Vol. 47, No. 3 (2025) 443-452, DOI: 10.24874/ti.1940.04.25.07

Tribology in Industry

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RESEARCH

Performance Evaluation of Canola Oil-based Nano-Cutting Fluid with TiO_2 Nanoparticle Additive in CNC Milling Process with Minimum Quantity Lubrication (MQL) System

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Keywords:

Vegetable oil
TiO_2 nanoparticle additive
Nano-cutting fluid
MQL

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Received: 21 April 2025
Revised: 20 June 2025
Accepted: 4 July 2025

A B S T R A C T

Mineral oil-based cutting fluid is the most commonly used type due to its superior performance, but it has a large environmental impact. Therefore, this study explores the performance of canola oil with TiO_2 nanoparticle additives in the Minimum Quantity Lubrication (MQL) system in the CNC milling process with AISI 1045 steel workpieces cut using a 4-flute endmill. The variations in the concentration of TiO_2 mass fraction used were 0.1%, 0.15%, and 0.2%. The results showed that using a nano-cutting fluid with 0.15% TiO_2 reduced the cutting temperature by up to 56.52% compared to the dry-cutting method. In addition, this cutting fluid also produced the lowest surface roughness (0.722 μm) and negligible tool wear (0.246 mm). The results indicate that the combination of canola oil and TiO_2 can be an effective, environmentally friendly alternative in improving machining performance compared to conventional cutting fluids.

1. INTRODUCTION

Industrial sectors such as the automotive field are included in large-scale production that requires speed, accuracy, and high quality. These production needs can be met with the use of Computer Numerically Controlled (CNC) machines with their advantages [1]. The manufacturing industry produces metal products involving machining processes such as drilling, turning, milling, and grinding to form the workpiece as desired. The process requires good results, namely good precision and surface roughness. In the machining process, there is friction between the workpiece and the tool, which can cause the temperature to rise so that it affects the surface quality of the workpiece [2]. To improve the quality of the machining process, the use of cutting fluid is one of the important parameters because of its main function as a coolant and consideration of the pollution produced [3]. During the machining process the friction generated by the tool with the chip causes an increase in temperature and cutting force, with the use of cutting fluid the cutting force can be reduced to extend the tool life [4].

Mineral oil is the most used medium as a cutting fluid because it has good machining performance [5]. Because it comes from non-renewable resources, cutting fluid development efforts must be made to realize an environmentally friendly and sustainable manufacturing process, because the availability of petroleum and environmental problems will be a serious problem [2]. According to the statement of Teti et al. [6] the global consumption of cutting fluid reaches more than two million tons per year; therefore the development of environmentally friendly cutting fluid is highly expected in the manufacturing industry.

Occupational environmental health issues and climate change are driving strict policies in the global manufacturing industry, so environmentally friendly vegetable oil-based nanofluids are explored as a replacement for convention cutting fluids due to their superior tribological performance [7]. Vegetable oils have biodegradation properties of up to 100%, which is better than mineral oils [8]. Vegetable oils cannot be directly applied as lubricants, as they are suitable for a modest temperature range due to their oxidative stability [9].

Vegetable oils have poor viscosity and stability at high temperature operations, and they become viscous and even freeze at low temperatures [2]. Efforts to improve the performance of cutting fluid in this study are by adding titanium dioxide (TiO_2) nanomaterials to improve wettability, thermal conductivity, and heat transfer [3,10]. Nanomaterials have exceptional thermal and electrical conductivity at the nanoscale level compared to bulk materials [11]. In line with that Gulzar et al. [12] stated that additives in pure oil can reduce significant friction and excellent anti-wear properties. The same thing is shown by Duan et al. [13] research it was shown that the surface roughness value of aluminum alloy 6061 was reduced by up to 72.1% compared to dry conditions in the micro milling process using nano cutting fluid vegetable oil based.

Various machining processes using MQL are considered a better substitute than conventional flood lubricating methods [14]. Based on the research of Yildirim et al. [15] in the MQL method, cutting force, tool wear, and cutting temperature are reduced, while surface quality is well improved. When compared with the flood lubricating method, less cutting fluid is used to obtain higher efficiency, nano cutting fluid is also better than flood lubricating and MQL methods with pure oil base [16]. In this study, the performance of canola oil will be tested with TiO2 nanoparticle additives with varying mass fraction concentrations including, 0.1%, 0.15%, and 0.2%.

