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EFFECT OF FINISHING PROCESSES ON THE SURFACE QUALITY OF TITANIUM PARTS MANUFACTURED BY THE LASER POWDER BED FUSION PROCESS

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Abstract. *Finishing of titanium part comprising mechanical and / or chemical processes are options to achieve necessary surface roughness in accordance with the functional requirements of the part. Low surface roughness is still one primary challenge of parts manufactured by L-PBF (Laser Powder Bed Fusion), a metal additive manufacturing technology. By applying this manufacturing technology, the production of structurally optimized parts is possible, thus enabling a reduction in part weight, raw material wasting and production time. In the aerospace industry, these characteristics are highly desirable to weight reduction of airframe, as well as increasing the manufacturing processes efficiency. At the same time, the structural integrity of the part must be ensured. This work presents an investigation of mechanical and chemical processes for the surface finishing of a complex part manufactured in Ti6Al4V alloy by L-PBF process for aerospace application. The test results showed an arithmetical mean* R_a *of the generated geometry parts of around 15 µm produced by L-PBF. Additionally a value of 9 µm was achieved after the shot peening process. By applying electrochemical polishing this value was improved to nearly 7 µm. In spite of this promising outcome, a high roughness deviation took place in accordance with the different inclination and shape of the part surfaces. Therefore, additional developments should be conducted to determine specific parameter sets of the finishing processes according to each as-additive manufactured surface conditions in order to achieve more uniform surface roughness throughout the part.*

Keywords: *laser powder bed fusion; titanium; post-processing; surface quality; aerospace.*

1. INTRODUCTION

Laser powder bed fusion (L-PBF) is an additive manufacturing (AM) process in which a powder is melted by the application of a laser beam. The laser fuses the powder at a specific location for each layer subject to the design (ASTM F2792, 2012). The powder is applied in a bed, which is controlled by a piston, that is lowered the defined equidistant layer thickness each time a layer is finished. In this process, it is possible to use a great variety of different materials, such as plastics, metals and ceramics (Wong and Hernandez, 2012).

With the L-PBF process it is possible to manufacture complex and lightweight parts within the manufacturing constrains. At the same time, this process expands the current design limits and opens a completely new dimension of possible designs with almost any prealloyed metal powder. Whereas, in the aerospace industry, the main goal is to build the lightest practical aircraft while securing high safety standards (Wong and Hernandez, 2012).

A potential for nearly 50% weight reductions have been demonstrated for an optimized AM titanium part versus its traditionally machined counterpart. An additional potential advantage of the AM process is the reduction of carbon emissions during part manufacturing compared to traditional processes like casting and machining (Edwards and Ramulu, 2014). As well as the abstinence of complex tools and the possibility for on-demand-production.

The main uses for titanium in aerospace are in compressor blades and wheels, stator blades, rotors, and other parts in aircraft gas turbine engines. The second largest end use is in airframe structures, such as landing gear, ducting, pylon, wing spar, frame, rib, stringer, fitting, and in structures where resistance to heat is important (Henriques, 2009).

In the aerospace industry, titanium is the preferred material. It allows weight savings compared to steel, it reduces the occupied space compared to aluminum parts and it allows high operating temperatures. Furthermore is has a high corrosion resistance and is compatible with composites (Boyer, 1996). However, the use of titanium is strongly limited due to its higher cost relative to other material options. Thus, any method that can produce more cost effective titanium parts is desirable (Edwards and Ramulu, 2014).

Despite the significant potential advantages for adaptation of AM over traditional processes, the primary requirement for any structural application will be to ensure that mechanical performance is acceptable and reliable. With respect to static and fatigue performance, which is the dominant concern for commercial aerospace structures, it has been found that AM Ti6Al4V alloy is comparable to wrought material (Brandl et at., 2010), but are highly susceptible to issues associated with AM, such as porosity, residual stress and surface condition. As well as the difference in part properties due to the build-orientation during production. Post-processing, like Hot Isostatic Pressing (HIP), heat treatment, stress relief, surface finishing and peening also have a strong influence on the mechanical and fatigue performance of AM parts (Leuders *et al*., 2013).

