

Analysis of Tool Wear Mechanisms and Surface Roughness in High Speed Hard Turning of AISI 4340 Steel Using PVD Coated Carbide Inserts

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Received: 12 December 2025, Revised: 17 March 2026, Accepted: 31 March 2026, Published: 01 April 2026

KEYWORDS

AISI 4340 steel
PVD-coated Insert
Hard Turning
Surface Roughness
Tool Wear

ABSTRACT

This study investigates surface roughness and tool wear progression during dry hard turning of heat-treated AISI 4340 steel using PVD AlTiN-coated carbide inserts. Experiments were conducted at cutting speeds of 60, 95, 180, and 250 m/min, with a constant feed of 0.1 mm/rev and depth of cut of 0.5 mm over a fixed cutting length of 360 mm. Surface roughness (Ra) was measured after three successive cuts at each speed and analyzed using a general linear model (GLM). The results reveal a non-monotonic response of surface roughness, with Ra decreasing as cutting speed increased up to 180 m/min and then rising at 250 m/min. In contrast, flank wear increased with cutting speed, reaching 63 μm at 60 m/min, 152 μm at 95 m/min, 455 μm at 180 m/min, and 690 μm at 250 m/min. Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS) analyses indicated a transition in wear mechanisms from mild adhesion and oxidation at lower speeds to severe flaking, edge chipping, crater formation, and coating delamination at higher speeds. Although the smoothest surface was obtained at 180 m/min, the pronounced flank wear at this speed highlights a trade-off between surface quality and tool condition, suggesting potentially unstable cutting despite low roughness. In comparison, a moderate cutting speed of 95 m/min provides the best overall balance between acceptable surface finish and controlled tool wear. These findings underscore the importance of understanding non-monotonic roughness behaviour, progressive wear, and coating degradation for selecting optimal cutting parameters and improving machining stability in hard turning applications.

1. Introduction

The AISI 4340 (Ni-Cr-Mo) is a high-strength, tough alloy steel and is of great interest in rigorous applications because of its superior wear resistance, extended fatigue life, and good surface finish after suitable heat treatment. It has been widely used in nuclear and defense aerospace hydraulic systems, machine tools, automotive parts, crankshafts, and shafts [1]. AISI 4340 steel combines high strength and

toughness for challenging parts, gears, shafts, aircraft landing gear, and structural components. After hot rolling, it is quenched and tempered to attain these properties, making it a common choice in the aerospace and automotive sectors [2]. It's hard to cut the steel because of its superior hardness and strength. There are roughness of the work surface, tool wear, and high machining temperature, which can be likely attributed to the inappropriate cutting conditions. This

may trigger spontaneous tool wear, chatter vibration, and irregular cutting, notably at dry turning. The strength and toughness build up the forces therefore, special tools and fixed parameters are necessary to keep surface finish [3]. The most important factor in the control of machining efficiency, tool life, and workpiece surface quality is the wear of a tool. Typical modes of cutting tool wear include flank wear, crater wear, and attrition wear, which influence the machining process very significantly. Among various wear mechanisms, flank wear is the most prevalent and arises from abrasive contact on the flank face, which adversely affects dimensional accuracy and surface finish. Hence, flank wear is commonly employed as a main response for tool life [4, 5]. Ni et al. showed that abrasive wear is likely associated with the hard particles on the workpiece material, resulting in surface defects and dimensional inaccuracies, especially when machining hard alloys [6] [7]. Hassanpour et al.'s study is based on material exchange between the tool and the workpiece under high temperature and pressure, with adhesion and eventual detachment of material, followed by tool geometry alteration [8]. Some studies have investigated the reasons for tool wear and its relationship with surface roughness, the findings reveal that differences in cutting speed, feed, and depth of cut strongly impact flank wear, built-up edge, and surface finish loss [9]. For the machining of AISI 4340 low-alloy steel, cutting speed (V_c) and feed rate (f) significantly influence tool wear and roughness (R_a). The optimal parameters for minimizing tool wear and attaining better surface finish are at V_c 73.73 m/min, f at 0.1 mm/rev, and a nose radius of 1.2 mm [10]. Moreover, it has also been reported that coated $Al_2O_3/TiCN$ coated tools increase the life of tools and decrease wear while turning AISI 4340, but at high-speed conditions, thermal mechanical wear mechanisms such as adhesion, oxidative wear, chipping, and abrasion are intensified [11].

