

Chapter 2

Cutting Tool Materials and Tool Wear

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Abstract The chip formation in machining operations is commonly accomplished by a combination of several elements working together to complete the job. Among these components, cutting tool is the key element that serves in the front line of cutting action. Cutting action becomes a challenge when it comes to machining difficult-to-cut materials. Titanium and its alloys are among the most difficult-to-cut materials which are widely used in diverse industrial sectors. This chapter aims to provide a historical background and application of different cutting tools in machining industry with a main focus on the applicable cutting tools in machining titanium and titanium alloys. Selection of appropriate tool material for a certain application is directly influenced by the characteristics of material to be machined. In this context, a brief overview of the metallurgy of titanium and its alloys is also presented. Recent progresses in tool materials, appropriate tools for cutting titanium alloys, and their dominant wear mechanisms will also be covered in this chapter.

2.1 Introduction

Nowadays, aerospace, power generation, oil and gas, marine, and medical industries are among rapidly developing business which plays an important role in almost every aspects of the human's life as well as the global economy. Due to their inherent nature, the majority of mechanical parts employed in these industries are usually used in severe climate conditions. Structural parts of aircrafts' fuselage, components of jet engines, blades of compressors and turbines, combustion

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chambers, and exhaust nozzles are among several examples of such components. Typical material to be used in these applications must possess wide range of desirable properties which include but not limited to low density and high specific strength to weight ratio especially at elevated temperature, resistance to corrosion, and chemical inertness.

Titanium is a favourite choice and one of the most extensively used material for the above-mentioned applications as its specific strength to weight ratio especially at high temperatures is higher than its steel and aluminium counterparts, which makes it the material of choice for aerospace and power generation industries. In addition, titanium and its alloys exhibit remarkable resistance to corrosion and are capable of sustaining in marine environments where other architectural materials such as metals demonstrate limited lifecycle. Such corrosive environments are also very common in oil and gas industries. Furthermore, titanium shows superior elasticity which is a desirable characteristic for flexible parts when cracks or disintegration must be suppressed. Showing promising non-magnetic characteristics, titanium has been also used in computer industry as a substrate for hard disk drives which promotes data storage process by avoiding any electromagnetic interference. Chemical inertness or bio-adaptability is another desirable characteristic that titanium possesses which makes it an ideal candidate for medical applications such as implants.

Despite several advantages offered by titanium in comparison to the other commonly used materials in industries, many manufacturing challenges arise when it comes to machining titanium and its alloys. These challenges are mainly originated from mechanical, thermal and chemical characteristics of titanium. These characteristics include low modulus of elasticity, poor thermal conductivity, chemical reactivity at high temperatures, and finally hardening characteristics. As a result of these features, titanium is being classified as a hard-to-cut or difficult-to-cut material. Due to these inherent characteristics, cutting tools for machining titanium and its alloys must be wisely selected to mitigate these machining challenges.

2.2 What is Titanium?

Titanium is a silver colored shiny metal with the atomic number of 22 and the chemical symbol of Ti which was initially discovered in 1791 by William Gregor, an English chemist and mineralogist. Martin Heinrich Klaproth, a German chemist, named this newly discovered element titanium for the Titans of Greek mythology [1]. Titanium constitutes 0.565 % of the earth crust and is the 9th plentiful element and also the 4th plentiful structural metal in the earth crust after aluminum (8.23 %), iron (5.63 %), and magnesium (2.33 %) [2]. Only aluminum (8.23 %), iron (5.63 %), and magnesium (2.33 %) can be found more than titanium in earth's crust. The magnitude of obtainable titanium is more than zinc, copper, nickel, tin, lead, and chromium put together [2].

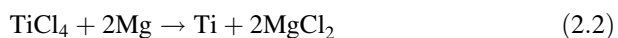
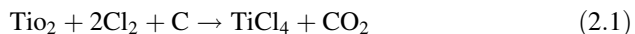
Titanium can be found in two major commercial minerals namely ilmenite and rutile [1]. It can be also found broadly all around the world in natural waters, animals and plants' bodies, sands, and rocks. Ilmenite is a crystalline iron titanium oxide (FeTiO_3) which is steel-gray or iron-black. In contrast, rutile is a mineral composed primarily of titanium dioxide (TiO_2) with blood red or brownish color.

It can come into question that despite its relatively widespread presence in nature, why titanium is very expensive and is not as widely used as other conventional engineering metals such as aluminium [3]. Titanium is an expensive material because its extraction process is tremendously costly and labor intensive. The Kroll method which is currently being used to extract and refine the titanium consists of several steps that must be performed for each batch of ore at high temperature [2].

Difficulties toward extraction of titanium can be summarized as follows [4]:

- Reducing agents like carbon cannot be used to reduce the ore because it forms titanium carbide (TiC), if carbon and titanium are heated together. The resultant product will not be pure metal and will be very brittle due to the presence of the carbide.
- The alternative options are either sodium or magnesium as reducing agents which are also expensive to extract from their ores.
- In addition, the titanium oxide (TiO_2) must be first converted to the titanium chloride (TiCl_4) to make it able to react with sodium or magnesium. As a result, the chlorine cost is also imposed to the cost of titanium in addition to the other cost such as energy cost.
- The titanium chloride must be handled carefully to prevent any contact with water because it aggressively reacts with water.
- The presence of oxygen or nitrogen makes the titanium brittle; hence, the reduction process of titanium must be performed in an inert argon atmosphere rather than in the air.
- Despite production of iron in the blast furnaces which is a continuous and efficient process, titanium is extracted from its ore in a batch process at which titanium chloride is heated with sodium or magnesium to produce titanium. This process generates some waste products that must be separated to achieve pure titanium. The whole process should be entirely set up again for a new batch which makes the process very slow and inefficient.

Four different approaches are currently used to extract the titanium from its ore. These approaches include Kroll, Hunter, Cambridge, and Armstrong processes [2] among them the Kroll method has been the prevailing commercial process for production of titanium since the 1940s [3, 5]. The following chemical equations show the basic concept of the Kroll method [3, 6].



Reaction (2.1) produces an oxygen free tetrachloride from titanium dioxide and reaction (2.2) forms the titanium sponge. The titanium sponge is then further processed depending on the final product applications. The detailed description of the Kroll method can be found in [2, 3, 6].

2.3 Metallurgy of Titanium and Its Alloys

Titanium has two types of crystal structure namely Alpha (α) and Betta (β) [7]. In temperatures below 882 °C, titanium can be found in hexagonal closely packed (hcp) α phase crystal structure. While temperature goes beyond 882 °C, the α phase undergoes an allotropic transformation to a body-centered cubic (bcc) β phase. This phase remains stable up to the melting point of titanium (1,668 °C) [8, 9]; however, adding certain elements may alter the transformation temperature [9]. Figure 2.1 shows the two allotropic forms of titanium.

Adding Aluminum (Al), Gallium (Ga), Oxygen (O), Nitrogen (N), and Carbon (C) raises the transformation temperature. These elements stabilize the α phase and they are known as α stabilizer. In contrast, applying elements such as Vanadium (V), Molybdenum (Mo), Niobium (Nb), Iron (Fe), Chromium (Cr), Nickel (Ni), Manganese (Mn), and Cobalt (Co) lowers the transformation temperature. Similar to α stabilizer, these elements are called β stabilizer [8, 9]. One of the most commercially used element in titanium alloys is aluminium which is among the α stabilizers [8].

