Journal of Mechanical Engineering Science and Technology ISSN 2580-0817
Vol. 9, No. 1, July 2025, pp. 75-89

Influence of Different Nanoparticles on Thermophysical Properties and Wear Resistance of Corn Oil-Based Cutting Fluid in MQL-CNC Milling Machining

M. Nuril Anwar Habiby[1], Poppy Puspitasari[1,2*], Aminnudin[1], Diki Dwi Pramono[1], Ahmad Atif Fikri[1], Mariyam Jameelah Ghazali[3]

[1]*Department of Mechanical and Industrial Engineering, Universitas Negeri Malang, Indonesia*
[2]*Centre of Advanced Material and Renewable Energy, Universitas Negeri Malang, Indonesia*
[3]*Department of Mechanical and Manufacturing Engineering, Universiti Kebangsaan Malaysia, Malaysia*
**Corresponding author: poppy@um.ac.id*

Article history:
Received: 1 January 2025 / Received in revised form: 24 March 2025 / Accepted: 15 April 2025
Available online 25 April 2025

ABSTRACT

Vegetable oil-based cutting fluids have emerged as a promising innovation in machining operations, supporting the advancement of sustainable and eco-friendly manufacturing practices. This study delves into the development of a biolubricant derived from corn oil, enriched with 0.15% mass fractions of various nanoparticles, including calcium carbonate ($CaCO_3$), copper oxide (CuO), and multi-walled carbon nanotubes (MWCNT). These nano-cutting fluids were applied through the Minimum Quantity Lubrication (MQL) method during CNC milling of AISI 1045 steel. The investigation focused on evaluating thermophysical properties, including density, thermal conductivity, and dynamic viscosity, as well as tool wear performance. The results demonstrated that CuO nanoparticles yielded the highest density, while MWCNT exhibited superior thermal conductivity and viscosity. Among all samples, the fluid with MWCNT showed the most effective performance in minimizing tool wear. This study highlights the potential of nanoparticle-enriched vegetable-based cutting fluids as high-performance, environmentally responsible alternatives to conventional mineral oil-based lubricants, promoting greener machining in the manufacturing industry.

Keywords: *Corn oil, CNC milling, MQL, nano-cutting fluid, thermophysics, wear resistance.*

I. Introduction

In the modern manufacturing industry, computer numerical control (CNC) machining is one of the technologies widely used to improve product quality and efficiency [1],[2]. An essential factor in minimizing friction and thermal buildup during machining operations lies in the appropriate selection and application of cutting fluids, which serve dual roles as both lubricants and coolants [3],[4]. During machining, the use of efficient and effective cutting fluids is essential for reducing tool wear, increasing the tool's lifespan, and improving the surface polish of the machined parts [5]–[7]. Dry cutting has long been used to reduce machining costs and environmental pollution, but friction and adhesion will increase, so mineral oil-based cutting fluids are also used, which are not environmentally friendly.

Along with the development of nanomaterial technology, recent research has introduced the concept of nano-cutting fluid, a basic coolant and lubricant fluid mixed with very small nano-sized particles [8],[9]. Incorporating nanoparticles into cutting fluids has demonstrated significant enhancements in thermophysical characteristics, including viscosity, thermal

DOI: 10.17977/um016v9i12025p075

conductivity, density, and specific heat capacity while also increasing the wear resistance of cutting tools throughout machining operations [10]–[13].

Currently, vegetable oils such as corn oil are starting to be widely used as base cutting fluids in research due to the fact that they are ecologically friendly, non-toxic, and easily biodegradable, offering an innovation for a sustainable alternative cutting fluid compared to mineral oils, which are commonly used on the market [14]–[17]. The extensive usage of mineral oil-based cutting fluids may elevate machining expenses and result in environmental issues, while also contributing to pollution and health hazards [18]. On the other hand, the availability of mineral oil raw materials is increasingly depleted, so solutions are needed to address various existing problems to produce a more effective machining process in the future [19],[20]. In addition, there is still a problem where mineral oil, as the basic material of cutting fluid, is sprayed a lot using the flood method, resulting in the liquid coming out continuously, which will have a bad effect on the environment. With this problem, the cutting fluid spraying method known as MQL that can be a solution to this problem and is more environmentally friendly. Specifically, by using a combination of high-pressure air and cutting fluid to spray into the cutting zone, chips can be efficiently cooled and cleaned, MQL technology has the advantage of being able to control cutting fluid sample usage accurately and low, namely 10-100 ml/hour only, much lower than flooding cutting fluid, namely 1200 L/h. With the development of science and awareness of the importance of environmental protection, it is crucial to conduct research on resource conservation, sustainable, eco-friendly manufacturing, and effective energy use.

Among the various vegetable oils available, corn oil has emerged as an attractive candidate for use as a cutting fluid base. The advantageous physicochemical qualities of maize oil, such as low viscosity, high flash point, and beneficial fatty acid composition, enhance the efficacy of cutting fluids in machining applications [21]. In addition, corn oil contains compounds that are more biodegradable, making it a more sustainable substitute for mineral oils. Vegetable oil has low thermal stability and is more oxidative because it contains unsaturated fatty acids, but this can be overcome by modifying it using the addition of additives.

Many kinds of studies have been conducted to investigate the role of nanoparticles in enhancing cutting fluid efficacy. Nanoparticles, such as metal oxides (CuO, TiO_2, Al_2O_3, ZnO, SiO, Fe_2O_3), metal nitrides (AlN, SiN, hBN), metal carbides (SiC), and carbon forms (graphite, CNT, MWCNT), are commonly incorporated into mineral oil-based cutting fluids. These nanoparticles significantly enhance the thermophysical properties and wear resistance of these fluids [22]. Research on the use of nanoparticles in vegetable oil-based cutting fluids, particularly corn oil, is still in its infancy. In addition, although many studies have examined the performance of each nanoparticle individually, there is no clear consensus on the performance of which type of nanoparticle is most effective in the machining process, especially in CNC milling.

Cutting fluids combined with nanoparticles have several potential benefits. Various nanoparticles possess distinct characteristics and may influence the interaction among the cutting fluid, cutting tool, and workpiece [23]–[25]. Consequently, it is essential to perform a comprehensive analysis of the impact of various nanoparticles on the thermophysical properties and wear resistance of vegetable oil-based nano-cutting fluids, particularly in CNC milling machining processes, which is anticipated to provide clearer guidance for the manufacturing industry in selecting appropriate cutting fluids for specific machining applications. Previous studies have predominantly examined the effects of a single type of nanoparticle, lacking a comprehensive comparison among various nanoparticle types. This has left a research gap in understanding how different nanoparticles influence the thermophysical properties and wear resistance of corn oil-based nano-cutting fluids in CNC milling processes. Therefore, this study aims to address that gap by performing a comparative analysis of multiple nanoparticles incorporated into corn oil-based cutting fluids.

