate goal is to develop and validate sustainable and effective machining techniques for the AISI 4340 steel that can be seamlessly integrated into industrial applications, promoting both environmental sustainability and operational efficiency.

2. Materials and methods

2.1 Formulation of cutting fluids

This study aims to develop an environmentally sustainable cutting fluid for machining, focusing on oil-in-water emulsion formulations using safe components. Table 1 shows the substances used in the formulation process. Nanofluids are created by dispersing stable nanoparticles in the base fluid with the aid of magnetic stirrers, ultrasonic homogenizers, and surfactants. The formulation excludes prohibited compounds like chlorine or nitrosamines, following a simpler approach with fewer additives for easier treatment and disposal. For instance, in formulating a 1% weight of molybdenum disulfide cutting fluid, sodium dodecyl sulphate (SDS) (0.4 g) is used as a surfactant in 100mL of coconut oil, followed by stirring and sonication until homogenized. This process is replicated for 2% and 3% weight formulations. Figure 1 shows the methodology for cutting fluid formulation. The methodology ensures the cutting fluid meets performance criteria while addressing environmental concerns and aligning with sustainable machining practices.

Table 1 Materials for cutting fluid preparation

Material	Description
Base oils	Coconut oil
Water	pH value 7.72
Emulsifier	Sodium dodecyl sulphate (SDS)
Suspension	Molybdenum disulfide nano particles (1%, 2%, 3%)

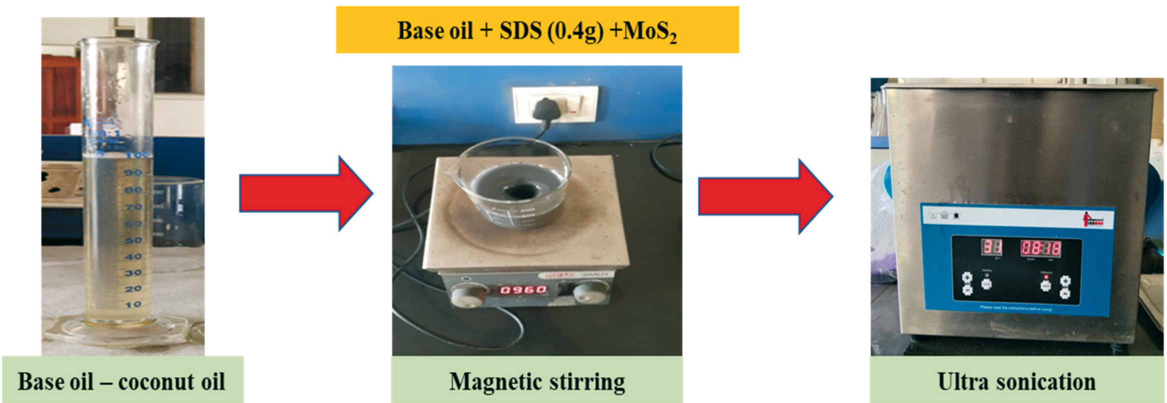

Fig. 1 Cutting fluid formulation

2.2 Thermal and frictional characteristics of nanofluids

2.2.1 Thermal properties of nanofluids

Thermal conductivity is crucial for enhancing heat transfer at the tool - workpiece interface during cooling. A hot disc thermal constants analyser was used to determine thermal conductivity and specific heat. The thermal conductivity of formulated cutting fluids with molybdenum disulfide nanoparticles was tested at room temperature with varying concentrations (1 wt.%, 2 wt.%, 3 wt.%). Figure 2 shows the correlation between nanoparticle weight percentage and thermal conductivity.

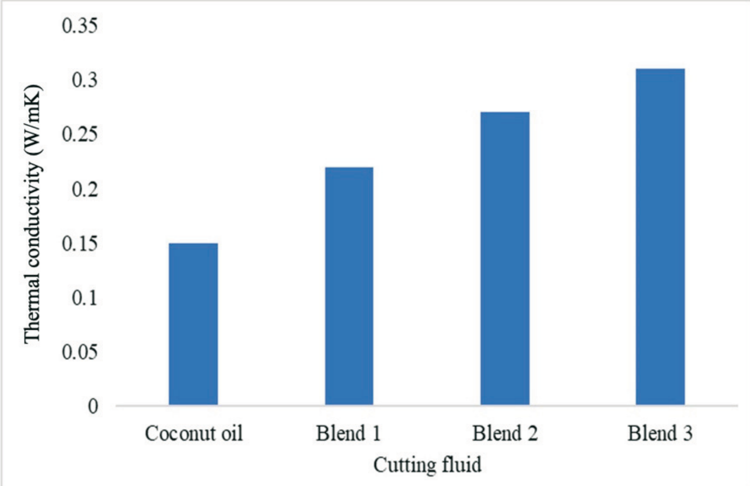

Fig. 2 Thermal conductivity

The thermal conductivity of a nanofluid depends on the thermal conductivity of the base fluid and that of nanoparticles. The higher thermal conductivity of nanoparticles enhances the overall thermal conductivity of nanofluids. As the weight percentage of molybdenum disulfide nanoparticles increases, a more solid material with higher thermal conductivity is added to a constant volume of base fluid, resulting in a proportional increase in thermal conductivity. The highest recorded thermal conductivity was 0.31 W/mK at a 3 wt.% concentration of molybdenum disulfide nanoparticles.

Figure 3 shows the relationship between nanoparticle weight percentage and specific heat fluctuation. Specific heat decreases as nanoparticle concentration increases. The addition of solid nanoparticles reduces specific heat due to the lower nanoparticle weight percentage compared to that of the base fluid. In Figure 4, the specific heat capacities of cutting fluid blends and pure coconut oil are compared with Blend 3 (3 wt.% of molybdenum disulfide) having the highest value at 2.642 J/g°C. This indicates the superior heat absorption and dissipation of Blend 3 compared to other blends and pure coconut oil, suggesting its potential to manage heat effectively in machining. As a result, the tool and workpiece performance and durability are enhanced.

