The influence of laser parameters and scanning strategies on the mechanical properties of a stochastic porous material

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HIGHLIGHTS
• Stochastic architectured porous materials were additively manufactured in Titanium and Stainless Steel
• The effect of laser parameters and scan strategies on strut thickness and strength of porous materials were investigated
• A linear relationship was found between the specific enthalpy, delivered by the laser to the melt-pool, and strut thickness
• The optimum rate of energy for maximising strength of a porous material for a given stiffness was material dependent
• Maximizing the strength:stiffness and strength:weight ratio of a porous material is dependent on the scan strategy used

GRAPHICAL ABSTRACT

ABSTRACT
Additive manufacturing enables architectured porous material design, but 3D-CAD modelling of these materials is prohibitively computationally expensive. This bottleneck can be removed using a line-based representation of porous materials instead, with strut thickness controlled by the supplied laser energy.

This study investigated how laser energy and scan strategy affects strut thickness and mechanical strength of porous materials. Specimens were manufactured using varying laser parameters, 3 scan strategies (Contour, Points, Pulsing), 2 porous architectures and 2 materials (Titanium, Stainless Steel), with strut thickness, density, modulus, mechanical strength and build time measured.

Struts could be built successfully as low as 15° with a minimum diameter of 0.13 mm. Strut thickness was linearly related to the specific enthalpy delivered by the laser to the melt-pool. For a given stiffness, Titanium specimens built at low power/slow speed had a 10% higher strength than those built at high power/fast speed. The opposite was found in Stainless Steel. As specimen stiffness increased, the Contour Strategy produced samples with the highest strength:stiffness and strength:weight ratio. The Points strategy offered the fastest build time, 20% and 100% faster than the Contour and Pulsing strategies, respectively. This work highlights the importance of optimising build parameters to maximize mechanical performance.

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1. Introduction

Additive manufactured (AM) architected porous materials are now viable choices for the engineer in a variety of fields [1–4]. In orthopaedics, implants have traditionally been machined, forged or cast solid pieces of metal, that are orders of magnitude stiffer than the natural bone [5]. These implants, can now be composed of low stiffness architected porous materials produced by AM [6], from established biocompatible metals like Titanium, Cobalt Chrome, and Tantalum [7–9]. Orthopaedic devices therefore now have the potential to match the stiffness of cancellous bone throughout the skeleton which may enable new treatment options in the management of osteoarthritis, particularly for early intervention in young patients. However, a challenge is to ensure that at low modulus, AM porous materials have the maximum strength to guarantee implant survival in a high cyclic load environment.

Existing AM porous materials research has investigated different architectures (unit cell types), characterising the strength and stiffness of the structures at varying porosities. Most structures investigated are non-stochastic architectures which include variations of cubic crystal system structures [10–12], space filling polyhedrons [13] and trippy periodic structures [14–17]. A few researchers have also looked at pseudo-randomised versions of crystal system structures [7] and fully stochastic architectures [18]. However, little attention has been paid to optimising manufacturing parameters (e.g. laser power, scanning speed) and scan strategy for the mechanical performance of these structures.

Parameter optimisation has been performed for solid AM parts focusing on achieving maximum material density and a desired microstructure [19–21]. For porous materials, parameter studies have prioritized geometric accuracy and material density. The few AM porous material studies that have considered build parameters and mechanical performance, have briefly explored the effect of varying laser parameters on the mechanical properties of the structure. Specifically looking at mechanical properties with respect to relative density (i.e. strength or stiffness-to-weight), whereas for bone replacement scaffolds it would be more suitable to optimise parameters to ensure maximum strength of the architected material with respect to stiffness. Also, AM porous material parameter studies tend to only be performed on BCC unit cell architecture, and thus have not considered how the variety of build angles, such as are encountered in stochastic architectures are affected [11,22].

For research that investigates the effect of laser parameters on AM material properties, such as strut size [1,11,22], structure porosity or material density, either a single laser parameter is explored in isolation [22] or an equation for ‘laser energy density’ is used [1,20,21]. These equations attempt to relate Laser Energy ($E$) delivered to the melt-pool to some combination of laser power ($P$) and exposure time ($t$) or to laser scan speed ($u$), hatch spacing ($h$) and layer thickness ($l$). Eq. (1), shows typical models used.

$$E = P \times t \text{ or } E = \frac{P}{u \times h \times l}$$  

These models do not include important process variables, and typically generate a process parameter window or a collection of data points with no distinct trend when graphing a property such as strut thickness against the laser energy density [1,19], thus making it difficult to scale or predict values outside the tested experimental range [23]. A more useful term comes from laser welding origins, where Hann et al. [24] and King et al. [25] relate melt-pool width and depth to the absorbed energy density or specific enthalpy ($\Delta H$) delivered by the laser to the powder bed. Where specific enthalpy is a function of Absorptivity ($A$), thermal diffusivity ($D$) and density ($\rho$) of the powder and of the laser parameters, namely, laser power ($P$), laser scan speed ($u$) and laser spot diameter ($\Theta$).

$$\Delta H = \frac{AP}{\rho \sqrt{\pi D u \Theta^3}}$$  

For a given scan geometry, if strut thickness can be assumed to be proportional to melt-pool width and depth, then a strut thickness versus enthalpy plot should produce a scalable model with a distinct and mathematical trend.

