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A Study of the Effect of Suspended Nanoparticles in Waste Cooking Oil on Cutting Force and Surface Roughness During the Turning of Inconel 718

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ABSTRACT

Inconel 718 is the most widely used nickel-based superalloy, used in the aerospace, automotive, and energy industries due to its exceptional thermomechanical properties. However, machining Inconel 718 remains a great challenge in modern manufacturing, marked by high cutting forces, rapid tool wear, and poor surface finishes. This study addresses the need for sustainable lubrication solutions by investigating nanolubricants formulated with Al2O3 nanoparticles suspended in waste cooking oil (WCO), transforming a common waste product into an eco-friendly, high-performance machining aid. The research evaluates the mechanical properties of these nanolubricants and their impact on cutting force and surface roughness at three nanoparticle concentrations (0.5%, 0.75%, and 1.0%) and cutting speeds (25, 50, and 100 m/min). The 0.75% concentration demonstrated optimal performance, reducing cutting force by 35.85% and improving surface roughness by up to 62.04% compared to dry machining. Although performance declined at higher speeds due to thermal degradation of the lubrication film and limitations in MQL spray penetration at elevated cutting velocities, these findings highlight the potential of WCO-based nanolubricants to enhance machining efficiency and support more sustainable manufacturing practices, which contribute to SDG 9 (Industry, Innovation and Infrastructure).

Keywords: Inconel 718, Machining efficiency, Nanolubricants, Sustainability, Waste cooking oil.

1. INTRODUCTION

Machining is a manufacturing process that involves removing material from a workpiece to achieve a specific shape, size, and surface finish. This is accomplished using various cutting tools and techniques, such as turning, milling, drilling, and grinding. Cooling and lubrication play a crucial role in machining for several reasons. Friction between the cutting tool and the workpiece generates heat, which must be dissipated to prevent damage to both the tool and the workpiece. Excessive heat can accelerate tool wear and shorten its lifespan. Lubrication reduces friction and wear, helping to prolong the tool's life. Effective cooling and lubrication also enhance surface quality by preventing issues like built-up edge formation, thermal distortion, and other defects that can compromise the final product. Additionally, cooling assists in chip removal, preventing chip buildup in the cutting zone and ensuring a smoother machining process [1].

Nickel-based superalloys, such as Inconel 718, are essential in industries where exceptional resistance to high temperatures, mechanical stress, and oxidation is required. Widely used in aerospace, nuclear power, and oil and gas applications, this alloy is highly valued for its superior

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mechanical strength and stability under extreme conditions [2]. However, these desirable properties make machining Inconel 718 particularly difficult, as it requires high cutting forces and often results in a poor surface finish [3].

The elevated cutting forces and substantial heat generation during the machining of Inconel 718 exacerbate tool wear and surface roughness, underscoring the critical need for effective friction-reduction strategies. Without adequate lubrication, the intense heat generated can cause tool deformation and built-up edge formation, further degrading the machining performance. Conventional lubricants help address these issues by forming a protective layer to reduce direct contact at the cutting interface, but their limitations, such as high consumption rates, environmental concerns, and insufficient performance at extreme conditions, highlight the necessity for more efficient alternatives like nanolubricants [4]. Nanolubricants offer superior performance by enhancing heat dissipation, lowering friction, and reducing tool wear. By incorporating nanoparticles, such as metal oxides, they form a stable tribofilm that improves thermal conductivity and wear resistance [5]. These enhancements result in better heat dissipation, lower friction, and reduced tool wear in high-performance applications. Studies show that integrating multi-walled carbon nanotubes (MWCNTs) and silica nanoparticles into hydraulic oil improves thermal management and reduces friction [6]. Additionally, recent research highlights the effectiveness of carbon-based nanolubricants for improving lubrication in aeronautical machining processes, particularly by minimizing heat generation and wear at the tool interface [7].

Oil-based nanolubricants have gained significant attention due to their environmental friendliness, biodegradability, and superior lubrication properties. Coconut oil-based nanolubricants, enhanced with nanoparticles like CuO, exhibit excellent thermal stability and friction-reducing properties, making them suitable for metal cutting applications [8]. Similarly, Al_2O_3 nanoparticles suspended in vegetable oil-based MQL have demonstrated improvements of approximately 30% in surface roughness and 25% in cutting forces during the milling of Inconel 718, confirming the effectiveness of this approach for difficult-to-cut superalloys[9][10]. Vegetable oils such as sunflower and soybean oil form thicker lubrication films, improving anti-wear performance and load-carrying capacity in comparison to traditional mineral oils [11][12]. Fresh cooking oils, including palm and olive oil, when infused with TiO_2 nanoparticles, enhance thermal stability and wear resistance, making them viable for industrial use [13].

Waste cooking oil (WCO) offers a sustainable and environmentally friendly approach to producing nanolubricants by repurposing a commonly discarded resource. Using WCO as a base oil reduces environmental pollution and promotes circular-economy practices by recycling waste into valuable industrial products. This approach not only lowers lubricant production costs but also reduces dependence on conventional mineral oils, which are non-renewable and contribute to environmental degradation. WCO-based nanolubricants, when infused with nanoparticles such as Al_2O_3, exhibit enhanced lubrication performance, improved viscosity, and better thermal stability, making them a promising alternative for various industrial applications. By converting waste into high-performance lubricants, this strategy supports both economic efficiency and sustainable development [14].

