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Investigation of surface roughness in turning AISI 1020 steel using Minimum Quantity Lubrication (MQL) with recycled cooking oil

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Abstract

This study investigates the influence of the Minimum Quantity Lubrication (MQL) technique and spindle speed on the surface roughness of AISI 1020 steel during turning operations. recycled cooking oil was utilized as an environmentally friendly MQL lubricant, offering potential as a substitute for conventional mineral oils. In this experiment, two independent variables were considered: lubrication condition (MQL and dry cutting) and spindle speed, tested at three levels (630 rpm, 800 rpm, and 1000 rpm). The dependent variable was surface roughness. MQL was selected for its ability to enhance cooling and lubrication efficiency while minimizing environmental impact. Experimental results indicated that at a spindle speed of 1000 rpm, surface roughness achieved 2221 µm with MQL, compared to 2824 µm without MQL. These findings highlight that recycled cooking oil-based MQL significantly improves the surface finish and demonstrate that the proper combination of lubrication parameters and spindle speed enhances machining quality. Moreover, this research supports sustainable manufacturing by promoting the use of recycled cooking oil as a green lubricant alternative.

Keywords:
Recycled cooking oil, Minimum Quantity Lubrication (MQL), Spindle Speed, Surface Roughness, AISI 1020 Steel

1 Introduction

The development of technology in the era of Industry 4.0 has driven the manufacturing sector to improve production efficiency and quality continuously. In modern industry, the speed and accuracy of machining processes are not only key performance indicators but also play a significant role in determining the quality of the final product. One of the main parameters that affects machining quality is surface roughness.

Machining plays a vital role in the manufacturing industry and has been known since the Industrial Revolution. Among machining methods, turning is one of the most widely used, particularly for producing cylindrical products. This process is carried out by rotating the workpiece while the cutting tool moves along its surface, removing material and generating chips. Until today, turning has remained an essential method for producing high-precision cylindrical components, including those made from AISI 1020 steel. This material is classified as a low-carbon steel with good formability, making it widely utilized in both the automotive and manufacturing industries [1].

Various studies have shown that machining parameters, such as spindle speed, feed rate, and depth of cut, significantly influence surface roughness. In general, increasing spindle speed and decreasing feed rate tend to produce smoother surfaces [2–3]. In addition, the use of cutting fluids is essential for reducing surface roughness and extending tool life. One of the environmentally friendly methods that has been widely studied is Minimum Quantity Lubrication (MQL), which employs a minimal amount of lubricant sprayed directly onto the cutting zone [4]. This method has been proven effective in improving surface quality while reducing environmental impact [5]. Approximately 85% of cutting fluids worldwide consist of mineral oil-water mixtures [6]. However, their excessive use raises ecological and health concerns due to the presence of phosphorus, sulfur, chlorine, and zinc. As an eco-friendlier alternative, MQL can replace conventional flood cooling [7].

Investigated the effect of turning using MQL and dry cutting on surface roughness and power consumption in medium-carbon steel [8]. The results showed that dry cutting on ST42 produced the highest surface roughness, while MQL on ST60 provided the best result, with a surface roughness of 1.097 µm at a spindle speed of 1500 rpm and a feed rate of 0.157 rev/mm. Studied the implementation of MQL in external thread machining of magnesium material [9]. The optimal condition was achieved at a 10 mm diameter, 0.46 mm depth of cut, and 424 rpm spindle speed, resulting in a peak error of 0.012 mm and a height error of 0.0115 mm. For angular error, the best result was obtained at a depth of cut of 0.23 mm and a spindle speed of 212 rpm, with a mistake of 0.3866°. The use of coconut oil–based MQL improved thread accuracy and surface quality compared to dry cutting. The application of natural oils using the MQL method has been shown to significantly affect turning quality. MQL with coconut oil resulted in a surface roughness of 1.563 µm, which was better than dry cutting, which reached 2 µm [10].

