



Evaluation of MQL performances using various nanofluids in turning of AISI 304 stainless steel

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Abstract

In recent years, the need for eco-friendly machining processes has increased dramatically in order to limit the excessive use of conventional cutting fluids, thereby reducing their negative effects on both the environment and the operator's health. In this context, environmental alternatives such as dry cutting, minimum quantity lubrication (MQL), and nanofluid-assisted MQL have been demonstrated to be effective in overcoming this problem. In the present work, an attempt was made to improve the machining characteristics performance in turning of AISI 304 austenitic stainless steel (ASS) under dry, MQL and nanofluids, and hybrid nanofluid-assisted MQL conditions, with respect to surface roughness (Ra), main cutting force (F_c), and cutting temperature (T). The main purpose of this experimental study is to evaluate and compare the effect of dispersed nano-additives into the vegetable cutting fluid on the responses under consideration. As nano-additives, multi-walled carbon nanotube (MWCNT), nano molybdenum disulfide (MoS_2), and nano graphene particles have been used. Additionally, the effects of lubricating conditions on flank wear (VB) were investigated. In the end, statistical analysis, regression modeling, and multi-criteria optimization based on desirability function were performed. The results revealed that the Ra , F_c , and T as well as VB were found to be lower with the use of nano graphene-reinforced nanofluid-assisted MQL followed by nano graphene/ MoS_2 -reinforced hybrid nanofluid-assisted MQL, MWCNT/ MoS_2 -reinforced hybrid nanofluid-assisted MQL, MWCNT-reinforced nanofluid-assisted MQL, nano MoS_2 -reinforced nanofluid-assisted MQL, and MQL, respectively, as compared to dry condition. Finally, it is worth mentioning that the nano graphene has the capability to perform as a lubricant/coolant, thus contributing positively to the turning process.

Keywords Nanofluid · MQL method · Nano MoS_2 · MWCNT · Nano graphene · Stainless steel · Turning

1 Introduction

Machining of AISI 304 (ASS), which is extensively employed in various industrial applications, is well-known as very challenging due to its low thermal conductivity and work hardening tendency. High cutting forces, high temperature generation at the cutting zone, and rapidly progress in tool wear are

the common problems encountered during its machining. These difficulties can have a negative impact on the cost and surface integrity of the machined part. Therefore, delivering the cutting fluids into the cutting area while machining of such materials is one of the effective methods proven by researchers to figure out the above-mentioned issues, thereby increasing cutting performance [1]. The critical roles of these cutting fluids are to reduce the cutting forces and cutting temperatures and also to transport out the chip from the cutting region as well as to increase the cutting tool's life [2]. Due to these roles, the cutting fluids have been frequently and excessively used. Even though this employment of cutting fluids by conventional wet lubricating strategy improved the overall machining productivity, it has adversely affected both the environment and the operator's health due to their petroleum-based nature, applying ample amount, being toxic, etc. In addition, the lubricant can also be contaminated, not only causing environment and health concerns, but also decreasing

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machining efficiency by making fluids lose their characteristics [3].

Proceeding from that, dry cutting, MQL, and nanofluid-assisted MQL have been applied in the metal working industry as alternative techniques to replace wet lubricating applications, consequently mitigating environmental issues, health concerns, and production costs. Excluding the use of lubricant, the dry cutting concept, which has received attention from research community in the past, can be used. However, it has its own machining limitations such as excessive tool wear, heat dissipation, and poor surface integrity, especially in the case of hard-to-cut materials [4]. These drawbacks led the researchers to explore another conscious strategy known as MQL in the recent past. The MQL strategy involves using a minimum quantity of lubricant (oil) in principle. In this process, an optimal amount of cutting fluid (usually at a flow rate that varies between 10 and 500 ml/h) associated with compressed air is pulverized as micro-droplets to the cutting zone. Numerous published studies have shown that the MQL mode produces better F_c , T , Ra , and VB results than wet and dry conditions [5–8]. In literature, Li and Lin [9] used the MQL approach in micro-grinding operation, and they concluded that this approach provided an improvement in Ra and reduction in F_c . Similarly, an enhancement by 15% in the matter of Ra and F_c was reported by Singh et al. [10] in turning of hard-to-cut material under MQL technique. Bedi et al. [11] studied the impact of cutting speed on Ra and F_c when turning AISI 304 under dry and MQL conditions, and they found that MQL provided better Ra and lower F_c than dry turning. Rajaguru and Arunachalam [12] have investigated the machining of super duplex stainless steel under different coolant environments to improve its machinability. Turning experiments were performed under dry, flood, and MQL conditions to enhance the machinability in respect of F_c and Ra . Findings have indicated that the MQL method outperformed other conditions. Also, Uysal [13, 14] investigated the milling of AISI 430 under MQL at flow rates of 20 ml/h and 40 ml/h from the perspective of cutting temperature and flank wear. The outcomes showed that MQL at a flow rate of 40 ml/h delivered acceptable results in comparison to MQL at a flow rate of 20 ml/h.

The application of the MQL approach in machining operations exhibited various benefits such as limited harmful effects on the environment caused by the abundant use of the conventional cutting fluid, less production cost, and increased workers' safety [15]. Nevertheless, it has its own restrictions related to the mediocre cooling function because of the incapability of the lesser oil flow rate to fully limit heat generation at both primary and secondary machining regions in the cutting of hard-to-machine materials [16]. Therefore, there appears to be a need to improve the cutting performance of the MQL process. In this way, the applications of nanofluid-assisted MQL [17, 18] and hybrid nanofluid-assisted MQL

[19] have recently become important research trends in order to enhance MQL efficiency. Researchers have tried various nanoparticles with lubricating properties such as Al_2O_3 (aluminum oxide), MoS_2 (molybdenum disulfide), CuO (copper oxide), Fe_2O_3 (iron oxide), and MWCNT (multi-walled carbon nanotube) [20–22]. Das et al. [21] carried out the hard turning experiments of HSLA steel using three different nanofluids (Al_2O_3 , CuO , and Fe_2O_3) and compared the results with regard to the F_c and Ra . Based on the experimental results, it was concluded that CuO -reinforced nanofluid performed better than other nanofluids. Öndin et al. [22] evaluated the performance of MWCNT particle-enriched vegetable cutting fluid in straight turning of PH 13-8 Mo stainless steel and obtained that MQL and MWCNT-assisted nanofluid MQL reduced the surface roughness by 5% and 12%, respectively, in comparison with dry cutting. Uysal et al. [23] added 1% nano MoS_2 particles to the vegetable cutting fluid in milling of AISI 304 steel. The authors noticed an amelioration in surface roughness compared to MQL and dry environments. Patole and Kulkarni [24] analyzed the machinability characteristics including cutting force and surface roughness of AISI 4340 under MWCNT-assisted nanofluid MQL. They observed that the nanofluid-assisted MQL method yielded an improved surface roughness than conventional cooling. Singh et al. [25] used nano graphene-reinforced vegetable oil in nanofluid-assisted MQL machining in order to ameliorate the machinability regarding tool life, cutting forces, and cutting temperature. Findings have underlined a maximum of a 190% improvement in tool life, 40% reduction in cutting forces, and 42% reduction in cutting temperature when compared to dry cutting. However, the use of hybrid nanofluids is still a relatively new research trend, with only a small number of studies conducted to investigate their performance. For instance, Sharma et al. [26] studied the influence of nano Al_2O_3 particle-reinforced nanofluid and nano Al_2O_3 /MWCNT-reinforced hybrid nanofluid on F_c and Ra during straight turning of AISI 304. The research showed that the potential of hybrid nanofluid was notably better than nanofluid. Jamil et al. [19] have claimed that the application of hybrid nanofluid (Al_2O_3 /MWCNT) underscored an 8.72% reduction in Ra , 11.8% reduction in F_c , and 23% enhancement in tool life. Gugulothu and Pasam [27] reported the reduction in T , Ra , F_c , and VB in turning of AISI 1045 steel using 2 wt% concentration of MWCNT/ MoS_2 -reinforced hybrid nanofluid-assisted MQL condition compared to 0.5, 1, 1.5, 2.5, and 3 wt% concentrations.

