Challenges in Machining of Titanium Alloys with Proper Tooling & Machining Parameters - A Review

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Abstract: Modern advanced mechanical applications have been using and improving non-traditional Materials for decades. Refinements of exotic metals and super alloys have led to advanced materials with superior strength and elasticity, super heat and corrosion resistance, and low weight, among other desirable properties. One such metal is titanium. Titanium and its alloys are being used in the most advanced applications in several industries, including the aerospace and medical fields. The very properties of titanium and its alloys that make them desirable for use in extreme conditions cause them to be extremely difficult to machine. After all, it should not be surprising that a material that resists heat and pressure is difficult to cut. Modern advances in machine technology and old-fashioned trial and error have led to the discovery of preferred ways of machining titanium. Generally, you can assure good tool life and work quality by rigid machine setups, aggressive use of the right coolant, sharp and proper tools, slower speeds, and heavier feeds. In this Review, we will learn the properties and applications of titanium and titanium alloys. This review will also identify and addresses the challenges related to machining titanium.

Key words: Titanium Alloy, Machining, Tool wear, work piece

I.INTRODUCTION

Machining of Titanium and its alloys is a challenging task, due to its properties. Titanium alloys are widely used in the aviation and space sectors, as well as in bio-implants, including knee and hip prostheses and cochlear devices, due to the excellent mechanical and chemical properties and biocompatibility. However, titanium has poor machinability. The cutting temperature, quality of the machined surface, burr formation, and tool wear are the major issues, and increase the final product cost. Milling is a mechanical machining process that is widely used to create three dimensional (3D) free-form features in materials including metals, polymers, and ceramics. The machinability of titanium has been studied experimentally via orthogonal machining, turning, and milling. (Haron, 2001) has reported low tool life during machining of Ti–6Al–4V. A fine grain tool insert showed comparatively longer tool life. Further, (Haron and Jawaid, 2005) have reported effect of machining on the microstructure of Ti–6Al–4V. In recent years, some studies have shown that changing geometric parameters and structure of cutting tools can effectively improve the machinability (Tamakawa et al., 2007; Zhang et al., 2009). The studies show that the changes of tool edge radius and the micro-texture implanted into rake face of the cutting tool can affect machinability of the cutting tool (Liu et al., 2009). In metal cutting process, the common changing range of cutting edge radius is mainly from 1 μm to 100 μm (Wang, 2016).

Cutting force represents relevant process information in machining (Toh, 2004; Liu et al, 2011). It assists understanding of critical machining characteristics such as machinability, surface integrity, machined work piece accuracy, power consumption, machine tool chatter, and tool life. Cutting force is usually influenced by tool geometry and material, work piece material properties, machining conditions, and cooling technique. Exploring interactions between machining characteristics and tool performance is beneficial to achieve an accurate optimization of machining process. High reliability and resistance to failure of the components in various engineering applications can be achieved through developing good machined surface integrity. In general, surface integrity of machined work piece depends on tool material and its state of wear. In addition, it is also affected by surface alterations such as feed marks, re-deposited materials, and cracks (Devillez et al, 2011). Controlling machining process parameters is essential to produce high integrity machined surface. Surface finish of the machined work piece is influenced by cutting tool's nose radius and feed rate parameter (Dogra and Sharma, 2012; Petropoulos, 1973).

It is important to understand and define the term 'machinability'. Trent quips "the machinability of an alloy is similar to the palatability of wine – easily appreciated but not readily measured in quantitative terms" (Ezugwu et al, 2007). Unfortunately, there is no single unified definition or parameter one can use or measure to determine the machinability of a material. A material may show desirable machinability according to one criterion, but poor machinability according to another. Furthermore, there are so many practitioners involved in the machining process that it becomes subjective. This includes the opinions of the engineer planning the cutting process using CADCAM to the machinist operating the rig on the shop floor. Relative machinability may change depending on which cutting process is used (turning vs. milling); tool material chosen (tungsten carbides, cubic boron nitrides); or even machining environment (cryogenic, room temperature). Despite the lack of solid definition, today machinability tends to be assessed by a combination of the following criteria: tool life; material rate of removal; cutting forces; surface finish; and chip shape (Ezugwu et al, 2007). Within the metal processing industry there are four fundamental machining processes: turning, milling, drilling and grinding. In this review the process of metal cutting, focus is on improving the quality of the work piece and tool wear

II. CHIP FORMATION

Chip morphology and segmentation play a predominant role in determining machinability and tool wear during the machining of titanium alloys. At lower cutting speeds the chip is often discontinuous, while the chip becomes serrated as the cutting speeds are increased (Jiang and Shivpuri, 2004). Due to its importance, the chip segmentation phenomenon has been extensively investigated and studied worldwide. Attempts to describe the chip morphology in cutting titanium and its alloys date back to the work performed by Cook (Cook, 1953). He investigated the chip morphology of titanium at different cutting speeds and proposed a thermodynamic theory for chip formation. (Nakayama et al., 1988; Shaw and Vyas, 1993) proposed the periodic crack formation theory in machining hard steel. (Komanduri et al., 1982) studied the chip formation process during the cutting of Ti–6Al–4V and proposed the well-known 'catastrophic shear chip' theory. Other early investigations into chip segmentation in the cutting of titanium alloys were performed by Lee (Lee, 1985; Gente and Hoffmeister., 2001)

In general, adiabatic shearing is considered to be responsible for serrated chip formation. Materials that have both low thermal conductivity and yield stresses which exhibit high sensitivity to temperature are more susceptible to adiabatic shear. (Recht, 1964) developed a classical model for shear instability where the temperature gradient in the work piece and the strain hardening behaviour of the material are considered as factors to initiate shear instability in the work piece. Increasing temperatures in the primary shear zone due to shear deformation weaken the material by thermal softening. The low thermal conductivity limits the heat energy to diffuse in the work piece; therefore, the deformation is concentrated in shear bands, leading to serrated chip formation (Komanduri and Turkovich, 1981; Burns and Davies, 2002). The material failure under adiabatic shear localization is related to large plastic deformation and microscopic damage (Komanduri and Brown, 1981).

(Timothy and Hutchings, 1984) showed that the void formation in adiabatic shear bands in titanium alloys is closely associated with the thermal softening and local melting of the metal in the shear bands, which cause the sharp drop in the shear stress-strain response.

Supporting findings were also reported in (Giovanola, 1988), where the propagation of adiabatic shear bands is considered as a major ductile failure mechanism which results in material separation along shear band. (Owen and Vaz, 1999) adopted this process and used a fracture criterion together with a failure softening model to describe void growth mechanism in machining titanium alloy *Ti*-6*Al* -4*V*. (Barry et al., 2001) reported experimental evidence of cracks on the chips collected during machining of titanium alloy *Ti*-6*Al* -4*V*.

The segmented chips lead to the variation of chip thickness. In addition, lower elastic modulus cause excessive work piece deflection and moves away from the cutting tool. When the cutting edge moves forward, the work piece springs back. This leads to deflection, vibration, and chatter.

Variation of chip thickness the critical cutting speed for the onset of shear instability and chip segmentation is very low during machining of titanium alloys. At or above critical cutting speed, segmented chip formation involves localized shearing which is associated with the generation of cyclic forces (Sun et al, 2009) and acoustic emission. These dynamic cyclical and pulsating forces are due to varying thickness and width of chips which lead to rough machined surface, chatter, and cutting tool tip breakage (Ezugwu and Wang, 1997; Sun et al, 2009; Abele and Frohlich, 2008).

According to Vyas and Shaw (Vyas and Shaw, 1999), thermal origin and periodic development of cracks in the work piece surface are the two theories of the origin of saw tooth chips. Increased strain rate and decreased thermal softening increase the tendency for saw tooth chip formation. The material in micro cracked bands undergo adiabatic shear when the cutting speed (temperature) is high enough and materials undergo a phase transformation. Continuous gross cracks and discontinuous micro cracks which occur across the chip width are involved in saw tooth chip formation (Vyas and Shaw, 1999). The frequency of the cyclic loads, load sensor, and acoustic emission signals is found to correspond to the frequency of chip segmentation (Vyas and Shaw, 1999; Barry et al, 2001). The behaviour of the dynamic cyclical and pulsating forces is complex and depends on all the factors associated with the cutting process. The vibration frequency is found independent of feed but the amplitude of the vibration is found to increase initially then decrease at lower feed range. Amplitude and frequency are found to increase with further feed increase (Sun et al, 2009). The amplitude of force fluctuation increased linearly with increasing depth of cut. The frequency of the cyclic force is found to increase with cutting speed; the amplitude of the cyclic force is found to decrease with speed increase, then stabilizes and then decreases with further speed increase. At the stabilized zone, the cyclic force frequencies are found to be multiples (approximately) of 260 Hz, the intrinsic harmonic frequency of the cutting. The cutting speed at which the cutting force starts to increase with increasing cutting speed is much lower when machining titanium alloys. This makes it difficult to increase the machining speed of titanium alloys that periods of large force fluctuations (dynamic force) occur red randomly during machining and are superimposed on the static force. These force fluctuations are more significant in the thrust and cutting directions than in the feed direction (Sun et al, 2009). Continuous and uniform shearing with smaller slipping angle (38°) is found for the continuous chip period. On the other hand, a narrow shear band with heavier deformation and larger slipping angle (55°) is noted in the sharp "saw tooth" period. In case of the periodic saw tooth chips, shearing with both smaller and larger slipping angles is found (Sun et al, 2009). Sharp, periodic, and a periodic "saw teeth" are found in the continuous chips. In the periodic segmented chip region, the segmentation frequency can be calculated through dividing cutting speed by the length of un deformed surface (Barry et al, 2001; Sun et al, 2009). This agrees very well with the cyclic force frequency and indicates that the cyclic force fluctuation is caused by the segmented chip formation process. This also agrees with the relation between the segmentation frequency and cyclic force frequency obtained by variation of strain, load, and acoustic emission (Vyas and Shaw, 1999; Barry et al, 2001).

III. TOOL WEAR

Choosing the right tooling is essential for optimizing cutting performance in the harsh conditions characteristic of machining titanium. Our goal is to accomplish a balance between tool life, production rate, and part quality, while keeping costs as low as possible. Achieving this balance involves trial and error. You should be aware of some of the most common problems associated with machining titanium and titanium alloys, as well as the strategies used to optimize tool performance.

Wear tendencies are slightly different when comparing titanium and titanium alloys to steel. **Notching** is common and corresponds to where the hardened top layer of titanium contacts the tool. This can occur at the depth of cut line. Hardened top layers may be caused by any prior casting, heat treating, or machining of the work piece.

Titanium also has a strong tendency for chemical reactivity with tool materials, which can cause welding or a built-up edge (BUE). During BUE, titanium actually welds to the tool surface, which in turn pulls away from the tool over time, taking tool material with it. This can result in rapid chemical wear or crater wear.

Material wear processes are found at all places where materials are in mechanical contact with each other (Ingle, 1993). Wear is often present as combinations of several different physical wear mechanisms and the ones most likely to be present during mechanical contact are: abrasive, adhesive, diffusive, chemical, and wear due to plastic deformation (Davim and Astakhov, 2008; Luigino et al,2007). The dominating wear mechanism depends on the surfaces, the contact area between them, materials, topography, hardness, etc.

