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The influence of laser parameters, scanning strategies and material on the fatigue strength of a stochastic porous structure

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ABSTRACT

Additive manufactured (AM) porous materials behave quantitatively and qualitatively differently in fatigue than bulk materials, and the relationships normally used for the fatigue design of continuous bulk materials are not applicable to AM porous materials particularly for low stiffness applications.

This study investigated how the manufacturing methods and the material used during powder bed fusion affects the compressive strength and high cycle fatigue strength of a stochastic porous material for a given stiffness. Specimens were manufactured using varying laser parameters, 3 scan strategies (Contour, Points, Pulsing) and 4 materials. The materials investigated were two titanium alloys: commercially pure grade 2 (CP-Ti) and Ti6Al4V ELI, commercially pure tantalum (Ta) and a titanium-tantalum alloy (Ti-30Ta).

The trends observed during fatigue testing for monolithic metals and statically for solid and porous AM materials were not always indicative of the high cycle fatigue behaviour of porous AM materials. Unlike their solid counterparts, porous tantalum and the titanium-tantalum alloy had the greatest fatigue strength for a given stiffness, 8% greater than CP-Ti and 19% greater than Ti6Al4V ELI. Optimisation of the laser parameters and scan strategies was found to also increase the fatigue strength for a given stiffness of porous AM materials by 7–8%.

1. Introduction

Maximising strength of additively manufactured (AM) porous metals at low stiffness remains a challenge for engineers, particularly in applications under high cyclic loads [1–3]. One such application is in orthopaedics, where bone repair and regeneration can be driven by strain response with respect to load [4–6]. Thus, to accelerate bone regeneration, a porous scaffold or porous coating on an implant should have a stiffness similar to or less than the bone that is being replaced (0.05–0.5 GPa for trabecular bone and 7-30 GPa for cortical bone [7]). The porous structure must then not only have maximum strength, but more importantly, maximum fatigue strength as it is constantly under varying loads. The manufacturing methods, the architecture of the structure and the base material all provide opportunities to maximize the static and fatigue strength of AM porous materials.

The manufacturing methods in powder bed fusion can be optimised to increase the strength of a porous material for a given stiffness. Previous work has shown that the strength of a porous material could be increased up to 10% for a given stiffness by altering the laser parameters or scanning strategies used during manufacture [8]. It was shown that the optimisation of laser power was material specific, whilst a contour scan strategy produced stronger structures than a points or pulsing scan strategy, regardless of material. This was driven by changes in internal porosity and microstructure caused by the altering of the thermal history of the melt-pool [9–14]. The role of laser parameters on improving material density, strength and microstructure for solid AM parts [9,14–17] has also been studied whilst generally for porous materials research has focused on improving mechanical properties with respect to relative density (i.e. strength or stiffness-to-weight) [18–20]. The above work has solely reported on static mechanical properties and thus there is a lack of research investigating the effect of laser parameters on fatigue properties of AM porous materials.

The majority of research on AM porous materials has investigated different architectures, characterising the static strength and stiffness of structures at varying relative densities. Typically, non-stochastic architectures are investigated [19,21–25], with pseudo-random structures [26] and fully stochastic architectures [8,27] receiving far less attention. When the fatigue behaviour of porous AM materials is investigated, compression – compression fatigue testing is usually performed, with materials exhibiting a three – stage fatigue behaviour

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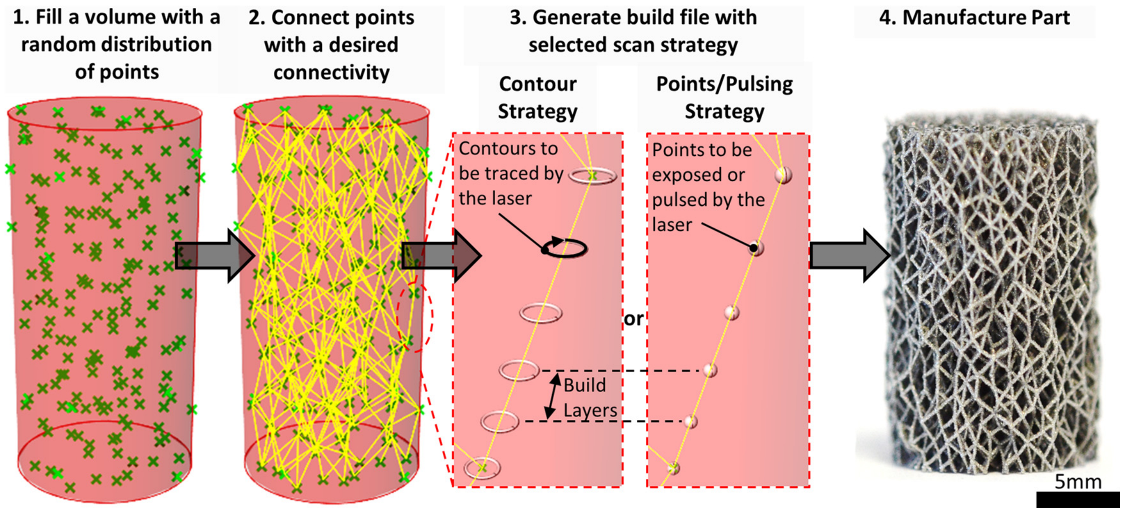

Fig. 1. Manufacturing Workflow from Specimen Design to Build File Generation to Manufacture. Note: 1–3 are simplified for clarity and not to scale.

