The Influence of Cutting Parameter under Sustainable Machining Approaches on Surface Roughness of AISI 4340

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ABSTRACT

This study presents the result of surface roughness (SR) during milling AISI 4340 under sustainable machining techniques of minimum quantity lubrication (MQL) and cryogenic using liquid nitrogen (LN_2). Along with MQL, Treated Recycled Cooking Oil (TRCO) using waste Palm Oil is used to promote a greener cutting condition. Taguchi L9 orthogonal array and ANOVA are used to investigate the effect of cutting parameters (cutting speed, feed rate, depth of cut and width of cut) on the measured output value. Statically, in both conditions results show that cutting speed and feed rate are the parameters that affect the surface roughness. ANOVA analysis for MQL cutting found that feed rate contributed 87.39% of the output value. While in the cryogenic condition, cutting speed is the main factor that affects the SR value, representing 54.83%. At a lower cutting speed, the SR yield during MQL is lower compared to cryogenic conditions. At a higher cutting speed, the SR value in the cryogenic condition is better than that in MQL condition. However, when the feed rate increases, the SR value is almost similar in both conditions. This finding shows that using this experimental condition with TRCO can improve the SR value even at a higher cutting speed.

Keywords: *Treated Recycle Cooking Oil (TRCO); Minimum Quantity Lubrication (MQL); Cryogenic (LN_2); Sustainable Machining; Taguchi*

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Introduction

Removing heat from the cutting region during machining is important because excessive heat is associated with many quality problems in the metal cutting operation. The heat that is generated at primary and secondary shear zones is transferred to the cutting tool and weakens its mechanical bonding, leading to changes in the cutting tool geometry. The blunt tool accelerates tool wear, thus affecting the surface roughness (SR) of the finished part and its final dimensional accuracy [1]. Moreover, the heat that is generated above the material's recrystallisation temperature may lead to surface microstructure alteration. These occurrences are associated with various surface quality problems such as poor SR, white layer formation, microstructure distortion and residual stresses [2]. These problems are common in the automotive and aerospace industries, and they reduce parts' functionality and increase the rejection rate of finished parts [3]. A common way to improve the surface quality is to apply a lubricant/coolant during machining. However, the excessive use of cutting fluid poses a problem to machining sustainability, especially given current global issues.

In line with this situation, dry cutting, minimum quantity lubrication (MQL) and cryogenic coolant have been extensively studied by researchers to limit the usage of cutting fluid and thus eliminate the problems associated with the usage of MWF. Dry cutting uses no MWF, thus eliminating any related costs. However, dry cutting is associated with a high value for both thermal and mechanical loading, thus being more prone to damaging the work surface when compared with the situation in which cutting fluid is used [4]. MQL is a method of delivering cutting fluid to the cutting edge by mixing a minute amount of cutting fluid with pressurised air to form a mist of cutting fluid, which is then sprayed to the cutting region by a nozzle. The fluid consumption of MQL varies from 0.2 to 500 ml/hour as opposed to that of flood coolant at 30,000 to 60,000 ml/hour [5]. As soon as the mist from the MQL encounters the hot surface of the cutting zone, the heat is carried away by the vaporisation and cools down the cutting process, thus leaving the oil particles on the tool surface. These oil particles act as a tribofilm that reduces the friction at the tool–chip interface, resulting in better SR and longer tool life [6]. Still, the effectiveness of MQL also heavily depends on the quality of the supplied oil mist to the cutting zone. In cryogenic machining, the cutting edge is cooled down by cryogenic gas or liquid such as liquid nitrogen (LN_2) and carbon dioxide (CO_2). These gases are known to be environmentally friendly and do not harm humans. Cryogenic cooling effectively reduces the cutting temperature, thus improving the surface integrity of the machined part. However, a proper delivery system of cryogenic coolant to the cutting edge is crucial because excessive exposure of the workpiece and the cutting tool to this cryogenic temperature may lead to work tool hardening, which increases energy consumption during cutting. Furthermore, cryogenic coolant does not provide better lubrication than the cutting oil.

