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Surveying about Different Techniques that are involved in Machining Titanium Bars

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ABSTRACT

Lots of research and developments have been made in accepting the behavior of engineering materials when machining at higher cutting conditions. Developments attained from research and development activities in this area have particularly enhanced the machining of difficult-to-cut titanium alloys that have traditionally exhibited low machinability due to poor thermal conductivity, high strength at elevated temperature, resistance to wear and chemical degradation, etc. These alloys are used extensively where the strength-to-weight ratio and corrosion resistance are of the utmost significance. Even though there have been prodigious developments in the development of cutting tool materials which have significantly improved the machinability of a large number of metallic materials, including cast irons, steels and some high temperature alloys such as nickel-based alloys, no equivalent development has been made for cutting titanium alloys due primarily to their abnormal characteristics. A worthy accepting of the cutting tool materials, cutting conditions and functionality of the machined component will lead to efficient and economic machining of titanium base super alloys. This paper evaluation the main problems associated with the machining of titanium as well as tool wear, the mechanisms responsible for tool failure. Step growth in productivity, hence lower manufacturing cost, without contrary result on the surface finish and surface integrity of the machined component. It was found that the straight tungsten carbide (WC/Co) cutting utensils remain to maintain their superiority in almost all machining processes of titanium alloys, whilst CVD coated carbides and ceramics have not replaced cemented carbides due to their reactivity with titanium and their relatively low fracture toughness as well as the poor thermal conductivity of most ceramics. Cubic Nitride Boron (CBN) outfits are also normally used for machining harder alloys such as titanium and nickel alloys. The implements are expected to endure the heat and pressure developed when machining at higher cutting conditions because of their high hardness and melting point. An effort has been made to debate special machining methods, such as Rotary cutting, High pressure coolant delivery, Cryogenic cooling, Minimum Quantity Lubrication and the use of ledge tools, which have shown some success in the machining of titanium alloys.

Introduction

Titanium and its alloys are used widely in aerospace because of their excellent combination of high specific strength (strength-to-weight ratio) which is maintained at high temperature, their fracture resistant characteristics, and their exceptional resistance to corrosion [1]. They are also being used increasingly in other industrial and commercial applications, such as petroleum refining, chemical processing, surgical implantation, pulp and paper, pollution control, nuclear waste storage, food processing, electrochemical and marine applications. The conventional engineering materials available in the range of alloys and in all the wrought forms: such as billet, bar, plate, sheet, strip, hollows, extrusions, wire, etc. Regardless of the increased usage and production of titanium and its alloys, they are expensive when compared to many other metals because of the complexity of the extraction process, difficulty of melting, and problems during fabrication and machining. Near net-shape methods such as castings, isothermal forging, and powder metallurgy have been introduced to reduce the cost of titanium components. Nevertheless, most titanium parts are still manufactured by conventional machining methods. Almost all types of machining operations, such as turning, milling, drilling, reaming, tapping, sawing, and grinding, are employed in producing aerospace components [1]. For the manufacture of gas turbine engines, turning and drilling are the major machining operations, whilst in airframe production; end milling and drilling are amongst the most important machining operations.

The machinability of titanium and its alloys is generally measured 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 unfavorably. Additionally, its high strength maintained at prominent temperature and its low modulus of elasticity further impairs its machinability. The poor machinability of titanium and its alloys have led many large companies to invest large sums of money in developing techniques to minimize machining cost. Reasonable production rates and outstanding surface quality can be achieved with

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conventional machining methods if the unique characteristics of the metal and its alloys are taken into account.

Titanium alloys can also be used as airframe structure where the operating temperature exceeds 130°C [2], the conventional maximum operating temperature for aluminum alloys. In aero-engines, titanium alloys are widely used in both low and high pressure compressors and for components subjected to high centrifugal loads such as disks and blades that have reduced flow diameters as well as for components which operate under severe fatigue conditions. Titanium alloys also have the leaning to form localized shear bands and can also maintain their high strength levels at elevated temperature in addition to their low modulus of elasticity and thermal conductivity [4]. These characteristics cause high temperatures at the cutting interfaces during machining. The thermal conductivity of Titanium alloy is lower than the thermal conductivity of Inconel 718 alloy and AISI 1045 steel respectively. These properties result in higher tool wear rates, solution wear and smaller chip-tool contact area which adversely affect tool life during machining.

Titanium alloys

Alloying additions of titanium alloys

Pure titanium undergoes an allotropic transformation at 882°C, changing from the low-temperature close-packed hexagonal α phase to the higher-temperature body-centered cubic β-phase [1, 6]. Alloying elements in titanium alloying tend to stabilize either α phase, or the allotrope β phase that alters the transformation temperature and changes the shape and extent of the α-β field. Elements that raise the transformation temperature are α-stabilizers, these being aluminum (Al), oxygen (O), nitrogen (N) and carbon (C), of which Al is a very effective α-strengthening element at ambient and elevated temperatures up to 550°C. The low density of Al is an important additional advantage. O, N and C are regarded as impurities in commercial alloys. However, O is used as a strengthening agent to provide several grades of commercially-pure titanium offering various combinations of strength and fabricability. Even though the addition of tin (Sn) or zirconium (Zr) also strengthen the α phase, these elements have little influence on the transformation temperature because they exhibit extensive solubility in α- and β-titanium and are known as 'neutral elements'.

