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Tool life and surface roughness in dry condition down milling of hardened AISI4340 at high cutting speed

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KEYWORDS

Tool life
Surface roughness
AISI 4340 steel
Down milling

ABSTRACT

Machining hardened AISI 4340 is very challenging when precision tolerances are essential. This study presents the down milling of hardened AISI 4340 at high cutting speeds in dry cutting conditions using PVD tungsten multilayer TiAlN/AlCrN-coated carbide inserts. The machining trials were performed according to the Taguchi method L9 with variable cutting parameters: cutting speed (300–400 m/min), feed rate (0.15–0.30 mm/tooth), axial depth of cut (0.3–0.5 mm), and radial depth of cut (0.2–0.5 mm). The evaluated machining outputs are tool life and surface roughness, as these outputs are major concerns in determining machining productivity. The S/N ratio from Taguchi analysis indicates that cutting speed contributes the most significant effect on surface roughness, followed by feed rate, width of cut, and depth of cut. Meanwhile, for tool life, the feed rate is the dominating factor, followed by width of cut, depth of cut, and cutting speed.

1.0 INTRODUCTION

AISI 4340, an alloy steel widely employed in various industries, poses machining challenges due to its unique blend of strength, toughness, and heat treatability. Researchers, recognizing its difficulty to machine, have explored the effects of different machining settings and positions for this steel (Roy et al., 2018). The enhanced properties of this steel make it the preferred choice for

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various applications, including automobile crankshafts, aircraft landing gear beams, and heavy-duty gears.

To examine AISI 4340 while aligning with principles of sustainability—covering environmental, social, and economic factors—the recommended cutting condition is dry machining. Dry cutting, involving the complete elimination of hazardous cutting fluids (coolant or lubricant), stands out as an environmentally friendly machining method that significantly mitigates adverse effects (Goindi & Sarkar, 2017). Both the cost and environmental impact of machining witness substantial reductions when lubricants are omitted (Gupta, 2020). According to Ahmad et al. (2021) a major benefit of dry cutting is that this approach is characterized by its cleanliness.

Furthermore, the rising demand for high-quality products with superior surface finishes, driven by new applications of AISI 4340 in various fields, compels manufacturers to enhance productivity by improving surface quality to remain competitive in the market. The surface topography of any machined surface is influenced by several factors, with surface roughness (Ra) being the most significant. Figure 1 summarizes the range of Ra values for various machining processes, indicating that, for milling processes, the common Ra value falls between 0.8 and 6.3 μm.

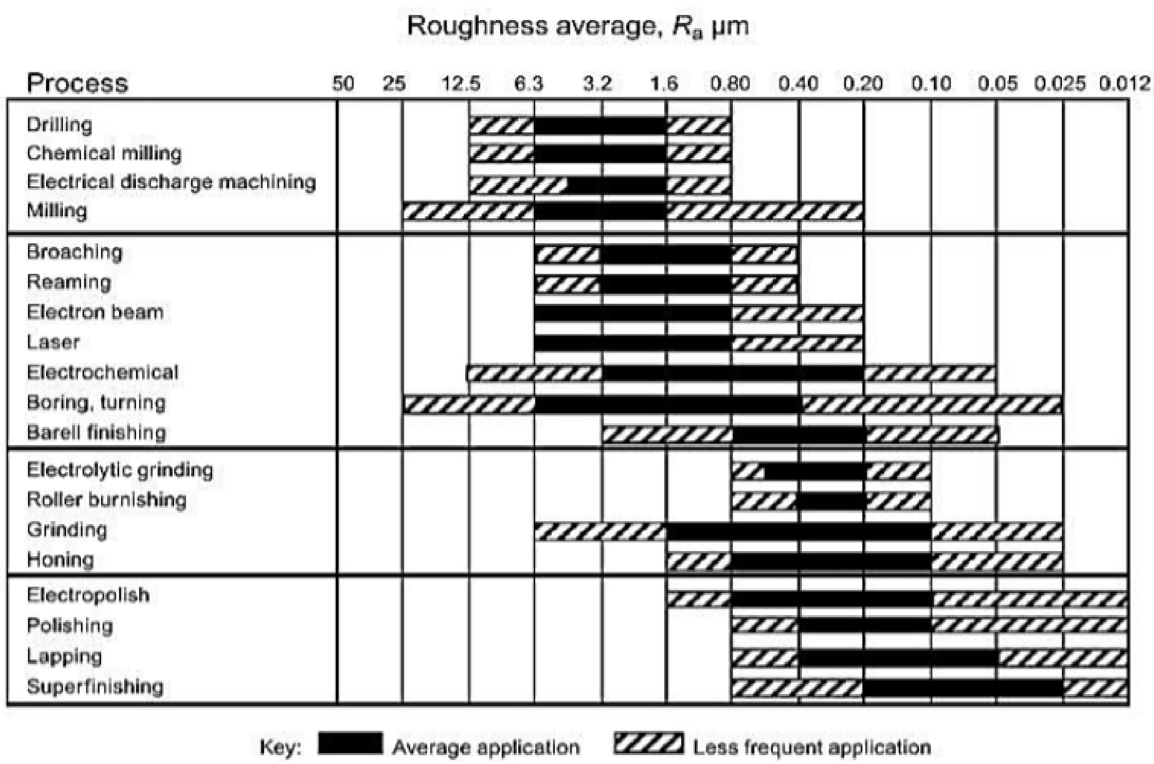

Figure 1: Typical surface finish in machining process. (Source: Muhammad et al., 2019).

