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Investigation of the Wear Behavior of PVD Coated Carbide Tools during Ti6Al4V Machining with Intensive Built Up Edge Formation

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Abstract: Tool wear phenomena during the machining of titanium alloys are very complex. Severe adhesive interaction at the tool chip interface, especially at low cutting speeds, leads to intensive Built Up Edge (BUE) formation. Additionally, a high cutting temperature causes rapid wear in the carbide inserts due to the low thermal conductivity of titanium alloys. The current research studies the effect of AlTiN and CrN PVD coatings deposited on cutting tools during the rough turning of a Ti6Al4V alloy with severe BUE formation. Tool wear characteristics were evaluated in detail using a Scanning Electron Microscope (SEM) and volumetric wear measurements. Chip morphology analysis was conducted to assess the in situ tribological performance of the coatings. A high temperature-heavy load tribometer that mimics machining conditions was used to analyze the frictional behavior of the coatings. The micromechanical properties of the coatings were also investigated to gain a better understanding of the coating performance. It was demonstrated that the CrN coating possess unique micromechanical properties and tribological adaptive characteristics that minimize BUE formation and significantly improve tool performance during the machining of the Ti6Al4V alloy.

Keywords: PVD coating; Ti6Al4V; crater wear; built up edge (BUE); tribo-films



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1. Introduction

Titanium alloys are widely used in many industries, especially the aerospace and automotive sectors, due to their superior mechanical properties such as high corrosion resistance, biocompatibility, and good strength-to-weight ratio. However, they are considered to be difficult-to-cut materials due to a set of unique characteristics that severely affect machinability [1,2]. Titanium alloys retain strength even at elevated temperatures, leading to work hardening or strain hardening of the workpiece during machining. Their low thermal conductivity results in high cutting zone temperatures and consequent rapid tool wear [1,3]. They also have a high chemical affinity which causes intensive Built Up Edge (BUE) formation, especially during rough turning at low cutting speeds, contributing to premature tool failure and chipping [1,4,5].

Cemented carbide tools are the most widely used tools for titanium machining. Tool wear of cemented carbide tools during titanium machining is controlled mainly by two wear mechanisms: the first is adhesion wear that results in BUE formation and the second is diffusion wear causing crater wear formation. Adhesion caused BUE formation on both the flank and the rake surfaces of the cutting tool plays a significant role in flank wear [1,6]. Due to the diffusion of tool material into the workpiece material as it passes over the tool surface, crater wear ensuing from the high cutting temperature generated during titanium machining determines the degree of wear on the rake surface of the tool [7,8]. The predominant wear mechanism, however, can vary depending on the machining conditions. Typically, rough turning of the titanium alloys at lower cutting speeds is associated with severe BUE formation [9–11]. However, during finish turning at high speeds crater wear

becomes the predominant wear mechanism due to significantly higher cutting temperature generation [10–12].

Many research studies have considered the use of PVD coated tools to address these issues. However, in most cases, PVD coated tools perform worse than uncoated tools, since the unstable structure of the formed BUE facilitates detachment and surface damage of the coating layer [13,14]. Multiple research studies [1,12,15] have concluded that coatings such as TiN, TiC, TiCN, TiN-TiC, TiN-Ti(C,N)-TiC, $\text{Al}_2\text{O}_3/\text{TiC}$, Al_2O_3 , and HfN feature higher tool wear rates than uncoated tools. However, several researchers [16,17], have reported a slight improvement in the tool performance of a single layer PVD TiN or a multilayer PVD TiN/TiCN/TiN and TiAlN coating at high cutting speeds compared with uncoated tools. Although coated carbide tools have had significant success in the machining of cast irons, steels, and many superalloys, they are yet to achieve the same level of efficiency when it comes to titanium machining. Extensive research is still required to address the tool wear issues during Ti6Al4V machining especially at a combination of low cutting speeds with a high depth of cut (i.e., rough turning) that promotes significant BUE formation. Since the performance of the cutting tool is strongly associated with the conditions of the machining process, PVD coatings used for Ti6Al4V machining must be selected according to the tribological interactions taking place at the tool–chip interface. The micromechanical and tribological characteristics of the coatings must be tailored to address the underlying predominant wear mechanism.

For machining applications with intensive BUE formation, the coating's lubricity [6] becomes a significant factor in determining its overall performance. A CrN coating is generally used to machine nonferrous alloys due to its low chemical affinity with nonferrous materials [18]. CrN is known for its high chemical stability, good corrosion and oxidation resistance [19], improved toughness, and lower friction coefficient [20–23]. These properties are highly beneficial for the machining of sticky titanium alloys. It was previously shown that the CrN coating performs better compared to (Ti, Al) N coatings in some cutting tool applications, especially at low cutting speeds, due to its high resistance to adhesive wear and strong coating–substrate adhesion [24]. Therefore, a self-lubricating CrN coating was developed in the present study to minimize BUE formation during the rough turning of a Ti6Al4V alloy and improve tribological interaction at the tool–chip interface. The performance of this CrN coating was compared with that of uncoated tool and the widely used commercial AlTiN coating recommended in industry.

The authors, in a previous research paper [11], have shown that CrN coating, deposited by Fine Cathode (FC) arc deposition process, improves tool performance during high-speed machining (finish turning) of Ti6Al4V alloy. This was due to the formation of Cr_2O_3 tribofilm with thermal barrier characteristics that reduced the propagation of crater wear. The authors also found evidence of the lubricating properties of Cr_2O_3 tribofilm. In the current research paper, detailed investigation of a CrN coating deposited by an advanced plasma-enhanced arc Superfine Cathode Process (SFC) [25] is conducted to assess tool performance during the rough turning of a Ti6Al4V alloy. The main goal of this research is to demonstrate that the unique micromechanical and tribological characteristics of the developed CrN coating can improve tool performance during the rough turning of a Ti6Al4V alloy associated with strong BUE formation giving maximum economic benefit to the industries by reducing machining downtime and tooling cost. This investigation also suggests that CrN coating can possibly be considered as a general-purpose coating to be used for a wider cutting range condition.

2. Experimental Methods

2.1. Coating Deposition and Characterization

All the coatings investigated in the present study were deposited on Kennametal CNMG432 and polished Sandvik Coromant SPGN120308 cemented carbide uncoated inserts. The Kennametal CNMG432 were used to conduct the machining tests whereas all coating characterization were done on the flat polished Sandvik Coromant SPGN120308

inserts. Both the inserts have the same cemented carbide grade and have same microstructural composition. The commercial AlTiN coating was supplied by Kennametal. This advanced PVD coating is designated as KC5010 grade and is recommended for machining nonferrous metals and superalloys. The CrN coating was deposited by a cathodic arc ion plating process using an AIP-S20 PVD (Kobe Steel Ltd., Kobe, Japan) deposition system. This coating system uses an advanced plasma-enhanced arc superfine cathode process (SFC) [25], which is a novel, magnetically controlled cathodic arc source. The SFC process enables the deposition of smooth coatings with low compressive residual stresses. A 105 mm diameter Cr target with 99.9% purity powered in the arc mode was used to deposit the CrN coating. The substrates were cleaned with acetone in an ultrasound bath for 16 min before the deposition process. After pumping-down to a pressure of 1×10^{-2} Pa, the substrate was cleaned in situ by argon ion etching for 7.5 min at a substrate bias voltage of 400 V and pressure of 1.33 Pa. The substrate was heated to 500 °C and rotated at 5 rpm during the process. The CrN coating was deposited at a bias voltage of −50 V for 20 min at 4.0 Pa pressure, using nitrogen as a process gas.

The coating thicknesses were determined on the polished Sandvik Coromant SPGN120308 cemented carbide inserts using a BC-2 Miba Coating Group ball crater system and a steel ball with a diameter of 25 mm. The thicknesses were confirmed with optical measurements of the coatings' fractured sections done on a Vega 3-TESCAN scanning electron microscope (SEM) (Brno Kohoutovice, Czech Republic). The surface morphology of the coatings was evaluated using an Anton Parr Tosca™ 400 atomic force microscope (AFM) (Graz, Austria). The system was operated in the tapping mode using commercial silicon probes with a resonant frequency of 285 kHz and a force constant of 42 N/m. The scan size was maintained at 25 µm × 25 µm. The image processing and data analyses were performed using Tosca™ analysis software (Version-7.4.8341).

An XRD X-ray Diffraction System from Proto Manufacturing Limited (LaSalle, ON, Canada) with Cu-Kα (1.544 Å) radiation was used to determine the crystal structure and preferred orientation of the CrN and AlTiN coatings. Residual stresses were measured via a $\sin^2 \psi$ technique with a LXRD Stress Analyzer from Proto Manufacturing. These measurements were performed with a 1.0 mm round aperture in (422) and (200) planes identified at 2θ angles of 130° and 80° for CrN and AlTiN coatings, respectively. A Gaussian function was used to fit the diffraction peaks.

