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Machinability aspects in dry turning of Ti6Al4V alloy with HiPIMS coated carbide inserts

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Owing to their unique mechanical properties, titanium alloys have been and will be used extensively in a myriad of industries ranging from aerospace to automotive to medical field. Hence, a continuous improvement in the performance of the coated inserts with hard materials capable of enhanced tribological and wear resistive properties is necessary. The present work contributes to investigation of the influence of cutting parameters in turning operations of the alpha-beta titanium alloy- Ti-6Al-4V. Tungsten carbide inserts of K20 grade is coated with TiAlN and AlCrN monolayer coatings by high power impulse magnetron sputtering (HPPMS). Machinability of Ti6Al4V alloy is studied at different cutting speed, feed ranging from 60 to 120 m/min and 0.1 to 0.25 mm/rev with constant depth of cut of 0.5 mm to evaluate the optimum turning parameters under dry environment. The tool wear is observed initially under an optical microscope and nature of wear is observed with scanning electron microscope (SEM). It is witnessed that the AlCrN coated inserts have an upper edge over the TiAlN coated inserts due to better adhesion and thermal stability of the coating. Tool wear and surface finish is found to be optimum at cutting speed of 100 m/min, feed of 0.1mm/rev and depth of cut 0.5 mm. The present will provide useful and economic machining solutions for the high speed machining of titanium alloys by effective utilization of coated tungsten carbide inserts.

Keywords: Machinability, HiPIMS, Ti-6Al-4V alloy, dry machining, flank wear, PVD Coated inserts, TiAlN, AlCrN

1 Introduction

Ti-6Al-4V alloys are titanium based materials whose applications range from automotive, biomedical, dental and aerospace industries thanks to their excellent wear resistance, high stiffness and biocompatibility[1]. They also exhibit excellent corrosion resistance which is an important characteristic for use in chemical, petrochemical and marine environments[2]. It is a commonly used material for various applications such as connecting rods, valves, rocker arms, camshaft, fan blades of airplanes, which usually work under high pressure and temperature environments[3]. Moreover, it also has varied applications such as dental implants, hip joints, knee joints because of its excellent compatibility to human body[4]. Despite owing to these properties titanium is not yet explored to a greater extent due to its poor machinability.

Ti-6Al-4V is considered as a 'difficult to machine' material as it shows poor surface finish integrity and rapid tool wear when compared to other metal alloys. The low thermal conductivity and the work hardening properties of this alloy are held accountable for the poor machinability. This alloy also bonds very strongly with the tool not only during shearing but also when the chip breaks as it leaves the workpiece, causing massive tool wear. This poor machinability of the alloy can be addressed by dry machining[5-7]. Dry machining is ecologically sound method of manufacturing where the amount of waste produced is minimal. Owing to this characteristic, it has been considered a necessity for manufacturing enterprises in the future. Taking into consideration the new environmental protection laws for occupational safety and health regulations industries will be forced to turn to dry machining[8].

The implementation of dry machining of titanium alloys can be improved by selection of better coating material and coating techniques. Chemical vapour deposition (CVD) or physical vapour deposition (PVD) techniques are used to coat carbide cutting tools with hard monolayer and multilayer coatings. PVD coated tools have always shown better results in comparison to CVD coated tools, keeping coating thickness and material constant. Advancements in

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PVD technique enables researchers to deposit thinner coating giving sharper edges and complex shapes at low temperature. Cutting inserts with TiAlN coating and coated by PVD method exhibit high hardness, wear resistance and chemical stability which makes it most commonly used in machining process. In comparison with other coated cutting tool types, they offer higher benefits not only in machining performance but also in terms of tool life. High speed turning is generally done when dry machining is taken into account. During dry machining high speed turning is preferred because it has high material removal rates followed by low cutting forces, reduction in lead time and high precision and better surface finish parts[9]. The machining of Ti-6Al-4V is generally done by various tool materials which include ceramic, multi layered carbide coated inserts, cubic boron nitride (cBN), polycrystalline diamond (PCD) etc. These appear to give a better performance while machining but the cost of these tools limits the use in engineering applications. Tungsten carbide inserts have been used since very long time for continuous machining of hard to cut materials such as stainless steel, nickel based alloys and titanium based alloys in the speed range of 20-60 m/min. Such cutting speeds give low material removal rates causing reduction in production line. Hence, high speed machining is preferred to increase the material removal rates as well as achieve better surface[10,11]. This research is aimed to investigate machinability indices of Ti-6Al-4V during high speed machining with different coated inserts. TiAlN and AlCrNare selected for coating the carbide inserts with PVD magnetron sputtering process.

