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Investigation on Chips Morphology of Machining AISI 4340 under Cryogenic and Cryogenic MQL Conditions

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Abstract

AISI 4340 is a medium-carbon, low-alloy steel that is widely used in heavy industries due to its exceptional material properties, such as high hardness and high wear resistance. However, these features present significant challenges to the manufacturer, thus necessitating further exploration to improve its machinability. To address this issue, this study aims to analyse the chip morphology, namely chip serration, chip saw-tooth distance, and chip thickness collected during end milling of AISI 4340 under two cutting conditions of cryogenic LN_2 cooling and the combination of cryogenic LN_2 and Minimum Quantity Lubrication (cryoMQL). By varying the cutting parameter of cutting speeds (*Vc*), feed rates (*fz*), axial depths of cut (*ap*), and radial depths of cut (*ae*) in these two conditions, the results indicate that the combination between cryogenic and MQL yield better results in terms of less chip serration, decrease saw-tooth distance and thinner chips when compared to the standalone coolant technique of cryogenic LN_2. The results can be attributed to both the cooling effect of LN_2 and the lubricating effect of oil from the MQL technique, which effectively reduce the cutting temperature and limit temperature build-up at the tooltip. These combinations reduce tool wear, lower friction, and decrease heat generation during cutting, thus improving the machinability of AISI4340 especially in critical application.

1. Introduction

AISI 4340 is a medium carbon low alloy steel in combination with nickel, chromium, and molybdenum [1]. This alloy is widely used in aerospace, nuclear, and automotive applications due to its high nickel content, which enhances its strength, corrosion resistance, weldability, and processability compared to other steels [2]. It has a low machinability factor and is categorised as a difficult-to-cut material due to its high hardness, high plasticity, low thermal conductivity, and high toughness [3–4]. These properties lead to faster tool wear, premature tool failure, low material removal rates (MRR), and high cutting forces [5]. In addition, AISI 4340 tends to undergo surface hardening during machining, making chip control more challenging and increasing tool wear [6]. Although often viewed as waste, a thorough understanding of the mechanisms behind chip formation is crucial as it offers valuable insights into the material's machinability [7]. Good machinability should have low power consumption, reduce tool wear, and produce a high-quality surface finish while minimising environmental impact and cost. To improve machinability, machining processes are typically accompanied by cutting fluid using flood methods as a fluid delivery system to remove excess heat from the cutting area. However, the use of excessive cutting fluid should be controlled because it is often associated with health issues and does not guarantee environmental sustainability [8]. Thus, this study aims to explore more sustainable cutting fluid methods, specifically cryogenic cooling and Minimum Quantity Lubrication (MQL), and to examine their effects on chip morphology.

Cryogenic coolants use liquid gases like nitrogen, hydrogen, oxygen, carbon dioxide, and normal air. In machining, liquid nitrogen (LN2) at -196 °C or carbon dioxide at -78.5°C are commonly used [9]. Cryogenic coolants in metal cutting lower cutting temperatures, reduce tool wear and surface roughness, improve the material removal rate (MRR), and enhance machinability. Additionally, cryogenics are cleaner, safer, and more sustainable as the liquid gases evaporate, preventing workpiece contamination [10-11]. This method is also used in hard machining. Gupta et al. [12] found that machining medium carbon steel AISI 1040 with cryogenic cooling improved machinability better than dry machining, with improvements of 55.45%, 125.9%, and 61.94% in tool flank wear, surface roughness, and cutting force, respectively. These improvements were due to the reduced cutting temperature. However, the cryogenic coolant nozzle must be correctly positioned to prevent the workpiece's and cutting tool's surface hardening from excessive exposure to the cryogenic substance [13]. In addition, cryogenic coolants have been found to provide less effective lubrication in the cutting zone compared to oil-based cutting fluids [13].

