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Experimental Comparison of Micromilling Pure Titanium and Ti-6Al-4V

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ABSTRACT

Pure titanium is the ideal metallic material to be used for producing dental implants due to its good corrosion resistance and biocompatibility. However, pure titanium does not present high mechanical resistance, which can be a limiting factor. Recently, the pure titanium is being replaced by titanium alloy with aluminum and vanadium (Ti-6Al-4V). This study deals with micromilling machinability of pure titanium and Ti-6Al-4V considering mechanical properties, the forces measured during the process, surface roughness, top burr height, and chips morphology. The cutting tests are performed for the constant depth of cut and cutting speed, and a range of feed per tooth from 0.5 to 4.0 $\mu\text{m}/\text{tooth}$. Results show no significant differences in roughness and burr formation whereas higher forces are found for the titanium alloy compared to pure metal. Both materials produce long chips for smaller feeds.

INTRODUCTION

Pure titanium (CP-Ti) is the ideal titanium-based material to be used in the manufacturing of implants because of its properties: good corrosion resistance, biocompatibility and reasonable mechanical resistance [1, 2]. However, due to fatigue failure the chances for a surgery for implant removal are seen to be increased [3]. The titanium alloy Ti-6Al-4V presents higher mechanical resistance preserving the essential properties for implants, However, several studies have reported that Ti-6Al-4V alloy might cause some long-term health problems to the patient due to the release of aluminum

and vanadium inside the person organism. Diseases like Alzheimer, neuropathy and osteomalacia have been reported as long-term consequences of the presence of these elements in the body of patients as they remain in the human body for several years [4]. Zaffe *et al.* [5] analyzed titanium plates and Ti-6Al-4V screws removed from patients that presented local inflammation and biopsies. They found out indications that biological perturbations may be related to aluminum release from the tested biomaterials.

Titanium based metals are considered difficult-to-machine materials, especially due to their low thermal conductivity [6, 7]. Kikuchi [8] performed an experimental study where the cutting temperature was estimated by measuring the thermal electromotive force a tool-workpiece thermocouple during milling of four different dental materials: pure titanium, Ti-6Al-4V, Ti-6Al-7Nb and brass. A high difference between the cutting temperature of the alloys and pure titanium was detected due to the low thermal conductivity.

Micromilling of titanium alloys presents the same difficulties of the mesoscale process, but with the additional factor of size effect. In micromilling, cutting edge radius dimension is often of similar dimension to the undeformed chip thickness. This change of the cutting mechanics leads to the appearance of the minimum chip thickness, below which there would be no actual material cutting, but only the plastic deformation of the material followed by elastic recovery, phenomenon called ploughing [9]. Rezaei *et al.* [10] aimed to define the minimum chip thickness of Ti-6Al-4V alloy during micromilling by analyzing cutting forces, specific cutting forces, surface roughness and the grooves surface images. The transition from ploughing to shearing was different when analyzing forces (6-12 $\mu\text{m}/\text{tooth}$) and roughness (1.5-6 $\mu\text{m}/\text{tooth}$).

Titanium alloy Ti-6Al-4V has been extensively studied in recent years. Carou *et al.* [11] produced a review on micromilling of titanium and its alloys. It summarizes the main published papers on topics like surface integrity, cutting tools, cooling systems and finite element modelling. Özel *et al.* [12] developed a finite element model to predict burr formation in micromilling of Ti-6Al-4V alloy considering the variation of the cutting edge radius. As titanium is a difficult to machine material, it wears the tool quickly. Therefore, they analyzed the variation of the edge radius with cutting length and its influence in top burr height and concluded that a bigger cutting edge radius leads to higher burr formation. Cheng *et al.* [13] developed a method for minimization of burr formation in micromilling of Ti-6Al-4V by coating the surface to be machined with a resin and then removing it. In the experimental validation of the method, their results showed that feeds per tooth smaller than minimum chip thickness presented higher burr formation for down milling cutting. Also, they found out that feed per tooth is the main parameter influencing top burr size. Thepsonthi and Ozel [14] applied an experimental design based on Taguchi method to verify the optimal cutting conditions for micromilling Ti-6Al-4V alloy. They used three factors (feed per tooth, spindle speed and depth of cut) with three levels each. They analyzed burr formation and surface roughness. Their result showed that higher feed rates lead to better surface finishing and higher depths of cut lead to less burr formation. However, most published papers do not cover machinability criteria as a whole like surface roughness, burr formation, cutting forces, tool wear etc. Kim *et al.* [15] developed one of the most complete published works on micromilling machinability of Ti-6Al-4V. They analyzed the effects of cutting speed and feed per tooth in cutting forces, surface roughness, burr formation and microchips morphology and found out that lower feeds lead to higher burrs and that cutting speed did not present a big influence in burr formation. Also, they found that increased cutting speed lead to smoother surface finishing as well as higher feeds. However, their study lacked a material