II. Material and Methods

1. Materials

The base fluid and raw materials used were corn oil (Mazola, Indonesia). The additive material mixed into the base fluid used various types of materials, namely $CaCO_3$ nanoparticles made from shellfish waste, CuO, and MWCNT with a mass fraction of 0.15% (wt). Utilizing a CNC milling machine, the nano-cutting fluid sample's performance was used to ascertain its level of wear resistance with an MQL spraying method on AISI 1045 steel, the dimensions of AISI 1045 steel are 50 mm × 50 mm × 20 mm (L, W, H). The cutting tool used in the machining process was a high-speed steel (HSS) SOLID endmill with a diameter of 8 mm, has four flutes, and is 70 mm long.

2. Production of Nano-Cutting Fluid Samples

The production of nano-cutting fluid samples involved two steps: ultrasonic homogenization and stirring [26]–[28]. The sample preparation process commences by mixing the nanoparticle additive into corn oil and stirring it using a magnetic stirrer at a speed of 1250 RPM for 20 minutes, as per previous studies [29]. Subsequently, it was subjected to ultrasonic homogenization for 30 minutes to achieve a high degree of dispersion [30]. The stages of the nano-cutting fluid sample preparation process and the experimental design are shown in Figure 1 and Table 1.

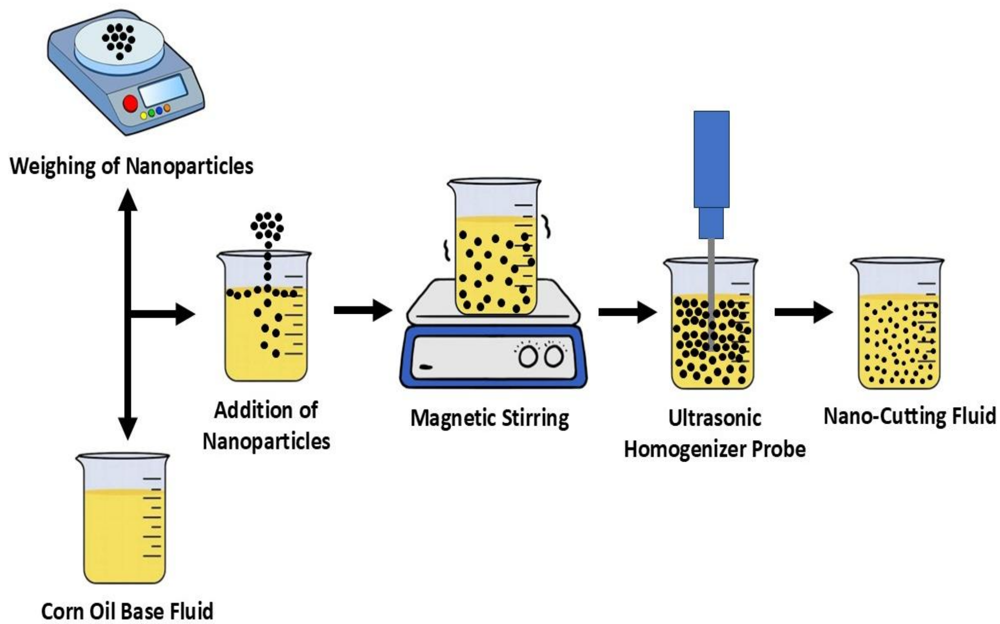

Fig. 1. Schematic of nano-cutting fluid sample preparation

Table 1. Experimental research design

No	Sample names	Concentration of nanoparticles (wt%)	Lubricating condition
1.	Corn oil	0	MQL
2.	CO + $CaCO_3$	0.15	MQL
3.	CO + CuO	0.15	MQL
4.	CO + MWCNT	0.15	MQL

3. Experimental Setup of CNC Milling

The performance of maize oil-based nano-cutting fluid samples with varying additions of distinct nanoparticles was identified and assessed using the CNC milling machining process ($CaCO_3$, CuO, MWCNT) to be sprayed using the MQL method. In addition to various CNC milling machine components that will be used to determine the performance of nano-cutting fluid as a sample, there is also an MQL preparation consisting of a compressor to provide pressure to the nano-cutting fluid sample during the machining process, flow control to ensure constant air pressure, oil tank as a place for nano-cutting fluid samples when spraying, and nozzle to spray samples in the form of mist with parameters as carried out in further research [31]. Figure 2 shows the CNC milling machining parameters used, and Table 2 for the MQL parameters.

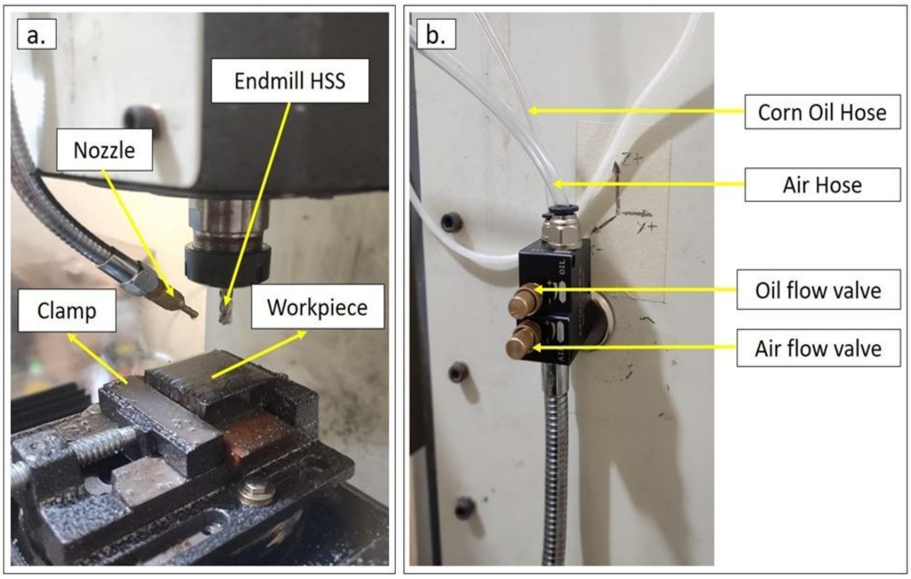

Fig. 2. Experiment setup, (a) CNC milling, (b) MQL system

Table 2. CNC milling machining parameters

CNC milling	Parameter	MQL	Parameter
Spindle speed (rpm)	3000	Nozzle distance (mm)	20
Feed rate (mm/rpm)	0.10	Nozzle angle (°)	45
Dept of cut (mm)	1.5	Nozzle diameter (mm)	2
Cutting speed (m/min)	110	Pressure (bar)	4

