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Machining Challenges in Ti-6Al-4V Part Manufacturing

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ABSTRACT

Titanium alloy Ti-6Al-4V (Grade 5) is most popular material for Aerospace, Biomedical and Automobile field due to its inherent properties like high corrosion resistance, high strength to weight ratio is minimum, dimensional stability at elevated temperature. Titanium alloy metallurgy influences the machining process due to low modulus of elasticity, strain hardening, poor thermal conductivity and highly chemical reactivity. This article focuses on main difficulties impairing the machinability of Ti-6Al-4V. Machinability performance considered on following criteria: tool wear, chip morphology, lubrication techniques & their attributes on surface integrity. Finally described best techniques and proposed study on basis of present state of research in field of Titanium alloy machining.

Keywords— **Chip morphology, Lubrication techniques, Surface integrity, Tool wear.**

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I. INTRODUCTION

Titanium alloy most popular material having high strength to weight ratio, which is maintained at elevated temperatures [1]. The Ti-6Al-4V (α-β) offer high toughness, superb corrosion & creep -resistance, bio-capability [2]. It shows useful performance at temperatures up to about 600oc & 60% lighter than general steel [3]. As reason which is used in aerospace industry, where high strength & low weight are consciously important.

The machinability of titanium and its alloys is generally considered to be poor owing to several inherent properties of the materials. Titanium is very chemically reactive and therefore, has a tendency to weld to the cutting tool during machining, thus leading to chipping and premature tool failure. Its low thermal conductivity increases the temperature at the tool/ workpiece interface, which affects the tool life adversely. Additionally, its high strength maintained at elevated temperature and its low modulus of elasticity further impairs its machinability [4].

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According to C.T. Olofson, Problems in machining titanium originate from three basic sources: high cutting temperatures, chemical reactions with tools and relatively low modulus of elasticity. Unlike steel, titanium does not form a built-up edge on tools, and this behavior accounts for the characteristically good surface finishes obtained even at low cutting speeds. Unfortunately, the lack of a built-up edge also increases the abrading and alloying action of the thin chip which literally races over a small tool-chip contact area under high pressures. This combination of characteristics and the relatively poor thermal conductivity of titanium results in unusually high tool-tip temperatures. Titanium's strong chemical reactivity with tool materials at high cutting temperatures and pressures promotes galling and tool wear. Mechanical problems result from titanium's relatively low modulus of elasticity, half that of steel. The low modulus coupled with high thrust forces required at the cutting edge can cause deflections in slender parts. Distortion of that kind creates additional heat, because of friction between the tool and workpiece, and problems in meeting dimensional tolerances [5].

This article focuses on difficulties occurred during machining of Ti-6Al-4V part on CNC Lathe Machine through experimental work. It shows relationship between machining parameters like cutting speed, feed, depth of cut and surface integrity including study of tool wear, lubrication techniques.

The cutting processes usually lead to the production of large amount of chips that must be handled efficiently. In addition, chip formation affects machining forces, cutting temperature, tool life, and workpiece surface integrity. Therefore, it is important to understand the cutting conditions that result in chips that are easy to handle and minimize the negative effects on the cutting tool and workpiece surface. The formation of adiabatic shear bands is the most studied feature when analyzing the chip development during cutting of titanium alloys [11], [12].

Chip morphology can also be predicted by modeling and simulation process, although the predictions are not always accurate. For example, according to the conclusions of Calamaz et al. [12], in a study where they used a cutting speed 60m/min and Feed rate 0.1m/min rev for turning the Ti-6Al-4V alloy, the chips obtained from simulation were continuous while in the real cutting process the chips were segmented.