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Abrasive wear: Abrasion is a wear mechanism that arises from hard particles that abrade on a softer material (Childs et al, 2000). The mechanism appears on almost all contact surfaces that have a relative velocity against each other and is dependent on the relative hardness of the abrading particles and abraded material. Most abrasion starts with two-body abrasion but switches to three-body abrasion at a certain point, when wear-off particles have been formed. Two-body abrasion often results in much higher wear rates than three-body abrasion does.
The abrasive wear often increases with increasing temperature, due to the decrease in material hardness at elevated temperatures (Childs et al, 2000; Wright and Bagchi, 1981).

Adhesive wear: Adhesion occurs when temperatures and pressure are high. Small particles are welded together when two metals are forced together (Childs et al, 2000; Luigino et al, 2007). When the two metals also have a relative velocity against each other, as is the case in metal cutting, the small welds formed by adhesion will cause micro pieces of the tool to break loose.
The adhesion of work piece material on the cutting tool could form a built up edge (BUE) (Wright and Bagchi, 1981) and in that case the wear rate due to adhesive wear could be very high (Ingle, 1993). In the case when high speeds and temperatures cause adhesion junctions between work piece material flowing past the flank face and the cutting tool material, carbide particles can be plucked from the WC/Co cutting tool into the chip. This wear mechanism has been referred to as attrition wear (Wright and Bagchi, 1981).

Diffusion/dissolution wear: When two materials are in contact with each other, atoms from one material could diffuse into the other, causing diffusion or dissolution wear. Diffusion or dissolution wear mainly occurs at high temperatures and is strongly depending on the solubility of cutting tool material in work piece material (Luigino et al, 2007). It is believed that diffusion between cutting tool and work piece material is the dominating mechanism for crater wear at high cutting speeds (Wright and Bagchi, 1981).It is also supposed that diffusion causes the tool to be depleted of some atoms, making the material softer and more sensitive to abrasive and adhesive wear.
Chemical wear: Chemical wear arises from chemical reactions, such as oxidation or forming of compounds, which occur on clean surfaces at high temperatures (Childs et al, 2000). Oxide layers could act as a protection against wear at the surface during mechanical contact, but they could also speed up the wear rate, depending on the formation rate of the oxide and the hardness and topography of the other surface. In the case when the oxide formed on the surface is too brittle, chipping will occur and the oxide will fall off. Formation and breaking of junctions will lead to removal of tool material from the surface (Wright and Bagchi, 1981).
Wear due to plastic deformation: The combination of high cutting forces and high temperatures could result in plastic deformation of the tool's cutting edge and give the tool a new geometry so it loses its initial characteristics. Plastic deformation could occur both at the surfaces and at the cutting edge (Childs et al, 2000; Ingle, 1993).
Cutting tool wear: The extent of cutting tool wear depends on the tool material and geometry, work piece 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, were the insert is worn during machining. The physical wear mechanisms can be further divided and classified when discussing wear of cutting tools during machining. Two basic areas of tool wear are flank wear and crater wear, but several other mechanisms also occur (Yen et al, 2004). Tool lifetime is often measured in terms of crater or flank wear according to ISO 3685:1993 (Davim and Astakhov, 2008). Tool wear characteristics are often represented as a plot of material wear versus sliding distance, or time of cut, for a certain tool-work piece combination.

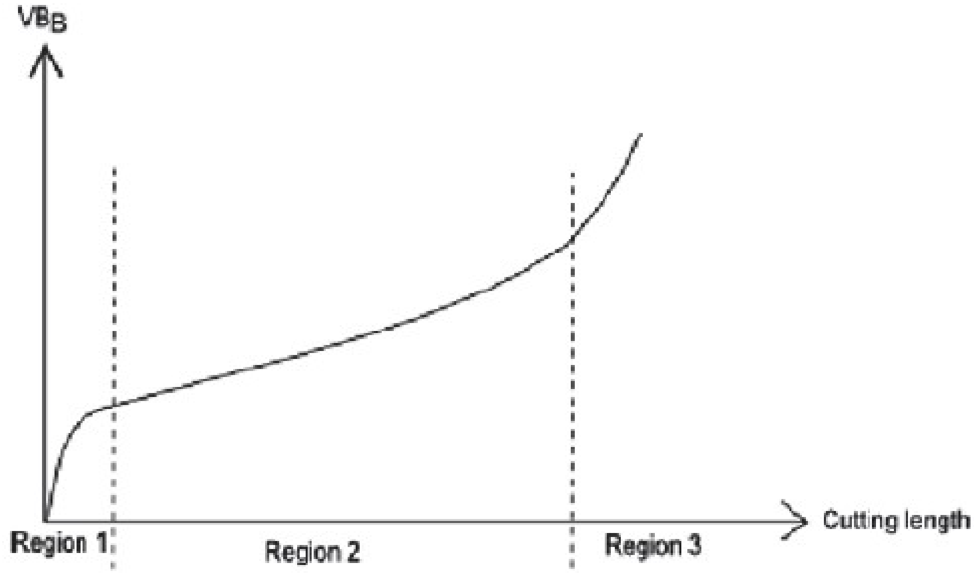

Figure No 1: Graph of the width of flank wear Vs Cutting length.

Figure No. 1 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 (Davim and Astakhov, 2008).
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.

Crater wear: Crater wear is wear located at the rake face of the tool, in the form of a crater (Childs et al, 2000). 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 (Childs et al, 2000).
Flank wear: Flank wear is wear formed on the cutting tool's relief surface as a flat-worn surface. Investigations of flank wear (Childs et al, 2000). Suggest that flank wear depends mostly on abrasion from unwanted rubbing of clearance face against work piece material. Flank wear is measured as the width of flank wear land, VBB, and is often measured microscopically (Childs et al, 2000).
Chipping: Chipping is when a small material piece of the cutting tool edge breaks loose. This is an unpredictable wear mechanism that could occur when the cutting tool is subjected to sudden loads or thermal shocks due to low fracture toughness (Childs et al, 2000; Ingle, 1993).
Fracture: Fracture wear is often observed on a heavily worn tool that runs under tough cutting conditions. The cutting tool edges break totally due to very high temperatures and cutting forces (Wright and Bagchi, 1981).
Notch wear: Notching is mainly caused by a fracture process or a chemical reaction as discussed by Turkes et al. Notching happens when excessive localized damage occurs at the flank and rake face simultaneously, causing a single groove formation. Once formed, a notch will cause poor micro-finish on the machined part and many times proceeds into fracture wear.
Chatter: Chatter, 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 (Turkes et al,

2011). Titanium alloys deflect nearly twice as much as carbon steel, giving a larger bouncing action when the cutting edge enters the cut.

Significant researches on machining titanium alloys have been performed to enhance the tool life to an acceptable level (Sharma et al, 2009) by analyzing its causes (Boothroyd and Knight, 2005). Stress, temperature, and vibration in the machining zone are the three main factors that enhance the cutting tool damage (Zhao et al, 2002). Tool wear, surface integrity, and productivity are correlated and depend on the cutting conditions such as depth of cut, speed, feed, presence of coolant, cutting tool materials, etc. (Childs et al, 2001). Generally, tool damage mechanisms are adhesion, thermal diffusion, chemical reaction, abrasion, chipping, fracture, plastic deformation, and fatigue (Hartung et al, 1982). Most of these damages increase drastically with the increase of temperature. The contribution and generation of heat vary with tool and work material combination and mainly on speed (Boothroyd and Knight, 2005). The diffusion occurs at high cutting temperature where cutting tool and work material elements diffuse into each other's structure. The plastic deformation takes place at high cutting temperature when a cutting tool fails to withstand the stress on cutting edge (Trent and Wright, 2001; Barrow, 1973). In machining processes, the material is subjected to extremely high strain, strain rate, and temperature, thus cutting tool and machined surface have to go through severe conditions (Ying-lin et al, 2009). Ying-lin (Palanisamy et al, 2009) found that the generated temperature in the machining zone is so high that it can damage the finished surface of titanium alloys easily. This temperature can melt titanium alloy chips and enhance adhesion of chips to the tool and machined surface. Cutting fluids are well accepted by the industrial community to remove heat-generated and heat induced lubrication at the tool–work piece and chip–tool interfaces during the machining process (Ezugwu et al, 1997). This method is easy to use and it is a proven technology. However, improper coolant delivery location and low pressure can lead to adverse effects including premature tool failure due to abrasion and thermal shock resulting in severe chipping of the tool while machining titanium alloys (Ezugwu, 2005). The higher coolant pressure (above 70 bars) properly directed at the cutting point enhance the tool life and machined surface significantly (Ezugwu et al, 2007; Vosough and Svenningsson, 2004). Cryogenic cooling by liquid nitrogen also improves the tool life during machining titanium alloys (Venugopal et al, 2007). Similar to the coolant technology, there are other techniques such as vibration analysis (tap testing) (Fan Y et al, 2011; Leigh et al, 2000), thermally enhanced machining (Follansbee, 1989; Lennon, 2004), use of high conductive cutting tool and holder (Takeyama, 1983), and hybrid machining (Dandekar et al, 2010) that are potential applicants to improve machinability and productivity. Researchers are continually engaged to improve the applicability of these techniques for the industrial community. when the depth of cuts change from few micrometers or less to several hundred micrometers (Komanduri and Hou, 2002). According to Komanduri (Komanduri and Turkovich, 1981), “the machining of titanium alloys is a typical case of distinct gross inhomogeneous plastic deformation involving periodic upsetting and intense shear localization in a narrow band. It is suggested that the continuous chip formation models, such as the classical Merchant–Piispanen model and the use of parameters derived from the model (such as the chip thickness ratio and shear angle) should be discontinued in describing machining characteristics of titanium alloys”. While performing machining inside a scanning electron microscope, Komanduri et al. (Komanduri and Turkovich, 1981) noted that freshly sheared surface of the chip rolls onto the tool and causes intense contact. Continuous contact occurs at or near the apex of the tool with the chip segment for a substantial time of the chip segmentation cycle as there is no relative motion between the segment and the tool due to chip segmentation. In addition, high reactivity of titanium with commonly used cutting tool material such as cemented carbides, nitrides, oxides, borides, diamond, cubic boron nitride, etc. contributes to high tool wear. The temperature at the shear band is very high due to intense shear concentration and low thermal conductivity of titanium alloys (Komanduri and Turkovich, 1981). According to Vyas and Shaw (Vyas and Shaw, 1999), thermal origin and periodic development of cracks in the work piece surface are the two theories of the origin of saw tooth chips. Increased strain rate and decreased thermal softening increase the tendency for saw tooth chip formation. The material in micro cracked bands undergo adiabatic shear when the cutting speed (temperature) is high enough and materials undergo a phase transformation. Continuous gross cracks and discontinuous micro cracks which occur across the chip width are involved in saw tooth chip formation (Vyas and Shaw, 1999).

