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Original Article

The Effects of TiAlN Coated Carbide Inserts in Milling Hardened JIS SKD11 Cold Work Tool Steel

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Abstract - *This research explores the behaviour and performance of TiAlN-coated carbide inserts during the dry milling of hardened JIS SKD11 tool steel, especially in regard to tool life, wear mechanism, surface finish, vibration character, and chip formation during the operation at different cutting speeds and feed rates. Results of the study indicate that the cutting speed is the most influential of the die cutting parameters in determining the tool life, as the higher cutting speeds quickly lead to advanced wear of the tool and diminish the wear resistance of the tool significantly. A better surface finish was produced at lower feed and cutting speeds due to lesser thermal and mechanical loads on the cutting edge. At higher cutting speeds, advancing notch wear was the main mechanism of tool wear, while greater amounts of tool wear produced commensurately higher amounts of vibration and lesser machining stability. The morphology of the chips produced changed from continuous to segmented as the cutting temperature increased, indicative of thermal softening and cutting zone instability. The research is of great significance in demonstrating the behaviour of TiAlN-coated carbide inserts in hard milling and shows the necessity of ascertaining certain cutting parameters to optimize tooling and surface quality in machining hardened steels.*

Keywords - *TiAlN coating, Hard milling, JIS SKD11 steel, Tool wear, Tool life, Surface roughness, Vibration analysis, Chip formation.*

1. Introduction

Due to an increase in demand for durable and high-performance products, steel components in hardened form have become a lot more prevalent in a few industries. To guarantee better wear resistance, engineers and manufacturers often choose more durable and costly materials for key components such as molds, gears, dies, aerospace components, and precision machinery. Nevertheless, these materials have attributes that make them difficult to machine [1, 2]. Conventional manufacturing routes rely on heat treatment after soft machining, a sequence that increases lead time and production cost [2].

The development of hard machining has made this process more straightforward, as hardened parts can now be machined to their final dimensions directly. Tools made of Polycrystalline Cubic Boron Nitride (PCBN) and some ceramics, which have high hot hardness, have been shown to be very effective in this area [1, 3, 4]. Nevertheless, the relatively high cost of these tool materials limits their adoption, particularly for moderate-hardness steels and medium-volume production. This has encouraged the exploration of alternative tool solutions that deliver acceptable performance at lower cost.

Coated carbide tools should be taken into consideration as a viable option. Newer coatings, particularly Physical Vapor Deposition (PVD) coatings like TiAlN, offer a good tradeoff of cost and consistent performance while machining. TiAlN coatings offer a good range of properties like thermal stability, oxidation resistance, and good wear behaviors, making them a good coating for hard machining. [1, 5-7]. To support wider adoption of hard machining in industry, it is essential to evaluate both tool performance and the resulting surface quality. Thus, this study focuses on hard milling using TiAlN-coated carbide tools under dry cutting conditions and varying machining parameters.The application of coatings to improve cutting tool performance is long established. The introduction of coated cemented carbide inserts in 1969 significantly influenced the metal cutting sector, allowing higher cutting speeds and productivity [8, 9]. At present, some 70 % of cemented carbide tooling utilized within industries uses some type of coating for hard machining applications [10-12]. The interactions between coatings and substrates are essential in determining the performance of a tool. The substrate must be of adequate hardness and toughness to support the coating layer. If a deficiency occurs, the coating will undergo spalling and eventually will promote the rapid failure of the tool [13].

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As a result, carbide materials have gained a dominant position in industry, commanding 85% of coated cutting tools owing to their unsurpassed hardness and their ability to be coated thoroughly in a variety of coating systems, such as TiN, TiAlN, TiCN, and multilayer coatings, which outperform High-Speed Steels (HSS) [14]. TiAlN-based PVD coatings continue to gain prominence due to their high chemical stability, oxidation resistance, hot hardness, and thermal barrier effects, which collectively enhance tool performance during high-speed dry machining [1, 5, 15, 16]. Previous research has shown that TiAlN-coated carbide tools can endure high cutting temperatures and maintain their hardness even with high-speed machining, making them ideal for machining hardened steels [17, 18]. The durability of TiAlN under severe thermal and mechanical loads contributes to stable machining environments in hard milling.

Several studies on hardened steels have highlighted how different tool coatings influence machining performance. Jukka et al. [19] reported differences in behavior in coating materials TiN and Al_2O_3 during turning of stainless steels, where, from the tool nose, failure emerged as the primary wear mechanism when cutting forces were high. Vitor et al. [1] reported that TiAlN coating has higher wear resistance than TiN, especially at high speed and temperature. TiAlN continues to be mostly used for more demanding machining conditions due to its excellent wear behavior, along with thermal stability and resistance to corrosive materials.

