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Experimental study on the feasibility of graphite nanoparticles with fruit tree-based vegetable oils for nanofluid MQL in milling AISI 304 stainless steel

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KEYWORDS

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MQL
Face milling process
Sustainable machining
Nanofluid concentration

ABSTRACT

Using nanofluid in minimum-quantity lubrication (MQL) can improve lubrication performance as a green lubricant technology. However, the impact of nanoparticle concentration in various vegetable-based oils on machining performance is still uncertain. Therefore, this study aims to investigate the effect of graphite nanoparticles with different concentrations (0, 0.3 wt%, 0.6 wt%, and 0.9 wt%) on various vegetable-based oils (virgin coconut oil, olive oil, and palm oil) for MQL during milling AISI 304 stainless steel. The machining test was used with constant parameters: a cutting speed of 160 m/min, a feed rate of 0.05 mm/rev, and a depth of cut of 0.2 mm. The experimental results indicate that palm oil-based nanofluids added with a range of 0.3 wt% and 0.6 wt% graphite nanoparticles produce the best lubricant performance. Even 0.3 wt% graphite concentration provides the maximum reduction of cutting force and surface roughness at 29.6% and 57.2%, respectively, compared to the dry condition. The best performance of this concentration was consistent across all types of vegetable oils used.

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1.0 INTRODUCTION

Austenitic stainless steels, such as AISI 304, have desirable characteristics that make them the most versatile grade of stainless steel, which finds extensive application across many industries. Among the applications that are utilized the most frequently are those that are utilized in the automobile industry, food processing, pharmaceuticals, and chemical equipment. Besides that, a number of aerospace components, including valves, bushings, cryogenic tanks, shafts, specific screws, welded construction, and components exposed to harsh chemical conditions, make use of this steel grade (Muthuswamy, 2022)(Kumar et al., 2022). Moreover, AISI 304 stainless steel contains a significant proportion of chromium and nickel, which contribute to its austenitic structure but also lead to lower thermal conductivity and work hardening tendency than other steel types (Čička et al., 2023). As a result, this material is difficult to cut because of its low thermal conductivity, which causes heat accumulation at the cutting edge and can induce thermal deformation of both the workpiece and the tools. It tends work-part hard quickly, increasing cutting force and potentially leading to excessive tool wear and poor surface finish during machining (Dubey et al., 2021)(Binali et al., 2023).

These issues can be addressed by applying cutting fluids to the cutting zone while machining materials that are difficult to cut, such as AISI 304 stainless steel. The primary objective of utilizing cutting fluids throughout the machining process is not only to reduce the cutting temperatures and forces but also to effectively remove the chip that is created in the cutting zone. It will contribute to improving the overall machinability as well as the life of the cutting tool (Chinchanikar et al., 2021)(Kazeem et al., 2022). However, excessive use of cutting fluid based on mineral oil during the machining process can pose significant risks to human health and environmental problems. Cutting fluids based on minerals offers many benefits, but they also pose significant risks to human and environmental health. A review study reported that the use of cutting fluids in the manufacturing industry is still around 85% using mineral oil-based fluids (Wang et al., 2024). Research on occupational exposures to cutting fluids derived from mineral oil has shown that operators working in the machining industry are at increased risk for developing allergy disorders and other ailments. Inflammation of the skin, lungs, and throat have all been linked to breathing in cutting fluids through the skin or the air. Cutting fluids derived from mineral oil can spread a variety of diseases, including skin inflammation, cancer, respiratory diseases like asthma, and other lung conditions (Shokoohi et al., 2015). Furthermore, the limited biodegradability of cutting fluid waste makes it impossible to release it into the environment without first undergoing the appropriate treatment (Antonicelli et al., 2023)(Wickramasinghe et al., 2020). An increase in total manufacturing costs of 17–20% is attributed to the utilization of machining fluid from a financial perspective (Pal et al., 2020; Ahmad et al., 2021; Elsheikh et al., 2021). Therefore, it is crucial to explore options that reduce the need for cutting fluids and develop eco-friendly solutions that improve the machinability of stainless steel.

Minimum Quantity Lubrication (MQL) has gained popularity as a greener, cleaner, more cost-effective, and ecologically friendly machining technique. This method involves delivering a small amount of lubricant (between 10 and 300 mL/h) to the cutting zone, accompanied by compressed air (4-6 bar) (Bai et al., 2023)(Ismail et al., 2024). The pressurized air cools the cutting region and assists with chip removal. At the same time, the lubrication mist forms a protective layer on the workpiece-tool interface, reducing friction and releasing heat via evaporation or flushing (Sharma et al., 2023). Numerous thorough investigations have confirmed the efficacy of MQL compared with dry cutting. These studies have consistently shown that MQL not only matches but frequently improves standard flood cooling approaches in various aspects. The study focuses on MQL's performance to successfully reduce tool wear, increase surface finish, and sustain lower cutting temperatures, consequently increasing overall machining efficiency (Wang & Liu, 2023)(Rizal et al., 2024). Babu et al., (2019) compared dry cutting, flooding, and MQL processes for milling 304 stainless steel using vegetable-based olive oil. They found that MQL can minimize wear and surface roughness by 70% and 66%, respectively, compared to flood cooling conditions. Araújo et al., (2017) conducted an assessment to compare the efficacy of different edible vegetable oils, such as cottonseed, babassu nut, canola, sunflower, corn, and soybean, with a non-edible vegetable-based fluid called LB2000, in the milling process of AISI 1045 steel. Cottonseed and canola oils proved to be highly effective among the tested oils. In the study conducted by Bai et al., (2020), five commonly used vegetable oils such as cottonseed, palm, castor, soybean, and peanut, were chosen as the base oils to assess the lubrication performance of the tool-workpiece interface during milling AISI 45 steel. This evaluation was done in comparison to synthetic cutting fluid through experimental methods. Palm and cottonseed oils, characterized by higher concentrations of saturated fatty acids, were found to be more appropriate as base oils for MQL applications.

