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The effect of defects on the mechanical response of Ti-6Al-4V cubic lattice structures fabricated by electron beam melting

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ABSTRACT

Electron Beam Melting (EBM) as a means of Additive Manufacturing (AM), is of interest for the fabrication of intricate geometries for cellular materials in areas where complex architectures are needed, e.g. biomedical implants. Most studies have focused on specific geometries and so the effect of the structure on mechanical performance is not well understood. Many kinds of micro- and macro-scale defects can arise in additively manufactured components, so assessment of their influence on properties is needed. In this work, lattices of Ti-6Al-4V having a cubic structure have been manufactured by EBM, and the effect of heat treatments above and below the β-transus temperature on microstructure and compression response have been investigated. The former modifies only slightly the α + β structure and mechanical performance whereas the latter leads to coarse alternating α and β lamellae packets and α at the prior grain boundaries with a 10% loss in yield strength. The variation in the compressive yield stress with strut diameter is in good accord with simple models based on compressive deformation rather than shearing or buckling. Internal pores for struts aligned with the build direction are found around the edges of the solid form, in regions which seem to be associated with the EB scan pattern. Struts normal to the build direction show more significant defects but their redundancy means that they do not compromise the compressive performance in the build direction. Using a particle size in the range 45–100 μm minimum weld-track sizes were experimentally and numerically identified to be 176 and 148 μm in depth respectively with a depth-to-width ratio of 0.55. This produced a beam pass of the order of 300 μm oversizing small features (struts of 0.4 and 0.6 mm nominal diameter) when a contour around the strut periphery was applied.

1. Introduction

Lattice or micro-truss materials prepared by additive manufacturing (AM) have attracted interest due to the prospect of tailoring properties by the selection of different topologies. These structures belong to the class of materials known as cellular solids which comprise an interconnected network of struts or membranes [1]. These structures have been studied by x-ray imaging techniques [2] to characterise their structural configuration in three dimensions (3D) enabling relationships such as Eq. (1) [3] for the failure strength, σ*, in terms of the relative density, ρ_r, and parent material strength, σ_s:

$$\sigma^* = C\sigma_s\rho_r^{3/2} \quad (1)$$

to be evaluated where C a constant of proportionality (varying from 0.1 to 1 for metal foams [4]). In contrast to other cellular solids, lattice structures are often observed to fail dramatically and cooperatively due to the layer configuration [5]. This makes the failure strength more difficult to identify than in foams where there a clear plateau stress is common. Although there is no general rule to identify maximum strength prior failure, common practice is to define the failure strength as the intersection with the curve of a line matching the slope of the linear section at an offset strain [6]. Here in this work this method was used with an offset of 0.2%.

It is well known that structural predictions using models as

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the previously mentioned may not be accurate due to the variation of exponents and constants as the geometry changes. Additionally, structural models may underestimate the integrity of solid parts by not taking into account process features giving structures which do not meet the ideal assumptions, having internal porosity or being undersized [7]. In this context it should be recognised that there is often a disparity between the intended structural design and that achieved in practice. For example, volumetric defects are often present [8] and wall/strut thicknesses and geometries are not always faithfully reproduced due to manufacturing constraints. Furthermore for metallic lattices the microstructure arising from AM may be very different from that characteristic of the bulk alloy. From a performance optimisation viewpoint it is essential that these process related issues are well understood. Previous work [6] has shown that morphological defects in the struts and a lower intrinsic strength of the alloy as additively manufactured over that for the bulk are responsible for a significant decrease in matrix strength as the relative density of the lattice is decreased. This work suggests that the probability and influence of defects becomes higher as the strut dimensions are refined in scale however, the level of defects introduced is strongly related to the material deposition strategy [9] and thus indirectly also to the material being processed.

Up until now much of the focus of research has been on the instrumentation associated with additive manufacturing and its control. Further research on the effect of material deposition strategies and the influence of alloy microstructure is needed in order to optimize the structural performance of EBM components [10]. Consequently we have investigated the sensitivity of the compressive performance to defects in EBM scaffold structures. This is coupled with an investigation of the effect of alloy condition on properties comparing "as-built" and homogenized Ti-6Al-4V microstructures achieved by heat treatments above and below the β-transus temperature. In addition an analytical approach has also been developed to compare results with expectations.