2. METHODOLOGY

2.1 Materials

In this study, the brand of canola oil used was tropicana slim. Properties of canola oil are shown in Table 1.

Table 1. Canola oil properties [17].

Properties of Canola Oil	Values
Kinematic viscosity @40 °C (mm^2/s)	41
Kinematic viscosity @100 °C (mm^2/s)	20
Viscosity index	185
Flashpoint (°C)	290
Density @15°C (g/m^3)	0.914 – 0.917
Thermal conductivity (W/m.K)	0.188

The dimensions and mechanical properties of the workpieces are shown in Figure 1 and Table 2. The tool type used for cutting is an endmill with a diameter of 8 mm, length of 70 mm, and 4 flutes from the SOLID brand.

Table 2. Mechanical properties of AISI 1045 steel [18].

Properties	Values
Tensile Strength, Yield	355 MPa
Ultimate Tensile Strength	600 MPa
Young's Modulus	209 GPa
Poisson's Ratio	0.290

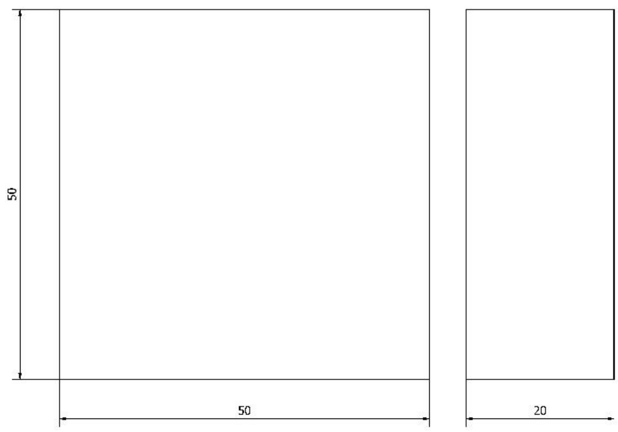


Fig. 1. Dimension of AISI 1045 steel.

2.2 Preparation of nano-cutting fluid samples

Preparation of nano cutting fluid with canola oil as the base oil using two-step method [5]. Canola oil was mixed with TiO_2 nanoparticles using a magnetic plate stirrer for 15 minutes with a rotation speed of 1250 rpm. Furthermore, the sample was sonicated for 30 minutes so that the nanoparticles were completely dispersed in the cutting fluid sample. The sonication method can disperse better which allows smaller particle agglomeration to occur than stirring with a magnetic stirrer alone [19,20]. The preparation steps are illustrated in Figure 2. The design of experimental of this cutting fluid research can be seen in Table 3.

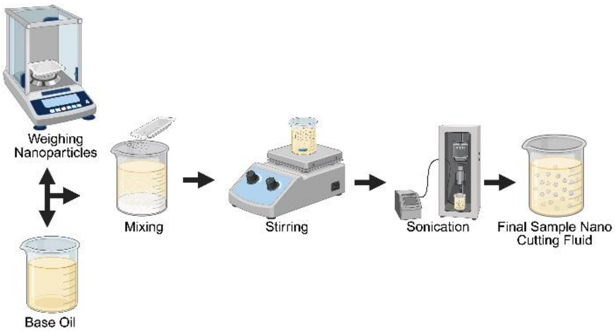


Fig. 2. Scheme of nano cutting fluid preparation.

Table 3. Design of experiment.

Sample	Concentration (wt%)	Lubrication Method
Dry Cutting	-	No Lubricant
Dromus	-	MQL
Pure Canola Oil	0	MQL
Canola + 0.1 % TiO_2	0.1	Nano MQL
Canola + 0.15 % TiO_2	0.15	Nano MQL
Canola + 0.2 % TiO_2	0.2	Nano MQL

2.3 CNC machining setup

The CNC milling machining process is used in this study to identify and determine the performance of corn oil-based nano-cutting fluid samples with various variations in the mass fraction concentration of $CaCO_3$ nanoparticles to be sprayed using the MQL method, in addition to the various CNC milling machine components used for experiments, MQL preparation is also required, which consists of a mist-shaped spraying nozzle, a compressor to apply pressure to the nano-cutting fluid sample during the machining process, and a flow control to ensure constant air pressure. The CNC milling machining parameters shown in Table 4. These parameters are used during CNC milling operations to cut AISI 1045 steel workpieces to determine the values of surface roughness, cutting temperature, and tool wear after the machining process.

