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INFLUENCE OF PROCESS PARAMETERS ON THE CORRELATION BETWEEN IN-SITU PROCESS MONITORING DATA AND THE MECHANICAL PROPERTIES OF Ti-6Al-4V NON-STOCHASTIC CELLULAR STRUCTURES

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ABSTRACT

Selective Laser Melting (SLM) facilitates the formation of complex, stochastic or non-stochastic, metallic cellular structures. There is a high level of interest in these structures recently, particularly due to their high strength to weight ratios and osteoconductive properties. While the ability to in-situ monitor the SLM process is of key importance for future quality control methods.

In this work lattice structures were fabricated, using the single exposure scanning strategy, on a Renishaw 500M SLM machine. The build process was also monitored using a co-axial in-situ process monitoring system.

It was found that by increasing the energy input, through increasing the laser power and/or exposure time, the lattice strut diameters, within the 1.5 mm diamond unit cells, increased from 119 to 293 μm , resulting in the major pore diameter decreasing from 1,106 to 932 μm . The effect of systematically altering the laser beam spot size on the cellular structures was also evaluated. It was observed that by doubling the laser beam spot size, that there was a 17 % reduction in strut diameter and a 22 % reduction in mechanical strength of the structures. It was also observed that at constant energy input levels, the lattice structures created using a focused laser exhibited an 81% lower mechanical strength than the structures created using a de-focused laser. Thus, demonstrating that the mode of energy input is critical to achieving the desired strength in these structures.

Based on the outputs from the in-situ monitoring system, a broadly linear correlation was obtained between the laser input energy, the associated process monitoring data generated and the mechanical strength of the lattice structures.

1 INTRODUCTION

Additive manufacturing (AM), also known as three-dimensional (3D) printing, is a process where parts are generated layer by layer [1]. This process can allow for the creation of complex structures that cannot be fabricated using traditional methods [2]. The development of AM has largely been driven by the medical, automotive and aerospace industries. This is due to the increased need for individual part customisation in medical applications and the need for lightweight parts in the aerospace and automotive industries [3][4][5].

Selective laser melting (SLM) is a form of AM that can be used for the production of complex shaped metallic parts, such as cellular structures [6]. Lattice structures are a type of cellular structure that are composed of a non-stochastic in-fill, consisting of a high volume of open pores. These type of structures typically possess high strength to weight ratios, osteoconductive features, low thermal conductivity levels as well as having excellent vibration attenuation properties [7] [8]. To date, there has been a considerable level of research on the fabrication of lattice structures made from titanium and titanium based alloys using SLM methods [9][10] [12] [13].

Conventionally, to produce lattice structures using SLM the size of the unit cell and strut thickness is predetermined in the CAD file. To achieve the desired strut dimension, usually several hundred microns in diameter, several scan contours or hatch scans are required [10]. However, some researchers have also looked at creating lattice structures using a “single-exposure” method [10][12][14]. During the single exposure method, instead of the laser scanning a contour and hatching a cross sectional area, it fires a single exposure of the laser at a defined point for a given period of time. As a result, the strut diameter is equal to the width and shape of the melt-pool created. This method of lattice fabrication has a number of potential advantages over the conventional method, such as (a) smaller achievable minimum feature size, (b) reduced computational cost and (c) reduced build time due to the decreased number of laser exposures and jumps between the individual exposures [11]. As the process parameters dictate the properties of the meltpool, which in turn dictates the properties of the struts, it is critically important to understand the effect of varying these parameters.

Previous authors such as Ghouse et al. assessed the effect of laser power and exposure time, on the mechanical properties of stochastic structures fabricated using this method [11]. In their work it was shown that as power and exposure time increased, the mechanical performance of the part increased. No details were provided regarding the effect of these parameters on the open pore size within the structures, possibly due to the random nature of the pore size present

within stochastic structures. Ahmadi et al also evaluated the effects of laser power and exposure time, on the mechanical properties of non-stochastic structures [15]. Again however, no results regarding the effect of these parameters on the major pore size within the structures was presented.

A further topic addressed in the current study is the correlation of in-process monitoring data, to the resultant printed part properties. To-date there have been very few reports investigating this correlation. One example is by Bisht et al. who demonstrated that there was a direct correlation between meltpool “events” and the reduction in tensile properties of typical dog bone samples [16]. In their work colour maps, generated by the process monitoring (PM) system, were manually analysed, and used to calculate the volume of defects within the samples. A difficulty however with this method of analysis is that it is extremely time consuming and therefore has limited potential for in process control.

