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Original Research Article

Post processing of Ti6Al4V manufactured using high power laser powder bed fusion

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Abstract: To further increase the adoption of additive manufacturing in the industry, it is important to leverage the technology's potential for serial production to drive down the cost of manufacturing. The use of high-powered laser beam has been envisaged as the potential technique to improve the productivity of additive manufacturing processes such as laser powder bed fusion. Since a large beam spot size is normally used at high laser power, the rougher surfaces obtained in the as-built condition can be a limitation for medical applications. As such, post processing of the parts manufactured is required to enhance the surface quality. This study investigates the effect of post processing on the surface roughness and mechanical properties of Ti6Al4V manufactured at high laser power. The samples manufactured using developed process parameters were subjected to hot isostatic press annealing and polished by centrifugal barrel finishing. The surface roughness and mechanical properties obtained are presented and discussed.

I. Introduction

Additive manufacturing (AM) is a powerful technology that has many benefits over traditional manufacturing techniques such as reduced material waste, reduced lead time and ability to manufacture highly complex structures thus making it suitable for manufacturing of customized parts. Although additive manufacturing allows for the manufacture of complex parts often required for medical applications, the actual production of parts is limited by low process speeds that lead to high part cost. Machine manufactures and researchers are now focusing on expanding the capabilities of this technology by developing machines with higher productivity and larger build chambers to allow for faster consolidation rates and serial production. This will in turn cap the cost of part manufacturing, thus making the technology more accessible by the industry. The use of high-powered lasers with enlarged beam size has been envisaged as one of the promising techniques that can be used to improve the productivity of LPBF since a large area of powder can be instantly melted thus reducing the time required to scan each layer. However, high power with high scanning speed process has some peculiarities. On the one hand, high process speeds require a high energy input that increase vaporization/ instabilities in the process and provokes defects such as porosity [1, 2]. The larger beam size also has the effect of increasing the surface roughness due to a larger molten pool that is formed. For reliable clinical usage, the surface topography and mechanical properties of medical implants made by AM must be evaluated. Managing the build process and the use of several post-processing steps are necessary to enhance the surface topography, mechanical properties, and biological performance in their use. Some common surface improvement methods include sand blasting, shot peening, electropolishing, chemical etching, grinding, etc.; but these methods are skill operator dependent, labor intensive, and can be difficult to apply uniformly on complex geometries. Conversely, centrifugal barrel finishing (CBF) is much used because it is a versatile surface treatment method with low-cost equipment [3,4]. Titanium and its alloys are excellent materials for medical applications due to their mechanical properties, including those conferred by the surface such as fatigue strength, resistance to corrosion and bioactivity [5,7]. The purpose of this study is to investigate the effect of post processing in the form of heat treatment and surface finishing on the surface topography and mechanical properties of Ti6Al4V samples manufactured at high laser power.

II. Material and methods

Gas atomized Ti6Al4V (Grade 5) powder characterized with spherical morphology was used in this study. The powder was supplied by TLS-GmbH, and the 10th, 50th, and 90th percentiles of the equivalent diameters were 24 µm, 41 µm, and 57 µm, respectively. Vertical round dog-bone tensile specimens with a gauge length and gauge diameter of 35 mm and 6.5 mm, respectively, were built using an in-house developed LPBF system equipped with a multi-mode 5 kW IPG TLS 5000 fiber Laser. The samples were manufactured using developed parameters at a laser power of 2 kW, layer thickness of 50 µm, volumetric energy density of 133.3 J/mm^3, and consolidation rate of 15 mm^3/s. The laser beam spot size, scanning speed, and hatch distance used are not disclosed as this is considered propriety information. Upon manufacturing, the samples were heat treated and polished by CBF to investigate the surface roughness and mechanical properties. Table 1 shows the post processing conditions applied.

