A Review of the Machinability of Titanium Alloys

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Titanium alloys find wide application in many industries, due to their unrivalled and unique combination of high strength-to-weight ratio and high resistance to corrosion. The machinability of titanium alloys is impaired by their high temperature chemical reactivity, low thermal conductivity and low modulus of elasticity. In this paper, the machining fundamentals specific to titanium alloys are presented and the machining of Ti6Al4V with conventional and advanced cutting tool materials is reviewed. The experimental results from several sources are discussed and form the basis of a collaborative research project between academia and industry. The selected aerospace benchmark component is presented and milling strategies for machining performance enhancement are discussed.

Additional Keywords: Ti6Al4V, manufacturing

Nomenclature

a	depth of cut [mm]
f	feed [mm]
h	chip load [mm]
R	surface roughness [μm]
T	temperature [°C]
V	speed [m/min]

Greek Symbols

α	phase, hexagonal close packed crystal structure
β	phase, body centred cubic crystal structure
λ	thermal conductivity [W/m.K]
ρ	density [g/cm^3]

Subscripts

a	average
c	cutting
e	radial
x	maximum
n	revolution
p	axial
v	tool face
z	tooth

1. Introduction

Titanium alloys are used in the aerospace and biomedical industries due to their exceptional strength-to-weight ratio and superior corrosion resistance[1]. The amount of titanium in the structure of an aircraft will increase from approximately 7 %[2] to 15 % of the structural weight in the next generation of aircraft such as Boeing 787 or Airbus 350 XWB[3] for a competitive advantage. Therefore, a growing market niche for high value titanium machined components is perceived. Machining is a major cost contributor, but at the same time a differentiating factor. The main focus in process development during the last few years in the aerospace industry has been high performance machining of aluminium alloys. This results in a significant gap between the material removal rates of aluminium and titanium alloys[2]. Figure 1 illustrates Ti6Al4V's machinability by comparing it to the machinability ratings[4] of other materials, with 1018 steel as benchmark. Many of the same qualities that enhance titanium's appeal for most applications, also contribute to its being one of the most difficult-to-machine materials[5].
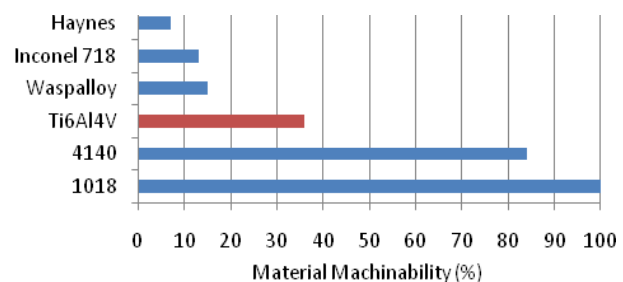

Figure 1: Comparison of the machinability ratings of some popular materials[4]

Titanium alloys are subdivided into α-alloys, β-alloys and α/β-alloys. These alloys form part of the light metals group, due their low density of $\rho = 4.5$ g/cm³. These alloys also show a high hot strength and can therefore be used at elevated temperatures[6] up to 600 °C, which is much higher than the 350 °C considered as the operating temperature[7] of compressor blades. Titanium alloys are characterised by a low thermal conductivity of $\lambda = 7$ W/m.K, combined with a melting point (1650 °C/1930 K) which concentrates high cutting temperatures[7]. Ti6Al4V is the most popular for low thermal stress[8, 9] aircraft parts and belongs to the α/β-alloys. This alloy comprises about 45-60 % of the total titanium products in practical use[1, 10] and is formed by a blend of alpha and beta favouring alloying elements. The α-alloy (hexagonal close packed) is hard and brittle with strong hardening tendency. The β-alloy (body centred cubic) is ductile, easily formed with strong tendency to adhere[7]. This alloy can be produced in a variety of formulations, depending on the application. The aluminium content may reach up to 6.75 % (by weight) and vanadium 4.5 %. The oxygen[10] content may vary from 0.08 % to more than 0.2 % and the nitrogen may be adjusted up to 0.5 %. Raising the content of these elements, especially oxygen[11] and nitrogen, will help to increase the strength. Equally, the lower additions of oxygen, nitrogen and aluminium will improve

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ductility, stress-corrosion resistance, fracture toughness and resistance against crack growth[11]. In order to cope with the challenge of large scale structural parts and the rising number of smaller parts, an understanding of the machining demands of titanium alloys is needed. This paper examines the current state of research in turning and milling; and compares the latest tool materials for the machining of Ti6Al4V. Innovative lubrication strategies, tool coatings and tool geometries are evaluated for future development. It also shows a benchmark component from a collaborative research study and a tool wear characterization map from which remedial actions and original strategies are developed to efficiently mill Ti6Al4V.