An issue arose in the manufacturing sector due to studies on cutting fluids based on vegetable oil with excellent degradability capabilities. Vegetable oil's performance as a lubricant in metal cutting has recently emerged as a significant concern. Furthermore, to offer alternatives to the mineral oil that has long been utilized in the machining business, many studies have sought to determine various kinds of vegetable oil that are appropriate for lubricating metal cutting. Additionally, improvements in MQL lubrication technology allow lubrication to be used in near-dry cutting processes, an essential part of green manufacturing (Ghani et al., 2014)(Wickramasinghe et al., 2020). Vegetable oil is safe and biodegradable; however, its primary ingredient, fatty acid triglycerol, doesn't have enough pressure resistance (Zhang et al., 2022). Due to the high pressures and temperatures experienced in the cutting zones of machining processes, vegetable oil lubricant is unable to provide the necessary anti-friction and heat transfer. Furthermore, it's important to note that a small quantity of liquid may not be enough to complete the cooling task because it evaporates quickly at high temperatures (Sarikaya et al., 2021)(Wang et al., 2024). A nanofluid lubricant for MQL applications can be made by mixing vegetable oil with nanoparticle additions, thus overcoming this constraint.

Nanofluid is formed by incorporating nanoparticles or nanofibers, typically less than 100 nm, into a base fluid like mineral oil, vegetable oil, deionized water, etc. (Şirin & Kıvak, 2019). This nanofluid functions as a lubricant in MQL devices, where it is converted into a mist and then spread onto the surfaces of the cutting tool and workpiece to create a thin film layer. The deposition of nanoparticle droplets onto the workpiece and cutting tool surface leads to the formation of a thin tribo-film layer, significantly reducing friction and achieving highly effective lubrication (Hegab et al., 2018). Common nanoparticle used in nanofluid may include aluminum oxide (Al_2O_3) (Duan et al., 2020; Elsheikh et al., 2021), cupric oxide (CuO) (Elsheikh et al., 2021), hexagonal boron nitride (hBN), molybdenum disulphide (MoS_2) (Gaurav et al., 2020), zinc oxide (ZnO) (Ibrahim et al., 2022), graphite, carbon nanotubes (CNT), and another similar solid nanoparticle (X. Wang et al., 2020).

Extensive research has been carried out on the milling process of a variety of alloys, employing a variety of base oils and nanoparticles. Bai et al., (2019) investigated the lubricating capability of several nanofluids in milling titanium alloy Ti-6Al-4V. The six nanofluids used were Al_2O_3, SiO_2, MoS_2, CNTs, SiC, and graphite, with cottonseed oil as base oil. The study discovered that Al_2O_3 and SiO_2 provided the best workpiece surface morphology. Barewar et al. (2021) investigated the performance of traditional MQL and nanoparticle-based (Ag/ZnO) MQL. They found that the surface roughness and cutting temperature values of nanofluid-MQL were 13.07% and 8.6%, respectively, lower than those of basic MQL. Edelbi et al., (2023) also investigated the effects of ZnO and Al2O3-based nanofluids on MQL-assisted milling of Ti6AL4V. In their comparison, they found that the MQL based on ZnO nanoparticles resulted in lower tool wear and better surface quality.

Studies on the effect of nanoparticle concentration added to base oil have also been reported by several researchers. Talib and Rahim (2018) investigated the utilization of jatropha oil, with and without the addition of hexagonal boron nitride (hBN) nanoparticles, at concentrations of 0.05% and 0.5% by weight. The purpose was to study its effectiveness in machining AISI 1045 steel under the MQL technique. Their research showed that the addition of 0.05% of hBN nanoparticles greatly improved the tribological and lubricating characteristics of the MQL system. Venkatesan et al., (2020) conducted machining of Hastelloy-X using nanofluid-MQL, where hBN nanoparticles (0.25 and 0.50 wt%) were added to coconut oil. The addition of hBN at a concentration of 0.25 wt% resulted in a substantial decrease in cutting force, surface roughness, and tool wear. This improvement can be attributed mostly to the reduction in chip adhesion and wear abrasion. Sen et al., (2020) conducted a study to evaluate the effectiveness of milling Inconel 690 using a nano-green lubricant in MQL conditions. The study assessed the cutting force, cutting temperature, surface roughness, and tool life of palm oil reinforced with nano-silica at concentrations ranging from 0.5% to 1.5%. This investigation found that the best machining conditions were those with 1% silica-deposited palm oil. Duan et al. (2020) also studied what happened when different amounts of Al_2O_3 nanofluid made from cottonseed oil (0% to 2.0%) were added to milling AISI 1045 steel. They found the ideal concentration to reduce cutting force and surface roughness was 0.2% to 0.5%.

According to previous studies, understanding the impact of nanoparticle concentration in vegetable-based oils on machining performance is important. The literature indicates that the concentration of nanoparticles used in nanofluids varies from one study to another. Therefore, it is essential to determine the appropriate concentration of nanoparticles in the base fluid. Furthermore, it is possible to understand the benefits of using graphite nanoparticles and various vegetable oils derived from fruit trees, such as virgin coconut oil, olive oil, and palm oil, to enhance the machinability of AISI 304 stainless steel. However, a limited number of studies have compared different types of base oils with varying quantities of graphite nanoparticles for face-milling AISI 304 stainless steel. Therefore, the main objective is to investigate the advancements of graphite nanofluid lubricant in comparison to pure MQL and dry machining. An experiment was conducted on nanofluid MQL milling of AISI 304 stainless steel with three different vegetable oils (virgin coconut oil, olive oil, and palm oil) under different concentrations of graphite (0.3 wt%, 0.6 wt%, and 0.9 wt%). The lubrication performance of the cutting tool and workpiece interface was experimentally evaluated using the following parameters: the cutting force, machined surface roughness and morphology, and chip formation.

