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Comparative analysis of up and down milling on surface quality and tool life in dry machining of hardened AISI 4340

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KEYWORDS

Up milling
Down milling
Surface roughness
Tool life

ABSTRACT

Dry machining of hardened steel generates heat, wears tools quickly, and reduces surface quality, with few studies comparing up/down milling under dry, high-speed conditions. This study examines effects of up/down milling on surface roughness and tool life during dry milling of hardened AISI 4340 steels. Tests followed Taguchi L9 array, using cutting speed (V = 300–400 m/min), feed rate (F = 0.15–0.3 mm/tooth), depth of cut (DOC = 0.3–0.5 mm) and width of cut (WOC = 0.2-0.5mm). For up milling, F impacted surface roughness most (58.07%), followed by V (34.95%). In down milling, F dominated (77.69%), with DOC at 10.34%. Minimum surface roughness for up milling (0.198 µm) occurred at V = 400 m/min, F = 0.15 mm/tooth, DOC = 0.4 mm. For down milling, best surface (0.165 µm) was achieved at identical parameters. V primarily affected up milling tool life (72.16%) with longest life (4.11 minutes) at V = 300 m/min, F = 0.15 mm/tooth, WOC = 0.2 mm and DOC = 0.3 mm. In down milling, F was the main factor (99.85%), producing longest tool life (25.33 minutes) under same parameters. These results provide insights for machining hardened AISI 4340 steel and developing efficient practices.

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1.0 INTRODUCTION

AISI 4340 is a high-strength, low-alloy steel widely used in aerospace, automotive, and tooling since its mechanical properties have superior tensile strength, fatigue resistance, and toughness. In most applications, AISI 4340 are heat-treated to improve wear resistance along with service life. Usually, the hardness is above 45 HRC. However, machining hardened AISI 4340 poses significant challenges, particularly under dry cutting conditions, where the absence of cutting fluids leads to elevated temperatures, increased tool wear, and compromised surface integrity (Zheng et al.,2019; S. R. Das et al., 2017).

Surface roughness and tool life are two critical parameters in evaluating machining performance. Achieving superior surface quality and prolonged tool life during milling under dry conditions is critical for sustainable manufacturing, as dry machining reduces environmental impact by eliminating cutting fluids but increases thermal and mechanical stresses on the tool and workpiece. Besides that, a low surface roughness is essential for ensuring dimensional accuracy and component functionality, while prolonged tool life reduces machining costs and downtime (Sahoo & Sahoo, 2012). Several studies have investigated the influence of machining parameters—such as cutting speed, feed rate, depth of cut, and tool geometry—on these performance metrics during the machining of hardened steels (Suresh et al.,2012; Sahu & Choudhury,2015; Pal et al., 2014). However, the role of milling orientation, defined by the direction of the cutting tool path relative to the material structure or grain flow, has received comparatively less attention.

Milling orientation, including conventional (up) and climb (down) milling, as well as inclined milling directions in complex geometries, affects chip formation, heat distribution, tool engagement, and vibration characteristics (Saini et al., 2012; Meddour et al., 2015). Down milling generally produces better surface quality, with higher hardness and lower roughness, compared to up milling (Ahammed et al., 2022; Khan et al., 2022). This is attributed to the compressive nature of cutting forces in down milling, as opposed to tensile shear forces in up milling (Ahammed et al., 2022). However, up milling in dry conditions generates higher cutting forces, specific energy, and power consumption (Pa et al., 2013). Moreover, chip formation differs between up and down milling, with up milling producing shorter chips (Ahammed et al., 2022; Khan et al., 2022)

According to Pissolatti et al. (2022), lower surface roughness was achieved through descending down milling and ascending up milling. This outcome is attributed to the orientation of the cutting force components, particularly the component normal to the machined surface in the most critical region of the workpiece, which effectively pulled the workpiece against the tool and vice versa. Conversely, descending up milling and ascending down milling yielded suboptimal results due to the orientation of the force components, which caused excessive tool bending, thereby separating the tool and workpiece.

In a recent study, Aminy et al. (2024) investigated the surface roughness and tool wear in milling of AISI 4340 steel using a 4-flute end mill. The study highlighted that increased cutting thickness led to higher surface roughness and tool wear, emphasizing the need for optimized cutting parameters to enhance machining performance. These findings underline the sensitivity of hardened AISI 4340 to variations in material removal rate and thermal stress during machining, especially under dry conditions where cooling and lubrication are absent.

Another study by (Hassanpour et al., 2024)examined the impact of tool flank wear on surface integrity during high-speed hard milling of AISI 4340 steel. The findings indicated that flank wear significantly affects surface roughness and white layer thickness, which are critical for the fatigue life of machined components. As tool wear progresses, the cutting edge becomes less effective at shearing material cleanly, leading to increased friction, heat generation, and plastic deformation at the surface. This thermal and mechanical degradation contributes to the formation of undesirable microstructural alterations such as white and heat-affected layers.

Furthermore, a study by (Wojciechowski et al., 2023) focused on the ploughing phenomena in tool flank face-workpiece interface during ball-end milling. The research demonstrated that tool wear and surface inclination angles influence ploughing forces, thereby affecting surface finish and tool life. The study revealed that increased flank wear alters the effective cutting geometry, intensifying the ploughing effect especially at low inclination angles. This not only accelerates tool degradation but also leads to inconsistent surface textures, highlighting the need for optimized tool engagement strategies.

Despite these insights, there is a noticeable gap in literature concerning the role of milling orientation under dry conditions. Most studies have concentrated on other factors such as cutting speed, feed rate, and tool geometry, with limited emphasis on how the directionality of milling influences machining outcomes. By systematically varying the milling direction while keeping other parameters constant, we seek to uncover potential correlations between orientation and machining performance. Our findings could provide valuable insights for optimizing dry milling processes, potentially leading to improved surface finish and extended tool life in industrial applications.

Therefore, this study aims to investigate the effects of different milling orientations of up and down milling on surface roughness and tool life during the dry machining of hardened AISI 4340 steels. By analyzing the performance outcomes across multiple orientations, the research seeks to identify optimal milling strategies that enhance surface quality and prolong tool life in dry environments. The findings are expected to contribute to the development of more efficient and sustainable machining practices for hardened alloy steels.