Research by [7] revealed a relation between tool wear, cutting temperature and tool vibration with the workpiece SR and tool life. When cutting under MQL condition, the heat is effectively carried away by the chips via the pressurised air of the MQL system. The cutting vibration and tool wear are reduced because the oil provides an ample lubrication barrier that reduces the friction at the cutting tool–workpiece interface. As the result, the SR improved by 89% while tool life prolonged by 267% when compared with dry cutting. The result is also consistent with that of Rahim et al. [8], who found that the application of MQL reduced the cutting temperature by 10% to 30% when compared with dry cutting. The effective coolant/lubrication is supported by the chip produced in the experiment. Thinner chips were produced, indicating a lower cutting temperature and less chip–workpiece friction during the cutting process by using the MQL method. Based on Taguchi analysis during AISI 4140 MQL machining, the SR of the work material is mainly contributed by the feed rate. This finding is consistent with that of Abidin et al. [9], who also found that feed rate is the effective parameter that determines the quality of the product surface of AISI 4140. Increasing the feed rate value will yield a poorer surface finish because of higher vibration during the cutting process [10]. Other researchers found out that the MQL method is not effective when applied at higher cutting speeds. Kedare et al. [11] investigated the effect of cutting under MQL and flood conditions for different cutting speeds and depths of cut. The SR values are lower than those of the flooding method at all cutting speeds (160–300 m/min). However, the value does not vary considerably when the cutting speed and depth of cut increase. A similar result was obtained by [12] when cutting AISI 4140 in MQL, flood and dry conditions. At a higher cutting speed, the influence of coolant/lubricant is reduced because of the lack of oil mist penetration in the cutting region. At a higher cutting speed, the tool–chip is in a fully elastic condition and prevents the oil from penetrating the cutting region. At a lower cutting speed, the tool–chip is in a partially elastic condition, thus enabling the cutting fluid to enter the gap between the chip–tool interface by the capillary action to form a thin lubricant film that reduces friction [13].

Different types of cutting oil used during machining with MQL also contribute to the outcome of the machining process. Werda et al. [14] conducted an experiment to explore the effect of cutting oil on the SR of the work material. Vegetable-based cutting oil yields lower SR compared with alcohol-base cutting oil during dry cutting. This better result is due to the complex structure of fatty acids in the vegetable oil, thus providing high oxidation stability, which is important during high-temperature machining to help maintain the oil properties throughout the process [15]-[16]. Similarly, these scholars found that using palm oil as a cutting fluid improves machinability in terms of SR, cutting force and tool life when compared with other types of vegetable oil-based cutting fluid. In Malaysia, most industrial and domestic frying oil is palm fruit-based. Estimations suggest that 50,000 MT of used frying oils, both vegetable oils and animal fats are disposed of yearly in Malaysia without treatment [17].

This study focuses on the effect of MQL and cryogenic conditions on SR when machining AISI 4340. Treated recycled cooking oil (TRCO) is proposed as the MQL cutting fluid due to its availability in Malaysia; in addition, it is more suitable than fresh palm oil for human consumption. In addition, biodiesel based on renewable energy of used cooking oil has become one of the initiatives in automotive industries to lessen the carbon footprint and attain a greener transportation system. Thus, this work also plays a small part in creating a more sustainable industry by utilising TRCO in the product life cycle when machining the metal parts.

Methodology

Material, cutting tools and TRCO

This experiment uses a block of pre-hardened AISI 4340 high-strength low-alloy steel with dimensions of 178 × 102 × 52 mm and an average hardness of 32HRC. AISI 4340 alloy steel is widely used in the automotive and aircraft industries to produce structural components due to its excellent toughness and strength properties. A PVD (TiAlN/AlCrN) multilayer coated carbide indexable end mill is used to machine the metal surface.

