Mechanical Properties and Deformation Behaviour of ARCH and BCT Lattice Structures Manufactured by Selective Laser Melting

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Abstract. In this study, a new lattice structure ARCH is proposed, ARCH lattice structure and traditional lattice structures BCT were fabricated from 316 L stainless steel by SLM. Mechanical properties and deformation behavior of the lattice structures were experimentally investigated. The results show that the ARCH lattice structures have better mechanical property and energy absorption capability than BCT lattice structures. Under the same relative density, the compressive strength and elastic modulus of the ARCH lattice structure is 121.27% and 60.48% higher than the BCT lattice structure, and the ARCH lattice structures have better energy absorption properties than the BCT lattice structures.

Key words: lattice structure; selective laser melting; mechanical properties; energy absorption properties

1. Introduction

Lattice structures are porous structure composed of repeating cellular unit, which widely developed and used in aerospace, automobile, biomedicine and other fields because of their low density, high specific strength, high specific stiffness, good energy absorption ability, excellent thermal and acoustic insulation properties, etc. [1] However, the lattice structure is difficult to be manufactured with traditional manufacturing process due to its highly complex spatial structure. Additive manufacturing (AM) technologies are very suitable for making lattice structures. As a kind of the AM technologies, selective laser melting (SLM) have been successfully used to fabricate complex lattice structures for various purpose. The body-centered cubic (BCC), body-centered tetragonal (BCT), face-centered cubic (FCC), gyroid cellular (GC), rhombic dodecahedron (RD) and the structure derived from them were widely studied.

Shen et al. [2] tested three kinds of BCC lattice structures, and the results show that the SLM technique offers a viable method for manufacturing high-performance lattice structures. Long et al. [3] proposed a BCT lattice structure by removing the constraint of isotropy size in BCC lattice structure. The experimental result show that comparing to BCC structure, the relative density of BCT optimized structure increase only by 3.7%, but the elastic modulus and yield strength increase by 121.5% and 77.3%. Hao et al. [4] evaluates the manufacturability and performance of SLM produced GC lattice
structures. The results reveal that the GC lattice structures can be manufactured free of defects by the SLM process without the need of support structures with a wide unit cell size range of 2 to 8 mm, the struts within the lattice structures with smaller unit cell sizes have higher densities and relative densities and the yield strengths and Young’s module both decrease with the increase in the unit cell size of the lattice structures. Xiao et al. [5] experimentally studied the load bearing capacity of the RD lattice structures, the results showed the similar failure mode in both quasi-static and dynamic loadings, and the shear failure along the 45° shear band. Cao et al. [6] proposed a modified RD lattice structure, compare with the original RD lattice structure, the compressive modulus and initial yield strength can increase 79% and 55% respectively.

In previous research little attention has been focused on the arch strut lattice structures. In this paper, a new arch strut lattice structure is proposed. The aim of this paper is to compare the mechanical properties and deformation behaviour of arch strut and straight strut lattice structures.

2. Lattice geometry

![Figure 1. The CAD model of lattice structures](image)

The geometry of the arch strut and straight strut unit-cell is given in Figure 1. (a) and (e). The arch strut unit-cell was named ARCH and the straight strut unit-cell is BCT. The centreline of ARCH is arched (the ratio of height and span of the arch is 0.45), as shown in Figure 1. (b), it is well known that compare with other structures, arch can afford bigger pressure. Dimensions of the lattice unit cells are defined in Figure 1. (c) and (g), arch strut of 1 mm and straight strut of 0.92 mm in diameter at the same relative density 0.2 has been selected for the experiments. The samples for mechanical testing are constructed. The CAD model of ARCH lattice structure and BCT lattice structure for compression testing are shown in Figure 1.(d) and (h) by merging 7 unit cells in x-, y- and 3 unit cells in z-directions.

3. Experimental details

3.1. Material and Fabrication

The lattice structure samples were made from 316L stainless steel powder which was produced by LPW Technology Ltd., UK. The particle size distribution of the 316L stainless steel powder is 10 ~ 45 μm. The ARCH and BCT lattice structure sample were fabricated by SLM using the LASERTEC 30 SLM printer from DMG with the material 316 L stainless steel. The laser power was 245 W, the layer thickness was 50 μm and the laser scanning speed was 1 m/s. Thermal treatment was applied at 1150 °C for 2 hours to reduce the residual stress. The lattice structure samples are displayed in Figure
2. three samples of each structure were fabricated to carry out the repeated experiments.

3.2. Tests
The lattice structure sample static compression testing was carried out on an INSTRON 5984 testing machine at room temperature under a uniaxial loading strain rate of 0.05mm/min. A digital camera was used to record the compress deformation of the samples.

