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Micromilling of Equal Channel Angular Pressing Titanium

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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. Severe plastic deformation techniques such as equal channel angular pressing (ECAP) can be used to improve its properties by means of grain refinement. This study deals with micromilling of pure titanium powder workpieces consolidated by ECAP. Its machinability is evaluated measuring cutting force, surface roughness, top burr height, and chips morphology and it is made a comparison with commercial pure titanium workpieces. 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 between ECAP workpieces and commercial alloy considering roughness and burr formation whereas higher forces are found for the ECAP titanium. Both materials produce long chips for smaller feeds.

Keywords: micromachining, machinability, ECAP, pure titanium.

1. Introduction

Commercially pure titanium (Cp-Ti) is the ideal titanium-based material to use in the manufacturing of dental implants because of properties such as good corrosion resistance and biocompatibility as well as satisfactory mechanical resistance [1]. However, several notices of implant failures, especially due to fatigue failure, made it necessary to choose a material that reduces the chances of a surgery for implant removal [2].

Some material processing operations are being studied in order to be applied to improve mechanical properties of commercially pure titanium, so it can be better suited for dental implants. One of them is the use of grain refinement by severe plastic deformation (SPD). Severe plastic deformation processes consist in applying a high strain in the material, reducing the grain size, but without changing the part dimensions. As a consequence, mechanical properties, such as resistance, hardness and ductility, will be affected. Equal channel angular pressing (ECAP) is one of the SPD methods used [3]. In ECAP processing the material is pressed through a channel bent by an abrupt angle. Deformation occurs by shearing when the material passes by the angle. Several ECAP passes can be performed, achieving ultra-fine grained microstructure by accumulative strain.

Equal channel angular pressing has been gaining more attention since 2001, with the number of articles published in international journals about it significantly increasing. There are plenty of studies covering the impact of ECAP on the mechanical properties and microstructure of metals [4, 5], but almost none about the changes on the machinability of the material. Considering machinability, only three papers [6,7,8] and a doctoral thesis [9] were found using commercially pure titanium processed by ECAP in mesoscale.

Antoniali et al. [6] evaluated how ECAP processing affected the machinability of Grade 2 Cp-Ti after four ECAP passes by measuring cutting forces

during turning and compared the results with the Ti-6Al-4V alloy. The authors concluded that ECAP pressing decreases machinability as specific force for ECAP titanium achieved values similar to Ti-6Al-4V alloy. Campos et al. [8] conducted a study on the mechanical behavior and machinability of Grade 2 Cp-Ti powder consolidated by ECAP processing with two passes. Samples were too fragile because of hydrides contamination which harmed the machinability tests, performed by measuring cutting forces during milling process. No significant difference between machining both materials were detected.

Taking into consideration that machining is an essential stage of dental implants manufacturing, understanding the parameters for machining ECAP titanium is very important. Therefore, this study aims to analyze the micromilling machinability of pure titanium processed by ECAP and compare it to conventional pure titanium considering cutting forces, surface roughness, burr formation and chips morphology.

2. Materials and methods

The ECAP workpieces were processed using a device developed by Thermomechanical Processing Laboratory – Biomaterials of UFRJ [10]. Both materials were machined by micromilling. Due to the feed per tooth used in these processes are comparable to the tool cutting edge radius, size effect can affect machining results as the tool can plastically deform the material rather than shearing it, if feed per tooth is too small. Also, as ECAP has a big impact in grain size, this can also affect machining results as in terms of tool wear, chips morphology and cutting forces [11].

2.1. Material Processing using ECAP

Commercial grade 2 pure titanium workpiece was prepared from annealed bars. For the ECAP workpiece, grade 2 pure titanium powder was processed by ECAP (Fig. 1a), using the process for metallic powder consolidation along with grain

refinement. Titanium powder was inserted in an ASTM 304 stainless austenitic steel tube. It was carried out with the matrix at 375°C, below the recrystallization temperature of titanium, and it was performed 4 passes using route C, where the sample is turned 180° by the longitudinal axis after each pass. Also, the sample was heated inside the matrix for 10 minutes before the process begin. After the ECAP processing and consolidation of the titanium powder, the material was cut in pure titanium small bars. From these small bars, a few samples for flexure and hardness tests were manufactured. Due to the small dimensions of the samples that were tested and, they were mounted on bakelite pucks so they could be fixed on the dynamometer for the micromilling tests, as shown in Fig. 1b.