X-Ray Photoelectron Spectroscopy (XPS) was used to determine the formation and chemical composition of the tribo-oxides. A Kratos AXIS Supra (Kratos Analytical, Manchester, UK) spectrometer with a hemispherical energy analyzer collected the XPS spectra. X-rays were generated with an Al anode source. The Al-Kα X-ray source was operated at a constant acceleration voltage of 15 keV and an emission current of 25 mA. The system's base pressure was not higher than 2×10^{-9} Torr and the operating pressure did not exceed 2×10^{-8} Torr. A 4 kV Ar+ beam was used to sputter-clean the samples for 5 min before any spectra were collected. A 50 µm beam was used to obtain all the data. All survey and high-resolution spectra were collected at pass energies of 160 eV and 40 eV, respectively. All spectra were obtained with the Kratos patented charge neutralization system. High-resolution data was calibrated by setting the C1s C–C peak to 284.8 eV. Analysis of the data was performed by CasaXPS Version 2.3.18 software.

The micromechanical properties of the coatings were evaluated using a Micro Materials NanoTest P3 system (Micromaterials, Wrexham, UK). Nanoindentation was performed in a load-controlled mode at a peak load of 50 mN and a dwell period of 5 s. A Berkovich diamond indenter was used to perform 40 indents per coating. The indenter was calibrated according to ISO14577-4 [26]. The load was adjusted to minimize the influence of the sample's surface roughness and to keep the indentation contact depth within 1/10 of the coating's thickness. This was to ensure that coating-only (load-invariant) hardness was measured in combination with the coating-dominated elastic modulus. The same instrument was used to perform nanoimpact tests on the coatings. The tests were done at room temperature using a cube-corner indenter. The indenter was accelerated 12 µm

away from the coating surface with a 20 mN force that was used to produce an impact every 4 s for a total duration of 300 s. Five tests were performed at different locations for each coating.

Scratch tests were conducted with an Anton Paar-RST3 Revetest[®] Scratch Tester (Graz, Austria). A Rockwell diamond indenter with a 20 μm end-radius was used for the tests, which were performed in progressive mode. A 3-scan procedure was adopted for all tests. This procedure consisted of a pre topography scan at a 0.5 N load, a progressive load scratch scan in which the load was steadily increased from 0.5 N to 5 N, and a post topography scan at 0.5 N load. The total scratch length was 0.5 mm with a ramping load rate of 7.02 N/min and scan speed of 0.78 mm/min. Three scratch tests were performed for each sample. Multi-pass wear tests were also performed with the same RST3 system. Each wear test was carried out at a constant load of 0.75 N for 5 passes with a Rockwell diamond indenter with a 20 μm end-radius. The track length was maintained at 1 mm. The toughness of the coatings was evaluated by means of a modified Palmqvist toughness method with the RST3 system, as per ISO 28079 standard [27]. A load of 100 N was used for the test. The toughness values were calculated by dividing the load with the summation of the total crack lengths from crack tip to indentation corner from all four corners of the indent.

To investigate the correlation between the temperature and the friction coefficient at the tool workpiece interface, a specially designed instrument, described in [28], was used. This apparatus can mimic the adhesive interaction that occurs during machining at the tool–workpiece interface. The test is performed by rotating a coated pin in between two polished Ti6Al4V alloy discs. To simulate the friction conditions at the tool–workpiece interface, the discs were progressively heated from 25 °C to 800 °C. A load of 2400 N was applied to create plastic strain at the contact surface. The friction coefficient was calculated using the ratio between the shear strength of the adhesive bonds and the normal contact stress generated at the interface. Three tests were conducted for each coating, and the estimated magnitude of error for the coefficient of the friction value was approximately 5%.

2.2. Cutting Tests and Chip Morphology Analysis

To evaluate the wear behavior, progressive tool wear studies were performed within a NAKAMURA SC450 turning machine under wet turning conditions. An ASTM B265 Grade 5 Ti6Al4V aerospace alloy was used as the workpiece material. All tests were conducted on cemented carbide (WC, 6% Co) grade K313 CNMG432 turning inserts supplied by Kennametal. A MCLN-5° Kennametal Kenloc[™] tool holder under a flood coolant condition was used for the tests. XTREME CUT 290 semisynthetic cutting fluid, which is designed for machining aerospace alloys, was used during cutting. The coolant was maintained at a flow rate of 14 L/min. Table 1 outlines the cutting parameters used to conduct the machining tests. The selected cutting conditions chosen were based on industry recommendations. Figure 1 shows the experimental setup for the turning operation. A maximum flank wear of 300 μm was set to be the tool life criterion, as per ISO 3685:1993 [29]. The flank wear measurements were made with a Keyence optical microscope (model VHX-5000 Series, KEYENCE America, Elmwood Park, NJ, USA) during the cutting tests. The scatter of tool life measurements was approximately 10%.

Table 1. Cutting parameters for machining of Ti6Al4V alloy.

Machining Operation	Cutting Tool Substrates	Workpiece Material	Workpiece Hardness, HRC	Speed, m/min	Feed, mm/rev	Depth of Cut, mm	Coolant Condition
Turning	Kennametal CNMG432 Grade K 313 Turning inserts	ASTM B265 Grade 5 Ti6Al4V alloy	37–38	45	0.15	2	Flood

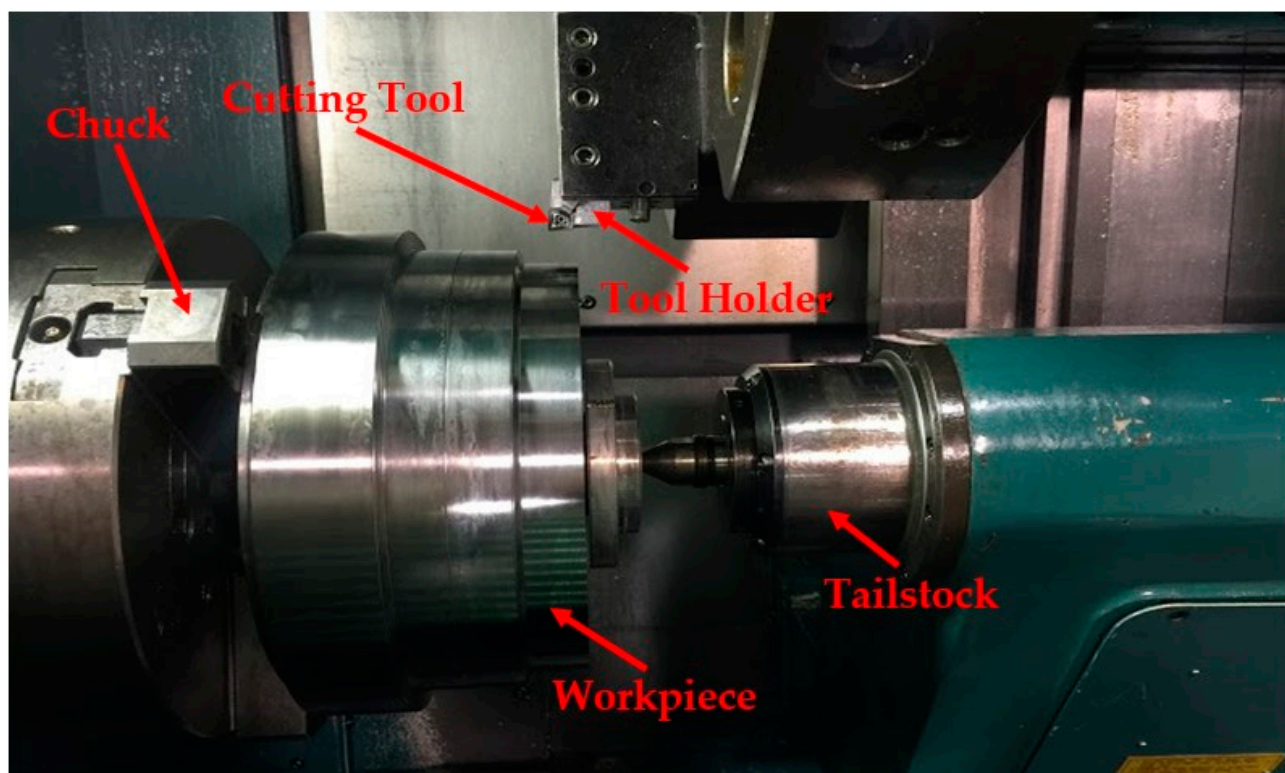


Figure 1. Experimental setup for turning operation.