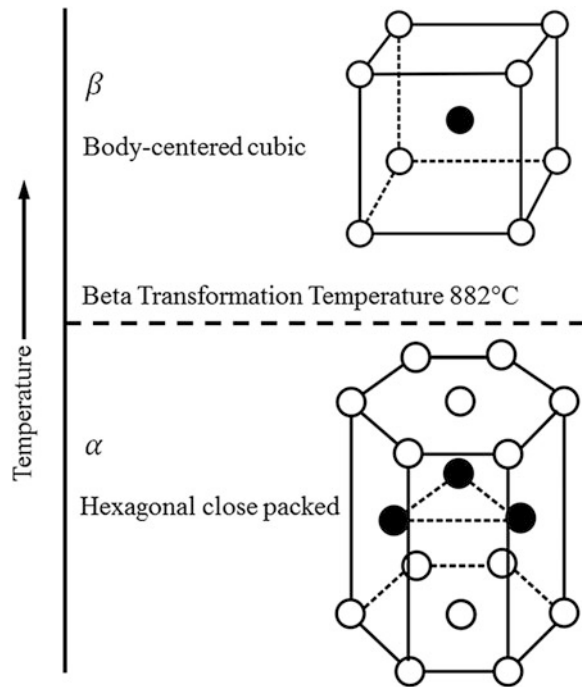
An impure material which can be a mixture of either pure or relatively pure chemical elements with an additive metallic material is called alloy. The additive materials are normally called elements while the primary metal which the elements are added to is usually called base metal. The alloy normally preserves the positive features of a base metal while adding some additional valuable benefits. The mechanical properties of alloy might be quite different from those of base metal as well as its individual constituents.

Although pure (unalloyed) titanium shows acceptable corrosion resistance, it is not being used in its pure state. Titanium is commonly alloyed with small amounts of some other elements such as Aluminium (Al) and Vanadium (V) to promote mechanical properties [9]. Titanium alloys can be divided into several categories based on the alloying condition and possible additive elements that can be added to the microstructure of titanium [8].

2.3.1 Alpha (α) Alloys

The alpha (α) alloys are single phase titanium alloys which consist of α stabilizer or some other neutral alloying elements [7, 8]. These titanium alloys maintain their tensile strength up to 300 °C and also exhibit exceptional creep stability. These

Fig. 2.1 The two allotropic forms of titanium [9]



titanium alloys are not heat treatable and their microstructural properties cannot be modified by heat treatment. As these alloys lose their tensile strength in temperatures above 300 °C, their primary applications are cryogenic applications or where great resistance to corrosion is compulsory. One of the frequently used alpha (α) alloys is Ti5-2 $\frac{1}{2}$ (Ti-5Al-2 $\frac{1}{2}$ Sn) [7].

2.3.2 Near Alpha Alloys

It has been proven [8] that workability and strength of titanium alloys can be improved by adding a small portion (1–2 %) of β stabilizers. The near alpha (α) titanium alloys are highly α -stabilised and include small quantities of β -stabilizing elements. These alloys are described by their α phase microstructure containing small quantities of β phase. Due to their high similarity to α phase alloys, near alpha (α) alloys are capable of working at elevated temperatures between 400 and 520 °C [9]. Hence, near alpha (α) titanium alloys are primary candidates for aerospace applications, especially components of jet engines where the parts are being utilized at elevated temperatures. Ti 8-1-1 (Ti-8Al-1Mo-1V) and IMI 685 (Ti-6Al-5Zr-0.5Mo-0.25Si) are some examples of this family of titanium alloys [7].

2.3.3 Alpha-Beta ($\alpha + \beta$) Alloys

If the amount of beta stabilizer added to the titanium is larger (4–6 %) than that in near alpha (α) alloys (1–2 %) a new category of titanium alloys called $\alpha + \beta$ alloys will be generated [8]. Different combinations of microstructures and consequently mechanical properties can be developed by heat treating $\alpha + \beta$ alloys. The heat treatment improves the strength and makes this category of titanium alloys a principal choice for elevated temperature's (350–400 °C) application. IMI 550 (Ti-4Al-2Sn-4Mo-0.5Si) and specially Ti 6-4 (Ti-6Al-4V) which is one of the most commonly used titanium alloys in industry belong to this group [7].

2.3.4 Metastable Beta (β) Alloys

By further increasing the amount of β stabilizers (10–15 %), β phase is retained in a metastable state at room temperature [8]. The metastable β alloys include a small portion of α stabilizers to increase the strength. Demonstrating high toughness, high strength, great hardenability, and forgeability over a wide range of temperatures, this family of titanium alloys is a potential candidate for structural parts in aerospace applications.

2.3.5 Beta (β) Alloys

A titanium alloys which contain a large amount (30 %) of β stabilizers is called beta β alloy. Due to high density and also poor ductility, this family of titanium alloys has some particular applications specially where burn-resistance and corrosion-resistance is required [8].

2.3.6 Titanium Aluminides

Titanium aluminide (TiAl) is an intermetallic chemical compound comprises three main intermetallic compounds: gamma TiAl (Ti3Al (γ)), alpha 2-Ti3Al (Ti3Al (α_2)) and TiAl3 [10].

The term intermetallic or intermetallic compound is generally refers to solid-state phases containing metals. Although both alloys and intermetallic compound contain more than one element, they cannot be categorized under a same classification due to some differences. Alloy is normally referred to a solid solution of a base metal and some various elements which has metallic properties while intermetallic materials are chemical mixtures of two or more metals. The crystal

structure of intermetallic materials are different from the crystal structure of the metals it's made from.

To achieve some superior properties such as excellent heat and oxidation resistance, pure titanium can be alloyed by titanium aluminide. However, despite their great characteristics, aluminide-based titanium alloys exhibit poor ductility and low fracture toughness [8].

2.4 Titanium as a Hard-to-Cut Material

In spite of having several available academic resources and research papers on machining and machinability of materials, defining a certain border between hard materials and hard to cut materials is still a challenging task. Hence, the differences between hard material and hard-to-cut material must be clarified prior to any discussion about machining and machinability of titanium.

Among the mechanical properties, strength and hardness have the highest impact on the machining performance or simply ease of machining for certain material [11]. It may be concluded that increasing the material strength leads to larger cutting forces and higher temperatures which make the material more difficult to cut. However, machining tests shows that the materials with higher strength or hardness do not necessarily require larger cutting forces in machining. It has been shown [12, 13] that machining of medium carbon steel AISI 1045 (ultimate tensile strength $\sigma_R = 655$ MPa, yield strength $\sigma_{y0.2} = 375$ MPa) requires lower cutting force and lower cutting power which results in lower cutting temperature, lower residual stresses, and greater tool life in comparison to those acquired in the machining of stainless steel AISI 316L ($\sigma_R = 517$ MPa, $\sigma_{y0.2} = 218$ MPa) [14]. Higher hardness of work material is another factor that accelerates the tool wear and decrease the tool life which is one of the indicators of machinability [11]. Table 2.1 shows the approximate values of hardness and typical machinability ratings for some work materials.

As can be seen in the Table 2.1, comprising low hardness does not necessarily mean that the material with lower hardness can be easily machined. Very low hardness negatively affects the machining performance. For example, low carbon steel which has relatively low hardness, is usually classified under the material with low machinability due to its high ductility. High ductility results in the poor surface finish due to tearing of the metal during chip formation [11].

For instance, the machinability rating for steels AISI 8620 and AISI 8630 with brinell hardness ranging from 190 to 200 is 0.6; while, for plain titanium with brinell hardness of 160, this rating dramatically drops to 0.3 (see Table 2.1). Taking above-mentioned criteria into consideration, it can be concluded that although machinability of a certain material can be dramatically affected by hardness; however, hardness is not a unique performance measure for ease or difficulty of machining.

Table 2.1 Approximate values of Brinell hardness and typical machinability rating for selected work materials [11]

Work material	Brinell hardness	Machinability rating
Base steel: B1112	180–220	1.00
Low carbon steel: C1008, C1010, C1015	130–170	0.50
Medium carbon steel: C1020, C1025, C1030	140–210	0.65
High carbon steel: C1040, C1045, C1050	180–230	0.55
<i>Alloy steels 24</i>		
1320, 1330, 3130, 3140	170–230	0.55
4130	180–200	0.65
4140	190–210	0.55
4340	200–230	0.45
4340 (casting)	250–300	0.25
6120, 6130, 6140	180–230	0.50
8620, 8630	190–200	0.60
B1113	170–220	1.35
Free machining steels	160–220	1.50
<i>Stainless steel</i>		
301, 302	170–190	0.50
304	160–170	0.40
316, 317	190–200	0.35
403	190–210	0.55
416	190–210	0.90
Tool steel (unhardened)	200–250	0.30
<i>Cast iron</i>		
Soft	60	0.70
Medium hardness	200	0.55
Hard	230	0.40
<i>Super alloys</i>		
Inconel	240–260	0.30
Inconel X	350–370	0.15
Waspalloy	250–280	0.12
<i>Titanium</i>		
Plain	160	0.30
Alloys	220–280	0.20
<i>Aluminum</i>		
2-S, 11-S, 17-S	Soft	5.00
Aluminum alloys (soft)	Soft	2.00
Aluminum alloys (hard)	Hard	1.25
Copper	Soft	0.60
Brass	Soft	2.00
Bronze	Soft	0.65

The term machinability is commonly used to describe the ease or difficulties of machining for a certain work material. The machining performance is governed by several contributing factors in addition to mechanical properties of work material. Machining processes, cutting tools, and cutting conditions are among the

important factors that affect the machinability of certain material on the top of its mechanical properties.