Elements that produce a decrease in the transformation temperature are β-stabilizers, involving two types, β -isomorphous and β-eutectoid. The most important β-isomorphous alloying additions are molybdenum (Mo), vanadium (V), niobium (Nb). These elements are mutually soluble with β-titanium, increasing addition of the solute element progressively depressing the β to α transformation up to ambient temperature, β-eutectoid elements have restricted solubility in β-titanium and form intermetallic compounds by eutectoid decomposition of the β-phase. The two most important examples of such elements used in commercial alloys are copper (Cu) and silicon (Si).

Classification of titanium alloys

Titanium alloys may be divided into four main groups, according to their basic metallurgical characteristics: α alloys, near α alloys, α-β alloys and β alloys [1, 6].

α alloys:

These contain α-stabilizers, sometimes in combination with neutral elements, and hence have an α- phase microstructure. One such single phase α-alloy, Ti 5-2½ (Ti-SAl-2½Sn), is still available commercially and is the only one of its type to survive besides commercially pure titanium. The alloy has excellent tensile properties and creep stability at room and elevated temperatures up to 300°C. α- alloys are used chiefly for corrosion resistance and cryogenic applications [1, 6].

Near α alloys:

These alloys are highly α -stabilized and contain only limited quantities of β-stabilizing elements. They are characterized by a microstructure consisting of α - phase containing only small quantities of β phase. Ti 8-1-1 (Ti-8Al-1Mo-1V) and IMI 685 (Ti-6Al-5Zr-0.5Mo-0.25Si) are examples of near α- alloys. They behave more like α -alloys and are capable of operating at greater temperatures of between 400 and 520°C [1, 6].

α-β alloys:

This group of alloys contains addition of α - and β-stabilizers and they possess microstructures consisting of mixtures of α- and β-phases. Ti 6-4 (Ti- 6Al-4V, designated IMI 318) and IMI 550 (Ti-4Al-2Sn-4Mo-0.5Si) are its most common alloys. They can be heat-treated to high strength levels and hence are used chiefly for high-strength applications at elevated temperatures of between 350 and 400°C [1, 6].

β alloys:

These alloys contain significant quantities of β-stabilizers and are characterized by high hardenability, improved forgeability and cold formability, as well as high density. Basically, these alloys offer an ambient temperature strength equivalent to that of α-β alloys, but their elevated temperature properties are inferior to those of the α-β alloys [1, 6].

As much as the gas turbine engine is concerned, the most important alloys are those in the near α and α-β groups, the α-β alloy Ti--6Al-4V being the most commonly used titanium alloy, accounting for over 45% of the total titanium production. Titanium aluminides are one of the new alloys introduced for aerospace as well as for automotive applications primarily because of their impressive high temperature properties. In fact, the very impressive high temperature properties of these alloys position them adequately to compete with nickel base alloys in the hot sections of aircraft engines as well as in automobile engine valves. Like wise new materials, titanium aluminides are extremely difficult to machine. The toughness, high temperature properties and fatigue properties of conventional alloys and their derivatives are being improved by new processing techniques such as super plastic forming and advance powder metallurgy processing techniques [2].

Machining of titanium alloys

Progress in the machining of titanium alloys has not kept rapidity with advances in the machining of other materials due to their high temperature strength, very low thermal conductivity, relatively low modulus of elasticity and high chemical reactivity. Therefore, success in the machining of titanium alloys depends largely on the overcoming of the principal problems associated with the inherent properties of these materials, as discussed below [1]:

High cutting temperature:

It is well known that high cutting temperatures are generated when machining titanium alloys and the fact that the high temperatures act close to the cutting edge of the tool are the principal reasons for the rapid tool wear commonly observed. As the large proportion (about 80%) of the heat generated when machining titanium alloy Ti-6Al-4V is conducted into the tool because it cannot be removed with the fast flowing chip or bed into the workpiece due to the low thermal conductivity of titanium alloys, which is about 1/6 that of steels. About 50% of the heat generated is absorbed into the tool when machining steel. Investigation of the distribution of the cutting temperature is that the temperature gradients are much steeper and the heat-affected zone much smaller and much closer to the cutting edge when machining titanium alloys because of the thinner chips produced and the presence of a very thin flow zone between the chip and the tool which causes high tool-tip temperatures of up to about 1100°C [1].

High cutting pressures:

The cutting forces recorded when machining titanium alloys are reported to be similar to those obtained when machining steels, thus the power consumption during machining is approximately the same or lower [1]. Much higher mechanical stresses do, nevertheless, occur in the immediate locality of the cutting edge when machining titanium alloy. Higher stresses on the tool when machining Ti-6Al-4V (titanium alloy) than when machining Nimonic 105 (nickel-based alloy) and three to four times those observed when machining steel Ck 53N (Fig. 1). This may be attributed to the unusually small chip-tool contact area on the rake face, (which is about one-third that of the contact area for steel at the same feed rate and depth of cut) and partly to the high resistance of Ti-alloy to deformation at elevated temperatures, which only reduces considerably at temperatures in excess of 800°C.

Chatter:

Chatter is another main problem to be overcome when machining titanium alloys, especially for finish machining, the low modulus of elasticity of titanium alloys being a principal cause of the chatter during machining. When subjected to cutting pressure, titanium deflects nearly twice as much as carbon steel the greater spring-back behind the cutting edge resulting in premature flank wear, vibration and higher cutting temperature. In effect, there is a bouncing action as the cutting edge enters the cut. The appearance of chatter may also be partly ascribed to the high dynamic cutting forces in the machining of titanium. This can be up to 30% of the value of the static forces due to the adiabatic or catastrophic thermoplastic shear process by which titanium chips are formed [1].