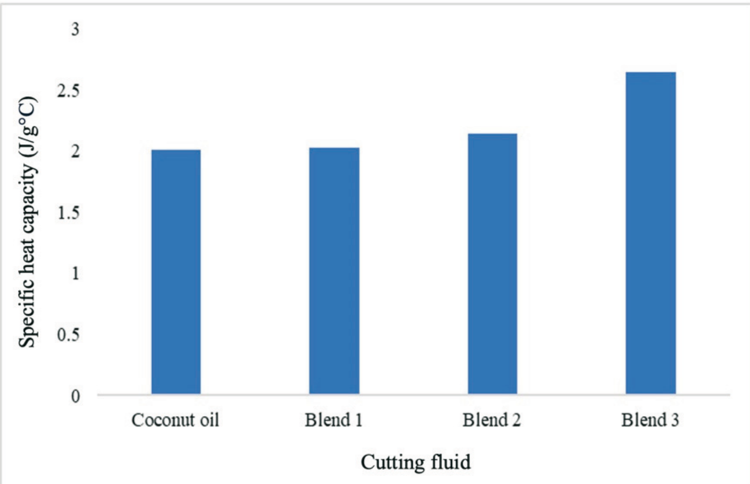

Fig. 3 Specific heat capacity

2.2.2 Coefficient of friction

The evaluation of machining performance with nanofluid-based minimum quantity lubrication (MQL) depends significantly on the tribological characteristics of cutting fluids. These were assessed using a TR-20 pin-on-disc tribometer. The pin was 8 mm in diameter and

50 mm in height, while the disc had a track diameter of 100 mm and rotated at 1500 rpm under a continuous load of 4 kg. Experiments were conducted at various time intervals from 30 to 180 seconds. Figure 4 shows the temporal variation of the Coefficient of Friction (COF).

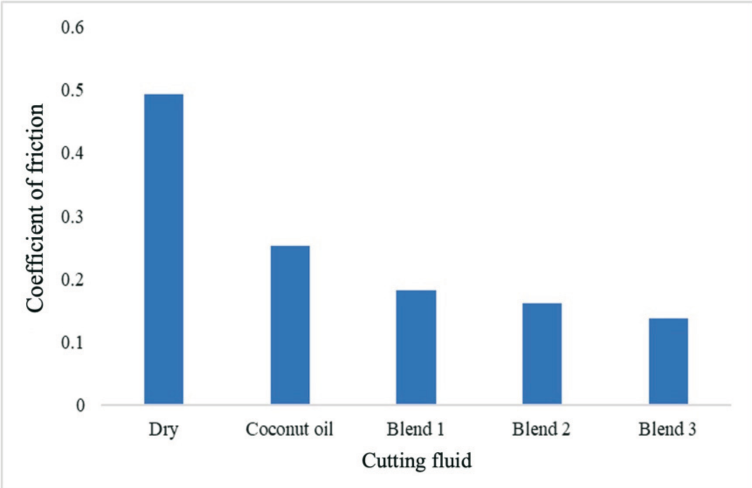

Fig. 4 Coefficient of friction

As the weight percentage of molybdenum disulfide nanoparticles increases, the coefficient of friction (COF) decreases. The COF values for nanofluids with 1 wt.%, 2 wt.%, and 3 wt.% of MoS_2 nanoparticles were measured at 0.183, 0.162, and 0.138, respectively. Nanofluids form a thin film between the sliding surfaces, thus reducing the COF. In dry conditions, the maximum COF value of 0.493 is observed, while MoS_2 nanofluids with 3 wt.% nanoparticles exhibit the lowest COF value of 0.138.

2.3 Machining and methods

The turning operations were conducted using a Kirloskar Turnmaster 35 lathe, as shown in Figure 5. In the experiments, a cylindrical rod made of AISI 4340 alloy steel, with a diameter of 90 mm and a length of 400 mm, was used. The AISI 4340 alloy steel, with a hardness ranging from 45 to 55 HRC, finds extensive application in various industries for manufacturing shafts, gears, and aircraft landing gear. It comprises 0.35% carbon, 1.40% chromium, 95.95% iron, 0.70% manganese, 0.20% molybdenum, and 1.40% nickel by weight.

Fig. 5 Experimental turning centre – a Kirloskar Turnmaster 35 lathe

An HSN^2 (2^{nd} generation TiAlxN super nitride) coated carbide SNMG 120408 tool insert was installed on a PSBNR 2525M12 tool holder shown in Figure 6. The experiments were based on the design of the experiment using the Taguchi technique. Three cutting parameters were chosen for experimentation: cutting speed, feed rate, and depth of cut. Furthermore, one of the crucial input criteria was the kind of cutting fluid employed. As a result, four input parameters were utilized, each with varying levels, as shown in Table 2.

(a) (b)

Fig. 6 (a) Insert and (b) Tool holder

For each experimental run, a new cutting tool insert was employed, and the cutting fluids were delivered to the cutting zone using the MQL method. Throughout the investigation, the pressure of air was maintained at 5 bar, and the rate of flow was set at 300 mL/hr. The nozzle was positioned perpendicular to the tool, maintaining a constant distance of 10 cm from the tool and workpiece interface, as shown in Figure 7.

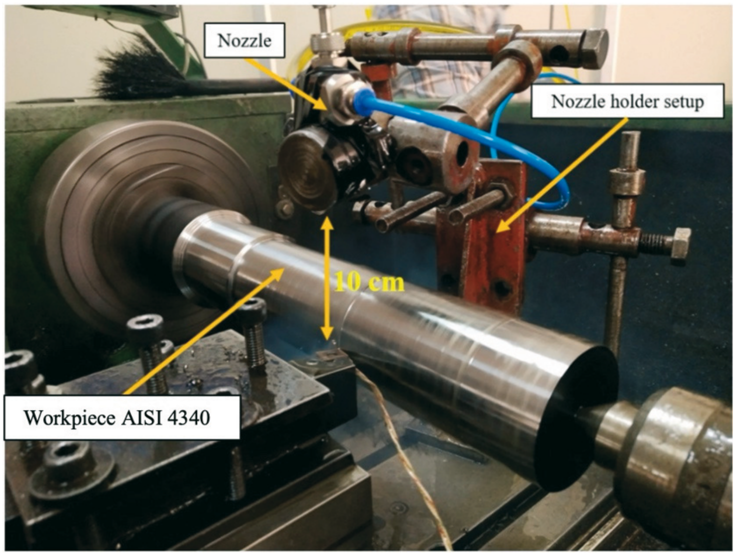

Fig. 7 Positioning of the nozzle for machining

2.4 Design of experiments

An appropriate design of experiments makes it possible to assess the individual and interactional impacts of many elements that might affect the output results. The Taguchi method was used to determine the experimental design. The L27 orthogonal array used for investigation is shown in Table 3.