The lack of process parameters-signatures-qualities relationships for AM systems, has been highlighted as an issue by the National Institute of Standards and Technology [17]. This report outlines that more research into the process parameter-process signature-part quality relationship is required, if more advanced process control is to be developed in the future.

This study firstly aims to determine the effect that varying process parameters has on the properties of the printed lattice structure. Specifically using the single exposure method of fabrication for lattice structures the aim is to:

- (a) evaluate the effect of increasing the laser beam spot size on the mechanical properties of the diamond based non-stochastic cellular structures,
- (b) evaluate and compare the effect of varying the laser power, exposure time and laser beam spot size on both the strut and major pore size diameter, within diamond based non-stochastic cellular structures,
- (c) compares the effect that decreasing the theoretical energy input through either laser power, exposure time or laser spot size variations has on the structure’s mechanical properties.

This study also evaluated the effectiveness of the Renishaw in-situ process monitoring system, InfiniAM Spectral, to establish a process parameter-process signature-part quality relationship for each of the parts created.

2 MATERIAL AND METHODS

2.1 MATERIALS & EQUIPMENT

This study was carried out using a Renishaw RenAM500M SLM machine. This production scale system is equipped with a 500 W Yb:YAG ($\lambda = 1.07 \mu\text{m}$), laser with Gaussian beam profile. The in-focused laser has a beam spot diameter of approximately $75 \mu\text{m}$ ($1/e^2$). This system is also equipped with an in-situ process monitoring system, called InfiniAM Spectral. The InfiniAM Spectral system uses a number of photodiodes to gather data relating to the thermal and optical emissions ejected by the meltpools created during the build process, as well as providing feedback on the laser energy input [18]. The MeltView module, consisting of two co-axial photodiodes that detect in different wavelength ranges, gathers information relating to the meltpool. While the LaserView module employs a single photodiode to monitor the laser input energy. The RenAM500M is a point based system, in that the laser fires for a given amount of time after which it switches off and moves a defined distance, known as the point distance, to the next point location before firing again for a given time, known as the exposure time. In order to increase the laser spot size, the focal offset distance (FOD) was varied. By increasing the FOD from 0, the focal plane of the laser is shifted below the build plate, as shown in Figure 1 (right). This results in the laser spot size at the build plate surface increasing.

Figure 1: Left: Diagram showing the effect of shifting the focal offset distance (FOD), with respect to the build plate. Right: Diagram showing the effect of shifting the focal plane in a negative and positive direction [19].

2.1.1 Test specimen

All test specimens were manufactured using Ti-6Al-4V Extra Low Interstitials-0406 grade 23 powder, with typical powder particle diameters in the range 15 to $45 \mu\text{m}$, obtained from AP & C. The test specimens were printed to the requirements of the ISO 13314 standard, which explains the method of compression testing porous metallic structures. The lattice structures had dimension of $15 \times 15 \times 28 \text{ mm}$ (L x W x H), as shown in Figure 2. This figure also illustrates the 1.5 mm diamond unit cell used to in this work. This cell type was chosen due to its potential

application in the biomedical industry, due to its close packing, along with the ease at which it can be produced using SLM methods. All samples built in this study were built using the single exposure method, as described above, whereby the strut diameter is equal to the width and shape of the melt-pool created at each firing of the laser. After the samples were removed from the build plate, they were cut to a length of 20 mm using a precision saw, the samples were then washed in an ultrasonic bath and dried. Cutting the samples to this way ensured that both ends of the samples were flat and even, prior to mechanical testing.

To assess the effect of varying laser power and exposure time on the lattice properties and the PM data generated, 25 different power and time variations were selected for assessment, each with a sample size of 4 ($n=4$). To assess the effect of increasing the laser spot size on the lattice structure's properties, parts were printed at five different laser spot sizes, each with a sample size of 6 ($n=6$), at constant power and exposure time. All samples were built with a layer height of 30 μm .

Figure 2: Schematic showing diamond unit cell and the major pore size within the cell (left). Example of a printed Ti6Al4V lattice structure (right).

