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HIGH SPEED MILLING OF TITANIUM ALLOYS

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Abstract:
Titanium alloys are on account of their unrivalled qualities wide spread in certain industries. Despite the growing demands, the machining technology of titanium has stagnated for the last 20 years. In this paper, the specific machining fundamentals of titanium as well as the main parts of the process chain are presented in a literature survey. The allegorised results and recommendations are origin for an industrial research project, which is currently conducted at the PTW.

Key Words: Titanium, HSC, Aerospace

1. INTRODUCTION

Due to their unique properties titanium alloys are widely spread in aviation industry, automotive, biomedical and oil industry, whereas the largest market for the use of titanium products like tanks, planking, structural parts, turbine blades or jet nozzles is surely the aerospace industry [14, 38]. The usage of titanium parts increases with growing requirements in the component properties [38]; additionally a further growth of the civil air traffic is predicted for the next years [1]. Therefore the efficiency of titanium machining is one of the major challenges in production engineering.

2. PROPERTIES OF TITANIUM ALLOYS

Titanium alloys are subdivided into three main groups: α- alloys, β- alloys und α/β- alloys, whereas the most popular one in aircraft construction [1, 8, 19, 29, 30, 38] for parts under low thermal stress is TiAl6V4, which belongs to the α/β- alloys. Titanium alloys are noncorrosive and belong to the light metals, due to their low density of $\rho = 4{,}5\ \mathrm{g/cm^3}$. Compared to aluminium alloys they have up to triple amounts of tensile strengths and therefore an advantageous ratio of strength to density. Furthermore, they offer a high ratio of yield stress to tensile strength ($R_{p0,2}$ / $R_m = 0{,}9$) as well as high tenacity and resilience, whereas the amounts of deformation are higher compared to steel due to the lower Young's modulus of $E = 110.000\ \mathrm{N/mm^2}$. Besides, titanium alloys show a high hot strength and can thus be used at elevated temperatures up to 600 °C [38] depending on the composition. They are characterised by a low thermal conductivity of $\lambda = 4$ to 16 W/m*K, combined with a high thermal capacity $c_p \approx 520$ J/kg*K [2]. Titanium alloys are highly reactive with small-atomic elements, especially the atmospheric gases oxygen, nitrogen and hydrogen [1, 38], causing embrittlement. They also react with all known cutting tool materials including PCD, ceramics and PCBN [31, 38].

2.1 Problems when cutting titanium alloys

The given properties of titanium alloys make it reasonable to assign them to the difficult-to-cut materials. The problems in titanium machining can be traced back to the following causes [1, 2, 16, 17, 18, 21, 32, 38]:

- *High thermal stress at the cutting edge due to the low heat dissipation by the chips and the work piece.*By the combination of low thermal conductivity and high thermal capacity

30 % more heat must be absorbed by the cutting edge compared to the machining of steel (Ck 45). When machining titanium, the cutting temperatures are approximately twice as high [1]. Diffusion and adhesion processes are thus enhanced, high temperature gradients occur whereby thermal stress emerges [2].

- *High pressure loads on the cutting edge through reduced contact surface.* This is explained by the low plasticity of titanium alloys [1] and further increased at elevated cutting speeds due to the decreasing shearing angle [6].
- *Highest pulsating loads due to the formation of segmented chips, which is rooted in the hot strength behaviour of the material.*
- *Tool failure by chippings due to high cutting forces and self- induced chatter.*
- The combination of a low Young's modulus with a high yield stress ratio allows only small plastic deformations. The material is elastic and keeps springing back under cutting pressure. At the flank face this leads to a lower effective clearance angle. Thus friction is enhanced and chatter is supported. Besides high cutting forces the low excitation frequencies, caused by relatively low rotation speeds, propagate chatter.
- *Vibration affinity of unstable work pieces due to the low Young's modulus.*
- *Danger of wear by diffusion due to high reactivity of titanium, involving the weakening of the cutting material.*
- *Strong affinity to adhesion due to the heat accumulation in the cutting zone, involving tool failure.*
- *Hazard of exoergic reaction of titanium chips with atmospheric oxygen*

All this embarrassments cause conflict with the industrial implementation of high speed milling of titanium alloys, because elevated thermal stress which come along with high cutting speeds strongly propagates tool wear. Many publications in the context of titanium machining deal with the analysis of wear mechanisms and wear progress [e.g. 4, 5, 6, 7, 9, 20, 31]. In the following the emphasis lies though in the feasibility of high-speed parameters, where fewer publications are available yet.

