Residual Stress, Porosity and Surface Roughness for Laser Powder Bed Fusion Manufactured Ti6Al4V at High Laser Powers

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Abstract— **The use of high-powered lasers presents a unique opportunity to improve the LPBF productivity since a larger beam spot size and higher scanning speeds can be utilized to increase the process build rate. In this study, a custom-built LPBF system equipped with a 5kW fiber laser was used to investigate residual stresses, porosity, and top surface roughness using x-ray diffraction and computed micro-topography techniques. It was shown that it is possible to produce samples with low residual porosity and top surface roughness using high laser powers and build rates, and the effect of scanning speed and hatch spacing on residual stress, porosity, and surface roughness is presented and discussed. The results of this study have revealed the potential benefits of using high powered laser to increase the build rate, thus improving the LPBF productivity.**

Keywords—Laser Powder Bed Fusion, Residual stress, Porosity, High power Selective Laser Melting, Titanium alloys, Surface roughness

I. INTRODUCTION

Laser Powder Bed Fusion (LPBF) is an emerging technology with a potential for high design freedom. As such, this technology has attracted many industries such as aerospace and medical since complex geometries are especially required [1]. Indeed, the unpreceded design flexibility, reduced material waste, and improved lead-time are the main benefits of additive manufacturing technologies like LPBF over conventional manufacturing routes. Despite its numerous advantages, several factors still hinder the widespread adoption of this technology as the end manufacturing technique. Some of these are random porosity, poor surface finish, high residual stresses, anisotropy of mechanical properties, etc. Aerospace parts are regularly subjected to high mechanical and thermal loads during their service life, and accordingly, certified parts are required to have high density, surface integrity, strength, and fatigue resistance [2].

In LPBF, the most influential variables are the process parameters, which include, among others, laser power, scan speed, hatch spacing, layer thickness, etc. Cumulatively with powder material properties, scanning, and building strategies, process parameters will consequently define a microstructure and part properties. The main research thrust has been to identify and tune the effect of process parameters on the end part structure and resulting properties. The achievable density after processing is the first and perhaps the most important concern in LPBF, hence achieving nearly full dense parts has been a focus of many earlier investigations [2-8]. Similarly, the build-up of residual stresses and the obtainable surface quality of LPBF parts are amongst other major issues of the process and have been the subject of many studies [9-14].

In recent years, machine manufacturers and researchers are focusing on expanding the capabilities of their machines by increasing the build rates and build volumes. For example, some equipment manufacturers, such as SLM Solutions and Concept laser, are employing multiple lasers to scan the build area to increase the build rate (e.g. SLM 800 and X line 2000R). This principle is called "Parallelisation" and the number of laser sources used can increase the theoretical build rate linearly [15]. Another method is to use high-powered lasers with a beam focal spot that has a larger diameter to instantly melt a larger area of the powder thus reducing the time required to scan each layer [16-18]. Thus, the focus of this study is to investigate the influence of high-powered laser on residual stress, porosity, and surface roughness of LPBF manufactured Ti6Al4V. This work will be the first to investigate these three properties in Ti6Al4V alloy manufactured at high laser powers; and contribute to the body of knowledge especially regarding process development and upscaling, in pursuit of increasing the LPBF productivity. The properties investigated are important in LPBF since they directly influence the structural integrity and mechanical properties of the part being manufactured.

II. MATERIALS AND METHODS

Gas atomized Ti6Al4V powder characterized with smooth spherical morphology was used in this study. The powder was supplied by TLS-GmbH, and the 10th, 50th, and 90th

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percentiles of the equivalent diameters were 24 µm, 41 µm, and 57 µm, respectively. Nine cuboid samples (12 mm x 12 mm) were manufactured using a custom-built LPBF system equipped with a 5kW IPG YLS 5000 Ytterbium fiber laser operating at 1076 nm wavelength. The samples were processed at different laser powers and build rates as shown in Table 1. At 2000W, the scan speed was kept fixed and only varied the hatch spacing to change the build rate, while at 750W and 650W, the build rate was changed by varying the scan speed. The beam spot size, scan speed, and hatch spacing are not disclosed as this is considered proprietary information linked to the Aeroswift, see Ref. [19].

Processing of the samples took place under Argon atmosphere, with the layer thickness kept constant at 50 µm. All the samples were manufactured directly onto the base plate without support structures. Samples were scanned by the laser beam using the parallel scanning strategy (back-and-forth) with the y-direction aligned to the track length, see Fig 1.