Criteria for tool materials:

High cutting temperatures, high mechanical pressure and high dynamic loads in the machining of titanium alloys, which result in plastic deformation and/or fast tool wear, cutting tools also suffer from strong the chemical reactivity of titanium. Titanium and its alloys react chemically with almost all tool materials available at cutting temperature in excess of 500°C due to their strong chemical reactivity. The tendency for chips to pressure weld to cutting tools, severe dissolution-diffusion wear, which rises with increasing temperature, and other abnormal characteristics already mentioned, demand additional criteria in the choice of the cutting tool materials. These problems may be minimized by employing very rigid machines, using proper cutting tools and set-ups, minimizing cutting pressures, providing abundant coolant flow and designing special tools or non-conventional cutting methods [1].

Tool materials for machining titanium alloys

Major improvements in the rate at which work pieces are machined usually result from the development and application of new tool materials. Over the last few decades, there have been great advancements in the development of cutting tools, including coated carbides, ceramics, cubic boron nitride and polycrystalline diamond. These have found useful applications in the machining of cast irons, steels and high temperature alloys such as nickel-based alloys. However, none of these newer developments in cutting tool materials have had successful application in improving the machinability of titanium alloys because of the dominant qualities required of tool materials, which are: (i) high hot hardness to resist the high stresses involved; (ii) good thermal conductivity to minimize thermal gradients and thermal shock; (iii) good chemical inertness to depress the tendency to react with titanium; (iv) toughness and fatigue resistance to withstand the chip segmentation process; and (v) high compressive, tensile and shear strength.

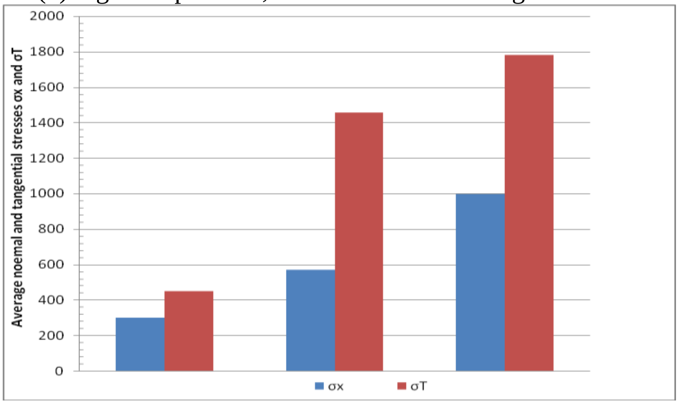


Fig 1. Normal and Tangential Stresses in machining [1]

Work material	Steel Ck53N	Nimonic 105	Ti-6Al-4V
Tool material	Carbide P10	Carbide K10	Carbide K10

Straight tungsten carbide (WC/Co) cutting tools have proven their superiority in almost all machining processes of titanium alloys and interrupted cutting (end milling, tapping, broaching and planning), drilling and reaming being performed best by high-speed steel tools [1]. The better performance of the WC/Co grades has recorded, no matter which wear mechanism is taking place. Many trials are carrying out involving various tool materials in the continuous turning of Ti-6AI-4V, also confirmed the K grade carbides as the best choice. It was suggested that those WC/Co alloys with Co contents of 6 wt% and a medium WC grain size (about 0.8 and 1.4 μm) gave the optimum performance. A recent study advises that straight cobalt-base tungsten carbide cutting tools implanted with either chlorine or indium are very effective in the machining of titanium and their alloys. It has been proven that steel cutting grades (P grades of ISO codes) of cemented carbides are not suitable for machining titanium alloys because of the greater wear rate of the mixed carbide grains than that of the WC grains and because of their thermal properties. All coated carbide tools tested (cemented carbides coated by TiC, TiCN, TiN-TiC, Al203-TiC, TiN-Ti(C,N)-TiC, Al203, HfN, and TiB2,) also show greater wear rates than those of straight grade cemented carbides. It is found that a very fine grain TiN/steel compound coated with a layer of TiN (using the PVD technique) shows outstanding performance when end milling titanium alloy at high cutting conditions beyond those possible with carbide end mills. General-purpose high-speed steel tools are often suitable in the machining of titanium. However, the best results have been achieved with highly alloyed grades.

Even though ceramics have improved in quality and found increased application in the machining of difficult-to-cut materials, especially high-temperature alloys (such as nickel-based alloys), they have not replaced cemented carbides and high-speed steels due to the poor thermal conductivity of most ceramics, their relatively low fracture toughness and their reactivity with titanium.

The super hard cutting tool materials (cubic boron nitride and polycrystalline diamond) have also shown a good performance in terms of wear rate in the machining of titanium [4]. However, their applications are limited due to their high price.

Tool failure modes and wear mechanisms

A number of specific studies on tool failure modes and wear mechanisms when machining titanium alloys have been conducted [1]. Cutting tool materials encounter severe thermal and mechanical shocks when machining titanium alloys, the high cutting stresses and high temperatures generated at and/or close to the cutting edge greatly influencing the wear rate and hence the tool life. Notching, flank wear, crater wear, chipping and catastrophic failure are the prominent failure modes when machining titanium alloys, these being caused by a combination of high temperature, high cutting stresses, the strong chemical reactivity of titanium, the formation process of catastrophic shear chips, etc.

Special tool materials tend to have different responses to different wear mechanisms when machining titanium alloys. Because of the rapid loss of their hardness at elevated temperatures above 600°C, high speed steel tools suffer severe plastic deformation which accelerates the rate of wear. Plastic deformation can also be a major contributor to wear mechanisms of other tool materials when machining titanium alloys, especially in the case of high-speed machining, due to the presence of high compressive stresses and the development of high temperatures close to the cutting edge [1].