Based on previous studies, the usage of nanofluids in the MQL method improved its machining performance. However, the preformed researches especially on machining of AISI 304 (ASS) under hybrid nanofluid-assisted MQL are relatively seldom. Actually, no published research has been found in literature that assessed and compared the effects of dispersed nano graphene, nano MoS_2 and MWCNT particles,

and their hybrids such as nano graphene/MoS₂ and MWCNT/MoS₂-enriched MQL into the vegetable cutting fluid on different machining responses. Therefore, with this objective, an attempt was made in this study to improve the machining characteristics performance with respect of surface roughness (*Ra*), main cutting force (*F_c*), cutting temperature (*T*), and flank wear (*VB*) by adding MWCNT, nano MoS₂, nano graphene particles, and their hybrids (MWCNT/MoS₂ and nano graphene/MoS₂) to the vegetable cutting fluid in straight turning of AISI 304 (ASS). Ultimately, to explicate the experimental findings from different aspects, statistical analysis, regression modeling, and multi-criteria optimization were performed.

2 Experiments and methodology

This section outlines a brief description of the nanofluids' preparation, workpiece material, cutting tool, CNC machine tool, and lubricating environments used in this experimental work as well as machining characteristics measurements.

2.1 Preparation nanofluids

In order to formulate a nanofluid, there are at least two key ingredients that should be incorporated. These ingredients are cutting fluid and nano-additive(s). Indeed, this present work involved the use of a commercial vegetable-based oil as the cutting fluid and three types of commercially available nanoparticles. These particles are nano molybdenum disulfide (MoS₂), multi-walled carbon nanotubes (MWCNT), and nano graphene. The technical properties of the nanoparticles are listed in Table 1. The nanoparticles were dried in a drying oven at 120°C for 2 h, and then the 0.1 wt% of these particles were blended into the vegetable cutting fluid. For proper blending of nanoparticles with vegetable cutting fluid,

Daihan WiseTis HG-15D digital homogenizer was employed at 5000 rpm for 1 h. Similarly, the hybrid nanofluids were also produced by mixing both nano MoS₂ and MWCNT particles at 0.05 wt% for each and nano MoS₂ and nano graphene particles at 0.05 wt% for each with the vegetable cutting fluid. For producing a stable mixture, sodium dodecyl sulfate was added for carbon-based nanoparticles, and lecithin was added for nano MoS₂ particles in the preparation process. In the end, the five sets of prepared nanofluids were pulverized through the MQL system.

2.2 Workpiece material, cutting tool, and CNC machine tool

AISI 304 austenitic stainless steels having a diameter of 70 mm and a length of 300 mm were selected as workpiece material to ascertain the machinability indices in turning trials. Its corresponding chemical composition and mechanical properties are presented in Table 2. Turning tests were carried out by using a CNC lathe having a maximum spindle speed of 4200 rpm. In the experimental studies, Sandvik brand Ti (C, N)/Al₂O₃/TiN-coated TNMG 160408-MM 2025 tungsten carbide (WC) cutting tools and MTJNL 2525M 16M1 tool holder were used. The experimental set-up is shown in Fig. 1.

2.3 Cutting parameters and conditions

Cutting speed and feed with three different levels were chosen as variable cutting parameters, and depth of cut was kept constant. It should be emphasized that the cutting parameters were selected purely based on the cutting tools' manufacturer recommendations as well as the details available in literature. For each set of turning experiments, the machining time was settled at 20 s. In the same context, dry, pure MQL, nanofluid-assisted MQL, and hybrid nanofluids were implemented as the cutting conditions. The complete details of cutting

Table 1 Technical properties and specifications of nanoparticles

Properties	Nano MoS ₂	MWCNT	Nano graphene
Color	Gray	Black	Gray
Purity (%)	99.9	99	99
Thermal conductivity (W/mK)	35	~ 3000–5000	~ 3000–5000
Surface area (m ² /g)	120	275	120–150
Density (g/cm ³)	4.8	2.1	2
Thermal expansion (4–6 m/m/dg-K)	/	106	106
Young's modulus (GPa)	/	910	1000
Tensile strength (GPa)	/	10–60	10–20
Thickness	/	/	5–8 nanometers
Diameter	/	9.5 nanometers	5–10 micrometers
Length	/	1.5 micrometers	/
Dimensions	10–20 nanometers	/	/

Table 2 Chemical composition and mechanical properties of AISI 304

Chemical composition of AISI 304						
C (%)	Si (%)	Mn (%)	P (%)	S (%)	Ni (%)	Cr (%)
0.071	0.39	1.31	0.036	0.022	8.02	18.16
Mechanical properties of AISI 304						
Ultimate tensile strength (N/mm ²)			636	Elongation (%)		68
Yield strength (N/mm ²)			456	Reduction of area (%)		75
Hardness (HB)			175			

parameters and conditions are given in Table 3. A total of 63 cutting experiments were performed, taking into account that the cutting parameters (V_c and f) were defined as continuous variables and different lubricating conditions were termed as categorical variables.

2.4 Measurements of turning characteristics

In this study, four prominent turning criteria, namely surface roughness (R_a), main cutting forces (F_c), cutting temperature (T), and flank wear (VB), were analyzed under different cutting conditions. The main cutting force and cutting temperature were recorded using online mode and surface roughness as well as flank wear measured using offline mode. The surface roughness measurements were performed at three different points along the workpiece by utilizing a Mitutoyo surfest-210 device having a cutoff length of 0.8 mm. Ten measurements were made at each point, and arithmetic averages were determined. The cutting forces and the cutting

temperatures were measured by Kistler piezoelectric dynamometer (type 9257B) and Optris® CTlaser 3MH1 two-wire infrared thermometer with a measuring interval of 150–1000°C, respectively. Flank wear experiments were repeated twice, and the reported value represents the average of flank wear value obtained by at least five measurements using SOIF XJP-6A trinocular microscope device.

3 Results and discussion

In this section, the responses were evaluated based on the various conditions and cutting parameters.

