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REGULAR PAPER

Machinability Performance of Single Coated and Multicoated Carbide Tools During Turning Ti6Al4V Alloy

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Abstract

This paper presents the machinability performance of uncoated, single-coated, and multicoated carbide tools during turning of Grade 5 (Ti6Al4V) Titanium alloy, which is challenging to machine due to its distinctive material properties. Coated tools with single-coated Titanium Aluminium Nitride (TiAlN) and multi-coated layer of Titanium Aluminium Nitride with Aluminium Chromium Nitride (TiAlN + AlCrN) coated inserts were utilized to assess surface roughness (Ra), tool wear rate (R), and chip morphologies under various cutting conditions using dry machining. Analysis of the used tools revealed that coated tools exhibited improved tool life and surface quality compared to uncoated tools across all cutting conditions. Multi-coated tools of TiAlN + AlCrN demonstrated a tool life increase of up to 15% compared to uncoated and single-coated tools, with surface roughness improvements ranging from 30 to 45% depending on cutting speed. Chip morphology analysis indicated an increase in the chip reduction coefficient with higher cutting speeds for all tool types. Coated tools exhibited the lowest chip-reduction coefficient due to the presence of TiAlN and AlCrN coatings, which control the tool chip contact length. Conversely, uncoated chip morphology resulted in larger chip thickness values compared to coated tools, particularly at cutting speeds above 100 m/min, attributed to poor heat dissipation and chemical reactions at the tool chip interface. Energy dispersive X-ray scanning electron microscopy (SEM/EDXS) analysis of worn uncoated inserts revealed a higher tendency towards Titanium adhesion compared to coated tools. The proposed multi-layer coatings of (TiAlN + AlCrN) used for dry machining proved highly beneficial for achieving economic machining objectives and may reduce the need for lubrication when processing Ti6Al4V alloys.

Keywords Ti-6Al-4 V · Tool coatings · Chip morphology · Surface roughness · Tool wear · TiAlN · TiAlN + AlCrN

Abbreviations

TiAlN	Titanium Aluminium Nitride
AlCrN	Aluminium Chromium Nitride
Ti	Titanium
Al	Aluminum
Ti6Al4V	Grade 5 Titanium Alloy
SEM/EDXS	Energy dispersive X-ray scanning electron microscopy
Ra (μm)	Surface roughness
R	Wear rate
V_c (m/min)	Cutting speed

Ahsen Ali and Muhammad Younas have contributed equally to this work.

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HRB	Brinell hardness
F (mm/rev)	Feed rate
a_p (mm)	Depth of cut
Φ	Shear angle
Gs	Segmentation ratio or degree of segmentation
t_c (mm)	Chip thickness
f_{cs} (Hz)	Chip segmentation frequency
R	Chip thickness ratio
r'	Chip compression ratio (1/r)
VB (μm)	Flank wear
BUE (μm)	Bulit up edge

1 Introduction

Titanium is essentially the ninth most common element in the earth's crust (0.63% by mass) [1]. One of the most important mechanical properties of titanium alloys is their high strength-to-weight ratio. Titanium when compared to aluminum and steel, it is found 60% denser than aluminum and 45% lighter than steel [2, 3]. Pure titanium also shows good strength at all temperatures but at the same time, pure titanium is quite expensive too. In addition to its lightweight properties, titanium has high corrosion and high-temperature resistance [4]. The comparison of yield strength of different materials with Ti6Al4V alloy is shown in Table 1, that shows higher yield strength of Ti6Al4V alloy comparative to other material at all temperatures.

Titanium alloy presents poor machinability and reduces the tool life relative to other materials, especially when machining at high speed. During the cutting process, a significant degree of generating heat in the shear region decreases the performance of the cutting insert. A variety of cutting materials is being used to investigate the performance of carbide inserts using dry machining [5], thus, tool deterioration should be controlled to minimize the cost of production and consequently increases tool life.

Cutting speed and tool wear has a great impact on surface roughness, chip morphology and chip geometry. Chip formation affects the wear progression due to the combined effect of chip and tool, thereby generating crater and flank wear [6]. The poor machinability of titanium and its aerospace alloys is due to the low thermal conductivity, high reactivity, low elastic modulus, and high hardness of these alloys. The unique combination of physical and mechanical properties of titanium-based alloys has been widely reported to influence numerous machining responses such as surface roughness [7], tool life [8], energy consumption [9, 10] and vibration of the machine tool [11]. Therefore, the investigation into the study of tool wear, surface roughness, and chip formation during the machining process is of prime interest to researchers and industries.

Table 1 Properties of different materials [5, 38]

Material	Thermal conductivity W m^{-1} K	Specific heat capacity J kg^{-1} C	Tensile strength M Pa
Aluminum 7075-O	173	960	96.5
AISI 4340 Steel	44.5	475	786
Ti6Al4V	6.7	526.3	1100
WC–Co (6–10%)	60–80	200–400	1440

High Speed Machining (HSM) is effective for producing high-quality surfaces and has the advantages of reduced thermal impacts on the machined parts. A large amount of the radiating heat is carried away by the cutting chips and partly by the tool. HSM is mostly preferred and usually applied in the aeronautics department, automotive and the manufacturing industries such as machine devices, gear, and tooling utilized in the making of household apparatuses, optics, and so forth [5, 12]. Dry machining has also attracted remarkable interest amongst researchers and machining industries to create a clean and healthy environment [13]. Therefore, dry machining is preferred for a wide range of advantages, including no atmosphere pollution, significant cost reduction, chips can be sold out, cost-effective, and old machines can be modified [14]. Coated tools assist dry machining because coating helps to reduce friction and minimize the cause of heat generation at the tool-workpiece interface [15]. Dry machining being the cleanest approach was employed in the current work. In recent years, there has been an increasing awareness of health and environmental issues, leading to the implementation of new legislations and stricter rules to achieve cleaner production and minimize harmful effects. Moreover, it also helped in eliminating tool wear due to temperature variations that might be encountered while using a coolant [5]. This will help to achieve stable high temperatures of tools to attain long tool life. Some materials like aluminum work best in dry machining as these materials have a tendency to weld coolant with the tool. This reduces the problem of built-up chips on the tools and workpiece that helps clean machining. The adverse impact of coolants or fluids on the environment as well as on the cost is taken into consideration.

Surface roughness is also one of the crucial economic factors for the enhancement of the tool life while machining. It is affected by several factors that include the type of material being machined, cutting parameters (cutting speed, feed rate, and depth of cut), cutting environment (dry, wet, cryogenic) and the tool geometry used during machining [16, 17]. The critical parameters that affect integrity and roughness, were the feed and cutting speed, whereas the influence of depth of cut is negligible. The best-finished surface could be achieved with high cutting speed and low feed rate. Zain et al. [18]

analyzed the impact of cutting speed, feed and tool radial rake angle on surface roughness. It was observed that minimum surface roughness is obtained using maximum rake angle, a minimum rate of feed, and maximum spindle speed. Ramesh et al. [19] performed different experiments thereby concluded that the predominant aspect influencing surface roughness is cutting feed. Sambo et al. [20] computed the parameters that affect cutting forces in additively manufactured titanium alloy were the cutting speed and feed. Studies [5, 21] have also determined major problems with methods controlling tool failure during titanium machining. Significant factors which particularly increase surface roughness are the type of material and tool used, selected machining parameters, tool nose radius, length and diameters of the selected material, chip morphology and geometry, fluctuations in the cutting forces, material hardness including generated heat at tool-chip region.