After every 600 m of cutting length, the tools were inspected with a SEM and an Alicona Infinite Focus G5 3D surface measurement system (Alicona Manufacturing Inc., Bartlett, IL, USA). The focus-variation technology of the Alicona system was used to generate 3D topographic images of the cutting inserts and measure the volumetric difference between the worn and new tool. To measure the built up volume and crater wear volume, 3D volume dataset of a worn tool after every 600 m of cutting length were compared against a reference 3D volume dataset of the same tool corner collected prior to machining using the Alicona system. A postprocessing software package Measure Suite aligns the two datasets and calculates the built up and crater wear volume by measuring the difference in volume of the worn tool above and below the reference dataset. Chip analysis was conducted using standard practices [30]. A JEOL JSM-7000F high-resolution SEM was used to perform EBSD analysis of the chip cross sections. The SEM was operated at a 25 kV accelerating voltage and 60 μm aperture size. The sample was tilted to 70°, and a working distance of between 10 to 12 mm was maintained. The CCD detector was kept at an insertion distance of 186 mm.

3. Results

3.1. Tool Wear Performance Studies

Tool wear performance was investigated under wet rough turning conditions. The tool wear progression with respect to cutting length for uncoated, AlTiN coated, and CrN coated tools is illustrated in Figure 2. The highest tool wear intensity was observed for the AlTiN coating, followed by the uncoated tool and the CrN coated tool. The tool life of the CrN coated tool improved by approximately 232% compared to the AlTiN coated tool and 155% compared to the uncoated tool.

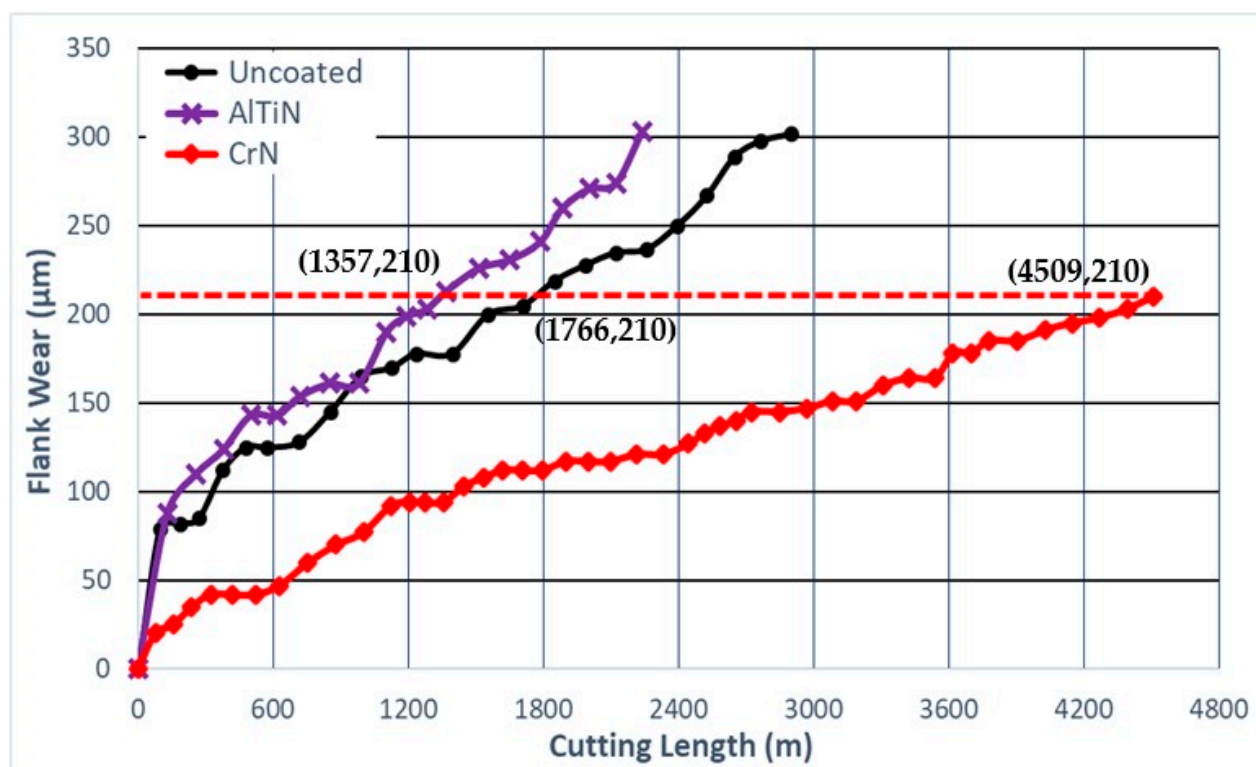


Figure 2. Flank wear vs. length of cut data of wet rough turning for uncoated, AlTiN and CrN coated tools showing significant tool life improvement for CrN coated tool.

Progressive tool wear studies were conducted after every 600 m of cutting length using an SEM combined with 3D imaging by Alicona. The progression of tool wear for uncoated, AlTiN coated, and CrN coated tools is shown in Figures 3–5, respectively. Two tool wear phenomena were observed: intensive adhesive interaction at the tool/chip interface and crater wear. Both the 3D and SEM images of the uncoated and AlTiN coated tools showed significant BUE formation and propagation of crater wear as cutting progressed. Figures 6 and 7 show the formation of BUE and crater wear with respect to cutting length for uncoated, AlTiN coated, and CrN coated tools. Both the uncoated and the AlTiN coated tools show significant BUE formation compared to the CrN coated tool. The instability of the BUE formation is also evident by the strong fluctuation in peak volume compared with the previous passes (Figure 6). The lower BUE formation in the CrN coated tool decreased the possibility of tool edge chipping following its removal. The CrN coating also showed a reduction in the crater wear intensity and delay in the propagation of crater wear as machining progressed. Thus, lower BUE formation and delayed crater wear resulted in a much more uniform increase in tool wear, which, in turn, prevented rapid failure of the CrN coated tool. It is important to note here that the reduced crater wear values obtained for the uncoated tool (Figure 7) were due to the BUE covering the crater wear on the tool. This can be confirmed by the 3D and SEM images (Figure 3a,b and Figure 5a,b).

3.2. Coating Characterization

Detailed investigations were conducted to assess the mechanical properties and structure of the coatings. The SEM images of the fracture sections of the coatings are shown in Figure 8. Both the AlTiN and CrN are monolayer coatings with a cubic microstructure, with the thickness of the AlTiN coating being 1.94 μm and that of the CrN coating being 1.83 μm (Figure 8; Table 2). Figure 9 shows the XRD data for both AlTiN and CrN coatings. Three distinct diffraction peaks for the (111), (200), and (220) crystallographic planes were observed in both coatings. The intensity of the (200) peak was the highest in both the AlTiN

and CrN coatings, indicating that they have a preferred (200) orientation. The micromechanical properties and residual stress values of the coatings are shown in Table 2. It is evident that the CrN coating has a higher compressive residual stress, lower hardness, and higher plasticity index than the AlTiN coating. The plasticity index is given by the quotient of the plastic work and the total plastic and elastic work during indentation [31]. For the high tool load characteristic of titanium machining, a higher plasticity index indicates a coating's higher toughness and durability [32]. Toughness is a material's ability to resist crack propagation as well as its energy absorption during the deformation that leads to fracture [33]. The modified Palmqvist toughness test confirmed the higher toughness of the CrN coating (see Table 2). Since the substrates were the same in both cases, the differences in the toughness values were solely due to the composition of the coatings. As reported in the literature, higher compressive residual stress also helps prevent crack propagation in the coatings [34]. The fatigue fracture resistance properties of the coatings were evaluated using nanoimpact testing in relation to the final depth of the penetration during impact. The lower depth of the penetration in CrN indicates the superior performance of this coating under repeated loading, in addition to better fatigue resistance (Figure 10).

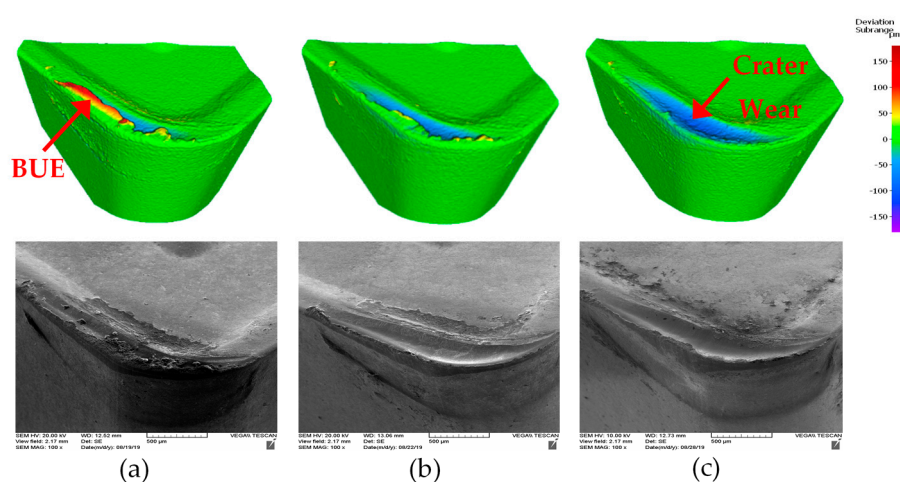


Figure 3. 3D progressive wear data for uncoated tool highlighting progression of built up layer and crater wear after different length of cut: (a) 600 m; (b) 1200 m; (c) 1800 m.

