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Design and fabrication of functionally graded components by selective laser melting

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Abstract

The control of structure formation of additive manufacturing simplifies the fabrication of functionally graded components (FGC), which changes in the physical properties can be achieved via structural design. In this research, selective laser melting (SLM) technology was used to fabricate structures with gradient lattice designs. The structure was varied in strut thickness continuously and linearly in single direction for cubic and honeycomb unit cells. Results showed that the complex design was successfully built and achieved nearly full-dense strut. Compression test results showed that the stress-strain curves of both cubic and honeycomb lattice structures oscillate with multiple peak loads, suggesting ductile characteristics. However, lattice structures with graded thickness tend to oscillate upward as the strut diameter increases.

Introduction

Recently, lightweight metallic lattice structures have gained more attention due to their unique shock energy absorbing ability. This makes them suitable for use in applications like bone-mimicking biomaterials, heat exchanger or other load-bearing applications [1-4]. However, the fabrication of metallic lattice structures is still challenging which requires novel manufacturing techniques to overcome inhomogeneity within the cell architectures. In addition, metallic lattice structures have very different deformation behavior from conventional dense metals, thus requiring a special set of compression testing methods for porous and lattice metals such as ISO standard 13314:2011 (Mechanical testing of metals -- Ductility testing -- Compression test for porous and lattice metals).

Selective Laser Melting (SLM) is a layer additive manufacturing process that can be used to manufacture complex metal components. This is achieved by selectively melting metal powder, layer by layer, according to the 3D design model. One of the advantages of this manufacturing process is its ability to manufacture dense, complex metal parts in net shape, such as metallic lattice structures [1, 2, 5-8].

A wide range of lattice structure designs exist, with widely varying shapes and internal geometries. The lightweight porous structures currently used at present can be broadly divided into two categories: first is the more conventional block structure which consists of straight vertical solid walls with a few holes [9]. The solid walls can be arranged to form rectangular, triangular, hexagonal or other shapes. Secondly, lattice designs have a more open structure which allow for easier removal of metal powders, and usually allow for lattice structures with lower volume fractions to be built.

Much work has been done in trying to optimize the function of metallic lattice structures, by varying the geometry, volume fraction, and unit cell size of the structure [5, 8]. This study intends to expand on previous works by proposing a new approach to optimizing metallic lattice structures, through the novel application of functionally-graded thickness along the vertical direction. Varying the thickness of the walls of the structure would allow for opportunities to optimize the shock absorbing capabilities of the lattice structure while minimizing the amount of material used to build the high-performance functionally graded components.

Experimental procedure

Four groups of lattice structure were designed (C1, C2, H1, H2): two different orientations of cubic unit repeating structure and honeycomb unit repeating structure (Figure 1). For groups of C1 and H1, the struts were either parallel or perpendicular to the build direction (BD), which is along the z-axis. For groups of C2 and H2, lattice structures also consisted of angled struts. The size of cubic unit was 2 mm x 2mm x 2mm. The size of honeycomb unit was 1 mm for every strut of hexagonal face and 2 mm height. Each group consists of the following samples: functionally graded components with strut diameter changing linearly from 0.4 mm to 1.2 mm, and structure with uniform strut diameter of comparable material volume as FGC. Average size of samples was 14.2 mm x 13.0 mm x 11.6 mm (length x width x height). Three duplicates were printed for each design.

