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Machinability of Titanium Grade-5 Alloy (Ti-6Al-4V) During Turning Processes: A Review

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Abstract - *Titanium grade-5 alloy Ti-6Al-4V is the most common alloy widely used in Aerospace and Automotive industries, Petrochemical applications and Biomedical parts manufacturing; this is due to its excellent combination of mechanical properties and high corrosion resistance at elevated temperature, but on other hand Ti-6Al-4V alloy shows poor machinability during machining processes because of its low thermal conductivity, low elastic modulus, high strength and high chemical reactivity. The machining characteristics of titanium alloy grade-5 Ti-6Al-4V have not been completely reported so far, this paper focuses on turning process of this alloy in cases of; tool materials used, special techniques employed to improve cutting process machinability, cutting tool failure modes and wear mechanisms, cutting forces, cutting temperature and surface integrity.*

Key Words: Ti-6Al-4V alloy; Especial Techniques; Tools wear.

1. INTRODUCTION

Titanium and its alloys have an excellent grouping of mechanical properties and corrosion resistance which makes them very attractive for numerous applications as well as in power generation gas turbines, aerospace industries, chemical plants, automotive industries, and many other applications and industries. The low thermal conductivity, low elastic modulus, high hardness at high temperature and high chemical reactivity are the main factors for low down machinability of those alloys [1-5].

The machining characteristics of titanium alloy grade-5 Ti-6Al-4V have not been fully reported, this paper focuses on the turning process for this alloy in cases of chip formation, cutting forces, cutting temperature and the influences of its properties on the machinability of the process.

Fig-1: Titanium crystal-bar [1].

2. Titanium Alloys Classification

Titanium alloys are divided into four categories: alpha alloys (α), near-alpha alloys, alpha-beta alloy (α + β), and beta alloys (β) [2,4,5].

2.1 Alpha (α) alloys

Pure titanium and titanium alloyed with α-stabilizer are classified as α-alloys. They are non-heat treatable and are weldable. They have low to medium tensile strength, good notch toughness, and excellent mechanical properties at cryogenic temperature.

2.2 Near-alpha (α) alloys

These alloys are highly α-stabilized and contain only limited quantities of β-stabilizing elements. They behave more like α-alloys and are capable of operating at a greater temperature between 400C° and 520 C°.

2.3 Alpha-Beta (α + β) alloys

These alloys feature both α and β phases and contain both α and β stabilizers. The simplest and most popular alloy in this group is Ti-6Al-4V alloy, which is mainly used in the aerospace industries. Alloys in this category are easily formable and exhibit high room-temperature strength and moderate high-temperature strength. The properties of these alloys can be altered through heat treatment.

2.4 Beta (β) alloys

Beta (β) alloys contain transition metals, such as V, Nb, Ta, and Mo, which stabilize the β phase. Beta alloys are readily heat-treatable, weldable, and have high strength. However, β alloys are prone to ductile-brittle transition and thus are unsuitable for cryogenic applications. Beta alloys have a good combination of properties for sheet, heavy section, fasteners, and spring applications.

Table-1: Selected properties of Ti-6Al-4V alloy in its two main metallurgical conditions [2-4,6].

Material	TS [MPa]	YS [MPa]	E [GPa]	H [HV]	K [W/m.K]
Ti-6Al-4V (Annealed)	895	825	110	340	7.3
Ti-6Al-4V (Solution+ age)	1035	965	-	360	7.5

TS-Tensile strength; YS-Yield strength; E-Elastic modulus; H-Hardness; K-Thermal conductivity.

Table-2: Chemical composition of Ti-6Al-4V alloy (wt%) [7-10].

Content	Composition
C	0.05
Fe	0.09
N	0.01
O	-
Al	6.15
V	4.4
H	0.005
Ti	Balance

3. Properties of Titanium Grade-5 Alloy (Ti-6Al-4V)

Titanium grade-5 alloy being the most commonly used titanium alloy, accounting for over 45% of the total titanium production [1,2]. The Ti-6Al-4V alloy is employed commonly in two metallurgical conditions: annealed, and solution treated and aged [4]. Table 1 gives the mechanical properties of Ti-6Al-4V alloy [2-4,6]. Table 2 shows the chemical composition of Ti-6Al-4V alloy [7-10].