In addition to the aforementioned considerations, AISI 4340 demands enhanced tool life - a measure of the duration a cutting or machining tool can efficiently perform its designated task before wearing down, dulling, or losing its operational effectiveness (Bag et al., 2019). Tool life significantly influences production efficiency, quality, and operational costs, rendering it a critical factor in the manufacturing environment. Maximizing tool life is imperative for efficient and economical machining, as tools with prolonged lifespans obviate the need for frequent changes. Frequent tool changes can result in increased downtime and higher tool replacement costs.

To extend the lifespan of tools, manufacturers often employ various strategies, including meticulous material selection, optimization of cutting parameters, and efficient tool maintenance and reconditioning procedures. According to Kovrizhnykh (2008), Lee and Shaffer's equation, commonly employed in end milling operations, articulates the relationship between tool life (T), cutting speed (V), feed rate (f), depth of cut (d), and material-specific constants (C), as depicted in the Equation (1).

$$T = \frac{C}{(V \times f \times d)} \tag{1}$$

Numerous researchers have contributed valuable insights into how machining conditions impact the surface roughness and tool life of AISI 4340 HSLA steel. As highlighted by Sifa et al. (2020), tool life and surface roughness are critical parameters influencing the quality and efficiency of the final product. A precise understanding and control of these factors can lead to improved productivity, cost savings, and heightened customer satisfaction. This significance is particularly evident in high-speed milling operations, where cutting speed and feed rate notably influence tool life and surface roughness.

Da Silva et al. (2020) conducted a study on machined surfaces of hardened AISI 4340 steels through turning and grinding operations. The turning process, especially at a cutting speed of 300 m/min, yielded superior results in roughness parameters, promoting a better surface finish. Interestingly, the use of cutting fluid in turning did not outperform dry cutting conditions. Whereas Das et al. (2017) employed a CVD (TiN/TiCN/Al2O3/TiN) multilayer coated carbide tool for dry hard turning of AISI 4340 steel (49 HRC). Their study, employing factorial experiment designs and Taguchi's L9 Orthogonal array, revealed that feed and cutting speed significantly impact flank wear and surface roughness. Wagri et al. (2023) investigated the machining of annealed AISI 4340 alloy steel using a coated carbide tool. Their experiments varied the depth of cut, rate of feed, and machining speed, showing that feed rate had the greatest influence on surface finish, with cutting speed being the second most influential factor. Lubis et al. (2019) performed dry machining experiments on AISI 4340 alloy steel using different cutting tools. The study showed that higher cutting speeds led to elevated temperatures at the cutting tool, with the ceramic cutting tool demonstrating lower temperatures and achieving smaller roughness values. Şahinoğlu et al. (2019) investigated the impact of coolant and cutting settings on surface roughness when milling AISI 4340 with CBN tools. They found that the feed rate had the greatest impact on surface roughness, with an increase in feed rate leading to higher roughness values.

BM et al. (2022) aimed to examine how heat treatment settings affect tool life and surface roughness in AISI 1040 dual-phase steel. Their study, using Taguchi's design technique and ANOVA, revealed that depth of cut and cutting speed were the main variables influencing tool life and surface roughness. A previous study on other materials, such as the one conducted by An et al. (2014), investigated cutting forces, surface roughness, chip generation, and tool wear during the hard milling of 30Cr3 using a PVD-AlTiN coated cemented carbide tool. Experimental results indicated that increasing cutting speed from 70 to 110 m/min improved surface finish and reduced cutting forces. However, surface finish was negatively impacted by feed rate and depth of cut. Mane et al. (2020) explored ideal cutting parameters to reduce cutting temperatures and forces during hard turning, finding that feed had the greatest impact, followed by cut depth and speed. Yazid et al. (2019) studied the impact of machining parameters on surface roughness and cutting tool life during high-speed milling of aluminum alloy 7075-T6 under MQL conditions. Feed rate and cutting speed were identified as critical parameters affecting tool life and surface roughness. Rizal et al. (2025) revealed that the surface roughness improved more than 50% by adding 0.3 wt% graphite in the MQL lubricant in milling AISI 304 stainless steels. On the other hand, Hadi (2025) investigated the effect of nano-hybrid cryogenic MQL during milling Ti-6Al-4V alloy found that the addition of nanoparticles notably reduced the coefficient of friction (COF), that improved machinability significantly.

In this study, AISI 4340 steel (50 HRC) was machined under dry conditions using a multilayer coated carbide (TiAlN/AlCrN). The effects of machining conditions on surface roughness and tool life were measured, offering insights that the machining industry can apply to improve surface roughness and extend tool life, contributing to a sustainable environment.

2.0 METHODOLOGY

2.1 Workpiece Material

The material used for the workpiece was AISI 4340, a high-strength alloy steel with a martensitic structure. The actual hardness of the material was 32 HRC and then it was hardened to 50±2 HRC. The dimension of the workpiece was with the length (178 mm) × width (102 mm) × height (55 mm).

