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# HEAT TREATMENT INFLUENCE ON MICROMILLING OF ADDITIVELY MANUFACTURED TITANIUM

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***Abstract.*** *Recently, miniaturized products are being used as working tools by many fields, highlighting the medical and dental industries. With the development of Additive Manufacturing (AM) processes, these features can be produced with less material waste and with wide design possibilities by applying a 'near-net-shape' technique. Although, the AM parts require post-processing techniques to reach the required material properties, dimensions and surface roughness and to reduce undesirable residual stresses. In this aspect, the micromilling process is usually applied to attain the desired dimensions and surface roughness and heat treatments to attain the desired material properties and to reduce residual stress. Nonetheless, the micromilling process can be done before or after the heat treatment. In this perspective, this research analyses the surface roughness results for the micromilled AM parts before and after the heat treatment, which is in important for planning the manufacturing route for these parts. Thus, this work aims to compare the surface roughness results of $S_a$, $S_q$, $S_{sk}$, $S_{ku}$ when performing the micromilling process on AM parts by Laser Powder Bed Fusion (LPBF), with and without heat treatment. For the experiments, the tool size, feed and cutting speed were varied in a full factorial design of experiments. After that, the surface roughness parameters were analyzed and compared for both workpieces. With the achieved results, it can be concluded that the surface texture ($S_{sk}$) for the heat-treated and non-heat-treated samples present a predominance of peaks. Also, there is a presence of inordinately high peaks and/or deep valleys on the surface ($S_{ku}$), which can present an interference of the chips left on the surface not removed by the ultrasonic cleaning. By the analyses of the arithmetic mean deviation ($S_a$) and the root mean square height ($S_q$), a better surface quality was achieved when micromilling the samples before the heat treatment for greater tool size, for the specific set of parameters used. With the smaller tool size, a greater surface roughness was achieved if compared to the bigger tool size, though the difference between the samples were not expressive. Moreover, the results achieved in this work can be applied to improve the surface quality of the AM parts used in industry.*

***Keywords:*** *Machining. Micromilling. Additive manufacturing. Titanium. Heat treatment.*

## 1. INTRODUCTION

Titanium and its alloys are commonly applied for manufacturing microcomponents for medical, odontological, aerospace and aeronautical industries due to their high corrosion resistance, excellent mechanical strength and low density (Baldo, 2013). Apart from the conventional machining, additive manufacturing (AM) is an alternative process that can be applied in order to optimize the production of these microparts. Among its benefits, Uhlmann *et al.* (2015) and Chen *et al.* (2017) highlight its lower resource consumption, complex shapes production, less material waste and the possibility of a rapid manufacturing in a variety of materials.

Even with these benefits, applying AM strategies on metallic materials lead to high surface roughness and residual stresses on the outcomes, what can be improved with micromilling process and heat treatments, respectively. In these perspective, Campos *et al.* (2020) made a comparison on the micromilling machinability of commercial and AM Ti6Al4V workpieces. The authors considered cutting forces, surface roughness, burr formation and chip morphology for the analysis, though the residual stresses on the surface or a heat treatment effect was not analyzed. In the same area, Cardoso and Davim (2010) aimed to optimize the surface roughness on the microsurface of an aluminum alloy by observing the relationship of $R_a$ and feed rate. For the optimization, the authors used an analytical relationship between two roughness average and machining time. Although, in their work, the sample was conventionally manufactured and the surface roughness of an area was not analyzed.

Regarding the microstructure effects of heat treated samples on the micromilling process, Aksin and Karpat (2019) investigated the machining forces and surface roughness while micromachining commercially pure titanium. The authors observed that as the sample's microstructure becomes more equiaxed, its hardness increases, what also increases the machining forces. Although, the surface roughness gets better with increasing forces, as a possible decrease in the material ductility. On the other hand, Ahmadi *et al.* (2018) analyzed the effect of heat treatment on a commercial Ti6Al4V alloy and found that the surface roughness was better for the microstructure with lower hardness and fine equiaxed grains. This comparison confirms Aksin and Karpat (2019)'s statement that there is a complex interplay between process parameters and process outputs during micromilling.

