Materials and Design 63 (2014) 783–788

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Short Communication

High specific strength and stiffness structures produced using selective laser melting

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ARTICLE INFO

Article history:
Received 8 April 2014
Accepted 28 May 2014
Available online 12 July 2014

ABSTRACT

Selective Laser Melting (SLM) was used to fabricate scaffolds using the titanium alloy Ti–6Al–4V. Two types of high porosity open-cell structures were manufactured: the first built from topology optimised designs with maximised stiffness, and the second from gyroid labyrinths. In mechanical compression tests the scaffolds demonstrate exceptional strength- and stiffness-to-weight ratios. In particular, for densities in the range 0.2–0.8 g/cm^3 the topology optimised scaffolds have specific strength and stiffness that are superior to those of comparable materials in the literature. In addition, the optimised scaffolds have the benefit of being elastically isotropic. The results of finite element calculations accurately match the measured stiffness of the scaffolds. Calculated strain energy distributions provide insight into how the high stiffness and strength of the optimised designs is connected to their efficient distribution of load.

1. Introduction

Light-weight porous materials are becoming increasingly attractive for a number of applications. They are used to reduce weight in automotive and aerospace industries, improve thermal insulation properties, increase noise and vibration suppression, and match bone stiffness and aid osseointegration of medical implants [1]. In addition, they are used as a core in composite sandwich construction and in a variety of filter applications. There are a number of different methods for the production of porous materials (see, e.g., [2]). Examples include the foaming of liquid metals, conventional press-and-sinter powder metallurgy using space holders, replication, and additive manufacturing (AM) techniques such as Selective Laser Melting (SLM). Among these methods, only AM offers the opportunity to produce complex three-dimensional purpose-designed structures.

Additive manufacturing covers a group of advanced manufacturing technologies that fabricate parts directly from a computer solid model without the need for an expensive tool or die set. These techniques are unrivalled in their ability to produce parts with almost no geometrical constraints. One such AM technique is SLM, whereby metal powder is melted using a high intensity infrared laser beam that traces the geometry of each layer. After exposure of a layer, the build chamber descends ~50 μm, a fresh layer of powder is spread on top and the next layer is produced. This process continues until the part is complete. Due to its layer-by-layer nature, AM facilitates the fabrication of porous open cell scaffolds with complex internal architectures by allowing precise control of the porosity (including pore size, shape and interconnectivity). As SLM requires the removal of unmelted powder from within the structure, it is not possible to use SLM to create closed-cell "foams". The requirement to maintain open porosity is an advantage for applications such as bone replacements or filtration, although the requirement to maintain open porosity does result in a decrease in the theoretically attainable strength and stiffness [3]. This paper presents an analysis of open-cell materials produced with AM and shows that they have exceptionally high stiffness and strength.

Given its high strength and stiffness to weight ratios, titanium is a natural choice for producing parts with SLM. Its applications include light-weight and energy absorbing structures [4,5], biomedical scaffolds [6–14], and cores for sandwich construction [15–17]. To date, the emphasis has been on structures produced from relatively simple unit cells, including BCC/octahedral [4,5,12,15,17], rhombic dodecahedron [13], tetrahedral [6] and auxetic [18] structures. The flexibility of the SLM manufacturing process means that it is possible to design a structure for function, rather than to satisfy the geometric constraints of the manufacturing process. Unit cells

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http://dx.doi.org/10.1016/j.matdes.2014.05.064
0261-3069/

that are particularly optimised for high specific strength and stiffness could significantly improve the overall properties of these structures. The resultant constrained optimisation problem is suited to the framework of topology optimisation (see, e.g., [19]), which does not *a priori* prescribe the geometry or connectivity of the structure.

Two types of open cell, periodic scaffold architectures are considered in this paper. The "gyroid" (Fig. 1(a)) structure has previously been proposed as being particularly suited to additive manufacturing as it is self-supporting and can be built over a wide range of cell sizes with good agreement to the original CAD models [20,21]. The "optimised" (Fig. 1(b)) structure has been specifically designed using topology optimisation to have high stiffness. It is natural to expect that this structure will have high strength, but it is important to verify this experimentally.