As industries continue to seek machining solutions that maximize efficiency while minimizing costs, TiAlN-coated carbide inserts stand out as a cheaper alternative to the more expensive PCBN and ceramic tools. Nevertheless, the number of studies assessing the performance of TiAlN-coated carbide inserts in milling hardened JIS SKD11 under dry conditions is limited. Most studies focus on turning operations, or on a single parameter in isolation, such as tool wear or surface finish. What is still primarily overlooked is the interplay between tool wear, tool life, vibration, surface finish, and chip formation during the hard milling of SKD11.

Consequently, the focus of this thesis is on the performance of TiAlN-coated carbide inserts while hard milling JIS SKD11 cold work tool steel. This study investigates the tool life, wear, surface finish, vibration, and chip formation at different cutting speeds and feed rates in dry machining. This study aims to provide recommendations on the use of TiAlN-coated carbide tools for dry machining in precision and durable tool manufacturing sectors.

2. Methodology

This section outlines the details of the experiments conducted to evaluate the performance of TiAlN-coated carbide inserts when dry milling JIS SKD11 cold work tool steel. The research was carefully planned and executed, involving the same procedures, materials, cutting parameters, measurement systems, and methods, so that the results could easily and faithfully follow the same pattern as the procedures used in machining research. Every part of the experiment complied with the framework of the international standards used for the study of tool wear and tool life.

2.1. Workpiece Material

The subject of this study is JIS SKD11 cold work tool steel, which is commonly utilized in designing and crafting molds, dies, and other types of precise tools. This kind of steel is not only tremendously hard, achieving a hardness of 58 HRC after the heat treatment process, but also highly wear-resistant. Because of these highly desirable characteristics, this steel is a prime candidate for assessing cutting tool performance in hard and severe machining environments [1, 20, 21]. The chemical composition of JIS SKD11 steel is shown in Table 1. The steel was supplied in a fully annealed condition, and its hardness was checked before and after the cutting tests to make sure it remained consistent. This specific type of steel is widely associated with being used to create industrial tools and dies that possess high hardness levels, which makes it appropriate to analyze the wear and performance of cutting tools for industry-related conditions [22, 23].

Table 1. Chemical composition (Wt %) of JIS SKD11

Element	C	Cr	Fe	Mn	Mo	Si	V
Wt %	1.6%	11%	84.7%	0.6%	1.2%	0.4%	0.5%

2.2. Cutting Tool Material

The cutting tools used in this study are TiAlN-coated carbide inserts made by Kyocera, with the ISO code BDMT 110308ER-JT, specifically designed for high-speed milling of hardened materials [23]. The geometry of the inserts is shown in Figure 1 as follows:

Rake Angle	:	15°
Clearance angle	:	10°
Cutting-edge radius	:	0.4 mm

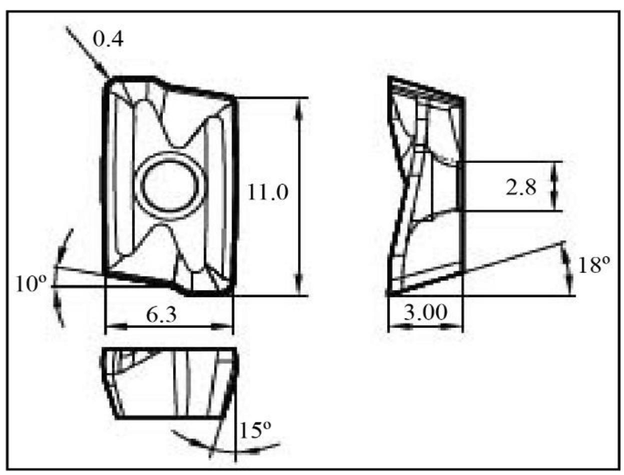


Fig. 1 Geometrical elements of insert BDMT 110308ER-JT

The TiAlN coating was applied using Physical Vapor Deposition (PVD). This coating makes the tool more resistant to wear, able to withstand high temperatures, and better protected against oxidation. TiAlN is especially useful in dry machining, where the lack of coolants causes the tool to heat up more [20, 24, 25]. These properties make TiAlN-coated tools very well-suited for machining hard materials such as JIS SKD11. Implementing PVD coating allows the tool to endure high temperatures and lessens the amount of friction created while cutting. This not only prolongs the tool's lifespan but also enhances the surface finish of the tool. Research indicates that TiAlN-coated tools retain their hardness even at elevated temperatures, which is essential to maintaining effectiveness when milling hardened steels at high rates [6, 22].

2.3. Experimental Setup and Equipment

The milling tests were carried out on a Mazak Vertical Center 410A-II CNC milling machine, which provides high precision and stability during machining, as shown in Table 2.