2.0 EXPERIMENTAL PROCEDURE

The material used for the workpiece was AISI 4340, a high-strength alloy steel of a hardness 50±2 HRC with dimension of 178 mm (length) × 102 mm (width) × 55 mm (height). The cutting tool utilized in the experiment is a Physical Vapor Deposition (PVD) carbide with multiple coatings of TiAlN/AlCrN and WC-Co, specifically the Sumitomo grade AXMT123504PEER-G ACP200. The geometry of the cutting tool is shown in Figure 1. The tool holder employed in the experiment is the EChain brand, model EAX2032EL-180 and the detailed specification is illustrated in Figure 2.

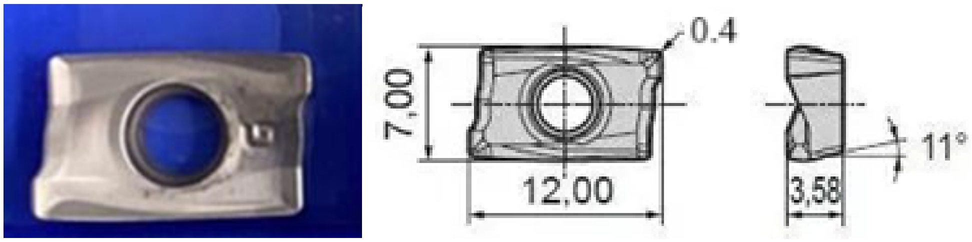
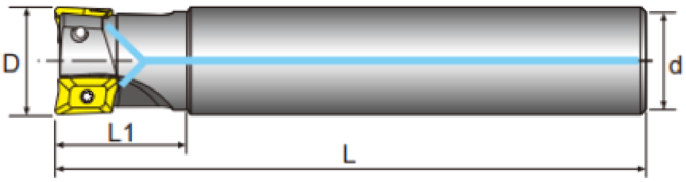


Figure 1: Schematic diagram of the cutting tool AXMT (Source: Sumitomo 2023).



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

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

The experimental work was carried out using 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 × 660 × 635 mm, A Axis -/+ 120 degrees, B Axis 360 degrees, Spindle Taper BT40, Spindle Speed 10000 rpm, Motor 22 Kw and Table size 210mm diameter.

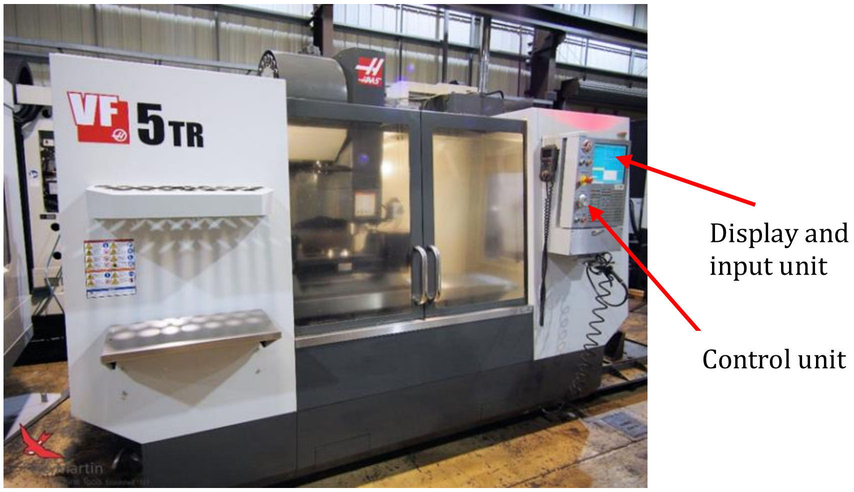


Figure 3: 5-axis vertical machine center.

Table 1 presents a comprehensive summary of the experimental design (DOE) utilized in this study, encompassing three distinct levels aligned with industry and previous research for cutting speed, V (300, 350, 400 mm/min), feed rate, F (0.15, 0.20, 0.30 mm/rev), width of cut, WOC (0.20, 0.35, 0.50 mm) and depth of cut, DOC (0.3, 0.4, 0.5 mm). Taguchi L9 was employed to conduct the experimental run.

The average surface roughness (Ra) values were recorded with a Surftest 310 Mitutoyo® roughness tester with a cut-off of 0.8 mm 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 (VBB) was measured using a 1080P full HD WiFi Digital Microscope (adjustable magnifications, up to 230x). 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: Experiment design.

No.	V (m/min)	F (mm/tooth)	WOC (mm)	DOC (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 data were derived from a sequence of nine trials, each utilizing both down and up milling methods, with three distinct inputs applied across four machining parameters. In total, 18 experiments were executed. It is important to emphasize that the output parameters are expressed as mean values, accompanied by a range of variations resulting from repeated experiments. The analyzed outputs are subsequently organized for further analysis.

Surface Roughness, Ra

The result for Ra is presented in Figure 6 illustrates both up and down milling processes obtained according to the corresponding experiments. A lower Ra value indicates better surface quality on the machined surface. Ra, or arithmetic average roughness, is a commonly used parameter to measure surface roughness. It represents the average deviation of the surface profile from the mean line. As the Ra value decreases, it signifies that the surface has fewer irregularities and imperfections. Manufacturers often specify Ra values for different applications, with lower values typically required for high-precision components or those subject to high stress or wear.

Referring to Figure 4 the Ra values for up milling range between 0.198 µm and 0.441 µm, meanwhile down milling is from 0.165 µm to 0.298 µm. The lowest Ra value for up milling, 0.198 µm, is achieved when V is 400 m/min, F is 0.15 mm/tooth, WOC is 0.50 mm, and DOC is 0.4 mm. For down milling, the lowest Ra value, 0.165 µm, occurs at V of 400 m/min, F of 0.15 mm/tooth, WOC of 0.5 mm, and DOC of 0.4 mm. Nevertheless, this study indicates that, under the specified parameters, high-speed milling in a dry environment for down milling process result in better surface quality compared to up milling. According to Hadi et al. (2013), Down milling produces less tool wear and better surface finish because it starts with the maximum chip thickness, leading to a more stable cutting process. It results in lower cutting forces and heat generation compared to up milling, reducing surface damage. Efficient chip removal in down milling prevents chip recutting, contributing to improved surface integrity and roughness. Up milling causes higher friction and heat since the tool starts cutting with zero chip thickness, increasing surface roughness.