Table 2 Parameters and levels

Parameters	**Level 1**	**Level 2**	**Level 3**
Speed (m/min)	100	120	140
Feed (mm/rev)	0.1	0.15	0.2
Depth of cut (mm)	0.2	0.3	0.4
Wt % of nano particles	1%	2%	3%

2.5 Measuring devices

The output parameters chosen for evaluation were surface roughness, forces generated during machining, and cutting temperature. Specific measurement equipment was selected for each parameter. Surface roughness was determined using a Mitutoyo portable SJ 210 surface roughness tester, which is a stylus-type tester with a tolerance of ±1.5%. Cutting force was assessed using a Kistler 9257B dynamometer with an accuracy of ±0.1 N. Cutting temperature was determined using a K-type thermocouple with a tolerance class of ±1.5 K and a measurement range of -40 to 375 °C. Figure 8 shows the measuring instruments used in the study.

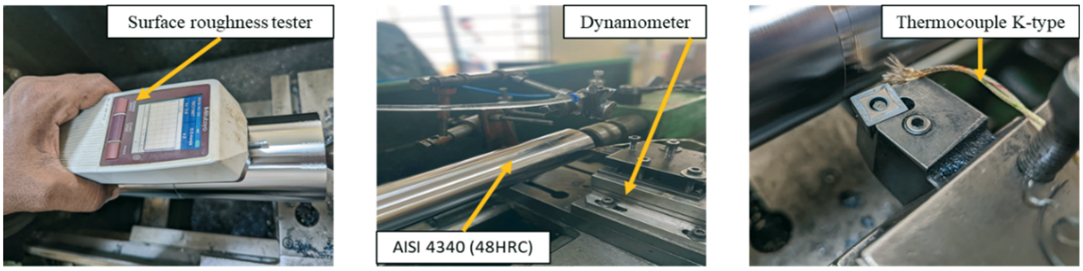

Fig. 8 Measuring devices

Table 3 Design of experiments based on the Taguchi orthogonal array

Run	Speed (m/min)	Feed (mm/rev)	Depth of cut (mm)	Wt. % of nano particles
1	100	0.10	0.2	1%
2	100	0.10	0.3	2%
3	100	0.10	0.4	3%
4	100	0.15	0.2	1%
5	100	0.15	0.3	2%
6	100	0.15	0.4	3%
7	100	0.20	0.2	1%
8	100	0.20	0.3	2%
9	100	0.20	0.4	3%
10	120	0.10	0.2	2%
11	120	0.10	0.3	3%
12	120	0.10	0.4	1%
13	120	0.15	0.2	2%
14	120	0.15	0.3	3%
15	120	0.15	0.4	1%
16	120	0.20	0.2	2%
17	120	0.20	0.3	3%
18	120	0.20	0.4	1%
19	140	0.10	0.2	3%
20	140	0.10	0.3	1%
21	140	0.10	0.4	2%
22	140	0.15	0.2	3%
23	140	0.15	0.3	1%
24	140	0.15	0.4	2%
25	140	0.20	0.2	3%
26	140	0.20	0.3	1%
27	140	0.20	0.4	2%

2.6 Grey relational analysis (GRA)

GRA is a multi-optimization method that deals with uncertainties arising from discrete data and insufficient information. It uses a grayscale approach, where areas with no information are represented as black and areas with sufficient information are represented as white. GRA is based on the principles of normality, symmetry, totality, and proximity, which are rooted in geometric mathematics. Figure 9 shows the flow diagram that outlines the necessary steps in GRA for the investigation.

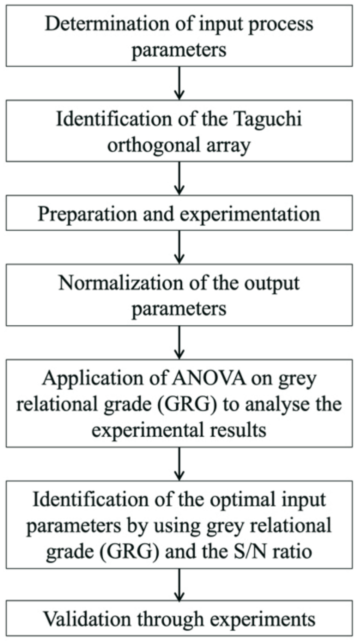

Fig. 9 Steps in GRA

2.6.1 Data preprocessing

Data preprocessing is a crucial step in grey relational analysis (GRA) due to potential variations in the range and units of different data sequences. This step is particularly important when dealing with data sequences that have highly dispersed ranges or varying target directions. The goal of data preprocessing is to convert the original sequences into comparable formats. In the initial stages of data pre-processing, experimental results are normalized to a range of 0 to 1.

Surface roughness heights, cutting force, and cutting temperature are critical factors in the turning process, directly impacting machining performance. Minimizing these output characteristics is essential for achieving optimal machining results. To prioritize quality characteristics that are "the-smaller-the-better" for all these performance indicators, the original sequence is normalized using Equation (1).

$$Y_i^p(k) = \frac{\max.Y_i^0(k) - Y_i^0(k)}{\max,Y_i^0(k) - \min.Y_i^0(k)} \tag{1}$$

2.6.2 Grey relational coefficient (GRC) and grey relational grade (GRG)

In machining performance analysis, the grey relational coefficient (GRC) and grey relational grade (GRG) are closely related tools used to evaluate the relationship between machining parameters and their performance outcomes. The GRC quantifies the similarity between individual data sequences, while the GRG aggregates these coefficients to provide an overall measure of relational grade. Together, GRC and GRG help identify optimal machining conditions and enable more informed decision-making, particularly when dealing with uncertain or incomplete data.

