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Experimental Investigation of Tool Life and Chip Thickness Using Vegetable Oils as Cutting Fluids under MQL

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Abstract

Cutting fluids play a vital role in machining operations by reducing friction and heat, facilitating chip removal, and enhancing both tool life and product quality. Although mineral-based oils are commonly used in flood lubrication, their toxicity and environmental impact have raised concerns. As a result, alternative methods like dry machining and Minimum Quantity Lubrication (MQL) have gained attention for reducing oil consumption. This study investigates the use of vegetable oils as MQL cutting fluids in the turning of AISI 4130 steel, revealing that vegetable-based fluids outperform conventional options. MQL significantly improves machining efficiency compared to flood and dry conditions. The study also examines chip formation dynamics, especially in hardened AISI 4340 steel, where high temperatures and tool wear pose challenges that can be mitigated through sustainable practices like MQL with bio-based fluids. Among the oils tested, coconut oil proved to be the most effective, producing thinner chips and larger shear angles at higher cutting speeds. The findings indicate that coconut oil excels at reducing chip thickness and increasing shear angles during high-speed cutting. Future research will further compare bio-based fluids with synthetic oils and dry machining to optimize processes for greater sustainability and performance. Under MQL, vegetable oils show significant performance improvements over blasocut oil, with soybean oil achieving the lowest cutting forces, reducing them by 9% compared to blasocut. It also improves surface roughness by 4.23%, 8.56%, 15.24%, and 16.98% compared to other oils. Temperature and power consumption are also reduced by 3% to 19% compared to other oils. The study emphasizes the benefits of bio-based cutting fluids in MQL, highlighting their superiority over conventional methods in terms of surface quality, tool longevity, and environmental impact.

Keywords: *AISI 4130 Steel, Chip Thickness, Machining, MQL, Sustainability, Surface Roughness, Tool Life, Vegetable Oils*

1.0 Introduction

Cutting fluids are indispensable in machining operations, fulfilling critical roles such as heat dissipation, lubrication, chip control, and corrosion prevention. In processes like drilling, milling, and turning, cutting tools generate substantial heat and friction. Cutting fluids play a crucial role in dissipating this heat, thereby preventing tool wear and thermal damage while ensuring the dimensional accuracy and surface finish of the machined parts. They act as effective lubricants, which not only extend tool life but also enhance machining efficiency by improving cutting performance and precision. Furthermore, cutting fluids aid in chip control by facilitating the efficient removal of chips from the cutting zone, which is essential for maintaining process stability and preventing interruptions that could compromise the quality of the finished components. Additionally, they form a protective barrier against corrosion, safeguarding both the cutting tools and workpieces from environmental degradation

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over time. In recent years, there has been a significant shift towards more environmentally friendly alternatives to traditional cutting fluids, such as vegetable oils. Which often contain petroleum-derived oils and additives that can pose risks to ecosystems and human health. Vegetable oils present a sustainable alternative because they are derived from renewable resources and are biodegradable, thereby reducing their environmental footprint throughout their lifecycle. Moreover, advancements in the formulation have enabled vegetable oils to provide comparable or even superior performance in terms of lubrication, heat dissipation, and corrosion protection compared to their petroleum-based counterparts. This versatility makes vegetable oils suitable for a wide range of machining applications while aligning with global trends towards stricter environmental regulations and sustainability goals. As a result, the adoption of vegetable oils in machining represents a proactive step towards achieving more sustainable and responsible manufacturing practices, ensuring both operational efficiency and environmental stewardship in the machining industry.

Minimum Quantity Lubrication (MQL), being the most sustainable machining technique, has demonstrated significant outcomes in numerous studies[1]. In MQL, chip disposal is facilitated by a combination of high-pressure air and fluid, simplifying the process[2]. The use of MQL results in notable temperature reduction. By enabling shorter contract lengths and improved chip extraction, MQL contributes to reduced machining forces[3,4]. Anandita[5] explored variations in chip thickness and observed a direct correlation between feed rate with cutting velocity. Iruj *et al.*[6] showed that The hybrid technique provides enhanced lubrication and cooling, effectively reducing machining heat and temperatures, thereby improving metal-cutting processes and benefiting the manufacturing sector through optimized parametric combinations of cryogenic and MQL agents. Syed Hammad Ali *et al.*[7] discussed the potential future aspects of MQL for research and industrial execution. Ross *et al.*[8] confirmed that using nano MQL during machining operations led to an average decrease of approximately 65% in the generated temperature compared to conditions without coolant. The research included an examination of chip thickness and shear angle calculations, both essential for comprehending the specific energy needs and forecasting cutting forces during machining operations. This study evaluates the use of different bio-based cutting fluids, synthetic oils, and dry cutting conditions. It seeks to shed light on the impact of varying cutting speeds on chip thickness when employing vegetable-based cutting fluids under MQL conditions. The findings aim to provide critical data for optimizing machining processes for hardened AISI 4340 steel. Du *et al.*[9] explained Cutting performance and cutting fluid infiltration characteristics into the tool-chip interface during MQL milling. Rajeswari[10] showed The cutting force during wet turning is reduced, from 5.89 kgf to 4.91 kgf and surface roughness is reduced from 0.832 µm to 0.629 µm compared with dry turning. Saleem *et al.*[11] found 16% higher hardness value was observed closer to the machined surface, than that of bulk material. Pal *et al.*[12] showed the sufficient quantity of graphene nanoparticles in nanofluid MQL drilling can boost the lubrication performance and increase the stability of the lubrication film, which improves the drilling characteristics.