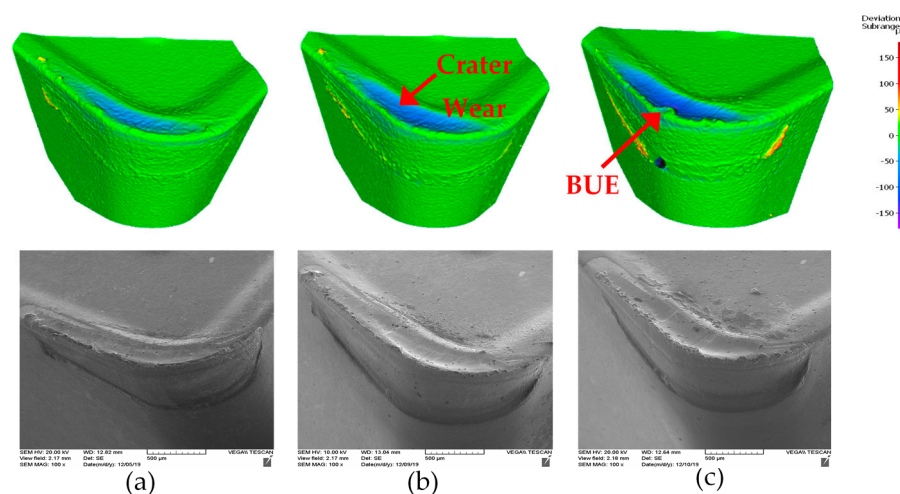


Figure 4. 3D progressive wear data for AlTiN coated tool highlighting progression of built up layer and crater wear after different length of cut: (a) 600 m; (b) 1200 m; (c) 1800 m.

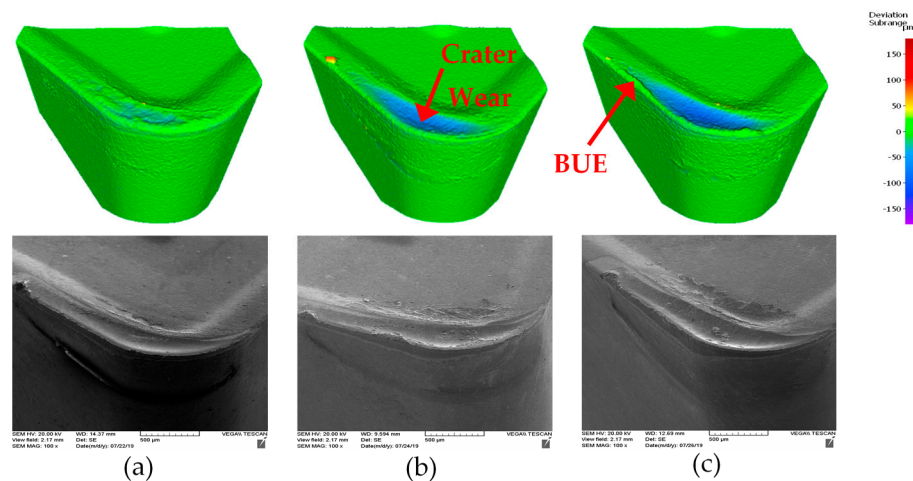


Figure 5. 3D progressive wear data for CrN coated tool highlighting progression of built up layer and crater wear after different length of cut: (a) 600 m; (b) 1200 m; (c) 1800 m.

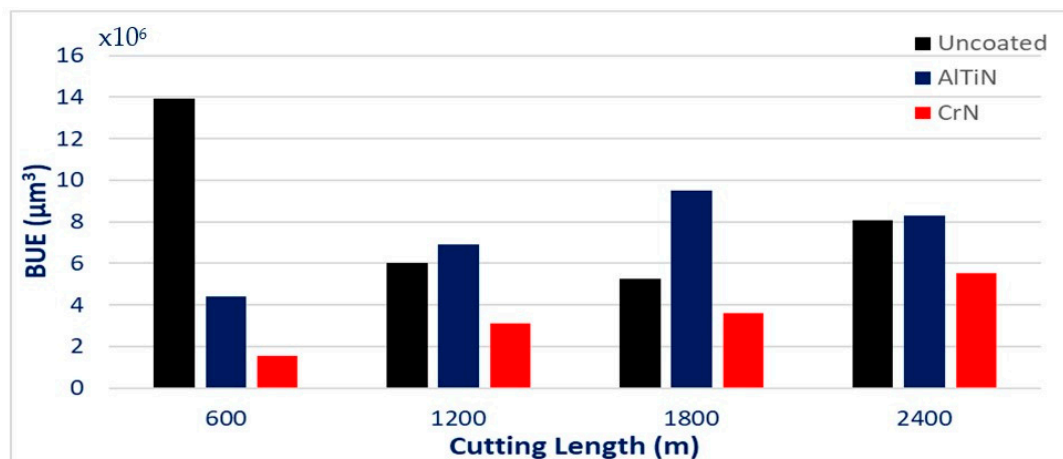


Figure 6. Built up volume progression vs. length of cut for uncoated, AlTiN and CrN coated tools considering the peaks above reference surface of the original tool.

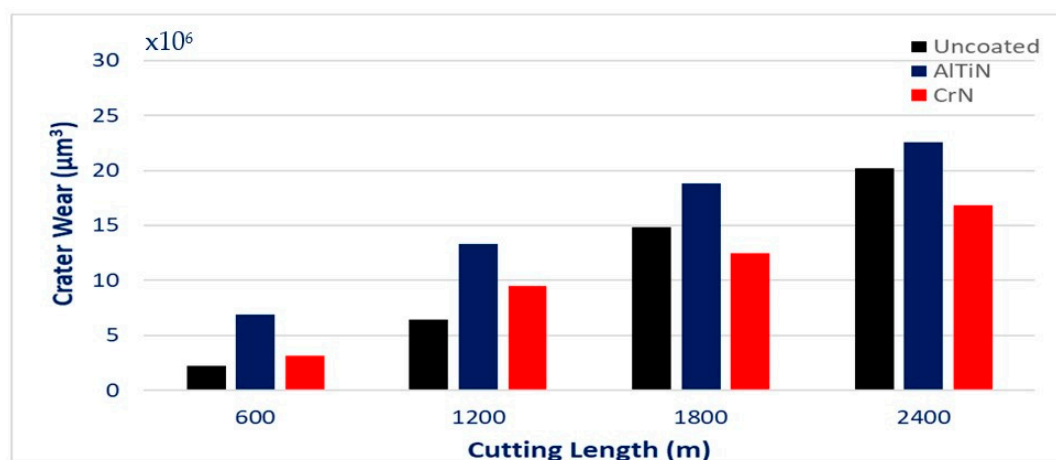


Figure 7. Crater wear volume progression vs. length of cut for uncoated, AlTiN and CrN coated tools considering the peaks below reference surface of the original tool.

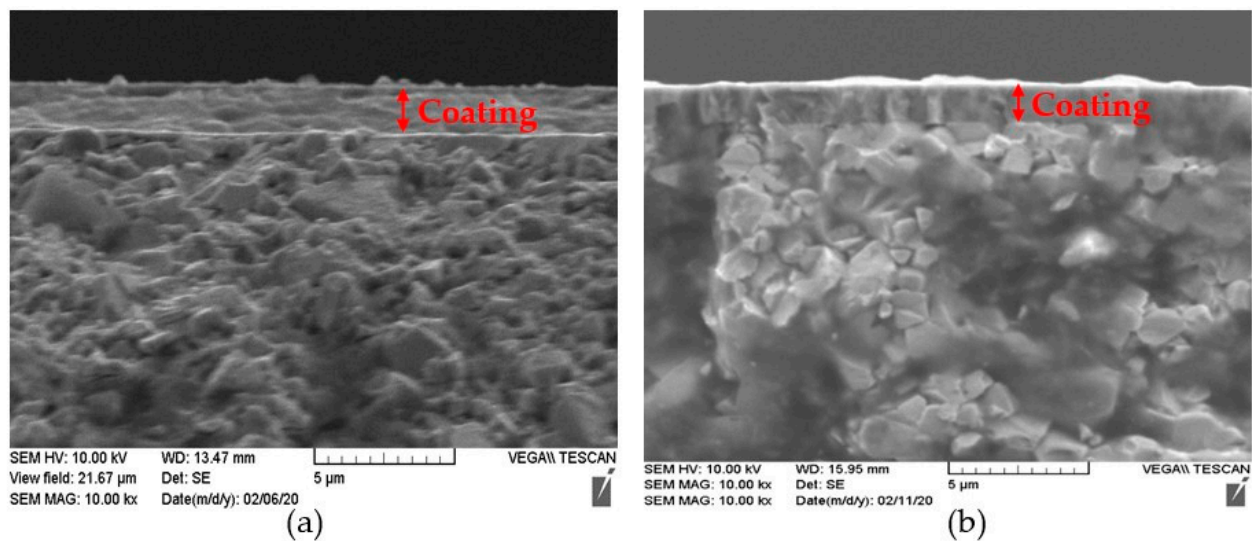


Figure 8. SEM images of fracture sections of the studied PVD coatings highlighting coating thickness: (a) AlTiN; (b) CrN.