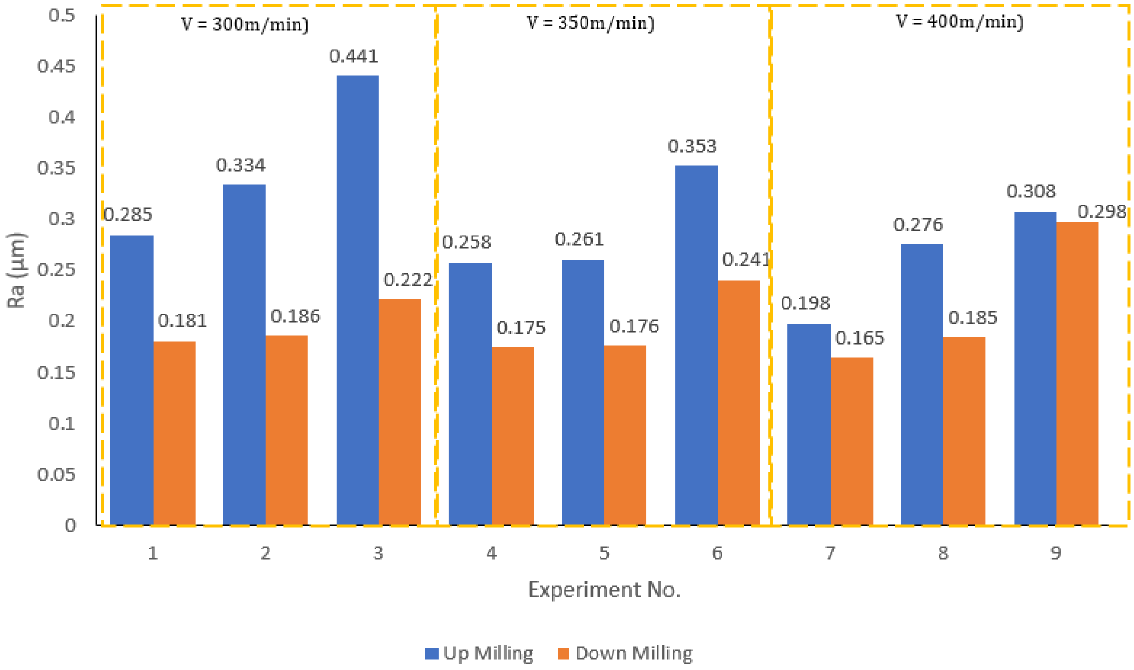


Figure 4: Experiment results for the surface roughness.

Analysis using the Taguchi method was performed to identify and determine the optimal machining parameters, namely V (m/min), F (mm/tooth), WOC (mm) and DOC (mm) to the surface finish in machining AISI 4340 workpieces. The smaller is better criterion was used in this study because a smaller Ra indicates better machinability. Tables 2 - 3 show the response for the signal to noise ratio for up and down milling. From the tables it shows that the F has the highest delta value followed by V, WOC and DOC for up milling. For down milling, F has the highest delta value followed by DOC, WOC and V. The increase in surface roughness can be attributed to higher feed rates, as a more rapid feed results in more aggressive material removal, thereby leading to rougher finishes. Specifically, it is observed that elevated feed rates enhance the quantity and size of chip formations, which consequently results in increased surface roughness. (Hossain et al., 2025; Achadiah et al., 2021; Sakinah Shahruddin et al., 2023).

Machining experiments on hardened tool steels indicate that feed rate is most strongly linked to surface roughness (Le et al., 2022). According to Abbas et al., 2016, table feed rate has the greatest effect on the data variation followed by factor depth of cut. Besides that Cakir et al., 2009 mentioned that the feed rate is a dominant parameter in machining, and it produces a high increase in surface roughness when it increases. In fact, the feed rate is the main factor used in kinematic models for surface roughness prediction, and in almost all experimental studies, the feed rate is one of the most significant parameters related to surface roughness. When the feed rate decreases, the surface roughness decreases since the feed marks responsible for roughness are less pronounced (Abellán-Nebot et al., 2024)

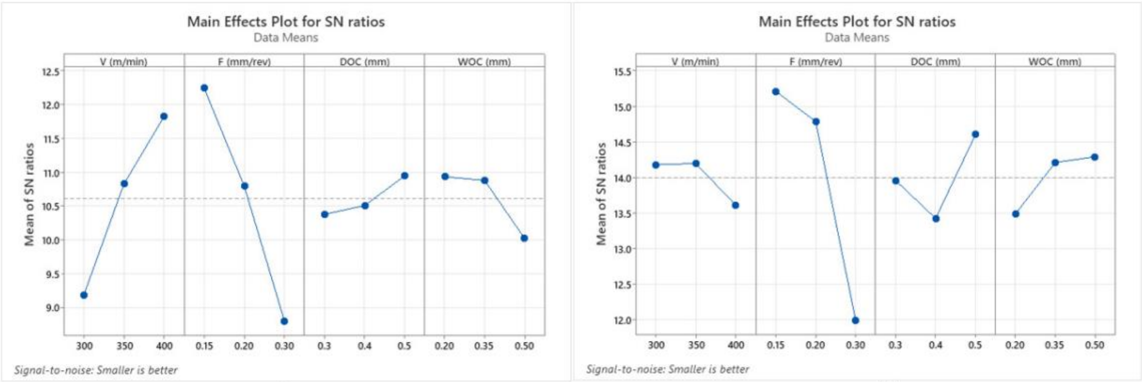
Table 2: Respond table of surface roughness for signal to noise ratio on up milling process.

Level	V (m/min)	F (mm/tooth)	WOC (mm)	DOC (mm)
1	9.180	12.246	10.376	10.933
2	10.826	10.791	10.507	10.879
3	11.826	8.795	10.948	10.020
Delta	2.646	3.451	0.572	0.913
Rank	2	1	4	3

Table 3: Respond table of surface roughness for signal to noise ratio on down milling process

Level	V (m/min)	F (mm/tooth)	WOC (mm)	DOC (mm)
1	14.18	15.21	13.95	13.48
2	14.20	14.79	13.42	14.21
3	13.61	11.98	14.60	14.29
Delta	0.59	3.23	1.18	0.81
Rank	4	1	2	3

Figure 5 shows the plot of the signal to noise ratio for the surface roughness. The signal to noise ratio found that the optimal machining conditions for the AISI 4340 50HRC workpiece for up milling is at V = 400 m/min, F = 0.15 mm/tooth, DOC = 0.5 mm and WOC = 0.20. For down milling the optimum condition is at V = 300 m/min, F = 0.15 mm/tooth, DOC = 0.5 mm and WOC = 0.50. Optimum conditions are important during machining in order to achieve results with the desired quality.



(a) (b)

Figure 5: S/N plot for surface roughness (a) up milling (b) down milling.