Table 2. Specification mazak vertical center 410A-II CNC

Maximum spindle speed	12,000 rpm
Maximum power	25 hp
Spindle type	ISO 50
Tool holder	Capable of holding two inserts with a diameter of 16 mm

The holder was built to distribute the cutting forces uniformly across the inserts to minimize the risk of the tool fracturing. A dry machining setup reflecting industrial scenarios where coolants may be excluded for environmental, economic, or pragmatic reasons was utilized [26]. Dry machining also allows for a better understanding of how TiAlN-coated tools perform under high-temperature conditions.

2.4. Cutting Parameters

The cutting parameters were chosen to test how well the TiAlN-coated carbide inserts perform under different cutting conditions. These settings are similar to those used in earlier studies on the hard milling of hardened steels [1, 22]. The chosen cutting parameters are as follows in Table 3. These cutting speeds are representative of typical conditions in hard milling applications, where high-speed milling is often employed to improve machining efficiency [27]. The feed rates were selected to cover a range of material removal levels and to examine how they affect tool wear and the quality of the surface finish [20]. The depth of cut was kept the same so that the influence of cutting speed and feed rate on the tool's performance could be examined more clearly. The parameters enable researchers to investigate systematically how changes in cutting speed and feed rate affect tool wear, tool life, and overall machining efficiency of the tool. These parameters were used in studying the machining of TiAlN-coated tools in previous studies [1, 18, 25].

Table 3. Selected cutting parameters

Cutting speeds	150, 175, and 200 m/min
Feed rates	0.10, 0.15, and 0.20 mm/tooth
Depth of cut	0.4 mm (constant for all tests)

2.5. Experimental Procedures

The machining tests were carried out following a planned experimental procedure to ensure consistency across all trials. After each milling pass, the following measurements were taken:

2.5.1. Tool Wear

Tool wear was checked using a Nikon toolmaker's microscope, and the flank wear (VB) was recorded at each stage of the machining process. The tool was considered worn out when the flank wear reached 0.3 mm, following the ISO 8688-2:1989 (E) standard for testing tool life. This standard method ensures that tool performance can be compared consistently under different cutting conditions [20, 21].

2.5.2. Surface Roughness (Ra)

Surface roughness was measured using a Mitutoyo SurfTest SJ-400, which has a precise probe to check the average finish of the surface. The roughness was recorded after each cut to see how different cutting settings affected the surface quality [1].

2.5.3. Vibration

An accelerometer collecting data through the tool holder recorded vibration data in the form of waveforms (showing changes over time) and spectra (showing different frequencies). The vibration data are useful in determining the stability of the tool and the point of tool wear. Unstable tool vibrations suggest that the tool wear progresses quickly. Operating at a higher vibration is a sign of an unsteady cutting with the tool [28].

2.5.4. Chip Formation

The shape of the chips produced in each milling pass was carefully observed. They were classified as continuous, segmented, or ribbon-like, depending on their appearance. This helps to understand how heat and forces affect the cutting process [6, 20, 23].

3. Result and Discussion

3.1. Tool Life Evaluation

Figure 2 shows wear patterns on TiAlN-coated inserts when dry milling. It was noted that increasing cutting speeds always resulted in reduced tool life, regardless of the constant feed rate. This is typical in hard milling, where cutting temperature becomes the major issue due to speed. For the maximum speed in this study, at 200 m/min, tool life was very brief, between 1.05 and 2.18 minutes. This narrow time range indicates that at some point, the temperature is too high and the feed rate influence is diminished, because the dominant