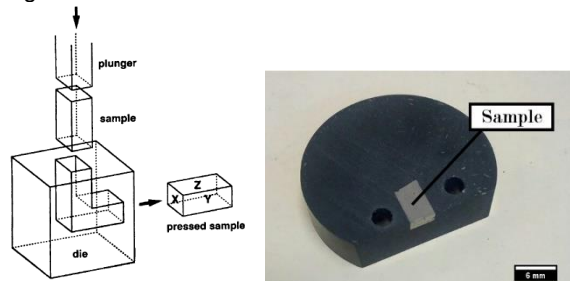


Fig. 1. A) ECAP scheme [12]; b) ECAP workpiece in bakelite pucks.

Microstructures of both materials were analyzed under an optical microscope after a chemical attack with Kroll's reagent and are shown in Fig. 2. It can be seen that pure titanium is composed by equiaxed coarse alpha grains with dimension in the order of 20-30 µm. For the ECAP sample, due to the reduced grain size and the limitation of the optical microscope used, it was not possible to apply a higher magnification so the microstructure could not be fully identified. However, it is of common knowledge that Cp-Ti processed by ECAP presents refined fine alpha grains.

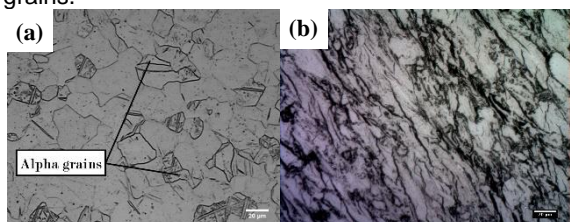


Fig. 2. Microstructure of a) Cp-Ti and b) ECAP Cp-Ti.

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 ECAP titanium were found to be 168 HV30 and 320 HV30, respectively.

2.2. Micromilling experimental apparatus

The micromilling experiments were performed on a CNC Mini-mill/GX using 500 µm carbide square-end-mills with 2 flutes. The microtools were analyzed under a Zeiss scanning electron microscope, model DSM 940. The measurements yielded a cutting edge radius of 2-2.5 µm, 10 µm corner radius and 26° helix angle.

For force measurements, a Kistler dynamometer MiniDyn 9256C2, a 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. Force results were analyzed using the average of the maximum resultant force per tool revolution for 40 revolutions

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

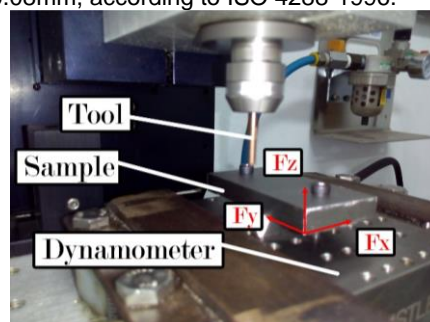


Fig. 3. Force components and experimental set-up.

Top burr height measurement was performed by taking the profile of each groove. 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 morphology analysis. Chips and grooves surface are analyzed in SEM and a digital microscope (USB AM3715TB Dino-Lite Edge).

2.3. Machining parameters

The workpiece surfaces were pre-machined using a 3 mm diameter milling tool to avoid axial depth of cut variation using the following parameters: cutting speed of 37.7 m/min, feed per tooth of 0.015 mm and axial depth of cut of 30 µm.

Micromilling tests used a feed per tooth range that considered the cutting edge radius value ($r_e = 2.0-2.5$ µm) in order to clearly detect both ploughing and shearing regions. Cutting speed, axial, depth of cut and cutting length were kept constant during machining (40 µm, 28.3 m/min and 4 mm). Full immersion machining was chosen so that the tool would engage in both up and down milling. Dry cutting was used.

In order to study the tool wear influence on the measured outputs, the tests were conducted in two batches. Tests in batch A were performed with increasing feed per tooth and the tests in batch B were carried out with decreasing feed per tooth, as shown in Table 1. Each batch was machined with a new tool.