Along with increased industry-wide awareness of sustainability, research into environmentally friendly lubricants has grown rapidly. Many researchers are now attempting to replace petroleum-based cutting fluids with renewable alternatives. Among the vegetable oils studied are castor oil, palm oil, and Calophyllum oil [6]. the effect of coconut oil cutting fluid flow rate using the MQDL method on turning aluminum 6061. Results showed that increasing the flow rate reduced surface roughness, increased chip length, and decreased tool wear. In conclusion, a higher cutting fluid flow rate improves surface quality and machining efficiency [18]. The study reported in [19] compared synthetic oil, soybean oil, and palm oil for dry machining of magnesium AZ31. Results showed that using palm oil achieved the lowest surface roughness of 1.147 µm, significantly lower than the maximum roughness of 5.925 µm. One promising alternative that has recently gained attention is the use of recycled cooking oil as a base fluid in MQL. Investigated the production of biolubricants derived from recycled cooking oil. The study produced biolubricants with favorable characteristics, making them feasible for use as eco-friendly lubricants [11].

Recycled cooking oil, often a byproduct of frying processes and typically discarded, has considerable potential as a machining fluid, particularly after proper filtration and modification. However, the effectiveness of recycled cooking oil in MQL turning applications still requires further investigation, especially regarding the surface roughness of the machined product.

In Palu City, the high consumption of cooking oil by small-scale culinary businesses, such as street vendors and local eateries, generates a significant amount of recycled cooking oil. According to data from the Central Statistics Agency [12], approximately 2681 food stalls and eateries may produce such waste. Nevertheless, its utilization remains very limited, and much of it is improperly disposed of, thereby causing environmental issues. As a sustainable alternative, recycled cooking oil can be used as a machining fluid via MQL. Even so, its effectiveness in improving the surface quality of turning operations still needs to be explored in greater depth.

Several studies on MQL using various types of vegetable oils have been conducted; however, the use of recycled cooking oil as a lubricant for turning AISI 1020 steel has rarely been explored, particularly regarding the influence of spindle speed on surface roughness. This indicates that the topic has received limited attention in previous research. This study focuses on applying recycled cooking oil in an MQL system to machine AISI 1020 steel, emphasizing the analysis of spindle speed effects on surface roughness to develop an environmentally friendly, sustainable machining method.

Based on the above explanation, this research is considered essential for investigating surface roughness in turning AISI 1020 Steel Using MQL with recycled cooking oil. This study aims to evaluate how spindle speed affects surface roughness when turning AISI 1020 steel with MQL using recycled cooking oil, compared to dry cutting, to understand better the effectiveness of environmentally friendly lubrication techniques in improving machining performance.

2 Research methodology

2.1 Materials and equipment

This study used AISI 1020 steel in cylindrical form, with a diameter of 20 mm and a length of 125 mm, as the workpiece. The leading equipment used included a conventional lathe, an electric lubricant pump, an insert-cutting tool, and a Surface Roughness Tester to measure surface roughness. The cutting fluid in the MQL method was recycled cooking oil that had been previously filtered. The chemical composition of AISI 1020 steel is shown in Table 1.

Table 1. Chemical composition of AISI 1020 steel

Inspection Items		*Chemical Composition (wt.%)*				
		C	SI	MN	P	S
		X100	X100	X100	X100	X100
Spec.	*Min*	15	20	0.85	0.016	0.021
	Max	20	24	1.067		
	Result	20	24	1.067	0.025	0.024

2.2 Experimental methods

This study was carried out experimentally by comparing two cutting conditions, namely without MQL and with MQL (Fig. 1), using recycled cooking oil as the cutting fluid. Each condition was tested at three spindle speeds: 630, 800, and 1000 rpm. The parameters kept constant included a depth of cut of 0.2 mm, a feed rate of 0.103 mm/rev, the insert type, and a cutting length of 100 mm. The dependent variable analyzed was the surface roughness of the turned workpiece.

Surface roughness was measured using a Surface Roughness Tester at several cutting points to obtain more representative data. The measurement results were then compared between the conditions with and without MQL to determine the effectiveness of recycled cooking oil as an alternative cutting fluid.

