TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 68, Issue Special I, May, 2025

INFLUENCE OF LAYER THICKNESS ON COMPRESSIVE BEHAVIOR OF KAGOME STRUCTURES

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Abstract: *This study focuses on the behavior of mechanical metamaterial structures under compressive loads and investigates the influence of production parameters on final properties of Kagome structures manufactured through stereolithography (SLA) using photopolymer resin. Tough 2000™ is a resin used for engineering applications developed by Formlabs, known for its high tensile strength, stiffness, and impact resistance and provides an ideal material for lightweight yet durable lattice designs. The study evaluates the influence of layer thickness on mechanical performance and the results revealed that increasing the number of layers reduces structural strength due to cumulative deformation effect and increases the ductility of the materials. The findings highlight the versatility of SLA-printed Kagome lattices for advanced engineering applications requiring lightweight, high-performance materials with tunable mechanical properties.*
Keywords: *FDM, Stereolithography, Kagome structures, Compression Testing, Microscopy, 3D printing*

1. INTRODUCTION

In recent advances of design optimization methods, cellular lattice structures have emerged as a growing point of research, both in engineering and material science [1]. Mechanical metamaterial structures are realized by multiplying one element, usually called "unit-cell" along 3 orthogonal axes. An example of the unit cell can be seen in Figure 1, as it was used to create the structures investigated in this research. These metamaterials are widely investigated as they exhibit improved mechanical properties, including high specific strength, stiffness, and energy absorption capacity [2].

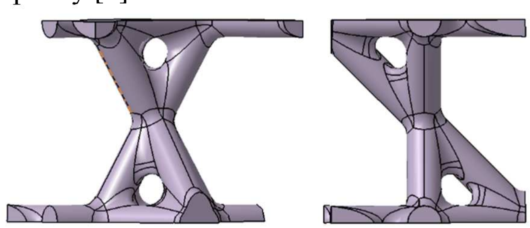


Fig. 1. Unit cell of a Kagome structure.

Inspired from traditional Japanese basket-weaving patterns, the Kagome lattice features a triangular arrangement of nodes and struts that provides isotropic mechanical properties and resistance to deformation under various loading conditions [3]. Their unique geometry is specially created to combine lightweight characteristics and superior mechanical performance. These attributes make Kagome lattices highly desirable for applications in aerospace [4], automotive [5], and biomedical [6] industries, where these robust combinations of material properties are essential.

The advancement of additive manufacturing (AM) technologies has revolutionized the fabrication of complex geometries like Kagome structures. From the various technologies of 3D printing, SLA technology has gained notoriety for its ability to create high precision and smooth surface finishes [7]. SLA employs a layer-by-layer photopolymerization process using ultraviolet (UV) light to cure liquid resin into solid parts with fine features and tight tolerances that are challenging or impossible to achieve using traditional manufacturing methods.

2. MATERIALS AND METHODS

To create 3D structures, the first step is to think about the link between the unit cell and the dimension of the desired specimens. In this case, Catia@ 3D modelling software was used to realize the CAD model seen in Figure 2. After finalizing the 3D model, a slicer software is used to create the layers that will be imported in the 3D printer to be manufactured. The specialized software used was PreForm@ and 3 different layer thicknesses were investigated, with more details presented in Table 1, as the layer dimension influence the time of the print, the dimension of the obtained part, the quality of the surface and the number of layers needed to create the prototypes [8], along with the number of support geometries used and the material needed. All these parameters have been previously studied in various domains and presented variations in mechanical properties of the parts with the layer thickness, thus remaining an open discussion on which is the right balance between number of layers (implicitly their size) and time-efficiency, taking also into account the surface finish on the final parts [9].

For the current research, the layer thickness chosen was 0.1 mm, 0.05 mm and the optimization with adaptive setup, which improves the time by creating different sizes in critical areas.

Table 1

Printing parameters setup in the PreForm software.

Layer thickness	Total print time	Number of layers	Volume of resin
0.1 mm	2 h 46 min	294	27.63 ml
0.05 mm	5 h 58 min	587	24.81 ml
Adaptive	2 h 46 min	294	27.63 ml

The manufacturing of specimens for compression testing was done with a Form3+@ SLA printer from Formlabs and the material used was a photosensitive resin with a composition described by the manufacturer as: *Urethane Dimethacrylate (45-65%), Methacrylate Monomer (15-25%), Isobornyl methacrylate (10-20% and phenyl bis(2, 4, 6-trimethylbenzoyl)-phosphine oxide (<0.6%)* [10, 11], commercially known as Tough 2000.

