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Ti6Al4V lightweight lattice structures manufactured by laser powder bed fusion for load-bearing applications

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ABSTRACT

Additively manufactured (AM) lattice structures allow complex-shaped and custom parts, with superior design that cannot be produced by traditional methods. For medical implants, AM lattice structures are aimed at matching the elastic modulus of bone while providing strength and allowing bone in-growth for long-term stability. In this study, relatively thick struts are investigated in an attempt to match the properties of cortical bone, which is meant for the internal structural integrity of the implant, while a smaller lattice may be used for near-surface parts of an implant. In this work we investigate additively manufactured lattice samples produced by Laser Powder Bed Fusion (LPBF) of Ti6Al4V ELI, with samples having approximately 50% regular porosity. In particular, we experimentally compare two designs: diagonal and rhombic. MicroCT-based static loading simulations are used to highlight stress hotspots in the two designs, to highlight possible failure locations. Physical compression testing to initial failure and subsequent microCT highlight the locations of initial failure, which correlate well with the simulation stress hotspots. Both designs show excellent strength (120–140 kN failure load) and effective compressive elastic modulus corresponding well to simulations. Differences between microCT-based simulations of the produced lattices and those of ideal design parameters can be attributed mainly to surface roughness, and slightly thinner manufactured struts of the as-built lattices, with similar trends for the two model designs. These results validate experimentally that both designs are suitable for load-bearing applications.

1. Introduction

The advantages of additive manufacturing (AM) are the reduction of the time from the concept of the part to its production, reducing the material, the flexibility and freedom of design, multi-materials, gradient-structures and composites in a single cycle, the production of unique alloys/compositions and the simultaneous production of functional parts [1,2]. Products fabricated through laser-based AM processes are used in the medical field, dentistry, aerospace, automotive and power industries, to name only a few. Despite the high degree of complexity possible by Laser Powder Bed Fusion (LPBF), some limitations exist – in particular for overhanging structures, and hence the size and shape of the deliberate pore spaces in cellular structures are limited [1]. These limitations are caused by the track-by-track, layer-by-layer nature of LPBF. Fast heating/melting/cooling in LPBF leading to non-equilibrium metallurgical process cause significant differences in mechanical properties of the LPBF objects in comparison with traditional casting and forged parts [3]. Further studying the microstructure, physical, mechanical properties and heat treatments of AM parts to compile high quality requirements for high-specification components is a relevant and important task for the greater use of the relatively new AM technologies by industry [1,2,4]. Obtaining lightweight structures with mechanical properties close to the properties of bones is another important task for the widespread adoption of LPBF for biomedical applications such as customized implants or in the aerospace field, where strength, reliability and low weight are the most important issues [5,6].

Additive manufacturing of Ti alloys has been the topic of investigation of numerous researchers over the last few years [7]. Ti6Al4V is one of the principal biomaterials for implants but its properties are far from human bones: Ti6Al4V alloy has a density of 4.43 g/cm^3, which is twice heavier than cortical bone (1.99 g/cm^3). Ultimate tensile and compression strengths and the elastic modulus are all higher in Ti6Al4V alloy by more than 5–7 times in comparison with hard bone tissues. By producing a metal

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lattice structure by LPBF, the mechanical properties of the metal lattice can be approximated to the properties of bones [8,9]. The production of latticed Ti6Al4V structures by additive manufacturing has been reviewed recently by Tan et al. [10] who mention that among the many lattice designs, not only one ideal solution exists for any specific task and there may be many optimal solutions (i.e. lattice designs). However, there is still a need for additional analysis of AM lattice structure designs to validate their physical compressive strength when produced by additive manufacturing because its mechanical performance depends on the manufacturing strategy and process parameters [3,11,12].

In this work, LPBF lattice structures of two designs were tested. This testing involved non-destructive microCT analysis before compression, physical compression testing and microCT analysis after compression, as well as optical microscopy. MicroCT allows inspection for presence of defects such as internal porosity in the struts, for surface roughness and CAD model deviations. Static load simulations were conducted on the lattice structures (using the CAD data) to analyze the maximum Von Mises stress distributions and compare these between two designs. A microCT-based load simulation was also applied to the two LPBF samples of different design types and compared to their ideal stress distributions. In this way the differences could be analyzed and the effect of build imperfections can be related directly to the mechanical properties, found by physical compression testing. MicroCT analysis of compressed lattices also highlight locations of failure, correlating to the stress regions found by simulation. The lattices tested here were designed with 50% density and large unit cells resulting in strut thickness values >1.5 mm. The aim was to match the properties of cortical bone, and provide an analysis of lattices meant for load-bearing applications. The lattice density is expected to affect the effective elastic modulus irrespective of the strut thickness (determined by the unit cell size selected). The thicker struts are selected to ensure accurate manufacturing and less effect of manufacturing imperfections, compared to lattices with thin struts. The two designs were selected based on their availability in software tools, their relatively simple design and both are applicable to bone implants.