Table 1: Post processing experimental conditions

Sample designation	Heat treatment condition	Surface condition
Set 1	Standard annealing at 950ºC for 2 hrs., furnace cooling	As built condition
Set 2	Hot isostatic pressing (HIP) at 950ºC, 100 MPa for 2 hrs., furnace cooling	Polished

The heat treatments were carried out under Argon atmosphere using Carbolite tube furnace for Set 1 samples and EPSI HIP vessel for Set 2 samples. Regarding CBF polishing, the samples were firstly polished with 10 mm x 10 mm angle-cut ceramic media at a rotational speed of 85 rpm for 5 hours, followed by fine polishing using 4 mm zirconia balls for 3 hours. An industrial CBF machine, CB320-CBF from Inovatec Machinery, was used to perform the polishing operation. The barrel was loaded to approximately 50% capacity with the specimens, abrasive media, water, and a small amount of LC-13 polishing lubricant. The surface roughness was characterized using a portable stylus roughness tester MarSurf-PS1 and optical microscopy. The tensile properties and tension-tension fatigue performance were measured using Instron 1342 mechanical testing machine. The fatigue tests were conducted at room temperature using fatigue stress ratio of 0.1 at a frequency of 15 Hz. Analysis of the fractured specimens was carried out using scanning electron microscope and x-ray computed tomography.

III. Results and discussion

Surface roughness

The surface quality of LPBF parts is an important parameter in the medical and aerospace industries since it directly influences the surface properties of the parts, such as fatigue strength. The surface roughness of the samples was measured before and after polishing, and the measurement results are presented graphically in Fig. 1, along with images of the sample before and after polishing. The corresponding micrographs and cross-sectional images of the surface morphology are shown in Fig. 2, where valleys, peaks, and partially melted particles can be clearly observed on the surface before polishing. These imperfections caused a higher surface roughness in the as-built condition, with a roughness average of 22.3 µm (±1.5). After CBF, the surface roughness average was significantly reduced to 0.7 µm (±0.2). This is because during CBF, the impacting media to the surface of the sample result in the removal of the partially melted particles and roughness peaks due to abrasion of materials making repeated contact with the media. Although CBF resulted in lower surface roughness, the process struggled with the valleys associated with laser contouring defects, thus resulting in residual cavities like the ones shown in Fig. 2b.

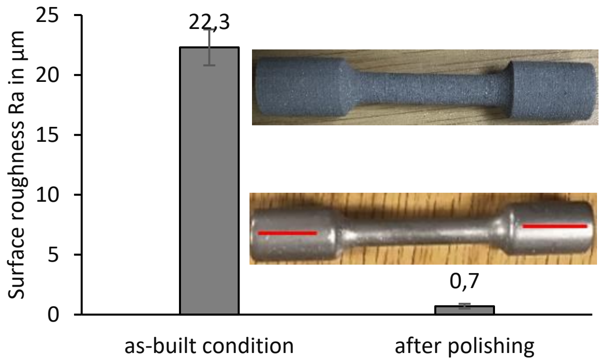

Figure 1: Average surface roughness before and after polishing.

Tensile properties

Fig. 3 shows the tensile properties of the specimens following post heat treatment and surface polishing as highlighted in Table 1. For set 1 specimen, the minimum yield strength (YS) was achieved according to ASTM F2924-14 (a minimum of 825 MPa for YS, 895 MPa for UTS, 6 % for elongation), however, the ultimate tensile strength (UTS) was slightly below the minimum. Set 1 specimens also had lower elongation compared to set 2 specimens which underwent HIP and CBF. The elongation at break is generally more sensitive to porosity as compared to the strength. Fig. 4 shows fracture surfaces of set 1 and set 2 specimens, and it can clearly be observed that set 1 specimen had lack of fusion defects which were not present in the specimen that underwent HIP.

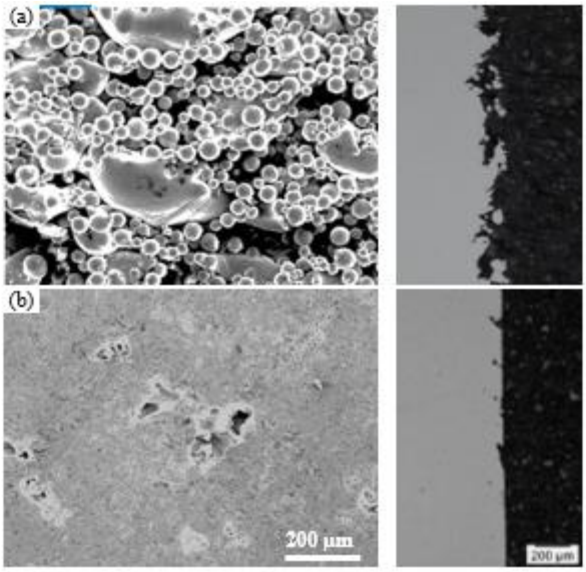

Figure 2: SEM and Cross-sectional images of the samples; (a) before and (b) after polishing, showing the surface morphology.