2.0 EXPERIMENTAL PROCEDURE

2.1 Workpiece Material

The workpiece being processed was stainless steel 304, a difficult-to-cut material that finds extensive use in automotive, aerospace, food processing, medical, and chemical industries due to its high strength, fracture toughness, and resistance to corrosion. Table 1 displayed the material's chemical composition, whereas Table 2 presented its mechanical properties. The workpiece was rectangular, 120 mm in length, 50 mm in width, and 30 mm in height.

Table 1. Chemical composition of AISI 304.

C (%)	Cr (%)	Ni (%)	Mn (%)	Si (%)	P (%)	S (%)	Balance Fe (%)
0.071	18.16	8.02	1.31	0.39	0.036	0.022	66.345–74

Table 2. Mechanical properties of AISI 304.

Property	Value
Ultimate tensile strength (MPa)	505
Yield strength (MPa)	456
Hardness (HB)	175
Elongation (%)	68
Reduction of area (%)	75

2.2 Nanofluid Preparation

In preparing a nanofluid of graphite vegetable-based oils for the lubricant of MQL, a multi-step process was employed to ensure thorough dispersion and stability of graphite nanoparticles. The technical characteristics of graphite nanoparticles include an average size of 80 nm, a purity of 99%, a density of 2.6 g/cm^3, a layered structure, and a black appearance. Figure 1 shows the results of scanning electron microscopy (SEM) and energy dispersive x-ray analysis (EDAX) conducted on graphite nanoparticles that were employed in this study.

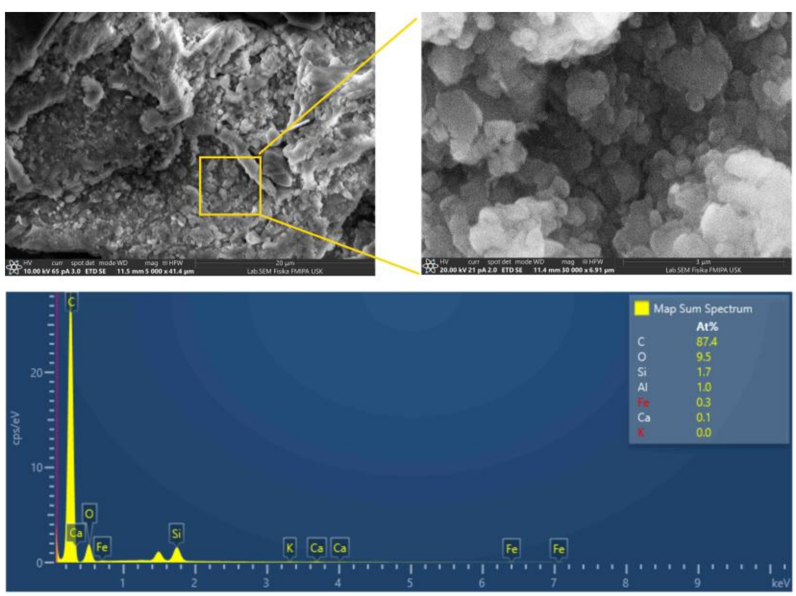

Figure 1: SEM and EDAX analysis of graphite nanoparticle.

Figure 2 depicts the step-by-step process used to prepare graphite nanofluid. Initially, after weighing each graphite nanoparticle concentrations of 0.3 wt%, 0.6 wt%, and 0.9 wt% in based oil, mechanical stirring was performed at a speed of 400 rpm for 30 min. This stirring step was repeated two times, guaranteeing a homogeneous mixture of nanoparticles within the base oil. Following this, the mixture was de-agglomerated using an ultrasonic homogenizer at 40 kHz for 30 min. This technique effectively breaks down any remaining nanoparticle clusters to achieve a uniform dispersion. In the last stage, the nanofluid was mixed again for 30 min at 1000 rpm using a magnetic stirrer to ensure that the graphite nanoparticles were evenly distributed throughout the base liquids. The vegetable-based oil properties of pure oil and nanofluids, as listed in Table 3, are used in the machining tests.

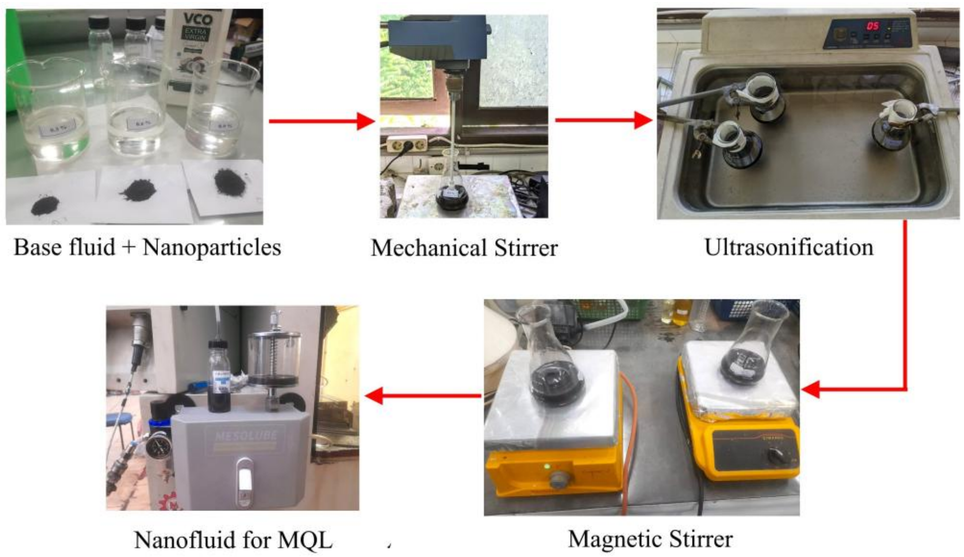

Figure 2: Graphite nanofluid preparation using a two-stage method.

Table 3. Different lubrication conditions.