4. Thermophysical Test of Nano-Cutting Fluid

The density of the nano-cutting fluid samples was assessed at ambient temperature using an analytical digital balance for mass measurement, while the corresponding volume was acquired using a pycnometer [32]. Thermal conductivity testing was carried out using KD2 Pro to determine the heat transfer performance in nano-cutting fluid samples [33]. Dynamic viscosity testing is carried out to analyze the level of viscosity or resistance to fluid flow in the nano-cutting fluid sample using the NDJ-8S Viscometer [34]. The findings from numerous tests will be statistically evaluated using the SPSS program to derive inferences based on data or inferential statistical groupings of Analysis of Variance (ANOVA) by comparing the means using One-Way ANOVA.

5. Tool Wear Measurement

Measurement of HSS endmill cutting tool wear was carried out using a Sinher binocular optical microscope type XSZ-107 BN to determine the area of wear at intervals of four flutes in the HSS endmill [35]. Then the wear length is measured using Image J software to determine the edge wear length Vbmax. The length of wear that develops on the edge side of this cutting tool is used to calculate its wear. The results of the wear measurement on each flute will be averaged to obtain the endmill wear value, which is repeated 3 times for each parameter to be averaged again.

III. Results and Discussions

1. Density of Sample Nano-Cutting Fluid

Figure 3 will show the results of the density measurement of corn oil-based nano-cutting fluid samples mixed with various types of nanoparticles ($CaCO_3$, CuO, and MWCNT). When nanoparticles are added, the density value will rise. When nanoparticles are present, the system's overall mass rises, which inevitably raises the density. The density of the fluid increases with the number of nanoparticles added [35],[36]. Because the nanoparticles in the corn oil sample have a higher density than the base liquid, it has a lower density value than the other samples. This result is in accordance with the published report by Kotia & Ghosh, who found that density will increase with the presence of nanoparticles [38]. Each type of nanoparticle has different properties in influencing the density of the base oil [39]. CuO has the highest density value, then MWCNT, and the lowest density value is $CaCO_3$. The density of the cutting fluid will have an impact on its performance. As a cutting fluid's density grows, so does its capacity to generate hydrostatic pressure. Therefore, increasing hydrostatic pressure can facilitate the entry of cutting fluid into the cutting zone during machining operations.

Based on the results of statistical analysis using ANOVA, it can be seen that there are differences between the groups tested in the data, which states that the data obtained has very strong evidence to reject the null hypothesis. This shows that the differences between the groups tested are very statistically significant. This means that the results of this ANOVA analysis indicate that there are significant differences between the groups tested in the research or experiment conducted, as shown in Table 3.

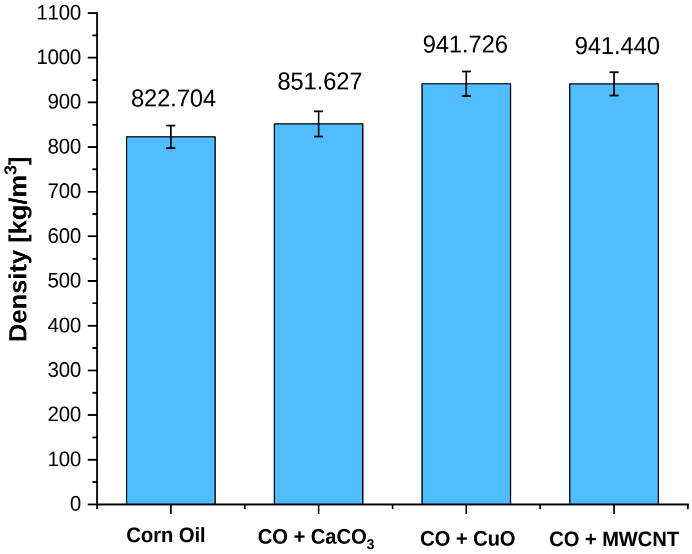

Fig. 3. The density of corn oil-based cutting fluid samples.

Table 3. ANOVA analysis on density test results

ANOVA					
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	33190.729	3	11063.576	5376.112	0.000
Within Groups	16.463	8	2.058		
Total	33207.192	11			

2. *Thermal Conductivity of Sample Nano-Cutting Fluid*

Figure 4 illustrates the thermal conductivity values of the corn oil-based nano-cutting fluid with various kinds of nanoparticles included. The results demonstrate that the incorporation of MWCNT nanoparticles significantly enhances thermal conductivity, but $CaCO_3$ and CuO nanoparticles have no measurable impact on thermal conductivity values. The type of base fluid nanoparticle, temperature, manufacturing process, concentration, form, and thermal conductivity of the nanoparticles are some of the variables that might affect the thermal conductivity value [40]–[42]. The insignificant thermal conductivity value in the addition of $CaCO_3$ and CuO nanoparticles can occur because each particle's property affects the Brownian Motion of the nanoparticles, where the motion of this force is the random movement of particles in the sample suspension solution.

