Surface Roughness and Micro hardness studies of dry machined Ti–6% Al–4% V with PVD-coated and uncoated carbide insert

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Abstract

Titanium and its alloys are attractive materials due to their unique high strength–weight ratio that is maintained at elevated temperatures and their exceptional corrosion resistance. In machining titanium alloys, generally, the cutting tools wear off very rapidly because of the high cutting temperature resulted from the low thermal conductivity and density of the work material. The surface of titanium alloy is easily damaged during machining operations due to their poor machinability. This paper gives the investigation on surface integrity of machining titanium alloy Ti–6% Al–4% V with coated carbide cutting tool. The experiments were carried out under dry cutting conditions and compared with uncoated carbide cutting tool. The cutting speeds selected in the experiment were 90, 100, 105 and 115 m min -1. The depth of cuts was 1.8, 2.0 and 2.2 mm. The feed rates used in the experiment were 0.135, 0.1475, 0.1725, 0.185 mm /tooth. For a range of cutting speeds, feeds, and depths of cut, measurements of surface roughness of machined surface, micro hardness were taken and studied. Microstructure alterations were studied for all the range of parameters with coated and uncoated carbide cutting tools.

Keywords – Carbide, PVD-coated, Surface Roughness, Micro hardness, Dry machining

I. INTRODUCTION

Increasing productivity in the metalworking industry through cost reduction without using the cutting fluid and at the same time saving the environment are benefits that can be gained from the implementation of dry machining. It should be noted that eliminating the cutting fluid involves the absence of its positive functions during the cutting process. The cutting fluids acts as the lubrication in reducing the friction, coolant in dissipating the heat and assistance in chip flow as flushing. High mechanical and thermal loads on the cutting tool and the machined surface, which increased tool wear and surface integrity alteration effects. To elucidate such damage phenomena, several studies have been developed on the milling process of titanium alloys [1–7]. Moreover, tool wear, tool life, cutting forces, and other cutting parameters under orthogonal and oblique cutting have been investigated [1, 8–13]. When the thermal property of titanium alloy is considered, the low thermal conductivity fails to dissipate the heat that generated during the cutting process; hence, heat becomes a main source of damage. In relation to dry machining, the absence of coolant fluids has the potential to increase the generation of heat during the cutting process more extensively and consequently. For this purpose, a study was carried out on the surface integrity of titanium alloy machined under a dry machining environment including surface roughness (in Ra parameter) and microhardness.

II. Experimental work

A. Materials

The insert-type cutting tool for end milling operation, rhomboidal in shape of length 11.5mm and width 6.5mm, made of uncoated carbide (WC–Ti/Ta/Nb–Co) (coded as Tool A) and multilayer PVD-coated alloyed carbide (WC–Ti/Ta/Nb– Co+TiAlN) (coded as Tool B) are used in this study. During end milling experiments, each insert was mounted on a tool holder to provide the end mill tool with a nominal diameter of 14 mm and tool signature of cutting rake angle of - 6°, axial rake angle of - 6°, and radial rake angle of - 2°. The properties for both cutting tools are given in Tables 1 and 2. The titanium alloy coded as Ti–6% Al–4% V is used as a work piece material in this study. The chemical composition and physical properties of Ti–6% Al–4% V are given in Tables 3 and 4. Fig.1(a) represents the base metal microstructure and Fig.1(b) shows a typical machined plate and Fig.1(c) represents the CNC Vertical Machining centre in which the experiments were conducted and Fig.2 represents the cutting tool holder and carbide inserts.