Table 4. Parameters of CNC milling.

Parameters	Values
Spindle speed	3000 rpm
Feeding speed	0.12 mm/rpm
Depth of feed	1.5 mm
Cutting speed	110 m/min
Lubrication method	MQL
Cutting fluid flow	105 ml/h
Spraying angle	45°
Spraying distance	20 mm
Nozzle pressure	4 Bar
Workpiece	AISI 1045 Steel
Nozzle diameter	2 mm
Tool	Endmill HSS
Feeding type	Facing

In the machining process of CNC milling that will be carried out, there is a cutting zone consisting of a cutting tool, workpiece, chuck, 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 shows the experimental equipment that will be used in this research, namely the CNC miiling machining process to determine the performance of the nano-cutting fluid sample.

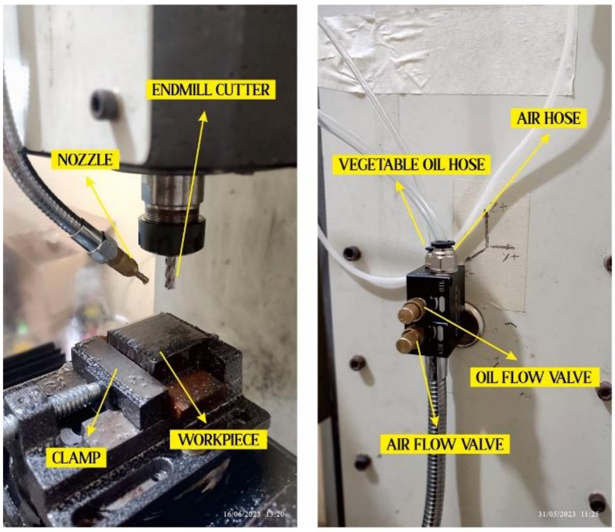


Fig. 3. Set-up for machining using MQL system.

2.4 Additive Nanoparticle Characterization

Analyze the morphological of nanoparticles using SEM analysis brand FEI type Inspect-S50. Then FTIR to identify the functional groups of nanoparticles using Shimadzu IR Prestige 21. After that, characterization aimed at knowing the crystal structure of nanoparticles can be done on XRD using the PANalytical brand X'Pert PRO type.

2.5 Thermophysical Properties Test of Nano-Cutting Fluid

Measurement of sample density is done by weighing the sample using digital scales, the volume value is obtained from the number of samples put into the pycnometer. Dynamic viscosity measurements using an NDJ-8S viscometer against temperature changes that occur. Measuring the thermal conductivity value using KD2 pro thermal properties analyzer.

2.6 Rheology Test of Nano-Cutting Fluid

The shear stress value comes from multiplying the shear rate value by the dynamic viscosity, where the equation of the shear rate is shown in Equation 1 [21]:

$$\gamma = \frac{2\,\omega\,\mathrm{R_{c}2}\,\mathrm{R_{b}2}}{\mathrm{x}^2\,(\mathrm{R_{c}2}\,\mathrm{R_{b}2})} \qquad (1)$$

where γ is shear rate (/s), ω is angular speed of the shaft (rad/sec), Rc is vessel radius (cm), Rb is spindle shaft radius (cm), x is shear rate radius (cm).

2.7 Tribology Test

The surface roughness value of the CNC milling machining process was measured using a Mitutoyo SJ-301. The edge wear of the endmill tool was measured using a Sinher XSZ-107 BN binocular microscope to assess the quality of the tool and machining operation [22]. Cutting temperatures during machining operations were measured with a FLIR E60 thermal imaging camera.

3. RESULT AND DISCUSSION

3.1 Characterization of TiO_2 Additive Nanoparticles

SEM was used to identify the morphology of the TiO_2. The results are shown with various magnifications of 50.000x and 100.000x in Figure 4.