In this experiment, TRCO is used to replace the conventionally used cutting fluid. The TRCO is treated and purchased from Universiti Teknikal Malaysia as an effort towards a sustainable machining environment. The initial stage of producing TRCO is started by collecting used cooking oil (UCO) from a franchise restaurant. For the treatment process, the acquired UCO is filtered to remove all the visible residues and particles. Then, with every 50 g of UCO, 10 wt.% of palm kernel activated carbon (PKAC) is added to the UCO. PKAC is a by-product of palm oil processing; palm oil is easily available in Malaysia and Indonesia, and it is known to have excellent absorbent properties due to its higher surface area. PKAC is usually used to neutralise chemical substances and odour from wastewater [34]. The size of the powder PKAC is between 250 - 297 microns in diameter. The mixture of UCO–PKAC is then heated between 100 to 110 °C for 80 minutes to ensure that all water content is removed from the mixture. The oil sample solution is then filtered to remove excess PKAC powder. The properties of TRCO are presented in Table 1 while Table 2 lists the details of the experiment condition.

Table 1: Properties of TRCO before and after treatment [18]

Properties	Before treatment	After treatment
Density at 25 °C (g/ml)	0.9284	0.9294
Viscosity at 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

Table 2: Experimental conditions

Machine Tool	:	Vertical milling (DMG-ECO) 8000 RPM spindle speed
Work specimen	:	AISI 4340 HSLA Steel (C=0.37%, Si=0.33%, Mn=0.80%, P=0.014%, S=0.002%, Cr=1.70%, Mo=0.22%, Ni=1.33%, Fe= Balance)
Cutting Tool Insert		
Cutting insert	:	PVD multicoated TiAlN/AlCrN grade ACP200
Tool holder	:	32 mm diameter, 5 indexable inserts (WEX 2032E)
Tool geometry	:	Rake angle=28°, clearance angle=11°, thickness=3.58 mm
Process Parameters		
Cutting speed, *Vc*	:	300, 350, 400 m/min
Feed rate, *fz*	:	0.15, 0.2, 0.3 mm/tooth
Axial DOC, a_p	:	0.5, 0.6, 0.7 mm
Radial DOC, a_e	:	0.3, 0.5, 0.7 mm
MQL Supply	:	Air: 8.0 bar, lubricant: 60 ml/hr, 2 external nozzles, nozzle distance, *d*=25 mm, elevation angle=60°, cutting fluid= TRCO
Cryogenic Supply	:	LN_2, pressure= 2 MPa, flow rate=1.159 × 10^{-3} m^3/s, elevation angle=45°

Experimental procedure

This metal's block is downmilled using a straight-line surface machining strategy on a DMG-ECO, vertical milling machine with 8000 RPM spindle speed capacity. PVD (TiAlN/AlCrN) multilayer coated carbide end mill insert is fixed to a 32 mm diameter tool holder manufactured by Sumitomo. The tool holder consists of five indexable cutting inserts, but only one insert is utilised to avoid tooltip runout during wear measurement. The experiment is conducted under MQL with a mixture of compressed air and TRCO as the cutting fluid at a rate of 60 ml/hr via two nozzles. For comparison, the experiment is repeated under cryogenic condition by using LN_2. To avoid excessive cooling, only one nozzle supplying LN_2 is used during the experiment. Table 2 lists the details of the experiment condition. The average surface roughness (*Ra*) measurement is taken according to ISO 4288 (2) 1996. For each tested parameter, the SR value was taken three times at three different locations along the feed direction of the workpiece by using a Mitutoyo portable SR tester. The stylus movement of the portable SR tester is set at 5.6 mm at an evaluation distance of 4 mm and a cut-off value (λc) of 0.8 mm. Figure 1a illustrates experimental setup for cutting under MQL condition using 2 nozzles. While Figure 1b illustrates the experimental setup for cryogenic cutting and the LN_2 flow during machining process.