This study aims to explore and evaluate the potential of vegetable oils as cutting fluids in MQL during the turning of AISI 4130 and AISI 4340 steels. Specifically, it seeks to compare the performance of coconut, canola, and soybean oils against conventional mineral-based oils in terms of cutting forces, surface roughness, temperature, power consumption, chip formation dynamics, and tool wear. By focusing on the application of bio-based fluids under MQL, the study intends to demonstrate the potential for enhancing machining efficiency, tool longevity, and sustainability, while reducing the environmental impact associated with traditional flood lubrication methods. The ultimate goal is to optimize machining processes for better performance, surface quality, and environmental sustainability by identifying the most effective bio-based cutting fluid for use in high-speed steel turning operations.

Additionally, the experimental study explores how these cutting environments affect the machining performance, aiming to enhance the efficiency and sustainability of the machining process. By investigating the interaction between cutting speed, chip formation, and lubrication, the study offers a comprehensive understanding that could lead to improved tool life, reduced cutting forces, and better surface quality in the machining of hardened steel. This research is particularly significant for industries seeking to adopt more environmentally friendly practices while maintaining high-performance standards in their manufacturing processes.

2.0 Experimental Study

An experimental study was conducted to analyze the variations in chip thickness during turning operations on hardened AISI 4340 steel, with a hardness range of 52 to 54 HRC, using a CNC lathe machine. The workpiece used in this experiment measured 90 mm in diameter and 250 mm in length. The research focused on understanding how different cutting parameters impact chip formation and overall machining performance. By examining the changes in chip thickness, the study offers valuable insights into optimizing cutting conditions to enhance efficiency and quality in machining processes. Additionally, the investigation explored the effects of using advanced tooling materials and coatings to extend tool life and improve performance when machining hardened steel. The study tested Canola, Coconut, and Soybean oils under Minimum Quantity Lubrication (MQL) at various cutting speeds. For comparison, synthetic oil under MQL conditions and dry machining were also evaluated. Table 1 provides a detailed summary of the properties of the fluids used in this study.

The experiments maintained a constant feed rate and depth of cut, with only the cutting speed being varied for each trial. This study focused exclusively on the effect of changing cutting speeds while keeping feed rate and depth of cut constant. The specific cutting parameters were: cutting speeds of 12,000, 13,200, and 14,400 m/s, a feed rate of 0.125 mm/rev, and a depth of 0.25 mm. Figure 1 displays the MQL setup used during the experiments. The MQL system facilitated a controlled cutting fluid flow ranging from 50 ml/hr to 150 ml/hr, ensuring a precise application of cutting fluid at the micro level. The selection of MQL parameters was informed by an

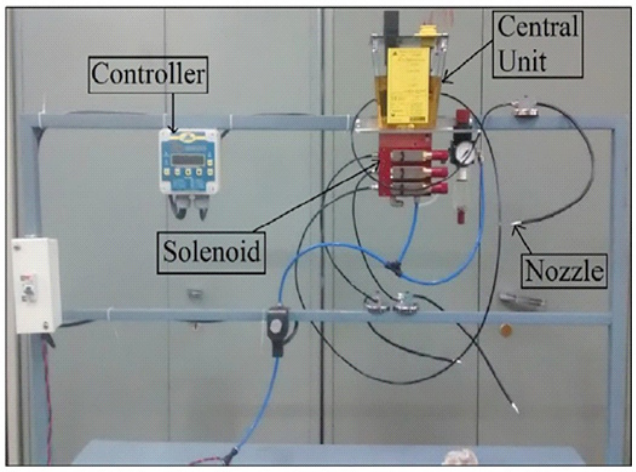


Figure 1. MQL system used.



Figure 2. Experimental set-up.