Generally speaking, although hard materials are generally hard to cut, but every hard to cut material is not necessarily hard. In the other word, hard to cut materials or materials with low machinability are not necessarily very hard materials. It may come into question that why titanium is a hard-to-cut material. This question will be answered in the next section.

Historically, titanium has been always considered as a material that is difficult to machine. As a result of the widely acceptance and the emerging application of titanium in many industries, valuable experiences accompanied by a broad base of knowledge have been acquired regarding machining titanium and its alloys.

It has been determined that when it comes to machining titanium and its alloys, the majority of tool materials that show great performance in machining other materials, exhibit moderate to poor performance. Difficulties in machining titanium alloys are caused by a combination of the following features.

2.4.1 Poor Thermal Conductivity

During the cutting process, energy is consumed to form the chip by plastically deforming the workpiece body or to overcome friction. Almost all of this energy is then converted into heat and consequently increases the temperature in the cutting zone. The main heat sources during cutting operations are as follows (see Fig. 2.2):

- Primary shear zone at which the heat is mainly generated by plastic deformation of workpiece due to shearing.
- Secondary shear zone at which the heat is generated by a combination of shearing and friction on the tool rake face.
- Tertiary shear zone at which the heat is produced due to friction between newly machined and the flank face of the cutting tool.

Although the heat generated at the cutting zone softens the workpiece material and facilitate easier cutting, it is generally considered as an undesirable phenomenon that must be prohibited or kept minimized. The heat generated during machining is primarily dissipated by the discarded chip. A quite smaller portion of the heat is also dissipated by means of workpiece and cutting tool.

Due its poor thermal conductivity (about 15 W/m °C), the heat generated during machining titanium and its alloys is not easily dissipated from the cutting zone [7]; therefore, a vast amount of heat is trapped on or near the cutting zone which intensifies the temperature. It has been observed [7, 15, 16] that depending on the tool material, up to 50 % of the heat generated during machining can be transferred to the cutting tool. However, this magnitude may reach 80 % during machining titanium and its alloys. Figure 2.3 compares the distribution of thermal load when machining titanium alloy Ti-6Al-4V and Steel CK45.

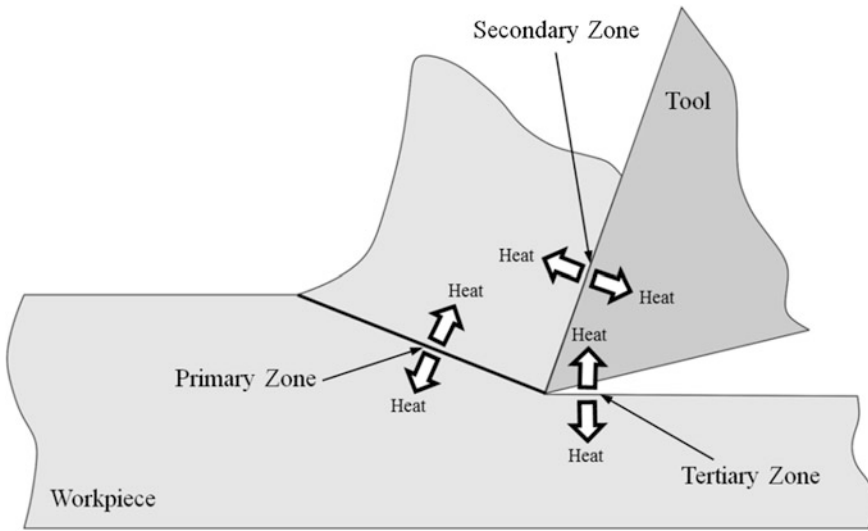


Fig. 2.2 Cutting zones and their corresponding generated heat

The concentrated heat at the cutting zone when machining titanium and its alloys sometimes reaches $1,100\text{ }^{\circ}\text{C}$ [17]. The elevated temperature near the cutting zone where tool and workpiece are in touch can rapidly deteriorate the cutting edge and make it dull. Continuing machining using a tool with dull cutting edge may generate more heat and cease the tool life.

2.4.2 Low Modulus of Elasticity and the Consequent Springback

Titanium has superior elasticity which makes it an ideal candidate for those applications where flexibility without the possibility of cracks or disintegration is desired. However, titanium's elasticity imposes another barrier toward machining. In comparison to the other metals, titanium's modulus of elasticity is relatively lower. Low modulus of elasticity results in relatively higher strain and consequently more deformation under a certain magnitude of force. In the other word, low modulus of elasticity makes titanium more bouncy [18]. During machining operations, when the tool touches the workpiece and cutting force is applied, titanium's elasticity makes the workpiece spring away from the tool, which causes cutting edge being rubbed against the workpiece surface rather than performing cutting action. Rubbing rather than cutting increases the friction and consequently further raises the temperature at the cutting zone. Rubbing also destroys the surface quality and dimensional accuracy.

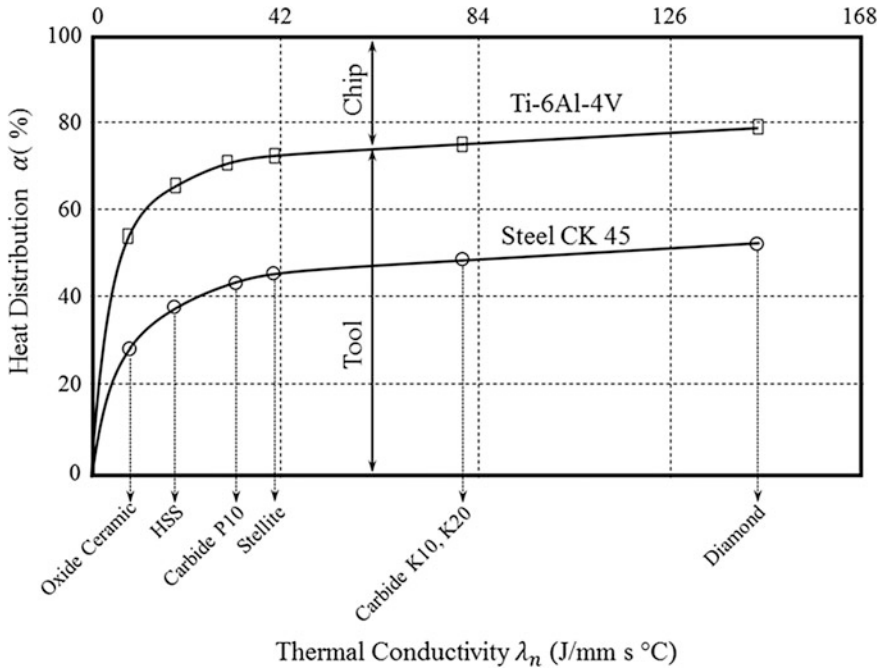


Fig. 2.3 Distribution of thermal load when machining titanium and steel [7, 16]

2.4.3 Chemical Reactivity

Despite its chemical inertness at room temperatures which makes it one of the best options for medical implants, titanium becomes highly reactive tools when the temperature goes beyond 500 °C. When the temperature increases, chemical reaction occurs between titanium and cutting tools which quickly obliterate the tool [7, 9]. As a result, the majority of currently available cutting tools, even the hardest ones, are not appropriate for machining titanium and its alloys due to chemical affinity which deteriorate the cutting tool by initiating chemical wear.

2.4.4 Hardening due to Diffusion and Plastic Deformation

It has been previously established that due to its poor thermal conductivity, the heat generated during machining titanium cannot be freely dissipated from the cutting zone. This localized heat is capable of raising temperature up to 1,100 °C.