Fig.2 provides information on the effect of temperature on Ti-6Al-4V alloy properties [3,4]. As temperature increases; the thermal conductivity k increases (Fig.2a), decreases of hardness H (Fig.2b), decreases of ultimate tensile strength UTS (Fig.2d). With increasing temperature seem to be positive for machining, in terms of heat removal rate and magnitude of cutting force respectively. But the decrease of elastic modulus E (Fig.2c) results in more weakness for workpiece deflection and vibration during machining [3,4].

4. Applications of Titanium Grade-5 Alloy (Ti-6Al-4V)

Because of its superb mechanical properties and corrosion resistance, Ti-6Al-4V alloy cover up 50% of worldwide utilization [4] in many areas and applications as following: Aerospace Industry: airframe structure, wings, landing gear, floor support structure, engine fan discs and blades, compressor disc, and compressor blades [1,2,4,7,11]. Automotive Industry: frame structures, suspension springs, armor, body, engine outlet-intake valves, and connecting rods [1,2,4,11]. Medical Applications: hip, knee joints, and dentals [1,2,4,7,11].

Petrochemical: for building heat exchanger and reactors, because of high level of corrosion resistance and heat tolerance [1,11].

5. Machinability of Titanium grade-5 Alloy (Ti-6Al-4V)

Titanium grade-5 alloy is difficult to cut (poor machinability), due to its peculiar characteristics (Table1). High cutting temperatures generate during machining of this alloy as a result of its low thermal conductivity. About 80% of the heat generated when machining titanium grade-5 alloy is conducted into the tool material because of the low thermal conductivity of Ti-6Al-4V alloy [2].

High chemical reactivity with almost all cutting tool materials at cutting temperatures excess of 500 C° [2]. Low elastic modulus which is an attitude cause of the chatter during machining and high hardness-strength (high resistance to deformation) at high temperatures.

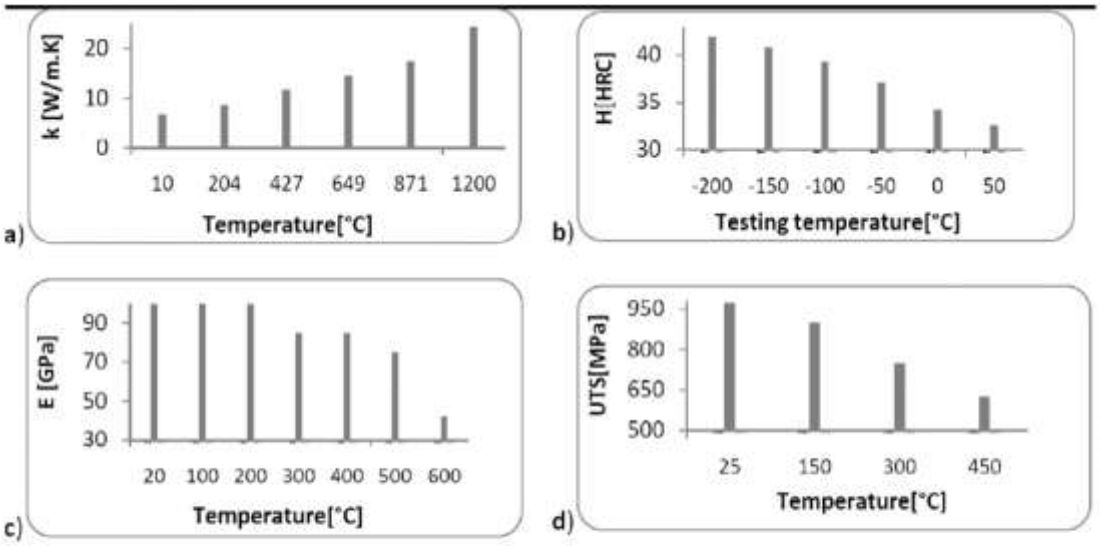

Fig-2: Influence of temperature on the properties of Ti-6Al-4V alloy [3,4].

