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Surface texture on micromilling of a Ti6Al4V alloy for biomedical implants

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Abstract
Biomedical implants production involves some machining process. The low machinability of titanium and titanium alloys require an adequate selection of cutting parameters to ensure the efficiency of cutting operation. Depending on the biomedical implant size and surface quality, a precision machining process as micromilling is necessary to meet values of surface roughness and texture expected. This work goals to evaluate the surface texture on micro-end-milling operations of an ASTM grade 5 titanium. A combination of roughness parameters (linear profile and surface texture) and surface images obtained by 3D laser microscopy was applied to surface formation comprehension. Workpieces were machined with 24 m/min cutting speed, 12 and 18 µm/tooth, 30 µm depth of cut and width of cut of 60% of tool size. Micromills of coated carbide with (Al,Ti)N of 300, 400, 800 and 900 µm diameters were applied for micro-end-milling operations (~2.5 µm cutting edge radius). Results indicated a surface formation transition between feed per tooth values due to minimum cutting thickness and elastic recovery. Profile roughness parameters were better to understanding micromilled surface formation than surface texture parameters due to high anisotropy of machined surface showed by texture aspect ratio (Str ≈ 0.2). A strong correlation between pairs Rq and Rz was noticed in the range of machining conditions evaluated. Feed of 18 µm/tooth presented a 99% correlation between Rz and tool size while feed of 12 µm/tooth presented a 0.07% correlation. Surface texture of ASTM grade 5 titanium is influenced by micromilling conditions, even the cutting parameters no close to edge radius scale. An adequacy of tool size and feed per tooth is relevant to surface formation control to biomedical implants application.

Micromachining; Roughness; Surface; Titanium.

1. Introduction

The titanium alloys are particularly good to be used as biomaterials due to its excellent biocompatibility [1], low density and hight strength-weight ratio [2]. However, titanium implants can present poor cell adhesion and bio-inertness, affecting processes like tissue integration [3].

There are many methods of surface modification that can improve biocompatibility, among them the subtractive, the mechanical processes have the goal to change the surface morphology trough shaping or roughening the surface, improving the bond of tissues [4]. The micromilling process is a highly effective option of mechanical process to produce directional textures on implants surfaces with the desired shape, finishing and dimensional accuracy [5].

Research shows that surfaces that are rougher in a micrometre scale have better results in cell adhesion than smooth surfaces [6]. So, it is suitable for improving the surface biocompatibility as the micromilling process can achieve mean roughness even lower than 0.3 µm [7].

The main challenges in the micromilling of titanium alloys are caused by the titanium's poor thermal conductivity that leads to high cutting temperatures and adhesion between the workpiece material and the cutting tool [8]. However, these challenges can be addressed by parameter optimization to improve titanium machinability, tool life and surface quality [9-11].

It is possible to evaluate surface textures and quality using roughness parameters that can point not only the surface smoothness, but also its aspect, isotropy, and homogeneity, using heigh, amplitude, and spatial roughness parameters [12].

To better understand this subject, the present study uses the roughness parameters analysis to investigate the effect of micromilling parameters, such as the feed and tool diameter, in the generated surface texture.

2. Methodology

2.1. Micromilling

The micromilling process was conducted in a CNC made by ROMI, model D600, with a high-speed spindle coupled to it. The workpieces were small cylinders of 8 mm in diameter and 5 mm high, made of ASTM grade 5 titanium (Ti6Al4V), a commercial titanium alloy. The microtools used in this study was made by Mitsubishi Materials, model MSTAR MS2MS, made of ultra-micro grain carbide and (Al,Ti)N coated, with 300, 400, 800 and 900 µm in diameter. The micromills are top end mills, with two teeth and ~2.5 µm cutting edge radius.

As detailed in figure 1, the workpieces were fixed in a tool holder, and the setting of the zero in Z axis was done by image, using a digital camera aligned to the top surface of the workpiece.

The workpieces were machined with 24 m/min cutting speed, 12 and 18 µm/tooth feed, 30 µm depth of cut and width of cut of 60% of tool diameter. The haster strategy adopted was linear unidirectional, always doing upmilling. Every test was repeated, resulting in 16 samples.

