Machining of Titanium Alloy Ti-6Al-4V for Biomedical Applications

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Titanium alloy has properties like outstanding corrosion resistance and very good biocompatibility whicht makes this material very interesting for biomedical applications. Due to its material properties titanium alloy poses a challenge for machining operations. A sound understanding of the alloy behaviour during the machining process is essential to achieve shape and dimensions tolerances of the product with minimum costs and machining times.

0 INTRODUCTION

Titanium is a commonly used material for biomedical applications. Properties like high strength, low weight, outstanding corrosion resistance and very good biocompatibility make titanium and titanium alloys the perfect material in a wide range of applications which demand high levels of reliable performance [1]. Owing to a large number of available titanium alloys, it is possible to select materials and forms that suit the requests of a specific application in the best way. The full range of alloys reaches from high ductility commercially pure titanium used where extreme formability is essential, to fully heat treatable alloys with strength above 1300 MPa. Shape-memory alloys based on titanium further extend the range of useful properties and applications.

Titanium alloys, specially Ti-6Al-4V are among the most widely used and promising materials for medical implants. The excellent chemical and corrosion resistance of titanium is to a large extent due to the chemical stability of its solid oxide surface layer to a depth of 10 nm, [2]. Under in vivo conditions the titanium oxide (TiO_2) is the only stable reaction product whose surface acts as the catalyst for a number of chemical reactions. However, micromotion at the cement-prosthesis and cement-bone is inevitable and consequentl,y titanium oxide and titanium alloy particles are released in the cemented joint prosthesis. Sometimes this wear debris accumulates as periprosthetic fluid collections and triggers a giant cell response around the implants [3]. TiO_2 film such as the ones anodically formed in aqueous electrolytes, consists mainly of anatase and is an n-type semiconductor with a low electronic charge conductivity and a high resistance to anodic current [4].

The relatively high cost of titanium machining has hindered a more wide application. To minimize the inherent cost problems, successful applications must take advantage of the special features and characteristics of titanium. This requires a more complete understanding of titanium alloys as compared to other competing materials, including the interplay between cost, processing methods, and performance [5]. The machinability of titanium and titanium alloys is limited by some characteristics and is considered difficult, due to its relatively high tensile strength, low ductile yield, 50% lower modulus of elasticity (104 GPa) and approximately 80% lower thermal conductivity than that of steel [6]. The lower modulus of elasticity may cause greater 'spring back' and deflection effect of the workpiece. Therefore, more rigid setups and greater clearances for tools are required. In the tool contact zones high pressures and temperatures occur (the tool-to-workpiece interface). The amount of heat removed by laminar chips is only approximately 25% while the rest is removed via the tool [14]. Due to this phenomenon titanium alloys can be machined at comparatively low cutting speeds. At higher temperatures caused by friction the titanium becomes more chemically reactive and there is a tendency for titanium to "weld" to tool bits during machining operations. Over-heating of the surface can result in interstitial pickup of oxygen and nitrogen, which will produce a hard and brittle alpha case.

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Carbides with high WC-Co content (K-grades) and high-speed steels with high cobalt content are generally suitable for the use as cutting materials in titanium machining operations [6]. Turning operations of titanium alloys should have cutting depths as large as possible, cutting speeds V_C from 12 to 80 m/min and approximately 50% lower when high-speed steel (HSS) tools are used. The heat generated should be removed via large volumes of cooling lubricant. Chlorinated cutting fluids are not recommended because titanium can be susceptible to stress corrosion failures in the presence of chlorine. CBN/PCBN and Poly Crystalline Diamond (PCD) tools are employed at high speed machining of titanium alloy [7].