Further studies on advanced coatings, including $TiAlN/AlN$ and $TiN/TiCN/TiAlN$ multilayers, have also been reported to have great benefits for wear resistance, reduction in cutting force, and lower surface roughness during machining hardened steels. [12] Additionally, the study found that multi-coated tools $TiN/TiCN/TiAlN$ are optimal for high-speed milling of AISI 4340 steel, showing the lowest cutting force, flank wear, and surface roughness (0.08–0.32 μm). Key wear mechanisms were flank wear, chipping, adhesion, abrasion, and crater wear [13].

Regarding the AISI 52100 steel, the PVD AlC/CrN -coated inserts provide better surface finish results than CVD and uncoated cutting tools, which supports the fact that cutting parameters have a major effect on

finished surface quality [14]. A separate study demonstrated that PVD coatings tend to exhibit superior performance. In another study on duplex stainless steel, it was shown that the $TiAlN$ coating provided better performance in dry cutting compared with other PVD coatings, whereas the $TiAlSiN$ coating could have reduced efficacy as a result of oxidation [15]. Moreover, during dry hard turning of AISI 4340 steel, $TiAlN$ PVD-coated inserts have been shown to reduce cutting temperatures while suppressing the formation of built-up edges and obtain a good surface roughness in optimal conditions [16]. Bag et al. confirm the benefits of hardened AISI 4340 using PVD-coated carbide tools for dry hard turning [17]. Previous findings have shown that optimized dry turning can achieve a high-quality surface finish, often achieving surface roughness values below 0.3 μm , similar to the grinding process [18]. Studies also suggest that dry hard turning results in shorter machining time and lower overall cost due to a higher material removal rate, which results in reduced cycle times and increased productivity. Moreover, no cutting fluids are required in dry turning, thereby leading to the reduction of production cost and environmentally friendly manufacturing [19], [20]. These improved wear resistance and thermal stability features of PVD coatings (like $TiAlN$) are attributed to their better mechanical properties and chemical inertness at elevated temperatures [21]. In particular, hard turning of AISI D3 and AISI 4340 steel, abrasion as one of the primary wear mechanisms has been identified [22]. Moreover, a number of investigations have indicated that PVD $TiAlN$ coatings can extend the tool life, diminish chip thickness, and enhance chip forming performance for hard turning processes [23]. This strengthens the critical role of advanced coating technologies in mitigating tool wear and enhancing machining performance for hard-to-cut materials [24]. Also, improved chip forming action and reduced friction at the cutting tool-workpiece interface further enhance the machining performance [25]. Moreover, the performance of the $AlTiSiN$ and $AlTiN$ coatings on AISI 304L in literature has been established, where they exhibited better wear resistance, less cutting force, and a better work surface quality [26]. New PVD coatings at optimal cutting conditions are possible paths to increased hardness and higher tribological properties, which in turn would enhance the machining of difficult-to-machine alloys by counteracting typical wear mechanisms and increasing tool life [27]. The selection of PVD or CVD coatings is largely application-dependent, with PVD-coated tools typically providing improved tool life and superior surface finish in hard turning, particularly during finishing operations, whereas CVD coatings

may be preferred for roughing operations where higher thickness and resistance to abrasive wear are critical [26]. Additionally, the PVD and CVD coated tools are usually relevant to a specific cutting application; however, in general, it can be concluded that PVD coatings are generally better for tool life and surface finish in hard turning and finishing operations, while CVD coatings may work best for roughing operations, which require higher abrasive wear resistance [28].

Das et al. [29] studied surface roughness, flank wear, and chip formation while dry hard turning at medium cutting speeds with CVD multilayer coated cemented carbide inserts to parametric optimization and economic considerations. However, at higher hardness of workpieces and high cutting speeds, the wear behaviour is not well understood towards coating-dependent initiation to transition in wear mechanisms, especially for PVD AlTiN-coated carbide inserts. The current study aims to bridge this gap by using PVD AlTiN-coated carbide tools to study the tool wear evolution, surface integrity, and wear mechanisms in a wider range of cutting speeds. Combined with scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) analyses, this study provides detailed information on the wear mechanisms of tool coatings at both moderate and high speeds through elemental distribution analysis on worn tools. This approach enables the identification of practical cutting conditions that balance surface quality and wear progression, offering valuable insights for industrial hard turning applications and highlighting the potential of advanced PVD coatings for improved machining performance.

