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Performance evaluation of multilayer coated carbide tools in machining hardened AISI430 at high cutting speed under minimum quantity lubrication

Jaharah A Ghani [1*], Saima Yaqoob [1,2], Nabil Jouini [3], Afifah Zakiyyah Juri [1],
Che Hassan Che Haron [1], Shalina Sheik Muhamad [4]

[1] Department of Mechanical and Manufacturing Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, MALAYSIA.
[2] Department of Industrial and Manufacturing Engineering, NED University of Engineering and Technology, PAKISTAN.
[3] Mechanical Engineering Department, Prince Sattam Bin Abdul Aziz University, SAUDI ARABIA.
[4] Technical Support Division, Alurtron, Malaysian Nuclear Agency, MALAYSIA.
*Corresponding author: jaharahaghani@ukm.edu.my

KEYWORDS

Hard turning AISI 4340
MQL
Tool life
Wear mechanism
Taguchi method

ABSTRACT

This study focuses on investigating the cutting tool performance of a chemical vapor deposition (CVD) coated carbide tool in machining hardened AISI 4340 alloy steel under environmentally friendly sustainable minimum quantity lubrication (MQL) environment. The input parameters for turning experiments were configured in a high-speed regime, with the cutting speed (V) varying from 300 to 400 m/min, the feed rate (F) between 0.1 and 0.2 mm/rev, and depth of cut (DOC) in the range of 0.2 to 0.4 mm using a multilayer coated carbide tools TiCN/Al$_2$O$_3$. The experiments were randomly conducted using the Taguchi method L9 orthogonal array, which accommodated three factors, each with three levels. The longest tool life of 7.10 min was noticed under low machining parameters at a cutting speed, V=300 m/min, F=0.1 mm/rev, and DOC=0.2 mm. Analysis using S/N ratio revealed that the machining speed has a most profound influence on tool life in comparison to feed rate and depth of cut. Wear mechanisms such as cutting-edge chipping was commonly observed, whereas at high depth of cut catastrophic failure was noticed due to the flaking of the cutting tool material.

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Abbreviations

MQL : Minimum quantity lubrication
CVD : Chemical vapor deposition
V : Cutting speed
F : Feed rate
DOC : Depth of cut
S/N : Signal to noise ratio
ANOVA : Analysis of variance
BUE : Build up edge

1.0 INTRODUCTION

Machining, a term in manufacturing, encompasses a range of technologies and processes. In the modern era, machining is increasingly executed with computer assistance for enhanced accuracy and precision. In response to escalating environmental concerns, researchers have proposed eco-friendly solutions for various machining operations to reduce the contribution of greenhouse gases to global warming. Typically, machining processes employ various lubricants to control heat generation in the machining region and enhance process output. Cutting fluids offer improved lubrication, enhanced heat dissipation, anti-corrosion properties, and water solubility when combined with water and enriched with wetting agents and EP additives (Osama et al., 2017). However, the addition of these agents poses detrimental impact on environment. Incorrect disposal causes contamination of water and soil. Therefore, these fluids proper treatment before disposal, which eventually increased the manufacturing cost (Ahmad et al., 2021). In this concern, sustainable machining techniques has gained prominence in recent times, with ongoing efforts to investigate innovative alternatives that are both bio-accountable and cost-effective (Debnath et al., 2014). Recent advancements in sustainable machining practices encompass various techniques, including dry cutting, minimum quantity lubrication (MQL), cryogenic cooling (Cryo), high-pressure cooling (HPC), and hybrid cooling (Liu et al., 2019).

In MQL machining, very less amount of cutting fluid particularly, biodegradable oil is combined with compressed air to deliver the efficient lubrication at the tool-workpiece interfaces (Ismail et al. 2024; Mahboob Ali et al., 2019; Pereira et al., 2017). Moreover, MQL utilizes high-speed airflow ranging from 0.6 to 0.8 MPa to atomize the oil to serve as the lubrication function. The atomization of MQL is possible by the arrangement of following crucial components in the MQL setup, which includes compressor, pressure regulator, oil filter, pressure gauge, and nozzle assembly (Said et al., 2019). Kasim et al. (2023) in an evaluation compared the performance of three cooling/lubrication conditions: dry, cold air, and cooled MQL. It was revealed that better surface quality with minimum surface roughness (R_a) of 0.185 µm was attained using cooled MQL at 10 °C, while highest roughness was observed under dry condition, attributed to high machining temperature and associated rapid tool wear. Şahinoğlu, (2023) also affirmed that MQL environment proves to be notably effective in achieving outstanding surface finish with less energy consumption than dry and food environment when machined heat-treated AISI 52100 workpieces. The effectiveness of MQL in machining various advanced materials can be further improved with nano-particles and simultaneously spraying cryogenic coolant (Noor et al., 2023). Özbek, (2023) comprehended the performance of vegetable-based oil mixed with multi-walled carbon nanotubes (MWCNT) and graphite nanoplatelets (GNP) in the turning of difficult-to-cut super alloy Udimet 720. The results demonstrated that MWCNT showed a significant reduction in tool wear of approximately 51%, followed by GNP (39%) and pure MQL (35%), in comparison to a dry environment at low machining parameters (V = 40 m/min, F = 0.04 mm/rev, and DOC = 0.6 mm). Moreover, MQL combined with cryogenic coolant can extend tool life by providing abrasive resistance to tool flank wear. In a related study, it was established that combined MQL and LN2 environment produced favorable cooling and lubrication, resulting in a 32.77% reduction in machining temperature and a 56.99% decrease in flank wear (Özbek et al., 2023).