Tables 4 and 5 present the results of the ANOVA analysis for the machining outputs of up and down milling, respectively. The last columns of Tables 4 and 5 indicate the percentage contribution of each factor to the total variation, reflecting their degree of influence on surface roughness. A higher percentage contribution denotes a stronger influence of that factor on machining performance.

According to Table 4, feed rate (F) was found to be the major factor affecting surface roughness in up milling (58.07%), followed by cutting speed (V) at 34.95% and width of cut (WOC) at 6.86%. The strong effect of feed rate can be explained by its direct impact on chip thickness: higher feed values generate larger chip sections, leading to increased cutting forces and vibration, which deteriorates surface quality. This agrees with the findings of Tomadi et al. (2022) and Ancio et al. (2015), who reported that feed rate was the most dominant factor influencing surface roughness in milling of hardened steels. The influence of cutting speed is also significant because higher speeds increase cutting temperature, which can soften the material locally and improve surface finish up to a critical level, as also noted by Lai et al. (2023).

Meanwhile, the ANOVA results for down milling (Table 5) show that feed rate (F) again plays the dominant role (77.69%), followed by depth of cut (DOC) at 10.34% and width of cut (WOC) at 4.95%. The higher contribution of feed in down milling can be attributed to the mechanics of chip formation, where chip thickness starts at its maximum and decreases towards zero, making the process highly sensitive to feed variation. This finding is in line with the observations of Yan et al. (2019), who reported that in down milling, feed per tooth strongly governs surface finish due to the initial high cutting load at the tool–workpiece entry. The effect of DOC, although less dominant, becomes more noticeable in down milling since higher depths of cut increase the engagement area and tool deflection, thereby affecting surface integrity.

Table 4: Results of ANOVA for surface roughness for up milling.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
V (m/min)	2	0.013414	34.95%	0.013414	0.006707	307.98	0.003
F (mm/rev)	2	0.022287	58.07%	0.022287	0.011143	511.69	0.002
WOC (mm)	2	0.002634	6.86%	0.002634	0.001317	60.46	0.016
Error	2	0.000044	0.11%	0.000044	0.000022		
Total	8	0.038378	100.00%				

Table 5: Results of ANOVA for surface roughness for down milling.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
F (mm/rev)	2	0.011564	77.69%	0.011564	0.005782	15.71	0.060
DOC (mm)	2	0.001540	10.34%	0.001540	0.000770	2.09	0.324
WOC (mm)	2	0.001044	7.02%	0.001044	0.000522	1.42	0.414
Error	2	0.000736	4.95%	0.000736	0.000368		
Total	8	0.014884	100.00%				

In both cases, the feed rate (F) emerges as the dominant factor affecting surface roughness. This indicates that adjusting the feed rate has the most significant impact on achieving desired surface roughness outcomes in both milling techniques. The secondary and tertiary factors influencing surface roughness differ between up and down milling. These differences highlight the importance of considering the specific milling technique when optimizing machining parameters for desired surface roughness outcomes. Understanding the relative contributions of these factors enables manufacturers to prioritize parameter adjustments and achieve more precise control over the machining process and resulting surface quality.

Tool Life

Tool life is a critical measure in machining operations that quantifies the duration a cutting tool can effectively perform before it needs replacement due to wear. Figure 6 shows the tool life output on the work material obtained during the experiments of the AISI 4340 material. The tool life shows the value between 0.77 – 4.11 minutes for up milling and 8.70- 25.33 minutes for down milling. Therefore, it shows that up milling demonstrates shorter tool life spans, which indicating faster wear rates and potentially higher replacement frequencies.

In contrast, down milling exhibits substantially longer tool life durations, suggesting improved tool durability and efficiency in this cutting mode. Hadi et al. (2013) found that the reduced tool life associated with up milling, as compared to down milling, is primarily attributed to the presence of higher and progressively increasing cutting forces, elevated friction and heat generation at the tool–workpiece interface, greater susceptibility of the workpiece to dynamic instability and vibration, as well as inefficient chip evacuation, all of which collectively intensify tool wear mechanisms. The same results were shown from the reseachers (Hadi et al., 2013; Riza et al., 2013) that down milling generally results in longer tool life compared to up milling.

The highest tool life of 25.33 minutes occurs during down milling at lowest V = 300 m/min, F= 0.15 mm/tooth, WOD = 0.20 mm and DOC = 0.3 mm. The lowest tool life value of 0.77 minutes occurs during up milling at higher V = 400 m/min, F = 0.30 mm/tooth and WOC = 0.35 mm and with the same DOC = 0.3 mm. These findings underscore the importance of optimizing machining parameters to extend tool life, thereby enhancing process efficiency, productivity, and cost-effectiveness in machining operations (Bazaz et al., 2023).

Analysis using the Taguchi method in this study employed the 'bigger is better' criterion because a larger tool life indicates better machinability. Tables 6 and 7 display the response for the signal-to-noise ratio providing valuable insights into the relative importance of different cutting parameters. According to Table 6, in up milling, cutting speed (V) was identified as the most dominant factor influencing tool life, as indicated by the highest delta value, followed sequentially by feed rate (F), depth of cut (DOC), and width of cut (WOC). This trend corroborates the findings of Ojolo and Ogunkomaiya (2014), who reported that spindle speed accounted for the largest contribution to tool life, followed by feed rate and depth of cut in machining with tungsten carbide tools.

The consistency between both studies underscores the pivotal role of cutting speed, which governs the thermal and mechanical loading at the tool–workpiece interface. Higher cutting speeds intensify heat generation and accelerate wear mechanisms such as crater wear, diffusion, and thermal softening of the tool material, thereby exerting the greatest influence on tool life. Although the magnitude of feed rate and depth of cut contributions may vary with tool material and cutting environment, their effects remain secondary to cutting speed, reaffirming its status as the principal determinant of tool performance.

Besides that, Abbas et al. (2021) reported that an increase in cutting speed results in greater heat generation, which is primarily absorbed by the cutting tool. This elevated thermal load raises the tool temperature and subsequently promotes crater wear through thermally induced mechanisms. In addition, flank wear intensifies with cutting speed due to abrasive interactions arising from friction between the tool and the workpiece. These findings indicate that both thermal and mechanical wear mechanisms are strongly correlated with cutting speed.