2. Materials and Methods



Fig. 1. Overview of the experimental setup and characterization equipment used in the machining setup

2.1 Material and Heat Treatment

The AISI 4340 steel rods were procured from Peoples Steel Mills (Pakistan) and used as the workpiece material for machining experiments in this study. The as-received rods were of a hardness of 30 HRC. The base material for the workpiece is selected for hardening treatment in order to reach the necessary hardness for hard turning. The round rods were austenitized at 850°C for 2 hours in an RJX-45 box furnace and quenched in HJ-20 oil until close to room temperature. Then, the rods were further tempered at 480 °C for 120 min in order to release internal stresses and to improve toughness while keeping high hardness. The chemical composition was determined by a Spectro lab M9 spectroscope Figure 1(a), and microstructure was investigated by a Versamet 2 (Metallurgic suite) optical microscope Figure 1(b). The ultimate hardness of the heat-treated rods was determined by means of an Insize Rockwell tester (ASTM E18), and a final value of 55 ± 1 HRC is reported in Figure 1(b). The heat-treated rods were very lightly machined to remove oxidized and irregular surfaces prior to actual experimental machining.

2.2 Experimental Setup

Turning tests were performed on a Goodway CGL-2 CNC lathe equipped with a FANUC Oi-TF controller, Figure 1 (c), in dry conditions. The tool work piece arrangement for machining of the heat-treated AISI 4340 steel is illustrated in Figure 1(d). Turning trials were conducted at four different cutting speeds: 60 m/min, 95 m/min, 180 m/min, and 250 m/min. The feed rate was maintained at 0.1 mm/rev, and the depth of cut was set to 0.5 mm for all tests. All tests were performed in a dry environment, and fresh cutting inserts were used for each cutting speed. The insert was mounted on a Tagutech PCLNR 2020 K12 tool holder. The experimental design is summarized in Table 1, and the complete machining design is provided in Table 2. For each cutting speed, three consecutive passes of 120 mm were performed using the same insert, resulting in a total cutting length of 360 mm per trial.

2.3 Cutting Tools

A commercially available PVD-coated Mitsubishi carbide insert (CNMG 120404) with a 0.4 mm nose radius was used in this study. The insert features 80° rhombic geometry and an MA-type chip breaker design. The insert was mounted on a Tagutech PCLNR 2020 K12 tool holder. The design of the experiment is highlighted in Table 1 and full machining design data are given in Table 2. Three consecutive 120 mm passes were cut with the same insert at each cutting speed, resulting in a total cut length of 360 mm per trial.

2.4 Tool Wear Measurement

Flank wear (VB) was measured after each cut of 120 mm using a Dino Lite Premier AM7013MT digital microscope. Final flank wear values correspond to the tool condition after the third cut, giving a total cutting length of 360 mm for each cutting speed. The ISO 3685 criterion of $VB = 300 \mu\text{m}$ was used only as a reference threshold to interpret tool condition and severity of wear, rather than to determine complete tool life, since the experiments were conducted at a fixed cutting length. Fig 1(e) shows the setup for wear measurement and post examination.

2.5 Surface Roughness Measurement

Surface roughness (R_a) was measured using a Mitutoyo SJ-310 surface roughness tester in accordance with ISO 4287/4288 standards. A cut-off length of 0.8 mm, an evaluation length of 4.0 mm, and a probe speed of 0.5 mm/s were used for all measurements. The instrument was calibrated before use, and the selected measurement parameters were adopted in line with a previous study [30]. Fig. 1 (f) shows the surface roughness measurement setup.

For each cutting speed, surface roughness was measured after each successive cut of 120 mm. Three measurements were taken at different locations on the machined surface for every cut, and the results were reported as mean $\pm$ standard deviation. Since four cutting speeds and three successive cuts were examined, a total of 36 roughness measurements were obtained for statistical evaluation.

To assess the effects of machining conditions on surface finish, the surface roughness data were analyzed using a general linear model (GLM) in Minitab.

The integrated approach implemented in this study allowed the tool wear evolution to be related to surface quality, with such an analysis being supported by SEM/EDS analysis of the wear mechanisms.