Table 1 shows the main chemical compositions, and the workpiece hardness is 50±2 HRC, determined by the average value of six measurements and Table 2 shows the mechanical properties of AISI 4340.

Table 1: Chemical composition of AISI 4340 (wt.%) (Source: Selvam & Sivaram, 2018).

Elements	**C**	**Si**	**Mn**	**Cu**	**Cr**	**Ni**	**Mo**	**Fe**
wt.%	1.270	0.211	0.456	0.294	0.412	1.41	0.203	95.6

Table 2: Mechanical properties of AISI 4340 (Source: Abbas et al., 2020).

Properties	**Value**
Ultimate tensile strength (MPa)	1195
0.2% yield strength (MPa)	1114
Elastic modulus, E (GPa)	206
Reduction in area (%)	59
Elongation (%)	9.3

2.2 Cutting Tool

The cutting tool utilized in the experiment is a Physical Vapor Deposition (PVD) carbide with a multiple coating of TiAlN/AlCrN and WC-Co ends, specifically the Sumitomo model AXMT123504PEER-G ACP200. The geometry of the cutting tool is illustrated in Figure 1, and detailed parameters of the carbide tool can be found in Table 3.

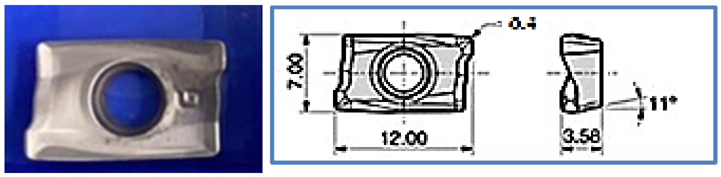

Figure 1: Schematic diagram of the cutting tool AXMT (Source: Sumitomo, 2023).

Table 3: Details parameter of cutting tool (Source: Sumitomo, 2023)

Parameter	Dimension
Length of the cutting edge	12.00 mm
Width of cutting tool	7.00 mm
Thickness of cutting tool	3.58 mm
Rake angle, α	28 °
Relief angle, θ	11°
Nose radius, r_{ε}	0.40 mm

2.3 Tool Holder

The tool holder employed in the experiment is the EChain brand, model EAX2032EL-180. The geometry of the tool holder is illustrated in Figure 2, and detailed parameters of the holder can be found in Table 4.

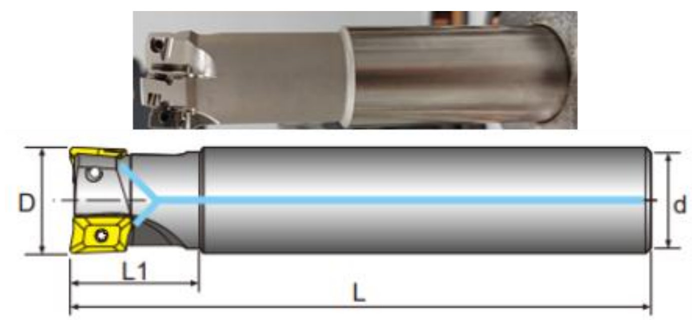

Figure 2: Tool holder (Source: EChain, 2023).

Table 4: Details parameter of tool holder (Source: EChain, 2023).

Parameter	Dimension
D	32 mm
d	32 mm
L	180 mm
L1	60 mm
Number of cutting tool	5

2.4 Machining Experiments

The experimental work was carried out on a 5-Axis Vertical Machine Center brand HAAS model VF-5/40TR as shown in Figure 3. This machine is equipped with Haas Control, Traverses X Y Z 1270 x 660 x 635mm, A Axis -/+ 120 degrees, B Axis 360 degrees, Spindle Taper BT40, Spindle Speed 10000rpm, Motor 22Kw and Table size 210mm diameter.

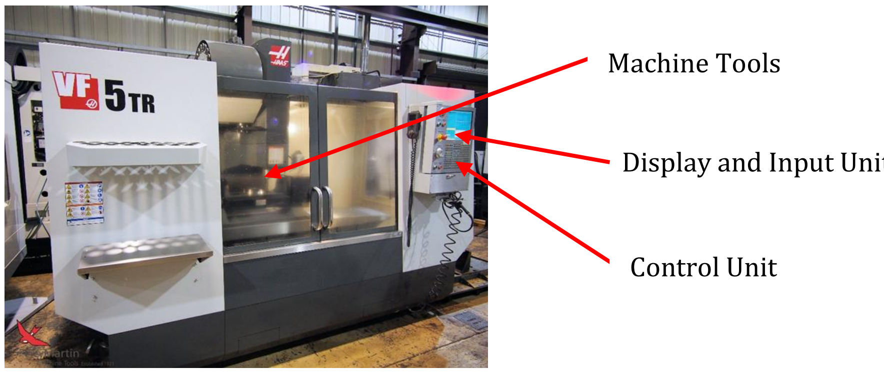

Figure 3: 5-axis vertical machine center.

