An Insight: Machining of Titanium Alloys & Associated Tool Wear

Mangal Singh Sisodiya¹, Vivek Bajpai¹

¹Department of Mechanical Engineering, Indian Institute of Technology (ISM) Dhanbad, India
Email ID: mangal_284@yahoo.com

Abstract. Titanium alloy has some important applications in the aerospace industries along with other sectors, but its machinability efficiently is still a topic of intent research. Several factors work together to hinder its effective machining by various cutting tools. Although work has been done to some extent by some well cutting tools such as carbide tools however, very little work has been stated and established by using CBN tools or cryogenically treated CBN tools. The review has been done elaboratively to bring out various aspects of titanium alloy and its machining by various conventional cutting tools along with the CBN cutting tool.

1. Introduction

Titanium in its alloy form is primarily used in aerospace industries mainly because of three factors which are high specific resistance, fracture resistance and an exceptional corrosion resistance. They are also being used in various other industrial and commercial areas including paper and pulp, food processing, etc. They are indeed well-known engineering materials available in various alloys and forms. However, although being used extensively, they are quite expensive when compared to other metals due to problems during fabrication & melting, difficult melting, etc. E.O. Ezugwu et al. (1995) [1] stated that titanium and its alloys are not so good due to certain inherent properties as follows:

• Titanium is quite reactive and tends to weld to the cutting tool leading to tool failure.
• It has low thermal conductivity which indirectly affects tool life
• It’s high strength at higher temperatures and low elastic modulus further makes it difficult to machine.

All these inferences have been further supported in the works of H. Hong et al. (1993) [2]. Such poor machinability have led big companies to invest in large amounts in developing techniques so that machining cost is reduced. [1]

2. Allotropes of Titanium

R.M. Duncan et al. [3] stated that Titanium undergoes allotropic transformation at 882°C from low temperature hexagonal α-phase to high temperature BCC β-phase. The alloying elements changes the transformation temperature [4]. Elements which help to raise the transformation temperature are specifically the α-stabilizers and, aluminium which is an important α-strengthening element at normal and temperatures till 550°C [5]. On the other hand, elements which decrease the transformation temperature are the β-stabilisers which includes β-isomorphous and β-eutectoid [5]. The work further states that β-isomorphous alloying substances are readily soluble in β-titanium but the β-eutectoid compounds are soluble to a certain extent in β-titanium.
3. Inherent Unfavourable properties of titanium

Though researchers and scholars have helped to evolve the machining of this element and still a lot of efficient work remains, the main hurdle being faced is due to certain inherent properties which are enlisted and described as follows:

- **High Cutting Temperature:** It is specified in the work of W. Konig (1979) [6] that 80% of the total heat generated during machining of titanium is taken up by the tool due to poor thermal conductivity of titanium and hence, it is well known by now that very high cutting temperatures are created while machining this hard material and that too, close to the cutting edge of tool which is a major cause of tool wear.

- **High Cutting Pressure:** The cutting forces while machining titanium are almost same as when machining steel [7]. W. Konig (1979) [6] has stated that there exists high stresses in tools when machining titanium than while machining nickle-based alloy and three to four times of that while machining steel Ck 53N. This may be attributed to the small chip-tool contact area on the rake face of the tool [8] and due to the resistance offered by titanium alloy to deformation at higher temperatures which reduces at temperatures above 800°C [9].

- **Low modulus of elasticity & consequent springback:** A Pramanik (2014) [10] states that the low modulus of elasticity leads to bouncy conditions in titanium, i.e. to say that there is more strain and hence, deformation in titanium under a certain degree of force.

- **Hardening due to Diffusion and Plastic Deformation:** G. He (1985) [11] brought out the fact that when the temperature of cutting zone attains 600-700°C and crosses it, diffusion of oxygen and nitrogen molecules from the air takes place which eventually hardens the surface layer of the titanium workpiece. M. Donachie Jr. (1982) [12] brought out the fact that titanium retains its strength at even higher temperatures unlike most other metals. It is also recollected that both the phenomenon of diffusion and plastic deformation are responsible for hardening of titanium while machining it however, plastic deformation is the more pronounced factor [13,14].