Type of Vegetables Oils	Saturated Fatty Acid (%)	Flash Point (°C)	Viscosity (mm²/s)			
			Pure Oil	0.3% Graphite	0.6% Graphite	0.9% Graphite
Olive Oil	70 – 75	310	36.08	45.2	53.5	63.8
Virgin Coconut Oil	85 – 90	309	32.24	38.5	43.2	57.1
Palm Oil	40 – 46	270	38.86	49.5	58.3	66.4

2.3 Experimental Setup

The machining test was performed on a CNC milling machine (AGMA A-8), which used a carbide-coated cutting tool insert (APMT1135-M2, gradeVP15TF), with a tool shank diameter of 14 mm. The experimental setup, depicted in Figure 4, included various cutting conditions: dry cutting, milling with MQL pure oil, and milling with graphite nanofluid vegetable-based oils (virgin coconut oil, olive oil, and palm oil) with nanoparticle concentrations of 0.3 wt%, 0.6 wt%, and 0.9 wt%, respectively. The nanofluid lubricant was delivered through a MQL system (Mesolube MQL-10201) at a constant rate of 50 mL/h, using 4 bars of compressed air. Furthermore, the nozzle was positioned at a 30° angle relative to the cutting surface. To ensure uniform application, the distance between the nozzle and the cutting zone was consistently kept at 30 mm throughout the cutting zone.

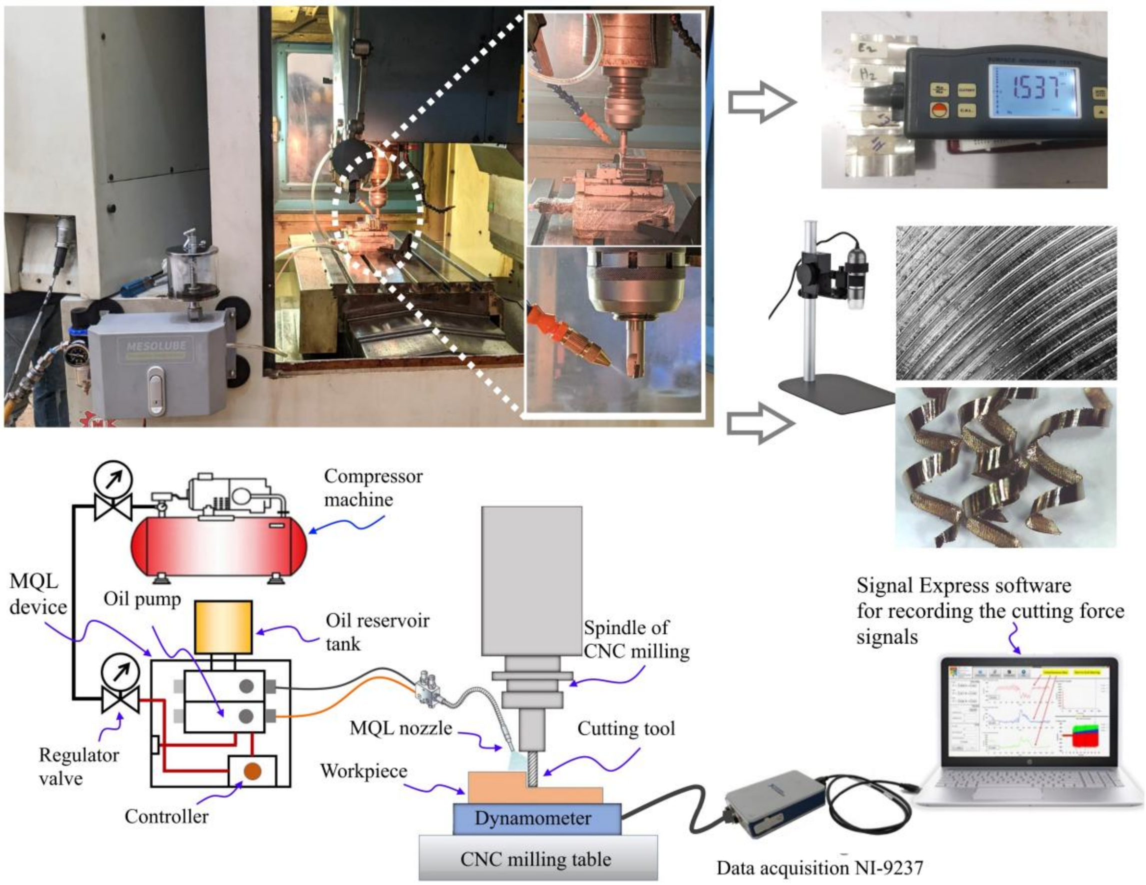

Figure 4: Experimental setup.

The face milling tests are performed with a cutting speed of 160 m/min, a feed rate of 0.05 mm/rev, and a depth of cut of 0.2 mm. Each cutting experiment is performed at a length of 50 mm. A stationary dynamometer-3A recorded the three components of the cutting force values F_x, F_y, and F_z during milling operations (Rizal et al., 2023) (Rizal et al., 2024). The resultant force, F_R, could be determined by the equation as follows:

$$F_R = \sqrt{F_x^2 + F_y^2 + F_z^2} \quad (1)$$

where F_x, F_y and F_z represent cutting force in the x-axis, y-axis, and z-axis directions, respectively. The surface roughness was assessed using a Surface Roughness Tester (Landtek SRT6200), which measures the average surface roughness, R_a. To ensure the reliability of the experimental data, three sets of repeated trials were performed, each conducted under a different location. The analysis of the machined surface morphology under different lubricant oils and concentrations of nanoparticles was performed using a Dino-Lite AM2111 optical microscope with a magnification of 210x.

3.0 RESULTS AND DISCUSSION

3.1 The Effect of Graphite Nanofluid on The Cutting Force

The cutting force is important in machining because it reveals the process's power and energy consumption. Cutting parameters, vibration, workpiece materials, tool characteristics, machine tool dynamics, cutting fluid tribological properties, and cutting fluid were among the many controllable and uncontrollable elements that affected cutting force. High cutting forces raise contact zone temperatures, increasing tool wear, reducing machining accuracy, and degrading workpiece surface quality (Bai et al., 2020). Hence, the effectiveness of lubrication and cooling was assessed using an analysis of the lubrication performance in the contact zone. Figure 5 shows the relationship between nanofluid concentration and the cutting force component. Specifically, it demonstrates the change in cutting force at a cutting speed of 160 m/min when graphite nanofluid based on different vegetable oils is used.