Table 5 presents a comprehensive summary of the experimental design (DOE) utilized in this study, encompassing three distinct levels aligned with industry and previous research standards for cutting speed, feed rate, width of cut, and depth of cut. Taguchi L9 was employed to conduct the experimental sequence as shown in Table 6. The sequence is randomly chosen. Previous study (Lubis et. al 2024) utilized Taguchi method to examine the effect of CNT's type, load, and sliding speed on lubricated friction and wear of Titanium Alloy Ti10V2Fe3Al.

The average surface roughness (Ra) values were recorded with a Surftest 310 Mitutoyo® roughness tester with a cut-off of 0.8 mm as shown in Figure 4 by contact stylus across the feed direction taken at the beginning of cutting to prevent tool wear effect. Measurements were repeated five times for each run with the values then averaged for further analysis. The average width of flank wear (VB_B) was measured using a 1080P full HD WiFi Digital Microscope (adjustable macgnifications, up to 230x) in Figure 5. Passes for each experimental trial varied according to the tool wear progression measurements. The flank wear land (Vb) was measured until it reached 0.3 mm according to tool life criteria ISO 8688-2 (ISO 8688-2(E)).

Table 1: Factors and level used in the experiment.

Factor/Level	**1**	**2**	**3**
Cutting speed (mm/min)	300	350	400
Feed rate (mm/rev)	0.15	0.20	0.30
Width of cut (mm)	0.20	0.35	0.50
Depth of cut (mm)	0.3	0.4	0.5

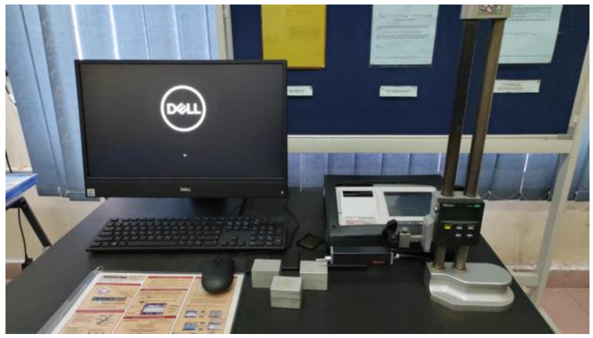

Figure 4: Surface roughness apparatus.

Figure 5: Digital microscope for flank wear measurement.

Table 2: Experiment parameter for the study.

No.	Cutting Speed (m/min)	Feed Rate (mm/tooth)	Width of cut (mm)	Depth of Cut (mm)
1	300	0.15	0.20	0.3
2	300	0.20	0.35	0.4
3	300	0.30	0.50	0.5
4	350	0.15	0.35	0.5
5	350	0.20	0.50	0.3
6	350	0.30	0.20	0.4
7	400	0.15	0.50	0.4
8	400	0.20	0.20	0.5
9	400	0.30	0.35	0.3

3.0 RESULTS AND DISCUSSION

The experimental results discussed include surface roughness and tool life. These results were obtained through nine experiments using the down milling process, with input parameters listed in Table 6.

3.1 Surface Roughness

The data for surface roughness is presented in Table 7 illustrates both the surface roughness obtained and the corresponding experiments. A lower Ra value indicates better surface roughness on the machined surface.

Table 7: Experiment results for the surface roughness.

No.	**Cutting Speed (m/min), V_c**	**Feed Rate (mm/tooth), f_z**	**Width of Cut (mm), a_e**	**Depth of Cut (mm), a_p**	**Surface Roughness (μm), R_a**
1	300	0.15	0.20	0.3	0.550
2	300	0.20	0.35	0.4	0.456
3	300	0.30	0.50	0.5	0.500
4	350	0.15	0.35	0.5	0.424
5	350	0.20	0.50	0.3	0.339
6	350	0.30	0.20	0.4	0.423
7	400	0.15	0.50	0.4	0.495
8	400	0.20	0.20	0.5	0.449
9	400	0.30	0.35	0.3	0.427

Referring to Table 7 the surface roughness values range between 0.339 μm and 0.55 μm, indicating a roughness similar to the finishing process. The lowest surface roughness value, 0.339 μm, is achieved when the cutting speed is 350 m/min, the feed rate is 0.2 mm/tooth, the width of cut is 0.50 mm, and the depth of cut is 0.3 mm. The highest surface roughness value, 0.55 μm, occurs at a cutting speed of 300 m/min, a feed rate of 0.15 mm/tooth, a width of cut of 0.20 mm, and a depth of cut of 0.3 mm. Nevertheless, this study indicates that, under the specified parameters, high-speed milling in a dry environment may result in better surface quality.

Analysis using the Taguchi method was performed to identify and determine the optimal machining parameters, namely cutting speed (m/min), feed rate (mm/tooth), width of cut (mm) and depth of cut (mm) to the surface finish in machining AISI 4340 workpieces. The smaller is better criterion was used in this study because a smaller surface roughness indicates better machinability. Tables 8 and 9 show the response for the signal to noise ratio and the average (Mean of Mean) for this simulation. From the tables it shows that the cutting speed has the highest delta value followed by feed rate, width of cut and depth of cut.

Table 8: Respond table for signal to noise ratio.

