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Thermophysical, rheological and tribological properties of palm oil with hybrid CuO/MWCNT additive nanoparticles as cutting fluid on CNC machining

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KEYWORDS

Cutting Fluid
Biolubricant
Nanotribology
Wear
MQL

ABSTRACT

Biolubricant has abundant availability, non-toxic, and environmentally This study aims to analyse the performance of palm oil-based coolant with CuO/MWCNT nanomaterial additives in the CNC milling machining process on thermophysical, rheological and tribological properties including surface roughness, wear debris morphology, and tool wear compared with machining results using commercial coolant. The addition of CuO, MWCNT and hybrid nanoparticle additives to palm oil resulted in an increase in density, thermal conductivity and viscosity, and had good stability up to 20 days. The rheology of palm oil with CuO, MWCNT and hybrid nanoparticle additives has newtonian fluid behavior at temperatures 40ºC and 100ºC. The results of palm oil with CuO/MWCNT nanomaterial hybrid additives as a CNC machining coolant influence improving lubrication properties. The performance of palm oil with MWCNT additive as a CNC machining cutting fluid produces the lowest surface roughness and tool wear, and produces chips with smooth morphology, and silver chip colour. It is concluded that palm oil with MWCNT additive has the best tribological and wear resistance test results among commercial cutting fluids or other samples, so it has the potential to be used in industry to replace commercial mineral oil-based cutting fluids.

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1.0 INTRODUCTION

Along with increasing development and population growth, it encourages increased development in the industrial sector to support the fulfillment of human needs. Machining cannot be separated from the contact between one element and another, this contact results in wear (Salafudin et al., 2020). Tool wear in machining (milling, turning, and drilling) is defined as the loss of material from the cutting edge of the tool during operation due to interaction with the workpiece material (Karandikar, 2019). Lubricants are used to reduce friction and wear on machine elements such as machining by applying lubricant, preventing direct contact between parts in the machine element (Smook et al., 2022).

Lubricants as coolants are used to improve the efficiency of the machining process, provide better surface quality, and extend cutting tool life. Coolants generally contribute to a large portion of the total machining cost. By choosing the right type of coolant, the effectiveness of the machining process and the resulting workpiece quality can be improved, resulting in low total machining costs. Currently frequently used mineral oil-based coolants can cause skin diseases and health problems to people or operators when often in close contact (Zheng Yang et al., 2022).

Lubricants used globally today are generally made from petroleum, coal or natural gas. Inefficient lubricant oil recycling techniques are very harmful to the ecosystem. According to estimates, 50% of lubricating oils are discharged into the environment and 95% of these discharged lubricants adversely affect human life and ecosystems (Xu et al., 2019). As concerns over the impact of their use on the environment and the rapidly depleting resources of conventional petroleum-based lubricants grow, industrial oils are a major concern (M. Ali et al., 2023). Due to their high utilization and long-term pollution effects, there is a need for alternative sources to produce biodegradable lubricants (Ocholi et al., 2018).

Biolubricants are also derived from renewable vegetable oils. Vegetable oils have gained more attention as industrial fluids in the last three decades. The effect of these vegetable oils is very important for industrial applications (Shreeshail et al., 2021). Biolubricants are gaining popularity and acceptance globally due to their sustainable, non-toxic, and environmentally friendly properties. The basic chemical structure of a biolubricant is a major determinant of its biodegradability. Many factors such as humidity, pressure, metal type, air, and temperature change the chemical composition of the base oil used in biolubricants (Salih & Salimon, 2021). Biolubricants can be classified according to their natural chemical composition (Narayana Sarma & Vinu, 2022). Biolubricants can be produced from edible sources. Examples of existing biolubricants are palm, sunflower, coconut, olive, soybean, peanut oil, rapeseed oil, and linseed oil (Almasi et al., 2021).

Palm oil has a higher viscosity value and good lubrication properties, especially in the boundary lubrication regime, when compared to petroleum. This is because vegetable oil contains fatty acids that are not possessed by petroleum (Gasni et al., 2019). One of the main drawbacks of using vegetable oils, including palm oil, as lubricants is their performance at low temperatures. These lubricants can become cloudy and harden at low temperatures, which can affect their lubrication performance (Dandan et al., 2019). A study has been conducted on the performance of palm coolant and mineral coolant in machining, coconut coolant showed better surface roughness compared to mineral coolant in turning AISI 304 austenitic stainless steel. In milling AISI 420 stainless steel palm oil-based coolant showed better surface roughness and tool life. During turning of AISI 9310, palm oil coolant helps to increase the metal removal rate (MRR) which means it helps higher feed rates (Shreeshail et al., 2021). The use of palm oil as a lubricant has not been widely used by the community, because palm oil has the disadvantage of being easily oxidized (Syahrullail et al., 2019). Based on these weaknesses, mixing palm oil and hybrid CuO/MWCNT nanomatrials is carried out to improve its performance (Puspitasari, Pramono, et al., 2023).

To overcome the disadvantages of palm oil, blending with nanomaterial additives can be done. Nanolubricant is a type of nanofluid consisting of nanoparticles with dimensions less than (100 nm) and lubricating base fluids, such as water or oil (Al-Janabi et al., 2021). In recent decades, Nanolubricants have gained much attention due to scientific evidence showing that Nanolubricants are better in terms of thermal conductivity, heat transfer, and tribology than conventional lubricants (Chakraborty & Panigrahi, 2020). Nanolubricants have been carried out in several studies. In fact, adding small amounts of nanomaterials to lubricants has a favorable effect on reducing friction and wear. The improvement is due to their small size, as nano additives can fit into the contact area, causing a positive lubrication effect (Mariño et al., 2023). Based on this, nanomaterials used in reducing problems with friction and surface wear, one of which uses Copper oxide (CuO) and Multi-Walled Carbon Nanotubes (MWCNT) nanomaterials (Puspitasari, Permanasari, et al., 2023).

Hybrid CuO/MWCNT nanomaterials also show potential as lubricant performance enhancers in industrial machinery applications. CuO/MWCNT is a nanoparticle-based material that has unique chemical and physical properties. Copper (II) oxide (CuO) is one of the transition metal oxide compounds that has characteristics as a semiconductor. Copper (II) oxide can be applied as solar cells, photodetectors, photocatalysts, and field emission displays (FEDs) (Sundari et al., 2018). According to Alves et al. (Alves et al., 2016) CuO nanoparticles show great potential in lubrication, using low concentrations and reducing costs. CuO nanoparticles at 0.1 wt% showed better antiwear performance compared to other concentrations. Multi-Walled Carbon Nanotubes (MWCNT) is one of the cylindrical carbon structures with diameters in the order of nanometers. MWCNT has excellent unique characteristics, one of the uniqueness in this structure is its advantages in terms of strength, electrical properties, and good heat conducting properties (Dorbani et al., 2022). According to Jansson (Jansson, 2021) mixed MWCNTs and observed that the addition of 0.15 wt% can reduce the friction and wear rate of steel contacts by 81% and 97%.

Nanolubricant is a nanoparticle contained in the base lubricant as a coolant, so it can have a positive impact on CNC testing performance. This study was conducted by varying the biolubricants, namely palm oil biolubricant, palm oil biolubricant with CuO additives, palm oil biolubricant with MWCNT additives, palm oil biolubricant with hybrid CuO/MWCNT additives to find the best performance among these biolubricants and their thermophysical properties. This research uses CNC milling 5 axes, with HSS chisels, and the specimen used is AISI 1045 steel to determine its tribological properties

2.0 EXPERIMENTAL PROCEDURE

2.1 Materials

The material used for cutting fluid sample preparation is palm oil used as base oil. Properties of CuO nanoparticle used will be shown in Table 1. CuO/MWCNT nanoparticles used for additives. Properties of MWCNT will be shown in Table 2.