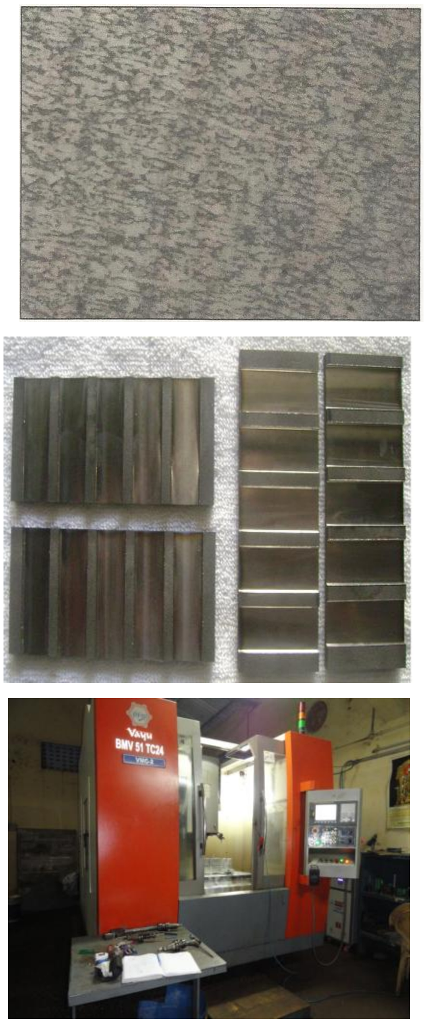

Fig.1. (a) Micro graph of base metal at 200X, (b) machined plate, (c) CNC vertical machining centre

Fig.2. Cutting tool holder and inserts used

B. *Experimental set-up*

A three-axis CNC vertical milling centre with a spindle speed up to 10,000 rpm was employed in this study. The machine tool was equipped with a hydraulic clamping system to fasten the work piece material firmly on its bed. Prior to machining trial using Tools A and B, these six surfaces of work piece material were machined by light face milling in order to remove the hard layer on the outer surface of the work piece material due to the forming process in factory line production. A series of experimental works were carried out with cutting conditions mentioned in the beginning of this paper. They are a cutting speed (Vc) of 90–115 m/min, feed (f) of 0.135–0.185 mm/ tooth, axial depth of cut (aa) of 1.8–2.2 mm, and radial depth of cut (ar) of 7.7 mm. The tool life rejection criterion for this study is flank wear of VB equal to 0.3 mm. The observation and measurement of the width of flank wear were carried out by a tool-makers microscope. Surface roughness was measured and observed using a surface profilometer.

Table I
Mechanical And Physical Property Of Tools

Substrate properties	Tools A and B
Content	68.80% WC, 9.60% Co, 19.70% Ti/Ta/Nb
Grain size (mm)	1-2.5
Hardness 25 °C (HV_{10})	1475
Hot hardness 800 °C (kg/mm^2)	591
Density (g/cm^3)	11.3
Conductivity (W/mK)	43
Thermal expansion (10^{-6}/K)	6.03
Young's modulus (GPa)	510
Traverse rupture (GPa)	2.23

Table II
Properties Of Coating Material For Tool B

Coating material	TiAIN
Method of deposition	PVD
Coating design (total of 9	3 layers
Hardness 25°C (HV_{10})	2300
Thermal cond. 727 °C	29
Thermal exp. (10^{-6}/K)	8.63
Melting point (°C)	3025
Density (g/cm^3)	4.11

For the other observations and measurements on machined surface integrity, the samples were taken from, after completion of DOC (depth of cut) 1.8mm, 2mm and 2.2mm. When the flank wear occurred of VB= 0.3 mm for each cutting condition it is considered as tool failure. The samples were prepared by hot mounted in Bakelite, ground using SiC paper, followed by a micro cloth using diamond suspensions (slurry) 9, 6, and 1mm and finally polished by a microcloth using SiO2 solution. The microhardness tests were conducted on those specimens.

TABLE III
Chemical Composition Of Titanium Alloy Ti–6% Al–4% V

Elements	Minimum	Maximum
Al	5.5	6.0
Zr	3.6	4.4
Mo	1.8	2.2
Sn	1.8	2.2
Fe	-	0.3
O_2	-	0.2
Si	-	0.1
C	-	0.1
N_2	-	0.05
H_2	-	0.0125
Y	-	0.005
V	-	4
Ti	to 100%	

TABLE IV
Physical Properties Of Titanium Alloy Ti–6% Al–4% V

Tensile strength (MPa)	827
Yield strength (MPa)	812
Creep stress (MPa)	240
Hardness (HRc)	~36
Density (kg/m^3)	4540
Linear thermal expansion	9.9
Thermal conductivity	08-12

III. Results and discussions

A. Surface roughness

All average Ra data recorded from each cutting condition during experiments are presented in Table V. From this table it can be seen that Ra values produced by Tools A and B are generally improved from the low level to the mid level of cutting conditions. However, an inverse trend is observed from the mid level to the high level where the Ra value is increased. From these results, it can be concluded that among three level cutting conditions, the best Ra value is given by the mid-level cutting condition. Moreover, there is a tendency that cutting speed has a significant effect on determining surface roughness.

