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Original Article

Investigation of sustainable machining of Ti-6Al-4V using graphene enhanced minimum quantity lubrication

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ABSTRACT

Titanium alloys such as Ti-6Al-4V are widely used in aerospace, biomedical, and defense industries due to their excellent strength-to-weight ratio and corrosion resistance. However, their low thermal conductivity, high chemical reactivity at elevated temperatures, and hardness pose significant machining challenges, often leading to increased tool wear and poor surface quality. While traditional flood cooling techniques can address these issues, they introduce environmental and health hazards. As an eco-friendlier alternative, the Minimum Quantity Lubrication (MQL) technique has gained traction. Recently, nanofluids especially those enhanced with g nanoparticles have shown promise for improving thermal conductivity and lubrication in machining. This study investigates the effects of cutting speed, feed rate, and nanoparticle concentration on the machinability of Ti-6Al-4V under sustainable machining conditions using nanofluid-assisted MQL (NFMQL). Experiments were conducted on a CNC lathe with three lubrication conditions: pure MQL, 0.5% wt. GNP-enhanced fluid, and 1.0% wt. GNP-enhanced fluid. Surface roughness, flank wear, and chip morphology were evaluated at cutting speeds of 80, 100, and 120 m/min and feed rates of 0.12, 0.18, and 0.24 mm/rev. The results demonstrate that the addition of 0.5% GNP significantly improves surface quality and reduces tool wear. According to Taguchi S/N analysis, the optimal conditions for minimizing surface roughness were a cutting speed of 80 m/min, a feed rate of 0.18 mm/rev, and 0.5% GNP concentration. Microscopic examinations confirmed less tool wear with 0.5% GNP due to improved lubrication and smoother chip flow. Furthermore, chip morphology analyses revealed that increasing feed rate raised chip peak height, while higher cutting speeds reduced peak height and valley depth due to improved thermal stability.

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INTRODUCTION

Titanium is a valuable material due to its low density, non-magnetic properties, and exceptional strength-to-weight ratio, which makes it a popular choice in various industries such as aerospace, medical, and nuclear power [1]. Its alloys are particularly useful in these industries because they offer superior corrosion resistance, biocompatibility, and good heat resistance. Notably, the aerospace sector—the largest consumer of titanium alloys, using about half of the world's total reserves—relies heavily on these materials for critical applications. Among titanium alloys, Ti-6Al-4V is the most used; however, its intrinsic properties, such as low thermal conductivity and high chemical reactivity with

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cutting tools, make it challenging to machine, resulting in poor surface finish, reduced tool life, and high tool wear [2]. To mitigate these machining difficulties, cutting fluids are traditionally employed, yet conventional fluids can be harmful to the environment, pose risks for operators, and incur significant costs.

With the growing emphasis on sustainable manufacturing, researchers have turned to Minimum Quantity Lubrication (MQL) as an eco-friendly alternative to flood cooling. In an MQL system, only a small amount of cutting fluid is delivered as fine droplets to the tool–workpiece interface via compressed air [3, 4]. This method not only reduces fluid consumption but also promotes efficient chip removal and minimizes the accumulation of heat. Specifically, about 70% of the generated heat is discharged with the chips, thereby decreasing friction and cutting forces, which in turn improves the working performance of the tool and allows for increased feed rates [5–8].

Recent industrial developments have further heightened the need for cutting fluids with enhanced cooling and lubrication properties. In response, the advent of nanofluids has opened new avenues for advancing the performance of cutting fluids under MQL conditions. Nanofluids are innovative formulations produced by homogenizing nanoparticles into a base fluid at controlled concentrations via either one-step (direct synthesis or physical vapor deposition) or two-step (dispersion into the base fluid) methods [9–11]. The incorporation of nanoparticles can significantly modify the thermal conductivity, viscosity, specific heat, and density of the base fluid, thereby enhancing both its cooling and lubricating capabilities. Researchers have investigated various solid particle lubricants—such as Cu, O, Al_2, O_3, and graphite—with the aim of tailoring the thermo-physical and tribological properties of the cutting fluid for improved machining performance [12].

Nanoparticles used in these applications are typically classified into four main categories: metal-based (e.g., Cu, Ag, Au), metal oxide-based (e.g., TiO_2, Fe_3O_4, ZnO, Al_2O_3), carbon-based (e.g., graphene, carbon nanotubes), and hybrid or mixed metal-based nanofluids [13]. Among these, metal oxide nanofluids are the most commonly used in industry due to their cost-effectiveness, while carbon-based nanofluids, despite offering superior thermal improvements, are hindered by higher costs. Hybrid systems that combine different nanoparticles are also investigated to harness synergistic effects.

Several investigations have examined the effect of nanoparticle-enriched cutting fluids on machining performance under MQL conditions. Prasad and Srikant [14] studied the turning of AISI 1040 steel using cutting fluid mixed with various percentages of nano graphite particles. Their results indicated that increasing the nanoparticle concentration led to higher pH values, greater viscosity, and enhanced thermal conductivity, along with reductions in tool wear, surface roughness, knot temperatures, and cutting forces. The best processing performance was obtained at a 0.3% nano graphite concentration and a flow rate of 15 ml/min.In another study, Rahmati et al. [15] performed end milling of AL6061-T6 alloy using MoS_2 nano lubrication, where a 0.5 wt% concentration enhanced the surface quality through improved nanoparticle polishing, filling, and rolling in the cutting zone. Jamil et al. [16] examined the turning of Ti–6Al–4V in deionized water enhanced with Al_2O_3 and multi-walled carbon nanotubes (MWCNTs), finding that hybrid nanoadditives reduced average surface roughness by 8.72%, cutting force by 11.8%, and tool wear by 23% compared with low-temperature cooling. Thakur et al. [17] reported that in EN-24 steel turning, SiC-based nanofluids in MQL yielded better machining performance—in terms of surface roughness, cutting forces, and cutting temperature—than pure MQL, with MQL flow rate and the wt% of SiC nanoparticles emerging as critical parameters. Li et al. [18] further contributed by investigating surface grinding using nanofluid MQL where a mixture of six nanoparticles (MoS_2, polycrystalline diamond, ZrO_2, Al_2O_3, CNT, and SiO_2 in non-polluting palm oil) produced the lowest grinding temperature and fewer surface defects with CNT nanofluid due to its large contact angle and superior boiling heat transfer capacity.