Table 1: Properties of CuO additive nanoparticle.

Properties	Description
Brand	Loba Chemie
Color	Black
Particle Size	30-50nm
Purity	99%

Table 2: Properties of MWCNT additive nanoparticle.

Properties	Description
Brand	XFNANO
Outer Diameter	10-20nm
Inner Diameter	5-10nm
Length	0.5-2um
Purity	>95%

While the material used for experiments when applying MQL Cutting Fluid in the milling machining process is AISI 1045 steel with a workpiece size of 50 mm x 50 mm x 20 mm (L x W x H). The chemical composition and mechanical properties are shown in Table 3 and Table 4. SOLID brand high speed steel (HSS) endmill diamater 8 mm with 4 flutes, the specifications of the HSS endmill used will be shown in Table 5.

Table 3: Chemical composition of AISI 1045 steel.

Element	C	Mn	Si	P	S	Fe
Component (%)	0.045	0.69-0.83	0.19-0.29	0.008-0.039	0.015-0.02	Balance

Table 4: Mechanical properties of AISI 1045 steel.

Mechanical Properties	AISI 1045 Steel
Hardness (BHN)	163
Ultimate Tensile Strength (MPa)	569
Yield Strength (MPa)	343
Elongation (%)	20
Modulus of Elasticity (GPa)	205
Machinability (%)	55
Shear Modulus (GPa)	80

Table 5: Spesification of endmill HSS.

Spesification	HSS
Material	Hight Speed Steel
Brand	SOLID
Diameter (mm)	8
Full length (mm)	70
Number of flute	4 flute

2.2 Cutting Fluid Samples Preparation

Cutting fluid samples were prepared using a two-step method through a series of steps consisting of stirring and homogenization processes (Al-Janabi et al., 2021; A. R. I. Ali & Salam, 2020; Chakraborty & Panigrahi, 2020; Nugroho et al., 2023). The sample preparation process begins with mixing 0.15wt% CuO, MWCNT and hybrid CuO/MWCNT additives nanoparticles into palm oil and stirring using a magnetic stirrer for 20 minutes with a rotation speed of 1250 rpm (Al-Janabi et al., 2022). Followed by a homogenization process using an ultrasonic homogenizer for 30 minutes to obtain a sample with an excellent dispersion level in the cutting fluid sample. The cutting fluid samples preparation process in this study will be shown in Figure 1 and the experimental design in this study is shown in Table 6.

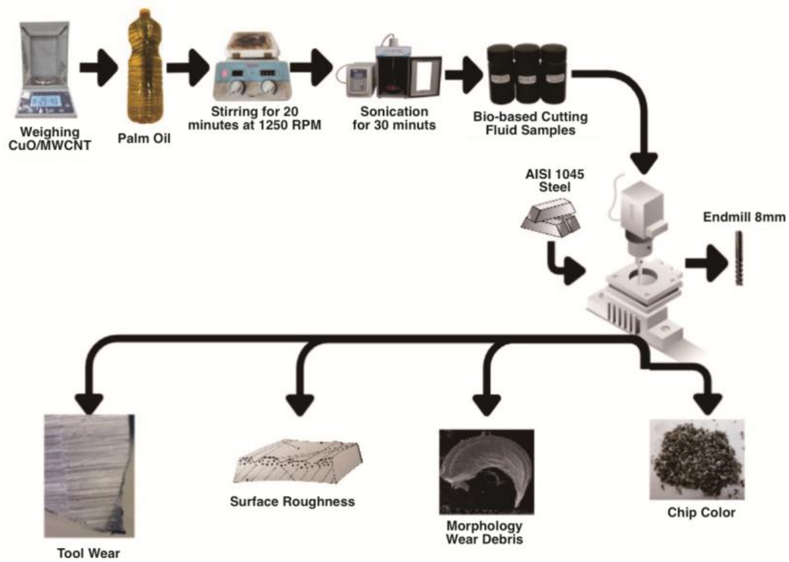


Figure 1: Cutting fluid sample preparation.

Table 6: Experimental design.

No.	Sampel	Nanoparticles concentration (wt%)	Lubricating condition	Sample codes
1.	Without cutting fluid	-	-	Dry
2.	Dromus (Comersial Cutting Fluid)	-	MQL	Dromus
3.	Palm Oil	-	MQL	PO
4.	Palm Oil + CuO	0.15	MQL	PO + CuO
5.	Palm Oil + MWCNT	0.15	MQL	PO + MWCNT
6.	Palm Oil + Hybrid CuO/MWCNT	0.15	MQL	PO + Hybrid

2.2 Setup for CNC Milling and MQL System

The CNC milling machining process was used in this study to identify and evaluate the performance of palm oil-based cutting fluid samples with various additive nanoparticles. These samples were sprayed using the Minimum Quantity Lubrication (MQL) method. In addition to the

CNC milling machine components used in the experiments, MQL preparation was also required. This setup included a mist-shaped spraying nozzle, a compressor to apply pressure to the cutting fluid sample during the machining process, and a flow control to maintain constant air pressure. The CNC milling machining scheme with MQL is shown in Figure 2 with the machining parameters shown in Table 7.

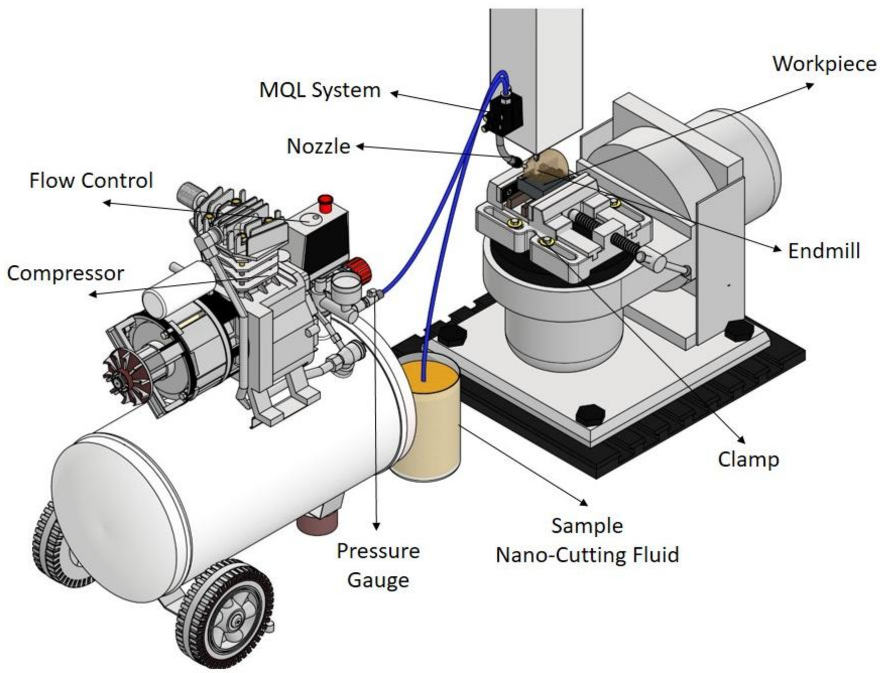


Figure 2: Schematic of milling experiment.

Table 7: CNC machining parameters.

Milling Parameters	**Parameter Setting**
Milling way	Face Milling
Tool Type	Endmill Cutter HSS Diameter 8 mm
Workpiece	AISI 1045 Steel
Spindle Speed (rpm)	3000
Feed Rate (mm/min)	0.12
Dept of Cut (mm)	1.5
Cutting Speed (m/min)	110
Cooling Type	MQL
MQL Nozzle Distance (mm)	20
MQL Nozzle Angle (°)	45
MQL Pressure (Bar)	4

In the CNC milling machining process that will be carried out, there is a cutting zone consisting of a cutting tool, workpiece, clamp, and spraying nozzle. In addition, inside the nozzle there are MQL spraying parts consisting of valves and hoses for the discharge of cutting fluid when it will be sprayed to form a fogging aerosol. Figure 3 showed the experimental equipment used in this study, namely the CNC milling machining process, to determine its performance on tribological properties.

