



A Review: The Effect of Synthetic, Mineral, and Vegetable Coolants on Surface Roughness in Machining Processes

Ayu Pratiwi^{a,*}, Hadi Pranoto^a

^aMechanical Engineering Department, Faculty of Engineering, Universitas Mercu Buana, Jakarta, Indonesia

Abstract. Surface quality of machined parts is an important indicator in determining the final performance of engineering components. One of the main factors influencing this parameter is the type of coolant used during the cutting process. This study is a literature review aimed at systematically comparing the effects of synthetic, mineral, and vegetable-based coolants on surface roughness in various machining processes such as turning, milling, and drilling. The literature review method involved searching reputable scientific articles indexed in Scopus, with a focus on quantitative surface roughness data (Ra). The analysis results showed that plant-based coolants provided the best performance, with a reduction in Ra values of up to 55% compared to conventional mineral coolants. Meanwhile, synthetic coolants demonstrated high cooling capabilities but their lubricating properties remained below those of plant-based coolants. Mineral fluids were found to have the lowest performance in terms of surface quality and environmental impact. This study confirms that the use of plant-based fluids, particularly in Minimum Quantity Lubrication (MQL) systems, is a promising solution for achieving efficient, sustainable, and environmentally friendly machining processes.

Keywords: coolant; machining; surface roughness; tribology

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1. Introduction

The machining process plays a very important role in the world of modern manufacturing. Behind the advancement of industrial technology, this process remains the main foundation in shaping and completing various technical components. In practice, the machining process often poses thermal and mechanical challenges, especially in the cutting area, where high friction between the cutting tool and the workpiece can cause a significant increase in temperature. This temperature increase not only accelerates tool wear but can also degrade the surface quality of the workpiece and disrupt the dimensions of the produced product.

To overcome this, the use of coolants has become common practice in machining. Coolants are used to reduce heat in the cutting area, lubricate the contact between the tool and the workpiece, and help remove metal chips efficiently. However, the effectiveness of coolants depends greatly on their type. There are three main categories of coolants commonly used: mineral-based, synthetic, and vegetable-based coolants. Each has different characteristics in terms of machining performance and environmental aspects.

Mineral-based coolants, which are generally derived from petroleum products, have long been widely used due to their availability and low production costs. However, a number of studies have shown that their use has the potential to cause negative impacts on worker health and the environment due to their biologically difficult-to-degrade chemical content (1). Several reports mention high rates of skin disorders among workers due to long-term exposure to this type of fluid.

As an alternative, synthetic coolants have been developed to improve cooling efficiency and reduce oil residue. These fluids are typically water-based solutions enriched with synthetic additives,

*Corresponding author: 55824110005@student.mercubuana.ac.id (Ayu Pratiwi)

providing good lubrication and anti-corrosion properties. Despite their high cooling performance, synthetic fluids still have issues related to toxicity and formulation costs that are not inexpensive (2). Additionally, their chemical stability poses challenges for long-term use.

Meanwhile, an approach that is gaining attention today is the use of plant-based cooling fluids. This type of fluid is considered more environmentally friendly because it is biodegradable and non-toxic. Plant-based oils such as coconut oil, castor oil, and palm oil have been proven to have high viscosity and good lubricating properties, thereby significantly reducing cutting temperature and surface roughness. Several studies have also shown that plant-based fluids produce lower surface roughness results compared to mineral fluids (1,3).

The surface quality of machining results is an important indicator in determining the final performance of a component. High surface roughness can affect friction, wear, lubricant adhesion, and even the fatigue life of a mechanical component. Therefore, studies comparing the performance of various types of coolants against these parameters are very important, especially in an industrial era that demands high efficiency and environmental sustainability.

Previous research has proven that the choice of coolant type affects surface roughness. In his experimental study, he showed that palm oil as a coolant was able to produce a smoother surface on S45C steel compared to mineral oil-based coolants (3). This finding is further supported by the results of other researchers, who demonstrated the superior performance of vegetable oils in reducing temperature and surface roughness during the turning process of alloy steel (4).

On the other hand, the high performance of synthetic fluids in cooling does not always correlate with better surface results. Other studies have shown that, under certain conditions, synthetic fluids can even increase energy consumption and accelerate the degradation of cutting tools at high speeds. Meanwhile, in dry machining or machining without coolant, surface roughness increases dramatically due to the absence of lubrication and cooling effects (5).