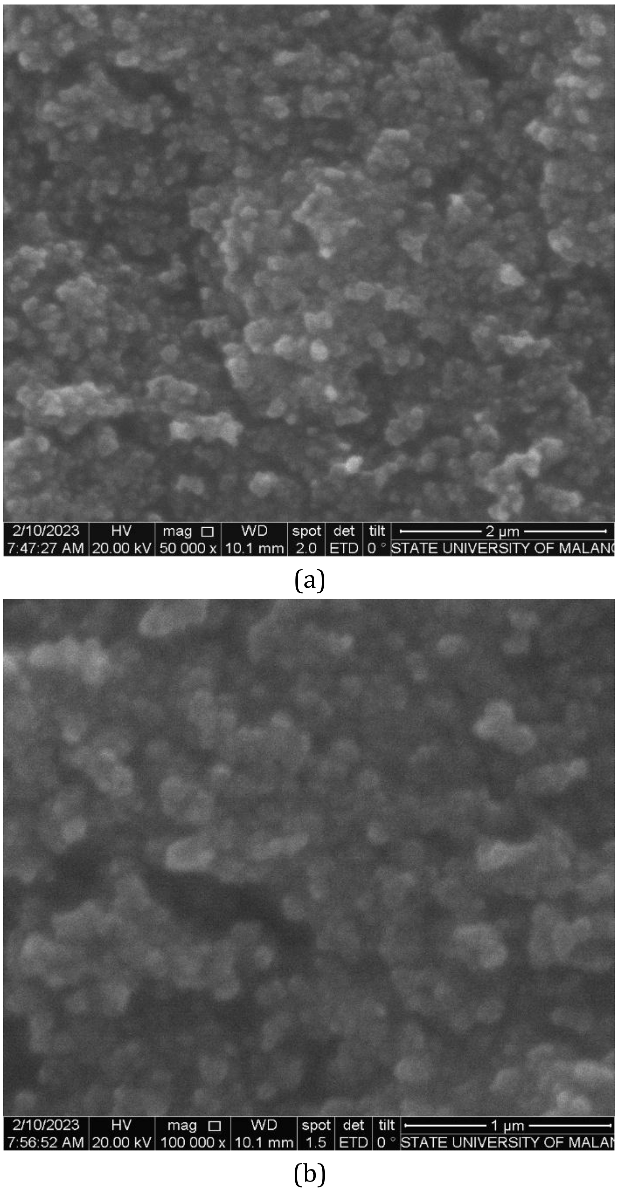


Fig. 4. Morphology of TiO_2 additive nanoparticle with magnification of (a) 50.000x and (b) 100.000x.

Based on the SEM results shown in Figures 4a and 4b, the morphology of TiO_2 nanoparticles is spherical in shape and has a tendency to agglomeration [23,24]. Its spherical shape makes it possible to create a rolling effect on nano cutting fluid [25].

XRD testing of the TiO_2 additive nanoparticle was conducted to identify the phase and crystal size. The crystal size was calculated using the Scherrer equation, which is shown in Equation 2 [3,23].

$$d = \frac{K\,\lambda}{\beta\cos\theta} \qquad (2)$$

Where d is crystallite diameter; K is 0.9; λ is Wavelength 1.5406 Å; and β is Full Width Half Maximum (FWHM).

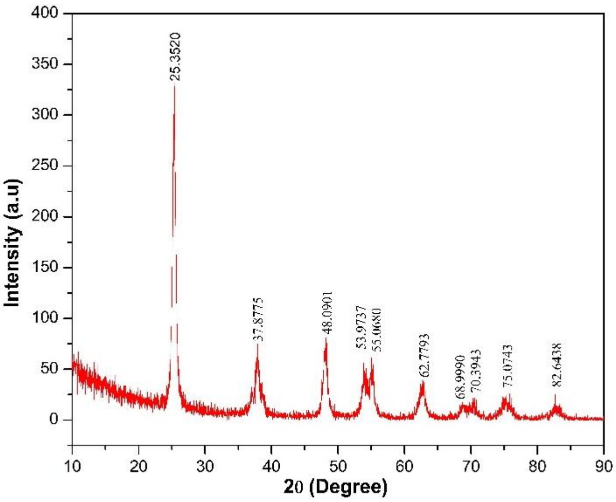


Fig. 5. XRD result of TiO_2 additive nanoparticle.

Based on Figure 5, the XRD graph shows that the TiO_2 nanoparticles used have strongest diffraction peaks at 25.352° and 48.0901°. Therefore, according to Ali *et al.* [25] The sample was in the anatase phase, due to the absence of the diffraction peak in the range of 27.4° that is characteristic of the rutile phase. For its crystallite size, calculate using the Scherrer equation, showing the 20.2806 nm crystallite size.