3. CURRENT STATE OF RESEARCH: “HSC OF TITANIUM ALLOYS”

Conservative references about roughing of titanium alloys report about “traditional” cutting speeds of about 50 m/min [e.g. 12, 13, 14, 32, 44]. However, the term “high speed cutting” refers to cutting speeds which are about five to ten times higher than conventional speeds [27], whereas the axial depth of cut is about $a_p = 0,5$ mm and the radial cutting width is about $a_e = 0,5$ mm to 2 mm [45]. The improved performance of cutting at high speeds is represented by the material removal rate and the feed rate in the following equations:

$$Q = a_p * a_e * v_f \ (cm^3/min) : v_f = f_z * z * n \ (m/min) : v_c = \Pi * d * n \quad (m/min)$$

The effect of decreasing cutting forces, which occurs at elevated speeds [28], can be approved experimentally for titanium as well. The decrease of forces is relatively unincisive, compared to aluminium or steel as shown in Figure 1 and 2 [28, 38].

In [29] a “slower wear progress” is described when working with high cutting speeds compared to conventional milling, whereas most of the publications document a disproportionately high wear increase at elevated speeds. According to [8, 11] most of the reported cutting parameters in the literature are too conservative, because they are optimised to high tool life travel and do not take into consideration that primary processing time can cause much higher costs than a higher amount of cutting tools.

In the following, the state of research regarding high speed cutting of titanium alloys is presented and the effects on the cutting process are described. Also dependencies and influencing variables are depicted. Based on this it can be highlighted how industrial implementation of HSC of titanium can be realised.

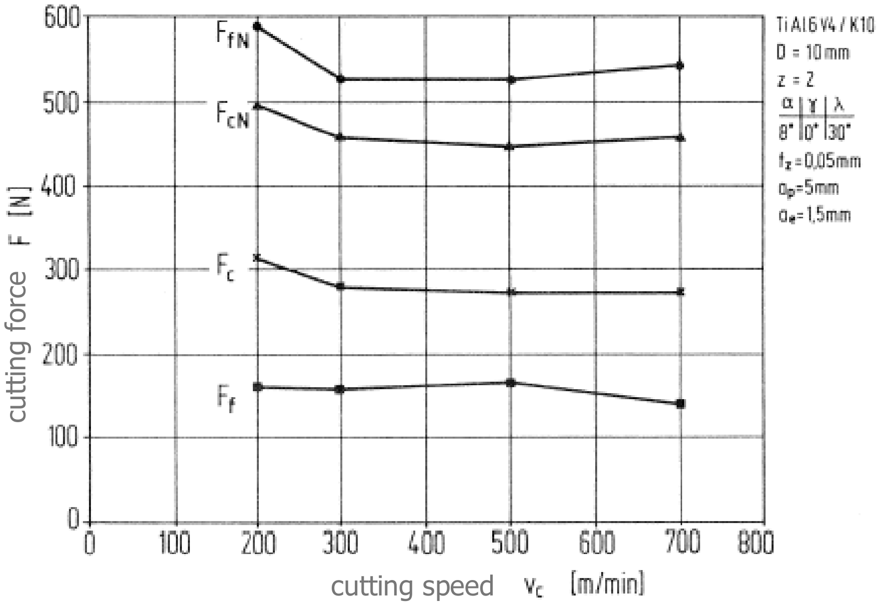


Figure 1: Cutting forces at elevated cutting speeds, TiAl6V4, carbide tools [38].