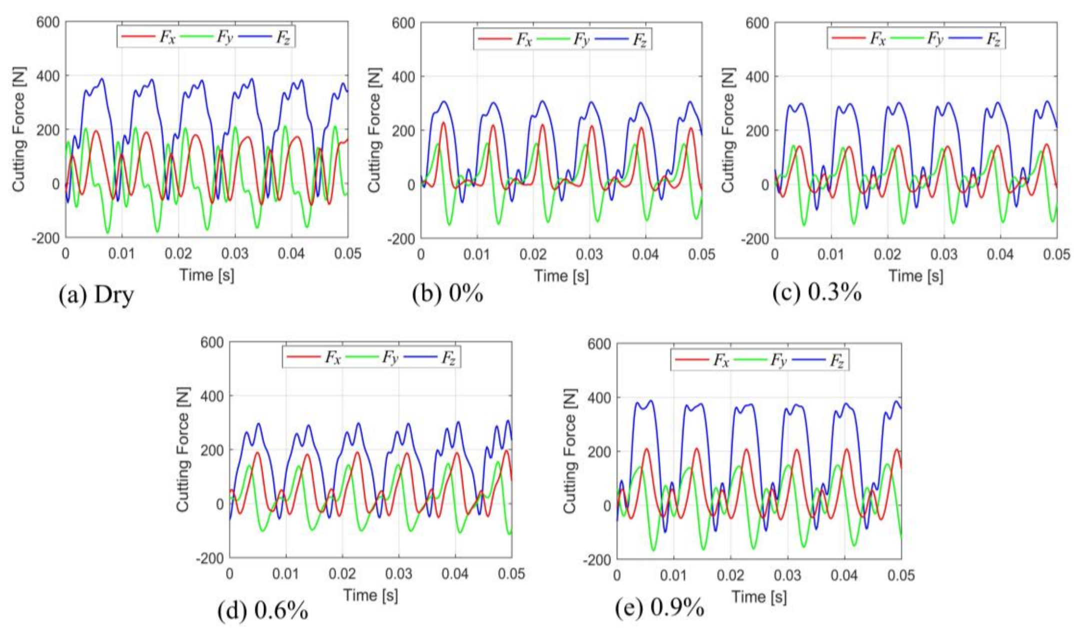

Figure 5: Typical of cutting force signals (sample olive oil nanofluid); (a) dry condition; (b) pure olive oil; (c) nanofluid 0.3% graphite; (d) nanofluid 0.6% graphite; (e) nanofluid 0.9% graphite.

Based on Figure 5, the thrust force F_z exhibited the greatest force due to the face milling operations. The cutting edges generate significant resistance as the tool's full width engages with the material. This resistance emerges as a thrust force in the axial direction (z-axis), often greater than the forces in the feed and cutting directions. Meanwhile, the magnitudes of cutting forces F_x and F_y were roughly identical. In a dry-cutting environment, the cutting force was the highest compared to other cutting environments using MQL. It means that the presence of nanofluid entering the cutting zone effectively lowers friction between the tool and the workpiece, as well as between the tool and the chips.

The graph demonstrates the effect of varied concentrations of graphite in vegetable oil on milling operations using various vegetable oils. The cutting force was evaluated at Minimum Quantity Lubrication (MQL) cutting conditions, using graphite nanoparticles dispersed in olive oil, virgin coconut oil, and palm oil at concentrations of 0.3 wt%, 0.6 wt%, and 0.9 wt%. Experimental results consistently demonstrated reduced cutting force when graphite nanoparticles were present in all tree-based vegetable oil nanofluids. The decrease in cutting force can be attributed to graphite's laminar lattice configuration. A substance with several layers, such as graphite, forms a bond facilitated by a weak van der Waals attraction force between the layers. As a result, when this graphite nanofluid is properly distributed, it provides effective nanoscale lubrication.

Moreover, exfoliating bulk graphite into a few layered graphites enhances thermal conductivity to a greater extent (Gupta et al., 2020). Furthermore, an appropriate concentration of nanoparticles in the fluid reduces the cutting force, especially when the fluid has a high viscosity. These findings align with Gaurav et al., (Gaurav et al., 2020), discoveries, which indicate that viscous cutting fluids can build a boundary lubrication film with a higher viscosity index, even at elevated temperatures, by creating a stable boundary layer.

The performance of various cutting fluids on average cutting forces in the *x*-direction (main cutting force, F_x), y-direction (feed force, F_y), and z-direction (thrust force, *F*z) is shown in Figure 6. Compared to all lubricated environments, the highest cutting force is observed in a dry-cutting environment. For main cutting forces, pure oil MQL milling with olive oil, virgin coconut oil, and palm oil yields 210.8 N, 165.8 N, and 78.3 N, respectively, lower than the 192.3 N observed in dry cutting. Notably, the thrust force significantly decreases with pure oil MQL, dropping from 364.2 N in dry conditions to 272-279 N, representing a 23-25% reduction. Similarly, pure oil reduces feed force by 15-23% compared to dry cutting across all oil types. This improved performance is attributed to the effective penetration of fine droplets from the air-oil mixture into the cutting zone and the excellent lubrication properties of oil-based lubricants.