2. Methods

Approximate gyroid labyrinths were generated using an implicit surface representation via the function

$$f(x,y,z) = \alpha - (\sin y \cos x + \sin x \cos z + \sin z \cos y), \quad (1)$$

where α is chosen to give the desired solid fraction, and x, y and z are the three spatial directions that each range over an interval of length 2π to generate a single unit cell. Values of $f(x, y, z)$ less than zero specify points inside the solid scaffold. This approximate representation arises from the simplest Fourier component expansion of the gyroid minimal surface (e.g., [22]). Gyroid scaffolds were generated at nominal solid fractions of approximately 5%, 10% and 15% using α values of 1.32, 1.125 and 1.06, respectively. The "optimised" unit cells at solid fractions between 7% and 20% were generated using the level set method of topology optimisation, as documented in previous work [23,24]. The objectives in the optimisation problem were a linear combination of the bulk modulus of the scaffold and the diffusivity within the pore space. In addition, the scaffolds were required to be macroscopically isotropic. This is a proxy for optimising the Young's modulus for every loading direction. Optimised scaffolds at a higher solid fraction as found previously [23] were used as starting structures for the optimisation. However, a higher computational resolution of $60 \times 60 \times 60$ elements within the base cell was required to facilitate the generation of optimised scaffolds at solid fractions below 20%. The scaffold representations were smoothed prior to manufacture via SLM.

Scaffolds were manufactured on a Realizer SLM100 machine using Ti–6Al–4V powder sourced from TLS Technik in Germany. The details of the powder are shown below in Table 1, while the processing parameters are summarised in Table 2. The following

Table 1
Selected characteristics of the Ti–6Al–4V powder (TLS Technik GmbH) used in this work.

Powder composition (wt%)						Powder size (μm)		
Ti	Al	V	O	N	Fe	d_{10}	d_{50}	d_{90}
Balance	6.25	4.04	0.14	0.02	0.22	25	37	51

Table 2
Laser parameters used.

	On powder setting		On solid setting	
Parameter	Contour	Fill	Contour	Fill
Laser power (W)	100	140	140	200
Scan speed (mm/s)	1500	1500	1500	1250

scanning strategy was used: each layer was divided into areas that had at least one layer of solid below ("on solid") and those that were built "on powder" (the overhangs/downward facing surfaces). Due to the lower thermal conductivity of powder compared to solid, the "on powder" areas require a lower laser energy, which was achieved through the use of a lower laser power. Layers were scanned using a contour and fill approach, and the direction of the fill vectors were rotated 90° from one layer to the next. The layer thickness, laser scan spacing and beam compensation were kept constant at 0.05 mm, 0.1 mm and 0.15 mm, respectively.

Fig. 2 shows stereo microscope photographs of the fabricated SLM scaffolds at a nominal solid fraction of 10%. After fabrication, the scaffolds were separated from the substrate and the support structure was removed. The scaffolds were then glass-bead blasted to remove any lightly bonded powder and finally cleaned with compressed air. The dimensions and weight were measured to a precision of 0.01 mm and 0.001 g, respectively, in order to determine the overall density of the structure.

Initially, scaffolds containing $5 \times 5 \times 10$ unit cells were tested in compression on an Instron 5982. The strain in the sample was determined by averaging the reading from two 10 mm extensometers on opposite sides of the sample. Unit cell sizes of 3.33 mm and 5 mm were used, meaning that the 10 mm extensometers located correctly on the flat sections of the samples. The scaffolds were cycled five times at 0.5 mm/min to approximately 50% of the yield point. The Young's modulus was calculated on the last four of these cycles and averaged to give a single data point. After the last cycle, the load was increased at the same strain rate until failure occurred.

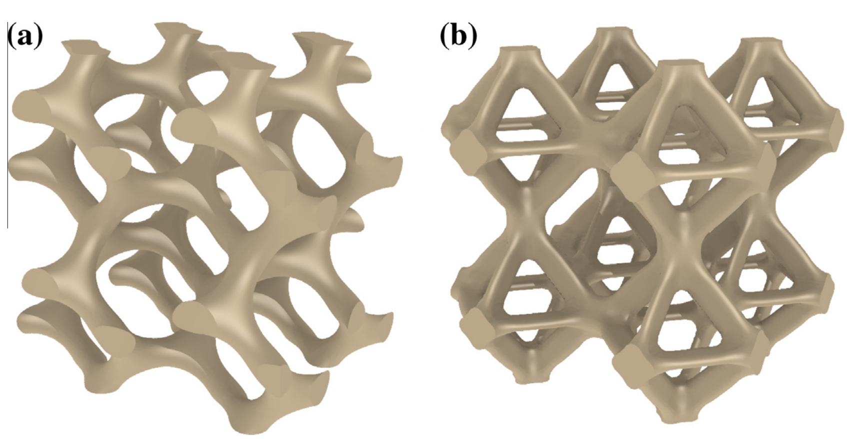

Fig. 1. Visualisations of $2 \times 2 \times 2$ base cells of the (a) gyroid and (b) optimised scaffolds at a 10% nominal solid fraction.