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Effect of spindle speed and air pressure on surface roughness and tool wear in MQL turning of S45C steel using recycled cooking oil

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Abstract

The turning process of S45C steel often encounters challenges, including poor surface finish and rapid tool wear, while the extensive use of conventional cutting fluids raises environmental and health concerns. Minimum Quantity Lubrication (MQL) has emerged as a sustainable alternative; however, studies investigating the combined effects of spindle speed and air pressure in MQL turning using used cooking oil remain limited. This study aims to experimentally analyze the coupled effects of spindle speed and air pressure on surface roughness and tool wear in the turning of S45C steel using an MQL system with recycled cooking oil. A complete factorial design was used, with each spindle speed (800, 1000, 1200 rpm) tested at each air pressure level (1, 2, 3 bar). The experiments were conducted on a conventional lathe with a feed rate of 0.017 mm/rev, depth of cut of 0.5 mm, and a carbide insert tool. Surface roughness and tool wear were measured as outcomes. The results show that the MQL application reduced surface roughness and tool wear compared to dry cutting. The lowest surface roughness (Ra = 2.609 µm) and the minimum tool wear (VB = 0.046 mm) were obtained at a spindle speed of 800 rpm and an air pressure of 2 bar under MQL conditions. These findings demonstrate that MQL with used cooking oil provides adequate lubrication and cooling, enhances machining performance, and supports sustainable and environmentally friendly manufacturing practices.

Keywords:
Turning, S45C steel, spindle speed, air pressure, Minimum Quantity Lubrication (MQL), surface roughness, tool wear

1 Introduction

The manufacturing industry is a strategic sector that plays a significant role in supporting a country's economic growth and technological advancement. One of the key aspects of this industry is the machining process, which involves the shaping of materials through the interaction between a cutting tool and a workpiece to produce components with the desired shape and dimensions. Among various machining processes, turning is the most widely used due to its ability to produce cylindrical shapes with high precision [1].

One of the materials commonly used in industry is S45C steel, a medium-carbon steel widely used in shafts, gears, and other machine components. This material possesses good strength and hardness, which can be enhanced through heat treatment. However, S45C steel also has limitations, such as low corrosion resistance, limited weldability, and brittleness when not properly tempered. In addition, its moderate machinability requires careful determination of cutting parameters to achieve good surface quality and prolonged tool life [2].

In an effort to improve machining efficiency and product quality while reducing environmental impact, the Minimum Quantity Lubrication (MQL) method has gained widespread application. The MQL system uses compressed air to deliver a minimal amount of cutting fluid to the cutting zone, thereby reducing the need for conventional coolants and chemical waste [3]. Several studies have shown that MQL performs more effectively than dry cutting, especially at low spindle speeds, as it can reduce surface roughness and extend tool life.

Numerous previous studies have highlighted the effectiveness of using bio-lubricants in MQL systems, Mazwan et al. (2024) reported that palm oil produced better surface roughness and lower tool wear compared to sunflower oil, which was attributed to its higher viscosity (41.9 mm^2/s) compared to sunflower oil (38.2 mm^2/s), enabling the formation of a more stable lubricating film [4]. Similarly, Setyarini et al. (2021) found that coconut oil achieved the lowest surface roughness of 1.0843 µm and the least tool wear of 0.0344 cm^3 compared to other natural oils [5]. This indicates that lubricant viscosity characteristics significantly influence machining quality. Recycled cooking oil-based MQL significantly improves the surface finish and demonstrates that the proper combination of lubrication parameters and spindle speed enhances machining quality [6].

Although lubricant performance is also influenced by other physical properties such as thermal conductivity and heat capacity, these parameters play a secondary role in MQL systems. In MQL, cooling is primarily provided by compressed air, while the lubricant primarily reduces friction by forming a thin lubricating film. Therefore, viscosity is considered the most critical parameter governing oil-mist stability and tribological performance. For this reason, the present study focuses on viscosity as the primary lubricant characteristic, while other thermal properties are beyond its scope.