Surface quality is greatly influenced by the stair effect, which is the stepped approximation by layers of curves and inclined surfaces as shown in Figure 1. This effect is present to a greater or lesser degree in L-PBF process as consequence of the additive deposition and fabrication of layers (Strano *et al*., 2013).

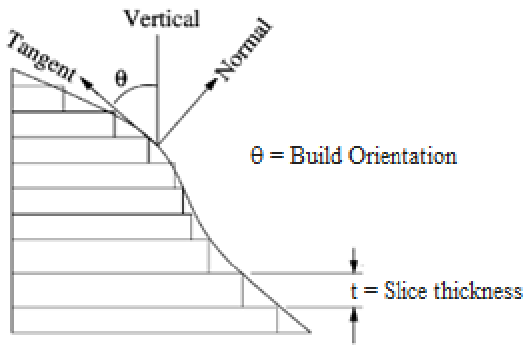


Figure 1. Staircase effect in AM parts (Pandey *et al*., 2003).

Furthermore, a smooth surface is limited by the balling phenomenon (spheroidisation of the melt pool) that occurs during laser melting. Balling is the breakup of the melt pool into small spheres resulting in discontinuous melt tracks. This effect limits the L-PBF process resolution (Mumtaz and Hopkinson, 2010), therefore limiting the formation of very sharp geometries. Hence, if a smooth surface is needed, a post-processing is required, which for complex titanium parts can be a very time consuming procedure.

In addition, depending on the material used, a surface roughness value, R_a, of between 7.6 - 15.2 μm can be expected for parts built by laser-based powder bed AM processes (Wohlers, 2017). However for many applications this is insufficient, and R_a values of as low as 3 μm or less are often required, particularly in the aerospace industry (Dadbakhsh *et al*., 2010). It is therefore necessary to develop a technique to massively increase the surface quality of L-PBF built parts (Gordon and Dhokia, 2015).

There is little research reporting on the experimental study of the surface roughness of complex metal L-PBF parts by finishing process. This study firstly analyzed the surface roughness at different surface inclinations of complex titanium L-PBF parts in order to identify the major contributions to reduce the surface roughness. Following this, a new approach was proposed comprising the optimization of the L-PBF process parameters to improve the surface characteristics as the basis for the post-processing.

This paper describes first investigations for the shot peening process and electrochemical polishing, and shows successful results in terms of surfaces quality improvements. It highlights the relation between the previous surface roughness obtained by the L-PBF process and the results after post-processing.

The authors recognize that in order to fully evaluate the effects of a finishing process on a given part, a number of material properties need to be assessed. The focus of this work was surface roughness as this provides an initial indication of the removal or modification of the material at the surface. According to Pyka *et al.* (2013), it is directly related to a number of functional properties, such as fatigue life.

The proposed study was used to analyze two existing AM finishing techniques, shot peening (SP) and electrochemical polishing (ECP), in a real case scenario of finishing a representative titanium airframe part. By assessing their strengths and limitations, further refinements to these processes can be explored.

Concisely, the purpose of this particular study was to evaluate the effect and appropriateness of these two potential candidates of finishing techniques for complex titanium part built by L-PBF.

2. EXPERIMENTAL PROCEDURE

A representative actuator support around 100 mm in length, width and height was designed as shown in Figure 2. Three parts were manufactured by L-PBF, heat treated and finished.

