Machining Challenges in Ti-6Al-4V.-A Review

Patil Amit S.
Department of Mechanical Engineering
MET'S IOE,Bhujbal Knowledge City,Nashik, Maharashtra, India

Ingle Sushil V.
Department of Mechanical Engineering
MET'S IOE,Bhujbal Knowledge City,Nashik, Maharashtra, India

More Yogesh S.
PG Student, Department of Mechanical Engineering
R.H.SAPAT College of Engineering,Nashik, Maharashtra, India

Nathe Manik S..
PG Student, Department of Mechanical Engineering
S.V.I.T, Chincholi, Nashik, Maharashtra, India

Abstract- Titanium alloy (Ti-6Al-4V) Grade 5 is most popular alloy widely used in Aerospace, Automobile and Biomedical part manufacturing due to its inherent properties like high strength to weight ratio is minimum at elevated temperature, dimensional stability, great corrosion resistant etc. but on other hand Ti-6Al-4V shows machining challenges on base performance criteria like metallurgical aspect, chip formation, cutting tool wear, lubrication strategy and surface integrity. In this paper study of various machining problem discussed by different researchers and their probable solution, which helps to reduce tool wear, high surface finish with effective lubrication strategy by reducing machining complexity. The conclusion presented at the end which highlights easy trends and future work for improving Titanium alloy machining.

Keywords – chip formation, lubrication strategy, metallurgical aspect, surface finish, tool wear, Ti-6Al-4V

I. INTRODUCTION

Titanium alloy most popular material having high strength to weight ratio is minimum 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].

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]. As per study of Siekmann "machining of titanium and its alloys would always be a problem, no matter what techniques are employed to transform this metal into chips." The poor machinability of titanium and its alloys have led many large companies (for example Rolls-Royce and General Electrics) to invest large sums of money in developing techniques to minimize machining cost [6]. Reasonable production rates and excellent surface quality can be achieved with conventional machining methods if the unique characteristics of the metal and its alloys are taken into account [7]. According to investigation of 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].

Most of researchers have been described various methods & tricks to machine the Titanium alloy but still it shows challenges to Titanium alloy part manufacturer. However new machining methods, technology continuously developed by researchers for that purpose additional literature always needed.

This article focuses on Metallurgical aspect of Ti-6Al-4V and its behavior during machining, Chip formation and Cutting Tool wear, Lubrication during machining& surface integrity. These are responsible for manufacturing challenges during working with Titanium alloy. The main conclusions presented at end, with some recent techniques and future research area.

II. METALLURGICAL ASPECT OF TITANIUM ALLOY (GRADE 5)

Titanium has been recognized as an element (Symbol Ti; atomic number 22; and atomic weight 47.9) for at least 200years [12]. Titanium was first discovered by the mineralogist and chemist, William Gregor in 1791. Four years later, Martin Klaproth, based on the story of the Greek mythological children, the Titans, named the element as titanium. After that, more than 100 years were necessary to isolate the titanium metal from its oxide. Finally, the first alloys, as well as the popular Ti-6Al-4V alloy, were developed in the late 1940s. The Ti-6Al-4V alloy is the most common used alloy among the commercially available titanium alloys. The reason for this success is the good balance of its properties and the intensive development and testing of this alloy during the approximately last 60 years [13]. Titanium alloys are widely used in different industries that require excellent mechanical resistance at high temperatures and resistance to corrosion. However, machining of titanium alloys presents some difficulties caused by the particularities in term of metallurgical properties [10], [11]. We are focusing on metallurgical property of Ti-6Al-4V; Table 1 gives chemical composition of Ti-6Al-4V (Grade 5) [15].

TABLE I. CHEMICAL COMPOSITION OF TITANIUM ALLOY (GRADE- 5)

Material	Aluminum (Al)	Vandium (V)	Iron (Fe)	Oxgen (O)	Titanium (Ti)
wt%	6%	4%	0.25% (max.)	0.2% (max.)	89.75%

Pure titanium (Ti) undergoes a crystallographic transformation, from hexagonal close packed, hcp (alpha, α) to body-centered cubic, bcc (beta, β) structure as its temperature is raised through 1620ºF / 882°C. Alloying elements, such as tin (Sn), when dissolved in titanium, do not change the transformation temperature, but elements such as aluminum (Al) and oxygen (O) cause it to increase. Such elements are called "α stabilizer." Elements that decrease the phase-transformation temperature are called "β stabilizers." They are generally transition metals. Commercial titanium alloys are thus classified as "α," "α-β," and "β." The α-β alloys may also include "near α" and "near β" alloys depending on their composition [14]. If the amount of beta stabilizer added to the titanium is larger (4–6 %) than that in near alpha (α) alloys (1–2 %) a new category of titanium alloys called α + β alloys will be generated [16]. Different combinations of microstructures and consequently mechanical properties can be developed by heat treating α + β alloys. The heat treatment improves the strength and makes this category of titanium alloys a principal choice for elevated temperature's (350–400°C) application. IMI 550 (Ti-4Al-2Sn-4Mo-0.5Si) and especially Ti-6Al-4V.which is one of the most commonly used titanium alloys in industry belong to this group [8]. During machining these alloys metallurgy influences the some properties as per many researchers observation at very high-speed dry turning of Ti-6Al-4V, the white layer was not form on surface [18], [19]. These works present a change in the grain direction in line with the tool pass, but no phase transformation in the machined surface exist, even when using a wide range of cutting speed. However, a particular thin zone (thickness from 0.5 to 5 μm) was observed near to the machined surface with grains quasi-parallel to the cutting direction [18]–[21].

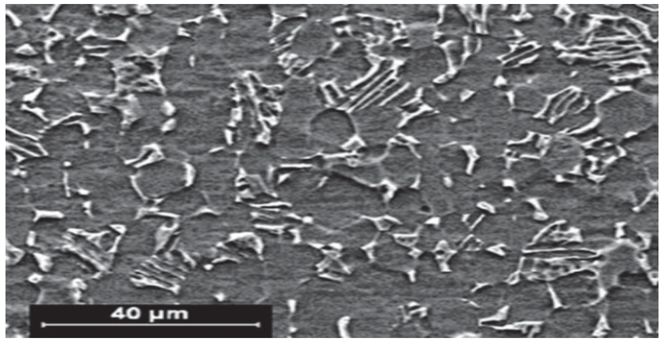

Figure 1. Microstructure of the Ti-6Al-4V alloy [17]

As discussed earlier, the Ti-6Al-4V is the most highly used titanium alloy, which can be generally found in two phases α and β. the microstructure of the Ti-6Al-4V alloy, as shown in Fig.1 [17]. The high temperatures generated during cutting caused by the low thermal conductivity of the Ti-6Al-4V alloys can produce a softened zone under the surface [21]. It has been found that the roughing affects the microstructure of the machined surface but not significantly compared to the finishing pass that defines the thermo mechanical state of the real surface [21].

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	-

Table 2 gives comparison of Ti-6Al-4V with mild steel which shows Ti-6Al-4V have low thermal conductivity, low elastic modulus, high hardness and strength at elevated temperature, metallurgical characteristics that make them somewhat more difficult to machine than steels of equivalent hardness. The fact that Ti-6Al-4V sometimes is classified as difficult to machine by traditional methods in part can be explained by the physical, chemical and mechanical properties of the metal. For example:

- Titanium is a poor conductor of heat. Heat, generated by the cutting action, does not dissipate quickly. Therefore, most of the heat is concentrated on the cutting edge and the tool face, influencing negatively the tool life.
- Titanium has a strong alloying tendency or chemical reactivity with materials in the cutting tools at tool operating temperatures. This causes galling, welding and smearing along with rapid destruction of the cutting tool.
- Titanium has a low modulus of elasticity, thus it is more "springy" than steel. This means that the workpiece tends to move away from the cutting tool unless heavy cuts are maintained. Slender parts tend to deflect under tool pressure and this can cause chatter, tool rubbing and hence tolerance problems. Rigidity of the entire machining system is consequently very important, as is use of sharp properly shaped cutting tools [24]-[25].
- Titanium's work-hardening characteristics are such that titanium alloys demonstrate a complete absence of "built-up edge". Because of the lack of a stationary mass of metal (BUE) ahead of the cutting tool, a high shearing angle is formed. This causes a thin chip to contact a relatively small area on the cutting tool face and results in high loads per unit area. These high forces, coupled with the friction developed by the chip as it passes over the cutting area; result in a great increase in heat on a much localized portion of the

cutting tool. All this heat (which the titanium is slow to conduct away), and pressure, means that tool life can be short, especially as titanium has a tendency to gall & weld to the tool surface [24].

