

Fracture toughness and tensile strength of 316L stainless steel cellular lattice structures manufactured using the selective laser melting technique



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ABSTRACT

Selective Laser Melting (SLM) process is a metallic additive manufacturing technique that directly manufactures strong, lightweight and complex three dimensional parts in a layer-by-layer to scan and melt the metal powder for aerospace applications. However, there are still certain evaluation criteria such as fracture toughness and tensility of cellular structure made by SLM which were not reported before.

This study presents new and novel methods in additive manufacturing and evaluates the local failure mechanism of 316L cellular lattice structures made by SLM under uniaxial tension and three point bending load. The effect of different build directions of the 316L lattice structure on the fracture toughness properties are compared to the Ashby and Gibson models. Also, the effect of different build directions on tensile properties of 316L cellular structures has been investigated.

Microcomputer tomography (CT) reveals that the cellular structure parts with different build directions were manufactured free of defect by the SLM. The density of the lattice structure samples was found at 1.35 g/cm^3 for both vertical and horizontal building directions while the relative density of solid struts is 96.25%. The tensile and fracture toughness properties in vertical building direction samples are higher than those samples that were built in horizontal building direction. There was no big difference between the Ashby and Gibson micromechanical model to predict fracture toughness and Single Edge Notch Bend (SENB) test results from 0.2 to 0.5 MPa $\text{m}^{0.5}$.

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1. Introduction

Today, most of the research in aerospace applications tends to be focused on increasing energy efficiency and reducing fuel consumption and exhaust emissions. Extensive efforts are still needed, however, to find ways of reducing the components' overall material consumption and weight, thereby saving increasingly scarce natural resources. Many previous studies have examined the use of high specific strength materials, such as magnesium, aluminium, titanium and high strength steels [1–3]. Other research has focused on structural design adaptations to the actual loading condition, such as the sandwich design, which helps to reduce weight by stiffness or by reducing the numbers of joining elements [4], but these strategies still require highly complex geometries to be reliably produced, and, in practice this confronts the manufacturing method with substantial challenges.

Additive manufacturing (AM) technologies, such as the

Selective Laser Melting technique, allow complex 3D lattice structures to be produced [5,6] while also reducing the time and costs of production. Parthasarathy [7] have found that AM technologies allow flexibility of design and provide very few feature sizes for fabricating closed or open cell structures with locally variable stiffness and optimized compatibility. Currently there is great demand for lightweight components in aerospace applications in order to reduce the rate of fuel consumption and carbon emissions, and this requires more effort to improve the performance of the lightweight structures produced. Also, in the aerospace sector, the Ti-6Al-4V alloy is promising due to its balanced and well-studied properties. Current studies in the field of AM of lightweight structures have investigated the influence of process parameters on the quality of the parts produced, such as laser power and scanning speed, or the layer thickness of powder and the resulting mechanical behaviour [8].

Lattice structures are well known and their excellent low density and thus good specific properties used widely in aerospace and other transport sectors [6,9,16]. There are commercial suppliers of metallic lattice materials. The porous nature of these materials means they require a different set of

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manufacturing processes, tending to make the more expensive than conventional alternatives such as honeycombs or advanced alloys solids. The influence of cell size and volume fraction on the quality of the parts and their effect on mechanical behaviour has also been explored [6,9]. A few studies have addressed the failure mode and mechanical performance of different 3D metallic AM lightweight structures [10]. Brenne et al. [11] studied the local deformation behaviour of cellular structures to investigate the failure characteristics for the parts subjected to uniaxial loading.

In this context, the present study sought to investigate the local failure mechanism of a 316L stainless steel cellular structure manufactured by SLM under uniaxial tension loading. A fracture toughness test was conducted to evaluate the effect of utilising different build directions for the 316L AM cellular parts on the fracture toughness properties. The results obtained from the fracture toughness tests were compared with the Ashby and Gibson model. The tensile strength and elongation of the 316L stainless steel cellular structure was also addressed. Scanning Electron Microscopy (SEM), x-ray Computed Tomography (CT) scan and optical microscopy were used to examine the microstructural changes in both tensile test samples and Single Edge Notched Bend samples during the fracture.