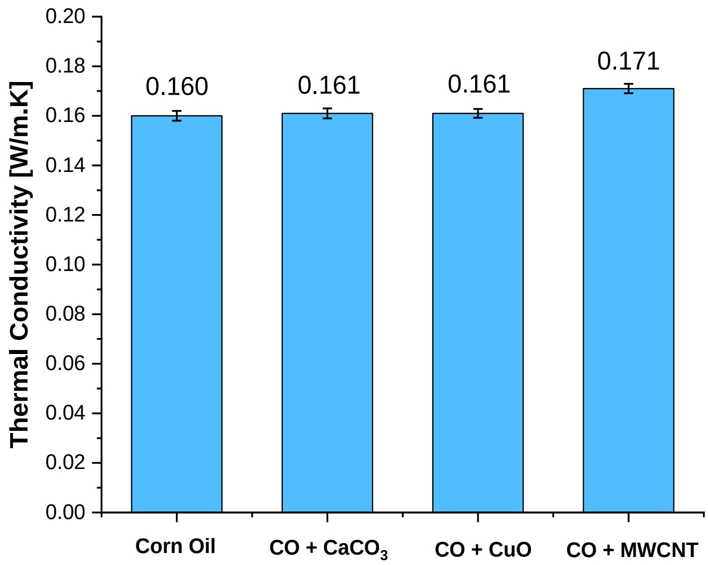

Fig. 4. Thermal conductivity of corn oil-based cutting fluid sample

MWCNT nanoparticles have the property of being able to diffuse more evenly in the base fluid when properly prepared, thus increasing the efficiency of better heat distribution. [42],[43]. Carbon nanotube material is known as one of the materials with higher thermal conductivity because it has a regular atomic structure [44]. Meanwhile, $CaCO_3$ and CuO nanoparticles as sample additives are likely to have greater agglomeration properties, namely the tendency for particles to clump together, thereby reducing the surface area and reducing thermal conductivity [40],[45],[46]. Thus, MWCNT nanoparticles have higher thermal conductivity in this study compared to $CaCO_3$ and CuO in nano-cutting fluid applications. This is also reinforced by statistical analysis of the results that the data generated from the experimental tests that had been repeated three times on each type of variable showed validity, and the use of MWCNT nanoparticles showed the best results in increasing thermal conductivity, as shown in Table 4.

Table 4. ANOVA analysis on thermal conductivity test results

	ANOVA				
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	0.0002560	3	0.00008533	78.769	0.000
Within Groups	0.00000867	8	0.000001083		
Total	0.0002647	11			

3. Viscosity of Sample Nano-Cutting Fluid

The dynamic viscosity test results for corn oil with different nanoparticle combinations are displayed in Figure 5. These findings demonstrate that, generally speaking, the corn oil sample containing the MWCNT mixture has the highest viscosity value, followed by $CaCO_3$, CuO, and the corn oil base fluid, which has the lowest viscosity. This is because the mixed MWCNT structure has properties that can increase surface interactions when spread in liquids, as the results explained in the article by Eltaggaz et al., it asserts that the base fluid's viscosity will rise due to the uniform dispersion of nanoparticles [34]. Increased surface interactions can also contribute to increased viscosity of nanofluids [47]. A high viscosity index characterizes excellent lubricant performance [48]. In addition, MWCNTs also have a non-crystalline structure, which can cause significant interactions when dispersed in base fluids, with increased viscosity [49].

It can also be observed that with increasing temperature, the viscosity will also decrease linearly. This finding is in accordance with previous research, which explains that there is an interaction between fluid molecules that weakens with increasing temperature, so that the viscosity of nano-cutting fluid also decreases [40], [50]. At different rotor speeds, it was observed that the viscosity did not change significantly; this is one of the characteristics that the nano-cutting fluid samples mostly have Newtonian properties. Dynamic viscosity testing in nano-cutting fluid research is important to analyze because when applied in a CNC milling machine, samples that have the right viscosity value will provide a thick layer in the bearing space, reducing wear and friction.

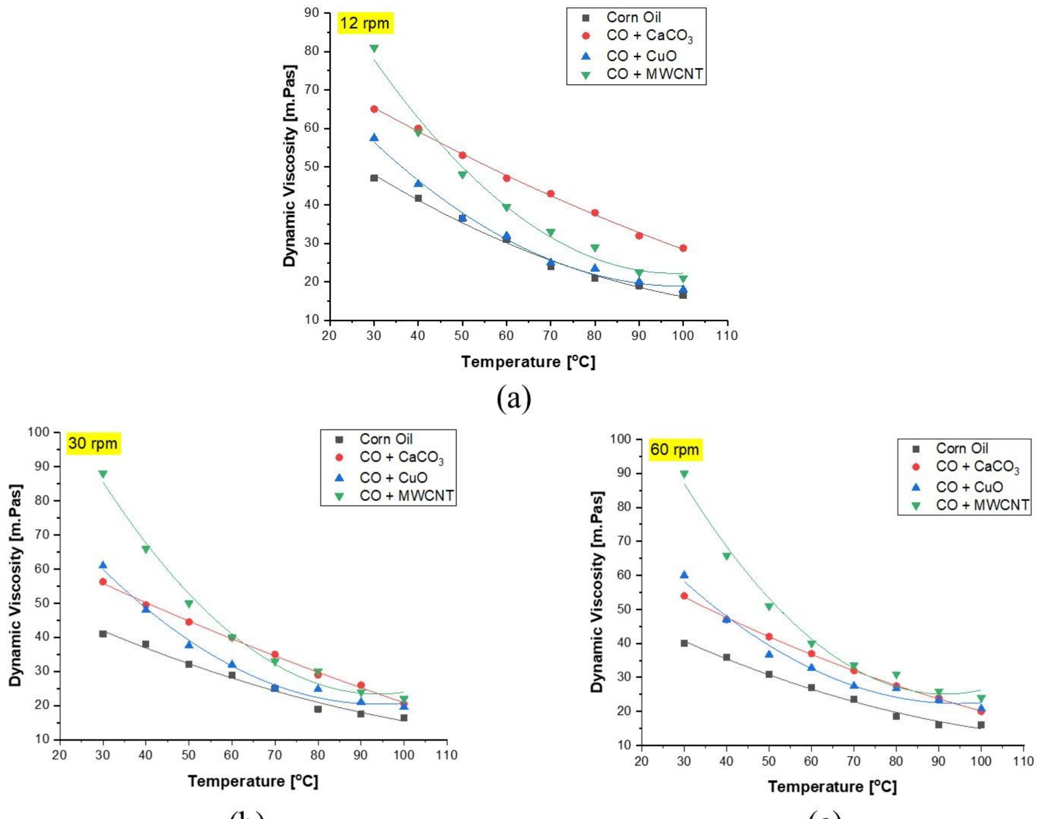

Fig. 5. Dynamic viscosity of corn oil-based cutting fluid samples at rotation speed (a) 12 rpm, (b) 30 rpm, (c) 60 rpm