Level	Cutting Speed (m/min)	Feed Rate (mm/tooth)	Width of Cut (mm)	Depth of Cut (mm)
1	6.011	6.251	6.540	7.327
2	8.107	7.724	7.222	6.801
3	6.818	6.962	7.175	6.809
Delta	2.096	1.473	0.681	0.526
Rank	1	2	3	4

Table 9: Respond table for Mean of Mean

Level	Cutting Speed (m/min)	Feed Rate (mm/tooth)	Width of Cut (mm)	Depth of Cut (mm)
1	0.5020	0.4897	0.4740	0.4387
2	0.3953	0.4147	0.4357	0.4580
3	0.4570	0.4500	0.4447	0.4577
Delta	0.1067	0.0750	0.0383	0.0193
Rank	1	2	3	4

In their recent study investigating the impact of cutting parameters on surface roughness, Bedene et al. (2023) underscored that, in dry machining conditions using AISI 1050 steel as the workpiece and coated carbide cutting tools, cutting speed emerged as the predominant factor influencing surface roughness. Feed rate closely followed as the second most influential factor, with reported contributions of 71.09% and 19.81%, respectively, under dry turning conditions. On a similar note, in a study on the effects of spindle speed, cutting feed rate, and depth of cut on surface quality in the end-milling process on aluminum samples conducted by Hayajneh et al. (2007), they found that cutting feed is by far the most dominant factor among those studied.

Figure 6 and Figure 7 show the plot of the signal to noise ratio and the average (Mean of Mean) for the surface roughness. Based on Figure 7, cutting speed has a significant effect on surface roughness followed by feed rate, width of cut and depth of cut. Referring to Figure 7, the signal to noise ratio found that the optimal machining conditions for the AISI 4340 50HRC workpiece is at a speed of 350 m/min, depth of cut of 0.3 mm, width of cut of 0.35 mm and a feed rate of 0.20 mm/tooth. Optimum conditions are important during machining in order to achieve results with the desired quality.

3.2 Tool Life

Table 10 shows the tool life output on the work material obtained during the experiments of the AISI 4340 material. When a tool approaches the end of its wear, its total cutting time is referred to as its tool life. A tool life able to specifies process efficiency, machining productivity, resource consumption, machining time, and cost (Bazaz et al., 2023).

Referring to Table 10, the tool life shows the value between 4 – 20.38 minutes. In Figure 8, it shows that the highest value of tool is at 20.38 minutes occurs when the cutting speed at 350 m/min, a feed rate at 0.3 mm/tooth, a width of cut at 0.20 mm and a depth of cut at 0.4 mm. The lowest tool life value of 4 minutes occurs at cutting speed of 400 m/min, a feed rate of 0.15 mm/tooth, a width of cut of 0.50 mm and a depth of cut of 0.4 mm.

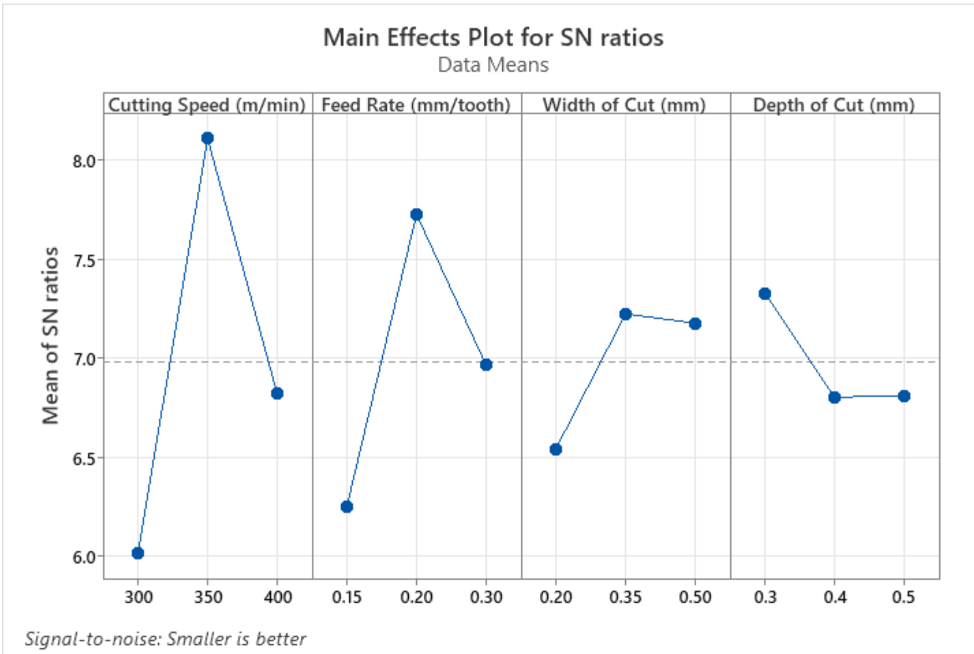

Figure 6: S/N plot for surface roughness.