Process parameters, such as spindle speed, feed rate, and MQL air pressure, also significantly affect cutting performance. Kazeem et al. (2022) reported that feed rate is the dominant factor influencing surface roughness by up to 97% [7], while Rachmadi et al. (2022) and Johan et al. (2025) found that increasing spindle speed is inversely proportional to surface roughness [8,9]. In a related study, El Rayes et al. (2023) conducted an experiment on AISI 1045 steel turning with variations in cutting speed (80, 120, and 160 m/min), depth of cut, and feed rate at three levels [10]. Their findings revealed that the optimal operating condition was achieved at f_r = 0.05 mm/rev, v*c* = 156.5 m/min, and a_p = 0.57 mm, producing the highest material removal rate (MRR) with good surface quality (*Ra* = 0.719 µm). Conversely, the combination of f_r = 0.09 mm/rev, vc = 82.3 m/min, and a_p = 0.50 mm resulted in lower cutting force and temperature, albeit with slightly reduced productivity. These results emphasize the importance of optimizing spindle speed and feed rate to balance productivity, cutting force, and surface integrity.

Furthermore, Supriyanto et al. (2022) demonstrated that an air pressure of 4 bar resulted in the lowest surface roughness (*Ra* = 0.830 µm) compared to 6 bar, which increased cutting temperature and power consumption [11]. Studies by Tobias et al. (2023) and Duc et al. (2021) also emphasized the importance of controlling air pressure in the MQL system, where excessively high pressure can cause lubricant droplets to be blown away from the cutting zone, while too low pressure limits lubricant distribution [12,13]. The optimal condition is achieved at moderate pressure, which maintains oil mist stability and enhances lubrication effectiveness.

Although many studies have examined the influence of machining parameters on surface quality under MQL conditions, most investigations have focused on individual parameters or fresh vegetable-based lubricants. Research specifically addressing the turning of S45C steel using used or recycled cooking oil as an MQL fluid remains limited. Nevertheless, recycled cooking oil possesses favourable natural lubricating properties and offers significant potential for sustainable machining by supporting circular-economy principles through waste reutilization [3].

Furthermore, previous studies predominantly analysed machining parameters, such as spindle speed and air pressure, independently, whereas the combined interaction between spindle speed and air pressure in MQL turning has not been systematically investigated. In particular, the role of air pressure in stabilizing oil-mist delivery and its interaction with spindle speed in simultaneously controlling surface roughness and tool wear has not been sufficiently clarified. Therefore, this study aims to experimentally analyze the coupled effects of spindle speed and air pressure on surface roughness and tool wear in the turning of S45C steel using a MQL system with recycled cooking oil. The findings are expected to provide new experimental insights into MQL parameter optimisation and to contribute to the development of environmentally friendly, sustainable machining practices.

2 Research methodology

2.1 Materials and equipments

This study used S45C steel as the workpiece material, which was prepared in cylindrical form according to the dimensions shown in Fig. 1. The initial workpiece had a diameter of 32 mm and a total length of 35 cm, of which 5 cm was clamped by the chuck, resulting in an effective turning length of 30 cm. The workpiece was machined into a stepped configuration comprising three sections, each 10 cm long. The turning experiments were conducted on a conventional lathe, GDW LZ350, with a spindle speed range of approximately 70–2000 rpm. During the experiments, the spindle speed was set at 800, 1000, and 1200 rpm according to the experimental design.

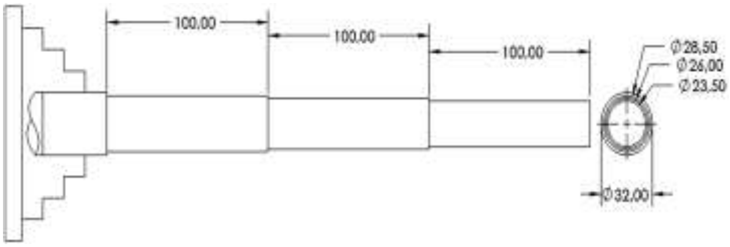


Fig. 1. Workpiece dimensions

The cutting tool employed was a carbide insert (ZCC-CT) grade YBC252, which falls within the ISO P10–P35 range and is suitable for machining medium-carbon steels such as S45C. This grade was selected due to its good wear resistance and stability under varying cutting conditions.

The MQL system consisted of an electric lubricant pump that served solely as a lubricant reservoir and a compressed air delivery system to transport the lubricant to the cutting zone. A DYN AIR DA7001 air compressor supplied compressed air from a 30 L tank, atomising and conveying the lubricant as a fine mist to the tool–workpiece interface. The air pressure was regulated at 1, 2, and 3 bar during the experiments.