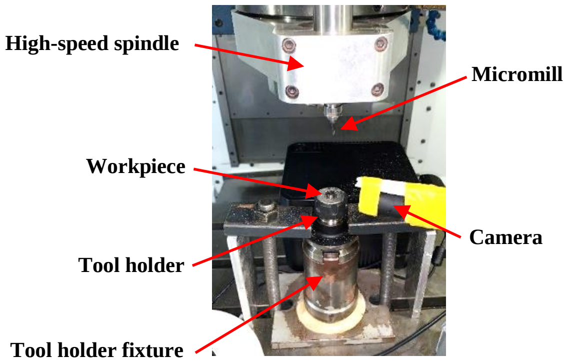

Figure 1. Micromilling process setup.

To simplify the experiments addressing, they will be named using A and B for the feed of 12 and 18 µm/tooth respectively, and the significative digit of the tool diameter (e.g., A4 indicates the 400 µm diameter tool and 12 µm/tooth feed).

2.2. Roughness Measuring

All the samples were submitted to image acquisition in a 3D laser microscope made by Olympus, model OLS4100. The software used to measure linear profile and surface roughness parameters was the Olympus LEXT. Six images were taken from each sample, two at the beginning, two at the middle and two at the ending areas of the milled surface, as shown in figure 2.

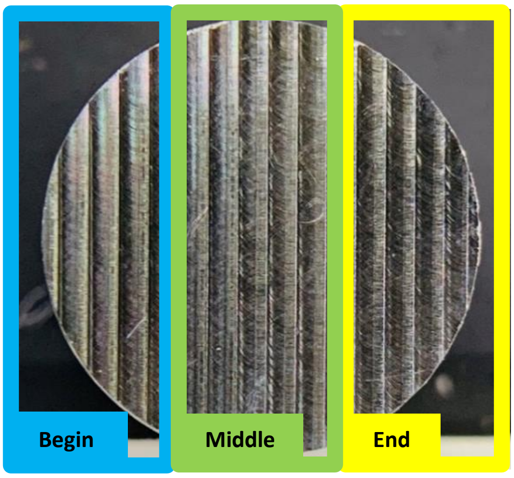

Figure 2. Milled areas considered for 3D laser image acquisition.

For the line profile roughness parameters, five lines were taken for each image, from the center to the peripheral regions of the toolpath.

3. Results and Discussion

3.1. Selecting roughness parameters

Looking at the surface roughness parameters, it would be complex doing any analysis or taking any conclusion due to the elevated level of anisotropy, indicated by the Str parameter. A Str parameter value closer to 0 indicate anisotropic surface [13]. In the experiments the values of Str varied between 0.105 e 0.245. This anisotropy occurs due to the nature of the applied process, as the linear milling path leads to a preferable analysis direction, following the toolpath.

The profile roughness parameters were then selected to do the analysis of the micromilled resulting surface texture. The linear profile roughness was measured along the toolpath.

Table 1 summarizes the values for the quadratic mean roughness Rq, comparing with the surface value Sq to show how much the anisotropy interferes with the analysis. The use of Rq and Sq for reference are preferable according to Fecske *et al.* [14]. Using the surface parameters can be useful for roughness measurements, but if the anisotropy is high, it will be difficult to properly evaluate the texture using only the surface parameters.

Table 1. Mean values of roughness Rq and Sq in micrometers.

Feed/µm/tooth	Tool diameter/µm			
	300	400	800	900
12	Rq - 0.153	Rq - 0.123	Rq - 0.102	Rq - 0.127
	Sq - 0.202	Sq - 0.209	Sq - 0.161	Sq - 0.197
18	Rq - 0.161	Rq - 0.144	Rq - 0.150	Rq - 0.186
	Sq - 0.213	Sq - 0.245	Sq - 0.245	Sq - 0.337

3.2. Roughness parameters correlations

Throughout the data, it is possible to establish significant correlations between some roughness parameters, which can make the analysis easier by having to compare less variables. The figure 3 presents the correlation between Rq, Rz, and Rdq parameters using global values. It is important to highlight that the presented correlations are nearly the same when done by machining test.