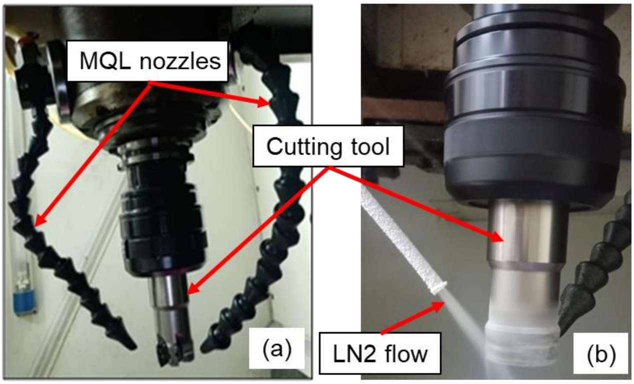

Figure 1: Experimental setup for; (a) MQL, and (b) cryogenic

Design of experiment and machining parameters

In this work, Minitab v18.1 software is used to design, plot, and analyse the data. Taguchi method is used for the design of experiment (DOE) by calculating a signal-to-noise (S/N) ratio to determine the variability of the parameter in the process. A higher S/N ratio is desired because it indicates the optimal level for the process parameters [19]. The output of the experiment is to determine the best parameter combination for minimising SR; thus, the-smaller-the-better S/N ratio is used for the calculation. Four input parameters, namely, cutting speed (*Vc*), feed rate (*fz*), depth of cut (a_p) and width of cut (a_e), at three levels of values are selected for this experiment (Table 2). Hence, according to the Taguchi approach, L9 (3^4) orthogonal array is the suitable number of experiments to facilitate four cutting parameters and three levels of the parameter's value [20]. Later, ANOVA analysis is performed to determine the percentage of influence of each parameter to the measured response. Table 3 outlines the nine experiments conducted in this study and the SR obtained for both cutting conditions.

Table 3: L9 orthogonal array of the experiment and SR result for MQL and cryogenic condition

Exp. no.	Cutting speed *Vc*	Feed rate, *fz*	Axial a_p	Radial a_e	Surface Roughness MQL	Cryogenic
1	300	0.15	0.5	0.3	0.134	0.165
2	300	0.2	0.6	0.5	0.178	0.20
3	300	0.3	0.7	0.7	0.209	0.235
4	350	0.15	0.6	0.7	0.141	0.149
5	350	0.2	0.7	0.3	0.174	0.142
6	350	0.3	0.5	0.5	0.182	0.176
7	400	0.15	0.7	0.5	0.129	0.135
8	400	0.2	0.5	0.7	0.166	0.16
9	400	0.3	0.6	0.3	0.179	0.161

Results and Discussion

Figure 2a illustrates that the highest S/N ratio indicates the optimum level for obtaining the best combination of the response. With the use of 'the smaller, the better' principle for S/N ratio calculation, the optimal factor combination for minimising SR Ra for MQL is a cutting speed of 400 m/min, feed rate of 0.15 mm/tooth, depth of cut of 0.5 mm and width of cut of 0.3 mm. The main effect plot graph in Figure 2 indicates that feed rate and cutting speed are the main parameters that affect the output value of SR, whereas DOC and WOC are the parameters that have the least effect. For comparison, the experiments were repeated under cryogenic condition to investigate the effect of cutting parameters on SR in different cutting conditions. Based on the S/N ratio from the main effect plot of Figure 2b, the optimum parameters for obtaining the lowest SR in the cryogenic condition is similar to those in the MQL condition. The feed rate and cutting speed are the parameters that heavily influence the surface quality of the machined surface. Theoretically, cutting under cryogenic condition will produce a finer SR in comparison to that under dry and wet conditions [21]. When compared to other cutting conditions, LN_2 offers lubrication at the cutting zone, thus reducing tool's sticking and wear and eventually producing a better surface roughness. When it comes to MQL, previous studies reveal that MQL machining produces finer SR at a lower cutting speed compared with cryogenic cooling [22]–[25]. The good surface finish during MQL cutting is due to the cutting oil effectively reducing the friction at the cutting zone. However, at a higher cutting speed, Kaynak [23] reported lower cutting force when cutting Inconel 718 under cryogenic condition, hence producing better SR. Thus, this work aims to investigate the SR value when machining AISI 4340 in both cutting conditions.