characterization which could explain some of the results they presented. There is also almost no study dealing with machinability of pure titanium in micromilling. Therefore, there is a lack of a complete study aiming to fully characterize the machinability characteristics of Ti-6Al-4V and pure titanium. The present work compares the micromilling machinability of pure titanium grade 2 and Ti-6Al-4V in different feed per tooth analyzing cutting forces, surface roughness, top burr height and chips morphology analysis.

EXPERIMENTAL WORK

Experiments are conducted using the statistical design of experiment approach in order to characterize the influence of feed per tooth on cutting forces, surface roughness, top burr height and chips morphology and the results are compared for both titanium-based materials including pure titanium and titanium alloy (Ti-6Al-4V).

Material and experimental apparatus

Two workpiece types were used: annealed commercial pure titanium (CP-Ti) grade 2 and annealed commercial Ti-6Al-4V. The initial workpiece dimensions are 50 x 25,4 x 5 mm.. Microstructures of both materials were analysed under an optical microscope after a chemical attack with Kroll's reagent and are shown in Fig.1. It can be seen that pure titanium is composed by equiaxed coarse alpha grains with dimension in the order of 20-30 μm . Titanium alloy presents equiaxed alpha grains mixed with alpha/beta small regions in between them.

Mechanical properties of CP-Ti grade 2 and Ti-6Al-4V were obtained from literature [9]. These include flexural modulus of 105 GPa and flexure strength 345 MPa, for pure titanium whereas Ti-6Al-4V has flexural modulus of 105 GPa and flexural strength of 900 MPa. Vickers hardness tests were also carried out for both materials using loads of 30 kgf for cycles of 20 s. The hardness values for pure titanium and Ti-6Al-4V were found to be 168 HV30 and 318 HV30, respectively.

The micromilling experiments were performed on a CNC Mini-mill/GX using 500 μm Mitsubishi Materials (MS2MSD0050) carbide square end mills without coating and with rake angle of 30°. The microtools were analyzed under a Zeiss scanning electron microscope, model DSM 940. The measurements yielded the cutting edge r_e radius of 2-2.5 μm , corner radius of 10 μm and helix angle of 26° as can be seen in Fig. 2.

For force measurements, the Kistler dynamometer MiniDyn 9256C2, the Kistler charge amplifier 5070A10100 and the data acquisition board USB 6251 from National Instruments were used. Figure 3 shows the axis configuration of force measurements in relation to the workpiece. Cutting force signals were analyzed using a fast Fourier transform (FFT) in order to identify if there is no influence of frequency band of interest and remove noise out of this range. After filtering, the average of the maximum resultant force per tool revolution for 40 revolutions is evaluated for each experiment.

For roughness and top burr height measurements, a profilometer Form Talysurf Intra120 with stylus 112/2009 with 2 μm corner radius was used. Three roughness measurements were performed along the feed direction on the bottom surface of each machined groove as showed in Fig. 4. Cut-off filter used was 0.08, according to ISO 4288-1996.

Top burr height measurement was performed by taking the profile of each groove as showed in Fig. 5. Five measurements in different positions along the groove were made. Also, SEM images were used to visually analyze burr formation. Chips were collected in all experiments. For the chips

morphology and grooves surface analysis SEM and USB AM3715TB Dino-Lite Edge handheld digital microscope images were used.