Regarding the selection of tool material, lower grade of cobalt and fine-grained carbide results in maximum tool life, however, sharp cutting edges were reported to be more fragile in comparison to honed cutting edges. Ceramic inserts were also not suitable for single point turning of titanium alloys [22]. Thus, the application of carbide inserts is recommended as they are less sensitive towards these conditions and perform better than other insert materials. Tungsten carbide H13 grade inserts were reported to perform better than others but still, their performance is limited. Carbide inserts provide better performance with coatings [23], thus authors recommended a combination of insert material and coating to improve high speed machining of Ti-6Al-4 V. Application of coating for protecting the surface of the tool is a widely used solution by manufacturers.

About 80% of the cutting tools currently utilize hard coatings which are used in manufacturing industries to achieve high productivity and precision [24]. These hard coatings have attractive properties, such as good thermal stability and high wear resistance. TiAlN, AlCrN, and a combination of this synthesized by the physical vapor deposition (PVD) process exhibit improved mechanical properties which include improved oxidation resistance and greater wear resistance [25]. When using these materials in tool coatings, the required mechanical properties of substrate material, including hardness, strength and elastic modulus, must be observed to increase the life of the cutting tool under extreme processing conditions [26]. The wear rate of AlTiN was also revealed to be higher around 45×10^{-7} mm^3/Nm than TiAlN as about 2×10^{-7} mm^3/Nm. While TiAlN showed the least wear rate [27] that makes TiAlN a desirable coating for titanium alloys machining. In the past, wear maps have been introduced for selecting the cutting conditions and identifying wear regions that give the best wear performance of the tool [28–30]. The multi-coatings on tools perform better at a larger depth of cut, feed rate as well as cutting speed. In this regard, the selection of another suitable tool coating is required to investigate the effect of multi-coatings on the turning of titanium alloys.

Chips morphology and characterization is another distinctive phenomenon to analyze the chip geometry. Calamaz et al. [31] described that the selection of processing parameters and surface roughness influences more on the geometry of the chips during machining. Mainly, chips are classified as continuous, discontinuous, continuous with build-up edge chips and segmented or serrated chips. Segmented chips also known as non-homogeneous chips, exhibits low thermal conductivity, strength metallic behavior and different shear strains and primary, secondary shear zones [32].

When machining Ti6Al4V alloy, the heat accumulation and adiabatic shearing results in sawtooth-like behavior with semi-conductive or segmented chips [33]. Also, chip adhesion greatly affects the tool sharpness, thus results in more tool deterioration. Due to high heat generation, a spark is produced and welds the chip pieces on the tooltip, resulting in a BUE on the tool-chip interface. It has been found that best finished surface and improved chip thickness are achieved by decreasing the rate of feed and increasing the spindle speed [17–19]**.** Geometrical analysis of chips reveals fundamental information related to energy consumption, tool life, surface finish, chip geometry variation and residual stresses. A significant number of studies addresses the major cause for various geometric parameters and their adaptability which includes segment ratio, equivalent deformed chip thickness, segmental width, shear angle, coefficient of chip contraction, chip segment frequency [12, 34–36]. This research aimed to investigate the behavior of surface roughness, chip formation and tool wear with cutting feed of 0.16 mm and speed ranging from 50 to 150 mm selected from the tool wear map [29]. The focused region is well-suited to analyze high and moderate tool wear region. Studying the tool wear mechanism in these regions would be beneficial in understanding tool and workpiece interaction which contributes to the formation of uncoated, single-coated and multi-coated tools appropriate for machining titanium alloys. Conducting an in-depth comparison of single-coated and multi-coated tools. This includes optimizing each type's cutting parameters to achieve superior surface quality or extended tool life, offering a unique perspective on tool selection and optimization.

2 Research Motivation

Machining of titanium alloys results in less tool life and poor machinability relative to other materials. During the cutting process, a huge amount of heat is generated at the shear zone that affects the tool performance. Many researchers have reported studies related to tool wear and concluded that the machinability is reduced at high speeds due to the adhesion of material at the tooltip. This leads to a high tool wear and machining cost while reducing the quality of the finished surface. The study of the behavior of different tool coatings is required to investigate the machining of titanium alloy and minimize production cost. Tool wear analysis and surface finish with regard to the performance of multi-coating will not only help to improve the quality of the products but also reduces machining costs.

The objective of this research is to investigate the surface roughness, tool wear and chip morphologies under various cutting conditions with respect to different cutting speeds using a dry machining approach. Thus, the current work is targeted to address the challenges that are present during the machining of titanium alloys that include high tool wear, low tool life and poor surface finish. To overcome these challenges, tool coatings were proposed and applied in the current research that remained helpful to reduce the surface roughness, tool wear and achieve the goal of sustainable manufacturing. Three types of inserts, uncoated, single coated Titanium Aluminium Nitride (TiAlN) and multi-coated Titanium Aluminium Nitride with Aluminium Chromium Nitride (TiAlN + AlCrN) were used and analyzed.

3 Material and Methods

3.1 Material Properties

Ti-6Al-4 V alloy grade 5 workpiece was used to perform experiments. The chemical composition of Ti-6Al-4 V given in Table 2. It was tested on the Optical Emission Spectrometer (Portable XRF XL3t GOLD + Carbon Analyzer Spectrophotometer) in order to find the material chemical and elemental composition. Portable XRF analyzer is significant in getting the results accurately and quickly, unlike other analyzers which necessitates the transportation of samples to the lab that may cause delay in results. Additionally, it offers both qualitative and quantitative evaluation of material composition.

The Brinell Hardening test was performed to check the indentation of the material. The Hardness of the workpiece was found to be 105 HRB. Cutting was performed on YIDA CNC machine and the experimental configuration for turning operation is shown in Fig. 1.

In the light of the above literature review regarding tool coatings, the first batch cutting inserts were coated with a single coating of TiAlN and in the second batch,

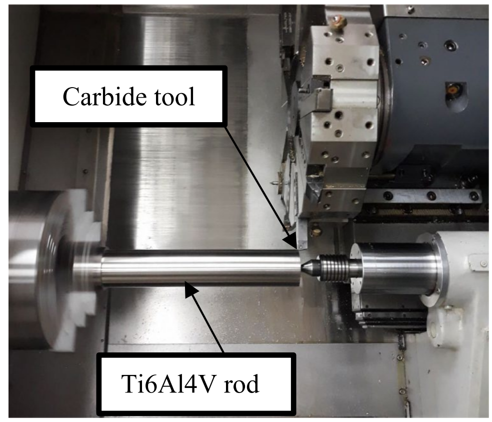


Fig. 1 Operational setup for dry turning

multi-coating of TiAlN and AlCrN were used to conduct experiments. For comparison, experiments were also performed with uncoated inserts to analyze the effect of these coatings. Coating thickness was taken to be 1.5 microns as suggested by literature review [37]. Three different levels of experiments were conducted using uncoated, single coated (TiAlN) and multi-coated (TiAlN + AlCrN).