This study is structured around three key objectives that guide the investigation into the potential of nanolubricants based on waste cooking oil (WCO) for enhancing machining performance. Each objective is designed to address critical aspects of lubrication performance, cutting efficiency, and machining quality during the turning of Inconel 718. The first objective of this study is to characterize the mechanical properties of suspended nanoparticles in waste cooking oil (WCO**)**. This involves examining key properties, such as viscosity, pH, and nanolubricant stability. The evaluation aims to assess the consistency and performance of WCO-based nanolubricants, ensuring that the aluminium oxide (Al_2O_3) nanoparticle suspension remains stable under various conditions. These characterizations are crucial to maintaining optimal lubrication performance during machining.

The second objective is to investigate the effect of nanoparticle concentration on cutting force and surface roughness during the turning of Inconel 718. This experiment assesses how different concentrations of Al_2O_3 nanoparticles (0.5%, 0.75%, and 1.0%) affect the machining performance. By monitoring variations in cutting force and surface quality, the study aims to identify an ideal nanoparticle concentration that balances effective lubrication with minimal resistance and improved surface finish.

The third objective is to analyze the influence of cutting parameters, such as cutting speed, on cutting force and surface roughness. In this phase, the impact of three cutting speeds (25 m/min, 50 m/min, and 100 m/min) on machining outcomes is evaluated. Keeping the feed rate and depth of cut constant, this analysis focuses on how varying speeds interact with the WCO-based nanolubricant to influence the cutting process, helping optimize the parameters for improved precision and efficiency.

Beyond its technical contributions, this study aligns with several United Nations Sustainable Development Goals (SDGs), reinforcing the broader relevance of the work within the global sustainability agenda. Most directly, the repurposing of waste cooking oil as a functional base fluid for nanolubricants supports SDG 12 (Responsible Consumption and Production) by diverting waste from disposal streams and transforming it into a value-added industrial resource [15]. This approach embodies circular-economy principles, reducing demand for virgin petroleum-based lubricants and lowering the overall environmental footprint of machining operations. The reduction in dependence on non-renewable mineral oils, combined with the use of biodegradable bio-based fluids, also contributes to SDG 13 (Climate Action) by minimizing the release of persistent pollutants associated with conventional cutting fluid disposal. Furthermore, by advancing the development of high-performance, eco-friendly lubrication technologies for manufacturing difficult-to-cut materials such as Inconel 718, this research supports SDG 9 (Industry, Innovation and Infrastructure) and contributes to cleaner, more resource-efficient industrial processes. Collectively, these connections demonstrate that adopting WCO-based nanolubricants in machining is not merely a technical improvement but a meaningful step toward more sustainable and responsible manufacturing practices.

2. MATERIAL AND METHODS

Initially, the preparation of waste cooking oil (WCO) nanolubricant was carried out to meet the objectives of this study. The preparation phase involved emulsifying the WCO and dispersing aluminium oxide (Al_2O_3) nanoparticles to achieve a uniform, stable mixture. Surfactants such as sodium dodecyl benzene sulfonate (SDBS) and Cocamidopropyl betaine (CAPB) were added to enhance suspension stability, while sodium calcium edetate (EDTA) was used to adjust the pH and mitigate corrosion.

2.1 Nano-lubricant Preparation

To prepare the nanolubricant for this study, aluminium oxide (Al_2O_3) nanoparticles were dispersed in waste cooking oil (WCO), the base fluid. The emulsification process was carried out to ensure a uniform and stable suspension by incorporating surfactants. Cocamidopropyl betaine (CAPB) was used to enhance dispersion, while sodium dodecyl benzene sulfonate (SDBS) served as a stabilizing agent to minimize nanoparticle aggregation and to increase the viscosity of the mixture.

The Al_2O_3 nanoparticles used in this study were in nanopowder form, with an average particle size of less than 50 nm, as measured, and a near-spherical morphology, supplied by Sigma-Aldrich (Germany). Cocamidopropyl betaine (CAPB), sodium dodecyl benzene sulfonate (SDBS), and ethylenediaminetetraacetic acid (EDTA) were all obtained from Take It Global Sdn Bhd, Malaysia. The component composition and preparation procedure adopted in this study were developed with reference to established nanofluid preparation protocols documented in the literature. The weight percentages of each constituent were determined using methodologies reported in prior bio-based nanolubricant studies, particularly in formulations employing vegetable oil emulsions with cationic and anionic surfactant combinations for machining applications [16]. The two-step preparation method is consistent with widely adopted nanofluid preparation practices as outlined in published nanofluid synthesis guidelines [17]. The pH of the formulation was maintained within the alkaline range of 9.2 to 10, in accordance with recommended practice for water-miscible metalworking fluid formulations to prevent corrosion of both the workpiece and machine components during machining operations. While no single governing international standard, such as ASTM or ISO, was exclusively applied to dictate the formulation ratios, the preparation process was guided by established literature-based protocols to ensure consistency, reproducibility, and comparability with existing studies in the field.