K-Thermal conductivity; H-Hardness; E-Elastic modulus; UTS-Ultimate tensile strength.

5.1 Effect of Properties on the Machinability

5.1.1 Thermal Conductivity

Low thermal conductivity of Ti-6Al-4V alloy causes a concentration of heat on the tool cutting edge, which influences negatively on the tool life [3,8,10,11]. The low thermal conductivity of this material does not allow the heat generated during machining to dissipate from the tool edge. This causes lofty tool tip temperatures and intense tool deformation and wear [5]. It has been observed that depending on the tool material, up to 50% of the heat generated during machining can be transferred to the cutting tool [11].

5.1.2 Elastic Modulus

Low elastic modulus of Ti-6Al-4V alloy allows the deflection of the minor workpiece under tool pressure, inducing chatter and tolerance troubles [3]. The low modulus of elasticity of this material causes greater workpiece spring back and deflection of thin-walled structures resulting in tool vibration, chatter, and poor surface finish [5,10]. During machining, whilst the tool touches the workpiece and cutting pressure is applied, titanium's elasticity makes the workpiece spring away from the tool, which causes cutting edge being rubbed alongside the workpiece surface rather than performing the cutting action. Rubbing rather than cutting raises the abrasion and as a result raises the temperature at the cutting region. However, rubbing as well as demolishes surface excellence and dimensional precision [11].

5.1.3 Chemical Reactivity

Reactivity with cutting tool materials causes galling, smearing and chipping of the workpiece surface and immediate tool wear. Reactivity with common gases such as oxygen, hydrogen and nitrogen directs to the formation of oxides, hydrides and nitrides, respectively. These phases cause embritlement and reduce the fatigue of the alloy [3]. The high chemical reactivity of titanium alloy causes the weld-chip on the tool faces, leading to hasty tool failure [5]. Even with its chemical inertness at room temperatures which makes it of the best options for medical implants. Titanium becomes greatly reactive whilst the temperatures go away over 500 C°.

5.1.4 Hardness and Strength

The high strength and hardness of titanium alloys require high cutting pressure that outcomes in deformation on the cutting tool during cutting. High dynamic shear strength while cutting induces coarse saw-tooth edges, producing tool notching [3]. Titanium alloys preserve strength at elevated temperatures and exhibit low thermal conductivity, this distinctive asset does not allow heat generated to dissipate from the cutting edge, causing high tool tip temperatures and excessive plastic deformation leading to higher cutting forces [5].

5.2 Influence of Cutting Parameters during Turning of Ti-6Al-4V Alloy

5.2.1 Cutting Speed

Cutting speed has the majority considerable influence on tool life, and increasing of cutting speed caused a linear increase dynamic force frequency during turning of Ti-6Al-4V alloy [2,3]. Turning experiments were carried out by Satyanarayana KOSARAJU et al. [8] using coated tungsten carbide inserts for cutting of Ti-6Al-4V alloy, it is found that cutting speed and depth of cut are significant cutting parameters affecting cutting force. S. THAMIZHMANII and S. HASAN [9] during turning of Ti-

6Al-4V alloy observed an improvement in surface quality at higher cutting speed with lower feed rate. Turning process of Ti-6Al-4V alloy using PVD coated carbide was performed by R. VINAYA and Anthony M. XAVIOR [10], the percentage influences of cutting speed was 25.51%, 8.6% and 7.2% on the output parameters of cutting temperature, surface roughness and cutting force respectively. Jagadesh T. and Samuel G. L. [12] have performed a micro turning of Ti-6Al-4V alloy using coated carbide tool (TiN/Al TiN), they obtained that when the cutting speed increases there is a decrease in cutting forces while uncut chip thickness is greater than the cutting edge radius that was because the increase in tool-chip interface temperature. During dry and wet machining of titanium Ti-6Al-4V alloy using uncoated carbide inserts, observed that surface roughness and energy consumption decreased by increasing cutting speed and material removal rate [13]. However, the similar outcome was obtained during dry high speed turning of Ti-6Al-4V alloy with PVD coated carbide inserts which was conducted by Rajendra PAWAR and Raju PAWADE [14], they have observed that the machined surface generated at 170 m/min has higher values of surface roughness (3.44 μm). Nevertheless further increase in the cutting speed to 190 m/min causes a reduction in the surface roughness to 1.34μm.