In summary, different material microstructures can directly affect the micromilling process quality, as demonstrated by Attanasio *et al.* (2013). For this reason, this paper aims to contribute with literature, as no previous work was found comparing the effect of heat treatment on surface roughness results when micromilling wrought and LPBF manufactured Ti6Al4V alloy. In this perspective, the present work aims to analyze some of the surface texture field parameters ($S_a$, $S_q$, $S_{ku}$ and $S_{sk}$), since these parameters are being increasingly applied in industries as a sophisticated method to address surface functionality of parts (Berglund *et al.*, 2020).

## 2. MATERIALS AND METHODS

### 2.1 Additive Manufacturing process

For manufacturing the workpieces used in this work, an OmniSint-160 LPBF equipment from the Brazilian company Omnitek was used. For the AM process, an Ytterbium fiber laser with a maximum power of 500 W and a 140 $\mu$m diameter laser beam focus were applied under Argon atmosphere. The process parameters used are summarized in Table 1. The measured density of the Ti6Al4V powder was 4.39 $\pm$ 0.001 $g/cm^3$, which was obtained by Helium pycnometry at the Nuclear Fuel Center – CCN/IPEN using the Micromeritics equipment – AccuPyc 1330 Pycnometer model. To analyze the powder granulometry, a particle analyzer equipment (Cilas Particle Size Analyzer - Model 1064 - from CCTM IPEN) using the Fraunhofer method was applied for measuring the particles average size. The results led to an average particle diameter of 43.47 $\mu$m.

After the AM process, some samples were submitted to an annealing heat treatment at 950°C for 60 min. As studied by Etesami *et al.* (2022), the annealing of an AM Ti6Al4V sample at lower transus temperature (900°C) results in a decomposition of $\alpha'$ to $\alpha$ and $\beta$ phases. In addition, Etesami *et al.* (2022) showed that the the ultimate tensile strength is higher for the samples without heat treatment.

Table 1: Values of parameters used for the experiments in each material

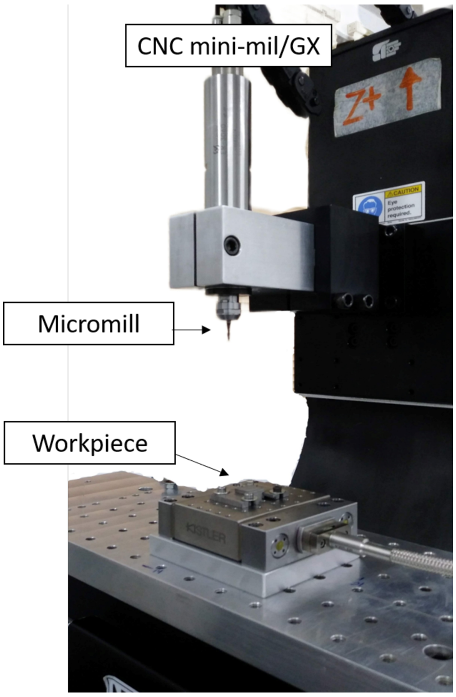
| Laser power [W] | Scanning speed [mm/s] | Layer thickness [$\mu$m] | Laser spot diameter [$\mu$m] | Scan spacing [$\mu$m] |
|---|---|---|---|---|
| 155 | 950 | 30 | 140 | 70 |

### 2.2 Micromilling process

The micromilling tests consisted in manufacturing slots on the workpieces with TiAlN coated tungsten carbide (WC) endmills with different set of parameters. The parameters used are shown in Table 2, and design of experiments applied was a full factorial design. The experiments were performed in a CNC Mini-mill/GX by Minitech Machinery Corporation with a motor model EM-3060 from Nakanishi brand. This machine presents a positioning error of 0.1 $\mu$m, a maximum feed rate of 1000 mm/min and a maximum spindle speed of 60000 rpm. Before the experiments the surface was flattened with a 2 mm diameter mill. After the performing the main experiments, one replica was made. An illustration of the experimental setup is shown in Figure 1a.