According to Bai et al. demonstrated that the workpiece material around the cutting edge region is subjected to a severe strain and undergoes several physical and metallurgical changes [26]. In this way Metallurgical properties create challenges in front of Ti-6Al-4V machining. As per Rahman et al. presented that the poor thermal conductivity of titanium alloys results in heat accumulation in the primary shear zone that contributes to shear localization and chip segmentation, which in turn leads to high temperatures and the associated alpha-beta phase transformation in the secondary deformation zone.

III. CHIP FORMATION

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 [27], [28].

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. [28], 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 [29]. 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 [30]. 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 [30]. 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 [31], [32]. 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 [32]–[36]. In case of adiabatic shear, the machining is dominated by thermal softening rather than strain hardening [33]-[34]. Localization of Shear leads to significant periodic variation of machining forces and subsequently chatters vibration [37]. 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.

Gente et al. [44]. Reported the chip formation of Ti–6Al-4V at very high cutting speed, ranging between 30 m × min-1 and 6,000 m × min-1 as shown in Fig. 2, 3 According to experimental results, the structure of segmentation was changed at the cutting speed exceeding 2,000 m × min-1. Furthermore; no change in specific cutting energy coincides with this change in structure [44].

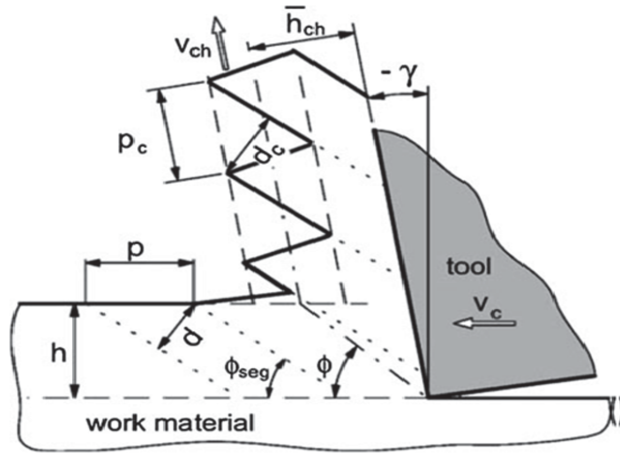

Figure 2. Schematic diagram of segmented chip formation at machining of titanium alloys [44].

Palanisamy et al. [45] studied the effects of HPC in machining of titanium alloys and observed that longer tool life and better surface finish were resulted when using HPC as shown in Fig. 4, 5. The microstructures and morphology of chip formation of 4340 steel, 6061-T6 aluminum alloy and Ti–6Al-4V titanium alloy were examined during orthogonal cutting tests under various levels of cutting speed [46]. The chip formation in Ti–6Al-4V titanium alloys appeared to be segmented at all speed, but it became continuous macroscopically at high speeds. The chip formation in machining titanium alloys is strongly influenced by the microstructural state of the material [38], [40].

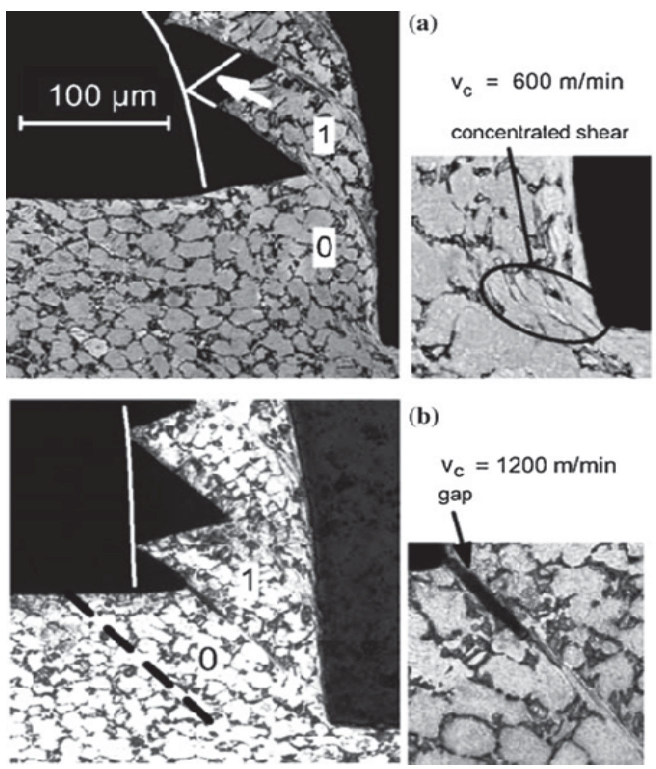

Figure 3. Different stages of titanium chip formation [44]. **a.** Cutting speed at 600 m/min **b.** Cutting speed at 1200 m/min

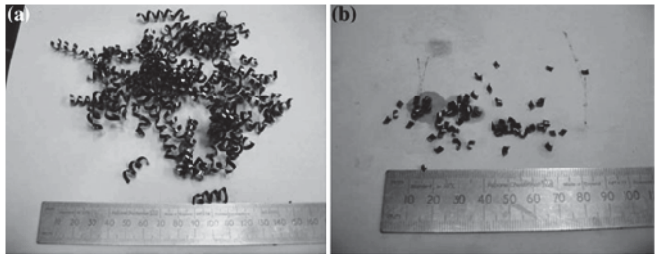

Figure 4. **a**. Chips obtained after 1 min cutting time (first cut) from the application of a standard pressure coolant and **b**. HPC [45]

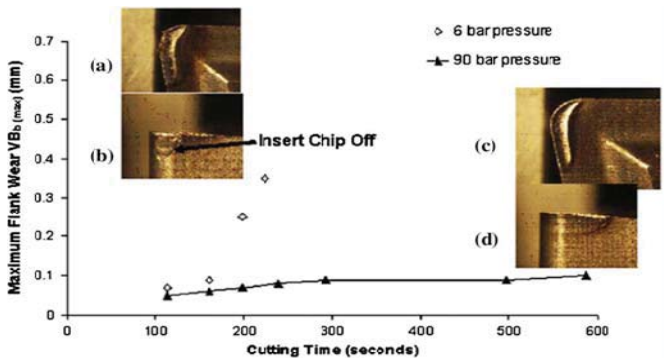

Figure 5. **a.** Tool wear along with a crater view and **b.** flank view of the insert obtained after tool chip-off with the application of standard pressure coolant. **c.** crater view and **d.** flank view of the insert [45]

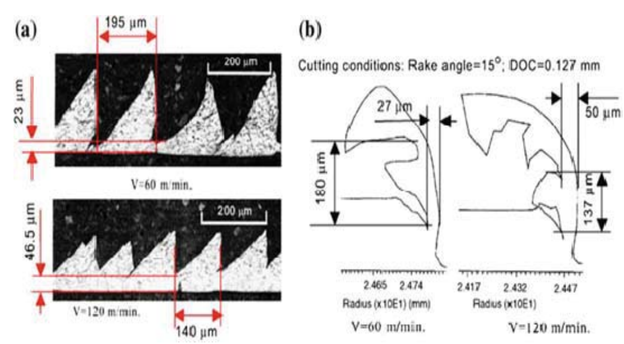

Figure 6. Titanium chip morphology: **a**. Experimental results; **b.** Simulation results [48]

The feasibility of dry cutting process in machining Ti–6Al-4V titanium alloys with cemented tungsten carbide tools was investigated in [41]. The rake angles 0, 15 and 30° as well as three cutting speeds (15, 30 and 60 m × min-1) and three feeds (0.1, 0.2 and 0.3 mm x rev-1) were used and morphology of chip formation, cutting force components and tool wear were recorded. A significant correlation was found between the evolution of cutting forces, the tool damage modes and the work part surface roughness, which all indicate the significant influence of the cutting parameters and the insert geometry on the tool wear and on the quality of the finish surface as shown in Fig. 6. Several analytical and numerical modeling of chip formation mechanism and morphology during machining titanium alloys are reported in literature [39], [42], [43] but none can adequately predict the chip formation profile.