Parameter optimisation is further complicated by varying methods of energy delivery. Two approaches have been adopted in literature for porous materials: the traditional contour-hatch [22] scanning strategy or the more novel single-exposure strategy [11], but a comparison between these scanning strategies is yet to be performed. Another potential scanning strategy to be explored is pulsing which may allow for better control of the melt-pool [26]. Finally, current studies only report on individual materials, thus cannot investigate how optimising laser parameters and scan strategy may change according to mechanical, material and thermal properties of the powder.

As the future of the architected material generation is likely to move from solid CAD modelling, which is computationally expensive, to line based representation, the relationship between laser parameters and scan strategy to strut thickness must be understood. In order to fully benefit from the potential of AM porous architected materials, there is a need to understand the build parameter rules independent of strut size, relative density, build angles and material. The aim of this research is to investigate how different laser parameters and scan strategies influence strut thickness and mechanical properties of porous materials, specifically looking to maximize the strength of a structure for a given stiffness.

2. Experimental method

2.1. Materials and manufacturing

All specimens in this study were manufactured on a Renishaw AM250, a metal powder bed fusion AM system. The system, equipped with a Gaussian beam CW fibre laser (max. 200 W, 70 µm spot, $\lambda = 1.07 \mu m$), was modified to include process monitoring equipment. The laser optical train was fitted with a beam splitter attached to two high speed cameras enabling imaging of the melt-pool and a photodiode was connected to the optics to monitor the laser input to the powder bed.

The AM250 is a pseudo-modulated (“move-fire”) system, meaning the laser is held at a point and fires for a fixed exposure time then turns off and moves rapidly to the next point by a set point distance and the process repeats along each scan vector. The main laser parameters, in combination with the different scanning strategies, which control the melting process are therefore Laser Power, Exposure Time, Point Distance and Layer Thickness. All specimens in this study were manufactured in both Titanium (Ti6Al4V ELI) and Stainless Steel (SS316L) spherical powder of particle size range 10–45 μm ($D_{50}$: ~27 μm) supplied by LPW Technology. Titanium and Stainless Steel were selected due to their prevalence in AM research as well as their orthopaedic relevance. Manufacturing occurred in an environment initially vacuumed to $-960$ mbar and then back filled with 99.995% pure Argon to 10 mbar with an $O$ content of $-0.1\%$. The following scan strategies were employed to manufacture the specimens:

2.1.1. Contour strategy

The most common build strategy in AM is the Contour–Hatch strategy. For a given 2D slice, the original CAD geometry contours are offset (typically by half the melt-pool diameter) and the resulting contour scans are traced by the laser, with the area enclosed by the contours being filled in with ‘hatch’ scans (Fig. 1a). However, issues arise with this approach at small scale, due to STL geometry and resolution errors resulting in limited laser interaction with the powder-bed, i.e. the slice data’s laser scan paths do not accurately reflect the intended geometry. This strategy also causes many scan vectors and jumps between scan vectors, resulting in a high amount of scanner delays and is computationally expensive. For the contour strategy employed in this research
the diameter of the contour scan was set equal to the spot size of the laser (70 μm), this was to ensure there was no need for interpolative calculations to generate additional border or hatch scans, strut thickness was then controlled purely by the laser parameters. Refer to Fig. 2 and Supplementary Video 1.

2.1.2. Points strategy

Only a few researchers have utilized a single-exposure or point-like-exposure strategy for manufacturing struts or porous structures [1, 10, 11]. To create a strut with the single-exposure approach, instead of the laser scanning a contour and hatching the intersecting geometry on a 2D slice (Fig. 1a), it fires a single exposure at the strut location for a specified period of time with the resulting strut thickness and morphology being equal to the width and shape of the melt-pool (Fig. 1b). The single-exposure approach is only possible when the struts of a porous structure are represented by lines as opposed to solid geometry.

The single-exposure approach is believed to be more suited for building porous structures in terms of both minimum feature size, computational cost and build time due to it reducing the complex geometry of a porous structure to a set of points of exposure where less jumps and scanner delays are caused. The drawbacks lie in the control of strut morphology as well as the manufacturability and mechanical competence of low angled struts. This is because as the build angle of a strut gets closer to the horizontal the overlap between the current layer’s melt-pool and the previous layer’s melted strut becomes less as has been depicted by several authors [27, 28].

This research utilized a novel interpretation of the single-exposure strategy, developed by Betatype Ltd. This new interpretation eliminates the problem where melt-pools would not overlap for low angle struts. The thickness of struts manufactured by the new Points Strategy was still determined by the melt-pool size and thus ultimately controlled by the laser parameters. Refer to Fig. 2 and Supplementary Video 2.