IV. STRESS ON CUTTING TOOLS

High stress on the cutting edge is due to reduced contact surface and low plasticity of titanium alloys (Abele and Fröhlich, 2008). It is already explained that the segments in chip generation involve gradual upsetting of the wedge shaped volume of material immediately ahead of the tool due to formation of saw-tooth. Fig. presents a picture of typical stress distribution on the cutting tool tip when saw tooth chips are formed (Duan, et al., 2013). It shows that the highest stress occurs at close proximity to the cutting edge. The maximum stress occurs within 0.1 mm from the cutting tool tip. The cutting tool geometry significantly influences the stress generated during machining (Wyen, et al., 2010). There is no stress after around 0.3 mm away from the tool tip when the rake angle -10° and this distance can be around 0.2 mm for 0° rake angle. This distances decreases with the increase of rake angle. Thus, the initial contact time and length on the tool face with the chip being formed is extremely small. Upsetting of the wedge shaped volume of material being formed causes high stress on the tool face owing to the small contact area. Thus, very high mechanical stresses occur in the immediate vicinity of the cutting edge when machining titanium (Campbell, 2006). Though the contact length increases as the chip formation process continues (Komanduri, 1982) the maximum force acts near the cutting edge (Ulutan, et al., 2013). The stress on cutting edge also increases with an increase in cutting speed due to the decrease of the associated contact length and shear angle (Ginting and Nouari, 2006; Jawaid et al., 1999). This mechanism is different from that of the continuous chip formation process (Komanduri, 1982). The stress on the rake and flank faces of a carbide tool during machining can be as high as 2600 and 1710 MPa respectively at speed 70 m/min and 0.1 mm feed (Ulutan, et al., 2013). The strength and hardness of titanium does not reduce significantly at elevated temperatures which contribute to higher stress at higher temperature on cutting tools (Campbell, 2006). Thus, cutting tools have to go through extreme stress conditions when machining titanium and wear out rapidly. The normal stress increases leading to a long intimate contact between the chip and rake surface as the rake angle decreases yielding higher apparent coefficient of friction.

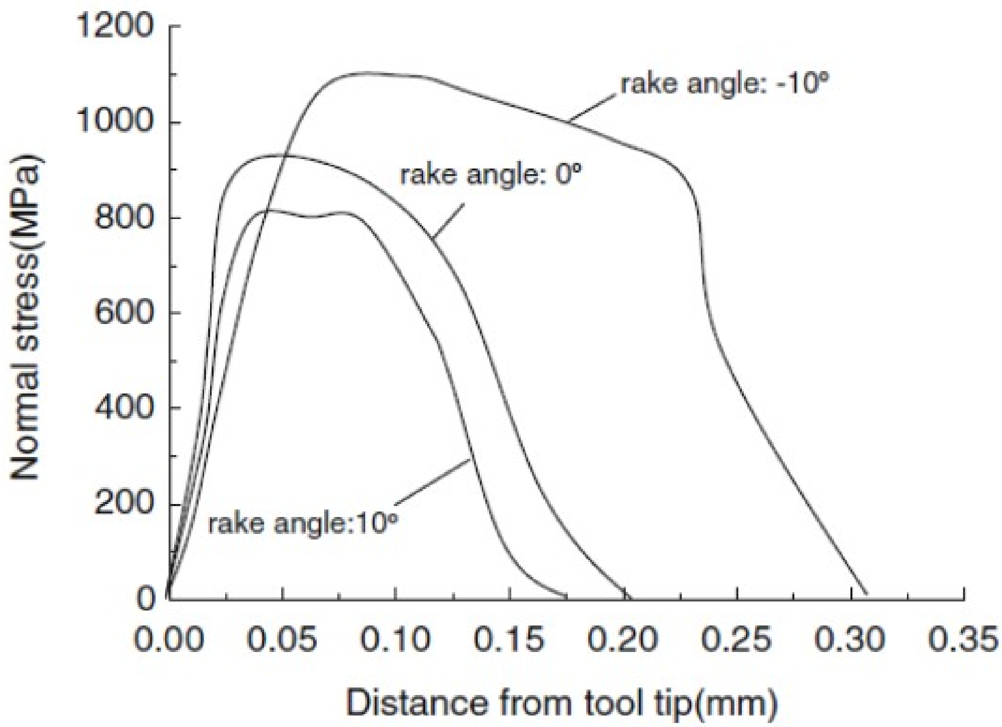

Figure No. 2: Normal stress for saw tooth chips at chip tool surface for different rake angles.

Figure shows, Normal stress for Saw-tooth chips at chip–tool surface for different rake angles (Duan, et al., 2013)

.High speed steels (HSS) tool, such as M33, M40, and M42, and tungsten carbide grade C-2 (ISO K20) cutting tools are mainly used for machining titanium and its alloys in industries. Though carbides are susceptible to chipping during interrupted machining it can achieve about a 60% improvement in metal removal rates compared to HSS (Campbell, 2006). Ceramic cutting tools are not generally used in machining titanium due to low fracture toughness, poor thermal conductivity and higher chemical reactivity with titanium. However, researchers in laboratory have tested all most all types of cutting tools, such as straight tungsten carbide tool (k10), cemented TiN tool, pure aluminium oxide type of ceramic tool, TiC coated tool, alloyed cemented carbide (W–Ti/Ta)C–Co, alloyed CVD-coated carbide (W–Ti/Ta/Nb)C–Co + (TiC+ Ti/CN + /TiN), CBN (American) tool, binder less CBN, sintered diamond tool and natural diamond tool (Takeyama et al., 1983; Haron et al., 2007; Takeyama et al., 1983; Jawaid et al., 1999; Jawaid et al., 2000; Jianxin et al., 2008; Rahman et al., 2006). The following discussion provides details on the performance of different kinds of cutting tool while machining titanium alloy (Ti-6Al-4V).

Excessive wear which is identified as chemical reaction and adhesion between the tool and work materials occurs in TiN added cermet and the TiC coated tools during machining. The ceramic and CBN tools also show large groove wear on the flank and rake face. Thus, these tool materials are not suitable for machining titanium alloys. However, only the carbide, sintered diamond and natural diamond tools show acceptable performance in machining titanium alloy. In addition, binderless CBN shows promising results in machining titanium alloys. The sintered diamond tool performs slightly better than its carbide contemporary at low speed but at higher speed both of these tools demonstrate almost similar performance. Tungsten carbide (k10) tool wear increases rapidly after 5 minute cutting at low speed (100 m/min) without coolant (Takeyama et al., 1983). However, the wear rate with the water-soluble type coolant is significantly low even after 30 minute cutting. At higher cutting speeds (198 m/min), the tool life becomes extremely short. On the other hand, natural diamond tooling showed minor wear even after 30 minute cutting at low (100 m/min dry) as well as at higher (198 m/min with coolant) cutting speeds. However, the tool wear was severe with further increase of cutting speed (300 m/min) even after cutting for only a few minutes. The other weakness is the low melting point of soldering material of natural diamond tool. If the machining is continued for long enough the soldering material melts and the cutting tip detaches from the holder (Takeyama et al., 1983). Polycrystalline cubic diamond (PCD) tooling shows very good performance during finish milling of low stiffness components of titanium alloy TiAl6V4. The tool life of PCD tooling can be achieved as high as 381 minutes with excellent surface finish and geometrical accuracy (Kuljanic et al., 1998). (Kuljanic et al., 18 1998) down milled TiA16V4 titanium with 32 mm diameter PCD tool at cutting speeds 90, 130 m/min, feed per tooth 125 mm, axial depth of cut 0.3 mm and radial depth of cut 5 mm. For their specific machining condition, 10° inclination of the cutter axis to the surface perpendicular to the machined surface and application of cooling lubricant (7% oil and water) provided best machining out comes. Generally, diffusion and dissolution processes are blamed for damage of PCD tooling due to high local temperatures resulting from the poor thermal conductivity of work piece materials (Nabhani, 2001). (Kuljanic et al., 1998a) argued that Ti has greater affinity to carbon. Thus, TiC film is formed on the diamond surface due to reaction between the work material and tool material during machining process. This film protects the tool from cratering under light cutting conditions.

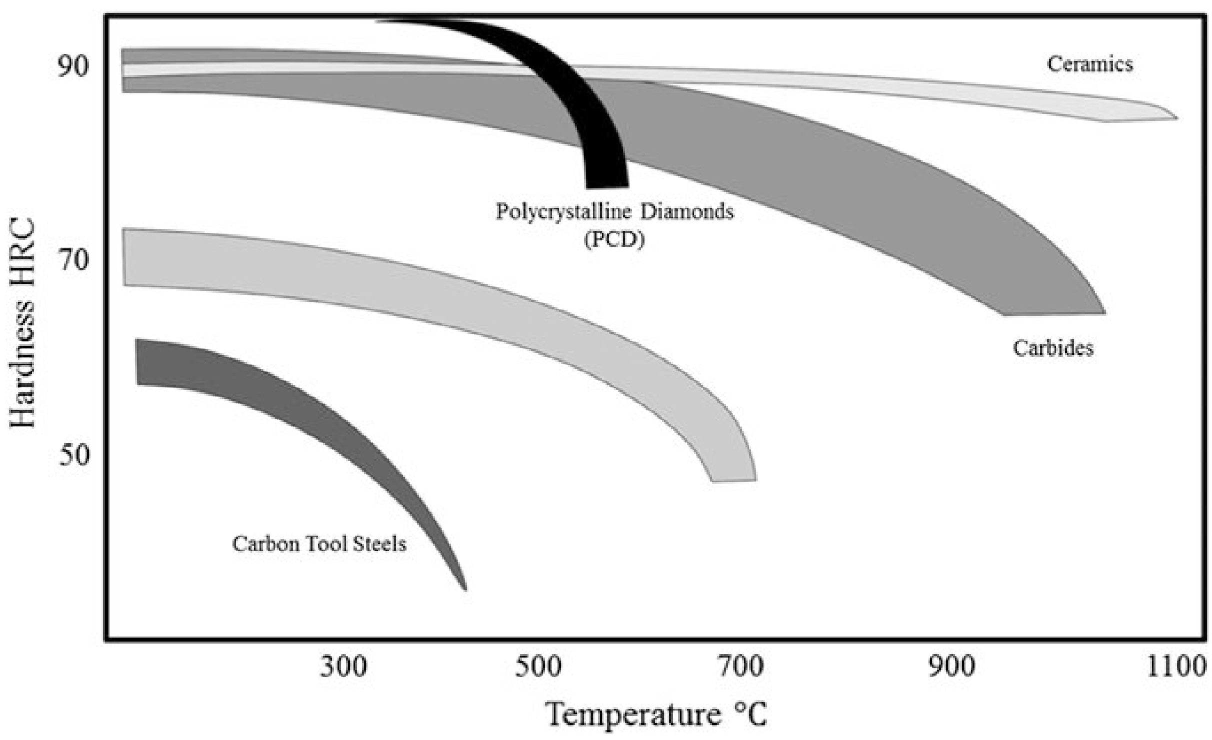

Figure No. 3: Comparison of the capability of the major families of cutting tools as a function of temperature.