Surface roughness measurements were performed using an Amitari AR-132B surface roughness tester, with a resolution of 0.001 μm and suitable for Ra evaluation. Tool wear was observed using a USB digital microscope with up to 1600× magnification, equipped with a monocular lens, enabling detailed visualization of flank wear on the cutting insert.

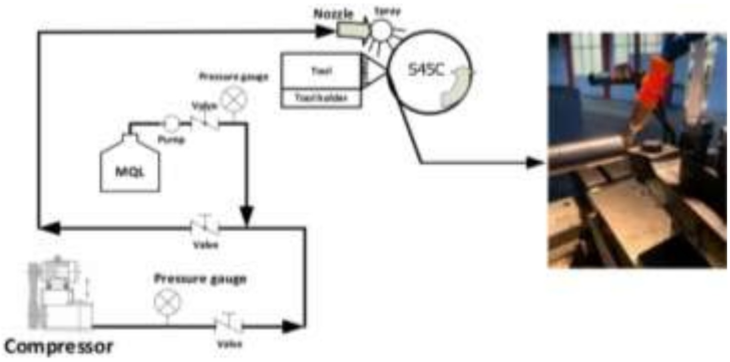
The cutting fluid used in the MQL system was filtered, recycled cooking oil, selected as an environmentally friendly lubricant. Based on prior characterization, the oil exhibited a viscosity of approximately 33 cP at 40 °C, which is suitable for forming a stable lubricating film in MQL applications.

2.2 Experimental methods

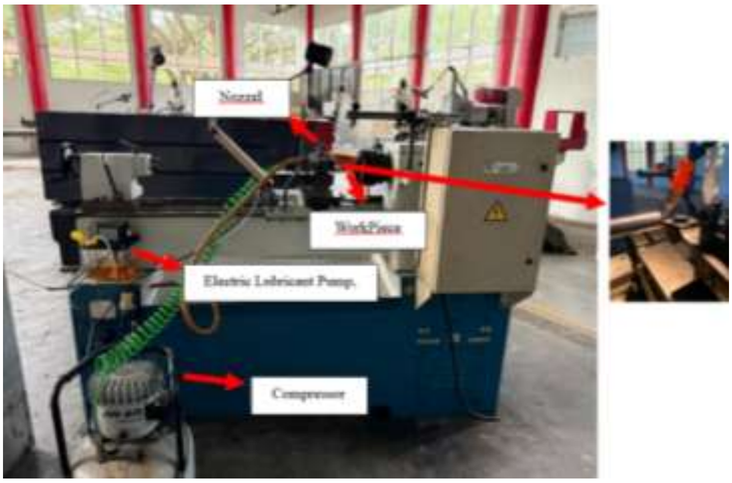
This study was carried out experimentally by comparing two cutting conditions, namely, without MQL and with MQL, using recycled cooking oil as the cutting fluid (Fig. 2). Each condition was tested at three spindle speeds (800, 1000, and 1200 rpm) and three air pressure levels (1 bar, 2 bar, and 3 bar). Each spindle speed level (800, 1000, and 1200 rpm) was combined with all air pressure levels (1, 2, and 3 bar). Therefore, each spindle speed was tested three times at different air pressures, yielding a total of 9 experimental parameter combinations for each cutting condition (dry cutting and MQL). The parameters kept constant included a depth of cut of 0.5 mm, a feed rate of 0.017 mm/rev, the type of insert, and a cutting length of 100 mm. The dependent variables analyzed were the surface roughness and tool wear 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.

Tool wear was measured using a digital microscope to observe the worn area on the cutting insert after each machining test. Images of the tool flank were captured at the location of the maximum wear zone to ensure accurate representation of the wear condition. The captured images were analysed in ImageJ, where the flank wear length (VB) was measured using a calibrated scale from a stage micrometre.



(a)



(b)

Fig. 2. (a) Schematic, (b) The turning process using the MQL method [6]

2.2.1 Preparation of MQL fluid

The used cooking oil employed 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 stage is crucial for enhancing the stability of the oil's properties, ensuring its suitability for use as a machining fluid.

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

1. **Moisture content**, tested using the oven-drying method at 105 °C in accordance with SNI 01-2891-1992, to ensure that the moisture level remains within a safe range, preventing corrosion or disturbances during the cutting process.
2. **Density**, measured using the pycnometer method following ASTM D1217, determines the fluid's mass density, which

influences its cooling and lubricating capabilities during machining.