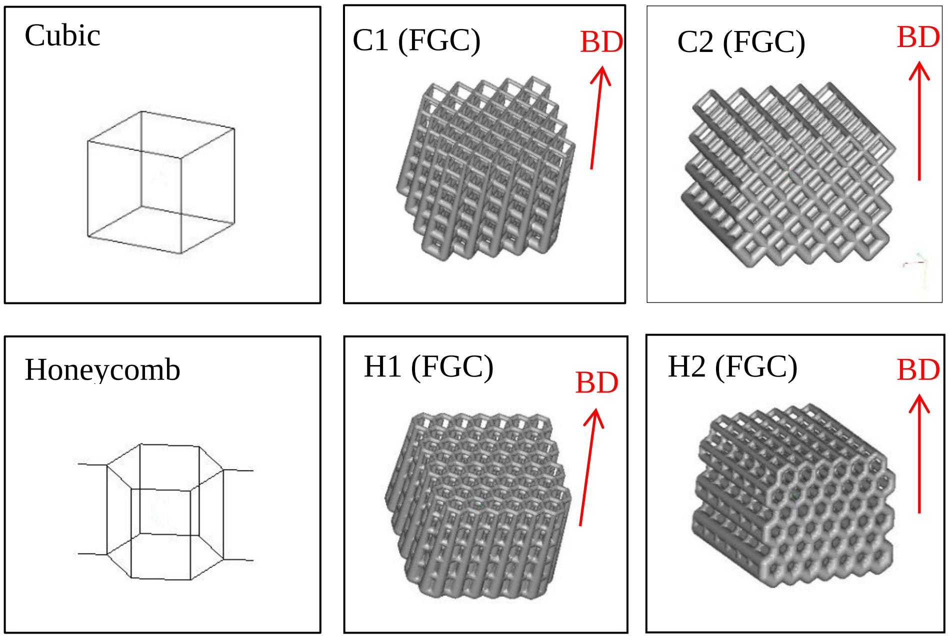

Figure 1 Designs of functionally graded components. Build direction is denoted as BD.

The lattice structures were designed with 3-matics software (Materialise NV) and then processed in Magics software (Materialise NV) before printing. The processed files were sent to SLM 250 HL (SLM Solutions Group AG) for printing with Ti6Al4V powder (TLS Technik GmbH & Co.) as material. The titanium alloy powder used was grade 23 with spherical particle size of 20 - 63 μm. Printing process parameters were 150 W laser power, 400 mm/s laser speed, 80 μm hatch spacing, and 30 μm layer thickness. After printing, the structures were separated from base plate by wire cutting.

Density of lattice strut was determined by Archimedes' principle using a weighing device (Mettler Toledo XS204) for measuring mass in air and mass in ethanol. Density of lattice structure was calculated by dividing mass in air with total volume of lattice structure obtained from multiplication of length, width and height of the structure. The calculated density of lattice structure was divided by 4.43 g/cm^3 (theoretical density of bulk Ti6Al4V) to get the values of relative density. Porosity was calculated by subtracting volume of solid portion from total volume of lattice structure. Volume of solid portion of the lattice structure was obtained by back calculating from the density of lattice strut and mass of lattice structure in air.

Struts of lattice structure were observed by light optical microscope (Olympus Upright Microscope MX51). Compression tests were performed with universal mechanical testing machine (Instron 5500R, Instron

4505, Shimadzu Autograph AG-X Plus) under 0.05 per minute strain rate. Some samples were cut to have smaller cross head area if machine force limit is exceeded. Video recording or photographs taken at regular intervals were done during the compression test to identify failure behavior of the structures.

Results and Discussion

The metallic lattice structures of cubic and hexagonal cell geometries with functionally graded designs built by SLM were shown in Figure 2. Specimens with uniform strut diameters of comparable volume fractions were also built for comparison in compressive properties.