1 DESIGN OF EXPERIMENT AND EXPERIMENTAL DETAILS

The objective of the study is to investigate the tool life and wear mechanism of coated carbides cutting tool when turning titanium alloy Ti-6Al-4V. The study investigates the wear progression and significant factors that affect the cutting tool life. A good understanding of wear mechanism when machining Ti-6Al-4V enables us to manufacture modern medical implants with complex shapes, which is the result of product functionality [11]. Machinability is defined as the ease or the difficulty with which a material can be machined under a given set of cutting conditions including cutting speed, feed, and depth of cut [13]. Machinability of a work material is accessed in terms of four factors: tool life, cutting forces, power requirements, and surface finish. It is obtained through a set combination of machining [13].

Machining tests were performed in Laboratory of cutting (LABOD) at the Faculty of Mechanical Engineering, University of Ljubljana on forged and LENS manufactured Ti-6Al-4V testing probes. Turning was performed in dry conditions and with a lubricant (Blaser Swisslube Vasco 5000), on EMCO turn 220 TM02 CNC machine. The used cutting tools were coated carbide cutting tool Sumitomo DCGT 070204 LFX ACZ 310 and cutting tool Sumitomo Electric DCMT 070204 NSU AC 2000. The tool wear evaluation was performed, comparison between dry and wet turning was given and optimal cutting parameters for Ti-6Al-4V with

coated carbides cutting tools proposed. The protocol for machining tests was defined by technological data base which was developed at LABOD for Cornet HPM project needs and implements ISO 3685:1993 standards [8] and [12].

LENS testing probes were manufactured on Optomec LENS 850R machine in the TIC LENS d.o.o. company in Celje. They were tested in order to provide comparison results between "classical" workpice made of Ti-6Al-4V and workpice manufactured with LENS technology, which is layer manufacturing technology. It produces a very fine weld bead, exposing the component to far less heat than conventional methods due to smaller and more controlled heat affected zone, which does not damage the underlying part. Once a geometry and material or material combination has been identified, LENS can rapidly produce a 3-dimensional prototype with good mechanical properties [9].
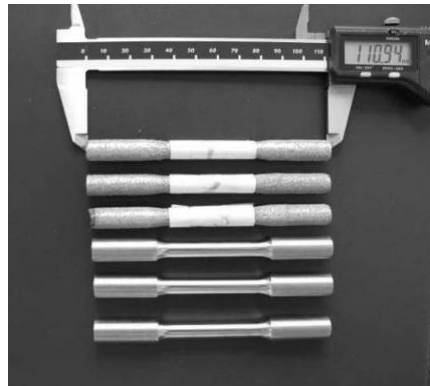

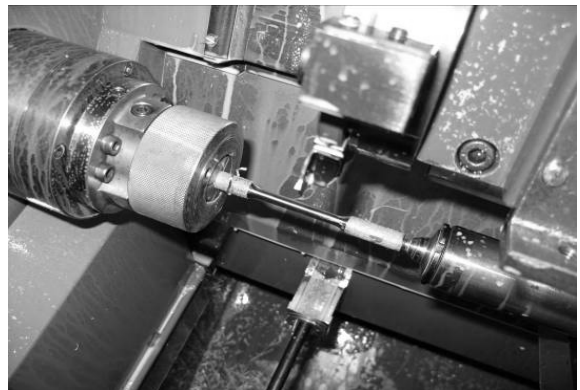Fig. 1. *Ti-6Al-4V testing probes (LENS and "classic") for machining tests*

Fig. 2. *Turning test of Ti-6Al-4V on EMCO turn 220 TM02 CNC machine*

Table 1. *Turning parameters on CNC machine and measured test results on testing workpieces with Sumitomo DCGT 070204 LFX ACZ 310*

a) Turning parameters on EMCO turn 220 TM02 CNC machine

Cutting depth a_p [mm]	RPM n [rpm/min]	Feed rate f [mm/rpm]	Cutting speed V_c [m/min]	Entering angle χ [°]	Diameter D [mm]
1	1920 to 3200	0.08	60	95	12

b) Turning time, tool wear (*VB*) on flank surface of the cutting tool and workpiece surface roughness