Cutting forces were also assessed in nanofluid MQL cutting environments with graphite nanoparticles dispersed in fruit tree-based vegetable oils at varying concentrations (0.3%, 0.6%, and 0.9% by weight). When dry cutting is compared to these environments, the most significant reduction in the main cutting force, 30.7%, is achieved with MQL olive oil containing 0.3% graphite, followed by a 29.7% reduction with nanofluid MQL palm oil (0.3%). Particle concentration influences the effectiveness of olive oil nanofluid with graphite. The main cutting force values for olive oil-based nanofluid MQL milling are F_x olive oil (0.3%) = 133.3 N, F_x olive oil (0.6%) = 171.6 N, and F_x olive oil (0.9%) = 194.5 N. Compared to the nanofluid with 0.3 wt% graphite, the main cutting force values increase by 28.7% and 45.9% for 0.6 wt% and 0.9 wt% concentrations, respectively, likely due to nanoparticle agglomeration increasing the friction coefficient (Maruda et al., 2023). Among the different nanoparticle concentrations in various vegetable oils, a concentration of 0.3% in the base oil is sufficient and the best to reduce cutting forces.

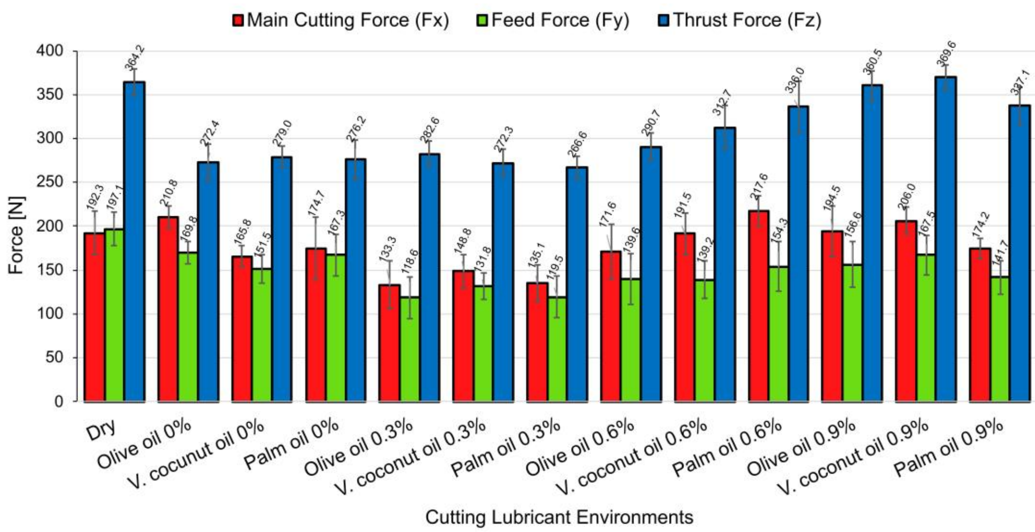

Figure 6: Variation of average three components under different graphite nanofluids.

According to Eq. (1), the resultant force F of the face milling process at each data point under different lubrication conditions was calculated and plotted, as shown in Figure 7. It is demonstrated that the resultant force in dry cutting was consistently higher than the MQL method. The results clearly demonstrate that 0.3% graphite nanofluid consistently yields the lowest resultant cutting force across all base oil variations. Using palm oil nanofluid achieves the highest resultant force reduction at about 29.6% while applying olive oil nanofluid results in a force reduction of 26.8%. When using 0.6 wt% graphite concentration, olive oil maintains its lubricating function with a force reduction of around 20%, while palm oil only reaches 14%. However, olive oil generally demonstrates better lubrication performance compared to palm oil.

Nevertheless, the performance of both oils as nanofluid lubricants in MQL is very good, with appropriate concentrations between 0.3 wt% and 0.6 wt%. The addition of nanoparticles significantly enhanced the base oil's ability to reduce friction and wear. However, concentrations greater than 0.6% will cause the cutting force to increase again. The findings align with previous research, indicating that MQL nanofluids with concentrations exceeding 0.6 wt% tend to increase cutting forces due to heightened frictional effects. This observation is corroborated by Şirin and Kıvak (Şirin & Kıvak, 2019), who reported that higher nanoparticle concentrations in MQL fluids increase friction at the tool-workpiece interface, resulting in elevated cutting forces.

Similarly, Gaurav et al. (Gaurav et al., 2020) found that lower concentrations of nanoparticles in MQL fluids can effectively reduce cutting forces; concentrations above 0.6 wt% result in particle agglomeration, exacerbating friction and increasing the forces required during cutting operations. Bai et al. (Bai et al., 2023) supported these findings by demonstrating that when the concentration of nanoparticles in MQL fluids exceeds a certain level, the beneficial effects of lubrication and cooling are outweighed by the detrimental consequences of heightened friction, resulting in elevated cutting forces. Getting consistent results from several studies shows how important it is to find the right ratio for nanoparticle concentrations in MQL applications.

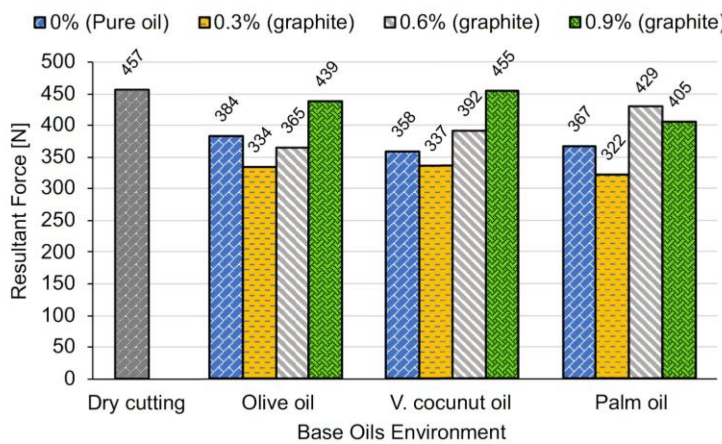

Figure 7: The resultant force of different nanofluids and base oils.