The mechanical properties of the Tough 2000 resin make it suitable for a relatively large range of applications, from jigs and fixtures to functional prototypes or ready-to-use parts. The literature survey showcased that mechanical properties of compression tests on specimens may exhibit variations (most common in the rage of 10-20%) [12, 13], so further investigations may fulfill the gap in the actual information and create the premises for new developments.

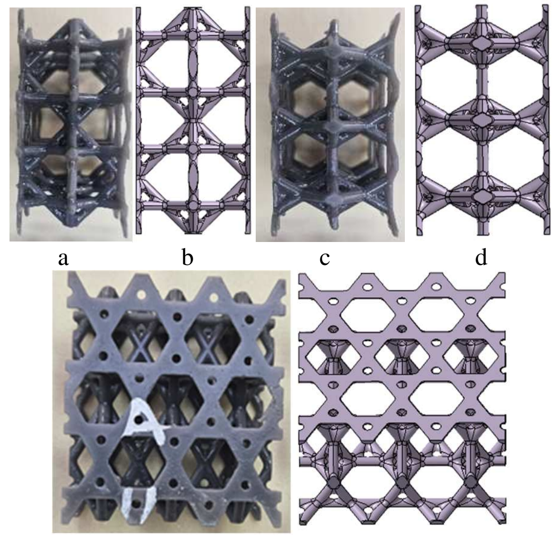


Fig. 2. Representation of real parts after post-processing (a, c, e) and CAD model (b, d, f) for visual comparison.

The parameters for the supports were selected at minimal values, with mini rafts used to attach the support to the build platform and with a density of 0.5 and a touchpoint of 0.5 mm, making them thinner and easier to detach from the principal structure. In Figure 3a a representation of the orientation of the structures on the build platform is presented, while in Figure 3b is highlighted how small the attachment points really are (compared to the useful part) for the support elements.

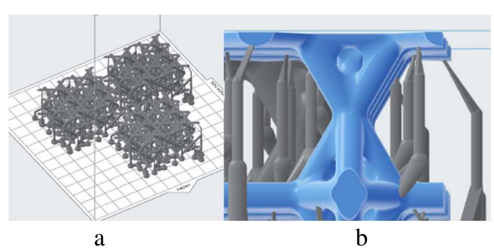


Fig. 3. Slicer software presentation.

Table 2

Material properties from the datasheet of Tough 2000

	Green	Post-Cured
Tensile Properties		
Ultimate Tensile Strength	29 MPa	46 MPa

Tensile Modulus	1.2 GPa	2.2 GPa
Elongation at Break	74%	48%
Flexural Properties		
Flexural Modulus	0.45 GPa	1.9 GPa
Thermal Properties		
Heat Deflection Temp. @ 1.8 MPa	42 °C	53 °C
Heat Deflection Temp. @ 0.45 MPa	48 °C	63 °C
Thermal Expansion (0-150 °C)	107 µm/m/°C	91 µm/m/°C

* "Data was obtained from parts printed using Form 2, 100 µm, Tough 2000 settings and post-cured with a Form Cure for 120 minutes at 80 °C. [10]".

Post-processing is one of the key factors that influence the behavior of additive manufactured parts from photosensitive resins. After a print is finished, the parts are carefully placed in IPA (isopropyl alcohol) and after the removal of support geometries that helped to create the zones that could not support themselves, the parts are inserted in a curing machine for hardening under UV light. The equipment used for this study was a Form Cure (Figure 4a) and the structures were equally spaced on the rotating platform and kept under curing for 60 minutes at a temperature of 70 °C as the manufacturer of resin recommended (Figure 4b is a schematic of how parts look inside the curing machine). Curing of the specimens was done with a UV light with a wavelength of 405nm.

a b

Fig. 4. Kagome structures positioned on the rotating table of UV curing machine Form Cure$^{@}$.