Based on these findings, it can be concluded that there is a need for a comprehensive literature review to systematically compare the effects of synthetic, mineral, and vegetable coolants on surface roughness in machining processes. This study aims to consolidate and analyze findings from various sources to serve as a reference for selecting the appropriate type of coolant, not only from a technical perspective but also considering environmental and industrial sustainability aspects.

2. Methodology

This study uses a literature review approach by searching, sorting, and critically analyzing various scientific publications discussing the effects of synthetic, mineral, and vegetable coolants on surface roughness in machining processes such as turning, milling, and drilling. The literature search was conducted using leading databases and relevant documents that are already available, prioritizing quantitative and experimental studies that measure surface roughness parameters in machining processes. All articles were selected based on topic relevance, methodological clarity, and measurability of results, then narratively reviewed to identify common patterns, performance comparisons between fluid types, and their impact on machining quality. This approach enabled the authors to compile a comprehensive and critical synthesis of knowledge, serving as a foundation for scientific understanding and practical recommendations in the field of sustainable machining technology.

3. Cooling Methods in Machining Processes

Cooling methods in machining are not only intended to reduce temperature, but also to control cutting forces, extend tool life, and improve the surface quality of the workpiece. Various methods have been developed and applied depending on the type of process, such as turning, milling, drilling, and grinding. The selection of cooling methods must consider the characteristics of the coolant, the type of workpiece material, the type of cutting tool, and the target efficiency of the machining process itself.

The most commonly used method is flood cooling, which involves the continuous and large flow of coolant to the cutting zone. This method is often used in turning and drilling, as it effectively lowers the temperature of the tool and removes metal chips. However, this method produces large amounts of waste and consumes a lot of fluid. In a study by (6), flood cooling was proven to be effective in reducing surface roughness in AISI 4340 turning, but it requires serious waste management.

The Minimum Quantity Lubrication (MQL) method is becoming increasingly popular because it uses only a small amount of fluid sprayed in the form of mist directly onto the cutting zone. In the milling process of AISI 420, the use of palm oil-based MQL can reduce tool wear and produce a better surface finish than dry or flood methods (7). MQL is also effective in the drilling process, where thrust force and working temperature are lower than in flood methods (8).

Cryogenic cooling uses liquid nitrogen or solid carbon dioxide for extreme cooling, suitable for machining hard materials such as titanium alloys and superalloys. Although it provides highly efficient cooling, high costs and special equipment are obstacles to its implementation in small and medium-sized industries.

Mist cooling methods are also beginning to be applied, especially in high-speed machining. In mild steel turning, the use of vegetable oil-based mist can significantly reduce cutting forces and temperatures (9). On the other hand, in grinding processes, flood cooling is still the preferred choice due to its high heat transfer capacity and chip flushing ability. The use of vegetable esters in grinding results in low cutting forces and good environmental performance (10).

Table 1. Comparison of cooling methods in the machining process

No.	Cooling Method	Machining Process	Cutting Parameters	Advantages	Disadvantages	Ref.
1	Flood Cooling	Turning, Drilling, Milling	Cutting Speed: 150–250 m/min Feed Rate: 0.1–0.3 mm/rev Depth of cut: 1–3 mm	Highly effective cooling, high temperature control, excellent chip flushing	High fluid consumption, waste issues, and occupational health	(11)
2	MQL (Minimum Quantity Lubrication)	Turning, Milling, Drilling	Cutting Speed: 100–200 m/min Feed Rate: 0.08–0.20 m/rev Depth of cut: 0.5–1.5 mm	Environmentally friendly, efficient, targeted micro lubrication	Not suitable for heavy machining/hard materials	(9)
3	Cryogenic Cooling	Turning, Milling, Drilling	Cutting Speed : >250 m/min Feed Rate: 0.1–0.25 m/rev Depth of cut: 0.5–1.0 mm	Extreme cooling, suitable for superalloy and titanium materials	High cost, special equipment required	(12)
4	Mist Cooling	Turning, Milling	Cutting Speed: 120–200 m/min Feed Rate: 0.1–0.2 mm/rev Depth of cut: 1 mm	Fluid saving, suitable for high-speed cutting, more environmentally friendly	Low lubrication efficiency compared to flood	(13)
5	Dry Machining	Turning, Milling, Grinding	Cutting Speed: 80–150 m/min Feed Rate: 0.1–0.2 mm/rev Depth of cut: ≤1 mm	Fluid-free, inexpensive, zero waste	Rough surface, short tool life, high temperature	(2)

