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Investigations of Surface Roughness and Temperatures in Vegetable Oil-based n-MQL Turning of AISI 4340 Steel

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Abstract: Machining of hard materials has been difficult and expensive because of poor surface smoothness, early tool failures, etc. When used in machining hard materials, such as medium and high carbon, cast steels, Inconel, and other alloys, nanomaterials combined with base fluids, such as water and oils, provide superior results in terms of surface finish and low cutting temperatures. To enhance our understanding of the field of machining and its applications, a comprehensive literature assessment on machining steels using nanofluids with/without the minimum quantity lubrication (MQL) approach was conducted. This research aims to investigate the performance of nanofluids (n-Al_2O_3, n-MoS_2, and n-graphene) mixed with coconut oil in various proportions and injected into the tool–work interface using the MQL mist system. Output responses, such as surface roughness values, and cutting temperatures, were measured. The cutting temperatures were determined using an infrared camera and a k-type thermocouple, and the surface roughness was determined using a Talysurf surface meter. Cutting parameters, such as cutting speed, feed rate, and depth of cut, were maintained constant throughout the experiments. The experiments comprised a single factor (MQL fluid) with eight levels. Multiresponse optimization using grey relational coefficients showed that n-Al_2O_3 and n-MoS_2 hybrid combinations with coconut oil yielded better results, i.e., higher ranks, compared with n-graphene mixtures in coconut oils. The experimental findings demonstrated that nanofluids outperformed pure coconut oil. Nano-Al_2O_3 combined with coconut oil produced a superior surface finish, lowered the cutting temperatures, and ensured minimum chip thickness.

Keywords: Turning, nanomaterial, MQL, hybridization

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1. Introduction

Machining of hard steel materials (hardness between 45 and 68 HRC) at high speeds, feed rate, or depth of cut results in severe tool wear owing to high heat generation at the tool–chip interface, surface integrity issues of the workpiece, etc. (Awale and Inamdar, 2015), (Das et al., 2017). One such hard material widely used in the industrial front is the AISI 4340 steel, which is a type of Ni-Cr-Mo steel material (also known as medium carbon steel) and is known for its good toughness and strength (yield and tensile). This steel is used chiefly in general engineering industries, automobile parts, machine building, etc. The material exhibits good mechanical properties when heat treated and possesses excellent wear resistance properties. Therefore, such steels are in demand even today. The process of machining (tool wear, surface deterioration, etc.) with such steel workpieces, specifically termed as hard turning, has been attempted and researched using different techniques, viz. use of advanced cutting tools, such as CVD and PVD coated tool inserts (Sushil et al., 2017); application of forced cooling systems with different temperature gradients, such as cryogenics (Roy et al., 2018), (Bag et al., 2020) and/or in ambient conditions; and use of nanomaterials in machining, to achieve better surface qualities (generally 1 μm), low energy consumption for machining, ease of machining by lowering cutting forces, and better cutting edged tools based on tool geometry, viz. nose radius and reduction of tool wear by decreasing cutting temperature gradients. Cutting tool lifespan and surface finish depend on the selection of a proper cutting tool material and its coatings (Singh, 2020). Under the MQL coolant approach, a fluid flow rate of 10–120 mL/h and pressurized compressed air of 4.0–6.5 bar are suggested for effective cooling/lubrication (Sharma et al., 2008). The specific heat of the coolant gas/fluid used in MQL determines the cooling efficiency. A coolant with a higher specific heat capacity may absorb more heat from the tool and workpiece. Selection of the MQL fluid has a strong effect on the output characteristics (Astakhov, 2011). In selecting machining parameters in machine tool, optimal mix of low feed rate and low depth of cut combined with high cutting velocity is conducive for lowering the machining force. Higher feed rates are expected to lower the cutting power. In every high speed machining process, the essential wear is the abrasion mechanism (Suresh et al., 2012). The complicated mechanisms associated with hard turning can be examined using strategies such as FEM and ANN, and the findings of the models can be approved with trial results (Shihab et al., 2014).