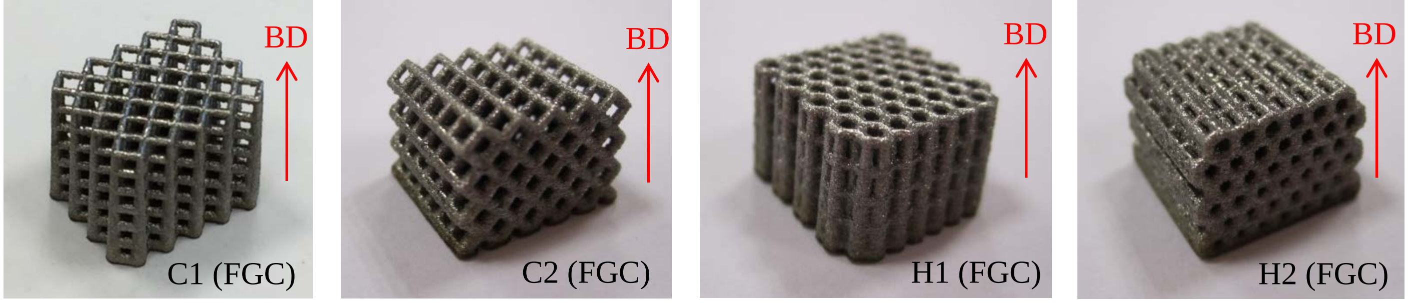

Figure 2 Fabricated functionally graded components for compression testing. Build direction is denoted as BD.

Table 1 shows the differences in porosity and density of the fabricated lattice structures versus the original design values. As shown in the table, the design strut diameters of the lattice structures with uniform strut were 0.995 mm, 0.875 mm, 0.844 mm, 0.858 mm for C1 (uniform), C2 (uniform), H1 (uniform), H2 (uniform), respectively. However, the measured strut diameters were 0.97 mm, 1.02 mm, 0.86 mm, 0.98 mm for C1 (uniform), C2 (uniform), H1 (uniform), H2 (uniform), respectively. This is why the design porosity was higher than the average porosity of the fabricated part in most cases. It was observed some partially-melted metal powders bonded onto the struts, rather than forming solid and continuous strut. The irregularities caused by powder adhesion may affect the mechanical properties of the part fabricated by SLM [1, 8]. Nevertheless, the calculated density of lattice structure was typically higher than 99%. Powder adhesion on the strut for cubic and honeycomb lattice structures is shown in Figure 3. Due to the manufacturing constraints imposed by SLM, it should be noted that struts of lattice structures cannot be longer than 2mm without support or orient at an angle less than ~40° with respect to the base plate.

Table 1 Porosity and density of the fabricated lattice structures versus design values

Design	Sample	Strut diameter (mm)		Porosity (%)		
		Design	Measured	Design porosity	Average porosity of part	Porosity difference*
C1	FGC	0.4 – 1.2	-	71.5	65.1 ± 0.3	9.0
	Uniform	0.995	0.968 ± 0.004	71.0	56.9 ± 0.2	19.9
C2	FGC	0.4 – 1.2	-	69.5	64.2 ± 0.4	7.6
	Uniform	0.875	1.021 ± 0.022	68.7	59.5 ± 1.8	13.3
H1	FGC	0.4 – 1.2	-	50.9	44.9 ± 0.9	11.9
	Uniform	0.844	0.858 ± 0.010	48.4	41.3 ± 0.4	14.8
H2	FGC	0.4 – 1.2	-	49.3	39.0 ± 0.2	20.9
	Uniform	0.858	0.976 ± 0.036	47.1	37.0 ± 0.4	21.4

* Porosity difference = (Design porosity - Average porosity of part) / Design porosity