After the experiments the surface roughness parameters for each slot experiment were measured three times in a 3D CCI optical interferometer from Taylor Hobson. For the measurements, the parameters of $S_a$ and $S_q$ were considered, which represents the arithmetic mean deviation and the root mean square height of an area, respectively. The skewness $S_{sk}$ and kurtosis $S_{ku}$ parameters were also measured, as they are related to the height distribution and to the peaks and valleys tip geometry, respectively (Rodrigues and Jasinevicius, 2020; Olympus, 2021). According to Seika and Kowalski (2014) and Silva (2004), some conclusions we can make from the surface roughness parameters considered are:

- $S_a$ cannot represent the punctual roughness profile, as it is an average value;
- $S_q$ is more sensitive than $S_a$ to large height variations;
- When the $S_{sk}$ parameter is positive, there is a predominance of peak on the surface. While negative, there is a predominance of valleys;
- The $S_{ku}$ values above 3 represents a large concentration of amplitudes on the surface. While values below 3 indicate the absence of extreme peaks and valleys;




(a) CNC Mini-mill/GX


(b) WC carbide micromill

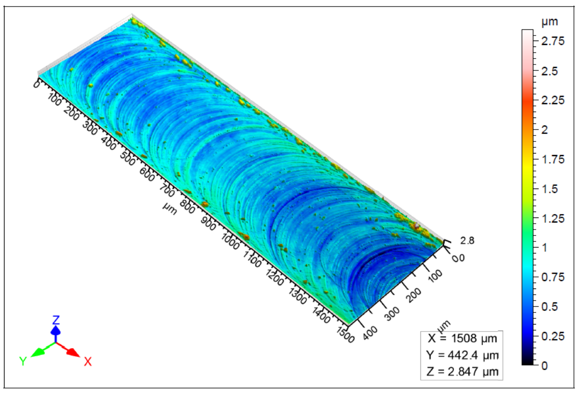
Figure 1: Experimental setup.

Table 2: Cutting parameters of the micromilling process.

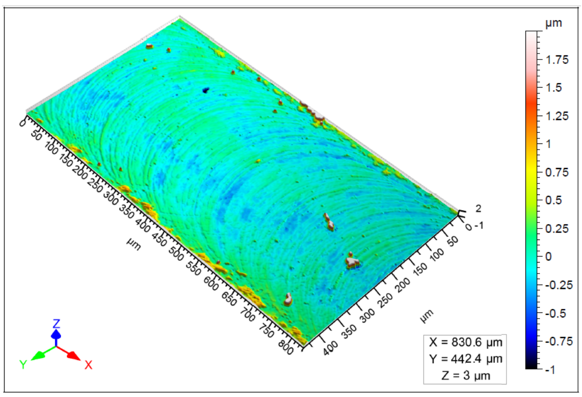
| | |
|---|---|
| **Cutting speed [m/min]** | 60 |
| **Feed [$\mu$m/tooth]** | 1, 1.5, 2 |
| **Tool diameter [mm]** | 0.5, 0.8 |

## 3. EXPERIMENTAL RESULTS

The surface roughness results obtained for the heat treated and non heat treated samples are presented in this section. Figures 2 and 3 show a 3D roughness profile of both samples after the micromilling process using the 0.5 mm and 0.8 mm tool diameter, respectively.