3. **Viscosity**, measured using a Brookfield viscometer at 40 °C according to ASTM D2270, is an indicator of the fluid's ability to form a lubricating film on the tool and workpiece surfaces, which directly affects lubrication effectiveness.

The results of the moisture content, density, and viscosity tests are presented in Table 1.

Table 1. Analysis results of recycled cooking oil content before and after filtration

Test parameter	Before filtration	After filtration
Moisture content (%)	0.243	0.146
Density (g/mL)	0.918	0.911
Viscosity (cP)	38	33

Based on these results, the filtered used cooking oil showed a decrease in moisture content compared to its pre-filtration level, making it safer for machining applications. Its density value was relatively close to that of fresh vegetable oil, indicating that its physical structure remained within acceptable limits. Meanwhile, the viscosity of used cooking oil was slightly higher than that of new oil due to repeated heating during frying. This condition actually provides an advantage, as higher viscosity allows the formation of a thicker and more stable lubricating film in the cutting zone. Overall, the characterization results indicate that filtered used cooking oil possesses adequate physical properties to be used as an MQL fluid and has potential as a sustainable alternative to fresh vegetable oil in environmentally friendly machining applications.

2.2.2 Surface roughness measurement method based on ISO 4287

The surface of a machined specimen experiences structural modifications caused by material deformation during the interaction between the cutting tool and the workpiece. These alterations lead to the formation of surface irregularities, commonly known as surface roughness, which reflect the material's microstructural condition after machining. Surface roughness not only determines a product's visual or aesthetic quality but also significantly affects its functional characteristics, including wear resistance, frictional behaviour, and tool life.

In this study, surface roughness was analysed in accordance with ISO 4287:1997, which defines surface roughness parameters based on the profile measurement method. Among these parameters, Ra (arithmetic mean roughness) was selected as the primary indicator because it provides a representative assessment of the average height deviations produced during the machining process.

Surface roughness measurements were performed using a Surface Roughness Tester at three specific locations along the cutting path, namely, the beginning, middle, and end, to ensure that the data accurately reflected the overall surface condition of the workpiece. The final roughness value was calculated as the arithmetic mean of the three measurements, thereby minimizing potential errors arising from variations in cutting conditions throughout the machining process. Through this method, the results not only depict the average surface quality but also provide valuable insights into the consistency of machining performance under different lubrication conditions, particularly in comparing dry cutting with MQL using recycled cooking oil.

2.2.3 Tool wear measurement method using digital microscope

The cutting tool undergoes gradual wear due to continuous friction and high temperature generated during the cutting process. Tool wear is a critical parameter that directly influences the quality of the machined surface, cutting force stability, and overall tool life. In this study, tool wear was measured as flank wear (VB), which occurs on the clearance face of the cutting tool and comes into contact with the workpiece during turning operations.

Tool wear measurements were carried out using a Hiview digital microscope, which captured high-resolution images of the worn area on the cutting insert after each machining test. Before imaging, the insert was cleaned with technical alcohol to remove oil residues, chips, and contaminants that could impair visibility of the wear marks. The microscope magnification was adjusted between 50× and 1600×, depending on the size and clarity of the worn area, to ensure optimal image quality.

Each image was captured at the location of the maximum wear zone, the point where the wear land appeared longest on the flank surface. The captured images were saved as JPEGs and labelled according to the corresponding cutting condition.

Subsequently, the wear length was measured using ImageJ software (NIH, USA). The software calibration was performed beforehand using a stage micrometre with a precision of 0.01 mm to determine the pixel-to-length conversion factor. After calibration, the wear image was opened in ImageJ, and the "Line Tool" was used to draw a straight line from the starting point to the end of the wear land. The actual wear length was then calculated automatically by the software based on the calibration scale, as can be seen in Fig. 3.