5.2.2 Depth of Cut

C. VEIGA et al. [3] observed that the vibrations increased with increasing the depth of cut up to 0.8 mm and then decreased, the jump of vibrations is perhaps caused by friction phenomenon and low Young's modulus. The percentage influences of the depth of cut was 36.54%, 24.36% and 49.39% on the output of cutting temperature, surface roughness and cutting force respectively, this outcome obtained during turning of Ti-6Al-4V alloy which has done by R. VINAYA and Anthony M. XAVIOR [10]. Experimental study conducted by Vikas UPADHYAY et al. [15] on the turning process of Ti-6Al-4V alloy with a cemented carbide bit (ISO S-grade), obtained that tangential cutting force is affected the most by the depth of cut.

5.2.3 Feed Rate

Often the tool life is not changed dramatically with a change in feed, but titanium alloys, however, are very sensitive to change in the feed rate [2]. Turning of Ti-6Al-4V alloy with PVD coated carbide conducted by R. VINAYA and Anthony M. XAVIOR [10] showed that the influence percentage of feed was 19.82%, 52.32% and 29.55% on the output parameters of cutting temperature, surface roughness and cutting force respectively. Experimental work of turning Ti-6Al-4V ELI alloy with PVD coated (TiAlN) inserts performed by V. G. SARGADE et al. [16], obtained that the feed rate is the most significant factor influencing the surface roughness and the cutting force is affected strongly by the feed rate. The optimum cutting parameters were achieved by MINITAB17 software, which is the cutting speed of 66.97 m/min and feed rate of 0.08 mm/rev [16]. J. NITHYANA et al. [17] optimized the cutting parameters in dry turning of Ti-6Al-4V alloy performed using nano coated carbide inserts, they observed that the feed rate is the dominant parameter affecting the surface roughness, which is followed by the cutting speed.

5.2.4 Cutting Edge Radius

Turning of Ti-6Al-4V alloy with PVD coated carbide inserts, the percentage influences of nose radius was 0.56%, 0.25% and 0.49% on the output parameters of cutting temperature, surface roughness and cutting force respectively [10], and surface roughness is mainly influenced by the edge radius of the cutting insert and uncut chip thickness [12]. DORLIN et al. [18] noted that the tool contact radius seems to have a significant effect on cutting forces, in the case of an acceptable worn cutting edge, also the cutting forces increase when the tool contact radius grows.

5.3 Especial Techniques Employed to Improve-ment Cutting Process Machinability

5.3.1 Micro-Grooved Tool

In order to diminish the friction on tool rake face, various micron-scale textures were projected on tool rake surface. Dry turning of Ti-6Al-4V alloy using a micro-grooved cemented carbide tool has performed by J. XIE [19] obtained that the micro-grooved tool may diminish cutting temperature by 103C° and more compared with a traditional plane tool. In the small material removal rate, the 25μm-depth micro-grooved tool could diminish cutting temperature and cutting force by 20% and 32.7% against traditional plane tools respectively. In large material removal rates, it diminishes cutting temperature by 27.2% and cutting force by 56.1% [19].

5.3.2 Minimum Quantity Lubrication

MQL is a sustainable alternative to synthetic cooling in terms of tool wear and surface roughness [6,20]. Ibrahim DEIAB et al. [21] have done a turning process on Ti-6Al-4V alloy using PVD coated cermet turning inserts, with cutting environment of mixture of low temperature air with internal vegetable oil based mist (MQL+CA). It has been found that (MQL+CA) strategy decreased the average cutting temperature by 26.6%, 17.9% and 17.5% than the temperature obtained in dry environment at cutting speed levels of 90, 120 and 150 m/min respectively.

5.3.3 Rotary Tooling

It has been shown conclusively that rotary tools give rise to several hundred degrees centigrade lower cutting temperatures when machining titanium alloys. Tool lives are approximately seven times those of conventional tools when machining Ti-6Al-4V alloy using the rotary tool at very high feed rates (up to 1mm/rev) [2]. Continuous rotation of the rotary tool minimizes the tool wear due to continuous change of specific solicited position on the cutting edge [3].