- **Mechanism of Chip formation:** A Hosseini et al. (2014) [15] says that titanium and its alloys probably has some unique combination of mechanical and metallurgical properties that actually make them extremely difficult to machine than their counterparts. Keeping in mind all the above shortcomings that might pop up while machining titanium and its alloy, a good cutting tool, therefore, must entail the following [16,17]:

4. Machining of Titanium Alloys by Various Tools

4.1. Machining of Titanium alloys with HSS tools:

Inspite of good toughness of HSS tools, the softening takes place at around 600°C and hence cannot be used for applications that has working temperature above 500°C [18,19]. It has been effectively brought out that HSS tools are not suitable for machining titanium and its alloys when the cutting speed exceeds 30 m/min [20,21]. However, some highly alloyed grades and certain general-purpose grades can definitely be used to machine titanium, but care has to be taken that the cutting speed does not exceed 30 m/min [22]. In case of machining of titanium alloys, the degradation of the tool takes place due to a lot of factors, however, it is predominantly due to the plastic deformation that takes place [23]. Further, the crater wear that takes places due to the high temperature that is produced by chips rubbing on the rake surface of the tool is also another major factor for tool deterioration [24]. Both these factors makes HSS tools unfit for machining titanium and its alloys.

4.2. Machining of Titanium alloys with carbide tools:

One of the most preferred carbide for machining of Titanium and its alloys is the straight grade cemented carbide (WC-Co) [25]. Cutting speeds greater than 60 m/min is not preferred while
machining with cemented carbide tools [26]. Higher speeds, i.e. greater than 60 m/min, leads to plastic deformation due to intense heat generation [27]. Apart from the diffusion wear, another type of wear that usually takes place in carbide tools is the adhesion wear and temperatures above 740°C and contact pressure of 0.23 GPa [28]. The adhesion wear increases as the tool material is progressively and repeatedly damaged.

Higher crater wear has been noticed in tools with coarser grains and higher flank wear has been noticed in tools with smaller grains [29]. The coating layer is removed by either abrasion wear or by the chemical reaction between the titanium workpiece and the coating such as titanium nitride and titanium carbonitride [30].

4.3. Machining of Titanium using Ceramic Tools:

A Chakraborty et al (2000) [31] reveals that ceramic tools have a higher compressive strength, hot hardness, better chemical inertness and oxidation resistance than its counterparts. However, they are subjected to mechanical and thermal shocks and they easily break away during interrupted machining due to being brittle and lacking toughness.

Kejia zhung et al 2014 [32] observed notch wear in ceramic tools mainly occur due to incidence of a hard film in workpiece surface.

Z. Yin et al 2015 [33] found that to ensure quality of machining surface and efficiency, special super-hard materials advance ceramics cutting tools have been progressively working for machining of difficult-to-cut materials via good wear resistance, high compressive strength and excellent chemical stability.

4.4. Machining of Titanium using PCD Tools:

Observations have stated that PCD tools has a much lower wear rate when utilised for machining of titanium due to the formation of titanium carbide as a protective coating on the rake face of tool [34]. They even show acceptable performance when utilised for machining of Ti-6Al-4V which is one of the common alloys of titanium [35]. Although it has an acceptable performance however, the high costs involved hinders its much widespread utilisation.

E.O. Ezugwu et al 2003 observed that special materials of polycrystalline diamond (PCD) and polycrystalline cubic boron nitride (pcBN) are used to maintain a high hardness at elevated temperatures [36]

4.5. Machining of Titanium by CBN Tools:

CBN is the second highest hard material, has a high melting point, high hot hardness at elevated temperatures and has a high oxidation resistance with stability upto 2000°C [37]. F Klocke (2011) [37] further specifies that the grains of CBN are extremely small (1-50μm) and are sintered together by binder under high temperature and pressure and are called polycrystalline cubic boron nitride or PCBN. Both CBN and PCBN tools are used to machine hard-to-cut materials like forged steels, alloy steels, etc [38]. It was reported that the combined effect of elevated temperature and compressive stress may reach at a stage that the tool is not being able to bear and hence, deformation and consequent wear starts [39]. Although CBN and PCBN tools can be utilised for higher cutting speed applications like 150 m/min for Ti-6Al-4V [40] but they are hardly used because of their expensive nature when compared to carbide tools and therefore, are not efficient economically.