2. Machining Challenges

The recommended cutting speeds (V_c) for titanium alloys of over 30 m/min with high-speed steel (HSS) tools, and over 60 m/min with cemented tungsten carbide (WC) tools, result in rather low productivity[8]. The machining challenges can be divided into thermal and mechanical tool demands. The tool face temperature (T_v) is a function of the cutting speed (V_c) and exposure time to this thermal load. The longer the duration of exposure time, the larger the volume of the tool edge, that is exposed to the critical tool temperature[12]. The combination of titanium's low thermal conductivity and the fact that approximately 80 % of heat generated[13] is retained in the tool; result in a concentration of heat in the cutting zone (thermal stress). These issues cause complex tool wear mechanisms such as adhesion and diffusion[14, 15]. Figure 2 illustrates the results from studies of the tool face temperature (T_v) when machining Ti6Al4V relative to cutting speed (V_c). Similarly, other researchers[16,17] also measured temperatures of 900 ℃ at a cutting speed of 75 m/min.
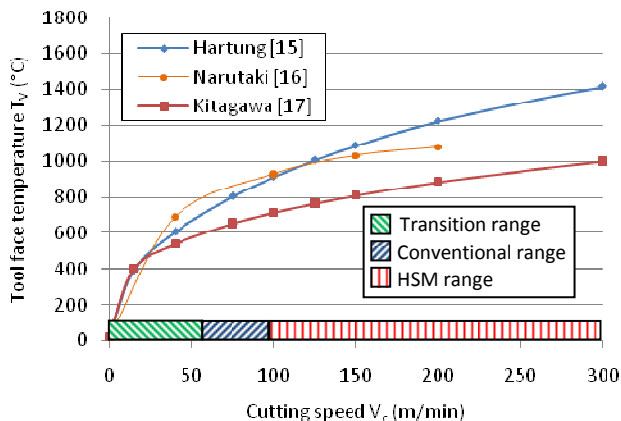

Figure 2: Tool face temperatures (T_v) when machining Ti6Al4V relative to the cutting speed (adapted from[15-17])

The mechanical demands are a combination of the work piece chip load on the cutting edge and machining vibrations. Ti6Al4V exhibits segmented chip formation and has been cited to cause much confusion in interpreting cutting data[12] in the pre 1980 era. Figure 3 illustrates a general continuous and serrated Ti6Al4V chip. The contact area of a serrated chip is found to be only a third[10] of the contact area of a continuous chip.

This results in high pressure loads on the cutting edge. Catastrophic tool failure, due to vibration while in cut, is caused by self-excited chatter[19] and forced vibrations due to
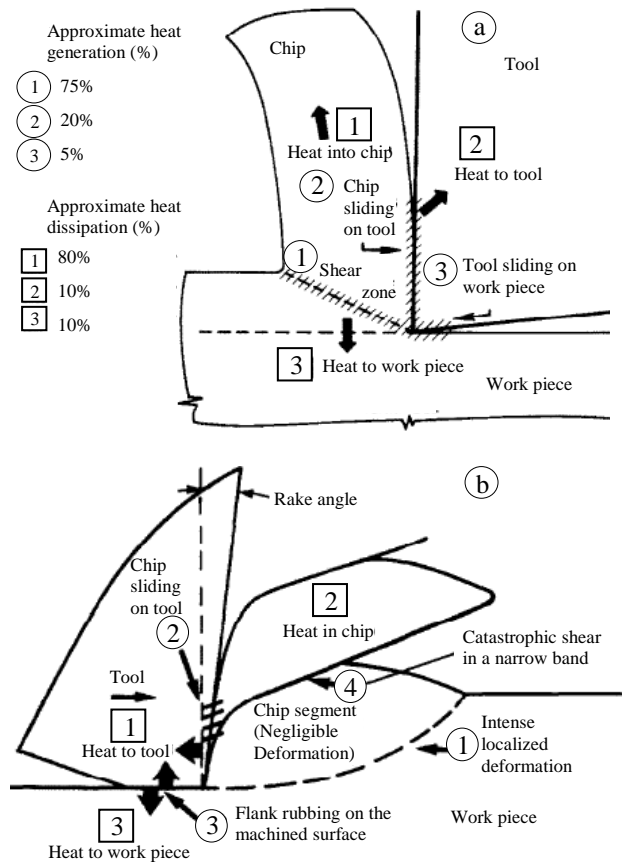

Figure 3: Contact area of (a) a continuous chip, and (b) a serrated Ti6Al4V chip[18].

the formation of shear localization[18] and the fluctuating friction force between the tool and chip flow. According to Shivpuri *et al.*[20] the chip segmentation phenomena significantly limits the material removal rates and causes cyclic variation of force. The combination of a low Young's modulus (114 GPa)[21], coupled with a high yield stress ratio allows only small plastic deformations[6] and encourages chatter and work piece movement away from the tool. Figure 4 illustrates the demands on the cutting tool material for different application areas in terms of strength, abrasion resistance and tribo-chemical wear resistance.
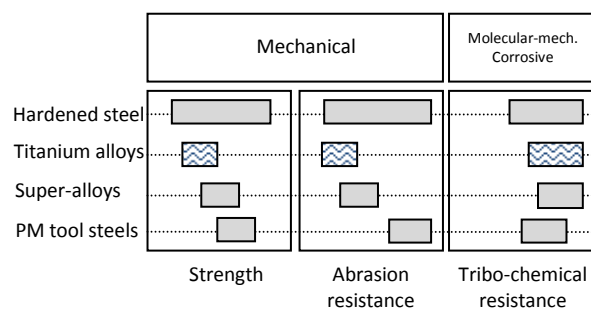

Figure 4: Relative demands on tool materials for different application areas (adapted from[22])

Ti6Al4V is associated with very much the same demands as Inconel718, although Inconel718 generates higher cutting forces[23] and is more abrasive[4]. The most challenging demands for a tool material to machine titanium alloys are the tribo-chemical and impact related wear mechanisms. Tribo-chemical wear is a combination of molecular-mechanical wear and corrosive wear and may be considered a thermally activated process whereby the work piece material and tool material react in such a manner as to remove material from the tool on an atomic scale[22]. Titanium's chemical reactivity becomes problematic at temperatures above 500 °C. Apart from diffusion wear, it has a strong affinity to adhere which leads to chip adhesion (also known as galling) onto the tool cutting surface. Once a built-up edge develops, tool failure follows rapidly[24]. The unexpected reaction of titanium chips with atmospheric oxygen causing a fire hazard is also a major concern in a workshop.