2.1.3. Pulsing strategy

Pulsing a laser can lead to a smaller melt-pool [26] and consequently may be able to produce finer features. By repeatedly firing the laser at each point in the Points Strategy the effect of pulsing can be explored. In addition to the typical laser parameters which control melt-pool size, new variables are available, namely the duty cycle (how long the laser is off between repeated exposures) and the number of repeated exposures per point. Refer to Fig. 2 and Supplementary Video 3.

2.2. Specimen design

All specimens were designed in Rhinoceros 5.0 (Robert McNeel & Associates) as line geometry with slice data (build files) generated through Material Engine 1.0 (Betatype Ltd). Material Engine is a CAD-CAM software platform that creates slice geometry for a variety of scanning strategies directly from line based geometry representation. It was therefore possible to compare different scanning strategies all generated from the same input CAD. Using this methodology, two structures were produced.

2.2.1. Characterization structure

To evaluate minimum feature size and the effect of laser parameters on strut size and build angle, a characterization structure with constant strut length and varying angles was designed (Fig. 2). The structure features struts of 4 mm length at 90°, 60°, 45°, 30° and 15° with respect to the build plate.

2.2.2. Stochastic architected material

A stochastic structure was produced for mechanical testing by filling a 3D volume with a random distribution of points using a Poisson Disk algorithm that maintains a specific minimum proximity. These points were then connected to each other to achieve a desired connectivity. Finally all struts below a specified angle were removed to optimise the structure for the AM build process. The designed structure was 13 mm × 21 mm to ensure after removal from the build plate it maintains a Height:Diameter ratio of > 1.5 and conforms to ISO 13314:2011 (Fig. 3).

2.3. Testing

The number of specimens manufactured and tested is summarised in Table 1, laser parameter values and ranges are also listed.

2.3.1. Evaluation of characterization structures

By varying the laser parameters and scanning strategy, the energy delivered to the melt-pool was altered to produce struts of different diameters. For the Contour and Points strategy, per laser power explored, 5 values of exposure time were chosen from the given range. For the Pulsing strategy, 2 parameter sets were selected at 50 W and 200 W and 5 values of repeated exposures per point were chosen from the given range. Thus 20 parameter sets per material per scanning strategy were manufactured and analysed giving 120 unique specimens (Table 1). The structures were first cleaned ultrasonically in Ethanol, then imaged using a scanning electron microscope (Hitachi S-3400N); strut thickness was measured utilising ImageJ [29]. For any successfully built specimen/strut, at least 10 measurements were taken from a variety of struts per strut angle from both Plan (Top) and Elevation (Front/Side) views. Measurements were then averaged and this was deemed ‘strut diameter’.

Fig. 1. Typical laser scanning strategies. Left: Traditional contour hatch scanning strategy. Right: Single exposure strategy.
2.3.2. Evaluation of stochastic architectured material

Samples were built either at a low power (50 W) or a high power (200 W) with exposure time and pulsing parameters (for the pulsed strategy) altered (Table 1). The same input geometry was used to generate all specimens with changes in strut diameter and thus specimen porosity and modulus being solely controlled by the laser parameters and scan strategy. Post build, samples were removed from the substrate by a low-force force controlled diamond blade high speed circular saw, ground parallel and cleaned ultrasonically in ethanol.

Overall structure relative density per unique specimen was measured by dry weighing with \( n = 5 \); dry weighing occurred in normal atmosphere conditions and relative density was calculated by dividing actual weight by the theoretical weight of the macro volume using a density of 4.42 g/cm\(^3\) for Ti6Al4V ELI and 8.1 g/cm\(^3\) for SS316L. A micro-CT (Bruker Skyscan 1172) was used to validate structure relative density and to measure internal porosity (pores in struts). 4 unique specimens were chosen per laser power per material per scanning strategy and a single sample of each type was scanned over a height of 5 mm with a 5 \( \mu \)m resolution. CT images were reconstructed and then analysed in CTAn 1.16.4.1 (Bruker microCT N.V.).

Quasi-Static compression testing was performed to ISO 13314:2011 [30] using a materials testing machine (Instron 8872) equipped with either a 5 kN, 10 kN or 25 kN load-cell depending on the specimen. Specimens were crushed between two parallel hardened (\( > 62 \) HRC) lubricated platens, a centring tool ensured specimens were in the centre of the platens. A preliminary specimen per type was compressed to 50% strain at a constant strain rate of 2 mm/min (\(-0.1\) strain/min) to estimate the yield strength. To determine the mechanical properties per unique specimen (\( n = 5 \)), samples were loaded to 50% strain at a constant strain rate of 2 mm/min. Since surface strain measurements have

![Fig. 2. Characterization Structure Manufacture Workflow.](image)

![Fig. 3. Stochastic porous structures.](image)
shown that there is localized plasticity at stresses well below the compressive strength of porous specimens which reduces the slope of the initial loading curve [31], a hysteresis loop starting at 70% and reversing at 20% of the estimated yield strength was used to determine the modulus (Fig. 4).