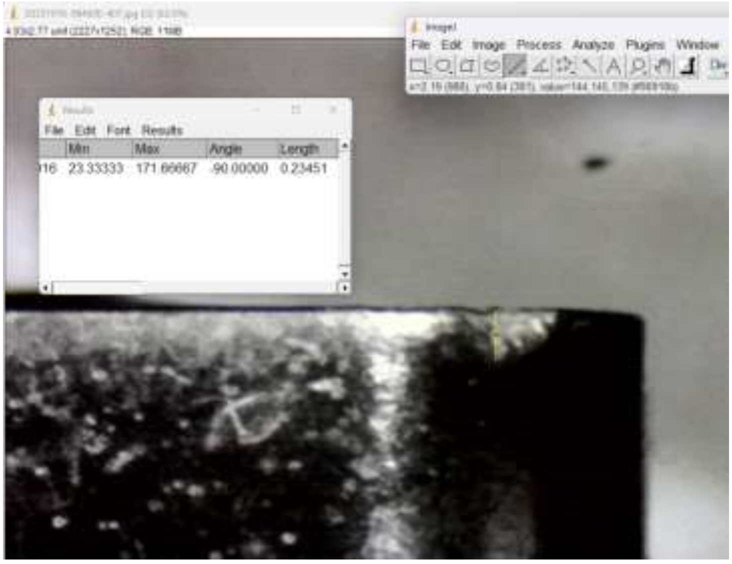


Fig. 3. Tool wear measurement

The value obtained from this measurement represents the maximum flank wear (VBmax) in millimeters. Only one measurement point, the area with the longest wear land, was evaluated for each cutting insert, as it best represents the tool's most critical wear condition.

The measurement results were analysed to determine the effects of spindle speed and air pressure on tool wear behaviour under both MQL and dry cutting conditions. The VBmax value was used as a comparative indicator, where higher values indicate greater tool degradation and shorter tool life. This approach provides a clear understanding of the cutting tool's tribological performance and the effectiveness of the MQL system using recycled cooking oil as a sustainable lubricant**.**

3 Results and discussion

3.1 Surface roughness test results

The experiment was conducted on S45C steel using MQL with recycled cooking oil and dry cutting (without lubrication). Each spindle speed variation (800 rpm, 1000 rpm, and 1200 rpm) was tested under three air pressure levels (1 bar, 2 bar, and 3 bar). Surface roughness (Ra) was measured at three points on each specimen.

The results of the study, shown in Fig. 4, indicate that surface roughness is significantly influenced by spindle speed, air pressure, and lubrication conditions. Across all machining parameters, MQL with recycled cooking oil consistently produced lower surface roughness than dry cutting. The lowest surface roughness (Ra = 2.609 µm) was achieved at 2 bar air pressure and 800 rpm spindle speed, while the highest (Ra = 4.714 µm) occurred at 1 bar and 1000 rpm. In contrast, under dry cutting conditions, the lowest roughness was 4.385 µm (2 bar, 1000 rpm) and the highest reached 6.144 µm (1 bar, 800 rpm).

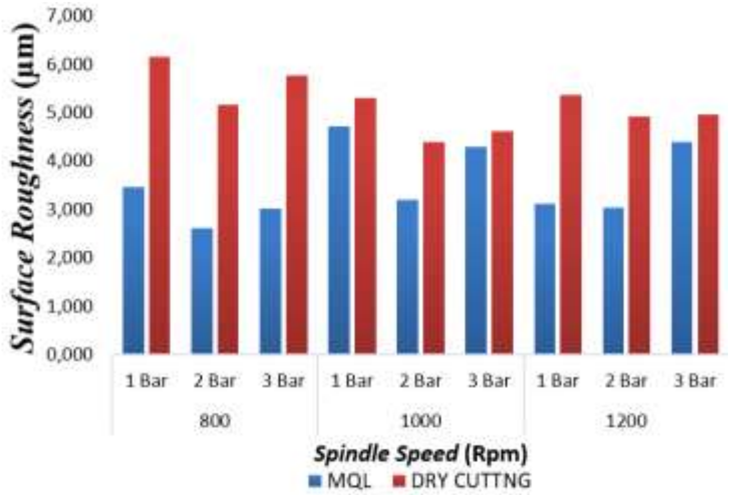


Fig. 4. Comparison of surface roughness (Ra) values at different spindle speeds under dry cutting and MQL conditions

An air pressure of 2 bar provided optimal oil-mist atomization, ensuring uniform lubricant delivery and effective heat dissipation. At 1 bar, insufficient lubricant transport resulted in unstable lubrication, whereas at 3 bar, excessive airflow tended to disperse the lubricant away from the cutting zone. Increasing spindle speed beyond 800 rpm increased cutting temperature, accelerated lubricant evaporation, and reduced film stability, leading to higher surface roughness.