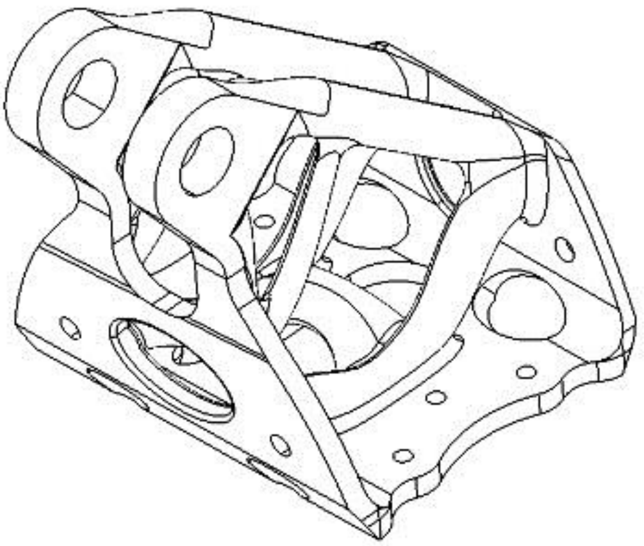


Figure 2 – Isometric views of the representative aerospace part.

Powder of Titanium Grade 5 ASTM Ti-6Al-4V with standard particle size of 20-60 μm was used as raw material. The L-PBF process parameters used to prototype the representative parts are shown in Table 1.

Table 1. Exposure parameters (Uhlmann *et al.*, 2015).

Exposure parameters	Volume hatch	Volume contour	Supports
Focus position x (mm)	2	1	0
Laser power *P* (W)	275	100	175
Scanning speed *v* (mm/s)	975	400	470

Layers thickness 50 μm

After the L-PBF process, the parts were cleaned from the residual powder used during the process and then stress released within the range of 480 to 650 °C, held at the selected temperature within ±14 °C for 1 to 4 hours, and cooled under inert gas in the stress-relieving furnace as per AMS-H-81200D (2014).

Subsequently, the parts were detached from the build-platform and the support structures were removed from each part. Thereafter, the parts were hot isostatically pressed at not less than 100 MPa within the range of 895 to 955 °C, held at the selected temperature within ±15 °C for 2 to 4 hours, and cooled under inert atmosphere in the autoclave to below 425 °C as per ASTM F2924-14 (2014) to achieve mechanical properties typically required for airframe parts.

The following steps describe the core of this particular study, comprising the analysis of the shot peening and electrochemical polishing effectiveness in reducing the surface roughness of a representative aerospace part of Ti6Al4V alloy manufactured by L-PBF. Moreover, the relation between different inclinations of the part surfaces and their surface roughness.

The three representative parts were measured and the surface roughness was determined. Three different measurement points per component were defined as shown in Figure 3. For each measurement feature (ground, bridge and borehole), three identical measurements with a width of 1 mm were taken to obtain statistically reliable results. The measurements were performed according to ISO 4288 (1996) using an optomechanical measuring system. The measurement length was 15 mm with five sections of measurements.

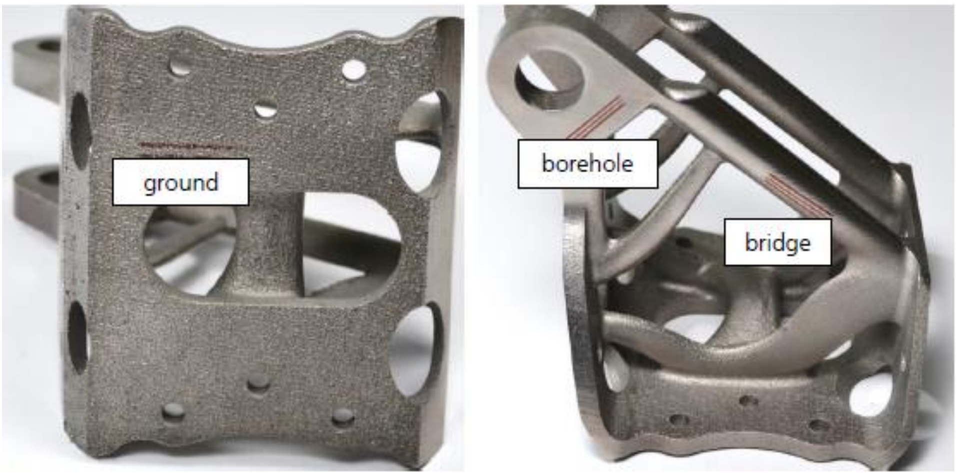


Figure 3. Labelling of the three representative parts for the surface determination.