Following the previous research on Ti6Al4V alloy [9, 28–30, 38], machining was done under dry conditions for cleaner machining goals. Cutting speeds were varied from 50 m/min to 150 m/min. whereas, feed rate and depth were kept constant i.e., 0.16 mm/rev and 1 mm, respectively.

4 Cutting Tool Details

H13 cutting inserts were used for single point turning of titanium alloy, tool details shown in Fig. 2. Dry machining tests were compared using uncoated, single-coated, and multi-coated inserts. A fresh insert was used for each experiment with all inserts supplied by SANDVIK and used on the same stock material as recommended by past researches [39]. The different types of tools used were 1) coating consists of a single layer of Titanium Aluminum Nitride Coating (TiAlN); 2) multilayer Titanium Aluminum Nitride and Chromium Aluminum Nitride (TiAlN + CrAlN) coating; and 3) uncoated as purchased tools. In multi-layer coating, TiAlN was deposited on the inner side while CrAlN was placed on the other side because of thermal conductivity [30].

Table 2 Chemical composition of Ti-6Al-4 V

Element	Fe	V	Al	O	C	N	Ti
Calculated %	0.2	4.3	5.7	0.16	0.07	0.045	89.81

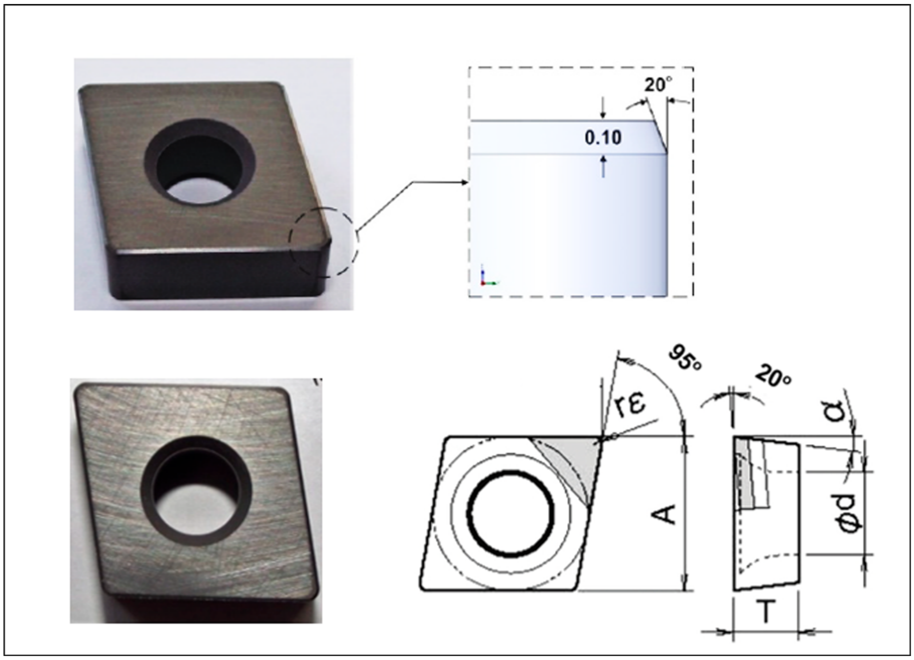


Fig. 2 Tungsten carbide turning insert (CCMW09T304H13) geometry (with the insert length (A) = 9.525 mm, nose radius (rε) = 0.4 mm, entering angle = 95^0, chamfer angle = 10^0, clearance angle (α) = 7^0, insert thickness (T) = 3.97, Ød = 4.2 mm.)

Table 3 Cutting parameters selected for experimentation

Cutting Speed (m/min)	50, 55, 60, 62.5, 65, 70, 100, 130, 150
Tool type	Uncoated H13 TiAlN coated TiAlN + CrAlN coated
Cutting feed (mm/rev)	0.16
Depth of cut (mm)	1
Length of Cut (mm)	100

5 Details of Experiments

A total of 27 experiments were performed on a 3 axis CNC machine details shown in Table 3. Nine different speed levels were selected for three type of tools i.e. uncoated, single-coated, and multicoated tools. A constant fed rate of 0.16 mm/rev and depth of cut of 1 mm was used for all tests. The cutting speed conditions were selected from literature as reported to have high tool wear for turning Ti6Al4V alloys [30]. The reason for selecting these specific conditions is that they fall under the low, moderate, and high tool wear regions corresponding to cutting speeds between 50 m/min and 150 m/min. The machining performance of uncoated and coated tools will be analyzed at this moderate feed rate for low, moderate and high tool wear conditions and compared for selection of the suitable coating.

Surface roughness after each cut was analyzed using a portable surface roughness meter. Three readings were taken after each experimental run to measure the average value of surface roughness (Ra_{avg}) for each of the uncoated, single-coated, and multi-coated tools.

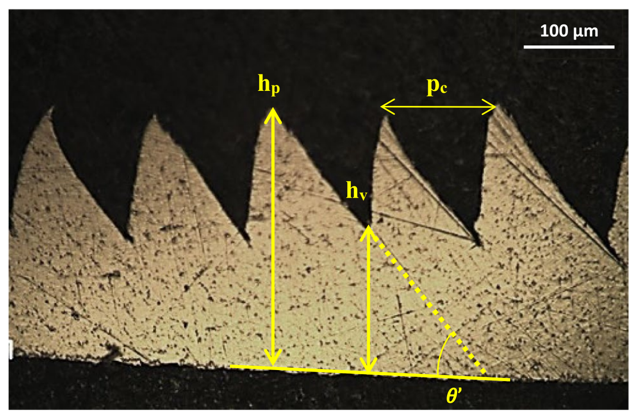


Fig. 3 Geometrical structure and parameters of the chip (h_p is the height of the peak, h_v is the height of valley, θ' is the complementary angle and p_c denotes tooth pitch, respectively)

For analyzing the morphology of chips, the chips after each cut were collected for grinding and polishing to reveals chips cross-section and geometry and for microscopic analysis to obtain the chip parameters. Optical microscopy was performed for analyzing the chip geometry, chip morphology and chip mechanism. Figure 3 indicates microscopic chips image highlighting deformed chip thickness, chip segmentation, saw-tooth peaks, continuous and separated portions.

During the machining, chips are formed due to workpiece plastic deformation. The shear angle formed along the side of the shear plane can be mathematically expressed by Eq. 1 [35, 40].

$$\Phi = \frac{\pi}{2} - \theta\prime \quad (1)$$

whereas, segmentation ratio or degree of segmentation (Gs), Chip segmentation frequency (f_{cs}), Chip thickness (tc), Chip thickness ratio (r), Chip compression ratio (1/r), can be calculated using Eq. 2 – Eq. 6 [36, 40];

$$Gs = \frac{hp - hv}{hp} \quad (2)$$

$$Fcs = \frac{Vc}{60 * Pc} \quad (3)$$

$$tc = hv + \frac{hp - hv}{2} \quad (4)$$

$$r = \frac{to}{tc} \quad (5)$$

$$r\prime = \frac{1}{r} \quad (6)$$

Wear measurement was done by using an Optical microscope OPTIKA 600. According to ISO 3685 tool life criteria [41], a cutting tool is useable until its maximum flank wear VB_{max} in under 0.6 mm. This standard also defines the workability of cutting tools based on average tool wear and should not increase a defined limit. Figure 4 demonstrates the wear land of the tool where maximum wear on the flank was measured according to ISO 3685 standard.