The experimental methodology adopted in this study was designed to distinguish from earlier optimization-focused studies on hard turning of AISI 4340 steel. In contrast to studies employing CVD multilayer coated carbide inserts, the present work utilizes PVD AlTiN-coated carbide inserts with a smaller nose radius and investigates machining at a higher workpiece hardness ($55 \pm 1 \text{ HRC}$) under an extended cutting speed range. A fixed feed, depth of cut, controlled cutting length, and a fresh insert for

each cutting speed were used to focus on wear progression and degradation mechanisms.

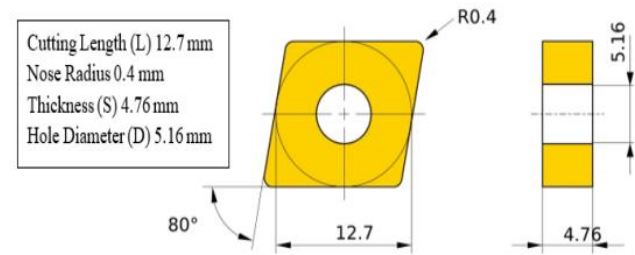


Fig. 2. Schematic of the selected PVD-coated carbide insert (CNMG 120404) [31].

Table 1

Workpiece and Setup Specifications

Parameters	Details/ Specifications
Material	AISI 4340 Steel
Workpiece Length	200 mm
Machining Length	120 mm
Workpiece Diameter	30 mm
Workpiece Hardness	$55 \pm 1 \text{ HRC}$
Tooling	Mitsubishi PVD-coated carbide inserts (CNMG 120404-MA)
Insert Coating	AlTiN (Aluminium titanium nitride)
Tool Nose Radius	0.4 mm
Tool Holder	Tagutec PCLNR 2020K12
Machine	Goodway CGL-2 CNC Lathe with FANUC Oi-TF control
Cutting Speeds	60, 95, 180, and 250 m/min
Machining Environment	Dry hard turning
Feed Rate	0.1 mm/rev constant

3. Results and Discussion

The chemical composition of the heat-treated AISI 4340 steel (Table 3) complies with the ASTM A29 specification. In steel, all three alloy elements, Cr, Ni, and Mo, contribute both to the strengthening and hardenability, while C enhances the wear resistance due to the formation of carbides. Its hardness was $55 \pm 1 \text{ HRC}$ (ASTM E18), indicating its suitability for hard turning applications. Respective microstructure (Fig. 3) was prepared as per ASTM E3 and illustrated the tempered martensitic matrix at a magnification of $400\times$ using a metallurgical microscope (Fig. 1 b). Typical of quenched and tempered AISI 4340 steel, this structure presents very high wear resistance combined with very good toughness. Understanding this microstructure is essential for an accurate investigation of its machining performance, as it directly affects tool wear and surface roughness,

influencing cutting forces and thermal stresses during machining [32].

Table 2

Machining trials showing three repeated cuts for each cutting speed.

Cut #	Cutting speed Vc (m/min)	Feed f (mm/rev)	Depth of cut ap (mm)	Pass length (m)	Environment	Insert condition
1	60	0.1	0.5	120	Dry	Fresh insert
2	60	0.1	0.5	120	Dry	Same insert
3	60	0.1	0.5	120	Dry	Same insert
1	95	0.1	0.5	120	Dry	Fresh insert
2	95	0.1	0.5	120	Dry	Same insert
3	95	0.1	0.5	120	Dry	Same insert
1	180	0.1	0.5	120	Dry	Fresh insert
2	180	0.1	0.5	120	Dry	Same insert
3	180	0.1	0.5	120	Dry	Same insert
1	250	0.1	0.5	120	Dry	Fresh insert
2	250	0.1	0.5	120	Dry	Same insert
3	250	0.1	0.5	120	Dry	Same insert

Table 3

The heat-treated AISI 4340 steel and its chemical composition

Elements	C	Mn	Cr	Si	Ni	Mo	Fe
Wt. (%)	0.38	0.76	0.99	0.3	1.72	0.235	Balance

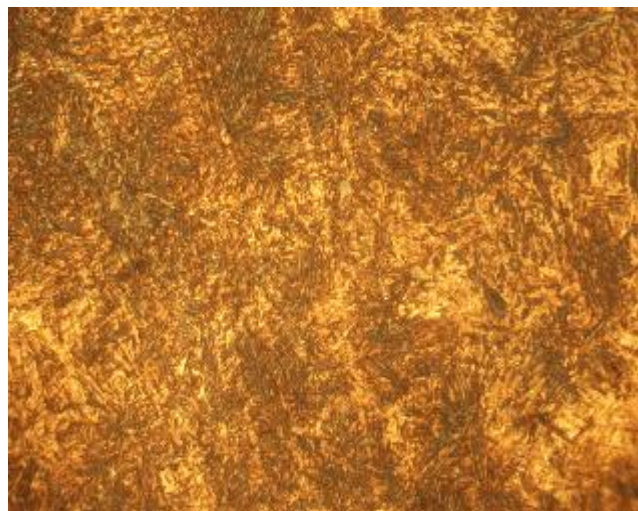


Fig. 3. Tempered martensitic microstructure of heat treated AISI 4340 steel.