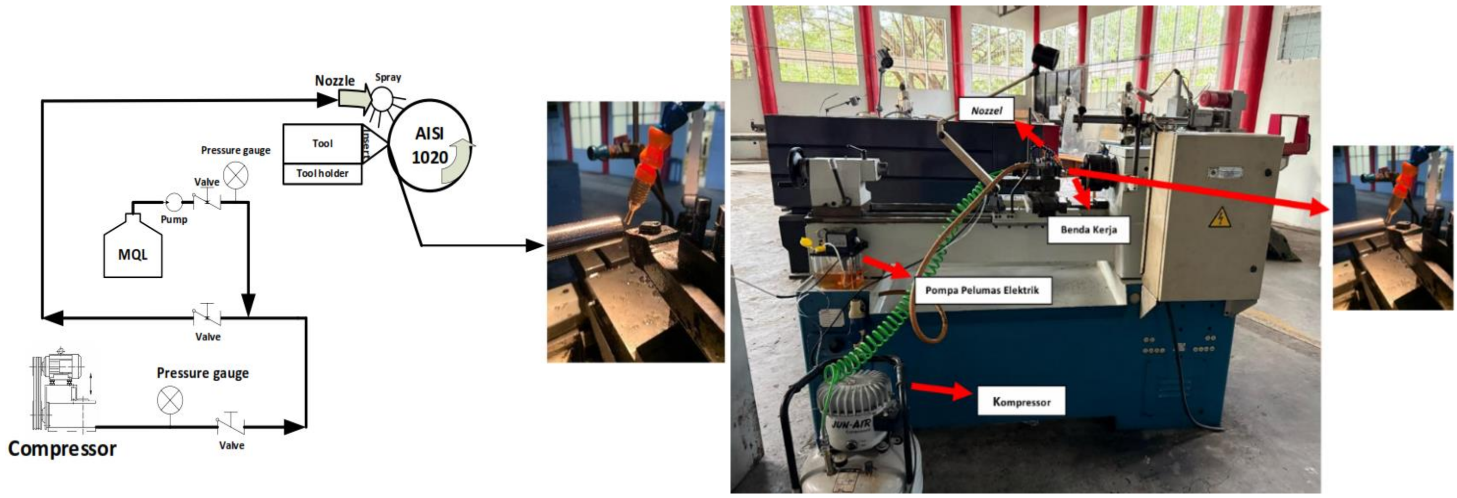


Fig. 1. Schematic of the turning process using the MQL method

2.2.1 Preparation of MQL fluid

The recycled cooking oil used as the MQL fluid was first filtered using a sodium bicarbonate solution to remove impurities, frying residues, and other contaminants that could affect cutting performance. This filtration process is essential to ensure that the oil possesses more stable characteristics and is suitable for use as a machining fluid.

After the filtration stage, a series of basic property tests were conducted to evaluate the quality of the oil, including:

1. Moisture content, tested using the oven-drying method at 105°C in accordance with SNI 01-2891-1992. This test aims to ensure that the water content in the oil remains within a safe limit, thereby preventing corrosion and disturbances during the cutting process.
2. Density, determined using the pycnometer method in accordance with ASTM D1217. This parameter relates to the fluid's specific mass, which can affect cooling and lubrication.
3. Viscosity, measured using a Brookfield viscometer at 40 °C in accordance with ASTM D2270. Viscosity is an important parameter that indicates a fluid's ability to coat the workpiece and cutting tool surfaces, thereby directly influencing lubrication effectiveness.

The test results for moisture content, density, and viscosity are presented in Table 2. Based on the data, the moisture content of the filtered recycled cooking oil decreased after filtration, making it safer for use in machining processes. The density of recycled cooking oil was relatively close to that of vegetable oils, indicating that its physical structure changes remained within acceptable limits. Meanwhile, its viscosity was slightly higher than that of fresh oil due to repeated heating during frying. This condition may provide an advantage, as higher viscosity allows for the formation of a thicker lubricating film in the cutting zone. Overall, the characterization results indicate that filtered recycled cooking oil possesses adequate physical properties for use as an MQL fluid and has the potential to substitute fresh vegetable oil in machining applications.

Table 2. Analysis results of recycled cooking oil content before and after filtration

Test parameter	Before filtration	After filtration
Moisture content (%)	0.682	0.295
Density (g/mL)	0.911	0.907
Viscosity (cP)	35	33

2.2.2 Surface roughness measurement method based on ISO 4287

The machined specimen surface undergoes structural changes due to material deformation during the interaction between the cutting tool and the workpiece. These changes result in a degree of surface roughness that reflects the surface's microstructural condition. Surface roughness not only affects the aesthetic quality of a product but also plays a vital role in the functional performance of components, such as wear resistance, friction, and tool life.

The surface roughness analysis in this study follows ISO 4287:1997, which defines roughness parameters using the profile method, including the Ra value (arithmetic mean roughness), which was used as the primary reference. This parameter was selected because it provides a comprehensive representation of the average surface irregularities produced during machining.

Surface roughness measurements were carried out using a Surface Roughness Tester at three different points, namely at the beginning, middle, and end of the cutting path, to ensure results representative of the entire workpiece surface. The final surface roughness value was obtained by averaging the measurements from these three points. This approach aimed to minimize measurement errors arising from variations in cutting conditions along the machining path.