[28]. In Stage 1 there is a settling in period where specimens accumulate a small amount of plastic strain slowly until Stage 2 where there is a very minimal accumulation of strain with increasing cycles, until finally in Stage 3 the strain increases very rapidly and the specimen fails catastrophically within a limited number of cycles. Increasingly, researchers have looked comparatively at different architectures and their static and fatigue properties [2,29–33] however this has been exclusively on non-stochastic architectures.

The base material of a porous structure naturally plays an important role in governing its behaviour and mechanical properties, such as its strength-to-stiffness ratio. In orthopaedics the trend is towards materials or alloys with low modulus, high strength, high fatigue strength and that are corrosion resistant and biocompatible [34,35]. Historically, Ti6Al4V has been used for solid orthopaedic implants due to its high strength and fatigue life. However, increasing research [36] and current commercial porous implants [18,26] have supported the use of commercially pure titanium (CP-Ti) and tantalum for porous features [37]. As a porous material, CP-Ti has a ductile failure mode as opposed to the brittle failure mode of Ti6Al4V. Despite its lower static strength, CP-Ti has been shown to have a higher relative fatigue strength for a given number of cycles-to-failure than Ti6Al4V [37,38] and better fatigue strength-to-weight [37]. Statically however, both as solid and porous AM parts, CP-Ti appears to have a lower static strength:stiffness ratio than Ti6Al4V [39].

Tantalum as a porous material for orthopaedics is attractive due to its corrosion resistance, biocompatibility, and ductility, however it is prohibitively expensive [36]. Preliminary work has shown that porous AM tantalum, whilst having a similar yield strength to CP-Ti, has a higher relative fatigue strength and better fatigue strength-to-weight than both titanium alloys discussed [37]. Alloying titanium and tantalum together can increase the strength and ductility of the resulting material whilst reducing modulus [1,35,39]. For both solid and porous AM parts, a 50% titanium – 50% tantalum alloy was shown to have a higher strength:stiffness ratio than CP-Ti and Ti6Al4V specimens [39]. The effect of tantalum content in a titanium – tantalum alloy has also been investigated and it was seen that a good combination of high strength-to-stiffness ratio, high elongation to failure and cost was with a 70% titanium – 30% tantalum alloy [40]. However, there is currently no fatigue data for either solid or porous AM titanium – tantalum materials.

For engineers looking to optimise the yield and fatigue strength for a given stiffness of AM porous structures, there are hurdles still to overcome. Most studies have limited or no samples tested in the higher cycle fatigue region (10^6 or higher cycles) and these studies also tend to present mechanical properties with respect to relative density or cycles-to-failure and not with respect to stiffness. Extracting and comparing stiffness data from these works can prove difficult as often the quasi-elastic gradient [41] and not the elastic modulus is reported. The quasi-elastic gradient, which is the slope of the initial loading curve during compression, is always lower than the elastic modulus as AM porous materials have localized plasticity at stresses well below their compressive strength, which reduces the slope of this initial loading curve [42]. There is also often ambiguity regarding how strain has been measured during testing and thus the existence of test machine compliance may be present.

The fatigue behaviour of AM porous materials is quantitatively and qualitatively different from that of bulk materials and the relationships normally used for the fatigue design of continuous materials are not applicable when designing AM porous materials [31]. Therefore, the aim of this work is to first investigate how laser parameters and scan strategies influence the high cycle fatigue properties of an AM porous material for a given stiffness. Following this, commercially-pure titanium, titanium Grade 23, tantalum and a titanium – tantalum alloy will be investigated to see the effect of material on static strength and fatigue strength for a given stiffness.

2. Material and methods

2.1. Specimen design and build file generation

A stochastic structure was designed by filling a volume with a random distribution of points using a Poisson Disk algorithm in Rhinoceros 5.0 (Robert McNeel & Associates). These points were then connected to each other, as zero thickness lines, to achieve a desired connectivity (Fig. 1), with struts below 30° being removed to optimise the structure for the AM process. The designed structure was a ⌀13 mm × 21 mm cylinder to ensure after removal from the build plate it maintained a Height:Diameter ratio of > 1.5 and conformed to ISO 13314:2011 [41]. Material Engine 1.0 (Betatype Ltd.), a software platform that creates slice data for a variety of scanning strategies directly from line geometry (Fig. 1) was used to generate build files. It was therefore possible to compare different laser parameters, scanning strategies and materials all generated from the same input CAD. The three scan strategies that were used are described below for a powder bed fusion system. Videos and diagrams of the scan strategies can be found in [8].

2.1.1. Contour strategy

For a given 2D slice (build layer), strut geometry contours are traced by the laser (Fig. 1). Traditionally, the area enclosed by the contours are