3.1 Surface roughness

In order to evaluate the quality of the machined parts, arithmetic surface roughness (R_a) is often considered the main valuable criterion. Figure 2 shows the variation of R_a as a

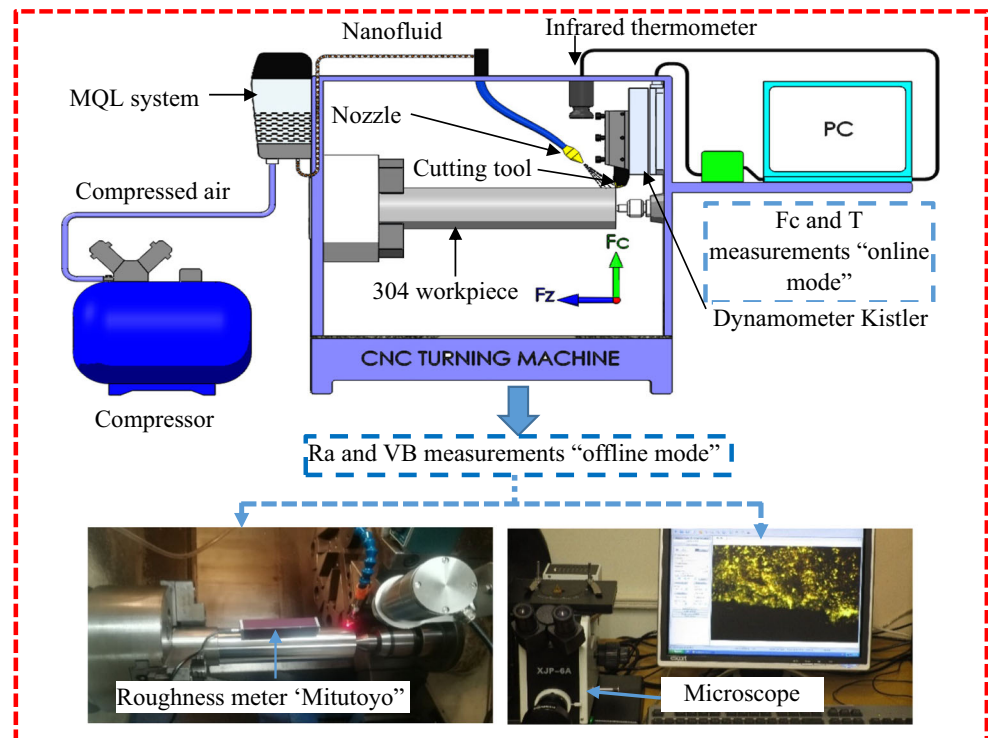
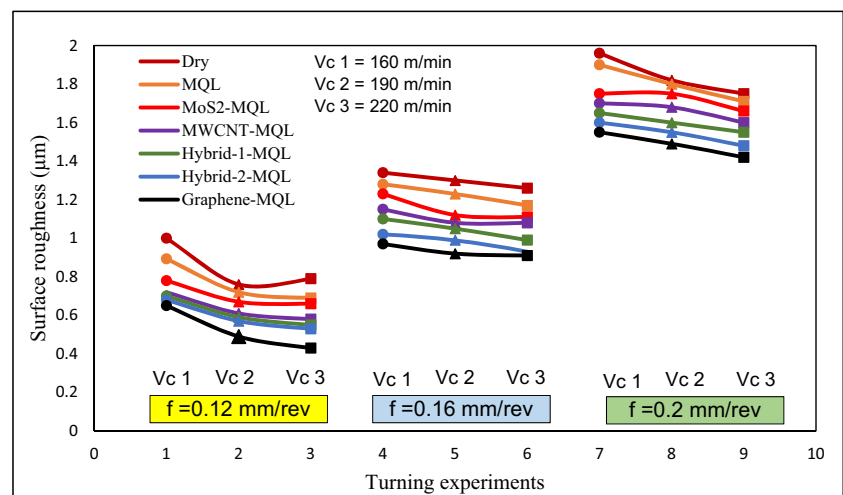
Fig. 1 Experimental set-up

Table 3 Turning parameters and cutting conditions

Parameters	Explanations
Cutting conditions	Dry MQL Nano MoS ₂ -reinforced nanofluid-assisted MQL (MoS ₂ -MQL) MWCNT-reinforced nanofluid-assisted MQL (MWCNT-MQL) Nano graphene-reinforced nanofluid-assisted MQL (graphene-MQL) MWCNT/MoS ₂ -reinforced hybrid nanofluid-assisted MQL (hybrid-1-MQL) Graphene/MoS ₂ -reinforced hybrid nanofluid-assisted MQL (hybrid-2-MQL)
MQL flow rate	30 ml/h
MQL pressure	5 bar
Nozzle angle	30 degree
Nozzle distance	30 mm
Nozzle tip diameter	1 mm
Cutting speed	160, 190, and 220 m/min
Feed	0.12, 0.16, and 0.2 mm/rev
Depth of cut	1 mm

function of cutting speed, feed, and lubricating conditions. It is clear that the R_a increased as the feed increased and decreased as the cutting speed increased. Probably, with increasing the feed, the increment in R_a is thought to be due to the generation of thick feed marks produced by the relative motion between the workpiece and the cutting tool [28]. In the turning process, thicker feed marks cause more improper surface finish, whereas an increment in cutting speed caused a decrease in R_a . This is due to the fact that increased cutting speed contributes to generating high heat in the cutting zone. As a result, the possibility of formatting the build-up edges (BUE) could be reduced, thereby R_a decreased [19]. Regardless of cutting parameters, the alteration in R_a was also dependent on the lubricating conditions. Arithmetic means of R_a under dry, MQL, MoS₂-MQL, MWCNT-MQL, graphene-MQL, hybrid-1-MQL, and hybrid-2-MQL conditions were determined as

1.33 μm , 1.27 μm , 1.19 μm , 1.13 μm , 0.98 μm , 1.09 μm , and 1.04 μm , respectively. It is clearly to be observed that there are improvements in R_a by approximately 4.9%, 10.43%, 14.86%, 26.29%, 18.36%, and 21.95% under MQL, MoS₂-MQL, MWCNT-MQL, graphene-MQL, hybrid-1-MQL, and hybrid-2-MQL conditions, respectively, as compared to dry cutting. This can be explained due to the absence of any lubricant. Similarly, the addition of nanoparticles to the vegetable cutting fluid in the MQL system induced the surface to be smoother, and hence lower surface roughness values were obtained as compared to pure MQL condition. This is because of the ability of nanoparticles to reduce coefficient of friction [16] thanks to their structures at nano level that help to format a thin layer at the rubbing zone, leading to separating the asperities of sliding surfaces effectively [29]. Interestingly, it can be seen that MWCNT/MoS₂ and nano

Fig. 2 The variation of R_a under different cutting conditions

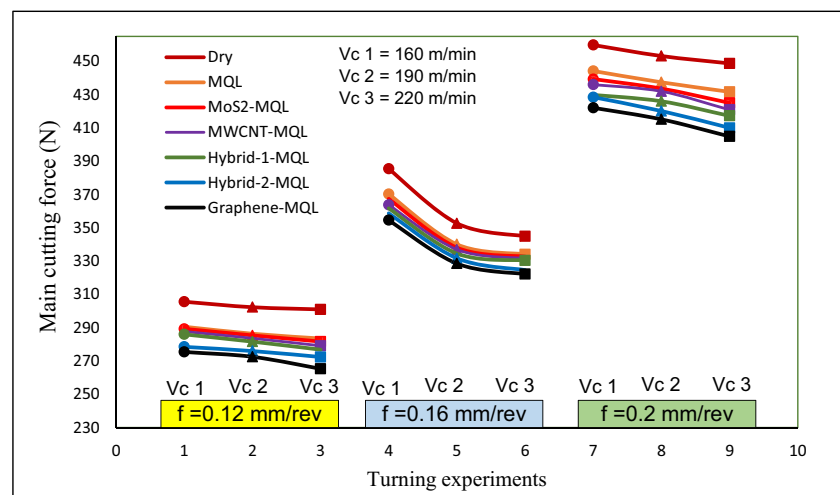
graphene/MoS₂-reinforced hybrid nanofluid-assisted MQL provided enhanced Ra compared to MWCNT and nano MoS₂-reinforced nanofluids. The primary reason is that combining between the nanoparticles (MWCNT/MoS₂ and nano graphene/MoS₂) and increasing their Brownian motion in liquid resulted in an increase in thermal conductivity of the formulated nanofluid, which resulted in a reduction in heat generated in cutting area due to its heat dissipation capability [27]. As a result, the turning operation could be completed smoothly, lowering Ra [22, 30]. However, only nano graphene-reinforced nanofluid produced better improvement in terms of Ra than other nanofluids and hybrid nanofluids. This is believed due to the nano graphene particles' nanoscale structure (platelets), which helps to excellently penetrate into the tool-workpiece interface, and its well lubrication properties [31, 32].