4. Performance of Nano-Cutting Fluid Samples on Tool Wear

In order to assess the effectiveness of the corn oil-based nano-cutting fluid sample with varying nanoparticle additives, Figure 6 displays the endmill tool's wear following its use in the CNC milling process. The findings demonstrated that adding nanoparticles to the nano-cutting fluid sample can decrease endmill tool wear during the CNC milling process. The reason for this is that nanoparticles have the ability to improve the cutting fluid's lubricating and cooling qualities [51], [52]. The lowest endmill tool wear value can be obtained from samples with a combination of corn oil and a mixture of MWCNT nanoparticles. The good performance shown in the use of MWCNT nanoparticles can be due to the heat transfer process carried out in the cutting zone which can occur effectively and efficiently, where the heat formed due to the extrusion of the workpiece carried out on the cutting tool so that friction occurs and heat is generated can be absorbed and removed effectively through small nanoparticle grains. This can occur because the sample has quite good heat transfer quality, indicated by previous thermal conductivity testing that MWCNT can obtain high thermal conductivity values [53], [54]. The use of $CaCO_3$ and CuO nanoparticles in vegetable oil-based cutting fluids has demonstrated notable effectiveness in minimizing cutting tool wear. These findings support the conclusion that nanoparticle additives can significantly reduce friction and thermal generation during machining. This aligns with the results reported by Surakasi et al., who emphasized the positive impact of nanoparticle-enhanced coolants in improving tribological performance [55]. MQL nanofluids have the best performance in reducing tool wear because they combine nano-cutting fluid with compressed air, which can spray cutting fluid into the friction pad gap so that it can reduce abrasion wear [56]. By engineering nanoparticles in nature, cutting fluids can create tribofilms that function as a thin layer that can reduce friction [57]. Based on the ANOVA results presented in Table 5, the data did not reach statistical significance at the 0.05 level, indicating that notable differences exist among the groups analyzed.

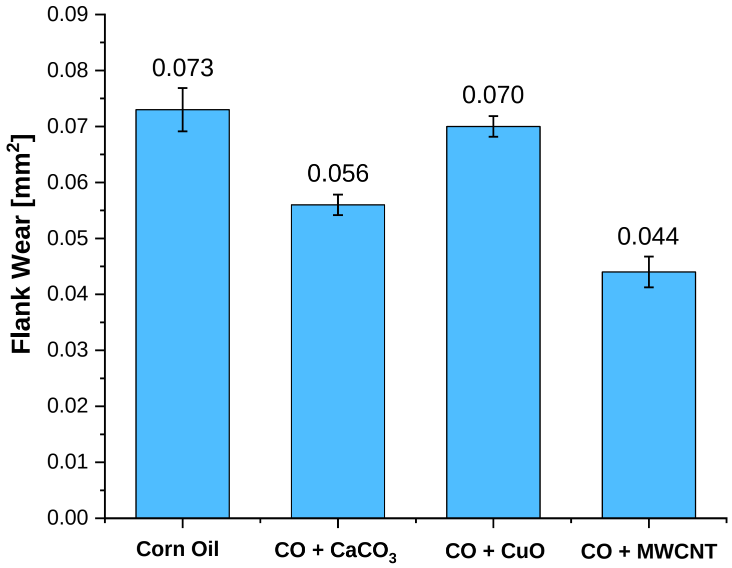

Fig. 6. Endmill tool wear measurement results after CNC milling process

Table 5. ANOVA analysis on flank tool wear test results

	ANOVA				
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	0.002	3	0.001	0.906	0.480
Within Groups	0.005	8	0.001		
Total	0.006	11			

Figure 7 shows a macro photo of tool wear on one of the endmill flutes after undergoing the CNC milling machining process. The highest wear was obtained when using corn oil samples without nanoparticle mixture, it was indicated by the presence of tool fracture in the tool wing area, then there was a burnt color, and a built-up layer, this condition occurred due to suboptimal lubrication, where the absence of a strong protective layer during the friction between the cutting tool and the workpiece led to increased heat generation in the cutting zone as a result of continuous chip formation [58]. In the use of a mixture of $CaCO_3$ and CuO nanoparticles, tool wear can be reduced as indicated by a reduction in fracture, but there is still a small built-up layer and burnt color in the area of edge wear that occurs, this can occur possibly due to the lack of ability to dissipate heat, the presence of a mixture of nanoparticles in the cutting fluid shows something positive because it can form a thin layer and form lubrication performance, but the ability to dissipate heat is not yet adequate [59].

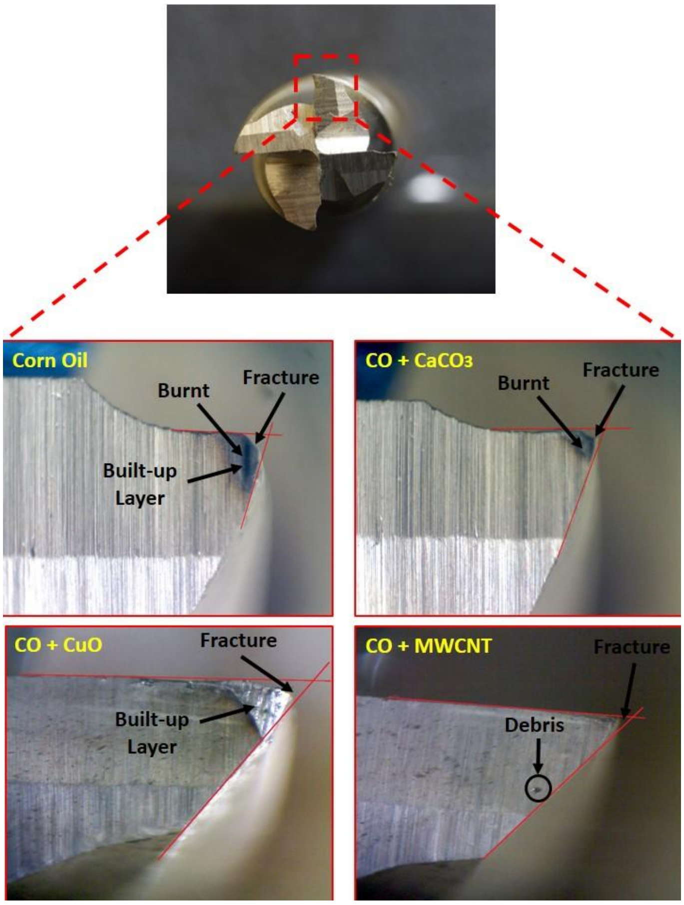

Fig. 7. Macro photo of tool wear on one of the endmill flutes

While the use of a mixture of MWCNT nanoparticles, tool wear can be reduced significantly, with a low level of fracture at the tip of the tool, this can happen because MWCNT nanoparticles have the ability to dissipate heat effectively, this is because the thin layer in the cutting zone produced by the cutting fluid contains small MWCNT particles as anti-friction, these nanoparticles can carry out their duties to withstand very good loads during the friction process, in addition, MWCNT nanoparticles contribute to the formation of a protective layer through a rolling effect, which helps reduce friction and enhance convective heat transfer. This characteristic enables the nano-cutting fluid sample to efficiently dissipate heat, thereby minimizing tool wear [60]. The findings align with theoretical studies from various sources, which suggest that incorporating nanoparticles into the base fluid significantly enhances its performance in reducing friction and wear [61].

