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Comparative study of tree-based vegetable and mineral oils as cutting fluids in milling AA7075 under MQL condition

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KEYWORDS

Minimum quantity lubrication
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Surface roughness
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ABSTRACT

The novel cooling technique utilized in machining, referred to as Minimum Quantity Lubrication (MQL), comprises the thorough blending and atomization of modest quantities of lubricants in along with compressed air. This approach is widely recognized for its environmentally conscientious and resource-conserving attributes. However, its advancement is constrained to the utilization of mineral oils due to their intrinsic resistance to degradation and the potential hazards they pose to both human well-being and the environment. Therefore, the objective of this study is to assess the milling performance of aluminum alloy 7075 under MQL techniques using three different vegetable oils: palm oil, virgin coconut oil, and olive oil, and then compare them to dry conditions, flood cooling with soluble oil, and MQL using mineral oil. The experimental results showed that olive oil exhibited the lowest cutting force across all conditions, with a 22% reduction compared to the dry condition. Furthermore, the lowest surface roughness values were obtained by utilizing virgin coconut oil with a 47.9% reduction compared to the dry condition. These findings show the significant impact of the MQL technique using vegetable oils with the cutting force and machined surface quality.

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1.0 INTRODUCTION

The growing demand for creating a work environment that prioritizes the health and well-being of employees in the machining industry has driven a push toward adopting eco-friendly machining methods. The word "green" in the context of machining operations includes several factors namely a healthy working environment that is free from hazards, adhering to quality standards, efficient use of energy and time, as well as aspects of production costs (Ghani et al., 2014)(Ahmad et al., 2021). Furthermore, Green machining is a technique developed to manufacture products that reduce resource consumption, cut operational costs, and promote environmental health. To efficiently utilize this technique, it is imperative to initially execute a machining operation without conventional Metalworking Fluids (MWFs), often described as dry or near-dry machining.

The adoption of MWFs is a common practice to enhance machining performance and machinability. This practice has gained popularity primarily because of its associated benefits, which include its capability to reduce the heat that is generated by friction during cutting, extend the life of the cutting tool, prevent built-up edges, facilitate chip removal, and enhance surface finish (Wickramasinghe et al., 2020). However, there are a lot of problems associated with the use of MWFs. These problems include environmental concerns, worker health and safety, fluid system maintenance, fluid pre-treatment and treatment, and proper waste disposal (Sharma et al., 2016). It is also important to note that the use of MWFs contributes to roughly 20% of the overall costs in machining operations (Khettabi et al., 2017). Although the use of dry machining may initially offer benefits, it is important to be cautious of tool wear and part quality. In situations where dry machining is not feasible, minimal quantity lubrication (MQL) can be used to help maintain a satisfactory tool lifespan and achieve the desired quality for machined products.

Minimum quantity lubrication (MQL) is a machining technique that includes the application of cutting fluids in extremely small quantities. Generally, the flow rate of these fluids ranges from 50 to 500 mL/h (Sultana & Dhar, 2022). The MQL process entails mixing a small amount of lubricant with air to create an aerosol, which is then sprayed into the cutting zone using a nozzle with compressed air. The MQL system comprises various components, including a controlled lubricant/fluid pump, an atomizer, and a discharge nozzle, among others. Each component within this system serves a unique function. For instance, the atomizer functions as an ejector system using high-pressure air to disperse the coolant into fine particles, which are subsequently transported to the cutting zone by air. On the other hand, the oil pump serves as a means through which the cutting fluid flows to maintain a consistent hydraulic load, due to the venturi effect occurring in the mixing chamber. It is important to note that as air passes through the mixing chamber, it atomizes the lubricant stream, transforming it into an aerosol composed of micron-sized particles. This aerosol is then released as a mist within the cutting area and it functions as both a coolant and a lubricant, effectively penetrating the tool-workpiece interface (Sharma et al., 2016).