3.1 Surface Roughness

The surface roughness results obtained under different cutting speeds and successive cuts are presented in Table 4 and illustrated in Fig. 4(a,b). Surface roughness was analyzed using a general linear model with cutting speed and cut number as fixed factors. The analysis showed that both variables had a statistically significant effect on surface roughness (Ra). Cutting speed significantly influenced ($F = 6.11, p = 0.002$), while cut number also had a significant effect ($F = 16.26, p < 0.001$), as shown in Table 5. The fitted model explained 62.89% of the total variation in surface roughness, with an adjusted R^2 of 56.70%, indicating that the model provided a reasonably good representation of the experimental trend.

The main effects plot in Fig. 1(b) showed that surface roughness decreased as cutting speed increased from 60 to 180 m/min, and then increased again at 250 m/min. The estimated mean Ra values were 0.9703 μm at 60 m/min, 0.7537 μm at 95 m/min, 0.6378 μm at 180 m/min, and 0.8414 μm at 250 m/min. These results indicate that the best overall surface finish was obtained at 180 m/min, whereas 60 m/min produced the highest average roughness among the cutting speed levels. The increased roughness at 250 m/min indicates that, while elevated cutting speed improved surface finish up to a point, beyond this, very high speed had the opposite impact on the overall performance of cutting. Such behavior could be attributed to a rise in thermal and mechanical loads at the tool–workpiece interface that can propagate faster tool wear and reduce cutting stability [33].

As can be seen from the grouped mean bar chart shown in Fig. 4 (a), these findings are further corroborated. At 60, 95, and 180 m/min, the increase in roughness from cuts one to three was modest. In contrast, the third cut at 250 m/min showed a clear increase in (and increased scatter) compared to both of the other cuts. This phenomenon indicated that a combination of high cutting speed and multiple cuts aggravated the degradation of the tool edge, in addition to the instability in the cutting zone [34]. The larger variation observed at 250 m/min also indicates less stable machining behavior under this condition.

These observations are consistent with the flank wear results obtained after the fixed cutting length. Flank wear increased substantially from 63 μm at 60 m/min to 690 μm at 250 m/min, with severe deterioration recorded at the highest speed. The marked rise in surface roughness at 250 m/min, particularly during the third cut, is therefore likely associated with severe wear progression, loss of edge integrity, and unstable chip–tool interaction, rather

than a simple linear effect of cutting speed alone [35] [36] [37].

Statistical and graphical analyses from the trends suggest that moderate cutting speed, especially near to 180 m/min yields a good surface finish at the present machining conditions. However, at 250 m/min. However, at 250 m/min, rapid tool deterioration and unstable cutting behavior led to a noticeable decline in surface quality.

Table 4

Surface roughness (R_a , μm) at different cutting speeds for successive cuts.

Cutting speed (m/min)	First cut (R_a , μm)	Second cut (R_a , μm)	Third cut (R_a , μm)
60	0.869 ± 0.011	0.986 ± 0.004	1.056 ± 0.042
95	0.655 ± 0.012	0.739 ± 0.022	0.867 ± 0.019
180	0.547 ± 0.027	0.624 ± 0.022	0.742 ± 0.055
250	0.383 ± 0.051	0.772 ± 0.166	1.370 ± 0.200

Table 5

General linear model analysis of surface roughness.