3. EXPERIMENTAL PROCEDURES

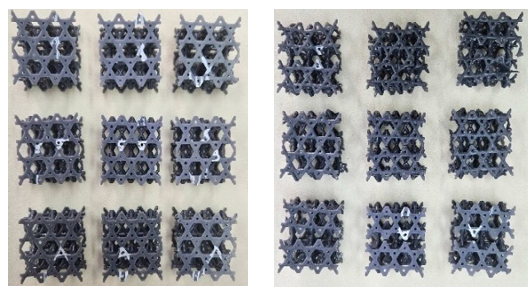
In Table 3, the average measured dimensions of the specimens are presented, along with the average weight.

Table 3

Measured values of investigated Kagome structures.

Layer thickness	Length [mm]	Width [mm]	Height [mm]	Weight [g]
0.1 mm	45.84	39.71	23.28	7.23
0.05 mm	45.81	39.72	23.30	6.9
Adaptive	45.85	39.79	23.25	7.26

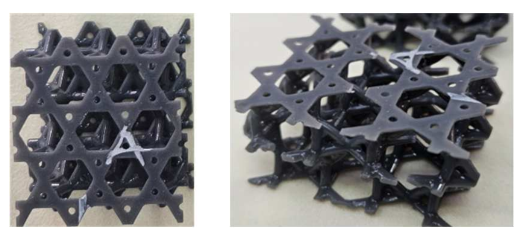
For compressive testing a Walter+Bai testing machine with a load cell of 100 kN was used, and the tests were performed according to ISO 604:2002 standard for plastics [14]. The speed of the crosshead was set at 2 mm/min and the criteria to stop the test was set for a drop of 50% in force value. In figure 5a, Kagome specimens are presented before compression, while in Figure 5b presents the structures after the tests.



a b

Fig. 5. Kagome structures.

The Kagome structure is presented in Figure 6a before the test was performed and in Figure 6b after compression test was performed, highlighting the area of failure and the behavior of the structure under compressive load.



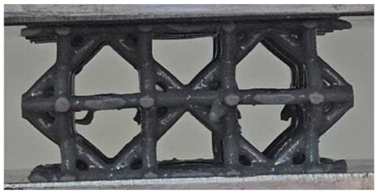
. a b

Fig. 6. Kagome structure before and after compression test.

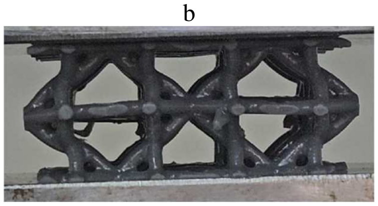
The testing was recorded, and Figure 7a represents the initial position, Figure 7b represents the position at 25% displacement, Figure 7c at 50% displacement, Figure 7d at

75% displacement and the final deformation of the Kagome structure is depicted in Figure 7e.

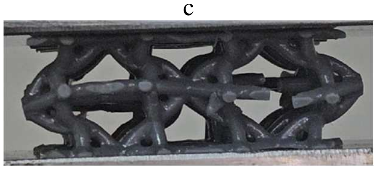
a



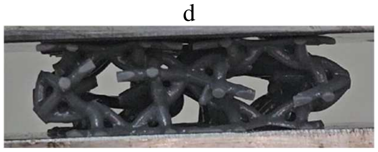
b



c



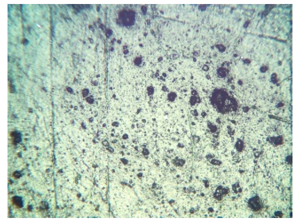
d

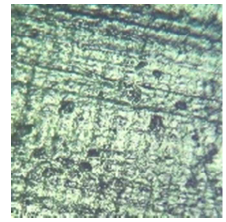


e

Fig. 7. Different stages of compression on Kagome structure.

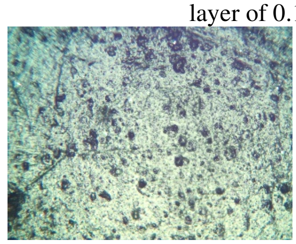
The surface was investigated with the help of electronic microscopy and the results are shown in Figure 8 for the surface and side investigations of specimens. As can be observed in Figure 8, there are some anisotropies present on the surface of the specimens, in all variations of layer thickness while on the side of the parts the layer can be distinguished, and some small irregularities are visible on the surface. Further research is needed to have a comprehensive understanding of how surface finishes are affected by changing the thickness of a printed layer.