Displacement between the platens was measured at 30 Hz by two LVDTs (RDP D6/05000A) to eliminate test-machine compliance (Fig. 4). Strain was the averaged measured LVDT displacement divided by the original specimen height and stress was calculated as the force measured from the load-cell divided by the original specimen cross-sectional area. Stress-Strain curves were produced for each test; elastic modulus was taken as the linear regression of the hysteresis loop whilst the yield strength (compressive proof stress) of the structure is determined as compressive stress at a plastic compressive strain of 1.0% relative to the elastic modulus (Fig. 4). Finally, a set of specimens compressed to only 10% strain were videoed for failure analysis.

Build time was also measured for each unique specimen and defined as all the scanning time including the laser firing time, scanner and jump delays and processing delays; essentially all the time required to build a single part except for physical powder dosing time.

3. Results

3.1. Evaluation of characterization structures

Struts ranging in build angles from 90° to 15° were successfully manufactured in both materials for all 3 scanning strategies. Table 2 lists the minimum strut diameter produced successfully for each scanning strategy per material whilst Table 3 lists the laser parameters used to produce the minimum strut diameters.

Increasing specific Enthalpy (Eq. (2)) resulted in an increase in melt-pool size and thus an increase in strut thickness (Figs. 5 and 6). The relationship between specific enthalpy and strut thickness was found to be linear for all materials, scanning strategies and build angles (Fig. 7). The relationship was found to be more accurate when specific enthalpy was calculated with actual laser power and exposure time/scanning speed (not requested power and speed) as measured by the process monitoring equipment.

3.2. Mechanical testing of stochastic porous structures

Manufactured specimens had relative densities ranging from 5 to 25% and moduli of 0.2–4.5 GPa for Ti6Al4V ELI and 0.3–5 GPa for SS316. All samples had the same structure, with different porosity and modulus a result of varying strut thickness. Typical stress-strain plots for both materials are seen in Fig. 4. A power relationship was modelled between yield strength and modulus (Fig. 8 & Fig. 10) as per Gibson and Ashby [32,33].$R^2$ values for all curve fits were 0.99 and error bars on plots (Fig. 8 & Fig. 10) are standard deviations.

Ti64 samples built at 50 W have up to 10% higher strength:modulus ($\sigma_y:E$) ratio than those built at 200 W (Fig. 8a). The opposite phenomenon is seen for SS316, where samples built at 200 W have up to 10% higher $\sigma_y:E$ ratio than those built at 50 W (Fig. 8b). For both materials, these relationships were consistent for all scan strategies (contour, points, pulsed). Internal porosity ($\Phi$) was found to increase with modulus or relative density and was significantly lower for samples built at 50 W than at 200 W, this was true for both materials and all scan strategies (Fig. 9).

Selecting the optimum curve for each strategy in terms of strength (i.e. samples built at 50 W for Ti64 and samples built at 200 W for SS316) and plotting the compressive yield strength vs. modulus; it was found that at low stiffness ($b$ 1.5 GPa) the $\sigma_y:E$ ratio is the same for all 3 strategies but as stiffness increases the Contour Strategy produces samples with the highest $\sigma_y:E$ ratio, then the points strategy
then pulsing (Fig. 10). No discernible variation in internal porosity was observed between samples built via the Points and Contour strategy for either material, however the Pulsing strategy had significantly more porosity than the other scanning strategies in both Ti64 and SS316.

Build time was found to vary linearly with relative density for all scanning strategies. The Points strategy offered the fastest build time, double the speed of the Pulsing strategy and 20% faster than the Contour strategy. Supplementary Video 4 (Stainless Steel) & 5 (Titanium) depict these trends. The Points strategy then pulsing.

Table 2

| Build angle | Strut thickness (mm) |
|-------------|----------------------|
|             | 90°      | 60°      | 45°      | 30°      | 15°      |
| Ti64 – points | 0.142 ± 0.014¹ | 0.153 ± 0.014¹ | 0.153 ± 0.014¹ | 0.174 ± 0.017² | 0.219 ± 0.029³ |
| Ti64 – pulsing | 0.154 ± 0.020³ | 0.161 ± 0.014¹ | 0.164 ± 0.020³ | 0.168 ± 0.020³ | 0.224 ± 0.022³ |
| Ti64 – contour | 0.151 ± 0.020³ | 0.164 ± 0.020³ | 0.163 ± 0.014¹ | 0.178 ± 0.010⁴ | 0.236 ± 0.029⁵ |
| SS316 – points | 0.133 ± 0.009⁷ | 0.147 ± 0.020⁶ | 0.145 ± 0.009⁶ | 0.168 ± 0.012⁸ | 0.218 ± 0.039⁹ |
| SS316 – pulsing | 0.130 ± 0.011¹ | 0.150 ± 0.012² | 0.154 ± 0.009⁸ | 0.174 ± 0.017¹ | 0.224 ± 0.024² |
| SS316 – contour | 0.137 ± 0.012¹ | 0.164 ± 0.019¹ | 0.152 ± 0.009¹₀ | 0.172 ± 0.017¹¹ | 0.238 ± 0.013¹⁰ |