Minimum Quantity Lubrication (MQL), also known as near dry machining, is a technique that utilises a minimal amount of cutting fluid (50 to 2000 ml/hour) mixed with pressurised air to create a mist that is sprayed onto the cutting region. This is in contrast to flood cooling, which consumes 500,000-1,000,000 ml/hour [14]. This MQL method provides a cooling effect from the compressed air while controlling the cutting zone temperature by lubrication. There have been numerous proofs of MQL's effectiveness in reducing cutting temperature [15] and cutting force [16]. However, it has also been reported that MQL can only work effectively at specific speed ranges. A study conducted by Hadad and Sadeghi [16] has proved that MQL can reduce force and improve surface quality at a speed of 100 m/min; however, at much lower and higher speeds (50 and 150 m/min), there is no or very small reduction of force recorded. At higher cutting speeds, more heat is generated, causing the cutting fluid in MQL to evaporate or degrade quickly. This reduces its lubrication effectiveness and leads to excessive heat buildup in the cutting zone [13]. In this study, combining cryogenic and MQL methods addresses standalone cutting fluid methods' cooling and lubricating limitations. This combination offers significant machining advantages, such as reducing cutting temperatures and friction and improving chip removal at higher cutting speeds [17]. The study of chip morphology is essential for understanding material machinability, which affects cutting time and cost [18]. Using a microscope or scanning electron microscope (SEM), chip serration, chip thickness, and chip sawtooth distance can be identified.

Chip serration occurs in every machining process, especially with hard alloys, because the chip surface moves toward the tooltip in the primary shear zone. This is due to thermal softening from plastic deformation, and cyclic cracks occur [19]. The high serration indicates that the cutting vibration is generated by high-frequency loads, which will affect tool wear [20-21]. Chip thickness depends on the shear plane; it increases as the shear plane increases [22]. This is because a larger shear plane requires more material to be deformed, producing a thicker chip during the cutting process. Higher feed rates also increase chip thickness by extending the length of tool-chip contact, thereby increasing cutting forces during the cutting process [15]. Meanwhile, the chip sawtooth distance can be observed from chip serration. It is influenced by cutting speed and temperature at the cutting zone [19].

Controlling chip flow is crucial for both machining quality and the final product. In metal cutting, chips come in three types: continuous, discontinuous, and continuous with built-up edges [23]. Discontinuous chips are desirable as they produce a better surface finish and extend tool life [24]. The choice of cutting fluid also plays a significant role in determining the type of chip produced. Past studies indicate that using cryogenic cutting fluids produces discontinuous and curly chips compared to the dry method [25]. Low temperatures during cutting weaken the welded junction between chips and make them harder and brittle, forming discontinuous chips. On the other hand, flooded and compressed air conditions typically result in continuous chip formation [19].

Previous research primarily focused on green lubrication methods to enhance machinability, improve surface integrity, and reduce tool wear. However, there is limited research on how different lubrication methods affect chip morphology. Therefore, this study aims to fill that gap by analysing chip morphology during end milling under two cutting conditions: cryogenic cooling and cryogenic MQL (cryoMQL). The study compares the impact of these methods on chip serration, chip thickness, and chip saw-tooth distance, providing new insights into the effectiveness of advanced lubrication techniques in machining.

2. Methodology

The experimental workpiece was a block of AISI 4340 with dimensions of 178 × 102 × 52 mm. This AISI 4340 is a high-strength low alloy steel with an average hardness of 32HRC. This experiment was done by end milling operated by a DMG-ECO vertical milling machine, and the cutting tool insert was performed using a PVD (TiAlN/AlCrN) multilayer coated carbide fixed to a 32 mm diameter tool holder. Both the cutting tool and tool holder were manufactured by Sumitomo. The MQL uses vegetable-based cutting oil with two nozzles with a flow rate of 60ml/hr directed to the rake face and flank face of the cutting zone. The cryogenic uses the LN_2 with a flow rate of 1.159×10^{-3} m^3/s that supplies directly to the cutting tool via a separate nozzle.

This study conducted experiments under two different machine conditions: cryogenic LN_2 and the combination between cryogenic LN_2 and MQL (cryoMQL), with the variation of milling parameters, including cutting speed (*V*), feed rate (*fz*), axial depth of cut (a_p) and radial depth of cut (a_e), to identify their influences on the chip's morphology. In this case study, five experiments were used for chip morphological analysis, and the specific experimental combinations are listed in Table 1. These experiments were selected to capture the variations in cutting speed and feed rate, as previous research has shown that these two parameters significantly influence chip morphology formation [15,19]. For each experimental parameter combination, experimental testing was conducted by performing end milling operations for a length of 178 mm. After reaching 178 mm, the experiment was stopped, and the chips produced were collected. The chips were then prepared as samples for further analysis using an optical microscope to investigate their morphology, focusing on the serration, thickness, and pitch-to-pitch length ratio.