In order to quantify and compare the effects of the different process parameters used, the total energy input (E') was used as a metric, and was calculated using equation 1, adopted from [19] and [20],

$$E' = \frac{Pt}{\pi\omega^2 l} \quad \left[\frac{\mu\text{J}}{\mu\text{m}^3} \right] \quad \text{Eq.1}$$

where, P is the laser power, t is the exposure time, l is the layer height and ω is the beam radius. ω is a function of the FOD and was calculated using equation 2, taken from [19].

$$\omega(z) = \omega_0 \sqrt{1 + \left(\frac{z}{z_r}\right)^2} \quad [\mu\text{m}] \quad \text{Eq.2}$$

where z , ω_0 and z_r is the FOD, the in-focused beam waist and the Rayleigh length of the beam respectively.

The input energies (E') associated with each power and time variation, calculated using equation 1, are illustrated in Figure 3.

Figure 3: Energy input (E') obtained at the laser powers between 50 and 150 W, as well as laser exposure time between 350 and 750 μs , (calculated using Eq. 1.).

To assess the effect of increasing the laser beam spot size on the lattice structures properties, one sample was selected from the above sample group and built using five different FOD values, with the maximum FOD value equal to the Rayleigh length of the beam. The FOD values were set to 0.0, 1.8 2.5 3.1 and 3.6 mm. This resulted in a 25 % incremental increase in the beam cross sectional area, up to a maximum increase of 100 %. All samples with an adjusted FOD were processed with a laser power and exposure time of 150 W and 350 μs respectively. This sample was selected, as at the point where the laser beam spot size doubled (i.e. at FOD= 3.6 mm), the theoretical energy input was similar to that obtained for a number of in-focused samples as detailed in Table 2. This allowed for a cross comparison to be carried out on the effectiveness of different 'types' of energy input. The energy input associated with each FOD value, and the beam radius (ω), can be seen in Table 1 below. As mentioned, a positive FOD value results in the focal plane been shifted below the build plate, see Figure 1 right, resulting in a converging laser beam. No negative FOD shifts were evaluated in this work as it has been shown to promote beam attenuation and other undesirable features [21] [22].

Table 1: Effect of increasing the FOD on the beam radius (ω) and the energy input (E')

<i>FOD</i> (mm)	<i>ω</i> (μm)	<i>E'</i> ($\mu\text{J}/\mu\text{m}^3$)
0	37.500	0.396
1.8	41.926	0.317
2.5	45.655	0.267
3.1	49.487	0.227
3.6	53.033	0.198

2.2 QUASI-STATIC TESTING

The mechanical properties of the lattice structures were evaluated using a static compression test, according to ISO 13314. This specifies the procedure for the mechanical testing of porous metallic structures [23]. Testing was carried out using a Tinius Olsen 50 kN machine, using either a 10 or 50 kN load cell, depending on the strength recorded for the initial sacrificial lattice structure tested for each parameter set as per ISO 13314. Testing was carried out at a crosshead displacement of 2 mm/min, resulting in an average strain rate of $\sim 10^{-2}$ strain/second. Prior to any testing a frame stiffness correction program was run 7 times on the mechanical tester. This allowed for the stiffness of the machine to be accounted for when calculating the strain measurements. This program was run to greater displacements, then the samples were tested to, and to the maximum force allowable by the given load cell. This ensured that and deflection in the machine was accounted for. As per ISO 13314, in order to determine the true elastic gradient (E) of the structures a preliminary test lattice was initially tested in order to determine the σ_{20} and σ_{70} values (20 and 70 % the plateau stress levels). However, due to the brittle nature of the plateau stress, the σ_{20} and σ_{70} values were taken as a function of the compressive stress, not the plateau stress. This method of compression testing has been reported in the literature [11], and has been deemed a suitable method of testing. Testing was carried out until the lattice structures were compressed to 60 %. A minimum of three structures of each sample variation was tested.

2.3 CHARACTERISATION

A Hitachi EM4000Plus SEM was used to obtain detailed images of the structures, with any image analysis been carried out using the ImageJ software. Strut diameters, measured from the SEM images, were based on 5 measurements at 5 different unit cells.

The size of the major pores within the lattice structures was calculated using equation 3 below,

$$\phi_{pore} = \phi_{pore}^{max} - \phi_{strut} \quad \text{Eq.3}$$

where, ϕ_{pore} is the pore diameter, ϕ_{strut} is the respective strut diameter and ϕ_{pore}^{max} is the theoretical maximum major pore size obtainable at an infinitesimally small strut diameter, as seen in Figure 2 left,. This value was determined using the Rhino CAD software.