Hard turning is an emerging manufacturing method that is used to manufacture cylindrical components with a high hardness surpassing 45 HRC. It is a well-established alternative to typical grinding procedures (Roy et al., 2018). Hard machining, which operates between 45 and 65 HRC, is critically reliant on several factors, such as; parametric settings, workpiece and tool material characteristics, as well as the type of cooling and lubrication used during the process. High thermal and mechanical loads induced during a hard turning process caused server damaged to the tool cutting edge and reduced its service life. Moreover, the wear induced on the tool edge can substantially affect the surface quality of machined surfaces, which is a prime attribute of hard turning process (Su et al., 2021). Besides, setup time caused by the replacement of the tool eventually increases the machining costs. Thus, it is essential to abridge the tool wear to attain desirable surface quality in a productive manner (Anand et al., 2019). In a study Kumar et al., (2020) revealed that the enhanced strength and hardness of the heat-treated workpiece material predominantly influences both machining force and surface finish. This is as a result of less generation of frictional heat with low feed values and material hardness, which helped in maintaining the cutting-edge geometry and consequently produced a better surface finish. Das et al. (2018) stated that under both dry and MQL environment the coated carbide tool predominant influenced by abrasion wear mechanism in machining AISI 4340 work material. The predominant wear type observed was abrasion. Butt et al. (2021) compared CVD and PVD coated carbide tools in machining hardened alloy steel (AISI 4340). It was revealed that PVD coated tool exhibited better surface quality at low and moderate cutting speeds, while CVD tool exhibited superior performance specifically at high cutting speeds. As per the findings presented by Wagri et al. (2023), feed rate stands out as the foremost dominating factor affecting the surface roughness, followed closely by cutting speed. As increasing feed rate results in the formation of feed marks and the generation of build-up-edges (BUE), which unfavorably influence the surface quality of processed material. Bag et al. (2022) optimized the machining parameters using Taguchi coupled Multi criterion decision making technique TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) for machining hardened alloy steel. The results revealed that cutting speed of 80 m/min, feed value of 0.05 mm/rev, and depth of cut of 0.2 mm is an optimum parametric setting for simultaneous reduction in machining temperature, tool flank wear, and surface roughness. Roy et al. (2020) examined hard turning of AISI 4340 alloy steel under MQL environment. They reported that high cutting speed led to tool chipping due to the development of high stresses surpassing the endurance limit of the tool. The obtained results of tool wear were analyzed using ANOVA, which revealed that the speed and cutting depth emerged as significant factors, contributing 58.69% and 36.16%, respectively. In contrast, the influence of feed rate was deemed non-significant, accounting for only 0.16%

The objective of this study is to utilize Minimum Quantity Lubrication (MQL) for the high-speed (300 to 400 m/min) machining of heat treated AISI 4340 using multilayer carbide tool. The range of machining parameters, particularly the machining speed and feed rate, was thoroughly selected based on the most recent literature relevant to hard-turning on AISI 4340 alloy steel (Jafarian Zenjanab et al., 2022). The referred study utilized ceramic inserts and considered the wide ranges of cutting speeds, ranging from 100 to 400 m/min utilizing cutting fluid based on CuO-nanofluids (different weights of boric acid additives) in a hard turning operation, which are disadvantageous to the environment and health of the worker (Tiwari et al., 2021). Therefore, this study mainly focuses on the utilization of sustainable MQL technique in hard turning of steel with cost effective coated carbide tools to evaluate its lubrication effectiveness in delivering favorable machinability results in the safest working environment. The primary focus of this study will remain on evaluating tool life and understanding the wear mechanism.

2.0 EXPERIMENTAL PROCEDURE

A round bar of AISI 4340 material with length 80 mm and diameter 60 mm has been used for the turning tests due to its commercial importance in manufacturing, defense, and automobile industries. The composition of AISI 4340 is presented in Table 1. The work material was thermally treated before experimentation to attain the desired hardness of 50 HRC. For this purpose, the material was subjected to a series of thermal treatments to achieve the desirable level of hardness. The procedure included 3 hours of curing at 840 °C, 1 hour of quenching at 830 °C, and 4 hours of annealing at 400 °C. This was repeated ten times, resulting in a range of hardness 50 HRC. Hardened AISI 4340 alloy steel following the heat treatment process demonstrates elevated toughness and strength, presenting substantial challenges during machining.