Based on Figure 2, the main effect plot for both cutting conditions revealed that feed rate and cutting speed are the most influential parameters that affect the value of SR. However, it does not indicate the significant factors and percentage of influence of each parameter to the measured response. The ANOVA results for both cutting conditions are shown in Tables 3 and 4. A lower *p*-value from the ANOVA's table represents a higher impact of that input factor on the measured output [26]. The contribution value, on the other hand, reflects the percentage of influence of each parameter on the measured response. Table 4 shows that the *p*-value for the feed rate and cutting speed is the lowest for SR in MQL machining, with contribution factors of 87.39% and 6.70%, respectively; radial DOC has the least impact (3.18%) on SR, which agrees with the finding by [27]-[28]. When cutting in cryogenic conditions (Table 5), cutting speed and feed rate have the lowest *p*-value and greatly affect the output value by 54.83% and 32.45%, respectively. Both outcomes from Tables 4 and 5 support the result obtained from the S/N ratio. Thus, the value of the feed rate and cutting speed should be optimised to achieve the lowest SR in MQL and cryogenic conditions.

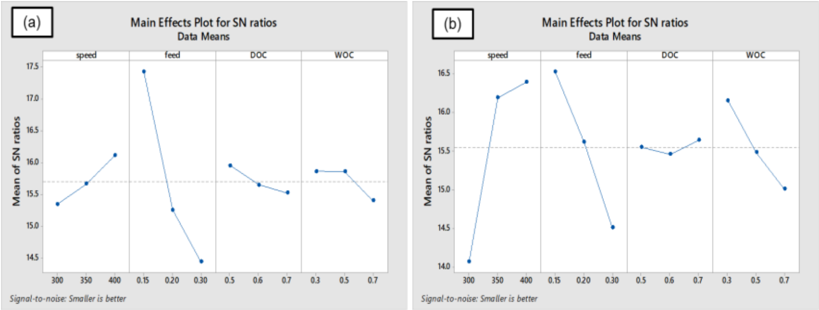

Figure 2 Main effect plot for SR in; (a) MQL condition, and (b) cryogenic conditions

Table 4: ANOVA SR under MQL condition

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	*P*-Value	*F*-Value
Vc	2	0.000368	6.70%	0.00037	0.00018	0.29	2.45
fz	2	0.004806	87.39%	0.00481	0.00240	0.03	31.99
ae	2	0.000175	3.18%	0.00018	0.00009	0.46	1.16
Error	2	0.000150	2.73%	0.00015	0.00008		
Total	8	0.005500	100.00%				

Table 5: ANOVA SR under cryogenic condition

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	*P*-Value	*F*-Value
Vc	2	0.004283	54.83%	0.00428	0.00214	0.005	187.12
fz	2	0.002538	32.48%	0.00254	0.00127	0.009	110.86
ae	2	0.000968	12.39%	0.00097	0.00049	0.023	42.30
Error	2	0.000023	0.29%	0.00002	0.00001		
Total	8	0.007812	100.00%				

The experimental result revealed that the SR value ranges from 0.134 to 0.235 µm for both cutting conditions (refer Table 3). These values are less than the 0.5 µm value that is usually produced by manual polishing. The lowest SR is attained during machining under MQL, whereas the highest SR is obtained during machining under cryogenic condition. Both occur at the lowest cutting speed. Figure 3 shows that MQL works better at a lower cutting speed during machining AISI 4340. As the cutting speed progresses, the SR value during cryogenic cooling improves slightly. However, the results are closely similar to the SR value for MQL. The highest improvement of SR is observed in experiment 5 with 18.4% SR reduction. Therefore, this experimental process and the utilisation of TRCO can produce a good surface finish similar to the cryogenic condition even at a higher cutting speed and feed rate.