Table 1. Design of experiments.

| Exp. | Batch | Feed (µm/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; 1.0; 0.5 | 4 to each level of feed per tooth (0 to 32 mm) |

3. Results and discussion

3.1. Cutting forces analysis

Maximum resultant force results for batches A and B for both materials are shown in Fig. 4. 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. The points for higher feeds of batch B could not be used due to problems during the experiments.

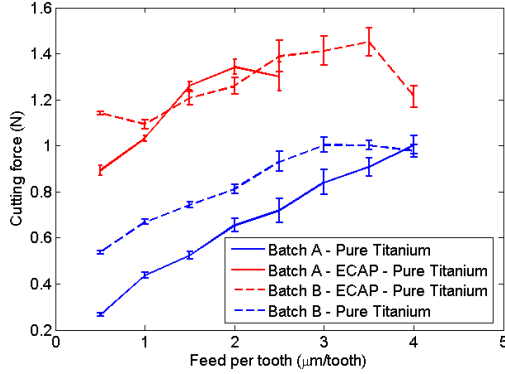


Fig. 4. Experimental cutting force results.

3.2. Surface roughness analysis

Figure 5 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 and 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.

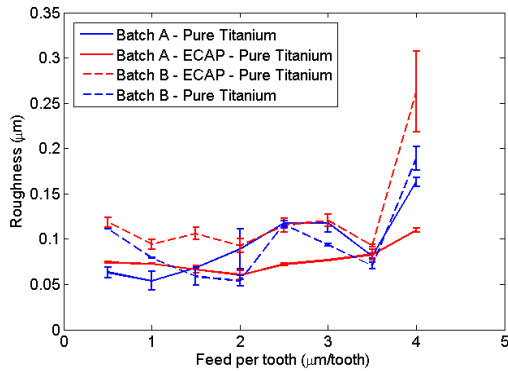


Fig. 5. Surface roughness results.

3.3. Top burr height analysis

As burr measurement is inherently variable, it was chosen to work with the average values of the top-burr values between the batches A and B, presuming that it would give a better idea of burr formation behavior when varying feed per tooth. It can be seen in the graph of Fig. 6 that during the up milling part of the

cutting machining process there was significantly less burr formation than in down milling for the commercial pure titanium material, presenting differences of more than 100% for most feeds.

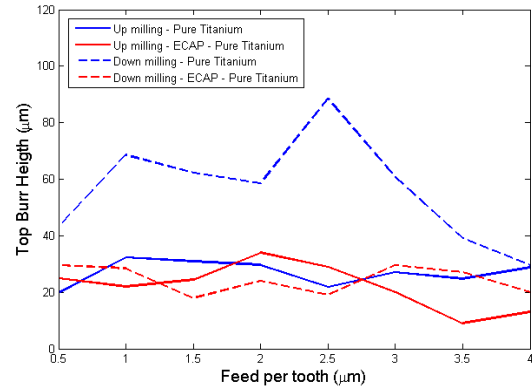


Fig. 6. Top burr height results for up and down milling.

These results are confirmed when analyzing the SEM images of the grooves showed in Fig. 7. It presents the top image for feeds per tooth of 1.0 and 3.5 $\mu\text{m}/\text{tooth}$ for increasing the feed and when decreasing the feed batches. Visually, it is noticed that for both batches, down milling presented more burr formation than up milling.

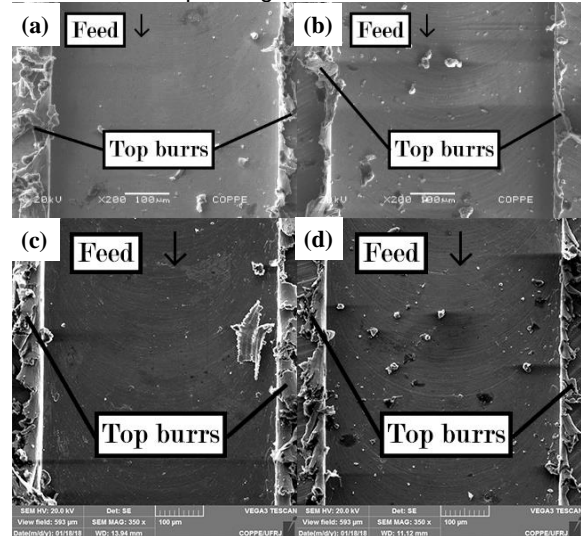


Fig. 7. SEM images: Cp-Ti a) 1.0 $\mu\text{m}/\text{tooth}$; b) 3.5 $\mu\text{m}/\text{tooth}$; ECAP-Ti c) 1.0 $\mu\text{m}/\text{tooth}$; d) 3.5 $\mu\text{m}/\text{tooth}$.