Binderless CBN tools which do not have any binder present to hold the tool material grains together show an improved high temperature durability and thermal conductivity (Rahman et al., 2006). These tools are manufactured by direct sintering of high-purity hexagonal boron nitride (hBN) at high temperature and pressure. For the similar machining conditions (speed 400 m/min, feed 0.058 mm/tool and depth of cut 0.05 mm) the tool life of a BCBN tool is very similar to that of PCD tools during milling Ti-6Al-4V (Zareena, 2002). BCBN tools exhibit lower flank wear and sharper cutting edge compare to that of sintered carbide, PCBN and PCD (with Co based binder) tools during turning of Ti6Al2Nb1Ta at speed 4.2 m/s, feed 0.15 mm/rev and depth of cut 0.5 mm with the application of high pressure coolant (Hirosaki et al., 2004). The tool life of a BCBN tool increases with the increase of cutting speed during milling of Ti-6Al-4V when depth of cut is constant and feed rate is low (0.075 mm/rev) (Wang et al., 2005a). During machining work piece material attaches to the flank face of the BCBN tool and tends to protect the tool from wear; albeit for a short time. The attached work piece material as well as particles of tool material is removed with subsequent machining and the consequence is an accelerated attrition wear on the flank face. Non-uniform wear in the flank is the dominant wear pattern for BCBN tool during machining Ti-6Al-4V. There evidence of diffusion-dissolution wear and attachment of work piece material to the rake face, but these are not main causes of tool failure (Wang et al., 2005a and 2005b)

Some coatings, such as, TiN (by physical vapour deposition) and TiCN + Al_2O_3 (by chemical vapour deposition) are shown to improve life of carbide tools (milling process) at high performance milling process (speed 55 m/min with radial depth-of-cut to tool diameter 19 ration 72.5%) (Jawaid et al., 2000). Both of these two cutting tool materials exhibit a tool life of 30 min (with radial depth-of-cut to tool diameter ration 72.5%) at the cutting speed of 55 m/min and a feed of 0.1 mm per tooth. TiCN (3.1µm) and AlSiTiN (3.9 µm) coatings (by arc evaporation) also show better performances (almost double the tool life) at a cutting speed range of 50–130m/min (turning) in wet and minimum quantity lubrication (MQL) conditions, compared to the uncoated carbide tools. The nano-crystalline structure with the multilayer architecture, better abrasion resistance and superior adhesion properties of AlSiTiN coating produces enhanced performance - better than TiCN (Settineri and Faga, 2008). All coatings may not increase performance, such as, HfC coating. A six micron thick HfC coated tool was seen to wear (in the turning process) at about 20 times the rate of the identical uncoated tool (Turkovich et al., 1982). Carbide tools with a larger grain size (1.0 µm) demonstrate better resistance to flank wear due to lower solubility of WC in titanium alloys than those with smaller grain size (0.68µm) during dry turning of Ti-6246 (Jawaid et al., 2000).

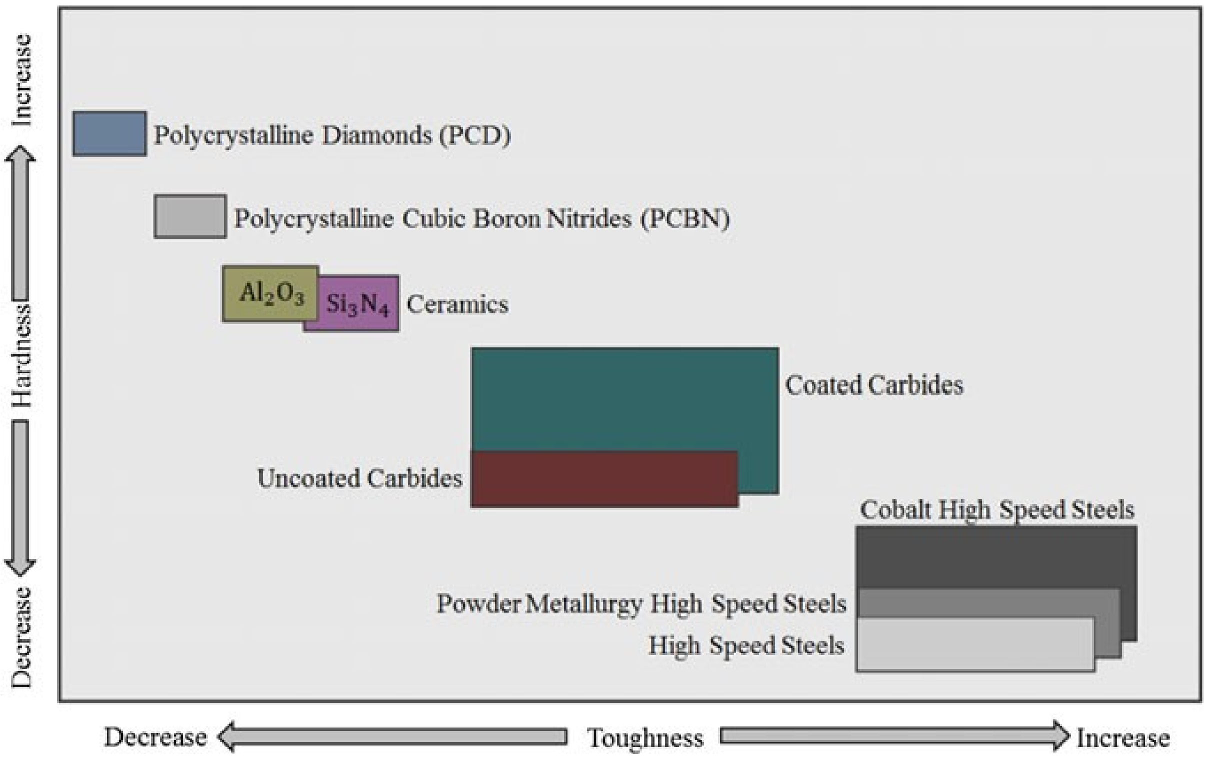

Figure No 4: Hardness versus toughness for some conventional cutting tool materials.

The main causes of tool wear for different cutting tools are: coating delamination (coated tool), adhesion, attrition, diffusion, plastic deformation and cracks (Jawaid et al., 1999; Jawaid et al., 2000; Jianxin et al., 2008). A typical picture of cracks on coating during machining of titanium alloy is shown below (Fig. No.5). The coating delamination mainly occurs at the rake face at high speeds and feeds. It occurs as early as 10 second into machining for some coatings. Thus, there is doubt on the effectiveness of those coating. However, multilayered thick coating prolonged tool life as the multilayer coatings exhibit greater wear resistance and higher adhesion strength to the substrate (Ezugwua et al., 2003). The two possible reasons of coating delamination are chemical reaction and difference in the thermal expansion coefficient between the coating matrix and the substrate. Adhesion of work piece material on cutting tool is very common during machining titanium. In some coated tools it takes place after the coating(s) has worn out/delaminated (Konig et al., 1991). With the progress of cutting, the welded (due to adhesion) work material on cutting tool is compressed and removed. This also leads to plucking of cutting tool grains which is called attrition wear. Attrition wear is observed on the rake face as well as flank face. Evidence of diffusion of cobalt and tungsten atoms into the work material has been reported when machining titanium with coated/uncoated carbide tools at reasonably higher cutting speed. The diffusion process, which is the main problem for machining titanium, comprises element diffusion and chemical reaction between the work piece and the tool. This type of wear is more active at high cutting speeds or when there is a high temperature at the tool–chip interface, and is enhanced by a strong chemical affinity between the work piece and the cutting tool materials (Molinari, 2002). The extreme temperature, pressure and the intimate contact at tool-chip interface offers a perfect condition for the diffusion of tool material to the work piece (Jawaid et al., 2000). Ti, Al, and V of the Ti–6Al–4V alloy are seen to diffuse into the WC (Co binder) tools during machining at higher cutting temperature. Under similar conditions, W and Co of the WC (Co binder) tool also diffuse into Ti–6Al–4V alloy (Jawaid et al., 1999; Su et al., 2006). These change the composition and alter the performance of cutting tool (Jianxin et al., 2008). The diffusion of Co from the cutting tool weakens the bonding among carbide grains and thus with the progression of machining, attrition wear exposes Co from the underneath of the newly removed carbide particles. Due to high temperature and stress plastic deformation takes place at cutting edge during machining of titanium. Plastic deformation becomes more sever at higher cutting speed and feed. This is due to the higher cutting temperature and smaller contact at tool-chip interface at high cutting speeds as mention earlier. It is thought that in the region of the highest compressive stress the yield stress in the tool was reduced, which resulted in plastic deformation of the tool (Jawaid et al., 2000).

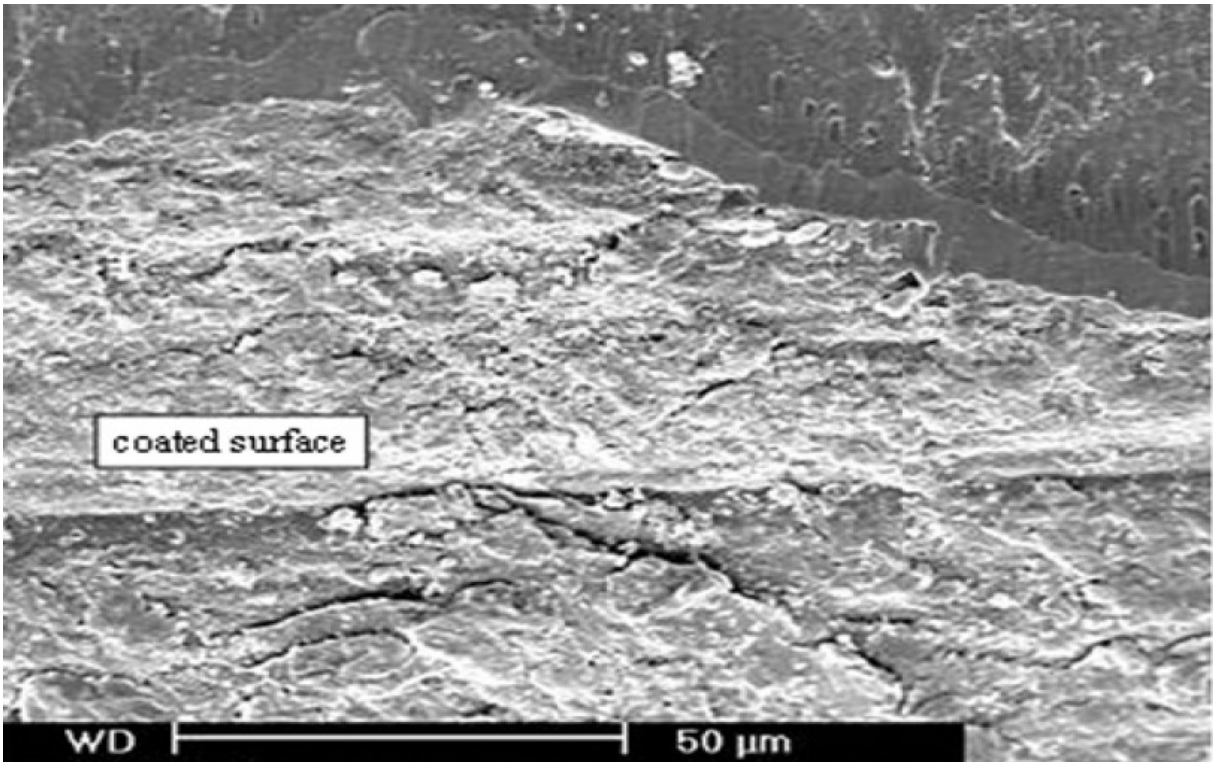

Figure No. 5: Cracks in the coating layer at the leading cutting edge after machining at speed 100 m/min, feed 0.15 m/min (Abdel-Aal et al., 2009).

Generally, several tool wear mechanisms take place simultaneously and those affect one another deteriorating and weakening the cutting tool and stimulating existing cracks to propagate. Among the above types of tool wear, diffusion and adhesive wear are the main mechanism to tool failure (Jianxin et al., 2008). Wears of carbide tools at different cutting conditions are shown below (Fig. No.6). According to (Jawaid et al., 1999) yield strength of the cutting tools reduces at higher cutting temperature and stresses generated on the flank face close to the tool nose which results in a greater wear rate at the nose area (Fig. No.6). It shows that abrasion by carbide grains as a dominant wear mechanism (Dearnly et al., 1986, Hartung, 1982).