3. Current State of Research in Turning of Titanium Alloys

Although the different mechanical loadings for turning are not as severe as in interrupted cutting (milling), research[22] indicates that the temperatures generated are significantly higher for turning under nominally the same conditions. As illustrated in figure 5[16, 25, 26] carbide tool materials were used for roughing experiments (conventional speeds, high feeds), while polycrystalline diamond (PCD) and Cubic Boron Nitride (CBN) tool materials were used for finishing experiments (high speeds, small feeds). The low experimental conditions clearly exemplify Ti6Al4V's machining challenges.
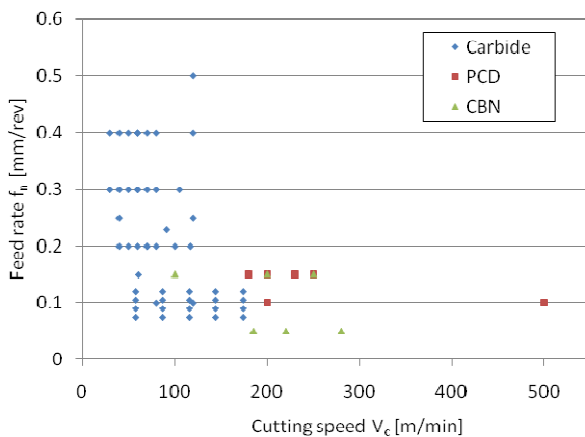

Figure 5: The conditions of research experiments on the turning of Ti6Al4V

Although experiments with carbide are conducted at higher cutting speeds, advisable industry norms for first stage (roughing) turning is still limited to cutting speeds of 30 - 50 m/min and feeds of 0.3 – 0.4 mm per rotation[27]. Finish turning operations are done at cutting speeds ranging from 80 – 120 m/min and feeds of 0.1 – 0.2 mm per rotation. From this figure it is evident that high speed machining is still a new titanium machining strategy and that not many experiments have been conducted with PCD and CBN tools. The performance of conventional tool materials are poor when machining Ti6Al4V at elevated

speeds and the development of cutting tool materials such as CBN and PCD may hold the answer to higher cutting speeds.

4. Current State of Research in Milling of Titanium Alloys

The key demand that distinguishes milling from turning is the interrupted cutting and the related mechanical and thermal shock loading. In milling the tool is subjected to cyclic heating and cooling, causing thermal shock. When the rate of cooling is increased significantly, the result is tool crack formation causing premature tool failure[28]. Su *et al.*[29] connect cyclic thermal shock directly with thermal crack initiation. It logically follows that an indiscriminate increase of cooling power will yield diminishing returns. Tool wear in milling of Ti6Al4V may be modelled as a thermo-mechanical high-cycle fatigue phenomenon in which the first order effects can be divided into work piece related and catastrophic tool failures[22]. Figure 6 illustrates the different cutting conditions of research experiments[7, 12, 29-33] on the milling of Ti6Al4V. Similar to turning, carbides are used for roughing (conventional speed, high feed) while experiments with PCD and binderless cubic boron nitride (BCBN) show promising results for high speed finishing operations. As indicated in the figure, the rough milling[34] of titanium alloys is also defined by conventional cutting speeds (around $V_c = 50$ m/min), but a lower feed per tooth limit ($f_z = 0.25$ mm/z) is evident compared to that for turning ($f_n = 0.5$ mm/rev). This clearly demonstrates the higher mechanical and thermal shock loading found in milling operations. Rough milling operations are still limited to cutting speeds of 30 - 60 m/min [35, 36] with feed rates of 0.1 – 0.25 mm/z[35, 36].
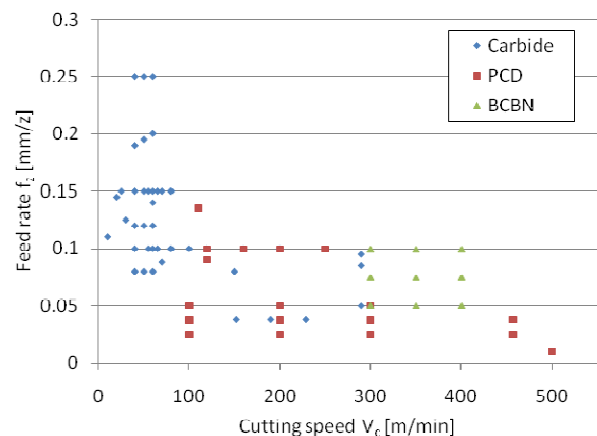