Table 2. Micromechanical properties of AlTiN and CrN coatings.

Coating	Architecture	Properties							
		Thickness, μm	Hardness (H), GPa	Elastic Modulus (E), GPa	Plasticity Index	H/E Ratio	H^3/E^2 ratio	Residual Stresses, MPa	Modified Palmqvist Toughness, $\text{N}/\mu\text{m}$
AlTiN	Monolayer	1.94	28.9 ± 2.0	516.52	0.46	0.056	0.090	-599 ± 168	1.37
CrN	Monolayer	1.83	20.37 ± 2.5	591.87	0.66	0.034	0.024	-979 ± 81	1.51

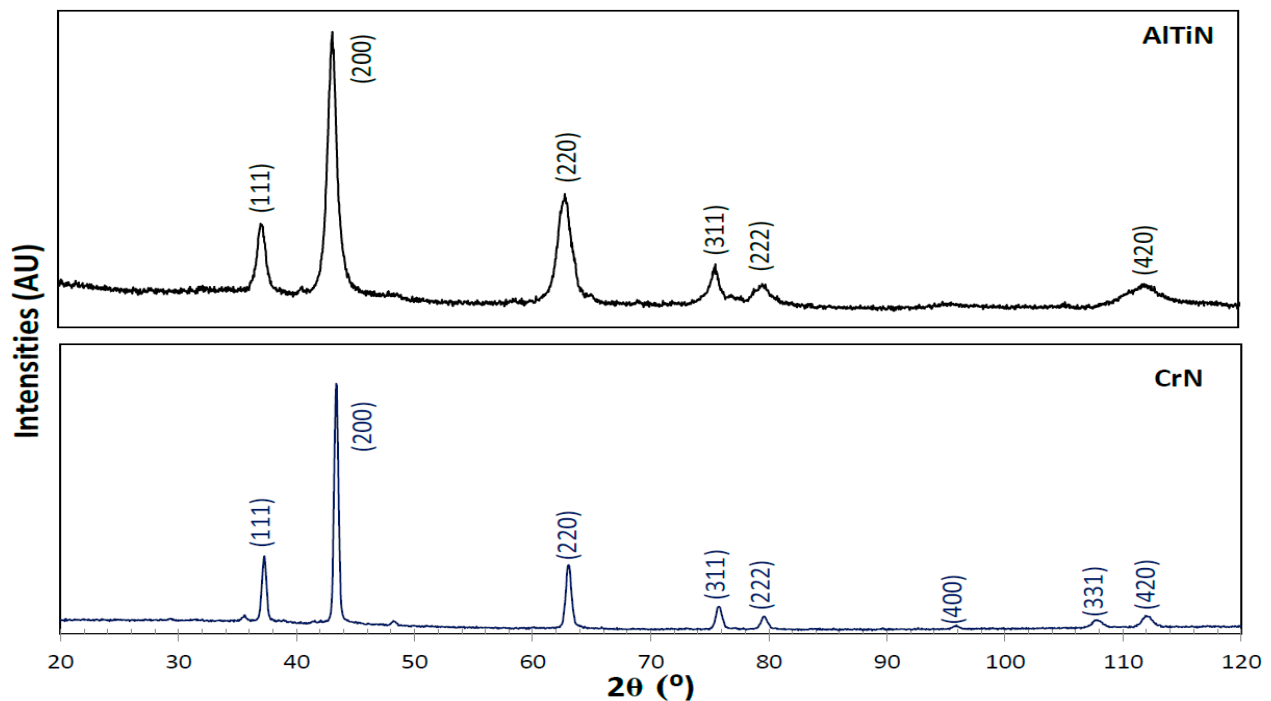


Figure 9. X-ray diffraction patterns of monolayered AlTiN and CrN coatings.

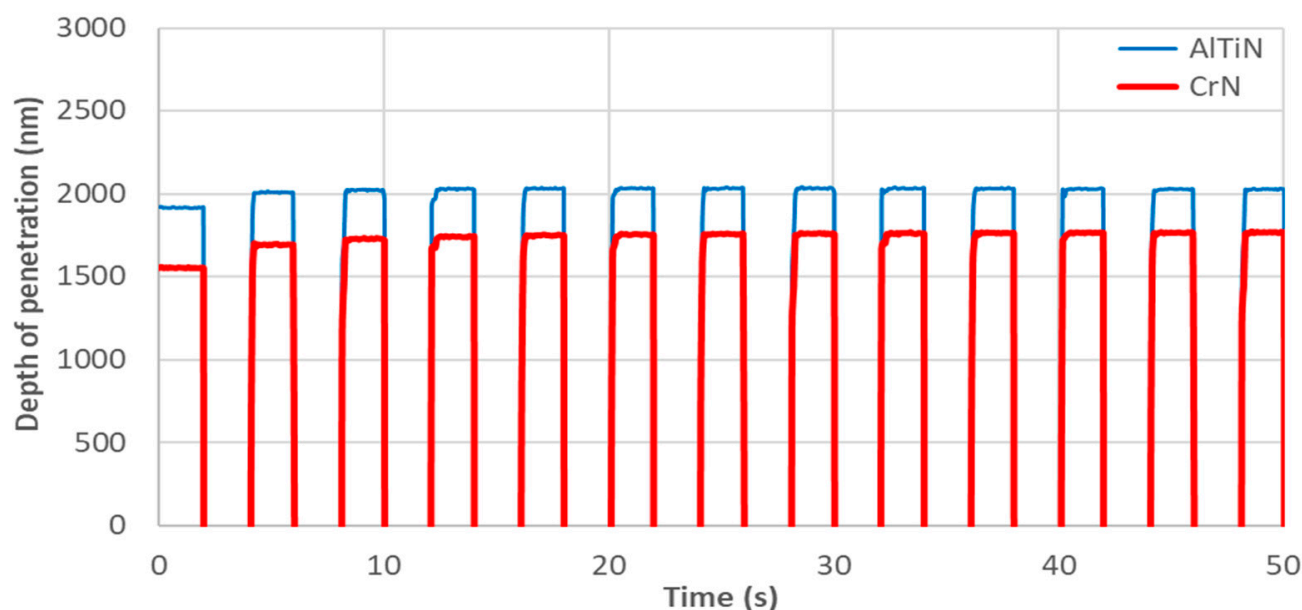


Figure 10. First 50 s depth of penetration obtained from nanoindent testing at a load of 20 mN for AlTiN and CrN coatings.