TABLE I. EXPERIMENTAL DESIGN

Sample No.	Parameters		
	Power (W)	*Build rate (mm^3/s)*	*Variable*
1	2000	18.0	*Hatch spacing*
2	2000	15.0	
3	2000	12.0	
4	750	6.8	*Scan speed*
5	750	5.6	
6	750	4.5	
7	600	5.4	*Scan speed*
8	600	4.5	
9	600	3.6	

Residual stress was characterized by the x-ray diffraction method before removing the samples from the baseplate. Lattice deformations of the Ti-α {213} were determined using CuKα (1.541838 Å) radiation source 25 kV, 4 mA (12 kV, 4 mA). The residual stresses were calculated considering plane stress conditions using X-ray elastic constants of ½S2=11.89×10^{-6} MPa-^{1} and S1= –2.83×10^{-6} MPa^{-1}. This method is described in detail by [20]. Porosity and surface roughness were measured using x-ray tomography following methods described by [8, 21].

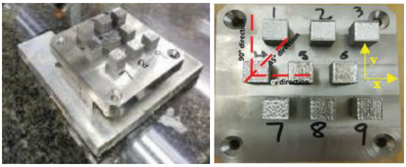

Fig. 1. Images of the samples investigated.

III. RESULTS AND DISCUSSION

Residual stress during LPBF is mainly due to thermal stress, and therefore, the stress at one point is related to its corresponding thermal history, which is also affected by the processing parameters. Fig. 2 shows the stresses measured in the different directions (i.e. 0°,45°,90° to the scanning direction and) the principal stresses (S1&S2). The stresses on the top surface are tensile because the shrinkage of top layers is restricted by the underlying layers as described by the temperature gradient mechanism [22]. Normally, residual stress in the scan direction is known to be the largest because the tracks mainly shrink along with the scanning the direction, and this is in good agreement with our results shown in Figure 2a, where the maximum stress was measured along the scan direction (i.e. 90°).

The effect of hatch spacing on residual stress is revealed by samples 1-3, which were manufactured at 2000 W at a fixed scanning speed. It can be seen that decreasing the hatch spacing lead to a reduction in residual stress, and this is believed to be mainly driven by the increased re-scanning of the tracks and heat accumulation, which in turn lowers the thermal gradient and consequently reduce the residual stress. It was also shown in other studies that re-melting results in increasing the peak temperature in the melt-pool and larger re-melted melt-pool size, thus, a larger re-melted melt-pool results in a large volume of material to cool and reduces the cooling rate [11, 22, 23].

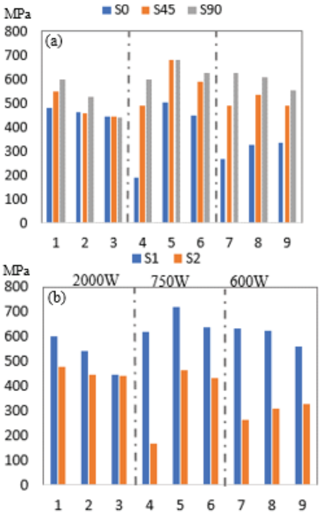

Fig. 2. Normal stresses (a) and principal stresses (b) were measured at the top surface of samples.

Considering samples processed at 750 W (i.e. 4-6) and 600 W (i.e. 7-9), the maximum residual stress can be seen to be decreasing slightly with decreasing scanning, except for the case of samples 4 and 7 which had somewhat lower residual stress than expected. In other work [24, 25], the maximum residual stress was seen to be increasing with decreasing scanning speed, and this was mainly because at higher scanning speeds the residual stress was relaxed by the formation of porosity [1]. This is probably the reason why samples 4 and 7 had lower residual stress, and this can also be seen in Fig. 3, where samples 4 and 7 had higher porosity compared to the other samples processed at the same laser power. Elsewhere [26-28], it was found that increasing the cross-sectional area of the melt pool by decreasing scanning speed leads to a reduction in cooling rate, more uniform shrinkage of the metal in and around the melt pool, and thus lower residual stress; and this is consistent with our results. Fig. 4 shows porosity distribution in the samples.