The average width of the wear region was calculated by simply dividing the area by length of wear. The actual cutting time was calculated for each experiment using Eq. 7 and the Wear rate (R) was calculated using Eq. 8.

$$t = \frac{\pi Dl}{1000fV_c} \quad (7)$$

where t = actual cutting time in minutes, D = Workpiece diameter in mm, l = length of cut in mm, f = Feed in mm/rev and V_c = cutting speed in m/min

$$R = log\left[\frac{VB}{l_s}\right] = log\left[\frac{VB}{1000tV_c}\right] \quad (8)$$

where VB is flank wear and R is a wear rate parameter. The same normalizing approach was used by [29]. Scanning Electron microscopy (SEM) was also carried out on the used cutting insert to quantity the materials transferred and understand the wear Phenomena.

6 Results and Discussion

6.1 Surface Roughness Comparison

Figure 5 presents the average surface roughness with respect to cutting speed for different types of tool coatings. It was observed that surface roughness is improved by increasing the cutting speed for all types of tool coatings. Multi-coated inserts give the best surface finish as compared to other tool inserts. The surface roughness achieved for the uncoated tool varied between 2.84 to 1.45 microns. Higher values were observed for uncoated inserts compared to both single coated and multicoated under all cutting conditions. This agrees to the report that in the case of uncoated tools the tool wear is greater compared to the coated tool and thus affect the surface roughness while machining titanium alloys [36]. Thus, best surface roughness up to 1 micron was achieved for multicoated tools at higher cutting speed.

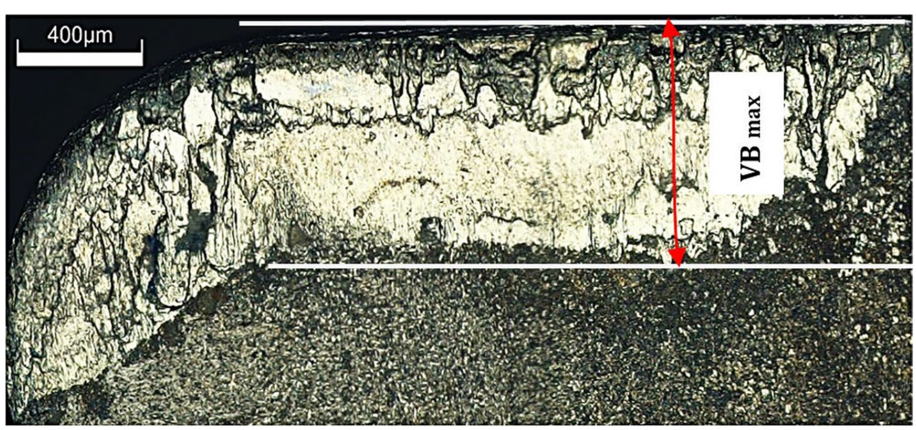


Fig. 4 Microscopic images showing the flank wear on the tool

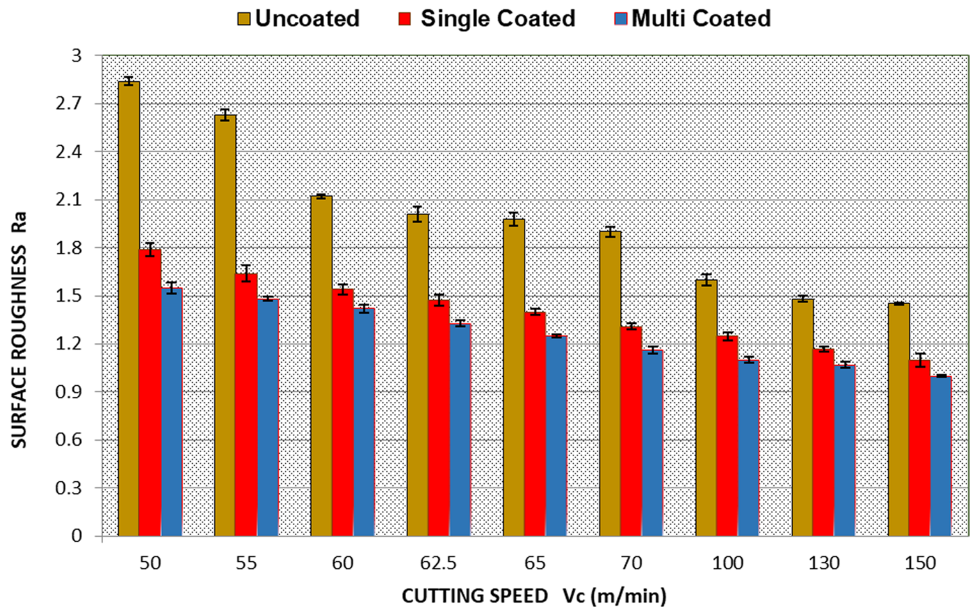


Fig. 5 Effect of cutting speed on the surface roughness for uncoated, single and multi-coated tools

7 Chip Morphology Analysis

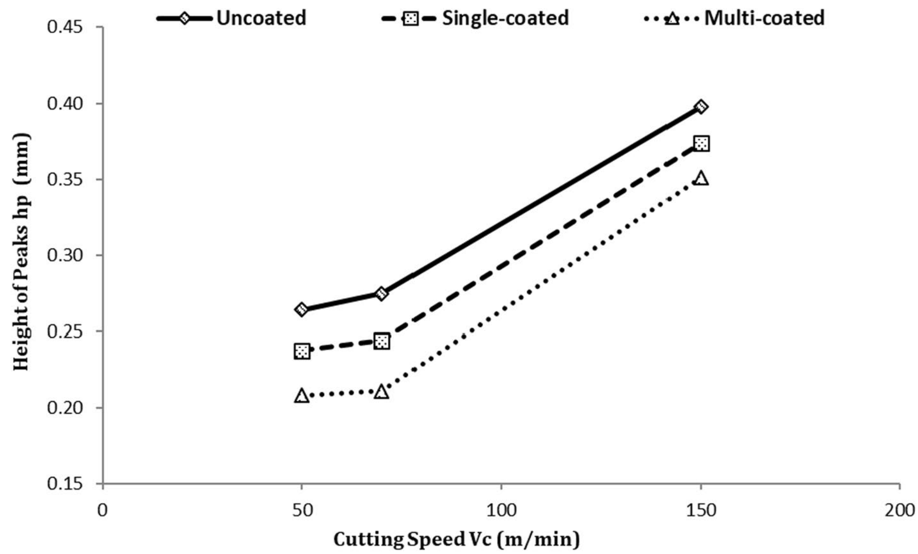
Machining of Titanium alloys produces serrated chips due to shear deformation and results in a saw-tooth like structure as already reported [33, 36]. The chip morphologies obtained under various cutting conditions (cutting speeds 50, 70, and 150 m/min) for uncoated, single coated and multi-coated tools were examined under microscope and and the chip geometric parameters using Eq. 1 to Eq. 6 is shown in Table 4.