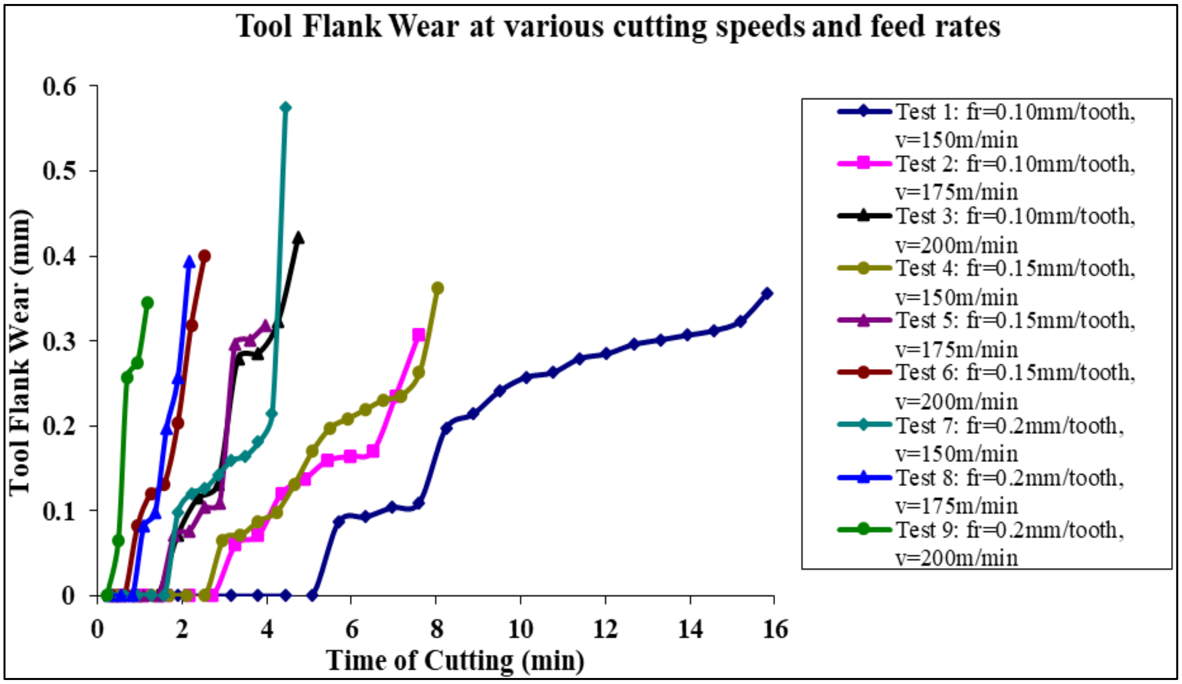


Fig. 2 Tool flank wear versus time of cutting under dry cutting conditions

Wear mechanisms shift from abrasion and micro-chipping to oxidation, coating diffusion, and softening [22]. On the other hand, the inserts have a higher tool life at 150 m/min, particularly at 0.10 mm per tooth, where the tool operated for almost double the time, 4.05 minutes, at the higher feed rates. There is a lower heat generation at the tool–chip interface at a slower cutting speed. This results in a slower wear rate of the coating and also delays the exposure of the carbide substrate.

Even though initial flank wear was greater at certain lower speeds (0.0876 mm and 0.0986 mm at 150 m/min for 0.10 and 0.20 mm/tooth, respectively), the wear increased at a much slower rate. This indicates that TiAlN coatings assist in keeping wear manageable during continuous cutting and postpone the onset of considerable wear [16, 29].

Figure 2 also clearly shows the typical three-stage wear pattern: (i) a running-in wear phase, where the coating adjusts to the cutting conditions, (ii) a steady-state phase, where the coating protects consistently, and (iii) a catastrophic phase, which starts when the protective layer breaks down. The longer steady-state phase at 150 m/min suggests that TiAlN sticks well to its substrate and keeps its hardness at moderate temperatures [16].

The trends observed in Figure 3 further support these interpretations. The consistent decline in tool life with increasing speed aligns closely with findings by Fang et al. [18] and Kurşuncu et al. [20], who both emphasized that wear increases during high-speed machining due to heat building up and higher cutting forces. Additionally, results from Vitor et al. [1] and Das et al. [24] confirm that when the cutting speed exceeds 200 m/min, the tool wears out much faster because of heat-related wear, such as oxidation, diffusion, and thermal fatigue.