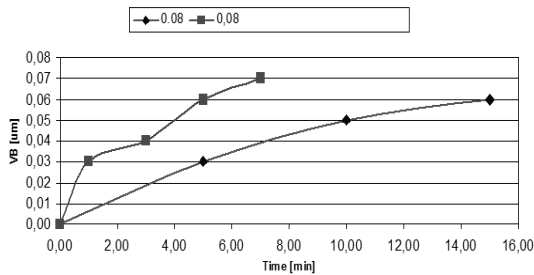|	lubricant	dry	lubricant	dry	lubricant	dry
Time T [min]	5	5	10	10	15	15
VB [mm]	0.03	0.06	0.05	0.19	0.06	0.25
VB_{max}	0.08	0.15	0.23	0.28	0.48	0.56
Ra [µm]	0.71	0.59	0.54	0.30	0.58	0.28

2 TOOL WEAR MECHANISM

Fig. 3. *Progression curves of coated carbide cutting tool at various cutting conditions for Ti-6Al-4V; the left curve is for dry cutting, the right curve for cutting with lubricant*

Tool wear mechanism for coated carbides is shown in Fig. 3. with progression curves for dry cutting and cutting with a lubricant. The curves are generally divided into three stages: the rapid initial progress, the relatively constant progress and the rapid-to-failure progress reaching VB_{max} 0.3 mm, which is the elimination criteria for cutting tools. This effect is especially visible at the progression curve for cutting in dry conditions. At low speed and low depth of cut, the tool is worn out mostly by rubbing and attrition. The wear that occurrs due to the depth of cut is smaller than the tool nose radius. After 4 minutes of cutting the tool wear passes from constant progress area into the rapid progress area. The chip flowing is partially stuck at the tool edge due to compressive force and an increase in temperature. In a dry environment, machining at a higher feed rate and/or at higher cutting speed will increase the temperature rapidly. An increase in temperature will induce the titanium to weld to the tool and form the built-up-edge-like layer. The welded material will help the wear progression.
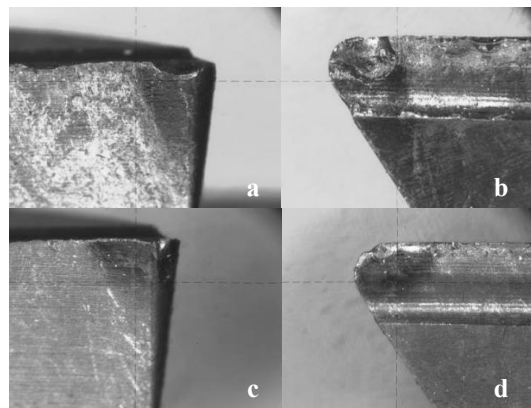

Fig. 4. *Tool wear after 15 minutes; a) flank surface-dry cutting, b)rake surface-dry cutting, c)flank surface-wet cutting, d) rake surface-wet cutting*

As seen in Figs. 4b and d when the critical tool wear approaches elimination criteria the crater wear appears. The reason for such tool wear is in adhesion to which the titanium alloy is particularly susceptible [10]. The compressive stress is considered small when chip is flowing on tool rake face, even though friction forces exist. This causes the chip to rub and scrap the tool material. The temperature of chip formation reaches over 1000°C which causes titanium to react stronger to certain tool materials. A

combination of both, friction force and high temperature cause the material to be welded to the tool. If the welded material to the tool surface receives the increased stress, this eventually causes the tool to fracture.