The trend obtained for the height of peak (h_p) values as a function of cutting speed is given in Fig. 6a. The trend is increasing because of the linear proportionality of chip thickness and segmented ratio respectively, with respect to cutting speeds as also reported elsewhere [33, 36]. The height of peak for multicoated inserts was observed to be less compared to uncoated tools due to the least deformed chip thickness and segmentation of the chips. Similarly, a linearly increasing trend was observed for the height of valleys (hv) as shown in Fig. 6b. This was the consequence of the high plasticity and low thermal conductivity and this fact become more noticeable on high cutting speed. As the height of the valley has a direct relationship with the height of the peak, therefore identical trends were observed under all cutting conditions for all tool coatings.

Table 4 shows the results obtained for chip compression and shear angles using geometric parameters of the chips. The chip segmentation ratio for all cutting speeds is plotted in Fig. 7. Cutting speed influences on the segmented portion of chip structure, higher the cutting speeds will increase the thermal softening of the titanium alloy. This segmentation ratio will affect and enhance the cracks initiation and propagation by lowering the spindle speed. The

Table 4 Calculation of parameters with the help of geometric variables for chip analysis

Sr No	V_c *m/min*	Φ	G_s	t_c (mm)	f_{cs} (Hz)	r	r'
Uncoated tool chips							
1	50	41.607	0.506	0.197	18.040	0.811	1.233
2	70	43.840	0.516	0.204	24.763	0.785	1.273
3	150	43.020	0.615	0.275	46.984	0.581	1.721
Single coated tool chips							
1	50	40.990	0.478	0.181	16.539	0.885	1.130
2	70	42.300	0.483	0.185	22.661	0.864	1.157
3	150	41.797	0.611	0.260	44.543	0.616	1.622
Multi coated tool chips							
1	50	40.040	0.428	0.164	13.394	0.978	1.023
2	70	41.170	0.430	0.166	20.817	0.966	1.036
3	150	40.870	0.605	0.245	41.700	0.654	1.529



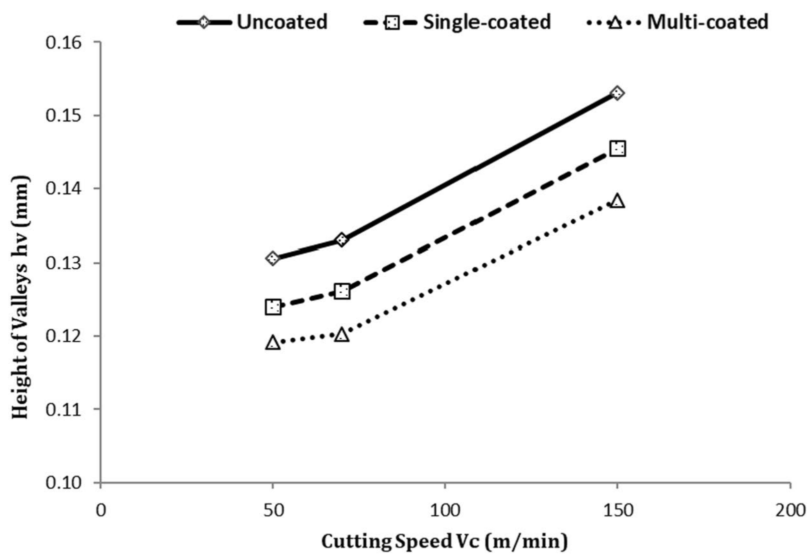


Fig. 6 Effect of cutting speed on **a** Height of peaks (h_p) and **b** Height of valleys (h_v), for uncoated, single and multi-coated tools

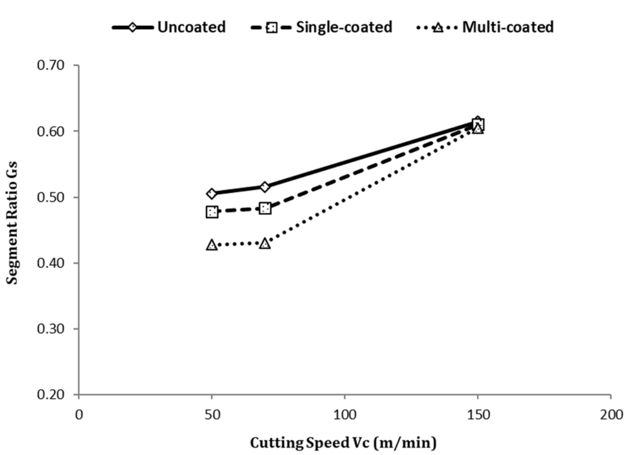


Fig. 7 Effect of cutting speed on the segment ratio (G_s) for uncoated, single and multi-coated tools

chip segmentation ratio generally increased by increasing the cutting speed, however, at low cutting speed, the segment ratio remained unaffected due to enhanced crack initiation and shear localization in the intermediate cutting speed range [42]. It was reported that cutting speed influences the segmented portion of chip structure as higher cutting speeds attributes to the thermal softening during cutting titanium alloy [36, 40]. Further, the changes in the segmentation has an impact on the surface roughness, tool wear, and energy consumed at the tool chip interface as reported earlier [28]. The chip segmentation ratio generally increased by increasing the cutting speed, however, at low cutting speed, the segment ratio remained unaffected due to enhanced crack initiation and shear localization in the intermediate cutting speed range [42]. The high segmentation ratio of the uncoated tool is therefore one of the reasons for the higher surface roughness of uncoated tools.

Chip thickness is another important parameter in the machinability analysis and the chip thickness depends upon the type of coating used and machining parameters [40]. Figure 8 shows the experimental results obtained for chip thickness of different tool coatings with respect to the cutting speed. Generally, the chip thickness increased by increasing cutting speed due to the unstable adiabatic shearing phenomenon. Comparatively, the uncoated chip morphology resulted in larger chip thickness values compared to the chips obtained for coated tools due to the poor heat dissipation at the tool-chip region, particularly above 100 m/min. It has been reported extensively by past researchers including Komanduri et al. [43], Astakhov et al. [44] and others [34] reported that chip formation in the case for machining of Titanium based alloys follows a different trend as compared to the conventional metals. Titanium based alloy form shear deformed chips even at lower speeds, as a result the conventional trend of decreasing chip thickness with increasing speed, which is well known for conventional alloys, is not the case for titanium based alloys. As has already been reported by Hernandz et al. [36]. This trend has been attributed in the past to strain hardening and localized thermal softening as well as low thermal conductivity of titanium based alloys [22, 29, 45].