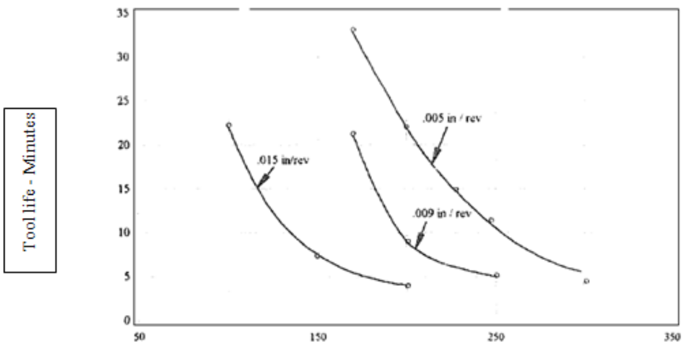
The tool life study has carried out on steel cutting grades (containing carbides other than tungsten) and straight WC/Co grades of cemented carbides when machining two commercially-available titanium alloys (an alpha-beta alloy and a beta alloy) and reported that plastic deformation occurred, especially at higher cutting speeds, and that a crater can also be formed by shearing on the rake face, both of these effects accelerating other wear mechanisms considerably. The tools tested also suffered diffusion during machining. The steel-cutting grades of cemented carbide are inferior to straight grades because of the presence of the mixed carbide grains (such as TiC and TaC). The mechanism of attrition acts preferentially on the mixed carbide grains, and tools containing mixed carbides also wear by diffusion quicker than WC/Co tools because these mixed carbides dissolve preferentially in titanium.

The rake and flank wear of the entire tool materials tested resulted from dissolution-diffusion and attrition when turning titanium alloys. Dissolution-diffusion wear predominated on the 'rake face' of all the uncoated cemented carbides and ceramics, except for sialon, where attrition is the competitive wear mechanism. On the 'flank face', attrition wear controls the wear rates of ceramics and steel-cutting grades of cemented carbides, whilst it is less predominant on the flank faces of straight grades of cemented carbides, which can probably be attributed to the increased toughness of WC/Co alloys compared to that of other grades. For these materials, dissolution diffusion wear controls the wear rates of flank wear. Coatings of TiN, TiC, A1203 and HfN on both the rake and flank faces are worn more rapidly than uncoated WC/Co by either dissolution-diffusion or attrition wear mechanisms. Coatings of TiB2 are relatively more resistant than others, as are CBN tools [1]. Notch wear, which severely affects ceramic tools, is caused mainly by a fracture process. However, a smoother notch wear surface (perhaps caused by reaction with the atmosphere) has also been reported with Sialon tools.

The presence of a 'flow zone" at the chip-tool interface will eliminate the sliding between them, thus maximizing the wear resistance. If a flow zone is formed the wear will be limited by the diffusion rate of the tool constituents through this layer. This process of wear is believed to occur at a lower rate compared to that caused by physical motion of the chip under sliding conditions (i.e. attrition); however, attrition has been found in other machining operations when a flow zone is present, It was found that WC/Co grades of cemented carbide and polycrystalline diamond are the best tool materials to machine titanium because a stable reaction layer is formed between the tool and the chip. The carbon from either WC/Co-based composites or polycrystalline diamond reacts with the workpiece to form TiC. This reaction layer has high deformation resistance at the cutting temperature and adheres strongly to both the tool and the chip. This layer quickly becomes saturated, limiting the mass transport of tool constituents from the tool surface and reducing the wear rate. The carbon redistribution results in surface weakening and embrittlement of the tool, which encourages chipping and increased tool wear rate. It is found that at high cutting speeds the high temperature developed enables chemical interactions between the work material and the coating layers to take place and the layers are thus rapidly removed resulting in the substrate acting as the cutting edge over most of the tool life.

Cutting parameters and tool geometry

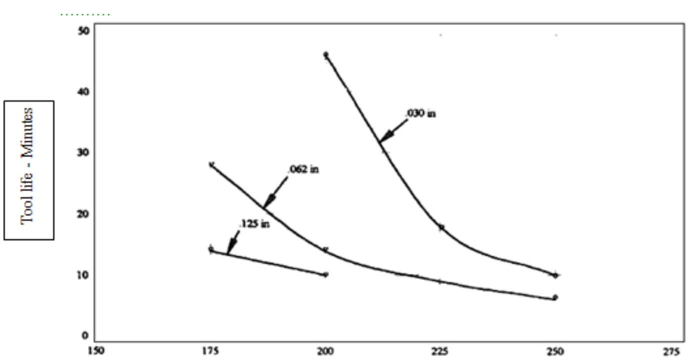
Data on cutting parameters have been developed experimentally on a wide variety of titanium alloys. Cutting speed has the most considerable influence on tool life. The latter can be plotted against cutting speed for a given cutting tool material at a constant feed rate and depth of cut Fig. 2 [1]. It can be seen that tool life is extremely short at high cutting speeds but improves dramatically as the speed is reduced. Another important variable affecting the tool life is the feed rate. Frequently the tool life is not changed dramatically with a change in feed, but titanium alloys, however, are very sensitive to changes in feed (Fig. 2) [1]. It is suggested that operation at high feeds is more desirable to increase productivity. When machining titanium, the effect of the depth of cut must be considered also. As indicated in Fig. 3[1], increasing the depth of cut from 0.75 to 3 mm decreases the tool life from 46 to 14 min at a cutting speed of 60 m/min.