Table 1 *List of experimental parameters under cryogenic LN2 and cryoMQL conditions*

Experiment No.	Cutting Speed (*V*) [m/min]	Feed Rate (*fz*) [mm/tooth]	Depth of Cut (*ap*) [mm]	Width of Cut (*ae*) [mm]
1	300	0.20	0.60	0.50
2	350	0.15	0.60	0.70
3	350	0.20	0.70	0.30
4	400	0.15	0.70	0.50
5	400	0.20	0.50	0.70

2.1 Sample Preparation

The chips collected from the experiments were molded using a hot automatic mounting press machine to capture the cross-sections of the chip samples and facilitate sample preparation. Next, the samples were ground using a grinding machine to remove the specimen's surface until the cross-sectional area of the chip sample was exposed. Sandpaper with grades 320 and 400 was used for this grinding process. After grinding, the samples were polished to achieve mirror-like surfaces. Finally, the samples were observed using an optical microscope at ×50, ×100, and ×200 magnifications. Fig. 1 illustrates the flow process of the sample preparation.

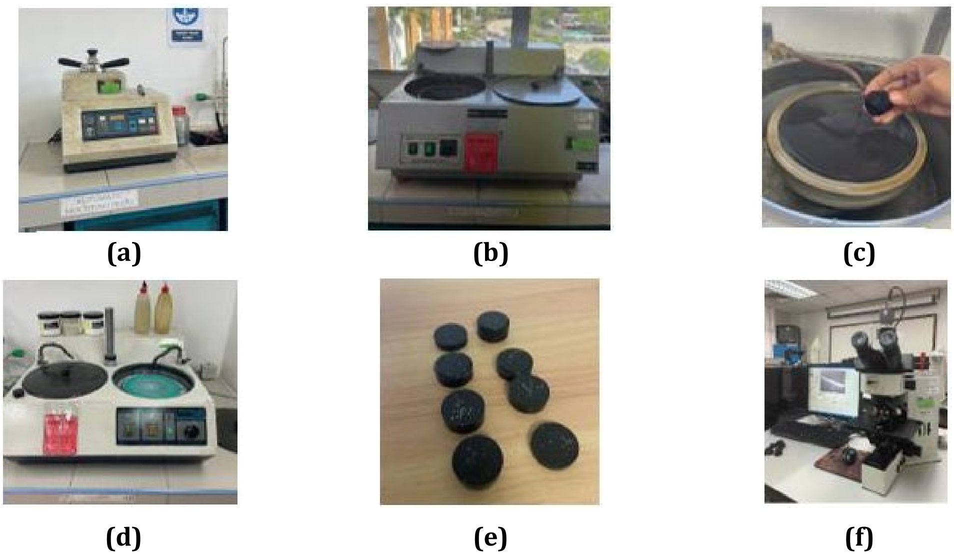


Fig. 1 *Sample flow preparation of experimental setup; (a) Automatic mounting press machine; (b) Grinder machine; (c) Sample grinding; (d) Polishing machine; (e) Prepared sample; (f) Optical microscope*

2.2 Sample Observation

The chip morphology was compared using an optical microscope with magnifications of ×50, ×100, and ×200. It was investigated using average results from 3 to 4 chip samples. Using the ImageJ software, the measurement of the chip serration of the maximum thickness of saw-tooth chip T, chip thickness at local shear deformation, t, and pitch-to-pitch, P_c distance was obtained, as shown in Fig. 2.

The thickness ratio (r) was calculated using Eq.1 to analyse the chip serration. According to Zhang and Guo [26], a ratio less than 0 indicates a higher degree of serration, whereas a ratio near or above 1 suggests minimal serration, which means continuous chips. The chip thickness was also determined using the equivalent chip thickness (h_{ch}) calculated using Eq. 2. The sawtooth chip has two different deformations: the shear band is distributed in the saw-tooth chip, and the trapezoidal chip is a saw-tooth shape [27]. Lastly, Fig. 2 shows the measurement from the highest pitch to pitch distance, Pc, for the chip sawtooth distance.