Source	DF	Adj SS	Adj MS	F-value	p-value
Cutting speed (m/min)	3	0.5327	0.177574	6.11	0.02
Cut	2	0.9455	0.472730	16.26	<0.001
Error	30	0.8724	0.029080		
Lack-of-fit	6	0.7175	0.119589	18.53	<0.001
Pure error	24	0.1549	0.006453		
Total	35	2.3506			

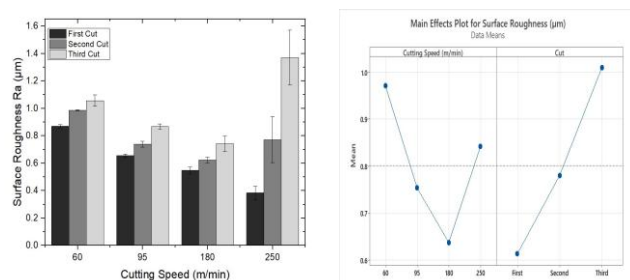


Fig 4. (a) mean R_a at various cutting speeds (b) main effects of cutting speed and cut number on R_a .

3.2 Tool Wear Mechanism

As shown in Fig. 5 and detailed in Table 6 under dry cutting conditions, the final flank wear values measured after the third cut were found to be: 63 μm at 60 m/min, 152 μm at 95 m/min, 455 μm at 180 m/min, and 690 μm at 250 m/min. The results indicate a clear trend of flank wear increasing with cutting speed. Since the experiments were conducted at a fixed total cutting length of 360 mm, the reported values represent wear progression after a controlled cutting length rather than complete tool life. However, it can be interpreted at higher cutting speeds of 180 m/min and 250 m/min that the wear values obtained were greater than ISO3685 reference criterion ($VB = 300 \mu\text{m}$), indicating severe tool degradation before the completion of the full cutting length.

The degree and progression of tool deterioration in Fig. 6, digital microscopic images reveal a transition from relatively mild wear at lower cutting speeds to severe edge chipping and adhesion with coating delamination at the maximum cutting speed. These wearing features are probably correlated to increased thermal and mechanical loading in the cutting zone [38].

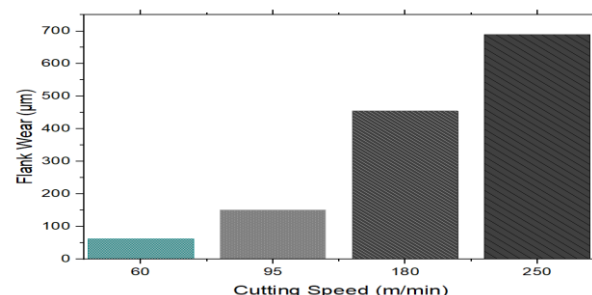


Fig. 5. Variation in Tool Wear for Different Speeds

Table 6

Tool wear at different cutting speeds

Speed (m/min)	Flank wear in (micron)
60	63
95	152
180	455
250	690

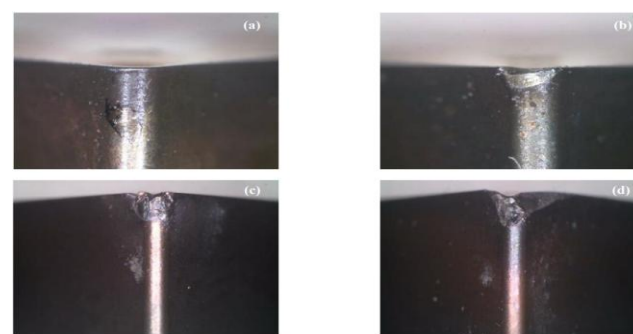


Fig. 6. Optical images of wear of tool progression at different cutting speeds

3.3 Cutting tool SEM EDS Analysis

The predominant wear type is adhesive wear observed from (Fig. 7) at the speed of 60 m/min with localized adhesion. Workpiece material was observed to be attached to the tool flank in SEM micrographs, and fine, uniform grooves appear, which are attributed to hard metallic carbides present in the AISI 4340 steel [39]. Melted chips were found to be attached to the tool surface, showing localized thermal conditions. Results of EDS showed high carbon and oxygen contents, indicating mild oxidative wear. The coating elements Al and Ti remained intact, and minimal W content implied that the substrate was still not exposed. These findings confirm that at low speed, adhesive and small-scale abrasion and oxidation occurred, but the coating remained largely intact [40]. These results from SEM demonstrate a marked rise in tool wear as cutting speeds rise. At 250m/min, the wear is also higher than the ISO 3685 threshold of 300 μm , indicating significant degradation occurred [41]. At elevated cutting speeds, gradual frictional heat generation probably promoted thermal softening and accelerated abrasive wear of the tool material [11]. The EDS spectra showed the strong signals of Fe, Cr, and Ni, confirming adhesion in the AISI 4340 base material on the surface of the tool [42]. Even if the coating was still essentially preserved, decreased Al and Ti peak intensities were indicative of a partial degradation of the coatings. Moreover, an oxygen peak confirmed the oxidation due to wear. At this intermediate speed, the tool wear was mostly affected by adhesion, abrasion, oxidation, and coating failure.