Andriya *et al.*[12] studied the effects of machining Ti-6Al-4V titanium alloy using PVD coated TiAlN carbide cutting tools. Five levels of input parameters were taken into consideration and they proposed that dry environment was best suited for titanium machining. They observed that feed and depth of cut are the most influential factors which lead to an increase in the surface roughness and cutting forces. Jaffery *et al.*[13] carried out research on the effect of wear mechanism on tool life of PVD coated carbide inserts during dry machining of TiAl6V4. He found that AlCrN showed better performance than NbN and Ti6Al coatings even above cutting speeds of 50 m/min. Cadena *et al.*[14] performed experiments to find the effect of PVD AlCrN coated carbide inserts for reducing the tool deterioration in the machining of TiAl6V4 alloy. He observed that. the heat treatment of the coating improves the wear behavior of the insert, resulting into better machining performance. Dongre *et al.*[15] has analyzed the machining of TiAl6V4 alloy using Al_2O_3 and TiN coated as well as un-coated inserts in dry, flooded lubrication system and mist lubrication machining environments. Flooded lubrication systems gave minimum surface roughness which was followed by and mist lubrication systems. Ibrahim *et al.*[16], carried out turning of Ti6Al4V ELI titanium alloy with three different tools, CVD coated multi-layer TiN- Al_2O_3-TiCN-TiN, PVD coated single layer TiAlN and uncoated carbide tool under dry conditions. They observed that surface roughness values under dry machining are mostly affected by the feed rate and nose radius. Further they found that coated cemented carbide tools generates machined surfaces free from cracks and tears. A. I. Gusri *et al.*[17,18], executed machining of Ti6Al4V ELI titanium alloy with CVD multilayer coated inserts (TiN-Al_2O_3-TiC-NTiN) at high cutting speeds under dry condition. They detected that the adhesion wear takes place post coating delamination. In another study on Ti6Al4V machining they observed that the trend lines of surface roughness value are higher at the initial machining. Also, they found that the feed rate is deciding factor to surface texture profile. Cotterell *et al.*[19], studied dynamics of chip formation during turning of titanium alloy Ti6Al4V ELI. A high speed imaging system was used for observing the chip formation cycle. They concluded that for the speed range of 4 – 140 m/min segmented chips were produced. Sorby *et al.*[20] carried out turning of Ti6Al4V alloy with uncoated and coated carbide inserts. They concluded that in titanium machining tool coating has little or no effect on the tool life. However, the continuous development of tool coatings leads to new materials and multi-layer coating systems, and it is expected that there will be important developments in this field in the near future.

Although, considerable literature on machining of titanium alloy by coated inserts is available, the correlation between machining performance and coating characteristics have rarely been stated. Furthermore, the literature review reveals that TiAlN is used commercially on a large scale for machining of hard to cut alloys, especially titanium and a substantial amount of research has been performed on

Table 1 — Chemical composition of Ti6Al4V

Element	Ti	Al	V	Fe	O	N	H	C
% by Weight (as tested)	82.92	5.92	3.87	0.19	0.13	0.053	0.0142	0.068