However, the mechanism of chip formation is still not completely understood, although shear instability and crack initiation and growth are the two main theories supporting this phenomenon [13]. In the case of machining titanium alloys, the mechanism is generally accepted to be based on thermo-plastic instability (also called adiabatic shear) within the primary shear zone, which occurs when the rate of thermal softening exceeds the rate of strain hardening [14]. In these alloys, the metallurgical transformation of α-phase (hexagonal close package) to β-phase (cubic body centered) during cutting process is also considered to foment the adiabatic shear because this last structure presents larger number of slip systems [14]. At low cutting speeds, initiation and propagation of crack is a mechanism of chip formation supported by some authors. The crack may start from the tool tip and propagates to the free surface of workpiece, or start from free surface and propagate toward the tool tip [15], [16]. According to A. Hosseini et al. when machining of titanium and its alloys, the chip is either formed by the propagation of crack from the exterior surface of the chip or development of adiabatic shear band which is primarily originated by the localized shear deformation [16]. In case of adiabatic shear, the machining is dominated by thermal softening rather than strain hardening [17]-[18]. Localization of Shear leads to significant periodic variation of machining forces and subsequently chatters vibration [19]. Cyclic variation of machining forces is not a desirable phenomenon as it imposes fatigue to the cutting tool or may cause chipping or breakage of cutting tool. It can be concluded from above-mentioned items that, titanium and its alloys comprise some unique mechanical and metallurgical characteristics that make them comparatively harder to cut than their other counterparts with equivalent hardness. In order to achieve an acceptable metal removal rate (MRR) at reasonable cost, appropriate tools, machining conditions, and processing sequence must be selected properly.

II. METHODOLOGY

This research study is mostly experimental and in this regard a number of machining experiments have been conducted. Initially samples of Ti-alloy (Ti-6Al-4V) of length100 mm and diameter 40 mm have been prepared for machining. A non conventional lathe machine (MTAB Slant Bed) has been used for turning the samples with varying cutting speeds. The feed rate (f) and the depth of cut (d) were varying from 0.05 to 0.3 mm/rev and 0.05 TO 0.6 mm respectively. To assess the machining challenges, tool life and average surface roughness (Ra) is considered criteria for Ti alloy machining. The whole process has been executed using PVD, CVD coated carbide inserts. During the entire cycle of experimental process, the time is recorded carefully for observing tool life in presence of different cooling techniques.

III. EXPERIMENTAL PROCEDURE

A. *Workpiece Material*

For experiment preparing the samples of Ti-6Al-4V bar of diameter 40 mm and length 100 mm has been cut from a long one. The chemical composition (wt. %) of that Ti bar is as follows in Table 1 [8]. After preparing the sample, the Ti-alloy bar was clamped on the MTAB CNC lathe machine using hydraulic 3-jaw chuck shown in Figure 1. During the machining process a cutting fluid of CAROL (Semi synthetic) has been applied to keep the cutting zone free from excessive heat and also to reduce friction.

B. *Machining Test*

The experiments were conducted on a MTAB CNC slant bed lathe machine centre with a maximum power of 7 kW and a maximum spindle speed of 6000 rpm. The cutting conditions employed in this investigation were cutting speed 20 m/min to 80m/min, feed 0.05 mm, axial depth of cut is varying from 0.05 mm to 0.6mm. Tool wear measurements of the insert were carried out using a HD camera system. After a period of machining, the photo of the worn clearance face was taken by digital camera; the surface roughness of the workpieces was measured by the aid of a stylus instrument. Surface roughness values of the workpieces were measured by MAHR-Perthometer M1 while measuring instrument and the measurements were repeated five times. To measure roughness of the surface of the workpiece, the cut-off length was taken as 0.3 mm and the sampling length is 5.8mm

TABLEI. Chemical composition of Ti-6Al-4V

Mat.	Aluminum (Al)	Vanadium (V)	Iron (Fe)	Oxygen (O)	Titanium (Ti)
wt%	6%	4%	0.25% max.	0.2% max.	89.75%

TABLEII. Mechanical properties of Titanium alloy (Grade 5)

Material	TS [MPa]	YS]MPa]	E [Gpa]	H [HV]	K [W/m.K]	β -Transus [°C]
Ti-6Al-4V (annealed bar)	895	825	110	340	7.3	995
Ti-6Al-4V (solution + age bar)	1035	965	-	360	7.5	995
AISI 1045 Cold-drawn	625	530	207	179	50.7	-

TS-Tensile strength; YS-Yield strength; E-Elastic modulus; H-Hardness; K-Thermal conductivity [9],[10], [1]