Experimental and analytical investigations of the shear localization phenomenon in orthogonal machining of commercially pure titanium alloys were reported in [42] and a thermo-plastic criterion for the onset of localization was presented. It was found that in a wide range of cutting speeds used, the flow localization in the machining Ti-6Al-4V is thermo-plastic. It was observed that at low cutting speeds, micro cracks preceded flow instability. Generally segmented chips occur during machining titanium alloys under wide range of cutting speeds and feed rates. This phenomenon is considered as a major concern during machining titanium alloys.

IV. Tool wear

The extent of cutting tool wear depends on the tool material and geometry, workpiece material, cutting parameters, cutting fluids and machine-tool characteristics. The wear land of the cutting tool insert is the area of the cutting tool, near the cutting edge, was the insert is worn during machining [47]. Two basic areas of tool wear are flank wear and crater wear, but several other mechanisms also occur [20]. Tool lifetime is often measured in terms of crater or flank wear according to ISO 3685:1993 [54]. Tool wear characteristics are often represented as a plot of material wear versus sliding distance, or time of cut, for a certain tool-workpiece combination. Figure 7 shows a schematic graph of the width of flank wear land (VBB) vs. cutting length, including different wear regions describing the evolution of tool flank wear. After plotting wear versus cutting length, the curve often has three distinct regions [47].

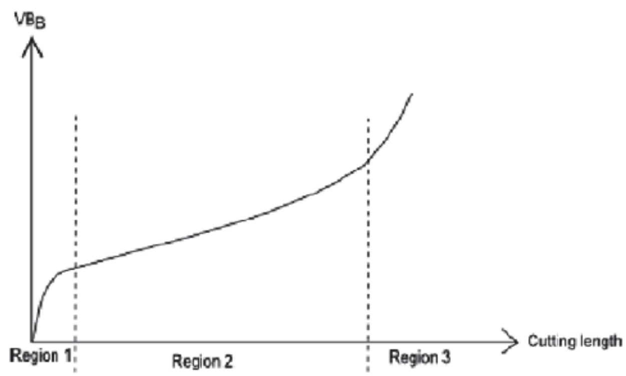

Figure 7. Schematic graph of tool wear evolution and its different regions [47].

Region 1: primary or initial wear region with relatively high wear rate depending on accelerated wear due to damage of tool layer during manufacturing
Region 2: steady-state region where normal operation for the cutting tool should occur.
Region 3: accelerated wear region, which stops with failure. This region is often accompanied by high cutting forces and temperatures in combination with severe tool vibrations. As per study of tool wear by Stina Odelros 2006, some basic type of wear is explained above [47].

- Crater wear is wear located at the rake face of the tool, in the form of a crater [53]. The rake face suffers from severe pressure and temperature loads, and crater wear is mainly caused by diffusive wear due to cutting tool material on the rake face dissolving into the chip material. Therefore, crater wear is very temperature sensitive and strongly depends on the solubility of tool material in the chip material. Crater wear is often measured by a profilometer as the maximum depth of the crater formed on the rake face of the tool [53].
- Flank wear is wear formed on the cutting tool’s relief surface as a flat-worn surface. Investigations of flank wear [53] suggest that flank wear depends mostly on abrasion from unwanted rubbing of clearance face against workpiece material. Flank wear is measured as the width of flank wear land, VBB, and is often measured microscopically [53] as shown in Fig. 8.

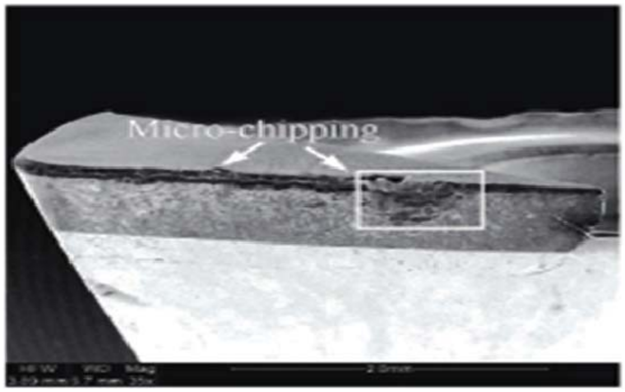

Figure 8. Flank wear at cutting tool surface [67].

- Notch wear is mainly caused by a fracture process or a chemical reaction as discussed by Turkes et al. [52].Notching happens when excessive localized damage occurs at the flank and rake face simultaneously, causing a single groove formation as shown in Fig.10 Once formed; a notch will cause poor micro-finish on

Figure 9. Chipping wear at cutting tool edge [68].

- Chatter wear also known as machining vibrations, is a self-excited vibration problem, resulting in waves on the machined surface. Although chatter is not a proper wear mechanism on its own, it is often associated with accelerated tool wear and loud noise levels. Chatter in titanium machining occurs because of the low modulus of elasticity of titanium alloys, causing deflection of the material when subjected to cutting pressure [50]. Titanium alloys deflect nearly twice as much as carbon steel, giving a larger bouncing action when the cutting edge enters the cut [52].

Figure10. Notch wear at cutting tool edge [14].

According to A. Hosseini et al. its chemical inertness at room temperatures which makes it one of the best options for medical implants, titanium becomes highly reactive tools when the temperature goes beyond 500 °C. When the temperature increases, chemical reaction occurs between titanium and cutting tools which quickly obliterate the tool [8], [71]. As a result, the majority of currently available cutting tools, even the hardest ones, are not appropriate for machining titanium and its alloys due to chemical affinity which deteriorate the cutting tool by initiating chemical wear [70].

Ezugwu and Wang [8] presented a review on the main problems associated with titanium machining, including tool wear and the mechanisms responsible for tool failure. They suggest that uncoated WC/Co cutting tools are better than most coated cutting tools for machining a titanium alloy. The high chemical reactivity of titanium causes welding of workpiece material on the cutting tool during machining, leading to chipping and premature tool failure. The prominent failure modes in titanium machining were: notching, flank wear, crater wear, chipping, and catastrophic failure. Different tool materials have different responses to different wear mechanisms. Crater wear is closely related to the chemical composition of the cutting tool. The conclusions presented by Ezugwu and Wang suggest that dissolution diffusion wear dominates on the rake & flank face for uncoated cemented carbides used for the turning of titanium alloys. At very high cutting speeds and temperatures, the conclusion is that plastic deformation and development of cracks due to thermal shock will be the dominating wear mechanisms. Change of feed rate, depth of cut or cutting speed give changes in the wear rates, and also suggest that cutting fluids have to be used during titanium machining to minimize high stresses and temperatures. The cutting fluid has to work both as coolant and lubricating agent to lower the cutting forces and avoid chip welding, which is a phenomenon often experienced during titanium machining [8].