The AFM images of 3D surface morphologies of the AlTiN and CrN coatings are illustrated in Figure 11. The arithmetical mean height (S_a) values were obtained from a scan size of $25\ \mu\text{m} \times 25\ \mu\text{m}$. As shown, the overall surface roughness of the CrN coating was lower than that of AlTiN. The lower roughness of the CrN coating contributes to its superior frictional properties. Scratch tests were conducted to analyze the behavior of the coatings under progressive loads. Wear tests, which are basically multi-pass constant load scratch tests, were also performed at a subcritical load of 0.75 N with the objective of studying the gradual deformation of the coatings. These studies provided information about frictional and wear characteristics, microscopic plastic deformation performance, and microcracking behavior at the subsurface/surface interface [35]. Figure 12 shows how the coefficient of friction changes for the coatings after one pass, three passes and five passes during repetitive wear test. It shows that although each of the coatings initially have a similar coefficient of friction, it increases less drastically in the CrN coating with further wear test passes, which indicates the more gradual deformation of this coating. The scratch test results showed that the deformation mechanism under a heavily loaded sliding contact was considerably different for the AlTiN and CrN coatings. The scratch test results for AlTiN and CrN coatings are illustrated in Figures 13 and 14, respectively. The coefficient of friction data obtained during the scratch test demonstrated the ability of the coatings to resist scratching within the layers. The CrN coating had a lower coefficient of friction, which signifies its superior ability to withstand peeling during friction. The scratch track of the CrN coating showed that the failure was caused by the plastic flow, and the deformation was highly localized, with little substrate exposure outside of the scratch track. In comparison, brittle failure with widespread substrate exposure outside of the scratch track was observed for the AlTiN coating. The performance of the coatings in the scratch test can be described in terms of their hardness, H/E , H^3/E^2 ratios, and residual stress, as summarized in Table 2. The H/E and H^3/E^2 ratios were calculated from coating's hardness (H) and coating's elastic modulus (E) obtained from nanoindentation tests. The H/E ratio signifies the elastic strain to failure characteristics of a coating, and the H^3/E^2 ratio refers to a coating's ability to resist plastic deformation [36]. The H/E and H^3/E^2 ratios of the CrN coating were lower than those of the AlTiN coating. The elastic modulus of both coatings was very similar. The lower H/E and H^3/E^2 ratios of the CrN coating can be thus ascribed to its considerably lower hardness. This combination of properties suggests that CrN is less brittle. The soft CrN coating, combined with its overall lower compressive residual

stress, can thus undergo greater plastic deformation under the given load. For machining applications in which BUE formation is prominent, such qualities of the CrN coating are very important since they prevent coating delamination when BUE is removed during machining, providing better tool protection. Thus, the enhanced performance of the CrN coating can be related to its lower hardness and toughness characteristics. It was previously shown that a coating with a low H/E ratio delivers better wear resistance in machining applications that feature adhesive wear. Thus, the elastic strain to failure characteristic (H/E ratio) is critical for attaining better tool life under heavy loaded tooling applications where severe surface layer deformation occurs during friction [28,37]. However, such behavior must be evaluated in conjunction with the coating's plasticity index values (Table 2). For heavy loaded applications, the coatings must have an enhanced capability to dissipate the frictional energy generated by severe surface layer deformation. The greater the energy dissipation, the lower the amount of energy expended on the deformation and damage of the substrate material. A higher plasticity index indicates greater energy dissipation under loading. Thus, the high plasticity index CrN coating exhibited better performance than the AlTiN coating. The plasticity index and the H/E parameter both have similar ramifications [4,38]. These parameters could be applied to assess the wear performance of a heavily loaded tribo-system under the severe adhesive wear conditions typical of titanium machining. Therefore, the CrN coated tool, which had a higher plasticity index and toughness combined with a lower hardness and H/E ratio, demonstrated superior tool wear performance and longer tool life.

3.3. Assessment of Tribological Performance

It is evident from Figures 3–5 that the BUE resulting from titanium adhesion and crater wear intensity is significantly reduced in the CrN coated tool compared with the uncoated and AlTiN coated tools. This wear behavior and subsequent tool life improvement could be attributed to the micromechanical (Section 3.2) and tribological characteristics of the CrN coating, which include lower hardness, H/E and H^3/E^2 ratios, and higher plasticity index compared to the AlTiN coating (Table 2). A lower H^3/E^2 ratio and hardness indicate the low brittleness of CrN, which also has a higher toughness. The scratch test revealed that the CrN coating failed due to localized plastic flow deformation and had a lower sliding contact friction. Such a combination of micromechanical properties provides the softer and tougher CrN coating with an enhanced capability to withstand intensive sticking without delamination, and improved tribological characteristics under heavy loaded tooling applications.

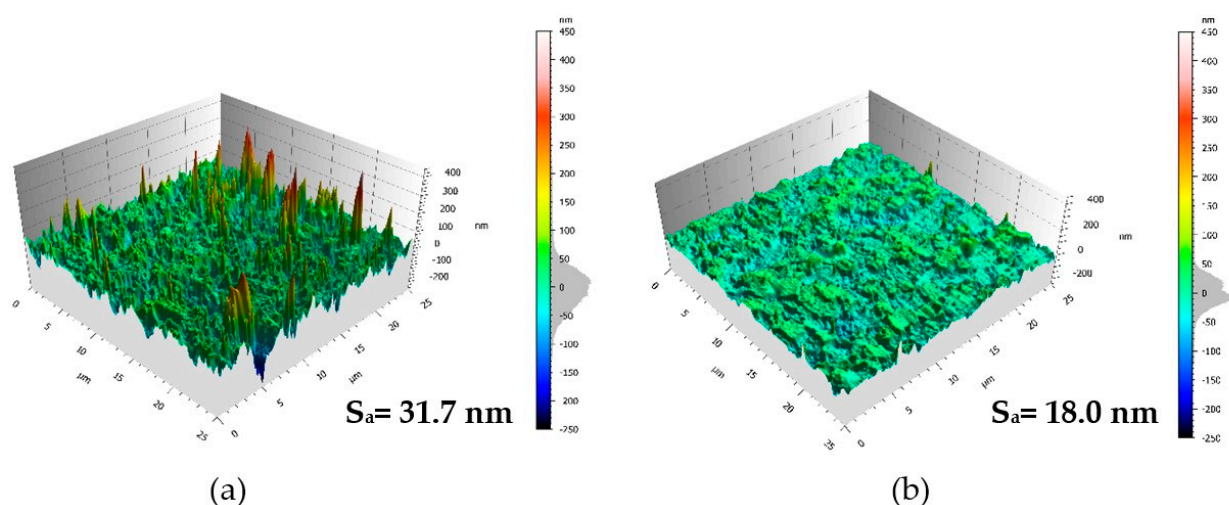


Figure 11. Atomic force microscope (AFM) images of surface topography of the coatings with arithmetic mean height (S_a) values: (a) AlTiN; (b) CrN.

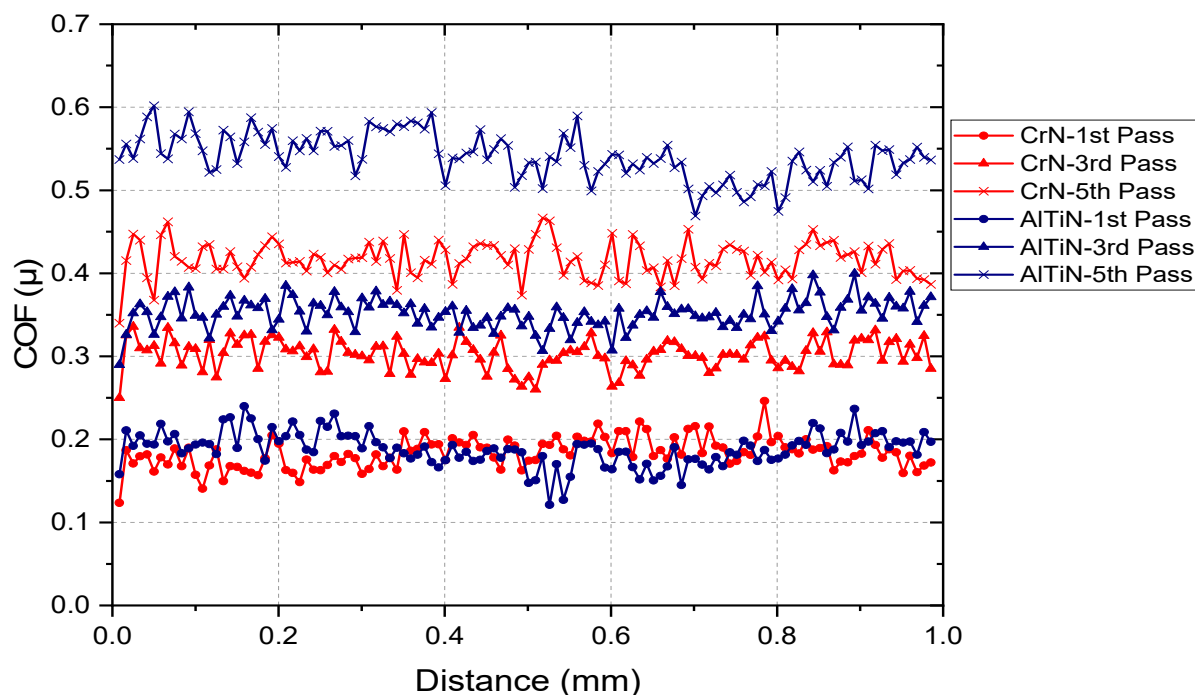


Figure 12. Evolution of coefficient of friction at different passes during repetitive wear test at 0.75 N for AlTiN and CrN coatings.