Fig. 2 *Measurement of chip serration using ImageJ software*

$$r = \frac{T - t}{T} \tag{1}$$

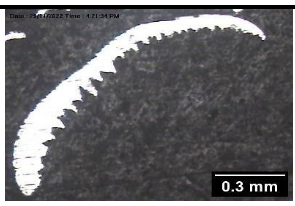
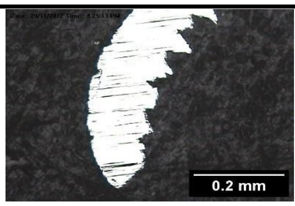
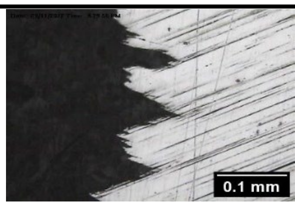
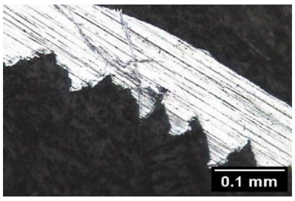
$$h_{ch} = T + \frac{T - t}{2} \tag{2}$$

3. Results and Discussion

3.1 Chip Morphology

Tables 2 and 3 show the sample chip morphology obtained from the experimental preparation under the optical microscope at ×50, ×100, and ×200 magnifications. A form of serrated or sawtooth chip is produced from both cutting conditions for this milling AISI 4340 due to the hardness of the material. This can be supported by previous researchers, who found that chip serration is mainly formed in every machining process, especially for machining hard alloys, due to the material's low thermal conductivity and high temperature at the cutting zone [28].

Table 2 *Chip morphology in cryogenic condition under a microscope with magnification of ×50, ×100, and ×200*

Experiment No.	Cryogenic		
	×50	×100	×200
1			
2			

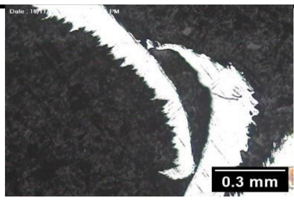
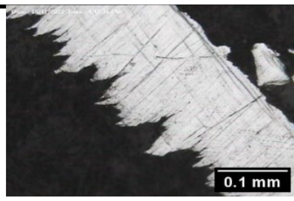
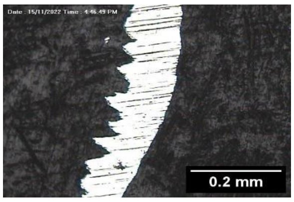
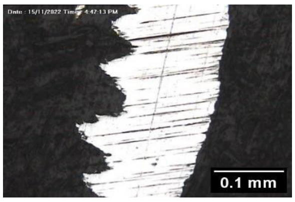
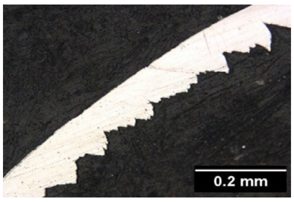
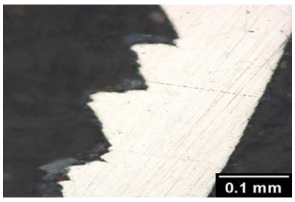
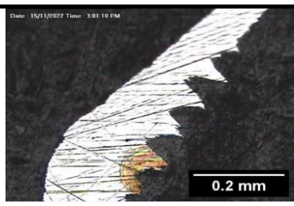
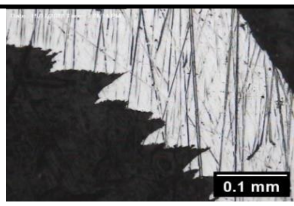
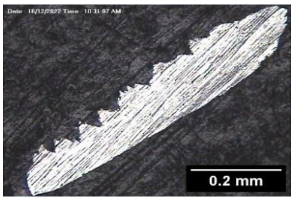
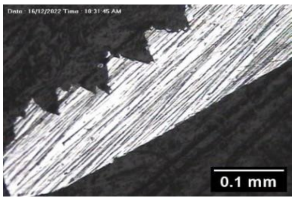
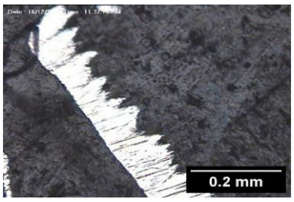
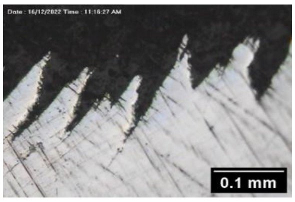
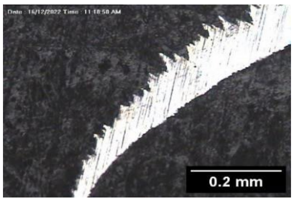
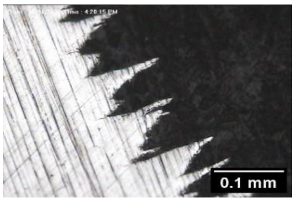
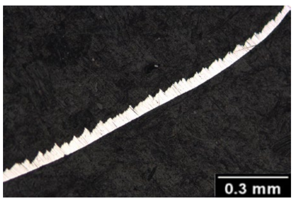
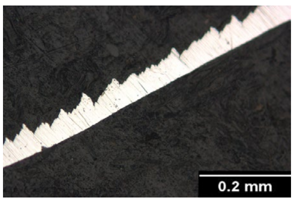
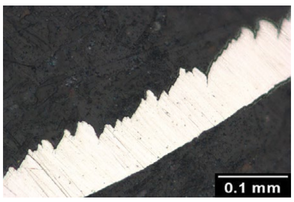
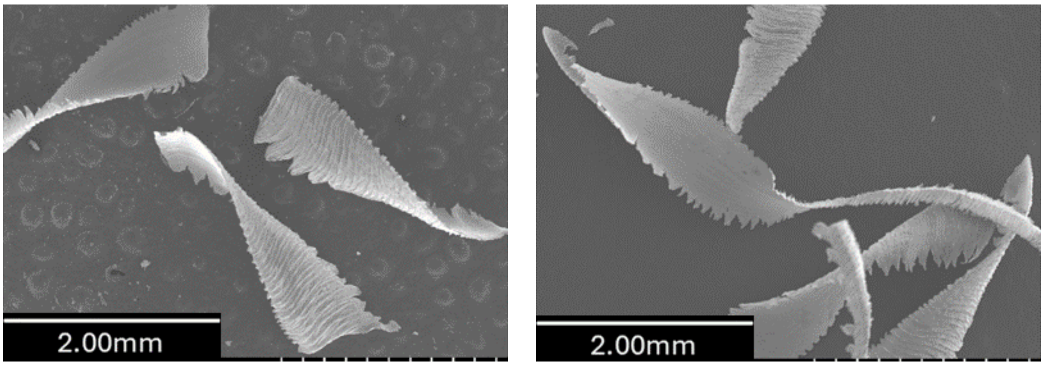
Experiment No.	Cryogenic		
	×50	×100	×200
3			
4			
5			