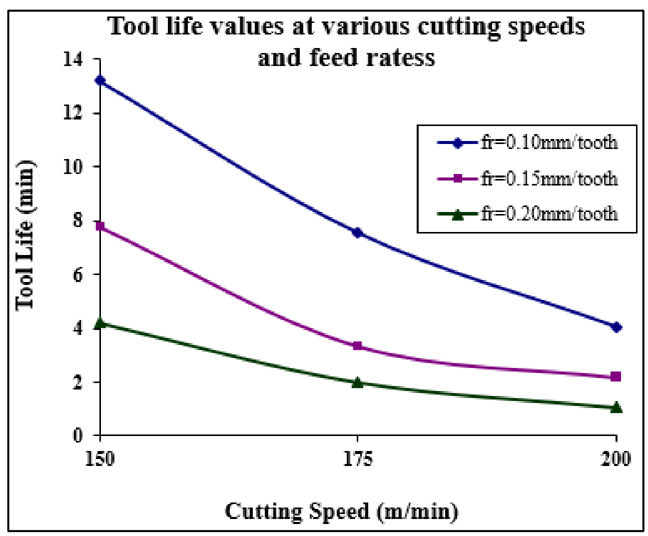


Fig. 3 Tool life values at various cutting speeds and feeds

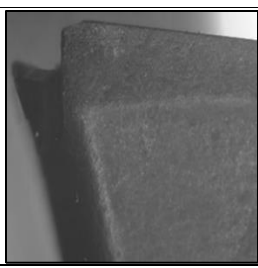
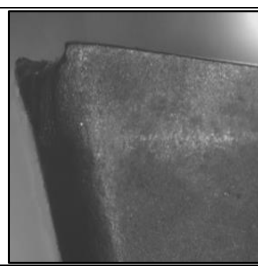
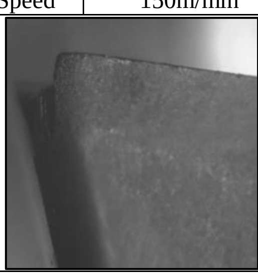
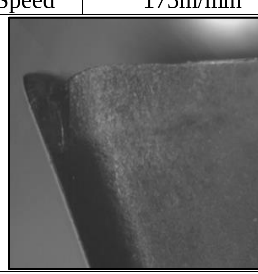
The tool coated with TiAlN also continued to perform operational duties across all testing conditions for over a minute at higher feed and speed rates. This suggests the ability to machine-harden steel to 58 HRC. That said, these findings also point to TiAlN-coated carbide tools as a cheaper, more economical choice as opposed to PCBN or ceramic tools at a lower, moderate speed, given the favorable tool life and overall performance.

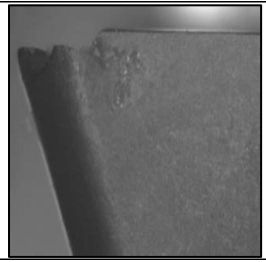
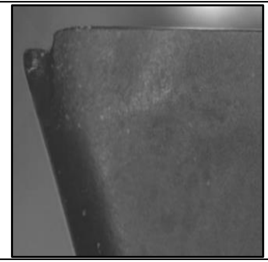
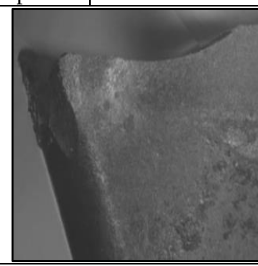
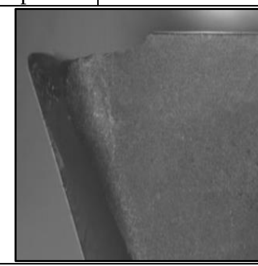
3.2. Tool Wear Pattern

Figure 4 shows the flank wear for all nine cutting conditions. The main type of wear seen in the experiments was notch wear, especially along the Depth-Of-Cut (DOC) line. This was most noticeable at higher cutting speeds (175–200 m/min) and feed rates (0.15–0.20 mm per tooth). Such wear is typical in hard milling, where high temperatures and repeated mechanical stresses build up at the DOC threshold [16, 30]. Kurşuncu et al. [20] also found that notch wear is a main cause of failure when machining hardened steels, because the coating softens quickly and the material experiences repeated tiny impacts.

Apart from notch wear, there is also clear evidence of adhesive wear. Material transfer from the work to the cutting edge is very evident at 0.20 mm/tooth and 200 m/min. Adhesion occurs when the local temperature rises above the softening threshold of the coating, causing aggregation of the work and tool. Removal of the bonded material usually pulls together the coating flakes, which erodes the protective layer and exposes the brittle carbide substrate, thereby accelerating wear [16]. These findings are consistent with Vitor et al. [26], who found that adhesion plays an important role in wear during high-temperature dry cutting of alloy steels.

Lower cutting speeds (150 m/min) led to more consistent tool wear, with the flank wearing down gradually instead of suddenly. At these speeds, the inserts kept their cutting edges, longer, and showed less chipping or coating peeling. As shown by Ranjan et al. [6] and Yu et al. [19], when thermal stresses are reduced, the tool wears down more gradually, and the coating lasts longer before failing during machining.

			
Test 1:		Test 2:	
Feedrate	0.10 mm/tooth	Feedrate	0.10 mm/tooth
Speed	150m/min	Speed	175m/min
			
Test 3:		Test 4:	
Feedrate	0.10 mm/tooth	Feedrate	0.15 mm/tooth
Speed	200m/min	Speed	150m/min

			
Test 5:		Test 6:	
Feedrate	0.15 mm/tooth	Feedrate	0.15 mm/tooth
Speed	175m/min	Speed	200m/min
			
Test 7:		Test 8:	
Feedrate	0.20 mm/tooth	Feedrate	0.20 mm/tooth
Speed	150m/min	Speed	175m/min

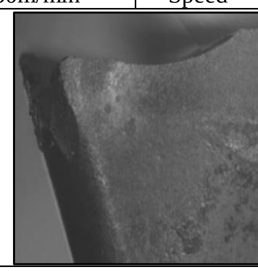
	
Test 9:	
Feedrate	0.20 mm/tooth
Speed	200m/min

Fig. 4 Tool wear of TiAlN coated carbide indexable insert under different cutting parameters

Understanding how mechanical loads and temperature interact is important when determining the type of wear that occurs. At high feed rate, the heavier chip load wears the tool edge down to a rounded profile, and a slight crack/burst is formed. At the same time, high cutting speeds generate heat that accelerates the rate of chemical and diffusive wear. This illustrates that in hard milling of a steel tool, tool wear is dominated by the mechanical forces acting on the tool and the heat generated by the cutting fluid and temperature.