FTIR testing was conducted to determine the functional groups of TiO_2 nanoparticle additives. The results of FTIR characterization in this study are shown in Figure 6.

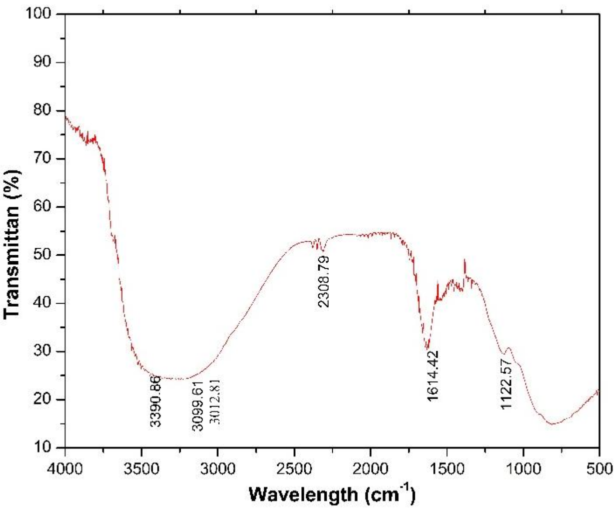


Fig. 6. FTIR results of TiO_2 additive nanoparticle.

Based on the main peaks identified along the wavelength of 3390.86 – 702.09 cm^{-1} in Figure 5, an analysis of the functional groups contained in TiO_2 nanoparticles can be obtained. The results of the analysis at a peak of 3390.86 cm^{-1} are associated with O-H vibration, at a peak of 1614.42 cm^{-1} indicates a Ti-OH bending mode, a peak of 2308.29 cm^{-1} is associated with C=O, at 1122.57 cm^{-1} is associated with Ti-O-Ti vibration, and 702.09 cm^{-1} is associated with O-Ti-O [26].

3.2 Thermophysical properties of nano-cutting fluid

Thermophysical properties include density, thermal conductivity, and viscosity. Figures 7, 8 and 9 are the test results for density, thermal conductivity and dynamic viscosity of nano cutting fluid samples.

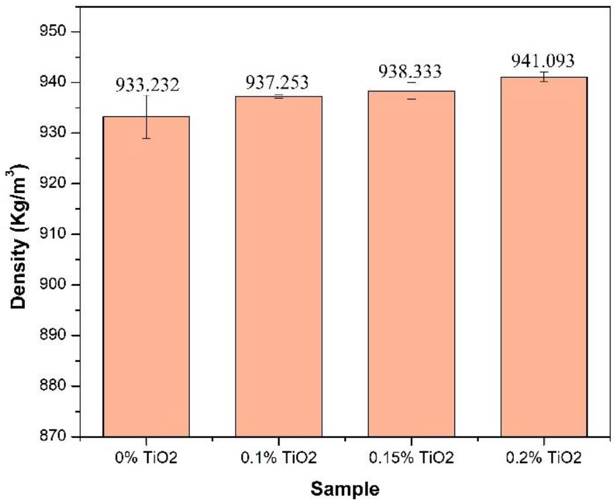


Fig. 7. Density of nano cutting fluid.

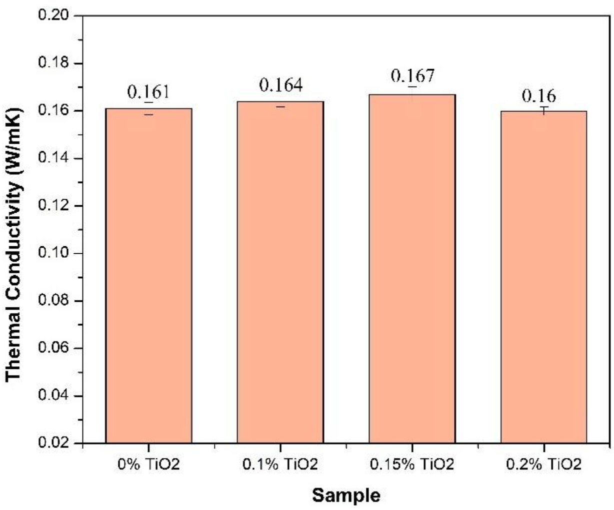


Fig. 8. Thermal conductivity of nano-cutting fluid.