It can also be seen from Table V that the Ra value produced by Tools A and B ranges from 0.45 to 0.93 mm and from 0.32 to 0.85 mm, respectively. These values indicate that there is significant discrepancy between Tools A and B. Therefore, when the range of Ra value produced by Tools A and B is concerned, the availability of uncoated material in Tool A is ineffective because they fail to produce better surface roughness than the coated one Tool B.

B. Micro hardness tests

Work hardening of the deformed layer beneath the machined surface up to 0.02mm caused higher hardness than the average hardness of the base material. However, the hardness of the subsurface at 0.03mm below the machined surface was below the average hardness recorded for the base material. The softening effect of the material at this level was probably due to over aging of titanium alloy as a result of very high cutting temperature produced at the local surface.

Further machining of the titanium alloy with the nearly worn tools tends to increase the hardening rate of the surface layer. Higher values of hardness were recorded at the higher cutting speed for the same feed rate. Minimal increment in hardness values were recorded when the feed rate was increased from 0.135 to 0.185 mm tooth −1 at the initial cutting stage. Significant increment in the micro hardness values was observed when comparing between the initial cut and the final cut.

When prolonged machining was carried out with higher flank wear, the hardness of the disturbed layer of the machined surface increased significantly. The highest hardness recorded was 324.175 HV when machining at a cutting speed of 115 m min −1 and feed rate of 0.185 mm tooth−1 after coated tool has failed. The highest hardness value was recorded at 0.005 mm beneath the machined surface.The increment in the hardness value was probably due to the work-hardening effect.

TABLE V
The Average Value Of Surface Roughness (Ra) For All Machined Surface Samples Produced By Tool A And Tool B

Cutting condition					Ra Average	
Level	V_c m/min	F mm/tooth	a_a mm	a_r mm	Tool A (uncoated)	Tool B (coated)
Low	90	0.135	1.8	7.7	0.89	0.72
	90	0.185	1.8	7.7	0.9	0.81
	90	0.135	2	7.7	0.82	0.75
	90	0.185	2	7.7	0.88	0.85
Mid	100	0.1475	2	7.7	0.58	0.48
	100	0.1725	2	7.7	0.82	0.59
	105	0.1475	2	7.7	0.45	0.32
	105	0.1725	2	7.7	0.64	0.41
High	115	0.135	1.8	7.7	0.87	0.69
	115	0.185	1.8	7.7	0.93	0.83
	115	0.135	2.2	7.7	0.92	0.76
	115	0.185	2.2	7.7	0.91	0.83

The variations of micro hardness depend on cutting condition and tool wear. The severity of cutting condition, from low to high level, and the progression of tool wear, from the initial to VB = 0.3 mm, play a non-negligible role in the value of micro hardness. The recrystallization and grain size can be directly related to the hardness values. The variations of micro hardness, in particular for the soft and the hard sub surfaces, are affected by the machining process. Indeed, micro hardness alteration may emanate from high temperature during dry machining coupled with the low heat conductivity of Ti–6% Al–4% V titanium alloy. When the work piece material is subjected to high cutting temperature and high cutting pressure generated during dry machining, a competing process between work hardening and thermal softening takes place and affects the fundamental behaviour of the work piece material.

Lapin and Pelachova [14], the softening process of the subsurface region can be characterized by the effect of ageing on micro hardness. The machined surface subjected to high cutting temperature during the machining process is similar to the ageing process. During ageing, the micro hardness of the lamellar and TiAl regions decreases with increase in ageing time.