With this method, the results not only demonstrate the average surface quality but also provide important information on the consistency of machining outcomes between conditions with and without MQL using recycled cooking oil.

2.2.3 Visual observation

Macro visual analysis was employed to observe differences in Ra values on the machined specimen surfaces. This method complements numerical data with a visual representation of surface irregularities. Observations were carried out using macro photography with a camera set to f/22 to capture precise details, allowing surface conditions to be compared under various cutting parameters, both with and without MQL. Macro photography techniques have been widely used in previous studies to support surface roughness analysis, as they can reveal microstructural features resulting from tool–material interactions [13]. Thus, the measurements obtained from the Surface Roughness Tester can be combined with visual evidence to identify surface defects, cutting groove patterns, and irregularity distributions that reflect the cutting mechanism and the effectiveness of the cutting fluid. In addition, the test results are presented as surface roughness graphs to illustrate the differences in Ra values between dry cutting and MQL conditions.

3 Results and discussion

3.1 Recycled cooking oil content test results

The filtration process was carried out to improve the quality of recycled cooking oil for use as a cutting fluid in a MQL system. Several parameters were tested, including moisture content, density, and viscosity of the recycled cooking oil before and after filtration. The analysis results of the oil characteristics before and after filtration are presented in Table 2.

The analysis results showed that the moisture content of recycled cooking oil decreased from 0.682% to 0.295% after filtration, indicating the process's effectiveness in reducing water content and improving thermal stability, thereby lowering the risk of oxidation. The oil density also decreased from 0.911 g/mL to 0.907 g/mL, suggesting a reduction in dissolved particles or contaminants. This value falls within the standard range (0.888–1 g/mL) [11], confirming that the oil remains suitable for use as a lubricant.

The oil's viscosity decreased from 35 cP to 33.3 cP, demonstrating the filtration process's success in removing fine contaminants. The final viscosity value is still consistent with the ISO VG 32 classification (28.8–35.2 cP at 40 °C) [14]. Therefore, the filtered recycled cooking oil meets industrial lubricant standards and remains feasible for application.

3.2 Surface roughness test results

The experiment was carried out on AISI 1020 steel using MQL with recycled cooking oil and the dry cutting method (without MQL). Each spindle speed (630 rpm, 800 rpm, and 1000 rpm) was tested three times, and surface roughness (Ra) was measured at three points (T1, T2, T3) for each sample.

Fig. 2 shows that increasing spindle speed, combined with MQL, significantly reduces surface roughness. At a spindle speed of 630 rpm, the surface roughness under dry cutting reached 5.084 µm, while with MQL it decreased to 3.169 µm. At 800 rpm, the roughness value under dry cutting was 3.094 µm, and with MQL it was reduced to 2.551 µm. Meanwhile, at 1000 rpm, the surface roughness under dry cutting was 2.824 µm, which significantly decreased to 2.221 µm with MQL.

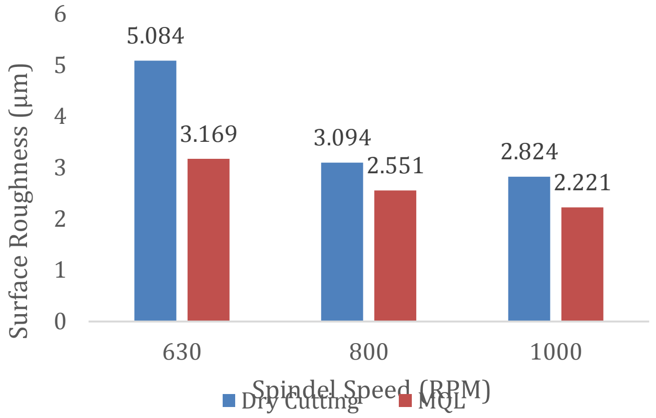


Fig. 2. Comparison of surface roughness (Ra) values at different spindle speeds under dry cutting and MQL conditions

Based on the measurements, increasing spindle speed from 630 rpm to 800 rpm and 1000 rpm consistently resulted in lower surface roughness at each speed. At 1000 rpm, the cutting force became more stable, producing a smoother surface finish. The application of the MQL system with recycled cooking oil consistently yielded lower roughness values than dry cutting.