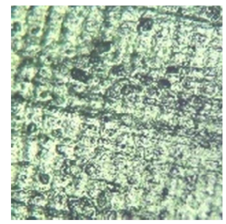




a b

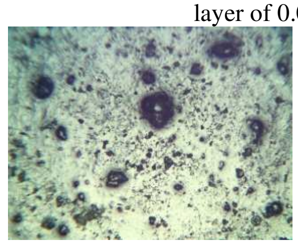
layer of 0.1 mm

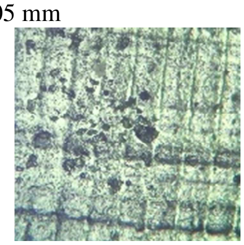




c d

layer of 0.05 mm





e f

adaptive layer

Fig. 8. Surface investigation of SLA printed parts.

4. RESULTS AND DISCUSSIONS

The results demonstrated repeatability, with the curves nearly overlapping for the same type of layer thickness, indicating consistent mechanical behavior across multiple tests highlighting the reliability of the manufacturing process. For the investigated different layer thicknesses, the results can be observed in Figure.

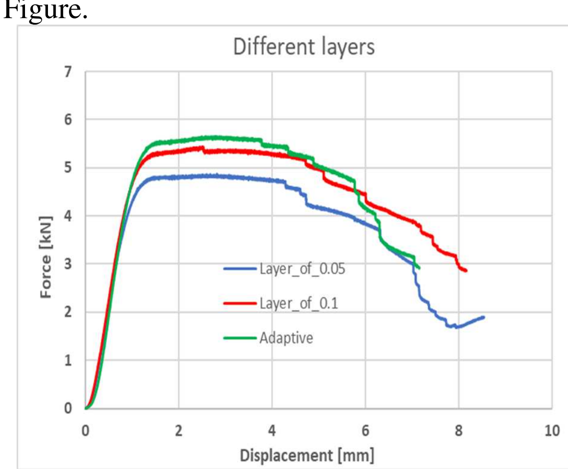


Fig. 9. Force-displacement representation.

From Figure 9 it can be stated that layer thickness has an influence on Kagome structures manufactured through stereolithography, exhibiting an increase in strength with the increase of layer thickness, while the ductility of the material increases with thinner layers. This can have a multitude of factors that contribute to material behavior, the most common being the improper layer bonding and chances of porous regions to be present as different areas exhibit a different hardening time. In Figure 10, a representation of the 3 different structures is presented and it can be observed that the adaptive layer structure can absorb the highest force, but also has the smallest deformation, and after testing it remained between the structure with 0.1 mm and 0.05 mm layers in terms of deformation. Also, the lowest force was obtained for structures with the lowest layer thickness. These Kagome structures displayed good load distribution capabilities, which may be further enhanced by structural optimization and applying the right post-process parameters such as time and temperature of curing under UV light to find the specific combination of properties desired in novel applications.

Fig. 10. 3 different structures after the compression test, having the layer thickness in order from left: adaptive, 0.1 mm, 0.05 mm

5. CONCLUSIONS

After investigating the compressive behavior of SLA-manufactured Kagome lattice structures created using Tough 2000 resin, it can be concluded that the mechanical metamaterials have a great potential for high-performance engineering applications where lightweight, yet durable structures are needed. The study revealed that layer thickness influences the mechanical properties of Kagome structures, and layers with 50 μm underperformed the structures with a bit higher layer thickness, and the superior compressive strength was observed in the structures with an adaptive layer and a similar number of layers as the 100 μm thickness, with the benefits of a lower production time and a similar surface finish quality.

These findings highlight the importance of optimizing layer thickness to achieve desired mechanical performance considering the time of production and the material cost as increased layers also used a slightly increased quantity of resin. With the help of SLA-printed Kagome structures, improvements can be made in shock absorption, energy absorption and load-bearing capacity for applications in aerospace, automotive, and biomedical fields, where lightweight materials with tunable mechanical properties are essential. Future research will focus on refining design parameters and exploring graded density configurations and enhancing mechanical properties with design optimization.

6. ACKNOWLEDGEMENT

This work was partially funded by the Research Grant PN-III-P2-2.1-PED-2021-1134, contract number 586PED/2022.