The relative density, $\bar{\rho}$, of each lattice structure was obtained using the dry weighing method. Whereby the mass of each structure was divided by the theoretical mass of the macro-volume ($L \times W \times H$) and taking the density of bulk Ti-6Al-4V to be 4.42 g/cm³. The length and width of the samples was determined by the boundary box of the CAD file, while the height of the

part was set to 20mm, having been cut to this length using a precision saw and verified using a Vernier callipers. A Mettler Toledo balance was used to measure the weight of each specimen to within 10 µg. The relative porosity, $\bar{\Phi}$, of each structure was then calculated using equation 4, adopted from [24].

$$\bar{\Phi} = 1 - \bar{\rho} \quad \text{Eq.4}$$

2.4 IN-SITU PROCESS MONITORING DATA ANALYSIS

During the build processes, the InfiniAM Spectral system was used for in-situ process monitoring during the build. This system provides feedback on the laser energy input and the level of emissions emitted from the melt pool during processing. The data can then be reconstructed into both 2D and 3D views in near real time [18].

Post-build analysis was carried out, using a Matlab script, on the raw data generated during the processing of each sample created, to assess if a process parameter-process signature-part quality relationship could be obtained.

To analyse the data generated per sample, the data detected by the PM system was plotted as a function of build plate location, for each layer. After which, a region of interest (ROI) was taken around each individual structure. The data generated within each ROI was then analysed individually, layer-by-layer. The sum, mean, maximum and minimum values of each of the respective data streams, within each ROI per layer, was then calculated. For example, the sum LaserView signal represents the sum of all the recorded signal intensities detected within a given ROI, at a single layer. Therefore for each structure there is three (2 x MeltView and 1 x LaserView) sum photodiode values per layer.

3 RESULTS & DISCUSSION

3.1 CHARACTERISATION

The effect of increasing the laser power and exposure time on the relative porosity, on the strut and major pore diameters of the lattice structures is shown in Figure 4 and Figure 5. By increasing the laser power from 50 to 150 W, at a constant exposure time of 350 µs, the strut diameter in the respective structures increased from 118.9 to 154.6 µm, while the relative porosity of the structures decreased from 96.3 % to 89.1 %. At the highest exposure time used of 750 µs, increasing the laser power from 50 to 150 W resulted in the strut diameters increasing from 235.3 to 292.9 µm, while the relative porosity of the structures decreased from 94 % to

83.8 %. A similar trend occurs for all the other power and time variations, as demonstrated in Figure 4.

Figure 4: Effect of exposure time at the different laser powers (at fixed FOD) on the relative density of the lattice structures.

Figure 5: Effect of exposure time at different laser powers (at fixed FOD) on the lattice structures strut and major pore diameter.

The effect of increasing the FOD, and thus the laser beam spot size, on the structures relative porosity and strut diameter can be seen in Figure 6 and Figure 7. It is observed that as the laser spot size is increased the structures relative porosity increases, while the strut diameters within the structures decreases. This result shows that as the structures relative porosity increases, from 89.0 % to 90.5 %, due to a reduction in the individual strut diameters, from 235.3 to 195.3

μm , the pore diameter increases from 989.5 to 1029.4 μm . This is due to the greater amount of free space within each unit cell, caused by the reduced strut diameters.

Figure 6: Effect of increasing the FOD, at fixed laser power and exposure time of 150 W and 350 μs , on the lattice structures relative porosity and laser beam radius.

Figure 7: Effect of relative porosity when plotted against strut diameter and major pore diameter.

The SEM images shown in Figure 8 top, demonstrate the effect of increasing the laser power and exposure time from 50 to 150 W and 350 to 750 μs , on the visual appearance of the lattice struts. These images demonstrated that struts processed with the lower energy input have much smaller diameters compared to the struts processed with the higher energy input. Along with this, the struts processed with the lower energy input have severe necking present, while the struts processed with the higher energy input values have far better connection between the layers. Necking occurs at layer boundaries when the energy input is sufficiently low, resulting in poor bonding between successive layers [11]. Figure 8 bottom, shows the effect of doubling

the laser beam cross sectional area on the lattice struts. Although small, the reduction in strut diameter can be seen from this image.