The surface roughness values obtained under MQL conditions were consistently lower than those under dry cutting at all spindle speed variations. This indicates that applying MQL with recycled cooking oil effectively reduces surface roughness. Furthermore, the graph shows that the reduction in surface roughness is more pronounced with MQL, particularly at 1000 rpm, resulting in the lowest roughness value. Thus, combining a higher spindle speed with MQL can produce superior surface quality in the turning of AISI 1020 steel [10].

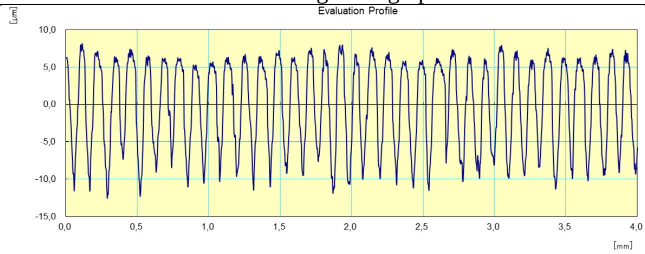
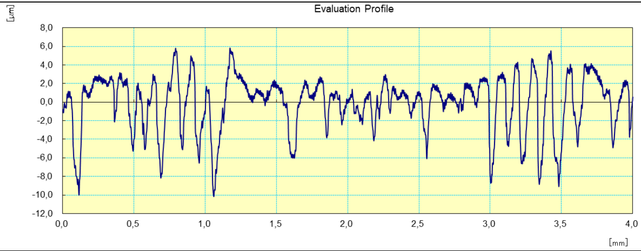
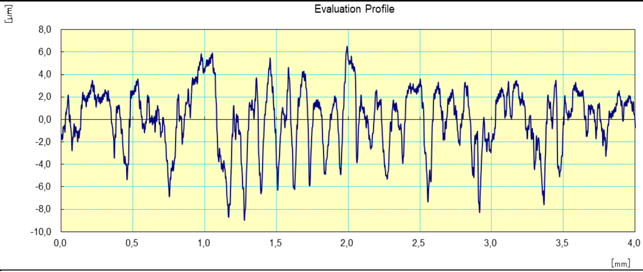
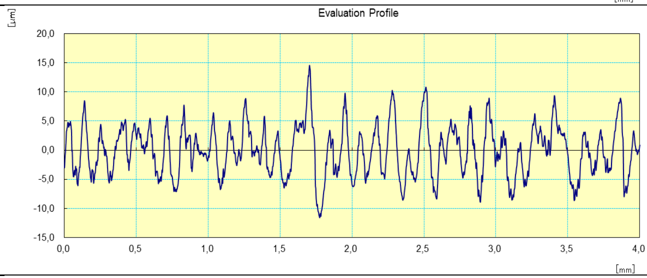
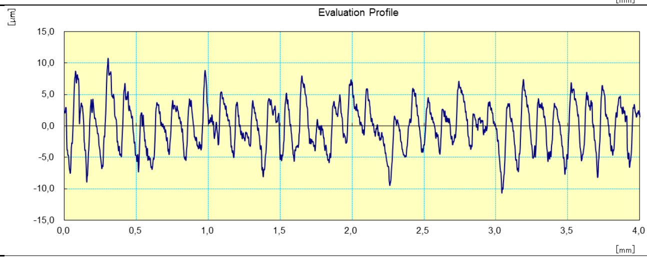
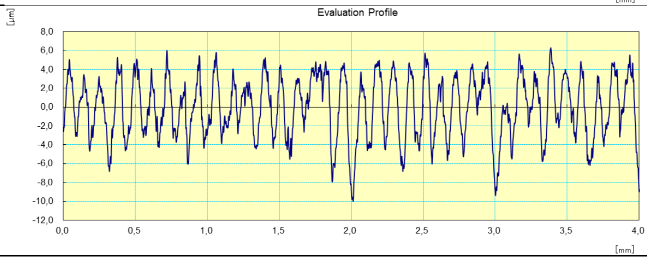
The mechanism of surface roughness reduction can be explained through several factors. At higher spindle speeds, the cutting force becomes more stable, thereby reducing the likelihood of vibrations that may cause irregularities on the workpiece surface. Increasing spindle speed also produces thinner chips and a smoother cutting action on the workpiece surface, thereby reducing roughness. The results of this study indicate that the MQL application significantly improves surface quality compared to dry cutting (without lubrication). Data analysis shows a significant relationship between spindle speed and surface roughness: the higher the spindle speed, the lower the roughness [2]. In addition, the use of MQL based on recycled cooking oil becomes increasingly effective at higher spindle speeds. Therefore, the combination of appropriate spindle speeds and MQL lubrication is essential to achieve optimal machining results in the turning of AISI 1020 steel.