When the temperature at the cutting zone reaches the range of 600–700 °C or exceeds this limit, oxygen and nitrogen molecules in the air are being diffused into the titanium workpiece and harden its surface layer [19].

In addition, in such an elevated temperature, most metals undergo thermal softening and lose their strength. Thermal softening can be considered as a desired phenomenon provided that it does not adversely affect the mechanical characteristics of workpiece as well as cutting tool. Thermal softening lowers the forces and energy required to perform machining operation.

However, when it comes to machining titanium and its alloys, the story will be different. Titanium preserves its superior strength at elevated temperatures [20]; hence, one of the main advantages of titanium which makes it an ideal choice for many applications turns into one of the principal challenges during machining. Maintaining its mechanical strength at high temperatures, comparatively higher cutting power is required to plastically deform titanium and produce chip. High cutting power and its consequent plastic deformation significantly hardens the machined surface. This is what usually referred to as strain-hardening or work-hardening.

It must be mentioned that, both diffusion and plastic deformation are influential in hardening titanium during machining operation; however plastic deformation is the predominant factor [9, 15].

2.4.5 Mechanism of Chip Formation

When machining titanium and its alloys, the chip is either formed by the propagation of crack from the exterior surface of the chip or development of adiabatic shear band which is primarily originated by the localized shear deformation [21–24]. In case of adiabatic shear, the machining is dominated by thermal softening rather than strain hardening [21, 22]. Localization of Shear leads to significant periodic variation of machining forces and subsequently chatters vibration [25]. Cyclic variation of machining forces is not a desirable phenomenon as it imposes fatigue to the cutting tool or may cause chipping or breakage of cutting tool.

It can be concluded from above-mentioned items that, titanium and its alloys comprise some unique mechanical and metallurgical characteristics that make them comparatively harder to cut than their other counterparts with equivalent hardness.

In order to achieve an acceptable metal removal rate (MRR) at reasonable cost, appropriate tools, machining conditions, and processing sequence must be selected properly.

Considering all above-mentioned challenges that can be faced during machining titanium and its alloys, a successful cutting tool must [26, 27]:

- Capable of maintaining hardness at high cutting temperatures due to the presence of extreme heat at the cutting zone (hot hardness).
- Possess good chipping resistance which is principally attributed to the formation of segmented chips.

- Demonstrate toughness and fatigue resistance to withstand against the cyclic machining forces during the formation of the segmented chips.
- Have low chemical affinity with titanium to minimize the possibility of reaction between tool and workpiece.
- Have high compressive strength.
- Have excellent thermal conductivity to scatter the heat generated during machining away from the cutting zone.

2.5 Cutting Tools: Historical Background and Chronological Advances

Cutting tools are frequently used in our every day's life. The regularly used cutting tools can be in the form of knives, razor blades, lawnmowers or more industrial tools in wood or metal working. Despite their widespread applications in modern lives, not too many questions have been raised about the origin and history of these tools. In the context of metal cutting or in general machining, a cutting tool is an instrument by means of which the metal is being removed from the workpiece body. In order to achieve successful cutting, cutting tools must be mechanically harder than the material to be machined.

Although cutting tools in their general form have been used by human beings for centuries; their modern history began during the industrial revolution in the nineteenth century. However, in the absence of systematic tool production before the twentieth century, the majority of the tools were prepared by their end users at local machine shops. As a result, having a combined knowledge of physics, chemistry, heat treatment, and also blacksmithing was among the necessary requirement for being a successful machinist. Before the twentieth century, cutting tools were mostly produced using carbon tool steels. These types of steel comprise high carbon content and can be successfully hardened.

One of the earliest-reported advances in cutting tool history was made in 1868 by Robert Forester Mushet, a British metallurgist, who discovered that hardness of steel and consequently tool life can be improved by adding tungsten [28] which has the second highest melting point of all elements after carbon and the highest melting point of all non-alloyed metals. Mushet steel is considered to be the first tool steel [28] which was later led to the discovery of high speed steels [29].

The emerging need for cutting tool material capable of enduring higher cutting speeds and resulting high temperatures led to a significant development which was made by American mechanical engineer Frederick Winslow Taylor during late 19th and early 20th century. He studied the cutting tools and their corresponding performances and proposed a novel tool life equation which is, in its augmented form, still one of the most widely used equations in metal cutting science and machining industry. Taylor also discovered that more durable steel, which is able to maintain its hardness at high temperature, can be achieved if it is being heated

close to its melting point. This type of hardened steel can be assumed to be the first generation of high speed steel (HSS) tools.

The introduction of HSS tool increased the practicable cutting speed four times in comparison to the previously used carbon steels [30]. In comparison to carbon steel tools, HSS tools owe their superiority to the alloying elements. The alloying elements make the steel harder and more heat resistant [31].

HSS tools can be divided into almost thirty different grades; while, all of these grades can be categorized in three principal classifications: molybdenum based grades (M series), tungsten based grades (T series), and molybdenum-cobalt based grades. Among these grades, M and T series are the most commonly used HSS tools in industry.

Performance of HSS tools can be further increased by application of coating. Different types of coating can be used to cover the surface of HSS tools; among them, titanium nitride is the most effective one that increase allowable cutting speed as well as tool life. Titanium nitride can be deposited on the HSS surface by means of physical vapour deposition (PVD) techniques.

Another material that was introduced to the cutting tool industry in early 20th was Stellite which is a non-magnetic, wear and corrosion resistant alloy of cobalt and chromium. The progressing trend in development of more advanced and durable cutting tool were further continued by the introduction of cemented carbide around the 1920s and ceramic inserts after the Second World War.

By the evolution of science and technology, traditional HSS and cobalt steel cutting tools were far outnumbered by new cutting tools made from carbides and ceramics. These tool materials are even now among the most widely used cutting tools for mass production of industrial parts.

Developed around 1930s, carbide tools comprise high modulus of elasticity, high thermal conductivity, and ultimately high hardness over a wide range of temperatures. Carbide tools, either uncoated or coated, are capable of reaching cutting speed of three to five times higher than their HSS counterparts [30]. Tungsten carbide (WC), titanium carbide (TiC), tantalum carbide (TaC_x), and niobium carbide (NbC and Nb_2C) are the most recognized hard carbides that can be used toward making carbide tools in industry. A typical carbide tool comprises these carbide particles bounded together in a matrix of cobalt using sintering process [32]. Among the carbide tools, tungsten carbide with 6 % cobalt binder was initially introduced to the industry in Germany in 1926 [32].

The mechanical characteristics and performance of carbide tools are greatly affected by the type of carbide. For instance, increasing the tungsten content will increase the wear resistance, but adversely affect the tool strength. Cobalt content also affects the mechanical properties of carbide tools. Increasing the cobalt content improves the toughness of the tool; however, it reduces the strength, hardness, and consequently wear resistance [32]. In comparison to the tungsten carbide, titanium carbide shows relatively higher wear resistance and lower toughness.

Ceramic cutting tools are another widely used category of cutting tools which were introduced to industry in the middle of the twentieth century. Ceramic tools mainly contain aluminum oxide (Al_2O_3), silicon nitride (Si_3N_4), and sialon

(a combination of silicon (Si), aluminum (Al), oxygen (O), and nitrogen (N)) grains sintered together under high temperature (1,700 °C) and pressure (more than 25 MPa) [32, 33]. In comparison to the majority of cutting tools that demonstrate a rapid softening rate at elevated temperatures, ceramic tools exhibit much slower rate and capable of retaining their hardness in such conditions. Despite their hot hardness, ceramic tools suffer from lack of toughness; as a result, any type of shocks or impact during machining must be avoided to prevent chipping or breakage.

New materials with superior characteristics had been continually introduced to the market during the twentieth century. These new materials were mostly utilized in such applications where high performance reliability was required during the service life. To cope with the rapid growth of industries and their corresponding necessities, more effective machining should have been applied. To achieve this ultimate objective, cubic boron nitride tools, polycrystalline cubic boron nitride tools, and polycrystalline diamond tools were introduced to the industrial market.

