Potential of Bio-Metal Cutting Fluid from Treated Recycled Cooking Oil for Metal Cutting Fluid Application

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ABSTRACT

Metalworking Fluids (MWFs) are extensively used to achieve a smoother machining operation, a better surface finish, and a longer tool life. Unfortunately, mineral-based metalworking fluids have negative impacts on the workers as well as the environment. This study focuses on the application of bio-MWF from treated recycled cooking oil (TRCO) in machining alloy steel (AISI 4340) metal as a case study. The TRCO from the oil-palm base is proposed due to its availability and not suitable to be consumed by humans. The minimum quantity lubrication (MQL) experimented for machining AISI 4340 with machining parameters recommended for finishing operation at a high-speed regime of machining AISI 4340. The results of cutting force and surface roughness were found to improve compared to dry cutting. Lower cutting force and good surface roughness were obtained. The chips collected from MQL cutting were also thinner and curlier compared to dry cutting which indicates lower friction occurred during the cutting process. The findings from this study indicate TRCO is suitable and has a good potential to be utilized as metal cutting fluid and it supports the Malaysian government policy to create a sustainable environment manufacturing process.

Keywords: *Treated Recycled Cooking Oil (TRCO); Minimum Quantity Lubrication (MQL); AISI 4340; High Speed Regime*

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Introduction

The advantages of metal working fluids (MWF) include removing temperature built-up at the cutting zone, lengthen the tool life, improving surface quality by preventing built-up edge formation, and facilitating the chips removal [1]. Unfortunately, mineral-based metalworking fluids have negative environmental impacts. During the storage and disposing stage of MWF, improper way of handling this substance may lead to water and soil contamination [2]. Raynor reported that vegetable-based cutting oils are less toxic, which allows the industries to significantly reduce the disposal costs, compared with commercial oils cutting fluids or mineral-based cutting fluids [3]. Ghani found that the tool life using lubricant of synthetic and palm oil were similar in machining FCD700 cast iron but due to the environmental impacts, palm oil is preferable [4].

A sustainable manufacturing process is very important as it stresses on environmental safety and creating a healthy workplace for the worker. As a result, the use of vegetable-based cutting oil has been studied as a safer and hazard-free alternative to mineral oil-based metal working fluids. In conventional machining, Metal Working Fluids (MWFs) are generally used to obtain a smoother machining process, a better surface finish, and a longer tool life. Unfortunately, mineral-based metalworking fluids have negative environmental impacts since the chemical substances that are found in MWF, such as phosphorus, chlorine, and zinc dialkyl dithiophosphate, are hazardous [5]. Improper handling of this substance during storage and disposal may lead to water and soil contamination [2]. Hence, Industries are obligated to consider using bio-metal cutting fluid (bio-MWF) and comply with environmental protection laws for occupational safety and health regulations [1]. Department of Commerce [6] defines sustainable manufacturing as a practice to create products through cost-effective processes that minimize the negative impact on the environment, save energy and natural resources. This concept is prioritizing the impact of the manufacturing process on the employee, community, and the product’s quality. From the implementation side, the adoption of sustainability principles in machining processes for all companies will benefit them in terms of cost-saving and improve their environmental management system with production remaining at the same capacity or slightly decreased [7].

A comparison between wet cutting (synthetic and palm oil), and dry cutting machining carried out by Jahara [4] found that the tool life in wet cutting is longer than dry cutting in machining FCD700 cast iron. The result for synthetic and palm oil were similar, but due to the environmental impacts, palm oil is preferable. Furthermore, commercial oil yields a poorer surface finish compares to biodegradable palm oil since it encompasses a special functional group containing oxygen, which allows the oil to adhere better to the metal surface. When compared to formulated fluids or commercial oil, Raynor reported that the uses of vegetable oils are more economical and safer for the environment as well as the worker [2]. In their experimental study, they found that commercial oil generates aerosol or mists that are approximately 30% to 90% higher than in the case of using vegetable oil. The mist that is produced during machining with MWF especially mineral-based cutting oil, exposes the worker to health risks such as skin and eyes irritation, respiratory problems, and various type of cancers [5]. To improve the machining condition, Fang and Obikawa [8] had designed an insert with internal high-pressure coolant to enhance the heat transfer from the cutting tool. As a result, the tool wear rate was decreasing and lengthened the tool life by two times. Fewer chip adherence was also observed at the tool flank face during machining Inconel 718. The effects of coolant concentration and working conditions on tool flank wear and tool life were evaluated when turning Ti-6Al-4V using water-miscible vegetable oil-based cutting fluid [9]. The work concluded that a combination of vegetable oils-based cutting fluid concentration (10%), low cutting speed (58 m/min), feed rate (0.1 mm/rev), and depth of cut (0.75 mm) was necessary to decrease tool wear. In a different study conducted by Perera [10] found that coconut oil is a better metal working fluid for mild steel, while soluble oil is more suitable to be used when machining AISI 304 steel. Wickramasinghe [11] had formulated a novel water-soluble MWF by mixing a coconut oil-based cutting oil with additives. The oil's performance evaluation was conducted for turning and end milling operations for AISI 304 stainless steel, mild steel, and cast iron. The tool surface temperature and surface roughness were measured during the machining experiments, and positive performances were observed when using the coconut oil-based MWF.