Experiments done by Grant PARKER [22] showed that the self-propelled rotary tool for hard turning of Ti-6Al-4V alloy achieved superior tool wear resistance and extraordinary improvement in tool life, relative to a fixed tool. Chipping appeared to be the dominant failure mode and lower cutting temperature associated. Self-propelled rotary tool (SPRT) turning tests were carried out for Ti-6Al-4V alloy by Utku OLGUN and Erhan BUDAK [23], the tests showed a superior tool wear resistance and extended tool life are achieved in rotary turning process, and also the cutting with flood and MQL cooling have positive effects on the tool life for SPRT [23].

5.3.4 High Pressure Coolant (HPC)

Turning operations on Ti-6Al-4V alloy were carried out with chemical-based water soluble oil as coolant by Suresh PALANISAMY et al. [24], obtained that tool life increases with increasing coolant supply pressure from 6 to 90 bar, the increase in tool life with HPC arises due to two interrelated mechanisms: the mechanical fracture and evocation of chips and due to improved thermal conditions during cutting Plain turning experiments were carried with uncoated microcrystalline (ISO grade K20) inserts by A. K. NANDY [25], showed that tool life improved at least by 250% over that in conventional wet environment when using a high pressure cooling with water-soluble oil, also the cutting forces are reduced significantly under high-pressure cooling environment. Rosemar B. DaSILVA et al. [26] achieved the same results with using polycrystalline diamond (PCD) inserts, the best results were encountered at 20.3MPa coolant pressure. The cutting fluids are supplied under high pressure and very close to the critical point on the secondary shear zone, which allows high cutting speed, adequate cooling and excellent chip breakability and removal. The application of this technique results in a segmented chip, lower cutting force, better tool life and acceptable surface finish [3,27].

5.3.5 Cryogenic Cooling Technique

For machining titanium alloys, this technique increase tool life, don't cause environmental pollution and improve productivity through the use of higher feed rate [3,27]. Six different lubrication techniques including cryogenic cooling (with liquid Nitrogen) evaluated by Syed WAQAR RAZA et al. [20] during turning operations of Ti-6Al-4V alloy with uncoated cemented carbide inserts, they have obtained that cryogenic cooling turned out to be a recommendable alternative by outperforming flood cooling, even at higher feed and speed [20]. Under LN_2 environment, a large reduction of 60% in the work-tool interface temperature is observed due to effective cooling at the shear zone. A large increase of 20% in the cutting force was observed [28]. Cryogenic cooling with liquid nitrogen jets enables substantial reduction in tool wear, both on creator and flank surfaces in turning operations of Ti-6Al-4V alloy by uncoated carbide inserts [29]. Experiments on the turning of Ti-6Al-4V alloy with PVD (TiAlN) coated tungsten carbide inserts were carried out by M. DHANANCHEZIAN and Pradeep M. KUMAR [30] , obtained that cryogenic cooling using liquid nitrogen reduced the cutting temperature, cutting force, surface roughness and tool wear by 61-66%, 35-42%, 35% and 39% over wet machining respectively.

5.3.6 Preheating and Hot Machining

Preheating the workpiece in order to minimize the required cutting force, improve surface finish and increase tool life. Preheating methods include laser beams, high frequency induction and others [3]. Using preheating condition in 330-360C° would be the best temperature for preheating conditions in machining Ti-6Al-4V alloy up to 60% of reduction of acceleration amplitude of chatter can be achieved, increase the tool life by 30% and reduction in surface roughness by 40 to 55% [31].

6. Tool Materials for Turning Titanium grade-5 Alloy (Ti-6Al-4V)

The paramount quality required of tool materials to improve the machinability of titanium alloys are: high hot hardness to resist the high stresses involved, good thermal conductivity to minimize thermal gradients and thermal shock, good chemical inertness to depress the tendency to react with titanium, toughness and fatigue resistance to withstand the chip segmentation process, and high compressive tensile and shear strength [2]. The main tool materials used in machining titanium alloys include: uncoated and coated cemented carbides (WC/Co), polycrystalline diamond (PCD), polycrystalline boron nitride (PCBN) and cubic boron nitride (CBN) [2,11,32]. To protect the tool against wear and to reduce the friction between chip and cutting tool various coating materials such as TiN, TiCN, TiAlN and many others such as Al2O3 are widely used [2,11,12,21,32]. According to Vamsi KRISHNA and Anthony XAVIOR [33] the application of cutting fluid is not necessary when machining of titanium alloy is carried out with cubic boron nitrate (CBN) and polycrystalline diamonds (PCD).