Jianxin et al. suggested that high cutting temperatures present during titanium machining with WC/Co cutting tools promote thermally related wear phenomena, such as element diffusion through tool-chip interface, which could give a change in composition of the material and a very high tool wear rate. Author performed test on Ti-6Al-4V material and got further result through Scanning Electron Microscope (SEM) analysis with an Energy-Dispersive Detector (EDS) detector, both diffusion and oxidation wear were observed by the authors during high cutting speeds. The main wear mechanisms occurring on the rake face during wear tests were found to be diffusion and adhesive wear. Through diffusion tests it was found that elements from the cutting tool material diffused into the workpiece material and that elements from the workpiece material diffused into cutting tool material at temperatures exceeding 400˚C [58].

As per the more study of tool wear, author suggest ideal properties of cutting tool material [1], they are beneficial for economical machining of Ti-6Al-4V. The properties are given below:

- High hardness at elevated temperatures to resist the high stresses involved.
- Chipping resistance especially due to the segmented chip formation.
- Toughness and fatigue resistance also to withstand the chip segmentation process.
- Reduced tendency to react with titanium.
- High compressive strength.
- Good thermal conductivity to minimize thermal gradients and thermal shock on tool.

V. Lubrication During Machining

Lubrication and cooling strategies for titanium machining operations are areas where the cutting process can be improved. During interrupted cutting the tool is subjected to cyclic heating and cooling that can cause thermal shock [62]. When the rate of cooling is increased significantly, the result can be thermal shock, causing catastrophic tool failure, if the thermal load (at elevated cutting speed) is too high for the tool material [64]. Su et al. [65] connect cyclic thermal shock directly with thermal crack initiation. The low thermal conductivity of Ti6Al4V causes a concentration of the heat build-up in the cutting zone [66]. When the cutting zone is shielded from the lubricant stream such as in cutting with deep axial immersion, the coolant needs to be focused on the cutting edge [64]. At high tool temperatures, typically above 550 ºC, the heat transfer mechanism between the cooling fluid and the tool surface changes to two phase high-speed flow [62]. The coolant is vaporized on contact with the heated tool surface, forming an insulating boundary layer on the tool surface. The phenomenon is also described as delayed surface wetting in heat transfer literature [62]. The performance of the different lubrication strategies for finish milling with PCD is shown in Fig. 11. Coated carbide tool materials with flood lubrication were used as benchmark. Su Y. stated the flood lubrication had the lowest flank wear rate, resulting in the longest tool life. This proves that PCD is not as susceptible to thermal shock as found with carbide [65]. The 80 bar through spindle lubrication (TSL) performed better than the 40 bar TSL and dry machining had an accelerated wear pattern. The lubrication pressure employed with the 40 bar and 80 bar TSL strategies enabled the insert to reach more than twice the tool life compared to dry machining, while flood lubrication reached more than three times the tool life of dry machining. Liquid Nitrogen cryogenic cooling [72] and minimum quantity lubrication (MQL) [73] also show promising results and should be considered in future research studies. As a result of the high temperatures encountered during the cutting process as well as the tendency for welding of chips to the tool, the use of coolant during the cutting process helps to alleviate these problems while increasing tool life. A plentiful amount of coolant will allow for good chip removal as well as a reduction in the thermal gradients present [8]. One particular study examined various cooling methods and discovered that a compressed cold nitrogen gas and oil mist provided the best extended tool life while milling Ti-6Al-4V with a coated cemented carbide tool [59].

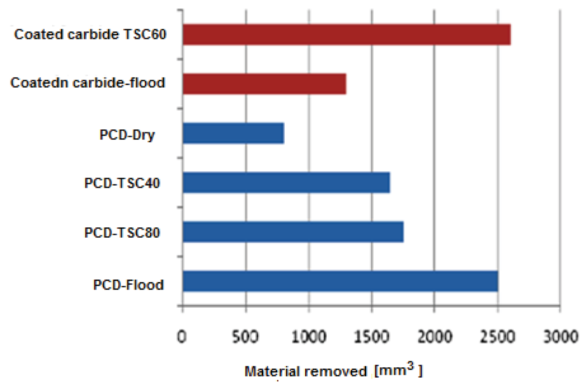

Figure 11. The performance of the different lubrication strategies for finish milling with PCD.**TSC**- Through spindle cooling

Also, it was noted in one particular study that the addition of liquid nitrogen cooling through a micro-nozzle could produce increased tool life up to five times greater than current emulsion cooling [61]. Another technique used to enhance tool life when machining is to use high pressure coolant. The addition of the coolant aids in lowering the tool temperature and also aids in reducing the welding of chips to the tool since the high pressure flow aids in creating discontinuous chips [57].A wide variety of cutting fluids are used to reduce cutting temperatures and to inhibit galling .Sulphurised mineral oils are used extensively and are usually flood cooling applied [56]. Water-base cutting fluids are also widely used and are either flood or mist applied. Tool life seems to be significantly improved, when a 5 % per cent barium hydroxide-water solution is used as a spray mist. However, it seems advisable to exhaust the fumes from the cutting area to protect the operator [63]. Good tool life can be obtained by using the spray-mist technique for all water-base coolants. The mist should be applied ahead of a peripheral milling cutter (climb cutting), and at both the entrance and exit of a face-milling-type cutter. Pressurizing the fluid in an aspirator system permits better penetration to the tool-chip area, better cooling, better chip removal, and better tool life by a factor of two [63]. With flood coolant, the chips tend to accumulate behind the cutter, and are occasionally carried through the cutter.

Catt and Milwain [78]. Found that extreme-pressure emulsion oil gives reasonable results, whilst those containing phosphates give the best results due to their good cooling properties and great anti-welding properties with a suitable lubricant. Difficulties were, however, experienced due to the activity of the fluid, which caused corrosion of the machine tool. Chlorine compounds are used partly because of their undoubted superiority for particular operations, such as grinding, broaching, and tapping. It was found that sulphur compounds led to sulphur attack on turbine blades made in titanium alloys, which led to an embargo on their use. Many of the early chlorinated cutting fluids containing chlorinated hydrocarbons also were effective, but these were banned because of their toxicity, it have been found that chlorokerosenes are equally effective without the attendant risks [78].Konig et al. [79]. suggested that the application of coolants could suppress the built-up edge that was observed generally during the face milling of titanium with HSS- and carbide-tools. Tests did however show, that the application of coolants as concentrates, emulsions, or solutions on a mineral oil, mineral oil free or synthetic, and basis in liquid jet or in spray cooling causes more wear than dry cutting. Work carried out at the Air Force Materials Laboratory [80]-[81], concluded that chlorine-containing cutting fluids do not always provide a better tool life. For particular alloys and operations, dry machining is preferred, which agrees with the observations of Konig and Schroder. Usually the heavy chlorine-bearing fluids excel in operations such as drilling, tapping, and broaching. The experiment result by Ibrahim Deiab et al. [75]. Lubrication effect on tool wear is shown in Fig. 12. When each parameter setting comprising of high and/or low levels of cutting speed and feed are plotted versus the lubrication techniques, the effects on the tool wear can be seen.

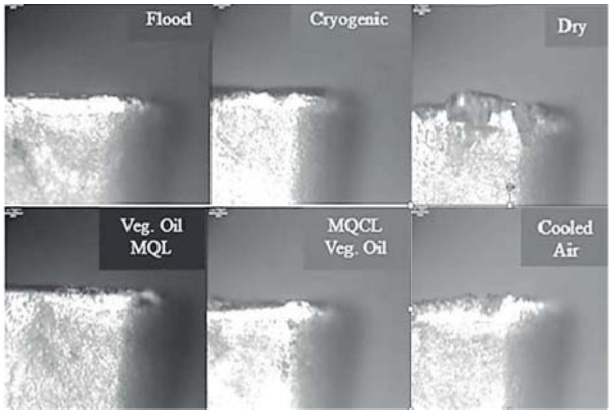

Figure 12. Lubrication strategies for finishing [75].