Table 3 *Chip morphology in cryoMQL condition under a microscope with magnification of ×50, ×100, and ×200*

Experiment No.	Cryogenic		
	×50	×100	×200
1			
2			
3			
4			
5			

Both cryogenic and cryoMQL results show discontinuation and a curly chip shape formed from the milling machining process. This resulted in discontinued and curly chip shapes from both cutting conditions performing a good chip breakability. It can also be observed that chips produced under cryoMQL conditions are shorter compared to those produced under cryogenic cutting. Shorter chips are preferable. Previous studies show that cryogenic cutting has a higher peak-to-valley (PV) ratio, indicating more unstable machining than cryoMQL cutting. A higher PV ratio means more vibrations, which can cause erratic and longer chip formation. In contrast, a lower PV ratio, as seen with cryoMQL cutting, results in fewer vibrations and more consistent, shorter chips [29].

Looking at a closer view of Fig. 3, the chips under cryogenic conditions have a more uniform shape, with a pronounced serrated pattern along the length of the chips. Serration is a common feature in high-speed machining with cryogenic cooling [20]. The cryogenic cooling method enhances chip breakability, potentially due to the significant reduction in material temperature, making the material more brittle and thus easier to fracture. This is also similar to the past research [30–31].



(a) **(b)**

Fig. 3 *Chip morphology for Experiment 5 at a cutting parameter of V = 400 m/min and fz = 0.20 mm/tooth under (a) cryogenic conditions; and (b) CryoMQL conditions*

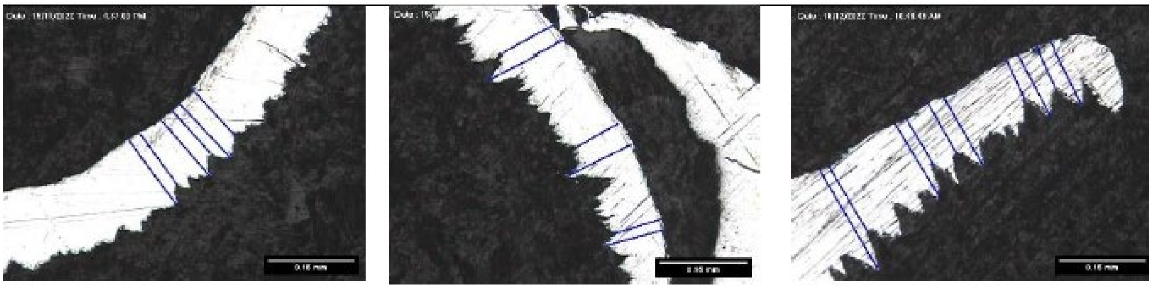
While the chips in cryoMQL conditions exhibit a more curved and elongated shape compared to the cryogenic condition, a distinct tail-like formation can be seen, especially at the ends of the chips, which indicated the chip formation appears more continuous and less brittle. This might be due to the lubrication effect of MQL, which can lower the cutting force and friction, leading to a more stable and continuous chip. This finding aligns with previous research, which indicated that the use of cryogenic cooling increases the hardness of the workpiece, thereby impacting the machinability of the process. In contrast, the addition of MQL in the cryoMQL condition improves the machining process by providing lubrication, reducing forces, and enhancing chip formation [32,33].