2. Experimental procedure

2.1. Materials and cellular lattice structure design

All of the cellular lattice structure samples were made from a 316L stainless steel powder with an average particle size of $30 \pm 10 \mu\text{m}$. The powder was almost spherical in shape, which led to good flow ability. Also, it had a narrow distribution of particle sizes and some irregular particles sticking to it – with the smaller sizes between 3 and $10 \mu\text{m}$, which resulted in a rough surface. The CAD software provided by simple-ware Ltd., UK was used to generate the cellular lattice structure samples with the gyroid unit cell model, as shown in Fig. 1: a, b and c, respectively. The gyroid unit cell (see Fig. 1: a) and the lattice structures were mathematically defined, and studied at different cell sizes and volume fractions [6,12], which process circular struts and spherical cores with the self-supported feature

extending the capability of SLM in producing cellular lattice structures. The volume fraction or volume percentage of the solid material in the cellular lattice structure, with the same volume of 15%, was used in all periodic lattice structures at different building directions and the cell sizes were also constant at 3 mm – as shown in Fig. 1: b and c.

2.2. The selective laser melting process

The SLM fabricating process was carried out on a concept laser (M1, ES Technology Ltd., UK). The SLM machine used a fibre laser at 1060 nm wavelengths with a nominal power of 200 W and a focussing diameter of between 50 and $200 \mu\text{m}$. The laser power, scanning speed and layer thickness were 200 W, 7 m/s and 0.03 mm, respectively. 6 gyroid cellular lattice structures with dimensions of $10 \times 20 \times 80 \text{ mm}$ for SENB test and another 6 with dimensions of $15 \times 15 \times 60 \text{ mm}$ were built on a base plate by the SLM process and cut off from the base plate using wire cutters (Electrical Discharge Machine EDM) – see Fig. 2.

2.3. Measurements and mechanical tests

A micro-CT scanner (Benchtop CT 160Xi, X-Tek) at a voltage of 120 KV was used to scan the lattice structure samples before and after the mechanical testing, and two dimensional slice images were collected. Software (VGstudio MAX2.1) was used to reconstruct the three dimensional models of the manufactured lattice structure samples to determine the internal defects and the solid strut volume. A scanning electron microscope SEM (HITACHI S-3200N) was used to characterise the failure behaviour; the strut deformation and the size of the cellular lattice structure samples. An optical microscope (Dino-lite Digital Microscope) was used to investigate the morphologies of the manufactured samples of the cellular lattice structures. The density and the relative density of the solid struts of the lattice cellular structures were measured. Six samples, manufactured in parallel and perpendicular to the building direction, were pulled under uniaxial tension tests using an EZ20 universal material testing machine (Lloyd instruments Ltd., UK) at a constant rate of loading 0.5 mm/min. The fracture toughness test was carried out at room temperature using an EZ20 universal material testing machine at a constant displacement 0.5 mm/min. This test method was for mode I (opening mode and

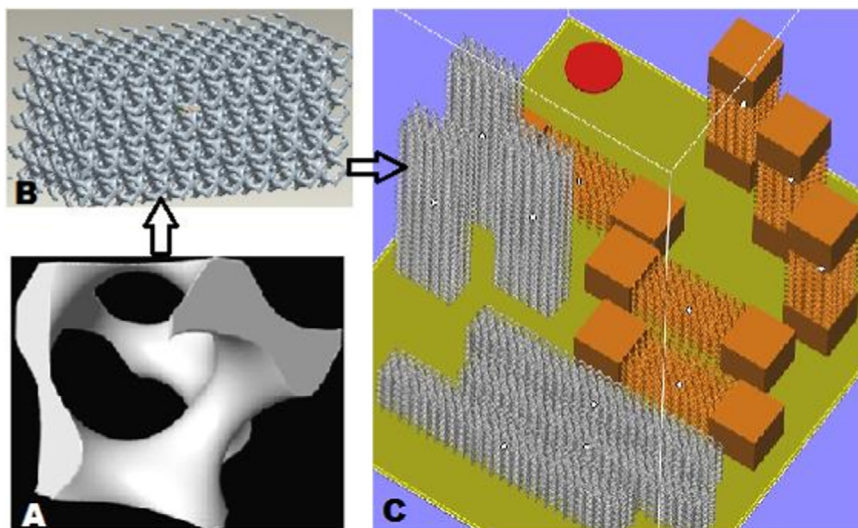


Fig. 1. (a) CAD models of gyroid unit cell and (b) periodic cellular lattice structures (c) models of samples at different building direction in the platform.

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