Extensive studies and investigations into the MQL have been reported previously. Mineral oils are primarily utilized as the conventional base oil in the MQL applications. Liao and Lin (2007) studied and investigated how the lubrication method affected the workpiece surface roughness and tool wear during high-speed face milling. The findings of their study revealed that the implementation of the MQL resulted in significant benefits in terms of extending the tool's life and enhancing the workpiece's surface quality. In another study, Kouam et al. (2015) investigated the effect of flow rate and dry conditions on chip shape when cutting AA 7075-T6 using a mineral oil-based MQL. The findings suggested that adjusting the feed rate, cutting speed, and the MQL flow rate could enhance the chip breakability of the ductile 7075-T6 aluminum alloy. However, Mineral oils, have low biodegradability and may lead to persistent pollution problems in the environment. Furthermore, mineral oils are incompatible with the idea of green manufacturing. To address these environmental concerns and reduce processing costs, some researchers have ventured into using vegetable oils as an alternative base oil for MQL.

In a study by Okafor and Nwoguh (2020), the milling of Inconel 718 was examined, employing the MQL technique along with coated carbide inserts. They performed a comparative analysis of conventional emulsion flood coolants and the MQL specifically using soybean oil at different flow rates. The results show that using a flow rate of 70 ml/h leads to enhanced surface finish and decreased cutting force in comparison to the use of flooded cooling. Yildirim et al. (2017) conducted a comprehensive comparison of vegetable oil's performance against synthetic oil, and mineral oils with varying flow rates in the milling process, using the Taguchi method. Compared to other oils that were analyzed, vegetable oil was found to extend tool life and reduce cutting force. This suggests that a minimal quantity of oil can be more effective at lowering temperatures than simply using air blowing. Similarly, Bedi et al. (2020) investigated the effectiveness of vegetable oil in the MQL while cutting AISI 304 stainless steel. The findings indicated that machining with rice bran oil results in lower cutting force, lower tool-tip temperature, reduced level of tool wear, and improved surface quality compared to dry conditions and the use of coconut oil. Furthermore, Yin et al. (2021) have studied and investigated a variety of vegetable oils for use in machining AISI 1045. They found that palm oil produced the least cutting force, minimized friction, and the smoothest surface on the workpiece.

As observed from previous studies, numerous varieties of vegetable oils remain uninvestigated and unexamined regarding their potential utilization as lubricants within the MQL technique. Moreover, the machining of aluminum metal predominantly relied on milling processes across diverse industries including aerospace, aviation, and other related sectors, primarily attributed to their high mechanical strength, low density, and corrosion resistance (Pang et al., 2023). Following this, it should be noted that aluminum alloys have a relatively low melting point, and their malleability increases as the cutting temperature rises. This leads to elevated levels of friction at the cutting interface under high temperature and pressure conditions, which can present challenges in achieving high-quality surface finishes.

The diverse lubricating characteristics inherent to various vegetable oils consequently give rise to discrepancies in their overall efficacy. Therefore, it is important to test with various vegetable oils as the MQL's base oil to assess the performance of each vegetable oil while milling aluminum alloys. The purpose of this investigation is to study the MQL conditions using three various vegetable oils and two mineral ones as compared to dry slot milling of 7075-T6 aluminum alloy. The aim is to determine the most suitable lubrication oil based on the specific cutting conditions, with a particular focus on factors such as cutting force and surface roughness.

2.0 EXPERIMENTAL PROCEDURE

The milling experiments were conducted on the AA-7075 aluminum alloy as part of the test study. The chemical composition of this alloy is typically outlined in Table 1. Furthermore, the experimental workpiece was a rectangular block with dimensions of 120 mm in length, 50 mm in width, and 30 mm in height. The experimental cutting conditions are presented in Table 2. Cutting tests were carried out on a Knuth UFM2 milling machine with a straight slot milling cutting configuration method using a carbide-coated cutting tool insert (APMT 1135-M2 VP15TF) with a tool shank diameter of 14 mm.