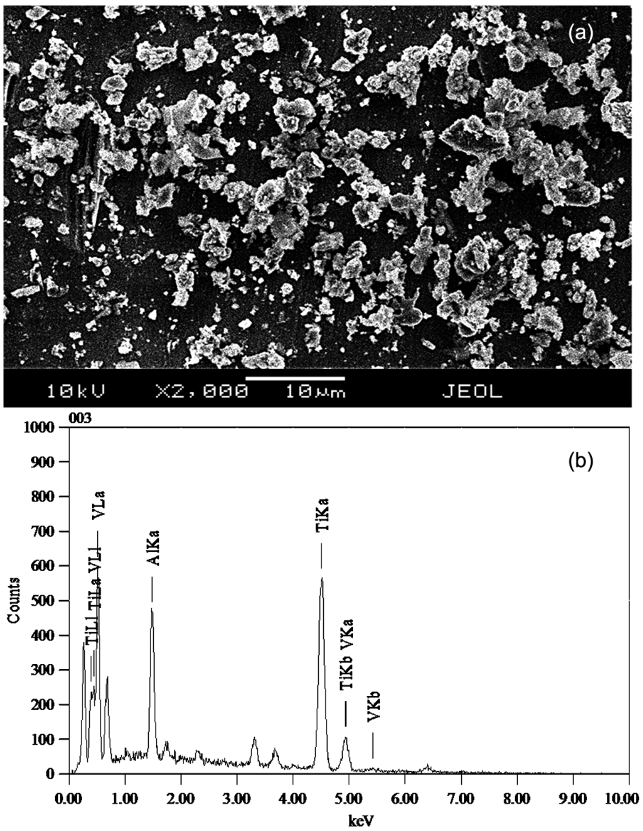

Fig. 1 — Microstructure and SEM EDS spectrum of Ti6Al4V

Fig. 2 — CNC Lathe used during machining

the same. However, comparatively less research has been carried out on the AlCrN coated inserts for machining of titanium alloys. It is also reported that compare TiAlN and AlCrN coated inserts can be the potential inserts for machining of titanium alloys,hence, in this research, an attempt is made to compare TiAlN and AlCrN coated inserts to observe the influence of cutting parameters on machinability aspects[21-23].

2 Materials and Methods

The work material used in the current study was Ti6Al4V titanium alloy. The actual chemical composition of Ti6Al4V is given in Table 1 as provided by supplier. The microstructure of Ti6Al4V indicating α+β phase and EDX profile are as shown in Fig. 1. The titanium alloy used in this research is in α+β phase which has inbuilt wide range of mechanical properties and possesses good manufacturability and moderate elevated temperature strength. The Ti6Al4V alloy round bar 35 mm in diameter and 250 mm long was used to conduct machining experimentation.

The turning operation for experimentation was carried out on CNC turning machine “Simple turn 5075 Siemens 802C”as photo shown in Fig. 2 having maximum spindle speed 2000rpm and 7.5kW capacity. The tool holder used is with ISO specification of PCLNL2525 M12 whereas inserts used for machining test are K grade rhombus shaped carbide inserts with rake angle of -6º and designation of CNMG120408 whichare further coated with TiAlN and AlCrN coatings having 4 to 6 micrometer coating thickness. High power impulse magnetron sputtering (HiPIMS); the latest PVD technique is used for the coating of both the inserts. The turning test parameters along with their variations are shown in Table 2. L16 orthogonal array has been conducted and the results of average of three readings are taken into consideration. The Vickers microhardness tester which has a digital indentation tester with Vickers indenter (ASTM E92) is used to evaluate microhardness of both coatings. The indentation load of 50 gf and dwell time of 10 s are used for the measurement. The microhardness values reported in this research are the average of it five values attained by different indentations at different locations. The surface roughness for the experiment was carried out using Taylor Hobson Surtronic Duo surface roughness tester. The value recorded indicates average surface roughness values obtained by at least four measurements and it is given in Table 3.

The measurement of cutting force was done by using kiestler 9257A piezoelectric dynamometer during machining length 40 mm and each measurement was captured for fresh new edge of the tool. The average tool wear was measured using Dino-Lite Edge digital microscope having Magnification of 20X to 220X and a Frame rate of 60 fps. The measurement of flank wear is carried out at minimum five different positions and an average for the same was considered to achieve precise value of tool wear. The surface morphology and further analysis of wear mechanisms were done under a scanning electron microscope (Quanta 200 type FEG SEM).

3 Results and Discussion

In the current research, the effect of machining parameters on surface roughness, cutting forces and tool wear was analyzed and were plotted.

3.1 SEM EDS of work piece and coated inserts

In this work, characterization of Ti6Al4V and coated insert is done to understand structure and presence of major alloying elements. Figure 1 depicts the microstructure of Ti6Al4V showing bimodal structures formed by the combination of two morphologies; globular structures, α and β phase. Ti6Al4V is an α-titanium alloy with HCP structure which provides relatively lower mechanical properties and better machinability index than the β-alloys. The characterization of this alloy shows that Ti6Al4V contains fine β phase in the α matrix. Moreover, microstructure reveals that β phase in Ti6Al4V is richer in Vanadium than the corresponding α phases. Along with microstructural study, Energy-dispersive spectroscopy (EDS) is also carried out which have confirmed elemental analysis of this alloy. Furthermore, the chemical characterization of both the coated inserts was done by SEM-EDS before machining. SEM EDS spectrum indorsing titanium, aluminium together with nitrogen of TiAlN coating and aluminium, chromium accompanied by nitrogen of AlCrN coating are as shown in Fig. 3(a and b) respectively.