An effort towards machining sustainability has motivated the author to study the performance of the treated recycled cooking (TRCO) oil as bio-MWF for machining AISI 4340 due to its availability in Malaysia and not suitable to be consumed by humans as compared to fresh palm oil. AISI 4340 is studied since it is widely used by various industries such as automotive, aerospace, and material for mould making.

Experimental Case Study

According to Ahmad [12] in their review, machining activities with AISI 4340 typically involve an excessive usage of cutting oil to ensure a good surface finish and to improve machining condition i.e. lower cutting force. Accordingly, to impose a greener metal machining process without jeopardising the product's surface and machining quality, a sustainable and greener cooling technique namely MQL that consumes a minimum amount of cutting fluid was used in this work. Later, comparisons were made using dry machining to investigate the effectiveness of using the MQL technique with new Bio-metal cutting oil from Treated Recycled Cooking Oil (TRCO) as the cutting fluid.

Preparation of TRCO

The Bio-Metal Cutting Fluid from Treated Recycled Cooking Oil (TRCO) was produced and purchased from Universiti Teknikal Malaysia Melaka (UTeM). The datasheets for the TRCO properties before and after treatment are given in Table 1. The used cooking oil (UCO) collected from the restaurant was used as feedstock for the TRCO production. The UCO's are from palm-based cooking oil used for deep frying in the restaurant. The received UCO is then filtered to remove any noticeable particles from the cooking process. Next, 10wt.% of palm kernel activated carbon (PKAC) is added to every 50 g of cleaned UCO to absorb excessive fat content, neutralize the chemical substance, and removE the unpleasant odour from the UCO. PKAC is a by-product of palm oil tree production and is abundant in Malaysia. The mixture is then heated at 110 °C for 80 minutes to remove water from the mixture. From Table 1, the reduced oil's viscosity value improves the wettability of the cutting fluid hence it will adhere better and longer at the cutting tool [13]

Table 1: Properties of TRCO before and after treatment

Properties	Before treatment (UCO)	After treatment (TRCO)
Density @ 25 °C (g/ml)	0.9284	0.9294
Viscosity @ 40 °C (cSt)	45.658	31.91
Peroxide Value (mEq O2/kg)	16	14
Free Fatty Acid, FFA (%)	0.38	0.3666
Acid Value (mgKOH/g)	1.456	1.122

Machining experiment

The machining experiment was conducted at the high cutting speed regime of cutting AIS I4340. AISI 4340 alloy steel is chosen due to its being commonly used in the automotive and aircraft industries to produce structural components. In this case study, the machining parameters were selected from the level combination as shown in Table 2.

Based on previous studies, cutting speed, feed rate, and radial depth of cut are the parameters that affect the output value of surface roughness [14] and cutting force [15] the most. Hence, for this case study four cutting conditions that represent different values of cutting speed, feed rate, and depth of cut were selected for comparison purposes and the results are shown in Table 3.