IV. Conclusions

The CNC machining using corn oil-based cutting fluid with various types of nanoparticles as additives, including calcium carbonate ($CaCO_3$), copper oxide (CuO), and multi-walled carbon nanotubes (MWCNT), significantly impacts the thermophysical properties of the nano-cutting fluid, such as dynamic viscosity, density, and thermal conductivity. While MWCNT offers the highest values for both thermal conductivity and dynamic viscosity, the addition of CuO nanoparticles results in the highest density. Dynamic viscosity testing reveals that the viscosity remains relatively constant across varying rotor speeds, indicating that the nano-cutting fluid samples in this study predominantly exhibit Newtonian flow behavior. Although incorporating nanoparticles can reduce tool wear, MWCNT demonstrates the most effective performance in minimizing tool wear among the nano-cutting fluid samples.

This study is limited by the use of only three nanoparticles ($CaCO_3$, CuO, MWCNT) at 0.15% concentration and testing focused on thermal properties and tool wear, without long-term stability analysis. Future research should explore different nanoparticles and concentrations for better cutting performance and efficiency, with corn oil-based fluids offering eco-friendly potential.

Acknowledgment

The authors would like to express their gratitude to Universitas Negeri Malang for the opportunity, support, and guidance they provided throughout the research process.

References

[1] K.C. Yao, D.C. Chen, C.H. Pan, and C.L. Lin, "The development trends of computer numerical control (CNC) machine tool technology," *Mathematics*, vol. 12, no. 13, p. 1923, 2024.
[2] S. Du, "Analysis of the application of intelligent CNC technology in machinery manufacturing," *Journal of Physics: Conference Series*, vol. 2649, no. 012010, 2023.
[3] J. Singh, S.S. Gill, M. Dogra, and R. Singh, "A review on cutting fluids used in machining processes," *Engineering Research Express*, vol. 3, no. 1, 2021.
[4] A.H. Abdelrazek, I.A. Choudhury, Y. Nukman, and S.N. Kazi, "Metal cutting lubricants and cutting tools: a Review on the performance improvement and sustainability assessment," *International Journal of Advanced Manufacturing Technology*, vol. 106, no. 9–10, pp. 4221–4245, 2020.
[5] R.S. Rathee, "Review of cutting fluid technologies in machining processes," *International Journal of Engineering Research and Development e-*, vol. 20, no. 11, pp. 1450–1454, 2024.
[6] S. Debnath, M.M. Reddy, and Q.S. Yi, "Influence of cutting fluid conditions and cutting parameters on surface roughness and tool wear in turning process using Taguchi method," *Measurement: Journal of the International Measurement Confederation*, vol. 78, pp. 111–119, 2016.
[7] N. Madanchi, D. Kurle, M. Winter, S. Thiede, and C. Herrmann, "Energy efficient process chain: The impact of cutting fluid strategies," *Procedia CIRP*, vol. 29, no. December, pp. 360–365, 2015.
[8] A. Roman, T. Fatima, S. Wakeel, M. Umer, M. Asif, and S. Ameen, "Nanochemistry: Exploring the transformative world of nanomaterials and their applications," *International Journal of Thermal Technologies*, vol. 13, no. 01, pp. 1–11, 2023.

[9] N. Baig, I. Kammakakam, and W. Falath, "Nanomaterials: A review of synthesis methods, properties, recent progress, and challenges," *Materials Advances*, vol. 2, no. 6, pp. 1821–1871, 2021.

[10] R.K. Singh, A.K. Sharma, A.R. Dixit, A. Mandal, and A.K. Tiwari, "Experimental investigation of thermal conductivity and specific heat of nanoparticles mixed cutting fluids," *Materials Today: Proceedings*, vol. 4, no. 8, pp. 8587–8596, 2017.

[11] C. Sabarinathan, N. Manikandan, V.P. Sureshkumar, S.S. Murugan, and G. Rathis, "Effect on tool life by addition of nanoparticles with the cutting fluid," *Materials Today: Proceedings*, vol. 33, no. 7, pp. 2940–2954, 2020.

[12] J.E. Manikanta, B.N. Raju, B.S.S. Phanisankar, M. Rajesh, and T.K. Kotteda, "Nanoparticle enriched cutting fluids in metal cutting operation: A review," *Lecture Notes in Mechanical Engineering*, no. March, pp. 147–156, 2023.

[13] D. Panjaya, A. Ginting, and D.Y. Nasution, "A review: The use of nanoparticles in cutting fluid as an effort to improve the performance of hard machining in sustainable MQL systems," *IOP Conference Series: Materials Science and Engineering*, vol. 1003, no. 1, 2020.

[14] Y.M. Shashidhara and S.R. Jayaram, "Vegetable oils as a potential cutting fluid-An evolution," *Tribology International*, vol. 43, no. 5–6, pp. 1073–1081, 2010.

[15] R.A. Kazeem, D.A. Fadare, O.M. Ikumapayi, A.A. Adediran, S.J. Aliyu, Akinlabi *et al.*, "Advances in the application of vegetable-oil-based cutting fluids to sustainable machining operations—A review," *Lubricants*, vol. 10, no. 69, 2022.

[16] R. Sankaranarayanan, R.J. Hines, S. Kumar, and G.M. Krolczyk, "A comprehensive review on research developments of vegetable-oil based cutting fluids for sustainable machining challenges," *Journal of Manufacturing Processes*, vol. 67, no. July, pp. 286–313, 2021.

[17] I.S. Afonso, G. Nobrega, R. Lima, J.R. Gomes, and J.E. Ribeiro, "Conventional and recent advances of vegetable oils as metalworking fluids (MWFs): A review," *Lubricants*, vol. 11, no. 4, 2023.