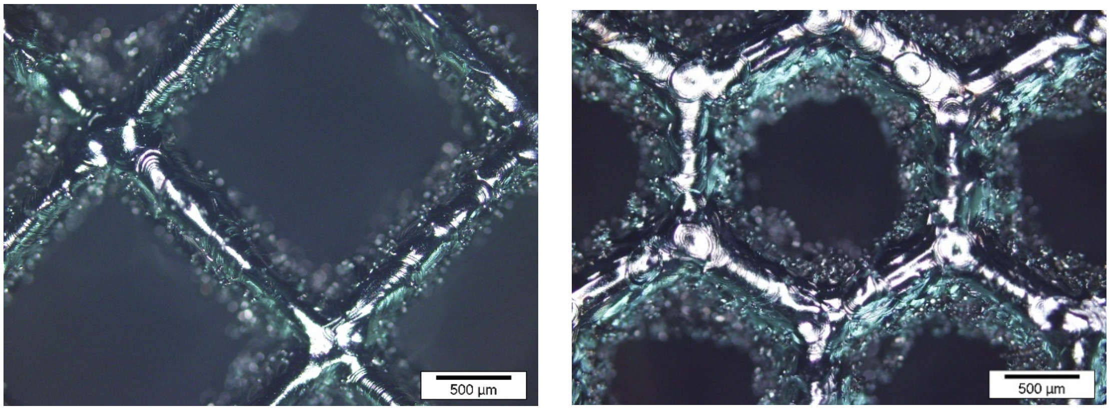

Figure 3 OM images showing powder adhesions on the struts, resulting in rough surface finish.

Figure 4-7 shows compression test results for different lattice structure designs, including cubic and honeycomb unit cells, different orientation, and various strut diameters – in graded and uniform shapes. Results reveal that when there were more vertical struts compressed parallel to the build direction, the overall first maximum compressive strength were higher, i.e. C1 > C2, H1 > H2. This means lattice structures with larger amount of vertical struts parallel to the build direction were stiffer and sturdier if compressed along the build direction. Similar phenomenon was reported by McKown et al. as significantly higher modulus occurred due to the presence of the vertical pillars or struts [2]. The same trend was observed for both FGC and uniform lattice structures.

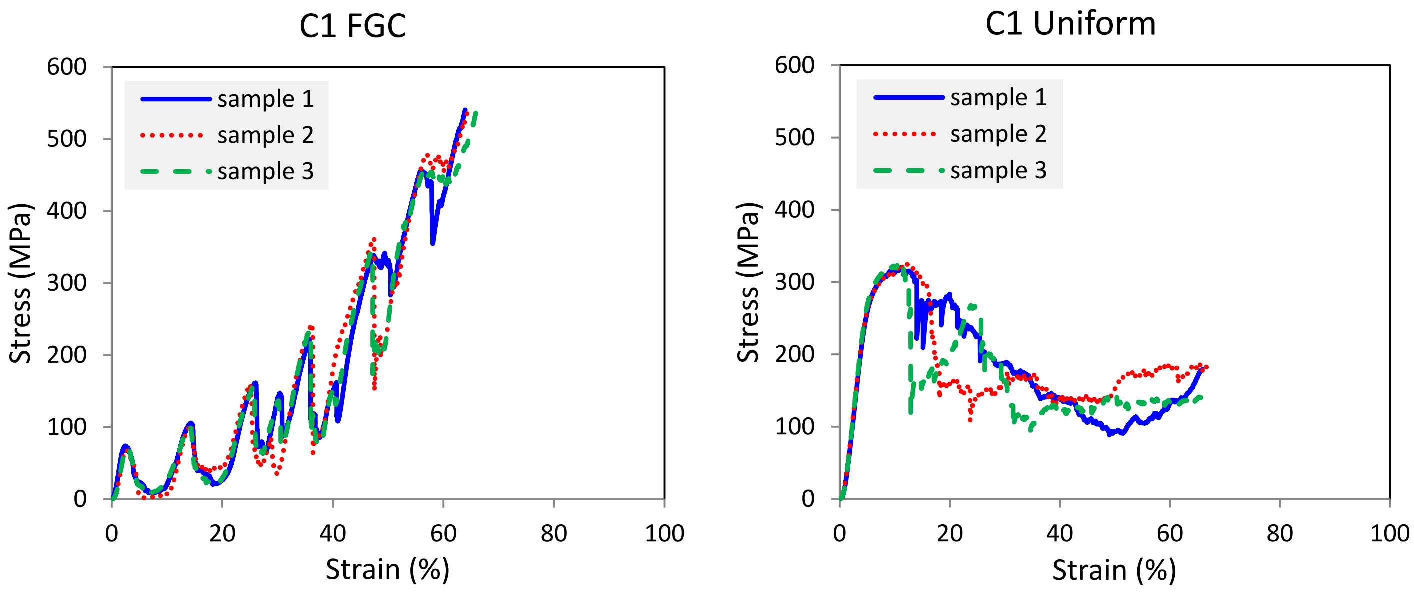

Figure 4 Compression test results for cubic lattice structures of design 1, denoted as C1.