These findings are consistent with previous studies reported in [12] and [13], which demonstrated that the application of MQL using vegetable-based cutting fluids significantly reduces surface roughness compared to dry machining. However, the present study extends previous work by demonstrating that used cooking oil, when applied under optimized MQL parameters, can achieve comparable improvements in surface finish. This confirms the potential of recycled cooking oil as an effective and environmentally friendly alternative cutting fluid for sustainable turning operations.

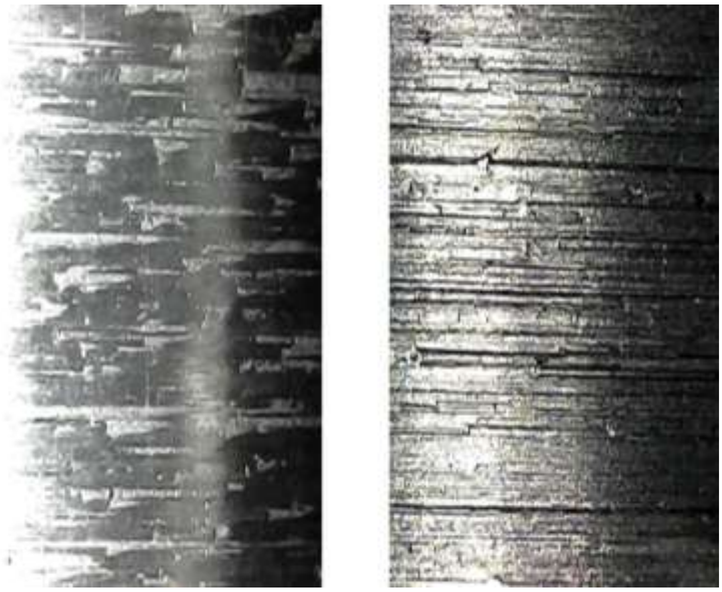
Theoretically, increasing spindle speed tends to reduce surface roughness due to smoother frictional interaction and shorter contact time between the cutting tool and the workpiece. However, the present study revealed a different trend: the lowest surface roughness (Ra) was observed at 800 rpm under MQL conditions. This can be attributed to the balance between heat generation and lubricant film stability. At spindle speeds 1000 rpm and 1200 rpm, more frequent tool–workpiece contact increases cutting temperature, causing the MQL lubricant to evaporate more rapidly and destabilize the protective film, which leads to higher friction and rougher surfaces.

A significant increase in spindle speed can cause micro-deformation due to excessive heat generation, thereby reducing machining quality [14]. At lower spindle speeds, the cutting process occurs with higher frictional resistance because the contact time between the tool and the workpiece is longer, which promotes the formation of a Built-Up Edge (BUE) and degrades surface quality. Conversely, at very high spindle speeds, the elevated cutting temperature leads to lubricant degradation and chip flow instability, thereby increasing surface roughness [15].

Excessive heat reduces lubricant stability and promotes micro-deformation on the workpiece surface, increasing surface roughness at higher spindle speeds. In contrast, at 800 rpm under the MQL system, the friction rate and cutting temperature remain relatively stable. With the aid of MQL at 2 bar air pressure, the lubricant can be evenly distributed and form a stable film layer between the tool and the workpiece. This layer helps lower the coefficient of friction and prevents the formation of BUEs, thereby producing a smoother surface even at lower spindle speeds.

3.2 Tool wear test results

Tool wear was observed to analyse the effects of spindle speed and air pressure on flank wear (VB) under MQL and dry cutting conditions. Representative images of tool flank wear under MQL and dry cutting conditions are shown in Fig. 5. The relationship between air pressure, spindle speed, and flank wear under MQL and dry cutting conditions is presented in Fig. 6. The results show that under MQL, the lowest flank wear (VB = 0.046 mm) occurred at 2 bar and 800 rpm, while the highest (VB = 0.084 mm) was observed at 1 bar and 1000 rpm. Under dry cutting, flank wear values were notably higher, reaching up to 0.235 mm at 1 bar and 800 rpm.



(a) (b)

Fig. 5. (a) MQL 800 Rpm 2 Bar, (b) dry cutting 800 Rpm 1 bar

Fig. 6. Comparison of tool flank wear (VB) under MQL and Dry cutting conditions

The tool wear results demonstrate a strong dependence on spindle speed, air pressure, and lubrication condition. In general, tool wear increased with increasing spindle speed due to higher cutting temperatures and intensified friction at the tool–workpiece interface. The highest tool wear was observed under dry-cutting conditions at 800 rpm and 1 bar air pressure, indicating insufficient lubrication and cooling in the cutting zone.