A. Ginting and M. Nouari [15] referred the instability or alteration of microstructure in the form of plastic deformation caused by high temperature during dry machining leads to the softening of the titanium alloy sub-surface. The effect of internal work hardening depends on the temperature, the time, and the mechanism of internal stress relaxation. During machining, especially the milling process, internal work hardening is an accumulation of a cycle process due to the natural cutting mechanism of milling as an interrupted cutting. The internal work hardening accumulation for heating occurs when the engagement of tool for cutting the work piece material (entry) occurs and accumulation for cooling occurs when the disengagement of tool from the work piece material (exit) occurs.

TABLE VI
Micro Hardness Values With Pvd Coated Tool B

Range	**Expt No**	**Ra (average)**	**Vc m/min**	**Aa (mm)**	**Hv (average)**
low	A1	0.52	90	1.8	322.775
low	A2	0.51	90	1.8	306.1
low	A3	0.45	90	2	311.325
low	A4	0.51	90	2	326.375
mid	A5	0.42	100	2	308.425
mid	A6	0.53	100	2	312.125
mid	A7	0.48	105	2	315.85
mid	A8	0.58	105	2	308.225
high	A9	0.89	115	1.8	308.15
high	A10	0.83	115	1.8	311.65
high	A11	0.45	115	2.2	315
high	A12	0.79	115	2.2	325.675

TABLE VII
Micro Hardness Values With Un Coated Tool A

Range	Expt No	Ra (average)	Vc m/min	Aa (mm)	Hv (average)
low	B1	0.89	90	1.8	315.3
low	B2	0.9	90	1.8	323.85
low	B3	0.62	90	2	305.075
low	B4	0.63	90	2	316.25
mid	B5	0.58	100	2	307.75
mid	B6	0.82	100	2	323.6
mid	B7	0.45	105	2	312.525
mid	B8	0.64	105	2	312
high	B9	0.87	115	1.8	315.325
high	B10	0.93	115	1.8	315.85
high	B11	0.72	115	2.2	312.425
high	B12	0.75	115	2.2	311.3

C. Micro structure alterations for coated and uncoated carbide cutting tools

Fig.3 (a) shows the microstructure for A4 with Ra value 0.51 and hardness value as 326 at cutting speed 90m/min, 3(b) shows the microstructure for A5 with Ra value 0.42 and hardness value as 308.4 at cutting speed 100 m/min, 3(c) shows the microstructure for A12 with Ra value 0.79 and hardness value as 325.6 at cutting speed 115 m/min.

For the cutting speed 90m/min, the micro structure of the surface with different tools used showed that the surface machined with uncoated tool shows severe plastic deformation of the surface grains at the edge. The grains at the subsurface remained unchanged. The deformation of the grain has lead to the higher hardness and lower surface finish as measured by the surface rough tester. In contrast to the uncoated tool the coated tool with TiAlN showed lower hardness. The effect of machining with the coated tool had produced higher surface finish as measured. Out of the coated tool the TiAlN has given higher surface finish. The edge grains are unchanged.

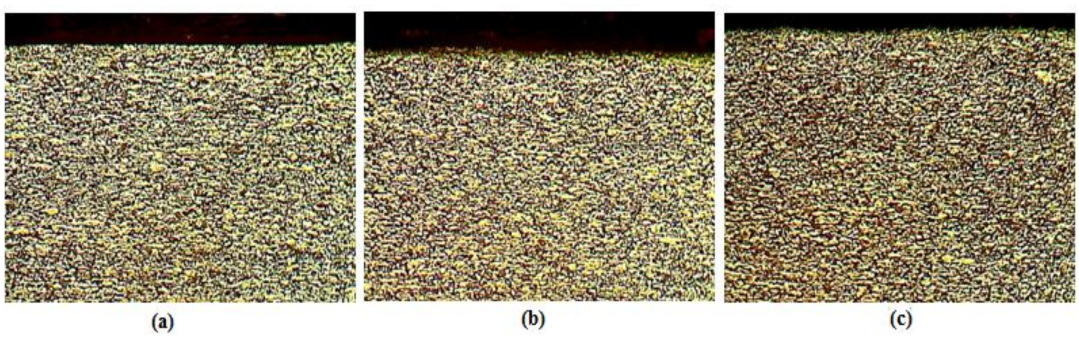

Fig.3. Micrograph with Coated carbide inserts with cutting speed at 90 m/min (b) 100 m/min (c) 115 m/min