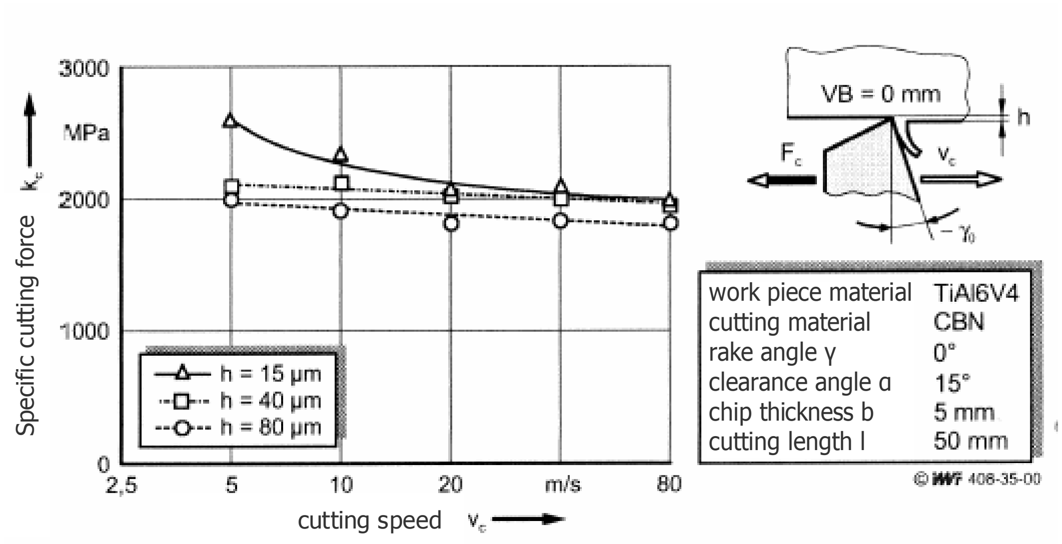


Figure 2: Specific cutting force at elevated cutting speeds, TiAl6V4, PCBN tools [43].

Figure 3 shows a survey according to [2] about the most important investigations about end milling of TiAl6V4 and the derivable recommendations.

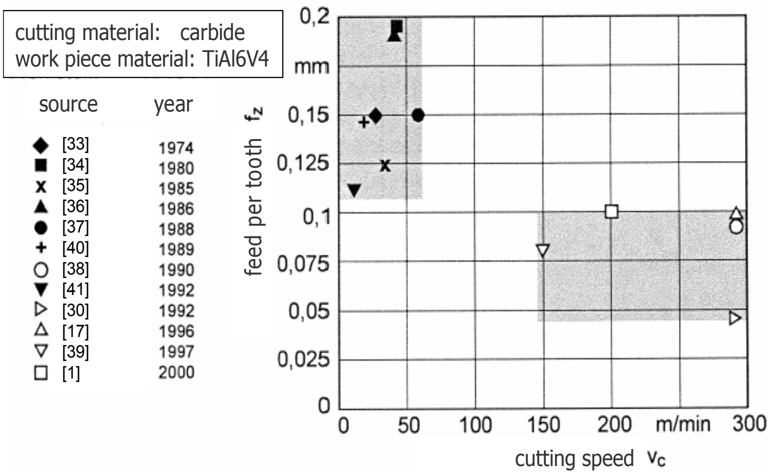


Figure 3: Investigated cutting conditions for end milling of TiAl6V4 [cp. 2].

By the use of low cutting speeds (left area in Figure 3) the thermal stress of the cutting edges can be kept low. The use of high feeds respectively cutting widths lead thus to high metal removal rates [2, 38, 39]. Recent work shows also favourable cutting conditions with lower cutting forces at elevated cutting speeds, as can be seen in the right part of Figure 3. Other investigations recommend cutting speeds between 100 m/min and 125 m/min [4, 5, 6], in Table I the further enhanced milling parameters of Illgner [38] are shown.

Table I: Parameters for high speed milling of titanium alloys [38].

titanium alloys						remarks
cutting wedge	carbides	α	β	γ	r	v_c= 1000 m/min
		20°	max 18°	o°	sharp	v_f= 800 m/min
						a_e= 1,5 mm, D=40 mm, z=1
chip form	segmented chips					in HSC area
specific metal removal rate	Q=4,5 cm^3/kW min at v_c=700m/min					Feed see line 7 others see line 1
surface quality	v_c [m/min]	500	700	wear criterion		
	R_a [µm]	1,95	1,1	VB=0,3 mm		
	R_z [µm]	6,5	4,5			
recommended cutting material	K 10					
suitable cutting speeds	K 10	v_{c30} [m/min]		wear criterion		
		295		VB=0,3 mm		
suitable feeds	carbides	f_z [mm]		v_f [mm/min]		see line 1
		0,1		800		