To determine full machinability of Ti-6Al-4V with coated carbides cutting tools the cutting forces were measured with a combination of dynamometer and dynamic analyser HP 3567A.
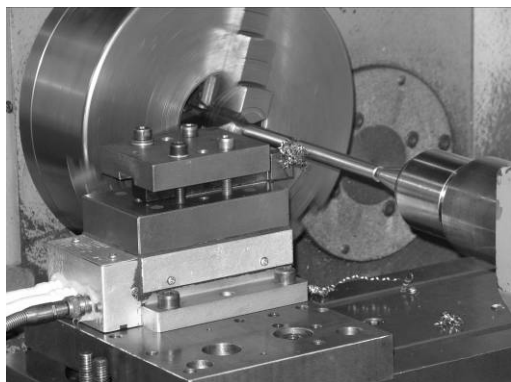

Fig. 5. *Cutting force measurement of Ti-6Al-4V with dynamometer placed under the holder*

The measured values of the cutting force are:
Specific cutting force k_{c1x1} = 733.28 N/mm^2
Specific feed force k_{f1x1} = 238.53 N/mm^2
Potency exponents: m_c = 0.05 and m_f =0.33

To provide comparative results between "classical" (forged) workpice made of Ti-6Al-4V and workpice manufactured with LENS technology 6 testing probes were machined with coated carbides cutting tool Sumitomo Electric DCMT 070204 NSU AC 2000 under same testing conditions. After the turning operation the surface roughness of the testing probes was measured and some conclusions were given.

The first comparison between both types of testing probes was the evaluation of chip formation and shape. At LENS testing probes the shape of the chips is more favourable which is visible in Fig. 6 a. Chips are crushed more and smaller and therefore, do not weld to the surface of the tool so intensely as at "classical" Ti-6Al-4V testing probes turning. They also do not block the machine and the cutting zone. At turning the "classical" Ti-6Al-4V testing probes the chips are longer, fail to crush well and form a hardly removable chip clump which is visible from Fig.

6 b. The surface roughness after machining was at LENS testing probes on average Ra = 1.2 µm and at "classical" testing probes on average Ra = 0.8 µm. Both values are still under Ra = 1.6 µm which is the upper limit for final machining operations.
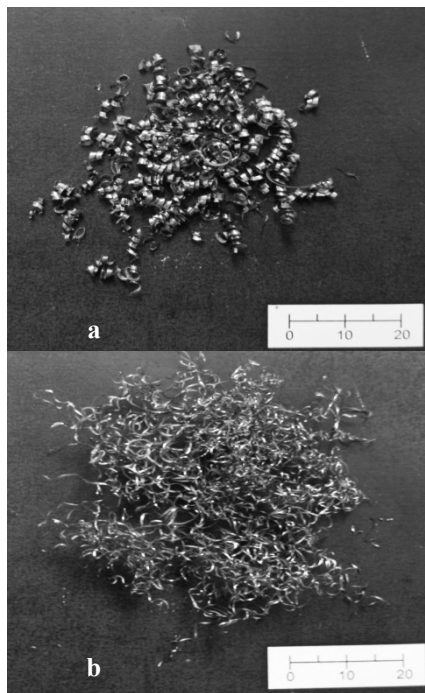

Fig. 6. *Chip formation at turning a) LENS ti-testing probes, b) »classical« Ti-testing probes*

3 CONCLUSIONS

At turning Ti-6Al-4V with lubricant we achieve a 40% longer tool life expectancy than at turning in dry conditions. The crater wear is visible after 10 minutes of turning time and is far more intense with cutting in dry conditions than with cutting with lubricant. Tool wear appears constantly in the first 10 minutes of turning. After that it increases rapidly to the point of critical tool wear due to material properties of titanium alloy Ti-6Al-4V. After 15 minutes this wear is so intense that the tool is worn out over the elimination criteria which is VBmax = 0.3 mm. Such a wear mechanism is typical for titanium alloy due to its affinity to adhesion wear at higher temperatures which appear in the cutting zone. Cutting speed used for cutting with coated carbides cutting tool is around 60 m/min which is

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the optimum setting for this tool-material combination. The feed rate has the strongest influence on the tool wear appearance. Turning of Ti-6Al-4V testing probes manufactured with LENS technology proved that we can reach the same or even better results regarding chip formation and surface roughness as with turning "classical" Ti-6Al-4V testing probes. This enables effective final machining processes to reach final shape and dimension tolerances of the products made with LENS technology.

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