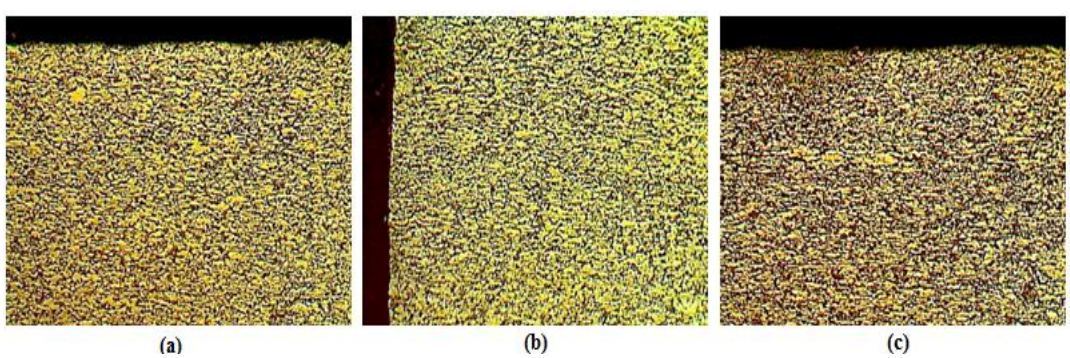

Fig.4. Micrograph with Un coated carbide inserts with cutting speeds (a) 90 m/min (b) 100 m/min (c) 115 m/min

Fig.4 (a) shows the microstructure for B1 with Ra value 0.89 and hardness value as 315.3 at cutting speed 90m/min, 4(b) shows the microstructure for B6 with Ra value 0.82 and hardness value as 323.6 at cutting speed 100 m/min, 4(c) shows the microstructure for B11 with Ra value 0.72 and hardness value as 312.6 at cutting speed 115 m/min. For the cutting speed 100 m/min, similar effect of the surface observed with different tools used at higher velocity and feed showed that the surface machined with uncoated tool shows severe plastic deformation of the surface grains at the edge. The grains at the subsurface remained unchanged. The deformation of the grain has lead to the higher hardness and lower surface finish as measured by the surface rough tester. In contrast to the uncoated tool the coated tool with TiAlN showed lower hardness. The effect of machining with the coated tool had produced higher surface finish as measured. Out of the coated tool the TiAlN has given higher surface finish. The edge grains are unchanged. It is observed that the coated tool with higher velocity showed similar gradient in the properties. All the tools have showed increase in surface finish with increase in velocity and feed rate and revolutions. For the cutting speed 115 m/min, the values of the Ra and Hardness showed different and in contrast to the first cases. The Ra value with the TiAlN showed lower which implies the higher surface finish. However the surface finishes on comparison with mid range parameters it is lower. Probably the higher heat input might have been the reason for it.

IV. Conclusions

In the present work, titanium alloy Ti–6% Al–4% V titanium alloy is dry machined (by end milling process) using uncoated and PVD-coated carbide tools to investigate the work piece surface integrity. The main results are summarised in the following:

- Cutting conditions and tool flank wear affect significantly the surface integrity.
- The best surface roughness value is produced at mid-level cutting condition (Vc = 100-105 m/min, f = 0.1475-0.1725 mm/ tooth, aa = 2.0 mm, ar = 7.7 mm) with a considerable sensitivity to the cutting speed.
- The Ra values produced by the uncoated carbide and the PVD- coated carbide tools range from 0.45 to 0.93 mm and from 0.32 to 0.85 mm, respectively. When the range of Ra value produced by Tools A and B is concerned, the availability of uncoated material in Tool A is ineffective because they fail to produce better surface roughness than the coated one Tool B.
- The top layer of the machined surface experience work hardening process, hence the hardness is higher than the average hardness of the work piece materials. However, the material beneath the top layer is softer as a result of over-aging of the materials.
- The highest hardness recorded was 324.175 HV when machining at a cutting speed of 115 m min −1 and feed rate of 0.185 mm tooth−1 after coated tool has failed.
- The coated tool showed better surface finish and hardness.
- The TiAlN showed consistent Ra values except at higher rpm.
- The uncoated cementite carbide tools showed poor surface finish and higher hardness due to higher deformation of the grains at the surface.
- The heating effect of the uncoated tool showed higher heating compared to the coated tools.