7. Tool Failure Modes and Wear Mechanisms when Turning Titanium grade-5 Alloy (Ti-6Al-4V)

Notching, flank wear, crater wear, chipping and catastrophic failure are the prominent failure modes when machining titanium alloys, these being caused by a combination of high temperature, high cutting stresses, the strong chemical reactivity of titanium, the formation process of catastrophic shear chip and other factors [2]. Syed WAQAR RAZA et al. [20] used an uncoated cemented carbide inserts (grade-H13A) with nose radius of 0.81mm, for turning of Ti-6Al-4V alloy under six different lubrication techniques (flood, dry machining, vegetable oil MQL, cooled air, cryogenic with liquid nitrogen and MQCL vegetable oil + cool air). It was observed that adhesive and abrasive wear mechanisms were dominant at the flank face; also diffusion and micro-chipping were observed along with the formation of BUE and BUL (Fig.3).

Experimental study performed by Rosemar B. DaSILVA et al. [26] using polycrystalline diamond (PCD) inserts for turning Ti-6Al-4V alloy under high pressure coolant delivery system. It was obtained that the flank (and nose) wear are the dominant failure modes when using conventional and high pressure coolant supplies. Adhesion and attrition are dominant wear mechanisms (Fig.4).

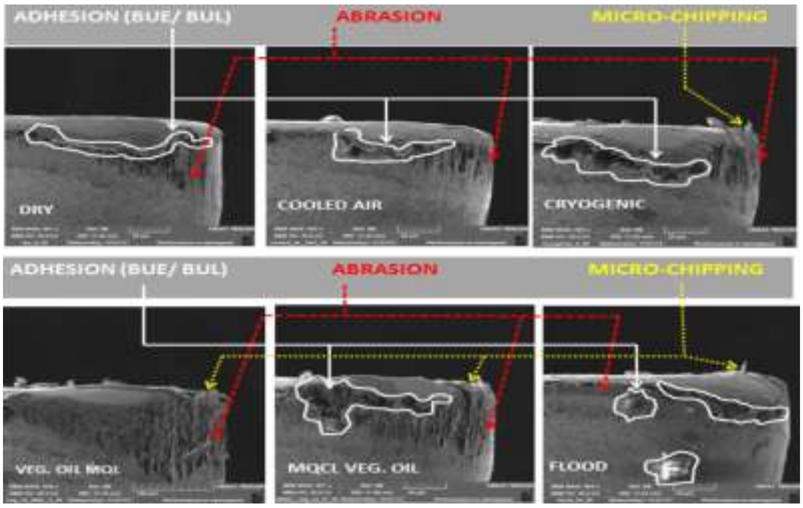

Fig-3: Scanning Electron Microscope (SEM) at feed=0.1mm/rev and cutting speed=120m/min [20].

Fig.5 presented the outcome was obtained by K. A. VENUGOPAL [29] during the turning process of Ti-6Al-4V alloy with (ISO K20 SNMA 120408) type uncoated carbide inserts with a nose radius of 0.8mm. It was observed that creator wear occurred predominantly by adhesion, dissolution and diffusion wear. The same outcomes obtained by Salman PERVAIZ et al. [34].