Experimental procedure

Before the actual experiments, the workpieces were pre-machined to avoid axial depth of cut variation. The cutting speed of 37.7 m/min. (4000 rpm), feed rate of 120 m/min. (feed per tooth of 0.015 mm) and axial depth of cut of 30 μm with a 3 mm diameter tool were employed in machining tests.

Feed per tooth range considering the cutting edge radius value ($r_e = 2.0\text{-}2.5 \mu\text{m}$) was chosen in order to clearly detect both ploughing and shearing regions as minimum uncut chip thickness for these materials lies between 1.5 and 3 μm . The cutting speed, axial depth of cut and cutting length were kept constant during machining. The full immersion machining was chosen so that the tool would engage in both up and down milling. The Fx direction of the dynamometer is aligned with feed direction. The cutting parameters are shown in Table 1.

In order to study the tool wear influence on the measured outputs, the tests were conducted in two batches. The tests in batch A were performed with increasing feed per tooth and the tests in batch B were done with decreasing feed per tooth, as shown in Table 2.

RESULTS AND DISCUSSION

In this section, the machinability measures including cutting forces, surface roughness, top burr height and chip morphology are analyzed as a function of feed per tooth in micro-milling of both pure titanium and titanium alloy. It can be seen, as expected, titanium alloy with aluminum and vanadium presented higher strength and hardness than pure titanium.

Cutting forces analysis

Maximum resultant force results for batches A and B for CP-Ti and Ti-6Al-4V are shown in Fig. 6. The error bars in Fig. 6 represent $\pm 1.96\sigma$ and they correspond to a 95% confidence interval. For both materials, there was a significant difference between the batches, indicating that tool wear probably had a significant influence on force results. The influence of feed per tooth on machining forces was found to be as expected. The higher forces are seen with increasing feed per tooth since the chip area increases with feed. Also, variation on cutting force values was higher for feed per tooth from 2.5 to 4 $\mu\text{m}/\text{tooth}$ as seen by the error bars. This was due to vibration on the machine-tool when volume of chip removal was increased.

Further, due to its higher mechanical resistance and hardness, titanium alloy presented higher forces for both batches. However, it can be seen that differences between the batches was higher for the titanium alloy, indicating the tool wear had more influence for this material.

Surface roughness analysis

Figure 7 presents the influence of feed per tooth on surface roughness for pure titanium and titanium alloy, considering both batches of experiments. Three regions with different trends can be identified in the figure. In Region I, between feeds of 0.5 to 1.5 $\mu\text{m}/\text{tooth}$, the roughness decreased when feed per tooth is increased. In Region II, between 1.5 and 3.5 $\mu\text{m}/\text{tooth}$, it can be seen that the roughness initially increased and then decreased or maintained at the same level. In Region III, between 3.5 and 4.0 $\mu\text{m}/\text{tooth}$, the roughness showed a rapid growth for higher feed values.

The Region I in Fig. 7 shows a decrease in roughness when feed/tooth is small, because in this region, the ploughing phenomenon occurs, where the material is plastically deformed rather than removed by shearing. The Region II presents a transition phase from ploughing to shearing and has feed values around the cutting edge radius ($r_e = 2.0\text{-}2.5 \mu\text{m}$). The Region III corresponds to pure shearing and roughness presents behavior similar to the conventional macro milling, where roughness increases for higher feed values.

Also, it can be seen in Fig. 7, a large variation in roughness value for some feed values between batches A and B. This can be related to the fact that roughness is deeply connected to the corner radius of the tool and can vary with tool wear. Regarding the comparison of roughness values between pure titanium and Ti-6Al-4V, it can be seen that there is no significance difference in roughness results between the two materials.

Top burr height analysis

For the top burr height results, the average was computed between the batches for up and down milling as burr measurements are found inherently noisy. The results are presented in Fig. 8. It can be seen that, in general, up milling presented a better result in terms of lower top burr height than down milling, which is also confirmed by SEM images of machined channels (Fig. 9) for both materials. The lower burr formation in up milling can be explained by the fact that in up milling chip thickness starts with small values meaning that a small volume of material is being deformed and removed. When the tool is in the down milling region, a higher volume of material, which has already been deformed, generates the top burr.