In an experimental study conducted by Veerabhadrarao et al. (2021), understanding the impact of nanomaterials and MQL technology on response variables, such as chip thickness, interface temperature, and workpiece surface characteristics, was the objective. Cutting speed, feed and depth of cut, and MQL settings were examined and verified with confirmatory tests. The findings of this experimentation form the basis for the next level of experiments performed in this study by selecting pure coconut oil, nanofluids, and hybrid mixtures as the factor variance.

2. Literature Survey

Nazma et al. (2019) observed that dry cutting is ecologically safer, more sustainable, and less expensive than cutting with coolants/lubricants according to the results of reviews conducted. However, the method is not suited for cutting operations that involve high heat generation. Mineral oil and other harmful cutting fluids can be successfully eliminated by utilizing vegetable oils, nanofluids, ionic liquids, and other methods. Another alternative to conventional cooling is cryogenic cooling.

Kui et al. (2021) explained that biodegradable, nontoxic, and easily disposable vegetable-based metalworking fluids are excellent lubricants for metal, alloy, and hybrid composite machining. Additionally, these vegetable oils are suitable for lubricating and cooling MQL delivery systems. Palm oil has the potential to be used in MQL machining instead of standard metalworking cutting fluids.

Ghuge et al. (2021) emphasized that while large-scale industries have created and implemented environmentally friendly concepts in India, the majority of medium- and small-scale industries are still unaware of the benefits of MQL systems. The developed MQL system was a low-cost and straight-forward method, thereby making it ideal for small operations.

MQL production indicates that cost-saving applications are possible because of the lower cost of handling the cutting fluids, as suggested by Boubekri et al. (2010).

Uysal et al. (2015) investigated the effects of cutting conditions on initial surface roughness and tool wear for martensitic steel. The vegetable cutting fluid was diluted with 1% nano-MoS_2 to create the nanofluid. Additionally, increasing the MQL flow lowered the tool wear and improved the surface finish.

An experimental study conducted by Anandan et al. (2021) compared graphene nanofluids with dry and pure MQL. The experiment included three degrees of cutting and feeding speeds to study cooling system behavior. Multi-objective optimization by ratio analysis (MOORA) was used to determine the optimal turning parameters. The researchers examined tool wear and surface roughness. The morphology of the chip was investigated using scanning electron microscopy. Graphene nanofluids reduced the surface roughness by 91%, tool wear by 95%, and cutting temperature by 82% in dry conditions and by 66% in oil conditions.

The influence of machining processes, such as turning, and the use of hybrid nanofluids was reviewed by Junankar et al. (2020). Prior research on hybrid nanofluids in turning operations was discussed. This review paper further examined factors such as nanoparticle size, base fluid, supply mode, and lubrication pressure of hybrid nanofluids.

Tuan et al. (2021) investigated the effects of variables on objective functions using analysis of variance (ANOVA) and a Box–Behnken experimental design. The findings demonstrated that nanoparticle amount, cutting speed, and feed exerted an effect on the surface finish of MoS_2 NFMQL hard turning. An oil-in-water emulsion containing MoS_2 nanoparticles improved surface roughness, microstructure, and topography compared with pure MQL. Tribofilms of MoS_2 enhanced the lubricity. White coatings, burn lines, and surface deformation were reduced owing to the superior cooling and lubrication properties of MoS_2 NFMQL. It improved the machinability of carbide tools, saved manufacturing costs, and combated climate change with the use of MQL in hard machining. This study explored the optimal MoS_2 nanoparticle concentration in MQL hard turning oil-in-water emulsion. The best value was found to be 1.2 wt% at 160 m/min cutting and 0.1 mm/rev feed.

Sharma et al. (2016) formulated a novel nanofluid by varying the amount of Al_2O_3 nanoparticles in base fluids. Thermal conductivity and viscosity were determined at all nanoparticle concentrations. The machining performance of the nanofluid on an AISI 1040 steel turning workpiece was examined using MQL minimization. The results of wet/MQL machining were compared with those of conventional cutting fluids. Al_2O_3 nanofluid clearly outperformed dry, wet, and MQL fluid environments in terms of surface roughness, tool wear, cutting force, and chip form.