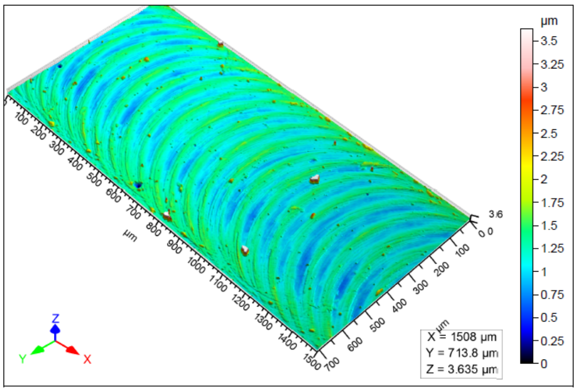

(a) Sample without HT



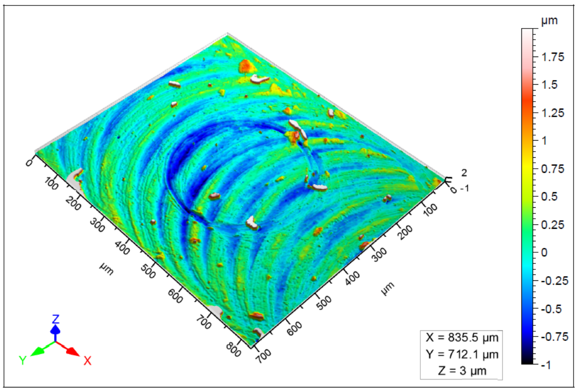

(b) Sample with HT

Figure 2: 3D surface roughness results for both samples under cutting speed of 60 m/min, feed of 1 $\mu$m/tooth and tool diameter of 0.5 mm.

The $S_a$, $S_q$, $S_{ku}$ and $S_{sk}$ results obtained for the experiments are plotted in Figures 5, 6, 7 and 8, respectively. From these pictures, it is possible to observe that due to size effect the results had a different behavior when tool size was changed. The $S_a$ and $S_q$ values, for example, were greater for the sample with heat treatment for the higher tool diameter. This behavior was not expected, since there is a reduction on the samples hardness and ultimate tensile strength after the heat treatment. Although, since the heat treatment reduces the brittleness of the material, it favors built-up edge and continuous chip formation. Indeed, built-up edge and continuous chip formation were observed during these experiments (Figure 4). Another observation of continuous chip formation worsening the surface roughness can be seen in Figure 3b. In this case, the blue ring on the surface was possibly formed due to chip being dragged on the surface. These observations can explain the higher $S_a$ and $S_q$ values obtained for the higher tool diameter.



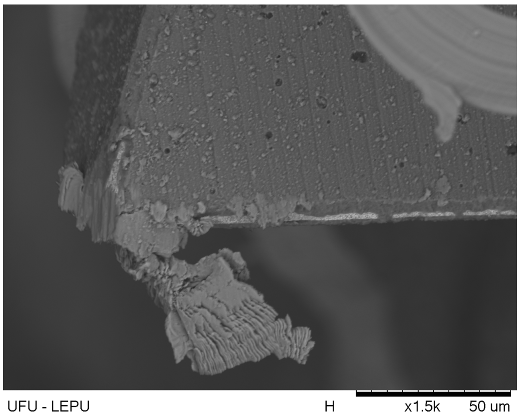

(a) Sample without HT



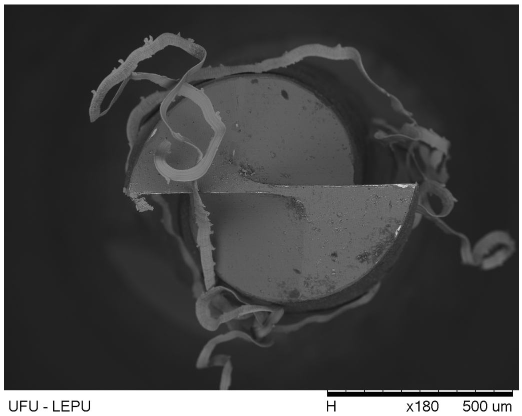

(b) Sample with HT

Figure 3: 3D surface roughness results for both samples under cutting speed of 60 m/min, feed of 1 $\mu$m/tooth and tool diameter of 0.8 mm.