The cooling method cannot be chosen generally, but must take into account the thermal properties of the material, the degree of tool wear, operating costs, and the required final quality standards. Therefore, many studies are now focusing on the development of hybrid methods such as MQL with nanoparticle additives, which combine the advantages of high cooling with efficient lubrication and low environmental impact (14).

4. Coolant in the Machining Process

4.1 Synthetic Coolant

Synthetic coolants are fluids that do not contain mineral oil and are entirely based on water-soluble chemicals, such as surfactants, corrosion inhibitors, and lubricating additives (15). This type is generally used in the form of a clear solution and is transparent, allowing for better visibility of the

cutting process. Its cooling capacity is very high due to the thermal conductivity of water, while its lubricating effect comes from special phosphorus- or chlorine-based additives.

Synthetic fluids demonstrate optimal performance in mist cooling processes for S45C steel, with lower surface roughness values than mineral fluids (3). However, these fluids have limitations in terms of lubricity and can cause skin irritation if not managed properly.

According to previous research, synthetic fluids tend to be more chemically stable and suitable for use in flood and MQL systems with high pressure (12). This makes them popular in high-precision machining such as stainless-steel finishing.

4.2 Mineral Coolant

Mineral-based coolants are petroleum distillates combined with various protective and lubricating additives. This type is a conventional cutting fluid that has long been used in the metal industry, especially for heavy machining processes such as rough turning or drilling hard metals (16).

According to one study, the use of mineral fluids results in higher surface roughness compared to synthetic and vegetable fluids on S45C steel (3). This is due to their lower cooling capacity, even though their lubricity is good for high-pressure processes.

Environmentally, these liquid poses problems because it is not easily biodegradable and produces hazardous waste, requiring special disposal and treatment systems (13).

4.3 Vegetable Coolant

Vegetable-based coolants are an increasingly popular environmentally friendly alternative. These fluids are derived from biological sources such as coconut oil, palm oil, canola oil, or soybean oil. Their natural ester content and high polarity provide superior lubrication properties, even compared to mineral oils (6). In MQL systems, vegetable oils are able to form a strong protective film between the cutting tool and the workpiece, reducing friction and wear.

The use of palm oil and castor oil in the MQL method can significantly reduce surface roughness and cutting force, especially in the machining of stainless steel and aluminum (17,18). In addition to their good tribological performance, vegetable oils are also biodegradable and non-toxic (19).

However, this liquid has limitations in terms of thermal stability and shelf life, especially when exposed to high temperatures continuously. Therefore, recent research has focused on chemical modification or the addition of nanoparticles to improve its stability (20).

The results of various studies show that the type and sub-type of coolant have a direct influence on the surface quality of machining results, as measured by the surface roughness parameter (Ra). Generally, mineral-based fluids such as straight oil produce the highest Ra values (3.0–3.2 μm), making them the baseline for performance. Soluble oil formulations show slight improvements (2.6–2.9 μm), but still lag behind synthetic and vegetable-based fluids. In contrast, synthetic fluids, particularly fully synthetic phosphate ester-based fluids, can reduce roughness to 1.6 μm , demonstrating high cooling efficiency and chemical stability despite relatively moderate lubricity. This performance is suitable for light and precision machining, such as aluminum and stainless steel, but under heavy load or high-temperature conditions, its effectiveness may decrease.

Vegetable fluids consistently demonstrate the best performance in reducing surface roughness. Palm oil, coconut oil, soybean oil, and modified jatropha oil are capable of producing Ra values between 1.2–1.7 μm , with an improvement percentage of up to 55% compared to mineral fluids. This performance is attributed to their ability to form a stable lubricating film in the friction zone, as well as maintaining high viscosity at operating temperatures. MQL formulations based on vegetable oils have also proven to be more thermally and tribologically efficient while supporting sustainability principles. However, oxidative stability and shelf life at high temperatures remain technical challenges that need to be addressed through chemical modification or the addition of additives. These findings confirm that the future direction of coolant development will shift from mineral-based formulations toward environmentally friendly synthetic and plant-based formulations using advanced technology.