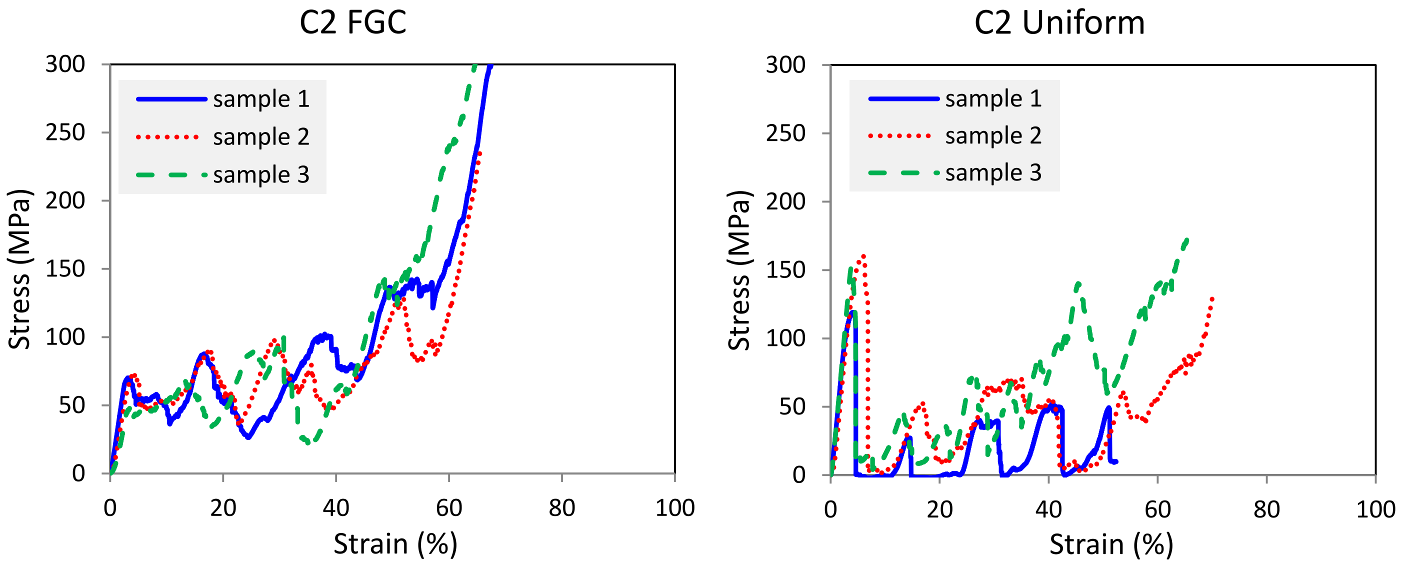

Figure 5 Compression test results for cubic lattice structures of design 2, denoted as C2.