3.2 Cutting force

Cutting force (F_c) is considered to be one of the main machining responses that assesses the power and energy consumption during the machining operations. However, many important variables such as the cutting parameters, the machine tool dynamics, characteristics of tool and workpiece material, and tribological properties of cutting fluid influence the cutting forces [16, 21]. Figure 3 presents the variation of F_c according to cutting speed, feed, and different lubricating conditions. Based on the results, it was clear that increasing the feed increased the main cutting force significantly. The major belief of the increase in cutting force is due to an increase in the chip cross-section causing an increment in friction force at the tool-chip interface [33]. Further, the cutting speed had substantially less effect on the F_c than the feed. At lower cutting speeds, higher cutting force values were recorded. This can be interpreted by increasing in the chip-tool contact length caused by the remaining chip in the rake face of the tool

over a long period of time [34]. Decreased cutting force was observed at high cutting speed ($V_c=220$ m/min). In general, with an increase in cutting speed, the temperature rises at the cutting region. Therefore, thermal softening occurs, thereby cutting forces reduced [35]. In addition, as shown in Fig. 3, it is obvious that the lubricating conditions also affected the cutting force. Cutting forces under dry, MQL, MoS₂-MQL, MWCNT-MQL, graphene-MQL, hybrid-1-MQL, and hybrid-2-MQL conditions were measured as 372.61 N, 357.55 N, 354.7 N, 352.38 N, 340.05 N, 349.32 N, and 344.48 N, respectively. There was a visible reduction in F_c by approximately 4.04%, 4.80%, 5.42%, 8.73%, 6.24%, and 7.54% under MQL, MoS₂-MQL, MWCNT-MQL, graphene-MQL, hybrid-1-MQL, and hybrid-2-MQL conditions, respectively, as compared to dry cutting. Low cutting forces were obtained with the application of MWCNT and nano MoS₂-reinforced nanofluid-assisted MQL method as compared to dry and pure MQL cutting environments. A good reason for this fact is attributed to the dispersion of MWCNT and nano MoS₂ particles into the cutting fluid, which enhanced the viscosity and thermal conductivity of the cutting fluid [16]. In addition, MWCNT particle-reinforced nanofluid caused lower cutting forces than nano MoS₂ particle-reinforced nanofluid. Similar observation is reported in literature [27] for superior performance of MWCNT than nano MoS₂. Moreover, lower cutting forces were obtained with the application of hybrid nanofluid-assisted MQL method. This can be due to the fact that the interaction of the combined nanoparticles helps to form adhesive film, thus more lubrication that leads to reduced friction between sliding surfaces, resulting in a declining magnitude of F_c [27]. Furthermore, the lowest cutting forces were measured while using nano graphene-reinforced nanofluid-assisted MQL method. As previously stated, this is due to the effective interaction of nano graphene particles with the cutting tool and the workpiece due to its superior lubricating and super thin nanoscale structure, resulting in reduced

Fig. 3 The variation of F_c under different cutting conditions and parameters



friction, minimizing cutting force, and improving dimensional accuracy of the machined part.

3.3 Cutting temperature

Cutting temperature (T) is an important index that helps to determine the quality of machining performance in terms of production efficiency. The main factor that directly affects the cutting temperature is the amount of heat produced at the cutting tool-chip interface. Figure 4 displays graphically the effects of dry, MQL, MoS₂-MQL, MWCNT-MQL, graphene-MQL, hybrid-1-MQL, and hybrid-2-MQL conditions and cutting parameters on the T in the cutting zone. Accordingly, it is highly visible that there is a significant growth trend in T with feed raising. This is justified due to the fact that increased feed is responsible for the rise of chip thickness, which impacts friction and hence leads to an increment in the heat generation and cutting temperatures [22]. Despite not having the same effect on T as the feed, increasing the cutting speed resulted in an increase in the T in the cutting area. It is well-known that increased cutting speed causes an increase in the plastic deformation speed. However, the effect of cutting speed on T can be explained by the inclusion of cutting fluid, which resulted in less heat being distributed into workpiece-tool-chip interfaces [11]. Irrespective of cutting parameters, the variation in cutting temperature was also found to depend on the cutting environment, as shown in Fig. 4. The highest cutting temperature was measured under dry conditions. The reason for this was primarily due to the lack of any lubrication [15]. Including the cutting fluid in the turning process, the cutting temperature was diminished by about 3.82%, 6.08%, 8.06%, 14.21%, 10.18%, and 12.29%, respectively, under MQL, MoS₂-MQL, MWCNT-MQL, graphene-MQL, hybrid-1-MQL, and hybrid-2-MQL conditions as compared to dry cutting. However, there was a slight decrease in T with the pure MQL method due to deficient in cooling effects, particularly

when machining of hard-to-cut materials [30]. Further, the addition of nanoparticles and their hybrids to the vegetable cutting fluid resulted in a better reduction in T in the cutting zone. A significant reduction of 14.21% in T with the use of nano graphene-reinforced nanofluid may be imputed to the superior thermal conductivity properties of the nano graphene particles than nano MoS₂ and MWCNT-reinforced nanofluids and their hybrids. It was suggested that higher thermal conductivity presents better heat extraction ability [36]. The obtained results are in good concordance with previous published work [37].

3.4 Comparison of performance outputs

In this section, a direct comparison of the effects of the cutting conditions on performance measures was made. To fulfill this purpose, the cutting parameters were kept constant as the cutting speed of 220 m/min and the feed of 0.12 mm/rev (experiment number 3). All performance indices (R_a , F_c , and T) were found to be better in the nano graphene-reinforced nanofluid-assisted MQL method as compared to other lubricating environments as shown in Fig. 5. Based on the experimental results, R_a values were reduced by 45.56%, 37.68%, 34.84%, 25.86%, 21.81%, and 18.86%, F_c values were reduced by 11.85%, 6.42%, 5.80%, 4.95%, 4.15%, and 2.60%, and T values were also reduced by 12.22%, 9.97%, 8.37%, 6.42%, 4.23%, and 2.26% under nano graphene-reinforced nanofluid-assisted MQL method as compared to dry, MQL, MoS₂-MQL, MWCNT-MQL, hybrid-1-MQL, and hybrid-2-MQL conditions. The main reason for this improvement of R_a and reduction of F_c and T is thought to be due to the better physical synergetic effect of nano graphene-reinforced nanofluid. Similar observation was documented in literature [31]. However, as not expected, it can be seen that nano graphene-reinforced nanofluid-assisted MQL outperformed its hybrid (graphene/MoS₂)-reinforced