At 180 m/min, SEM observations (Fig. 8) showed significant adhesion of workpiece material, coating flaking, edge chipping, and a noticeable crater formed by high-velocity chip flow. Under these high temperatures, adhesive wear became the main issue as the heat softened the tool surface [43]. Micro-cracks were found at some worn areas, especially near the cutting edge, demonstrating thermal cracks [44]. Localized edge chipping, as shown in the SEM image, further suggested mechanical weakening and failure of the cutting edge under high stress. The EDS spectra in Fig. 9. revealed that Fe and O peaks were still strong, indicating that heavy oxidation and material transfer had taken place, and reduction of the Al and Ti intensities suggested further deterioration of the coating [45]. The presence of W in the spectra confirmed that the carbide substrate had been uncovered [46]. These combined observations suggest a change in the dominant wear mechanisms at this

speed, which include material adhesion and oxidation wear in parallel, and the formation and edge chipping of the tool.

The tool suffered from critical flaking, including deep craters, edge chipping, and extensive flank wear, which was observed at high speed 250 m/min Fig. 10. SEM micrographs showed that the coating had been entirely removed, and the substrate was exposed. EDS spectra Fig. 10 data confirmed this, with high W content due to carbide substrate exposure and meaningfully reduced Al and Ti coating elements peaks. Strong Fe signals suggested strong work piece adhesion. The tool experienced a combination of severe abrasion, material adhesion, and excessive flaking wear, driven by high thermal and mechanical stresses [47]. Fracture at the cutting edge further indicated mechanical failure under extreme conditions.

The SEM-EDS study revealed that as cutting speed rises, adhesion, oxidation, and mild abrasive tool wear mechanisms developed for lower cutting speeds were replaced by severe flaking and material adhesion, oxidation, and coating failure. The protective TiAlN layer provided good wear resistance at low speeds but gradually wore down with increasing thermal loading, resulting in the exposure and degradation.