2. Materials and methods

12 cubes with periodic cellular lattice structures 25 × 25 × 25 mm^3 and solid top and bottom layers of 1 mm in thickness (Fig. 1) were produced by an EOSINT M280 system. Samples were fabricated at standard process parameters recommended by EOS for Ti6Al4V at 30 μm powder layer thickness. Argon was used as the protective atmosphere; the oxygen level in the chamber was controlled in the range of 0.07–0.12%. The chemical composition of the spherical gas-atomized Ti6Al4V (ELI) (−45 μm) powder from TLS Technik is given in Table 1. The 10th, 50th and 90th percentiles of equivalent diameter (weighted by volume) of the powder particles were d_{10} = 13 μm, d_{50} = 23 μm and d_{90} = 37 μm.

Rhombic and diagonal lattice structures were designed with a target 50% volume fraction (Fig. 1). In this case, the target volume fraction and large unit cell size with relatively thick struts are investigated in an attempt to match the properties of cortical bone,

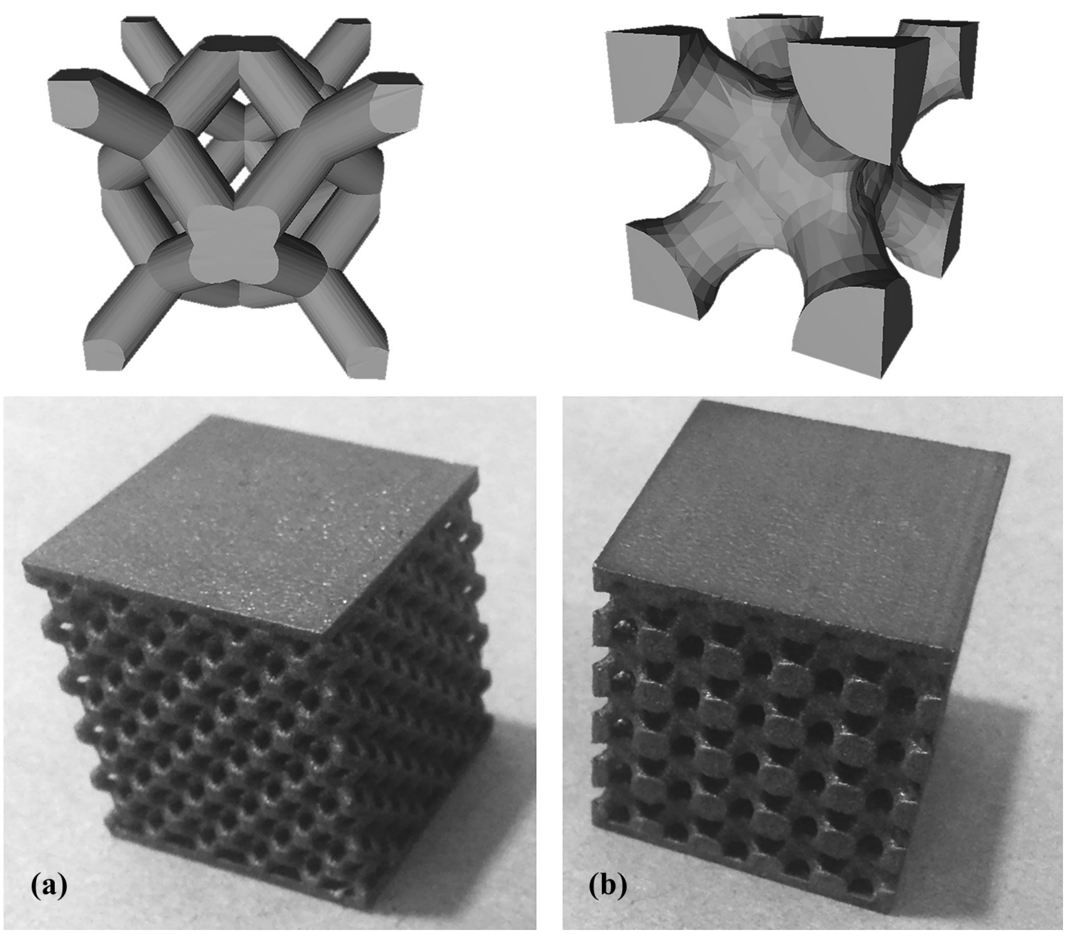

Fig. 1. CAD models of unit cells and LPBF tessellated lattice parts with rhombic (a) and diagonal designs (b).