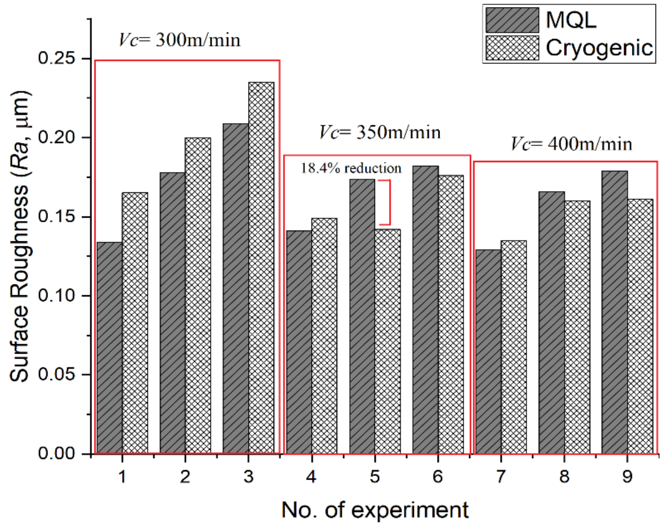

Figure 3: SR experimental results for various cutting parameters when cutting under MQL and cryogenic conditions

Previous researchers found that cutting in cryogenic conditions is more effective in high velocity while MQL is at low speed [29]. However, the findings of this study found that when the cutting speed is increased to 350 and 400 m/min, MQL-TRCO cutting can produce a surface roughness that is almost the same as machining in cryogenic conditions. This may occur because the use of plant-based lubricants for MQL-TRCO machining has a stable fatty acid structure to withstand increasing cutting temperatures [15]-[16].

Figure 4 depicts that the increasing value of feed rate from 0.15–0.3 mm/tooth will directly increase the SR value for both cutting conditions. The main effect plot (Figure 2) also indicates that the increasing value of WOC and DOC can be detrimental to SR because increasing these parameters will lead to a higher material removal rate, which will increase the vibration, thus affecting the SR [10], [30]-[31]. At a lower cutting speed of 300 m/min (Figure 4a), the SR value under the MQL condition is lower than that under the cryogenic condition at all feed rates. At a lower cutting speed, the tool–chip is partially elastic, thus enabling the cutting fluid to enter the gap between the chip–tool interface through capillary action to form a thin lubricant film that reduces friction [13]. Furthermore, the presence of TRCO at the cutting zone limits the contact area between tool and workpiece; hence, thinner chips are produced [12]. A higher SR under cryogenic cooling at a cutting speed of 300 m/min is probably a result of work hardening due to the excessive cooling at the cutting region at a lower cutting speed. According to Thakur et al. [32], the effect of work hardening is less at a high cutting speed compared with that at a lower cutting speed. Figure 4b shows that the SR value for MQL cutting is more sensitive to the variation of feed rate at a higher cutting speed. As the cutting speed varies from 300–400 m/min, the SR value under the cryogenic condition improves, although it becomes less noticeable at the feed rate increases. Figure 5 shows that increasing the cutting speed can help improve SR. The figure shows that the increasing value of cutting speed from 300–400 m/min yields finer SR at both feed rate values. This condition occurs because, at a higher cutting speed, the built-up temperature at the tool tip eases plastic deformation during shearing due to thermal softening of the workpiece. Similar results were obtained by other studies [33]-[34]. The SR value under cryogenic condition is more sensitive to variations in the cutting speed compared with that under MQL conditions.