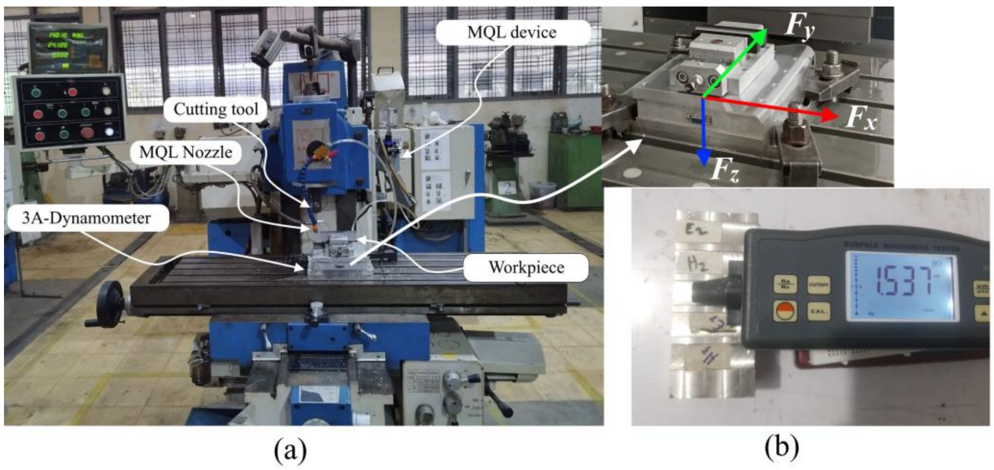

Figure 1: Configuration of the experiments: (a) Experimental setup; (b) surface roughness measurement

The experimental setup, as shown in Figure 1(a), comprised a range of conditions by which tests were conducted. These included dry cutting, machining with flooded cooling using soluble oil, and MQL using mineral oil SAE 20W-50, as well as vegetable oils such as palm oil, virgin coconut oil and olive oil. The main characteristics of these cutting oils are summarized in Table 3. Following this, the lubrication oil was transmitted through the Mesolube MQL-10201 minimum quantity lubrication system with a constant flow rate of 50 mL/h using 4 bars of compressed air. In addition, the nozzle was oriented at a 30° angle with respect to the cutting surface, and the distance between the nozzle and the cutting zone was consistently maintained at 30 mm. During the process of data collection, a 3A-stationary dynamometer was utilized to measure the three component cutting force, F_x, F_y, and F_z (Rizal et al., 2023). The milling force was subsequently sampled at a frequency of 5 kHz. The resultant force (F_R), which is affected by forces in the x, y, and z directions, can be calculated using this equation.

$$F_R = \sqrt{F_x^2 + F_y^2 + F_z^2} \tag{1}$$

where F_x, F_y, and F_z denote cutting force in the x, y, and z directions, respectively. To ensure the reliability of the experimental data, three sets of repeated trials were performed, each under different working conditions, to reduce the potential impact of external factors. It is also important to note that the machined surface quality was measured using a Surface Roughness Tester Landtek SRT6200 for measuring average surface roughness, R_a as shown in Figure 1(b). A Dino-Lite AM2111 optical microscope with a magnification of 210x was utilized to analyze the changes in the surface topography of the machined surface under various cooling conditions and lubricating oils.

Table 1: Chemical composition of AA-7075 aluminum alloy.

Elements	Si	Fe	Cu	Mn	Mg	Zn	Cr	Ti	Al
Weight %	0.4	0.5	1.5	0.3	2.6	5.9	0.3	0.2	Bal.

Table 2: Conditions and parameters used in milling test.

Operation	Slot milling
Feed rate, f_z (mm/tooth)	0.03
Depth of cut, d (mm)	0.2
Cutting speed, v (m/min)	40, 60, 80
MQL flow rate (mL/h)	50
Compressed air (bar)	4

Table 3: Characteristic of cutting oils.