Analyzing top burr height measurements for the ECAP, it can be seen that up milling and down milling presented similar results for all feeds per tooth, except for the two highest feeds, where up milling presented a better result. Thus, for all feeds, burr formation seems to maintained a constant level with the exception of the two highest feeds, where up milling presented a decrease in the top burr height. Figure 7 confirms that burr formation was similar for up and down milling as well as when varying feed per tooth.

3.4. Chips morphology analysis

Microchips images for the commercial and ECAP pure titanium experiments using feeds per tooth of 0.5 and 4.0 $\mu\text{m}/\text{tooth}$, the bottom and up limits of the feed range, can be seen in Fig. 8. Analyzing the images, along with the images presented in the appendix, the first thing noticed is that lower feeds generated long and connected chips. Thus, when increasing feed per tooth, microchips became very short going from a

length of more than 1 mm for 0.5 μm feed per tooth to around 200 μm for 4 μm /tooth. Usually, short chips are preferred when machining a workpiece 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. So, the longer a chip takes to break away, the longer it is taking to remove heat and cool the tool-material contact region.

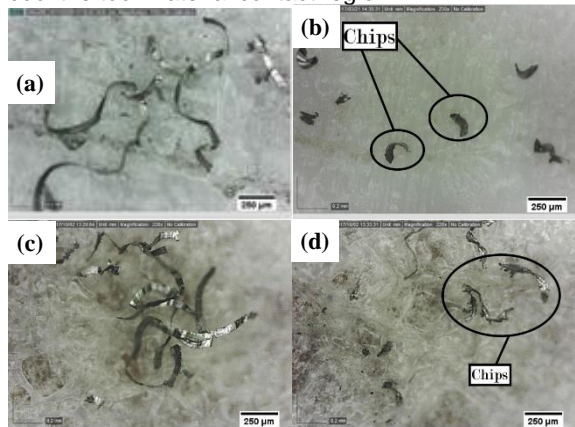


Fig. 8. Digital microscope images of chips: a) Cp-Ti – 0.5 μm /tooth; b) Cp-Ti – 4.0 μm /tooth; c) ECAP-Ti – 0.5 μm /tooth; d) ECAP-Ti – 4.0 μm /tooth.

However, chips length rapidly decreases, presenting small length for feeds above 1.5 μm /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, the more difficult it is for them to curl while in contact with the rake surface of the microtool. The chips break when they start to curl during the cutting process.

Chips morphology results for the ECAP sample for 0.5 and 4.0 μm /tooth and the behavior is similar. As feed per tooth grows, chip turn from the snarled format to loosen chips. The chip length varied from around 1 mm for 0.5 μm feed per tooth to around 400 μm for 4 μm /tooth.

4. Conclusions

This work analyzes the micromilling machinability of ECAP titanium at different feeds per tooth and compared with Cp-Ti. The machinability analysis included the cutting forces, surface roughness, top burr height and chips morphology. The following conclusions can be drawn from this study:

- Improved mechanical properties of ECAP titanium due to grain refinement lead to higher cutting forces than for commercial pure titanium;
- Surface roughness results showed no significant difference between the materials. General behavior of the influence of feed per tooth on roughness identified three cutting regimes: ploughing, transition from ploughing to shearing and shearing;
- Top burr height measurements indicated similar results for both commercial pure titanium and ECAP. 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 ECAP,

as feed per tooth grows, chip turned from the snarled format to loosen chips;

- Despite presenting higher forces, no significant differences in micromilling machinability could be identified between commercial pure titanium and pure titanium processed by ECAP.

Pure titanium processed by ECAP is a good candidate for use in manufacturing dental implants as well as titanium produced by other forms as additive manufacturing. This work is an initial study of the ECAP CP-Ti machinability and showed no significant differences between the mechanically improved and the regular material. It is suggested deeper studies and comparisons between machining materials that can be applied to the production of these parts.

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