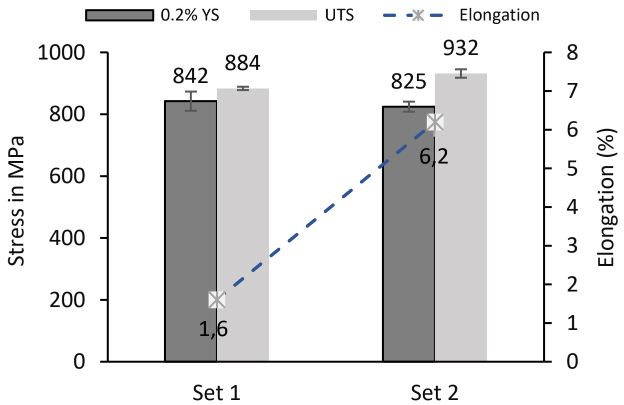

Figure 3: The tensile properties obtained for Set 1 and Set 2 specimens.

Lack of fusion defects are very harmful to the tensile properties of the part when the loads are applied transverse to the layer orientation since these defects induce the delamination among the synthesized layers. The actual load-bearing cross sectional area is also reduced, and the pores can be stretched apart perpendicularly to its major axis in tension and lead to crack initiation. The cracks then quickly coalescence and fracture prematurely with minimal necking/elongation [6]. HIP in the current study proved to be effective in enhancing the tensile properties.

Fatigue properties

Fig. 5 shows a plot of the maximum fatigue stress applied and the number of cycles endured by the specimens. Even though the data was limited for fatigue design, the results show a noticeable tendency of improved fatigue life for the specimens that underwent HIP and CBF.

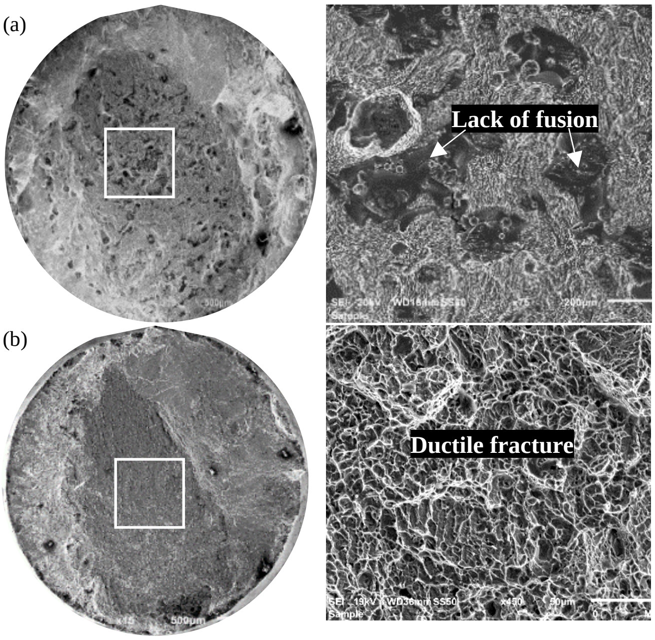

Figure 4: Fracture surfaces of: (a)Set 1 and (b) Set 2 specimens, showing lack of fusion defects and the fracture surface.

It is known that the fatigue life of materials is more sensitive to the surface condition [7,8]. The fatigue properties of AM materials with rough as-built surface can be dominated by the surface roughness rather than internal defects. Even though HIP and polishing in the current study slightly improved the fatigue life, unfortunately the fatigue strengths were still low due to the presence of pores embedded closer to the surface.