Table 2 — Cutting conditions

Sr .No.	Parameters	Value
1	Cutting Speed (V_c)	60,80,100,120 mm/min
2	Feed (f)	0.1,0.15,0.2,0.25 mm/rev
3	Depth of Cut (a_p)	0.5 mm (constant)

3.2 Microhardness

Coating microhardness has been evaluated using Vickers microhardness tester as shown in Fig. 4. The microhardness values were obtained in the range of 3060 -3670 HV for AlCrN coating and 2755 – 3260 HV for TiAlN coating deposited by magnetron sputtering. The average microhardness values for AlCrN and TiAlN monolayer coating were 3468 HV and 3148 HV respectively. It has been reported that TiAlN coating having higher adhesion strength showed low microhardness and it is due to crystal lattice orientation. The recorded range of microhardness readings for both these coatings in the literature is 30 to 34 GPa.

Table 3 — Surface roughness measurements for

Experiment No	Cutting Speed (m/min)	Feed (mm/rev)	Depth of cut (mm)	Surface Roughness (µm)	
				AlCrN	TiAlN
1	60	0-1	0.5	0.436	0.56
2	60	0.15	0.5	0.83	1.10
3	60	0.2	0.5	1.12	1.67
4	60	0.25	0.5	1.46	2.82
5	80	0-1	0.5	0.61	0.73
6	80	0.15	0.5	0.89	1.125
7	80	0.2	0.5	1.26	1.75
8	80	0.25	0.5	1.61	2.54
9	100	0-1	0.5	0.63	0.74
10	100	0.15	0.5	0.94	1.15
11	100	0.2	0.5	1.32	1.61
12	100	0.25	0.5	1.64	2.35
13	120	0-1	0.5	0.61	0.75
14	120	0.15	0.5	0.726	1.08
15	120	0.2	0.5	1.13	1.48
16	120	0.25	0.5	1.38	2.32

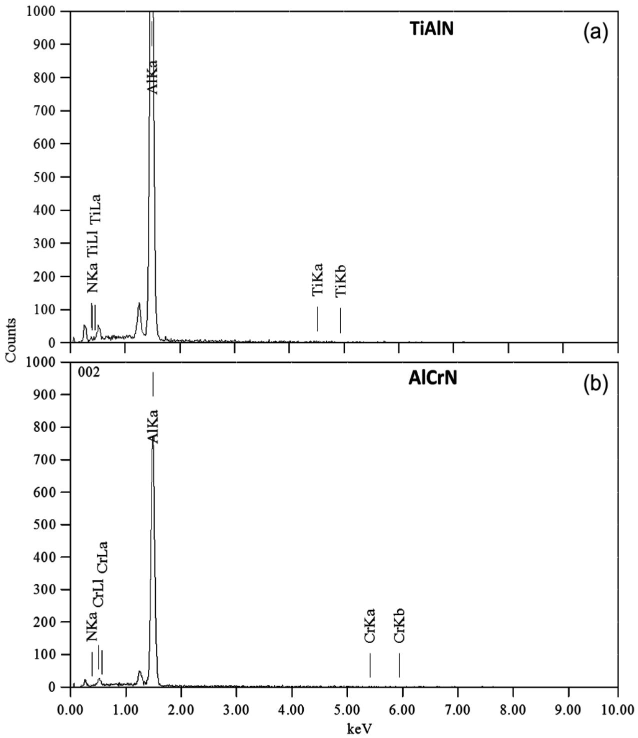

Fig. 3 — SEM EDS spectrum of (a) TiAlN and (b) AlCrN

3.3 Evaluation of surface roughness

In the present study, cutting feed among all machining parameters has major influence on surface finish of machined workpiece and it becomes deciding factor for fatigue life of finished product. The effect of feed on surface roughness at all cutting speed is shown in Fig. 5.