3.2 The Effects Graphite Nanofluid on The Surface Roughness

Surface roughness was an essential metric for evaluating the surface quality of the workpiece and a major factor for determining smoothness. A flawless machined surface was defined by a lack of surface roughness and no foreign adhered particles (Makhesana & Patel, 2022). The workpiece's corrosion resistance, fatigue strength, and contact stiffness were greatly affected by surface roughness. The workpiece's performance could be negatively affected by poor surface quality, which could cause it to fail prematurely than expected (Yin et al., 2021). Several machining factors, such as cutting tool shape, coating type, and cooling and lubrication technique, could influence the surface's roughness.

This study compared the effects of different nanofluid lubricants on surface roughness. Figure 8 displayed the mean surface roughness (Ra) values measured under MQL conditions on stainless steel 304 following milling with different vegetable oils containing different concentrations of graphite nanoparticles. As shown in Figure 8, the highest surface roughness value, measuring 2.786 µm, was recorded under dry cutting conditions. In contrast, the use of palm oil with a 0.3 wt% concentration of graphite nanoparticles resulted in the lowest surface roughness, measuring 1.193 µm. It represents a substantial 57.2% reduction in surface roughness compared to dry cutting and a 42.2% reduction when compared to pure palm oil. When the same nanofluid concentration was used with olive oil and virgin coconut oil, the surface roughness values were 1.572 µm and 1.777 µm, respectively. These values correspond to reductions of 43.8% and 36.2% in surface roughness compared to dry cutting conditions. These reductions are notably better than those achieved using pure oils, which only managed surface roughness reductions ranging from 39.2% to 12.5% compared to dry cutting. The improved cooling and lubricating characteristics of nanofluids lead to the enhanced surface quality. Vegetable oils, known for their high thermal conductivity, allow graphite nanofluids to effectively penetrate the machining area, dispersing friction-induced heat and minimizing damage to both the cutting tool and the machined surfaces. Heat dissipation efficiently reduces surface imperfections and improves surface quality.

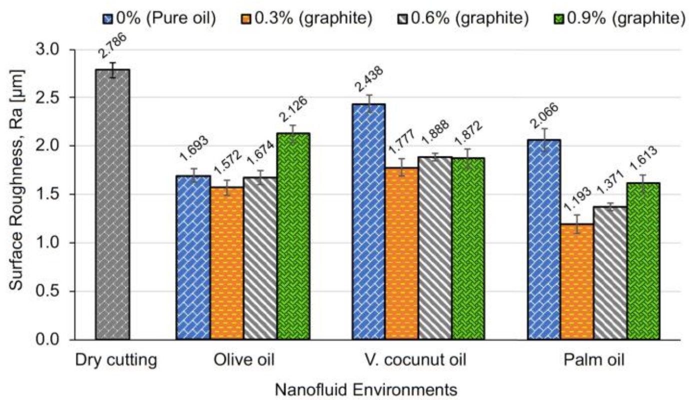

Figure 8: Variance in the surface roughness depending on different vegetable oil and nanoparticle concentration.

The nanofluid concentration of 0.6 wt% resulted in the second-largest decrease in surface roughness. The intrinsic lubricating and cooling characteristics of graphite nanofluids at high temperatures contribute to enhanced performance by reducing the coefficient of friction at the chip-tool interface (Gaurav et al., 2020). Comparative studies indicate that a nanofluid concentration of approximately 0.5 wt% to 0.6 wt% is ideal for attaining the desired rolling effect and creating a thin lubricating coating. When the concentration exceeds 0.75%, the nanoparticles start clumping together at the interface between the tool and the workpiece. It might have a negative impact on the machining process (Şirin & Kıvak, 2019) (Makhesana & Patel, 2022).

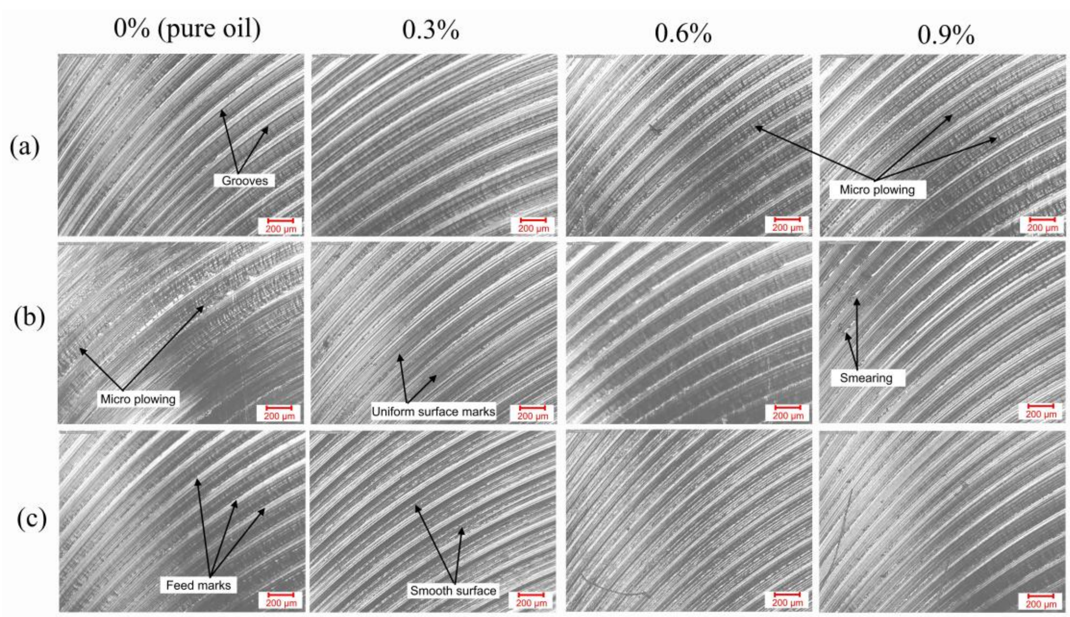

Figure 9: Surface morphology of machined surface under different lubricants MQL conditions: (a) olive oil; (b) virgin coconut oil; (c) palm oil.