SP was carried out using a direct pressure blast system at an application angle close to 90 degrees from horizontal. ASR110 peening media with an average diameter of 0.3 mm was used for this study. The Almen intensity for all samples was 0.20 mmA, which represents a common intensity for the present shot size and materials to be applied on aerospace components made of Ti6Al4V as per SAE J443 (2010). A coverage degrees of 100% was used as per SAE J2277 (2013).
An electrolyte of sodium chloride solution of 0.12 kg/L of water was used in the electrochemical polishing operating. In this application, the voltage was 3.0 V. An estimated metal removal rate was approximately 1.64 cm3/min./l000A at an electrolyte temperature of 40 °C. (Donachie, 2000). The ECP process parameters was set to remove 5-10 µm from the as-shot peened surface to exclude the surface deformation caused by the shot peening procedure but without significantly removing the compressed surface.

3. RESULTS AND DISCUSSION

The arithmetic mean deviation, R_a, and average peak-to-valley height, R_z, of three features ground, bridge and borehole of three representative parts (parts A, B and C) as built by L-PBF were measured and presented in Table 2 and Table 3.

Table 2. Average surface roughness, Ra (µm), as built.

Feature	part A	part B	part C	features average
ground	15	25	16	18
bridge	8	8	11	9
borehole	15	12	13	13
parts average	13	15	13	13.6

Table 3. Average surface roughness, Rz (µm), as built.

Feature	part A	part B	part C	features average
ground	94	142	81	105
bridge	55	54	61	57
borehole	95	71	85	84
parts average	82	89	76	82.0

In turn, Figure 4 and Figure 5 respectively show the R_a and R_z of these three features ground of three representative parts after SP. Also presented are the general averages R_a and R_z of features in relation to sample parts.

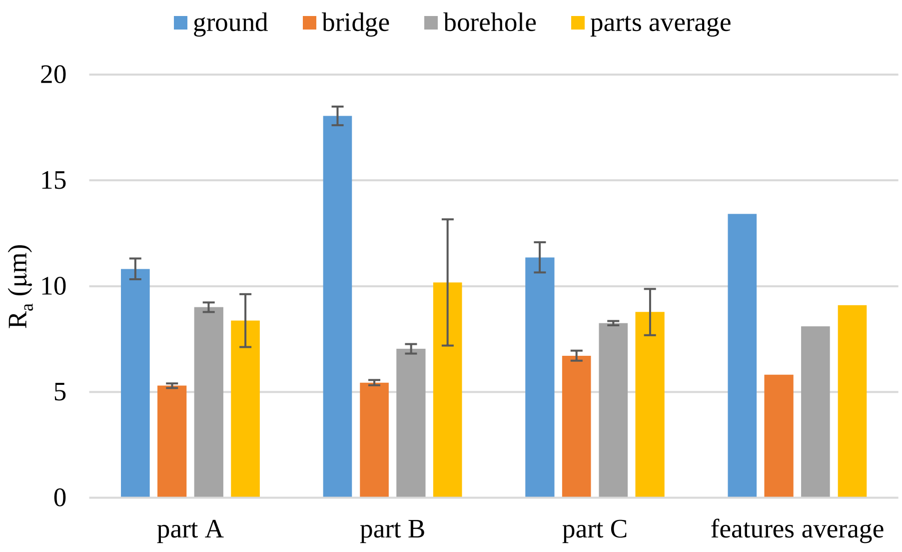


Figure 4. Average surface roughness, R_a (µm), after SP.