Type of Cutting Oils	Saturated Fatty Acid (%)	Viscosity (mm^2/s)	Density (g/cm^3)
Soluble oil	-	34.2	0.897
Mineral oil	-	36.1	0.889
Palm oil	40 – 46	33.7	0.871
Virgin coconut oil	85 – 90	32.4	0.886
Olive oil	70 – 75	35.4	0.957

3.0 RESULTS AND DISCUSSION

The cutting force serves the purpose of indicating and providing insights into the milling process and assessing the effectiveness of cutting fluid lubrication. An increase in cutting force can cause temperatures to rise and promote the occurrence of interface adhesion, both of which have a negative impact on the surface quality of the workpiece and the durability of the tool. As a result, the cutting force is crucial for enhancing machinability (Bai et al., 2023). Figure 2 shows the raw signal of the three-component cutting force during a slot milling operation with different cooling methods at a cutting speed of 60 m/min. The slot-cutting operation includes intermittent cutting, as the tool makes periodic contact with the workpiece. The force denoted as F_x represents the cutting force applied in the direction of the cutting action, which plays a primary role by performing the cutting process in milling operations. On the other hand, the force F_y represents the force component acting in the direction of the feed, indicating the resistance the workpiece encounters as the tool moves forward. The force F_z represents the axial force that the workpiece and tool apply along the main axis of the cutting tool in the spindle machine. In general, the cutting force pattern remains consistent under various cutting conditions.

Figure 2 demonstrates that the cutting force in dry conditions is the highest among all cutting conditions with cooling techniques. The main cutting force (F_x), feed force (F_y), and thrust force (F_z) were measured and recorded at 86.6 N, 77 N, and 113 N, respectively. Dry cutting results in increased friction between the cutting tool and the workpiece material. Furthermore, cutting without lubrication can cause chips to stick to either the cutting tool or the workpiece's surface. These factors can lead to the creation of a built-up edge, the recutting of chips, and the inadequate removal of chips. The cutting forces increase as the tool faces resistance from bonded chips and uneven chip flow. However, when using a coolant, either by the flooding method or with MQL on all lubricant oils, there is a significant reduction in cutting force. It is clearly seen in the comparison of all cooling conditions, the lowest cutting force is achieved when using MQL olive oil with the force F_x, F_y, and F_z were 56 N, 59 N, and 94 N respectively. It is clear that in all conditions of use of MQL, all cutting force components decrease in range 8 – 38 %, but the thrust force is still greater than the main cutting force and feed force. The higher thrust force in slot milling, in comparison to feed and cutting forces, is mainly attributed to the tool's entire engagement throughout the whole width of the cutting edge. This results in an extensive removal of material with each pass. This leads to a high axial force when the tool applies pressure to the workpiece over the whole depth of the slot.