Based figure 7, the highest density value was obtained in the canola oil sample + 0.2% TiO_2 with a value of 941.093 kg/m^3. While the lowest density value is obtained by pure canola oil, the value is 933.232 kg/m^3. The increase in density value occurs in canola + TiO_2 oil due to the increase in the mass fraction of nanoparticles in base oil with the same volume, so that the density value is directly proportional to the density between masses [27]. Based on these results, the addition of the volume of nanoparticle concentration in the nano-cutting fluid increased the density value [28].

Based on figure 8, the highest thermal conductivity value in this study was obtained for canola oil + 0.15% TiO_2 of 0.167 W/mK. The lowest value was obtained by canola oil + 0.2% TiO_2 with a value of 0.160 W/mK. Based on these results, contrary to the results of Xu et al. [29] and Ghodbane et al. [30] which shows a trend of increasing thermal conductivity as the concentration of nanoparticles increases. Cutting fluid can lose stability due to uneven dispersion. This phenomenon was found in the research of Duan et al. [31] those who find cutting fluid performance does not necessarily improve with increased concentration, and tends to experience a downward trend after reaching an absolute peak. Nano-cutting fluids that have high thermal conductivity will quickly dissipate heat due to friction between the tool and the workpiece [32].

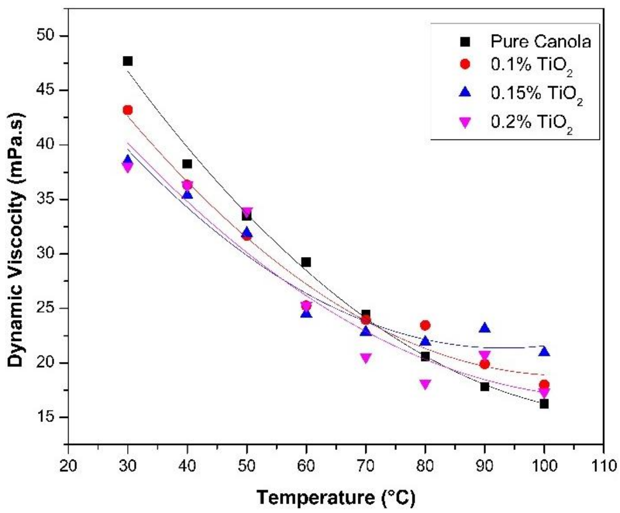
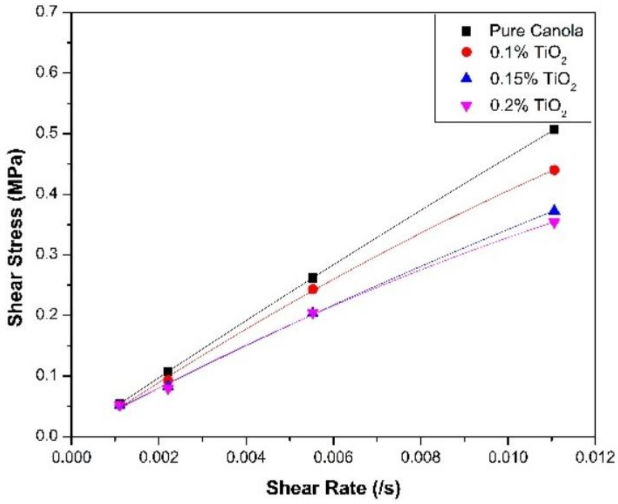


Fig. 9. Viscosity of nano-cutting fluid.

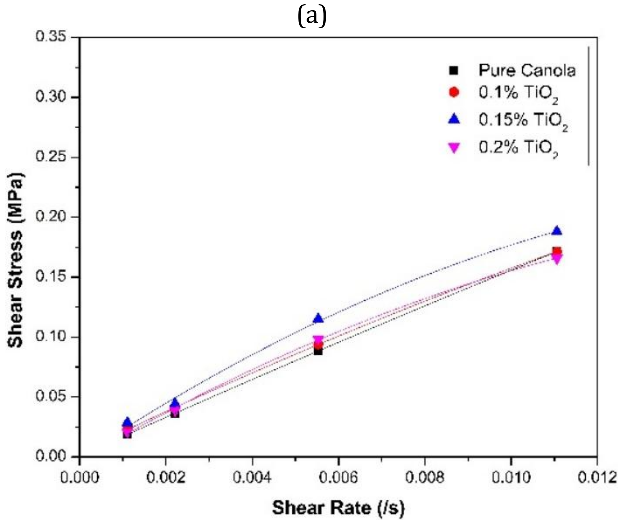
Viscosity testing is carried out in temperatures of 30 – 100°C. Based on the results shown in Figure 9, pure canola oil is highest at a temperature of 30°C with a value of 47.7 mPa.s. This can happen due to the natural properties of vegetable oils that tend to be thick and even frozen at lower temperatures [2]. When the temperature starts to touch the 80°C mark, pure canola oil decreases significantly compared to canola + TiO_2. In the end, canola + 0.15% became the highest viscosity value at 100°C, which was at 20.9 mPa.s, while pure canola was at 16.2 mPa.s. This has proven that viscosity is in line with thermal conductivity [33]. Overall, according to the existing theory, the viscosity value will be inversely proportional to the temperature [34].