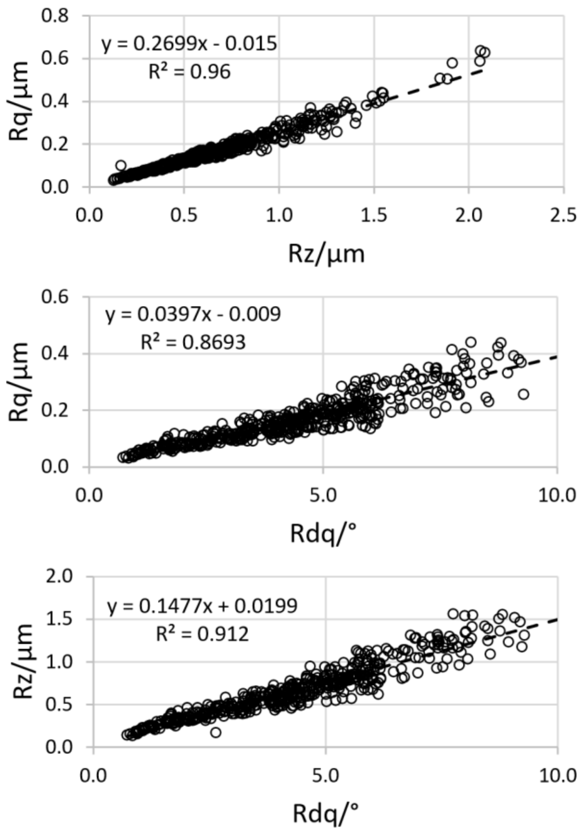

Figure 3. Linear correlations between Rq, Rz, and Rdq roughness parameters.

Comparing the correlations in figure 3, it is seen that the choice to conduct analysis would be the use of Rz due to its great correlation with both Rq and Rdq, while Rq and Rdq have a good correlation between them, but lesser than Rz correlations.

Other correlations can be done as well, also aiming to simplify the surface analysis. The parameters Rsk and Rku are important while evaluating a surface texture, but they are not easily measured. This work's findings are according to Pawlus *et al.* [12] definitions, showing that these assumptions are valid to micro milling process as well. Figure 4 shows the correlations to minimise the number of roughness parameters needed to evaluate the machined surface in the presented research.

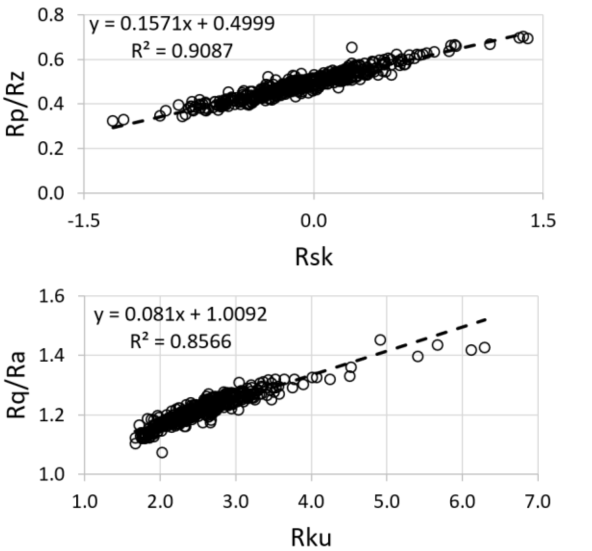

Figure 4. Linear correlations between Rp/Rz and Rq/Ra ratios with the Rsk and Rku roughness parameters, respectively.

Considering these correlations, a surface machined by micromilling process could be well enough evaluated using the roughness parameters: Ra, Rq, Rp, and Rz.

3.3. Surface evaluation

Looking into the Rsk values, it would be possible to stablish that the surface is stratified, a typical surface of multi processes, due to the negative values of the parameter [15]. The experiment B8 is the only exception, having a positive value of Rsk. The figure 5 shows this result, as the Rp/Rz ratio lower than 0.5 indicates negative values of Rsk. Only the micromilling process was done, leading to the assumption that this process is somehow resulting in a stratified surface due to tool pass-through.

However, the central region of the toolpath shows a different view. Inside this region the milling process occurred only once, without toolpath superpositions. The Rsk values there were higher, but the experiments B8, A4, B4, and B3 still shows negative values in the region. The stratification of the surface may be influenced by the path superposition, but it is not the only reason for that.