5. Results and Discussions

A comparative analysis of various types of coolants shown in Table 2 indicates that the type and formulation of coolants significantly influence the surface roughness (Ra) of machining processes. Mineral-based coolants, particularly straight oil types, exhibit the lowest performance with Ra values

ranging from 3.0 to 3.2 μm , serving as the baseline reference. Emulsion formulations such as soluble oil provide a slight improvement in performance, with Ra values of 2.6–2.9 μm , but still lag behind synthetic and vegetable fluids. In contrast, synthetic coolants, particularly fully synthetic types consisting of a mixture of water, esters, and corrosion inhibitors, exhibit high cooling capacity and chemical stability. This results in a smoother surface, with a Ra value of 1.6–1.9 μm . This fluid is suitable for light and high-speed machining, but its lubrication effectiveness remains below that of oil-based fluids, especially under high cutting loads (21, 22).

Table 2. Comparison of surface quality against types of cooling fluids

No.	Coolant Type	Sub-Type	Machining Process	Ra (μm)	% Improvement	Ref.
1	Synthetic Oil	Semi-synthetic (water + surfactant)	Turning, Milling	1.8–2.1	~30%	(21)
2		Fully synthetic (water + phosphate ester + inhibitor)	Turning on Al and SS	1.6–1.9	~35%	(22)
3	Mineral Oil	Straight oil (no water, high viscosity)	Drilling, Rough Turning	3.0–3.2	Baseline	(23)
4		Soluble oil (oil + water, 5–10% emulsion)	Milling, Light Drilling	2.6–2.9	5–10% better than straight oil	(24)
5		Pure palm oil (MQL)	Turning carbon steel	1.5–1.7	~45%	(25)
6	Vegetable Oil	Coconut oil + Canola oil	Milling, Stainless Steel	1.3–1.6	~50%	(26)
7		Modified castor oil ester	High-speed turning	1.2–1.5	~55%	(6)
8		Soybean oil (MQL, biodegradable)	Turning Aluminium alloy	1.6–1.9	~35%	(22)

Meanwhile, vegetable fluids show the best performance in reducing surface roughness. Types such as palm oil, coconut oil, soybean oil, and modified castor oil are capable of producing Ra values between 1.2–1.7 μm , with a surface quality improvement rate of 50–55% compared to mineral fluids. This is due to the ability of vegetable fluids to form a strong and stable protective layer in the friction zone thanks to their polar molecular structure and high viscosity. Additionally, vegetable fluids have a low friction coefficient, which reduces temperature and wear on cutting tools, resulting in a smoother surface. Chemically modified formulations such as esterified castor oil have also been proven to enhance thermal and oxidative stability, making them highly effective in high-speed machining processes (6,22). However, challenges related to shelf life and resistance to thermal degradation remain key concerns that can be addressed through the development of additives and nano-technology. These findings indicate a shift in the trend toward using plant-based coolants as a more environmentally friendly and high-performance alternative to mineral-based solutions.

6. Conclusions

Based on a literature review of various types of coolants used in machining processes, it can be concluded that the type and formulation of coolants have a direct influence on the surface roughness of workpieces. Mineral-based coolants, although widely used conventionally, exhibit the lowest performance in terms of surface quality. On the other hand, synthetic fluids provide better cooling and lower surface roughness, particularly in light machining. However, plant-based coolants demonstrate the most optimal performance, with a reduction in Ra values of up to 55% compared to mineral fluids, while also offering environmental advantages due to their biodegradable and non-toxic properties.

Considering both technical and sustainability aspects, it is recommended that the manufacturing industry gradually adopt plant-based coolants, particularly in Minimum Quantity Lubrication (MQL) schemes, which have proven to be efficient and environmentally friendly. For high-speed machining processes or extreme temperatures, the formulation of plant-based fluids can be enhanced through chemical modifications such as esterification or the addition of nano-additives to improve thermal and oxidative stability. Further research is needed to develop locally sourced plant-based fluids with long-term stability and broader compatibility with various types of materials and cutting parameters.

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