3.2 Chip Serration

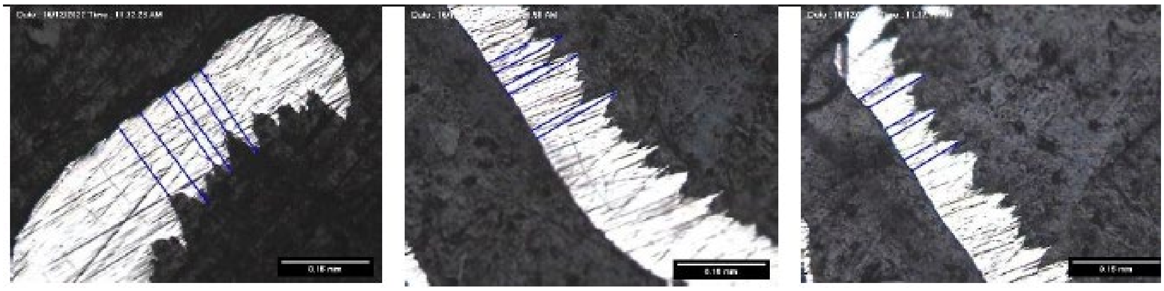
A serrated or sawtooth chip can be seen in every cutting environment, as shown in Tables 2 and 3. This chip serration is produced in every machining process, especially in hard machining material. Chip serration's primary attributes are cyclic cracks, shear localisation, and plastic deformation [19]. To compare the chip serration between cryogenic and cryoMQL, the chip thickness ratio is calculated using Equation 1 [27].

A large, more pronounced chip serration was observed at the highest cutting speed. Previous research has shown that higher cutting speeds generate high-temperature regions, facilitating machining through thermal softening [21]. Under both cutting conditions, the surface region's hardness contributes to the formation of sawtooth or serrated chips. Fig. 4 presents a sample calculation for determining serrated chips using the Average Height-to-Thickness Ratio, while Table 4 compares the two conditions. Referring to Table 4, the cryogenic condition consistently produces more serrated chips across all experiments, with values generally closer to 1, indicating more brittle behaviour and a less continuous chip formation process. This increased serration in cryogenic conditions may result from greater plastic deformation and higher friction [34].

In contrast, CryoMQL provides lubrication, reducing friction and improving heat transfer, thereby minimising plastic deformation. These results align with previous research, indicating that higher cryogenic cutting serration can result from insufficient lubrication compared to CryoMQL cutting [35]. Another study by Danish et al. [36] also found that cryogenic cutting produces more pronounced serrations in the chips compared to CryoMQL. It revealed that the cutting forces are higher in cryogenic conditions than in CryoMQL conditions.



Average Height-to-thickness ratio for Cryogenic =0.810



Average Height-to-thickness ratio for cryoMQL =0.776

Fig. 4 *Average Height-to-Thickness Ratio for Cryogenic and CryoMQL Conditions in Experiment 3. The ratio value for the cryogenic condition is closer to 1, indicating a more serrated profile compared to the cryoMQL condition*

Table 4 *Height-to-thickness ratio of the sawtooth chip*

Experiment No.	Cryogenic	CryoMQL
1	0.690	0.497
2	0.857	0.690
3	0.810	0.776
4	0.758	0.734
5	0.674	0.608

3.3 Chip Thickness

The study of chip thickness is important as it provides the insight of machining condition. According to Hariprasad et.al [37], thinner chips are favorable as it indicated better machinability due to lower cutting force and cutting temperature. The resultant chip thickness can be varied based on the machining's shear plane angle, the cutting force and the feet rate [38]. Referring to Fig. 5 for experiments 1 to 4, thinner chips can be produced when increasing the cutting speed and reducing the feed rate. These results align with previous researcher of Das et al. [39], who observed that by reducing the feed rate and increasing the cutting speed will limit the contact between the tool and the workpiece, hence producing thinner chips. While on experiment 5, a more reduced value of chip thickness can be observed. It is due to the lower value depth of cut (*ap*) is used during cutting which further reduces the contact between the tool and the workpiece. This finding is also consistent with the study by Storchak et al. [40].