[18] S. Ekinovic, H. Prcanovic, and E. Begovic, "Investigation of influence of MQL machining parameters on cutting forces during MQL turning of carbon steel St52-3," *Procedia Engineering*, vol. 132, pp. 608–614, 2015.

[19] A. Ruggiero, R. D'Amato, M. Merola, P. Valášek, and M. Müller, "On the tribological performance of vegetal lubricants: Experimental investigation on Jatropha Curcas L. oil," *Procedia Engineering*, vol. 149, no. June, pp. 431–437, 2016.

[20] R. Teti, D.M. D'Addona, and T. Segreto, "Microbial-based cutting fluids as bio-integration manufacturing solution for green and sustainable machining," *Journal of Manufacturing Science and Technology*, vol. 32, pp. 16–25, 2021.

[21] Ç.V. Yıldırım, Ş. Şirin, T. Kıvak, H. Ercan, and M. Sarıkaya, "An attempt towards green machining of Ni-based hastelloy C4 alloy: Effect of vegetable oils and their combination with TiO_2 and SiO_2 nanoparticles on outputs," *Sustainable Materials and Technologies*, vol. 37, no. June, 2023, doi: 10.1016/j.susmat.2023.e00668.

[22] K. Zadafiya, P. Shah, A. Shokrani, and N. Khanna, "Recent advancements in nano-lubrication strategies for machining processes considering their health and environmental impacts," *Journal of Manufacturing Processes*, vol. 68, no. PA, pp. 481–511, 2021.

[23] T.P. Gundarneeya and D.P. Vakharia, "Performance analysis of journal bearing operating on nanolubricants with TiO_2, CuO and Al_2O_3 nanoparticles as lubricant additives," *Materials Today: Proceedings*, vol. 45, no. 6, pp. 5624–5630, 2021.

[24] M.Z. Abdullah, K.H. Yu, H.Y. Loh, R. Kamarudin, P. Gunnasegaran, and A.

Alkhwaji, “Influence of nanoparticles on thermophysical properties of hybrid nanofluids of different volume fractions,” *Nanomaterials*, vol. 12, no. 15, 2022.

[25] H. Hegab, U. Umer, M. Soliman, and H.A. Kishawy, “Effects of nano-cutting fluids on tool performance and chip morphology during machining Inconel 718,” *International Journal of Advanced Manufacturing Technology*, vol. 96, no. 9–12, pp. 3449–3458, 2018.

[26] A. Chu, C. Li, Z. Zhou, B. Liu, Y. Zhang, M. Yang *et al.*, "Nanofluids Minimal Quantity Lubrication Machining: From Mechanisms to Application," *Lubricants*, vol. 11, no. 422. 2023.

[27] A.R.I. Ali and B. Salam, “A Review on nanofluid: Preparation, stability, thermophysical properties, heat transfer characteristics and application,” *Journal SN Applied Sciences*, vol. 2, no. 10, pp. 1–17, 2020.

[28] H.M. Ali, H. Babar, T.R. Shah, M.U. Sajid, M.A. Qasim, and S. Javed, “Preparation techniques of TiO_2 nanofluids and challenges: A review,” *Applied Sciences (Switzerland)*, vol. 8, no. 4, 2018.

[29] A.S. Al-Janabi, M. Hussin, M.Z. Abdullah, and M.A. Ismail, “Effect of CTAB surfactant on the stability and thermal conductivity of mono and hybrid systems of graphene and FMWCNT nanolubricant,” *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, vol. 648, no. April, p. 129275, 2022.

[30] M.F. Ismail, W.H. Azmi, R. Mamat, K.V. Sharma, and H.M. Ali, “Extensive stability assessment of TiO_2/polyvinyl ether nanolubricant with physical homogenization,” *Lubricants*, vol. 11, no. 2, 2023.

[31] A.K. Sharma, A.K. Tiwari, and A.R. Dixit, “Effects of minimum quantity lubrication (MQL) in machining processes using conventional and nanofluid based cutting fluids: A comprehensive review,” *Journal of Cleaner Production*, vol. 127, pp. 1–18, 2016.

[32] M. Gupta, V. Singh, R. Kumar, and Z. Said, “A review on thermophysical properties of nanofluids and heat transfer applications,” *Renewable and Sustainable Energy Reviews*, vol. 74, no. February, pp. 638–670, 2017.

[33] S.S.J. Aravind and S. Ramaprabhu, “Graphene wrapped multiwalled carbon nanotubes dispersed nanofluids for heat transfer applications,” *Journal of Applied Physics*, vol. 112, no. 12, 2012.

[34] P. Puspitasari, A.A. Permanasari, M.I.H.C. Abdullah, I.A. Habibi, and D.D. Pramono, “A comparative study on stability, thermal conductivity, and rheological properties of nanolubricant using carbon-based additive,” *Jurnal Tribologi*, vol. 42, no. November 2023, pp. 33–48, 2024.

[35] A. Eltaggaz, S. Ali, K. Badwal, and I. Deiab, “Influence of nanoparticle concentration in nanofluid MQL on cutting forces, tool wear, chip morphology when milling of Inconel 718,” *International Journal of Advanced Manufacturing Technology*, vol. 129, no. 3–4, pp. 1787–1800, 2023.

[36] N.F. Azman and S. Samion, “Dispersion stability and lubrication mechanism of nanolubricants: A review,” *International Journal of Precision Engineering and Manufacturing - Green Technology*, vol. 6, no. 2, pp. 393–414, 2019.

[37] A. Kotia, G.K. Ghosh, I. Srivastava, P. Deval, and S.K. Ghosh, “Mechanism for improvement of friction/wear by using Al_2O_3 and SiO_2/Gear oil nanolubricants,” *Journal of Alloys and Compounds*, vol. 782, pp. 592–599, 2019.

[38] A. Kotia and S.K. Ghosh, “Experimental analysis for rheological properties of aluminium oxide (Al_2O_3)/Gear oil (SAE EP-90) nanolubricant used in HEMM,” *Industrial Lubrication and Tribology*, vol. 67, no. 6, pp. 600–605, 2015.

[39] H. Babar and H.M. Ali, “Towards hybrid nanofluids: Preparation, thermophysical

properties, applications, and challenges," *Journal of Molecular Liquids*, vol. 281, pp. 598–633, 2019.

[40] K. Apmann, R. Fulmer, A. Soto, and S. Vafaei, "Thermal conductivity and viscosity: Review and optimization of effects of nanoparticles," *Materials*, vol. 14, no. 5, pp. 1–75, 2021.