The application of the MQL system using recycled cooking oil significantly reduced tool wear compared to dry cutting for all tested parameters. Among the investigated conditions, an air pressure of 2 bar provided the best lubrication performance, ensuring stable atomization and consistent lubricant delivery to the cutting interface. This condition minimized adhesive and abrasive wear mechanisms on the cutting tool.

At higher spindle speeds (1000 and 1200 rpm), tool wear increased even under MQL conditions; however, the wear rate remained lower than that observed in dry cutting. Increasing the air pressure to 3 bar did not further reduce tool wear, as excessive airflow tended to disperse the lubricant away from the cutting zone, reducing its effectiveness. These results indicate that spindle speed is the dominant parameter influencing tool wear, while optimized MQL air pressure plays a critical role in mitigating wear and extending tool life. The effect of spindle speed and MQL air pressure on tool wear is illustrated in Fig. 7.

Fig. 7. Tool wear

Research by Patole et al. (2021) shows that the MQL system can significantly reduce the wear rate of cutting tools compared to dry cutting [16]. In their study, Patole et al. (2021) found that micro-lubrication can form a stable thin film between the cutting tool and the workpiece, thereby reducing friction and slowing the mechanisms of adhesive and abrasive wear [16]. In addition, the cooling effect of pressurized air jets in the MQL system helps maintain cutting temperatures from rising excessively, which ultimately extends tool life.

The application of the MQL system at a spindle speed of 800 rpm and an air pressure of 2 bar improved lubrication stability in the cutting zone [17]. This condition effectively reduced metal-to-metal friction, minimized temperature rise, and slowed down the rate of tool wear. At a spindle speed of 800 rpm and sufficient air pressure, the MQL system effectively maintained a balance between lubrication and cooling during the turning process.

3.3 Correlation between tool wear and surface roughness

The relationship between tool wear and surface roughness is a critical aspect in understanding machining performance under MQL conditions. As the cutting process progresses, tool wear alters the geometry of the cutting edge, directly affecting the interaction between the tool and the workpiece surface.

In this study, the trend between flank wear (VB) and surface roughness (Ra) showed a direct correlation: as tool wear increased, surface roughness tended to rise. Under MQL conditions, the lowest flank wear value (VB = 0.046 mm) corresponded to the lowest surface roughness (Ra = 2.609 μm), both occurring at 2 bar air pressure and 800 rpm spindle speed. Conversely, the highest wear value (VB = 0.084 mm) under MQL, recorded at 1 bar and 1000 rpm, was associated with a rougher surface (Ra = 4.714 μm).

The progressive deterioration of the cutting edge can explain this correlation. As flank wear develops, the effective rake and clearance angles decrease, increasing the contact area between the tool and the workpiece. This results in higher friction and temperature in the cutting zone, promoting adhesion and micro-welding on the machined surface. The result is a rougher finish, characterized by irregular feed marks and surface tearing.

The MQL condition helps delay the onset of wear by maintaining a thin, stable lubricating film that minimizes direct metal-to-metal contact. This film reduces heat generation and improves chip evacuation, resulting in slower wear progression and more consistent surface quality. In contrast, dry cutting conditions exhibited accelerated wear and a rapid increase in surface roughness due to poor lubrication and elevated cutting temperatures.

Although MQL with recycled cooking oil has been shown to reduce tool wear and improve surface finish, the variable viscosity of used oil can make consistent quality control challenging. This variability should be considered, as it affects the formation of the lubricant film and the distribution of droplets in the cutting zone. Further research is recommended to evaluate the effects of viscosity variation and to develop standardization methods to ensure consistent fluid properties.

4 Conclusions

This study investigated the effects of spindle speed and air pressure on surface roughness and tool wear in the turning of S45C steel using a MQL system with recycled cooking oil. The results show that applying MQL significantly improved machining performance compared to dry cutting. The optimal condition was achieved at a spindle speed of 800 rpm and an air pressure of 2 bar, resulting in the lowest surface roughness and reduced tool wear. Spindle speed was identified as the dominant factor influencing tool wear, while appropriate air pressure was crucial for adequate lubrication and cooling. These findings confirm that recycled cooking oil has strong potential as an environmentally friendly alternative cutting fluid for sustainable turning operations.

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