In the case of carbon-based nanoparticles, Jamil et al. [16] examined the wear behavior of textured tools during the turning of Ti-6Al-4V by adding graphene as a nano additive to canola oil under MQL conditions. Their results, when compared with pure canola oil and dry cutting, showed superior outcomes in terms of tool life and surface roughness; reductions in flank wear were also observed at cutting speeds of 80 m/min, 130 m/min, and 180 m/min. Kalita et al. [19] investigated MQL grinding on EN24 steel and cast iron using MoS_2 nanoparticles coated with organic matter dispersed in soybean oil and paraffin oil, noting lower friction losses, reduced specific energy consumption, and minimized tool wear. Sinha et al. [20] examined nanofluids prepared by dispersing zinc oxide (ZnO) and silver (Ag) nanoparticles in deionized water during the grinding of Inconel 718, resulting in lower coefficients of friction, reduced grinding forces, and improved surface integrity. Nam et al. [21] reported that the addition of nano diamond particles to a base oil during MQL microdrilling led to lower torques and thrust forces, with improved lubrication and cooling facilitating the removal of burrs and chips.

Further studies have reinforced the potential of carbon-based additives. Hegap et al. [22] investigated the effects of MWCNT-enriched cutting fluid on the surface roughness of Ti-6Al-4V during turning, reporting a 38% reduction in surface roughness with a 4% concentration, while a 2% concentration improved surface quality by 50%. Gupta et al. [23] compared the impact of nanoparticles—aluminum oxide, molybdenum disulfide, and graphite—added at a 3% level to a vegetable-based cutting fluid under MQL conditions during turning. Their findings indicated that the fluid supplemented with graphite provided the best sustainable machinability in terms of cutting force, tool wear, cutting temperature, and surface roughness, particularly at lower cutting speeds, lower feed rates, and higher approach angles.

Singh et al. [24] further investigated the turning of Ti-6Al-4V using a mixture of graphene and canola oil. They observed that graphene particles at weight percentages of 0.2%, 0.5%, and 2.0% separated within 24 hours, whereas a 1 wt% concentration remained stable for up to 72 hours. The 1 wt% graphene-enriched formulation outperformed both dry machining and MQL without additives by improving tool performance and extending tool life. In another study, Shuang et al. [25] explored the machining of Ti-6Al-4V using graphene oxide (GO)-enriched nanofluid as a coolant. Their investigation—spanning cutting speeds of 80, 160, and 240 m/min, feed rates of 0.05 and 0.1 mm/rev, and nanoparticle concentrations of 0.1%, 0.3%, and 0.5% (with a total of 36 experiments)—demonstrated significant improvements in surface roughness and effective reduction of tool-tip adhesion by adjusting cutting conditions.

In addition to studies involving carbon-based nanofluids, several researchers have focused on metal oxide systems. Eltaggaz et al. [26] investigated the effects of Al_2O_3 nanoparticle-enriched cutting fluid under MQL during the turning of Ti-6Al-4V. Their results highlighted improvements in surface roughness, power consumption, and tool life, with feed rate and nanoparticle concentration being crucial factors. Sodavadia and Makwana [27] evaluated tool wear and surface roughness during the turning of AISI 304 stainless steel using coconut oil mixed with nano boric acid particles, which enhanced thermal conductivity and heat transfer while decreasing specific heat relative to the base oil. Gaurav et al. [28] compared the performance of pure jojoba oil and mineral oil (LRT 30) under MQL-assisted turning of Ti-6Al-4V, and demonstrated that the addition of low-concentration MoS_2 nanoparticles improved surface roughness and cutting forces by 35–47%, although higher nanoparticle concentrations led to increased cutting forces due to the formation of larger particle clusters. Yi et al. [29] analyzed the effects and mechanisms of nanographene oxide suspension-based coolant on cutting forces, surface quality, and chip morphology in the drilling of Ti-6Al-4V, using tungsten carbide (WC) tools manufactured by ISCAR under carefully controlled machining conditions, which resulted in a 17.21% reduction in cutting force and a 15.1% improvement in surface roughness.

Milling studies have also been conducted to optimize cutting parameters using nanofluids. Songmei et al. [30] aimed to determine optimal cutting parameters in the milling of Ti-6Al-4V by incorporating different concentrations (1% and 2%) of nanoparticles including Cu, graphite, MoS_2, and Al_2O_3; their ANOVA analysis indicated that cutting depth was the primary factor influencing milling forces, with nanoparticle type, concentration, and feed rate also playing significant roles—among which Cu and graphite exhibited the highest impact. Singh et al. [31] conducted experimental studies on the turning of titanium alloys (Grade 5) and found that hybrid nano cutting fluids in an MQL system significantly reduced cutting forces and improved surface roughness, although increasing the concentration beyond 0.75% by volume did not yield further improvements. Kumar and Prasada [32] investigated the effects of nano cutting fluids on surface roughness during the MQL-assisted turning of duplex stainless steel-2205, ranking their effectiveness as CuO > SiC > Al_2O_3 and identifying feed rate as the most influential parameter, followed by cutting depth, nanoparticle concentration, and cutting speed. In the realm of tool wear, Yıldırım et al. [33] reported that machining Waspaloy superalloy with nanoparticle-enriched cutting fluids under varying lubrication conditions (dry, MQL, and nano-MQL) resulted in minimal tool wear when Al_2O_3-enriched vegetable-based cutting fluid was used, especially at lower cutting speeds and feed rates. Gupta et al. [34] examined the properties of various nano cutting fluids (Al_2O_3, MoS_2, and graphite) in turning Inconel-800 under MQL conditions, concluding that MoS_2 and graphite-based fluids performed better at higher cutting speeds, while Yıldırım [35] determined that, for milling AISI 316 material, the optimal parameters were achieved with a 1% nano graphite concentration, a flow rate of 40 ml/h, and 8 bar pressure for surface roughness, and a 1% concentration with 80 ml/h flow rate and 8 bar pressure for cutting temperature.