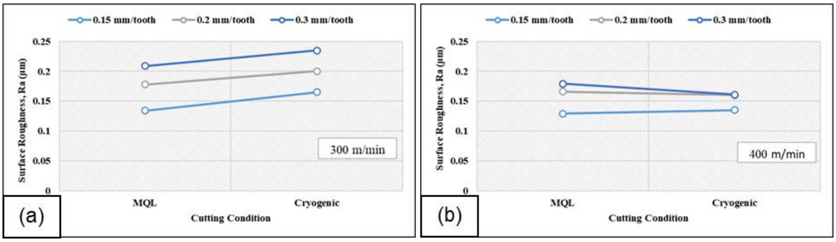

Figure 4: Effect of cooling/lubricating on SR at different feed rates with constant cutting speed; (a) 300 m/min, and (b) 400 m/min

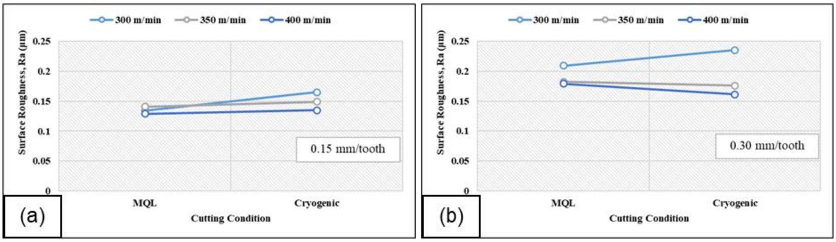

Figure 5: Effect of cooling/lubricating on SR at different cutting speeds with constant feed rate; (a) 0.15 mm/tooth, and (b) 0.3 mm/tooth

On top of that, the value of surface roughness can affect the tool life of the cutting tool. Figure 6 shows the average flank wear (*Vbavg*) of the cutting tool when machining in MQL and cryogenic condition for experiment 8. The figure also displays the value of surface roughness at six stages of tool wear rate starting from *Vbavg* at 0.096 mm until 0.3 mm before the tool fail at 37.04 min and 40.64 min for MQL and cryogenic, respectively. At the *Vbavg* value between 0.15 mm and 0.10 mm, the wear rate for cryogenic cutting can be seen rapidly built-up compared to MQL cutting and the value of SR during cryogenic cutting is higher than MQL cutting. It is probably due to the heat has not yet accumulated at the cutting zone; thus, the lubricating action of the cutting oil is shown to be effective. However, as the tool wear is progressing at the value of *Vbavg* >0.15 mm, the wear rate can be seen rapidly progressed in MQL condition while slowly progressed in cryogenic condition. The cryogenic substance effectively removed the heat, while the effectiveness of the cutting oil to lubricate depreciate as the cutting temperature increased [35]. Thus, resulting rapid tool wear and subsequently increasing the SR value. Finally at the critical wear point of *Vbavg* = 0.25 mm, the wear value is rapidly grown for both cutting but in a slowly trend as compared to MQL. It owns to the fact in the cryogenic conditions, the accumulate heat is effectively removed and prevented the thermal softening of the tool thus slowing the disintegration of tool's coating material [36]. The harden tool and effective heat control prevent tool chipping, thereby reducing the sliding-sticking zone which associated to the increased value of SR and cutting force [37].

Figure 7 depicts the progressive tool wear in both cutting condition. The MQL cutting produces flank wear that extends to the rake face by 0.781 mm as compare to cryogenic cutting by 0.412 mm. It shows that the cryogenic cutting reduces the contact between the cutting tool and the workpiece resulting reduction of friction and finer SR. However, the improvement of tool life in MQL cutting when compared to cryogenic cutting is only 10%. It maybe contributes by the effectiveness of TRCO during the MQL cutting that capable to retain it lubrication property even at higher cutting temperature.