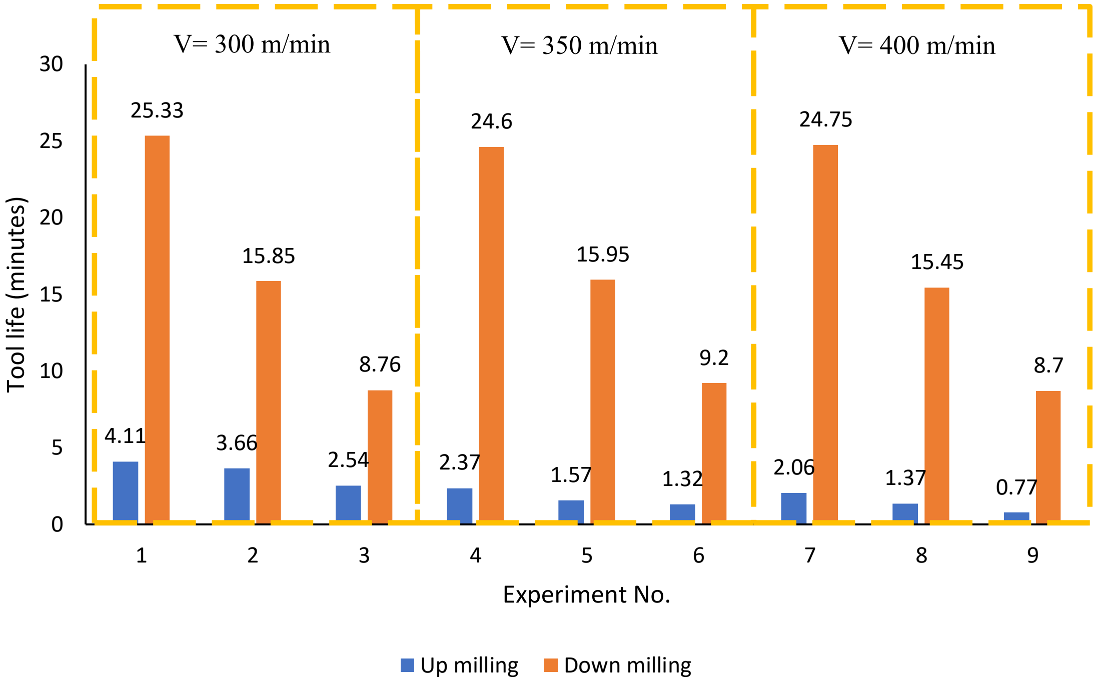


Figure 6: Experiment results for the tool life.

Table 6: Response table of tool life for signal to noise ratio for up milling.

Level	**V (m/min)**	**F (mm/tooth)**	**WOC (mm)**	**DOC (mm)**
1	10.548	8.683	5.808	4.642
2	4.608	5.974	5.498	6.653
3	2.247	2.746	6.097	6.109
Delta	8.301	5.937	0.599	2.011
Rank	1	2	4	3

For down milling as in Table 7 shows that feed rate was identified as the most significant parameter affecting tool life, surpassing the impact of cutting speed (V), depth of cut (DOC), and width of cut (WOC). Sakinah Shahruddin et al. (2023) found that feed rate impacts tool life by affecting cutting temperature and surface condition more strongly in down milling because of the tool-workpiece interaction dynamics unique to this milling type. According to Yingfei et al., 2017, feed rate was also identified as a primary factor affecting tool wear, with an influence of 83% when dry milling Stellite 6 alloy.

Table 7: Response table of tool life for signal to noise ratio for down milling.

Level	**V (m/min)**	**F (mm/tooth)**	**WOC (mm)**	**DOC (mm)**
1	23.64	27.92	23.71	23.64
2	23.72	23.94	23.54	23.72
3	23.48	18.97	23.59	23.48
Delta	0.24	8.95	0.17	0.23
Rank	2	1	4	3

Figure 7 presents the signal-to-noise (S/N) ratio plots for tool life under both up and down milling conditions. For up milling, the optimal machining parameters for the AISI 4340 (50 HRC) workpiece were obtained at a cutting speed (V) of 300 m/min, a feed rate (F) of 0.15 mm/tooth, a depth of cut (DOC) of 0.5 mm, and a width of cut (WOC) of 0.35 mm. A pronounced decline in the S/N ratio was observed with increasing cutting speed, confirming its detrimental influence on tool life. This is attributed to the intensified heat generation and elevated tool–chip interface temperatures at higher cutting speeds, which accelerate diffusion wear, crater wear, and thermal softening of the cutting edge. Similar observations have been reported by Abbas et al. (2021) and Bag et al. (2020), who demonstrated that cutting speed plays a decisive role in tool life reduction due to its strong link with thermal wear mechanisms. Although feed rate also exerted a negative influence, its effect was comparatively less severe, being primarily associated with increased chip load, mechanical stresses, and abrasion. DOC and WOC contributed only marginally within the tested range, indicating a secondary role in tool wear progression under up milling.

By contrast, in down milling, the optimal machining conditions were achieved at a cutting speed (V) of 350 m/min, a feed rate (F) of 0.15 mm/tooth, a DOC of 0.3 mm, and a WOC of 0.35 mm. Here, feed rate emerged as the most critical parameter, with the S/N ratio declining sharply as feed rate increased from 0.15 mm/tooth to 0.30 mm/tooth. This pronounced sensitivity can be explained by the elevated cutting forces and intensified tool–workpiece contact stresses inherent to down milling, which accelerate flank wear and edge chipping. Cutting speed, DOC, and WOC, however, demonstrated relatively flat trends, suggesting limited influence on tool life under the tested conditions. These findings are consistent with Ojolo and Ogunkomaiya (2014), who also reported that feed rate can dominate tool life deterioration when mechanical loading exceeds the thermal contribution.

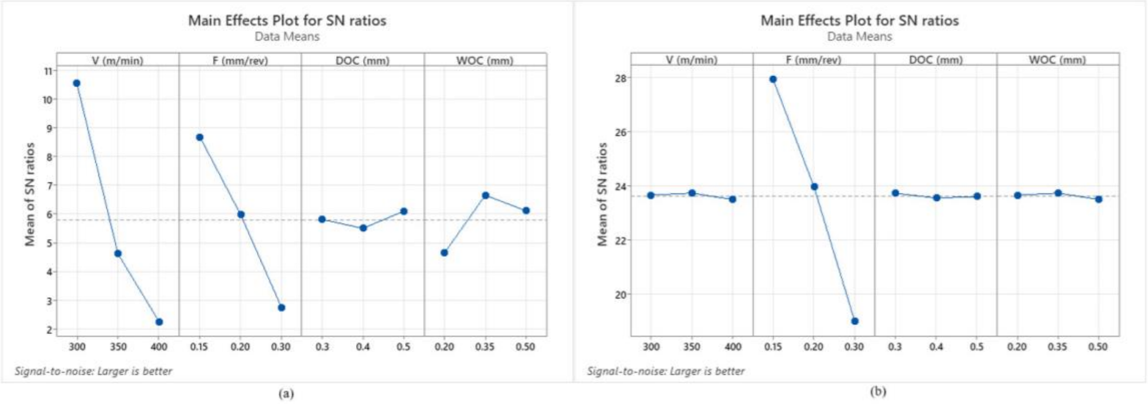


Figure 7: Signal to Noise plot of tool life (a) up milling (b) down milling.