Recent literature further expands the scope of nanofluid applications in machining. For example, Ibrahim et al. [36] developed a water-based graphene nanoplatelet nanofluid to enhance the grinding performance of Ti-6Al-4V under MQL conditions. Singh et al. [37] investigated the influence of graphene-enriched nanofluids together with textured tools on the machining behavior of Ti-6Al-4V, reporting improvements in tool life and reduced cutting forces. Lisowicz et al. [38] examined the role of graphite micropowder in the finish turning of Ti-6Al-4V under MQL, finding beneficial effects on tool life and surface quality. Duc et al. [39] studied nano cutting fluids in hard milling and identified critical MQL parameters affecting machining performance, while Abdelkrem et al. [40] detailed the influence of nanoparticle concentration on cutting forces, tool wear, and chip morphology during Inconel 718 milling. Kara [41] focused on Al_2O_3 nanoparticle added MQL lubricants and their effects on sustainable manufacturing, while Dalke et al. [42] provided a comprehensive review of nanofluids in machining, examining performance and sustainability aspects. Bastas [43] systematically reviewed sustainable manufacturing technologies, including the use of environmentally friendly cutting fluids, and Kumar et al. [44] summarized state-of-the-art applications of nano MQL in sustainable machining processes.

Despite these significant advancements, several research gaps remain. Many studies have focused on isolated machining outputs—such as surface roughness, cutting forces, or tool wear—without a comprehensive evaluation that encompasses chip morphology, surface integrity, and tool degradation under varying cutting conditions and nanoparticle concentrations. Moreover, systematic investigations specifically addressing the effects of graphene nanoparticle-enriched cutting fluids for the turning of Ti-6Al-4V under MQL conditions remain limited.

Thus, the objective of the present study is to systematically investigate the effects of graphene nanoparticle-enriched MQL cutting fluids on the machining performance of Ti-6Al-4V alloy. By evaluating critical parameters such as surface roughness, tool wear, and chip formation mechanisms across different cutting speeds, feed rates, and

Table 1. Chemical properties of Ti-6Al-4V alloy

Combination of elements by weight %								
C	**Ti**	**Al**	**V**	**Fe**	**O_2**	**Cu**	**H**	**N**
0.02%	88%	5.72%	4.10%	<0.02%	<0.2%	0.12%	0.005%	0.022%

Table 2. Properties of base fluid

Viscosity at 40 °C	Density at 20 °C	Flash point	Ester ratio	Mineral oil content	Zinc ratio	Chlorine ratio	Sulfur ratio	Color
35 mm^2/s	0.90 g/cm^3	333 °C	>90%	% 0	% 0	% 0	% 0	Yellow

nanoparticle concentrations, this research aims to provide comprehensive insights into the optimization of sustainable manufacturing practices for high-precision applications. The novelty of this study lies in its holistic approach. Prior research by Prasad and Srikant [14], Rahmati et al. [15] etc. generally focused on isolated parameters—such as cutting forces, surface finish, or tool life—under conventional or nanofluid-assisted conditions. In contrast, our work integrates surface roughness, tool wear, and chip morphology within a single experimental investigation, thereby addressing a significant research gap. By systematically comparing different GNP concentrations, our findings offer practical insights into the threshold beyond which nanoparticle aggregation may negate the benefits of enhanced lubrication, and they provide guidance for optimizing machining parameters in sustainable manufacturing environments.

MATERIALS AND METHODS

In this section, we detail the experimental approach used to evaluate the sustainable machining of Ti-6Al-4V with graphene nanoparticle–enhanced MQL. The methodology encompasses the selection and preparation of cutting fluid, the workpiece and cutting tools, the configuration of the MQL system and, and the experimental design based on Taguchi's L27 orthogonal array.

Workpiece and Cutting Tool

Commercially available titanium alloy (Ti-6Al-4V) material was used for turning experiments. A cylindrical rod with a diameter of 50 mm and a length of 200 mm was used as the workpiece. The chemical content of the titanium alloy is given in Table 1.

Turning of Ti-6Al-4V alloy was carried out on SPINNER TC400 52 MC model CNC lathe. During the turning experiments, carbide PVD-coated inserts (TNMG160408 – MF1, TS2000) with 60° insert angle, 0.8 mm corner radius and 6 cutting edges produced by Seco Tools company were used. The tool used is a hard micro-grained and wear resistant quality tool designed for superalloys and titanium alloys as well as many stainless steels. PTGNR 2020k-16 model tool holder of ISCAR company was used to connect the inserts to the lathe. A new cutting edge was used after each test so that wear and different lubrication conditions could be measured accurately.

Table 3. Specification of nanoparticle

Nanographene	Value	Unit
Purity	99.9+	%
Thickness	5	nm
Diameter	7	μm
Surface Area	135	m^2/g
Conductivity	1100–1600	s/m

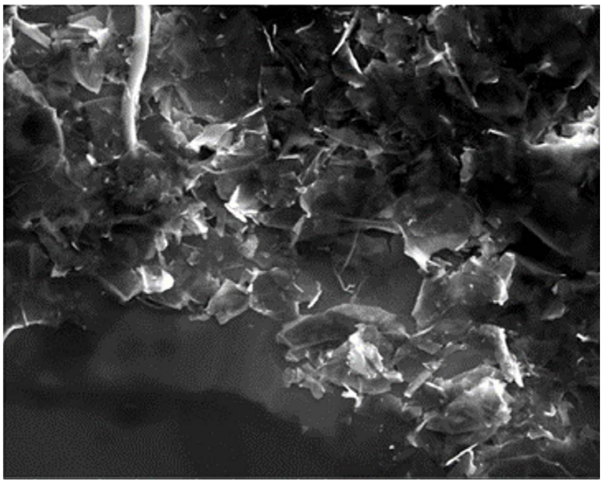

Figure 1. GNP SEM image (10 μm).