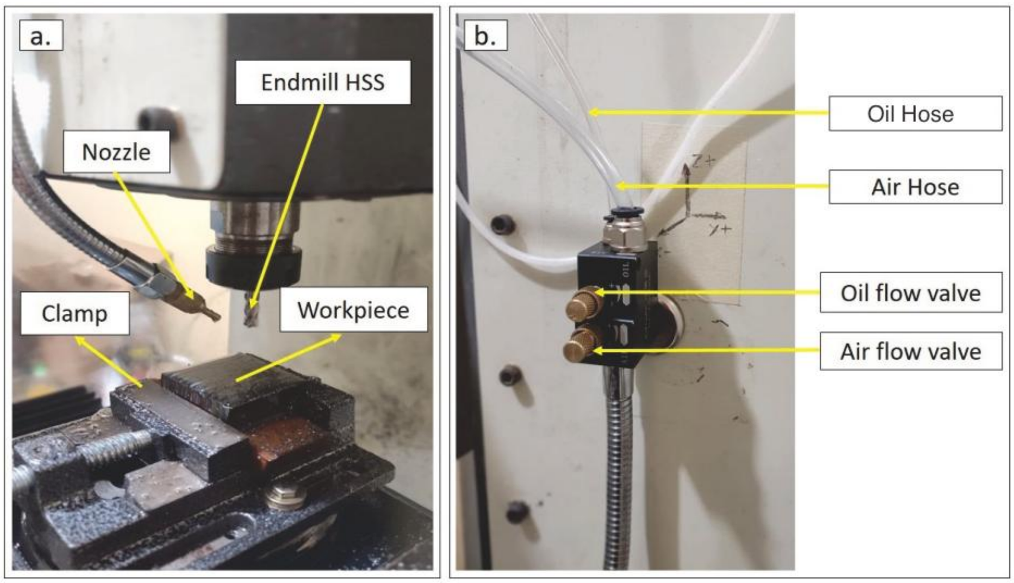


Figure 3: Experimental equipment, (a) cutting zone, (b) spraying section.

2.3 Characterization of Additive Nanoparticles

The morphology of additive nanoparticles were performed using scanning electron microscopy (SEM) FEI Inspect-S50, Japan (Bai et al., 2023; Elshaer & Ibrahim, 2020; Puspitasari, Ayu Permanasari, et al., 2023). The phase identification and crystallite size of additives nanoparticles were measured using X-ray diffraction (XRD) PANanaltyical Expert Pro (Pramono & Puspitasari, 2024; Trihutomo et al., 2023). The functional group additive nanoparticles was measured using Fourier transform infra-red (FTIR) model IR Prestige 21 Shimadzu (Pramono et al., 2023).

2.4 Thermophysical Test of Cutting Fluid Samples

Density testing of cutting fluid samples using analytical digital scales conducted at room temperature. The mass value is obtained from the weight of the sample, while the volume is measured using a pycnometer (Gupta et al., 2017; Puspitasari, Pramono, et al., 2024). Thermal conductivity testing was conducted to determine the heat transfer performance of the nano-cutting fluid sample using KD2 Pro (Sajid & Ali, 2018). Dynamic viscosity testing was conducted to analyze the viscosity level or resistance value of the given flow to calculate the rheological value of the cutting fluid sample NDJ-8S Viscometer tool at 40°C and 100°C (Bhattad, 2023; Pownraj & Valan Arasu, 2021). Sedimentation testing was conducted to determine the level of separation between additive nanoparticles solids and palm oil using the sedimentation method through gravity. The suspension was kept for 0, 4, 8, 12, 16, and 20 days.

2.5 Rheological Test of Cutting Fluid Samples

The rheological properties of this research are used to determine the flow type of cutting fluid that studies the relationship between shear rate and shear stress. To obtain the shear rate and shear stress values, the results of the cutting fluid dynamic viscosity test are needed (Sujith et al., 2019). To calculate the shear rate value can use Equation (1), while to calculate the value of shear stress can use Equation (2).

$$\gamma = \frac{2\omega {R_c}^2 {R_b}^2}{x^2\left({R_c}^2 - {R_b}^2\right)} \tag{1}$$

where γ is the shear rate (1/s); ω is the angular velocity (rad/sec); R_c is the container radius (cm); R_b is the rotor radius (cm); x is the radius at which the shear rate is calculated (cm).

$$\tau = \mu \times \gamma \tag{2}$$

where τ is shear stress (mPa.s); μ is dynamic viscosity (kg/m.s); γ is shear rate (1/s).

2.6 Tribological Test of Cutting Fluid Samples

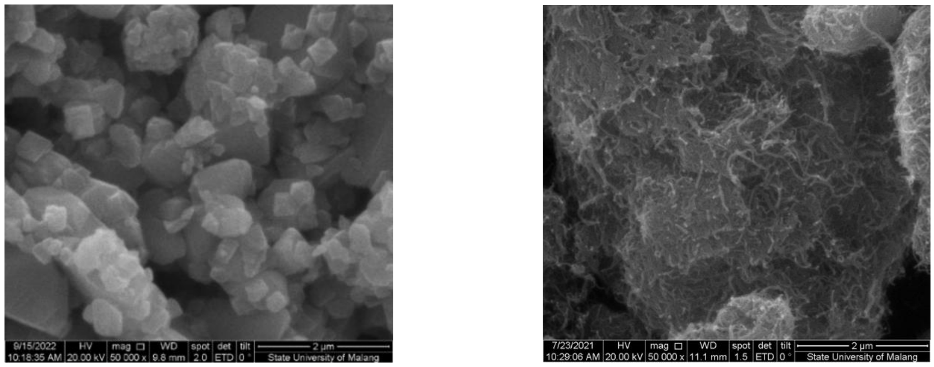
HSS endmill tool wear was performed using a Sinher Binocular optical microscope type XSZ-107 BN to be able to determine the wear area at the interval of 4 HSS endmill flutes (Eltaggaz et al., 2023). Then, the wear length was measured using ImageJ software to determine the tool wear length. This cutting tool wear is measured on the edge side based on the length of wear that occurs on that side. Surface roughness testing is carried out, namely, to determine the level of roughness on the surface of the AISI 1045 workpieces resulting from the CNC milling machining process. Surface roughness testing is carried out on specimens that have been machined using cutting fluid samples (Makhesana et al., 2022; Riyanto et al., 2023). Wear debris morphology is performed to analyze the chip characteristics of AISI 1045 workpieces that have been machined, wear debris morphology is performed using a scanning electron microscope FEI Inspect-S50, Japan. Chip color analysis is carried out to determine the color formed during the workpiece cutting process, because the formation of chips in the machining process will be able to be an illustration to identify excessive heat in cutting and determine the performance of each cutting fluid sample. This chip color analysis will be carried out using a macro camera (G. Sharma et al., 2017).

3.0 RESULTS AND DISCUSSION

3.1 CuO and MWCNT Additive Nanoparticles Characterization

3.1.1 Morphology of CuO and MWCNT Additive Nanoparticles

The morphology of the nanoparticle additive was obtained from SEM test at 50000 × magnification, Figure 4(a-b) shows the morphology of CuO and MWCNT nanoparticle additive.