Madhu et al. (2015) noted that mist application with uncoated inserts reduced cutting temperatures by nearly 25% and coating inserts by approximately 22%. The use of mist reduced cutting temperatures by 60% for uncoated inserts and 50% for coated inserts. The cutting temperature increased with speed and feed. Cutting temperatures were comparable, but uncoated inserts were hotter. The effect of temperature on the work material was found to be significant in the study. Dry machining produced few continuous chips, but mist machining produced continuous long chips. Moreover, dry machining with uncoated and coated inserts (average six cutting operations) exhibited rapid tool wear with mist cooling. In terms of wear, it outperformed dry machining. No tool wear was observed in any of the operations for both coated and uncoated inserts using mist machining.

The key finding of Shaikh et al. (2021) was that vegetable-based cutting fluids were not widely used owing to oxidation and thermal instability. On the contrary, gaseous-based coolant lubricants left no residue and were safer for the operator. MQL was more workable and sustainable than conventional flood application, which needed lubrication and cooling improvements. Nanofluids lubricated the tools and prevented workpiece hardening. For machining, the inability of nanofluids to disperse and the high cost of nanoparticles were the major obstacles. Cryogens, as a coolant and lubricant, have been shown to be more environmentally friendly. However, the initial setup, maintenance, and viability of the shop floor must be addressed. Solvent lubricants require more access to enter the cutting zone. Although dry cutting is considered the most sustainable option, it causes high thermal stress and tool degradation. Haq et al. (2008) demonstrated a new method to optimize the drilling parameters for Al/SiC metal matrix composites with multiple responses by utilizing orthogonal arrays and grey relational analysis (GRA). Multiple responses, such as surface roughness, cutting force, and torque, were considered when optimizing these parameters. Grey analysis resulted in a relationship grade. ANOVA determined the parameters that contributed significantly to the grey relational grade. Pawade et al. (2011) employed Taguchi GRA to optimize high-speed turning of Inconel 718 using multiple performance measures. The parameters of cutting speed, feed rate, depth of cut, and edge geometry had the highest grey relational grade and improved the turning performance in terms of cutting forces and surface roughness.

3. Experimental Setup

Turning experiments with one factor (type of MQL fluid) and eight levels were conducted on the Kirloskar (Turn Master 40) lathe machine, as shown in Fig. 1. An MQL unit was used to create mist lubrication, which was delivered at pressures of 4–5 bar at room temperature onto the steel workpiece under study.

AISI 4340 steel workpiece in the form of a round bar of dimensions 50–60 mm diameter × 350 mm length was held between the lathe centers, as shown in Fig. 2. Initial skinning of 2–3 mm of the work surface (truing and rounding) was done to maintain uniform diameter throughout its length. An actual working length of 300 mm was made available for test runs. The cutting tool was fed twice to attain a total cutting length of 600 mm.

The chemical composition of the AISI 4340 workpiece specimen was as follows: 0.379% C, 0.245% Si, 0.607% Mn, 0.012% S, 0.018% P, 0.984% Cr, 1.322% Ni, 0.226 Mo, 0.203% Cu, 0.014% V, 0.012% Co, 0.004% Ti, 0% W, 0.037% Al, 0.010% Pb, 0.008% Nb, and remaining 95.849% Fe.