MQL System Cutting Fluid and Nano Particles

In the turning operations, the UNIST cooling/lubrication system was employed. The MQL system (Unist) delivered small amounts of coolant to the tool-chip interface, applying minimal lubrication in the cutting zone with a pressure of 4 bar and a flow rate of 100 ml/h. The cutting fluid used in both the pure MQL experiments and the preparation of nanofluids was an ester-based fluid, Vascomill CSF35, supplied by the Blaser company. The properties of this base fluid are listed in Table 2. For nanofluid preparation, graphene nanoparticles obtained from NanografiTM (Türkiye) were used. Due to their superior properties, including high modulus of elasticity, lightweight, low coefficient of friction, high thermal conductivity, and chemical stability, GNPs significantly enhance the cutting fluid's performance. The technical specifications of the GNPs are detailed in Table 3. Also SEM image of graphene nano particle is given in Figure 1.

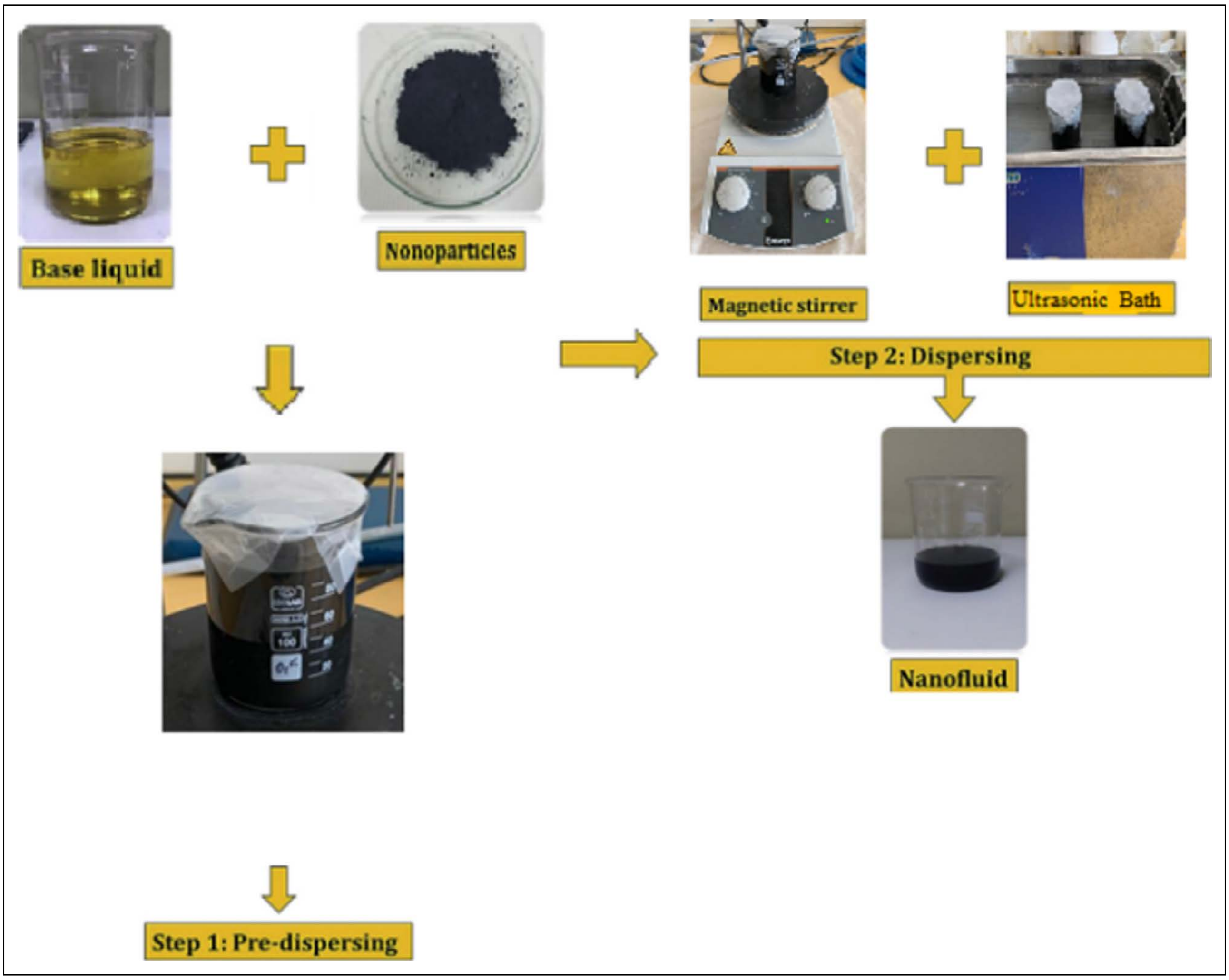

Figure 2. Preparation of nanofluid.

Preparation of Cutting Fluid

A two-step mixing process (Fig. 2) was employed to prepare the nanofluids without using any additional dispersants. Graphene nanoparticles were incorporated at concentrations of 0.5% and 1% relative to the total weight of the base cutting fluid. These concentrations were selected based on literature recommendations indicating that such loading levels provide optimal performance in similar machining applications [11, 13]. Although dispersants are sometimes added to improve nanoparticle dispersion, prior studies have demonstrated that prolonged magnetic stirring followed by ultrasonic agitation can yield a stable and homogeneous dispersion of graphene nanoparticles without extra additives [11, 13]. In our procedure, the nanoparticle weight was calculated as a percentage of the base fluid's total weight. After the nanoparticles were added, the mixture was stirred at 750 rpm for 90 minutes using a magnetic stirrer, and then further agitated in an ultrasonic bath for an additional 60 minutes to ensure thorough dispersion. The nanofluids were prepared immediately prior to the experiments, preventing any observable aggregation during machining tests. Moreover, stability tests on samples kept for 12 and 24 hours revealed no significant agglomeration, further confirming the robustness of the dispersion method.