The formulation consisted of 50% water by weight, alongside WCO, olive oil, CAPB, and SDBS. A densimeter was employed to measure the specific quantities of oil and water precisely. The ingredients were initially mixed using a magnetic stirrer set at 250–300 rpm to achieve homogeneity. Aluminium oxide nanoparticles, at a concentration of 0.5% by weight, were then added to the mixture. To adjust the pH and prevent corrosion, ethylenediaminetetraacetic acid (EDTA) was incrementally added until the pH reached 9.2.

Following the initial mixing, the nanolubricant was sonicated for 3 hours at 15% amplitude using an ultrasonic device. To maintain consistent conditions and prevent overheating, the sonication process included 15-minute intervals every hour, during which the lubricant was agitated with the magnetic stirrer. This thorough preparation process ensured a well-dispersed and stable nanolubricant for subsequent machining experiments. The composition of nanolubricant is summarized in Table 1.

Table 1: Component composition for nanolubricant.

Nanoparticles	CAPB	SDBS	EDTA	Waste cooking oil	Olive oil	Water	total
0.5% AI_2O_3 1g	7.25% 14.5g	7.25% 14.5g	0.5% 1g	31.5% 63g	3% 6g	50% 100g	100% 200g
0.75% AI_2O_3 1.5g	7.25% 14.5g	7.25% 14.5g	0.5% 1g	31.5% 63g	3% 6g	50% 100g	100% 200.5g
1% AI_2O3 2g	7.25% 14.5g	7.25% 14.5g	0.5% 1g	31.5% 63g	3% 6g	50% 100g	100% 201g

2.2 Inconel 718

The workpiece material is Inconel 718, with a cylindrical shape measuring 100mm long and 45mm in diameter. The Inconel 718 workpiece is shown in Figure 1.

Figure 1: Inconel 718 material used as workpiece for the experiment.

2.3 Cutting Tool

The TNMG160408 NN LT10 carbide cutting tool was selected for this study due to its suitability for machining Inconel 718, a material known for its high strength and abrasive nature. This cutting tool possesses the following key specifications:

- Insert Type: TNMG (triangular insert for versatile turning operations)
- Grade: NN (general-purpose grade, suitable for medium machining conditions)
- Coating: LT10 (provides high wear resistance and thermal stability)

The tool's coating and geometry were specifically chosen to withstand the elevated temperatures and mechanical stresses encountered during the turning of Inconel 718. Its enhanced thermal resistance helps minimize tool wear and ensures consistent performance throughout the experimental trials. By maintaining tool integrity, the cutting tool supports accurate measurements of cutting force and surface roughness. A picture of the cutting tool is shown in Figure 2.

Figure 2: TNMG160408 NN LT10 cutting tool.

2.4 CNC Turning Experimental Setup

For the CNC turning process, the Inconel 718 workpiece was securely mounted in the machine's chuck to ensure proper alignment and stability during machining. Figure 3 shows the main components of a CNC turning machine. The TNMG160408 NN LT10 carbide cutting tool, selected for its exceptional hardness and thermal resistance, was installed and precisely positioned to achieve accurate cutting angles and optimal engagement with the workpiece. The machine's controller was programmed with specific parameters, including spindle speed, feed rate, and depth of cut, tailored to the properties of Inconel 718 and the objectives of the study.

The lubrication system was configured to deliver the nanolubricant efficiently to the cutting zone using the Minimum Quantity Lubrication (MQL) technique. This approach ensured minimal fluid consumption while providing effective cooling and lubrication. The MQL setup featured two symmetrically positioned nozzles, each angled toward the cutting tool tip, one on each side of the cutting tool, as shown in Figure 4. This configuration ensured balanced and precise delivery of the nanolubricant, fully covering the tool-workpiece interface to enhance cooling and reduce friction.

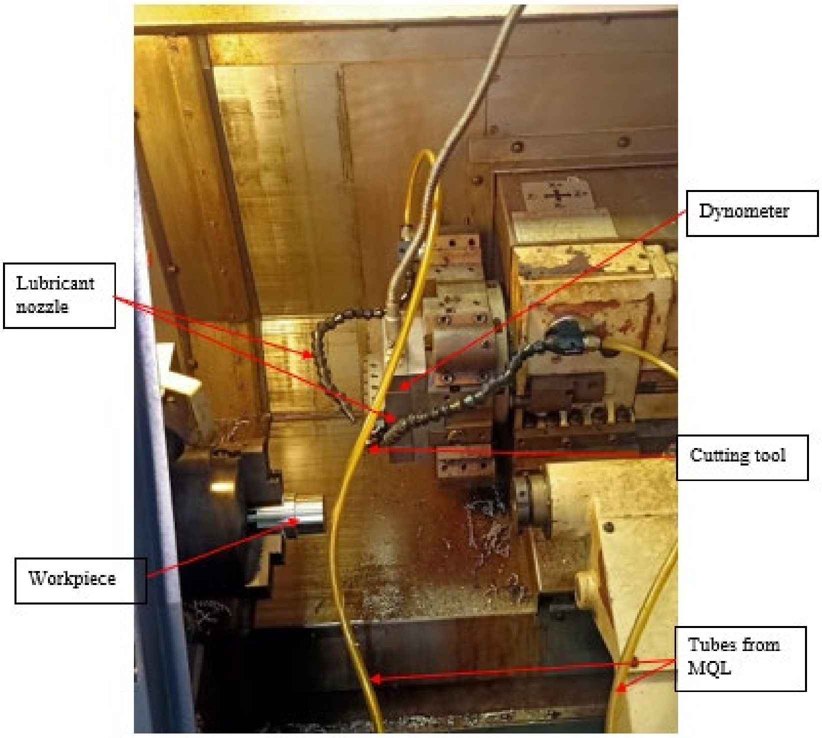


Figure 3: CNC turning machine.