To better determine the effect of the tool size, feed per tooth and heat treatment on the surface roughness results, an analysis of variance (ANOVA) was performed for each result separately. Tables 3, 4, 5 and 6 shows these results. As it can be observed from the ANOVA results, tool size and heat treatment parameters and its interaction had a statistically significant influence on Figures 5, 6, 7 and 8 results. However, feed per tooth influence is inconclusive due to its lower F-value.




(a) Material adhered in the tool tip




(b) Continuos chip tangles in the tool

Figure 4: Images of the 0.8 mm tool diameter.

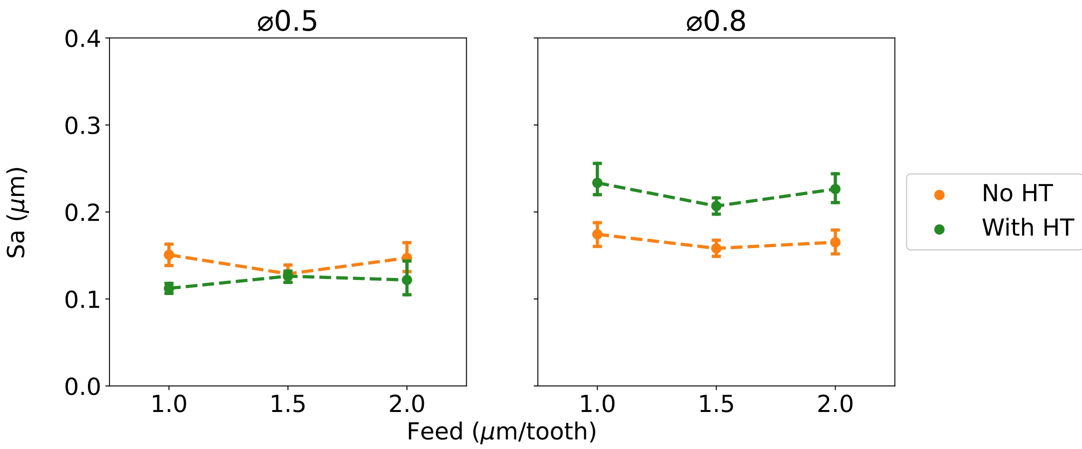



Figure 5: $S_a$ results

Observing the surface's morphology results (Figures 7 and 8), it can be concluded that there is a peak predominance on the surface, as $S_{sk}$ results were greater than zero for all experiments. Additionally, the $S_{ku}$ results greater than three for the experiments show that the surface presents extreme peaks and valleys, what can be related to the chips left on the surface even after ultrasonic cleaning.

Table 3: ANOVA results for analyzing $S_a$.

| **Source** | **DoF** | **Adj SS** | **Adj MS** | **F** | **P** |
|---|---|---|---|---|---|
| Tool | 1 | 0.030953 | 0.030953 | 134.96 | 0.000 |
| Feed | 2 | 0.001593 | 0.000796 | 3.47 | 0.065 |
| Heat treatment | 1 | 0.002260 | 0.002260 | 9.85 | 0.009 |
| Tool*Feed | 2 | 0.002531 | 0.001266 | 5.52 | 0.020 |
| Tool*Heat treatment | 1 | 0.010732 | 0.010732 | 46.79 | 0,000 |
| Feed*Heat treatment | 2 | 0.000620 | 0.000310 | 1.35 | 0.296 |
| Tool*Feed*Heat treatment | 2 | 0.000391 | 0.000196 | 0.85 | 0.450 |
| Error | 12 | 0.002752 | 0.000229 | | |
| Total | 23 | 0.051832 | | | |