Overall, residual stress is seen to be increasing with increasing the build rate as shown in Fig. 5, where outliers are shown with a red border line representing the samples that had a higher percentage porosity. This can be interpreted as the effect of scanning time. A higher build rate will reduce the time the laser spent scanning the layer and increase the thermal gradient, thus increasing the residual stress.

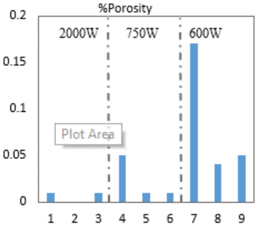

Fig. 3. Micro CT porosity measurements.

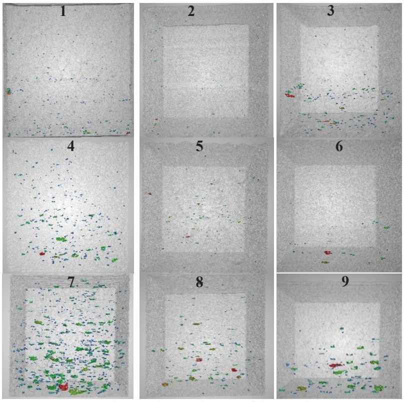

Fig. 4. Micro CT images of the samples.

The arithmetic mean areal roughness (Sa) of the top surface is plotted in Fig. 5a along with a CT image of the top surface. It can be seen that the hatch spacing had a minimal effect, within the range applied, on the surface roughness of the samples processed at 2000 W (Fig. 5b).

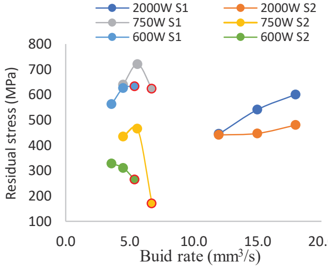

Fig 5. Variation of principal stresses with the build rate.

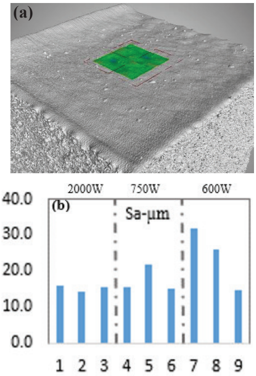

Fig. 5. An area where surface roughness was measured (a), and Sa values in analyzed samples (b).

In LPBF, the surface roughness is affected by wetting and the time of solidification of adjacent tracks, which in turn are strongly influenced by the amount of energy input [11, 28-32]. High energy input, obtained by either increasing the laser power or decreasing the scan speed or a combination of both, will melt the powder and form a large enough melt pool that would ensure melt flow and wetting of adjacent tracks. Moreover, a high energy input will produce a melt pool having a relatively long solidification time to wet a large surrounding area. Another factor affecting the surface roughness is the satellite powders sintering to the top surface, which is also a contributing factor to the roughness measurements. The surface topography of sample 5 and sample 7 was relatively uneven, and this is probably caused by a combination of the unstable melt pool and inhomogeneous layer deposition. Sample 7 has the highest porosity in the image near the top surface, and also the highest roughness at the top surface.

IV. CONCLUSION

The use of high-powered lasers equipped with a larger beam focal spot size is one of the promising methods for improving the LPBF productivity since larger volumes of metal powder can be melted in a shorter time. In this study, a customized laser system equipped with a 5 kW fiber laser was used to investigate the development of residual stress, porosity, and surface roughness on Ti6Al4V samples. These are among the most important response variables in LPBF since they affect the structural integrity and performance of the part. A thorough investigation was carried out using XRD and micro-CT to quantify residual stress, porosity, and top surface roughness. A trend in decreasing residual stress with decreasing hatch spacing and scanning speed was observed, and this is mainly due to heat accumulation at smaller hatch spacing, and increased interaction time at lower scanning speeds. Both of these scenarios lead to a reduction in thermal gradients and consequently reduces the residual stress. It was also shown that it is possible to produce coupons with low residual porosity using high build rates, and this is positive for the improvement of LPBF productivity. The top surface roughness of the samples produced at a high build rate was also shown to be smoother compared to the other samples produced at lower build rates. However, the vertical surface was not characterized in this study and will be the focus of a future study. Nevertheless, this study is the first to reveal the potential benefits of using high powered laser to increase the build rate, while obtaining lower residual porosity, residual stress and top surface roughness, which is positive for upscaling of the LPBF process. This work will be of interest to machine manufactures and researchers working towards the improvement of the LPBF productivity.

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