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Experimental study on compression response of additively manufactured lattice structures

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Abstract

The intricate nature of lattice structures poses challenges for conventional manufacturing approaches, necessitating the adoption of Additive Manufacturing (AM) methods. This work presents design of three novel biomimetic lattice structures namely Modified Schwarz Primitive (MSP), Tetrahedral (TLS) and octagonal prism with square hole (OPL). Digital Light Processing (DLP) based AM technology was utilized for fabrication and the compressive strength and porosity was evaluated. The results shown that the MSP have the highest porosity of 68.6 % whereas the OPL exhibited the highest compressive strength of 9.63 MPa.

Keywords: Biomimetic structures; Digital light processing; Acrylonitrile butadiene styrene; Compressive strength.

1. Introduction

Lattice structures are porous structure composed of repeating cellular unit. These structures are extensively used in the automotive, aerospace and biomedical application due to its high-performance features like ultra-light weight, high specific stiffness, good energy absorption capability thermal insulation and acoustic insulation [1]. The ability to create intricate, yet functional, facades and interior elements made it suitable for light weight structural components. Conventional techniques, such as investment casting, gel casting, tape casting and solvent casting are implemented to manufacture lattice structures [2,3]. The overall process is not feasible for some intricate lattice designs and also concerning time and cost. Therefore, Additive Manufacturing (AM) comes into existence to address the manufacturing issues related to conventional manufacturing techniques [4][5].

Digital light processing (DLP) is a form of AM technology that utilises a digital light projector to systematically solidify photopolymer resin over several layers, therefore producing tangible objects [6]. The regions of the resin that are exposed to electromagnetic radiation solidify, creating a solid layer. Once one layer has cured, the platform ascends by a little increment that corresponds to the thickness of that layer. The following layer is thereafter projected and subjected to curing. This technique is iterated through successive layers until the whole thing is constructed. Post processing is done by removing the printed structure from the build platform and rinsed with isopropyl alcohol to remove any uncured resin. The cleaned structure is then kept in a UV chamber to fully harden the resin thus improving the mechanical properties. In this work, three different lattice structures namely MSP, TLS and OPL were designed using fusion 360 software. The structures were printed using a DLP 3D printing method and the effect of compressive strength on the designed structures were evaluated.

2. Design, Material and experimental procedure

2.1 Biomimetic structure design

The MSP structure mimics the complex curvature of natural cellular forms, promoting efficient load distribution. This design is similar to bamboo-inspired hierarchical micro lattice structures, which exhibit high strength and energy absorption due to their hollow and gradient features[7]. The TLS design is based on tetrahedral symmetry, provides a robust framework similar to triply periodic minimal surfaces (TPMS) found in nature. TPMS structures are known for their stability and are utilized in applications requiring shock absorption and structural integrity[8]. OPL design high material volume capacity enhances strength, paralleling the dense support structures in biological materials. This approach aligns with the optimization strategies seen in bio-inspired lattice structures, which effectively balance strength and porosity [9]. The design of the three biomimetic lattice structures was done using Fusion 360 Auto CAD software. Figure 1 illustrates all the modelled designs and their respective unit cell designs.

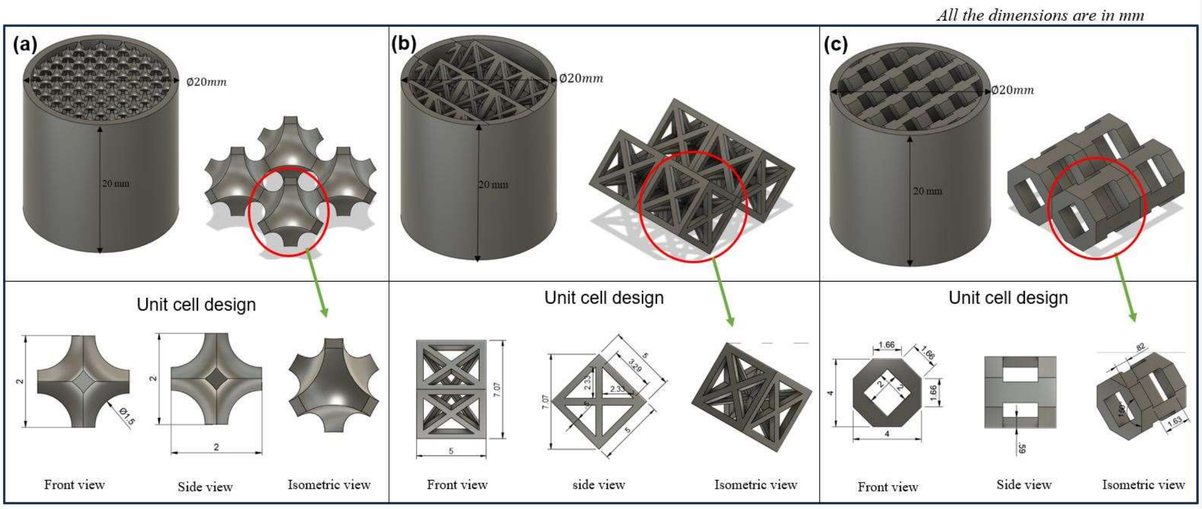

Figure 1. Biomimetic lattice structures and their respective unit cells (a) MSP (b) TLS and (c) OPL.

