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Mechanical Performance of Functionally Graded Lattice Structures Made with Selective Laser Melting 3D Printing

Dheyaa S J Al-Saedi[1] and S H Masood[2]

[1] College of Engineering, University of Misan, Maysan 62001, Iraq
[2] Swinburne University of Technology, Hawthorn, Victoria 3122, Australia

E-mail: smasood@swin.edu.au

The selective laser melting (SLM) process is a metal-based 3D printing technology which is capable of fabricating cellular structures for various engineering applications. This study aims to investigate the compressive mechanical performance and energy absorption capability of uniform and functionally graded lattice structures fabricated using this process. A solution heat treatment was carried out to explore its effect on the mechanical properties of the printed Al-Si12 lattice structures. The as-built condition of SLM lattice structures underwent brittle failure and demonstrated non-ideal energy absorption behaviours, while heat treatment was found to significantly improve deformation and energy absorption performance. The deformation behaviour of the heat-treated lattice structure exhibited distinct responses with typical stress strain curves, providing ideal compressive regions. Calculation of energy absorption showed that the gradually denser lattice structure absorbed higher levels of energy than the uniform lattice structure.

1- Introduction

Additive manufacturing technology (AM) is a term used to describe the group of 3D printing processes that manufactures physical components directly from computer aided design (CAD) data. In these technologies, a 3D CAD model is designed using CAD software and then separated into two-dimensional layers. AM offers many technical and economic benefits over traditional manufacturing technologies, including saving money and time for low-volume production [1], offering tool-free and low environmental impact fabrication [2], and manufacturing highly geometrically complex structures [3]. Therefore, this technology has attracted the attention of many researchers and engineers in various fields such as aerospace, defence, and biomedical development.

Selective laser melting (SLM) is one of powder bed-based 3D printing technologies that is most widely utilised in fabrication of 3D metal components from a range of metallic powders [4]. SLM uses laser beams to selectively melt powder particles on the machine substrate, allowing them to bond with each other and thus, in a layer-wise fashion, incrementally, the component is fabricated. The main advantage of SLM technology is its ability to produce customized complex structures with tailored functionalities and properties, such as 3D periodic lattice structures which would be difficult or impossible to make using traditional manufacturing technologies.

A lattice structure is a porous structure composed of periodical 3D cellular units. It is one of the best candidate structures for many engineered applications due to unique properties such as its high strength to mass ratio, acoustic excellence, thermal isolation, and impact and energy absorption. Applications of these structures include personal protective equipment [5], and marina, aerospace, and implant applications [6, 7]. A great deal of effort and attention has thus been paid to investigating the performance and characteristics of these lattice structures.

It has been found that the mechanical performance and deformation behavior of lattice structures can be significantly influenced by the architecture of the unit cells, construction materials, manufacturing techniques, and volume fractions used [8, 9]. Gibson and Ashby [8] are considered the pioneers in this subject, and they extensively studied the performance of metallic foam and cellular honeycomb structures. They also developed theoretical models that describe the relationship between volume fraction and mechanical performance. Choy et al. [9] and Hasan et al. [10] investigated the deformation responses and mechanical properties of cubic, honeycomb, and diamond lattice structures made of Ti-6Al-4V fabricated using SLM. The effect of the manufacturing processing parameters on the strut lattice and compressive properties of these lattice structures were also experimentally studied by Qiu et al. [11]. The aspect-ratio, architecture and orientation of strut lattice structures have also been researched [2].

However, most current studies are extensively focused on investigation of deformation behaviours and failure mechanisms of different types in SLM lattice structures. It has been found that brittle fracture and shear band fractures along the 45° angle throughout the structure are the main cause of lattice structure failure under compressive and tensile loads [9, 11]. This makes lattice structures less desirable for energy absorption applications, especially in personal protective equipment.

Recently, increased interest in lattice designs for more advanced energy absorption applications has enabled the creation of a new class of lattice structures, which have been termed functionally graded lattice structures (FGLS). These FGLS can be defined as structures in which the density of solid material changes gradually over the volume, leading to a corresponding change in mechanical properties [12, 13]. It has been shown that FGLS offers distinct collapse and energy absorption behaviours, which make them more favourable for applications requiring these functions.

In this study, the compressive performance and energy absorption capability of Al-12Si functionally graded lattice structures manufactured using SLM technology are investigated and compared to those found in uniform lattice structures. Half of the fabricated lattice structures were thermally treated using a T6 solution heat treatment process, then uniaxial compression tests were conducted to study the collapse response under compressive loads of both types of lattice structures. Scan electron microscopy and optical microscopy were used to study the surface morphology and surface fracture modes of the samples.