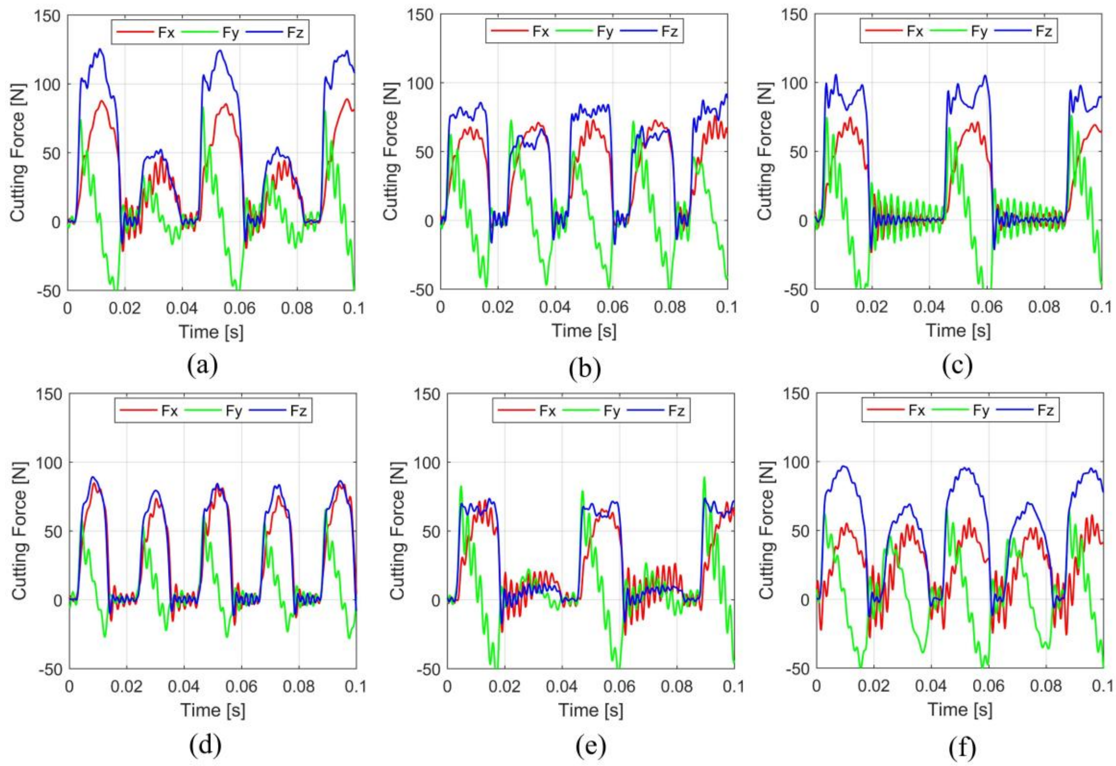

Figure 2: Typical cutting force during slot milling operation: (a) dry condition; (b) Flooded cooling using soluble oil; (c) MQL mineral oil; (d) MQL palm oil; (e) MQL virgin coconut oil; (f) olive oil.

To conduct a comprehensive investigation into the effects of lubrication on the machining process, while maintaining a consistent depth of cut and feed rate, ensuring a thorough and accurate assessment of the impact of various lubrication conditions. The measured cutting forces were compared under three different situations namely dry, flood, and minimum quantity lubrication (MQL) approaches, as shown in Figure 3. In this study, the cutting speed was varied at three levels including 40 m/min, 60 m/min, and 80 m/min, to study its impact on consistency.