The deviation sequence, $\Delta_{oi}(k)$, can be calculated as follows:

$$\Delta_{oi}(k) = \left| y_r^p(k) - y_i^p(\mathrm{k}) \right|, \tag{2}$$

where $y_r^p(k)$ is the reference sequence, and y_i^p(k) is the comparability sequence. After the data preprocessing stage, the next phase in grey relational analysis involves calculating the grey relational coefficient. This coefficient is determined using the following equation:

$$\xi_i(k) = \frac{\Delta_{\min.} + \xi\Delta_{\max}}{\Delta_{o,i}(k) + \xi\Delta_{\max}} \tag{3}$$

$$\Delta_{\min} = \min_{\cdot\forall jil}\min \cdot \forall k\left|Y_r^p(k) - Y_j^p(k)\right|$$

$$\Delta_{\max} = \max_{\cdot\forall ji}\max_{\cdot\forall k}\left|Y_r^p(k) - Y_j^p(k)\right|$$

where

- $\xi_i(k)$ is the value associated with *i* at time *k*.
- $\Delta_{\min}$ is the minimum difference between two variables across all j and *l* indices.
- $\Delta_{\max}$ is the maximum difference between two variables across all j indices.
- $\Delta_{o,i}(k)$ is the difference between $Y_r^p(k)$ and $Y_j^p(k)$ at time *k*.
- $Y_r^p(k)$ and $Y_j^p(k)$ are variables representing values at time k for different indices *r* and j.
- ξ is the identification coefficient; its value lies between [0,1] ,0.5 when all parameters are given equal importance.

In the last phase of GRA, the grey relational grade is determined. This grade is computed as the average of the grey relational coefficient associated with the individual performance attribute. The computation of the GRG follows Equation (4):

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n}\xi_i(k) \tag{4}$$

where, γ_i is the GRG for the i_{th} experiment and n is the number of experiments.

3. Results and discussion

3.1 Comparative analysis of the cutting fluids

Experiments are conducted using minimum quantity lubrication (MQL) on a range of nanofluids with varying nanoparticle concentration, during the turning of AISI 4340 steel. The study involves comparing these cutting fluids based on surface roughness, force of machining, and temperature at the machining zone. The aim is to determine which cutting fluid demonstrates superior lubrication performance. Table 4 shows the response data from the experiments.

3.1.1 Surface roughness

The experimental results demonstrate a significant enhancement in surface quality achieved by using molybdenum disulfide-based nanofluids in MQL turning, particularly with a 3 wt.% concentration of MoS_2 nanoparticles, which is shown in the graph in Figure 10. Nanofluids with 3 wt.% MoS_2 demonstrate the most favourable surface roughness values, making them a highly desirable choice for machining. The fluid with 1% MoS_2 nanoparticles has an average surface roughness of 1.172 µm, while the fluid with 2% MoS_2 nanoparticles has that of 1.155 µm. In contrast, the fluid with 3% MoS_2 nanoparticles shows the smallest average surface roughness of 0.836 µm.

The results indicate that higher concentrations of MoS_2 nanoparticles lead to reduced surface roughness, indicating superior surface finish performance compared to lower concentrations. The fluids with 3 wt.% MoS_2 nanoparticles exhibit superior thermal conductivity and lower coefficient of friction (COF), which enhances cooling and lubrication in the machining zone. These nanofluids form a stable lubricating and cooling layer over the surface being machined, thus improving the surface quality, reducing the tool wear, and resulting in a smoother finish. Comparing the surface quality achieved with the 3% MoS_2 blend to that achieved with other blends and traditional MQL turning, the 3% MoS_2 blend demonstrates superior effectiveness in enhancing the surface finish during machining operations.

Table 4 Response data from experiments

Run	Cutting temperature (CT)	Surface roughness (SR)	Cutting force (CF)
	(ºC)	(µm)	(N)
S1	115	1.250	130.45
S2	100	1.275	140.21
S3	95	0.898	125.67
S4	110	0.910	145.67
S5	105	0.995	135.89
S6	90	0.851	128.34
S7	105	1.290	132.34
S8	110	1.275	128.90
S9	85	0.805	123.78
S10	100	1.305	138.90
S11	82	0.795	123.67
S12	120	1.295	130.12
S13	95	0.829	142.56
S14	87	0.810	127.89
S15	135	0.822	126.45
S16	90	1.280	136.78
S17	82	0.873	122.34
S18	100	0.802	129.56
S19	85	0.865	108.90
S20	105	1.255	131.45
S21	95	0.903	122.89
S22	85	0.805	123.56
S23	114	1.241	139.78
S24	105	1.009	127.23
S25	75	0.809	129.78
S26	105	1.280	136.56
S27	95	1.270	144.67

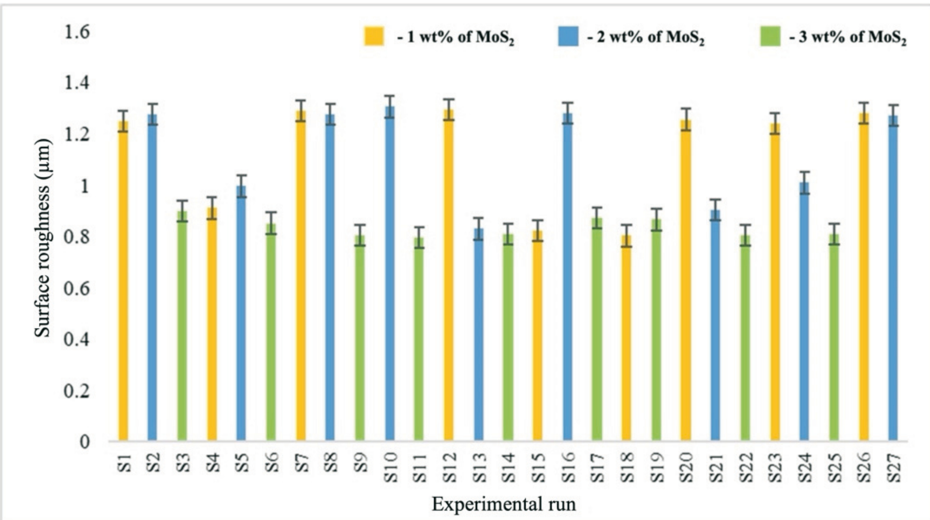

Fig. 10 Comparison of surface roughness values achieved in the experimental runs

3.1.2 Cutting temperature

The experimental results in Figure 11 show that nanofluids with 3 wt.% MoS_2 nanoparticles had the most favourable cutting temperatures, averaging 84.33°C, compared to those of 111.67°C for 1% MoS_2 and 100.5°C for 2% MoS_2. This suggests that higher MoS_2 concentrations result in lower temperatures during machining, indicating better heat reduction. The study also revealed that nanofluids with 3 wt.% MoS_2 exhibited superior thermal conductivity, likely due to the increased surface area from the suspended nanoparticles. This enhancement in thermal conductivity improves the heat dissipation of the base fluid, leading to lower cutting temperatures during machining operations.