Cutting speed - feet/minute
Work Material: Ti-6AI-4V (Solution treated and aged 388 BHN)
Tool material: C-2 (883) Carbide

Fig. 2. Effect of cutting speed and feed on tool life in turning Ti- 6AI - 4V [1]

When machining titanium alloys, the tool geometry has a considerable influence on the tool life. It was suggested that a new tool geometry, consisting of a high clearance angle (from l0 to 15 °) together with a high negative rake angle (from - l0 to - 150), increases the tool life of straight cemented tungsten carbide (WC/Co) significantly compared with the standard tool geometry (- 5 ° rake angle and 5 °clearance angle) [1].



Cutting speed, feet/min
Work Material: Ti-5AI-2Sn (Annealed 321 BHN)
Tool material: C-2 (883) Carbide

Fig. 3. Effect of cutting speed and depth of cut on tool life in turning Ti-5AI-2Sn [1]

Cutting fluid

The high temperature and the high stresses developed at the cutting edge of the tool are the principal problems when machining titanium alloys. To minimize the problem, a cutting fluid must be applied, as a basic rule. The cutting fluid not only acts as a coolant but also functions as a lubricant, reducing the tool temperatures and lessening the cutting forces and chip welding that are commonly experienced with titanium alloys, thus improving the tool life. The correct choice of cutting fluid has a significant effect on tool life. Abundant, uninterrupted flow of coolant will also provide a good flushing action to remove chips, minimize thermal shock of milling tools and prevent chips from igniting, especially when grinding titanium [1]. Additionally, a high pressure coolant supply can result in small, discontinuous and easily disposable chips, unlike the long continuous chips produced when machining with a conventional coolant supply.

It is 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 a restriction 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 [1].

It is 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, basis in liquid jet or in spray cooling causes more wear than does dry cutting. Work carried out at the Air Force Materials Laboratory [1], concluded that chlorine-containing cutting fluids do not always provide a better tool life. For particular alloys and operations, dry machining is preferred. Usually the heavy chlorine-bearing fluids excel in operations such as drilling, tapping, and broaching.

According to Chandler [8], water-base fluids are more efficient than oils. He found that a weak solution of rust inhibitor and/or water-oil (5-10%) solution are the most practical fluid for high-speed cutting operations. Slow speed and complex operations may require chlorinated or sulfurized oils to minimize frictional forces and the galling and seizing tendency of titanium. Chandler [8] pointed that chlorinated cutting fluids should be used with great caution because of their potential to cause stress corrosion cracking.

It was found that the machining of titanium with a lubricant containing a chlorine additive developed surface films of a thickness equal to or less than 150 μm (1500 Å) and a chlorine content of at most 3 at.%. Similar films with 1.5 at.% and 100--150 μm (1000-1500 Å) thickness were obtained by machining titanium with demineralized water. The work concluded that the prohibition of machining titanium with lubricants containing chlorine additives can no longer be maintained.

Special machining techniques

The inability to improve cutting-tool performance by developing new cutting-tool materials has been very frustrating. Likewise, very little improvement in productivity has been experienced by exploring new combinations of speeds, feeds, and depths of cut. However, increased productivity and long tool life have been achieved by special machining techniques, including specially designed ledge tools and rotary tools.

Ledge tools

Ledge tools are characterized by a thin cutting edge that overhangs a small distance equal to the desired depth of cut (Fig. 4). The advantage of these tools, developed by the General Electric Company, lies in the limited maximum flank wear of the tools during machining. As cutting proceeds, they first achieve maximum flank wear and then the length of the overhang wears back without further development in flank wear due to a restricted clearance face. Thus the tools can perform for a long time, as the tool life is not limited by the amount of flank wear but by the size of the edge. Because of its restricted geometry these tools are applicable only to straight cuts in turning, facing, boring, face milling, and some peripheral milling operations [1].

Rotary tools

Rotary cutting tools are in the form of circular discs that rotate about their central axis in addition to the main cutting and feed motion (Fig. 5). It has been shown conclusively that rotary tools give rise to several hundred degrees centigrade lower cutting temperatures when machining titanium alloys (Fig. 6). The tool life improvements are considerable when machining difficult-to-cut materials with rotary tools due to their superior wear-resistivity (Fig. 7), which may be attributed to their unusual characteristics such as continuous shifting of the cutting edge during machining and lower cutting temperature. The tool lives are approximately seven times those of conventional tools when machining Ti- 6A1-4V using rotary tools at very high feed rates (up to 1 mm/rev), achieved without sacrificing the surface finish or the stability of the cutting process. Due to the cutting edge being circular the rotary tool can also lead to a very fine machined surface, provided that the tool spindle assembly is adequately rigid. Although the improvement in tool life achieved by rotary cutting is very significant, very few industrial applications have been reported. The reasons for this may be their reduced effectiveness for machining complex surfaces and the requirement for either rigid machine- work systems or light cuts.

High pressure coolant delivery

The idea of delivering coolant under high pressure to the cutting region in order to increase tool life during machining began in early 1950s.