3.3. Surface Roughness

Surface roughness results in Figure 5 show that Ra values generally rise as the tool wears, reinforcing that surface quality is closely tied to the state of the cutting edge. In theory, higher cutting speeds should lead to better surface finishes because they reduce built-up edge and promote a smoother shear plane. However, in this study, no consistent link between cutting speed and roughness was found. Instead, tool wear had the strongest influence on the surface texture, particularly as the tool approached the end of its life [31].

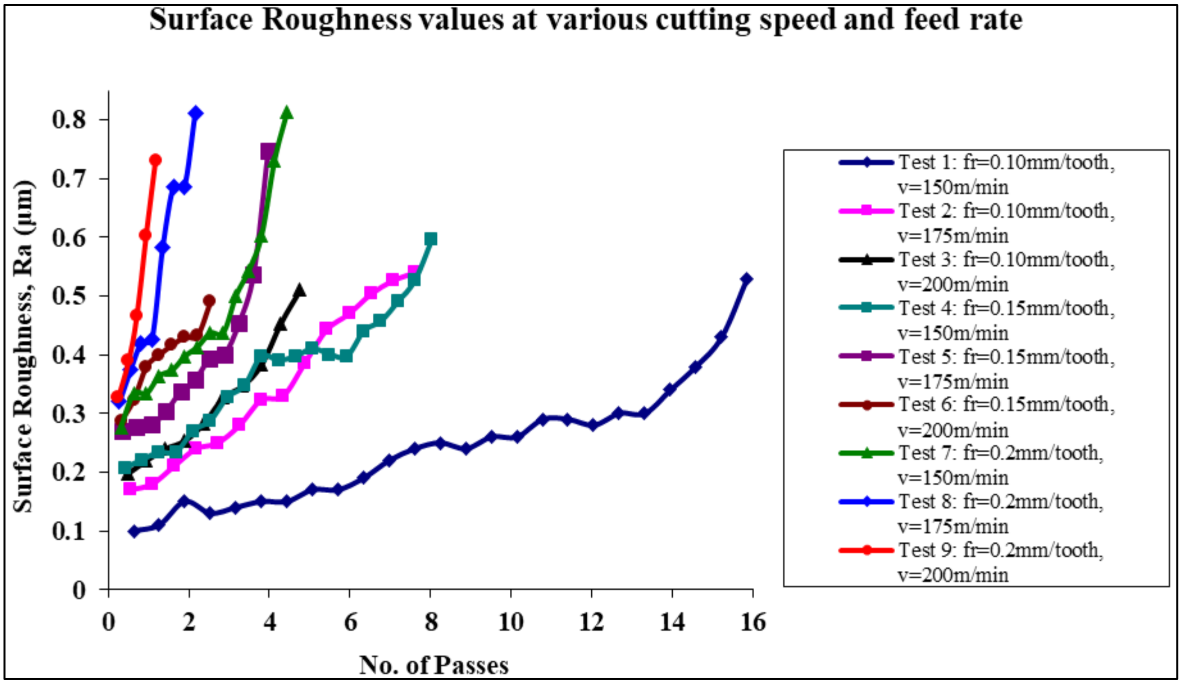


Fig. 5 Surface roughness values at various cutting speeds and feed rates

As wear deepened, the cutting-edge radius increased, causing more rubbing and ploughing instead of pure shearing. This produced rougher surfaces, loss of geometric accuracy, and visible feed marks. The deterioration intensified once the coating layer failed, and the less wear-resistant cemented carbide substrate engaged the workpiece [16, 32].

This corresponds with the typical failure progression observed in hard milling of tool steels. Moreover, higher feed rates caused the surface to become rougher because the chips removed were thicker and the cutting forces were greater, which in turn led to small vibrations and uneven chip formation [32]. Although surface roughness did not follow a straightforward pattern, it was most closely related to the condition of tool wear rather than to cutting speed or feed rate alone. This finding supports the common practice of using surface roughness as an alternative criterion to flank wear when determining limits in high-precision machining [33, 34].