A closer look at each setting tells us that at low speed and feed, which is the representative setting with the insert and the study at hand, the best performance in terms of lowest flank wear of the tool is given by the MQCL with vegetable oil. Fig.12 shows this behavior using optical microscope. It was seen that while the flood cooling technique using a synthetic coolant outperforms others in general, cryogenic machining follows closely and Minimum quantity cryogenic lubrication (MQCL) also offers close results. The use of cooled air emerges as a better alternative against dry machining and so does MQCL with vegetable oil against MQL using the same. Even though the cooled air used in this setup is not as cold and compressed as conventional air cooling systems for machining plus importance of nozzle configuration cannot be neglected in this regard [76], [77].

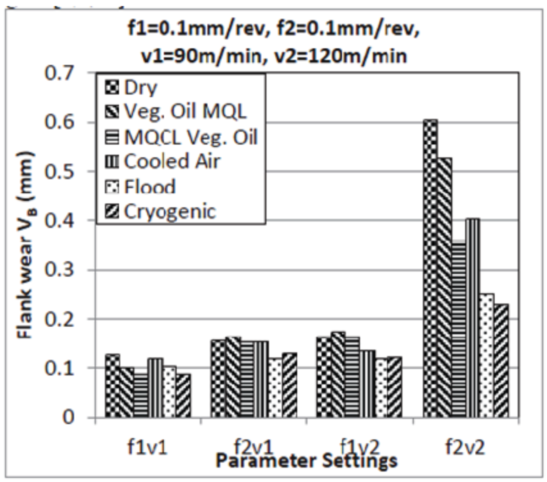

Figure 13. Tool Wear with lubrication techniques. [76], [77]

Titanium Machining guide says, Kennametal drills are high-performance, solid carbide tools. To optimize their performance, they must be adequately cooled. With the proper coolant flow, tool life and higher maximum effective cutting speeds can be reached. In Milling and Turning processes, applying coolant using our newest technology coolant delivered at the cutting edge, through-the-tool coolant, or coolant nozzles as shown in Fig. 14. to each insert is an optimal way to increase tool life and maximize productivity. Coolant nozzles direct a concentrated stream of coolant to the cutting edge, providing multiple benefits. First, the cutting edge and workpiece are kept as cool as possible. Second, the cutting edge and workpiece are also lubricated for a minimum coefficient of friction. Finally, the coolant stream effectively forces the cut chips away from the cutting edge, thereby eliminating the possibility of re-cut chips. Provide a generous “volume” of coolant when machining titanium, and when applying drills and mills in a vertical application to improve chip evacuation and increase tool life. It is important to use a high coolant concentration to provide lubricity, which will aid in tool life, chip evacuation, and finer surface finishes.

Figure 14. Kennametal beyond blast Technology (through cutting tool)

High-pressure coolant, either through the tool or through a line adjacent and parallel to the tool, should always be considered for increased tool life and production. Do not use multi-coolant lines. Use one line with 100% of the flow capacity to evacuate the chips from the work area as shown in Fig. 15.

Figure 15. One line coolant flow with high volume of coolant

VI. Surface Integrity

Titanium is generally used for a material for parts requiring the greatest reliability, and therefore the surface integrity must be maintained. However, the surface of titanium alloys is easily damaged during machining and grinding operations due to their poor machinability, damage appearing in the form of micro cracks, built-up edge, plastic deformation, heat-affected zones, and tensile residual stresses [8].Titanium alloys have very high tensile strength and toughness, light weight,extraordinary corrosion resistance, and ability to withstand extreme temperatures. However, the high cost of both raw materials and processing limit their use to military applications, aircraft, spacecraft, medical devices, connecting rods on expensive sports cars, some premium sports equipment and consumer electronics. Surface finish plays vital role in service life of components, to ensure a great reliability of sensitive aeronautical components, surface integrity of titanium alloys should be satisfied. Therefore, it required to optimize process parameters like cutting speed, feed and depth of cut while machining titanium components for better surface finish and also high tool life in order to reduce the tool cost. In order to reduce high temperatures in the machining zone, cutting fluids are employed in machining. Cutting fluid improves the surface conditions of the work piece, tool life and the process as a whole [83].Moaz H. Ali et al. [85]. developed model by using finite element modeling (FEM) for predicting surface roughness with feed cutting force at different feed rates for the face milling process under dry cutting conditions. It was found that there is good agreement between the trend of feed cutting force and surface roughness at different feed rates. Therefore, finite element modeling is useful to predict the value of feed cutting force to control the surface roughness rather than conducting experiments. FEM can lead to reduced machining time and manufacturing cost as well. This is because the accuracy of both values of the cutting force for the experimental and predicted model was about 97%. It is also found that the main cutting force gives no indication of surface roughness [85].

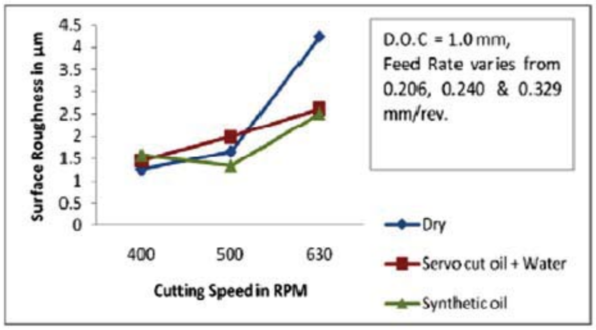

Figure16. Response Graph between Cutting Speed and Surface Roughness [83].

M. Venkata Ramanaa et at. [83] performed experiment on surface roughness at different machining conditions as per their observations, when the cutting speed is low, the surface roughness is also low for dry, servo cut oil + water and synthetic oil conditions, but under higher cutting speeds the surface roughness is high for dry machining compared to servo cut + water and synthetic oil conditions. It is also observed as shown in Fig. 16. That the surface roughness is less for synthetic oil compared to other conditions. Fig. 17 shows the variation between feed rate and surface roughness. When the feed rate is low, the surface roughness is also low for synthetic oil conditions compared to the dry and servo cut oil + water conditions, but under higher feed rates, the surface roughness is high for servo cut oil + water conditions compared to dry and synthetic oil conditions.Fig. 17. shows the variation between feed rate and surface roughness. When the feed rate is low, the surface roughness is also low for synthetic oil conditions compared to the dry and servo cut oil + water conditions, but under higher feed rates, the surface roughness is high for servo cut oil + water conditions compared to dry and synthetic oil conditions. It is, also observed that the surface roughness is less under synthetic oil conditions for low feed rates. Figure 18. shows the variation between depth of cut and surface roughness. When the depth of cut is low, the surface roughness is also low for synthetic oil conditions compared to the dry and servo cut oil + water conditions, but under higher depth of cut, the surface roughness is high for synthetic oil conditions compared to dry and servo cut oil + water conditions. It observed that the surface roughness is less under synthetic oil conditions for low depth of cut [83]. Investigation by Ibrahim Deiab et al. [75]. the effect of changing parameters on the average surface roughness (Ra) using various lubrication. It can be seen that at low feeds the surface roughness is much less and increases slightly upon using higher speed for same feed. Flood cooling appears to be the lubrication of choice when using low feed but not for high feed with cryogenic machining giving slightly better results.

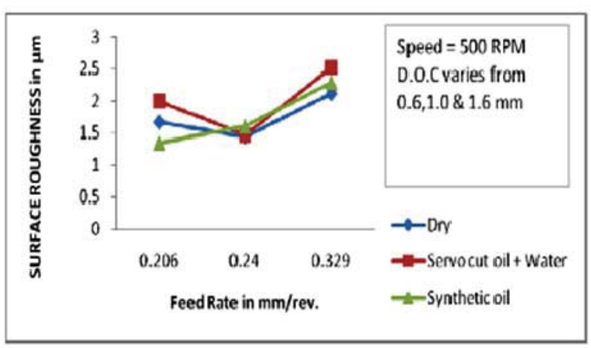

Fig. 17. Response Graph between Feed Rate and Surface Roughness [83].