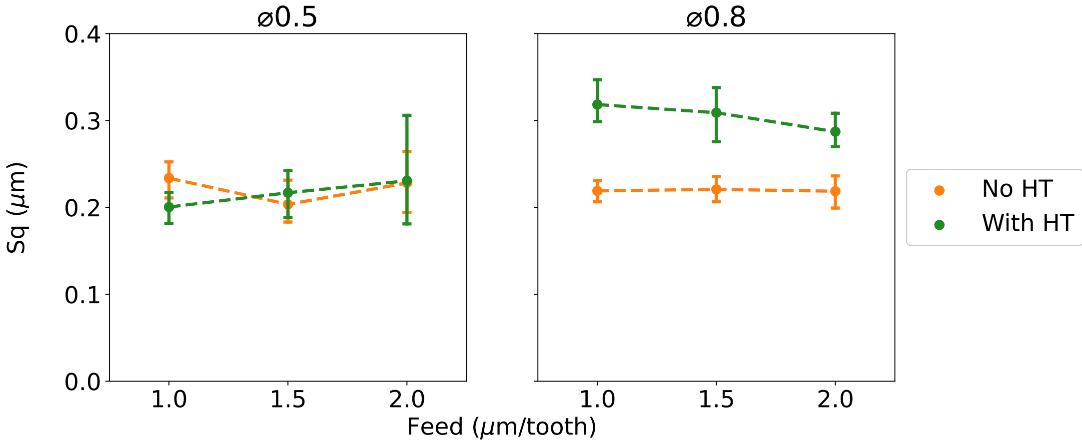



Figure 6: $S_q$ results

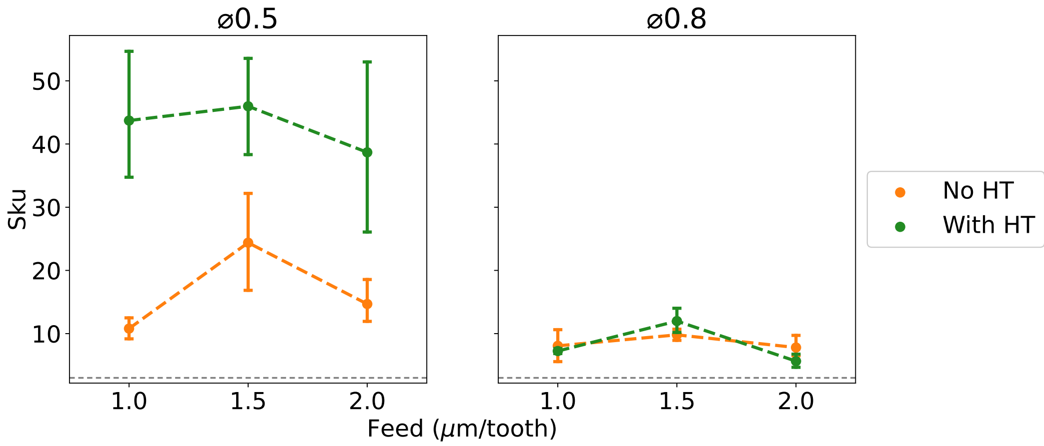



Figure 7: $S_{ku}$ results

Table 4: ANOVA results for analyzing $S_q$.

| **Source** | **DoF** | **Adj SS** | **Adj MS** | **F** | **P** |
|---|---|---|---|---|---|
| Tool | 1 | 0.016627 | 0.016627 | 22.32 | 0.000 |
| Feed | 2 | 0.004006 | 0.002003 | 2.69 | 0.108 |
| Heat treatment | 1 | 0.009976 | 0.009976 | 13.39 | 0.003 |
| Tool*Feed | 2 | 0.003107 | 0.001554 | 2.09 | 0.167 |
| Tool*Heat treatment | 1 | 0.017501 | 0.017501 | 23.50 | 0.000 |
| Feed*Heat treatment | 2 | 0.001213 | 0.000607 | 0.81 | 0.466 |
| Tool*Feed*Heat treatment | 2 | 0.001567 | 0.000783 | 1.05 | 0.379 |
| Error | 12 | 0.008937 | 0.000745 | | |
| Total | 23 | 0.062934 | | | |