Fig. 4 — Vicker's Micro-Hardness Tester and its Close-up View

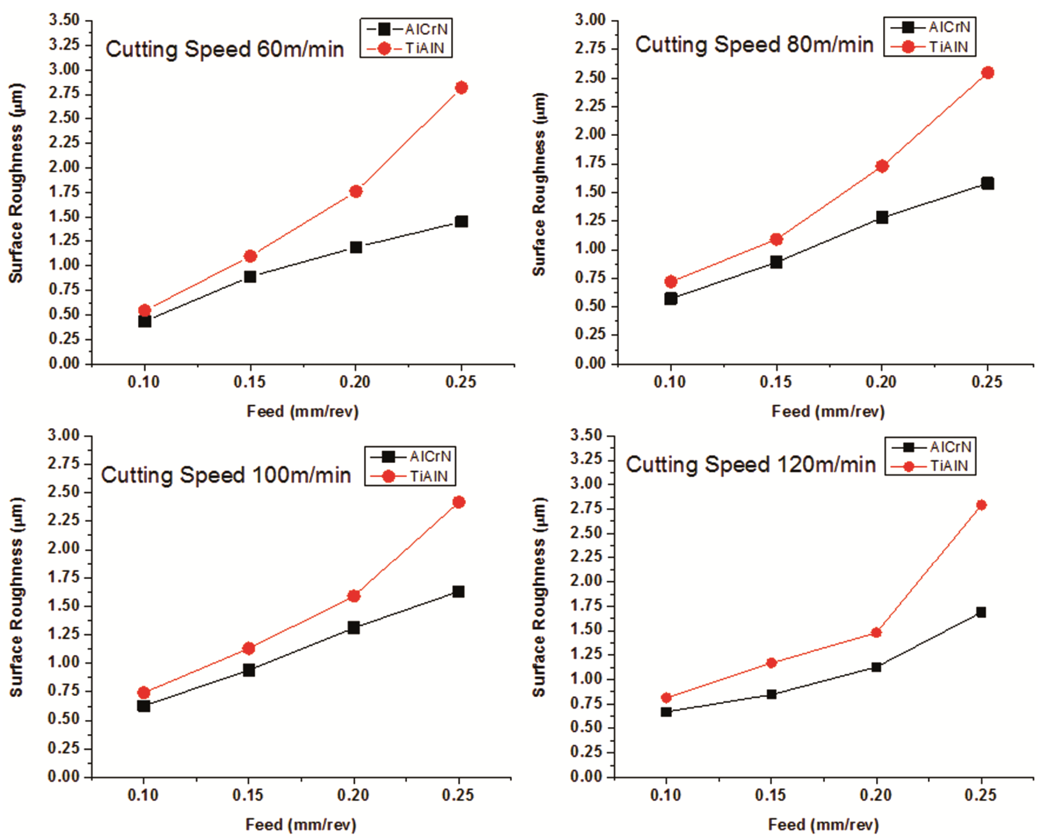

Fig. 5 — Effect of feed on machined surface roughness at cutting speed of 60 m/min to 120 m/min

Surface roughness values for AlCrN and TiAlN coatings obtained in the range from 0.43 µm to 1.65 µm and from 0.56 µm to 2.82 µm respectively. Best surface finish values of 0.436 µm and 0.56 µm was achieved for AlCrN and TiAlN coated insert respectively, at lower cutting speed of 60 m/min and low feed of 0.1 mm/rev.

The graphs of effect of feed on machined surface roughness clearly reveal increasing nature of roughness at all cutting speeds. The influence of feed on surface finish and increasing nature of surface roughness can be attributed by following expression. According to this expression arithmetic surface roughness value is directly proportional to square of feed[24].

$$R_a = \frac{0.0321\ f^2}{r_\varepsilon}$$

The lowest surface quality was achieved with the cutting speed of 60 m/min, the 0.25 mm/rev feed, which resulted in a surface roughness value of 2.82 µm. The formation of a built up edge (BUE), mainly on the chip roots, contributed to the increase in the surface roughness.

Also, it has been observed from the graph that the surface roughness for TiAlN coated inserts increases with an increase in feed rate for all cutting speed. But for AlCrN coated inserts it has been observed that the surface roughness does not deviate even for increase in feed. It may be attributed to the fact that AlCrN formed protective layer of chromium oxide which inhibits the formation of built up edge. Chromium oxide layer has better thermal stability than aluminium oxide layer of TiAlN coating. In addition, it was reported that the Cr in the AlCrN coating provides better adhesion strength[24,25] which leads to retain coating on the surface, eventually results in better performance.

