

## MICROMILLING OF Ti-6Al-4V SAMPLES PRINTED BY SELECTIVE LASER MELTING (SLM)

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**Abstract.** 3D printing process through Selective Laser Melting has gained attention in manufacturing near net shape components, due to less material consumption and its innovation potential in terms of capability of generating complex geometries. On the other hand, printing strategies leaves the SLM parts with a periodic waviness surface, related to the thickness of the fusion powder layer, and anisotropies regarding its printing direction. Although, for industrial application, some parts are required to have reference surfaces, dimensional and geometric tolerances, and/or specific roughness that are obtained by machining processes. However, the effect of waviness and anisotropy on the machinability, specifically on the micromachining process, are barely known. Therewith, the aim of this study is to analyze the effect of waviness and anisotropy over micromilling process outcomes for Ti-6Al-4V samples printed by SLM. On average, the results have shown that the anisotropy of the samples influences their machinability, with the cutting forces, roughness and burr formation higher in one direction. Moreover, experiments with smaller diameters tools and higher rotations provided the best results. Hence, the effect of anisotropy on the machinability of these parts can be highlighted, which can be used to increase efficiency and to reduce manufacturing costs.

**Palavras-chave:** Micromilling. Ti-6Al-4V. SLM. Additive Manufacturing

### 1. INTRODUCTION

3D printing manufacturing techniques oriented to metallic materials have attracted modern industries' attention, since it allows achieving mechanical properties similar to those made by traditional methods and also building complex parts with a design freedom (Duda and Raghavan, 2016). One technique applied to produce near full dense and functional metallic parts is the Selective Laser Melting (SLM) (Chen *et al.*, 2017).

The SLM process is a specific technique used to build 3D parts through the application of an high intensity laser as energy source. Hence, the laser is used to selectively melt and fuse the material in a powder bed, layer by layer, according to the computer aided design (CAD) (Yap *et al.*, 2015). Figure 1 illustrates how this process works.

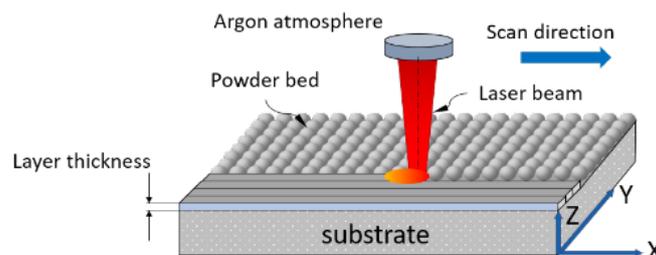


Figura 1: Selective Laser Melting process

Besides the advantages of the SLM process, its outcome parts present a surface with periodic undulations and anisotropies related to the printing direction (Bremen *et al.*, 2012). Although, in industrial applications, some parts are required to have tight geometrical and dimensional tolerances that can not be achieved by SLM process, what requires additional

machining processes.

Micromilling is one of the techniques that can be applied to SLM printed parts in order to achieve dimensional tolerances for precise applications. Although, due to size effects, applying this process to printed materials, which are anisotropic and porous, becomes even more challenging. Since no many researches were developed in this topic for drilling titanium, if compared to materials as steel and aluminum (Jaffery *et al.*, 2016; Kuram and Ozcelik, 2015), this work aims to analyze micromilling process outcomes for Ti6Al4V samples printed by SLM. To do so, cutting forces, surface roughness and burr formation were analyzed for this material, which is widely applied in industry due to its properties.

## 2. MATERIALS AND METHODS

To make the experiments, the samples were printed and then machined. The following subsections presented the materials and methods used in these two phases.

### 2.1 Ti-6Al-4V Samples manufacturing

Samples of Ti6Al4V measuring 12×12×6 mm were printed with a 40 μm grade powder. The scanning strategy used a 5 to 5 mm sequential sweep range and a 67° inter-layer rotation. The parts were printed in Argon atmosphere using an OmniSint-160 SLM 3D printer, and the parameters used are shown in Table 1, as approached by Podestá (2018).

Tabela 1: SLM process parameters

Laser Power [W]	Scanning speed [mm/s]	Layer thickness [μm]	Laser diameter [μm]
155	950	30	70

### 2.2 Micromilling tests

The micromilling experiments were done using miniaturized carbide mills from Rewiid with diameters (D) of 0.8 and 0.5 mm, with two flutes, TiAlN coated WC-Co substrate, with a helix angle of 35° as illustrated in Figure 2.