2.2 Materials and methods

Acrylonitrile Butadiene Styrene (ABS) [DLPDBBK01- Photocentric] was selected as the candidate materials for printing different biomimetic structures. The lattice structures were printed using a DLP printer (Liquid Crystal MAGNA). The curing is done by isopropyl alcohol for 4 hr at 60°C. The compression test of the printed lattice structures was performed according to ASTM D695-15. Universal testing machine (UTM - Jinan Hensgrand Instruments) at 5mm/min was utilized for evaluating the compression strength. Moreover, the porosity of the sample and the volume fractions were found out using the equations 1 and 2 respectively. Figure 2 shows the DLP printed used in the current study and the printed lattice structures.

$$Porosity\ (\%) = \frac{total\ volume - structural\ volume}{Total\ vlume} \times 100 \tag{1}$$

$$Volume\ fraction = \frac{Material\ volume}{Total\ volume} \tag{2}$$

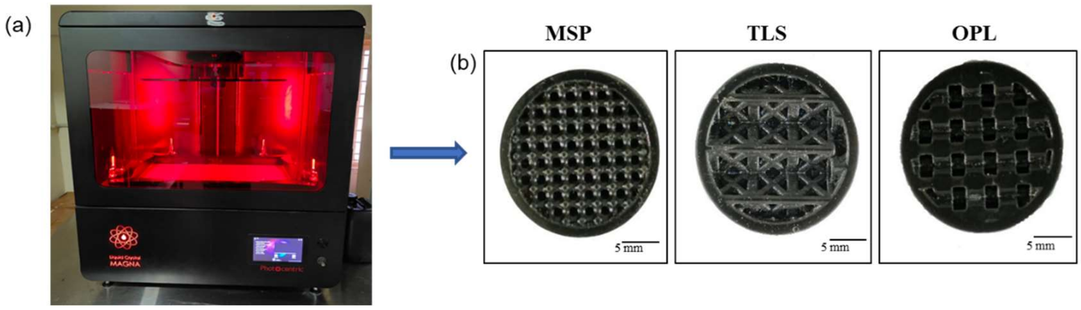

Figure 2. (a) DLP 3D printer used in the study (b) Fabricated lattice structures.

2.3 Printing process

ABS (Acrylonitrile Butadiene Styrene) resin is a viscous material that must be prepared before printing. It may involve stirring, heating, or filtering the resin, depending on the specific product. Pour the resin into the vat. The vat is a reservoir that holds the resin during the printing process. It should be filled to the appropriate level, as indicated by the printer manufacturer. Level the build platform. The build platform is the surface on which the print will be formed. It must be level so that the print is uniform and accurate. The 3D model must be sliced into horizontal layers before it can be printed. This is done using a slicing software program, which converts the model into a series of images, one for each layer. Send the sliced model to the printer. The sliced model is transferred to the printer using a USB drive or SD card. Start the printing process.

Once the model is loaded on the printer, the printing process can be started. This involves projecting light from the DLP projector onto the resin in the vat. The light cures the resin, forming a solid layer of the print. The printing process is repeated for each layer of the model. The printing process parameters employed in the study are layer height 50 microns, exposure time 6000 milli seconds, bottom exposure time 50000 milli seconds, lift distance 10 mm, lift speed 200 mm/min and retract speed 160 mm/min respectively. Once all of the layers have been printed, the print is complete. Remove the print from the build platform. Once the printing process is complete, the print must be removed from the build platform. This can be done using a spatula or other tool. Post-process the print. After the print has been removed from the build platform, it may need to be post-processed. This may involve washing, curing, or sanding the print, depending on the specific resin used.

3. Results and discussion

The compressive testing setup, stress-strain behaviour, and fracture modes of the three different printed lattice structures were shown in Fig. 3(a)-(c). Compressive testing of DLP-printed ABS lattice structures involves multiple processes. The lattice deforms in the elastic phase but recovers to its original shape when the load is removed. The material enters plastic deformation as stress increases, causing permanent alterations and preventing structure recovery. Strain hardening may temporarily resist deformation. The structure collapses when the lattice buckles or breaks under load. The material continues to deform and crush with low stress after failure, losing load-bearing capacity. The structural and mechanical properties of different lattice designs given in Table 1.

The compressive strength was carried out to assess the variation in compressive strength between the various lattice designs such as the MSP, TLS and OPL. OPL exhibits the highest compressive strength of 9.63 MPa due to higher material volume of 2864.69 mm^3. The structure also reported a lower porosity of 54.38 % despite having a dense material which is suitable for supporting grater loads without collapsing. MSP, despite having lower volume (1968.89 mm^3) and higher porosity (68.64 %), has a slightly higher compressive strength than TLS. This suggests that the specific design of MSP allows for more efficient load distribution, compensating for its lightweight nature. TLS exhibits the lowest compressive strength of the three structures despite having intermediate material volume (2106.34) and porosity (66.46 %). This may be due to the less distribution of material across the lattice design resulting in reduced structural stability.