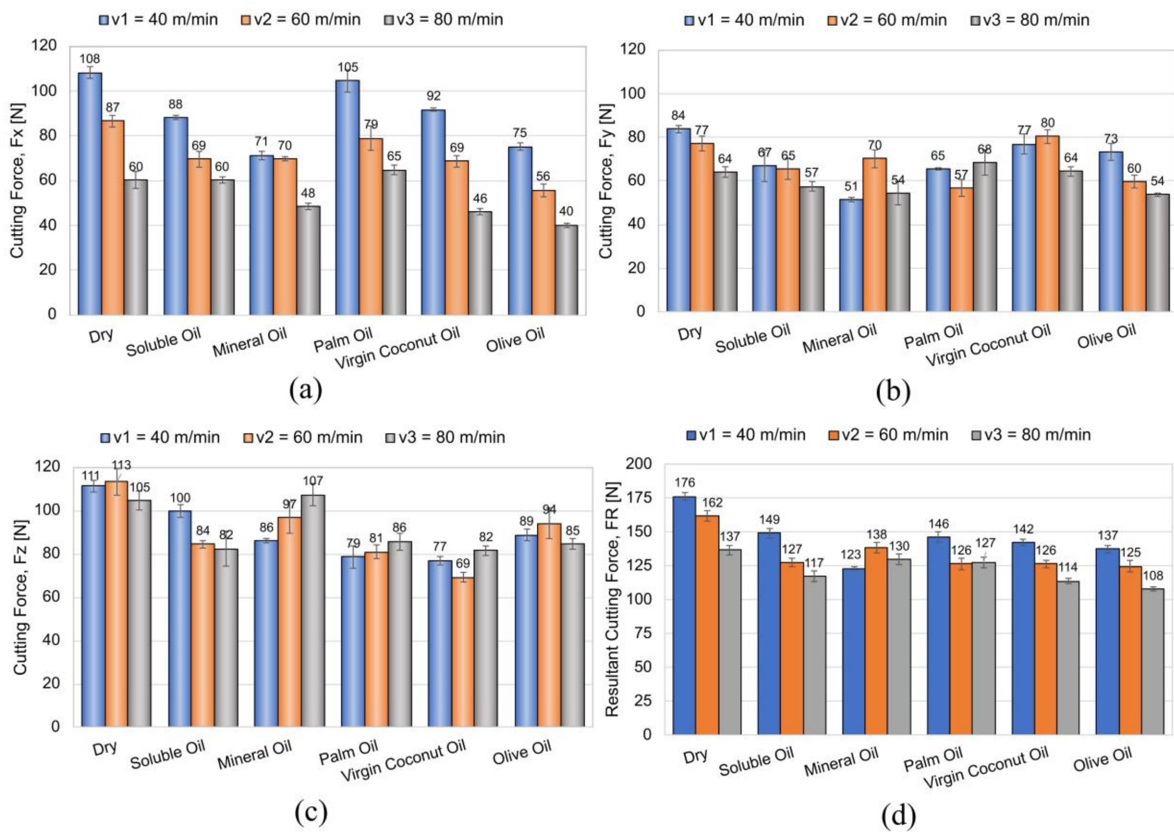

Figure 3: The maximum amplitude of cutting force under different cooling methods: (a) F_x; (b) F_y; (c) F_z; (d) F_R.

The effect of cutting speed on all force components is graphically represented in Figure 3(a). From the figure, it can be seen that as the cutting speed increases, the cutting force decreases, with the force F_x descending more than the other force components. This occurrence is largely attributed to the role of the F_x force as it takes the lead in the cutting process while working on the workpiece. In the same manner, the highest force of the feed movement, denoted by F_y in Figure 3(b), occurred at the beginning of the cut due to the linear relationship between the cutting area and the force required to advance the feed. Meanwhile, the z-axis force, denoted as F_z, showed minimal variations. This can be linked to its predominant role in sustaining the vertical position of the workpiece, as shown in Figure 3(c). The relationships between cutting forces and cutting parameters demonstrate the effects of changes in cutting speed and feed movement on the specific components of cutting force and chip load. Reduced contact time between the tool and workpiece at faster cutting speeds results in decreased friction and cutting forces.

Subsequently, the comprehensive lubricating performance is shown in Figure 3(d), which specifically relates to the resultant cutting force. Throughout this experiment, there was minimal difference in performance between the MQL approach and flooded cooling. When comparing the cutting forces of the MQL palm oil, virgin coconut oil, and olive oil with the resultant cutting force, F_R, in dry conditions, an average reduction of 15%, 19%, and 22%, was observed respectively. Furthermore, the use of mineral oil, resulted in a reduced cutting force with the MQL reaching approximately 16%, while with flooded cooling using soluble oil, it amounted to 17%. This finding shows that the lubrication effects of vegetable oil are equivalent to that of mineral oil when applying both flooded and the MQL techniques. Baldin et al. (2023) reported similar trends in the variation of cutting force while employing various cooling methods for face milling of AISI 1045. The findings show that the use of mineral oil resulted in the lowest cutting force, followed by vegetable-based oils. In addition, these results also are in line with the findings presented by Rahim et al. (2015) who indicated that the MQL technique can reduce the cutting force by approximately 5% to 28% compared to dry cutting. Accordingly, the results obtained in this study suggest that the effectiveness of the MQL is comparable to that of flooded cooling using mineral oil.

These results demonstrate that MQL, especially when applied to vegetable oils, is an effective and practical way to decrease cutting forces, on par with conventional flooding cooling using mineral oils. However, the percentage reduction in cutting force due to cooling also depends on the type of material, cutting method, geometry, and condition of the tool used.