Table 2: Machining parameters for the experimental work

Parameters		Level 1	Level 2	Level 3	Unit
Cutting speed, V	:	300	350	400	m/min
Feed rate, f	:	0.15	0.2	0.3	mm/tooth
Axial DOC, a_p	:	0.5	0.6	0.7	mm
Radial DOC, a_r	:	0.3	0.5	0.7	mm

The down milling experiments were carried out in both dry and MQL conditions using a DMG-ECO, vertical milling machine using a PVD multicoated TiAlN/AlCrN grades ACP200 insert. The insert was fixed to the 32 mm diameter tool holder and was replaced with a new one for every different cutting condition. To measure the cutting force, a Neo-MoMac dynamometer was used and clamped at the milling table together with the workpiece. The dynamometer and data acquisition system (DAQ) were connected via cable, for the acquisition of cutting force signal and can be observed in real-time at the monitor. The force measurements were taken during the first pass of the machining to disregard the influence of tool wear. After the first pass of each experiment, the machining was stopped and a portable Mitutoyo surface roughness tester was used to quantity surface profile at three different locations along the feed direction. The study of chips morphology was done by taking the chips samples at every cutting condition. The samples were analysed using Hitachi SU3500 Variable Pressure Scanning Electron Microscope (VPSEM) with the capability of a 40000x magnification field.

During MQL cutting, the TRCO was delivered to the cutting region using Coolubricator™ MQL system from UNIST. In MQL machining, the MQL parameter must be selected properly to ensure the dispersed cutting oil is capable to cool down the workpiece effectively. From the previous research, optimum machining with MQL can be affected by the choice of lubricant, the flow rate, and the pressure of the MQL mist [16], [17]. In fact, according to Sharma [18], the optimum value of the MQL mist pressure and spraying distance plays a major role that affect the machinability of the milling process. In this research, the flow rate of cutting fluid was set up to 60 ml/hr using two nozzles which can be sum up to 120 ml/hr This flow rate is based on the optimum value from the previous study by [19]–[21]. To ensure sufficient 60 ml/hr of cutting fluid were channeled to the cutting zone, the pulse generator from the MQL's control valve was set to 24 pulses/min, and samples of the dispersed cutting fluid were collected using an empty measuring beaker in one hour. In a meantime, the air metering screw was manually adjusted to determine the proper mix of air with the cutting fluid to avoid undesirable fogging of the fluid. Both nozzles were placed at 120° between jet direction and feed direction and at an elevation angle of 60° of 20 mm nozzles distance to ensure ample amount of fluids are supplied to the rake and flank face of the cutting insert [22]. In addition, the flow rate used in this experiment was also made based on the viscosity value of the TRCO. Liao [23] suggested that the flow rate of 60 ml/hr is the optimum value of flow rate that can yield the best wetting condition (better cutting fluid penetration) for a cutting fluid with a viscosity value of 28.8 cSt, which is close to the viscosity value of TRCO used in this experiment. MQL parameters throughout this experiment are kept constant.

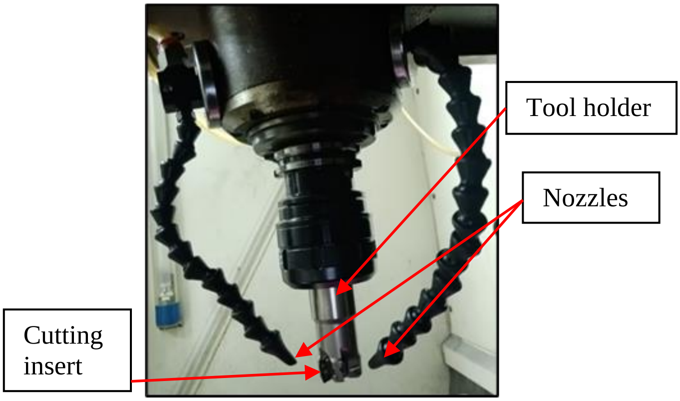

Figure 1: Experimental setup for MQL condition.

Result and discussions

The result of machining output of cutting force (*Fr*) and surface roughness (*Ra*) were compared between dry and MQL cutting conditions as in Table 3. From Figure 2 it is clearly shown that the cutting forces were reduced by about 10%-15% as compared with dry cutting. According to [12], MQL effectively lubricated the cutting surface and subsequently reduced the cutting force, reduce the surface roughness, and lengthens the tool life.

Table 3: Machining conditions and experimental results in this study

Exp. no.	*V* (m/ min)	*f* (mm/ tooth)	a_p (mm)	a_r (mm)	*Fr* (N)		*Ra* (μm)	
					MQL	Dry	MQL	Dry
1	300	0.15	0.5	0.3	243.2	245.7	0.134	0.194
2	300	0.3	0.7	0.7	356.8	396.8	0.209	0.219
3	350	0.3	0.5	0.5	306.5	356.92	0.182	0.192
4	400	0.2	0.5	0.7	309.4	361.7	0.166	0.177

The observation also revealed that experiment 1 resulted in the same cutting force values under both cutting conditions. Based on the previous literature, lower heat is generated at lower cutting speed, depth of cut, and feed rate [24]. Thus it can be said that the heat generated during experiment 1 was lower compared to other experiments which result in a similar cutting force produced in dry and MQL conditions. This experiment also revealed that at an increasing value of cutting speed, from 300 m/min to 350 m/min of experiments 2 and 3, reducing the value of cutting force in both MQL and dry conditions. This occurred due to the higher heat generated during higher cutting speed that weaken the strength of the workpiece material thus ease the shearing process [25].