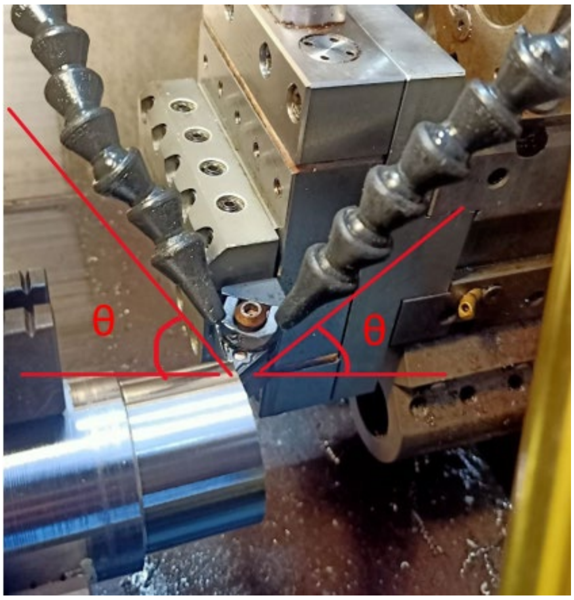


Figure 4: Position of lubricant nozzle.

Safety checks were performed to verify that all components were securely in place and the machine was free of obstructions. A trial run was conducted to validate the setup, and any necessary adjustments were made to optimize the process. Additionally, the dynamometer was set up by connecting its sensor to the cutting tool and calibrating the software for standard turning operations.

2.4.1 Cutting Parameters

The cutting parameters for evaluating the prepared nanolubricants were carefully established to ensure consistency and accuracy during the machining trials. Two variables remained constant throughout the experiment: the depth of cut and the feed rate. The depth of cut was fixed at 1.0 mm, while the feed rate was maintained at 0.5 mm/rev. The trials focused on varying two key factors: cutting speed and nanoparticle concentration in the nanolubricant.

To ensure measurement reliability and experimental repeatability, each machining condition was repeated three times, and the average value was used as the representative result for both cutting force and surface roughness measurements. For surface roughness (Ra), four measurements were taken at different locations along the machined surface after each run, and the average Ra value across all three repetitions was calculated to minimize the influence of localized surface anomalies and ensure a consistent and representative assessment of the overall surface finish. Cutting force data were continuously acquired during each machining pass using the Kistler dynamometer, and the stable region of the recorded signal was selected for analysis in each repetition. Averaging the results across three runs ensured that the reported cutting force and surface roughness values are statistically representative and free from the influence of isolated experimental inconsistencies, providing a reliable basis for comparing the performance of different nanolubricant formulations and cutting speeds.

To input the correct cutting speed into the CNC turning machine, which requires values in revolutions per minute (rpm) for the cutting speed, the following formula was used to convert the cutting speed from meters per minute (m/min) to rpm:

$$N = \frac{1000\,V}{\pi\,D} \tag{1}$$

Where:

- V = cutting speed (m/min)
- D = workpiece diameter (mm)
- N = spindle speed (rpm)

Since the depth of cut reduced the workpiece diameter by 1 mm after each run, the new diameter was used in the equation for subsequent calculations. This ensured precise adjustments to the spindle speed for each trial. The varying cutting speeds (25 m/min, 50 m/min, and 100 m/min) and nanoparticle concentrations (0.5%, 0.75%, and 1.0% by weight) were systematically applied to evaluate their effects on cutting force and surface roughness. Table 2 shows the total runs and cutting parameters for each different condition.

The cutting force data in this study were obtained using a Kistler dynamometer, as shown in Figure 3. A precision instrument that measures forces in three orthogonal directions: tangential (Fy), radial (Fx), and axial (Fz), shown in Figure 5, illustrates the direction of each force component. The dynamometer uses piezoelectric sensors to capture real-time force data during machining. For this research, the tangential force (Fy) was selected as the primary cutting force due to its direct correlation with the resistance encountered during material removal. The Kistler dynamometer's high sensitivity and accuracy ensured reliable force measurements across different cutting speeds and nanolubricant concentrations.

Table 2: Cutting Parameters.