Figure 8: SEM images of the lattice structures. Top: Demonstrates the increased strut diameter obtained after increasing the laser power and exposure time. The region highlighted by the arrow demonstrates the presence of the necking region between melt pools. Bottom: From left to right, Demonstrates the decreased strut diameter obtained after increasing the laser beam spot size. (ω is the laser beam radius).

As demonstrated in Figure 4, by increasing laser exposure time from 350 to 750 μ s, for each of the power variations, a near linear decrease in the lattice structures relative porosity occurred. This decrease in relative porosity occurred due to the higher input energy associated with the higher exposure time and laser power, forming larger strut diameters. This in return reduces the amount of open pore space within the lattice structures. This observation is supported by the results shown in Figure 5, where the effect of increasing the laser power and exposure time on the individual strut diameters within the structures, along with the major pore diameters is

presented. As expected, with increased laser power and/or exposure time, there was an increase in strut diameter and an associated reduction in major pore diameter. This is also demonstrated in Figure 8 top, whereby increasing the power and/or time, results in struts with larger diameters. Closer examination of this figure (top) shows necking regions between the meltpools used to fabricate the struts. This occurs due to the energy input been insufficient, thus resulting in poor bonding between the meltpools. This may result in the creation of regions of stress concentration, which in turn could reduce the load bearing strength of the structures. When the input energy was increased there was reduced evidence for the formation of this necking region between the meltpools, which would contribute to the higher strengths observed for these structures.

The effect of increasing the FOD, and thus the laser beam spot size, on the structures relative porosity and strut diameter is illustrated in Figure 6 and Figure 7. It was observed, that when the laser spot size was increased the strut diameters within the structures decreased, with an associated increase in the structure's relative porosity been obtained. The reduction in strut diameter is attributed to the decrease in input energy associated with increasing the laser spot size. Correspondingly, by increasing the FOD value the intensity of the laser at the center of the beam decreases. This is due to the change in beam profile associated with the de-focusing of the laser. The intensity at the center of the beam decreases with a power relationship, while the intensity of the beam decreases exponentially in the radial direction, as the FOD value increases as described by equation 1 in [25]. In summary, when the laser is de-focused, less material is melted during each laser exposure, which in turn results in smaller strut diameters and therefor an increase in the structures relative porosity. This effect is also demonstrated by the SEM images of the struts (Figure 8, bottom), where they get visibly smaller, as the beam radius (ω) is increased.

3.2 MECHANICAL PROPERTIES

Figure 9 presents the effect that increasing the relative porosity, obtained through increasing the laser power and/or exposure time, had on the compressive strength (CS) and Young's modulus (YM) of the structures. This result shows that when the relative porosity of the structures increased from 83.8 % to 96.3 % the compressive strength and Young's modulus decreased from 44.70 to 0.64 MPa and 18.40 to 0.28 GPa, respectively. With both sets of results presenting a linear decrease in values with increasing relative porosity.

Figure 9: Effect of increasing the input energy input on both the Young's modulus and compressive strength of the lattice structures. Insert: Lattice structure undergoing fracture during compression testing.

Figure 10 demonstrates the effect that increasing the laser beam spot size, at constant laser power and exposure time, had on the compressive strength and Young's modulus of the lattice structures. Increasing the beam radius from 37.5 to 53.0 μm , resulted in a doubling of the beam cross-section area and therefore a decrease in input energy by 50 %. This reduction in input energy resulted in a reduction in the compressive strength of the lattice structure by 21.7 %, from 19.23 to 15.06 MPa, while the Young's modulus reduced by 24.4 %, from 6.80 to 5.14 GPa. Note, the maximum positive and negative error bars for the Young's modulus and compressive strength was only 0.3 GPa and 0.13 MPa respectively.

Figure 10: Effect of increasing the FOD, at fixed laser power (150 W) and exposure time (350 μs), on the compressive strength of the lattice structures created.

Figure 11 shows the compressive strength of all the structures assessed in this study, as a function of energy input. It can be seen here that as the energy input is increased the compressive strength of the structures increases. The structures created with an energy input of

0.85 ($\mu\text{J}/\mu\text{m}^3$), at 150 W and 750 μs , achieved a compressive strength of 44.7 MPa. In contrast the structures created with an energy input of 0.13 ($\mu\text{J}/\mu\text{m}^3$), at 50 W and 350 μs , achieved a compressive strength of just 0.278 MPa. For each of the power variations the experimental data was fitted to a linear curve, with R^2 values ranging from 0.9916 to 0.9989, indicating that a linear increase occurs when the exposure time is increased regardless of laser power. For the FOD data a linear fit was also obtained with an R^2 of 0.9715 been obtained, indicating that a linear decrease in part strength is obtained for focal shifts up to the Rayleigh length of the beam.