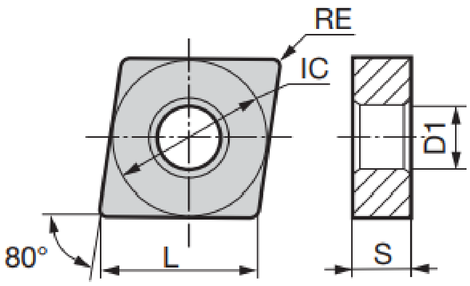
The experimental runs were performed with in a laboratory setting under ambient condition at a temperature of 24°C. For the turning tests CNC machine (TORNADO T4), cost effective multilayer coated carbide tools $TiCN/Al_2O_3$ having 0.4 mm tool nose radius, rake angle of -6°, relief angle 6°, and tool cutting edge angle of 95° have been used. Figure 1 shows the schematic diagram of the cutting insert used in the experimental trials. Tool nose radius of 0.4 mm was selected for this study based on previous literature Natasha et al. (2018), which reported the machinability of AISI 4340 steel at high cutting speed. Table 2 shows the detail of selected cutting tool.

Table 1: Composition of AISI 4340 alloy steel (Wt. %).

C	Ni	Cr	Mn	Si	Mo	Cu	P	S	Fe
0.412	1.41	1.270	0.456	0.211	0.203	0.294	0.015	0.006	Balance

Table 2: Details of selected coated carbide tool (Sumitomo catalogue, 2023).

Coating element	Description
Coating material	$Al_2O_3/TiCN$
Hardness	91.1 HRA
Transverse rupture strength (TRS)	2.5 Gpa
Coating thickness	20µm



Parameters and Dimensions
Radius, RE=0.4 mm
Cutting length, L=12.9 mm
Inscribed circle, IC=12.7 mm
Thickness, S=7.76 mm
Hole Diameter, D1= 5.16 mm

Figure 1: Schematic diagram of the cutting tool with parameters dimensions (Sumitomo catalogue, 2023).

The MQL system produced by UNIST with bio-based coolube 2210XP lubricant was used for this study. This low-viscosity liquid cutting fluid possesses no oxidizing properties and has a high flash point (> 200 °C), demonstrating improved wettability. It tends to penetrate deeply into the machining zone without inducing thermal shock to the carbide tool. Commercially available flexible spray nozzles having diameter 3 mm with conical tip are used to deliver MQL to the machining zone through the rake and flank side of the tool. Each nozzle was configured at 60 ml/h flow rate; thus the total flow rate of 120 ml/h has been employed during each experimental trial. The MQL parameters were carefully selected based on previous literature. Sarıkaya & Güllü, (2014) optimized the MQL flow rate for medium (80 m/min) to high cutting speed (200 m/min) considering (60 and 120) ml/h flow rates. It was found that 120 ml/hr MQL flowrate produced more profound machinability results at high cutting speed. Nozzle standoff distance of 30 mm and nozzle angle 45° were also chosen based on previous literature. Gajrani et al. (2019) presented a detailed investigation on optimizing the following parameters: lubricant composition, nozzle spray angle, and its distance from the tool while machining H-13 steel. It was revealed that 30 mm is an optimal standoff distance if taking into account the respective coverage area and the force exerted by the mist on the tool. Whereas MQL aerosol ejected from 45° angular nozzle can effectively enter the air boundary periphery generated by the revolving workpiece during the turning process. It is noteworthy to state that a consistent MQL setting was employed throughout all experiments to maintain a uniform lubrication environment. The experimental setup along with MQL setup and respective nozzles arrangement is illustrated in Figure 2.

Table 3 shows factors and levels used whereby Taguchi L_9 orthogonal array was adopted to generate respective experimental scheme. The selected L_9 array has the efficiency to accommodate three factors at three levels in less experimental runs. The progress of the tool flank wear was measured using a microscope model Zeiss Stemi 2000-C. The flank wear land (Vb) was measured until it reached 0.3 mm as specified by ISO 3685 (ISO, 1993).