7. REFERENCES

[1] Gautam, R., Idapalapati, S., *Compressive Properties of Additively Manufactured Functionally Graded Kagome Lattice Structure*, Metals , vol. 9, n. 5, p. 517, 2019.

[2] du Plessis, A., Razavi, N., Benedetti, M., Murchio, S., Leary, M., Watson, M., Bhate, D., Berto, F., *Properties and applications of additively manufactured metallic cellular materials: A review,* Progress in Materials Science , vol. 125, n. 100918, 2022.

[3] Nan, J., Fuchi, W., Yangwei, W., Zhang, B., Cheng, P., et al. *Effect of structural parameters on mechanical properties of Pyramidal Kagome lattice material under impact loading*, International Journal of Impact Engineering, vol. 132, n. 103313, 2019.

[4] Liu, J., Xu, M., Zhang, R., Zhang, X., Xi, W., *Progress of Porous/Lattice Structures Applied in Thermal Management*

Technology of Aerospace Applications, Aerospace , vol. 12, n. 827, p. 120827, 2022.

[5] Lee K., et. al., *A parametric study on compressive characteristics of wire-woven bulk Kagome truss cores*, Compos Struct , vol. 92, p. 445–453., 2010;.

[6] Lee, S., Lee, K. G., Lee, J., Cho, Y., Ghim, M., *Three-dimensional kagome structures in a PCL/HA-based hydrogel scaffold to lead slow BMP-2 release for effective bone regeneration*, Bio-Design and Manufacturing, vol. 6, , 2023.

[7] Coșa, A., Negru, R., Șerban, D., *Development of Kagome-based functionally graded beams optimized for flexural loadings*, European Journal of Mechanics / A Solids, vol. 109, n. 105474, 2025.

[8] Wise, S., Bobbio, L., Russo, A., Simpson, T., Besse, A., *Strength Comparison of Topology Optimized Lattice From Printed SLA Resin, Electroplated Resin and PBF Aluminum Alloy*, in 33rd Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference, Austin, 2022.

[9] Bieler, S., Weinberg, K., *Behavior of additively manufactured lattice structures unter compressive loading*, in Applied Mathematics & Mechanics, Aachen , 2023.

[10] Formlabs, «Tough 2000 Datasheet,» Formlabs, 2022.

[11] Formlabs, «Safety Data Sheet of Tough 2000 resin,» Formlabs, EU, 2022.

[12] Riccio, C., Civera, M., Grimaldo Ruiz, O., Pedulla, P., Rodriguez Reinoso, M., Tommasi, G., Vollaro, M., Burgio, V., Surace, C., *Effects of Curing on Photosensitive Resins in SLA Additive Manufacturing*, Appl. Mech., vol. 2, 2021.

[13] Xu, Q., Jiang, L., Ma, C., Niu, Q., Wang, X., *Effect of Layer Thickness on the Physical and Mechanical Properties of Sand Powder 3D Printing Specimens*, Frontiers in Earth Science, vol. 9, 2021.

[14] ISO 604:2002, Plastics — Determination of compressive properties. International Organization for Standardization; ISO: Geneva, Switzerland, 23, 2002.

Influența grosimii stratului de printare asupra comportamentului la compresiune al structurilor de tip Kagome

Acest studiu investighează comportamentul acestor structurilor de metamateriale mecanice sub sarcini de compresiune și influența parametrilor de producție asupra proprietăților finale ale structurilor Kagome fabricate prin stereolitografie (SLA), utilizând rășină fotopolimerică. Tough 2000™ este o rășină dezvoltată de Formlabs pentru aplicații inginerești, cunoscută pentru rezistența ridicată la tracțiune, rigiditate și rezistență la impact, fiind un material ideal pentru proiectarea structurilor ușoare și rezistente. Studiul evaluează influența grosimii stratului asupra performanței mecanice, iar rezultatele relevă că o creștere a numărului de straturi reduce rezistența structurală din cauza efectului cumulativ al deformării și crește ductilitatea materialelor. Concluziile subliniază versatilitatea structurilor de tip Kagome realizate prin SLA pentru aplicații inginerești avansate care necesită materiale ușoare, performante și cu proprietăți mecanice ajustabile.
Cuvinte cheie: *FDM, Stereolitografie, Structuri Kagome, Testare de compresie, Microscopie, Imprimare 3D*

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