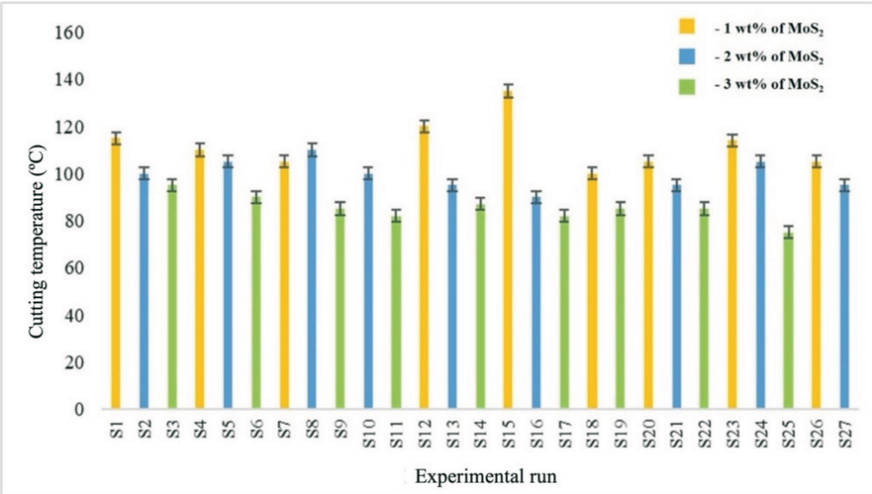

Fig. 11 Comparison of cutting temperature values in the experimental runs

3.1.3 Cutting force

The experimental results, graph in Figure 12, indicate that nanofluids containing 3 wt.% MoS_2 exhibit the most favourable cutting force values for machining operations. Coolants with 1% MoS_2 nanoparticles had an average cutting force of 134.22 N, while those with 2% MoS_2 averaged 135.36 N. In contrast, coolants with 3% MoS_2 nanoparticles exhibited an average cutting force of 127.87 N. This suggests that higher concentrations of MoS_2 nanoparticles result in lower average cutting forces, likely due to the formation of a thin tribo-film between the tool and workpiece, which reduces the coefficient of friction and improves lubrication. Therefore, a higher weight percentage of MoS_2 nanoparticles in the coolant may lead to more efficient machining operations with reduced cutting forces.

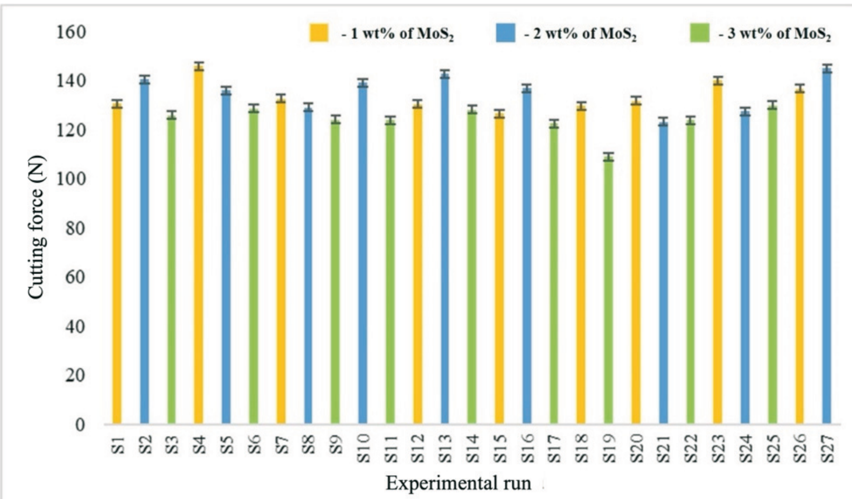

Fig. 12 Comparison of cutting force values in the experimental runs

3.1.4 Chip morphology

The chip morphology during machining provides valuable insights into the process efficiency and quality. Chip colour can indicate the cutting interface temperature, with blue or purple hues suggesting higher temperatures and increased tool wear. Serrations on the chip edge can indicate fluctuations in the cutting condition or the material property, which affects the surface finish. A continuous, smooth chip flow indicates stable cutting conditions and efficient material removal. Achieving the desired chip morphology requires a careful selection of parameters, tools, and fluids.

Figure 13 shows the chips from the S19 and S11 runs with 3 wt.% MoS_2 nanofluid; the chips exhibit curled shapes without serrations and no discoloration, indicating stable cutting. In contrast, the S5 run with 2 wt.% MoS_2 nanofluid produced golden-brown chips with subtle serrations; this suggests more demanding conditions. The S23 run with 1 wt.% MoS_2 nanofluid resulted in blue-hued chips with serrations; this indicates elevated temperatures and potentially aggressive machining, affecting tool wear and surface finish.