In addition, the introduction of TRCO palm-oil base during MQL machining is believed significant to reduce the cutting force as well as the coefficient of friction as it offers stability and retain its viscosity even at higher cutting temperature due to its longer chain length and high saturation of fatty acid [26]. Further increased in cutting speed at 400 m/min for experiment number 4 shows no significant differences from experiment 3 in MQL cutting. This is probably due to a decrease in cutting oil wetting capabilities, which occurred when the viscosity of the cutting oil reduced as a result of higher cutting temperatures at the higher cutting speed [27]. However, when compared to dry cutting, machining in the MQL condition showed the highest cutting force reduction with 14.5% improvements during experiment 4. Thus it can be said that TRCO has a good potential to be used during higher cutting speed with lower feed rate value.

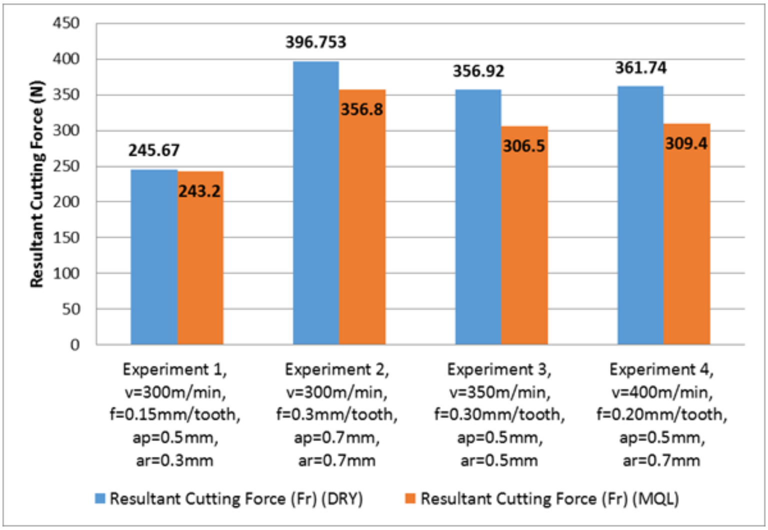

Figure 2: Resultant force measured in MQL and dry cutting conditions.

Figure 3 shows the result of surface roughness acquired in dry and MQL conditions. In general, finer surface roughness was obtained in the MQL condition as compared with the dry cutting condition. It is clearly shown that the average surface roughness (*Ra*) was significantly improved in the MQL condition by around 30% as compared with the dry condition at a low feed rate and depth of cut while maintaining the same cutting speed of 300 m/min. The good surface finish obtained in MQL cutting was believed due to the cutting oil that effectively reducing the friction at the cutting zone.

It was also observed that higher feed rate, axial and radial depth of cut lead to higher surface roughness in both cutting conditions. Meanwhile, higher cutting speed improved the surface roughness. The highest values of average surface roughness were recorded during experiment number 2 which employed the maximum value of feed rate, depth of cut, and width of cut. According to [28]–[30], when a larger amount of material was taken away during the shearing process, the high power load will cause vibration hence is detrimental to the surface roughness. Meanwhile, the highest improvement of surface roughness can be seen with the presence of cutting fluid during experiment number 1 as opposed to experiments 2, 3, and 4. According to [31], the tool–chip interface is partly elastic at lower cutting parameters, allowing the cutting fluid to reach the gap between the chip–tool interfaces through capillary action, forming a thin lubricant layer that decreases friction hence improves the surface roughness. In addition, [32] reported that, at lower cutting parameters, the MQL's mist provides an oxide protective layer on the tool surface hence reduce the friction between the tool and workpiece. The presence of vegetable cutting oil also improves the addition of the oxide layer since it has some functional groups containing oxygen, which allows it to adhere better to the metal surface [33].