Figure 6: The conditions of research experiments on the milling of Ti6Al4V

High speed milling refers to cutting speeds which are five to ten times higher than conventional speeds[37]. Finish milling of Ti6Al4V shows promising results at cutting speeds in the range of 175-200 m/min[12, 16], with a feed per tooth of 0.025 – 0.05 mm/z[16, 32]. The axial depth[12] of cut is low ($a_p = 0.5$ mm) and the radial immersion[38] ranges from $a_e = 0.5$-2 mm. As the depths of cut are typically shallow in high-speed machining (HSM), the radial forces on the tool and spindle are low. Deep immersion can result in severe chatter vibration[39] and a low immersion saves spindle

bearings, guide-ways and ball screws. Although experiments[7, 33, 40] with CBN, PCD and BCBN milling this alloy show promising results, more experimental research and cost studies are needed.

5. Evaluation of Cutting Materials for Titanium Alloys

The term *toughness* should be interpreted not necessarily as the engineering quantity, fracture toughness, but more so as the resistance to chipping or catastrophic failure[22]. Figure 7 shows that there are always trade-offs between higher cutting speeds and higher feed rates. The tougher high-speed steel (HSS) and Micro-grain cemented carbide are predominately limited by their hot hardness (property to withstand the thermal load), whereas PCD, being deformation resistant at higher temperatures, is primarily limited by its toughness (property to withstand mechanical loading).

Tool failure can be initiated by one or a combination of several forms of wear, which in an advanced stage may lead to overload or fatigue and catastrophic tool failure[22]. Note that flank and crater wear are gradual and more predictable than fracture, which occurs suddenly. The key to designing high performance cutting tools is to identify the most economical scheduled replacement time (SRT) used in the industry for the specific component. Thus the tool suppliers can optimize the operational conditions, whereby the cutting tool will withstand the demands of the machining process for a longer period of time than the SRT. These optimum operational conditions are defined as the safe zone[42, 41]. The following section examines the performance of different tool materials for machining Ti6Al4V.
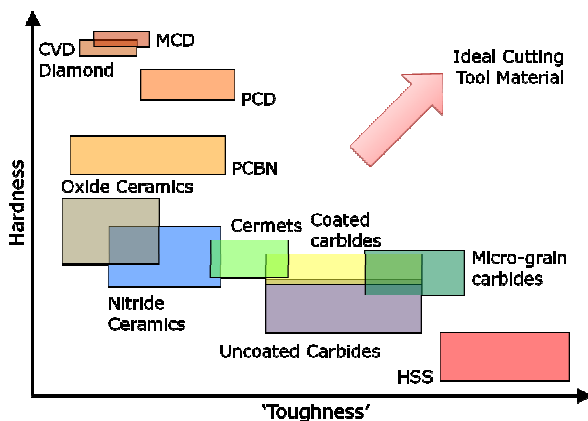

Figure 7: Comparison of different tool materials' properties relative to the machining demands (adapted from[41])

5.1 Machining with carbide tool materials

Straight tungsten carbide (WC–Co) tools are reported[43] to have superiority in performance in the milling of titanium alloys. In another study[44] with carbide on the dry end milling of a titanium alloy, the following optimum cutting conditions were obtained, $V_c = 88$ m/min ($f_z = 0.20$ mm/z), $V_c = 113.5$ m/min ($f_z = 0.15$ mm/z) and $V_c = 163$ m/min ($f_z = 0.10$ mm/z), as the best compromise among cutting speed, material removal rate (MRR) and tool life (TL). Uncoated carbide (WC) inserts were used for orthogonal

continuous and interrupted cutting at conventional cutting speeds. They[6] studied the cutting performance under dry cutting, minimal quality lubrication (MQL) and flood coolant. According to the authors, MQL was an effective alternative approach to flood coolant during high-speed turning of Ti6Al4V. Bryant[27] confirmed that $V_c = 45$ m/min is the usual cutting speed for machining titanium with uncoated straight grade cemented carbide (WC-Co) tools. As illustrated in figure 2 this cutting speed will generate tool face temperatures of more than 500 °C and according to research[45] titanium alloys are very reactive with carbide cutting tool materials at these temperatures. As a result micro-abrasion and attrition are the main causes of carbide tool wear[16], due to the adhesion and diffusion of the work piece material.

5.2 Machining with CBN tool materials

Zoya and Krishnamurthy[46] studied CBN tools under finishing conditions ($f_z = 0.05$ mm/z and $a_p = 0.5$ mm) at cutting speeds up to 350 m/min. They evaluated the performance of these tool materials with Ti6Al4V. It was concluded that it is a thermally dominant cutting process and a critical tribo-chemical wear temperature of 700 °C can be a decisive factor for tool life. It was also mentioned that the prominent wear mechanism of CBN tools is diffusion. In another study[25] the cutting performance of different CBN tool grades were evaluated for high-speed finishing operations of Ti6Al4V, with various coolant supplies. The type of tool wear, failure modes and cutting forces were studied. The experimental results revealed that different grades of CBN tools gave lower performance, in terms of tool life, compared to uncoated carbide tools. In addition to this, despite the relatively good cutting performance of CBN, carbide tools are still generally preferred for high speed finishing operations, because of their lower cost[6]. In a study with polycrystalline CBN (PCBN) cutting material, it was mentioned[40] that higher cutting speeds lead to decreasing cutting forces. This is due to the cutting tool material that is able to keep its strength at elevated temperatures, whereas the work piece material softens at the cutting edge. Complementary to this, research[33] with binderless CBN (BCBN) indicated that longer tool life could be achieved in high-speed finishing operations, compared to conventional PCBN (85 – 95 % CBN). BCBN is distinguished by its high thermal conductivity, hot strength and thermal shock resistance. This innovative cutting material is regarded as one of the most important novel materials for HSM of titanium alloys.