Figure 8 indicates that top burr values are higher for small feeds per tooth, which can also be confirmed by observing the SEM images in Fig. 9. Indeed, higher feeds lead to smaller top burr heights. This happens because as feed per tooth decreases and gets closer to the cutting edge radius, shearing of the material starts to be replaced by ploughing mechanism where the material is plastically deformed more than machined through shearing. By comparing the burr height results of CP-Ti with Ti-6Al-4V, it can be seen that the results are similar with the exception of a few specific points and no significant difference could be determined.

Chips morphology analysis

Microchips images for the pure titanium and titanium alloy obtained from the experiments using the feed per tooth of 0.5 and $4.0 \mu\text{m/toot}$, are shown in Fig. 10. Analysing the images, it can be seen that lower feeds generated long and continuous chips. When increasing feed per tooth, microchips became very short going from a length of more than 1 mm for $0.5 \mu\text{m}$ feed per tooth to around $200 \mu\text{m}$ for $4 \mu\text{m/tooth}$. Usually, short chips are preferred in machining, as long chips can roll up the tool and have more chances to be cut again during the process, which can prejudice surface finish. Also, chips are responsible for removing heat from the cutting region. Therefore, the longer a chip takes to break away, the longer it requires to remove heat and cool the tool-material contact region. However, the chip length rapidly decreased after machining with feeds above $1.5 \mu\text{m/tooth}$. The long chips for the small feeds probably happened because the chip thickness is given by the feed per tooth. The thicker the chips, more difficult it is for them to curl while in contact with the rake surface of the microtool. Probably, the chips break when they start to curl during the cutting process.

For titanium alloy, the chip length decreased with increasing feed per tooth varying from a length of around 0.5 mm for $0.5 \mu\text{m}$ feed per tooth to around $200 \mu\text{m}$ for $4 \mu\text{m/tooth}$. Feeds higher than 2.0

$\mu\text{m}/\text{tooth}$ showed smaller chips. For 0.5 and 1.0 $\mu\text{m}/\text{tooth}$ feeds, despite them being longer than for other feeds, the chips are found curly in shape, which is a more desirable shape than the snarled one as they are less likely to cause damage to the tool or the machined surface.

CONCLUSIONS

This work presented a comparison between the micromilling machinability of pure titanium and Ti-6Al-4V at different feeds per tooth (from 0.5 to 4.0 $\mu\text{m}/\text{tooth}$). The machinability measures included the cutting forces, surface roughness, top burr height and chips morphology. The following conclusions can be drawn from this study:

- Titanium alloy presented higher strength and hardness, but similar elastic modulus as pure titanium. The mechanical properties directly influenced the forces during micromilling processes. Cutting forces for titanium alloy were higher than for CP-Ti and results indicated a high influence of tool wear for machining Ti-6Al-4V;
- Surface roughness results show no significant difference between the two materials. The general behavior of the influence of feed per tooth on roughness identified the three cutting regimes: ploughing, transition from ploughing to shearing and shearing;
- Top burr height measurements indicated similar results for both pure titanium and titanium alloy. Also, up milling presented better results in terms of smaller top burr heights than down milling because in up milling a small volume of material is plastically deformed while in down milling a higher volume has the possibility of becoming burrs;
- Chips morphology results showed that for pure titanium, chips changed from a snarled long shape to short chips with increasing feed. For the titanium alloy, with higher feeds, the chips are found to be curly and short.

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Table 1

Parameter	Value
Tool diameter	500 μm
Spindle speed	18000 rpm
Cutting speed	28.3 m/min.
Feed per tooth	0.5 – 4.0 μm
Axial depth of cut	40 μm
Radial depth of cut	500 μm
Cutting length	4 mm
Cutting system	Dry cutting

Table 2

Exp.	Batch	Feed ($\mu\text{m}/\text{tooth}$)	Machined length (mm)
1 to 8	Batch A	0.5; 1.0; 1.5; 2.0; 2.5; 3.0; 3.5; 4.0	4 to each level of feed per tooth (0 to 32 mm)
9 to 16	Batch B	4.0; 3.5; 3.0; 2.5; 2.0; 1.5; 2.0; 0.5	4 to each level of feed per tooth (0 to 32 mm)