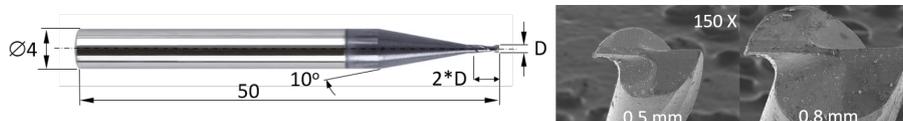


Figure 2: General dimensions and view of the miniaturized mills

Slots under different conditions were micromilled in the printed Ti6Al4V samples using two different directions, 0 and 90 degrees, as shown in Figure 3. Where the 0° milling direction corresponds to a cut parallel to the last printed layer.

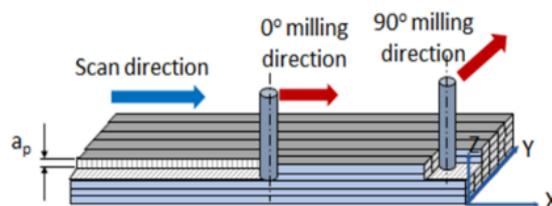


Figure 3: Milling directions

The tests were performed in a 3 axis Schaublin 48V CNC Vertical Machining Center, without cutting fluid. Since this machine allows a maximum rotation of 10000 RPM, the tests were limited to lower cutting speeds and the cutting parameters were chosen based on other literature researches with similar conditions (REHMAN *et al.*, 2018; Vipindas *et al.*, 2018; Zhang *et al.*, 2016). The cutting forces measurement was done using a 9367C Kistler. Figure 4 brings an experimental apparatus view and the cutting parameters for each slot are presented in Table 2. For all experiments, depth of cut ( $a_p$ ) and feed (f) were kept constant at 0.2 mm and 0.001 mm/tooth, respectively. Slots 1-4 were milled in 0 degrees and slots 5-6 in 90 degrees. For each slot a new tool was used and a total of 8 microtools were needed for the experiments.

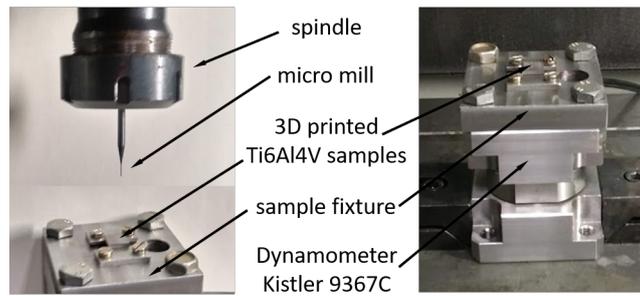


Figura 4: Experimental apparatus view

Tabela 2: Design of experiments for micromilling tests

Experiments	Diameter [mm]	Vc [m/min]	N [RPM]
Exp1 and Exp5	0.5	7.8	5000
Exp2 and Exp6	0.5	11.8	7500
Exp3 and Exp7	0.8	12.6	5000
Exp4 and Exp8	0.8	18.8	7500

### 3. RESULTS

From the tests made, the surface roughness, burr formation, and cutting forces were estimated to observe the relation between these results and the cutting parameters used. The obtained results are presented in the following subsections, together with the statistical analysis of the data.

#### 3.1 Forces analysis

Forces data were acquired in room temperature in a frequency of 1000 Hz and a low pass filter with cutoff frequency of 75 Hz was used for filtering it (Figures 5 and 6). As it can be seen, for the same conditions, the average cutting forces were lower for 90° milling direction. Also, observing the green lines in Figures 5 and 6, in this direction there is greater periodicity and stability of the obtained data, regardless of the cutting speeds used. Since the strategy used for printing the samples adopted a 67° rotation between layers, a reduction on the anisotropy of the material is expected, if compared to a material printed without rotating, because the structure of the final workpiece will become more homogeneous. Although, for the micromilling process, where the cutting process removes from six to seven layers of printed material with the depth of cut used, the size effects influences on the interaction between the tool and the workpiece during cutting. Observing the arrange of the printed layers cut, the fact that the forces are higher in 0° milling direction can be attributed to the fact that, in this direction, the tool follows the same path made by the laser in the manufacture of the last layer of the sample. In other words, there is an active contact of the tool with the filaments of molten material, which presents high hardness and favors a more disordered force behavior. This constant contact of the tool with the melted layer of material does not happen in 90° direction, where the tool periodically passes through the filaments reached by the laser, with a spacing between them, resulting in smaller and more stable cutting forces in that direction.