2- Material and methods

Cubic lattice structures with dimensions 30 x 30 x 30 mm were modelled using Creo Parametric 3.0 CAD software. The designed lattice structures were built from F2CCz unit cells of 5 x 5 x 5 mm as repetitive cellular cells to create 3D truss lattice structures, as shown in figure 1. This cellular model was chosen based on Rehme's study [14], which investigated different types of lattice unit cells and concluded that the F2CCz provided better relationships between mechanical properties and volume fraction. An FGLS was designed with a density that increased from top to bottom continuously throughout six structural layers at a 50% increase rate. The gradual density increase was achieved by manipulating cell strut thickness, which varied from 350 μm to 1270 μm for the six layers of FGLS.

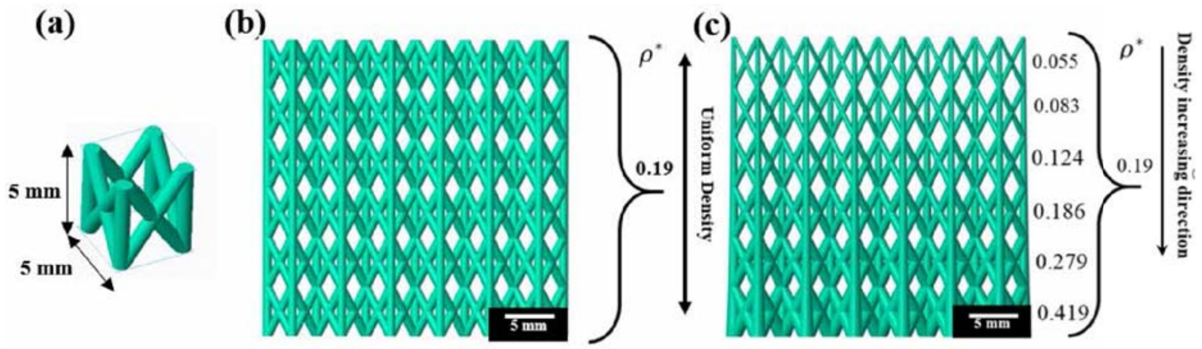

Figure 1. CAD model of (a) F2CCz unit cell, (b) uniform and (c) functionally graded lattice structures

The designed lattice structures were fabricated using the ProX200 SLM process supplied by 3D Systems (USA), which utilises aluminium-silicon alloy (AlSi-12) as a build material. The powder particles of Al-12Si were spherical in shape and in the range of 40 ± 5 µm. The processing parameters included 285 W laser power, 2,500 mm/s laser scan speed, 100 µm laser hatch spacing, and 40 µm deposition thickness; these were chosen based on Dheyaa's study [12] to fabricate the lattice structures.

A solution heat treatment of type T6 was performed on a half of the fabricated lattice structures in an air atmosphere using an electrical furnace with load capacity 1,300 °C. The type T6 method included heating the samples at 520 °C with a soak time of 1 hr, followed by water quenching to room temperature. Then, the samples were artificially age heated at 160 °C for 6 hours; this was followed by air cooling.

Quasi-static compression tests were carried out on the fabricated-SLM uniform and functionally graded lattice structures for both as-built (AS) and heat-treated (HT) conditions. The tests were conducted using an MTS Criterion model 43 universal testing machine with 50 kN capacity. The tested lattice structures were placed at centre of two cross heads, as shown in figure 2. The deformation speed was 1 mm/min, applied downward, which resulted in a strain rate of 5.5 × 10-4 s^{-1}, following ASTM standard E9-09.

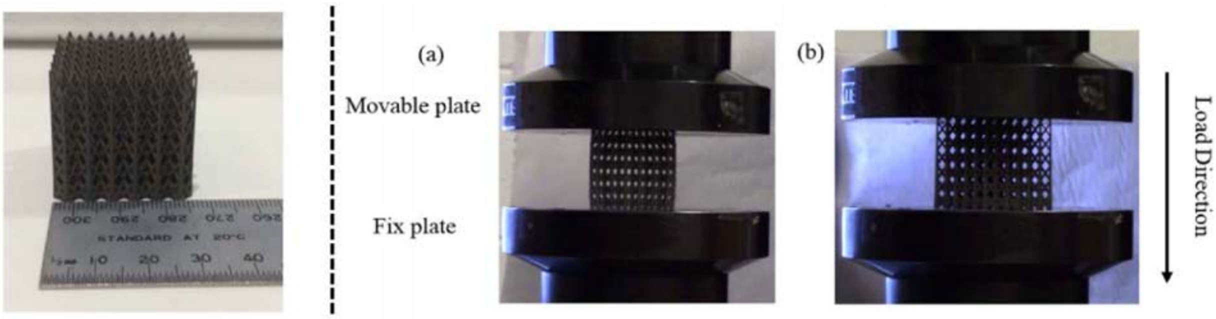

Figure 2. Fabricated SLM – FGLS structure (left), and compression test set up of (a) uniform lattice structures, and (b) FGLS

