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

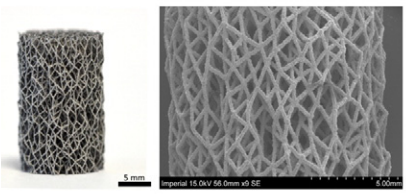
Shaaz Ghouse [a], Sarat Babu [b], Richard J. Van Arkel [a], Kenneth Nai [c], Paul A. Hooper [a], Jonathan R.T. Jeffers [a],*

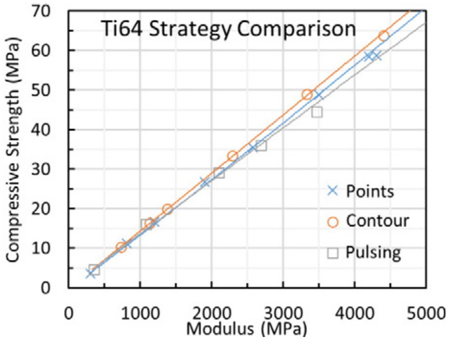
[a] *Department of Mechanical Engineering, Imperial College London, London SW7 2AZ, United Kingdom*
[b] *Betatype Ltd., 61-63 Rochester Place, London NW1 9JU, United Kingdom*
[c] *Renishaw PLC, New Mills, Wotton-under-Edge, Gloucestershire GL12 8JR, United Kingdom*

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 meltpool, 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





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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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* Corresponding author.
E-mail address: j.jeffers@imperial.ac.uk (J.R.T. Jeffers).

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1. Introduction

Additive manufactured (AM) architectured 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 architectured 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 filing polyhedrons [13] and triply 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 architectured 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.

$$E = P \times t \text{ or } E = \frac{P}{u \times h \times l} \tag{1}$$

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 (ΔH) delivered by the laser to the powder bed. Where specific enthalpy is a function of Absorptivity (A), thermal diffusivity (D) and density (ρ) of the powder and of the laser parameters, namely, laser power (P), laser scan speed (u) and laser spot diameter (Ø).

$$\Delta H = \frac{A \cdot P}{\rho\sqrt{\pi \cdot D \cdot u \cdot \varnothing^3}} \tag{2}$$

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 architectured 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 architectured 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, $\lambda = 1.07$ μm), 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