Figure 2. The lathed uniaxial tensile samples and the lattice structure samples

4. Results and discussion

4.1. Compression properties
The quasi-static compression stress-strain curves of ARCH and BCT are shown in Figure 3. At the beginning of the compression, the stress-strain curves are non-linear and concave. The causes of this phenomenon maybe the uneven upper surface of the lattice sample. With the process of compression, the stress-strain curves entered a linearity stage, then the lattice start to damage and the stress-strain curves entered a long yield plateau. Finally, the entire structure collapses, struts are pressed together and densified, the stress-strain curves rise sharply. The compressive strengths and elastic modulus of ARCH and BCT lattice structures samples can be obtain from the stress-strain curves. Because of there is no clear first peak on the stress-strain curves, the arithmetical mean of the stresses between 20% and 40% of compressive strain is taken as the compressive strength of the lattice structure samples. The compressive strength of the ARCH lattice structure samples is 63.57 MPa, and the compressive strength of the BCT lattice structure samples is 28.73 MPa. The compressive strength of the ARCH lattice structure is 121.27% higher than the BCT lattice structure at the same relative density of 20%. The elastic modulus determined by gradient of the elastic straight lines determined by elastic loading and unloading between stresses of 70% of compressive strength and 20% compressive strength. The elastic modulus of the ARCH lattice structure samples is 3.37 MPa, and the elastic modulus of the BCT lattice structure samples is 2.10 MPa. The elastic modulus of the ARCH lattice structure is 60.48% higher than the BCT lattice structure at the same relative density of 20%.

Figure 4 shows the quasi-static compression deformation behaviour of ARCH and BCT lattice structures samples under increasing strain. The main failure mode of ARCH lattice structure samples is diagonal direction inclined compacted collapse, and the BCT lattice structure sample is vertical direction compacted collapse.
Figure 3. The quasi-static compression stress-strain curves lattice structures samples

(a) ARCH

(b) BCT

Figure 4. The quasi-static compression deformation behaviour of lattice structures sample

4.2. Energy absorption of lattice structures

The specific energy absorption (SEA) and energy absorption efficiency are two important indicators to measure the impact resistance and energy absorption properties of lattice structures [1, 7]. The definition of SEA is namely absorbed energy per unit mass, and the SEA can be calculated by:

\[
SEA = \frac{\int_0^\varepsilon \sigma(\varepsilon) \, d\varepsilon}{\rho_r}
\]

Where, \(\sigma\) is the stress of the lattice structures [MPa]; \(\varepsilon\) is the strain of the lattice structures; \(\rho_r\) is the relative density of the lattice structures.

The energy absorption efficiency (\(\eta\)) is the ratio of the absorbed energy to the corresponding compression stress and the \(\eta\) can be calculated by:

\[
\eta = \frac{\int_0^\varepsilon \sigma(\varepsilon) \, d\varepsilon}{\sigma}
\]

The SEA and energy absorption efficiency curve were obtained by calculating the experiment data as shown in Figure 5. The SEA of ARCH and BCT lattice structures increase with the increase of the strain. The SEA of ARCH and BCT is very close and the SEA of BCT is a little bit higher than ARCH when the strain of the samples is less than 12.3%. While when the strain is bigger than 12.3% the SEA of ARCH is increase rapidly and much higher than BCT with the increase of strain. The SEA of
ARCH is 90.1% higher than BCT when the strain is 50%. The energy absorption efficiency of ARCH and BCT is firstly increased and then decreased with strain increase. When the strain is less than 10.7%, the energy absorption efficiency of ARCH and BCT are basically the same, with the increase of strain the energy absorption efficiency of ARCH is higher than BCT and the difference between the two structures are getting bigger. The energy absorption efficiency of the ARCH and BCT is reaches the maximum at the strain is 50 % and 61 % respectively, and the maximum energy absorption efficiency of the ARCH is 39.8% higher than BCT. Based on the analysis of the Figure 5, the ARCH lattice structures have better energy absorption properties than the BCT lattice structures.

![Graph](image)

Figure 5. The energy absorption properties of lattice structures

5. Conclusion
In this paper, a new lattice structure ARCH is proposed, ARCH lattice structure and traditional lattice structures BCT were fabricated by SLM. Mechanical properties and deformation behaviour of the lattice structures were numerically and experimentally investigated were carried out to compare with traditional lattice structure. The following conclusions can be drawn from the present study:

- Under the same relative density, the compressive strength of the ARCH lattice structure is 121.27% higher than the BCT lattice structure and the elastic modulus of the ARCH lattice structure is 60.48% higher than the BCT lattice structure. The ARCH lattice structure has better mechanical properties than the BCT lattice structure.
- In the compression process, the lattice structure deformation is stable and continuous, there is no signs of local brittleness failure. The main failure mode of ARCH lattice structure samples is 45° inclined collapse, and the BCT lattice structure sample is compacted layer by layer.
- The SEA and energy absorption efficiency of ARCH and BCT with little difference at the beginning, then the SEA and energy absorption efficiency of ARCH increase rapidly and much higher than BCT. The ARCH lattice structures have better energy absorption properties than the BCT lattice structures.

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