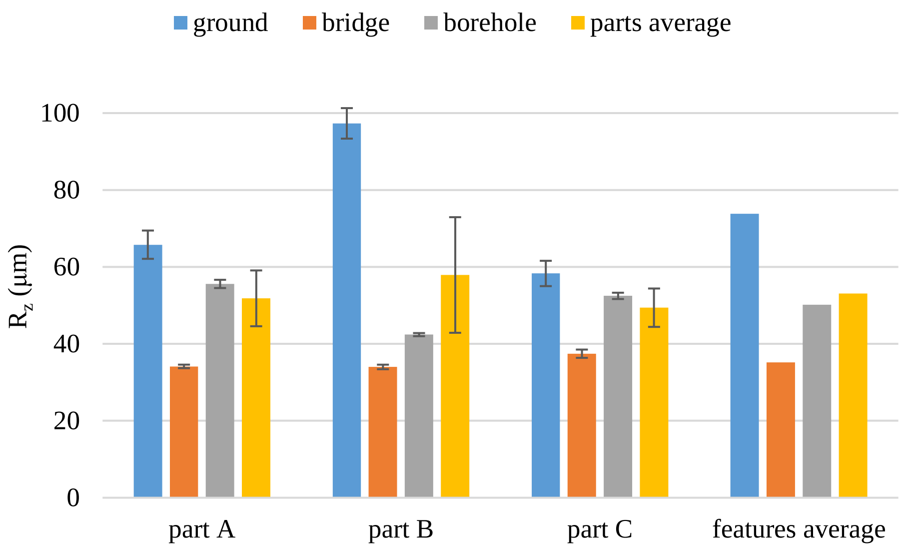


Figure 5. Average peak-to-valley height, R_z (µm), after SP.

The surface roughness of the parts showed significant improvements after SP. The R_a improved from around 13 µm (average as-built R_a of three representative parts) to about 9 µm. Analogously, the average R_z was decreased from 82 µm to 53 µm. However, it can be noted that the roughness and standard deviation were higher in the ground than the other features in all three parts of sampling. This coincides with the area where most support structures were removed. Moreover, the inclination and shape of the features in relation to their build-orientation influenced the surface roughness of these areas. Herein, the bridge feature exhibited lower surface roughness.

Thus, the three representative parts were electrochemically polished and taken again to measure the surface roughness effect. The results are shown in Figure 6 and Figure 7.

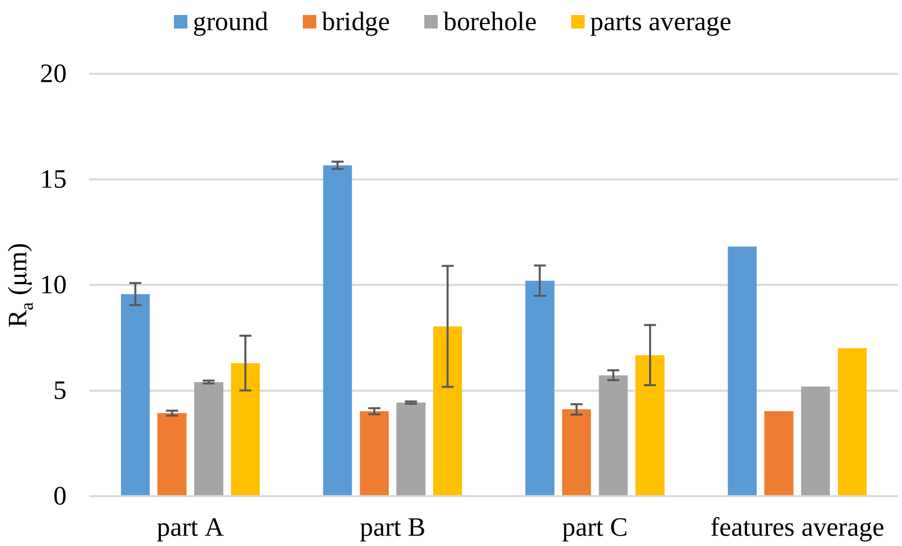


Figure 6. Average surface roughness, R_a (µm), after SP and ECP.

Through ECP, an additional improvement to the surface roughness was achieved. The R_a of the parts decreased from 13 µm (average R_a of the three representative parts after SP) to 9 µm. The same applied for the R_z of the three representative parts. The value of 9 µm R_a, after the SP process, could be improved to nearly 7 µm R_a by ECP. However, ECP was not able to reduce the surface roughness deviation among the features ground, bridge and borehole. As the representative parts were fully immersed in the reagent, the ECP process uniformly etched all the surfaces.