Fig. 4 The variation of T under different cutting conditions and parameters

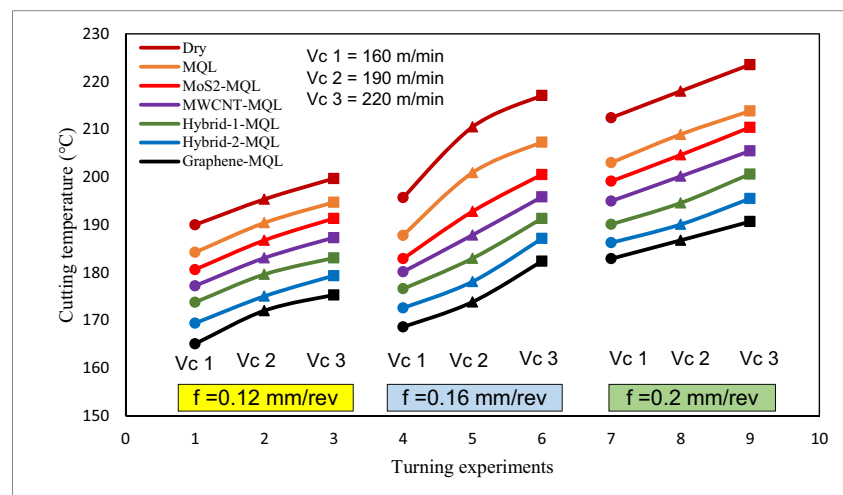
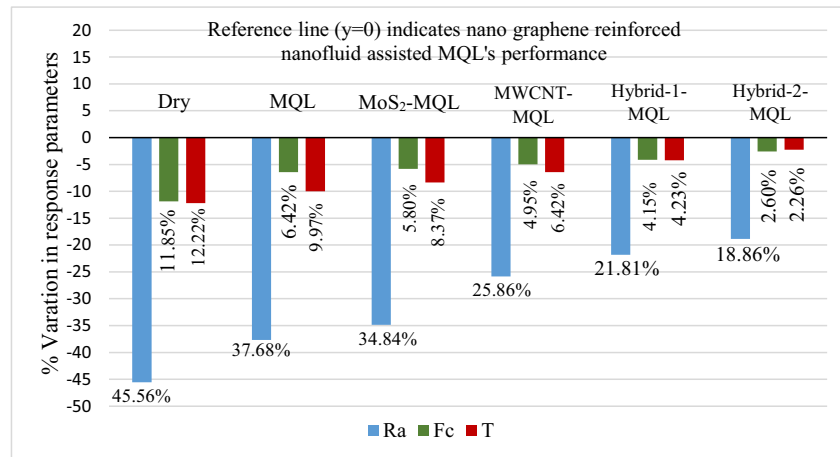


Fig. 5 Effect of nano graphene-reinforced nanofluid-assisted MQL on performance outputs against other lubricating conditions.



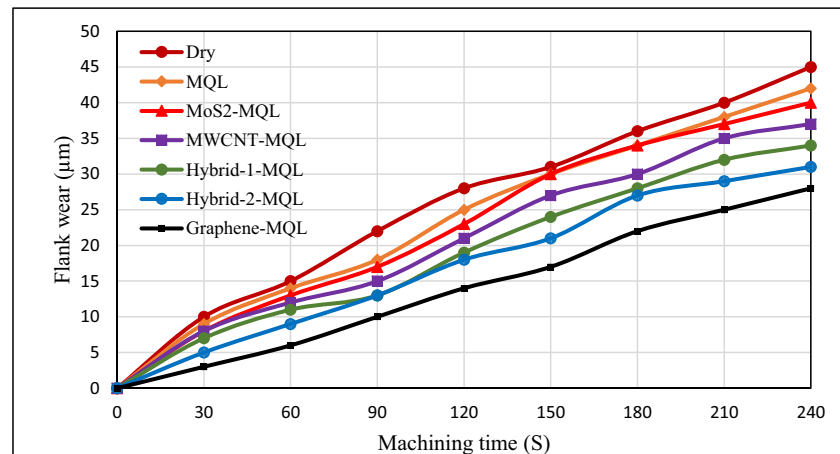
nanofluid-assisted MQL. This result can be attributed to the higher weight percentage of graphene (0.1%), which improves the wettability of the nanofluid, allowing nano graphene platelets to successfully penetrate into the cutting tool-workpiece interface, reducing friction and heat generation, and thus contributing to improved machining performance (Ra , Fc , and T). This is in accordance with justification reported in literature [32, 37, 38].

3.5 Flank wear

In the current work, a set of turning experiment tests were conducted at constant cutting parameters ($V_c=190$ m/min and $f=0.12$ mm/rev) to assess the positive and negative impacts of the investigated lubricating conditions, especially nano MoS₂, MWCNT and nano graphene nanofluids, and their hybrid nanofluid-assisted MQL method on VB in straight turning of AISI 304. The behaviors of flank wear are given in Fig. 6 in accordance with machining time. Based on the measurement results, significant reductions of 6.67%, 11.11%, 17.78%, 48.89%, 24.44%, and 33.33% in VB were observed by utilizing MQL, MoS₂-MQL, MWCNT-MQL, graphene-

MQL, hybrid-1-MQL, and hybrid-2-MQL conditions, respectively, as compared to dry cutting. The main reason for dry cutting's poor performance can be attributed to the fact that the lack of lubricant exposes the cutting tool to extreme high heat generation, resulting in increased friction between cutting tool-chip-workpiece interfaces. As a result, adhesion or welding of the chips on the rake face occurs, and this leads to deteriorating the sharpness of the cutting edge. Similar explanations were stated in literature [28, 39]. Likewise, noticeable reductions of 4.76%, 11.90%, 45.24%, 20%, and 28.57% in flank wear were also noticed under MoS₂-MQL, MWCNT-MQL, graphene-MQL, hybrid-1-MQL, and hybrid-2-MQL conditions, respectively, as compared to pure MQL environment. It is thought that insufficient cooling of the pure MQL method is due to its inability to effectively penetrate into the cutting zone. And this may be the main reason for its moderate performance. Overall, the addition of nano-additives to the vegetable cutting fluid ameliorates its thermal-physical properties, thereby resulting in less VB . It is clearly obvious from Fig. 6 that the best machining performance in terms of lower VB was observed under the nano graphene-reinforced nanofluid-assisted MQL method. Its hybrid performance

Fig. 6 The evolution of VB with respect of machining time under different cutting conditions and parameters.



(nano graphene/MoS₂-reinforced hybrid nanofluid) was ranked second, followed by MWCNT/MoS₂-reinforced hybrid nanofluid-assisted MQL, MWCNT-reinforced nanofluid-assisted MQL, and nano MoS₂-reinforced nanofluid-assisted MQL. This fact is because of the higher thermal conductivity, low viscosity, spreadability, and improved wettability properties of nano graphene-reinforced nanofluid [39] and so forth. Hence, it can conclude that nano graphene platelets are better for using as a cooling/lubricating agent to improve the thermal-physical properties of the vegetable cutting fluid. Doing so has the potential to contribute positively to the turning process. This research highlighted similar outcomes to research performed by Singh et al. [25] for the potential of nano graphene particles to act as lubricant/coolant agent in turning operations.