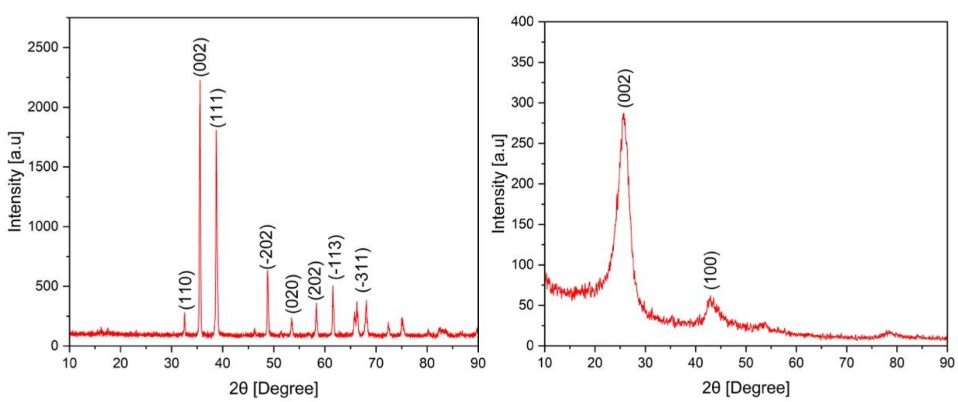
(a) (b)

Figure 4: SEM results of additive nanoparticles (a) CuO and (b) MWCNT with 50000x magnification.

Figure 4(a-b) shows the morphology of the CuO and MWCNT additive nanoparticles. Based on figure 4(a) shows the presence of agglomeration with angular paricle shape. The morphological characterization of CuO was investigated by SEM as shown in Figure 4. From the obtained images, we can observe a large number of uniform nanoparticles (NPs) with an average particle size of 40-60 nm (Davarpanah et al., 2015). Figure 4(b) shows that MWCNTs have a cylindrical particle shape wave, with agglomeration (Puspitasari, Ayu Permanasari, et al., 2023). The sheets bend when their height exceeds a certain level. The direction and angle of bending depend on the morphology of each sheet. The nanotubes within each sheet confine the nearest border and attract the outermost nanotubes to the border through Van Der Waals forces, thus resulting in oriented growth. However, CNTs in such thin sheets result in random curvature and tangling due to weak confinement in the thickness direction. With the increase of sheet thickness, the alignment of CNTs can be improved due to the clustered effect (M. Zhang & Li, 2009).

3.1.2 Crystallite Size and Phase of CuO and MWCNT Additive Nanoparticles

The crystallite size and phase of the nanoparticle additive were obtained from XRD test, Figure 5(a-b) shows the morphology of CuO and MWCNT nanoparticle additive.



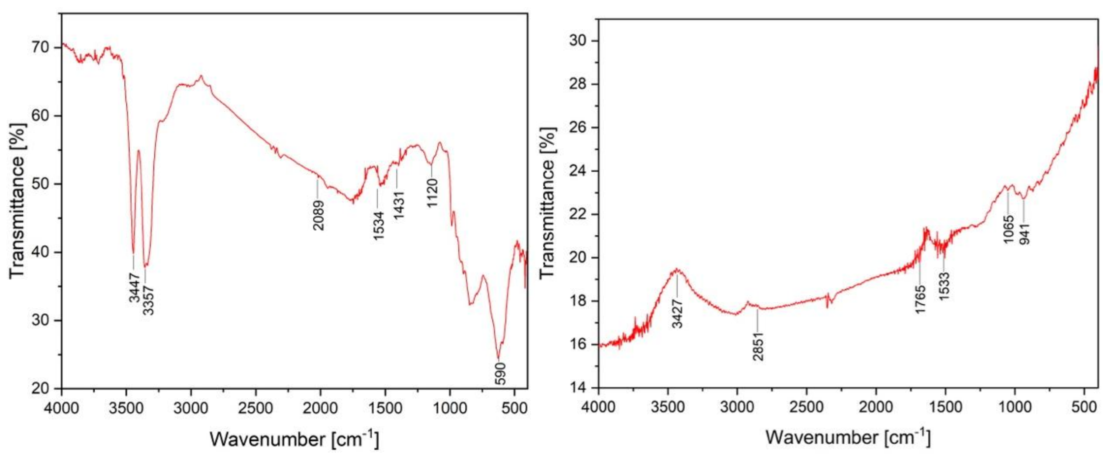
(a) (b)

Figure 5: XRD results of (a) CuO and (b) MWCNT additive nanoparticles.

Based on Figure 5(a) the XRD test results on CuO additive nanoparticle show that the Miller Index (hkl) at each individual peak is (110), (002), (111), (-202), (020), (202), (-113), (-311). The peaks of CuO were determined to be pure copper oxide, and from the sharp diffraction peaks of the sample, indicating that CuO is monoclinic (Zhu et al., 2018). The result of crystallite size calculation using Scherrer Equation is 63.788 nm. Based on Figure 5(b), the XRD results of MWCNT nanoparticle additives show that the MWCNT has an amorphous crystal structure pattern. The Miller index (hkl) on each peak is (002) and (100) indicating the presence of carbon on the peak (Puspitasari, Ayu Permanasari, et al., 2023).

3.1.3 Functional Groups of FTIR CuO dan MWCNT Additive Nanoparticles

The functional groups of the nanoparticle additive were obtained from FTIR test at wavelength 4000-400cm^{-1}, Figure 6(a-b) shows the morphology of CuO and MWCNT nanoparticle additive.



(a) (b)

Figure 6: FTIR results on (a) CuO and (b) MWCNT.

Based on Figure 6(a) FTIR graph on CuO additive nanopaticles shows that there are valleys identified and obtained at wavelengths of 3300 cm^{-1}, 1614 cm^{-1}, 933 cm^{-1}, 759 cm^{-1}, 701 cm^{-1}, 650 cm^{-1}. Furthermore, for each valley can be analyzed and obtained functional groups that have been identified on CuO, namely O-H, C-C, C-H, Cu-O.

Table 10: Functional groups of CuO additive nanoparticles.

Band	Main Peak	Typical Bond Assignment	Reference
1	3300	O–H *stretching*	(S. Sharma et al., 2021)
2	1614	C–C *vibrations*.	(Siddiqi & Husen, 2020)
3	933	C–H *bending*	(Velsankar et al., 2020)
4	759	C–H *bending vibration*	(Dolai et al., 2020)
5	701	Cu–O *vibration*	(Pakzad et al., 2019)
6	650	Cu–O *stretching vibration*	(Anuar & Sheng, 2021)

Based on Figure 6(b) FTIR graph on MWCNT additive nanoparticles shows that there are valleys identified and obtained at wavelengths 3427 cm^{-1}, 2851 cm^{-1}, 1725 cm^{-1}, 1533 cm^{-1}, 1065 cm^{-1}, 941 cm^{-1}. Furthermore, for each valley can be analyzed and obtained functional groups that have been identified on MWCNT, namely O-H, C-H, C=O, C=C, C-O, C-C, and C-C.

Tabel 11: Functional Groups of MWCNT Additive Nanoparticles

Band	Main Peak	Typical Bond Assignment	Reference
1	3427	O–H *stretching*	(Pizzutto et al., 2011)
2	2851	C–H *stretching*	(Misra et al., 2007)
3	1725	C=O *stretching*	(Yusrizal et al., 2022)
4	1533	C=C *stretching*	(Javaid et al., 2020)
5	1065	C–O *stretching*	(Haryńska et al., 2019)
6	941	C–C *stretching*	(Xue et al., 2018)

3.2 Termophysical Properties of Cutting Fluid Samples

3.2.1 Density of Cutting Fluid Samples

Figure 7 shows that the addition of nanoparticle additives to palm oil has the effect of increasing its density. These results are in accordance with research conducted by Kotia & Ghosh (Kotia & Ghosh, 2015) which explains that the increase in density value occurs as the concentration of nanoparticles added increases. This happens because the increase in nanoparticle additives, the mass in the cutting fluid sample will also increase which causes a linear increase in density value. Nanofluids have a higher density value than the base oil, because the density value of nanoparticles that have been added and contained in vegetable oil has a higher density value (Kotia et al., 2018; Yılmaz Aydın & Gürü, 2022).