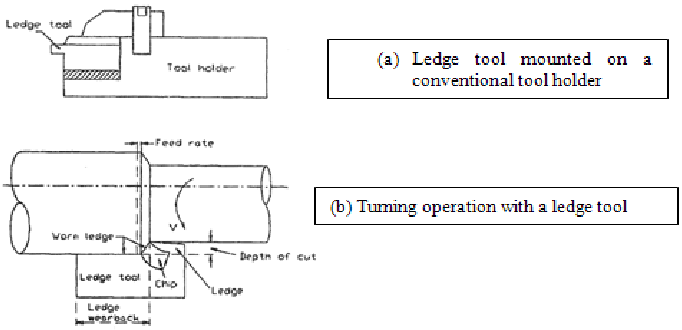


Fig 4. Ledge tool [1]

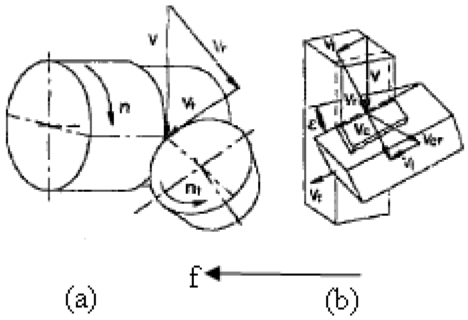
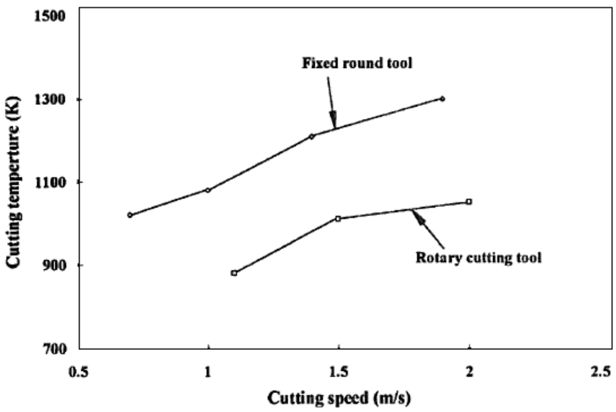
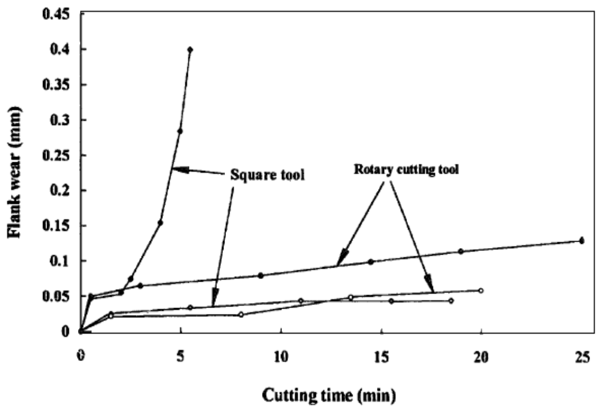


Fig.5 Rotary cutting tools [1,2]



Feed rate: 0.4 mm/rev, Depth of cut: 0.25 mm

Fig 6. Measured temperature in turning Ti-6AI-4V [1]



◊ ○ - Cutting speed 60 m/min, ♦ ● - Cutting speed 120 m/min

Fig 7. Tool wear curves in machining Ti-6AI-4V [1]

The primary objective of this machining technique is to significantly reduce the temperature generated at the tool–workpiece and tool–chip interfaces when cutting at higher speed conditions. This is achieved by directing coolant under high pressure at the chip–tool interface. This process can also achieve high chip breakability and control through increased chip up curl and compressive stress. Flood cooling of the cutting zone can effectively reduce the cutting temperature when machining at lower speed conditions with significant sliding region and where relatively low cutting temperatures are generated. The coolant also acts as a lubricant, thus minimising friction and lowering component forces and consequently tool life.There is very limited access of the coolant to the tool–workpiece or tool–chip interfaces which are mainly under seizure condition when machining at high speed conditions [2].

Ability to deliver coolant at high pressure very close to the critical point on the secondary shear zone can improve machinability at higher speed conditions. The trustworthiness of this technique of coolant delivery has been thoroughly investigated over the years. Initially, this technique was unpopular because of associated equipment cost and also the fact that low speed machining was the preferred mode of production as machine tools were not capable of high speed machining applications. The manufacturing industry have recently adopted a more radical approach to increasing the rate of production and high pressure coolant delivery technique is a viable means of achieving this strategy in addition to providing an effective removal (by flushing) of the chips from the cutting area. The high speed coolant jet traverses the surface faster, thus significantly lowering the film boiling action of the coolant at the cutting area. This consequently minimises heat transfer to the cutting tool. The high pressure coolant jet creates a hydraulic wedge between the tool and the workpiece, penetrating the interface with a speed exceeding that required even for high speed machining and also alters the chip flow conditions [2]. The penetration of the high energy jet into the tool–chip interface reduces the temperature gradient and eliminates the seizure effect, offering an adequate lubrication at the tool–chip interface with a significant reduction in friction. Fig. 8 is a typical set-up of the high pressure delivery system when machining a titanium alloy disc.

The benefits of high pressure coolant supply seem more obvious when machining commercially available titanium, Ti6Al4V alloy with cemented carbide (coated and uncoated) tools as well as with Polycrystalline Diamond (PCD) tools as shown in Figs. 9 and 10. These figures clearly show that remarkable tool life can be achieved with high pressure coolant supplies. There is negligible difference between coated and uncoated carbide tools in terms of recorded tool life, hence there is no tangible benefit in machining with coated carbide tools with associated additional cost. These improvements can be achieved without compromising the surface finish generated, circularity and hardness variation of the machined surfaces.

Tool life generally increased with increasing coolant pressure where lower cutting temperatures are expected. The effect of coolant delivery under high pressures is clearly shown in Fig. 10 where encouraging tool life was obtained when machining the titanium alloys with PCD tools at much higher cutting speeds, up to 250 m/min, conditions that were not possible under conventional coolant supply.