Experimental Design

Turning parameters were determined according to the recommendations of the company that manufactured the insert and the results of the literature review. Parameters such as cooling conditions, cutting speed and feed during turning of Ti-6Al-4V alloy are given in Table 4. The cutting depth was taken as 1 mm for each experiment. Ti-6Al-4V alloy is machined through 40 mm. The nozzle positioned at an approximately 45° angle to the rake face, with a distance of 15 mm from the cutting zone. As a result of the experiments, the average surface roughness (Ra), tool wear and chip morphology were investigated. The experimental setup is given in Figure 3. For this study, three different cutting speeds, three different feed rates and three different nanographene concentration ratios were selected for the analysis of the effects on the surface roughness values, also three different cutting speeds and three different concentration ratios were selected for the tool tip flank wear analysis. Various experiments were performed based on Taguchi's L27 orthogonal array. Each experiment was repeated twice for the reliability of the experiments.

Figure 3. The experimental setup.

RESULTS AND DISCUSSION

In this study, the titanium alloy Ti-6Al-4V was machined using turning operations. The objective was to investigate how various cutting parameters affect machinability when nano graphene is added at different concentrations to the cutting fluid in an MQL system. Under the defined conditions, the experiments examined the influences on surface roughness, tool flank wear, and chip morphology. A Taguchi L27 orthogonal array was used for the surface roughness tests, while a Taguchi L9 orthogonal array was employed for assessing tool flank wear. The results of these experiments, along with their analyses and interpretations, are presented below.

Surface Roughness

The measured surface roughness values and signal-to-noise (S/N) ratios for the machined surfaces at various parameter levels during the turning experiments are presented in Table 5. The measurements were carried out in the NANOVEA brand profilometer device. The surface roughness was measured every 10 mm along the piece and from 3 different positions along the circumferential direction its average values were used. Surface roughness measurements were made after each experiment in order to avoid surface oxidation and not affect the results. Taguchi's method utilizes the S/N ratio to assess quality characteristics that deviate from the target value, where 'S' represents the mean value of the results and 'N' represents the undesired variability. The analysis of each parameter's effect (cutting speed, feed rate, and concentration ratio) on surface roughness is illustrated in the S/N response table. The experimental results for surface roughness were analyzed using Minitab 21 statistical software. Table 6 presents the S/N response table for surface roughness, the key quality characteristic of this study. The optimal levels for minimizing surface roughness were determined to be a cutting speed of 80 m/min (A1), a feed rate of 0.18 mm/rev (B2), and a nanoparticle concentration ratio of 0.5% (C2).

According to the test results, the lowest Ra value was observed at 80 m/min cutting speed, 0.18 mm/rev feed rate and 0.5% nanographene added cutting fluid as shown in Figure 4. While previous studies suggest that higher cutting speeds and feed rates generally increase surface roughness due to elevated temperatures and deformation in the cutting zone, the experimental results in this study reveal a different trend. As can be seen in Figure 5, at nanoparticle concentrations of 0% and 0.5%, surface roughness initially increases and then decreases as cutting speed rises. This suggests that while elevated cutting speeds may initially introduce greater thermal and mechanical effects, leading to higher roughness, at certain cutting speeds, improved fluid dispersion and reduced tool-workpiece adhesion may result in lower roughness values.

The presence of nanoparticles in the cutting fluid plays a crucial role in modifying tribological conditions. The experimental results demonstrate that at a 0.5% nanoparticle concentration, surface roughness generally improves across

Table 5. L27 Test results and S/N ratios

Experiment no.	A Cutting speed (m/min)	B Feed rate (mm/rev)	C GNP concentration ratio (%)	Surface roughness (µm)	Surface roughness S/N ratio (dB)
1	80	0.12	0	0.763	2.349509
2	80	0.12	0.5	0.63	4.013189
3	80	0.12	1	0.875	1.159839
4	80	0.18	0	0.86	1.310031
5	80	0.18	0.5	0.611	4.279176
6	80	0.18	1	0.904	0.876631
7	80	0.24	0	0.93	0.658405
8	80	0.24	0.5	0.81	1.8303
9	80	0.24	1	1.23	-1.7981
10	100	0.12	0	1.22	-1.7272
11	100	0.12	0.5	1.04	-0.3407
12	100	0.12	1	1.26	-2.0074
13	100	0.18	0	1.06	-0.5061
14	100	0.18	0.5	0.871	1.19964
15	100	0.18	1	1.44	-3.1672
16	100	0.24	0	1.14	-1.1381
17	100	0.24	0.5	0.825	1.67092
18	100	0.24	1	1.33	-2.477
19	120	0.12	0	1.12	-0.9065
20	120	0.12	0.5	0.888	1.03174
21	120	0.12	1	1.33	-2.477
22	120	0.18	0	1.11	-0.9844
23	120	0.18	0.5	0.82	1.72372
24	120	0.18	1	1.45	-3.2274
25	120	0.24	0	1.05	-0.4238
26	120	0.24	0.5	0.909	0.82872
27	120	0.24	1	1.23	-1.7981

different cutting speeds. However, increasing nanoparticle concentration to 1% results in a deterioration of surface roughness, suggesting that excessive nanoparticle loading can lead to aggregation and instability, reducing lubrication effectiveness.