Tables 8 and 9 show the results of the ANOVA analysis for the tool life of up and down milling, respectively. For up milling results in table 8 shows that cutting speed is the dominant factor, contributing 72.16% to the total variance (Seq SS = 7.10647). The F-value for cutting speed is 3.55323, and the P-value is 0.212, indicating that while it accounts for most of the observed variation, its effect is not statistically significant at the conventional 0.05 level. Feed rate accounts for 25.87% of the total variance (Seq SS = 2.54807) with an F-value of 0.89893 and a P-value of 0.523. This suggests that feed rate has a moderate influence on the response but is not statistically significant within the tested range. The width of cut has a minimal contribution (1.08%, Seq SS = 0.10607) to the total variance. Its F-value is 1.202 and the P-value is 0.454, indicating a negligible and statistically insignificant effect.

Table 8: Results of ANOVA for tool life for up milling.

Source	**DF**	**Seq SS**	**Contribution**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
V (m/min)	2	7.10647	72.16%	7.10647	3.55323	80.57	0.012
F (mm/rev)	2	2.54807	25.87%	2.54807	1.27403	28.89	0.033
WOC (mm)	2	0.10607	1.08%	0.10607	0.05303	1.20	0.454
Error	2	0.08820	0.90%	0.08820	0.04410		
Total	8	9.84880	100.00%				

According to Table 9, feed rate exhibits the most significant effect on the response variable in tool life of down milling, accounting for 99.85% of the total variance (Seq SS = 386.919 out of 387.506). It has a very high F-value (3294.800) and a P-value of 0.000, indicating a statistically significant effect at conventional significance levels. Both cutting speed and width of cut contribute minimally to the total variance, with Seq SS contributions of 0.204 (0.05%) and 0.265 (0.07%), respectively and their P-Values (0.364 and 0.307) are not statistically significant.

Table 9: Results of ANOVA for tool life for down milling.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
V (m/min)	2	0.204	0.05%	0.204	0.102	1.74	0.364
F (mm/rev)	2	386.919	99.85%	386.919	193.460	3299.48	0.000
WOC (mm)	2	0.265	0.07%	0.265	0.132	2.26	0.307
Error	2	0.117	0.03%	0.117	0.059		
Total	8	387.506	100.00%				

The graph in Figure 8 presents the relationship between cutting time and flank wear (Vb) for two different milling strategies (up milling and down milling) under two experimental conditions (Experiment 1 and Experiment 9). The results indicate a distinct contrast in tool wear behavior between the two milling approaches at highest and lowest tool life for both milling processes.

Under Experiment 1, down milling exhibits a gradual and consistent increase in flank wear over time, reaching approximately 0.31 mm after 30 minutes of cutting. This suggests stable wear progression and extended tool life. In contrast, up milling in the same experiment condition shows a rapid increase in flank wear, exceeding 0.35 mm in less than 7 minutes, indicating accelerated tool degradation and significantly shorter tool life.

For Experiment 9, both milling methods begin with higher initial wear values. However, down milling shows a moderate rise in wear, stabilizing just below 0.35 mm, while up milling demonstrates extremely rapid tool wear, surpassing 0.35 mm in under 2 minutes of cutting. This reflects severe cutting conditions leading to early tool failure in up milling. In the study by Hadi et al. (2013) found that up milling leads to increased tool wear compared to down milling. Their study, focused on tool wear in milling, showed that tool flank wear propagation in up milling operation is more rapid than in down milling.

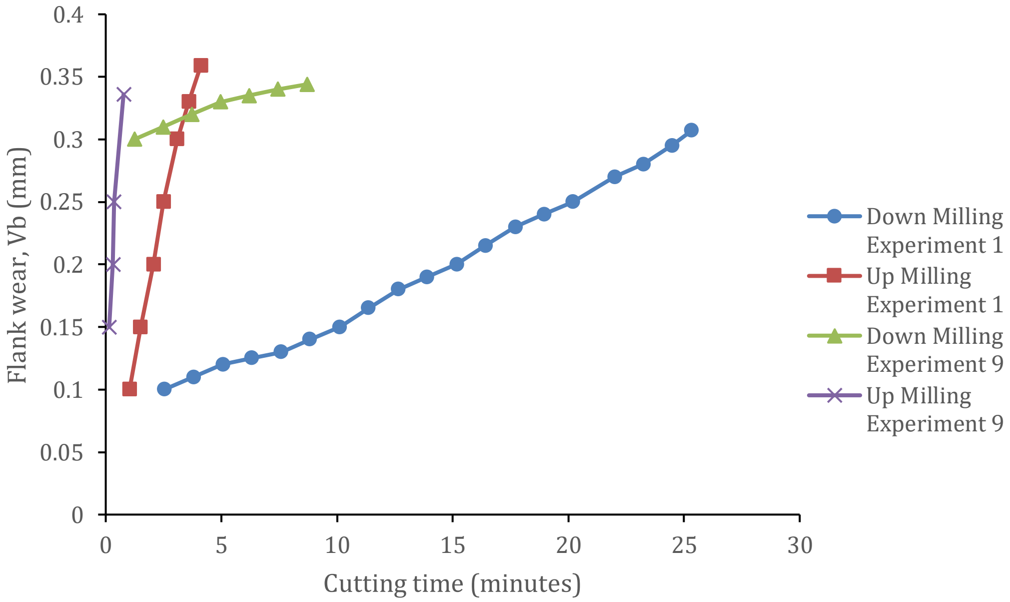


Figure 8: Growth of flank wear in dry condition for up and down milling.

Overall, the findings suggest that down milling offers superior tool wear performance and prolonged tool life compared to up milling, especially under harsh cutting conditions. The results underscore the critical influence of milling strategy and parameter selection on tool wear mechanisms during hard milling operations.