According to the published literature, the shear angle ranges from 35 to 44° for orthogonal machining of Titanium alloy Ti-6Al-4 V [13, 46]. Figure 9 shows the shear angle (Φ) of uncoated, single-coated, and multicoated with respect to cutting speeds. The shear angle increases from 50 to 70 m/min and then decreases after 70 m/min. This can be attributed to the presence of high tool wear region due to the formation of Titanium Nitride at the tool- work piece interface as already reported [30, 47]. It was observed that more buildup edge (BUE) were produced at the cutting nose

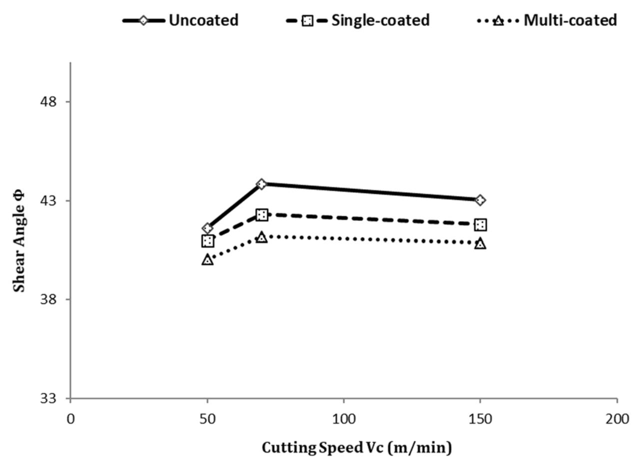


Fig. 9 Effect of cutting speed on the shear angle (Φ) for uncoated, single and multi-coated tools

of single and multi-coated inserts as compared to uncoated inserts. This results in high tool wear and surface roughness in single and multi-coated inserts. This means that single and multi-coating gave effective thermal barrier because of lower thermal conductivity. In addition to shear angle, the dimensions of newly formed rake angle were noticed and it was concluded that shear angle increases with increasing rake angle as also reported elsewhere [48]. This was attributed to the chip serration and discontinuous chip formation.

The chip compression ratio is the inverse of the chip thickness ratio and its range must be greater than 1 [13, 33]. It depends on the edge radius and the cutting angle. As the cutting angle and the radius of the cutting edge is increased, the chip compression ratio increases [13, 36]. Chip compression ratio is plotted against cutting speed in Fig. 10. It shows an increasing pattern with increasing cutting speed for all tool types. The chip compression ratio is low for the coated tool because of the layer of TiAlN and AlCrN coating that

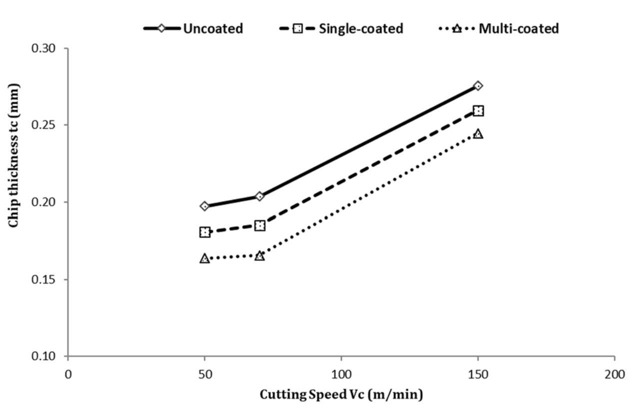


Fig. 8 Effect of Cutting Speed on the Chip thickness for uncoated, single and multi-coated tools

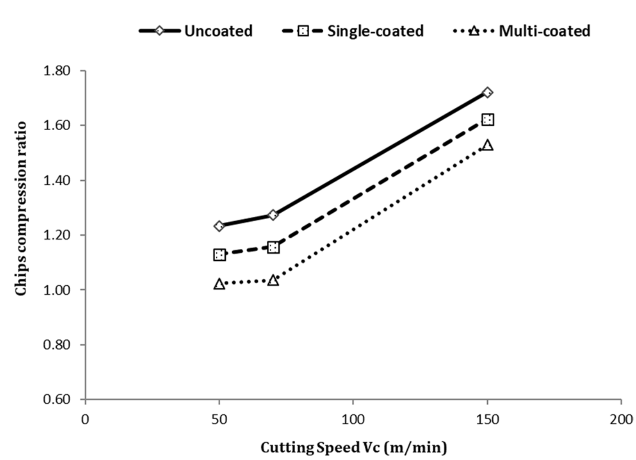


Fig. 10 Effect of cutting speed on the chip compression ratio

affects the tool chip contact length due to lowering the coefficient of friction [49, 50].

8 Tool Wear Analysis

During the experimentation and optical microscopy of the coated and uncoated inserts, it was observed that more BUE were produced at the cutting edge/ zone of uncoated inserts as compared to single and multi-coated inserts. The BUE increases the cutting forces and results in higher surface roughness in the case of uncoated inserts. Figure 11 shows the microscopic images of the tool with BUE highlighted.

Average and maximum tool wear remained under standard limit for all experiments, as prescribed under ISO 3685 [51]. Cutting speed has high impact on tool wear as higher cutting speeds tend to produce more tool wear. At higher cutting speeds higher temperature is produced which decreases hardness of tool material leading to abrasion and diffusion [52, 53]. This phenomenon increases both maximum and average tool wear. For uncoated tools, the tool wear was maximum compared to single and multi-coated tools for all the cutting speed. At lower speeds, from 50 to 65 m/min, single coated perform slightly better than uncoated inserts, while the performance of multi-coating is significantly better than both uncoated and single-coated inserts. At lower speeds, the temperature generated is relatively lower than the temperature at higher cutting speeds which results in low tool wear. It has also been reported [30] that at lower cutting speeds uncoated inserts form a stable external layer and hence they perform nearly equal to coated inserts at low speeds. While at higher cutting speeds (70–100 m/min), multi-coated inserts perform much better than uncoated inserts. From previous research on machining Ti6Al4V alloys at high cutting speeds, coating also start to chemically react with the workpiece material [30, 38, 54]. The BUE was also observed on inserts at higher cutting speeds. It was observed that for speed 130 m/min, single layer performed nearly equal to uncoated inserts while in case of multi-coating tool wear was less than both uncoated and single-coated inserts. For uncoated and single-coated tools, high cutting speed results in poor heat dissipation, particularly above 100 m/min [38, 55]. As highlighted for multicoated tools, coating delamination was also observed in the microscopic images of the multicoated tools.

Figure 12 presents the comparison of 'R' plotted against the cutting speed for various tool types used in the current study. It can be observed that the wear rates of uncoated inserts are higher than coated inserts. At higher speeds, the performance of the coated tools improves because at higher temperature aluminum oxide is produced that prevents excessive heat from penetrating further into the inserts [56]. Furthermore, less tool wear at higher temperatures can be attributed to the oxidation resistance of AlCrN coating [30].

There is a trade-off between choosing output response parameters during machining Ti6Al4V alloys. These responses include surface roughness, tool wear, forces, and energy as well as machining productivity. High speed machining may benefit the surface roughness of the components produced, but that may not be good for tool life and cost of production. Thus, it may require a selection of cutting parameters that can optimize the output response as desired and suitable for a particular operation. Therefore, high-speed machining above 130 m/min results in low tool life and improved surface integrity of the parts manufactured. It has been noted that for a speed of 150 m/min, tool wear for multi-coated tools can be reduced to 7% for TiALN coated and 12% for multicoated TiAlN + AlCrN compared to uncoated tools. Whereas surface roughness can be improved in the range of 31–47%, depending upon the cutting speed and the tool coating used as illustrated in Table 5.

Further, all the inserts used in machining tests were examined and analyzed on VEGA3 TESCAN SEM and the analysis was carried out as shown in Fig. 13a. In this study, the material transfer on the flank face was analyzed in terms of mass percentage, in the flank wear land. In order to understand Titanium reactivity and adhesive tendency with tools material, Energy dispersive X-ray scanning electron microscopy were carried out using line scans that provides a visual representation of the composition in pulses or count per second (CPS) is shown in Fig. 13b.