The trend of the compressive strength shows that the OPL > MSP > TLS. The highest value obtained from OPL is 12.37 % enhanced strength than a similar work reported using a 3D printed X- lattice structure with 8.57 MPa of compressive strength [10]. These biomimetic lattices hold promise in fields requiring lightweight structures with tailored mechanical properties. High porosity in MSP could be advantageous in biomedical implants needing bone integration and vascularization, while OPL's high compressive strength makes it suitable for load-bearing applications like orthopedic implants. Additionally, TLS's stability could be beneficial in aerospace structures where weight and durability are critical. Linking these results to such applications underscores their practical relevance.

Table 1 Structural and mechanical properties of different lattice designs

Lattice design	Material volume (mm^3)	Porosity (%)	Pore size (mm)	Volume Fraction	Compressive strength (MPa)

MSP	1968.89	68.64	1.5 – 2.0	0.31	8.03 ± 0.26
TLS	2106.34	66.46	1.3 – 4.0	0.33	7.34 ± 0.19
OPL	2864.49	54.38	1.0 – 2.0	0.45	9.63 ± 0.21

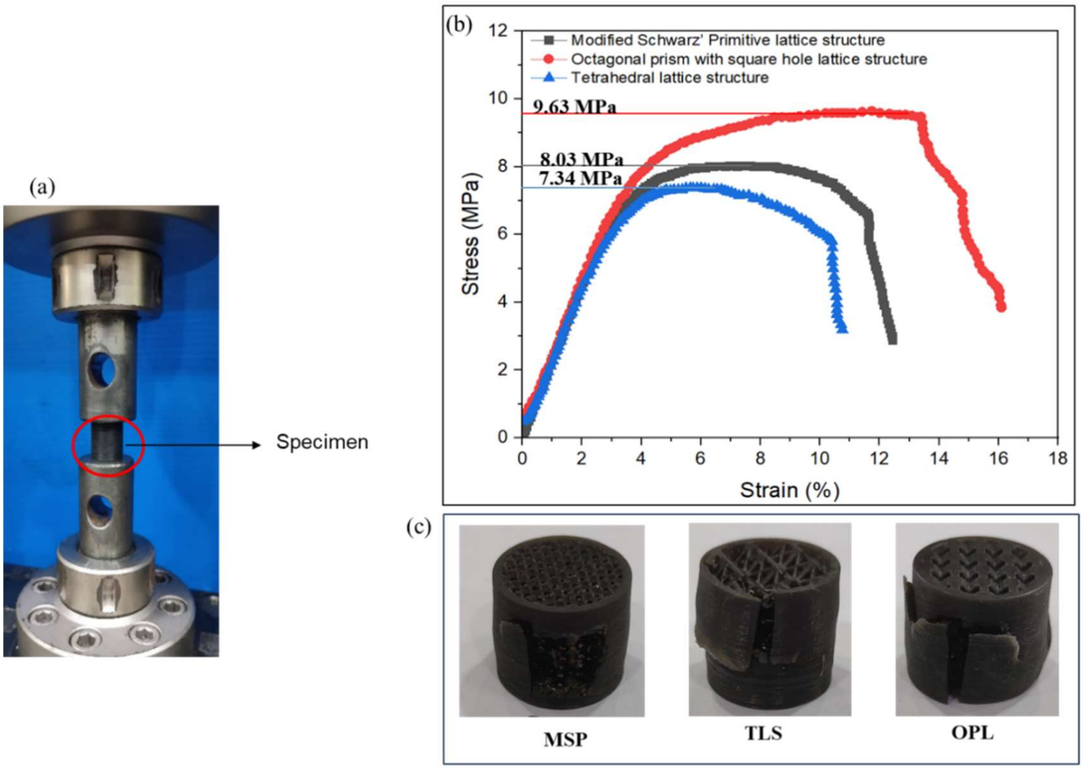

Figure 3. (a) Compression strength measurement using UTM (b) stress strain curve of the compression test (c) deformed lattice structures after compression test.

4. Conclusions

The additive manufacturing based DLP was utilized to manufacture three different lattice structures is presented in this work. Utilizing lattice structures proves to be an effective strategy for weight reduction. The highest compressive strength was reported in OPL structure exhibiting a value of 9.63 MPa whereas the lowest value of reported in TLS as 7.34 MPa. Highest porosity value of (68.6%) was achieved with MSP lattice structure. The highest compressive strength reported OPL structure is 31.2% stronger than the TLS structure with lowest compressive strength. Future work suggests exploring multi-material printing to further enhance the structural integrity and functionality of these lattice designs. Investigating alternative materials could expand potential applications, while refining lattice geometry through advanced optimization provide even greater customization for targeted uses in biomedical or aerospace fields.

Credit authorship contribution statement

Praveen A S: Writing – review & editing, Resources, Investigation. Belgin Paul: Writing – review & editing, Supervision, Methodology, Investigation. Arun Arjunan: Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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