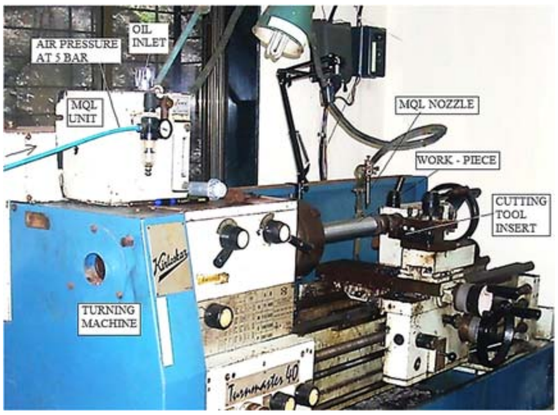

Fig. 1. Turning machine (Kirloskar Make)

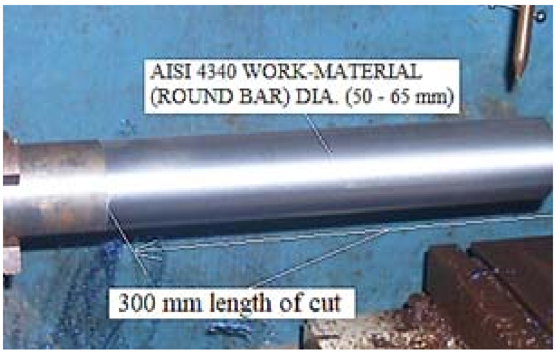

Fig. 2. Loading of the AISI 4340 workpiece between the Centers

Cutting tool inserts used were Kyocera carbide turning inserts CNMG120408GT grade CJ225P (uncoated carbides). For every cut, a fresh tool tip was employed.

Based on the research of VeeraBhadraRao et al. [12], the following parameters for machining were held constant throughout the machining cycles:

1) Cutting Speed (V) = 100 m/min
2) Feed rate (*f*) = 0.28 mm/rev
3) Depth of Cut (doc) = 0.3 mm
4) MQL Nozzle Distance with respect to tool–chip interface = 5 mm
5) MQL Nozzle Orientation Angle with respect to the tool surface = 110º

Fig. 3. Digital weighing unit and digital ultrasonicator

Nanomaterials (n-Al_2O_3, n-MoS_2, and graphene) were mixed in virgin organic coconut oil (cold pressed) in various proportions, as shown in Table. 1, using a digital ultrasonicator, which was run for 30 min–1 h for each nanofluid mixture, as shown in Fig. 3 and Fig. 4. A digital weighing unit was employed to weigh the proper proportion by weight of nanomaterials with coconut oil. Ultrasonication was employed to mix the nanomaterials thoroughly with the coconut oil and to avoid agglomeration of the suspended nanoparticles. For proper dispersion and homogeneity of the nanoparticles in the fluid, 30 min–1 h of ultrasonication has been recommended in most research studies.

Fig. 4. Nanofluids with varying %wt in CC oil

The APS size of n-Al_2O_3 and n-MoS_2 was 30–50 nm and that of nanographene was 5–10 nm thick × 5–10 µm long, certified by Ultrananotech Pvt. Ltd, Bangalore, suppliers. Approximately 20 g of each nanomaterial was used in this experiment.

Fig. 5. Talysurf surface meter for measurement of work surface roughness in microns

Fig. 6. Cutting temperature measurements using an infrared camera (left) and k-type thermocouple (right)

Output responses, such as surface roughness values (in Ra.) in microns were measured across the length of the workpiece using the Talysurf (Mitutoyo make) surface meter. Ten readings were noted, and the average values are listed in Table 2.

Dual measurements for temperatures were noted u sing an infrared camera and a K-type thermocouple setup, as shown in Fig. 6. However, only the tool tip temperature values measured using the infrared camera were considered because the K-type thermocouple sensor was placed below the heel of the insert, which provided 30°–40° lower values than those measured with the infrared camera. The consistency of the temperature measurements was checked using both temperature systems with respect to each other. Maximum tool tip temperatures (tool–chip interface temperature values) are shown in Table 2.

During each MQL fluid turning process, the chips were collected and their thicknesses were measured using a digital outside micrometer having a least count of 1 μm. The readings of chip thickness in mm are presented in Table 2.