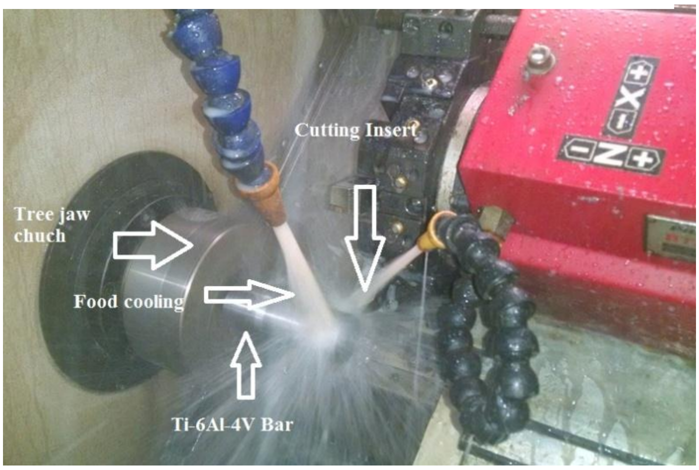


Fig.1 Experimental set up

The resources are utilized for this experimental work is given below:-

- CVD coated carbide insert OFCT 120404-MF1,890 and PVD coated LENX 120404-MF1,TS2000
- Tool holder (PCLNR 2525M12 JET)
- Lathe machine (MTAB SLANT BED)
- Surface Roughness Tester (MAHR-Perthometer M1)

After every cut, the surface roughness of the machined sample has been assessed by the MAHR-Perthometer M1 surface roughness measuring instrument. The coated carbide inserts which have been used in the experiment are suitable for machining of this type of super-alloys. The geometry of the both types of inserts is listed below:

CVD coated carbide insert OFCT

- Insert shape: Octahedral
- Hole shape: Cylindrical
- Chip breaker: Double-sided
- Cutting edge length: 12 mm
- Thickness: 6 mm
- Nose radius: 0.4 mm.

PVD coated carbide insert LENX

- Insert shape: Rhombus
- Hole shape: Cylindrical
- Chip breaker: Single-sided
- Cutting edge length: 12 mm
- Thickness: 6 mm
- Nose radius: 0.4 mm.

After every cycle of machining, the cutting inserts have been examined under the HD camera system to assess the tool wear; some images have been also saved by the camera shown in Fig.2

During machining coolant is forcefully spread at cutting zone for better heat dissipation and reduce thermal shocks.

IV. RESULT AND DISCUSSION

The tool life has been assessed by the duration as long as the insert has cut the workpiece maintaining the average surface roughness Ra up to 1.5 μm. It has been considered that this surface roughness value is acceptable by the industries for finishing cut, after getting the tool life for varying cutting speeds, Depth of cut with lubrication methods. These all values are plotted on following graph papers for two different types of carbide inserts. The graphs have been shown in Figure 2 to Figure 7.

TABLE III. Experimental Results for CVD Cutting tool

Run	Cutting speed (m/mm)	Feed Rate (mm/rev)	D.O.C (mm)	L.T.	T.L. (min)	Ra (μm)
1	20	0.11	0.18	Flood	45	1.81
2	20	0.15	0.2	TSL	40	1.77
3	20	0.17	0.11	Dry	13	3.31
4	20	0.18	0.05	Flood	30	1.55

From the experimental results Cutting speed, feed, depth of cut lubrication techniques are responsible for tool life, surface finish. These factors are mainly important in precision of part manufacturing with economical criteria. From observations machining of Ti-6Al-4V is really challengeable because material having poor thermal conductivity and low modulus elasticity.

TABLE IV. Experimental Results for PVD Cutting tool

Run	Cutting speed (m/mm)	Feed Rate (mm/rev)	D.O.C (mm)	L.T.	T.L. (min)	Ra (µm)
1	20	0.11	0.18	Flood	47	1.81
2	20	0.15	0.2	TSL	42	1.95
3	20	0.17	0.11	Dry	16	2.14
4	20	0.18	0.05	Flood	33	1.22
5	20	0.05	0.05	Flood	67	0.72
6	20	0.3	0.6	TSL	26	1.43
7	50	0.11	0.18	Flood	22	1.11
8	50	0.15	0.2	TSL	19	1.5
9	50	0.17	0.11	Dry	13	2.9
10	50	0.18	0.05	Flood	28	1.56
11	50	0.05	0.05	Flood	33	1.77
12	50	0.3	0.6	TSL	8	3.2
13	80	0.12	0.18	Flood	20	3.71
14	80	0.13	0.2	TSL	19	3.41
15	80	0.1	0.11	Dry	12	5.32
16	80	0.05	0.05	Flood	18	2.24
17	80	0.07	0.05	Flood	23	1.39
18	80	0.08	0.6	TSL	17	2.21