[41] Z. Said, S.M.A. Rahman, M.A. Sohail, and B.S. Bibin, "Analysis of thermophysical properties and performance of nanorefrigerants and nanolubricant-refrigerant mixtures in refrigeration systems," *Case Studies in Thermal Engineering*, vol. 49, no. March, p. 103274, 2023.

[42] M.Z. Sharif, W.H. Azmi, M.F. Ghazali, N.N.M. Zawawi, and T.Y. Hendrawati, "Stability and thermal conductivity of mono and hybrid nanoparticles dispersion in double-end capped PAG lubricant," *Lubricants*, vol. 11, no. 1, 2023.

[43] Z. Lyu, A. Asadi, I.M. Alarifi, V. Ali, and L.K. Foong, "Thermal and Fluid dynamics performance of MWCNT-water nanofluid based on thermophysical properties: An experimental and theoretical study," *Scientific Reports*, vol. 10, no. 1, pp. 1–14, 2020.

[44] N.M. Saidi, M.N. Norizan, N. Abdullah, N. Janudin, N.A.M. Kasim, M.J. Osman *et al.*, "Characterizations of MWCNTs nanofluids on the effect of surface oxidative treatments," *Nanomaterials*, vol. 12, no. 7, 2022.

[45] M. Khalili Najafabadi, K. Hriczó, and G. Bognár, "Enhancing the heat transfer in CuO-MWCNT oil hybrid nanofluid flow in a pipe," *Journal of Results in Physics*, vol. 64, no. July, 2024.

[46] A. Kotia, P. Rajkhowa, G.S. Rao, and S.K. Ghosh, "Thermophysical and Tribological properties of nanolubricants: A review," *Heat and Mass Transfer/Waerme- und Stoffuebertragung*, vol. 54, no. 11, pp. 3493–3508, 2018.

[47] V. Kumaresan and R. Velraj, "Experimental investigation of the thermo-physical properties of water-ethylene glycol mixture based CNT nanofluids," *Journal Thermochimica Acta*, vol. 545, pp. 180–186, 2012.

[48] H.M. Mobarak, E.N. Mohamad, H.H. Masjuki, M.A. Kalam, K.A.H. Al Mahmud, M. Habibullah, and A.M. Ashraful, "The prospects of biolubricants as alternatives in automotive applications," *Renewable and Sustainable Energy Reviews*, vol. 33, pp. 34–43, 2014.

[49] A. Haldar, A. Kotia, N. Kumar, and S.K. Ghosh, "Enhancing the tribological properties of hydraulic oil-based nanolubricants using MWCNT-SiO_2 hybrid nanoparticles," *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, vol. 44, no. 6, pp. 1–13, 2022.

[50] W. Safiei, M.M. Rahman, R. Kulkarni, M.N. Ariffin, and Z.A.A. Malek, "A comprehensive review on thermal conductivity and viscosity of nanofluids," *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, vol. 91, no. 2, pp. 15–40, 2022.

[51] K. Szwajka, M. Szewczyk, and J. Zieli, "The effect of the addition of silicon dioxide particles on the tribological performance of vegetable oils in HCT600X + Z / 145Cr46 steel contacts in the deep-drawing process," *Materials*, vol. 18, no. 73, 2025.

[52] S.Z. Heris, H. Pourpasha, Y. Mohammadfam, R. Javadpoura, Y. Li, and B. Su, "Experimental investigation of the thermophysical and tribological properties of nano-TiO_2-MnO_2-doped graphene oxide/base oil ternary hybrid nanofluids," *Arabian Journal for Science and Engineering*, 2024.

[53] H. Hegab, U. Umer, M. Soliman, and H.A. Kishawy, "Effects of nano-cutting fluids on tool performance and chip morphology during machining Inconel 718," *International Journal of Advanced Manufacturing Technology*, vol. 96, no. 9–12, pp.

3449–3458, 2018.

[54] J.S. Agapiou, "Performance evaluation of cutting fluids with carbon nano-onions as lubricant additives," *Procedia Manufacturing*, vol. 26, pp. 1429–1440, 2018.

[55] R. Surakasi, S. Raja, V. Praveenkumar, Y. Ravikant, M.A. Rusho, S. Sharma *et al.*, "Enhanced tribological performance of transesterified corn oil biodiesel blends with CuO and TiO_2 nanoparticles: Experimental analysis on wear and friction reduction using environment friendly lubricants," *International Journal of Chemical Reactor Engineering*, 2024.

[56] S. Tiwari, M.A. Munish, K. Gupta, and M.A. Makhesana, "Performance assessment of nano - Al_2O_3 enriched coconut oil as a cutting fluid in MQL - assisted machining of AISI - 1040 steel," *The International Journal of Advanced Manufacturing Technology*, vol. 129, pp. 1689–1702, 2023.

[57] X. Bai, C. Li, L. Dong, and Q. Yin, "Experimental evaluation of the lubrication performances of different nanofluids for minimum quantity lubrication (MQL) in milling Ti-6Al-4V," *International Journal of Advanced Manufacturing Technology*, vol. 101, no. 9–12, pp. 2621–2632, 2019.

[58] G. Zhang, J. Zhang, G. Fan, C. Xu, and J. Du, "The effect of chip formation on the cutting force and tool wear in high-speed milling Inconel 718," *International Journal of Advanced Manufacturing Technology*, no. 0123456789, 2023.

[59] M. Li, T. Yu, R. Zhang, L. Yang, H. Li, and W. Wang, "MQL milling of TC4 alloy by dispersing graphene into vegetable oil-based cutting fluid," *International Journal of Advanced Manufacturing Technology*, vol. 99, no. 5–8, pp. 1735–1753, 2018.

[60] N. S. Ross, M. Ganesh, M.B.J. Ananth, M. Kumar, R. Rai, M.K. Gupta, and M.E. Korkmaz, "Development and potential use of MWCNT suspended in vegetable oil as a cutting fluid in machining of Monel 400," *Journal of Molecular Liquids*, vol. 382, no. April, p. 121853, 2023.

[61] Z.H. Sholiha and G. Jatisukamto, "Characteristics biolubricant enriched with nanoparticle additives: A review," *Journal of Mechanical Engineering Science and Technology (JMEST)*, vol. 4, no. 2, pp. 91–100, 2020, doi: 10.17977/um016v4i22020p091.