The application of MQL with recycled cooking oil has been proven to reduce the surface roughness of machined parts. This is supported by the tribological properties of recycled cooking oil, particularly its viscosity, which complies with the ISO VG 32 standard [14], as well as its density and moisture content that enhance lubrication performance. These characteristics allow the formation of a lubricating film, minimizing direct contact between the cutting tool and the workpiece surface. Reducing friction and heat in the cutting zone results in a smoother surface with lower roughness. Previous studies have also demonstrated that the application of MQL with natural-based oils can produce better surface quality in turning processes [11]. Therefore, recycled cooking oil not only serves as a cost-effective, environmentally friendly lubricant but also significantly improves the quality of machining processes.

3.3 Surface roughness test results

Macro observations were conducted to assess the visual details of surface roughness during turning, including tool marks, scratches, and irregularities resulting from the interaction between the cutting tool and the workpiece. This photo-based analysis complements the surface roughness test and has also been employed in previous studies [15]. The specimens were positioned horizontally, with the camera perpendicular to the surface, and the results of the observations are presented in Table 3.

Table 3. Visual observation data (macro photo)

	No	Spindle speed (RPM)	Macro photo	Surface roughness graph
MQL	1	630		
	2	800		
	3	1000		
Dry cutting	1	630		
	2	800		
	3	1000		

Based on the visual observation data (macro photographs) and surface roughness profile graphs in Table 3, it is evident that the application of the MQL method has a significant effect on the surface quality of turned AISI 1020 steel. Under MQL conditions, increasing the spindle speed from 630 Rpm to 1000 Rpm resulted in progressively smoother surfaces, as indicated by denser roughness profiles with reduced amplitudes. The sample at 630 RPM exhibited relatively coarse cutting marks with visible surface irregularities. At 800 RPM, the visual appearance showed improvement with shallower cutting grooves. The best condition was observed at 1000 RPM, where the surface appeared more uniform with lower roughness values. According to [16], reducing surface roughness has been shown to yield better results than traditional cooling methods. Thus, MQL not only extends tool life but also reduces surface roughness, thereby enhancing machining quality. In contrast, under dry cutting conditions, although increasing spindle speed also tended to improve surface quality, the results remained rougher compared to MQL. This was evident in deeper, more irregular cutting grooves at all speeds, as well as roughness profiles with greater fluctuations. Overall, these observations confirm that applying MQL with recycled cooking oil effectively reduces surface roughness, particularly at higher spindle speeds. The combination of MQL and a spindle speed of 1000 Rpm produced the smoothest surface compared to other conditions, while simultaneously supporting machining efficiency with superior surface quality. Dry turning generally results in higher surface roughness than lubricated turning. As reported by [17], workpieces machined without lubrication (dry cutting) exhibited higher roughness levels than those machined with MQL, mainly due to increased heat generated by direct friction without sufficient lubrication. Therefore, the application of MQL in the turning process significantly improves surface quality.

4 Conclusions

Based on the study titled "Investigation of Surface Roughness in Turning AISI 1020 Steel Using MQL with recycled cooking oil," it can be concluded that MQL with recycled cooking oil significantly reduces surface roughness (Ra) compared to dry cutting. Variations in spindle speed at 630 Rpm, 800 Rpm, and 1000 Rpm were shown to influence surface roughness, where higher spindle speeds consistently resulted in lower Ra values. The combination of MQL with a spindle speed of 1000 Rpm produced the best surface quality, with a roughness value of 2.221 μm, notably lower than 2.824 μm under dry cutting conditions. These findings demonstrate that recycled cooking oil as an MQL fluid not only improves machining quality but also provides an economical, environmentally friendly alternative that supports green manufacturing.

Future research should consider incorporating additional machining parameters, such as cutting force, chip formation, and tool vibration, along with temperature measurement, tool wear analysis, and variations in MQL flow rate, to provide a more comprehensive evaluation of recycled cooking oil performance under different machining conditions. Moreover, the use of environmentally friendly vegetable-based oils should also be further explored as sustainable alternatives to conventional lubricants, supporting the development of green manufacturing and more efficient machining processes.

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