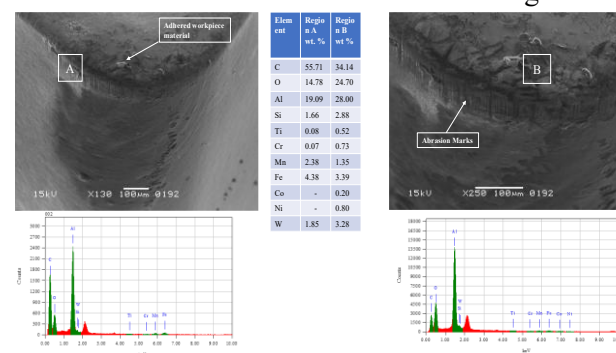


Fig. 7. Analysis of SEM and EDS (a) and (b) worn tool at V= 60 m/min

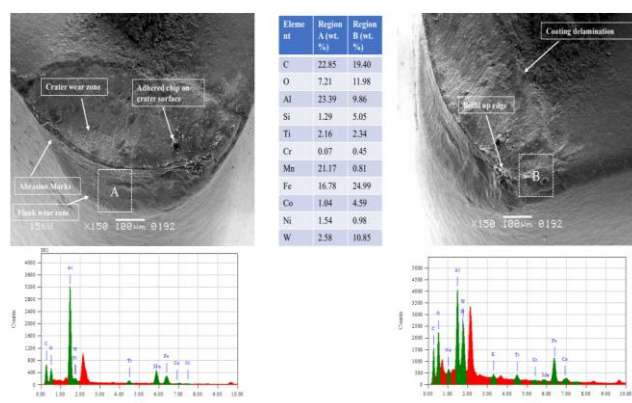


Fig. 8. Analysis of SEM and EDS (a) and (b) worn tool at V= 95 m/min

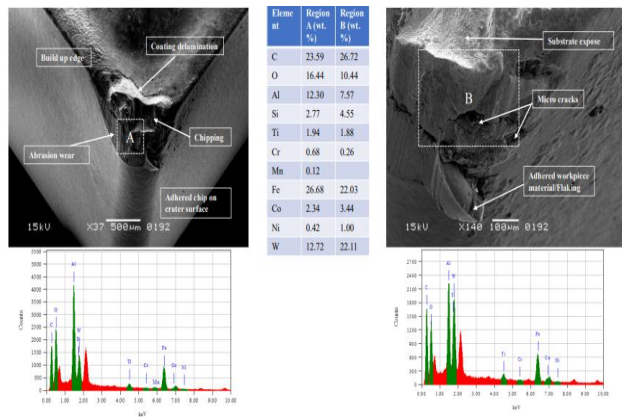


Fig. 9. Analysis of SEM and EDS (a) and (b) worn tool at $V = 180$ m/min

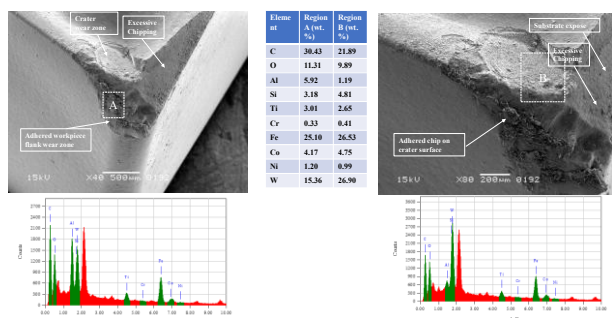


Fig. 10. Analysis of SEM and EDS (a) and (b) worn tool at $V = 250$ m/min

4. Conclusion

- Dry hard turning of heat-treated AISI 4340 steel (55 ± 1 HRC) with PVD AlTiN-coated carbide inserts showed that surface roughness and tool wear were strongly dependent on cutting speed under constant feed (0.1 mm/rev) and depth of cut (0.5 mm).
- The GLM analysis confirmed that both cutting speed and cut number significantly affected surface roughness. Cutting speed was statistically significant ($F = 6.11$, $p = 0.002$), while cut number showed an even stronger effect ($F = 16.26$, $p < 0.001$).
- Surface roughness followed a non-monotonic trend, decreasing from $0.9703 \mu\text{m}$ at 60 m/min to $0.6378 \mu\text{m}$ at 180 m/min, and then increasing to $0.8414 \mu\text{m}$ at 250 m/min. This indicates that moderate-to-high cutting speed improved surface generation initially, but excessive speed reduced machining stability.
- Flank wear increased markedly with cutting speed, reaching $63 \mu\text{m}$, $152 \mu\text{m}$, $455 \mu\text{m}$, and $690 \mu\text{m}$ at 60, 95, 180, and 250 m/min, respectively. The wear values at 180 and 250 m/min exceeded the ISO 3685 reference limit ($VB = 300 \mu\text{m}$), indicating severe tool deterioration after the fixed cutting length.

- SEM/EDS analysis revealed a progressive change in wear mechanism with increasing speed. At lower speeds, wear was mainly governed by mild adhesion, abrasion, and oxidation, whereas at higher speeds, coating flaking, edge chipping, crater wear, oxidation, strong material transfer, and substrate exposure became dominant.
- Although the lowest surface roughness was achieved at 180 m/min, this condition also produced excessive flank wear. Therefore, 95 m/min can be considered the most suitable cutting speed in the present study, as it offered a better compromise between surface quality, tool condition, and machining stability.
- Overall, the study shows that selection of cutting parameters in hard turning should not be based only on low roughness values, but also on tool wear progression and SEM/EDS-based wear mechanism evaluation to ensure reliable and economical machining performance.
- More advanced coating technologies need to be studied further, as with a greater number of layers, which can enhance the strength and abrasion resistance for stable cutting inserts. These novel coatings may solve problems including adhesion, chipping, and flaking of the coatings at high-speed machining conditions, resulting in extending tool life and increasing performance during long-term operation.

5. Abbreviations and Nomenclature

AISI	American Iron and Steel Institute
AlTiN	Aluminium Titanium Nitride
ASTM	American Society for Testing and Materials
CNC	Computer Numerical Control
CVD	Chemical Vapor Deposition
EDS	Energy Dispersive Spectroscopy
GLM	General Linear Model
HRC	Hardness Rockwell C
PVD	Physical Vapor Deposition
Ra	Arithmetic Average Surface Roughness
VB	Flank Wear
Vc	Cutting Speed
WC	Tungsten Carbide

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