On the other hand, slight improvements of surface roughness can be seen throughout experiments 2 until 4. It shows that, as the cutting speeds are increasing (from 300 m/min to 400 m/min), finer surface roughness was obtained. Theoretically, during higher cutting speeds, the temperature built up at the tool-tip eases the shearing process due to the thermal softening of the work material [34], [35] hence improve the surface of the work material. However, fewer improvements of MQL cutting compared to dry cutting may be contributed by the higher value of feed and depth/width of cut throughout experiments 2 until 4, which can accelerate the tool wear, causing high impact load during cutting [36] thus deteriorating the quality of work surface.

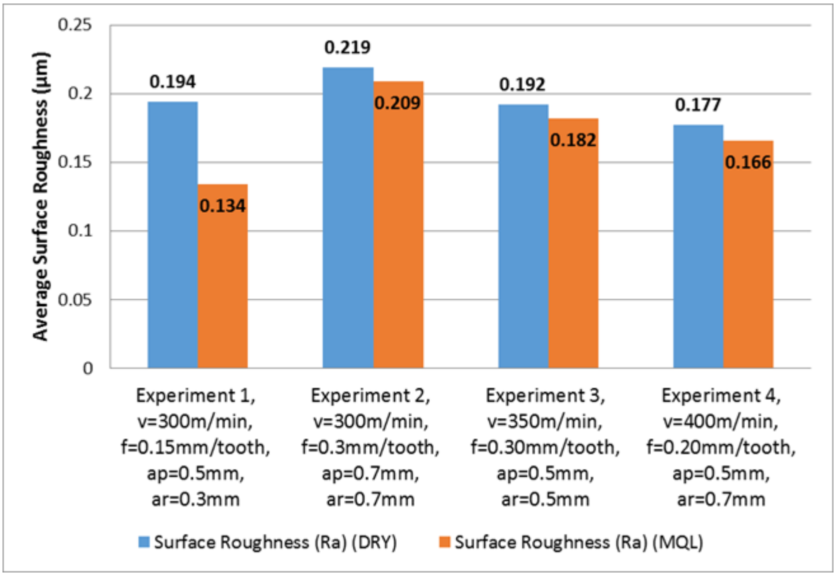

Figure 3: Surface roughness measured in MQL and dry cutting conditions.

Finally, the interaction between two measured outputs and the chip thickness were presented in Figure 4. Both resultant cutting force and surface roughness have a similar trend to each other. An increased cutting force also raised the surface roughness value. The highest value of cutting force and surface roughness can be seen when the feed rate and the depth of cut are at maximum values as in experiment 2. Meanwhile, the lowest cutting force and surface roughness was attained at the minimum cutting parameter. However, the increase of cutting speed can be beneficial to both cutting force and surface roughness in MQL and dry conditions as in experiments 2 and 4. The introduction of TRCO during machining also proved to help in reducing cutting force and improving the surface roughness in all experiments. The findings from this study were similarly obtained by Hadad and Sadeghi [37], they found that in machining AISI 4140 in MQL condition the cutting forces were reduced and the surface quality was improved as the cutting speeds progressing. In addition, Hadad and Sadeghi mentioned that the cutting fluids enable the reduction of cutting friction by limiting the contact area between the cutting tool and workpiece and produce thinner chips [37]. Thinner, shorter and curlier chips produce during machining are preferable as it indicates better machinability of the work material [38]. Ngaide [39] stated that MQL machining produced thinnest (higher cutting ratio) and curliest chips when compared to dry cutting which reduces the tool-chip contact length thus enables the reduction of friction between the sliding metal. As a result, better surface finish, lower cutting force, and longer tool life were achieved.