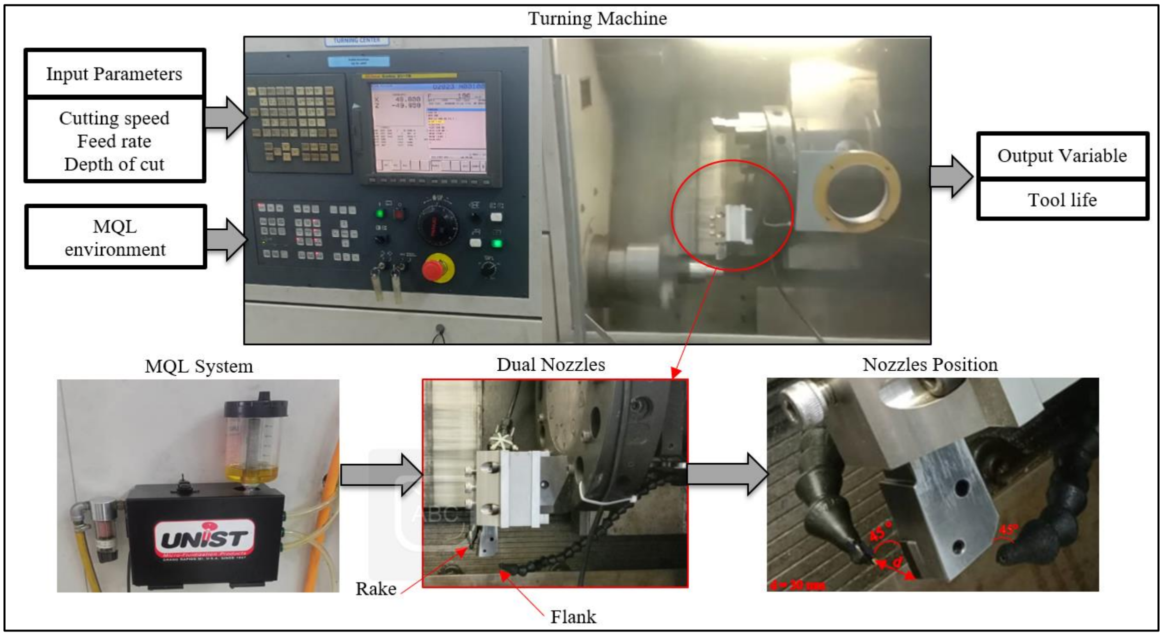


Figure 2: Experimental setup employed for the turning tests.

Table 3: Factors and levels used in the turning process.

Control Factors	Levels		
	1	2	3
Cutting speed (V) (m/min)	300	350	400
Feed rate (F) (mm/rev)	0.1	0.15	0.2
Cutting depth (DOC) (mm)	0.2	0.3	0.4

3.0 RESULTS AND DISCUSSION

Hard turning is a difficult machining process, produces enormous amount of heat in all three deformation zones. The cutting principal diagram, presented in Figure 3, illustrates the strategy for delivering cooling as well as lubrication to the deformation zones. Two nozzles were utilized, with one positioned at the rake, while other projected on the flank face of the tool, each serving a distinct purpose to enhance lubrication efficiency and mitigate machining heat. MQL was directed towards the flank face to provide lubrication between tool-workpiece interfaces and to reduce the machining heat in the primary and tertiary deformation zones. Conversely, MQL delivered to the rake face aims to reduce friction between the chip-tool, minimizing the heat in the secondary deformation zone. The cutting time or tool life for each experimental run is expressed in Table 4. The longest tool life of 7.10 minutes was achieved with a low combination of machining parameters in experiment 1. Whereas the lowest tool life of 0.86 minutes was observed in experiment 9 with high turning speed and feed value as a result of excessive heat generation. The tool life was limited due to wear formation on the flank side of the cutting insert, and it became evident that high machining parameters hastened the tool wear. This is illustrated in Figure 4, the wear curve notably accelerated at high combination of machining parameters. In contrast, the longest stable wear progression was observed in experiments 1 and 4 when combining the lowest (V=300 m/min) and moderate machining speeds (V=350 m/min) with the lowest feed rate of 0.1 mm/rev. Figure 5(a)-5(c) depicts the interaction between cutting speed and feed rate concerning the amount of tool wear. These illustrations highlighted that with an incremental change in feed rate to 0.15 and 0.2 mm/rev, the corresponding wear graphs skewed toward left and exhibited faster acceleration towards the severe wear stage. This is justified by the fact that the area of tool travel increased with a rising feed rate, producing frictional effect between the contacting surfaces, and promoting tool wear (Gupta et al., 2019). This phenomenon became notably more prominent at high machining speeds; V=350 and 400 m/min with all feed values and DOC combinations because high cutting speeds generate significant machining heat, leading to the degradation of main cutting geometry and consequently produced shorter tool life (Mustafa et al., 2023). It is important to elaborate that the hard turning process generally imposes high thermal stresses. With high cutting speed and feed rate, the tool's cutting edge undergoes substantial mechanical and thermal loads, experiencing high friction and restraining forces required for material removal. Consequently, this results in extensive plastic deformation of the tool material, contributing to wear and tool chipping. It is due to these critical reasons wear graph in Figure 5(b) and 5(c) skewed towards left and sharply accelerates towards the severe wear stage than the wear graph shown in Figure 5 (a).