3.4 Evaluation of main cutting force

The cutting forces are classified into three components; cutting force, speed force, radial force. The direction of feed force is along the direction of feed while main cutting force acts in the direction of cutting speed. Major cutting force has shown more influence on machinability compared to feed force and radial force, therefore it is discussed. Figure 6 shows variation of cutting force

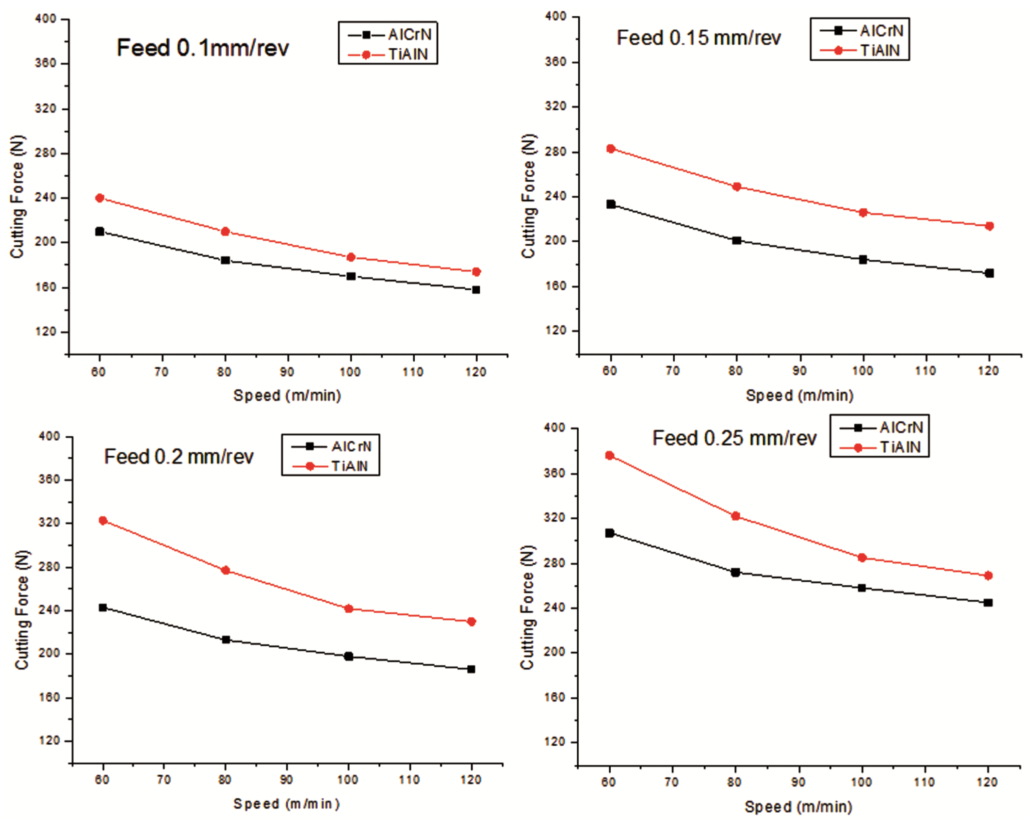

Fig. 6 — Effect of cutting speed on cutting force from feed of 0.1 mm/rev to 0.25 mm/rev

with cutting speed at various feeds, constant depth of cut 0.5mm.

Figure 6 indicates variation of cutting forces with respect to machining speed for AlCrN and TiAlN coated inserts. For both TiAlN and AlCrN coated inserts, graphs show falling behavior of cutting forces from cutting speed 60 m/min to 100 m/min and steady nature of cutting forces are observed further till cutting speed of 120 m/min. Highest values of major cutting forces of 376 N and 307 N for TiAlN and AlCrN coated insert respectively, are noted at low cutting speed (60 m/min) and high feed (0.25 mm/rev) is due to the fact that at low cutting speed, tool-work material contact time is high resulting in to high coefficient of friction and cutting temperature.

At higher cutting speed the machining temperature shoots up drastically and local work softening took place resulted into ease of machining advocating reduction in cutting forces between 100-120 (m/min) in the Ti6Al4V machining. Also, at higher cutting speed, contact time decreases which has contributed reduction in cutting force for AlCrN coated insert as compare to TiAlN coated insert.

3.5 Assessment of tool wear

In the machining of Ti6Al4V alloy, it is observed that flank wear has an unfavorable effect on surface finish, microstructure, induced stresses and cutting parameters. It is caused by abrasive and adhesive action between machine surface, leaving chips and cutting tool.