Fig. 7. Digital outside micrometer for measurement of chip thickness

Table 1 depicts the various MQL fluids employed for turning experimentation. The objective was to understand whether nanomaterials contributed significantly. The intention was also to determine the effect on the output responses and to ascertain the best MQL fluid that provides minimum surface roughness, low cutting temperatures, and minimal chip thickness. Weight percentages of the nanomaterials were selected based on previous research data and articles [17-20]. The nanofluid mixtures were introduced into the MQL unit, which were then impinged on the work surface at 4–5 bar oil pressure.

Ten readings each for surface roughness (Ra) and chip thickness were recorded, as shown in Table 2.

Table 1. Type of the MQL fluid used in the turning process

MQL Fluid used	**MQL Fluid Designation/Name**
Fluid I	Pure Coconut Oil (CC)
Fluid II	4% wt. n-Graphene + remaining CC
Fluid III	4% wt. n-Al_2O_3 + remaining CC
Fluid IV	0.5% wt. n-MoS_2+ remaining CC
Fluid V	4% wt. n-Al_2O_3 + 0.5% wt. n-MoS_2+ remaining CC
Fluid VI	4% wt. n-Graphene + 0.5% wt.n-MoS_2 + remaining CC
Fluid VII	2% wt. n-Graphene + 2% wt. n-Al_2O_3+remaining CC
Fluid VIII	2% wt. n-Graphene + 2% wt. n-Al_2O_3 + 0.5% wt. n-MoS_2 + remaining CC

Table 2. Measured values of average surface roughness (Ra) in μ, maximum cutting temperature (°C), and average chip thickness (mm) for different MQL fluids

Factor MQL fluid used	Average surface roughness (Ra) μ	Maximum cutting temperature on the tool tip (ºC)	Average chip thickness (mm)
Fluid I	2.382	127.6	0.283
Fluid II	2.394	129.1	0.287
Fluid III	2.144	118.6	0.288
Fluid IV	2.141	124.7	0.276
Fluid V	2.156	121.4	0.301
Fluid VI	2.26	128.4	0.278
Fluid VII	2.272	126.3	0.292
Fluid VIII	2.373	122.5	0.282

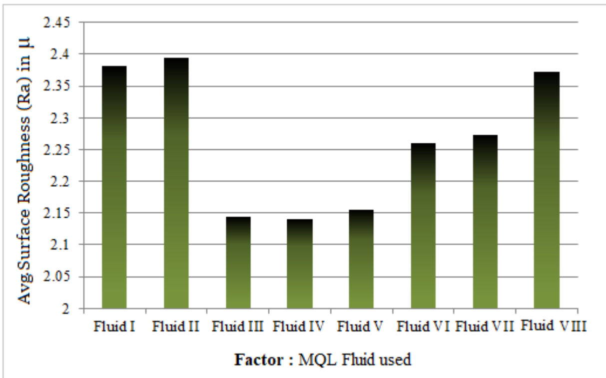

Fig. 8. Graph of average surface roughness (Ra) in microns vs. MQL fluid used

Based on the readings of surface roughness in Table 2, the graph of average surface roughness vs. MQL fluid was plotted, as shown in Fig. 8. Fluids III, IV, and V (Al_2O_3 and MoS_2) showed minimal surface roughness values as compared with graphene and hybrid graphene mixtures.

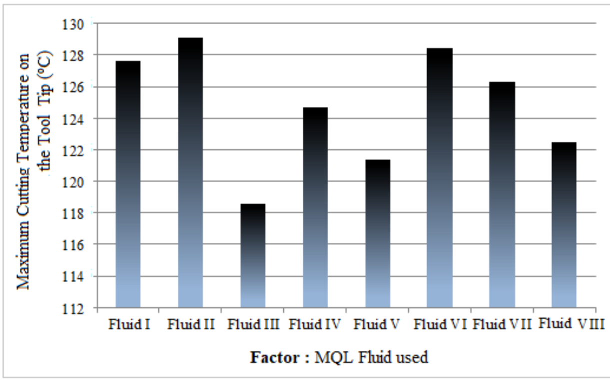

Fig. 9. Graph of maximum cutting temperature on the tool tip (°C) vs. MQL fluid used

Similarly, from the readings of maximum cutting tempearture given in Table 2, the graph of maximum cutting temperature vs. MQL fluid was plotted, as shown in Fig. 9. MQL Fluid III, i.e., 4% wt. n-Al_2O_3 + remaining CC, exhibited minimal temperature values as compared with other hybrid and pure fluid mixtures. MQL fluid V followed, showing the likely relative significance of n-MoS_2 in reducing the cutting temperature.