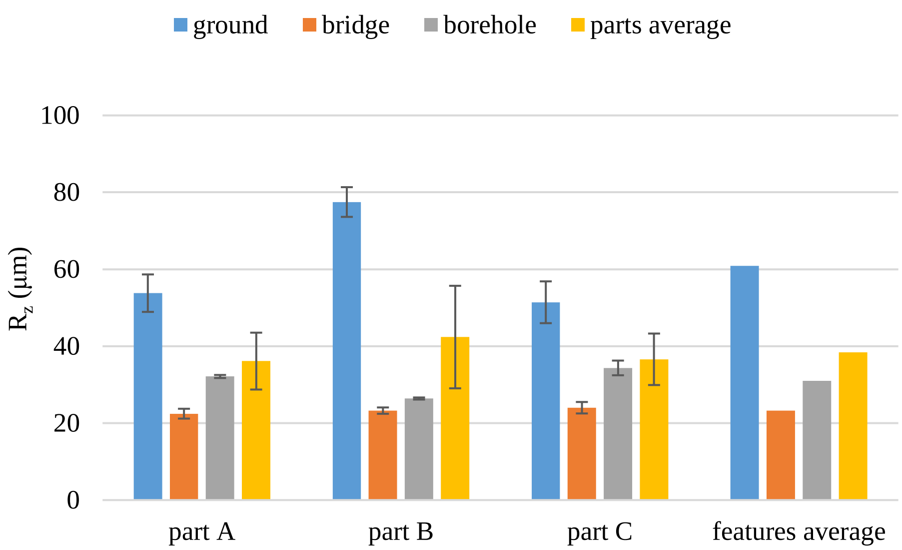
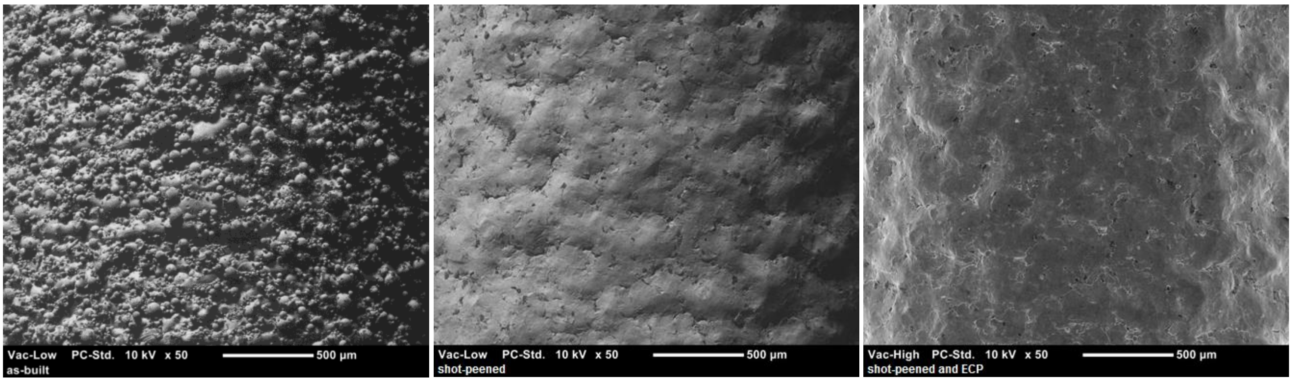


Figure 7. Average peak-to-valley height, R_z (µm), after SP and ECP.

As aforementioned, that surface roughness deviation can be attributed by stair effect (Strano *et al.*, 2013), balling phenomena (Mumtaz and Hopkinson, 2010) and the support structures grid occurred during the parts manufacturing by the L-PBF process. These in-process defects were consequently transferred to subsequent finishing processes. However, further study should be conducted to deeply understand these phenomena.