This work also reveals that the chip thickness is thicker under cryogenic conditions in comparison to cryoMQL conditions. This suggest that cryoMQL is more effective in reducing the tool-workpiece friction, resulting in smoother and thinner chips. These findings align with Yıldırım et al. [35], who similarly observed that smoother chips were formed under cryoMQL conditions compared to standalone cryogenic coolant in machining Inconel 625. Based on Fig. 5 Experiment 1, thicker chip formation was observed in both conditions. This can be attributed to the built-up edge (BUE) formation at much lower cutting speed of 300 m/min, which affect chip thickness by reducing the value of rake angle of the cutting tool. On the other hand, the addition of oil use in cryoMQL conditions improve the lubrication at the cutting edge hence controlling the formation of BUE. With that, smoother chips flow, thinner chips, and more continuous chips is produced during cryoMQL conditions when compared to cryogenic cutting. Beside that, a high-pressure mist during MQL cutting also improve the chips flow by reducing the adhesion of the chips at the rake face of the cutting tool [41]. In conclusion, the improve lubrication and high pressurized mist during hybrid condition of cryoMQL gives an advantage of better chips flow ability, resulting thinner chips and better machinability of the material.

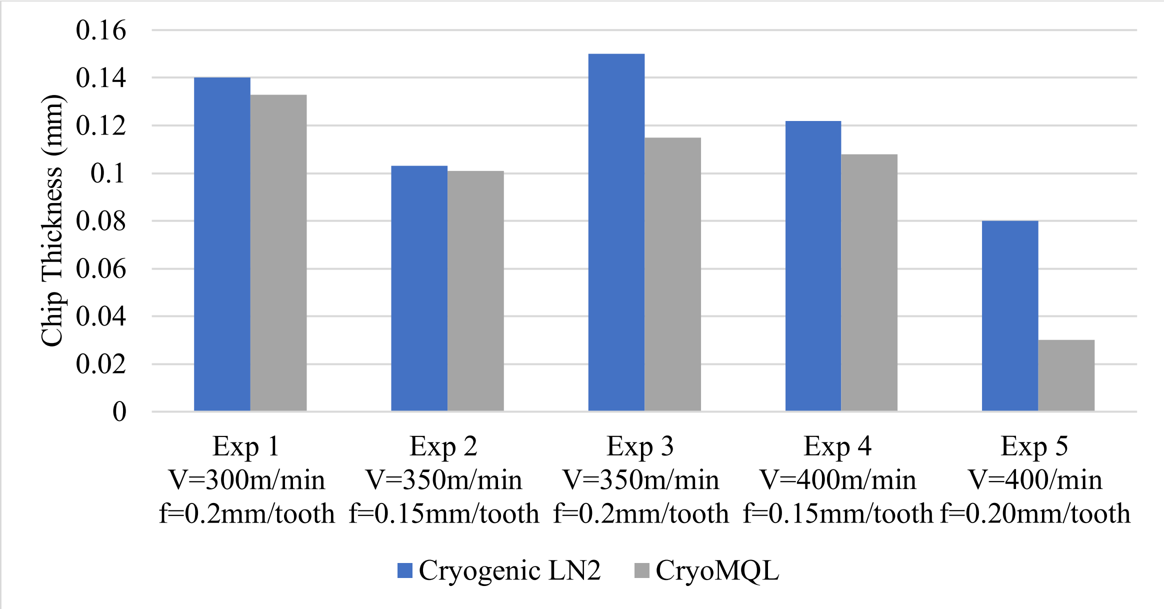


Fig. 5 *Comparison of chip thickness between cryogenic and cryogenic MQL*

3.4 Chip Sawtooth Distance

The chip sawtooth distance, which is the pitch-to-pitch distance between two successive points on a chip serration, is influenced by thermal softening, shear deformation, strain rate, and strain hardening [19]. According to Fig. 6, this distance increases with higher cutting speeds and feed rates due to reduced heat dissipation and shorter contact time [42]. Improved heat dissipation, on the other hand, decreases the sawtooth distance [19]. Observing the graph result, cryoMQL produced a smaller chip sawtooth distance than cryogenic condition. This can be attributed to the frictional effect and surface roughness during machining. This was also observed by Yıldırım et al. [35], who found that cryoMQL provides a better surface roughness due to better coolant and lubrication than cryogenic. This can be proven from the result on cryoMQL, which produces a small value in chip sawtooth distance by having less friction and heat generation due to better effects in cooling and lubrication.