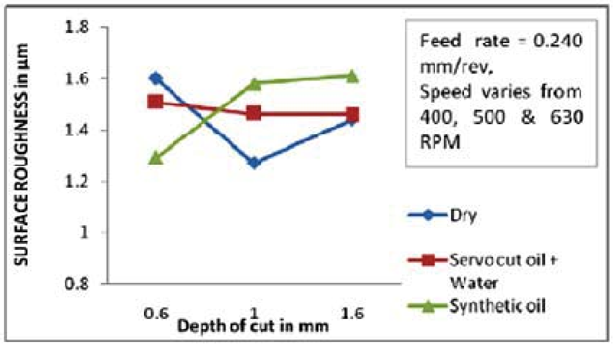

Figure 18. Response Graph between Depth of Cut and Surface Roughness [83].

At high speed, however, the use of cooled air as lubricant emerges as the better alternative. However, at low speed, it does not yield good surface finish [84]. It is also visible that in low feed cases, the surface roughness achieved through all techniques are close to each other, a trend not found at high feed. Moreover, an important point to note is the promise shown by both MQL and MQCL using vegetable oil over all. Referring back to Figure 13, we saw that high-feed-high-speed setting yielded very high tool wears (above 0.4 mm) compared to other settings in some strategies. This high wear is responsible for generating a smoother surface than high feed low speed case while incorporating dimensional inaccuracy, which means the material removed is reduced as the turning progresses.

Experimental study by Nambi Muthukrishnan et al. [82]. Gives surface roughness was very good with coolant compared with dry machining. Similar trend was observed for other depth of cut also for dry and wet machining as shown in Fig.19, 20. In both machining, surface roughness decreases as cutting speed increases. In dry machining, due to formation of Built-up-Edge (BUE), machined surface gets damaged by insert dragging over the surface of machined component with BUE [4], [5]. In wet machining the coolant prevents the formation of BUE and also reduced the heat generated in the interface. observed, this is attributed by plastic flow of material during the cutting process. Plastic flow of material on machined surfaces results in higher surface roughness values [4]. A figure 19, 20. Shows the influence of coolant on machining the workpiece with ceramic insert it is clearly understood that, surface roughness de-crease with increasing the cutting speed. It is obvious that, ceramic insert has high hardness at high temperature.

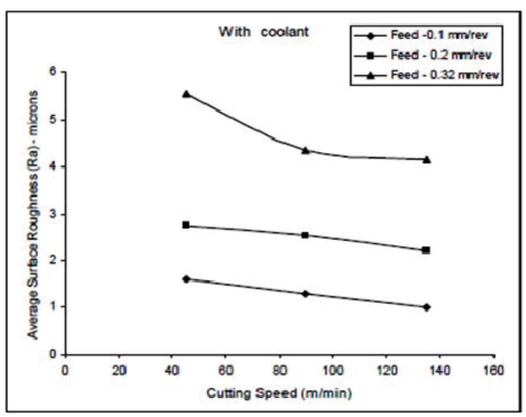

Figure 19. Surface Roughness V/S Cutting speed with coolant [82].

minimum, because of formation of BUE, which affects the surface quality of the machined component at lower cutting speeds; at higher cutting speeds formation of BUE is not noticed.

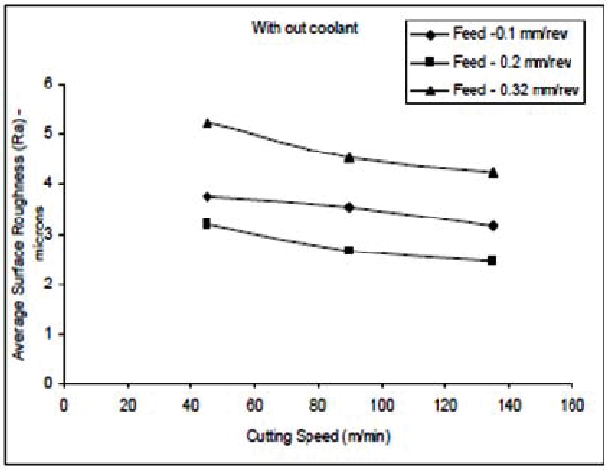

Figure20. Surface Roughness V/S Cutting speed without coolant [82].

As a result good surface finish is obtained. It is suggested to machine the Titanium alloy under wet machining which soften the machined surfaces under coolant. It makes the interface to efficient cooling by coolant to get optimum life [85].

VII. COCLUSION

From reviewing numerous literature, experimental results gives keen tool for efficient machining of Ti-6Al-4V were identified.

- Coated carbide cutting tool gives maximum material removal rate with high pressure through spindle lubrication system.
- Rigid clamping is necessary for avoiding effect of low modulus of elasticity of Titanium alloy for chatter free surfaces.
- Lubrication system influences tool life, surface finish and metallurgy of workpiece. Cryogenic lubrication with high pressure through spindle gives segmentation of chip and avoid thermal gradient of cutting tool tip, high pressure easily flown out the chips from cutting area as result greater surface finish and tool life.
- Surface finish is directly depending upon machining conditions. Good surface finish obtained at minimum depth of cut, maximum R.P.M., with low cutting speed in wet machining. Dry machining should be avoided for saving tool life and surface texture.

VIII. FUTURE WORK

- As per the reviewed literatures, experimental investigations about Ti-6Al-4V more research work are needed in following areas for easy machining.
- Chip formation techniques.
- Cutting tool material and their terminology.
- Computer aided manufacturing with five axis machining.
- Titanium alloy (Grade 5) machining strategies for better surface finish and Tool life.
- Lubricants and their effect on Titanium alloy.

REFERENCES

[1] A.R. Machado,J Wallbank. “Machining of titanium and its alloys-a review,” Journal of Engineering Man. Proc. Inatn. Mech. Engrs. Vol.204.