Figure 11: Effect of increasing laser energy input (E') on the compressive strength of the lattice structures investigated at the five power settings shown. Included in this diagram are values for the FOD obtained in the range from 0 to 3.6 mm (at 150 W and 350 μs).

Based on the relative porosity and strut diameters results obtained, the trends in Figure 9 to Figure 11 relating to the the strength (σ) and Young's modulus (E) of the structures are as anticipated. In that the mechanical strength increased with increasing relative density of the structures, or in this case decrease with increasing relative porosity. These results can be described by the Gibson and Ashby model, in equation 5 and 6 below [26].

$$\frac{\sigma}{\sigma_0} = C_1 \left(\frac{\rho}{\rho_0} \right)^n \quad \text{Eq.5}$$

$$\frac{E}{E_0} = C_2 \left(\frac{\rho}{\rho_0} \right)^m \quad \text{Eq.6}$$

Where σ_0 and E_0 are the strength and Young's modulus of the solid base material, taken as 970 MPa and 110 GPa in this study. An R^2 of value of 0.98 was obtained for equations 5 and 6 when fitted to the experimental data, with the constants C , n and m found to be 5.256, 29.138, 2.489 and 2.878 respectively. The mechanical results seen here are promising from a biomedical point of view, in that the Young's modulus and compressive strength achieved are

in the typical range of that of human trabecular and cortical bone, which have values of 0.1-4.5 to 3-20 GPa and from 2-17 to 33-193 MPa respectively[27][28].

The increased line slopes associated with the higher laser power levels, 100 to 150 W, seen in Figure 11, shows that the effect of increasing the exposure time on the structures compressive strength, has a greater effect at higher laser power levels, than at lower powers. This occurs due to the higher cumulative energy input associated with the higher laser power at longer exposure times, compared to the energy input obtained at lower powers, for similar exposure times.

The full effect of increasing the laser spot size, compared to varying the laser power or exposure time, on the mechanical properties of lattice structures can be seen in Figure 11. From this figure, reducing the energy input through increasing the laser spot size (FOD), did not result in a significant change in the mechanical strength of the structure. With approximately a 22 % reduction in part strength been obtained, by reducing the input energy by 50 %, achieved through doubling the laser beam spot size. This contrasts with the effect of reducing the energy input obtained by either reducing the laser power or exposure time. For example, the structure with a 100 % increased laser spot size, a laser power of 150 W and exposure time of 350 μ s, with a resultant energy input of 0.198 (μ J/ μ m³), has a compressive strength of 15 MPa. While the structure with an energy input of 0.198 (μ J/ μ m³), achieved with an in-focused laser, a power of 75 W and an exposure time of 350 μ s, had a compressive strength of just 2.91 MPa. Comparing the compressive strengths presented in Table 2, there is an 80.6 and 80.8 % difference in mechanical strength obtained, despite all structures having similar theoretical input energies.

Table 2: Effect of energy input mode on the mechanical properties of the lattice structures.

Power (W)	Exposure time (μs)	FOD (mm)	E' (μJ/μm³)	Compressive strength (MPa)
50	750	3.6	.198	15.01
50	550	0	.207	2.91
75	350	0	.198	2.88

This result demonstrates that while increasing the laser beam spot size has a significant effect on the theoretical energy input, the effect on the mechanical properties of the lattice structure is not as impacted as it would be through altering the laser power or exposure time. This observation is similar to that reported by Suder et. al. [29], for a study involving laser welding. In their work the depth of penetration in single bead welds decreased far less through increasing

the laser spot size than through decreasing the laser power, at similar power densities. Suder concluded that increasing the spot size effectively increased the total beam-powder interaction time, resulting in less rapid reduction in properties than expected [29]. This result demonstrates that the mode of energy input, either through laser power exposure time or spot size variation, is critical to achieving the desired mechanical strength of parts fabricated using this single exposure fabrication method.

3.3 IN-SITU PROCESS MONITORING DATA ANALYSIS

Due to the large amounts of data generated during the study only the data generated by the laser monitoring photodiode and one of the meltpool monitoring photodiodes is presented.