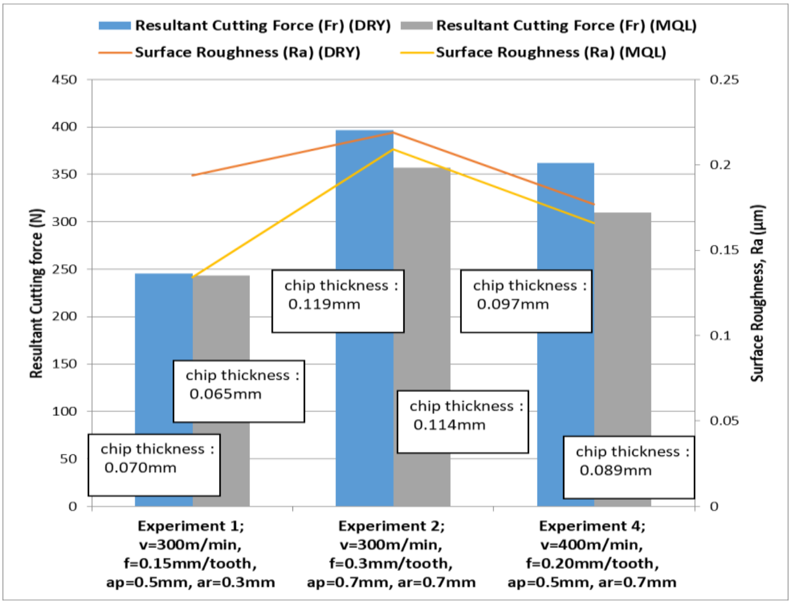

Figure 4: The interactions between measured output as well as chip thickness acquire during the experiment for both cutting condition.

From Figures 4 and 5, the lowest chips thickness can be observed during experiment 1 which reflects the lowest output value for both resultant cutting force and surface roughness. Meanwhile, the thickest chips were observed during experiment 2 whereby both of the output values were the highest. The chips' thicknesses were also reduced when the cutting speed was increased to 400 m/min during experiment 4. Figure 5 illustrates the morphology of chips collected during experiment 1 and 4 in MQL and dry condition. Chips that produced during experiment 1 can be seen were about the same shapes and sizes. That's explained why the cutting force values did not have such a big difference. However, as the cutting speed progress (experiment 4), the chips were thinner and curlier in MQL compare to dry cutting. Berlin [40] explained that thinner and curlier chips produced during MQL are due to the lower cutting temperature as the result of less contact area, less friction, and chip adhesion at the tooltip. The chips collected during MQL were 3% to 9% thinner than chips collected during dry cutting. The author also observed that high cutting force during machining yields thicker and longer chips. These results proved that MQL cutting is capable of producing thinner chips hence, improving the machining condition of the cutting process.

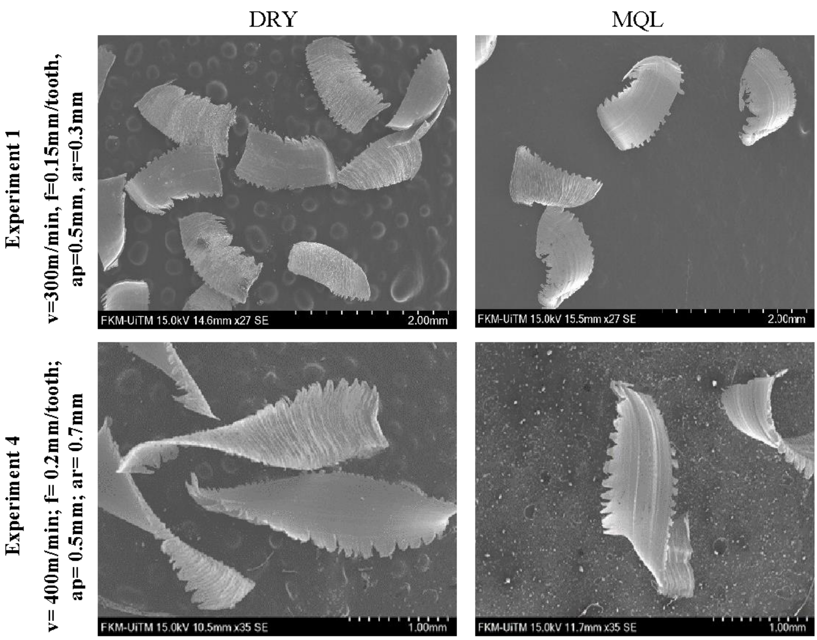

Figure 5: Shorter and curlier chips were collected during experiments 1 and 4 in MQL condition.

Conclusions

The result from the case study found out that the machining output of cutting force was improved by about 15%. Meanwhile, 30% improvements in surface roughness were recorded during MQL with TRCO as compared with dry cutting during experiment 1 at lower feed rate and depth/width of cut values. The introduction of TRCO also proved to be able to reduce the contact area between the cutting tool and workpiece as the results of thinner chips were produced during MQL cutting. Therefore, TRCO has a good potential to be used in addition to the mineral-based cutting fluid as it is more environmentally friendly. In addition, the waste from the cooking oil is utilized for further processing that will save our planet and consumer health, as if not there is a tendency for irresponsibility parties that will repack the recycled oil to be sold in the market as cooking oil.

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