In present study, turning of α+β titanium alloy has exhibited not only adherence of work-material on the insert edge but also rubbing action of chips while leaving tool. Also, built-up edge formed has exhilarated abrasion and diffusion during machining operations. Gradual wearing at tool tip and uniform coating de-lamination highlights the effectiveness of tool coating in turning of titanium alloys. The variation of flank wear with cutting speed at various feed and constant depth of cut of 0.5 mm is plotted in Fig.7. It can be revealed from the graph that both coated inserts have shown incremental wear behaviour for all cutting speeds. However, AlCrN coated tool showed better performance as compared to TiAlN coated tool even at higher cutting speed of 120 m/min. This is because of lower coefficient of friction and high wear resistance of AlCrN coating than TiAlN coating. The reason for incremental

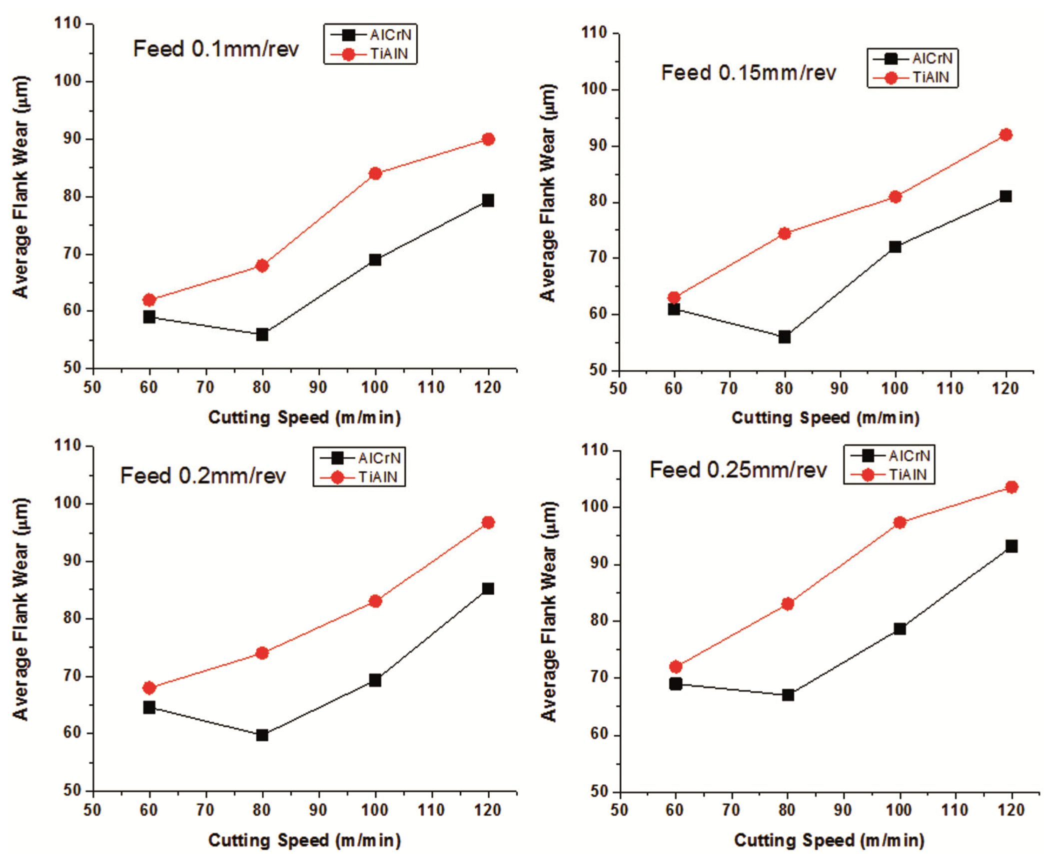

Fig. 7 — Effect of cutting speed on flank wear from feed 0.10 mm/rev to 0.25 mm/rev