These findings highlight that surface roughness trends are not purely linear and depend on interactions between cutting parameters, fluid behavior, and nanoparticle stability. Unlike conventional assumptions, the experimental results indicate that both lower and higher cutting speeds may exhibit advantages under specific lubrication conditions. Therefore, rather than attributing roughness variations solely to cutting speed and feed rate increases, it is necessary to consider tribological dynamics, heat dissipation mechanisms, and nanoparticle-fluid interactions. Future studies could further explore the critical threshold for nanoparticle concentration, beyond which lubrication performance is compromised.

Table 6. L27 Surface roughness S/N response table

Surface Roughness (Ra)			
Control Factors			
Levels	**A**	**B**	**C**
Level 1	**1.6310**	0.1217	-0.152
Level 2	-0.9437	**0.1671**	**1.8041**
Level 3	-0.6925	-0.2941	-1.6573
Delta	2.5747	0.4612	3.4614

Tool Wear

Using the Taguchi L9 experimental design, the effects of cutting parameters (cutting speed and concentration ratio) on the cutting tool flank wear were examined and the results for the optimum machining conditions were obtained. The S/N response table applied in the surface roughness analysis is also applied here. The flank wear val-

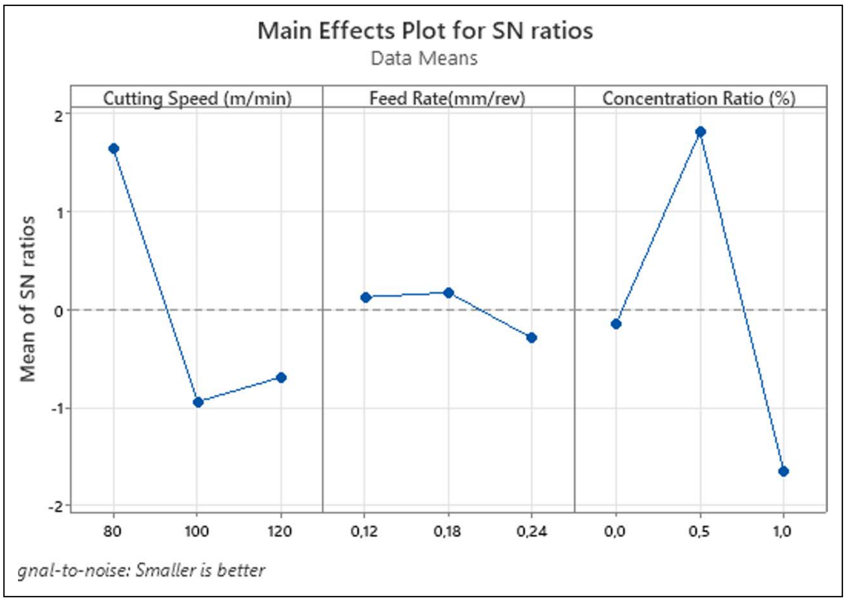

Figure 4. Main effect plot for S/N ratios.

Table 7. L9 results and S/N ratios for tool wear

Experiment no.	A Cutting speed (m/min)	B GNP concentration ratio (% wt.)	Flank wear (μm)	Flank wear S/N ratio (dB)
1	80	0	95.21	-39.7899
2	80	0.5	93.02	-39.3715
3	80	1	94.87	-39.5426
4	100	0	98.64	-39.8811
5	100	0.5	93.21	-39.3893
6	100	1	97.61	-39.7899
7	120	0	123.28	-41.8179
8	120	0.5	111.36	-40.9346
9	120	1	114.24	-41.1564

ues and S/N ratios after turning tests are given in Table 7. To characterize tool wear in this study, measurements were taken from multiple points along the flank surface of the cutting tool after each machining test. To ensure an accurate representation of the wear behavior, the most worn region of the tool was selected for analysis. This approach provides a realistic assessment of the tool's functional lifespan and helps in determining optimal machining parameters to minimize wear.

The high temperatures that occur during the processing of materials directly affect the life of the cutting tool. Tool wear is one of the most important problems that occur during machining. The wear of the cutting tool causes deterioration in the surface roughness of the workpiece and an increase in the cutting forces. Friction and cutting temperature are parameters that increase cutting tool wear. The turning process was performed along 120 mm at different cutting speeds (80, 100, 120 m/min) and different cutting fluid concentrations (0, 0.5, 1 % wt.) and a feed rate of 0.18 mm/rev, which was selected based on its optimal performance in previous experiments for surface roughness. The flank wear of the cutting tool was investigated. In the study, the S/N response table for tool tip flank wear, which has quality characteristics, is given in Table 8. Optimum levels for flank wear values obtained at 80 m/min cutting speed (A1) and 0.5% concentration ratio (B2), respectively.

It has been observed that the wear on the side surface of the cutting tool using a cutting fluid with 0.5% GNP at a cutting speed of 80 m/min is the least compared to other conditions. The dispersion of graphene nanoparticles in the cutting fluid facilitates easier processing and sliding movement in the cutting zone, thereby reducing wear. The excellent thermal conductivity of graphene is believed to contribute to a reduction in friction. Better results were noted at low cutting speeds, as the strength and hardness properties of the cutting tool are more adversely affected by the elevated temperatures generated in the cutting zone at higher speeds. Figure 6 presents optical microscope images of the cutting tool tips and edges after the experiments.