They also found modulus (E) to increase with relative density by a power law (Eq. (4)).

\[
\frac{E}{E_0} = C_2 \left( \frac{\rho}{\rho_0} \right)^m
\]

(4)

where \(E_0\), \(\rho_0\) and \(E_0\) are the properties of the base material (i.e. solid titanium or stainless steel) and \(C_2\), \(m\) and \(n\) are constants found experimentally. It is important to note these equations are only accurate to a relative density of 0.3 [33]. If Eq. (4) is substituted into Eq. (3) for relative density, a relationship between strength and stiffness is obtained, as seen in Eq. (5). This is the same relationship as the trend lines seen in Figs. 8 and 10.

\[
\frac{\sigma}{\sigma_0} = C_1 \left( \frac{E}{E_0} \right)^\# = C_3 \left( \frac{E}{E_0} \right)^\#
\]

(5)

Brittle failure was seen for structures built in Ti64, whilst a ductile failure mechanism was observed for the Stainless Steel specimens tested in this study (Fig. 4). The titanium structures had far superior strength for a given stiffness (approx. 2×) compared to the stainless steel structures. The Ti64 structures are also in the range of strength of cancellous bone for the same stiffness [5] which is highly encouraging for their adoption in new orthopaedic devices.

4.2. Effect of laser parameters and scanning strategies on material properties

This study highlights that the strength of AM architectured materials is a factor of many variables, including structure relative density, internal porosity, microstructure, quality of the strut junctions, strut thickness, weld-neck thickness and surface finish [11,33]. Figs 8 and 10 illustrates that as structure modulus and relative density increases, due to an increase in specific enthalpy (struts getting thicker), so does the internal porosity. This is corroborated in literature, as researchers have shown that for changing a single laser parameter (i.e. power, scanning speed etc.) whilst keeping all others constant results in curve for internal porosity with three distinct regions: a decreasing negative gradient region, a minimum (0 gradient) region and an increasing positive gradient region. At low enthalpies (negative gradient region) there is insufficient energy/heat to cause full melting of the powder particles and there is a lack of melt-pool overlap resulting in porosity. As enthalpy or laser energy increases (going from the minimum region to positive gradient region) eventually excessive heat and energy will cause increasing porosity due to excess evaporation and ablation of powder, denudation zones, keyhole porosity and a volatile turbulent melt-pool which results in splashing of molten material [19,22,35]. Only the minimum region and positive gradient region of the internal porosity curves were observed in Figs. 8 and 10. This was because unlike for AM solids, if there was not enough energy to cause full melting of the powder particles, a porous AM material would not successfully build for the scanning strategies, laser parameters and strut thicknesses explored in this research (Fig. 5).
For a given structure modulus, differences were observed in internal porosity depending on the laser power and scan strategy used. Maintaining a constant enthalpy whilst changing the laser parameters or scan strategy does not result in a constant internal porosity (Fig. 9). This was also found to be true for solid Ti64 \[19\] and SS316 \[36\] parts, where researchers varied the laser power and scanning speeds whilst maintaining a constant enthalpy; which resulted in variations in internal porosity. This is likely due to melt-pool turbulence and volatility not being constant with the quantity of energy delivered but varying with the rate and manner with which energy is delivered by the laser to the melt-pool \[22,37\].

Figs. 8 and 10 also highlight that in quasi-static compression testing of porous architectured materials, internal porosity in struts was not solely responsible for variations in strength between samples built at different powers or with different strategies. Changes in the laser parameters and scan strategy used during manufacture will affect the thermal history of the melt-pool and therefore the microstructure of the material \[37\]. This is confirmed in literature of both solid \[20,26,38\] and porous \[22\] AM materials, where changing the laser parameters and scanning strategies resulted in changes in microstructure and consequently changes in strength. Farshidianfar et al. \[39\] built SS316 samples with constant energy density (Eq. (1)) but different laser parameters via blown-powder laser AM. Between samples, they observed variations in peak and average melt-pool temperatures, time spent at peak temperature and cooling rates during solidification and subsequently different microstructures were seen in each sample. Li et al. \[26\] compared pulsed versus continuous build strategies and found that the pulsed-wave strategy had double the cooling rate which resulted in finer columnar microstructure when compared to the continuous-wave strategy. Furthermore, there is a breadth of AM research establishing the effect of the microstructure obtained after processing on the mechanical properties of AM parts \[37\].