3- Results and Discussion

3.1 *Deformation of AS-build lattice structures*

Figure 3 demonstrates the stress strain curve of the compression test data along with the inset captured video frames of the AS-condition of the SLM-made uniform lattice structure. It can be observed that major structural collapse occurred at about 7% of effective strain. After this collapse, the lattice structure lost approximately 93% of its strength. The mechanism failure of the lattice structure began with linear elasticity, followed by non-linear behaviours in which the solid struts began to bend under the applied loads. After a short period of bending, the solid struts exhibited brittle fractures, resulting in a diagonal shear band (45°), as shown in figure 3. The lattice structure was continuously weakened as the strain increased up to 59%, where the densification region was entered. This collapse behaviour agrees well with that reported in previous studies for aluminium lattice structures made using SLM technology [9, 11].

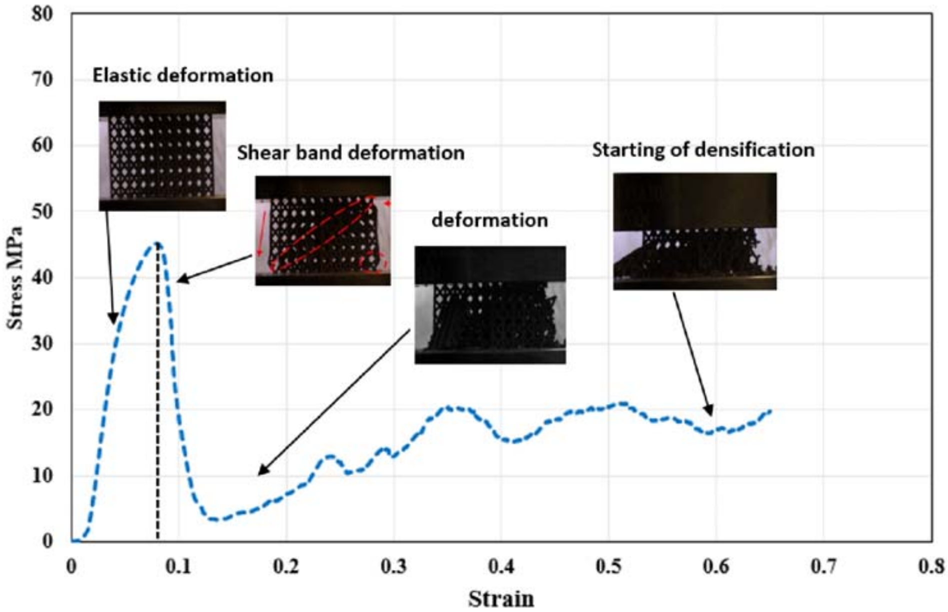

Figure 3. Stress strain curve of As-built (AS) condition uniform density lattice structure, with inserted video frames to show the deformation stages under compressive loading

3.2 *Deformation of HT-lattice structures*

The deformation behaviours of lattice structures following solution heat treatment type T6 improved significantly compared to the As-built deformation responses. Figure 4 shows the stress strain curves of HT lattice structures of uniform and gradual density types. The deformation behaviour of the HT uniform structure was found to be different than that seen in the As-built structure. It is clear from figure 4 that the stress-strain curve is more ideal, displaying something very close to the ideal collapse behaviour of cellular solid structures predicted by Gibson and Ashby [8]. The stress-strain curve includes a linear elastic region, followed by a long and smooth plateau stress region leading to the densification region. The effect of heat treatment clearly transfers the brittle collapse behaviour and low strain failure of As-built uniform structures to a long plateau region and allows high strain failure in the HT uniform structure. This difference can be attributed to the differences in the microstructure and resistance to fracture of the solid struts between HT and As-built uniform lattice structures, as shown in the magnified scanning electron microscope (SEM) images in figure 5.

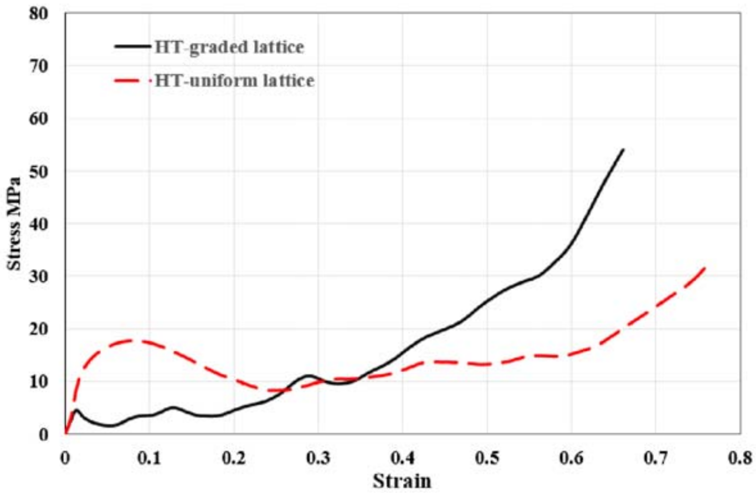

Figure 4. Stress strain curves of Heat Treated (HT) uniform and functionally graded lattice structures