4 Statistical analysis and multi-criteria optimization

In order to examine the degree of statistical significance of process parameters on machinability characteristics, analyses of variance (ANOVA) was introduced as provided in Table 4. Table 4 contains a statistical indicator known as the F-ratio, which is used to determine which control factors have a significant effect on the characteristic being evaluated (in this case, *Ra*, *Fc*, and *T*). Also, the degree of influence was explained with the percentage contribution (PC), which is the product of division of each parameter's sum of squares (SS) onto their total. The higher the PC, the higher the effect a

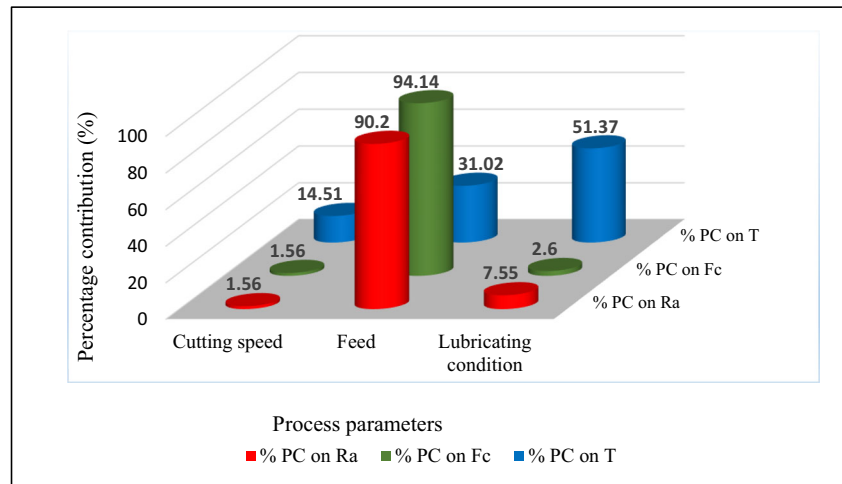
variable has on a measured response [40]. The analyses were carried out at confidence levels of 95% [41]. As a result of assessment of surface roughness results, it was obtained that the feed is the most significant cutting parameter affecting *Ra* with the F value of 4865.32 and percentage contribution of 90.20% followed by lubricating condition (*F* = 368.09 and PC = 7.55%) and cutting speed (*F* = 85.59 and PC = 1.56%). When the cutting force results were analyzed, the F values and the PC of cutting speed, feed, and lubricating condition were found to be 46.65 and 1.56%, 2815.38 and 94.14%, and 65.94 and 2.6%, respectively. In this case, feed has the greatest statistical signification for cutting force. As far as the cutting temperature results in the cutting zone were concerned, the effects of process parameters were ranked as follows: (1) lubricating condition with *F* = 875.58 and PC = 51.37%; (2) feed with *F* = 539.89 and PC = 31.02%; and (3) cutting speed with *F* = 252.49 and PC = 14.51%. Therefore, the process parameter with the dominate influence on *Ra* and *Fc* was the feed, while the effective cutting parameter affecting *T* in the cutting zone was the lubricating condition. This is in agreement with findings reported in literature [22]. Figure 7 depicts the ANOVA results in terms of percentage contributions of all process parameters to each measured outputs.

In order to perform the multi-criteria optimization task, adequate models should be established to describe the output indices in terms of the pre-defined design factors. A multi-regression analysis approach was employed to conduct the modeling task. This approach is extensively reported in establishing a relationship between the measured outputs and included process parameters [42]. Through this approach, it is

Table 4 ANOVA for (a) *Ra*, (b) *Fc*, and (c) *T*

Factors	Degree of freedom	Sum of squares	Mean of squares	F-ratio	PC (%)
(a) Surface roughness					
Cutting speed	1	0.18	0.18	85.59	1.56
Feed	1	10.41	10.41	4865.32	90.20
Lubricating conditions	6	0.84	0.14	368.09	7.55
Error	54	0.12	2.14E-003		1.03
Total	62	11.54			
(b) Cutting force					
Cutting speed	1	3730.51	3730.51	46.65	1.56
Feed	1	225,154	225,154	2815.38	94.14
Lubricating conditions	6	5959.39	993.23	65.94	2.6
Error	54	4318.54	79.97		1.8
Total	62	239,163			
(c) Cutting temperature					
Cutting speed	1	1597.60	1597.60	252.49	14.51
Feed	1	3416.07	3416.07	539.89	31.02
Lubricating conditions	6	5656.90	942.82	875.58	51.37
Error	54	341.68	6.33		3.1
Total	62	11,012.25			

Fig. 7 Percentage contributions of the process parameters on measured outputs



possible to derive a second-order model. Note that LC indicates the lubricating conditions that are coded as 1, 2, 3, 4, 5, 6, and 7 for dry, MQL, MoS₂-MQL, MWCNT-MQL, graphene-MQL, hybrid-1-MQL, and hybrid-2-MQL, respectively. The proposed regression models for Ra , Fc , and T are expressed in Eqs. (1) to (3), respectively. The accuracy of all yielded models (R^2) was higher than 0.98. The residual plot, which is defined as the difference among the measured values of Ra , Fc , and T and their predicted one, was used to assess the goodness fit of the simulated models.

$$Ra = 1.915 - 0.0188 * V_c - 0.74 * f - 0.1310 LC + 0.00753 * V_c * f + 0.000124 * V_c * LC - 0.126 * f * LC + 0.000024 * V_c^2 + 38.29 * f^2 + 0.00948 * LC^2 \quad (1)$$

$$Fc = 408.0 - 1.468 * V_c - 238 * f - 9.70 LC - 1.43 * V_c * f - 0.0010 * V_c * LC + 18.5 * f * LC + 0.00365 * V_c^2 + 7543 * f^2 + 1.091 * LC^2 \quad (2)$$

$$T = 146.3 + 0.428 * V_c - 201 * f - 6.76 LC + 0.026 * V_c * f - 0.0091 * V_c * LC - 12.70 * f * LC - 0.00050 * V_c^2 + 1478 * f^2 + 0.781 * LC^2 \quad (3)$$

Figure 8 presents the normal probability plots of models for Ra , Fc , and T . It was noticeable that most of the data points had fallen over the straight line pattern. Therefore, it can be indicated that the normality assumptions were verified [43], proving the precision of the regression models given. Moreover, it can be concluded that the yielded models were suitable and hence could be used to accomplish the optimization objective.

The desirability function (DF) was implemented in this research work to carry out the multi-criteria optimization goal. DF is considered one of the most popular approaches that determines the best solution in an easy and simple way. Through the DF approach, it is possible to integrate all desired purposes into unequaled desirable function (d_i) that ranges from $0 \leq d_i \leq 1$ [16], according to Eq. (4) [44]:

$$d_i = \begin{cases} 0 & \text{if } q_i \leq S \\ \left(\frac{q_i - S}{L - S} \right)^\alpha & \text{if } S < q_i < L \\ 1 & \text{if } q_i \geq L \end{cases} \quad (4)$$

where S and L present the smallest and the largest acceptable values of q_i , respectively, α is the weight parameter, and q_i presents the output to be optimized.

Herein, the process parameters were maintained within experimental range. The feasible solution, that led to minimizing simultaneously the measured outputs (Ra , Fc , and T), was chosen as the one possessing the higher desirability value. Figure 9 presents the contour plots underscored for Ra , Fc , and T at the higher desirability value (0.943). The ideal solution after multi-criteria optimization was found with the following parameters: the cutting speed of 188 m/min, feed of 0.12 mm/rev, and nano graphene-reinforced nanofluid-assisted MQL condition. Through this combination, the estimated values were found to be $0.51 \mu\text{m}$, 270 N, and 170°C for Ra , Fc , and T , respectively. Table 5 lists the optimum eight possible solutions derived by employing the DF technique. In addition, the optimum results delivered by the DF approach were compared with experimental run (experiment number 2 according to Figs. 2, 3, and 4), as provided in Table 6. According to Table 6, the obtained percentage deviations are within the acceptable range, i.e., within $< 5\%$, confirming the validity of the suggested optimal results achieved in this investigation.