3.1 Cutting material

HSS tools are well applicable for full cut operations ($a_p = d$) due to their high tenacity. For cutting speeds above 60 m/min fine grain WC-Co carbides should be used [2, 29, 30, 39]. According to [32] carbides of ISO- classification M should be favoured, whereas fine grain carbides (GS 0,07 – 0,1 µm) show a lower fracture toughness compared to coarser grains. Ginting et al. recommend carbides of type P [6], whereas in [38] carbides of type M are suggested. The cutting speed has a essential role in this decision. In contradiction to other references, machining of titanium alloys is, according to [8], not feasible with ceramics, PCBN or PCD.

According to [32] higher cutting speeds lead to decreasing cutting forces when using PCBN, because the cutting material can keep its hot strength, whereas the work piece material softens at the cutting edge and chips can be taken off easier. In [10] highest tool life could be realised with binderless cubic boron nitride (BCBN) in HSC conditions compared to conventional PCBN (85 – 95 % CBN, GS 1 – 3 µm). BCBN is distinguished by highest thermal conductivity, hot strength, thermal shock resistance and high mechanical strength and is regarded in [10] as the most important new cutting material for HSC of titanium alloys.

When regarding ceramics as a cutting material the literature survey is also inconsistent. Illgner [38] describes ceramics as inappropriate for titanium machining, whereas according to [32] the use of mixed ceramics at higher cutting speeds is possible. Whisker reinforced ceramics are, due to their good fracture toughness, and silicon nitride based ceramics due to their oxidation resistance well suitable for the machining of difficult-to-cut materials [32]. The development of a novel cutting material for titanium machining is, according to [11], one of the most difficult, unsolved problems of machining technology; the suitability of rare earth metal compounds is considered. Good tool life travels could also be reached in [15] when cutting TiAl6V4 with PCD at moderate speeds ($v_c = 110$ m/min). However, the more economic cutting velocity regarding machining time lay much higher [15]. Other good results with PCD are reported in [20].

3.2 Coatings

In this research field the references are also inconsistent. According to Ezugwu [32] uncoated carbide tools are only suitable for low cutting speeds when machining titanium. The results of [7] on the other hand show that the type or principal availability of a coating only has very small influence on the tool temperature. Also [38] could reach highest cutting speeds with uncoated tools. The control of the process temperature is a very influencing factor regarding process safety. Tool coatings increase hot strength, wear resistance, temperature stability and the resistance against oxidation wear and offers good lubrication properties [32]. Characteristic tool coatings for titanium machining are TiC, TiN, Al_2O_3, TiCN, TiAlN, TiZrN, TiB_2 and recently introduced diamond coatings [32]. Good results were also reported in [31] with moderate cutting speeds and multilayer CVD- TiCN + AL_2O_3, whereupon the CVD- coatings were superior to the PVD ones. Gey [2] reached highest tool life with TiAlN, in [8] promising results were made with TiCN.

3.3 Milling strategies

For a sufficient tool life the cutting edge has to leave the material with low mechanical loads to avoid tensile stress. This demand is fulfilled in down milling [e.g. 1, 2, 17, 21]. The milling strategy should be chosen in such a way, that the generated heat can be safely and continuously dissipated over a large and changing contact surface. Therefore front milling is to be preferred to hob milling [30]. Feed stop during material contact must be avoided, because cutting temperatures rise immediately and lead to tool failure [13, 21]. Large metal removal rates were reported in [14] with plunge milling strategies, where the high feed rates in z- direction put strain on the stiffest axis of the machine and the tool itself [cp. 18].

Improvements in part quality and productivity can be achieved by adaptive feed control [16], whereupon the implementation in industry is limited by the cost- intensive sensor technology.