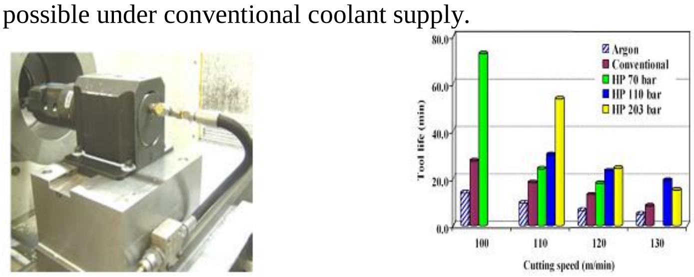


Fig 8. Setup for high pressure coolant delivery to the tool tip [2]

Fig. 9. Recorded tool life when machining titanium alloy with uncoated carbide inserts at various coolant pressures, conventional coolant flow and in an argon enriched environment(Source: [2]).

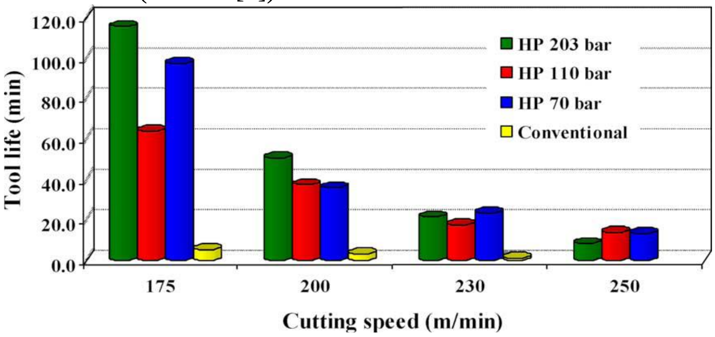


Fig 10. Recorded tool life when machining titanium alloy with polycrystalline diamond inserts at various coolant pressures and with conventional coolant flow [2].

Cubic boron nitride and ceramic cutting tools are not recommended for high speed machining of titanium alloys with high pressure coolant supply as they tend to suffer excessive nose wear and severe chipping and/or fracture of the cutting edge. Increase in cutting speed generally resulted in higher cutting temperature. It is, however, important to note that lower temperature was generated when machining at 500 m/min, relative to that recorded at 450 m/min. This can be associated with the erosion of the cutting edge due to severe thermal wear at the cutting edge. The use of high pressure coolant delivery will, however, require proper sealing of the machine tool to prevent leaking and spillage of coolant, the installation of a mist extractor on the machine tool as well as adequate ventilation of the machining environment in order to minimise health hazard to the operator by exposure to the coolant both in normal and mist/atomized forms [2, 4]. *Minimum quantity lubrication (MQL).*

It has long been observed that cutting fluids if not disposed off properly may adversely affect the environment. Machine operators in contact with cutting fluid develop severe reactions on the skin in addition to fumes, smoke, bacterial and odours. To solve some of these problems, 'clean machining' is now being emphasised. This concept is defined as machining with the use of minimum amount of coolants and/or the use of environmentally acceptable coolants. Minimal Quantity Lubrication (MQL) technology involves the application of very small amount of water and soluble oil, 6–100 ml/h, delivered in a compressed air stream, directed at the tool cutting edge. Encouraging results had been observed in grinding, milling and turning applications. These improvements in machining can be attributed to the lubricating oil that was able to get very close to the tool–chip and tool–workpiece interfaces under pressure, therefore reducing friction and component forces generated during machining. Temperature reduction at the cutting zone in MQL systems is achieved mainly by the cooling effect of the compress air and partially by evaporation. Significant amount of heat is absorbed to effect the evaporation of the lubricants, thus contributing to a significant temperature reduction at the cutting zone. Pressure welding of chips to the cutting edge is the main cause of tool failure when milling titanium alloys with HSS tools. With MQL this failure mode can be drastically reduced causing significant improvement to surface finish of the machined components. The MQL system has shown encouraging potentials for precision machining at low feed and high speed conditions. The main disadvantage of using this system is mist generation, which poses a health hazard to operators. This hazard can, however, be minimised with good mist extractors [2].

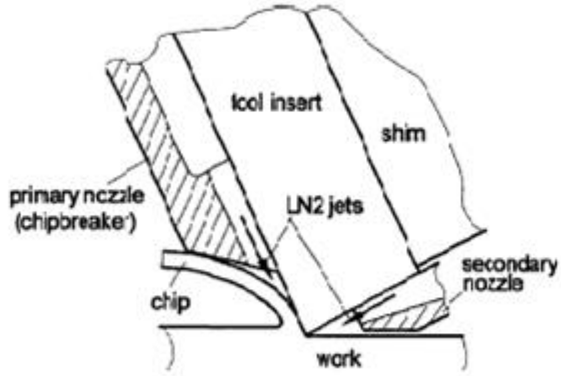


Fig. 11. Duel-nozzle system for localized LN2 supply [2].

Cryogenic cooling

Cryogenic cooling (Fig. 11) is an efficient way of maintaining the temperature at the cutting interface well below the softening temperature of the cutting tool material. Commonly used coolant is liquid nitrogen (LN2) because of its low cost and the fact that it does no harm to the environment. Tool wear rates when machining titanium alloy Ti–6Al–4V with cemented carbide using LN2 and under conventional cooling at a cutting speed of 132 m/min, feed rate of 0.2 mm/rev and a depth of cut of 1.0 mm showed a five – fold increase in flank wear for tools subjected to the conventional cooling.