Lubrication condition	Composition	Cutting speed (m/min)	Feed rate (mm/rev)	Depth of cut (mm)
Dry run	-	25	0.5	1.0
		50	0.5	1.0
		100	0.5	1.0
Nano lubricant (waste cooking oil)	0.5% AI2O3	25	0.5	1.0
		50	0.5	1.0
		100	0.5	1.0
Nano lubricant (waste cooking oil)	0.75% AI2O3	25	0.5	1.0
		50	0.5	1.0
		100	0.5	1.0
Nano lubricant (waste cooking oil)	1% AI2O3	25	0.5	1.0
		50	0.5	1.0
		100	0.5	1.0
Nano lubricant (new cooking oil)	0.5% AI2O3	25	0.5	1.0
		50	0.5	1.0
		100	0.5	1.0

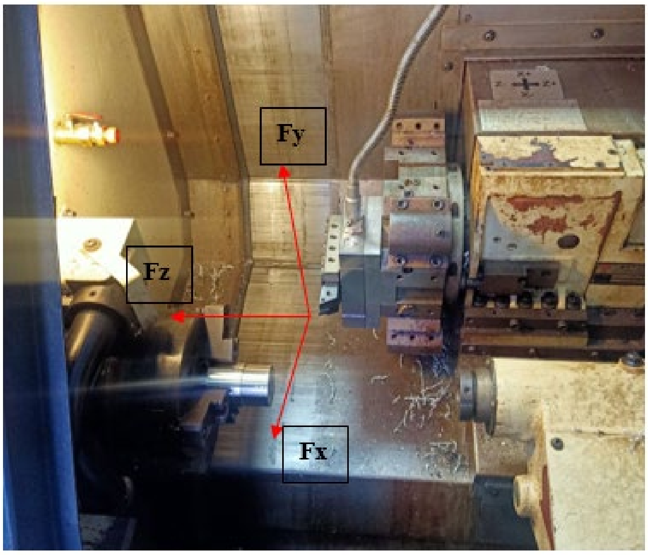


Figure 3: direction of the cutting force component.

Surface roughness measurements were performed using a Mitutoyo SJ-210 profilometer. The device was calibrated before each run, and the needle was brought into contact with the machined surface to measure the surface roughness (Ra). For each machining condition, four readings were taken at different locations on the workpiece, and the average Ra value was calculated to ensure accurate and consistent results. This approach minimized the effects of localized anomalies and provided a representative assessment of the overall surface finish.

3. RESULTS AND DISCUSSION

3.1 Mechanical Properties of Nanolubricant

To achieve the first objective, the mechanical characteristics of nanolubricants, including viscosity, pH, and physical properties, were analyzed. The results presented in Table 3 highlight variations in these properties with nanoparticle concentration and the type of base oil used.

The 0.5% WCO nanolubricant displayed the highest viscosity at 69.9 mPa.s and retained a thick, oil-like consistency with a strong waste cooking oil smell. This result is consistent with findings by [18], who noted that impurities in the base oil can significantly influence the physical characteristics of nanolubricants. The strong odor and condensed texture can be attributed to residual organic compounds in the waste cooking oil. The pH value of 9.8 indicates a slightly alkaline composition, typical for formulations based on recycled oils.

The 0.75% WCO nanolubricant exhibited a lower viscosity of 28.5 mPa.s, a lighter color, and a milder odor compared to the 0.5% WCO. This decrease in viscosity may be due to a more balanced nanoparticle concentration, which reduced clustering and allowed for better dispersion. The consistency suggests that the lubricant was stable enough to prevent excessive nanoparticle agglomeration. With a pH of 9.4, the nanolubricant maintained mild alkalinity while improving its sensory properties and flow characteristics.

In contrast, the 1.0% WCO nanolubricant showed a significant drop in viscosity (8.13 mPa.s) and a water-like consistency, with minimal odor. This suggests that excessive nanoparticle concentration caused poor dispersion and possible sedimentation. The increase in pH to 10 further reflects changes in composition that may compromise lubrication performance.

The 0.5% NCO nanolubricant had the lowest viscosity (5.81 mPa.s), a white, water-like appearance, and no strong odor, indicating the absence of impurities. However, its low viscosity suggests that it may provide less lubrication compared to WCO-based formulations under high-friction conditions.

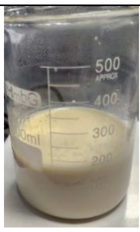
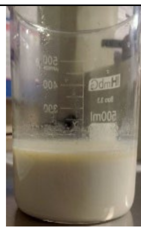
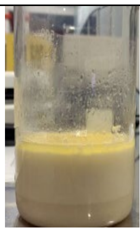
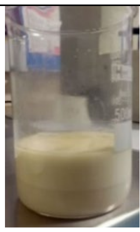
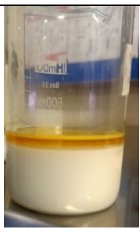
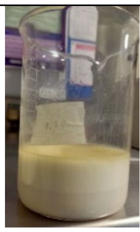
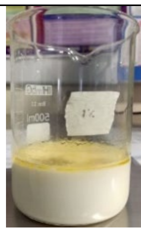
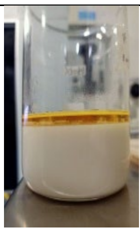
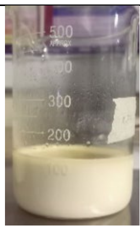
These results align with [19], who noted that nanoparticles improve lubrication by reducing friction and wear. The findings highlight that the 0.75% WCO concentration offers the best balance of viscosity, stability, and sensory properties, making it the most effective formulation for machining applications.

Table 3: Nanolubricants mechanical characteristics.