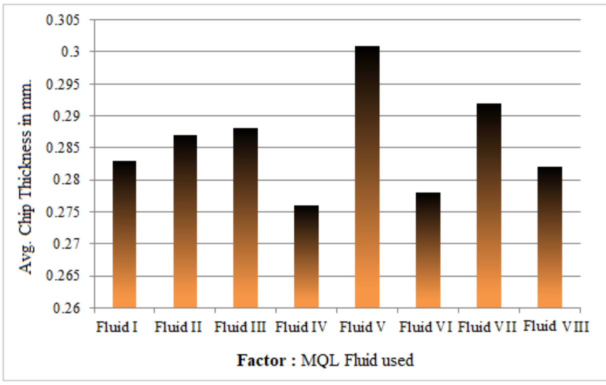

Fig. 10. Graph of average chip thickness in mm vs. MQL fluid used

Fig. 10 depicts the use of Fluid IV (0.5% wt. n-MoS_2 + remaining CC) as the MQL fluid. This fluid yielded minimum chip thickness, and hence, lower cutting forces owing to the good lubrication provided by n-MoS_2. It is evident from the graphs that n-Al_2O_3 and n-MoS_2 nanomaterial is better than n-graphene fluids and pure coconut oil-based fluids. All three responses can be converted to a single response element using the function of grey relation analysis, which can provide the best balance of nanofluid mixture between n-Al_2O_3 and n-MoS_2 .

4. Multiresponse Optimization: GRA

Julong Deng's (1982) theory converts a multiresponse process optimization problem into a single-response optimization situation using the objective function of the overall grey relational grade. Normalization of the response variables is used to convert the raw data to a comparable sequence for analysis. As shown in Eq. (1), a "smaller-is-better" normalization formula was used to convert the original sequence to a comparable sequence:

$$\textbf{Normalized Response} = \frac{(\text{maximum value of the responses in all runs}) - (\text{present value of the response})}{(\text{maximum value of the responses in all runs}) - (\text{minimum value of the responses in all runs})} \quad \text{Eq. (1)}$$

Table 3. Normalized values in grey relational grade analysis

	Avg. Surface Roughness	Max. Cutting Temp	Avg.Chip Thickness
Fluid I	0.047	0.143	0.720
Fluid II	0.000	0.000	0.560
Fluid III	0.988	1.000	0.520
Fluid IV	1.000	0.419	1.000
Fluid V	0.941	0.733	0.000
Fluid VI	0.530	0.067	0.920
Fluid VII	0.482	0.267	0.360
Fluid VIII	0.083	0.629	0.760

The deviation sequence, as defined in Table 4, was then calculated by subtracting the reference sequence from the comparable sequence after normalization. In all responses, the reference sequence was taken as 1.

Table 4. Deviation sequence values in grey relational grade analysis

	Deviation Sequence		
	Avg. Surface Roughness	Max. Cutting Temp	Avg.Chip Thickness
Fluid I	0.953	0.857	0.280
Fluid II	1.000	1.000	0.440
Fluid III	0.012	0.000	0.480
Fluid IV	0.000	0.581	0.000
Fluid V	0.059	0.267	1.000
Fluid VI	0.470	0.933	0.080
Fluid VII	0.518	0.733	0.640
Fluid VIII	0.917	0.371	0.240

The grey relational coefficient (GRC), as shown in Table 5, expresses the relationship between the ideal (best) and actual normalized response variables for all sequences. GRC is denoted by Eq. (2):

$$\boldsymbol{GRC} = \frac{(\text{Minimum Deviation Sequence}) + \zeta(\text{Maximum Deviation Sequence})}{(\text{Deviation Sequence in a particular run}) + \zeta\,(\text{MaximumDeviation Sequence})} \quad \text{Eq. (2)}$$

Where, ζ is the distinguishing coefficient, which is equal to 0.5 for all response variables.