[2] Durul Ulutan, Tugrul Ozel, "Machining induced surface integrity in titanium and nickel alloys: A review," International Journal of Machine Tools & Manufacture, 2011, vol. 51,pp. 250–280.
[3] P.J. Bridges, B. Magnus. "Manufacture of Titanium Alloy Components for Aerospace and Military Applications," Cost Effective Application of Titanium Alloys in Military Platforms, RTO-MP-069(II)
[4] L. Zhou, J. Shimizu, A,Muroya and H. Eda. "Material Removal Mechanism beyond Plastic Wave Propagation Rate," Precision Engineering, 2003,Vol. 27, No. 2, pp. 109-116. doi:10.1016/S0141-6359(02)00124-1
[5] C.T. Olofson, F.W. Boulger, J.A. Gurklis "MACHINING AND GRINDING OF TITANIUM AND ITS ALLOY," NASA TECHNICAL MEMORANDUM X-53312, 1965, pp. 5-26.
[6] H.J. Siekmann,Tool Eng.,1955,Vol.34,pp. 78-82.
[7] H.E. Chandler, Metals Handbook, 1978, pp. 845-852.
[8] Ezugwu, E.O., and Z.M. Wang. "Titanium alloys and their machinability – a review," Journal of Materials Processing Technology, 1997, Vol.68, pp. 262-272.
[9] Nambi Muthukrishnan, Paulo Davim, "Influence of Coolant in Machinability of Titanium Alloy (Ti-6Al-4V)," Journal of Surface Engineered Materials and Advanced Technology,2011,vol.1, pp.9-14
[10] Konig W., "Applied research on the machinability of titanium and its alloys," Proc. AGARD Conf. in Advanced Fabrication Processes, Florence, 1978.
[11] Sun J, Guo Y, (2008) "A new multi-view approach to characterize 3D chip morphology and properties in end milling titanium Ti–6Al-4V," Int. J.Mach.Tools Manuf.48:14861494.doi:10.1016/j.ijmachtools.2008.04.02
[12] Titanium Alloy Guide, RMITitanium Co., Niles, OH,2000.Avaiable:www.RMI Titanium.com
[13] C. Leyens, M. Peters, "Titanium and titanium alloys," Wiley-VCH, 2003.
[14] Titanium Machining Guide,Kennametal,pp.A18-A23
[15] Kali Dass, S. R. Chauhan,"Machinability Study of Titanium (Grade-5) Alloy Using Design of Experiment Technique," Scient. Res. Eng, 2011, vol.3, pp.609-21. doi:10.4236/eng.2011.36073.
[16] Joshi V.A., (2006) "Titanium alloys: an atlas of structures and fracture features," CRC Press, Boca Raton.
[17] Moussaoui K, Mousseigne M, Senatore J, Lagarrigue P, Caumel.Y,(2013),"Inflence of milling on surface integrity of Ti-6Al-4V." Adv.Mat.Res.698:127136 doi:10.4028/www.scientific.net/AMR.698.127
[18] P.J.Arrazola, Ainhra Garay, Irantzu Sactistan, L. M. Priarte, Dani soter, MGEP-MONDRAGON, Congress of Mach. Tool and Manu. Tech. Research and Technology Organization, France, 2013.
[19] Velásquez J, Tidu A, Bolle B, Chevrier P, Fundenberger J.J. (2010), "Sub-surface and surface analysis of high speed machined Ti–6Al-4V alloy,"Mater.Sci.Eng. A 527:2572–2578. doi:10.1016/j.msea.2009.12.01
[20] Mhamdi M, Boujelbene M, Bayraktar E, Zghal A, (2012). "Surface integrity of titanium alloy Ti-6Al-4V in ball end milling," Phys. Procedia. 25:355362.doi:10.1016/j.phpro.2012.03.096
[21] Moussaoui K, Mousseigne M, Senatore J, Lagarrigue P, Caumel Y., "Influence of milling on surface integrity of Ti-6Al-4V," Adv. Mat. Res.,2013, 698:127136.
[22] J. F. Kahl, D.Eylon, F. H. Froes, M. Field, "Machining of Titanium Alloys," Journal of Metals, 1985, Vol. 37, No. 4, pp. 27- 35.
[23] G.Lütjering, J.Williams, Titanium, Springer-Verlag, 2007.
[24] M. Donachie, Titanium: a technical guide, Metals Park, OH 44073: Asm. Intl., 1988.
[25] P. J. Bridges and B. Magnus, "Manufacture of Titanium Alloy Components for Aerospace and Military Applications," Research and Technology Organization, France, 2001.
[26] X.P. Zhanga,b, R. Shivpurib, A.K. Srivastavac, "Role of phase transformation in chip segmentation during high speed machining of dual phase titanium alloys," Journal of Materials Processing Technology,2014,vol.214,PP. 3048–3066
[27] C. Veiga, J. P. Davim, A.J.R. Loureiro, "REVIEW ON MACHINABILITY OF TITANIUM ALLOYS:THE PROCESS PERSPECTIVE," Rev.Adv. Mater. Sci.,2013,vol.34,pp.148-164
[28] M. Armendia, A. Garay, L.-M. Iriarte, P.-J. Arrazola, "Comparison of the machinabilities of Ti6Al4V and TIMETAL®54M using uncoated WC–Co tools," Journal of Materials Processing Technology,2010, vol.210, pp.-197-203.
[29] M. Calamaz, D. Coupard and F. Girot, "Sub-Millimeter Measurement of Finite Strains at Cutting Tool Tip Vicinit," Machining Science and Technology,2010,vol.14, pp.-244-257
[30] J. Barry, G. Byrne, and D. Lennon, " A fast tool servo design for precision turning of shaft on conventional CNC laths," International Journal of Machine Tools and Manufacture,2001,vol.41,pp.1055-1070.
[31] C. Van Luttervelt,THC Childs, IS Jawahir, F Klocke, PK Venuvinod, Present situation and future trends in modelling of machining operations progress report of the CIRP Working Group,'Modelling of Machining Operations,'CirpAnnals ManufacturingTechnology,1998, vol.47,pp.587-626.
[32] Vyas A, Shaw M, "Mechanics of saw-tooth chip formation in metal cutting,". J. Manuf. Sci. Eng.,vol 121(2),pp.163–172
[33] Barry J, Byrne G, Lennon D, "Observations on chip formation and acoustic emission in machining Ti–6Al–4V alloy," Int. J. Mach. Tools. Manuf.,2001,vol.41 (7), pp.-1055–1070.
[34] Komanduri R, Von Turkovich B, "New observations on the mechanism of chip formation when machining titanium alloysWear," Journal of Engineering Manufacture,1981,vol.69(2),pp.179–188
[35] E. O. Ezugwu, J. Bonneya, R. B. O. C da Silvab, O Çakir, "Surface Integrity of Finished Turned Ti-6Al-4V Alloy with PCD Tools Using Conventional and High Pressure Coolant Supplies," International Journal of Machine Tools & Manufacture,2007,Vol.47,pp.884-891.
[36] Sun S, Brandt M, Dargusch M, "Characteristics of cutting forces and chip formation in machining of titanium alloys," Int. J. Mach. Tools. Manuf.,2009,vol.49(7), pp.561–568
[37] Komanduri R, Hou Z-B, "On thermoplastic shear instability in the machining of titanium alloy (Ti-6Al-4V)" Metall. Mater. Trans.,2002,vol.33(9),pp.2995–3010
[38] Shivpuri R, Hua J, Mittal P, Srivastava A, Lahoti G, "Microstructure-mechanics interactions in modeling chip segmentation during titanium machining,"CIRP Ann. Manuf. Technol,2002,vol.51,pp.71–74. doi:10.1016/S0007-8506(07)61468-1
[39] Calamaz M, Coupard D, Girot F, "A new material model for 2D numerical simulation of serrated chip formation when machining titanium alloy Ti–6Al-4V," Jour. Mach. Tools. Manuf.,2008,vol.48,pp.275–288. doi:10.1016/j.ijmachtools.2007.10.014