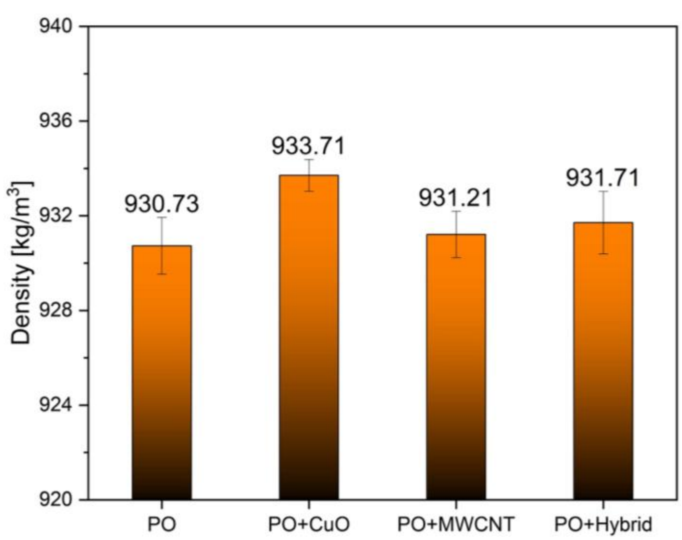


Figure 7: Thermal conductivity of cutting fluid samples.

The density of the cutting fluid will be able to affect the performance of the cutting fluid, the higher the density in the cutting fluid, the greater the hydrostatic pressure that will be generated by the cutting fluid. This hydrostatic pressure can help in accelerating the machining process by strengthening the flow of cutting fluid in the cutting zone, because a strong flow can carry more fluid and will help in a more effective cooling process and more optimal chip removal (Heyhat et al., 2021).

3.2.2 Thermal Conductivity of Cutting Fluid Samples

Figure 8. shows that the results of the largest value of the thermal conductivity of the fluid in this study were obtained in palm oil Nanolubricant + MWCNT with a thermal conductivity value of 0.165 W/m.K. This is because, with the addition of MWCNT can form a conductive path between palm oil with nanomaterials (Utama et al., 2015). MWCNT have better thermal conductivity due to the increased diameter of the nanotubes and are accompanied by more optical phonon modes that can experience an increase in energy and can contribute to thermal conductivity (Kumanek & Janas, 2019). The thermal conductivity value of MWCNTs is also significantly affected by the structure of the CNTs in the film (Puspitasari, et al., 2024). The conduction mechanism described by Aliev et al. (Aliev et al., 2007), suggests that MWCNTs are better conductors because pre-existing layers can form additional conduction pathways. In addition, the presence of defects in the CNT network can significantly affect the conductivity.

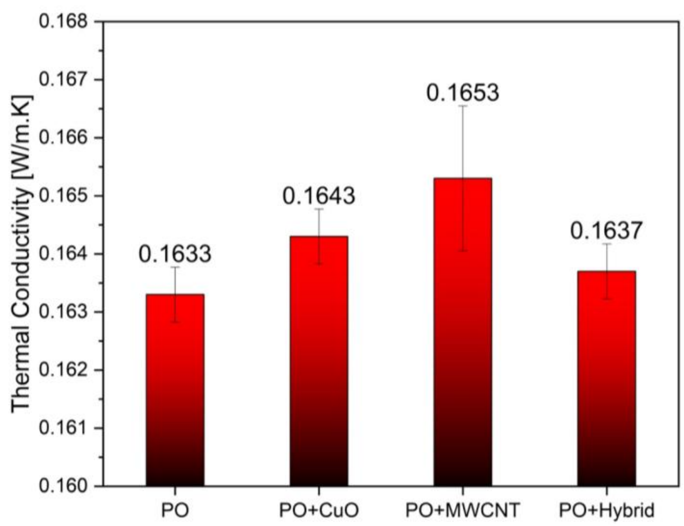


Figure 8: Thermal conductivity of cutting fluid samples.

3.2.3 Viscosity of Cutting Fluid Samples

Figure 9 shows that the largest value of the dynamic viscosity of the fluid in this study was obtained in palm oil + MWCNT nanolubricant with a dynamic viscosity of 43.45 mPa.s. This can occur because MWCNT can increase the viscosity, up to the saturation point and can increase the flow resistance because the hydrophobic surface of MWCNT produces strong Vander Waals forces between palm oil and MWCNT nanomaterials to bind to each other (Ross et al., 2023). Multiple cylindrical layers of MWCNTs are held together through Vander Waals forces. Vander Waals forces can increase the viscosity value of nano lubricants while at high temperatures can help particles overcome the attractive forces caused by these forces (Purwanto et al., 2023). Vander Waals force is an unbound interaction, and it can be an attractive force or a repulsive force. Attraction occurs when a pair of atoms approach each other within a certain distance. Repulsion occurs when the distance between the interacting atoms becomes smaller than the sum of their contact radius (C. Li & Chou, 2003).

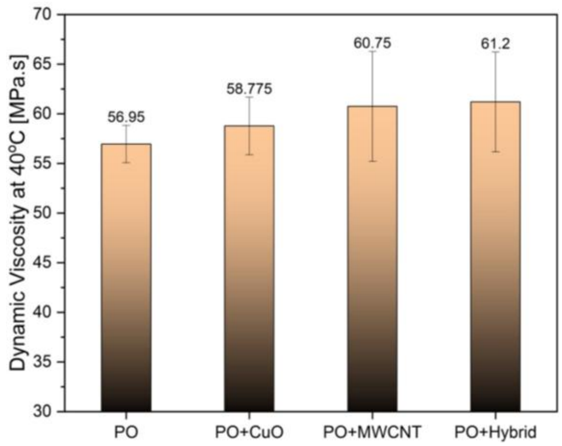
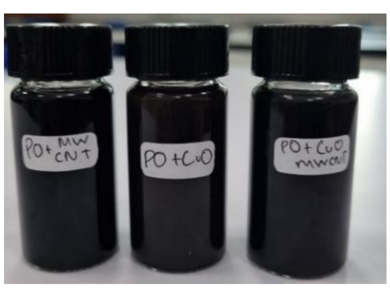


Figure 9: Viscosity of cutting fluid samples.

3.2.4 Sedimentation of Cutting Fluid Samples

Based on Figure 10, the cutting fluids sample has stability at 0 days and 20 days. Nanolubricant will be considered stable if the inter-particle concentration remains constant (Asmoro et al., 2023). The slow deposition of nanoparticles in the sample during stability testing indicates that the synthesis process was successful, and one of the influencing factors is the control of the sonication process. Minimizing the precipitation is the main goal in the synthesis of cutting fluid samples (Nugroho et al., 2023). Sedimentation can usually be based on sediment properties, including size, shape, specific weight and specific gravity and fall velocity. By identifying each of these variables, the sedimentation velocity (at the check point) can be predicted (Hambali & Apriyanti, 2016).