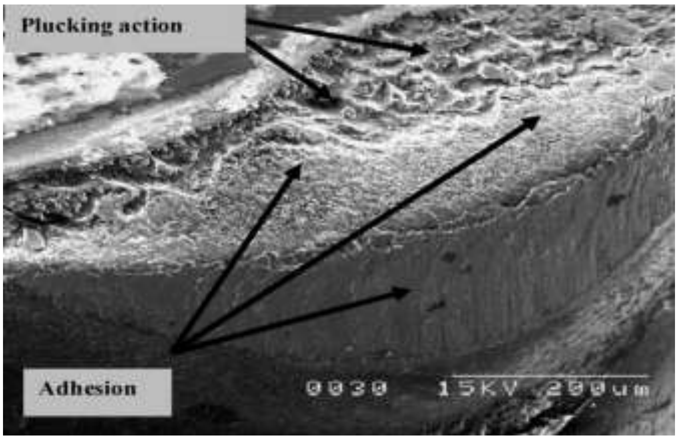

Fig-4: Worn PCD insert after machining with 11MPa coolant pressure at speed of 230m/min (tool life=17.5min) [26].

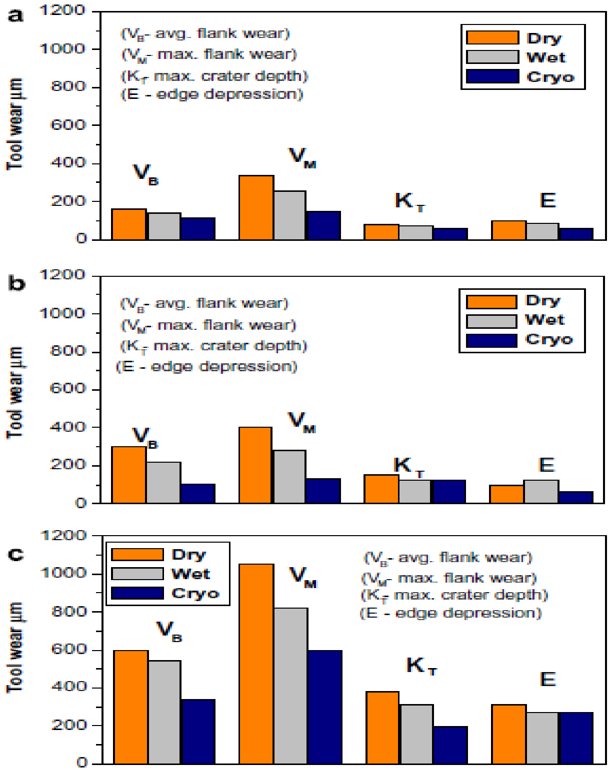

Fig-5: Different tool wears after 5min of machining at: (a) 70m/min; (b) 85m/min and (c) 100m/min, and feed of 0.20mm/rev in all the cases [29].

8. Conclusions

In conformity to the considerations obtained in this paper, we might draw the following conclusions. In general it is customary that the titanium and its alloys properties, including high strength at elevated temperature, low elastic modulus, chemical reactivity and low thermal conductivity effect in a negative way the machinability of titanium. However, mainly of the studies and examinations carried out on the machinability of titanium alloy grade-5 Ti-6Al-4V were based on various cutting conditions, that make it hard to evaluate and compare the outcome from various researchers. A number of methods for improving the machinability have been studied by global researchers and the common available reports show substantial developments in the machining processes, but there are needs of work to compare these procedures and verify the conditions which is most advantageous. Generally, there is a development to employ the environment friendly fluids to improve the machinability of titanium alloy grade-5 Ti-6Al-4V. Important raise in the cutting temperature may take place during the turning of titanium alloy grade-5 Ti-6Al-4V if no cooling procedure is used. New approaches for reducing cutting fluids application in machining of titanium alloy grade-5 Ti-6Al-4V have been examined and promising results such as dry machining, advancements on cutting tool materials have been reported. Moreover new coating technologies for various cutting tools have provided important advantages to reduce cutting fluid application in machining operation. Sustainable turning of titanium alloy grade-5 Ti-6Al-4V is cleaner, safer, and environmental-friendly method. Productivity is also high, as cryogenic cooling shows better results at higher feed rates. Tool life improves dramatically owing to the fact that cryogen able to be penetrating the chip–tool interface. Notching, flank wear, crater wear, chipping and catastrophic failure are the major failure manners when machining titanium alloy grade-5 Ti-6Al-4V, these being caused by a grouping of elevated temperature, high cutting stresses, and the high chemical reactivity of titanium.

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