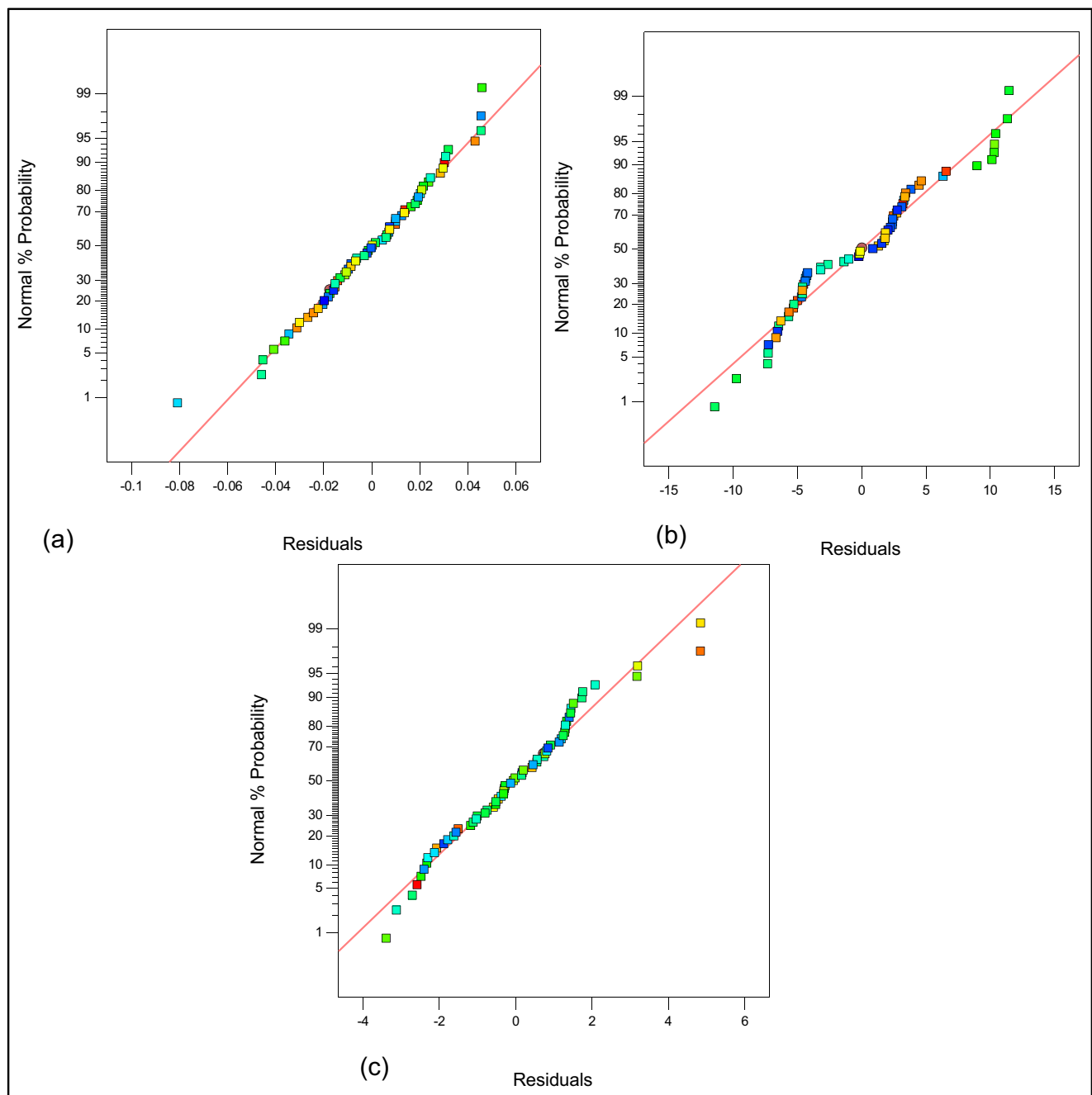


Fig. 8 Residual plots for normal probability of (a) *Ra*, (b) *Fc*, and (c) *T*

5 Conclusion

This research focuses on the analysis of surface roughness, cutting force, cutting temperature, and flank wear in the turning of AISI 304 austenitic stainless steel under various cutting parameters and conditions, such as dry, MQL, nano MoS₂-reinforced nanofluid-assisted MQL, MWCNT-reinforced nanofluid-assisted MQL, nano graphene-reinforced nanofluid-assisted MQL, MWCNT/MoS₂-reinforced hybrid nanofluid-assisted MQL, and nano graphene/MoS₂-

reinforced hybrid nanofluid-assisted MQL. The following conclusions were drawn after evaluating the data collected throughout the current work:

- Average surface roughness (*Ra*) was obtained to be 1.33 μm , 1.27 μm , 1.19 μm , 1.13 μm , 0.98 μm , 1.09 μm , and 1.04 μm under dry, MQL, MoS₂-MQL, MWCNT-MQL, graphene-MQL, hybrid-1-MQL, and hybrid-2-MQL conditions, respectively. Surface roughness was reduced by about 4.9%, 10.43%, 14.86%, 26.29%, 18.36%, and

Table 5 Optimum findings derived by desirability approach (DF) for multi-criteria Ra , Fc , and T

Process parameters			Outputs			Desirability
V_c , m/min	f , mm/rev	Lubricating conditions	Ra , μm	Fc , N	T , $^{\circ}\text{C}$	
188.86	0.12	Graphene-MQL	0.51	270.77	170.37	0.943
182.48	0.12	Graphene-MQL	0.526	272.67	169.25	0.942
202	0.12	Graphene-MQL	0.478	267.62	172.65	0.941
214	0.12	Graphene-MQL	0.457	265.89	174.57	0.936
180.85	0.12	Hybrid-2-MQL	0.59	277.21	172.77	0.899
171.68	0.12	Hybrid-2-MQL	0.62	280	170.99	0.899
194.50	0.12	Hybrid-2-MQL	0.560	273.20	175.40	0.897
199.77	0.12	Hybrid-2-MQL	0.55	272.06	176.34	0.895

21.95% when MQL, MoS₂-MQL, MWCNT-MQL, graphene-MQL, hybrid-1-MQL, and hybrid-2-MQL conditions were used, respectively, when compared to dry cutting.

- The cutting force (F_c) values were measured as 372.61 N, 357.55 N, 354.7 N, 352.38 N, 340.05 N, 349.32 N, and 344.48 N under dry, MQL, MoS₂-MQL, MWCNT-MQL, graphene-MQL, hybrid-1-MQL, and hybrid-2-MQL conditions, respectively. There was visible reduction in F_c by about 4.04%, 4.80%, 5.42%, 8.73%, 6.24%, and 7.54% under MQL, MoS₂-MQL, MWCNT-MQL, graphene-MQL, hybrid-1-MQL, and hybrid-2-MQL conditions, respectively, over dry cutting.
- The cutting temperature at the cutting zone was reduced by incorporating the vegetable cutting fluid into the turning process. In comparison with dry cutting, MQL, MoS₂-MQL, MWCNT-MQL, graphene-MQL, hybrid-1-MQL, and hybrid-2-MQL conditions, respectively, showed approximately 3.82%, 6.08%, 8.06%, 14.21%, 10.18%, and 12.29% lower cutting temperatures.
- Significant reductions of 6.67%, 11.11%, 17.78%, 48.89%, 24.44%, and 33.33% in flank wear were obtained by using MQL, MoS₂-MQL, MWCNT-MQL, graphene-MQL, hybrid-1-MQL, and hybrid-2-MQL conditions, respectively, over dry cutting.
- The addition of nanoparticles (nano MoS₂, MWCNT, nano graphene, and their hybrids) to the vegetable cutting fluid increases the solid-liquid interfacial contact zone,

providing improved thermal-physical properties of the cutting fluid, thereby resulting in less Ra , Fc , T , and VB .