Table 5. Grey relational coefficient in grey relational grade analysis

	Grey Relational Coefficient		
	Avg. Surface Roughness	Max. Cutting Temp	Avg.Chip Thickness
Fluid I	0.344	0.368	0.641
Fluid II	0.333	0.333	0.532
Fluid III	0.977	1.000	0.510
Fluid IV	1.000	0.463	1.000
Fluid V	0.894	0.652	0.333
Fluid VI	0.515	0.349	0.862
Fluid VII	0.491	0.405	0.439
Fluid VIII	0.353	0.574	0.676

The overall evaluation of multiple response characteristics was based on the grey relational grade (GRG), which is the average of the GRCs of all responses, as shown in Table 6. A higher GRG value indicates that the associated condition is optimal.

Table 6. Grey Relational Grade (GRG) Values and Ranks in GRA

	GRG	Rank
Fluid I	0.451	6
Fluid II	0.400	8
Fluid III	**0.829**	**1**
Fluid IV	0.821	2
Fluid V	0.627	3
Fluid VI	0.575	4
Fluid VII	0.445	7
Fluid VIII	0.534	5

Fluid III: 4% wt. n-Al_2O_3 + remaining CC was found to be the optimum MQL fluid that balanced all the response characteristics as per GRA.

5. Confirmatory Test:

The validity of the results was verified by running the confirmatory test. All other cutting parameters, such as cutting speeds, feeds, and depths of cut, were kept constant. "Smaller-the-better" was applicable for all the response variables, i.e., surface roughness, cutting temperatures, and chip thickness. After using 300 mm length of cuts for various steel bar specimens of sizes 45 mm, 50 mm, and 55 mm with the MQL fluid as 4% wt. n-Al_2O_3 + remaining CC, the results obtained were averaged and noted as shown in Table 7. It should be noted that 10 readings were averaged for each response reading.

Table 7. Results of the confirmatory test

Round Bar Work-Piece AISI 4340 (OD = Outside Dia.)	Avg. Surface Roughness (Ra) in Microns	Maximum Cutting Temperature (ºC)	Avg. Chip Thickness (mm)
1(OD = 55 mm)	2.045	120.2	0.276
2(OD = 50 mm)	2.132	117.5	0.255
3 (OD = 45 mm)	2.136	119.4	0.262
Average =	**2.104**	**119.0**	**0.264**

6. Conclusions

From the experimental study involving one factor (MQL fluid type) and eight levels, the following can be concluded:

1. Experimental designs of one factor can be managed using simple graphs, and comparative findings can be sorted. However, for multiresponse measurements and for the selection of levels that balance all responses, a multiresponse optimization, such as GRA, can be effectively implemented. In this way, MQL fluid type III qualifies the test and can be validated with confirmatory tests. ANOVA for such designs requires more replicates and a minimum of two factors, which is difficult with one factor experimentation.
2. From this experiment, it is evident that a hybrid mixture of nanomaterials in base oils can be effectively used in the machining process. Mainly, the responses that were minimum for MQL Fluid III were surface roughness and cutting temperatures; otherwise, chip thickness was found to be nearly the same for all types of MQL fluids.
3. MoS_2 acts as a strong lubricant, thereby enhancing the surface qualities. Al_2O_3 acts as a heat-resistant material that is not damaged by the cutting temperature and enters the tool material. Overheating of the tool nose and damage of the tool tip resulting from overheating are thus avoided. Graphene is less advantageous owing to the fact that it has good electrical and heat conductance properties, which can have negative effects in conducting the heat inside the tool materials.
4. Application of nanofluids in the form of mist lubrication can avoid the high costs of machining due to flooded lubrication and/or the use of costly coated tool insert materials, which is the major advantage of using vegetable oils with nanomaterials.

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