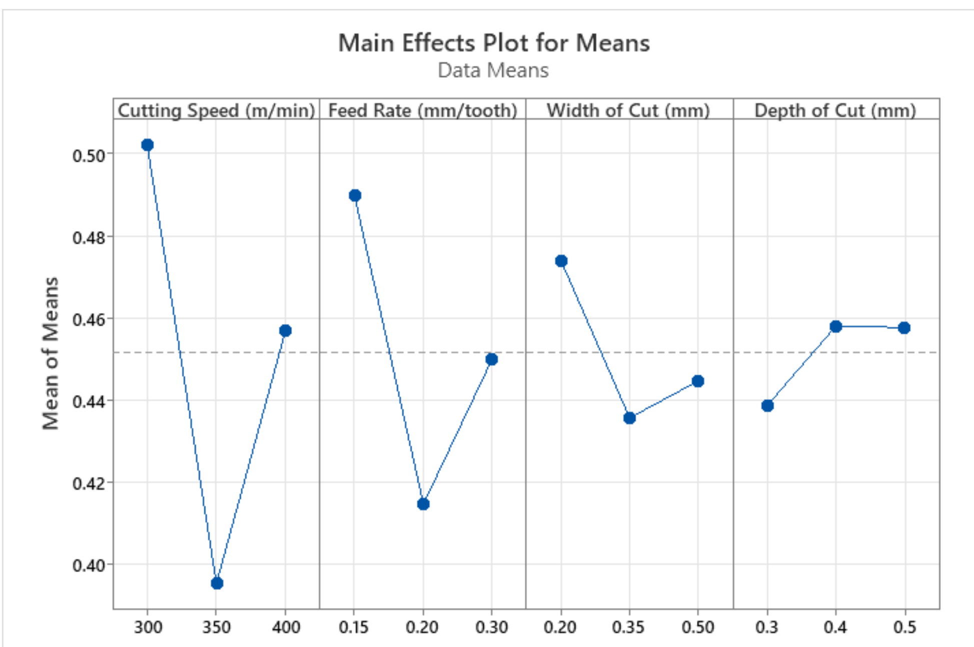

Figure 7: Mean plot for surface roughness.

Table 10: Experiments result for the tool life

No.	Cutting speed (m/min)	Feed Rate (mm/tooth)	Width of Cut (mm)	Depth of Cut (mm)	Tool life (minutes)
1	300	0.15	0.20	0.3	10 .45
2	300	0.20	0.35	0.4	4.12
3	300	0.30	0.50	0.5	11.45
4	350	0.15	0.35	0.5	8.78
5	350	0.20	0.50	0.3	3.28
6	350	0.30	0.20	0.4	20.38
7	400	0.15	0.50	0.4	4.00
8	400	0.20	0.20	0.5	12.00
9	400	0.30	0.35	0.3	12.00

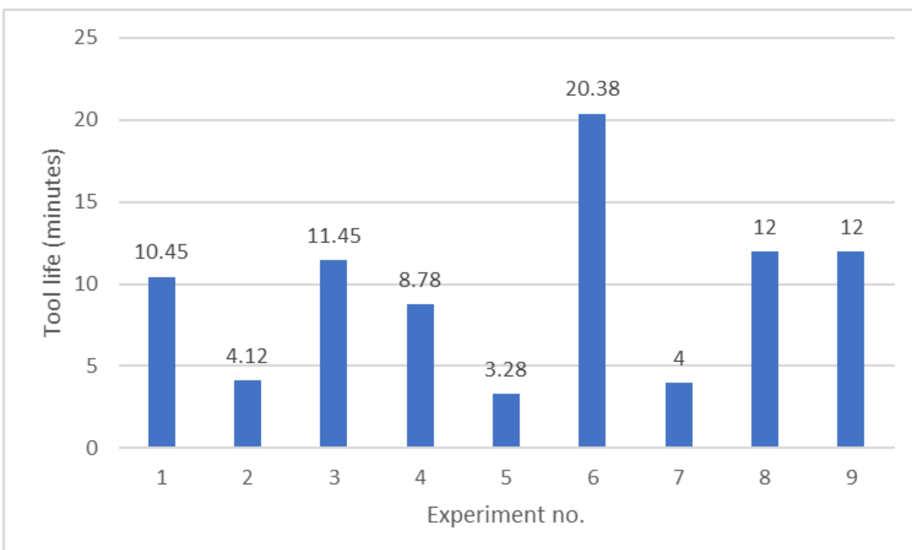

Figure 8: Tool life for the nine experiments.

Analysis using the Taguchi method in this study employed the 'bigger is better' criterion because a larger tool life indicates better machinability. Tables 11 and 12 display the response for the signal-to-noise ratio and the average (Mean of Mean) for this simulation. According to the tables, the feed rate exhibits the highest delta value, followed by width of cut, depth of cut, and cutting speed.

Table 11: Response table for signal to noise ratio.

Level	**Cutting Speed (m/min)**	**Feed Rate (mm/tooth)**	**Width of Cut (mm)**	**Depth of Cut (mm)**
1	17.95	17.10	22.72	17.43
2	18.46	14.73	17.58	16.84
3	18.40	22.98	14.51	20.54
Delta	0.51	8.25	8.21	3.70
Rank	4	1	2	3

Table 12: Response table for Mean of Mean.

Level	**Cutting Speed (m/min)**	**Feed Rate (mm/tooth)**	**Width of Cut (mm)**	**Depth of Cut (mm)**
1	8.673	7.743	14.277	8.577
2	10.813	6.467	8.300	9.500
3	9.333	14.610	6.243	10.743
Delta	2.140	8.143	8.033	2.167
Rank	4	1	2	3

In a study conducted by Soori & Areezo (2023) on the effect of cutting parameters on tool life and cutting temperature in milling AISI 1038 carbon steel, the results suggest that increasing feed rate, depth of cut, and cutting speed all lead to shorter cutting tool lives. This phenomenon is attributed to the greater heat generated in the cutting tool during the chip-generation process, resulting in increased tool wear.