3.3 Rheological properties of nano-cutting fluid

The shear rate and shear stress values of canola and canola + TiO_2 base oil will be evaluated through experiments at temperatures of 30 °C and 100 °C. The following is a graph of the relationship between shear rate and shear stress shown in Figures 10a and 10b.



(a)



(b)

Fig. 10. Rheological properties of nano-cutting fluid samples at (a) 30°C and (b) 100°C.

Based on Figure 10a, the highest shear stress value at 30°C temperature is 0.5 MPa obtained by pure canola oil at a shear rate of 0.012 /s. While at a temperature of 100 °C the highest value of shear stress is 0.18 MPa at a shear rate of 0.012 /s. The linear relationship between the shear stress value and the shear rate proves that vegetable oils exhibit Newtonian fluid characteristics [35]. The properties of Newtonian fluids are due to the concentration of their particles and the morphology of the spherical TiO_2 tends to exhibit Newtonian behaviour [33].

3.4 Tribological Properties

Tribological properties include surface roughness of the specimen, tool wear and cutting temperature that have been mapped with nano-cutting fluid samples. Figures 11, 13 and 14 are the results of surface roughness, cutting temperature and tool wear tests.

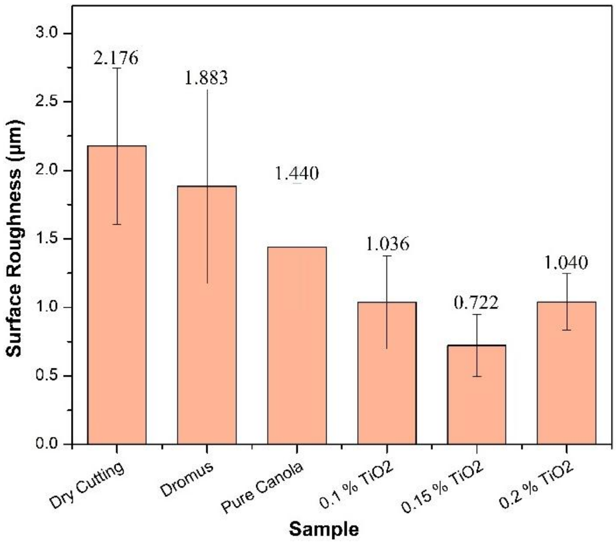


Fig. 11. Surface roughness test results.

Based on figure 11, the surface roughness value of the dry cutting operation was the highest, which was 2.176 µm. Meanwhile, nano cutting fluid with a concentration of 0.15% was the lowest of all samples, which was 0.722 µm. Based on these results, it is proven that nano cutting fluid outperforms dry cutting operations and the use of conventional lubricants [32]. This is due to the formation of tribo-film in the nano cutting fluid, causing a rolling effect that can reduce direct contact between the cutting tool and the workpiece [5,36]. Illustration of the rolling effect shown in Figure 12.

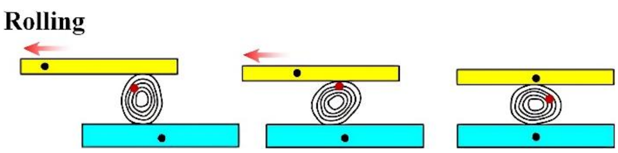


Fig. 12. Ilustration of rolling effect [5].