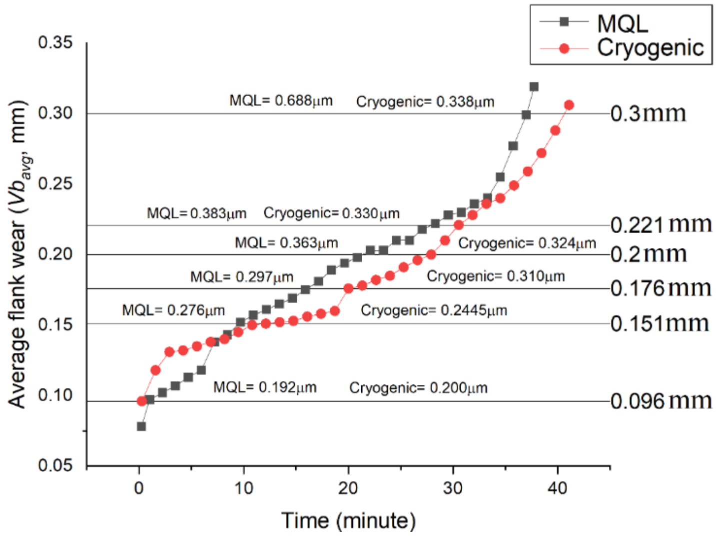

Figure 6: Comparison of average flank wear when cutting AISI 4340 in MQL and cryogenic conditions using experiment 8 for *Vc*= 400 m/min, *fz*= 0.2 mm/tooth, DOC= 0.5 mm and WOC= 0.7 mm

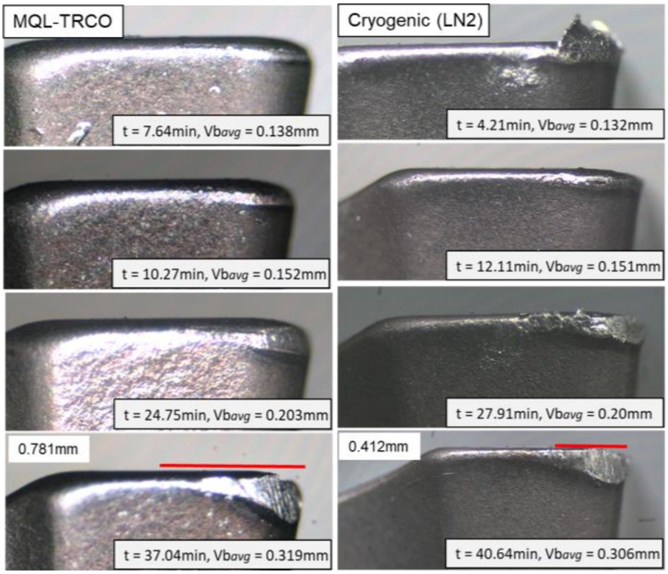

Figure 7: Progressive tool wear of AISI 4340 when cutting in MQL and cryogenic condition using experiment 8 for *Vc*= 400 m/min, *fz*= 0.2 mm/tooth, DOC= 0.5 mm and WOC= 0.7 mm

Conclusion

Cryogenic coolant is a medium that can effectively improve SR at a higher cutting speed, whereas MQL is more effective at improving SR at a lower cutting speed. This work proved that the use of TRCO during MQL cutting enables MQL to produce an SR value that is comparable to that of cryogenic cutting at a higher cutting speed. Based on the results, the following conclusions can be made:

i. The experimental parameters and setup can produce a surface finish of less than 0.5 µm;
ii. TRCO has the potential to be used as a sustainable cutting fluid;
iii. The lowest feed rate and highest cutting speed are the best combination for minimising SR under both cutting conditions;
iv. During MQL cutting statistical analysis showed that an 87.39% feed rate, a 6.70% cutting speed and 3.18% width depth of cut had the greatest effects on the SR;
v. For cryogenic cutting, a cutting speed of 54.83%, feed rate of 32.489% and 12% width depth of cut had the greatest effects on SR.

vi. Cryogenic cutting reduces the contact between the cutting tool and the workpiece as compared to MQL cutting
vii. This work conforms that MQL lack in cooling abilities while cryogenic substance is weak at providing lubrication between the tool and workpiece. Therefore, to overcome these problems, a combination between MQL and cryogenic techniques can be further explored to improve lubrication and cooling effects of a milling process.

Contributions of Authors

The authors confirm the equal contribution in each part of this work. All authors reviewed and approved the final version of this work.

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Conflict of Interests

One of the authors, Ahsana Aqilah Ahmad, is an assistant managing editor of the Journal of Mechanical Engineering (JMechE). The author has no other conflict of interest to note.

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