Nanolubricants	Temperature (Co)	Viscosity (mPa.s)	pH	physical characteristics
0.5% WCO	23.3	69.9	9.8	• Very condensed, oil-like color. • Strong smell of waste cooking oil.
0.75% WCO	23.2	28.5	9.4	• Less condensed, lighter color. • Milder waste cooking oil smell.
1.0% WCO	22.1	8.13	10	• Close to white color, thin like water. • Minimal, almost no smell.
0.5% new cooking oil	22.4	5.81	9.4	• White color, very thin like water. • No strong smell.

To further validate the suspension stability of the prepared nanolubricants, a visual stability assessment was conducted, as shown in Table 4, by observing all three WCO-based formulations over a period of 30 days at ambient temperature. Samples were examined at days 1, 4, 10, 20, and 30 following preparation. Visual inspection revealed a thin, oil-rich layer at the surface of all formulations, first becoming visible on day 4 and persisting throughout the observation period. This surface layer is attributed to the partial separation of the free oil fraction within the emulsion, a known behavior in bio-based oil emulsions resulting from the oxidation of residual fatty acids in the waste cooking oil. To counter this, sodium ascorbate was incorporated as an antioxidant, effectively inhibiting further oxidation and preventing the solidification of the surface layer observed prior to its addition. Below this thin surface film, the bulk of each formulation remained visually homogeneous, with no significant nanoparticle sedimentation detected at the bottom of the containers across all observation intervals, indicating that the nanoparticle suspension remained acceptably stable. The 0.75% WCO nanolubricant maintained the most consistent bulk appearance over the 30-day period, consistent with its superior lubrication performance during machining experiments. It should be acknowledged that Zeta Potential measurement, which provides a quantitative indicator of electrostatic repulsion between suspended nanoparticles, was not performed in this study. Future work is recommended to include Zeta Potential characterization to give a more rigorous assessment of colloidal stability, particularly at higher nanoparticle concentrations where agglomeration risk is more pronounced.

Table 4: Observation of nanolubricants over 30 days.

Days	0.5% WCO	0.75% WCO	1% WCO
1			
4			
10			
20			
30			

3.2 The effect of nanoparticle concentration on cutting force and surface roughness

In turning operations, the cutting force is composed of three components: tangential force (Fy), radial force (Fx), and axial force (Fz). Among these, Fy is the largest and most significant, as it directly reflects the resistance during material removal. Due to its dominance, Fy is used as the primary indicator for evaluating cutting performance. In this study, Fy is measured to assess the effect of nanoparticle concentration in waste cooking oil nanolubricants on friction reduction and machining efficiency. This approach aligns with industry practices, as Fy provides the most reliable measure of cutting performance.

The experimental runs were conducted to study the effect of nanoparticle concentration on cutting force during turning operations. The total number of experiments included dry runs and tests with different nanoparticle concentrations in waste cooking oil (WCO) and new cooking oil (NCO). Each experiment was performed at cutting speeds of 25 m/min, 50 m/min, and 100 m/min, with a constant feed rate of 0.5 mm/rev and a depth of cut of 1 mm. This controlled setup ensured that variations in cutting force could be attributed primarily to the type and concentration of the nanolubricants, enabling a clear comparison of their performance across different conditions.

For surface roughness (Ra), it was measured using a profilometer, with the needle in direct contact with the machined surface after each machining run. The device was calibrated to ensure consistent readings, and four measurements were taken for each condition and cutting speed. The average Ra value was calculated to minimize variability and improve reliability. Measurements were taken at multiple locations on the Inconel 718 surface to account for localized anomalies and provide a representative evaluation of the surface finish, which is crucial to ensuring the performance and quality of machined components.

3.2.1 The effect of cutting force at different nanoparticle concentrations for the Cutting speeds, V = 25, 50, and 100 (m/min).

At 25 m/min, the dry condition showed the highest cutting force due to increased friction. The 0.75% WCO nanolubricant achieved the greatest reduction, with a 35.85% decrease compared to dry machining, indicating effective lubrication. In contrast, the 0.5% WCO showed a modest 7.48% improvement, while the 1.0% WCO led to an 8.63% increase, likely due to nanoparticle agglomeration. The 0.5% NCO nanolubricant performed better than the 0.5% WCO but was less effective than the 0.75% WCO.

At 50 m/min, cutting forces decreased overall. However, the 0.5% WCO concentration unexpectedly increased the cutting force by 14.27%, suggesting insufficient lubrication coverage. The 0.75% WCO still reduced the cutting force by 2.31%, outperforming both the dry run and 0.5% NCO, though its improvement was less pronounced. The 1.0% WCO showed a slight 2.11% increase, indicating reduced efficiency at this speed.