5.3 Machining with PCD tool materials

Research studies[47] with PCD tools indicated that it could be a substitute tool material for finish turning operations. Supplementary work[48] indicated that PCD produced a better work piece surface integrity. In another Ti6Al4V turning study[49] the results revealed that PCD (CTB010) could achieve a 3 fold increase in tool life over tungsten carbide at a speed of 200 m/min ($f_z = 0.05$ mm/rev). Similarly, results[50] from a TA48 titanium alloy turning study with similar PCD tools, demonstrated a 4 fold increase in tool life over KC850 carbide at a cutting speed (V_c) of 75 m/min ($f_z = 0.25$ mm/rev). Narutaki and Murakoshi[16] showed that natural diamond tools used dry at $V_c = 100$ m/min lasted

longer than carbide tools used with a cutting fluid at the same speed. When used with a cutting fluid at $V_c = 200$ m/min, the diamond tool had the same wear rate as during dry machining at $V_c = 100$ m/min. This, in a way, corresponds with the findings[48] on the machining of γ-TiAl inter-metallic alloys. Their study showed that with a low pressure fluid supply, 2 µm and 10 µm grain size PCD produced similar tool life to that of using WC with a high pressure fluid supply. Regardless of all these positive findings in turning, very little data exists on finish milling of titanium alloys and even less, if any at all, on the rough milling of Ti6Al4V using PCD. Polycrystalline diamond exhibits high thermal conductivity and hot hardness, which can be ideal for finish milling Ti6Al4V. The lower transverse rupture strength (TRS) can be tolerated, if the correct milling strategy is applied. Finish milling experiments[12] reported a tool life of 215 min ($V_c = 457$ m/min), concluding that high-speed milling of Ti6AlV4 is possible with PCD. In addition to this, Kuljanic *et al.*[7] also reported a very long tool life (TL = 381 min) with good surface finish and geometrical accuracy in a finish milling operation. The main type of tool wear was found to be diffusion and adhesion. Nurul Amin *et al.*[30] studied the effectiveness of polycrystalline diamond *tool* materials and compared them to uncoated tungsten carbide–cobalt materials milling this alloy. They compared the tools with respect to the applicable cutting speed ranges; metal removal per unit tool life (MR/TL) and tool wear rates, tool wear morphology, surface finish, chip segmentation and chatter phenomena. The authors concluded that PCD inserts can be used effectively up to cutting speeds of 160 m/min, as the wear rate is quite low and the amount of metal removal per tool life unit is considered reasonable. Figure 8 summarizes the performance of the PCD tool materials, which illustrates the effect of tool properties, considering the various cutting conditions. The fine grain material has the highest TRS and coarse material the lowest value. Although the figure indicates that the fine grain material performed best overall, it was interesting to observe that there is a direct relationship between the performance and the transverse rupture strength of the materials.
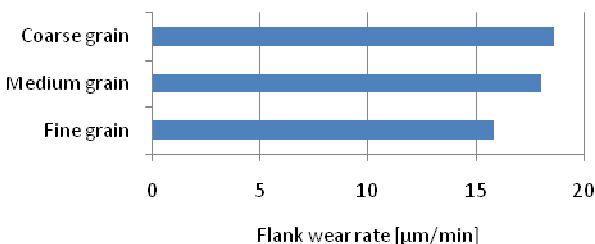

Figure 8: Performance of different grain size PCD materials; finish milling Ti6Al4V at elevated speeds[32]

Similarly, there is an inverse relationship between the grain size (increase in TRS), and wear performance. Research studies[51] indicated that the performance of fine grain PCD in experiments is a manifestation of the phenomenon envisaged by Barnett-Ritcey[12], namely that a tool material with sufficiently high temperature performance will be able to yield better machining productivity through the utilization of the thermal softening of Ti6Al4V by means of an α - β phase change.

5.4 Summary of cutting tool materials

Advances in cutting tool materials have resulted in an increase in material removal rate (MRR) when cutting titanium alloys. Cutting materials will always encounter extreme thermal and mechanical stresses close to the cutting edge during machining, due to the poor machinability of titanium alloys[4]. Therefore, the tool material's hot hardness[6] is a major requirement for Ti6Al4V machining tools. The softening temperatures of commercially available cutting materials are given in figure 8. Most tools lose their hardness at elevated temperatures, caused by the weakening of the inter-particle bond strength and the consequent acceleration of the tribo-chemical tool wear.