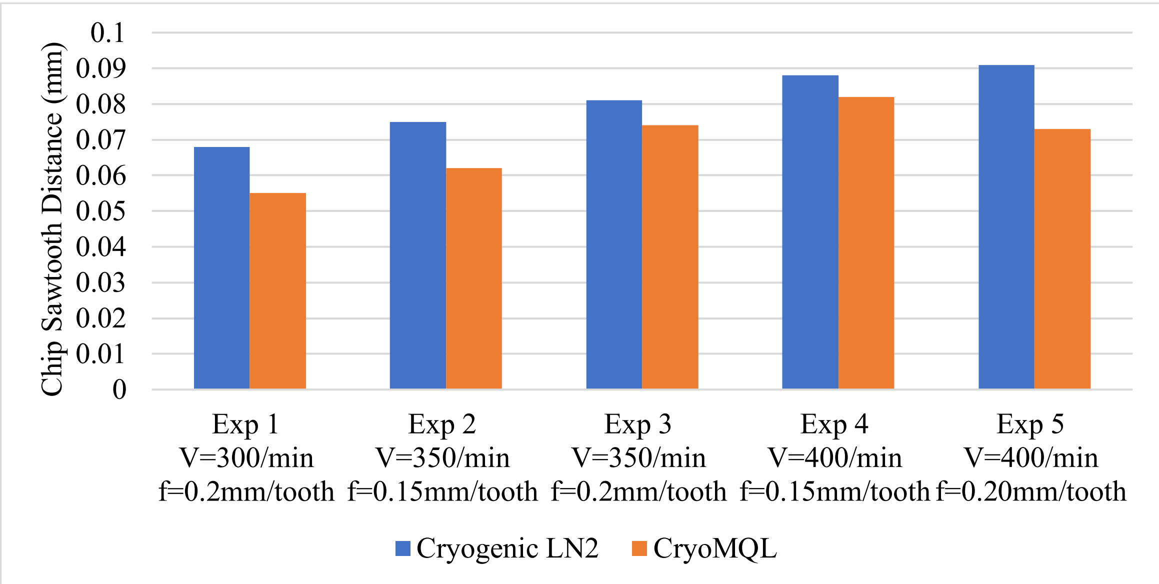


Fig. 6 *Comparison of chip sawtooth distance between cryogenic and cryogenic MQL*

Moreover, it can be related to the thermal softening and strain rate. Thermal softening and strain rates are less likely to happen during low cutting speeds. Thermal softening occurs by machining at a high cutting speed, increasing the chip sawtooth distance. However, this chip sawtooth distance can also be related to the tool wear during machining.

4. Conclusion

This study analyzed the chip morphology of AISI 4340 using an end milling technique under two cutting conditions namely cryogenic and cryoMQL. The findings indicate that the cryoMQL method produces smaller, less serrated chips, with thinner chips and closer sawtooth distances than the cryogenic condition. This results in reduced tool wear, friction, and heat generation due to more effective cooling and lubrication. Thinner chips also minimize cutting fluctuations, enhancing tool life and surface quality. Therefore, cryoMQL shows superior machinability for AISI 4340. Additionally, the study reveals that higher cutting speeds combined with lower feed rate produce better results with less chip serration, thinner chips, and shorter sawtooth distances, which are associated with better surface integrity and longer tool life. In conclusion, machining in cryoMQL conditions improves the machinability of AISI 4340, making it highly beneficial for applications in the High-speed machining (HSM) process of automotive and aerospace industries. Future research could focus on optimizing cutting parameters and exploring long-term effects to refine the cryoMQL process further.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***conceptualization, methodology, validation, supervision and writing – review & editing:*** *Ahsana Aqilah Ahmad;* ***conceptualization and facility:*** *Jaharah A.Ghani;* ***writing – review & editing:*** *Nurul Hayati Abdul Halim;* ***writing – review & editing:*** *Siti Mariam Abdul Rahman;* ***writing – original draft:*** *Adlan Hakimi Abdul Hamid. All authors reviewed the results and approved the final version of the manuscript.*

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