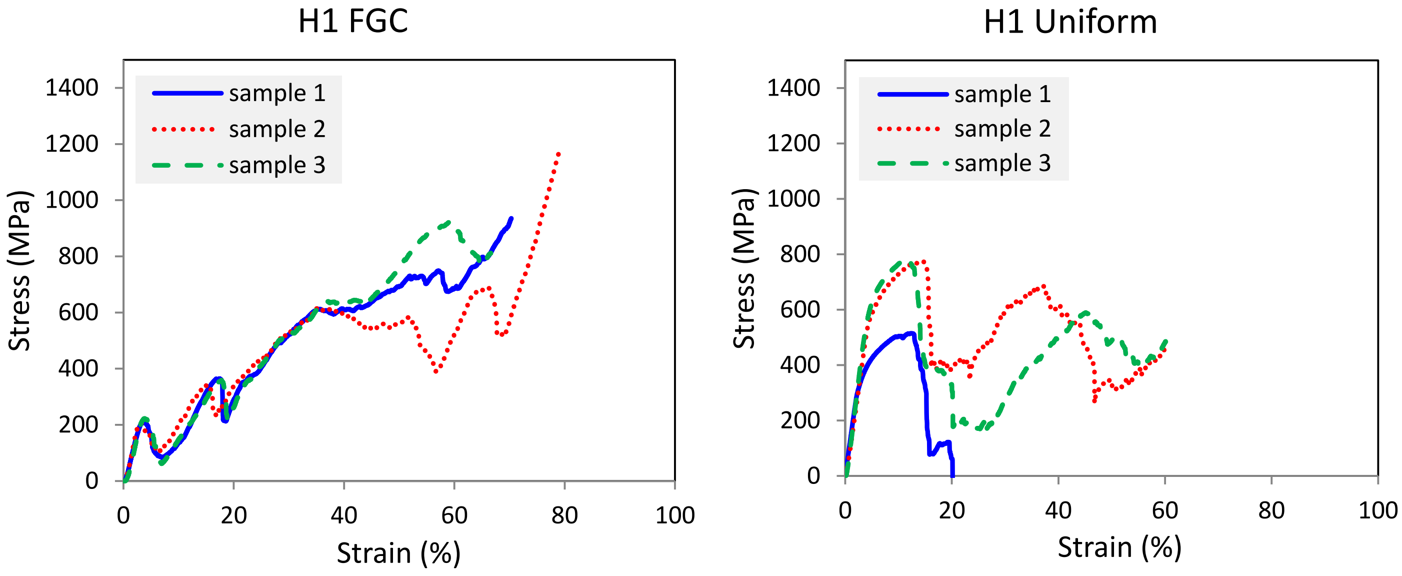

Figure 6 Compression test results for honeycomb lattice structures of design 1, denoted as H1.