Table 5: ANOVA results for analyzing $S_{ku}$.

| **Source** | **DoF** | **Adj SS** | **Adj MS** | **F** | **P** |
|---|---|---|---|---|---|
| Tool | 1 | 3414.0 | 3413.98 | 46.79 | 0.000 |
| Feed | 2 | 146.4 | 73.21 | 1.00 | 0.395 |
| Heat treatment | 1 | 1635.5 | 1635.55 | 22.42 | 0.000 |
| Tool*Feed | 2 | 7.43 | 3.71 | 0.05 | 0.951 |
| Tool*Heat treatment | 1 | 1639.41 | 1639.41 | 22.47 | 0.000 |
| Feed*Heat treatment | 2 | 130.44 | 65.22 | 0.89 | 0.435 |
| Tool*Feed*Heat treatment | 2 | 114.86 | 57.43 | 0.79 | 0.477 |
| Error | 12 | 875.51 | 72.96 | | |
| Total | 23 | 7963.6 | | | |

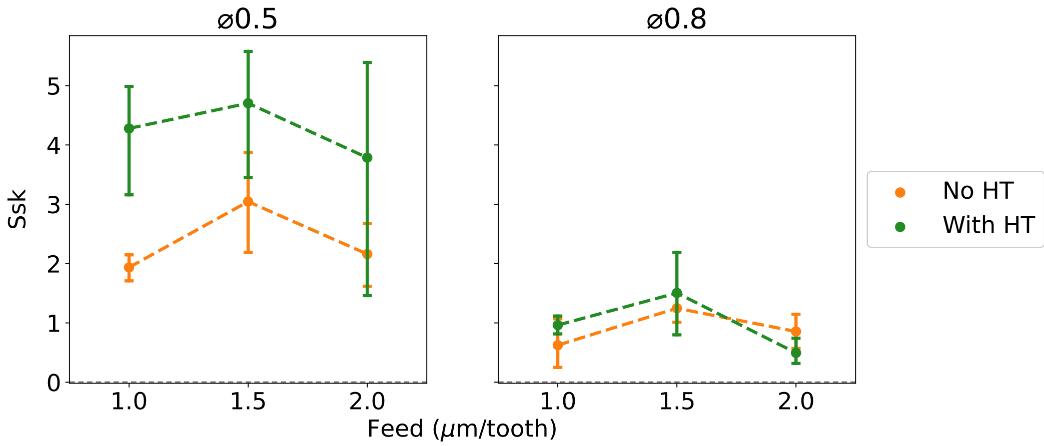



Figure 8: $S_{sk}$ results

Table 6: ANOVA results for analyzing $S_{sk}$.

| **Source** | **DoF** | **Adj SS** | **Adj MS** | **F** | **P** |
|---|---|---|---|---|---|
| Tool | 1 | 44.155 | 44.1545 | 72.90 | 0.000 |
| Feed | 2 | 3.562 | 1.7809 | 2.94 | 0.091 |
| Heat treatment | 1 | 12.884 | 12.884 | 21.27 | 0.001 |
| Tool*Feed | 2 | 0.4020 | 0.2010 | 0.33 | 0.724 |
| Tool*Heat treatment | 1 | 13.4291 | 13.4291 | 22.17 | 0.001 |
| Feed*Heat treatment | 2 | 1.6190 | 0.8095 | 1.34 | 0.299 |
| Tool*Feed*Heat treatment | 2 | 0.5472 | 0.2736 | 0.45 | 0.647 |
| Error | 12 | 7.2680 | 0.6057 | | |
| Total | 23 | 83.866 | | | |

## 4. CONCLUSIONS

This article addressed a comparison of the surface roughness results regarding the heat treatment of an additively manufactured Ti6Al4V alloy. From the results obtained, the following conclusions can be drawn:

- There is an influence of the heat treatment on surface roughness results, though no link could be established between the different tool sizes results due to size effect;
- Tool size and heat treatment condition are important parameters in micromilling and can be used in process optimization;
- For the tool of 0.8 mm diameter the $S_a$ and $S_q$ results were higher for the sample with heat treatment, what was possibly influenced by the ductility recover of the material, what favors built-up edge and continuous chip formation;
- The tool size and heat treatment as well as its interaction presented a statistically significant influence on surface roughness results;
- Feed per tooth interaction with surface roughness results was inconclusive;
- In all experiments made, there is a predominance of peaks on the surface obtained, as $S_{sk}$ values were greater than zero;

- As the $S_{ku}$ values were greater than three for all experiments, it can be concluded that the surface presents extreme peaks and valleys, what can be related to the chips left on the surface even after ultrasonic cleaning.

## 5. ACKNOWLEDGMENTS

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## 7. INFORMATION'S RESPONSIBILITY

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

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# INFLUÊNCIA DO TRATAMENTO TÉRMICO NO MICROFRESAMENTO DE TITÂNIO FABRICADO POR MANUFATURA ADITIVA

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***Resumo.*** *Recentemente, produtos miniaturizados estão sendo usados como ferramentas de trabalho por muitos campos, destacando as indústrias médica e odontológica. Com o desenvolvimento de processos de Manufatura Aditiva (AM), esses recursos podem ser produzidos com menos desperdício de material e com amplas possibilidades de design, aplicando uma técnica de "forma quase líquida". Embora, as peças fabricadas com aditivos exijam técnicas de pós-processamento para atingir as propriedades, dimensões e rugosidade superficial necessárias do material e para reduzir as tensões residuais indesejáveis. Neste aspecto, o processo de microfresamento é geralmente aplicado para atingir as dimensões e rugosidade superficial desejadas e tratamentos térmicos para atingir as propriedades do material e reduzir tensões residuais. No entanto, o processo de microfresamento pode ser feito antes ou depois do tratamento térmico. Nessa perspectiva, esta pesquisa analisa os resultados de rugosidade superficial para as peças fabricadas com manufatura aditiva antes e após o tratamento térmico, o que é importante para o planejamento da rota de fabricação dessas peças. Assim, este trabalho tem como objetivo comparar os resultados de rugosidade superficial de* $S_a$, $S_q$, $S_{sk}$, $S_{ku}$ *ao realizar o processo de microfresamento em peças fabricadas por manufatura aditiva por Laser Powder Bed Fusion (LPBF), com e sem tratamento térmico. Para os experimentos, o diâmetro da ferramenta e o avanço variaram em um design fatorial completo dos experimentos. Em seguida, os parâmetros de rugosidade superficial foram analisados e comparados para ambas as peças. Com os resultados obtidos, pode-se concluir que a textura superficial (*$S_{sk}$*) para as amostras tratadas termicamente e não tratadas termicamente apresenta predomínio de picos. Além disso, há uma presença de picos excessivamente altos e/ou vales profundos na superfície (*$S_{ku}$*), o que pode apresentar uma interferência dos cavacos deixados na superfície não removidos pela limpeza ultrassônica. Pelas análises do desvio médio aritmético (*$S_a$*) e da altura quadrada média da raiz (*$S_q$*), obteve-se uma melhor qualidade superficial ao microfresar as amostras antes do tratamento térmico para a fresa de maior diâmetro, para o conjunto específico de parâmetros utilizados. Já com a fresa menor, obteve-se uma melhor rugosidade se comparado à fresa maior, porém a diferença entre as amostras não foi expressiva. Com isso, os resultados alcançados neste trabalho podem ser aplicados para melhorar a qualidade superficial das peças fabricadas pela manufatura aditiva utilizadas na indústria.*

***Palavras-chave:*** *Usinagem. Microfresamento. Manufatura aditiva. Titânio. Tratamento térmico.*