In this study, structures with a given modulus but built by different laser parameters or scanning strategies had differences in strength...
caused by a combination of variations in internal porosity and microstructure. Brittle materials (Ti64) were likely more sensitive to internal porosity than ductile materials (SS316). For both materials at a given modulus or enthalpy, samples built at 50 W, had lower internal porosity, due to less melt-pool turbulence and volatility, than those built at 200 W [22,37]. Whilst this translated to samples built at 50 W having greater strength in Ti64, it was not the case in SS316. The greater strength of specimens built at 200 W versus 50 W in SS316 would therefore be driven by differences in microstructure rather than by internal porosity. The opposing trends observed for Ti64 and SS316 (Fig. 8) with respect to optimum laser power, can also be attributed to differences in the absorptivity, melting point, boiling point, thermal conductivity and density of the materials with respect to melt-pool thermal history and grain and phase structure development. Particularly Ti64’s lower density, lower thermal conductivity and higher absorptivity means titanium absorbs more laser energy in a given time whilst the melt-pool heat conducts away slower when compared to stainless steel.

There was no discernable variation in internal porosity between samples built via the Points and Contour strategy for either material, however the Pulsing strategy had significantly more porosity than the other scanning strategies. SEM and micro-CT imaging did not reveal any significant differences in surface finish or quality of strut junctions between strategies. Therefore, the greater strength of specimens built by the Contour strategy at higher stiffness or relative density can be attributed to variations in microstructure, as it has been shown that scanning strategy affects the thermal history of the melt-pool which consequently alters microstructure and strength [26,37,38].

As stated earlier, at low stiffness or minimum to very thin strut thicknesses, no significant variation was observed between the strength of the porous materials manufactured by the 3 scan strategies. This can be attributed to a change in failure mechanics and low effective or specific metal strength of the structure [11,22]. This is because at very thin strut thicknesses there exists very small weld-necks between melt-pools (Fig. 6) and poor quality strut junctions and there is premature failure due to these defects and therefore the differences in strength due to microstructure or porosity are not as visible.

4.3. Validity of the specific enthalpy model

This study has also shown that strut thickness in a porous material can be driven by laser energy alone, and the specific enthalpy model provides a good relationship for strut thickness. This means that a single line-based geometrical definition of a part can be assigned different thickness, stiffness, strength or density by building it with the appropriate laser parameters. Indeed, this approach allows for gradients of properties throughout the same single line-based part simply by changing the laser parameters throughout the part. This is important as the future

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Fig. 7. Strut thickness vs. specific enthalpy plots for a) the point strategy in SS316 (also typical for the pulsing strategy) and b) the contour strategy in Ti64. Plots are typical for both materials. Due to high number of data points and for graphical clarity, error bars not shown. Average S.D. for strut thickness measurements was 0.018 mm.
of architectured material generation is likely to move from solid CAD modelling to line based representations. It is particularly relevant in the orthopaedic field where stiffness gradients are common throughout the human skeleton.

Increasing specific enthalpy resulted in increases in strut thickness. It was seen that strut thickness varies linearly with specific enthalpy regardless of material, scanning strategy and build angle and that the model is accurate to ±50 μm over a large range of strut thicknesses. These findings are consistent with what other researchers have found for single track experiments [24,25] and thus provides more evidence to the validity of using the enthalpy model for predicting melt-pool or strut size. It was seen that as enthalpy increases, struts become more ‘stable,’ the weld-neck between melt-pools increased, the strut thickness and the strut angle became more consistent and the number of semi-fused particles on the strut increased as well (Figs 5 and 6). For a given enthalpy the lower the angle of the strut, the thicker it was (Fig. 7). This was caused by changing conductivity conditions, for vertical struts every layer is built upon solid material and so much of the heat in the melt-pool gets conducted away, whilst for low angle struts which are built partially on solid material and partially on powder the heat gets conducted away far slower as the powder has a lower conductivity than the solid material, consequently this greater heat in the melt-pool results in thicker struts.

For a given enthalpy, the contour strategy produced struts with a more consistent thickness across all build angles when compared to the points and pulsing strategies. It was expected that the points/pulsing strategy would be able to produce thinner struts than the contour strategy due to their ability to deliver energy to the melt-pool in a smaller area, however no difference was seen. Despite the contour strategy delivering energy over a larger area than the points/pulsing strategy, residual heat in the melt-pool may mean less energy needs to be delivered by the laser to create the same size melt-pool as from the points/pulsing strategy.

The other reason why no major difference was seen may be because...
the melt-pool depth needs to be significantly larger than the slice thickness (50 μm) to successfully build a competent strut and all three strategies were able to deliver the minimum energy required. If a smaller laser spot, thinner slice thickness and smaller powder size were used an observable difference may have been detected between strategies.