Strength is the property that resists the breakdown of the cutting edge (impact wear) when the mechanical load exceeds the physical properties of the tool material. Abrasion wear is caused by the action of the sliding chips in the shear zone, as well as by friction generated between the tool flank and work piece. Abrasion wear happens primarily due to the hard grain orientations in the titanium alloy, which can act like hard inclusions in the work material and is compounded by the part's hardness and strength properties. Figure 10 illustrates the importance of different tool characteristics that are required from innovative tool materials to efficiently machine Ti6Al4V.
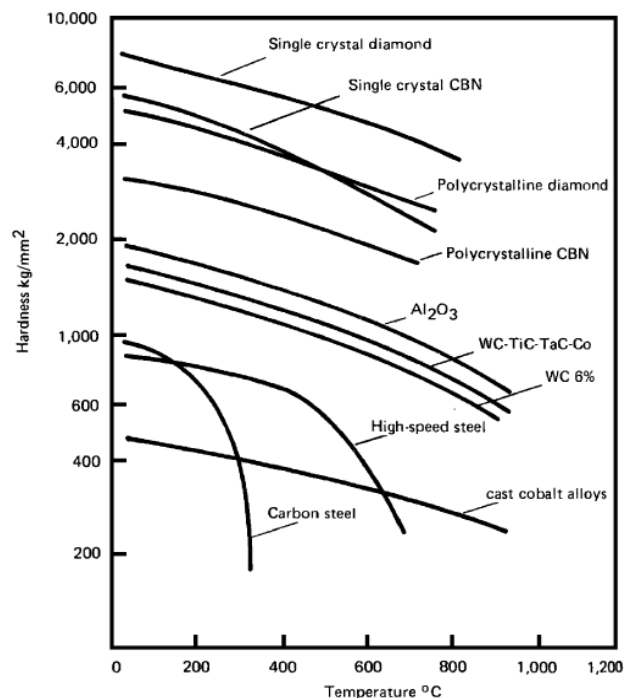

Figure 9: Typical hot hardness characteristics of some tool materials[6]

As illustrated in figure 10, the chemical wear resistance of the tool material is the first priority, followed by impact and abrasive wear resistance. Table 1 summaries the perform-ance of different cutting materials used to titanium alloys. As indicated in the table, although PCD materials perform well, it is still a very expensive cutting material that needs further development.
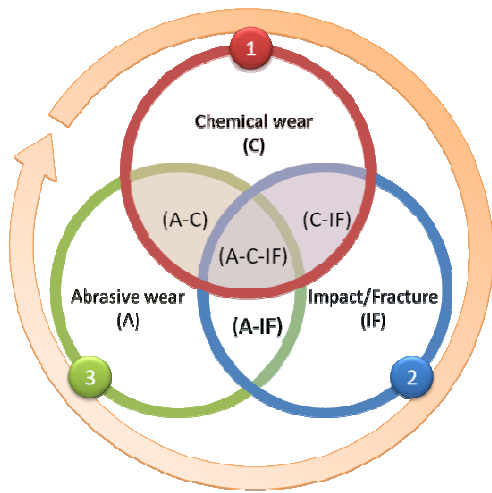
Figure 10: The importance of different tool characteristics required when designing a tool material for the machining of Ti6Al4V

	Coated carbide	PCD	BCBN
Tool life	average	good	very good
Heat conduction	good	good	very good
Hardness	average	very good	very good
Tendency of chipping	good	good	very good
Price	average	bad	N/A

Table 1: Tool material performance[32]

Although BCBN is the best cutting material for titanium alloys under high-speed conditions according to literature[33], it is still not commercially accessible and the price is not available. Coated carbide and HSS are cost effective, and still the most commonly used cutting materials for titanium alloys in the industry.

6. Lubrication Strategies

Lubrication and cooling strategies for titanium machining operations are areas where the cutting process can be improved. During interrupted cutting the tool is subjected to cyclic heating and cooling that can cause thermal shock[12]. When the rate of cooling is increased significantly, the result can be thermal shock, causing catastrophic tool failure, if the thermal load (at elevated cutting speed) is too high for the tool material[28]. Su *et al.*[29] connect cyclic thermal shock directly with thermal crack initiation. The low thermal conductivity of Ti6Al4V causes a concentration of the heat build-up in the cutting zone[7]. When the cutting zone is shielded from the lubricant stream such as in cutting with deep axial immersion, the coolant needs to be focused on the cutting edge[52]. At high tool temperatures, typically above 550 °C, the heat transfer mechanism between the cooling fluid and the tool surface changes to two phase high-speed flow[12]. The coolant is vaporized on contact with the heated tool surface, forming an insulating boundary layer on the tool surface. The phenomenon is also described as delayed surface wetting in heat transfer literature[12]. The

performance of the different lubrication strategies for finish milling with PCD is illustrated in Figure 11. Coated carbide tool materials with flood lubrication were used as benchmark.
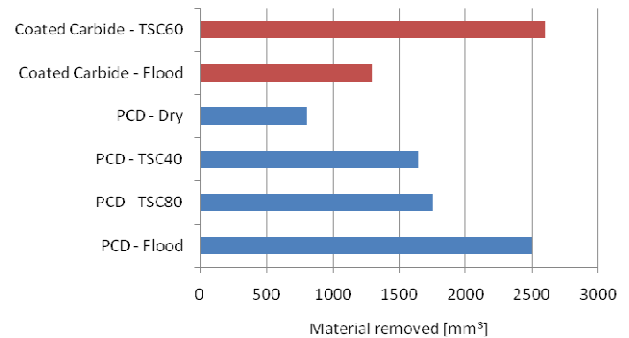

Figure 11: Different lubrication strategies for finish milling (adapted from[32])

Flood lubrication had the lowest flank wear rate, resulting in the longest tool life. This proves that PCD is not as susceptible to thermal shock as found with carbide[29]. The 80 bar TSL performed better than the 40 bar TSL and dry machining had an accelerated wear pattern. The lubrication pressure employed with the 40 bar and 80 bar TSL strategies enabled the insert to reach more than twice the tool life compared to dry machining, while flood lubrication reached more than three times the tool life of dry machining. Liquid Nitrogen cryogenic cooling[53] and minimum quantity lubrication (MQL)[54] also show promising results and should be considered in future research studies.