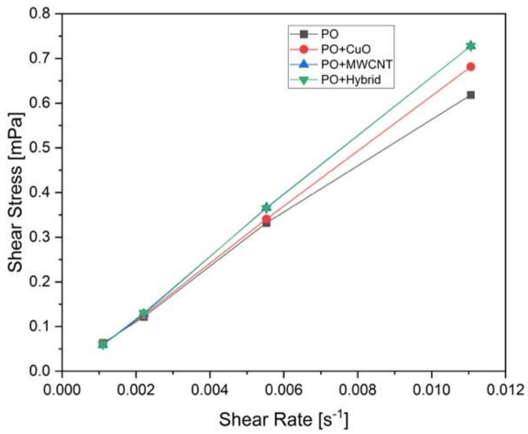
(a)

(b)

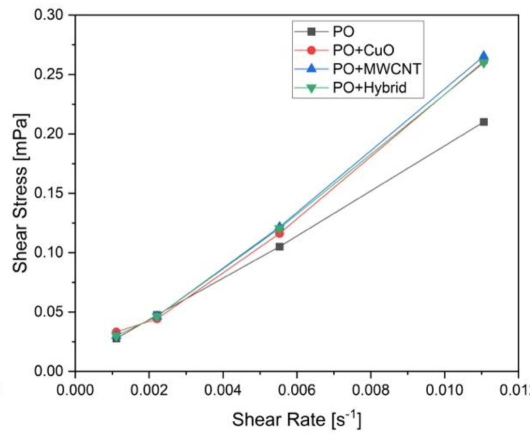
Figure 10: Sedimentation of cutting fluid samples at (a) 0 days and (b) 20 Days.

3.2.5 Rheological Properties of Cutting Fluid Samples

The results of the calculation of shear rate and shear stress values to determine the rheological properties of cutting fluid samples at temperatures of 40°C and 100°C in this study will be shown in Figure 11. Based on the comparison between the shear rate and shear stress values in palm oil and cutting fluid samples with different additive nanoparticles with the use of temperatures of 40°C and 100°C as shown in have Newtonian flow behavior. Newtonian fluids can have consistent performance in lubrication, especially in cutting fluid applications where loads and speeds can change. This consistency can maintain surface separation to help prevent excessive friction and wear in the machining process (George & Qureshi, 2013).



(a)



(b)

figure 11: rheological properties of cutting fluids at temperatures (a) 40°C and (b) 100°C.

3.3 Tribological Properties of Cutting Fluid Samples

3.3.1 Surface Roughness

Based on Figure 12, the lowest surface roughness value was obtained by the palm oil + MWCNT sample at 1.27 μm. This study found that lower surface roughness was obtained by using lubricant supplemented with MWCNTs into the MQL system during steel turning compared to dry condition (M. Zhang et al., 2009). Puspitasari et al., (Puspitasari, Permanasari, et al., 2023) explained that the smaller the nanoparticle size, the less friction. Thanks to the tubular shape and atomic structure of MWCNTs, it allows some mechanisms to work more effectively during cutting. MWCNTs exert a satisfactory effect on the contact surface when dispersed in the cutting zone, these occurring mechanisms are thought to play a role in the reduction of surface roughness by the incorporation of MWCNTs and the MQL method (Peña-Parás et al., 2019). The graph above shows that palm oil with hybrid CuO/MWCNT nanomaterials has a high surface roughness. This can occur because CuO nanomaterials have toxicity that can release Cu ions, which can induce the formation of reactive oxygen species and the toxicity is absorbed by other nanomaterials (Chang et al., 2012). This toxicity can jeopardize the structural integrity and functional properties of MWCNT, therefore the surface roughness of palm oil with hybrid CuO/MWCNT nanomaterials has a higher surface roughness. Chen and Lu (Chen & Lu, 2007) describe CuO nanoparticles interact with MWCNT through various mechanisms, such as electrostatic forces, Vander Waals interactions, or chemical bonds that can affect the properties and potential applications of the

MWCNT structure. These interactions can change the structural and electronic properties of MWCNTs, which can lead to a weakening of their mechanical properties and thermal conductivity.

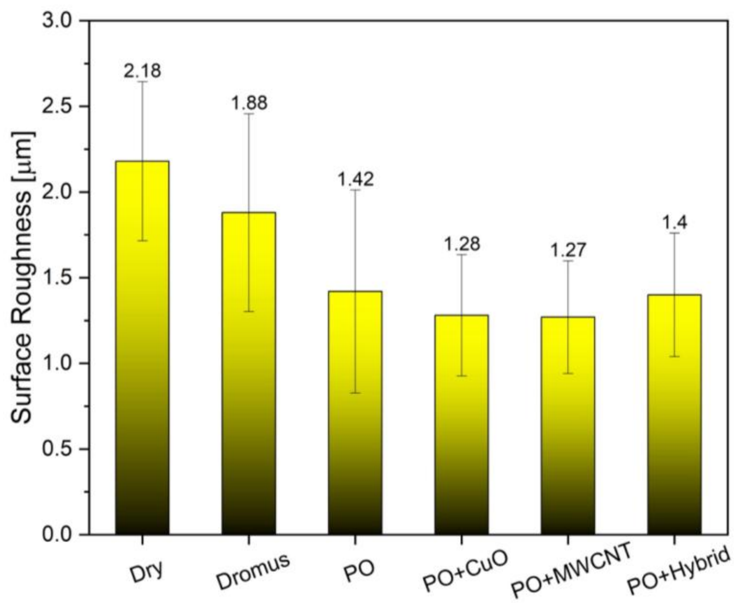


Figure 12: Tool wear after application of cutting fluid samples on CNC milling machining processes.

3.3.2 Tool Wear

Based on Figure 13. shows that the addition of nanoparticles additive to palm oil and used as cutting fluid can reduce tool acidity. The research has conducted a study that MWCNT mixed in vegetable oil is able to provide good feedback in reducing tool wear compared to dry condition cutting (Peña-Parás et al., 2019). MWCNT-based nanolubricants can easily penetrate the cutting zone and reduce friction and tool wear by providing better lubrication and removing heat from the cutting zone compared to dry conditions. All these effects allow the tool tip to maintain sharpness for a longer machining time, resulting in a better turning process (Öndin et al., 2020). This can happen, because MWCNTs have high atomic structure and specific surface area, excellent thermal conductivity, and can help evacuate more heat from the cutting zone, therefore leading to an improvement in the thermal conductivity and heat transfer coefficient of the lubricant (Miranda et al., 2019). When nanofluid is combined with MQL, it increases the thermal conductivity so that it can provide an excellent heat transfer effect and an effective anti-friction cushion that reduces abrasion wear on cutting tools compared to using other cooling methods. By engineering nanoparticles, it can improve the tribological properties of the cutting fluid, especially to form tribo-films (Tiwari et al., 2023). In the machining process using MQL, high-pressure lubricating oil enters the periphery of the rotating workpiece, penetrating deeper into the machining zone to provide the desired lubrication effectiveness, and high-pressure air holds the machining temperature well by providing effective cooling (Ghani et al., 2024).

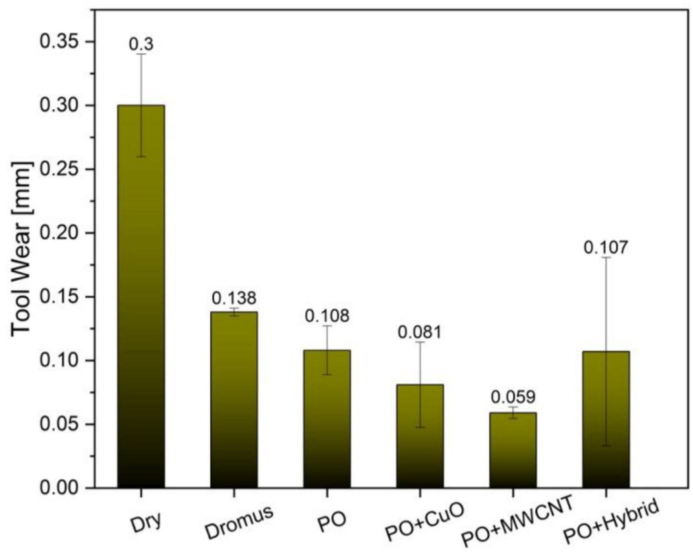


Figure 13: Surface roughness of workpieces resulting from the application of cutting fluid Samples in the CNC milling machining process.