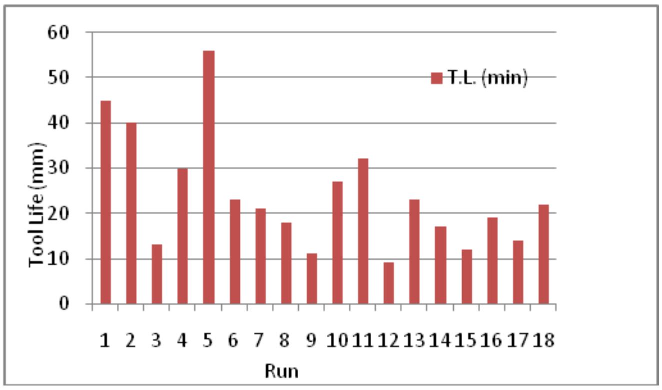


Fig.2 Tool Life Curve for CVD insert

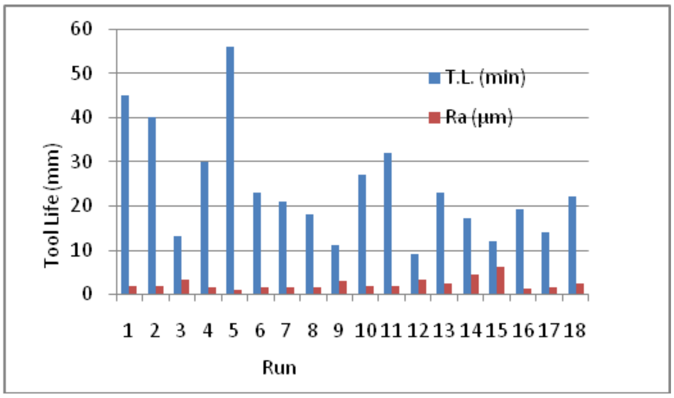


Fig.3 Tool Life and Ra value with CVD insert

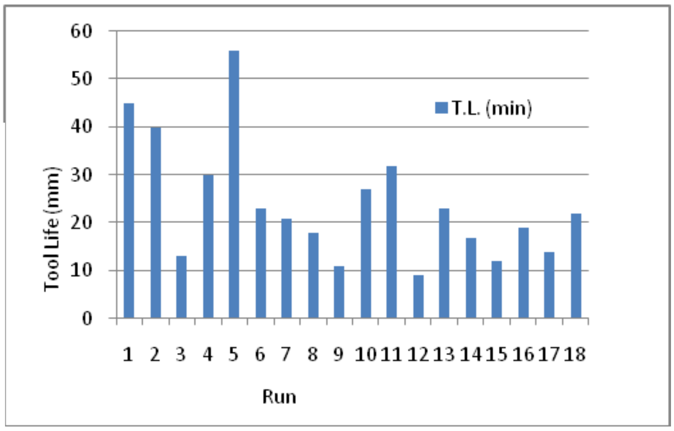


Fig.4 Tool Life Curve for PVD insert

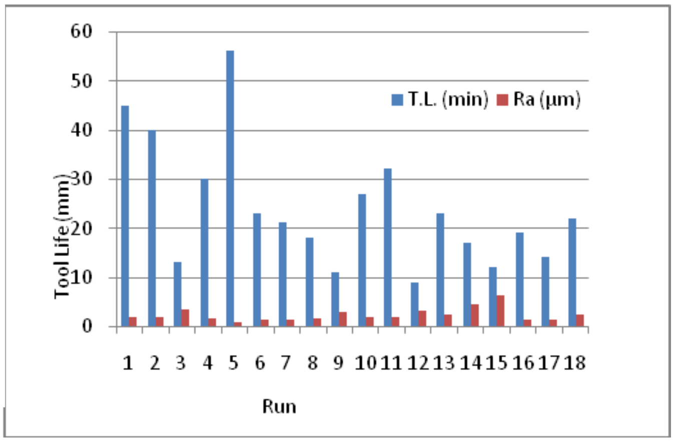


Fig.5 Tool life and Ra value with PVD insert

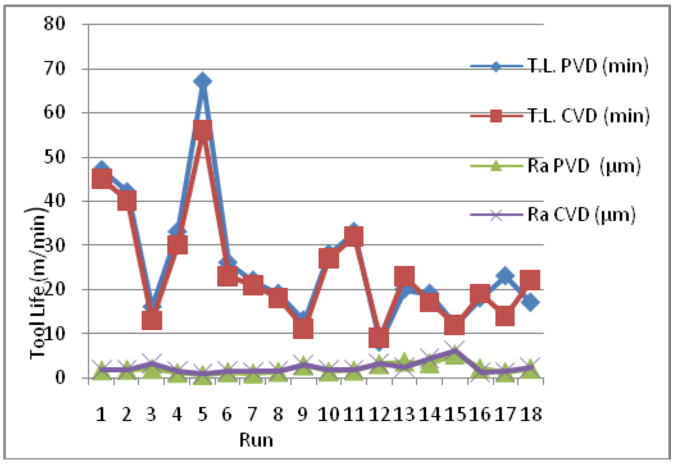


Fig.6 Comparison of Tool Life and Ra values of PVD & CVD coated Inserts

To compare the tool life, it has been noticed that PVD coated carbide tool shows longer life than the CVD coated carbide inserts at range of 20-80 m/min cutting speed with varying feed rates and depth of cut including different cooling system. It has been also detected that the tool wear is lower for PVD coated carbide inserts as compared to CVD coated carbide inserts shown in Figure 7. & the resulting surface finish is better by using the PVD coated ones. On the contrary, at higher cutting speeds, the tool life is reasonably better for PVD coated carbide inserts

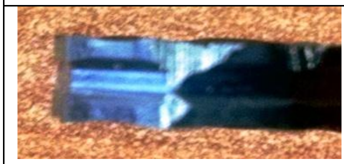
	Insert- CVD Cutting Speed-20 m/min Feed Rate-0.05 mm/rev D.O.C.-0.05 mm L.T.- Flood T.L.-56 min
	Insert-CVD Cutting Speed-50 m/min Feed Rate-0.3 mm/rev D.O.C.-0.6 mm L.T.-TSL T.L.-3.21 min
	Insert-CVD Cutting Speed-80 m/min Feed Rate-0.1mm/rev D.O.C.-0.11 mm L.T.- Dry T.L.-6.2 min
	Insert- PVD Cutting Speed-20 m/min Feed Rate-0.05 mm/rev D.O.C.-0.05 L.T.- Flood T.L.- 67 min
	Insert- PVD Cutting Speed-50 m/min Feed Rate-0.3 mm/rev D.O.C.-0.6 L.T.- TSL T.L.-8 min
	Insert- PVD Cutting Speed-80 m/min Feed Rate-0.1 mm/rev D.O.C.-0.11 mm L.T.-Dry T.L.-12 min