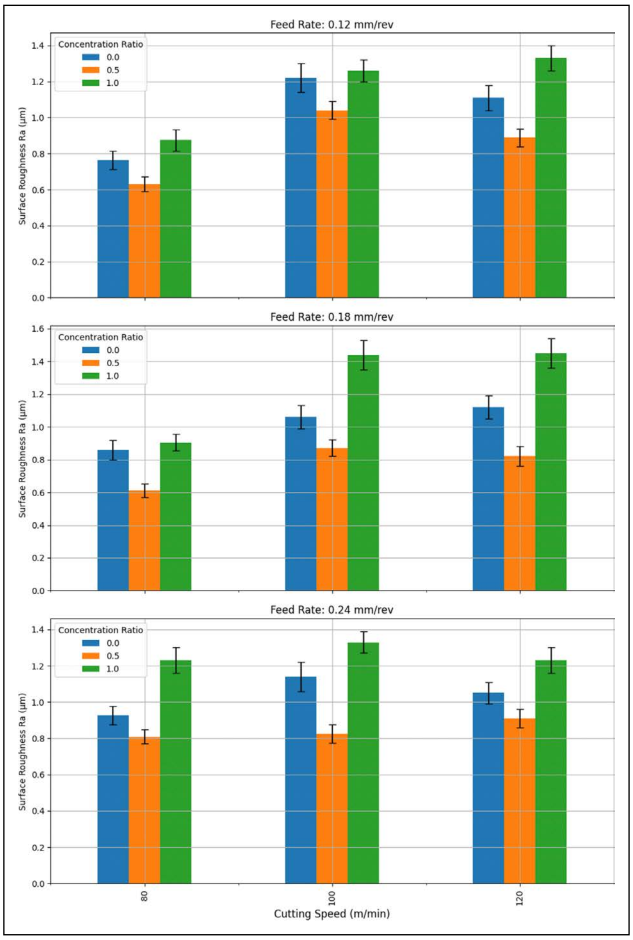

Figure 5. Surface roughness chart.

Chip Morphology

Images of some of the chips obtained after the experimental study were taken under an optical microscope. The results obtained when the chip morphology was examined are shown in Figure 7. Chips formed during machining of Ti-6Al-4V alloy are variable, forming peak height and valley height. Peak height (tP), valley height (tV) and tooth spacing (pc) were measured from the cross-sectional images of sawtooth chips obtained with an optical microscope. The total height of the chip, which is the continuous and separated part, is called the peak height (tP). The gap between the valley and the hill is called the tooth height (tT) and is calculated with the given equation (1).

$$tT=t_p-tv \quad (1)$$

The degree of segmentation (Gs) is the ratio of tooth height to crown height and is calculated by the following equation (2).

$$Gs=(t_p-tv)/t_p=tT/t_p \quad (2)$$

The chip segmentation frequency (fcs) is calculated by the following equation (3).

$$fcs=Vc/pc \quad (3)$$

where Vc is the chip speed.

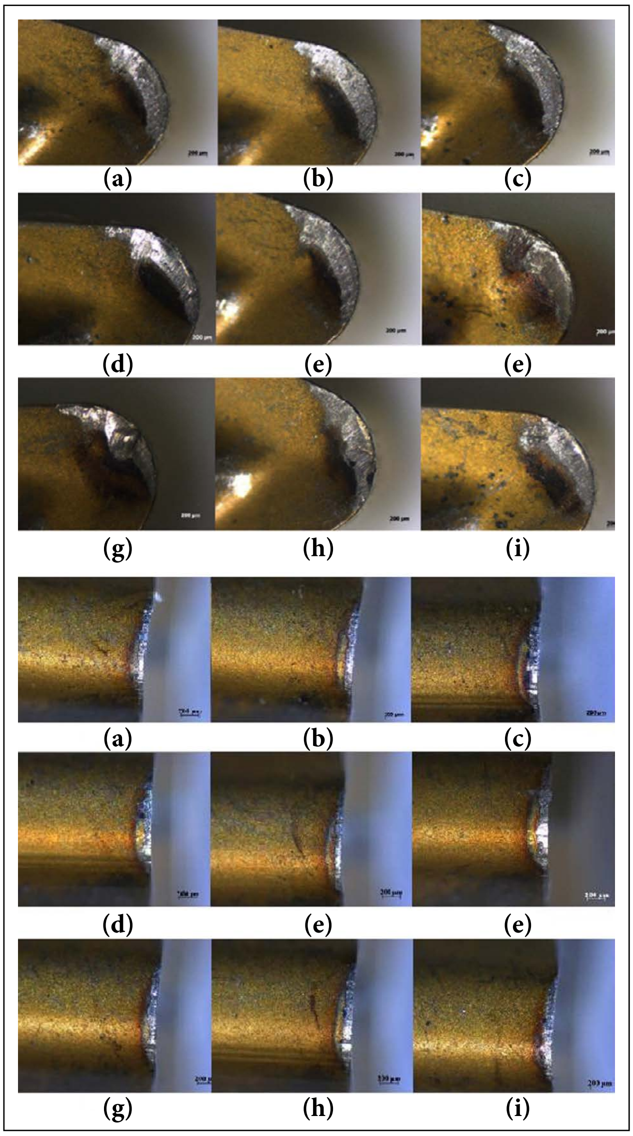

Figure 6. Optical microscope image of cutting tool tips and edges under 1 mm cutting depth (x50) 80 m/min **(a)** Pure MQL, **(b)** 0.5% GNP, **(c)** 1.00%,5 GNP, 100 m/min **(d)** Pure MQL, **(e)** 0.5% GNP, **(f)** 1.00%,5 GNP, 120 m/min **(g)** Pure MQL, **(h)** 0.5% GNP, **(i)** 1.00%,5 GNP.