This investigation of the surface roughness effect caused by the combination of finishing processes, first SP to remove adhered molten powders and crush the peaks of the surface topography and second ECP to slightly smooth the surface, as exemplified in Figure 8.

A summary of the surface roughness evolution caused by finishing processes related to part features are respectively shown in Figure 9 and Figure 10. It is noteworthy that is possible to reduce 46% of the initial surface roughness of a complex L-PBF part.



(a) (b) (c)

Figure 8. SEM micrographs of bridge feature for as L-PBF (a), after SP (b) and after combining SP and ECP (c).

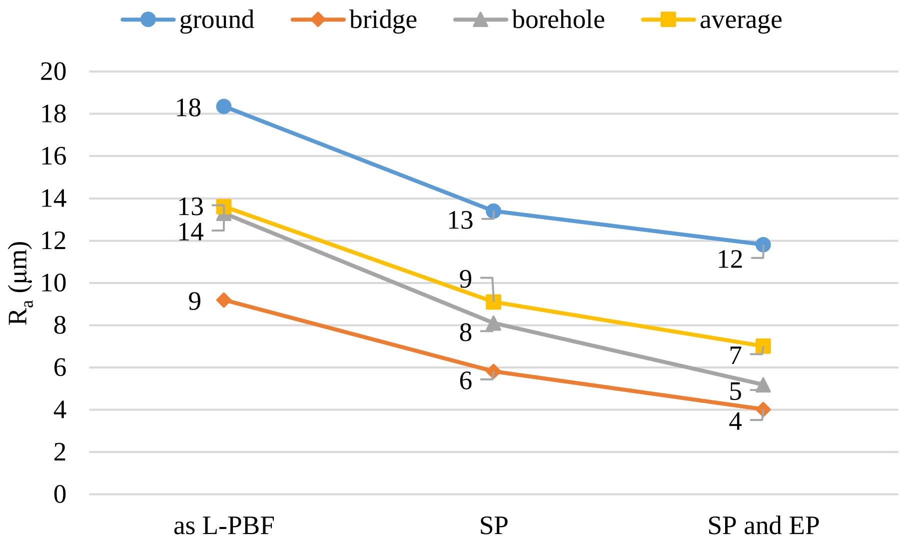


Figure 9. Evolution of the average roughness depth, R_a (µm)