Figure 14 depicts the mass percentage of Ti6Al4V elements detected on the scan surface of the uncoated, single-coated, and multicoated tools. It is evident that the workpiece materials, consisting of Ti, Al, and V, have transferred to the cutting tool. A significant amount of Ti adhesion to the uncoated tools was observed, which can be attributed as the main cause of accelerated tool wear observed for uncoated tools. These finding are consistent with the results reported by others [57, 58]. The amount of titanium on the flank face was found to be five times higher for uncoated carbide tools compared to multicoated tools. Conversely, a substantial increase in the amount of Al was found on the multicoated tool surface. This increase in aluminum in the region is believed to have formed a hard aluminum oxide layer, known for improved hardness in high-heat applications [59]. Vanadium showed the least tendency to transfer to any of the tools. Thus, it can be concluded from the analysis in this study that the improved performance (surface roughness and wear) of the multicoated tools is due to the lower tendency of Ti adhesion to the TiAlN + CrAlN tools. The BUE also causes further abrasion between the cutting chip and tool promoting tool wear in case of uncoated tools.

Reduction in the cutting tool temperature at the contact point is of the is essential in dry machining to achieved

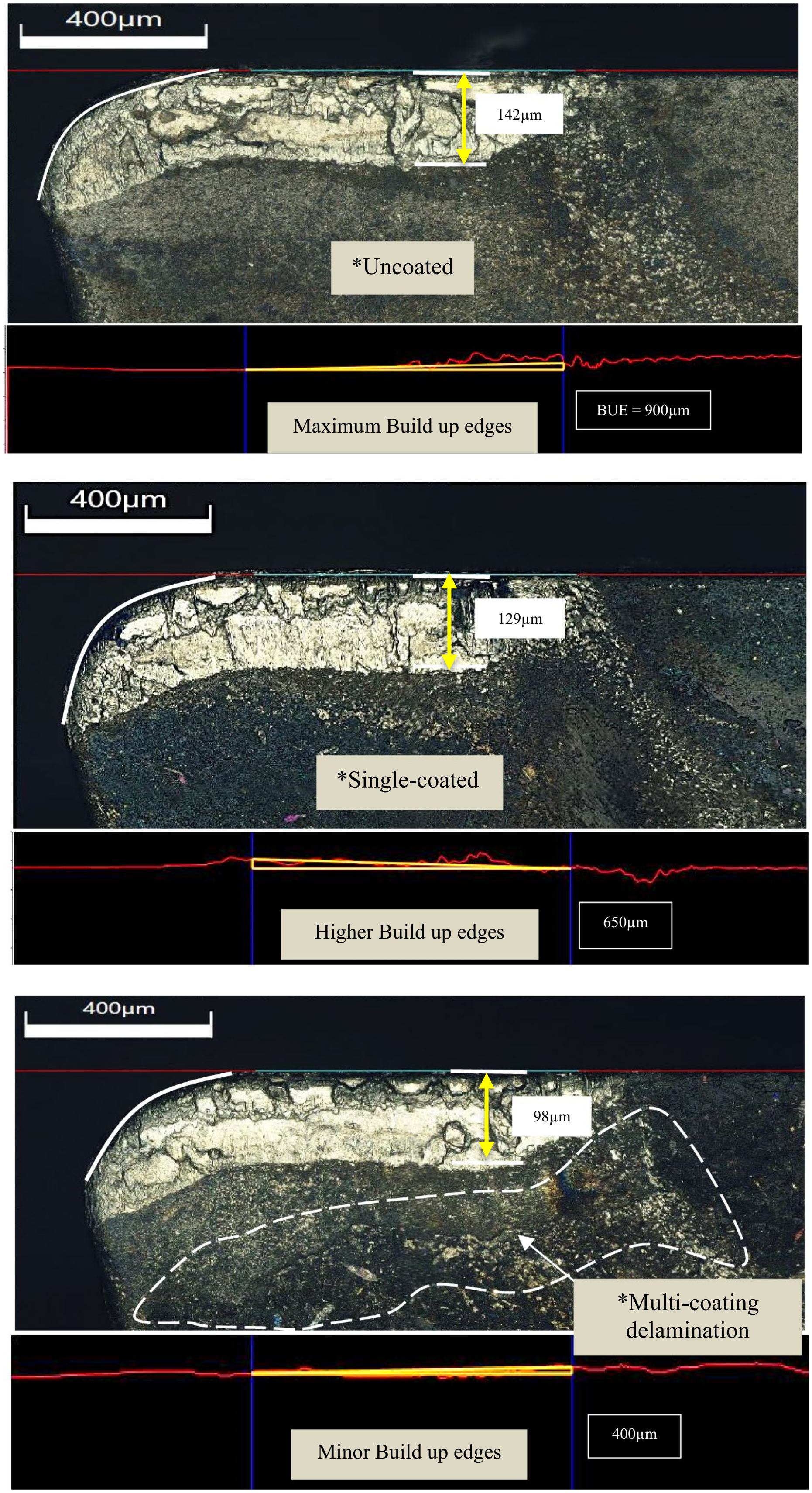


Fig. 11 Optical microscopy of BUE localization and VBmax of uncoated, single and multi-coated inserts

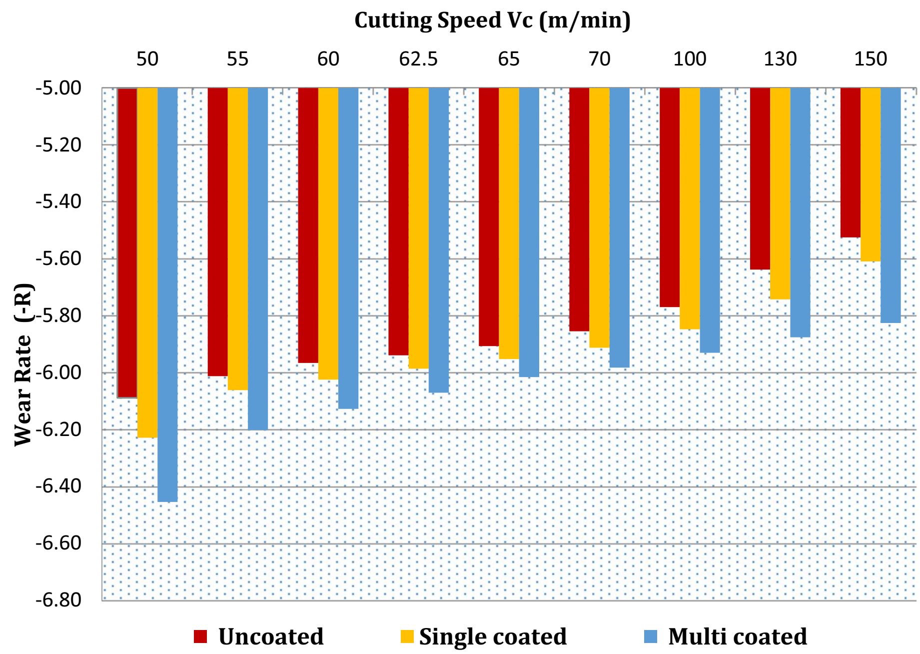


Fig. 12 Comparison of wear rates

Table 5 Percentage Improvement of response variables with respect to minimum and maximum cutting speed V_c (m/min)