[40] Bayoumi A, Xie J, “Some metallurgical aspects of chip formation in cutting Ti-6wt.% Al-4wt.% V alloy,” Mater. Sci. Eng.,1995, Vol.A190,pp.173–180. doi:10.1016/0921-5093(94)09595-N
[41] Calamaz M, Nouari M, Géhin D, Girot F, “modes of straight tungsten carbide in dry machining of titanium alloy,”Jour. De. Phy., 2006, vol. IV 134,pp.1265–1271. doi:10.1051/jp4: 2006134192
[42] Sheikh-Ahmad J, Quarless V, Bailey J, “On the role of microcracks on flow instability in low speed machining of CP titanium,” J Mach. Sci. Tech., 2004, vol.8, pp.415–430. doi:10.1081/ MST 200039867
[43] Bäker M, Rösler J, Siemers C, “Finite element simulation of segmented chip formation of Ti6Al4V,”J. Manuf. Sci. Eng., 2002, vol.124,pp.485–488.
[44] Gente A, Hoffmeister H W, “Evans C Chip formation in machining Ti6Al4V at extremely high cutting speeds,” CIRP Ann. Manuf. Technol.,2001,vol.50, pp.49–52. doi:10.1016/ S0007-8506(07)62068-X
[45] Palanisamy S, McDonald SD, Dargusch MS, “Effects of coolant pressure on chip formation while turning Ti6Al4V alloy,” Int. J. Mach. Tools Manuf.,2009,vol. 49,pp.739-743.
[46] Lee D, “The effect of cutting speed on chip formation under orthogonal machining,” J Eng Ind., 1985, Vol.107, pp.55–63.
[47] Stina Odelros, “Tool wear in titanium machining”, ISSN: 1650-8297, UPTEC K12006.
[48] Hua J, Shivpuri R, “Prediction of chip morphology and segmentation during the machining of titanium alloys,” J. Mater. Process. Technology, 2004, vol.150, pp.124–133.
[49] P.K. Wright, A. Bagchi, “Wear mechanisms that dominate Tool-life in Machining,” Journal of Applied Metalworking.,1981, vol.1, pp.15-23.
[50] E. Turkes, S. Orak, S. Neselie, S. Yaldiz, “Linear analysis of chatter vibration and stability for orthogonal cutting in turning,” International Journal of Refractory Metals and Hard Materials., 2011, vol.29, pp.163-169.
[51] S.S. Ingle. The micromechanisms of cemented carbide cutting tool wear. Doctoral thesis, McMaster University Hamilton, Ontario. 1993.
[52] E. Turkes, S. Orak, S. Neselie, S. Yaldiz, “Linear analysis of chatter vibration andstability for orthogonal cutting in turning,” International Journal of Refractory Metals and Hard Materials., 2011, vol. 29, pp. 163-169
[53] Machining Efficiencies, Tool wear photos.www.machiningefficiencies.com/toolwearpotos.html,Retrieved-2012-02-21)
[54] T. Childs, K. Maekawa, T. Obikawa, Y. Yamane. Metal Machining – Theory andApplications. Arnold: 2000, ISBN: 0-340-69159-X.
[55] J.P. Davim, V.P. Astakhov, Tools (Geometry and material) and tool wear. In: J.P. Davim (ed.). Machining – Fundamentals and recent advances. Springer: 2008, ISBN: 978-1-84800-212-8.
[56] Colton, R. M, “Experimental and Production Machining of Titanium Alloys,” ASTME Paper No. SP63-191 presented at the1962-1963, Creative Manufacturing Seminar of the American Society of Tool and Manufacturing Engineers, Detroit 38, Michigan (RSIC 0185).
[57] Rahman, M., Y.S. Wong, A.R. Zareena, Machinability of Titanium Alloys. JSME International Journal, 2003, Vol.469 (1), pp.107-115.
[58] D. Jianxin, L. Yousheng, S. Wenlong., “Diffusion wear in dry cutting of Ti-6Al-4V with WC/Co carbide tools Wear, ”International Journal of Surface Science and Engineering,2008, vol. 265, pp.1776-1783
[59] Su, Y., N. He, L. Li, X.L. Li,“An experimental investigation of effects of cooling/lubrication conditions on tool wear in high speed end milling of Ti-6Al-4V.” Wear, 2006, Vol.261, pp.760-766.
[60] Hong, S.Y., I. Markus, and W. Jeong, “New cooling approach and tool life improvement in cryogenic machining of titanium alloy Ti-6Al-4V,” Machine Tool & Manufacture, 2001, Vol.41, pp.2245-2260.
[61] Hong, S.Y., I. Markus, and W. Jeong, “New cooling approach and tool life improvement in cryogenic machining of titanium alloy Ti-6Al-4V,” Machine Tool & Manufacture, 2001, Vol.41, pp.2245-2260.
[62] Barnett-Ritcey D, “High-Speed Milling of Titanium and Gamma-Titanium Aluminide,” An Experimental Investigation. PhD dissertation, McMaster University, McMaster, Canada, 2004.
[63] Phillips, J. , "Cutter Geometry, 8-1-I Titanium", paper presented at the National Aeronautic and Space Engineering and Manufacturing Meeting of the Society of Automotive Engineers, October 6, 1964, at Los Angeles, California (Printed by the Boeing Company) (RSIC 0220).
[64] Wang Z, Sahay C and Rajurkar K, “Tool temperatures and crack development in milling cutters,” International Journal of Machine Tool and Manufacture, 1996, vol.36 (1), pp.129-140.
[65] Su Y, He N, Li L and Li X, An experimental investigation of effects of Cooling/Lubrication conditions on tool wear in high-speed end milling of Ti-6Al-4V, Wear, 2006,vol. 261(7-8),pp.760-766.
[66] Kuljanic E, Fioretti M, Beltrame L and Miani F, “Milling titanium compressor blades with PCD cutter,” Annals of the CIRP, 47(1), 1998, pp.61-64.
[67] SU Honghua, LIU Peng, FU Yucan, XU Jiuhua, “Tool Life and Surface Integrity in High-speed Milling of Titanium Alloy TA15 with PCD/PCBN Tools,” Chinese Journal of Aerontics,vol.25,2012,pp.784-790.
[68] Wsite:http://www.sandvik.coromant.com/engb/knowledge/materials/cutting_tool_materials/wear_on_cutting_edges/pages/default.aspx
[69] Y.C. Yen, J. Söhner, B. Lilly, T. Altan., “Estimation of tool wear in orthogonal cuttingusing the finite element method,” Journal of Materials Processing Technology. vol. 146, 2004, pp. 82-91.
[70] J. P. Davim (ed.), Machining of Titanium Alloys, Materials Forming, Machining and Tribology,DOI 10.1007/978-3-662-43902-9_1
[71] Yang X, Liu CR (1999). “ Machining titanium and its alloys,” Mach. Sci. Technol,vol.3(1),pp.107–139
[72] Ahmed MI, Ismail AI, Abakr YA, Nuru and Amin AKM, “Effectiveness of cryogenic machining with modified tool holder,” Jornal of Materials Processing Technology, 2007, vol.185,pp. 91-96.
[73] Brinksmeier E, Walter A, Janssen R and Diersen P, Aspects of cooling lubrication reduction in machining advanced materials, Proceedings of Institution of Mechanical Engineers, 1999, pp.769-778.
[74] Oosthuizen G, Joubert H, Treurnicht N, and Akdogan G. “High-speed milling of Ti6Al4V,” In: International Conference on Competitve Manufacturing, Stellenbosch, 2010.
[75] Ibrahim Deiaba,Syed Waqar Razaa,Salman Pervaiza, “Analysis of Lubrication Strategies for Sustainable Machining during Turning of Titanium Ti-6Al-4V alloy,” Procedia. CIRP ,vol17 ,2014, pp.766 – 771.
[76] Zhang S, Li JF, and Wang YW, “ Tool life and cutting forces in end milling Inconel 718 under dry and minimum quantity cooling lubrication cutting conditions,” J. Clean. Prod., 2012, vol.32, pp.81–87.
[77] Boswell B, and Chandratilleke TT. Air-Cooling Used For Metal Cutting. Am. J. Appl. Sci., 2009,vol.6(2),pp.251–262.

[78] E.J; CaR, D, Milwain, ISI Special Report 94, London, 1968, pp. 143-150.
[79] W. Konig, K.H. Schroder,47 th Meeting of AGARD Structural and Materials panel, Florence,1978,AGARD,London,pp.1.1-1.
[80] N. Zlatin, J.D. Christopher, J.T. Cammet, USAF Technical Report AFML-TR-7~,-165, Metcut Research Associates Inc., Cincinnati, Ohio, 1973
[81] N. Zlatin, USAF Technical Report AFML-TR-75-12 Metcut Research Associates Inc., Cincinnati, Ohio, 1975.
[82] Nambi Muthukrishnan, Paulo Davim, "Influence of Coolant in Machinability of Titanium Alloy (Ti-6Al-4V)," Journal of Surface Engineered Materials and Advanced Tech., Vol.1 No.1,2011, Article ID:4271
[83] M. Venkata Ramanaa, K. Srinivasulub, G Krishna Mohana Rao, "Performance Evaluation and Selection of Optimal Parameters in Turning of Ti-6Al-4V Alloy Under Different Cooling Conditions", INTERNATIONAL JOURNAL OF INNOVATIVE TECHNOLOGY & CREATIVE ENGINEERING (ISSN:2045-8711) VOL.1 NO.5 MAY 2011
[84] Su Y, He N, Li L, Iqbal A, Xiao MH, Xu S, and Qiu BG. Refrigerated cooling air cutting of difficult-to-cut materials. Int. J. Mach. Tools Manuf., 2007 vol.47 (6), pp. 927– 933.
[85] Moaz H. Ali a, Basim A. Khidhir b, M.N.M. Ansari a, Bashir Mohamed, "FEM to predict the effect of feed rate on surface roughness with cutting force during face milling of titanium alloy," HBRC Journal, vol.9,2013,pp. 263–269