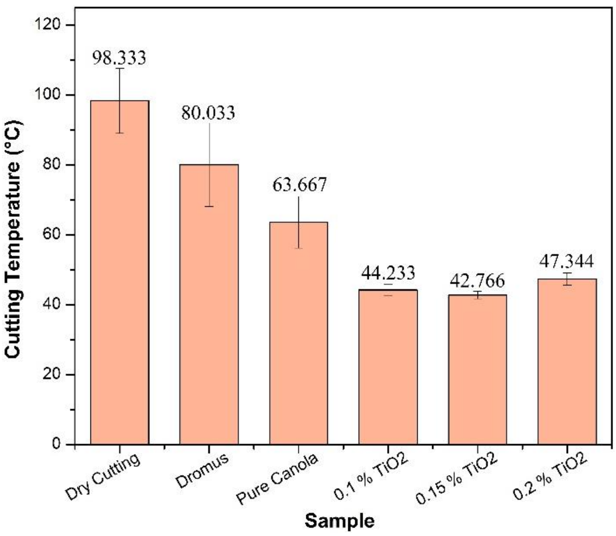


Fig. 13. Cutting temperature test results.

Based on Figure 13, the highest cutting temperature is in dry cutting operation , which is 98.3 °C. Meanwhile, canola + 0.15 % TiO_2 was the lowest with a value of 42.76 °C. Canola + 0.15 % TiO_2 is the most effective at reducing heat from the machining process compared to other variations of cutting fluid. Increased dry cutting temperature on the contact surface due to the high coefficient of friction due to the absence of lubrication [37]. The use of canola + 0.15% TiO_2 was able to reduce the cutting temperature by 56.52% from dry cutting operations. The addition of nanoparticles to the cutting fluid can improve wettability better because the small nano size and collaboration with MQL can penetrate the cutting zone well [38]. In addition, heat is quickly lost from the cutting zone due to its high thermal conductivity [39].

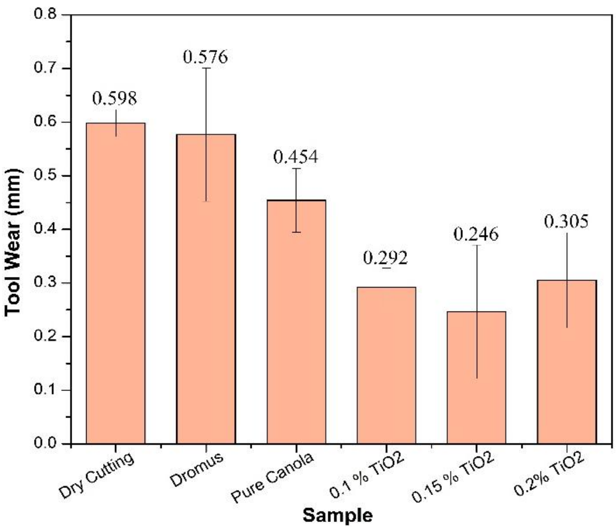


Fig. 14. Tool wear test result.

Based on Figure 14, the results of the edge wear measurement of the endmill chisel showed that dry cutting had the highest wear of 0.598 mm and the use of canola + 0.15 % TiO_2 as cutting fluid showed the lowest wear with a value of 0.246 mm. Dry cutting wear measurement results are the highest due to the absence of cutting fluid resulting in a lack of lubrication, cooling, and chip flow which causes higher mechanical & thermal loads on the tool resulting in wear [40]. The heat generated by friction between the surface of the tool and the workpiece during cutting causes an increase in temperature which can reduce the hardness of the material from the tool [41]. A tool that experiences wear has a geometric change in the tool that affects the surface of the workpiece, both the surface roughness and the desired dimensions [42].

4. CONCLUSION

This study evaluated the performance of canola oil as a cutting fluid with the addition of TiO_2 nanoparticles with three concentration variations. The results showed that the concentration of 0.15% TiO_2 showed the best performance with the highest thermal conductivity (0.167 W/mK) and the most stable viscosity at 100 °C (20.9 mPa.s). In CNC milling applications, this cutting fluid is able to reduce cutting temperatures by 56.52% compared to dry cutting, resulting in the lowest surface roughness (0.722 μm), and reducing tool wear (0.246 mm). This study explains that the effectiveness of nanoparticles does not necessarily increase as the concentration of the mass fraction increases, but depends on how well the concentration of the mass fraction is perfectly dispersed in canola oil. While thermal conductivity plays an important role in tribological properties that affect machining quality.

Acknowledgement

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

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