7. Performance Enhancement of Milling Strategies

Titanium alloys are used for high value components, not only components used in an aircraft's frame and engine, but also in the biomedical field. Workshops able of sustained growth will migrate toward higher-end work, meaning that a growing percentage of machining shops will encounter titanium alloys. Therefore attention to milling titanium is worth while in order to achieve higher productivity, when raising the cutting speed is not an option. Results[55] from research collaboration study details the effect of tool geometry on tool life. As illustrated in figure 12, the side clearance angle of the tool is the most influential.
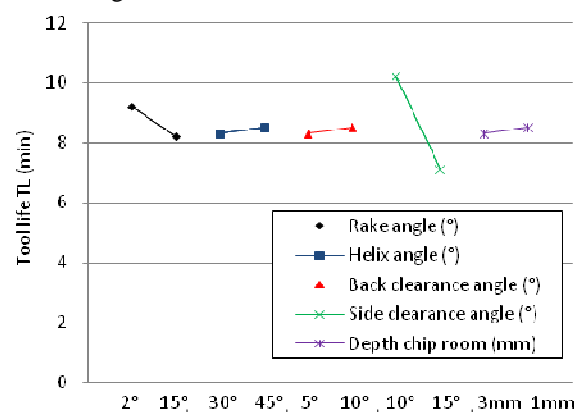

Figure 12: The effect different tool parameters have on tool life[55]

Another solution to protect tool materials from thermal load is the use of a coating. The perfect coating should have a high temperature resistance, a high toughness and limited thickness in the sub-10 micron range. Figure 13 shows results of different experimental coatings milling Ti6Al4V. None of these coatings improved tool life relative to the uncoated tool. It should however be noted that coatings like TiSiN were not tested in this study[55].
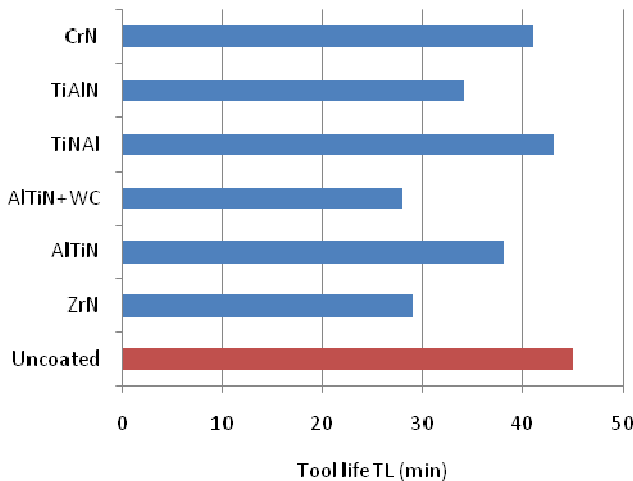

Figure 13: Tool life tests with different coatings milling Ti6Al4V at elevated speeds (adapted from[55])

An explanation might be that the coated surface is rougher, which leads to the sticking of the chips to the rake of the tool[56]. The cutting edge of the tool is also not as necessarily sharp as an uncoated tool and during preparation phase (before applying the coating) the tool material can become brittle[55]. Based on this study, it can be concluded that none of the experimental coatings are suited for HSM of Ti6Al4V. In a collaborative research study[57] between the academia and aerospace industry a benchmark part was used to understand the tool demands from the Ti6Al4V work piece and to improve the milling strategies used currently in industry. Table 2 illustrates the different operations to machine this component. The material removed (MR) per operation is indicated. Test 1 and test 2 are the result of various simulations and background experimental studies. Cutting tool materials and parameters were varied to improve the machining time for the benchmark component.

The revision of the machining strategies with new generation cutting tools showed a significant reduction from 116 to 41 minutes in the total machining time. An aluminium version of the same benchmark component required nominally 14 minutes to machine. Compared to the 41 minutes to machine a Ti6Al4V part, it is evident why titanium machining needs further experimentation. Figure 14 illustrates the first roughing operation of this component.
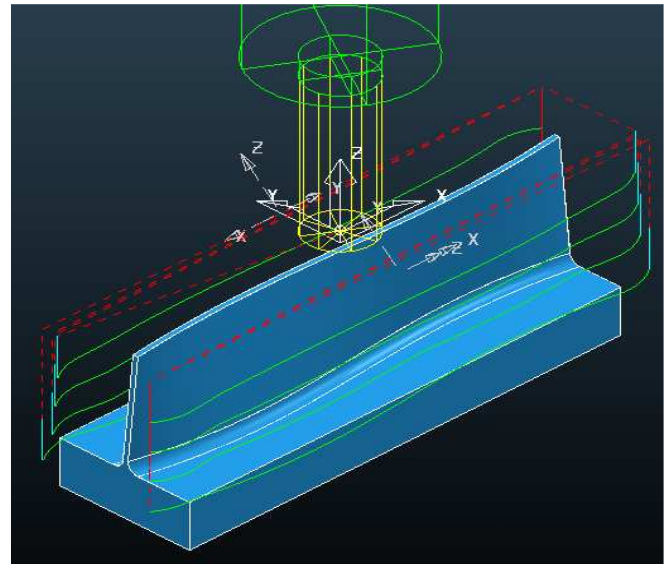