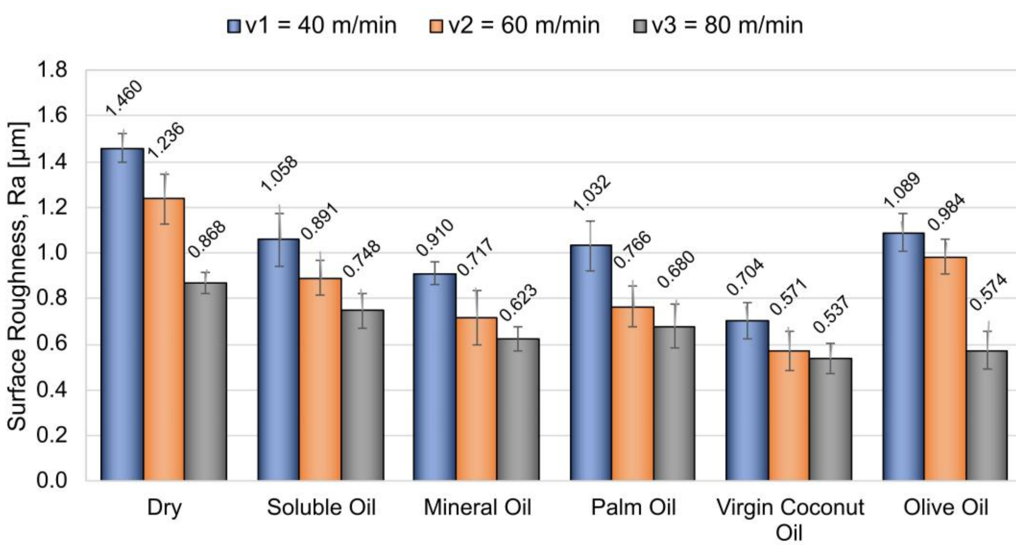

Figure 4: Surface roughness, R_a under different working conditions.

Under each working condition, three specific points were selected on the workpiece surface to measure the average surface roughness R_a. Figure 4 shows the average surface roughness values obtained throughout the milling process, specifically focusing on three different cutting speeds and their corresponding cooling methods. Accordingly, the observed trend indicated a decrease in surface roughness as cutting speed increased, and this pattern remained consistent for all cooling conditions. This clarifies the beneficial effect of increased cutting speed on surface roughness. These findings are in line with the results reported in previous studies, which investigated the milling process of both aluminum and steel alloys (Khettabi et al., 2017)(Binali et al., 2023).

In Figure 4, it can be seen that the surface roughness (R_a) in the dry condition at low cutting speed had the greatest value (1.460 µm) compared to the other groups. It is crucial to point out that the decrease in Ra during MQL milling with vegetable oils led to varying levels of performance improvement. The MQL milling process with virgin coconut oil had the lowest Ra value of 0.537 µm. This value was found to be 47.9% lower compared to the R_a value seen in the dry milling condition. Following this, the milling process with mineral oil produced a R_a value of 0.623 µm, which was discovered to be 35.9% lower compared to the R_a value seen in the dry condition. It was discovered that the utilization of the MQL when used with virgin coconut oil yielded similar results to the MQL when used with mineral oil. The results of the current study are in line with those reported by Fernando et al, (2020) who found that coconut oil had better heat absorption abilities and improved surface finish when cutting mild steel. Furthermore, it is crucial to recognize that the surface roughness achieved with virgin coconut oil exceeded the results obtained with mineral oil. The surface roughness values for the MQL milling using palm oil and olive oil were measured to be 0.574µm and 0.680µm, respectively, which were approximately 29.6% and 26.5% lower than the dry condition. However, when it comes to the MQL milling, olive oil in comparison to other vegetable oils, has been observed to result in a significantly rougher workpiece surface.