CONCLUSIONS

A study was conducted to assess the influence of machining parameters on surface roughness and tool life under dry cutting conditions for both up and down milling of AISI 4340 alloy steel. Following an extensive series of experiments and a thorough analysis of the results, the following conclusions were reached:

(a) The lowest Ra value for up milling, 0.198 µm, is achieved when V is 400 m/min, F is 0.15 mm/tooth, WOC is 0.50 mm, and DOC is 0.5 mm. For down milling, the lowest Ra value, 0.165 µm, occurs at V of 400 m/min, F of 0.15 mm/tooth, WOC of 0.50 mm, and DOC of 0.4 mm.

(b) Feed rate has a significant effect on surface roughness for both up and down milling process where Xu et al. (2025)also observed that the surface roughness on the XOZ plane for both up milling and down milling increases with the feed rate.

(c) The optimal machining conditions for surface roughness on AISI 4340 50HRC workpiece during upmilling is at V = 400 m/min, F = 0.15 mm/tooth, DOC = 0.5 mm and WOC = 0.20. For down milling the optimum condition is at V = 300 m/min, F = 0.15 mm/tooth, DOC = 0.5 mm and WOC = 0.50.

(d) The longest tool life, lasting 25.33 minutes, is achieved during down milling with the lowest parameters: V = 300 m/min, F = 0.15 mm/tooth, WOC = 0.20 mm, and DOC = 0.3 mm. In contrast, the longest tool life for up milling is 4.11 minutes, occurring under the same parameters.

(e) Feed rate is the factor that has the highest impact on the resulting tool life for down milling where Ahmad et al. (2022) report cutting speed accounting for ∼65% of tool life variation, with feed rate far less influential . For up milling cutting speed plays the most important factors that effect the tool life.

(f) Compared to up milling, down milling offers superior tool life and improved surface finish, making it more effective for machining hardened steel. This is mainly because, in down milling, the cutting force direction supports the workpiece, reducing friction, heat generation, and tool wear. Moreover, the feed rate plays a dominant role in influencing both tool life and surface roughness — higher feed rates tend to accelerate tool wear but can also optimize chip formation and heat removal, thereby affecting the overall machining.

In conclusion, this study supports and complements recent research indicating that feed rate and cutting speed are the dominant parameters affecting surface roughness and tool life during dry milling of hardened steels. The results affirm the importance of optimizing these parameters to enhance machinability and prolong tool life in industrial applications.

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REFERENCES

Abbas, A. T., Al Bahkali, E. A., Alqahtani, S. M., Abdelnasser, E., Naeim, N., & Elkaseer, A. (2021). Fundamental investigation into tool wear and surface quality in high-speed machining of Ti6Al4V alloy. Materials, 14(23). https://doi.org/10.3390/ma14237128

Abbas, A. T., Ragab, A. E., Al Bahkali, E. A., & El Danaf, E. A. (2016). Optimizing Cutting Conditions for Minimum Surface Roughness in Face Milling of High Strength Steel Using Carbide Inserts. Advances in Materials Science and Engineering, 2016. https://doi.org/10.1155/2016/7372132

Abellán-Nebot, J. V., Vila Pastor, C., & Siller, H. R. (2024). A Review of the Factors Influencing Surface Roughness in Machining and Their Impact on Sustainability. In Sustainability (Switzerland) (Vol. 16, Issue 5). Multidisciplinary Digital Publishing Institute (MDPI). https://doi.org/10.3390/su16051917

Achadiah, R., Setyarini, P. H., Pambayoen, M. A., Djunaidi, I. H., & Azizah, S. (2021). Effect of feed rate and depth of cut on face milling process on surface roughness of Al-Mg alloy using CNC milling machine 3 axis.

Ahammed, S.-S., Razin, A., Al-Nur, M., & Kaiser, S. (2022). Characterization of Machined Surfaces of Al-based Automotive Alloys with Different Levels of Si Content under Up Milling and Down Milling Operation. Acta Mechanica Slovaca, 26(1), 18–25. https://doi.org/10.21496/ams.2022.008

Ahmad A.A., Ghani J.A., & Haron C.H.C. (2022). Effect of cutting parameters on tool life during end milling of AISI 4340 under MQL condition AQILAH. Industrial Lubrication and Tribology, 74(4), 392–401. https://doi.org/https://doi.org/10.1108/ILT-08-2021-0295

Aminy, A. Y., Arsyad, H., Fahri, & Hayat, A. (2024). Investigation of surface roughness and tool wear in milling of AISI 4340 steel. Journal of Physics: Conference Series, 2739(1). https://doi.org/10.1088/1742-6596/2739/1/012042

Ancio, F., Gámez, A. J., & Marcos, M. (2015). Factors influencing the generation of a machined surface. Application to turned pieces. Journal of Materials Processing Technology, 215, 50–61. https://doi.org/10.1016/j.jmatprotec.2014.07.027

Bazaz, S. M., Ratava, J., Lohtander, M., & Varis, J. (2023). An Investigation of Factors Influencing Tool Life in the Metal Cutting Turning Process by Dimensional Analysis †. Machines, 11(3). https://doi.org/10.3390/machines11030393

Cakir, M. C., Ensarioglu, C., & Demirayak, I. (2009). Mathematical modeling of surface roughness for evaluating the effects of cutting parameters and coating material. Journal of Materials Processing Technology, 209(1), 102–109. https://doi.org/10.1016/j.jmatprotec.2008.01.050

Das, S. R., Panda, A., & Dhupal, D. (2017). Experimental investigation of surface roughness, flank wear, chip morphology and cost estimation during machining of hardened AISI 4340 steel with coated carbide insert. Mechanics of Advanced Materials and Modern Processes, 3(1).

https://doi.org/10.1186/s40759-017-0025-1

Hadi, M. A., Ghani, J. A., Che Haron, C. H., & Kasim, M. S. (2013). Comparison between up-milling and down-milling operations on tool wear in milling Inconel 718. Procedia Engineering, 68, 647–653. https://doi.org/10.1016/j.proeng.2013.12.234

Haryani Tomadi, S., Farah Huda Abd Halim, N., Najiah Dahnel, A., Sankar Gunasegaran, U., Eng Lim, J., & Syazwan Rosman, A. (2022). Optimization study on width of cut and cutting-edge radius during side milling of DAC 55 steel. Jurnal Tribologi 33, pp.125-136.