Exhibiting hardness of up to 4,500 HV, cubic boron nitride tools are the second hardest ever existing tools after diamond with hardness of more than 9,000 HV. CBN is a polymorph boron-nitride-based material which was introduced to the industry in 1957. This family of cutting tools owes its superior mechanical properties to their crystalline structure and its covalent link [33]. Cubic boron nitride is produced by exposing hexagonal boron nitride to elevated temperatures of up to 1,500 °C and extreme pressure 8 GPa [33]. CBN offers excellent high hot hardness at up to 1,500 °C and even sometimes higher up to 2,000 °C. Due to their extreme hardness, CBN tools show great wear resistance; however, they suffer from lack of toughness. Polycrystalline cubic boron nitride tools are produced by sintering cubic boron nitride crystals with a binder under high temperature, and high pressure.

Diamond is the hardest ever existing material that combines some desired properties such as extreme hardness, highest thermal conductivity at room temperature and low coefficient of surface friction all together [34]. Despite their early applications as a cutting tool, due to their brittleness, single crystal diamonds need to be used at the correct crystal orientation to achieve optimum performance and prevent fracture. To incorporate the superior characteristics of diamond while eliminating their weakness, single crystal diamond tools have been substituted by polycrystalline diamond (PCD) tools. PCD is a composite of diamond particles sintered together with a metallic binder under high temperature and pressure. Due to its extreme hardness, PCD tools demonstrate wear resistance almost 500 times greater than those of tungsten carbide [32]. Due to their high hardness, similar to CBN and PCBN tools, PCD tools are extremely fragile and exhibit low toughness. They also chemically react with iron which makes them an inappropriate option for machining steels.

Generally speaking, different types of cutting tool materials with divers characteristics are now being used in industry. Although these tool materials are coming from different origins with various properties, some performance measures are required to compare them and make a judgement about the applicability of a certain tool for a particular application. These performance measures are hardness, toughness and wear resistance [32].

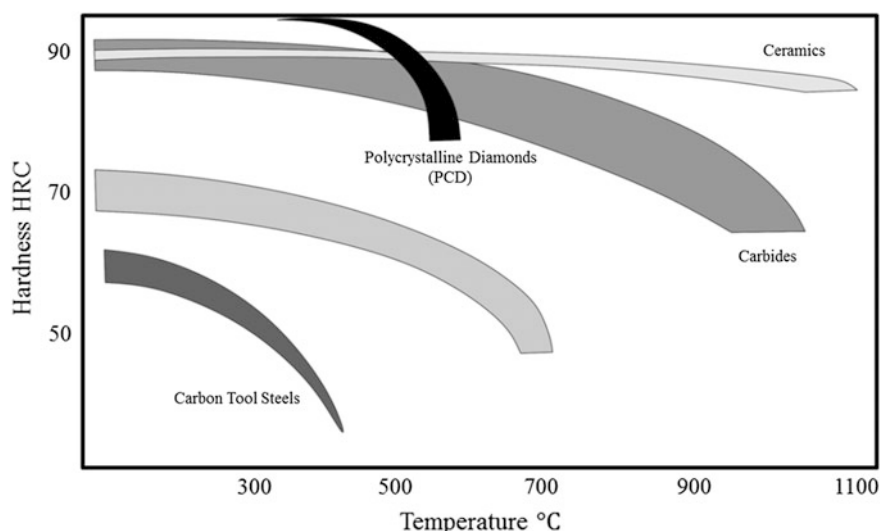


Fig. 2.4 Comparison of the capability of the major families of cutting tools as a function of temperature

Hardness is generally considered as the strength of intermolecular bonds in maintaining their shape without any permanent deformation. It can be also interpreted as the ability of a material in localizing deformation. In the context of cutting tools, hardness is defined as the ability to penetrate into the softer materials (workpiece). Hardness is also a performance measure which describes the capability of tool material in resisting against the permanent changes in shape and geometry during machining. This characteristic becomes more important when the cutting tool is exposed to the extreme heat generated during cutting operation. In this case, a successful cutting is the one with hot hardness which is capable of maintaining its hardness at high temperature [32]. Figure 2.4 compares the capability of the major families of cutting tools under temperature variation.

However, it must be pointed out that extreme hardness is not necessarily a desired feature as it is directly associated with tool fragility or brittleness. High hardness increases the sustainability of the tool against permanent change in shape and geometry during machining; while, it consequently lowers the fracture strength or toughness during impacts.

Throughout its service life, a cutting tool is subjected to different types of loading, unloading, vibration and other interfering factors. A successful candidate surviving these situations is the one who absorbs the energy imposed by cyclic forces and vibrations without showing any signs of fracture. This capability is generally refer to as toughness which is the ability of a cutting tool to absorb energy before fracture. Figure 2.5 shows the hardness versus toughness for some commonly used cutting tool material.

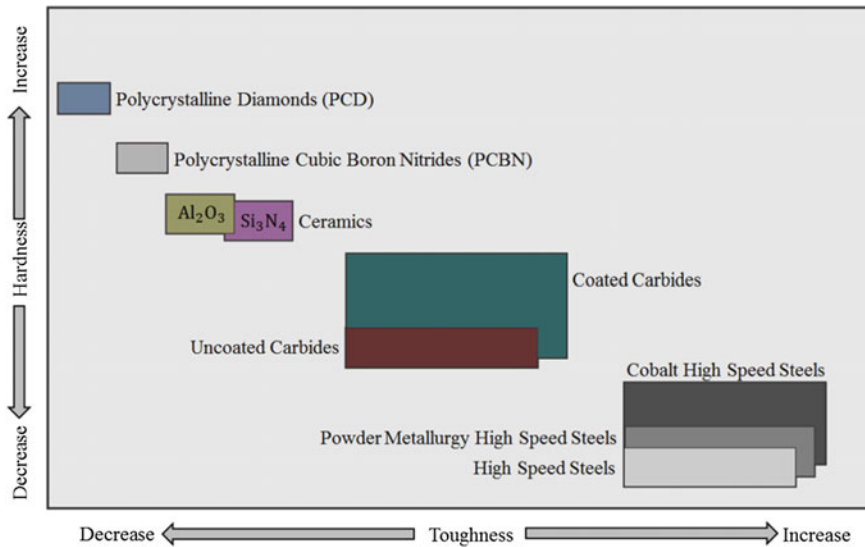


Fig. 2.5 Hardness versus toughness for some conventional cutting tool materials

Another desired characteristic that a successful cutting tool must possess is wear resistance. Wear is normally defined as the erosion of tool particles by means of another moving surface. Based on the definition of wear, wear resistance can be defined as the ability of cutting tool material to retain its integrity against erosion and eventually demonstration of acceptable tool life.

A desired cutting tool for particular application is the one who demonstrates a balanced combination of all aforementioned features. The question to be addressed here is what types of cutting tools are appropriate for machining titanium and its alloys.

2.6 Application of HSS Tools in Machining Titanium and Its Alloys

High Speed Steel (HSS) tools have been extensively employed for machining of a different kind of materials through the past decades. HSS tools show great toughness in comparison to other tool materials and capable of withstanding against the cyclic or intermittent loading and unloading. For this reason, they are primarily used for cutting operations at which interrupted or intermittent cutting is likely to occur. These include operations such as milling, drilling, broaching, and tapping. High speed steels are also appropriate for producing tools of complex shape such as helical milling, drilling, broaching, reaming, and tapping tools. However, when it comes to machining of hard-to-cut materials such as titanium or even tempered steels, HSS tools are not the best option to select.

In spite of their great toughness, HSS tools softening point is around 600 °C [35, 36]; therefore, there are not applicable in working temperatures above 500 °C [33]. It has been shown that HSS tools are not appropriate options for machining titanium and its alloys; especially, when the cutting speeds exceed 30 m/min [37, 38]. However, highly alloyed grades of HSS tools such as T5, T15, M33 and M40 series can be used toward machining of titanium and its alloys. Moreover, some other grades of HSS tools such as M1, M2, M7 and M10, which are called general purpose grades, can also be implemented in machining titanium. [27]. Great care must be taken to keep the cutting speed lower than 30 m/min limit specially when machining Ti-6Al-4V [27, 39].