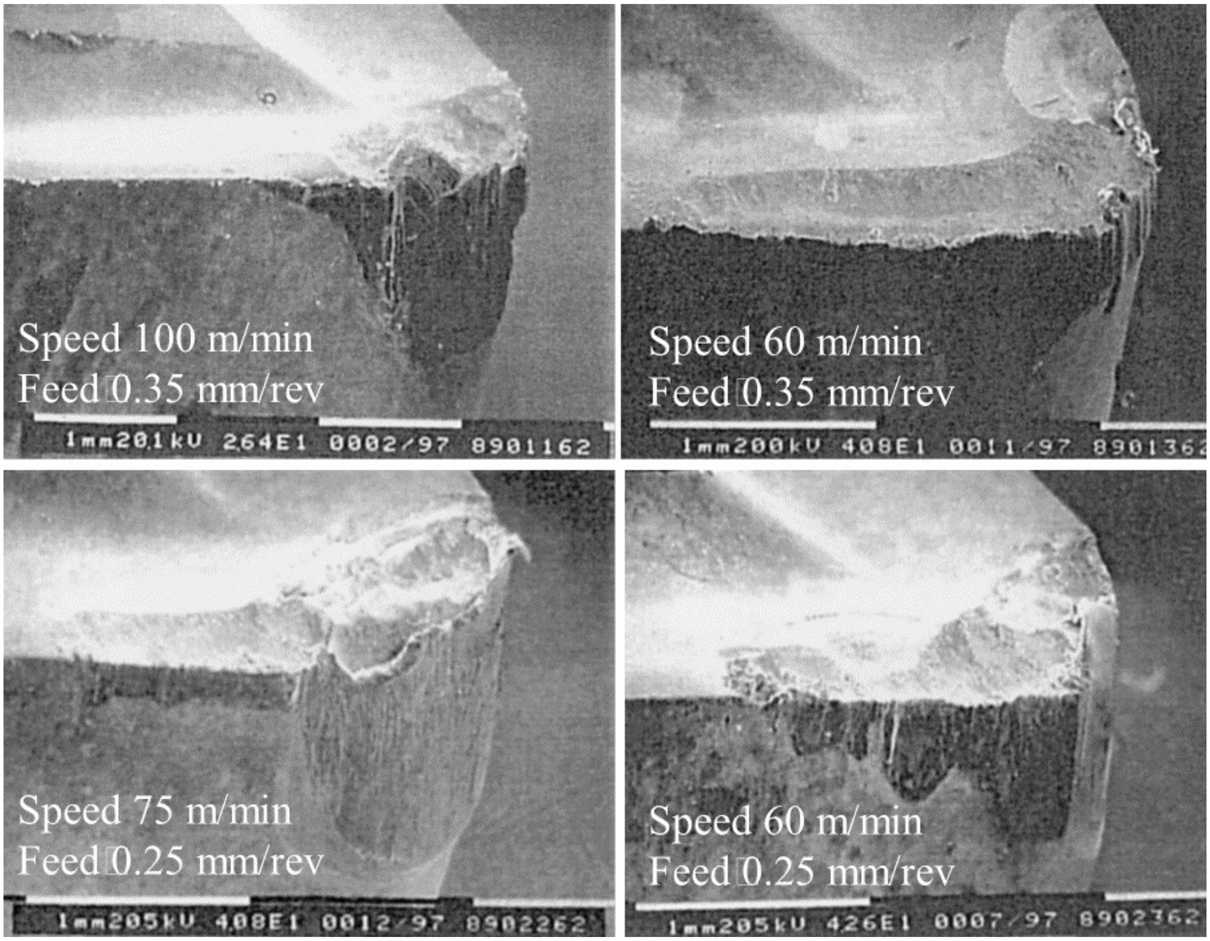

Figure No. 6: Wears of carbide tools at different cutting conditions. (Jianxin et al., 2008).

As discussed earlier, the cutting temperature is lower at lower machining speed and thus, the diffusion and chemical interactions between the carbide tool and titanium alloy is not significant. At low machining speed, the tool wear is caused by mechanical fatigue as well as existing micro-fractures or defects in the tool. Cyclic mechanical and thermal stresses due to formation of saw-tooth chips mainly cause fatigue. Tool particles are easily plucked off from the cracked zone and these are often rubbed on the tool faces by chips resulting in abrasion wear. Abrasion is the major wear mechanism that causes of flank wear when machining with carbide tools at lower speed conditions (Dearnly and Grearson, 1986; Takeyama et al., 1983; Ezugwu et al., 2003). (Turkovich et al., 1982) concluded that no tool materials show sufficient chemical stability for machining titanium to exhibit low wear rates due to low chemical solubilities in titanium. Thus, sliding between the tool and the chip needs to be eliminated to reduce wear. Due to adhesion a very thin layer of chip material forms on the tool face. This reduces the sliding between the tool and the chip, resulting in limited wear by diffusion of tool material through the adhered layer (Turkovich et al., 1982). The tungsten carbide based cutting tools form titanium carbide by chemical reaction with the titanium alloy, are commonly used to machine this material. The titanium carbide has high deformation resistance at cutting temperatures and adheres strongly to both the tool and the chip. Polycrystalline diamond which also forms TiC layer at the tool-chip interface shows better wear and deformation resistant than that of the tungsten carbide based cutting tools (Turkovich 1982). Fig.No.7 shows enlarged pictures of flank faces of two different carbide cutting tools. Smooth wear on the flank face is also noted underneath the adhered titanium on the flank face. The smooth wear pattern is due to the dissolution-diffusion wear mechanism. It seems that the dissolution-diffusion wears dominate on the flank face of the carbide inserts especially at high cutting speeds. Similar kind of wear is also noted in the rake face (Jawaid et al., 1999).

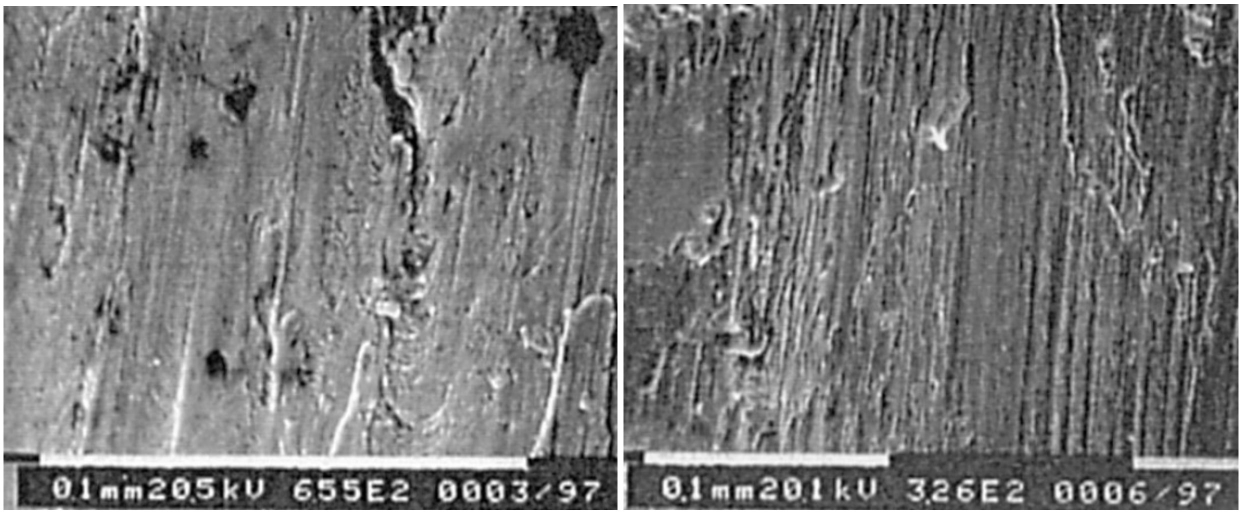

Figure No.7: Close-up view of the flank faces two different carbide cutting tools (Jawaid et al., 1999).

The theories (based on chemical dissolution of the tool material) to predict relative tool wear rate or tool wear do not work properly for machining titanium (Turkovich 1982). (Turkovich et al., 1982) carefully monitored the wear of polycrystalline diamond tools in turning of Ti 6A1-4V at 61.0 m/min. An adherent layer of titanium was seen on the rake face from the start of machining. After 15 minutes of cutting, 20 microns of wear was apparent on the rake face at different locations but there were regions with no wear. This kind of scallop wear on the rake face is also seen on the CBN and the coated carbide tools. Uncoated cemented tungsten carbide tools do not show this type of wear when machining Ti 6A1-4V, but a more conventional crater wear. Similar results i.e., smoothly worn area on rake and flank face of carbide inserts (94 wt.% tungsten carbide with 6 wt.% of cobalt binder) were noted while turning Ti-6246 titanium alloy. Abrasion wear mechanisms are seen to dominate the flank face and tool nose wear, and the maximum flank wear factor controls the tool life. Carbide tools with smaller grain size showed higher resistance to wear than that with larger grain size (Jawaid et al., 1999). Alloyed uncoated (W–Ti/Ta/Nb)C–Co and multi-layer CVD-coated (WC–Co)(TiCN/TiAlN/TiN) when end milling (radial depth of cut = 55% tool diameter, speed 100–125 m/min) of titanium alloy Ti-6242S under dry machining conditions showed acceptable tool life (5.82 to 21.2 min). Similar to other carbide tools, adhesion (attrition) and dissolution-diffusion are mechanisms of tool wear for these tools. The tool failure modes are plastic deformation and brittle fracture, such as, rake face flaking, cracking, chipping and fracturing (Haron et al., 2007). It was suggested (Turkovich et al., 1982) that this kind of wear pattern happens because of different interfacial conditions at different regions during chip generation. As mentioned earlier, a boundary layer of titanium forms at the tool-chip interface and the relative motion between the tool and chip is controlled by shear within the titanium chip material. At certain cutting conditions titanium (Ti 6A1-4V) adheres to the tool and sliding does not take place at the tool-chip interface. Part of the boundary layer quickly becomes saturated with some tool material which limits the further diffusion of tool materials to chips. Thus, no wear occurs in certain regions on the rake face of some tools. The existence of TiC layer on the surface of the tool indicates the diffusion of carbon through the TiC layer. From this finding, (Turkovich et al., 1982) developed model to calculate tool wear rate based on the rate of diffusion of carbon through the TiC layer. The developed model predicted diamond and tungsten carbide tool wear rate accurately.

V. IMPORTANCE OF COOLANT

The same properties that make titanium desirable cause it to be very difficult to machine, particularly its low thermal conductivity and elasticity. Because heat is not easily distributed through titanium, any heat generated during cutting tends to stay in the cutting area, this concentration of heat, sometimes upwards of 2,000°F (1093°C), causes severe problems for the cutting tool**.** High heat tends to shorten tool life through edge chipping and premature dulling due to excessive tool deformation. High cutting tool temperatures also cause a chemical reaction between the cutting tool edge and the chip, leading to crater wear. Titanium has a tendency to work harden, which leads to increased heat problems while hardening the work piece. Work hardening causes high cutting forces, which in turn may lead to depth-of-cut notching on the tool. On the work piece, work hardening not only compromises the part's fatigue strength, but also causes surface irregularities and dimensional inaccuracies. The elasticity of titanium tends to deflect the work piece during machining. If the work piece deflects enough, the tool rubs against the work piece causing excess heat, tool wear, and work hardening. Even if the tool is adequately engaged during the cut, the elasticity of titanium can lead to tool vibration, tool chatter, and poor part surface finish. These problems worsen if titanium and its alloys are cut in an environment that is not ideal. The ingredients needed for good results include the use of generous quantities of high-pressure coolant with appropriate chemistry, a capable machine tool, and proper tooling.