Taguchi method (criterion: Larger is better) is used for analysis the tool life output. Table 11 and Figure 9 show that the feed rate is the factor that has the highest impact on the resulting tool life followed by width of cut, depth of cut and cutting speed in cutting. Referring to Figure 10, the optimal parameters are at a cutting speed of 350 m/min, a feed rate of 0.3 mm/tooth, a width of cut of 0.20 mm and a depth of cut of 0.5 mm.

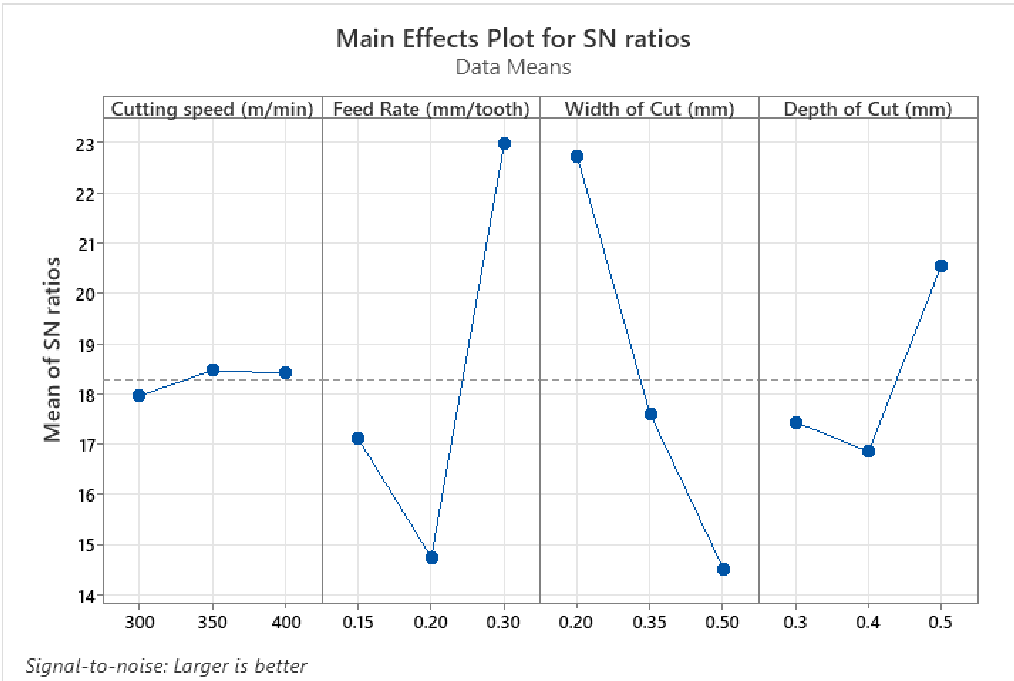

Figure 9: Signal to Noise plot of tool life.

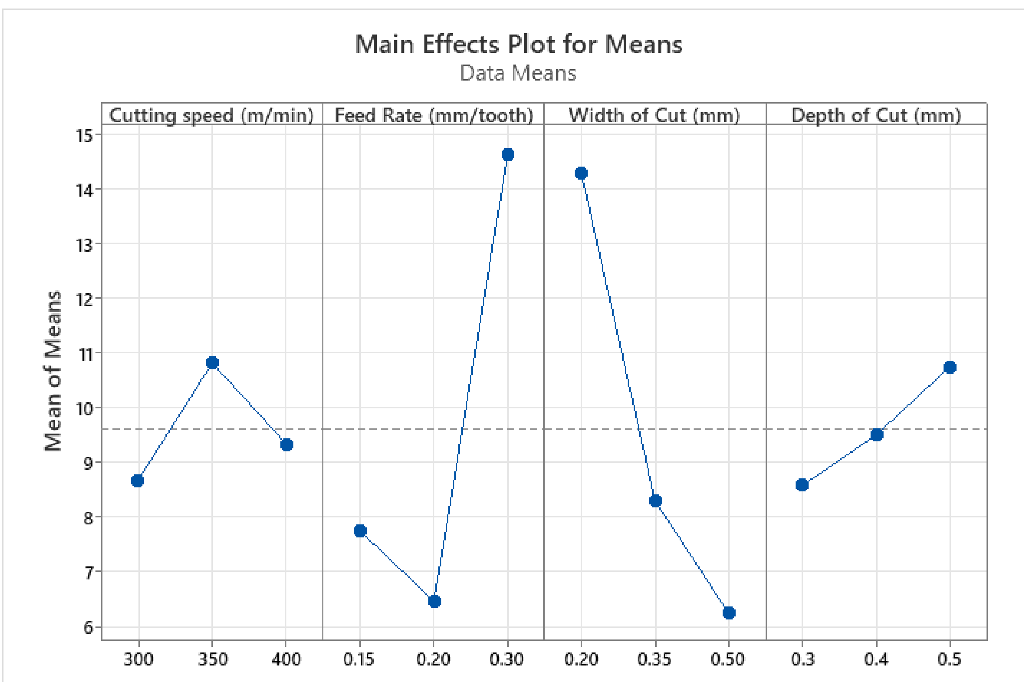

Figure 10: Mean plot for tool life.