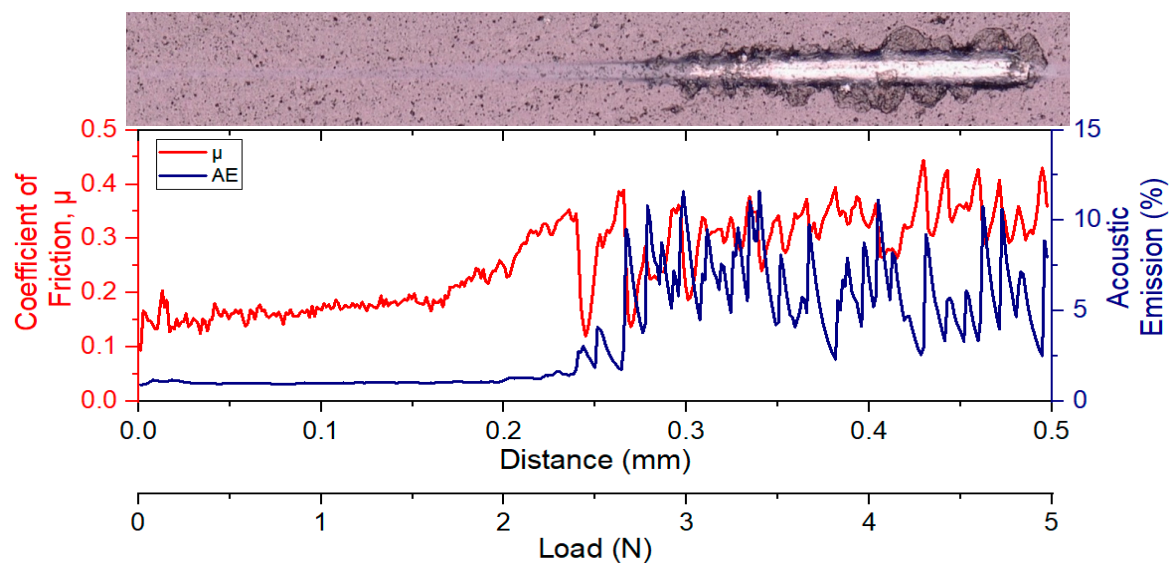


Figure 13. Optical images of the ramped load scratch test track with coefficient of friction and acoustic emission data for the AlTiN coating.

The tribological performance of the coatings, discussed in the following paragraphs, was evaluated through: (1) an analysis of tribo-film formation at the tool–chip interface during machining; (2) an evaluation of the coefficient of friction of the coatings with respect to temperature; and (3) an assessment of the chip characteristics (Table 3). All analyses confirmed that the CrN coated tool provided better tribological performance.

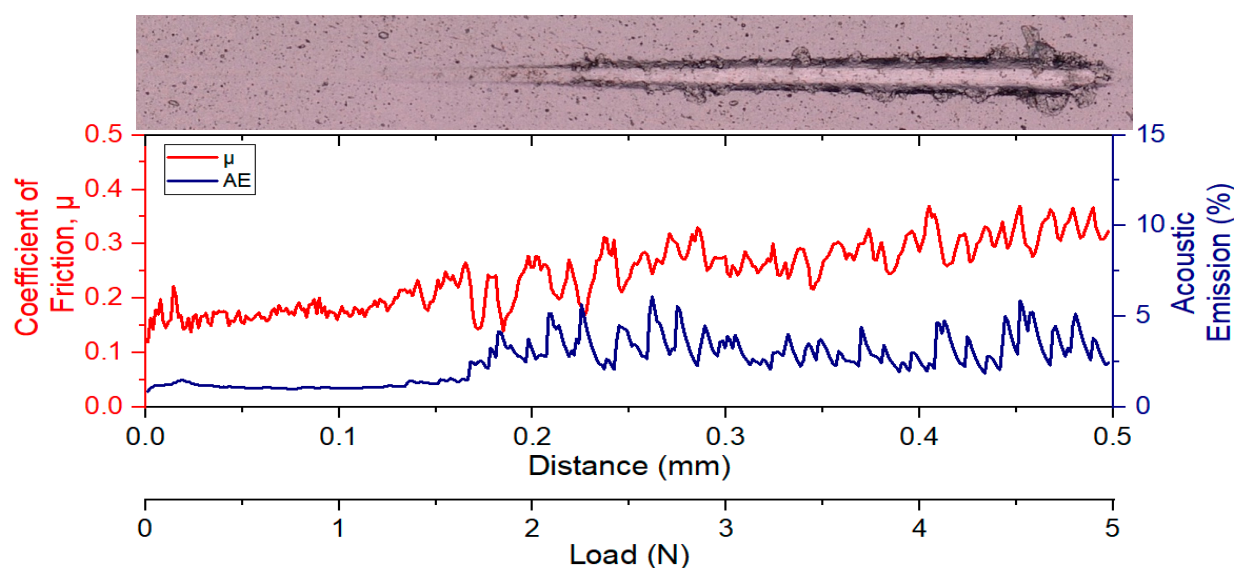


Figure 14. Optical images of the ramped load scratch test track with coefficient of friction and acoustic emission data for the CrN coating.

The tribological performance of the coatings, discussed in the following paragraphs, was evaluated through: (1) an analysis of tribo-film formation at the tool–chip interface during machining; (2) an evaluation of the coefficient of friction of the coatings with respect to temperature; and (3) an assessment of the chip characteristics (Table 3). All analyses confirmed that the CrN coated tool provided better tribological performance.

Table 3. Tribological performance evaluation through chip characteristics for AlTiN and CrN coatings.

Coating	Chip Compression Ratio—CCR	Φ —Shear Angle ($^{\circ}$)	(γ) Shear Strain	Chip Sliding Velocity (m/min)
AlTiN	1.11	51.90	0.56	50.0
CrN	1.36	58.23	0.39	61.1

The tribological performance of a coating is strongly dependent on its self-adaptive behavior. This is directly related to the coating’s ability to form beneficial tribo-oxides at the tool–chip interface during cutting [14]. Tribo-films influence tool wear behavior in two ways: by providing in situ lubrication that reduces the intensity of BUE formation and by serving as a thermal barrier on account of the low thermal conductivity of the generated tribo-oxides [14]. Figure 15 shows the coefficient of friction versus temperature data for the uncoated, AlTiN coated, and CrN coated tools. The instrument used to determine this correlation mimics the adhesive interaction present during cutting under a heavy load. The coefficient of friction values for the CrN coating were considerably lower than both the uncoated and the AlTiN coated tool, especially at temperatures between 550–700 $^{\circ}$ C, which are typical for the outlined machining conditions [10]. Such superior tribological performance from the CrN coating can be attributed to its ability to form lubricious and thermal barrier tribo-oxides during cutting. The XPS analysis on the worn tool confirmed tribo-film formation, as evident in Figure 16. The obtained data reveal that the CrN coating underwent tribo-oxidation and formed a Cr_2O_3 tribo-ceramic layer on the surface of the tool. These tribo-layers have a corundum structure [39] and provide lubricating characteristics [40] and enhanced thermal barrier properties at high cutting temperatures [41]. Cr_2O_3 tribo-films thus decrease friction at the tool–chip interface, thereby significantly reducing BUE formation as well as crater wear intensity during the machining of a Ti6Al4V alloy.

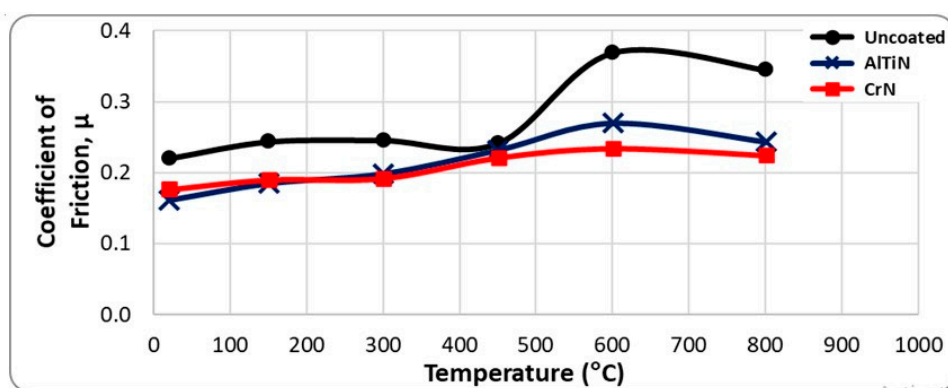


Figure 15. Coefficient of friction vs. temperature data for uncoated, AlTiN and CrN coated tools obtained from high temperature/heavy load tribometer.