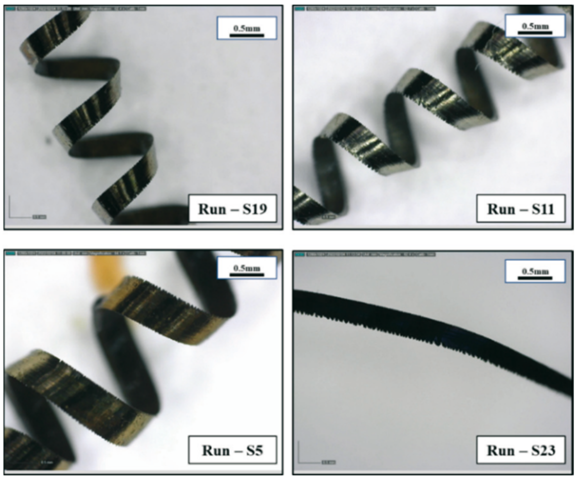

Fig. 13 Chip morphology in the selected runs

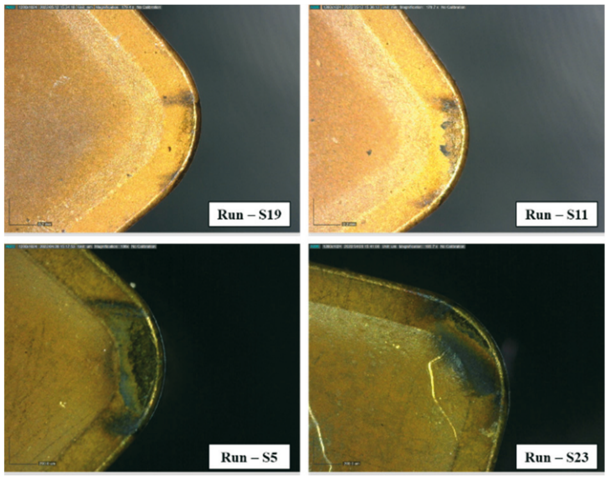

Fig. 14 Tool wear observed in four runs

3.1.5 Tool wear

Tool wear significantly impacts the machining quality, the workpiece accuracy, and the tool longevity. Using 3 wt.% MoS_2 nanofluids led to improved surface quality, cutting temperature, and cutting force, influencing the tool wear. Figure 14 shows varying tool wear under different conditions, emphasizing the impact of MoS_2 concentration. The S19 and S11 runs with 3 wt.% MoS_2 show minimal wear, indicating effective friction and heat reduction. In contrast, the S5 and S23 runs with 2 wt.% and 1 wt.% MoS_2 nanofluids, respectively, exhibit notable wear, suggesting less effective heat and friction reduction. The superior lubrication and cooling properties of 3 wt.% MoS_2 nanofluids reduce friction and heat, minimizing wear and extending tool life. The stable nanofluid lubricating layer further reduces wear by providing effective lubrication during cutting.

3.2 Multioptimization of process parameters based on the grey relational analysis (GRA)

The results from Table 4 were utilized to improve the process parameters for minimizing surface roughness, cutting forces, and temperature during machining. Data preparation involved using Equation (1) for all three output qualities. The $\Delta_{max}(k)$ and $\Delta_{min}(k)$ values were obtained from the table for individual responses. The deviation sequence was calculated using Equation (2). Table 5 shows the results of the deviation sequence and the comparability sequence for each value of i ranging from 1 to 27.

Once the deviation sequence and comparability sequence are calculated, the next step is to determine the grey relational coefficient (GRC) using Equation (3). Subsequently, the grey relational grades (GRGs) and their corresponding ranks are derived, as shown in Table 6. This table shows the GRC and GRG for each of the 27 experiments. As per Table 7, the S19 experiment exhibited the highest GRG, while the S23 experiment exhibited the lowest GRG. This suggests that the S19 experiment is very close to the optimal normalized value. Furthermore, the S19 experiment outperforms the other 26 experiments in various aspects.

Table 5 Normalized and deviation sequences

Note: CT-cutting temperature; SR-surface roughness; CF-cutting force.

Run	Normalized value			Deviation sequence		
	CT	SR	CF	CT	SR	CF
S1	0.3333	0.1078	0.4139	0.6667	0.8922	0.5861
S2	0.5833	0.0588	0.1485	0.4167	0.9412	0.8515
S3	0.6667	0.7980	0.5439	0.3333	0.2020	0.4561
S4	0.4167	0.7745	0.0000	0.5833	0.2255	1.0000
S5	0.5000	0.6078	0.2660	0.5000	0.3922	0.7340
S6	0.7500	0.8902	0.4713	0.2500	0.1098	0.5287
S7	0.5000	0.0294	0.3625	0.5000	0.9706	0.6375
S8	0.4167	0.0588	0.4561	0.5833	0.9412	0.5439
S9	0.8333	0.9804	0.5953	0.1667	0.0196	0.4047
S10	0.5833	0.0000	0.1841	0.4167	1.0000	0.8159
S11	0.8833	1.0000	0.5983	0.1167	0.0000	0.4017
S12	0.2500	0.0196	0.4229	0.7500	0.9804	0.5771
S13	0.6667	0.9333	0.0846	0.3333	0.0667	0.9154
S14	0.8000	0.9706	0.4835	0.2000	0.0294	0.5165
S15	0.0000	0.9471	0.5227	1.0000	0.0529	0.4773
S16	0.7500	0.0490	0.2418	0.2500	0.9510	0.7582
S17	0.8833	0.8471	0.6345	0.1167	0.1529	0.3655
S18	0.5833	0.9863	0.4381	0.4167	0.0137	0.5619
S19	0.8333	0.8627	1.0000	0.1667	0.1373	0.0000
S20	0.5000	0.0980	0.3867	0.5000	0.9020	0.6133
S21	0.6667	0.7882	0.6195	0.3333	0.2118	0.3805
S22	0.8333	0.9804	0.6013	0.1667	0.0196	0.3987
S23	0.3500	0.1255	0.1602	0.6500	0.8745	0.8398
S24	0.5000	0.5804	0.5015	0.5000	0.4196	0.4985
S25	1.0000	0.9725	0.4321	0.0000	0.0275	0.5679
S26	0.5000	0.0490	0.2478	0.5000	0.9510	0.7522
S27	0.6667	0.0686	0.0272	0.3333	0.9314	0.9728

The mean GRG is computed for each individual level of input parameters, including cutting speed, feed rate, depth of cut, and wt.% of MoS_2 nanoparticles. Table 7 shows a detailed breakdown of the average GRG for each individual level of the parameters. Among these parameters, the weight percentage of nanoparticles (Wt. % of NP) exhibits the largest difference (0.2699), indicating its significant influence on the quality of output parameters. In contrast, cutting speed, feed rate, and depth of cut exhibit smaller differences (0.0746, 0.0282, and 0.0492, respectively), suggesting relatively lesser variability in their influence on the output parameters. Since the weight percentage of nanoparticles is controllable, it can be adjusted to enhance the cutting process performance.

A higher value of GRG indicates closer proximity to the ideal value, signifying better product excellence. Thus, a higher value of GRG is preferred for optimal performance. In this study, the optimal parametric setting for minimum surface roughness, cutting temperature, and cutting force is identified as $A_3B_1C_1D_3$. This means that setting the parameters to A_1 for the cutting speed, B_2 for the feed rate, C_1 for the depth of cut, and D_3 for the weight percentage of MoS_2 NPs would lead to the best performance in terms of these factors.