In case of machining titanium and its alloys using HSS tools, cutting tool is rapidly deteriorated due to the presence of several factors among them, plastic deformation have the dominant effect and is considered to be the principal wear mechanism [7, 26]. Plastic deformation is principally originated by means of high compressive stresses and high temperatures generated during machining. It has been previously mentioned that when temperatures goes beyond 600 °C which is a common case when machining titanium alloys, thermal softening of HSS tools starts. Hence, HSS tools considerably lose their hardness which consequently accelerates plastic deformation at and around the tool nose or cutting edge. Plastic deformation of the tool nose and cutting edge makes the tool no longer functional. Another temperature related type of wear that has been observed when machining titanium alloys using HSS tools is the crater wear caused by intense temperature created while the chip is moving over the rake face [26, 40]. The combined effect of plastic deformation and crater wear rapidly destroy the HSS tools and thus makes it inappropriate choice for machining titanium and its alloys.

Although the performance of HSS tools can be further improved by application of coating, not all of those coated HSS tools can be used toward machining titanium and its alloys. Titanium nitride (TiN) and titanium carbonitride (TiCN) coated HSS tools are not suggested due to their chemical affinity with titanium. Their tendency to chemically react with titanium rapidly destroys the coating and leaves the tool surface unprotected. Other commonly used coatings for HSS tools such as chrome nitride (CrN), and titanium aluminum nitride (TiAlN) appear to be more advantageous in machining titanium alloys. However, HSS tools are not the material of choice for machining titanium and its alloys.

2.7 Application of Carbide Tools in Machining Titanium and Its Alloys

The term carbide tool is referred to a broad range of cutting tools that are made from carbide particles using different production methods [32, 41]. As previously mentioned in this chapter, carbide tools are mixtures of hard carbide particles (WC, TiC, TaCx, NbC, and Nb₂C) bounded together in a matrix of cobalt [33]. These tools are also referred to in industry as sintered carbide, cemented carbide or

Table 2.2 Effects of additive materials on the characteristics of carbide tools

	Positive effects	Negative effects
Cobalt (W)	Increase toughness and shock resistance	Decreases hardness and wear resistance
Tungsten carbide (WC)	Increase hardness and wear resistance	Decrease toughness
Titanium carbide (TiC)	Increases wear resistance	Decrease toughness
Tantalum carbide (TaC)	Increases hot hardness and prevent plastic deformation	

hard-metal as they made from the combination of hard carbide particles together. These cutting tools are either manufactured directly from a block of raw material by grinding or in the form of small inserts with specific geometry [33].

The commercially available carbide tools in the market are categorized either as straight grade carbides or as mixed grade carbides or mixed grade carbides. The former is composed of 6 wt% cobalt (Co) and 94 wt% tungsten carbide (WC) while the latter can be achieved by incorporating additive elements such as titanium carbide (TiC), tantalum carbide (TaC) or niobium carbide (NbC) [36]. In comparison to the tungsten carbide (WC), titanium carbide (TiC) demonstrates greater hardness reaching up to 3,200 HV [33] and it is mainly utilized to promote the wear characteristics of carbide tools [36]. Increasing the TiC content improves the wear resistance; but, it negatively affects the toughness and fracture strength of carbide tools. Although carbide tools have higher hot hardness than the carbon steel and high speed steel tools, their capability to endure high temperatures can be further improved by adding tantalum carbide. As a result, the machining can be performed at higher cutting speed without any concern about plastic deformation of the cutting edge due to resultant temperatures. The following table shows a brief summary of the effects of additive materials on the characteristics of carbide tools (Table 2.2).

Capability of carbide tools to resist against diffusion and oxidation wear along with their hot hardness can be improved by adding TiC, TiN, Al_2O_3 , TiCN, TiAlN, TiZrN, TiB₂ and diamond coatings.

One of the preferred carbide tools for machining titanium and its alloys is the straight grade cemented carbide (WC–Co) comprising 6 wt% cobalt (Co) and tungsten carbide (WC) grain size whitening the range of 0.8–1.4 μm [7, 27, 39, 42–44]. However, cutting speeds in excess of 60 m/min is not suggested for cemented tungsten carbide tools [44]. Application of higher cutting speeds (>60 m/min) is normally confined by plastic deformation due to intense heat [43]. Machining titanium and its alloys with low cutting speed (<45 m/min) eliminates the effects of thermal softening and also reduces the possibility of chemical reaction between tool and workpiece. As a result, mechanical and thermal fatigue, as well as micro-fractures is the dominant failure modes in such cases.

Increasing the cutting speed will result in elevating the temperature at the cutting zone. Due to the poor thermal conductivity of titanium, this intense heat remains at the cutting zone and elevates the temperature which may reach 500 °C and even higher [36]. The titanium becomes highly reactive and initiation of diffusion wear is

likely to occur at such temperatures. In such cases, the titanium atoms migrate from the workpiece and chemically react with the carbon content of carbide tools. This chemical reaction produces titanium carbide (TiC) [36, 39] which is extremely hard and it rigorously adheres to both the workpiece and tool. This strongly adhered layer of titanium carbide protects the tool from further diffusion.

Another type of wear when machining titanium and its alloys using carbide tools is adhesion wear which is likely to occur in temperatures above 740 °C in the presence of normal contact pressure of 0.23 GPa [45]. The tool material is repeatedly damaged and consequent adhesion wear is accelerated when these welded particles are detached by the flow of the chip over the rake face.

The grain size has a great effect on the wear resistance of carbide tools. The carbide tools with coarser grains show higher crater wear rate due to the fact that coarser grains are more susceptible to be pulled off when the chip slides over the rake face. The resistance of carbide tools against the crater wear can be improved by reducing the grain size; however, the carbide tools with smaller grain size demonstrates higher flank wear rate [46].

The coated carbide tools are generally produced using either CVD (chemical vapor deposition) or PVD (physical vapor deposition) techniques. CVD coatings greatly adhered to the carbide tools and improve the wear resistance. PVD coating also increase the wear resistance as well as edge toughness.

Application of coating reduces friction at tool-chip interface; hence, it lowers the cutting forces and also heat generated due to friction. In addition, the coating layer act as a shield and it protects the tool from thermal shocks during machining. However, the rapid increase in wear rate has been observed when the coating layer is removed after several pass of cutting and the tool is directly exposed to the workpiece. The situation worsens when machining titanium and its alloys using coated carbides. In this case, the coating layer is rapidly removed either by abrasion wear due to the fast flow of chip or by the chemical reaction between coating and titanium workpiece. Coating materials such as titanium nitride (TiN) or titanium carbonitride (TiCN) are vulnerable to chemical reaction with titanium and their application in machining titanium must be prohibited [47]. Research studies have proven that straight-grade cemented carbide tools with no coating exhibit better performance than those coated by TiC, TiN–TiC, Al₂O₃–TiC, TiN–Ti(C,N)–TiC, Al₂O₃ gamma layer, HfM, and TiB₂ [26]; hence, straight grade cemented carbide (WC–Co) with no coating is one of the most preferred carbide tools in machining titanium and its alloys.

2.8 Application of Ceramic Tools in Machining Titanium and Its Alloys

Ceramic tool demonstrates several promising and unpromising features simultaneously. They demonstrate much higher compressive strength than their HSS and carbide counterparts; however, they are very vulnerable to mechanical and thermal

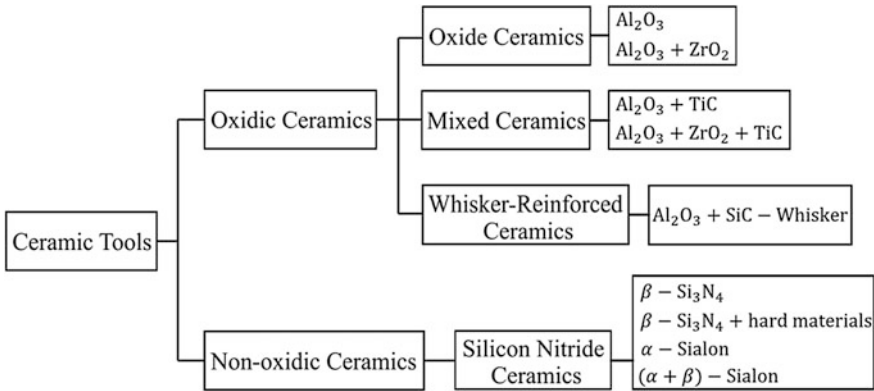


Fig. 2.6 Classification of ceramic tools

shock during machining and they easily break under heavy or interrupted machining due to brittleness and lack of toughness. In addition to great compressive strength, ceramic tools offer high hot hardness, chemical inertness and better oxidation resistance [48]. Ceramic tools owe their hot hardness to their high melting point and absence of binder as the second phase.