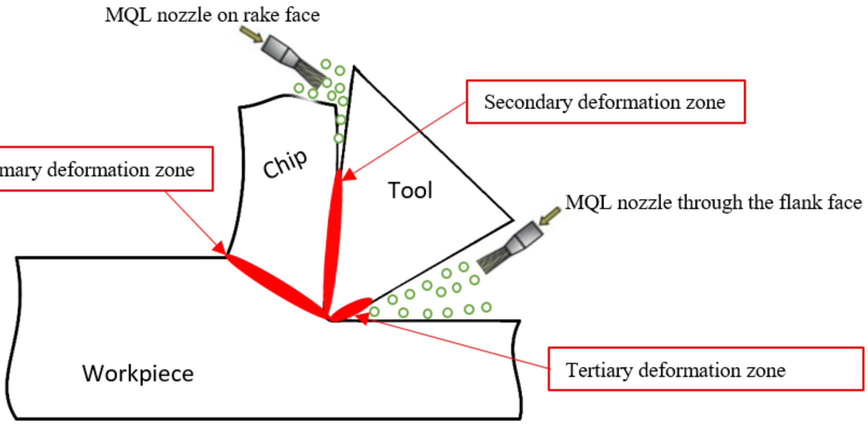


Figure 3: Schematic of cutting principle with lubrication arrangements.

Table 4: The tool life results for all the nine machining experiments.

Experiment Run	V (m/min)	F (mm/rev)	DOC (mm)	Tool life (min)	Signal to noise ratio (S/N)
1	300	0.1	0.2	7.10	17.03
2	300	0.15	0.3	4.59	13.27
3	300	0.2	0.4	2.84	9.07
4	350	0.1	0.3	5.72	15.15
5	350	0.15	0.4	2.58	8.23
6	350	0.2	0.2	1.98	5.93
7	400	0.1	0.4	2.11	6.49
8	400	0.15	0.2	1.69	4.56
9	400	0.2	0.3	0.86	-1.310

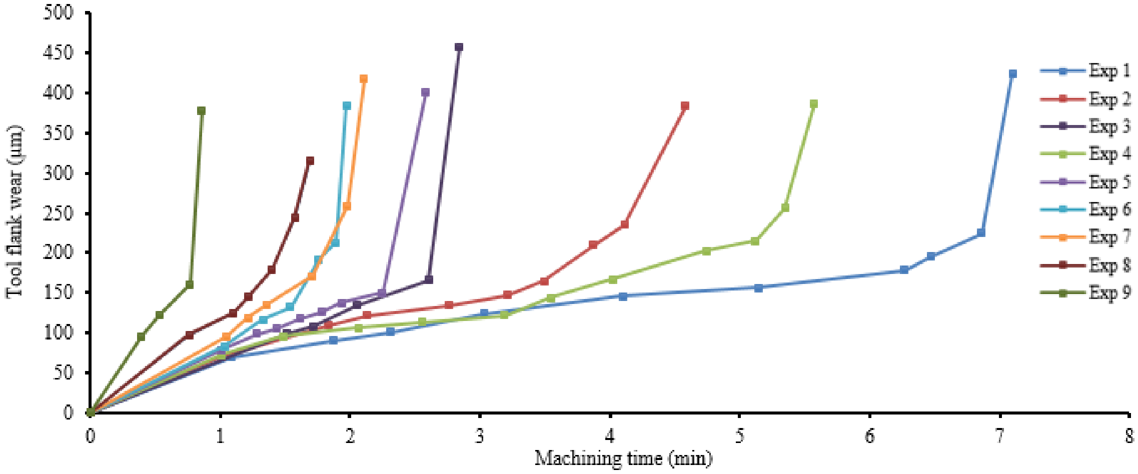


Figure 4: Flank wear (Vb) verses machining time (min).