5. Cryogenic Treatment
Cryogenics refers to the science of extremely low temperatures, be it lower than 120 K / -153°C [38] or 100 K / -173°C [41]. Cryogens are generally available as liquid gases such as liquid nitrogen, oxygen, helium, argon, etc. [42]. However, in case of machining, sometimes temperatures above 100 K / -173°C is also considered as cryogenics as in the case of cryogenic machining using solid and/or liquid carbon dioxide [43,44,45] and sometimes even to the extent of using chilled air at very low temperatures [46,47]. In case of cryogenic machining, the cryogenic component is introduced in the cutting operation in the form of cutting fluid to change the properties of the materials or to dissipate the heat generated due to cutting at the cutting zone [48]. Cryogenic processing or in other words cryo-processing is part of the heat treatment cycle as an extended process which eventually enhances the tool material properties [49]. Many advantages of such cold processing has been known for ages for example Swiss watchmakers used to leave watch components in the cold of the Alps for several months in order to improve upon the wear resistance of the parts [50,51]. For steel cutting tools, the austenite retained in any cutting tool can severely lead to tool wear and the cutting edge getting chipped off [52]. However, such a generic process cannot be recommended for all tools and it is necessary to study every tool individually for cutting process parameters which include hardness, toughness and wear resistance of tool [53]. It is previously noted that changes in tool material properties happens when the tool is being cooled down to cryogenic temperature and further, heated up to the room temperature [54].

It has been reported that cryogenic processing indeed increases the wear resistance of tool by up to 126% if we use HSS tools to machine grey cast iron or to machine carbon steel [55,56]. Firouzdor et al. (2008) [56] even studied the effect of tempering after doing the cryogenic process and came up with the conclusion that the tool life in this case increases by 49% when compared to tools which were non-tempered after the cryogenic process. Leskovsek et al. (2006) [57] studied the effect of tempering temperature on the wear resistance of tools. It was highlighted that the tool which was cryogenically treated and was tempered at 600°C performed a little better than tools which were only tempered at the same temperature. Molinari et al. (2001) [58] undertook a study and gave that the specimen which was un-tempered after doing the cryogenic treatment showed the most promising results in the sense of highest wear resistance. It is indeed a true fact that cryo-processing indeed improves tool materials and there are several theories given by several researchers for the same but none of them could explain the underlying reason [59]. The first such explanation for the improved properties was the transformation of retained austenite into martensite allotrope which is much harder [60]. Another explanation brings out that the cryogenic treatment done enhances more of carbide particles in the martensite matrix and further, refines the microstructure and provides a more uniform carbide distribution. These carbides were classified into primary carbides, large secondary carbides and small secondary carbides by Das et al. (2007) [61]. So far as titanium alloys are concerned, S. Y. Hong et al. (1999) [62] suggested that it will be beneficial to freeze the tool rather than cooling or freezing the workpiece but keeping in view the workpiece titanium, it was also put forward that it will be beneficial to cool the workpiece as well as freezing the tool enhances the tool properties, provides stability to cutting tool material and reduces friction between the tool and the workpiece at the cutting zone.

Although extensive work has been carried out already on cryogenic machining using cryogenic substance as a coolant but comparatively less work has been carried out on cryo-processing with no concrete explanations for the improvement in properties via cryo-freezing of tool has been provided yet.

6. Tool Wear

Researchers have actively studied about the machinability of Ti-6Al-4V and have concluded that PCBN (Polycrystalline Cubic Boron Nitride) and PCD (Polycrystalline Diamond) tools may be used to machine Ti-6Al-4V effectively [63]. PCBN allows for hard turning of workpiece materials for which the hardness is 58-62 HRC [64]. K. Bouacha et al. (2014) [65] optimised the various parameters of hard
turning and the responses that were recorded was tool wear, surface roughness, cutting forces and metal volume removed. The most important factors which attributed to the surface roughness was that of feed rate and cutting speed.

Y. Jia et al. (2018) [66] machined Ti-6Al-4V by PCBN Tools (Polycrystalline Cubic Boron Nitride) manufactured by DI Corporation in a dry turning operation. CBN insert’s performance depends largely also on the type and content of binder material. The most significant reason for such type of tool wear is the dissolution diffusion of binder material into the chip [67]. However, the Binderless CBN inserts (BCBN) are free from above effect and exhibit superior characteristics as well. A. R. Zareena et al. (2005) [68] machined titanium alloy using CBN, BCBN and PCD tools using high pressure lubricant and concluded that BCBN tools are free from cobalt binder and hence, there is no diffusion dissolution taking place and therefore, the tool life is more, surface finish is better and cutting forces are also less and hence, can be used effectively to machine titanium alloys both from an economic and functional point of view.

7. Conclusion

The previous works were reviewed extensively in connection to titanium alloy grade-5 turning using cryogenically treated as well as untreated CBN inserts although much needs to be still explored in this regard. There seemed to be a huge gap in context of variation of cryogenic treatment duration and treatment cycles with the study of its effects on tool wear on machining. Further, there seemed to be totally minute exploration on using solid CBN or binder less CBN for titanium machining and studying the wear on tool correspondingly. Hence, we propose to take up the variation of cryogenic duration and cycles on tool wear as a future work and dwell into the effects it produces.

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