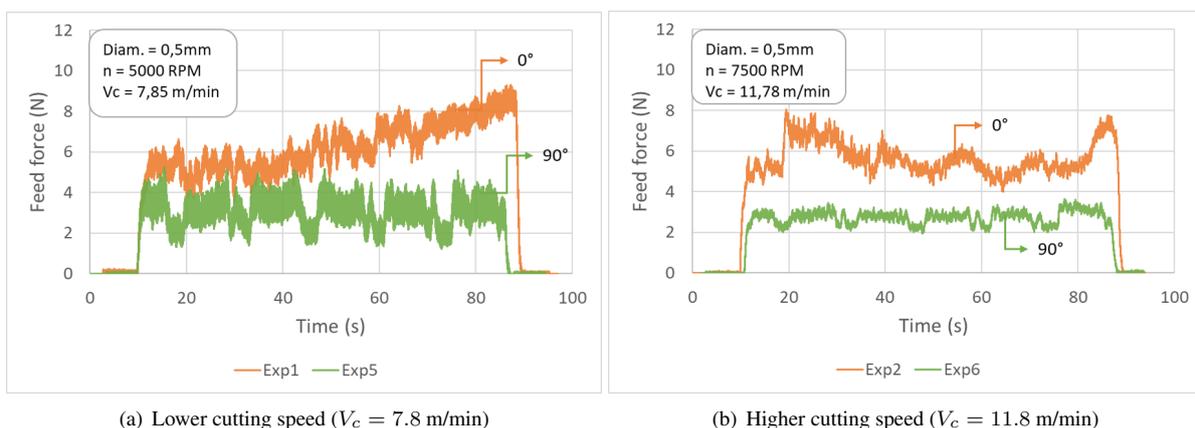


Figura 5: Forces results for slots made with tool diameter of 0.5 mm

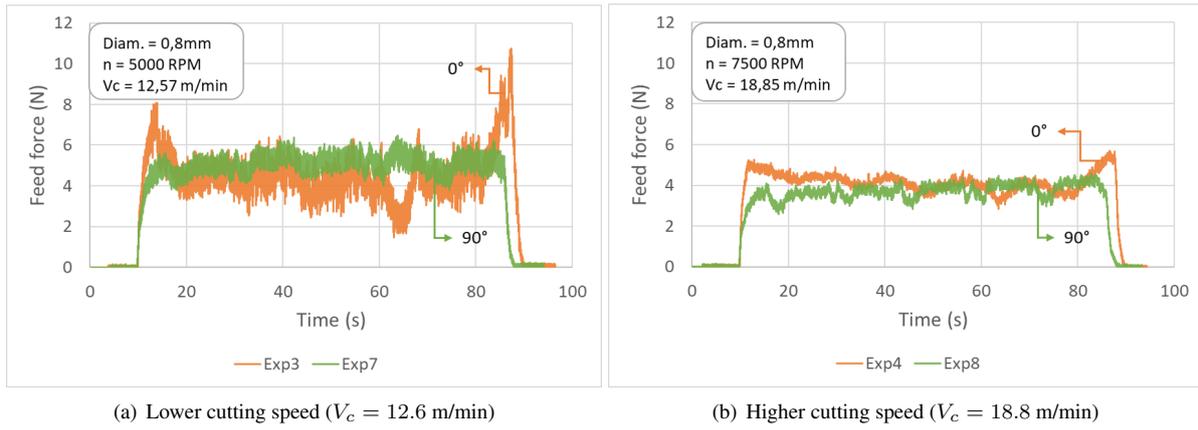


Figure 6: Forces results for slots made with tool diameter of 0.8 mm

Besides the presented results, the reliability of the acquired data was checked through the repetition of some experiments. The results for the same parameters led to a  $\pm 10\%$  variation, due to the re-positioning of the tool and workpiece.

### 3.2 Surface roughness results

After the experiments, the workpieces were analysed in a Taylor Hobson 3D CCI-Profilor for acquiring roughness measurements for each experiment. Figure 7 shows the arithmetic mean height of the assessed area ( $S_a$ ) obtained for each test. Considering the results, it can be noticed that, for  $0^\circ$  milling direction (Exp1-Exp4) surface roughness were also higher than for  $90^\circ$  milling direction. In addition, when comparing the surface roughness in different parts of the slot, a slightly increase along the slot was observed, due to tool wear growth. It can be also noticed from Figure 7 that for the Exp3, where the highest tool diameter were used with the lowest spindle speed, the roughness results presented the highest mean deviation. Also, in this experiment the highest peak of force was achieved (Figure 6).