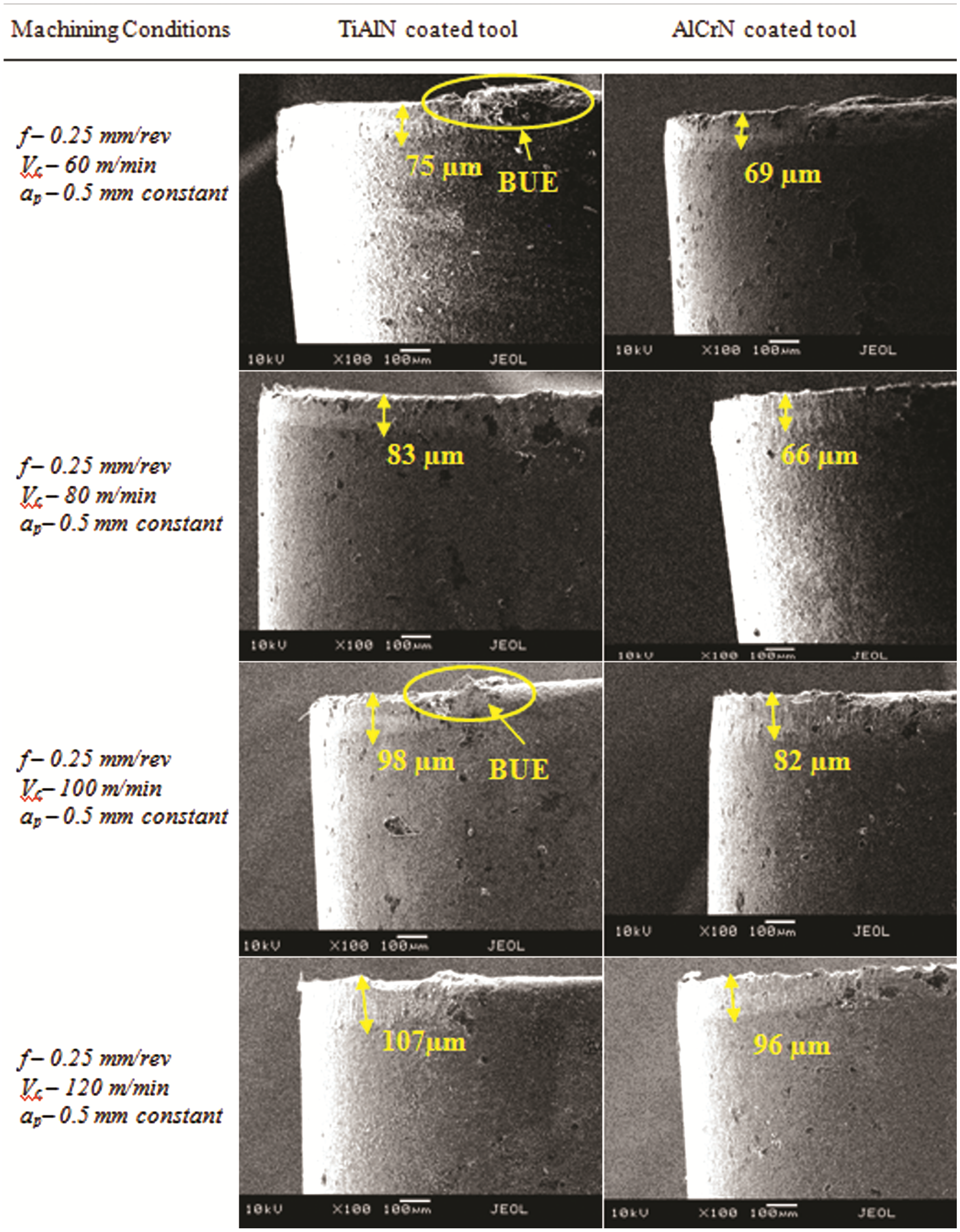

Fig. 8 — SEM images of flank wear

behaviour of flank wear is the result of thermal softening of tool tip by conduction of heat from the chips to the tool. In conjunction, at higher cutting speed temperature shoots up rapidly resulting into work hardening of Ti6Al4V. AlCrN coated inserts exhibited high wear resistance as compared to TiAlN inserts which is justified by SEM images of flank wear. Fig. 8 shows representative SEM images of flank wear for both coated inserts.

4 Conclusion

Based on performance and machining test results of various iterations of experiments performed to investigate machinability aspects and providing appropriate cutting parameters for high speed turning of Ti6Al4V.AlCrN coated inserts is deposited by high power magnetron sputtering technique shown superior microhardness of 33GPa along with highly dense structure. AlCrN coating is outperformed TiAlN coating at all cutting speeds during investigation of cutting forces and tool wear mainly due to better mechniacal and thermal stability. Turning at 100 m/min cutting speed and 0.1mm/rev feed has given least surface roughness value of 0.58 micrometer which indicates the feed is governing parameter for assessment of surface finish as compared to cutting speed, while the depth of cut has minimal effect on it.The abrasion flank wear is observed as dominant mechanism for all sets of experiments while built up edge formation was seen for cutting speeds of 60 m/min and 100 m/min and 0.2 mm/rev feed. Outcomes of this research work will be knowledgeable for Titanium alloy machining industries which will be a cost effective approach for machining of hard to cut Ti6Al4V alloy.

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