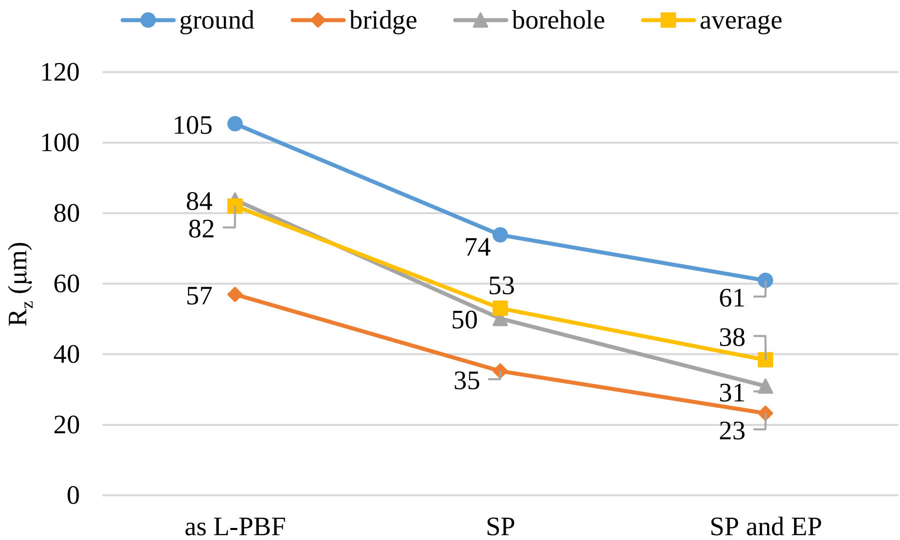
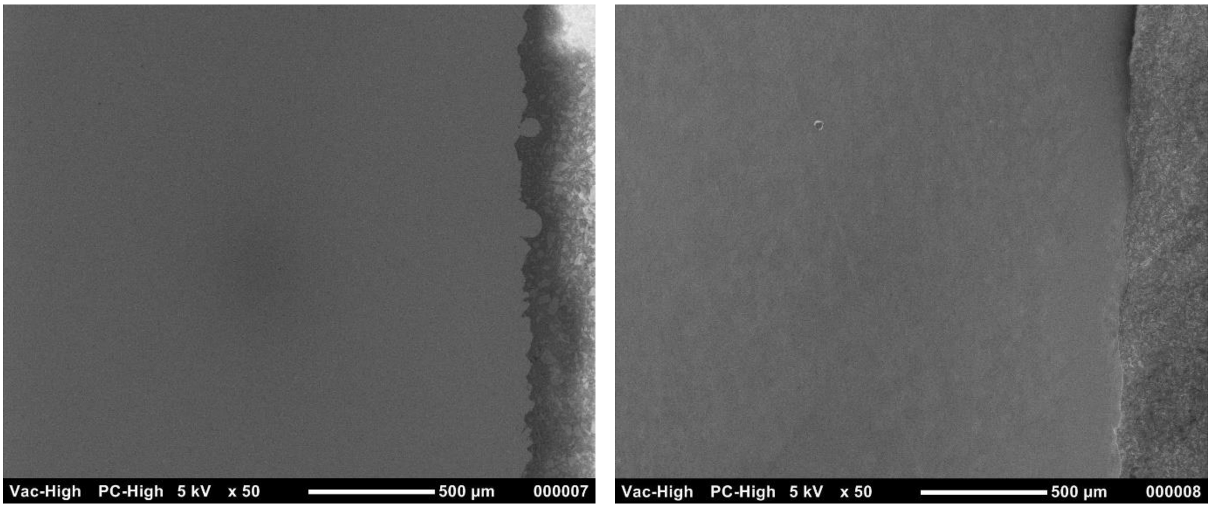


Figure 10. Evolution of the average peak-to-valley height, R_z (µm)

Figure 11 (a) shows the surface roughness caused by laser building process. The surface quality was improved by the combination of SP and ECP as shown in Figure 11 (b); however, there remains a surface waviness.

However, the high surface roughness deviation among part features should be treated. Firstly, one approach is to use different intensity and coverage in the SP procedure according to the initial surface roughness of each part features. Secondly, it is to increase the exposure time and the etching intensity of the parts during the ECP process to obtain a uniform surface roughness throughout the part. In another approach, developments of the L-PBF process parameters, such as the setting of the energy input in the contour region should be conducted in accordance with the surface inclination and shape of the part to achieve a uniform surface roughness throughout the part as the basis for the post-processing.



(a) (b)

Figure 11. SEM cross-section micrographs of bridge feature for as L-PBF (a) and after combining SP and ECP (b).

4. CONCLUSIONS

An investigation of surface roughness caused by the finishing processes of shot peening and electrochemical polishing was conducted for a representative aerospace part of Ti-6Al4V alloy made by the laser powder bed fusion (L-PBF) process. It was found that the support structures grid, slope and shape of the surface relative to build-orientation of the part on surface roughness had a significant impact on the surface roughness achieved by shot peening (SP) and electrochemical polishing (ECP) post-processing. A reduction of surface roughness was achieved after SP and subsequently ECP.

The lowest roughness value was obtained in convex surfaces, free of support structures grid, after combining SP and ECP. Differently to an as-milled reference (SAE J443, 2010), shot peening reduced the surface roughness compared to the reference as-additive manufactured. In turn, electrochemical polishing slightly smoothed the microscopic surface of Ti6Al4V parts. However, according to the process parameters used, both finishing processes were ineffective in lowering the surface roughness of representative aerospace part on a desired level of 3 μm Ra. An additional treatment should be taken into account to finish surfaces previously attached to support structures.

5. ACKNOWLEDGEMENTS

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