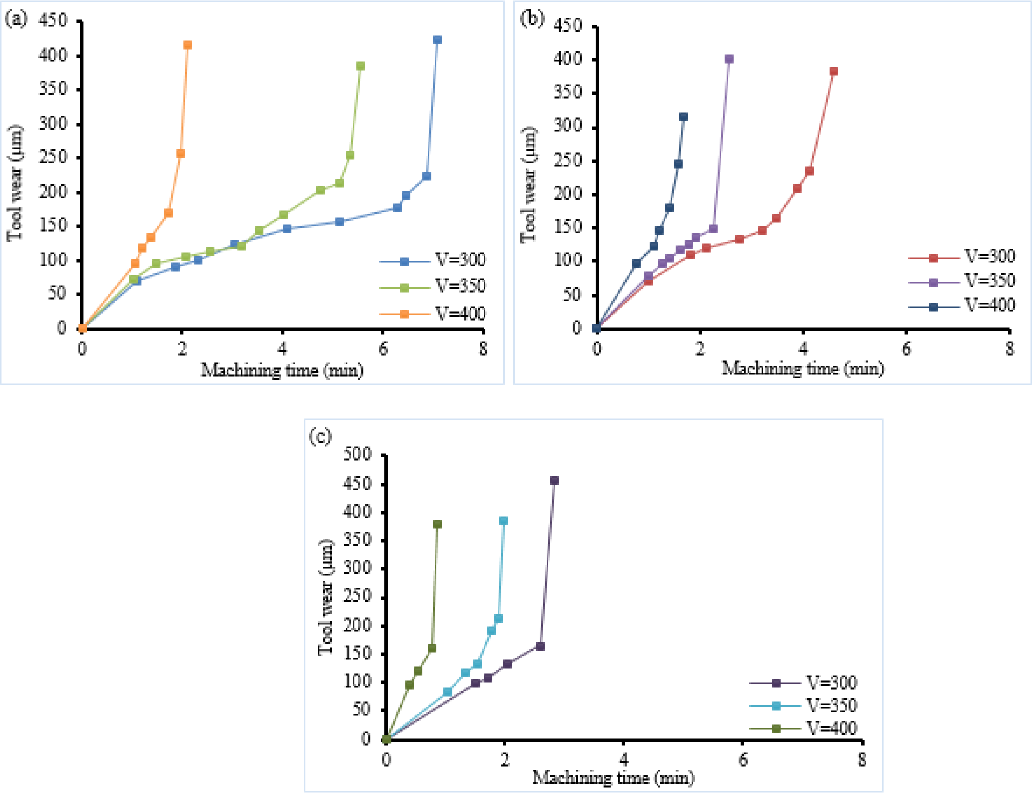


Figure 5: Trend of tool wear with varying feed rates (a) 0.1 mm/rev, (b) 0.15 mm/rev, (c) 0.2 mm/rev.

The obtained tool life results were analyzed based on Taguchi S/N ratio, considering larger the better method. The corresponding S/N ratios against each parametric setting is represented in Table 4. Figure 6 elaborates that the SN ratio plot for tool life, indicating that cutting speed is the most significant parameter affecting tool life, followed by the feed rate. However, the depth of cut is observed to be the least significant. Similar results can also be inferred from the ANOVA Table 5, considering 95% confidence level. It is evident that cutting speed contributed the most, with a maximum contribution percentage of approximately 49%, followed by feed rate (42%) and depth of cut (7%). Based on the mean of the S/N ratio (Figure 6), it was determined that the recommended turning condition for achieving longer tool life is at V= 300 m/min, F= 0.10 mm/rev, and DOC = 0.2 mm.

Table 5: ANOVA Table for tool life.

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**	**% Cont.**	**Significance**
V	2	17.36	17.36	8.68	28.18	0.034	49.08	Significant
F	2	14.87	14.87	7.44	24.14	0.040	42.06	Significant
DOC	2	2.51	2.51	1.25	4.07	0.197	7.1	Insignificant
Residual Error	2	0.61	0.61	0.31				
Total	8	35.35						

Figure 6: Mean of SN ratios of tool life.

3.1 Tool Wear Progression

The wear progress on the tool vary according to the machining parameters used. Figure 7 illustrate the progression of wear at different parametric settings for Experiment 1, 2, and 9. At low combination of machining parameters in Experiment 1, gradual wear has been observed throughout the turning process until the wear reaches to its maximum limit Vb>0.3 mm at 7.10 minutes. MQL at this parametric setting demonstrated effective lubrication effect due to the administration of cooling and lubrication under the action of capillary tubes and sharing of work material for an extended time. These factors contributed to better performance of MQL in the following two manner (a) high pressure lubricating oil enters the periphery of revolving workpieces, penetrates more deeply into the machining zone in order to provide desirable lubrication effectiveness, (b) high compressed air favorably restrained the machining temperature by providing effective cooling. The respective microscopic images of the tool also signify improved lubrication and cooling competence in Experiment 1, contributing to the relatively stable cutting-edge geometry of the tool. In experiment 2, the chip thickness increased with the increased in both feed rate and cutting depth. This induced thermal and mechanical loads on the cutting edge thus intensified friction and led to accelerated tool wear. More rapid tool wear and shorter tool life was observed in experiment 9, when high turning speed and feed value were employed with moderate cutting depth. This was expected because at high machining parameters tool could not sustain the harsh cutting conditions and entered the break in period more swiftly (Ghani et al. 2024). According to Ranjan Das et al. (2018), the incremental variation in tool flank wear is attributed to high compressive stresses resulting from elevated cutting temperatures induced by high machining speeds and feed rates, consequently reducing the hardness of the tool. It is crucial to note that the efficiency of MQL diminished with an increase in the relative motion between the tool and workpiece. This could be attributed to reduced timeframe for the dissipation of machining heat, leading to elevated temperatures. Consequently, the lubricating oil may burn or evaporate before reaching the machining zone. Within these circumstances, the flank wear width increased as a result of aggressive abrasion occurring at both the tool-workpiece and tool-chip interfaces. This led to further delamination of the tool coating. The cyclic impact of high cutting speed and feed rate heightened the likelihood of chipping and flaking, eventually pushing the tool to its maximum wear limit or causing catastrophic failure. Furthermore, it is vital to highlight that the simultaneous application of a high DOC and feed rate resulted in rapid tool failure, occurring immediately after the tool wear reached ⩽ 165 μm in Experiments 3, 5, and 9. This was expected as increased in feed and cutting depth increased tool contact area and uncut chip thickness. As a result, tool encounters escalated restraining force, leading to enormous shearing of the machined material under highly intensive mechanical stresses, which are high enough to promote tool wear and flaking of the tool (Mia et al., 2018).