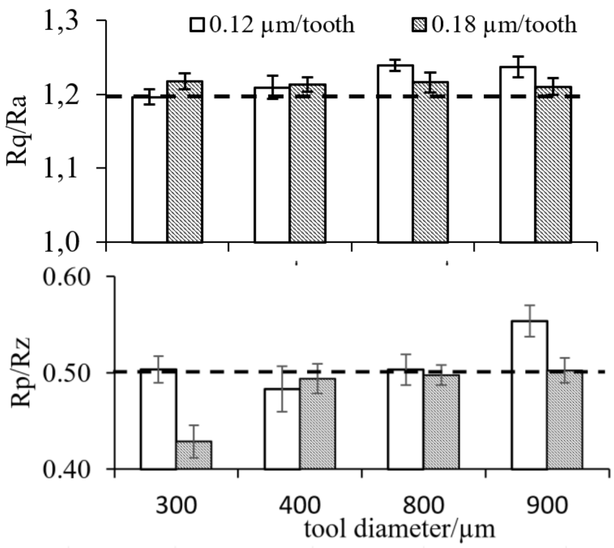

Figure 5. Rp/Rz ratio values for the experiments. Global values at the top chart and toolpath central region values at bottom.

Even with the experiments using parameters that minimizes the effect of the minimum uncut chip thickness, its effect is still present in the peripheral region. As the cutting edge gets closer to the tangential region during its rotation, the material being removed gets smaller and the removal mechanisms becomes dominated by ploughing and rubbing effects [11].

It can be assumed then that the minimum uncut chip thickness is playing an important role in the surface topography, in the sense that the region affected by it will have a different pattern compared with other regions.

The higher feed shows an opposite behaviour for a conventional end-milling process as the larger tool diameter increased the roughness when it should be lowered due to the higher stiffness of larger tools [16]. The lower feed had a slight effect on the roughness in relation with the tool size increase, what would be also unexpected for conventional end-milling processes. However, these results seem to agree with the findings of Bajpai *et al.* [17] and Vipindas *et al.* [18] for the micromilling of titanium, where the feed effect becomes more significant for larger tools.

Increasing from 12 to 18 µm/tooth, there was no effect on the Rp/Rz and Rq/Ra ratios, with the exception being the 300 µm tool, which have its Rp/Rz ratio reduced by 11%. With the exception already pointed, the increase in the feed do not change in the surface texture, apparently. On the other side, the feed influenced the roughness, what is expected, but its effect was higher on the larger tools. While the roughness raised about 60% for the larger tools, it only increased 9% and 17% for the 300 and 400 µm tools, respectively. The figure 6 summarizes the mean parameter Rz found and shown the linear correlation with the increasing size of tools.

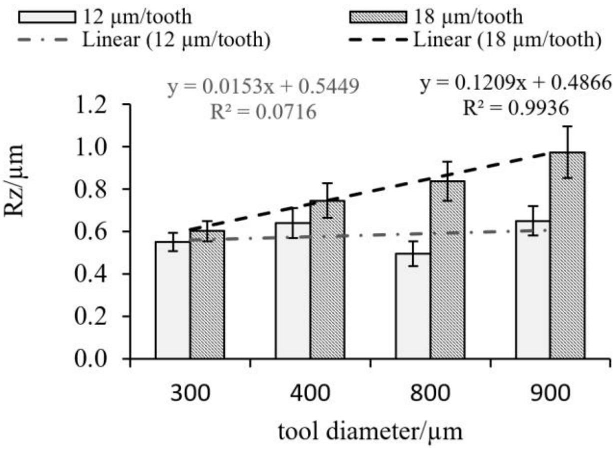

Figure 6. Rz roughness parameter and linear correlations with the tool size.

This effect may be caused due to the titanium properties and its machinability, having more removed material volume by increasing the feed and the tool size may cause an increase of elastic recovery, but this assumption needs more investigation.

Figure 7 shows 3D images mapping the machined surface heights. By comparing the surfaces generated by 300 and 800 µm tools, it is noticed how the surfaces for the smaller tool are similar while the larger tool produces different surfaces.

The analysis of surface image indicated that the minimum uncut chip thickness effect can be seen in cutting tangent region as it shows the deepest height values and seem to be smoother because the feed marks are barely visible in this region, as seen in the profiles shown in figure 8. Furthermore, the elastic recovery effect of the material can be seen from the height difference between the tangential and central regions because it is known that the tangential region is where tool pass-through occurs.