REFERENCES

[1] J.H. Xu, G.S. Geng, Experimental study on the milling of a Ti Beta 21S, Journal of Materials Processing Technology 129 (1–3) (2002) 190–192.

[2] K. Hirosaki, K. Shintani, H. Kato, F. Asakura, K. Matsuo, High speed machining of bio-titanium alloy with a binder-less PcBN tool, JSME International Journal, Series C: Mechanical Systems, Machine Elements and Manufacturing 47 (2004) 14–20.

[3] L. Li, N. He, J.H. Xu, Experimental Study on High Speed Milling of Ti Alloys, Materials Science Forum, vol. 471–472, Advances in Materials Manufacturing Science and Technology, Selected Papers from the 11th International Manufacturing Conference, 2004, pp. 414–417.

[4] R. Balkrishna, Y.C. Shin, A study on the high speed face milling of Ti–6Al–4V alloy, in: Proceedings of 2002 ASME

International Mechanical Engineering Congress and Exposition, New Orleans, LA, MED 13, 2002, pp. 277–286.

[5] E. Kuljanic, M. Fioretti, L. Beltrame, F. Miani, Milling titanium compressor blades with PCD cutter, CIRP Annals—Manufacturing Technology 47 (1) (1998) 61–64.

[6] A.R. Zareena, M. Rahman, Y.S. Wong, High Speed machining of aerospace alloy Ti–6Al–4V, in: 33rd International SAMPE Technical Conference—Advancing Affordable Materials Technology, November 5–8, 2001, Seattle, WA, vol. 33, 2001, pp. 739–750.

[7] D. Barnett-Ritcey, M.A. Elbestawi, Tool Performance in High Speed Finish Milling of Ti6Al4V, American Society of Mechanical Engineers, Manufacturing Engineering Division, MED, vol. 13, Proceedings of the ASME Manufacturing Engineering Division—2002, 2002, pp. 211–219.

[8] T. Kitagawa, A. Kubo, K. Maekawa, Temperature and wear of cutting tools in highspeed machining of Inconel 718 and Ti–6Al–6V–2Sn, Wear 202 (1997) 142–148.

[9] A. Ginting, M. Nouari, Experimental and numerical studies on the performance of alloyed carbide tool in dry milling of aerospace material, International Journal of Machine Tools and Manufacture 46 (7–8) (2006) 758–768.

[10] M. Nouari, A. Ginting, Wear characteristics and performance of multi-layer CVD-coated carbide tool in dry milling of titanium alloy, Surface and Coatings Technology 200 (18–19) (2006) 5663–5676.

[11] A. Ginting, M. Nouari, A study on tool performance to determine the optimal cutting conditions for dry end milling of an aeroengine material: Ti-6242S, Int. J. of Materials and Product Technology 31 (2008) 202–213.

[12] Sharif S and Rahim EA. Performance of coated- and uncoated-carbide tools when drilling titanium alloy—Ti-6Al4V.J Mater Process Tech2007; 185(1–3): 72–76.

[13] Beake BD, Smith JF, Gray A, et al. Investigating the correlation between nano-impact fracture resistance and hardness/modulus ratio from nano indentation at 25– 500°C and the fracture resistance and lifetime of cutting tools with Ti12xAlxN(x=0.5 and 0.67) PVD coatings in milling operations. Surf Coat Tech2007; 201(8): 4585– 4593.

[14] J. Lapin, T. Pelachhova, Microstructure stability of a cast Ti-45.2Al-2V-0.6- Si-0.7B alloy at temperatures 973-1073 K, Intermetallics 14 (2006) 1175-1180.

[15] A. Ginting, M. Nouari, Surface integrity of dry machined titanium alloys,International Journal of Machine Tools & Manufacture, 49 (2009) 325-332.

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