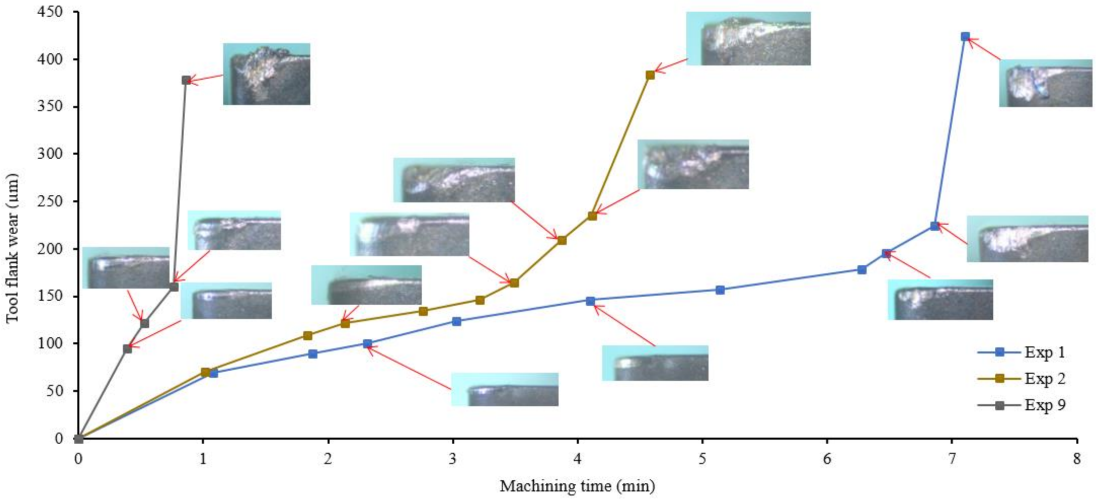
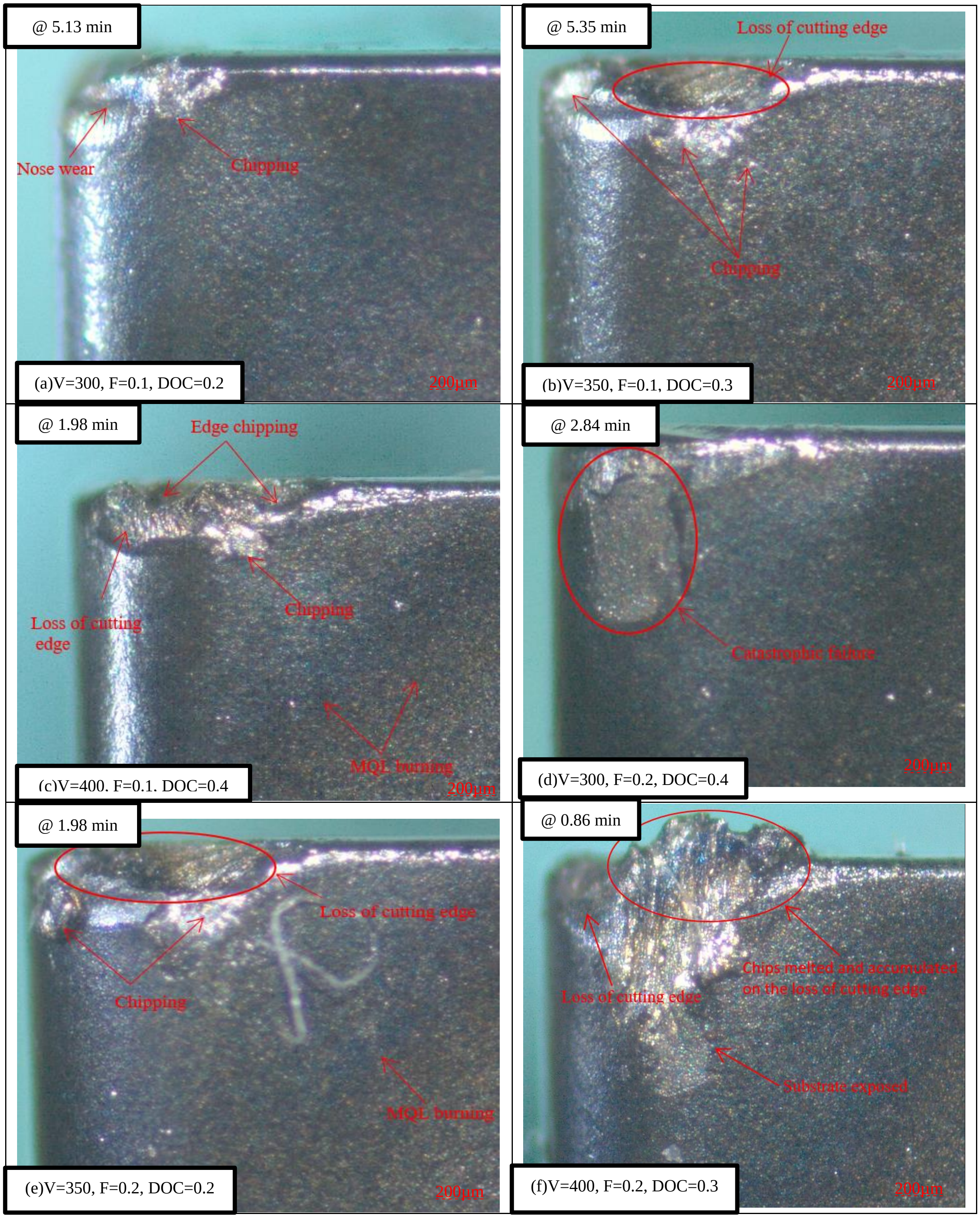