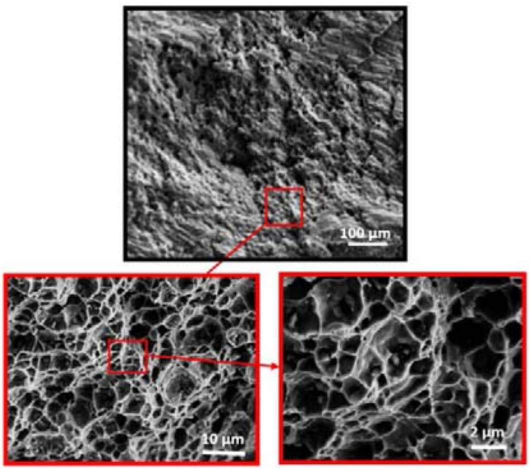

Figure 5. Different magnifications of SEM images of solid strut fracture surfaces of HT uniform lattice structures

Functionally graded lattice structures showed distinctive deformation responses under compressive loads. Figure 4 clearly shows the significant difference in the stress-strain curves of the graded structures compared to those of the uniform lattice structures. It can be seen that stress strain curve rises continuously with increasing compressive loads. This behaviour is tied to the sequential collapse of the structural layers. Figure 6 shows frames from a recorded video of the collapse stages under compression tests of HT-FGLS. From figure 6, it is clear that the structures deformed layer-by-layer, sequentially. The fluctuated decrease in collapse behaviour was thus eliminated in HT functionally graded structures, and the Al-12Si material exhibited high ductility, thus moving the previous brittle collapse towards more ductile behaviour under compressive loads. The effect of heat treatment improved deformation behaviour and reduced the compressive strength, increasing the fracture strain to 61%.

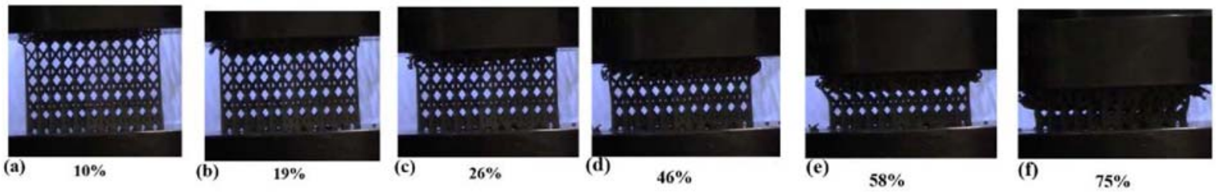

Figure 6. Captured video frames of deformation behaviours of HT – FGLS

3.3 *Energy absorption capability*

Table 1 shows the energy absorption (Wv) values of HT uniform and HT graded (FGLS) structures calculated based on the area under the stress-strain curve by numerical integration.

Table 1. Energy absorption values of HT- uniform and FGLS structures

Lattice structures types		**Energy absorption *Wv* (MJ/m^3) up to densification strain**
HT-lattice structures	Uniform	8.033
	Graded	8.335

The curves in Figure 4 demonstrate that HT-FGLS shows unique energy absorption behaviour under compressive loads. The calculated values of energy absorption were found to be higher in HT- FGLS than in HT-uniform lattice structures, with values of 8.335 and 8.033 MJ/m^3, respectively, obtained from the stress-strain curves. It can be observed that distinct behaviours of HT-FGLS begin with a much lower level of absorbed energy than the uniform lattice structure at around 10% compressive strain. Then, as the compression loads increase, the energy absorption level increases significantly with the sequential collapse of layers. It is clear that the gradual increase of absorbed energy is tied to the deformation behaviour of layer-by-layer deformation, beginning with the top layer.

4. **Conclusions**

This work demonstrated that a selective laser melting (SLM) additive manufacturing process can successfully produce Al-12Si functionally graded lattice structures (FGLS) with good manufacturability and repeatability. Conducting solution heat treatment has a remarkable effect on the deformation behaviours of SLM - Al-12Si material, eliminating brittle fracture and lowering strain failure by enhancing ductility. The compression test investigations showed that the FGLS exhibited distinctive characteristics in deformation under compressive loads. The collapse process of FGLS occurs layer-by-layer, beginning with the collapse of the lower density layers and then progressing to higher density ones in sequence. Energy absorption calculations reveal that this means that FGLS is able to absorb higher amounts of energy than uniform lattices. These results suggest that graded lattice structures are thus more attractive for applications requiring high impact or shock resistance.

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