4.4 Limitations

As stated earlier, whilst specific enthalpy may be accurate for predicting strut thickness or melt-pool track width it may not be the best indicator for internal porosity or microstructure. Varying the laser parameters and scanning strategies whilst maintaining a constant specific enthalpy does not guarantee constant internal porosity or a consistent microstructure. Another limitation of the study was that depending on build angle for a given enthalpy, the points/pulsing strut thicknesses vary by a greater amount than those manufactured by the contour strategy (Fig. 7). This means the structure will have had slightly different strut thicknesses at different angles for a given stiffness or density depending on what strategy it was built with.

A further limitation was due to a deviation from ISO 13314 [30]. The hysteresis loop which was used to calculate the elastic modulus, was based on a percentage of the estimated yield strength of a preliminary sample rather than the plateau stress. This was due to the brittle nature of the titanium alloy used, meaning titanium samples had a far lower and more varied plateau stress than the stainless steel samples. The resulting hysteresis loop was therefore very early on in the elastic portion of the stress-strain curve and gave a low modulus (modulus varies with the location of the hysteresis loop on the elastic/linear portion of the stress-strain curve). By using the yield strength to calculate the percentages for the hysteresis loop the results between the two materials tested were far more consistent and comparable. The low standard deviations of the results and compliance to theoretical models suggests this was appropriate.

Whilst differences were seen in the static mechanical and material properties between structures built via different scanning strategies and laser parameters, these differences may be reduced or exacerbated when loaded in fatigue. Fatigue testing of these structures will further elucidate the effect of internal porosity and microstructure when optimising laser parameters and scan strategies for mechanical performance as well as the suitability of these structures in orthopaedics and other cyclic loading applications.

5. Conclusion

This study demonstrated that the mechanical properties of a porous material produced by powder bed fusion are not only affected by its geometric properties (strut thickness, density, internal porosity etc.) but also by its method of manufacture. The method and rate of energy delivery and laser scan strategy had a significant effect on the strength of a stochastic porous structure for a given stiffness or density. When optimising laser parameters and scan strategy for a porous structure it was found that the optimum method of energy delivery is material dependent. As the future of the architected material generation is likely to move from solid CAD modelling, which is computationally expensive, to line based representation it is imperative to know how laser parameters and scan strategy relate to strut thickness. This study showed that using the specific enthalpy equations instead of traditional energy density equations can produce an accurate and scalable model relating strut thickness to the laser parameters.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.matdes.2017.06.041.

Acknowledgements

The authors wish to gratefully acknowledge the Engineering and Physical Sciences Research Council and Renishaw PLC for their financial and technical support of this study through grant number EP/K027549/1.

References

[1] L. Mullen, R.C. Stamp, W.K. Brooks, E. Jones, C.J. Sutcliffe, Selective laser melting: a regular unit cell approach for the manufacture of porous, titanium, bone ingrowth constructs, suitable for orthopedic applications, J. Biomed. Mater. Res. B Appl. Biomater. 89B (2) (2009) 325–334.
[2] M.J. Matthews, G. Guss, S.A. Kairallah, A.M. Rubenchik, P.J. Depond, W.E. King, De-
nudation of metal powder layers in laser powder bed fusion processes, Acta Mater. 116 (2016) 33–42.

[3] S. McKown, Y. Shen, W.K.S. Brooks, C.J. Sutcliffe, W.J. Cantwell, G.S. Langdon, G.N. Nurick, M.D. Theobald, The quasi-static and blast loading response of lattice struc-
tures, Int. J. Impact Eng. 35 (8) (2008) 795–810.

[4] V.J. Challis, X. Xu, L.C. Zhang, A.P. Roberts, J.F. Grotowski, T.B. Sercombe, High specific strength and stiffness structures produced using selective laser melting, Mater. Des. 63 (2014) 783–788.

[5] S.A. Goldstein, The mechanical properties of trabecular bone: dependence on ana-
tomic location and function, J. Biomech. 20 (11–12) (1987) 1055–1061.

[6] P. Heini, L. Müller, C. Körner, R.F. Singer, F.A. Müller, Cellular Ti–6Al–4V structures with interconneced macro porosity for bone implants fabricated by selective electron beam melting, Acta Biomater. 4 (5) (2008) 1536–1544.

[7] M. Mullen, R.C. Stamp, P. Fox, E. Jones, C. Ngo, C. Sutcliffe, Selective laser melting: a unit cell approach for the manufactur of porous, titanium, bone-in-growth con-
structs, suitable for orthopedic applications. II. Randomized structures, J. Biomed. Mater. Res. B Appl. Biomater. 92B (1) (2010) 178–188.

[8] S. Amin Yavari, R. Waustelle, J. van der Stok, A.C. Rienslåg, M. Jansen, M. Muller, J.P. Kruth, J. Schrooten, H. Weinas, A.A. Zadpoor, Fatigue behavior of porous biomate-
rials manufactured using selective laser melting, Mater. Sci. Eng. C 33 (8) (2013) 4849–4858.