When machining titanium, proper application of coolant can prevent premature tool wear and sudden tool failure. Three issues associated with machining titanium can be addressed through the proper application of coolant. These include proper chip evacuation, effective lubrication, and the prevention of steam.
Effective evacuation of chips prevents the chips, from lingering in the cutting area and causing problems. When chips fall back against the tool, they are sometimes needlessly re -cut, possibly damaging the tool or work piece. Chips also often need to be cooled before they break down and leave the cutting area. Proper delivery of coolant to the tool tip helps cool the chips and remove them from the area. Effective lubrication of the tool tip where it contacts the work piece prevents sudden tool failure and premature tool wear. Often the pressure of coolant delivery is not aggressive enough or the coolant does not have significant lubrication to lubricate the cut. Proper delivery of coolant lubricates the tool as it contacts the very hard
titanium work piece. Proper application of coolant to the tool tip can prevent the coolant from turning into steam. Since the cutting area can reach temperatures above 2,000°F (1093°C), if
the coolant is not applied with significant pressure, it can vaporize before it has a chance to do its job. Vaporizing coolant compounds the problems associated with chip evacuation, lubrication, and excess heat in the cutting area.

It is clear now that the efficiency of the titanium cutting process depends on the thermal/frictional conditions at the tool-chip interface. The use of coolant/lubricant improves the thermal/frictional conditions (Kovacevic et al., 1995). Thus, application of coolant is an integral part during machining of titanium alloy in machining industries. Coolant is more effective if it penetrates into the tool-chip and tool-work piece interfaces during cutting process. This can drop the cutting temperature as much as 30% (Sun et al., 2010) and also acts like lubricant which leads to a longer tool life (Kitagawa et al., 1997; Palanisamy et al., 2009). The efficiency of the heat removal process depends on the heat transfer coefficient between the coolant and the cutting zone (Nandy et al., 2009). Flood cooling is commonly/conventionally applied to reduce heat and induce lubricant into the tool-chip and tool-work piece interfaces (Bermingham et al., 2012). For high speed machining operations diluted solution of rust inhibitor and/or water soluble oil at 5–10% concentration can be used. On the other hand, chlorinated or sulfurized oils can be used for lower speeds and heavier cuts as these coolants minimize frictional forces which cause galling and seizing. Chlorinated oils may cause stress corrosion cracking if not cleaned properly (Campbell, 2006). At high cutting speed, the performance of conventional coolant techniques is limited due to inability to penetrate into the region adjacent to the cutting edge as coolants tend to vaporise at the high temperatures generated in the cutting zone (Ezugwu et al., 2003; Ezugwu, 2004).

To improve the effectiveness of cooling process, several technologies have been developed in recent years for controlling the temperature in the cutting zone in order to increase the overall effectiveness of the process like cryogenic cooling, solid coolants/lubricants, minimum quantity lubrication (MQL)/near dry machining (NDM), high pressure coolants (HPC), internal tool cooling and use of compressed air/gases (Sharma et al., 2009). Different cooling methods have been tested during machining of titanium, such as, MQL, high pressure coolant, liquid nitrogen and cold air.

In high pressure coolant, the coolant pressure can be as high as 90 bar compare to conventional coolant pressure of 6 bar. Smaller chips are generally generated during turning of Ti-6Al-4V with the application of high pressure coolant directed into the tool-chip interface in the secondary shear zone. This is because the higher pressure creates a more effective chip removal process (Palanisamy et al., 2009). High pressure coolant can increase the tool life by almost 3 times mainly by reducing the machining temperature during turning Ti-6Al-4V material. The improvement of tool life is presented in Fig. Under high pressure coolant, frequency of chip serration, shear-band thickness and average chip thickness increases. Thus chip morphology varies. The chip morphology and tool performance not only depend on pressure of coolant but also the coolant properties, such as, density, thermal conductivity, heat transfer coefficient and lubrication ability. These properties control the efficiency of cooling the cutting tool and chip breaking (by the momentum of coolant jet) process. The higher cooling rate and shorter chips provide longer tool life, lower machining forces and better surface finish. The better performance of water-soluble oil is found due to its higher momentum, thermal conductivity, heat transfer coefficient and lubrication ability compare to high-pressure neat oil (Nandy et al., 2009). The hardening effect on the machined surface is much lower when the high pressure coolant is used compare to that of conventional cooling. This is due to higher heat generation with conventional coolant supplies. Efficient cooling by high pressure coolant increases the access of the coolant to the machining zone. This reduces friction and heat generation which consequently lower temperatures and plastic flow. Thus, lesser hardening effect as well as micro-structural damage are generated when high pressure coolant is used (Ezugwu et al., 2007a).

The factors influence the effectiveness of high pressure coolant include the material type, the depth of cut, cutting velocity, tool geometry and the position of the nozzle outlet (Bermingham et al., 2012). The nozzle outlet needs to be close to the cutting edge in case of the milling operations (Palanisamy et al., 2009a). Two methods can be used such as coolant jet injected directly into the tool-chip interface through a hole in the tool rake face, and coolant jet injected into tool-chip interface through an external nozzle (Kovacevic et al., 1995). High-pressure cooling was applied in machining of titanium alloys by (Kovacevic et al.,1995; Machado et al., 1998 and Lacalle et al., 2000). The researchers reported reduction in cutting temperature, cutting forces and coefficient of friction at the chip–tool interface along with improvement in tool life and productivity.

In cryogenic cooling, liquid nitrogen is most commonly used as a coolant. This type of coolant has received great interest recently because of the inherent environmental benefits, such as; nitrogen is a safe, clean, non-toxic fluid that evaporates into the atmosphere leaving no mess and requires no expensive disposal. Ice build-up on tools/tool holders and unavailability of constant supply of liquid coolant are main disadvantages to this process (Bermingham et al., 2012). Cryogenic cooling with liquid nitrogen jets significantly extends the tool life by reducing the crater wear, flank wear and edge depression of the cutting tool insert during in turning of Ti-6Al-4V alloy. The reduction of tool defects is credited to lowering the machining temperature under cryogenic cooling (Venugopal et al., 2007). In addition, cryogenic machining reduces the cutting forces as well as coefficient of friction at the tool–work piece interface (Strano et al., 2013). Under the application of this type of coolant the wear mechanisms, i.e., adhesion–dissolution–diffusion, remain unchanged. The extent of titanium alloy layer deposit on the crater surface is lesser under cryogenic cooling. The benefit of cryogenic cooling is substantial at moderate cutting velocity (Venugopal et al., 2007). The amount of heat removed from the cutting zone depends on the duration for which the heated area is in contact with the coolant. The cold air–chip interaction time becomes shorter at higher cutting speed. Thus the cooling efficiency reduces with the increase of cutting speed (Sun et al., 2010b).

(Hong and Ding, 2001) introduced dispense of liquid nitrogen through micro jets to the flank, the rake, or both near the cutting edge and investigated cutting temperatures at different cooling conditions. Temperatures in cryogenic machining were compared with conventional dry cutting and emulsion cooling. It was noted that a small amount of liquid nitrogen applied locally to the cutting edge is superior to application of emulsion. The study found that cooling approaches in order of effectiveness (worst to best) to be: dry cutting, cryogenic tool back cooling, emulsion cooling, pre cooling the work piece, cryogenic flank cooling, cryogenic rake cooling, and simultaneous rake and flank cooling (Hong and Ding, 2001). (Dhananchezian and Kumar, 2011) modified the cutting tool insert by drilling holes so that liquid nitrogen can flow in the cutting zone for the efficient use of liquid nitrogen in the turning process. It was noted that cryogenic cooling by liquid nitrogen reduced the cutting temperature by 61–66%, cutting force by 35–42%, tool wear by 39% and surface roughness by 35% over wet machining.
(Sun et al., 2010b) took advantages of both the extremely low temperature of the liquid nitrogen and high pressure from the compressed air and developed new cooling approach. They applied liquid nitrogen cooled (cryogenic) compressed air to cool both the flank and rake faces of the tool. The effectiveness of this type of cooling is shown in the Fig.No.8. Cryogenic air at high pressure can easily penetrate into the cutting edge to reduce the cutting temperature and facilitate the chip removal by breaking. It was noted that the cryogenic compressed air show a significantly reduce the chip temperature but the cooling effect diminishes at higher cutting speed. The cooling effect is larger with a smaller feed than that with a larger feed at the same cutting speed (Sun et al., 2010b). In case of air cooling the heat from the cutting zone is removed by heat convection. The efficiency of heat removal depends

on the convection heat-transfer coefficient and temperature of the coolant. The heat convection coefficient (≈2000 W/m2 K) of air at high-pressure (4–7 bar) significantly increases over conventional dry air (≈20 W/m2 K) (Bareggi et al., 2008; Kops and Arenson, 1999). Thus, better reduction of temperature by applying compressed air at the cutting zone. In addition, pressurized cooled air (by LN2 at -196°C) further increases the heat removal rate and reduces chip temperatures. The cryogenic compressed air cooling affects the characteristics of the segmented chip and the transition from irregular to regular saw-tooth takes place (Sun et al., 2010).

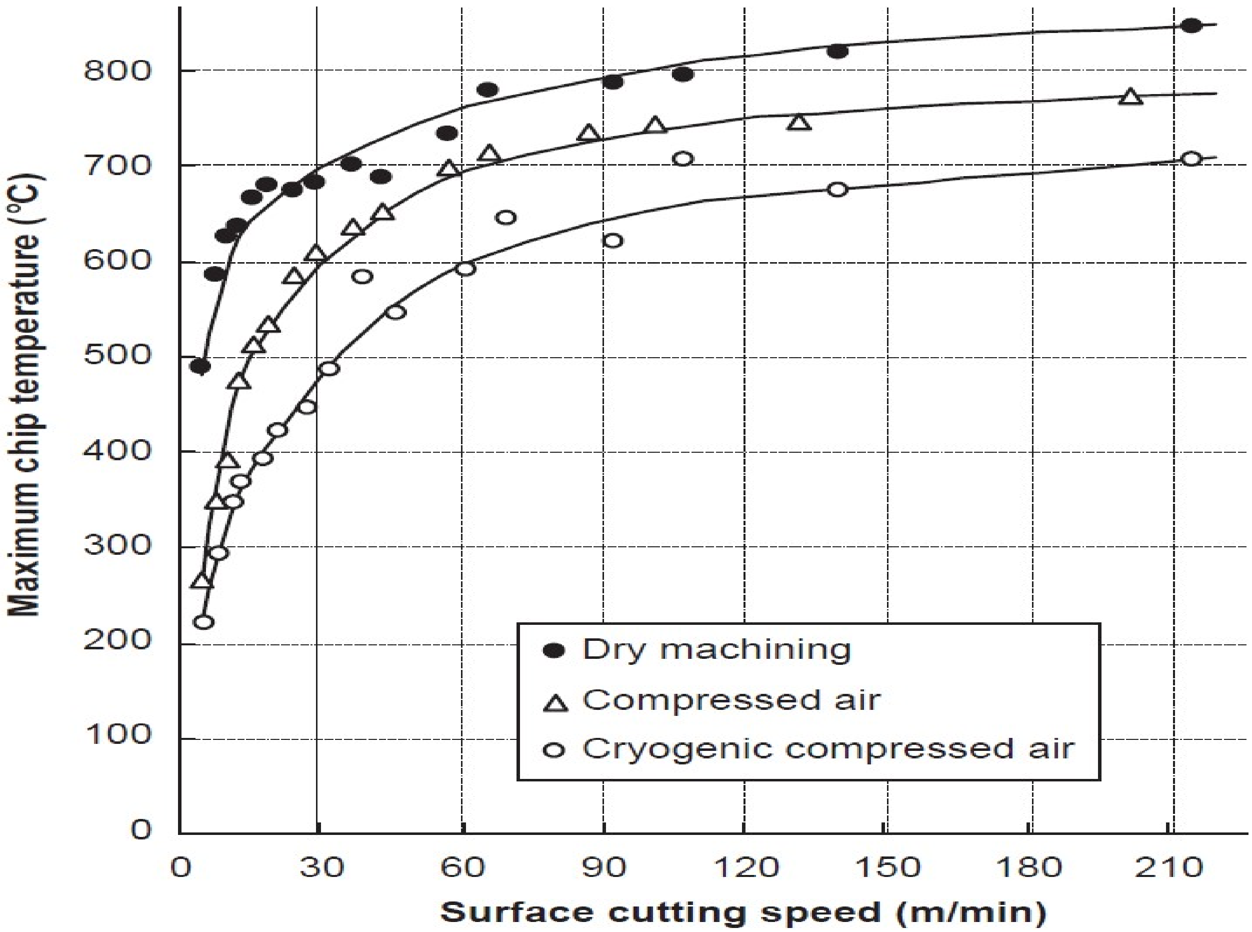

Figure No. 8: Surface cutting speed Vs Maximum chip temperature.