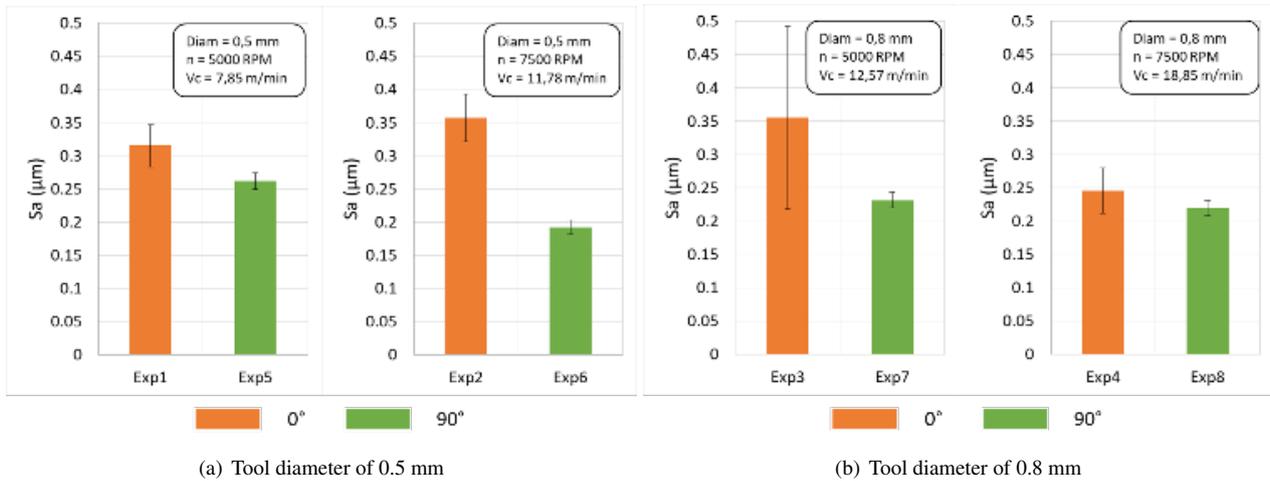


Figure 7: Surface roughness results

### 3.3 Burr formation estimation

The workpieces were also analysed in a SEM microscope to observe burr formation on the slots. After, ImageJ software was used for an quantitative estimation of the burr formation. Although, this estimative does not consider the volume of the burr, the results show a thinner burr thickness for experiments carried out in the  $90^\circ$  milling direction and higher speeds (Exp6 and Exp8). The pictures of the slots with the burr highlighted are shown in Figure 8.

The burr area for each experiment was estimated considering the scale and the pixels amount for the images in Figure 8. From this analysis, the comparisons between the up and down-milling burr formation are shown in Figure 9. As it can be seen, the up-milling direction shows a tendency to form less burr. This behavior was also observed by Campos *et al.* (2019) and Rehman *et al.* (2018), because in this direction the cut starts with a smaller volume of material being deformed and removed, what reduces the burr formation.