- When all nanoparticles added to the vegetable cutting fluid were compared, the nano graphene-reinforced nanofluid-assisted MQL performed better in terms of improving machining measures. It is mostly owing to its better thermal conductivity, superior lubricating qualities, and greater wettability, which allows the vegetable cutting fluid to enhance its cooling/lubricating capabilities.
- The ANOVA analysis revealed that the feed had the most effective influence on Ra and Fc , with contribution ratios of 90.20% and 94.14%, respectively, while the lubricating conditions had the most influence on T , with a contribution ratio of 51.37%.
- The simulated models obtained using multi-regression analysis were statistically significant in terms of R^2 , and their precision was verified using residual plots. As a result, the established models are useful for predicting Ra , Fc , and T in straight turning of AISI 304 (ASS) material.
- Based on multi-criteria optimization findings, it was suggested that a cutting speed of 188 m/min, feed of 0.12 mm/rev, and lubricating condition of nano graphene-reinforced nanofluid-assisted MQL method are practical solutions for dependently approaching the lower Ra , Fc , and T values.

Even though the results of this investigation were highly beneficial for industrial practice as technical guidelines for using nano MoS₂, MWCNT and nano graphene-reinforced

Table 6 Comparison between optimal solutions delivered by DF and experimental run

Run	Process parameters			Outputs		
	V_c , m/min	f , mm/rev	Lubricating condition	Ra , μm	Fc , N	T , $^{\circ}\text{C}$
DF	188	0.12	Graphene-MQL	0.51	270.77	170.37
Experimental run	190	0.12	Graphene-MQL	0.49	272.05	172.02
Deviation (%)				3.92	0.47	0.95

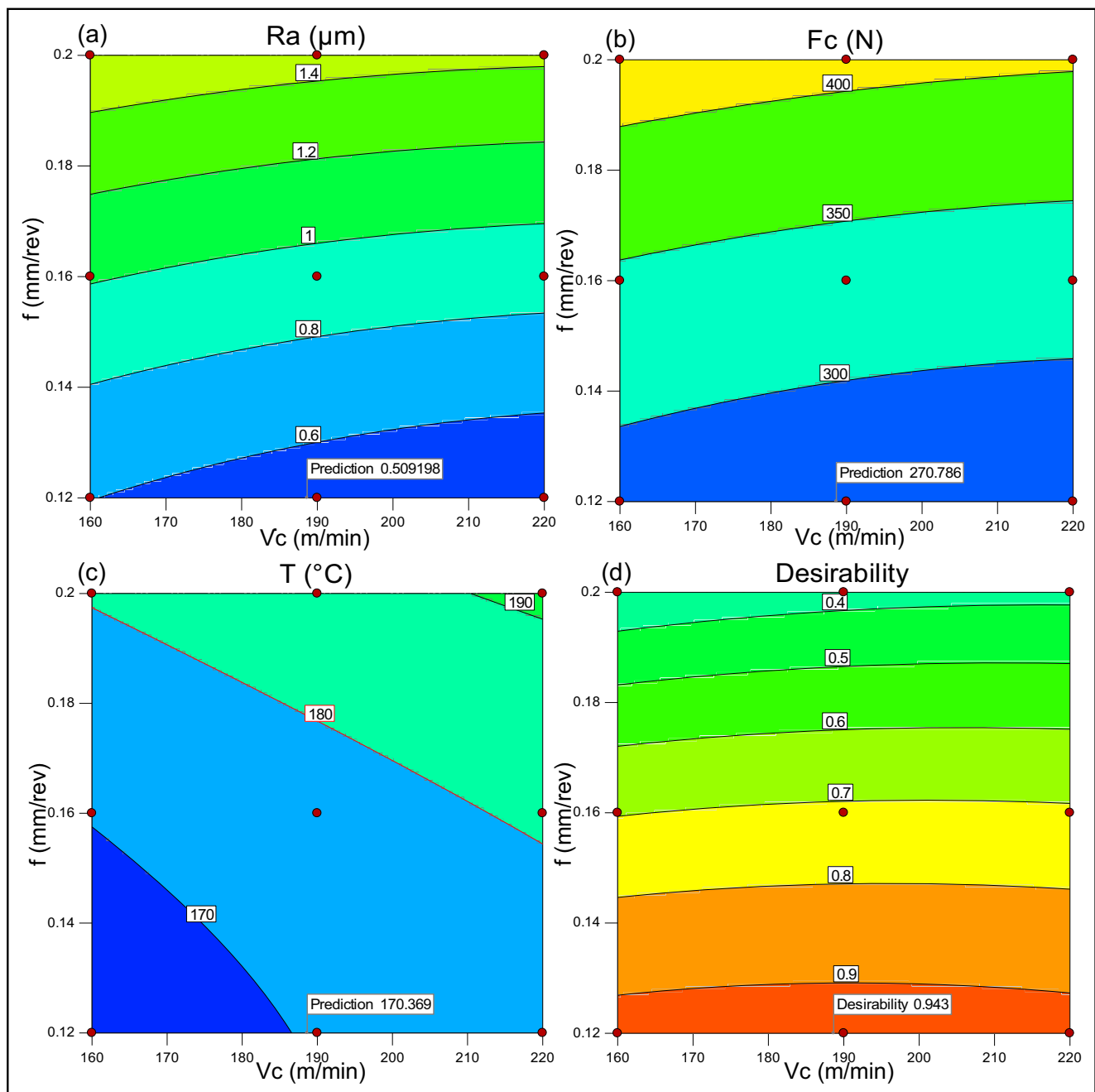


Fig. 9 Contour plots for (a) Ra , (b) F_c , (c) T , and (d) overall desirability

nanofluids, and their hybrids in the MQL method to improve turning process efficiency, some additional research is still needed to optimize the MQL flow rate and also to determine the effects of percentage weight and size of nanoparticles on the machining process performance.

Nomenclature V_c , Cutting speed (m/min); f , Feed (mm/rev); ap , Depth of cut (mm); Ra , Surface roughness (μm); F_c , Cutting force (N); T , Cutting temperature ($^{\circ}\text{C}$); VB , Flank wear (μm); *MQL*, Minimum quantity lubrication; MoS_2 , Molybdenum disulfide; *MWCNT*, Multi-walled carbon nanotube; *LC*, Lubricating conditions; MoS_2 -*MQL*, Nano MoS_2 -

reinforced nanofluid-assisted MQL; *MWCNT-MQL*, MWCNT-reinforced nanofluid-assisted MQL; *Graphene-MQL*, Nano graphene-reinforced nanofluid-assisted MQL; *Hybrid-1-MQL*, MWCNT/ MoS_2 -reinforced hybrid nanofluid-assisted MQL; *Hybrid-2-MQL*, Graphene/ MoS_2 -reinforced hybrid nanofluid-assisted MQL; *ANOVA*, Analysis of variance; *PC*, Percentage of contribution (%); *DF*, Desirability function; *ASS*, Austenitic stainless steel

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Author contribution Y. Touggui and U. Emiroglu performed the turning experiments. Y. Touggui evaluates studies and wrote the draft. A. Uysal designed CNC turning experiments, edited the draft, and discussed the results. S. Belhadi reviewed the draft. M. Temmar supervised the team.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

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