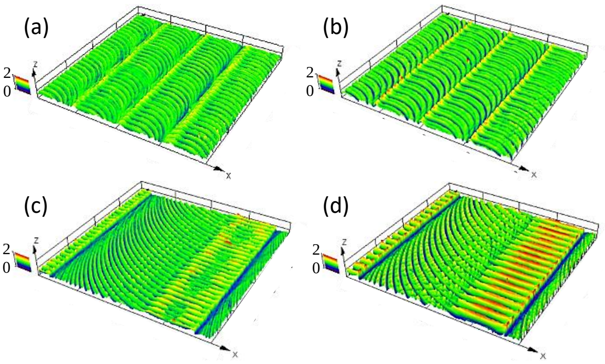

Figure 7. 3D height map for conditions (a) A3, (b) B3, (c) A9, (d) B9.

Other feature that shows the behaviour of titanium is that the larger tool produced a surface that could confuse the observer because of the pattern generated, what could indicate that the tool feed was in the opposite direction of the real one, while the smaller tool produced the expected pattern for a typical milling process. Once more the effect of elastic recovery plays a key role in the surface topography because the patterns became so different that the tool pass-through marks are more visible than the feed marks for the larger tools.

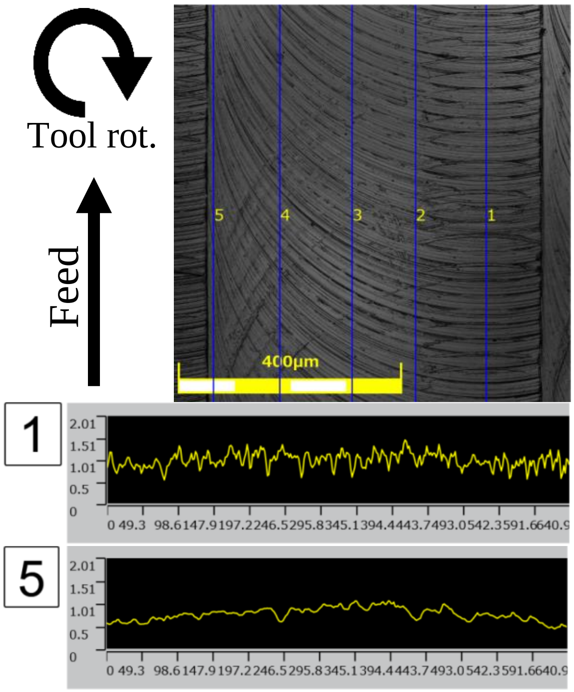

Figure 8. Linear profile roughness collection locations in a workpiece and the roughness profiles front center and tangential regions, indication of feed direction and tool rotation.

Concerning the elastic recovery effect, Jing et al. [19] concluded that it relies on the feed per tooth and the tool run out, while Lazoglu and Mamedov [20] measured the elastic recovery effect in real time during micromilling and indicated that the effect occurs during the tool passing. Both used a tool with 800 µm in diameter for micromilling titanium. Huang et al. [21] reported an elastic recovery ranging from 2.69 to 5.46 µm when milling titanium, while Zhao et al. [22] reported it ranging from 0.9 to 1.1 µm while micro grooving titanium. Considering that Rz values were under 2 µm, any of the values reported to elastic recovery would affect the results.

So, investigations about the elastic recovery during micromilling of titanium still needs to be better understood.

4. Conclusions

Micromilling titanium is a challenging process due to the material properties, and the evaluation of the resulting surface is especially important to improve its applications. With the present study data, it is possible to assume the following:

1. Micromilled titanium surface texture evaluation can be simplified by the measure of four roughness parameters: Ra, Rq, Rz, and Rp. Using the correlations between these parameters would be enough to evaluate the surface texture and quality, mainly when other roughness parameters are not disposal.
2. The process of micromilling titanium can produce a stratified surface, typically found in multi-processed surfaces, due to material properties and the effect of the minimum uncut chip thickness in the peripheral cutting region.
3. The increase in the feed makes the roughness be significatively affected by the tool diameter size for larger tools, while this increase was no apparent effect on the texture itself.

Having a better understanding of titanium properties while being micromilled is essential, so more experiments exploring the elastic recovery occurring in the process are needed, and the strong correlations presented may be used to evaluate the surfaces generated in the study.

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