There are researches to eliminate or reduce the consumption of cutting fluid with the increased awareness of environmental and health issues. Minimal quantity lubrication (MQL) method can reduce cutting fluid consumption in machining process. In MQL technique, a small quantity of lubricant is dispensed to the tool–work piece interface by compressed air flow internally/externally (Rahim and Sasahara, 2011; Coz et al., 2012). Very few researches on application MQL technique during machining of titanium alloy in the literature. (Rahim and Sasahara, 2011) studied the drilling of Ti–6Al–4V under different cooling conditions to understand the effectiveness of MQL compare to different lubricant types, such as, air blow and flood cooling. It was found that MQL technique gave comparable performance with the flood cooling condition. MQL technique with palm oil showed better performance than MQL technique with synthetic ester. But both of these reduced the work piece adherence on the cutting tool compared to the dry condition. The cooling effect of MQL techniques is limited. Thus, consequently a significant rise in the temperature is noted in the tool and work piece during the drilling process. Drilling temperature varies from 590 to 640 °C at cutting speed as low as 35 m/min with MQL. This temperature rise activates the tool wear mechanisms, reduces the tool life and affects the machining outcomes (Coz et al., 2012).

VI. CONCLUSION

A review was performed with aim to understand the machining challenges, tool wear, machining parameters and cooling technique to improve productivity of titanium machining processes. The two inherent properties of titanium alloy, such as low thermal conductivity and sawtooth chip formation are the root cause of all problems for machining of this material. These two properties are also related to each other. The low thermal conductivity induces local high temperature which contributes shear instability during chip formation, while the sawtooth chips causes variation of chip thickness, which causes variation of local temperature. Unfortunately, these two properties cannot be changed.

Coolant and conductive cutting tool holder removes the heat from the cutting zones. Coolant is more effective if it penetrates into the tool-chip and tool-work piece interfaces during cutting process. This can drop the cutting temperature and improves tool life or reduce tool wear. The solution for challenges of machining titanium alloy based on tool selection, adjusting cutting parameters, Coolants and environments.

REFERENCES

[1] Che-Haron, C.H. Tool life and surface integrity in turning itanium alloy. Journal of Material Processing Technology 2001, 118, 231–237.
[2] Che-Haron, C.H.; Jawaid, A. The effect of machining on surface integrity of titanium alloy Ti-6%Al-4%V. Journal of Materials Processing Technology 2005, 166, 188–192
[3] Tamakawa, K.; Sakutani, K.; Miura, H. (2007) Effct of micro texture of electroplated copper thin fims on their mechanical properties. *Journal of the Society of Materials Science Japan*, *56*(10): 907–912.
[4] Zhang, J.Y.; Yu, Q.X.; Pang, S.Q. (2009) Development and Prospection of PCBN cutting tool in The 21st Century. *Aeronautical Manufacturing Technology*, (6): 38–44.
[5] Wang, Z.W. (2016) Optimization of micro-texture for cemented carbide ball end mill base on friction properties. *Harbin University of Science and Technology*.
[6] Toh, C.K. A study of the effects of cutter path strategies and orientations in milling. Journal of Materials Processing Technology 2004, 152, 346–356
[7] Liu, P.; Xu, J.H.; Fu, Y.C. Cutting force and its frequency spectrum characteristics in high speed milling of titanium alloy with a polycrystalline diamond tool. Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering) 2011, 12(1), 56–62.
[8] Devillez, A.; Le Coz, G.; Dominiak, S.; Dudzinski, D. Dry machining of Inconel 718, workpiece surface integrity. Journal of Materials Processing Technology 2011, 211, 1590–1598.
[9] Dogra, M.; Sharma, V.S. Machinability and surface quality issues in finish turning of hardened steel with coated carbide and CBN tools. Materials and Manufacturing Processes 2012, 27, 1110–1117.
[10] Petropoulos, P.G. The effect of feed rate and of tool nose radius on the roughness of oblique finish turned surfaces. Wear 1973, 23, 299–310.
[11] Ezugwu EO, Bonney J, Da Silva RB, Cakir O (2007) Surface integrity of finished turned Ti–6Al–4V alloy with PCD tools usingconventional and high pressure coolant supplies. Int J Mach Tools Manuf 47(6):884–891.
[12] Jiang Hua and Rajiv Shivpuri, "Prediction of chip morphology and segmentation during the machining of titanium alloys", Journal of Materials Processing Technology 150, 2004, pp. 124–133.
[13] N.H. Cook,"Chip formation in machining titanium", in: Proceedings of the Symposium on Machine Grind. Titanium, Watertown Arsenal, MA, 1953, pp. 1–7.
[14] K. Nakayama, M. Arai, T. Kanda, "Machining characteristics of hard materials", CIRP 37 (1), 1988, pp. 89–92.
[15] M.C. Shaw, A. Vyas, "Chip formation in the machining of hardened steel", CIRP 42 (1), 1993, pp. 29–33.
[16] R. Konmanduri, T.A. Schroeder, D.K. Bandhopadhyay, J. Hazra, "Titanium: a model material for analysis of the high-speed machining process, advanced processing methods for titanium", in: D.F. Hasson, C.H. Hamilton (Eds.), The Metallurgical Society of ASME, 1982, pp. 241–256.
[17] Lee, "The effect of cutting sped on chip formation under orthogonal machining, J. Eng. Ind., Trans. ASME 107 (1), 1985, pp. 55–63.
[18] Gente, H.W. Hoffmeister, "Chip formation in machining Ti–6Al–4V at extremely high cutting speeds", CIRP 50 (1), 2001, pp. 49–52.
[19] Recht, R.F. (1964) Catastrophic thermoplastic shear. *Transactions of American Society of Mechanical Engineers*, 86:189–193.
[20] Komanduri, R.; Turkovich, B.F. (1981) New observations on the mechanism of chip formation when machining titanium alloys. *Wear*, 69(2):179–188.
[21] Burns, T.J.; Davies, M.A. (2002) On repeated adiabatic shear band formation during high speed machining. *International Journal of Plasticity*, 18(4):487–506.
[22] Komanduri, R.; Brown, R.H. (1981) On the mechanics of chip segmentation in machining. *Transactions of Mechanical Engineers Journal of Engineering for Industry*, 103(1):33–51
[23] Timothy, S.P., Hutchings, J.M. (1984) *Proc. 3rd Int. Conf. on Mechanical Properties at High Rates of Strain*, J. Harding, ed., Institute of Physics, Bristol, 70:397–404.
[24] Giovanola, H. (1988) Adiabatic shear banding under pure shear loading, part II: Fractographic and metallographic observations. *Mechanics of Materials*, 7(1):73–87.
[25] Owen, D.R.J.; Vaz, M. (1999) Computational techniques applied to high-speed machining under adiabatic strain localization conditions. *Computer Methods in Applied Mechanics and Engineering*, 171(3–4):445–461.
[26] Barry, J.; Byrne, G.; Lennon, D. (2001) Observations on chip formation and acoustic emission in machining Ti–6Al–4V alloy. *International Journal of Machine Tools & Manufacture*, 41(7):1055–1070.