Table 1. Properties of fluids used

Sr. No.	Elements		Soybean	Coconut	Canola
			Content (%)		
01	Kinematic viscosity	40°C	32.93	36.2	34
		100°C	08.08	6.67	7.8
02	Pour point °C		—09.0	20	—21
03	Flashpoint °C		240	240	328
04	Heat transfer coefficient		269.7 @180°	947@750°	251.4 @150°
05	Density		885	805	962

extensive literature review to ensure optimal experimental conditions. For this study, the MQL parameters were set with an air pressure of 7 bar, a fluid flow rate of 52 ml/hr, and a nozzle angle of 16°.

MQL is recognized as a sustainable method for applying cutting fluids directly to the machining zone, aimed at improving machining efficiency and minimizing environmental impact. In this research, vegetable-based cutting fluids were utilized under MQL conditions. The MQL setup, as shown in Figure 1, included an air pressure of 7 bar and an oil flow rate of 52 ml/hr, with a fixed nozzle angle of 16° throughout.

3.0 Results and Discussions

This study examined how chip thickness changes with cutting speed. To isolate the effect of cutting speed, feed rate and depth of cut were kept consistent throughout



Figure 3. Chips at 12000 m/sec.

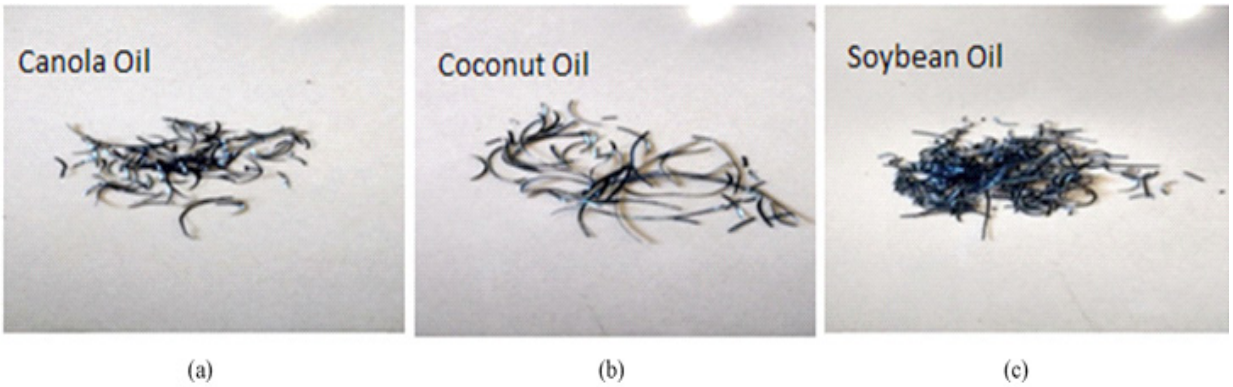


Figure 4. Chips at 13200 m/sec.

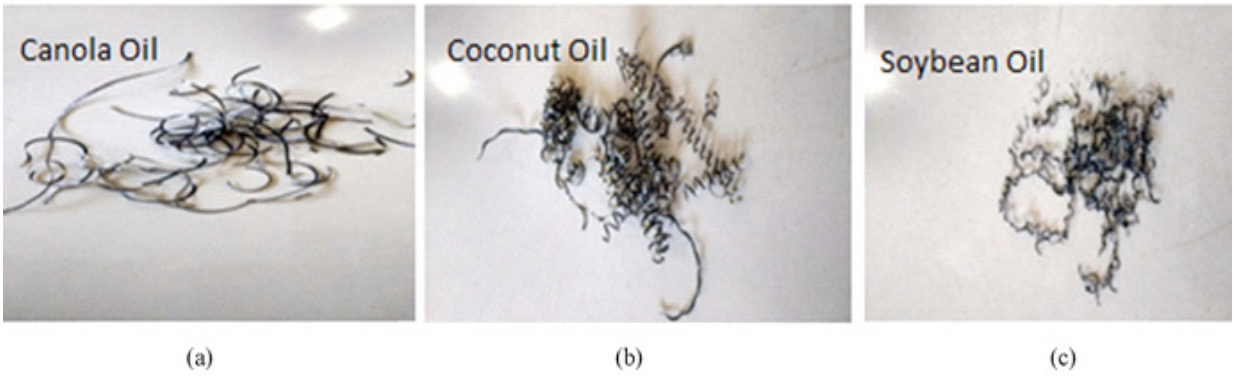


Figure 5. Chips at 14400 m/sec.



Figure 6. Chips at **(a)** 13200 m/sec **(b)** 14400 m/sec.

the experiments. Visual representations of the chips generated under these conditions can be found in Figures 3 through 6.