At 100 m/min, cutting forces generally decreased across most conditions, owing to faster chip evacuation and reduced contact time between the tool and the workpiece. However, the 0.75% WCO nanolubricant showed a 26.73% increase in cutting force compared to dry machining, a result warranting closer examination. This behavior is attributed to two compounding physical mechanisms that become significant at elevated cutting speeds. First, the thermal environment at 100 m/min is considerably more severe than at lower speeds, with heat generation at the tool-chip interface intensifying substantially. Waste cooking oil, being a bio-based fluid with a relatively lower thermal stability compared to synthetic lubricants, is susceptible to thermal degradation under these conditions [20]. At high cutting temperatures, the fatty acid chains within the WCO base can break down, compromising the integrity of the lubrication film and reducing its load-bearing capacity at the cutting interface. Second, the relatively higher viscosity of the 0.75% WCO formulation may have hindered the ability of the MQL spray to effectively penetrate the tool-chip interface at high cutting velocities. At elevated speeds, the chip formation rate increases rapidly, and a more viscous fluid may fail to reach the cutting zone in sufficient quantity before being deflected by the high-velocity chip stream, leaving the interface partially unlubricated [9]. The combined effect of thermal film breakdown and insufficient lubricant penetration therefore, explains the anomalous rise in cutting force observed at this speed for the 0.75% WCO concentration. This finding underscores the importance of matching lubricant viscosity and thermal stability to the intended operating speed range. It suggests that further formulation refinement, such as incorporating thermally stable nanoparticle additives or adjusting the surfactant ratio, could extend the effective operating range of WCO-based nanolubricants to higher cutting speeds.

In summary, the 0.75% WCO nanolubricant was the most effective at reducing cutting forces at 25 m/min and 50 m/min, highlighting its balanced formulation for low and moderate speeds. However, at 100 m/min, its performance declined, indicating the need for further optimization at higher speeds to prevent instability in the lubrication film. These results reinforce the importance of selecting an optimal nanoparticle concentration to achieve consistent lubrication and improved machining efficiency across varying cutting speeds.

Figure 6 illustrates the effect of cutting force at different nanoparticle concentrations for the cutting speeds of 25 m/min, 50 m/min, and 100 m/min.

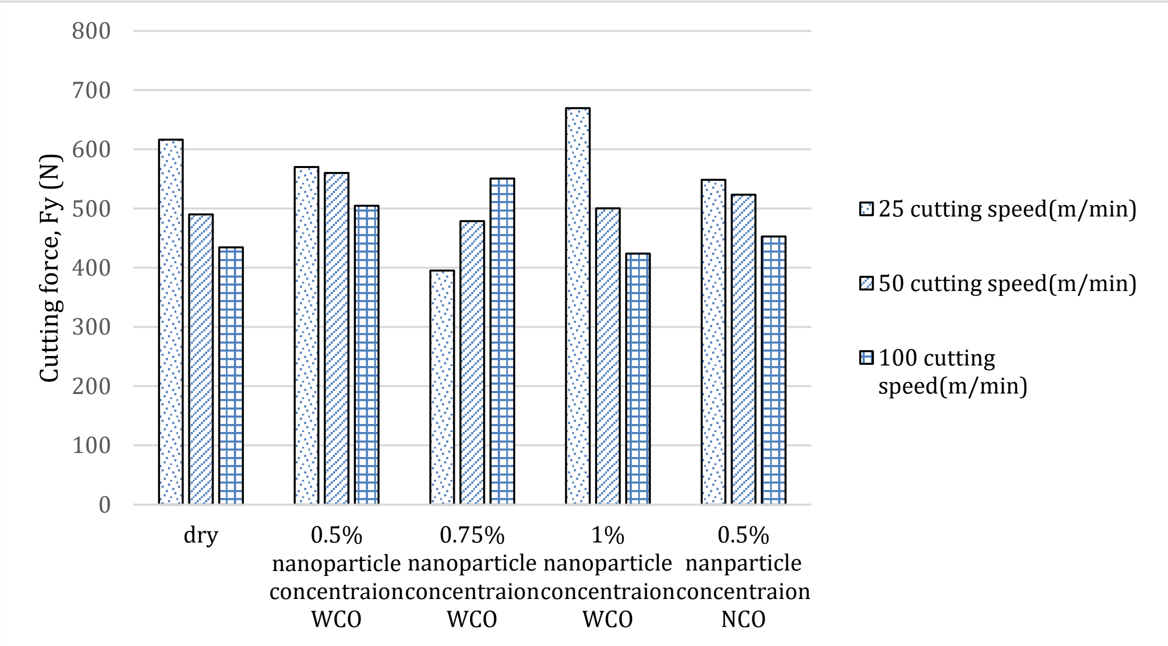


Figure 4: Comparison of the effect of cutting force at different nanoparticle concentrations for the Cutting speeds, V = 25, 50, and 100 (m/min).

3.2.2 The effect of surface roughness at different nanoparticle concentrations for the Cutting speeds, V = 25, 50, and 100 (m/min).

The surface roughness (Ra) results for different nanolubricant concentrations across cutting speeds of 25 m/min, 50 m/min, and 100 m/min, as shown in Table 5 and visualized in Figure 7, illustrate how lubrication conditions influence surface finish during machining.

At 25 m/min, the dry condition produced the highest surface roughness (5.009 µm) due to increased friction and prolonged tool-workpiece contact. The 0.75% WCO nanolubricant demonstrated the best performance, achieving a 52.78% improvement by reducing the Ra value to 2.366 µm, indicating the formation of a stable lubrication film. However, increasing the nanoparticle concentration to 1.0% resulted in a significantly higher Ra value of 4.989 µm, approaching the dry machining condition. Contrary to what might be initially assumed, this deterioration in surface quality is not attributable to excessive viscosity; the measured viscosity of the 1.0% WCO formulation was, in fact, the lowest among all WCO-based nanolubricants at 8.13 mPa·s, indicating a near-water-like consistency. Instead, the poor performance is more accurately explained by nanoparticle agglomeration. At higher particle loadings, the probability of inter-particle collision and clustering increases substantially, as the reduced inter-particle spacing leaves insufficient room for the surfactant layers to maintain separation between individual nanoparticles. These agglomerated clusters are unable to form a smooth, continuous tribofilm required for effective lubrication at the tool-workpiece interface. Rather than rolling between surfaces to reduce friction, agglomerated particles act as abrasive bodies, increasing surface irregularities and worsening the resulting finish. The drop in bulk viscosity further supports this interpretation, as it suggests that particle clustering has disrupted the structured suspension, reducing the fluid's ability to maintain a coherent lubricating layer under cutting loads[21].