[27] Sun S, Brandt M, Dargusch MS (2009) Characteristics of cutting forces and chip formation in machining of titanium alloys. Int J Mach Tools Manuf 49:561–568.
[28] Abele E, Fröhlich B (2008) High speed milling of titanium alloys. Adv Prod Eng Manag 3:131–140.
[29] Vyas A, Shaw MC (1999) Mechanics of saw-tooth chip formation in metal cutting. J Manuf Sci Eng Trans ASME 211:163–172.
[30] Ezugwu EO, Wang ZM (1997) Titanium alloys and their machinability—a review. J Mater Process Technol 68:262–274
[31] Barry J, Byrne G, Lennon D (2001) Observations on chip formation and acoustic emission in machining Ti–6Al–4V alloy. Int J Mach Tools Manuf 41:1055–1070.
[32] S.S. Ingle. *The micromechanisms of cemented carbide cutting tool wear.* Doctoral thesis, McMaster University Hamilton, Ontario. 1993.
[33] J.P. Davim, V.P. Astakhov. *2: Tools (Geometry and material) and tool wear.* In: J.P. Davim (edition). *Machining – Fundamentals and recent advances.* Springer: 2008, ISBN: 978-1-84800-212-8.
[34] F. Luigino, M. Fabrizio, L. Settineri, D. Umbrello. Wear modelling in mild steel orthogonal cutting when using uncoated carbide tools. Wear. 2007, vol. 262, p. 545- 554.
[35] T. Childs, K. Maekawa, T. Obikawa, Y. Yamane. *Metal Machining – Theory and Applications.* Arnold: 2000, ISBN: 0-340-69159-X.
[36] Y.C. Yen, J. Söhner, B. Lilly, T. Altan. *Estimation of tool wear in orthogonal cutting using the finite element method.* Journal of Materials Processing Technology. 2004, vol. 146, p. 82-91.
[37] P.K. Wright, A. Bagchi. *Wear mechanisms that dominate Tool-life in Machining.* Journal of Applied Metal working. 1981, vol. 1, p. 15-23.
[38] 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, p. 163-169.
[39] Sharma S, Dog rab M, Sur i NM (2 009) Coo li ng tech niq ues fo r improved productivity in turning. Int J Mach Tool Manuf 49:435–453
[40] Boothroyd G, Knight WA (2005) Fundamentals of machining and machine tools, 3rd edn. New York, CRC.
[41] Zhao H , Barber G C, Zou Q (2002) A study of flank wear in orthogonal cutting with internal cooling. Wear 253:957–962.
[42] T. Childs, K. Maekawa, T. Obikawa, Y. Yamane. *Metal Machining – Theory and Applications.* Butterworth Heinemann, Oxford
[43] Hartung PD, Kramer BM, von Turkovich BF (1982) Tool wear in titanium machining. Ann ClRP 31(1).
[44] Trent EM, Wright PK (2000) Metal cutting, 4th edn. Butterworth Heinemann, Oxford.
[45] Barrow G (1973) A review of experimental and theoretical techniques for assessing cutting temperatures. Annals of the CIRP 22(2):203–211.
[46] Ying-lin H-y,Gang L, Ming Z (2009) Use of nitrogen gas in highspeed milling of Ti-6Al-4V. Trans Nonferrous Met Soc China 19: 530–534.
[47] Palanisamy S,McDonald D, Dargusch S (2009) Effects of coolant pressure on chip formation while turning Ti6Al4V alloy. Int J Mach Tool Manuf 49:739–743.
[48] Ezugwu EO (2005) Key improvements in the machining of difficult to-cut aerospace superalloys. Int J Mach Tools Manuf 45(12–13): 1353–1367.
[49] Vosough M, Svenningsson I (2004) Influence of high pressure waterjet assisted machining on surface residual stresses on the work-piece of Ti–6Al–4V alloy. In: Proceeding of SPIE, SPIE, Singapore, Bellingham.
[50] Venugopal KA, Paul S, Chattopadhyay AB (2007) Tool wear in cryogenic turning of Ti-6Al-4V alloy. Cryogenics 47:12–18.
[51] Fan Y, Zheng M, Zhang D, Yang S, Cheng M (2011) Static and dynamic characteristic of cutting forces when high efficiency cutting Ti-6Al-4V. Adv Mat Res 305:122–128 36. Schmitz TL, Smith KS (2008) Machini.
[52] Leigh EP, Schueller JK, Tlusty J, Smith S (2000) Advanced machining techniques on titanium rotor parts. Presented at the American Helicopter Society 56th Annual Forum, Virginia Beach.
[53] Follansbee P, Gray GT (1989) An analysis of the low temperature, low and high strain-rate deformation of Ti-6Al-4V. Metall Trans A 20:863–874.
[54] Lennon AM, Ramesh KT (2004) The influence of crystal structure on the dynamic behavior of materials at high temperatures. Int J Plast 20: 269–290.
[55] Dandekar CR, Shin YC, Barnes J (2010) Machinability improvement of titanium alloy (Ti-6Al-4V) via LAM and hybrid machining. Int J Mach Tools Manuf 50(6):174–182.
[56] Takeyama H, Murakoshi A, Motonishi S, Narutaki N (1983) Study on machining of titanium alloys. Ann CIRP 32(1):65–69.
[57] Komanduri R, Hou ZB (2002) On the thermoplastic shear instability in the machining of atitanium alloy (Ti–6Al–4V). Metall Mater Trans 33A:2995–3010.
[58] Komanduri R (1982) Some clarifications on the mechanics of chip formation when machining titanium alloys. Wear 76:15–34.
[59] Komanduri R, Von Turkovich BF (1981) New observations on the mechanism of chip formation when machining titanium alloys. Wear 69(2):179–188.
[60] Duan, C.; Zhang, L. (2013) A reliable method for predicting serrated chip formation in highspeed cutting: analysis and experimental verification. *The International Journal of Advanced Manufacturing Technology*, 64(9-12): 1587-1597.
[61] Wyen, C.-F.; Wegener, K. (2010) Influence of cutting edge radius on cutting forces in machining titanium. *CIRP Annals - Manufacturing Technology*, 59: 93–96Campbell, F.C. (2006) Manufacturing Technology for Aerospace Structural Materials, 1st edition, Elsevier Ltd.
[62] Ulutan, D.; Özel, T. (2013) Determination of tool friction in presence of flank wear and stress distribution based validation using finite element simulations in machining of titanium and nickel based alloys. *Journal of Materials Processing Technology*, 213: 2217– 2237.
[63] Takeyama, H.; Murakoshi, A.; Motonishi, S.; Narutaki , N. (1983) Study on machining of titanium alloys. *Annals of the ClRP*, 32 (1): 65–69.
[64] Haron, C.H.C.; Ginting, A.; Arshad, H. (2007) Performance of alloyed uncoated and CVDcoated carbide tools in dry milling of titanium alloy Ti-6242S. *Journal of Materials Processing Technology*, 185: 77–82.
[65] Jawaid, A.; Che-haron, C.H.; Abdullah, A. (1999) Tool wear characteristics in turning of titanium alloy Ti-6246. *Journal of material processing technology*, 92–93: 329–334.
[66] Jawaid, A.; Sharif, S.; Koksal, S. (2000) Evaluation of wear mechanisms of coated carbide tools when face milling titanium alloy. *Journal of Materials Processing Technology*, 99(1): 266–274.
[67] Jianxin, D.; Yousheng, L.; Wenlong, S. (2008) Diffusion wear in dry cutting of Ti–6Al–4V with WC/Co carbide tools. *Wear*, 265(11): 1776–1783.

[68] Rahman, M.; Wang, Z.G.; Wong, Y.S. (2006) A Review on High-Speed Machining of Titanium Alloys. *JSME International Journal Series C*, 49(1): 11-20.
[69] Kuljanic, E.; Fioretti, M.; Beltrame, L.; Miani, F. (1998) Milling Titanium Compressor Blades with PCD Cutter. *CIRP Annals - Manufacturing Technology*, 47(1): 61–64.
[70] Nabhani, F. (2001) Machining of aerospace titanium alloys. *Robotics and Computer Integrated Manufacturing*, 17:99-106.
[71] Zareena, A.R. (2002) *High-speed machining of titanium alloys*, Master Thesis, National University of Singapore, Singapore.
[72] Hirosaki, K.; Shintani, K.; Kato, H.; Asakura, F.; Matsuo, K. (2004) High Speed Machining of Bio-Titanium Alloy with a Binder-Less PCBN Tool. *JSME International Journal Series C*, 47(1): 14-20.
[73] Wang, Z.G.; Wong, Y.S.; Rahman, M. (2005a) High-speed milling of titanium alloys using binderless CBN tools. *International Journal of Machine Tools and Manufacture*, 45(1): 105- 114.
[74] Wang, Z.G.; Rahman, M.; Wong, Y.S. (2005b) Tool wear characteristics of binder less CBN tools used in high-speed milling of titanium alloys. *Wear*, 258 (5-6): 752-758.
[75] Settineri, L.; Faga, M.G. (2008) Nanostructured cutting tools coatings for machining titanium. *Machining Science and Technology*, 12:158–169.
[76] Ezugwu, E.O.; Bonney, J.; Yamane, Y. (2003) An overview of the machinability of aeroengine alloys. *Journal of Materials Processing Technology*, 134: 233–253.
[77] Konig, W.; Fritsch, R.; Kammermeier, D. (1991) Physically vapor deposited coatings on tools: performance¨ and wear phenomena. *Surface and Coatings Technology*, 49(1): 316–324.
[78] Molinari, A.; P ellizzari, M.; Gialanella, S.; Straffelini, G.; Stiasny, K.H. (2001) Effect of deep cryogenic treatment o n the mechanical properties of tool steels. *Journal of Materials Processing Technology*, 118(1- 3): 350–355.
[79] Hartung, P.D.; Kramer, B.M.; Von Turkovich, B.F. (1982) Tool wear in titanium machining. *CIRP Annals-Manufacturing Technology*, *31*(1): 75-80.
[80] Dearnly, P.A.; Grearson, A.N. (1986) Evaluation of principal wear mechanisms of cemented carbides and ceramics used for machining titanium alloy IMI 318. *Material Science and Technology*, 2: 47–58.
[81] Turkovich, B.F.; Hartung, P.D.; Kramer, B.M. (**1982**) Tool wear in titanium machining. *Annals of the CIRP*, 31(1): 75–80.
[82] Kovacevic, R.; Cherukuthota, C.; Mazurkiewicz, M. (1995) High pressure water jet cooling/lubrication to improve machining efficiency in milling. *International Journal of Machine Tools & Manufacture*, 35(10): 1459–1473.
[83] Palanisamy, S.; McDonald, S.D.; Dargusch, M.S. (2009a) Effects of coolant pressure on chip formation while turning Ti6Al4V alloy. *International Journal of Machine Tools & Manufacture*, 49: 739–743.
[84] Palanisamy, S.; Townsend, D.; Scherrer, M.; Andrews R.; Dargusch, M.S. (2009b) High pressure coolant application in milling titanium. *Materials Science Forum*, 618–619: 89–92.
[85] Kitagawa, T.; Kubo, A.; Maekawa, K. (1997) Temperature and wear of cutting tools in high-speed machining of Incone1718 and Ti-6A1–6V-2Sn. *Wear*, 202: 142–148.
[86] Sun, S.; Brandt, M.; Dargusch, M.S. (2010a) Thermally enhanced machining of hard-to-machine materials—A review. *International Journal of Machine Tools & Manufacture*, 50: 663–680.
[87] Sun, S.; Brandt, M.; Dargusch, M.S. (2010b) The effect of a laser beam on chip formation during machining of Ti6Al4V alloy. *Metallurgical and Materials Transactions A*, 41: 1573–1581.
[88] Nandy, A.K.; Gowrishankar, M.C.; Paul, S. (2009) Some studies on high-pressure cooling in turning of Ti–6Al–4V. *International Journal of Machine Tools and Manufacture*, 49(2): 182–198.
[89] Bermingham, M.J.; Palanisamy, S.; Kent, D.; Dargusch, M.S. (2012) A comparison of cryogenic and high pressure emulsion cooling technologies on tool life and chip morphology in Ti–6Al–4V cutting. *Journal of Materials Processing Technology*, 212: 752–765.
[90] Ezugwu, E.O.; Bonney, J.; Yamane, Y. (2003) An overview of the machinability of aeroengine alloys. *Journal of Materials Processing Technology*, 134: 233–253.
[91] Palanisamy, S.; McDonald, S.D.; Dargusch, M.S. (2009a) Effects of coolant pressure on chip formation while turning Ti6Al4V alloy. *International Journal of Machine Tools & Manufacture*, 49: 739–743
[92] Palanisamy, S.; Townsend, D.; Scherrer, M.; Andrews R.; Dargusch, M.S. (2009b) High pressure coolant application in milling titanium. *Materials Science Forum*, 618–619: 89–92.
[93] Ezugwu, E.O.; Bonney, J.; Silva, R.B.D.; Akir, C.O. (2007a) 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*, 47: 884–891.
[94] Lacalle, L.N.L.D.; Perez-Bilbatua, J.; Sanchez, J.A.; Lorente, J.I.; Alboniga, J. (2000) Using high pressure coolant in the drilling and turning of low machinability alloys. *International Journal of Advanced Manufacturing Technology*, 16: 85–91.
[95] Strano, M.; Chiappini, E.; Tirelli, S.; Albertelli, P.; Monno, M. (2013) Comparison of Ti6Al4V machining forces and tool life for cryogenic versus conventional cooling. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 227(9): 1403–1408.
[96] Hong, S.Y.; Ding, Y. (2001). Cooling approaches and cutting temperatures in cryogenic machining of Ti-6Al-4V. *International Journal of Machine Tools and Manufacture*, 41(10): 1417–1437.
[97] Dhananchezian, M.; Kumar, M.P. (2011). Cryogenic turning of the Ti–6Al–4V alloy with modified cutting tool inserts. *Cryogenics*, 51(1): 34–40.
[98] Bareggi, A.; O'Donnell, G.E.; Torrance, A. (2008) Modelling and experimental analysis of high speed air jets used during metal cutting as a cooling technique. *Proceedings of the Third CIRP International Conference on High Performance Cutting*, 1: 337–346.
[99] Kops, L.; Arenson, M. (1999) Determination of convective cooling conditions in turning. *Annals of the CIRP*, 48: 47–52.
[100] Rahim, E.A.; Sasahara, H. (2011) A study of the effect of palm oil as MQL lubricant on high speed drilling of titanium alloys. *Tribology International*, 44: 309–317.