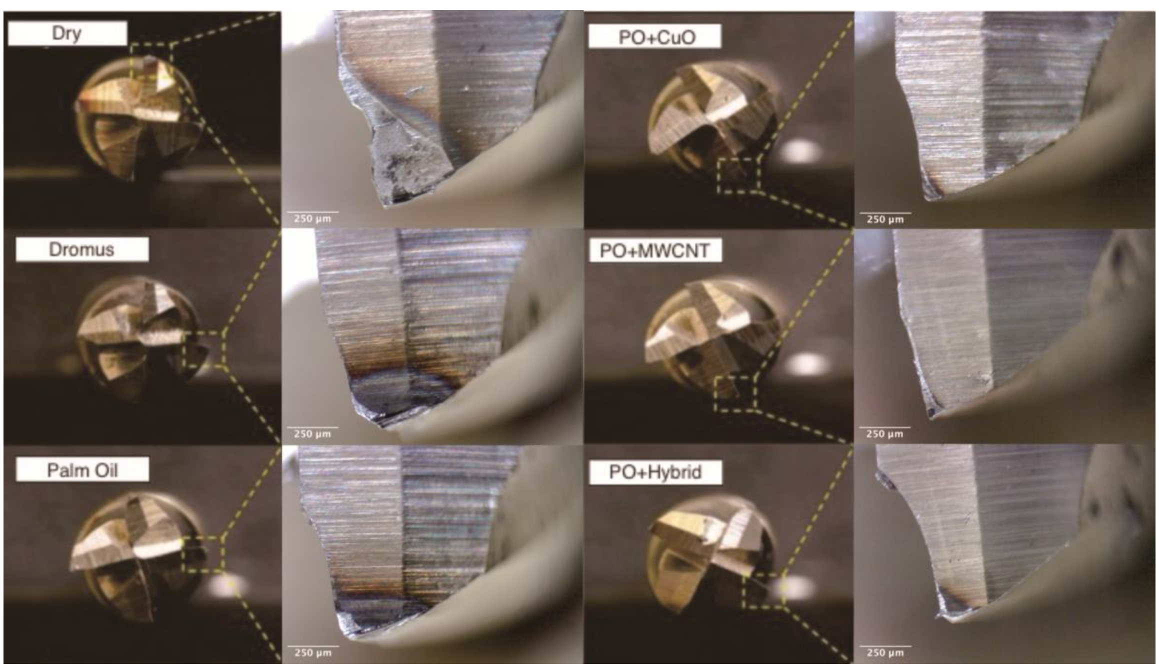


Figure: 14 Macro photographs of endmill tool wear.

Figure 14 shows a macro photo of the endmill tool after being used in the machining process. Based on figure 14. show that the dry machining conditions, high cutting tool wear is obtained because the workpiece and endmill will rub directly in the absence of adequate cooling media, resulting in high heat, and with it cutting tool wear will increase, at the same time (as illustrated in figure 15.b), because the cutting process produces chips that will accumulate around the cutting zone, so this heat will be trapped and cause increased cutting tool wear in the absence of cooling under high temperature and pressure (G. Zhang et al., 2023). The use of commercial cutting fluid obtained the highest cutting tool wear after dry and higher than using palm oil-based cutting fluid. Cutting tool wear is higher in mineral oils due to weaker adsorption resistance during the friction process, compared to vegetable oils which have a polar structure and fatty acids that allow producing a high strength lubricating film that interacts strongly with the contact surface (Jeevan et al., 2021). In machining using commercial cutting fluid and pure palm oil, a thin layer of lubricating oil is formed in the cutting zone (as illustrated in figure 15.c), but the thin layer cannot withstand the cutting force. While cutting fluid mixed with additive nanoparticles resulted in lower wear compared to other conditions. This occurs because, in the thin layer of lubricating oil formed in the cutting zone, small particles act as anti-wear agents with excellent load-bearing properties during the friction process. These nanoparticles play a role in forming a protective film that reduces friction by rolling over surfaces (as illustrated in figure 15.d). Additionally, the particles enhance convective heat transfer, allowing heat to dissipate more effectively. As a result, the reduced heat minimizes tool wear, leading to improved tool longevity (M. Li et al., 2018).

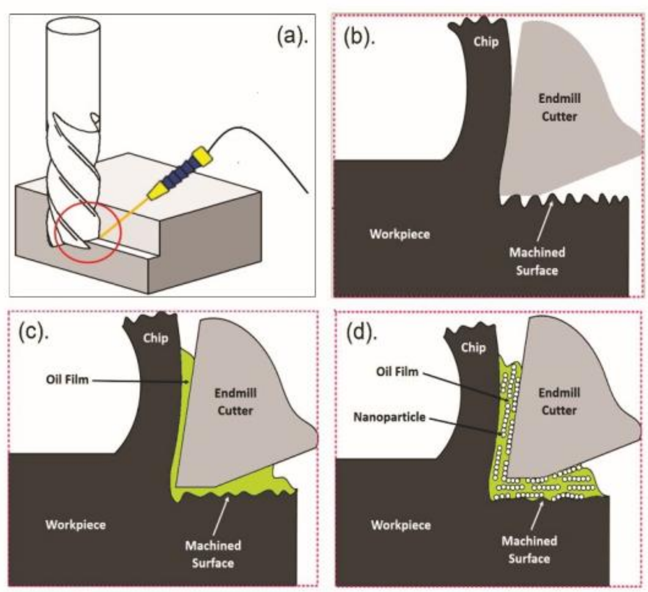


Figure 15: Schematic of milling machining conditions, (b) dry, (c) dromus and palm oil, (d) cutting fluid samples.

3.3.3 Morphology of Wear Debris

Figure 16 shows the SEM results of the wear debris morpholgy with normal, generalized, and magnified views. The chips collected after CNC milling test using dry media and MQL. Chips in dry condition show a small and irregular jagged surface, the high temperature made the chips change shape and become distorted (Zailani et al., 2024). while when using dromus chip wear debris shows a large and rough irregular jagged surface. Tests conducted using palm oil, palm oil + 0.15% CuO, palm oil + 0.15% MWCNT produce a good chip wear debris surface with a smooth surface and irregular small jagged. It is different when using palm oil + 0.15% CuO / MWCNT chip wear debris show an irregular large and rough jagged surface.