2. Experimental procedure

2.1. Structure design

A cubic unit cell (Fig. 1a) was designed in Netfabb® and replicated to generate a 4 × 4 × 4 cell 3D lattice structure (Fig. 1b). An octagonal cross-sectional profile was used to define each strut (Fig. 1c), which can be described with a relatively low number of triangles in the STL (Standard Tessellation Language) file, while aiming for a circular shape of a cylinder to be produced. The STL file (Fig. 1d) was then converted into 2D as "sliced" files for manufacturing purposes. Four different strut diameters were used; 0.8, 1, 1.5 and 1.8 mm each with a 5 mm unit cell size (a 20 × 20 × 20 mm sample).

The calculations to determine the relative density of the designed structures were therefore based on the smallest repeating element, being the ratio of solid volume, Vs, for three intersecting cylinders within the volume of a unit cell, V_u, shown in Fig. 1a and Eq. (2).

$$\rho_r = \frac{V_s}{V_u} = \frac{3V_c - 3V_{I2} + V_{I3}}{l^3} = \left(\frac{d}{l}\right)^2 \left[\frac{3\pi}{4} - \frac{d\sqrt{2}}{l}\right] \quad (2)$$

where V_c, V_{I2} and V_{I3} are the volumes of a cylinder of length L and diameter *d*, the intersection of two cylinders and the intersection of three cylinders respectively.

2.2. Manufacturing

2.2.1. EBM processing and raw material

The raw material comprised spherical Ti-6Al-4V prealloyed powder (Al 6.49, V 4.05, C 0.02, Fe 0.21, O 0.252, N 0.037 in wt%) of 45–100 μm particle size. The EBM process was set up to deposit layers of 70 μm in thickness. In each layer, the powder was first preheated with a defocused beam, using a sequence of 10 passes across the build envelope ('preheat' setting in Table 1). The material deposition process comprised a "hatching" step and three consecutive "contours" ('Net' setting in Table 1). While the hatching (a continuous filling process) started at an offset of 0.05 mm from the CAD contour, the contouring (three consecutive "rings") started with an offset of 0.15 mm from the CAD contour and 0.1 mm offset from each other. Such an arrangement, if optimized, is intended to melt the entire area while avoiding unmelted powder and over/under sizing. The beam offset, is intended to account for the size of the melt pool, intrinsically defined by the beam power and the material response to the incoming electrons. From electron beam theory [11,12], it is known that the melt pool penetration is, among other factors, a function of the beam parameters of speed and power given in Table 1. It is critical then to identify the optimal electron beam parameters and offsets, especially for thin components, in order to achieve the desired resolution. However, it should be noted that melting micro-sections of the order of a few spherical particles would leave an intrinsic defect fraction due to the part size and shape relative to the powder size. This could take the form of interstices and severe roughness. In this investigation, all samples were fabricated using the same offset and electron beam parameters, and were tested in a direction parallel to the build orientation, leaving the strut diameter as the only variable.

2.2.2. Fabricated samples

18 lattice samples were manufactured for compression testing: 12 (3 of each strut thickness) for testing in the "as-built condition" (i.e. with no further heat treatment) and 6 (of 1.5 mm strut thickness) were heat treated. In addition, 9 (66 × 16 × 16 mm) cuboidal samples were made from which tensile bars were machined. The samples were fabricated using the same titanium powder as used for the lattices, but using the EB '*Melt*' settings described in Table 1 tailored for the processing of larger samples without the requirement to produce fine features accurately. The '*Melt*' setting employed a faster speed and increased beam power with no contours included.

In order to investigate the occurrence of different defects in the material at various diameter sections, single strut or "rod" samples were produced in a vertical orientation each representing a single structural element representative of the loaded lattice members. The processing and beam parameters were the same as those employed for the lattice samples, Table 1. These samples, S1 to S7, were designed to be 0.4, 0.6, 1, 1.2, 1.5, 1.8 and 2 mm in diameter.

Additionally, a set of 18 diamond-like lattice samples were manufactured for comparison. Their geometry was designed to have the same geometric relationship as the interatomic bonds in the diamond crystal structure (strut elements orientated at 109.5° from each other) of relative density 0.2, 0.4, 0.10, 0.11, 0.18, and 0.24. Such samples were manufactured to highlight the differences in mechanical response from cubic lattices only, leaving their characterisation to be analysed in a further communication.

2.3. The effect of thermal treatment

Three thermal treatments were explored; "as-manufactured", heat treated high in the α + β region and heat treated above the β–transus temperature. The temperature profiles of the heat