At 50 m/min, the 1.0% WCO concentration again yielded a comparatively high Ra value of 4.1225 µm, consistent with its poor performance at the lower speed. This persistent underperformance across both speeds reinforces the argument that nanoparticle agglomeration, rather than any viscosity-related effect, is the governing factor limiting lubrication effectiveness at this concentration. The agglomerated particle clusters remain unable to penetrate the tool-chip interface uniformly, regardless of cutting speed, resulting in a surface quality that offers little advantage over dry machining conditions.

At 100 m/min, surface roughness generally decreased due to faster chip evacuation and shorter contact time. However, the Ra value for the 0.75% WCO nanolubricant increased to 3.5023 µm, indicating lubrication instability at high speeds. In contrast, the 0.5% NCO nanolubricant achieved the lowest Ra value (2.9163 µm), suggesting that its thinner composition allowed it to flow more effectively at higher speeds.

Table 5: surface roughness (Ra) at different nanoparticle concentration for the Cutting speeds, V= 25, 50, and 100 (m/min), measured in µm.

Cutting speed (m/min)	Dry run	0.5% nanoparticle concentration WCO	0.75% nanoparticle concentration WCO	1% nanoparticle concentration WCO	0.5% nanoparticle concentration NCO
25	5.009	2.7645	2.366	4.989	3.79
50	4.3625	2.519	1.6558	4.1225	3.634
100	4.3853	3.445	3.5023	4.0018	2.9163

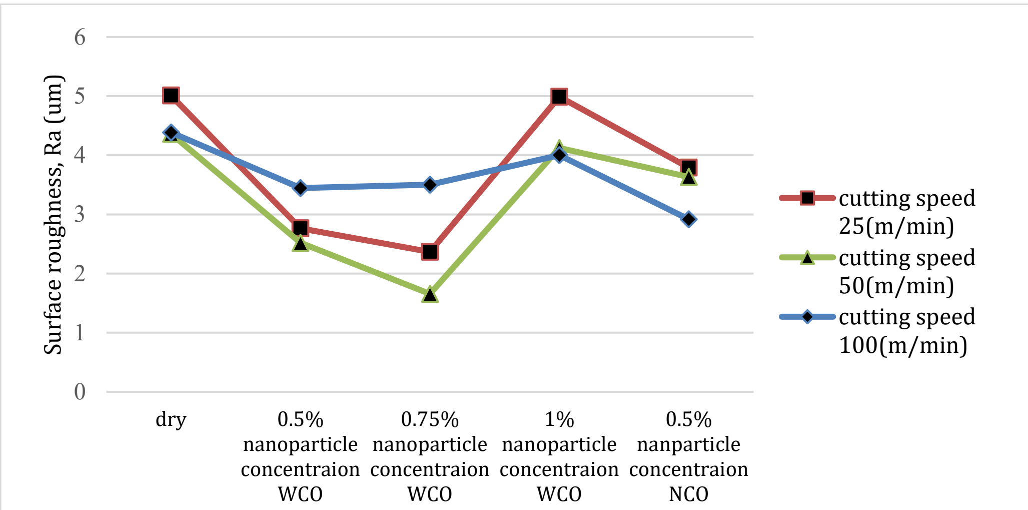


Figure 5: Comparison of the effect of surface roughness at different nanoparticle concentrations for the Cutting speeds, V = 25, 50, and 100 (m/min).

4. CONCLUSION

This study investigated the use of Al_2O_3 nanoparticle-enhanced waste cooking oil (WCO) as a sustainable nanolubricant for machining Inconel 718, a material known for its high strength and machining challenges. The study focused on characterizing the mechanical properties of the nanolubricants and evaluating their effects on cutting force and surface roughness at three concentrations (0.5%, 0.75%, and 1.0%) across cutting speeds of 25, 50, and 100 m/min.

The results demonstrated that the 0.75% WCO concentration provided the best overall performance, reducing cutting force by 35.85% and surface roughness by 62.04% compared to dry machining at moderate speeds, thanks to its balanced viscosity and stable nanoparticle dispersion. However, performance declined at the highest cutting speed, attributed to thermal degradation of the bio-based oil film and reduced MQL spray penetration efficiency at elevated cutting velocities. The 0.5% NCO nanolubricant performed well at higher speeds, benefiting from its lower viscosity for better flow into the cutting zone.

The findings highlight the significant potential of WCO-based nanolubricants to enhance machining performance while addressing sustainability by repurposing waste materials. This study supports the development of eco-friendly, cost-effective lubrication solutions, with future work recommended to optimize dispersion and explore hybrid nanoparticle formulations for enhanced performance.

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