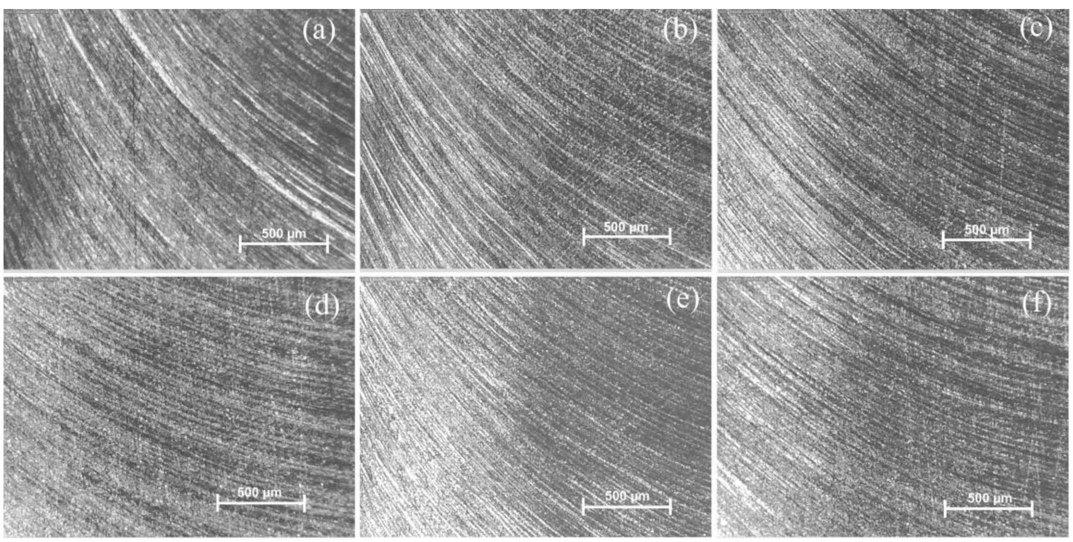

Figure 5: Optical images of machined surface at Vc = 60 m/min: (a) dry cutting; (b) flooding cooling;(c) MQL mineral oil; (d) MQL palm oil; (e) MQL virgin coconut oil; (f) MQL olive oil.

Figure 5 shows the main impact visuals, which show how the six cutting condition operations relate to the machined surface's microscopic texture. The milling process was carried out under dry conditions, flooding was done using soluble oil, and MQL was performed using mineral oil, palm oil, virgin coconut oil, and olive oil. Figure 5(a) shows that in dry conditions, the surface topography displays noticeable height differences and surface marks. More tool marks and surface imperfections may appear when coolant is not present because of the increased friction between the workpiece and the tool. On a machined surface, tool marks or patterns of feeding paths may stand out more. When working with aluminum alloys like AL 7075 during machining, this problem can occur due to built-up edges. These edges can create inconsistent chip formation, which in turn can impact the surface smoothness and topography. Additionally, they can leave traces on the machined surface.

Figures 5(b-f) demonstrate that the use of MQL cooling procedures significantly improves surface quality compared to cutting without any lubrication. The presence of lubrication in the contact zone reduces friction and heat, resulting in fewer and less conspicuous tool marks. While the surface texture of MQL virgin coconut oil may not differ significantly from other vegetable oils, it is evident that using this oil will result in the most obvious improvement in surface quality. This indicates that, when compared to more conventional techniques such as flooding with soluble oil or MQL with mineral oil, the MQL method using vegetable oils such as palm, VCO, or olive oil generates comparable surface quality.

CONCLUSIONS

In summary, three components cutting forces, and surface roughness were examined based on this experimental study. During the experiment, an investigation was conducted to examine and compare the lubricating effects of three types of tree crop-based vegetable oils and mineral oils in the MQL milling process of AA7075, and the results were compared with both dry and flooded conditions. Under the MQL conditions, the milling force was at its lowest when olive oil was utilized. Furthermore, the cutting force was reduced by 15% to 22% for vegetable oils used in the MQL approach compared to dry conditions. The surface quality of the workpiece in the MQL milling based on olive oil was the most inadequate, while that of vegetable oils had different degrees of improvement. Particularly, the MQL milling with coconut oil stood out as the most effective in enhancing the surface quality of the workpiece. When utilizing coconut oil, the surface roughness was reduced by 26.5% to 47.9% for the MQL-based vegetable oils compared to dry conditions. This led to a resulting surface roughness within the range of approximately 0.537 μm to 0.680 μm, demonstrating its correspondence with the finishing surface requirements. These result reveals that the utilization of vegetable oils in MQL milling can effectively reduce cutting forces and enhance surface quality, making it an eco-friendly machining of manufactured products.

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