[9] R. Waustelle, J. van der Stok, S. Amin Yavari, J. Van Humbeek, J.-P. Kruth, A.A. Zadpoor, H. Weinas, M. Muller, J. Schrooten, Additively manufactured porous tan-
talum implants, Acta Biomater. 14 (2015) 217–225.

[10] O. Rehme, Cellular Design for Laser Freeform Fabrication, Cuviller Göttingen, 2009.

[11] S. Toopanios, R.A.W. Mines, S. McKown, Y. Shen, W.J. Cantwell, W. Brooks, C.J. Sutcliffe, The influence of processing parameters on the mechanical properties of selectively laser melted stainless metal microlattice structures, J. Manuf. Sci. Eng. 132 (4) (2010) 041011.

[12] S. Arabnejad, R. Burnett Johnston, M.D. Theobald, The quasi-static and blast loading response of lattice struc-
tures produced using selective laser melting, Acta Biomater. 119 (2017) 351–360.

[13] M.J. Matthews, G. Guss, S.A. Kairallah, A.M. Rubenchik, P.J. Depond, W.E. King, De-
nudation of metal powder layers in laser powder bed fusion processes, Acta Mater. 116 (2016) 33–42.

[14] N.W. Hrabe, P. Heinl, B. Flinn, C. Körner, R.K. Bordia, Compression-compression fa-
iling unit cells: the mechanical and morphological properties, Materials 8 (4) (2015) 114 (2016) 33

[15] S. Ahmadi, S. Yavari, R. Wauthle, B. Pouran, J. Schrooten, H. Weinans, A. Zadpoor, Ad-
hesion of bone to additively manufactured cellular structures, J. Mat. Res. B Appl. Biomater. 99B (2) (2011) 313–320.

[16] M.J. Matthews, G. Guss, S.A. Kairallah, A.M. Rubenchik, P.J. Depond, W.E. King, De-
nudation of metal powder layers in laser powder bed fusion processes, Acta Mater. 116 (2016) 33–42.

[17] C.A. Schneider, W.S. Rasband, K.W. Eliceiri, NIH image to ImageJ: 25 years of image analy-
sis, Nat. Meth. 9 (7) (2012) 671–675.

[18] ISO13314, Mechanical Testing of Metals. Ductility Testing, Compression Test for Po-
rous and Cellular Metals, 2011.

[19] M.F. Ashby, A.G. Evans, N.A. Fleck, L.J. Gibson, J.W. King, H.D. Barth, V.M. Castillo, G.F. Gallegos, J.W. Gibbs, D.E. Hahn, C. Kamath, A.M. Rubenchik, Observation of keyhole-mode laser melting in laser powder-bed fusion additive manufacturing, J. Mater. Process. Technol. 214 (12) (2014) 2915–2925.

[20] D.B. Hann, J. Jammj, J. Folkes, A simple methodology for predicting laser-weld proper-
ties from material and laser parameters, J. Phys. D. Appl. Phys. 44 (44) (2011) 445401.

[21] W.E. King, H.D. Barth, V.M. Castillo, G.F. Gallegos, J. Gibbs, D.E. Hahn, C. Kamath, A.M. Rubenchik, Observation of keyhole-mode laser melting in laser powder-bed fusion additive manufacturing, J. Mater. Process. Technol. 214 (12) (2014) 2915–2925.

[22] S. Li, H. Xiao, K. Liu, W. Xiao, Y. Li, X. Han, J. Mazumder, L. Song, Melt-pool motion, temperature variation and dendritic morphology of Inconel 718 during pulsed-
and continuous-wave laser additive manufacturing: a comparative study, Mater. Des. 119 (2017) 351–360.

[23] R. Hasan, Progressive Collapse of Titanium Alloy Micro-Lattice Structures Manufactured Using Selective Laser Melting (PhD Thesis), University of Liverpool, 2013.

[24] O. Cansizoglu, O.L.A. Harrysson, H.A. West, D.R. Cormier, T. Mahale, Applications of structural optimization in direct metal fabrication, Rapid Prototyp. J. 14 (2) (2008) 114–122.

[25] C.A. Schneider, W.S. Rasland, K.W. Eliceiri, NIH image to ImageJ: 25 years of image analy-
sis, Nat. Meth. 9 (7) (2012) 671–675.

[26] ISO13314, Mechanical Testing of Metals. Ductility Testing, Compression Test for Po-
rous and Cellular Metals, 2011.

[27] M.F. Ashby, A.G. Evans, N.A. Fleck, L.J. Gibson, J.W. King, H.D. Barth, V.M. Castillo, G.F. Gallegos, J.W. Gibbs, D.E. Hahn, C. Kamath, A.M. Rubenchik, Observation of keyhole-mode laser melting in laser powder-bed fusion additive manufacturing, J. Mater. Process. Technol. 214 (12) (2014) 2915–2925.

[28] D.B. Hann, J. Jammj, J. Folkes, A simple methodology for predicting laser-weld proper-
ties from material and laser parameters, J. Phys. D. Appl. Phys. 44 (44) (2011) 445401.