Figure 7: Progress of tool flank wear verses machining time.

The microscopic images of the worn tool captured during the machining process are shown in Figure 8(a)-8(f). These images depict additional validation to support the findings discussed earlier. It has been observed that machining test performed at low cutting speeds of 300 m/min (Figure 6a) exhibited relatively stable cutting edge with less chipping, and loss of cutting edge geometry while experiments performed with high cutting speeds such as 350 m/min (Figure 6 (b),(e)) and 400 m/min (Figure 8 (c), 8(f)) revealed substantial amount of chipping, flaking and the deterioration of the cutting geometry justified the underline reason of shorter life. Gupta et al. (2020) also observed loss of cutting-edge geometry while turning hardened steel at high cutting speeds. Their findings revealed that the presence of hard particles within the work material contributes to the abrasion of the tool coating. This phenomenon results in elevated levels of friction and temperature generation, ultimately leading to the loss of cutting-edge geometry. It is worth noting that in all experimental runs, the dark area surrounding the cutting edge indicates a high-temperature condition, signifying the evaporation and burning of the micro lubricating oil. This phenomenon significantly contributed to the accelerated tool flank wear width. Interestingly, in the last run of experiment 9 the chips melted and accumulated on the cutting geometry, ends up in the formation of BUE as can be seen in Figure 6f. This may be due to temperature reduction offered by MQL aerosol when the chips entered and accumulated in the fracture region of the cutting tool.



(a)V=300, F=0.1, DOC=0.2

(b)V=350, F=0.1, DOC=0.3

(c)V=400, F=0.1, DOC=0.4

(d)V=300, F=0.2, DOC=0.4

(e)V=350, F=0.2, DOC=0.2

(f)V=400, F=0.2, DOC=0.3

Figure: 8 Microscopic images of the cutting tool with different parametric settings.

CONCLUSIONS

From the results obtained in machining harden AISI 4340 at high-speed cutting under minimum quantity lubrication it can be concluded:

a. Minimum Quantity Lubrication (MQL) demonstrates superior lubrication effectiveness at low machining parameters, effectively reducing machining heat and frictional effects. This contributes to minimizing damage to the cutting-edge geometry and extends tool life. However, its efficacy diminishes at high parametric settings due to increased machining heat, resulting in partial burning or evaporation of the micro-lubricating oil before reaching the machining zone.
b. The tool life is significantly affected by the cutting speed, followed by the feed rate and depth of cut. However, the depth of cut has showed least influence. Therefore, one can select either to use low or medium DOC in the range of study. Since at high DOC, it caused the catastrophic failure due to high impact during the cut.
c. The recommended cutting conditions obtained from the SN plot for turning within this range of machining parameters are V = 300 m/min, F = 0.10 mm/rev, and DOC = 0.2 mm.
d. The highest tool life of 7.10 min was observed at low combination of cutting parameters.
e. Wear mechanisms such as cutting-edge chipping was commonly observed, whereas at high depth of cut catastrophic failure was due to the flaking of the cutting tool material.

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