Figure 12 shows the sum of the LaserView and MeltView signals generated during the processing of a typical layer, from each of the power and exposure time variations samples, as a function of the theoretical input energy. In addition, the mechanical strength of each of the structures is also plotted as a function of their respective energy inputs.

Figure 12: Part strength, MeltView & LaserView module signal as a function of energy input. The R^2 value indicates the closeness to line fit.

As demonstrated in figure 12, as the energy input is increased, the LaserView and MeltView signals increase in a linear manner, similar to the compressive strength of the structures. This result indicates that there is a broadly linear relationship between input energy, the mechanical properties of the part and the data generated by the PM modules. This result indicates that there is a distinct process parameters-process signature- part quality relationship present between the process parameters used, the data generated by the PM system and the structures mechanical properties.

The results shown in Figure 12 demonstrate that there is a direct correlation between energy input, part quality and the resultant signals from the MeltView and LaserView modules. In this case the quality metric was the part's mechanical strength. While Figure 12 shows the signals obtained for just one layer within the lattice structures, an identical trend was observed at any other layer, albeit the actual PD signal values may differ.

As the LaserView module measures the laser energy input, a direct relationship between the theoretical energy input and this signal was expected, with Figure 12 demonstrating this. From this figure it was observed that as the theoretical input energy increased, the intensity of LaserView signal also increased, in a linear manner. The closeness of this relationship is evident, with the R^2 value of 0.9999 obtained when the data was fitted to a linear curve. This result indicates that the LaserView data has potential for use in identifying potential defects, which may occur within the lattice structures due to a laser error.

The intensity of the signal detected by the MeltView module was also found to increase in a broadly linear manner, as the theoretical input energy increases. A possible explanation for this increase is that, when more laser energy was input into the structures per laser exposure, larger meltpools were formed. These larger meltpools result in greater amount of emissions been created, which were then detected by the MeltView module.

This result demonstrates the relationship between the process parameters-process signatures-part quality, for lattice structures fabricated using the method in question. Using this type of result and by knowing what process signature to expect from the process monitoring data, for a given set of process parameters and part geometry, the quality of the resultant layers and final part may be estimated. Through layer-by-layer analysis, and with a thorough understanding of the relationship between process parameters-process signatures-part quality, defects could be detected within lattice structures if an un-expected process signature was detected at a given layer. However, further work is needed to verify how the process monitoring system and the mechanical response of the structures respond to defects within the structures.

4 CONCLUSIONS

This study investigated the effects of laser beam spot size, in addition to laser power and exposure time on the mechanical and topological properties of Ti-6Al-4V diamond based cellular structures, produced using a single exposure method. While the InfiniAM in-situ process monitoring system provided real-time processing information during the build process. The following are the conclusions drawn from this investigation;

- a) The effect of laser beam spot size was investigated, for the first time, on these types of structures. It was demonstrated that through a 100 % increase in the laser spot size, at fixed laser power and exposure time of 50 W and 350 μ s respectively, the theoretical energy input, the strut diameter and the mechanical strength of the structures reduced by 50.0 %, 17.0 % and 21.7 %, respectively. While the relative porosity of the structures increased by just 1.6 %. However, to gain a deeper understanding into the effect that increasing the laser beam spot size has on the structures, a detailed evaluation assessing the relationship between spot size, power and exposure time is required.
- b) In total, 25 variations of power and exposure time were investigated ($50 < W < 150$ and $350 < \mu s < 750$). It has been shown that as the laser power and/or the exposure time increase the relative porosity and mechanical properties of the structures decrease and increase respectively. It was demonstrated that as the strut diameter within the 1.5 mm unit cells increased from 119 to 193 μ m, due to the increasing energy input, the major pore diameter within the structures decreased from 1,106 to 932 μ m.
- c) This study also found that although increasing the laser beam spot size has a significant effect on the theoretical energy input, the effect on the mechanical properties is not as severe as reducing the input energy through laser power or exposure time reductions. It was shown, in Figure 11, that at similar energy input levels, lattice structures created using a focused laser exhibited up to 81% lower mechanical strengths than structures created using a de-focused laser. Demonstrating that the mode of energy input is critical to achieving the desired part strength.
- d) An in-situ process monitoring system was used to develop the process parameter-process signature-part quality relationship, for the lattice structures studied in this work. A broadly linear correlation was obtained between the laser input energy, the associated process monitoring data generated and the mechanical strength of the lattice structures.

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