Hot machining

The use of hot machining as a technique for improving machining operations has been under consideration since the decade ego. Metals tend to deform more easily when heated, thus enhancing machining. The use of hot machining in the manufacture of engineering components began in the late 20th century, a Century after it was first introduced. The principle behind hot machining is the reduction of the large difference in hardness of the cutting tool and workpiece, leading to reduction in the component forces, improved surface finish and longer tool life [2]. This process offsets various disadvantages like cost, vacuum requirement, metallurgical damage to the workpiece in addition to ensuring better surface finish, improved rates of production and tool life. Major benefits of this process are: increased metal removal rates; ability to machine hard and tough metals even when fully hardened and heat treated; no metallurgical damage to the machined surfaces, increase in tool life, suitability for interrupted cuts and cost saving in machining components. This technique can also be applied on titanium alloys for machining. This technique combines both cryogenically enhanced machining and plasma enhanced machining. Softening of the workpiece, thus ensuring easier machining, is achieved by plasma heating while nitrogen cooling prevents the tool from overheating, thus minimising thermally related tool failure modes to prolong tool wear (Fig. 12).

Surface integrity

Titanium is generally used for a material for parts requiring the greatest reliability, and therefore the surface integrity must be maintained. Though, 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. When machining titanium in a rude manner (such as using a dull tool) an overheated white layer can be produced, this may be harder or softer than the base materials.

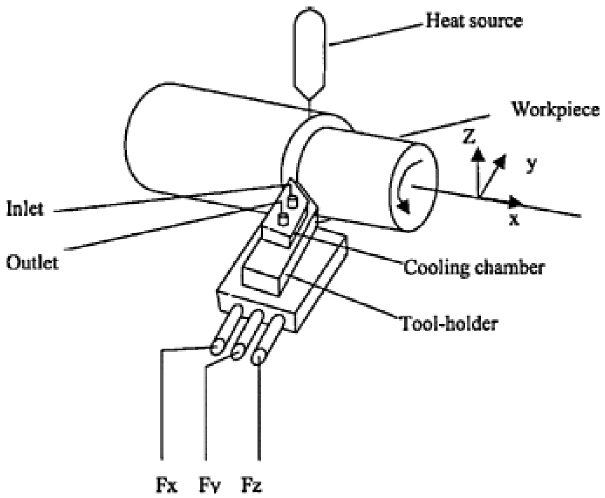


Fig 12. Setup of the hybrid machining process [2].

Under both gentle and rude machining conditions, however, the surface residual stresses appear compressive and their values differ according to the cutting conditions (such as the cutting speed). The surfaces produced under obnoxious conditions are also damaged by deformation and micro cracks, which contribute to the loss of fatigue strength and stress corrosion resistance in combination with the residual stress pattern discussed above [1].

Conclusions

1. Titanium and its alloys are considered as difficult cut materials due to the high cutting temperature and the high stresses at and/or close to the cutting edge during machining. The high cutting temperature is due to the heat generated during machining, the thin chips, a thin secondary zone, a short chip-tool contact length and the poor heat-conductivity of the metal, whilst the high stresses are due to the small contact area and the strength of titanium even at elevated temperature.

2. Straight grade (WC/Co) cemented carbides are regarded as the most suitable tool material available commercially for the machining of titanium alloys as a continuous operation. High-speed steel tools are also very useful for some interrupted cuts, but the development of new tool materials is still required. There is no adverse effect on surface finish generated when machining the Ti– 6Al–4V alloy with CBN tools.

3. Cutting tool materials undergo severe thermal and mechanical loads when machining titanium due to the high cutting stresses and temperatures near the cutting edge, which greatly influence the wear rate and hence the tool life. Flank wear, crater wear, notch wear, chipping and catastrophic failure are the prominent failure modes when machining titanium alloys. Flank and crater wear may be attributed to dissolution-diffusion, attrition and plastic deformation, depending on the cutting conditions and the tool material, whilst notch wear is caused mainly by a fracture process and/or chemical reaction.

4. As a basic rule, a cutting fluid must be applied when machining titanium alloys. The correct use of coolants during machining operations greatly extends the life of the cutting tool. Chemically active cutting fluids transfer heat efficiently and reduce the cutting forces between the tool and the workpiece.

5. The machining methods used for titanium are essentially those that have been used since titanium became used widely in the early 1960s. However, some special machining techniques such as the use of ledge tools and rotary tools and other non-conventional machining methods may be thought of as alternative methods to increase the metal removal rate in the production of titanium components, provided that the component geometry integrity permits this.

6. Great care must be exercised to avoid loss of surface integrity in the machining of titanium, especially grinding, or a dramatic loss in mechanical behavior such as fatigue can result

Generally, the crack-free, compressive residual stress produced during machining gives excellent fatigue properties, whilst surface damage and a tensile residual-stress pattern will result in a dramatic loss in performance.

The application of new techniques and recently developed cutting tool materials in the machining of titanium alloys have resulted in several fold increase in tool life without compromising the surface finish and integrity of the machined components. These improvements were achieved by reducing temperatures generated at the interface temperatures and by altering chip shape from continuous to discontinuous and segmented forms

There is a close relationship between the machinability rate and the mechanical properties of the work material (hardness and hot tensile strength), chemical composition (Mo equivalent value) as well as the chip morphology.

The formation of a protective layer of adhered material has been observed when machining Ti6Al4V alloy. The size of this layer decreases with increasing speed. As soon as this layer is removed, tool wear increases abruptly.

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