MQL (Minimum Quantity Lubrication) demonstrated superior performance in reducing cutting temperatures and preventing chip buildup compared to other methods. This resulted in smoother chips, decreased cutting forces, and improved chip evacuation. These findings align with previous research on chip thickness (Figure 7). Chip thickness is a critical factor affecting machining efficiency. Thinner chips consume less energy while maintaining productivity. A larger shear angle reduces cutting forces and heat generation. While increased cutting speed generally leads to higher temperatures, it also decreases cutting forces due to reduced material strength. Synthetic oil exhibited the best overall performance, producing the largest shear angle. Among bio-based oils, coconut oil excelled at higher cutting speeds, while soybean oil was more effective at lower speeds. Canola oil demonstrated intermediate performance. Both cooling and lubrication are essential for optimal machining, but their relative importance varies with cutting speed. At high speeds, cooling is paramount, while lubrication is more critical at lower speeds.

The observed values of chip thickness and shear angle are as follows:

a. **Canola oil:** At a cutting speed of 14,400 m/s, the minimum chip thickness was 26.50 mm, and the maximum shear angle was 80.81°, which reduced the specific energy required for machining.

b. **Coconut oil:** At a cutting speed of 14,400 m/s, the minimum chip thickness was 14.93 mm, and the maximum shear angle was 87.41°, leading to a decrease in the specific energy of machining.

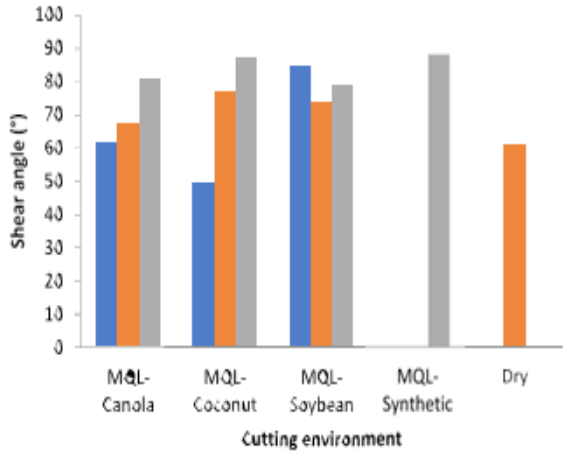


Figure 7. Shear angle comparison.

At higher cutting speeds, the likelihood of proper penetration of cutting fluid decreases. Proper penetration is more likely with cutting fluids that can effectively reach the tool-workpiece interface. This is consistent with previous studies indicating that the low viscosity index of coconut oil enhances its effectiveness at higher cutting speeds, making it more capable of shearing off chips compared to canola oil and soybean oil.

a. **Soybean oil:** At a cutting speed of 12,000 m/s, the minimum chip thickness was 19.45 mm, and the maximum shear angle was 84.82°, which reduced the specific energy required for machining. The performance of soybean oil at lower cutting speeds supports earlier studies, suggesting that its high viscosity index contributes

to better performance at lower speeds compared to coconut and canola oils.

For dry cutting and synthetic oil environments, single trials were conducted, yielding the following observations:

a. **Synthetic oil:** At a cutting speed of 14,400 m/s, the minimum chip thickness was 13.95 mm, and the maximum shear angle was 87.97°.

b. **Dry cutting:** At a cutting speed of 13,200 m/s, the minimum chip thickness was 64.95 mm, and the maximum shear angle was 61.09°.

Future research will compare bio-based fluids with synthetic oils and dry machining to optimize machining processes for better sustainability and performance. Soybean oil reduced cutting forces by 9%, surface roughness by up to 16.98%, and temperature and power consumption by 3-19% compared to blasocut oil. The study evaluated cutting fluids based on cutting forces, surface roughness, chip formation, tool wear, temperature, and power consumption.

4.0 Conclusions

Coconut oil and synthetic oils demonstrated exceptional performance when machining hardened steel at high speeds. These oils effectively reduced chip thickness and increased shear angle, leading to lower energy consumption, cutting forces, and heat generation. Although synthetic oil slightly outperformed coconut oil overall, the environmental benefits of coconut oil make it a promising option for further research under various machining conditions.

4.1 Key findings include

1. Coconut oil surpassed soybean and canola oils at high speeds due to its lower viscosity.
2. Coconut oil showed the best performance by producing thinner chips and larger shear angles at higher cutting speeds.
3. Synthetic oil delivered the best overall performance, with coconut oil close behind.
4. Dry cutting conditions resulted in the thickest chips and smallest shear angles compared to MQL conditions.
5. Both coconut and synthetic oils successfully minimized chip thickness and maximized shear angles, enhancing machining efficiency.
6. Coconut oil's environmental benefits, further research is needed to evaluate its performance across different cutting parameters.

These findings highlight the efficiency of certain cutting fluids and underscore the importance of continued research into sustainable machining practices.

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