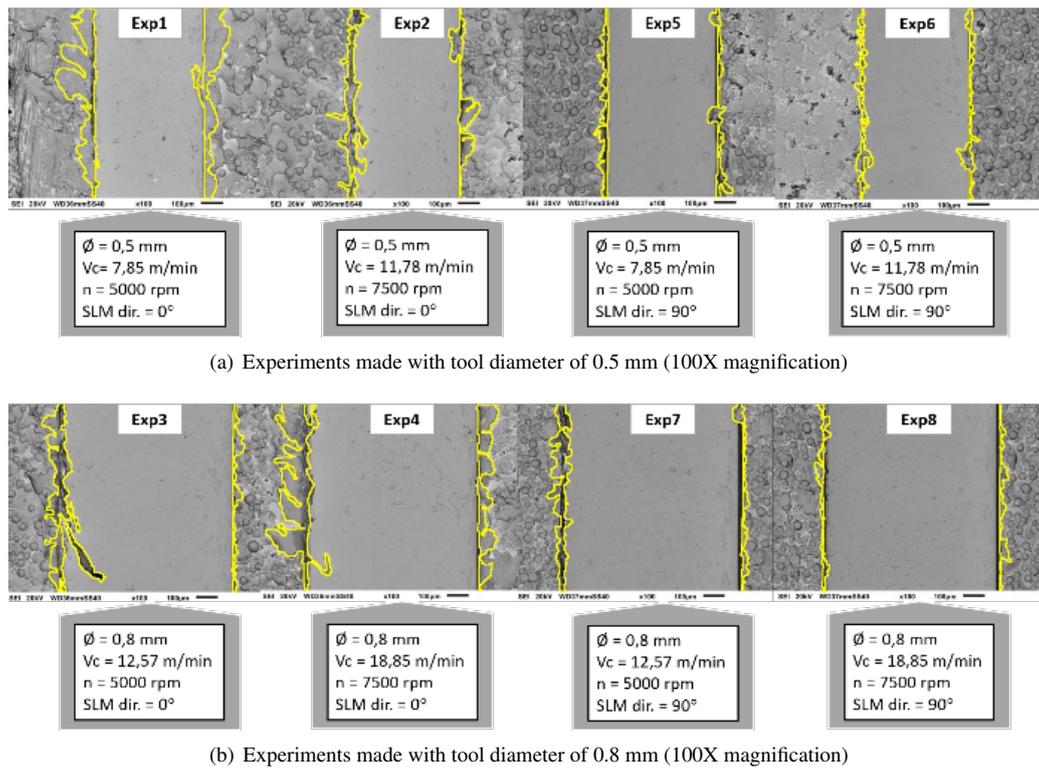


Figura 8: Burr formation results

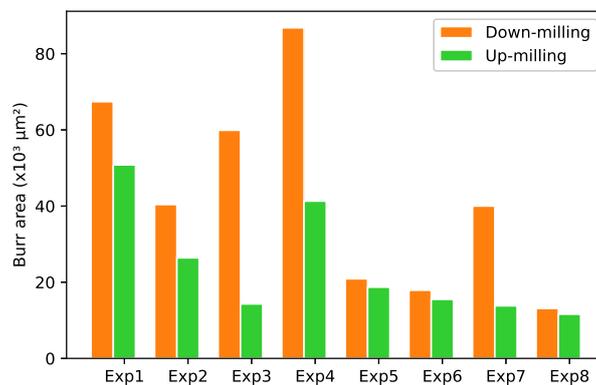


Figura 9: Burr area for up and down-milling in each experiment

### 3.4 Statistical analysis

From the obtained forces, roughness and burr results, a correlation analysis was made to check the influence of the milling parameters on the results. From the Pearson coefficient analysis (Figure 10), that allows to measure the interdependence relationship between two variables (Devore, 2010), it can be observed that printing direction was the parameter with greater influence on the results. These correlations are strongly negative, meaning that for 90° printing direction, the results of burr, roughness and forces were lower. From this, it can be concluded that the anisotropy of the material plays an important role on the micromilling of the SLM printed Ti6Al4V alloy.

Also, analyzing the burr formation, the speed has almost no influence on these results. In fact, according to Lekkala *et al.* (2011), who made an in-depth study on the burr formation in the micromilling processes and proposed an analytical model for its prediction, the cutting and feed velocities have an influence from low to negligible in the formation of burrs. According to the authors, the parameters that most influenced this mechanism were the depth of cut and the diameter of the tool (Lekkala *et al.*, 2011). In the present study, it is observed that the tool diameter was the second parameter that most influenced the results, but with a low correlation. In other hand, for roughness and forces results, the tool diameter presented a negligible influence on the results.

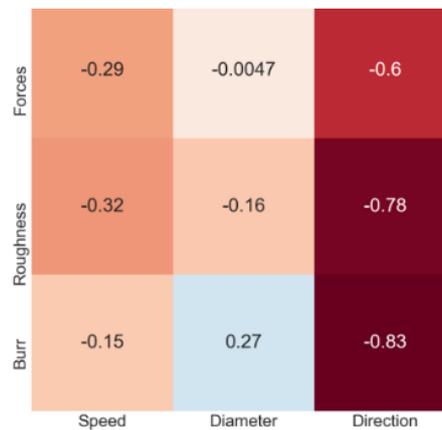


Figura 10: Correlation analysis between results and milling parameters

#### 4. CONCLUSIONS

This article covered an analysis of the micromilling process outcomes for Ti6Al4V samples printed by SLM. From the experiments made, it could be observed the influence of the samples anisotropy on the micromilling process results. On average, the data have shown that for milling the samples in the considered 90° direction, the machinability of the material was better, leading to lower cutting forces, burr formation and surface roughness. Moreover, experiments with smaller diameters tools and higher rotations provided the best results.

Thus, as a strong correlation is attributed to the printing direction of the samples through the Pearson coefficient analysis, the effect of anisotropy on the machinability of these parts can be highlighted. Hence, this study results can be applied to increasing process efficiency and reducing manufacturing costs on the micromilling of titanium alloys.

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#### 6. INFORMATION'S RESPONSIBILITY

The authors are responsible for the information included in this work.