Fig.7 Tool Wear at Different Machining Conditions

V. CONCLUSION

From the above experimental observations and comparative graphs for PVD & CVD coated carbide tools gives following conclusions.

- Tool life of PVD coated insert is better than CVD coated insert at varying machining condition.
- Minimum cutting speed, feed rate, depth of cut and Flood cooling gives better tool life and acceptable average surface roughness value for Ti-6Al-4V part.
- Dry machining is not recommended for Titanium alloy machining because it consume cutting tools fastly as well as worst surface finish.
- Ti-6Al-4V material shows poor machinability during machining because of strain hardening at cutting zone area.
- From the experimental values accepted machining condition for Ti-6Al-4V is given below.
    - ➢ Insert- PVD
    - ➢ Cutting Speed-20 m/min
    - ➢ Feed Rate-0.05 mm/rev
    - ➢ D.O.C.-0.05
    - ➢ L.T.- Flood
    - ➢ T.L.- 67 min
    - ➢ Ra.-0.72 µm

VI. PROPOSED WORK

Ti-alloy machining is still challengeable for Aircraft part manufacturers due to its inherent metallurgical properties, which influences the machinability and create challenges in material removing mechanisms for providing better solution following research is proposed in this area are

- Study and analysis of chip morphology.
- Cutting tool material selection.

- Cryogenic cooling techniques.
- Multi axis machining for high productivity.
- Finding machining parameters, which give better surface finish (0.3-0.8 µm).

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