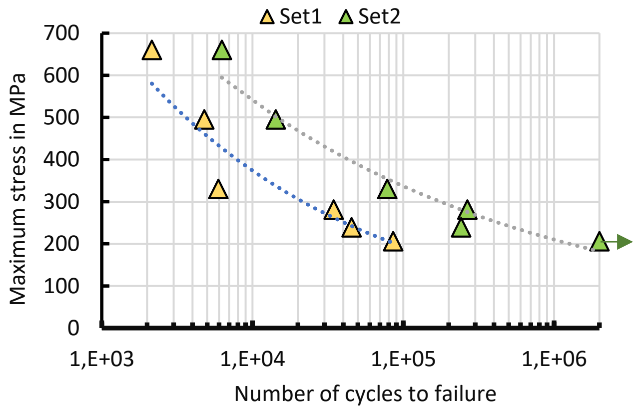

Figure 5: Axial fatigue response of Set 1 and Set 2 specimens.

Micro-CT images of the broken specimen are shown in Fig. 6, where an array of pores can be observed closer to the surface. The origin of these pores in the contour is unclear, however, could possibly be due to the lack of sufficient overlap between the starting and ending point of circular contour. HIP in the current study was ineffective in closing the pores near the surface, and as such the overall fatigue strength was still low even after polishing. In fact, it was shown that pores connected to the surface are difficult to remove by HIP since they allow infiltration of the pressurized argon gas into the channel cavity and prevent it from closing. Such pores can be effectively removed by optimizing the contour scanning strategy and parameters.

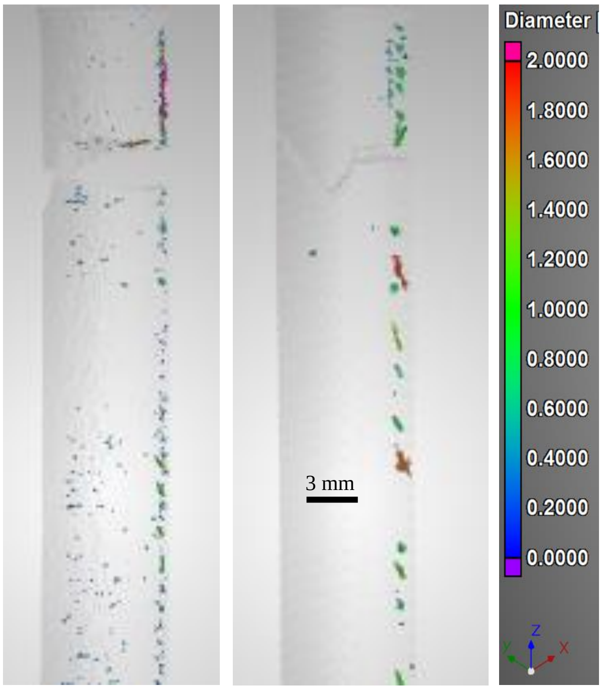

Figure 6: Micro-CT images showing an array of defects near the surface of: (a) Set 1, (b) Set 2 specimens.

IV. Conclusions

Post processing of Ti6Al4V samples manufactured at high laser power was performed to investigate the surface roughness and mechanical properties. The surface roughness in the as-built condition was found to be high mainly due to partially melted particles sticking to the surface, thus resulting in a surface roughness average of 22 µm. After surface finishing using CBF, the surface roughness was significantly reduced to 0.7 µm, but some small cavities remained on the surface. The tensile properties of the samples that were not HIP 'ed were found to be low due to the presence of lack of fusion defects. After HIP, the tensile properties were improved to obtain the minimum requirements per ASTM F2924-14.

Although the fatigue results showed a tendency for improved fatigue life after HIP and CBF, the overall fatigue strength was still low due to the presence of contour defects observed in both sample sets. Therefore, HIP can be used to close internal pores to improve the tensile properties; but may not close large pores connected to the surface. Surface finishing by CBF may also not completely remove contour defects near the surface. As such, the focus of future work will be on the optimization of contour scanning parameters to eliminate large defects near the surface to improve the fatigue strength.

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Author's statement

Conflict of interest: Authors state no conflict of interest.

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