3.4 Cooling lubricant

In this research field the references and recommendations are once more inconsistent. Some authors conduct their cutting experiments totally dry [4, 5, 6], whereas other researchers use conventional flood cooling [29, 30]. At low cutting speeds the use of full jet flood coolant can improve the lubrication performance and the heat eduction at the cutting edge [32, 13]. Under HSC- conditions the coolant has only negligible impact [32] on the process, because it vaporises at the cutting edge. High pressure cooling can get around this and is also very efficient regarding chip removal. Tool life could be increased by 300 % compared to conventional flood cooling [cited in 32]. Su et al. however report in [9] about a critical thermal shock when machining titanium with carbide tools and conventional flood cooling at high speeds and advise against it. When machining TiAl6V4 with PCD the use of flood cooling is recommended [15, 45]. Kneisel et al. [17] compared different cooling strategies and could not discover strong refinements of tool life (carbide K10, v_c = 700 m/min), the use of flood cooling always minimised tool life.

An efficient way to control temperatures when machining titanium is the use of cryogenic cooling [32]. However, the alternating thermal loads on the cutting material act adversarial when milling [9]. Additionally it comes to higher cutting forces because of the higher mechanical strength of the material at low temperatures [32]. In turning of TiAl6V4 with carbide tools and liquid nitrogen cooling fivefold tool life could be reached compared to conventional flood cooling [42]. Cooling with compressed, cold nitrogen gas when slot milling TiAl6V4 also led to higher tool life [9], the admix of oil mist resulted in tool life gain of 170 %.

3.5 Cutting edge geometry

In titanium machining the cutting edges of the tools should be kept sharp without rounding in order to avoid high cutting temperatures and forces, the tools should be replaced immediately when wear occurs [1, 2, 13, 21, 38, 45]. Due to the low plasticity of titanium and the attenuation of the cutting edge by the additional grinding operation, chip breakers and formers should not be used at all. The references and recommendations regarding the wedge angles are not consistent. While in [12] rake angles of γ = -5° to 0° are recommended, Gey [2] gets best results with angles about 15°. Illgner [38] attains highest tool life with rake angles of γ = 18°. König [12] recommends clearance angles of α = 10° to 12°, whereas the research work of Lopez et al. [8] shows that clearance angles of less than 18° cause very much friction and heat; clearance angles larger than 20° weaken the cutting wedge. The authors in [21, 38] recommend clearance angles of α = 18° likewise. To avoid chatter, variable cutting edge spacing by unequally spaced flutes is suggested in [16, 18]. A further possibility to ward off chatter is an “eccentric relief”, which damps vibration by rubbing at the work piece when the tool deflects [18].

3.6 Cutting forces

As described before, the cutting forces decrease with increasing cutting speeds. In [30] a clear minimum of all cutting force components is discovered when finishing with v_c = 300 m/min (cp. Figure 4), so that high tool life travels were possible (about 10 m).