Figure 14: Illustration of the simulated run for the first rough operation

High depths of cut (a_p) were possible with a large radial immersion (a_e). Using the wear characterization map illustrated in Figure 15, which is developed specifically for the milling of Ti6Al4V alloys, improved parameters and milling strategies were realised for the cutting of the corner fillet of the component. The used tools were examined with an optical microscope and scanning electron microscope (SEM) imaging and were characterized so as to categorize them into a failure region. Thus, remedial actions could be considered to improve the process. Both the roughing and the semi-finishing for this benchmark component can now be completed in less than 20 minutes.

Tool failure during the roughing operation took place after approximately 35 minutes of cutting time (or after 1½ components). Similarly it is calculated that the tool life in the aerospace industry should exceed 30 minutes to ensure an economical viable solution[55], as most scheduled tool replacement times (SRT) are less than this. Figure 16 illustrates the final Ti6Al4V product.

The titanium part had a good surface roughness value ($R_a = 1.01$ µm) and the component's accuracy was acceptable. Through an iterative approach a significant reduction in machining time was achieved, proving that the correct milling strategies are of critical importance.

	Operation	Test 1 [min]	Test 2 [min]	MR [cm³]	MR (%)
1	First Rough	7.09	7.09	283.898	61.01
2	Semi Finishing	12.25	12.25	141.858	30.49
3	Flat Area Finishing	2.32	2.32	1.665	0.357
4	Side Wall Finishing	12.16	12.16	33.957	7.30
5	Corner Fillet Roughing	49.02	0.3	3.608	0.775
6	Corner Fillet Finishing	30.96	4.1	0.348	0.074
7	Blade Final Finish	2.56	2.56	0	0
	Machining Time	**116.36**	**40.78**	**465.334**	**100**

Table 2: Summary of the operational for two experimental tests in order to reduce the total machining time of a benchmark component
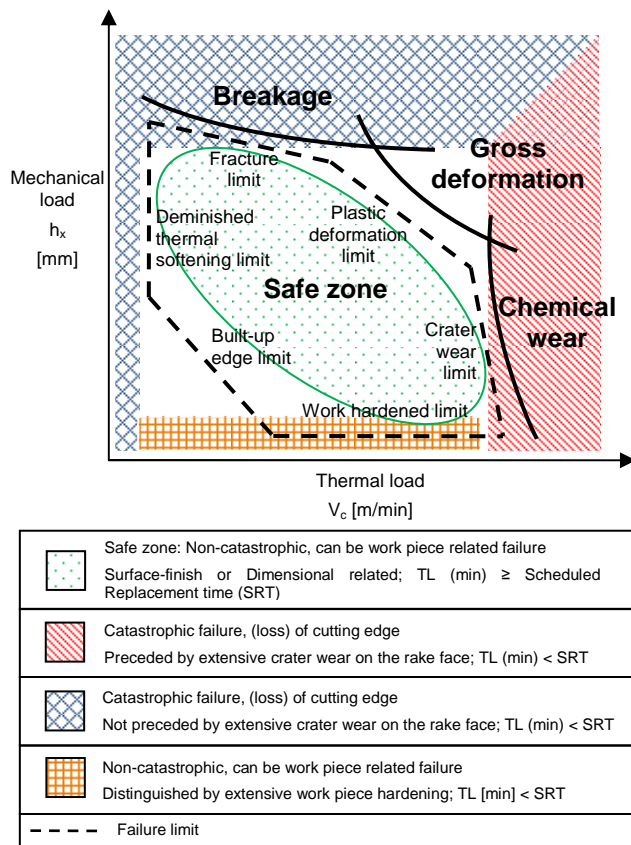
Figure 15: Tool wear map for milling of Ti6Al4V as a function of cutting speed and feed rate

Figure 16: The final product – a benchmark aerospace component

8. Conclusions

The key tool demands for efficient machining of Ti6Al4V were identified. The current state of research in turning and milling was examined and the latest tool materials for the machining of Ti6Al4V were compared. The present most efficient operating parameters for rough turning and milling, and for finish turning and milling were identified. The current slow cutting speed implies that roughing and finishing are still required to achieve productive material removal for titanium alloys. Innovative lubrication strategies, tool coatings and tool geometries for the machining of a benchmark Ti6Al4V component were evaluated for future development. A tool wear characterization map was illustrated and was used to identify the optimum cutting parameters. The preferred scheduled tool replacement time (SRT) for aerospace components was confirmed to be in the order of 30 minutes.

9. Acknowledgements

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