In Figure 7, the peak height (tP), valley height (tV), and tooth spacing (PC) determined for chip morphology are shown as a function of cutting speed, feed rate, and nanographene concentration. Aside from the varying parameters shown in each graph (a, b, c), the optimal machining conditions—80 m/min cutting speed, 0.18 mm/rev feed rate, and 0.5% nanographene concentration—remained constant throughout the analysis. This ensures consistency in evaluating the effect of a single variable at a time. When the Figure 7. was examined, it was observed that the most important effect on chip morphology was the cutting speed. It is seen that the peak height increases as the feed rate increases, and the peak height decreases as the cutting speed increases. While changes were observed between the values in the feed rate, it showed less variation in nanographene concentration than other parameters. Increasing the cut-

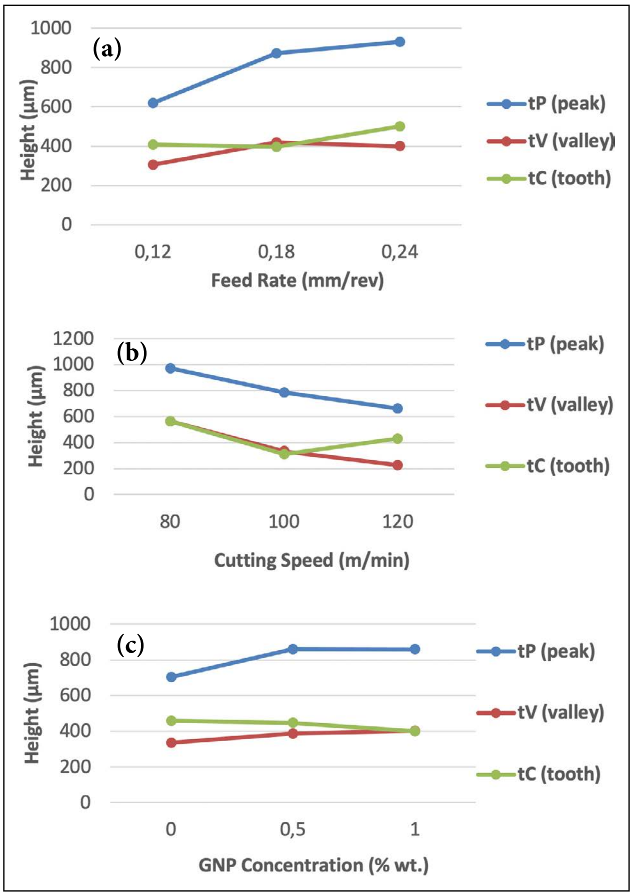

Figure 7. Variation of peak height, valley height, and tooth pitch with **(a)** feed rate, **(b)** cutting speed, and **(c)** nanographene concentration.

ting speed causes high heat generation and shear instability during the cutting process. This high temperature causes a decrease in peak height. A decrease is observed due to shear instability as the valley height changes in shear rate. When all values are examined, it is possible to say that the minimum values were obtained at a feed rate of 0.12 mm/rev. Image of the chip with 0.12 mm/rev feed rate and 80 m/min cutting speed is given in Figure 8.

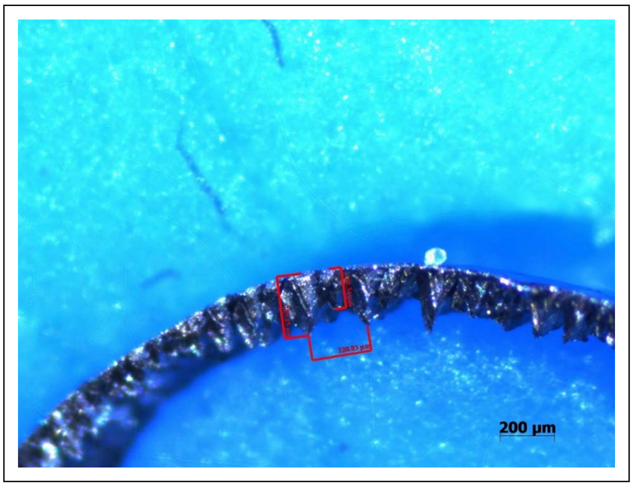

Figure 8. Optical microscope image of chips at 0.12 mm/rev feed rate and 80 m/min cutting speed (x50) (200 µm).

CONCLUSION

This study examined the machining of Ti-6Al-4V alloy using turning operations on a CNC lathe under Minimum Quantity Lubrication (MQL) conditions, comparing pure MQL with graphene nanoparticle (GNP)–enhanced MQL at 0.5 wt.% and 1.0 wt.% concentrations. Using Taguchi's L27 and L9 designs to assess surface roughness and tool wear, respectively, and by analyzing chip morphology, our work provides a comprehensive evaluation of key machining responses under enhanced cooling and lubrication conditions.

Experimental results indicate that a cutting speed of 80 m/min, a feed rate of 0.18 mm/rev, and a 0.5 wt.% GNP concentration led to improvements in surface quality and reduced tool wear. The observed benefits are attributed to the enhanced thermal conductivity and lubricity imparted by the nanoparticles, which help moderate cutting temperatures and reduce friction at the tool–workpiece interface. These findings support the potential of GNP–enhanced MQL in improving machining performance with a reduced environmental impact compared to conventional cutting fluids.

A notable aspect of this study is the simultaneous evaluation of multiple machining responses. Although the surface roughness and tool wear results consistently favor the aforementioned optimal parameters, chip morphology analysis revealed a nuance: the minimum chip peak height, which facilitates controlled chip segmentation, was observed at a lower feed rate (0.12 mm/rev). Rather than inconsistency, this difference highlights that the mechanisms driving chip formation—such as shear instability and local thermal effects—can vary from those affecting surface integrity and tool degradation. This observation underscores the need for multi-objective optimization in machining and illustrates the inherent trade-offs that must be considered in process design.

Future investigations may benefit from real-time monitoring of nanoparticle dispersion, extended machining tests to assess long-term stability, and further exploration of hybrid nanoparticle formulations. Such studies would help refine the process parameters and reconcile trade-offs among competing machining responses, ultimately contributing to a more sustainable and efficient machining process for titanium alloys.

Data Availability Statement

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

Author's Contributions

Kadir Özen: Conception, Design, Data Collection and Processing, Analysis and Interpretation, Literature Reviewer, Writer.

Mustafa Burak Sağener: Data Collection and Processing, Analysis and Interpretation, Writer, Literature Review.

Oğuz Çolak: Conception, Design, Materials, Critical Review.

Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Use of AI for Writing Assistance

Not declared.

Ethics

There are no ethical issues with the publication of this manuscript.

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