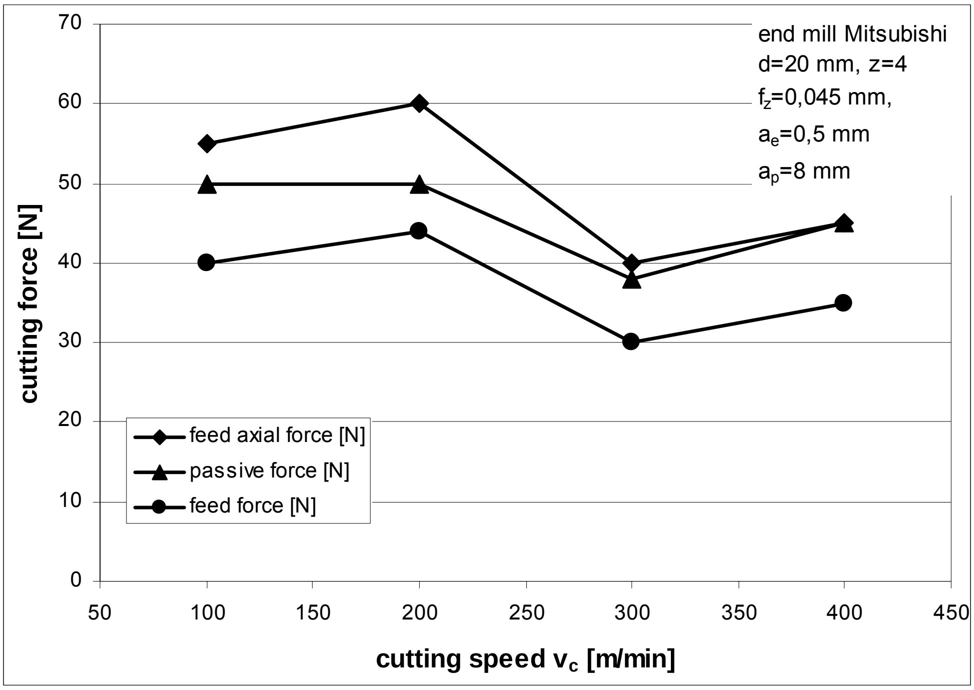
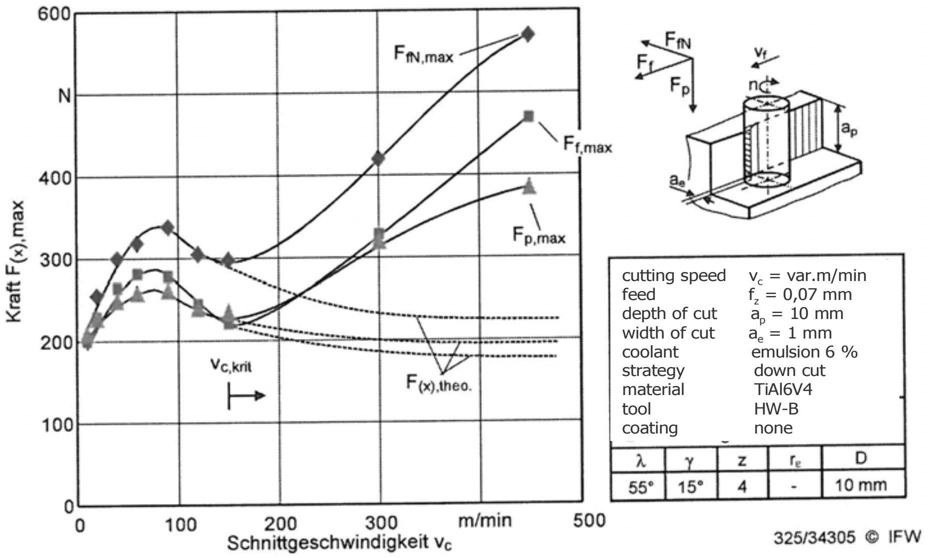


Figure 4: Cutting forces at elevated cutting speeds, material: Ti6Al2Sn4Zr4Mo, cutting material: carbide, ultra-fine grain [30].

Gey [2] discovered after an initial rise of the forces a reduction at about v_c = 90 m/min. Due to high friction and dynamic loads the cutting forces rise again after v_c = 150 m/min. (cp. Figure 5)



cutting speed v_c = var.m/min
feed f_z = 0,07 mm
depth of cut a_p = 10 mm
width of cut a_e = 1 mm
coolant emulsion 6 %
strategy down cut
material TiAl6V4
tool HW-B
coating none

λ	γ	z	r_e	D
55°	15°	4	-	10 mm

325/34305 © IFW

Figure 5: Cutting forces at elevated cutting speeds [2].

These discrepancies and the differences to Figures 1 and 2 show, that the critical cutting speed, where the cutting forces mount again, has to be determined for each application in particular and cannot be specified in general.

4. CONCLUSIONS

Efficient high speed milling of titanium alloys is possible. The characteristic decrease of the cutting forces could be shown by several researchers; the high thermal stress appears to be problematic when it comes to tool life. Various scientists emphasise the sensitivity of the process to the machining parameters [2, 29, 32, 38], so that every elemental change in the process has strong influence on stability, process safety and operating efficiency. The partial contrary results in literature show that there are, above all, still considerable obscurities at several points of the process chain. To find the most efficient combination of tool, machining parameters, milling strategy, etc. for the particular application, specific analyses are necessary. In [45] for example, a combination of moderate cutting speeds and enlarged cutting depths and widths led to most effective metal removal rates. A current industrial research project at the PTW deals with the process optimisation of high speed milling of integral aircraft parts of TiAl6V4. Large metal removal rates are only achievable with a selective harmonised set of cutting material, wedge geometry, coating, parameters, cooling lubricant and milling strategies.

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