Ceramic as a cutting tool material can be divided into two main classifications and four sub categories. These categories are presented in the Fig. 2.6.

As can be seen, two main categories of ceramics tools are oxide and non-oxide ceramics. The oxide ceramic family which includes pure oxide, mixed oxide and whisker-reinforced ceramics is also known as alumina based family as the base material in all of them is aluminium oxide or alumina (Al_2O_3). The non-oxide ceramic family mostly includes silicon nitride-based ceramics.

The pure oxide ceramic tools based on aluminium oxide (Al_2O_3) are very brittle and vulnerable to fracture; hence, their fracture toughness is normally improved by adding zirconium oxide (ZrO_2) [49]. Zirconium oxide increases the fracture toughness with no negative effect on wear resistance. However, this category of ceramic tools is barely used in machining difficult to cut materials due to their low thermal shock resistance and low fracture toughness at elevated temperatures.

In order to further improve the characteristics of ceramic tools, pure ceramic can be mixed with 5–40 % [49] of titanium carbide (TiC) or titanium carbonitride (TiCN). The obtained ceramic is called mixed oxide ceramic, which exhibits comparatively higher hot hardness, higher hardness and thermal shock resistance. However, adding titanium carbide adversely affects the fracture toughness of the tool.

The performance of ceramic tools can be even further enhanced by implementing 20–40 wt% silicon carbide whisker into the Alumina (Al_2O_3) as a base material [49]. This family of ceramic tools is known as whisker-reinforced ceramic tools. Silicon carbide whiskers act as reinforcement and remarkably increase the toughness of ceramic tools. Whisker-reinforced ceramic tools demonstrate 60 % higher fracture toughness than mixed oxide ceramics tools [49].

Despite their promising characteristics, lack of toughness and consequently low fracture strength make ceramic tools inappropriate choice for machining titanium and its alloys. Ceramic tools show a higher rate of rake and flank face wear in comparison to the straight grade cemented carbides [43]. However, among ceramic tools, sialons demonstrate relatively higher resistant to rake face wear, in comparison to the $\text{Al}_2\text{O}_3\text{-TiC}$ and $\text{Al}_2\text{O}_3\text{-30ZrO}_2$ [43].

Generally speaking, due to their fragility and lack of toughness, ceramic tools greatly suffer from notch wear and large groove wear when utilized toward machining of titanium and its alloys [44]. The notch wear is primarily initiated by the fracture process caused by cyclic forces generated during the formation of discontinues serrated chips. For these reasons, similar to HSS tools, ceramic are also not an appropriate option for machining titanium and its alloys.

2.9 Application of CBN Tools in Machining Titanium and Its Alloys

Boron nitride exists in the nature in the form of hexagonal boron nitride which is a soft material. In its hexagonal modification, boron nitride does not present the required characteristics to be considered as an appropriate cutting tool material. In order to achieve the desired characteristics, the hexagonal modification must be transferred into the cubic crystalline lattice. This process takes place by applying high-pressure and also high temperature. After the transformation of hexagonal boron nitride into cubic boron nitride, it reveals its superior characteristics as a cutting tool material.

CBN has the second highest hardness among the tool materials (after diamond) and also has a high melting point (2,730 °C); as a result, it shows outstanding high hot hardness in elevated temperatures. In addition, despite diamond that begins to graphitize already at about 900 °C, CBN shows superior oxidation resistance and it remains stable up to 2,000 °C with no sign of oxidation [49].

The crystal size of cubic boron nitride (CBN) is very small (1–50 μm); therefore, CBN grains are sintered together by means of binder under high temperature and pressure to form polycrystalline cubic boron nitride. This family of CBN tools is called PCBN tools [49].

Widely respected due their unique characteristics, CBN and PCBN tools are primarily used in the machining of hard-to-cut materials. Machining of forged steels (45–68 HRC), alloy steels (70 HRC), and nickel and cobalt based super alloys [50]. They are also the dominant tools for hard turning where high metal removal rate and acceptable surface roughness must be achieved simultaneously. Nose deformation of CBN tools has been reported when machining ($\alpha + \beta$) titanium alloys with 4.5 % aluminum (Al) and 4.5 % manganese (Mn) [51]. It has also been reported [51] that the combined effect of elevated temperature and compressive stress may reached a point at which the tool is no longer able to

sustain; thus, deformation and the wear initiate. Low cycle fatigue caused by the cyclic mechanism of chip formation, nose wear, chipping, and diffusion wear in the presence of nitrogen and oxygen are among other types of wear when CBN is used toward machining titanium and its alloys.

In conclusion, although CBN and PCBN tools are capable of reaching higher cutting speed (150 m/min for Ti-6Al-4V [52] and 185–220 m/min for $\alpha + \beta$ [51]) than carbide tools; they are not very popular in machining titanium and its alloys. This is mainly due to their expensive price that could be 10–20 times higher than their carbide counterparts and make their application not economically efficient.

2.10 Application of PCD Tools in Machining Titanium and Its Alloys

Diamond is the hardest existing material on the earth and is much harder than silicon carbide (SiC) and tungsten carbide (WC). In addition to extreme hardness, diamond also shows good resistance to wear and low coefficient of friction which give it numerous advantages over other types of cutting tools especially the abrasive ones. As manmade tools, PCDs are the combination of diamond particles (crystals) of different size bonded together by means of metallic bonder (usually cobalt). Depending on their grain size, PCD tools can demonstrate different characteristics and consequently different applications.

PCD tools with larger diamond particles (coarser grains) shows remarkable resistance to wear. However, coarser grains result in a tool with a rougher cutting edge, and consequently lead to lower a surface finish and a higher roughness of the workpiece surface. In contrast, the smaller diamond particles (finer grains) result in sharper edge and eventually higher surface finish but reduced tool life due to wear [32, 33]. To strike a balance between tool life and surface quality, general purpose PCD tools are usually made from medium size diamond particles to achieve an acceptable level of wear resistant as well as surface quality.

It has been observed that when applied for machining titanium alloys, PCD tools show much lower wear rate than carbide tools [53]. They also show acceptable performance in machining Ti-6Al-4V [54] which is among the most extensively utilized alpha-beta ($\alpha + \beta$) titanium alloys for producing compressor blades in aerospace industries. The lower wear rate of PCD tools in machining titanium alloys can be attributed to the formation of titanium carbide as a protective layer on the rake face of PCD tools due to the inter-diffusion of titanium and carbon. The hard layer of titanium carbide strongly adhered to the substrate and act as a barrier and prevents further diffusion of the tool material into the chip [47].

In general, if selected for proper applications, PCD tools have an acceptable performance in machining titanium alloys. However, the high tooling cost imposes a great barrier to their widespread application in this field.

2.11 Conclusion

Comprising high strength to weight ratio, corrosion resistance, fatigue resistance, and capability to work in high temperature, titanium is usually the primary candidate for aerospace, power generation, automotive and even medical industries. However, the widespread application of titanium is limited due to several reasons among them; the price and machinability are outstanding. Titanium has low modulus of elasticity, poor thermal conductivity, chemical reactivity, and hardening characteristics that together make it one of the most notorious materials to machine. Due to the above-mentioned characteristics, an appropriate cutting tool for machining titanium and its alloys should possess several characteristics to be considered as an ideal candidate. These characteristics include but not limited to the capability of maintaining hardness at high cutting temperatures, high toughness, resistance to cyclic loading and unloading, and also chipping resistance. It should also show low chemical affinity with titanium and also good thermal conductivity to dissipate the heat generate during cutting. Different cutting tool materials are candidates for machining titanium alloys; however, each of them exhibits some signs of limitation. Dramatic loss of hardness at high temperature makes HSS tools not good candidates for machining titanium and its alloys. Carbide tools are among the most widely used cutting tools in machining titanium and its alloys due to their comparatively acceptable combination of hardness and toughness. Although ceramic tools have high hardness and low chemical affinity with titanium, they are not appropriate for machining titanium and its alloys, due to brittleness and lack of toughness. CBN tools are very vulnerable to fracture and chipping primarily because of their extreme hardness. Consequently, their application as a cutting tool in machining titanium is confined to finishing operations. PCD tools are among other appropriate but expensive tools for machining titanium and its alloys. Although carbon content of the PCD tools is likely to react with titanium, this process is being eliminated by the formation of titanium carbide layer which strongly sticks to the tool and protect it from further diffusion wear.