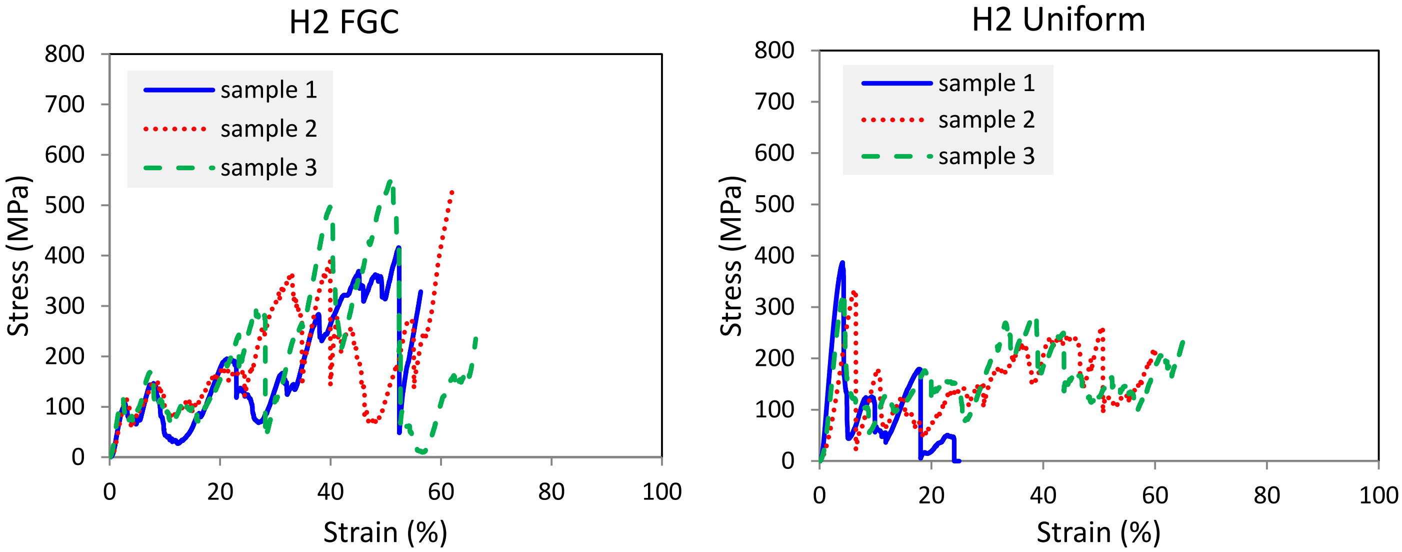

Figure 7 Compression test results for honeycomb lattice structures of design 2, denoted as H2.

The results of the compression study clearly show the difference in stress-strain response between different lattice structure with different types of unit cell designs as well as the effects of load direction on different build directions. In the cases of lattice structures with uniform strut diameters, typical stress-strain response that includes initial quasi-elastic gradient, plateau regions, as well as fluctuations of the stress-strain curve were observed. Similar, the stress-strain curve of the lattice structures with graded diameters is also composed of initial linear response, a number of plateaus and oscillations. However, the fluctuations were trending upward due to the increase in strut diameters, which translates to stronger regions that were more resilient to deformation. The results demonstrated that functionally graded components could potentially possess better shock absorbing ability as they could adeptly change the compressive response along the load direction.

Conclusions

Preliminary results of design and fabrication of metallic lattice structures with cubic and honeycomb unit cells were presented. It was observed that the fabricated part porosity was less than the porosity of design porosity, which was a result of partially-melted powder adhesion on the struts. Compression tests were also conducted on lattice structures with uniform strut diameters and graded strut diameters. The result showed a characteristic stress-strain response of the porous lattice structure. The influence of graded strut diameters was demonstrated as the fluctuations were trending upward, showing stiffer and stronger properties of the functionally graded structures. It is expected FGC can provide adaptable material properties in different loading conditions, as well as improved energy absorption capability while minimizing material usage.

Acknowledgments

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References

1. Campoli, G., et al., *Mechanical properties of open-cell metallic biomaterials manufactured using additive manufacturing.* Materials & Design, 2013. **49**: p. 957-965.

2. McKown, S., et al., *The quasi-static and blast loading response of lattice structures.* International Journal of Impact Engineering, 2008. **35**(8): p. 795-810.
3. Zhang, Z., S. Liu, and Z. Tang, *Crashworthiness investigation of kagome honeycomb sandwich cylindrical column under axial crushing loads.* Thin-Walled Structures, 2010. **48**(1): p. 9-18.
4. Cansizoglu, O., et al., *Properties of Ti–6Al–4V non-stochastic lattice structures fabricated via electron beam melting.* Materials Science and Engineering: A, 2008. **492**(1): p. 468-474.
5. Ahmadi, S.M., et al., *Additively manufactured open-cell porous biomaterials made from six different space-filling unit cells: The mechanical and morphological properties.* Materials, 2015. **8**(4): p. 1871-1896.
6. Li, P., *Constitutive and failure behaviour in selective laser melted stainless steel for microlattice structures.* Materials Science and Engineering: A, 2015. **622**: p. 114-120.
7. Li, P., et al., *Deformation behaviour of stainless steel microlattice structures by selective laser melting.* Materials Science and Engineering: A, 2014. **614**: p. 116-121.
8. Sing, S., et al., *Characterization of titanium lattice structures fabricated by selective laser melting using an adapted compressive test method.* Experimental Mechanics, 2016. **56**(5): p. 735-748.
9. Song, J., Y. Chen, and G. Lu, *Light-weight thin-walled structures with patterned windows under axial crushing.* International Journal of Mechanical Sciences, 2013. **66**: p. 239-248.