Hassanpour, H., Rasti, A., Khosrowshahi, J. H., & Farshi, S. S. (2024). Effect of ball nose flank wear on surface integrity in high-speed hard milling of AISI 4340 steel using MQL. Heliyon, 10(18). https://doi.org/10.1016/j.heliyon.2024.e37337

Hossain, S., Abedin, M. Z., Saha, R. K., Touhiduzzaman, M., & Hossen, M. J. (2025). Optimization of cutting temperature and surface roughness in CNC turning of Ti-6Al-4V alloy using response surface methodology. Heliyon, 11(1), e41051. https://doi.org/10.1016/J.HELIYON.2024.E41051

Kaltenbrunner, T., Krückl, H. P., Schnalzger, G., Klünsner, T., Teppernegg, T., Czettl, C., & Ecker, W. (2022). Differences in evolution of temperature, plastic deformation and wear in milling tools when up-milling and down-milling Ti6Al4V. Journal of Manufacturing Processes, 77, 75–86. https://doi.org/10.1016/J.JMAPRO.2022.03.010

Khan, A. A., Shoummo, M. R., & Kaiser, M. S. (2022). Surface Quality of Fe, Ni and Cr added Hyper-eutectic Al-Si Automotive Alloys under Up-milling and Down-milling Operation. Journal of Mechanical Engineering Science and Technology (JMEST), 6(1), 9. https://doi.org/10.17977/um016v6i12022p009

Lai, F., Hu, A., Mao, K., Wu, Z., & Lin, Y. (2023). Effect of Milling Processing Parameters on the Surface Roughness and Tool Cutting Forces of T2 Pure Copper. Micromachines, 14(1). https://doi.org/10.3390/mi14010224

Le, T.-H., Pham, V.-B., & Tien, D. H. (2022). Surface Finish Comparison of Dry and Coolant Fluid High-Speed Milling of JIS SDK61 Mould Steel. In Technology & Applied Science Research (Vol. 12, Issue 1). www.etasr.com

Meddour, I., Yallese, M. A., Khattabi, R., Elbah, M., & Boulanouar, L. (2015). Investigation and modeling of cutting forces and surface roughness when hard turning of AISI 52100 steel with mixed ceramic tool: cutting conditions optimization. International Journal of Advanced Manufacturing Technology, 77(5–8), 1387–1399. https://doi.org/10.1007/s00170-014-6559-z

Ojolo, S. J., & Ogunkomaiya, O. (2014). A Study of Effects of Machining Parameters on Tool Life. International Journal of Materials Science and Applications, 3(5), 183. https://doi.org/10.11648/j.ijmsa.20140305.19

Pa, N. M. N., Sarhan, A. A. D., Shukor, M. H. A., & Mohamed, M. A. H. (2013). Investigate the lubrication effects on cutting force and power consumption in up and down end milling. Advanced Materials Research, 748, 264–268. https://doi.org/10.4028/www.scientific.net/AMR.748.264

Pal, A., Choudhury, S. K., & Chinchanikar, S. (2014). Machinability Assessment through Experimental Investigation during Hard and Soft Turning of Hardened Steel. Procedia Materials Science, 6, 80–91. https://doi.org/10.1016/j.mspro.2014.07.010

Riza, A., Kuş, A., Arslan, R., Tekin, Y., & Ezentaş, R. (n.d.). A. R. Motorcu et al. Evaluation of tool life-tool wear in milling of inconel 718 superalloy and the investigation of effects of cutting parameters on surface roughness with taguchi method.

Sahoo, A. K., & Sahoo, B. (2012). Experimental investigations on machinability aspects in finish hard turning of AISI 4340 steel using uncoated and multilayer coated carbide inserts. Measurement: Journal of the International Measurement Confederation, 45(8), 2153–2165. https://doi.org/10.1016/j.measurement.2012.05.015

Sahu, S., & Choudhury, B. B. (2015). Optimization of Surface Roughness Using Taguchi Methodology & Prediction of Tool Wear in Hard Turning Tools. Materials Today: Proceedings, 2(4–5), 2615–2623. https://doi.org/10.1016/j.matpr.2015.07.218

Saini, A., Dhiman, S., Sharma, R., & Setia, S. (2014). Experimental estimation and optimization of process parameters under minimum quantity lubrication and dry turning of AISI-4340 with different carbide inserts. Journal of Mechanical Science and Technology, 28(6), 2307–2318. https://doi.org/10.1007/s12206-014-0521-8

Sakinah Shahruddin, N., Farah Huda Abd Halim, N., Madihah Mustafa, A., Haryani Tomadi, S., Akmal Mahad, M., & Yulian Adesta, E. T. (2023b). Effect of feed rate on tool wear and surface condition during milling of CFRP. In Jurnal Tribologi (Vol. 38).

Suresh, R., Basavarajappa, S., & Samuel, G. L. (2012). Some studies on hard turning of AISI 4340 steel using multilayer coated carbide tool. Measurement: Journal of the International Measurement Confederation, 45(7), 1872–1884. https://doi.org/10.1016/j.measurement.2012.03.024

Wojciechowski, S., Krajewska-Śpiewak, J., Maruda, R. W., Krolczyk, G. M., Nieslony, P., Wieczorowski, M., & Gawlik, J. (2023). Study on ploughing phenomena in tool flank face – workpiece interface including tool wear effect during ball-end milling. Tribology International, 181, 108313. https://doi.org/10.1016/J.TRIBOINT.2023.108313

Xu, W., Li, Q., Wang, L., Feng, Q., & Yuan, S. (2025). Analysis of the effect of different milling strategies on the surface quality of multiphase fibers and particle reinforced polymer matrix composites. Composites Part A: Applied Science and Manufacturing, 193, 108847. https://doi.org/10.1016/J.COMPOSITESA.2025.108847

Yingfei, G., de Escalona, P. M., & Galloway, A. (2017). Influence of Cutting Parameters and Tool Wear on the Surface Integrity of Cobalt-Based Stellite 6 Alloy When Machined Under a Dry Cutting Environment. Journal of Materials Engineering and Performance, 26(1), 312–326. https://doi.org/10.1007/s11665-016-2438-0

Zheng, G., Cheng, X., Li, L., Xu, R., & Tian, Y. (2019). Experimental investigation of cutting force, surface roughness and tool wear in high-speed dry milling of AISI 4340 steel. Journal of Mechanical Science and Technology, 33(1), 341–349. https://doi.org/10.1007/s12206-018-1236-z