Table 6 Grey relational coefficient and grey relational grade (GRG)

Note: CT-cutting temperature; SR-surface roughness; CF-cutting force.

Run	Grey relational coefficient			GRG	Rank
	CT	SR	CF		
S1	0.4286	0.3592	0.4604	0.4160	24
S2	0.5455	0.3469	0.3700	0.4208	22
S3	0.6000	0.7123	0.5230	0.6118	12
S4	0.4615	0.6892	0.3333	0.4947	15
S5	0.5000	0.5604	0.4052	0.4885	16
S6	0.6667	0.8199	0.4861	0.6576	9
S7	0.5000	0.3400	0.4396	0.4265	21
S8	0.4615	0.3469	0.4790	0.4291	20
S9	0.7500	0.9623	0.5527	0.7550	5
S10	0.5455	0.3333	0.3800	0.4196	23
S11	0.8108	1.0000	0.5545	0.7884	3
S12	0.4000	0.3377	0.4642	0.4007	26
S13	0.6000	0.8824	0.3533	0.6119	11
S14	0.7143	0.9444	0.4919	0.7169	7
S15	0.3333	0.9043	0.5116	0.5831	13
S16	0.6667	0.3446	0.3974	0.4695	17
S17	0.8108	0.7658	0.5777	0.7181	6
S18	0.5455	0.9733	0.4709	0.6632	8
S19	0.7500	0.7846	1.0000	0.8449	1
S20	0.5000	0.3566	0.4491	0.4353	18
S21	0.6000	0.7025	0.5679	0.6235	10
S22	0.7500	0.9623	0.5564	0.7562	4
S23	0.4348	0.3638	0.3732	0.3906	27
S24	0.5000	0.5437	0.5007	0.5148	14
S25	1.0000	0.9480	0.4682	0.8054	2
S26	0.5000	0.3446	0.3993	0.4146	25
S27	0.6000	0.3493	0.3395	0.4296	19

Table 7 Grey relational grade for four input parameters

Input parameters	Grey relational grade			Difference	Rank
	Level			= Max-Min	
	1	2	3		
Speed	0.5222	**0.5968**	0.5794	0.0746	2
Feed	0.5512	**0.5794**	0.5679	0.0282	4
Depth of cut	**0.5827**	0.5336	0.5821	0.0492	3
Wt. % of NP	0.4694	0.4897	**0.7394**	0.2699	1

ANOVA was conducted on the grey relational grade (GRG) to assess the impact of input parameters on output characteristics. The results show that the weight percentage of MoS_2

nanoparticles has the most significant impact, contributing 71.26% to the overall influence. In comparison, cutting speed, feed rate, and depth of cut have lower impacts, contributing 20.80%, 4.80%, and 2.51%, respectively. This highlights the importance of the weight percentage of MoS_2 nanoparticles in influencing the output characteristics.

Table 8 ANOVA based on the grey relational grade

Note: DoF- degrees of freedom; SeqSS- sequential sum of squares; AdjSS- adjusted sum of squares; and AdjMS- adjusted mean square.

Source	DoF	Seq SS	Adj SS	Adj MS	Contribution
Speed	2	0.1187	0.1187	0.0066	20.80%
Feed	2	0.0274	0.0274	0.0137	4.80%
Depth of cut	2	0.0143	0.0143	0.0072	2.51%
Wt.% of NP	2	0.4068	0.4068	0.2034	71.26%
Error	18	0.0036	0.0036	0.0018	0.63%
Total	26	0.5709			100.00%

The normal probability plot in Figure 15 clearly shows that the residuals align with the diagonal line, suggesting they are normally distributed. The scatter plot of residuals against fitted values also shows that the residuals are evenly distributed around zero, with no noticeable trend. The infrequent occurrence of residuals and the fact that all residuals fall within the range of ± 0.10 further support the validity of the model.

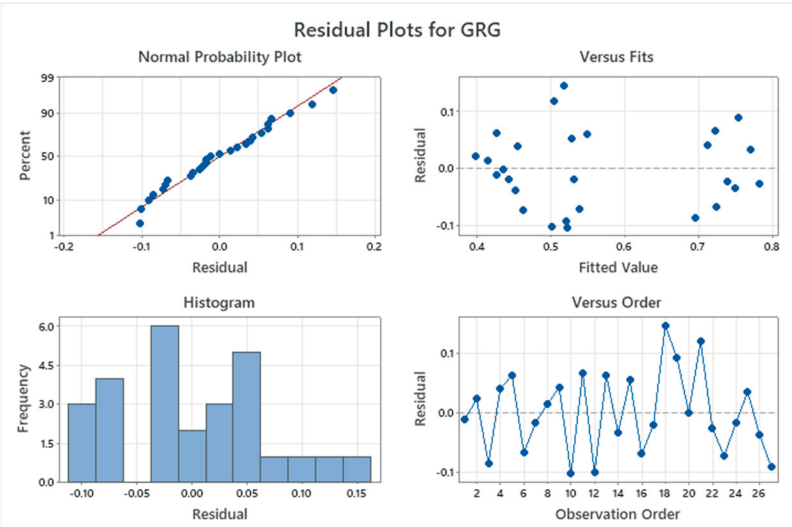

Fig. 15 Residual plots for GRG

3.3 S/N analysis for the grey relational grade (GRG)

After obtaining GRG, the outcomes were optimized using the Taguchi approach, widely recognized as the most precise optimization tool for a single response. The output for 27 tests was designated as GRG. The significance of controllable variables was assessed using the signal-to-noise ratio (S/N ratio). Higher GRG values led to lower surface roughness, cutting temperature, and cutting force, offering advantages for metalworking industries. The S/N technique applied for these responses followed a larger-the-best criterion. A higher S/N ratio indicates a better outcome, irrespective of the performance parameters. The optimal value of process variables is the level at which the S/N ratio is maximized. The response graph of the signal-to-noise ratio (S/N ratio) provides a clearer depiction of the impact of each input factor. As shown in Figure 16, the slope of the line connecting the levels accurately indicates the influence of each input factor. Specifically, the weight percentage of nanoparticles has a significant impact on the growth rate of GRG and its S/N ratios. The S/N ratio plots indicated that the optimal combination included a cutting speed of 120 m/min, a feed rate of 0.15 mm/rev, a depth of cut of 0.4 mm, and a weight percentage of nanoparticles of 3%, which can be depicted as $A_2B_2C_3D_3$.