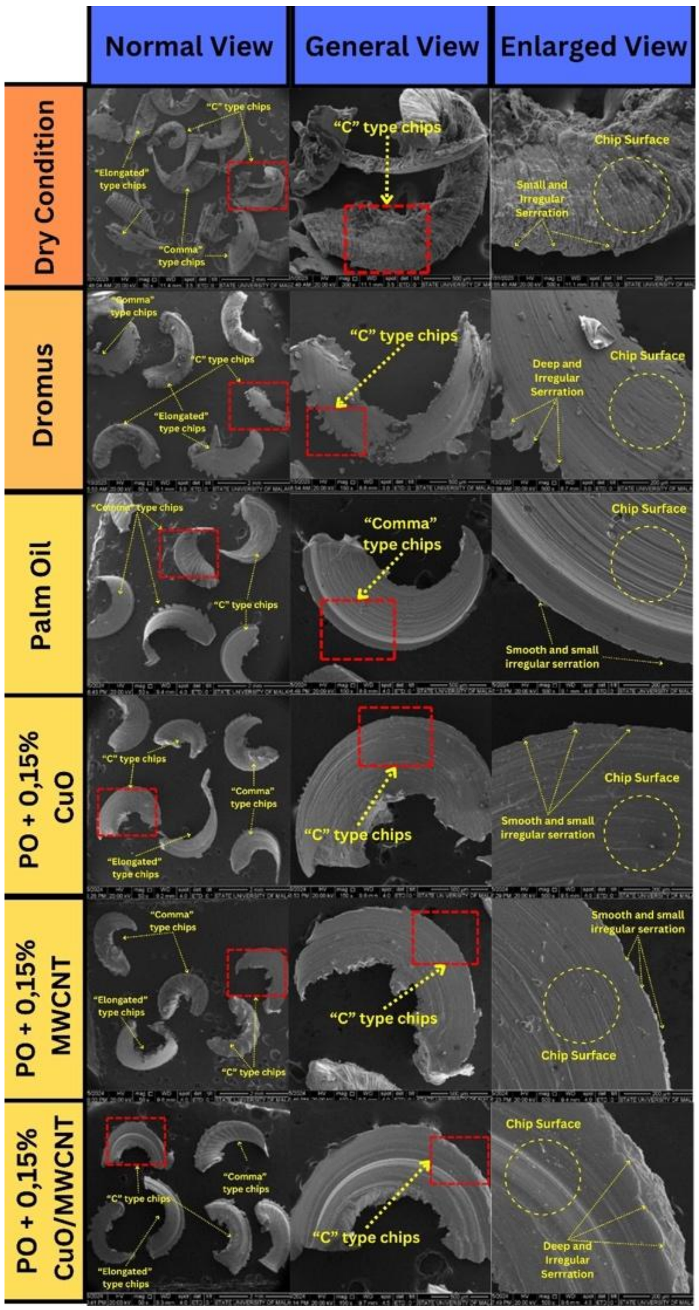


Figure 16: Chip morphology after application of cutting fluid samples on CNC milling machining processes.

Palm oil lubricants can produce a good chip wear debris surface because the vegetable oil content has a higher viscosity index which can ensure that vegetable oils will provide more consistent lubrication over a wide temperature range (Wang et al., 2020). CuO can improve the tribological properties of good chip wear debris due to the precipitation of nanoparticles on the contact surface, which can reduce the shear stress (Alves et al., 2016). Gulzar et al., (Gulzar et al., 2016) reported that the presence of elemental CuO on the surface of worn specimens indicates its tribo-sintering mechanism on the contact surface and forms a film that allows protection against friction and wear. The presence of MWCNTs has shown a substantial reduction in the finest chip wear debris. The addition of MWCNTs reduces the deposition of debris and micro pores in chip wear debris. MWCNTs can produce precise results and simple flushing of debris. This simple removal has produced small bumps, which further improves the surface quality. In addition, the high thermal conductivity of MWCNTs enhances heat dissipation and thus reduces plasma heat flux. In conjunction with these reasons, a considerable reduction in surface defects was achieved chip wear debris. MWCNTs clearly show that MWCNTs substantially improve the surface chip wear debris (Chaudhari et al., 2022).

3.3.4 Chip Color Analysis

Figure 17 shows the color results of wear debris. Wear debris during dry condition shows black and brown colors, while when using dromus wear debris shows brown color and there are also some silver wear debris. Tests carried out using palm oil produced silver wear debris color with a little brownish and black color. When using palm oil + CuO wear debris produced is slightly blue and there are some silver, then when using palm oil + MWCNT produces bright silver wear debris, while when using palm oil + CuO / MWCNT produces silver wear debris color with a little black and blue.

Figure 17. shows that palm oil + 0.15% MWCNT is the best, because it has a silver wear debris color. The silver wear debris color shows the base color of the workpiece used. The silver color can be interpreted that the lubricant is able to work well because it can maintain the original color of the workpiece. Palm oil + MWCNT has a bright silver wear debris color, this can occur because MWCNT has a tubular atomic structure and from this shape MWCNT allows several mechanisms to work more effectively during cutting (Peña-Parás et al., 2019). MWCNTs also have excellent thermal conductivity and can help evacuate more heat from the cutting zone (Miranda et al., 2019). MWCNTs have better thermal conductivity due to the increased diameter of the nanotubes and are accompanied by more optical phonon modes that can experience an increase in energy and can contribute to thermal conductivity (Kumanek & Janas, 2019).

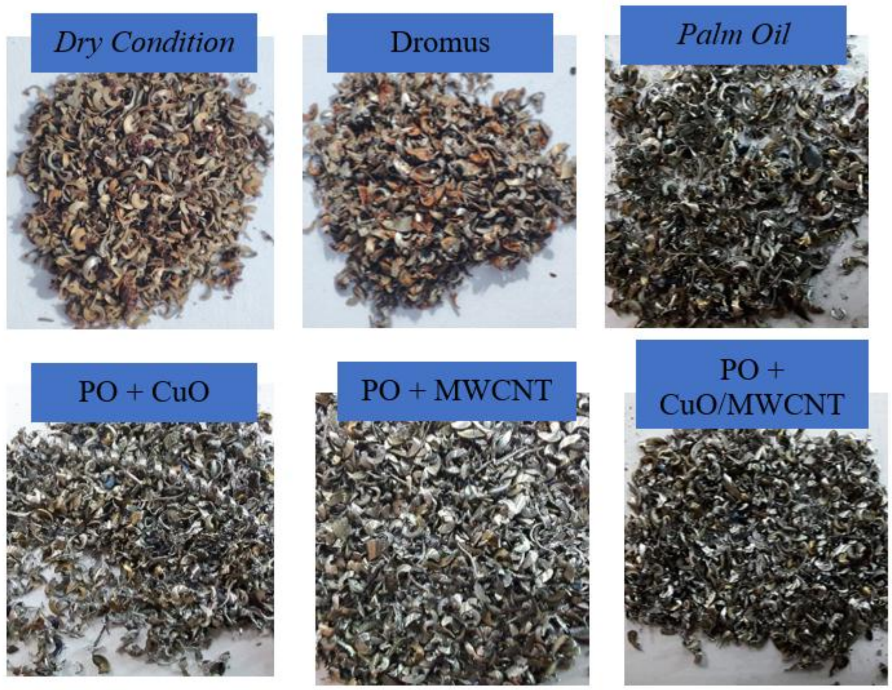


Figure 17: Chip color after application of cutting fluid Samples in CNC milling.

CONCLUSIONS

In this study, cutting fluid based on palm oil biolubricant with additional additives of CuO nanoparticles, MWCNT and hybrid CuO/MWCNT, then analyzed thermophysical properties including density, thermal conductivity, viscosity and stability. The rheology of palm oil and palm oil with CuO, MWCNT and hybrid CuO/MWCNT nanoparticle additives was also analyzed. The performance as cutting fluid in CNC machining process including surface roughness, tool wear and wear debris morphology were analyzed. The experimental findings have led to the following conclusions:

Thermophysical properties including density, viscosity, thermal conductivity and sedimentation, the addition of CuO, MWCNT and hybrid nanoparticle additives to palm oil resulted in an increase in density, thermal conductivity and viscosity, and had good stability up to 20 days. The rheology of palm oil with CuO, MWCNT and hybrid nanoparticle additives has newtonian fluid behavior at temperatures 40°C and 100°C. The results of palm oil with CuO/MWCNT nanomaterial hybrid additives as a CNC machining coolant influence improving lubrication properties. The performance of palm oil with MWCNT additive as a CNC machining cutting fluid produces the lowest surface roughness and tool wear, and produces chips with smooth morphology, and silver chip color. It is concluded that palm oil with MWCNT additive has the best tribological and wear resistance test results among commercial cutting fluids or other samples, so it has the potential to be used in industry to replace commercial mineral oil-based cutting fluids.

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