3.4. Vibration

Vibration analysis offers a deeper understanding of machining stability and how tools wear over time. As shown in Figure 6, the vibration amplitude rises noticeably as the tool wears, particularly at higher speeds and feed rates. This behaviour aligns closely with Ambhore et al. [28], who reported that worn tools often generate higher vibration levels due to increased contact instability and loss of tool sharpness. Following Fast Fourier Transform analysis (FFT), it was observed that the predominant frequencies of vibration remained within the spectrum of 0-500Hz, resonating with the expected behavior of the tool when in contact with the workpiece. While the tool is making cuts, the gain in vibration amplitude indicates the onset of chatter-like behavior, which is the consequence of the cutting edges of the tool becoming less sharp. The flank of the tool was wearing unevenly and changing the cutting force profile, eventually resulting in the chip thickness pattern in a way that would increase cutting vibration [32]. Increasing the feed rate to 0.20 mm per tooth can cause a major increase in vibration due to more mechanical stress applied to the system and thicker chips produced. As confirmed by Yu et al. [26], higher mechanical loads intensify dynamic instability, put more stress on the cutting edge, and speed up the failure of the coating, all of which were clearly observed in this study [31].

From an industrial perspective, the prior studies displaying the correlation between vibration and tool wear suggest the possible use of vibration as a nonintrusive and real-time tool condition monitoring technique. This serves as an excellent contributor towards the development of intelligent machining systems and their predictive maintenance capabilities [35, 36].

3.5. Chip Formation

The type of chip formation observed during machining provides critical insight into the thermo-mechanical conditions at the cutting zone. Understanding such phenomena gives valuable knowledge of the thermo-mechanical conditions in the cutting zone. Figure 7 shows representative SEM images of the chips collected during both the first and last cutting passes. Across all cutting conditions, segmented chips were consistently observed, which is a typical chip morphology when machining hardened cold work tool steels.

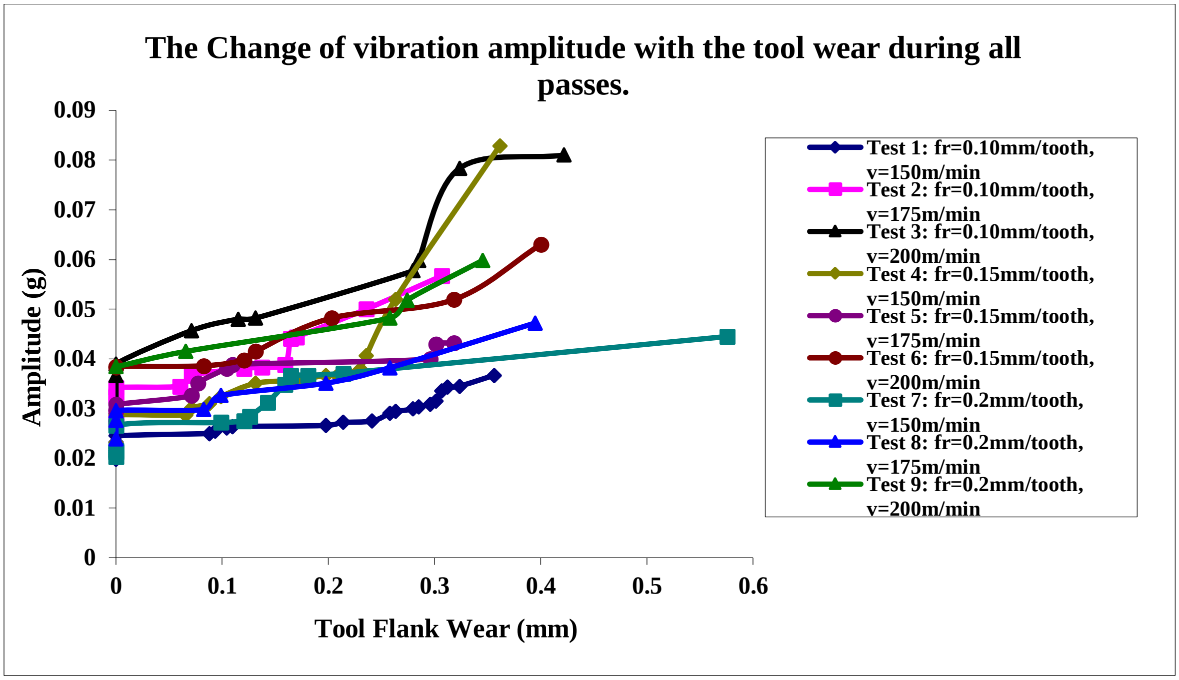


Fig. 6 Relationship between the vibration amplitude and the tool wear

Segmentation in such materials occurs due to the initiation and propagation of cracks from the outer chip surface or through the development of adiabatic shear bands. These shear bands form when localized thermal softening reduces material strength at the cutting edge, while the limited slip systems in hardened steels restrict plastic deformation, resulting in repeated fracture along the chip width [37, 38].