References

1. Britannica E (2001) Encyclopaedia Britannica Online. Encyclopædia Britannica
2. Gerdemann SJ (2001) Titanium process technologies. *Adv Mater Process* 159(DOE/ARC-2002-007)
3. Jackson M, Dring K (2006) A review of advances in processing and metallurgy of titanium alloys. *Mater Sci Technol* 22(8):881–887
4. Titanium (2014) <http://www.chemguide.co.uk/inorganic/extraction/titanium.html>
5. McQuillan AD, McQuillan MK (1956) Titanium, vol 4. Academic Press, New York
6. Habashi F (1997) Handbook of extractive metallurgy, vol 2. Wiley-Vch, Weinheim
7. Ezugwu E, Wang Z (1997) Titanium alloys and their machinability—a review. *J Mater Process Technol* 68(3):262–274
8. Joshi VA (2006) Titanium alloys: an atlas of structures and fracture features. CRC Press, Boca Raton

9. Yang X, Liu CR (1999) Machining titanium and its alloys. *Mach Sci Technol* 3(1):107–139
10. Voskoboinikov R, Lumpkin G, Middleburgh S (2013) Preferential formation of Al self-interstitial defects in γ -TiAl under irradiation. *Intermetallics* 32:230–232
11. Groover MP (2007) *Fundamentals of modern manufacturing: materials processes, and systems*. John Wiley & Sons, Hoboken
12. Astakhov VP, Xiao X (2008) A methodology for practical cutting force evaluation based on the energy spent in the cutting system. *Mach Sci Technol* 12(3):325–347
13. Astakhov VP (2006) *Tribology of metal cutting*, vol 52. Accessed Online via Elsevier
14. Outeiro J (2003) Application of recent metal cutting approaches to the study of the machining residual stresses. Department of Mechanical Engineering, University of Coimbra, Coimbra p 340
15. Child H, Dalton A (1968) ISI special report 94. London
16. Konig W (1978) Applied research on the machinability of titanium and its alloys. In: *Proceedings of AGARD conference advanced fabrication processes*, Florence
17. Fitzsimmons M, Sarin VK (2001) Development of CVD WC–co coatings. *Surf Coat Technol* 137(2):158–163
18. Pramanik A (2014) Problems and solutions in machining of titanium alloys. *Int J Adv Manuf Technol* 70(5–8):919–928
19. He G, Zhang Y (1985) Experimental investigations of the surface integrity of broached titanium alloy. *CIRP Ann-Manuf Technol* 34(1):491–494
20. Donachie Jr M (1982) Introduction to titanium and titanium alloys. American Society for Metals, *Titanium and Titanium Alloys Source Book*, p 7
21. Barry J, Byrne G, Lennon D (2001) Observations on chip formation and acoustic emission in machining Ti–6Al–4 V alloy. *Int J Mach Tools Manuf* 41(7):1055–1070
22. Komanduri R, Von Turkovich B (1981) New observations on the mechanism of chip formation when machining titanium alloys. *Wear* 69(2):179–188
23. Vyas A, Shaw M (1999) Mechanics of saw-tooth chip formation in metal cutting. *J Manuf Sci Eng* 121(2):163–172
24. Sun S, Brandt M, Dargusch M (2009) Characteristics of cutting forces and chip formation in machining of titanium alloys. *Int J Mach Tools Manuf* 49(7):561–568
25. Komanduri R, Hou Z-B (2002) On thermoplastic shear instability in the machining of a titanium alloy (Ti–6Al–4V). *Metall Mater Trans A* 33(9):2995–3010
26. Machado A, Wallbank J (1990) Machining of titanium and its alloys—a review. *Proc Inst Mech Eng B J Eng Manuf* 204(1):53–60
27. Siekmann HJ (1955) How to machine titanium. *Tool Eng* 34(1):78–82
28. Stoughton B (1908) *The metallurgy of iron and steel*. McGraw-Hill publishing company, New York
29. Oberg E, Jones FD (1918) *Iron and steel: a treatise on the smelting, refining, and mechanical processes of the iron and steel industry, including the chemical and physical characteristics of wrought iron, carbon, high-speed and alloy steels, cast iron, and steel castings, and the application of these materials in the machine and tool construction*. The Industrial Press, New York
30. Society of Manufacturing Engineers (2014) <https://manufacturing.stanford.edu/processes/CuttingToolMaterials.pdf>
31. Machinist (2014) <http://americanmachinist.com/cutting-tools/chapter-1-cutting-tool-materials>
32. Davim JP (2008) *Machining: fundamentals and recent advances*. Springer, London
33. Davim JP (2011) *Machining of hard materials*. Springer, London
34. Whitney ED (1994) *Ceramic cutting tools*. William Andrew Pub, Norwich
35. Kramer B (1987) On tool materials for high speed machining. *J Eng Ind* 109(2):87–91
36. Ezugwu E, Bonney J, Yamane Y (2003) An overview of the machinability of aeroengine alloys. *J Mater Process Technol* 134(2):233–253
37. Rahman M, Wang Z-G, Wong Y-S (2006) A review on high-speed machining of titanium alloys. *JSME Int J, Series C* 49(1):11–20

38. Pérez J, Llorente J, Sánchez J (2000) Advanced cutting conditions for the milling of aeronautical alloys. *J Mater Process Technol* 100(1):1–11
39. Hartung PD, Kramer B, Von Turkovich B (1982) Tool wear in titanium machining. *CIRP Annal Manuf Technol* 31(1):75–80
40. Trent EM, Wright PK (2000) *Metal cutting*. Butterworth-Heinemann, Boston
41. Upadhyaya G (1998) *Cemented tungsten carbides: production, properties and testing*. William Andrew
42. Che-Haron C (2001) Tool life and surface integrity in turning titanium alloy. *J Mater Process Technol* 118(1):231–237
43. Dearnley P, Gearson A (1986) Evaluation of principal wear mechanisms of cemented carbides and ceramics used for machining titanium alloy IMI 318. *Mater Sci Technol* 2(1):47–58
44. Narutaki N et al (1983) Study on machining of titanium alloys. *CIRP Annal Manuf Technol* 32(1):65–69
45. Sadik MI, Lindström B (1995) The effect of restricted contact length on tool performance. *J Mater Process Technol* 48(1):275–282
46. Edwards R, Edwards R (1993) *Cutting tools*. Institute of Materials, London
47. Rahman M, Wong YS, Zareena AR (2003) Machinability of titanium alloys. *JSME Int J Series C* 46:107–115
48. Chakraborty A, Ray K, Bhaduri S (2000) Comparative wear behavior of ceramic and carbide tools during high speed machining of steel. *Mater Manuf Process* 15(2):269–300
49. Klocke F (2011) *Manufacturing processes*. Springer, Berlin
50. Lin Z-C, Chen D-Y (1995) A study of cutting with a CBN tool. *J Mater Process Technol* 49(1):149–164
51. Zoya Z, Krishnamurthy R (2000) The performance of CBN tools in the machining of titanium alloys. *J Mater Process Technol* 100(1):80–86
52. Ezugwu E et al (2005) Evaluation of the performance of CBN tools when turning Ti–6Al–4V alloy with high pressure coolant supplies. *Int J Mach Tools Manuf* 45(9):1009–1014
53. Nabhani F (2001) Machining of aerospace titanium alloys. *Robot Comput Integr Manuf* 17(1):99–106
54. Kuljanic E et al (1998) Milling titanium compressor blades with PCD cutter. *CIRP Annal Manuf Technol* 47(1):61–64

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