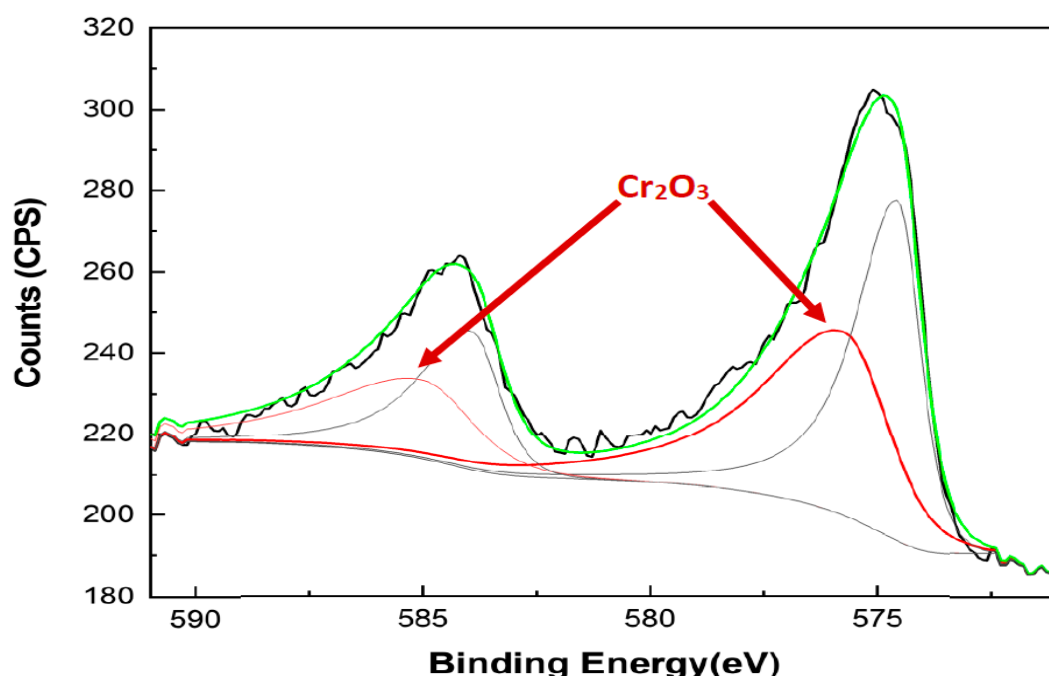


Figure 16. High resolution XPS data (Cr 2p spectrum) of worn rake surface of CrN coated insert confirming formation of Cr_2O_3 tribo-oxides.

Tribological interactions occurring at the tool–chip interface play a considerable role in forming the chips. The characteristics of the chips collected after approximately 50 m of machining length were evaluated, and the results are summarized in Table 3. The tribological characteristics of the AlTiN and CrN coatings compliment the coefficient of friction data shown in Figure 15. The chip compression ratio and shear plane angle were greater for the CrN coating. This indicates that a low shearing force acted on the chips produced by the CrN coated tool, which resulted in reduced cutting and frictional forces at the tool–chip interface. The chip sliding velocity was also lower in the CrN coated tool, which reduced the tool–chip contact length and friction at the tool–chip interface. This consequently impeded temperature rises at the cutting zone. The analysis of the coated tool’s chip characteristics thereby confirms that the reduction of friction at the tool–chip interface leads to increased tool life in the CrN coated tool.

In order to analyze the chip flow process, a cross sectional EBSD analysis was performed on chips collected during machining. Figure 17 shows the texture orientation maps and microstructure of the chips. The images demonstrate that the main deformed zone was largely close to the edge of the chip–tool interface, and both chips depict grain refinement in this region. However, the chips produced by the CrN coated tool showed the formation of ultrafine grains along the shear boundaries. This confirms the superior chip flow process in the CrN coated tool. The accelerated chip flow process also resulted in dynamic recrystallization of the grains with new grain orientation taking place as observed in the orientation maps. This may have increased slip planes and, consequently, enhanced chip plasticity.

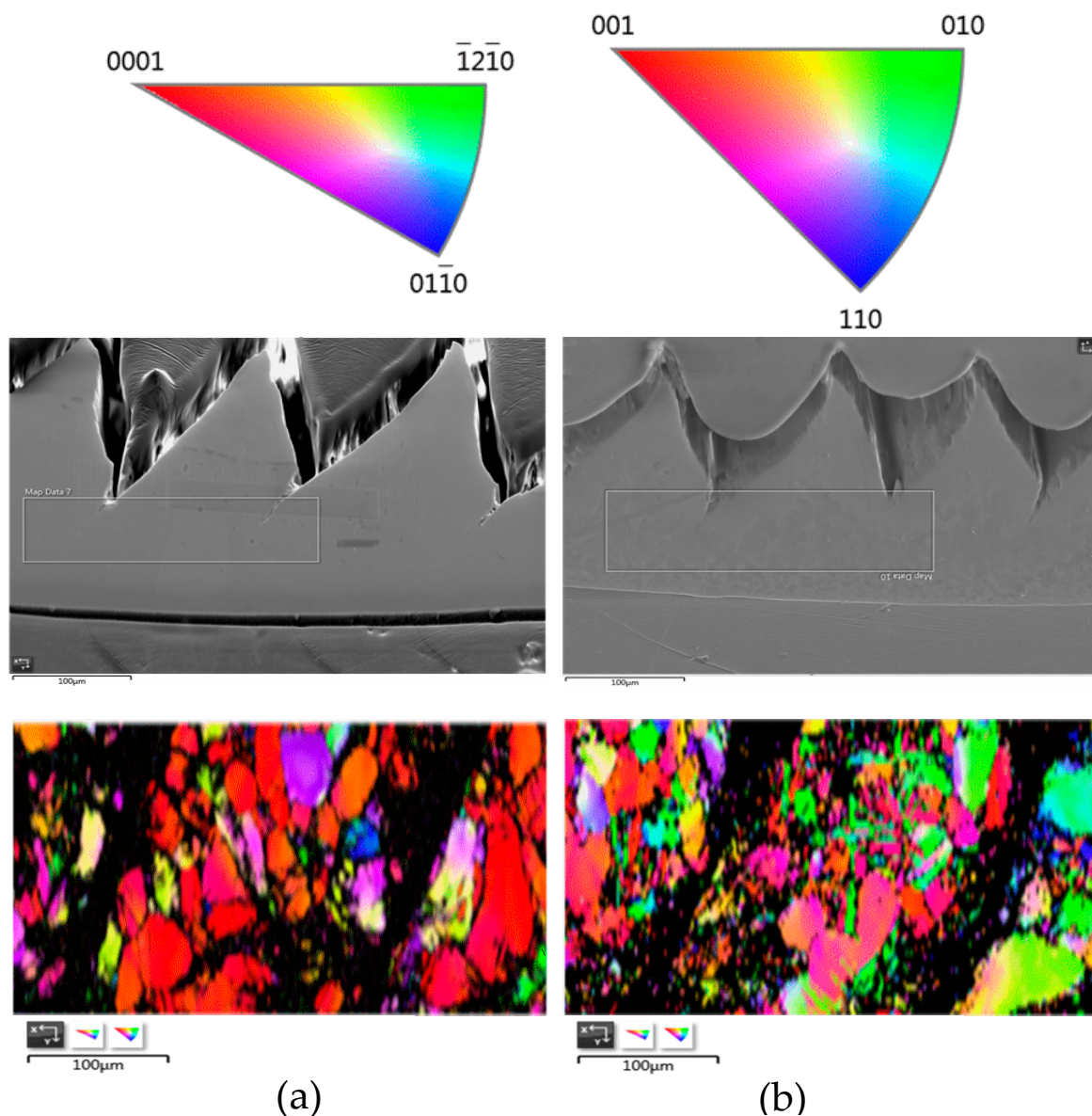


Figure 17. EBSD orientation, chip cross sections and phase map of chip cross sections: (a) AlTiN; (b) CrN.

4. Conclusions

Intense BUE formation occurs during the rough turning operation of a Ti6Al4V aerospace alloy. This phenomenon, combined with the high cutting temperatures generated during machining, results in rapid tool wear. An effective strategy for minimizing tool wear is the application of self-adaptive PVD coatings that generate lubricious and protective tribo-layers to counteract the underlying wear mechanisms. A monolayer SFC PVD CrN coating was demonstrated in the current research, which significantly improved tool life during Ti6Al4V machining as compared to commercial AlTiN coating. A CrN coating is capable of inhibiting the intensive detachment of the coating layer due to its unique combination of micromechanical and tribological characteristics. In addition, the coating generates Cr₂O₃ tribo-films during machining, which possess thermal barrier and lubricating characteristics. The developed CrN coating can impede the tool wear mechanism (cratering and adhesive interaction with the workpiece), thereby significantly prolonging tool life. The beneficial micromechanical and tribological properties, in conjunction with the adaptive behavior of the developed CrN coating, were demonstrated to have delivered superior performance under the outlined machining conditions for a Ti6Al4V alloy.

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