With stable, conventional cutting circumstances, the deformation across the chip width is usually the same, and the distance between chip segments tends to stay independent of the cutting speed. Nevertheless, with the increase in cutting speed, the depth and intensity of the saw-tooth features become more pronounced, which suggests much more thermal softening and strain localization. This behaviour agrees with the chips produced in the present study using TiAlN-coated carbide inserts in dry cutting conditions [38, 39].

During the early stages of cutting, chip morphology initially appeared as discontinuous ribbon-type chips, indicating relatively stable shear deformation. As tool wear progressed and cutting conditions became more thermally stressed, these ribbon-like chips transitioned into spiral and segmented forms, particularly at higher feeds (0.20 mm/tooth) and speeds (200 m/min) [40, 41]. This transition is clearly visible in Figure 7 and directly reflects the increased instability at the chip–tool interface.

The shift toward segmented and brittle chips with increasing cutting speed aligns with the observations of Yu et al. [26], who reported similar behavior in the high-speed machining of hardened steels. Likewise, Ranjan et al. [6] highlighted that increased thermal softening at elevated speeds promotes adiabatic shear and crack propagation, resulting in more pronounced chip segmentation.

As the cutting deepened and the tool suffered more wear, the shape and form of chips changed significantly. The chips became relatively flat on the upper surface, while the underside displayed wavy, uneven features, indicating unstable cutting forces and increased friction.

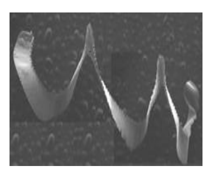
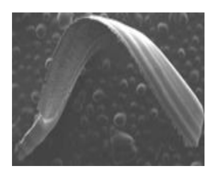
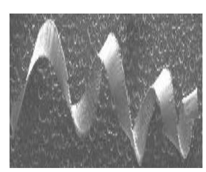
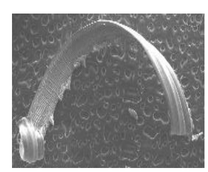
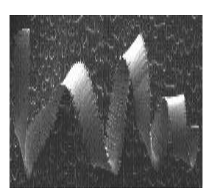
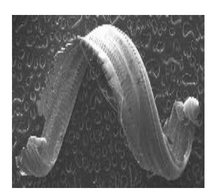
Condition			Chip formation in first passes	Chip formation in the last passes
TEST 1	FR: 0.1 mm/tooth	V: 150m/min		
TEST 5	FR: 0.15 mm/tooth	V: 175 m/min		
TEST 9	FR: 0.2 mm/tooth	V: 200 m/min		

Fig. 7 The types of chips formed during machining

In the later stages of wear, the interaction of strain hardening, rapid cooling, and the breakdown of the coating caused the material to form brittle chips riddled with cracks [42]. These brittle and cracked chips occur frequently during machining with worn and blunted tools, as the dull cutting edges and insufficient heat dissipation make the material more susceptible to cracking.

Over the course of the experiments, chips were observed to go from having a shape that resembled a ribbon to a spiral, and later to a brittle and segmented shape. These change patterns were closely related to tool wear, and the vibration increase patterns illustrated in Figure 6. This demonstrates that chips, which are a by-product of machining, can be used in a non-destructive way to analyze the tool condition and confirm that stable machining is taking place during the hard milling of SKD11 steel.

4. Conclusion

TiAlN-coated carbide inserts showed excellent performance when dry milling hardened JIS SKD11 cold work tool steel. The study found that cutting speed has the greatest impact on both tool life and surface quality, with higher speeds leading to faster wear and less stable machining. Notch wear on the flank face was the main type of tool failure across all tests, especially at higher cutting speeds and feed rates. Surface roughness also worsened as the tools wore, with the smoothest surfaces achieved at the lowest cutting speed and feed combination of 150 m/min and 0.10 mm per tooth.

Vibration levels increased gradually as the tool wore, showing a decline in tool stability and closely corresponding to the appearance of severe flank and notch wear. At the same time, the chips changed from a continuous form to more segmented and brittle shapes, reflecting the thermal and mechanical conditions in the cutting zone, especially during high-speed dry milling.

In general, these outcomes shed some light on the efficacy of TiAlN-coated carbide tools in hard-milling operations. The evidence in the work indicates that TiAlN-coated carbide inserts are indeed practical, inexpensive, and effective substitutes for much more expensive cutting tools, such as PCBN and ceramics, when machining hardened steels in dry conditions. The best performance will be a result of decreased cutting speeds and lower feed rates, applying a practical tool wear trade-off, machining stability, and surface quality retention.

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