Figure 11 displays the three cutting tools selected based on their tool life criteria: the longest (Experiment 6 with a tool life of 20.38 minutes), the average (Experiment 1 with 10.45 minutes), and the shortest (Experiment 5 with 3.28 minutes). No catastrophic failure occurred, and the flank wear measurement met the 0.3 mm criteria for all experiments. All experiments exhibited the same pattern of increased tool life.

The cutting tool life curve exhibits three distinct stages: an initial sharply increasing phase, a subsequent evenly increasing intermediate phase, and a final sharp decline characterized by a significant rise in wear. In the context of dry machining, the cutting tool is subjected to elevated temperatures and heat resulting from cutting friction. Furthermore, the tool experiences mechanical shock during milling operations, particularly when exposed to high cutting speeds and repeated cyclic loads.

Friction causes the coating material to wear off, exposing the cutting tool to higher temperatures and accelerating the wear rate (Ghani et al., 2016). This deterioration leads to accelerated wear on the flank and nose of the tungsten carbide tool.

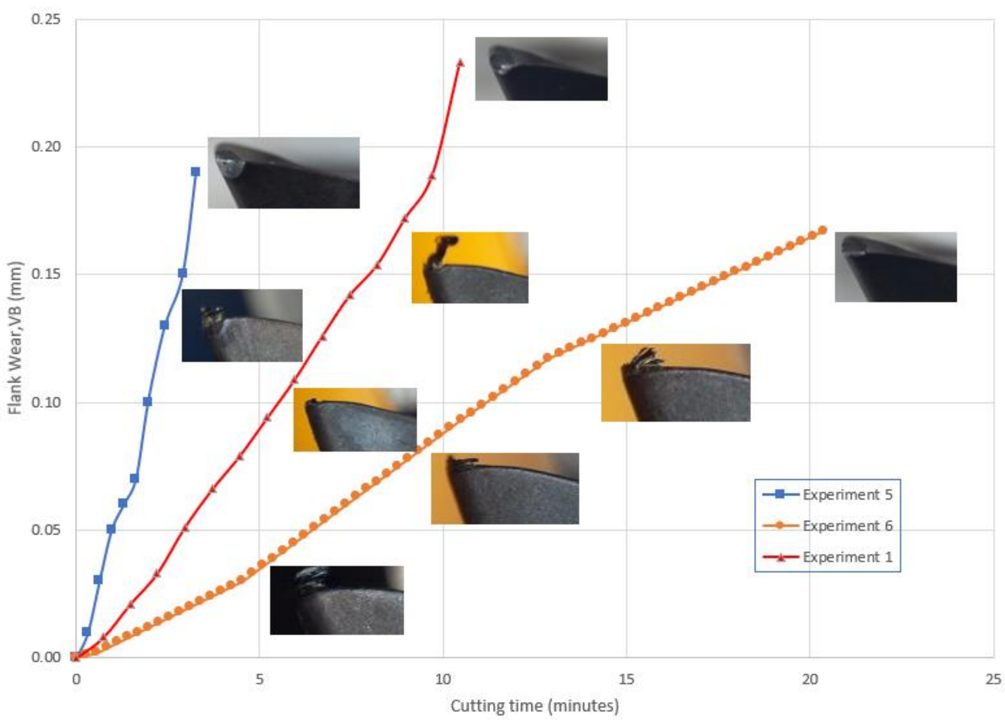

Figure 11: Growth of flank wear in dry condition.

This phenomenon is primarily attributed to the absence of cutting fluid, which typically serves as a lubricant and coolant in machining processes. The lack of lubrication in dry conditions exacerbates frictional forces and heat generation, contributing to the accelerated wear on the tool's flank. Understanding the dynamics of flank wear growth in dry conditions is crucial for optimizing machining processes and extending the overall tool life. Sohrabpoor et al. (2015) found that an increase in feed rate leads to larger forces, elevated heat, and heightened mechanical stresses on the tool's flank region, resulting in increased flank wear.

CONCLUSIONS

The effect of machining parameters on surface roughness and tool life in dry cutting conditions for the milling of AISI 4340 alloy steel were carried out. Based on a series of experiments and subsequent analysis of the findings, the following conclusions were drawn:

(a) Cutting speed has a significant effect on surface roughness followed by feed rate, width of cut and depth of cut. The optimal machining conditions for surface roughness is at a speed of 350 m/min, depth of cut of 0.3 mm, width of cut of 0.35 mm and a feed rate of 0.20 mm/tooth.

(b) Feed rate is the factor that has the highest impact on the resulting tool life followed by width of cut, depth of cut and cutting speed. The optimal parameters are at a cutting speed of 350 m/min, a feed rate of 0.3 mm/tooth, a width of cut of 0.20 mm and a depth of cut of 0.5 mm.

These conclusions highlight the crucial role of cutting speed for achieving optimal surface roughness and emphasize the significance of feed rate in maximizing tool life during the milling of AISI 4340 alloy steel in dry cutting conditions.

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