Condition	Response	Uncoated tools	Single-coated tools	Multi-coated tools	%age Improvement
150 m/min	Wear rate, *R*	−5.25	−5.61	−5.87	7% to 12%
	Surface roughness, (μm)	1.45	1.10	1.00	31% to 45%
50 m/min	Wear rate, *R*	−6.01	−6.07	−6.68	Up to 11%
	Surface roughness, (μm)	2.84	1.79	1.5	Up to 47%

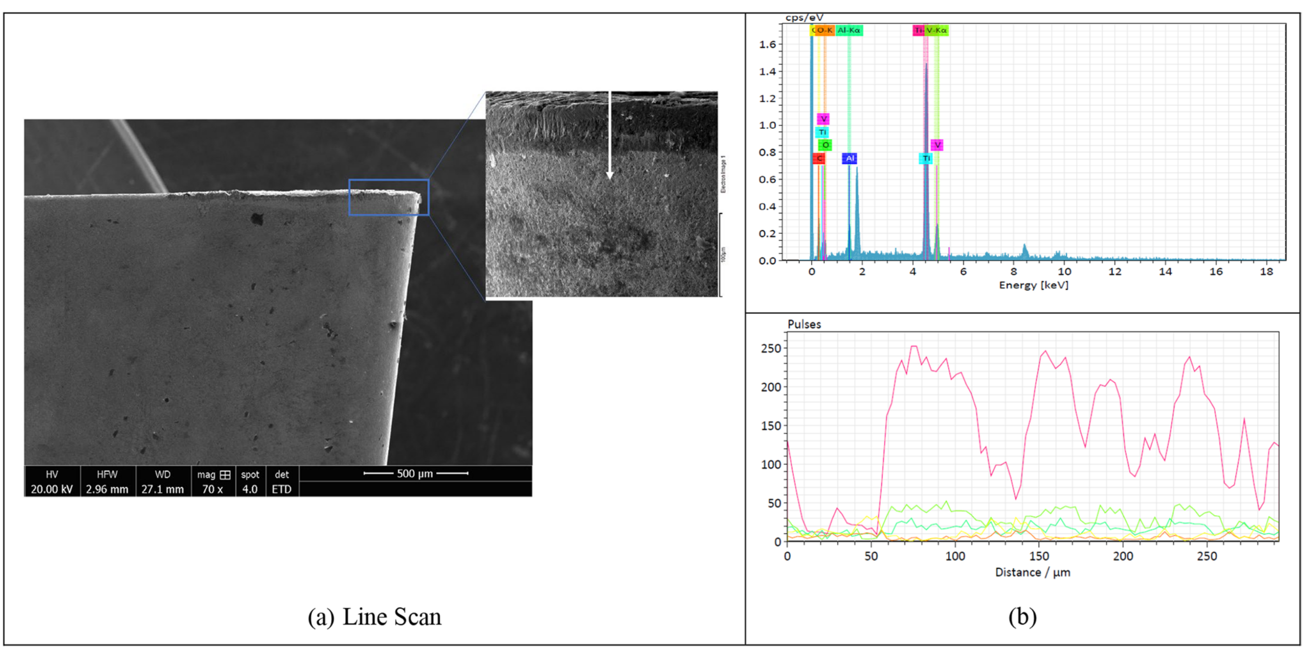


Fig. 13 **a** Location of line scan across the flank wear land; **b** pulses/distribution of various elements across flank face

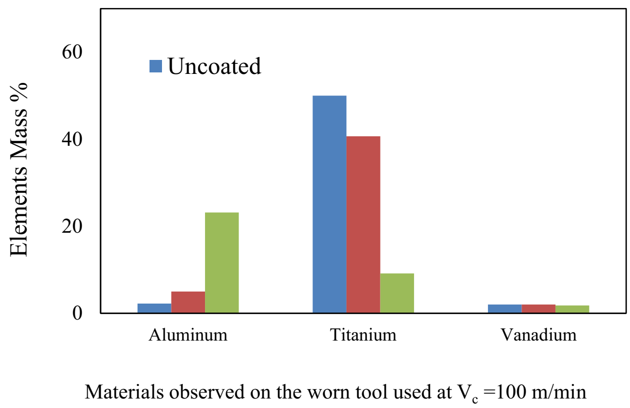


Fig. 14 Transfer of materials from the workpiece to the tool surface

enhanced tool life. Thus, it becomes very important to use heat and wear resistant tool coating that can minimize the temperature effects as well as the corresponding adhesion and abrasion of the tool. In addition, the proper choice of the cutting speed and feed rate needs to be considered for improved machinability as reported by many [7, 9, 29]. These results also support the observation of the tool wear and surface roughness observed in the current study.

9 Conclusions

This study was focused on the effect of various tool coatings (TiAlN and TiAlN + CrAlN) on the machinability of Ti6Al4V alloys under different cutting speeds (low, medium and high). Specific conclusions from the study are highlighted below:

1. It was observed that by using multi-coated inserts, tool wear can be reduced up to 12% as compared to uncoated and single-coated tools.
2. For multi-coated inserts, the surface roughness improved up to 47% owing to the better thermal conductivity at lower affinity of BUE on the tool coating.
3. Comparatively, the uncoated chip morphology resulted in larger chip thickness compared to the chips obtained for coated tools due to the poor heat dissipation at the tool chip interface at high cutting speeds, particularly above 100 m/min.
4. It was observed that more BUE is more likely to be present for uncoated inserts as compared to single and multi-coated inserts, which results in a high tool wear and, high surface roughness for uncoated inserts.
5. Multi coated TiAlN + CrAlN tools contributed considerably to the improvement in the surface roughness and tool wear. The performance of multi-layered coating was observed to be comparatively better than the uncoated and single-coated tool at higher cutting speeds.
6. Owing to the lower materials adhesion and improved machining performance of TiAlN + CrAlN tools, the results suggest that these coatings would improve the machinability of other hard to cut materials.

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Code availability Not apllicable.

Declarations

Conflict of interest The authors declare no competing interests.

Ethical approval The authors approve to observe the ethics standard of this journal.

Consent for publication All authors consent to the publications of the manuscript in this journal.

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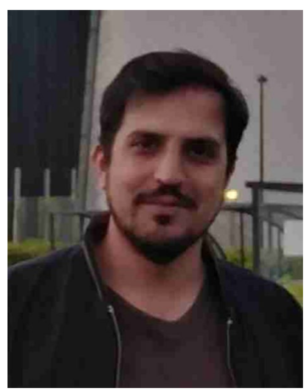

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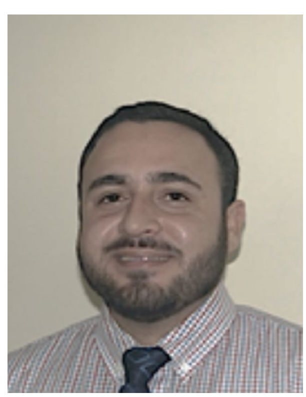

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