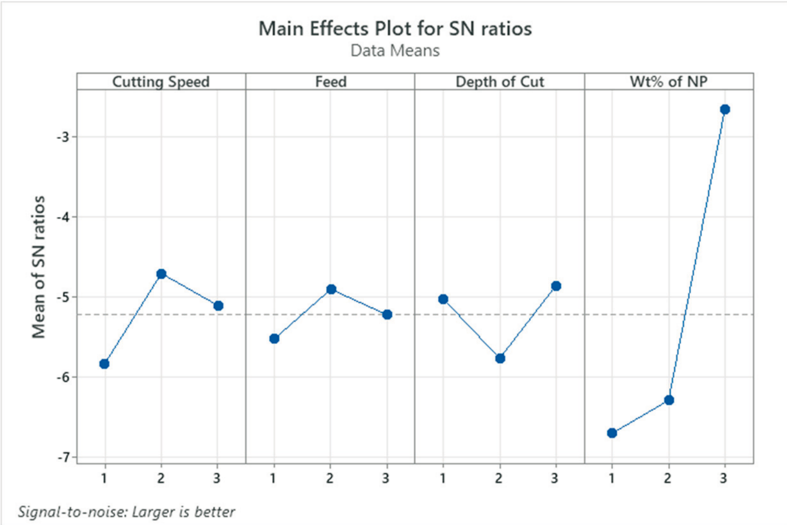

Fig. 16 Mean effect plot of the S/N ratio based on GRG

3.4 Confirmation test

The regression equations for the categorical parameters of GRG are computed and presented in Equation 5. The value of predicted GRG for the optimal combination ($A_2B_2C_3D_3$) is

$$GRG = 0.229 + 0.0286\,Speed + 0.0083\,Feed - 0.0003\,Depth\; + 0.1350\,Wt\%\;of\;NP \quad (5)$$

An experiment was conducted to validate the outcomes of the hybrid optimization technique, confirming optimal combinations like $A_2B_2C_3D_3$ identified through the S/N analysis of GRG values. These combinations were validated using regression analysis, comparing predicted values for surface roughness, cutting temperature, cutting force, and GRG with experimental values (Table 9).

The predicted and experimental values for surface roughness, cutting temperature, and cutting force were compared. The surface roughness value decreased from a predicted 0.865 μm to an experimental 0.845 μm. The cutting temperature value decreased from a predicted 85°C to an experimental 84°C, and the cutting force value dropped from a predicted 124.31 N to an experimental 120.34 N. The GRG value increased from a predicted 0.8448 to an experimental 0.8744. Validation showed an average error of 3.26% and an accuracy of 96.77%.

Table 9 Comparison based on optimal parametrical combinations

Note: CT-cutting temperature; SR-surface roughness; CT-cutting force; GRG- grey relational grade.

	Initial parameters	Optimal parameters using S/N analysis GRG			
		Predicted value	Experimental value	Difference	% Error
Levels	$A_1B_1C_2D_3$	$A_2B_2C_3D_3$	$A_2B_2C_3D_3$		
CT (°C)	85	88.71	84	4.71	5.60%
SR (μm)	0.865	0.845	0.821	0.024	2.84%
CF (N)	108.90	124.31	120.34	3.97	3.19%
GRG value	0.8448	0.8457	0.8544	0.0087	1.29%
Avg. error					3.23%
% Accuracy					96.77%

4. Conclusion

This study examines the efficacy of minimum quantity lubrication (MQL) and molybdenum disulfide-based nanofluids under MQL conditions in the turning process of AISI4340 steel. Grey relational analysis was utilized for multi-response optimization, with surface roughness (Ra, μm), cutting forces, and cutting temperature as the output responses. The experimental findings lead to the following conclusions:

- The experimental results indicate that molybdenum disulfide (MoS_2)-based nanofluids with a 3% weight concentration in the MQL turning exhibit superior performance in terms of surface roughness (Ra, μm), cutting force, and cutting temperature compared.
- The thermal conductivity of MoS_2 nanofluids increases with higher weight percentages of nanoparticles, reaching its maximum value of 0.31 W/mK at a concentration of 3 wt.% nanoparticles. This property is crucial for cutting fluids since it directly reflects their capacity to effectively disperse the heat produced during machining operations, hence aiding in the prevention of the tool and the workpiece overheating. The specific heat of the MoS_2 nanofluid was measured to be 2.642 J/g°C. This property is important as it indicates the ability of the fluid to absorb and release heat, which is crucial for maintaining stable temperatures during cutting operations.
- The coefficient of friction (COF) of nanofluids decreases as the weight fraction of MoS_2 nanoparticles increases. This pattern suggests that higher levels of MoS_2 nanoparticles lead to reduced friction between the cutting tool and workpiece during machining operations. Specifically, the COF was measured as 0.138 when MoS_2 nanoparticles were present at a weight concentration of 3%.
- In the investigation, surface roughness, cutting force, and cutting temperature were examined through a comparison of the experiment outcomes. Furthermore, there were observations made specifically about the wearing down of tools and the shape and structure of the chips produced. The nanofluid containing a 3% weight concentration demonstrated improved performance compared to the other two mixtures.
- Based on the chip morphology observations, the chips from the machining runs (S19 and S11), which used 3 wt.% of MoS_2 nanoparticles in the cutting fluid, appear to be the most favourable. These chips displayed stable characteristics with no discoloration, and they were curled without serrations, indicating stable cutting conditions and well-controlled parameters.
- The most effective combinations, shown as $A_2B_2C_3D_3$, were determined by analysing the signal-to-noise ratios of grey relational grade (GRG) data. The combinations consist of a cutting speed of 120 m/min, a feed rate of 0.15 mm/rev, a depth of cut of 0.4 mm, and the use of a cutting fluid based on coconut oil with a 3% weight concentration of MoS_2 nanoparticles. The relation between the projected values for surface roughness, cutting temperature, and cutting force and the experimental findings has been validated.
- The ANOVA analysis, utilizing grey relational grade, indicates that the weight % of MoS_2 nanoparticles is the primary input parameter that significantly affects the turning of AISI4340 steel when employing MoS_2 nanofluids under minimum quantity lubrication (MQL) conditions.

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