An important index to evaluate the workpiece's surface quality is surface morphology, which also provides a qualitative demonstration of surface quality. Figure 9 illustrates the visual impact of the correlation between the micrograph surface texture and the mass concentration of graphite in the MQL environment. These results were brought about by milling MQL with pure oil and three different concentrations of graphite nanoparticles (0.3 wt%, 0.6 wt%, and 0.9 wt%). As shown in the images, using pure-based oil MQL resulted in poor surface quality. The roughness of coconut oil stands out and aligns with the surface roughness results, as shown in Figure 8.

The peeling phenomenon and extra scratches in the feed marks were seen on the workpiece surface. The markings were large and deep. It proved that the cutting tool's sharp tip severely damaged the workpiece's processing surface and that pure-based oil was inadequate for lubrication. Findings from MQL milling of nanofluids showed a slightly reduced number of scratches on the workpiece surface when the graphite nanofluid concentration was 0.3 wt%, compared to the pure oil condition. In addition, although the scratches were not very deep, the workpiece surface showed signs of material side flow and peeling. These results demonstrated that nanofluids at this concentration outperformed under pure oil conditions in terms of MQL lubrication. The overall flatness of the milled plane was nevertheless of acceptable quality at a 0.6% nanoparticle concentration, even though the workpiece's surface was smooth and there was a small peeling.

A thin lubricating layer was generated by the nanoparticles deposited on the workpiece's surface; this film is essential for anti-wear effects and reducing wear. The result demonstrated that the workpiece's surface quality was good and that the nanofluid lubrication effect was better at this concentration. The surface quality, however, declined once more as the concentration rose. The amount of peeling and debris deposition, for instance, increased at a concentration of 0.9 wt%. The results showed that nanofluids' tribological properties may be enhanced with the right concentration of nanoparticles. However, nanofluids with a particularly high amount did not affect the friction qualities. Because there was such a high concentration of nanoparticles in the suspension, the particles clumped together as they moved, causing agglomeration (Maruda et al., 2023).

3.3 The Effects Graphite Nanofluid on Chip Formation

To truly understand the shifts in physical and chemical phenomena like cutting temperature and force, it was essential to study the chip formation process. The inspection of chip formation revealed the frictional properties in the tool-workpiece and tool-chip contacts. According to Musavi et al., (Musavi, Davoodi, & Niknam, 2019) the formation of chips produced by machining was greatly affected by factors such as the workpiece's machinable material qualities, cutting speed, feed rate, depth of cut, and insert geometry.

Figure 10 presents the chip formation process during milling operations utilizing minimum quantity lubrication (MQL) with olive oil nanofluid at nanoparticle concentrations of 0.3 wt%, 0.6 wt%, and 0.9 wt%. The results clearly indicate that the MQL method with nanofluid significantly affects the formation and shape of the chips produced.

When using nanofluid at a concentration of 0.3 wt%, the chips tended to roll up and exhibit a curly form. This characteristic remained consistent even when the nanoparticle concentration increased to 0.6%. This behavior suggests a substantial temperature gradient between the tool surface and the outer surface of the chip. The reduced temperature of the chip surface can be attributed to the higher concentration of graphite additives in the nanofluid, which enhances the cooling efficiency.

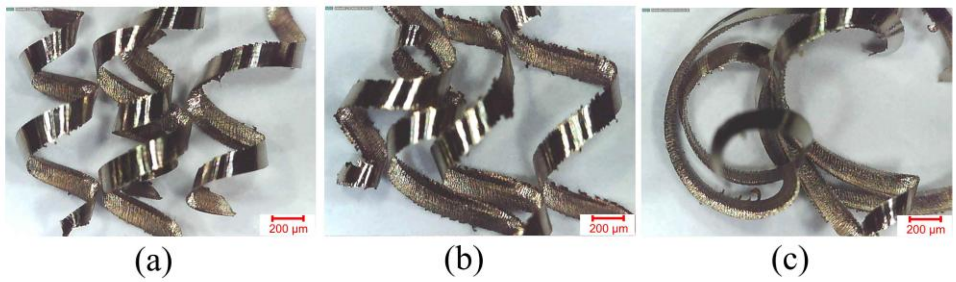

Figure 10: Chip formation morphologies at nanofluid using olive oil: (a) 0.3% graphite; (b) 0.6% graphite; (c) 0.9% graphite.

In summary, the experimental results demonstrate the effectiveness of tree-based vegetable oils as lubricants in MQL applications. When these oils are combined with optimal additive ratios, they significantly enhance the machinability of stainless steel 304. The use of olive oil nanofluid, particularly with the appropriate concentration of graphite nanoparticles, not only improves chip formation but also contributes to better temperature management during the milling process, leading to improved overall machining performance.

CONCLUSIONS

This study investigated the feasibility of several vegetable oils derived from fruit trees as lubricants in Minimum Quantity Lubrication (MQL), with and without the addition of graphite nanoparticles. The cutting force, surface roughness and morphology, and chip formation were assessed during the milling of AISI 304 stainless steel. The following are summaries of the findings obtained in this investigation.

a) The use of vegetable oil led to a reduction in cutting force and a significant improvement in surface quality and chip formation. The application of graphite nanofluid (0.3 wt%) combined with palm oil during the milling of stainless steel (AISI 304) led to the highest decrease in the cutting force among other oils and concentrations, a decrease of 29.6% compared to dry machining. The optimal concentration of graphite, ranging from 0.3 wt% to 0.6 wt%, significantly diminished the cutting forces. Increased quantities of graphite resulted in the agglomeration of nanoparticles, therefore elevating the cutting forces.
b) The use of graphite nanoparticles at a concentration of 0.3 wt% in palm oil led to a notable decrease of 57.2% in surface roughness relative to the dry cutting condition while machining stainless steel AISI 304. The following ingredients employed were olive oil and virgin coconut oil, demonstrating surface roughness reduction rates of 43.8% and 36.2%, respectively.
c) Using nanofluid at 0.3 wt% results in a curly shape on chips, indicating a temperature gradient between the tool surface and outer surface, attributed to graphite additives enhancing cooling efficiency.

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