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Mechanical response of shape-recovering metamaterial structures fabricated by additive manufacturing

Md Sahid Hassan, Luis A Chavez, Chien-Chun Chou, Samuel E Hall, Tzu-Liang Tseng and Yirong Lin

1 Department of Mechanical Engineering, The University of Texas at El Paso, El Paso, TX 79968, United States of America
2 W.M. Keck Center for 3D Innovation, The University of Texas at El Paso, El Paso, TX 79968, United States of America
3 Department of Industrial, Manufacturing, and Systems Engineering, The University of Texas at El Paso, El Paso, TX 79968, United States of America

* Authors to whom any correspondence should be addressed.

E-mail: mhassan2@miners.utep.edu and ylin3@utep.edu

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Abstract

Three different metamaterial structures were fabricated using stereolithography 3D printing and a shape recovering material. Mechanical properties and recovery efficiency were assessed after compression testing. All three structures exhibited similar initial specific compressive moduli, while the highest specific toughness was observed for the stretch-dominated structure. The three metamaterial structures were re-tested after shape recovery. Significant strengthening was observed for all structures, with the bend-stretch-dominated structure strengthening to the highest degree. This strengthening phenomenon was characterized as strain hardening. It was found that the strengthening is highly geometry dependent. The geometry with stretch-dominated behavior exhibited the highest mechanical properties after a second test was performed. Improvements in specific toughness of up to 67% were observed after the second compressive test.

Introduction

Material structures that are lightweight and with high specific properties are of great interest for many industries and applications [1]. Ranging from particulate [2] and fiber [3] reinforced composites to polymeric [4] and metallic [5] foams, scientists and engineers have aimed their efforts for years to develop material systems with engineered properties. A class of material system that has been known to exhibit low densities without compromising functional and structural properties is cellular solids [6]. Cellular solids are highly porous interconnected systems with an arranged complex pattern in their structure. Cellular structures can be found in many naturally occurring material systems that are strong and lightweight such as wood and bones [7]. Cellular solids and foams have found their way into different industries, from structural to biomedical and chemical engineering, as well as specific applications in which interconnected high-surface area is required [8–10]. Additionally, polymeric foams are widely utilized for shock-absorbing purposes [11]. However, one of the drawbacks of most man-made cellular solids is that their structures cannot be easily controlled during the fabrication process [12]. This lack of property control has limited their widespread implementation into various industries until reliable and predictable manufacturing techniques can be used.

One class of cellular structures that have emerged and gained great interest due to their higher property tunability is metamaterials. Metamaterials are man-made periodic structures that exhibit properties as a function of their geometry and arrangement but not due to their constitutive materials [12]. They have been used in recent years for several applications including sensors, energy harvesters, electrical and thermal property tuning, as well as control of mechanical characteristics [13–17]. Naturally occurring crystal structures have been used as models to develop mechanical metamaterials with designed properties as these structures have been studied for many years, and their response under specific conditions is well understood [18]. Crystal or lattice,
structures used for mechanical metamaterials are commonly divided into two groups: stretch-dominated, and bend-dominated. Bending-dominated structures usually exhibit a mechanical behavior that is more compliant, while structures that are stretch-dominated are more efficient in their strength [19]. Although structures with a stretch-dominated behavior are more efficient weight-wise, bending-dominated, and even structures that are composed of the two types of geometries can be used to achieve specific engineered responses [20].

While metamaterial structures hold great promise to develop strong and lightweight structures with predictable mechanical behavior, they were not practical to fabricate until recent years. Metamaterial structures have gained increasing attention recently due to the implementation of additive manufacturing (AM) [21–23]. AM enables the fabrication of very complex geometries through a layer-by-layer process during which the desired material system is selectively deposited. In addition to the fabrication of complex geometries, AM can also provide the ability to tune the properties of the individual layers being fabricated by means of change of materials or geometry [20, 24–26]. These property-on-demand characteristic positions AM as an extremely useful tool to fabricate material systems with higher levels of functionality. As a result of all these advantages, AM has been used to study the properties of different metamaterials in recent years [20–27]. While AM has been used to study the properties of different geometries in metamaterials in recent years, the capabilities of this manufacturing technique could be further leveraged by coupling material and geometrical properties in a single structure. Therefore, a study of the interaction between material and geometrical properties in 3D printed materials is of interest for many applications.

One research area of great interest for many industries is impact energy absorption layers. Metamaterial structures that can withstand mechanical impacts and deformations have been studied in the past [27]. Despite the great results observed in some of these works, the structures fabricated can only serve one load cycle as permanent deformation and failure are typically observed after testing. Therefore, structures that can be tuned for specific loads through geometry but can also serve more than one loading cycle are needed. In this work, we have studied the impact of using different geometries with a stereolithography (SLA) 3D printed material with shape recovery properties. Metamaterials with geometries that exhibit bending-dominated as well as stretch-dominated geometries were fabricated. Additionally, a structure that exhibits both properties was designed and fabricated. The shape recovery speed, as well as compressive mechanical properties of these 3D printed metamaterials were studied. Computational simulations were also used to understand the interaction between the geometrical and material phenomena present in the fabricated metamaterials.

Materials and methods

Geometries. Three different structures were fabricated for this study: Body Center Cubic (BCC), Face Center Cubic (FCC), and a combination of both structures (BFCC) [28]. BCC exhibits a bend-dominated behavior, FCC shows a stretch-dominated behavior, while BFCC exhibits both types of phenomena. Cellular structures comprised of $5 \times 5 \times 5$ unit-cells were fabricated, yielding an overall size of $25 \times 25 \times 25$ mm. The truss thickness of all the printed structures was kept at 1 mm. Schematics of the BCC, FCC, and BFCC unit-cell geometries are shown in figures 1(a)–(c).

Fabrication Process. The structures studied were fabricated using a Form 2 stereolithography 3D printer from Formlabs. Tough resin (Formlabs) was utilized to fabricate all specimens, and standard printing parameters were used. After fabrication, all specimens were subject to a post-curing process during which a temperature of 50 °C and UV light (405 nm, 9.1 W) was applied for 30 min [29].

Mechanical Testing. After post-curing, samples were subject to compression testing using an Instron 5866 load frame. During these tests, the samples were compressed at a rate of 1 mm min$^{-1}$ up to a deformation of 40% of their original length. After these tests, the samples were quickly unloaded to measure their initial speed of shape recovery. After the samples recovered for five days, they were re-tested under the same loading conditions to assess their mechanical performance.

Results and discussion

The three different metamaterial structures were successfully fabricated using SLA AM and are shown in figures 1(d)–(f). BCC geometry presented a density of $0.416 \text{ g cm}^{-3}$, BFCC of $0.245 \text{ g cm}^{-3}$, and FCC of $0.518 \text{ g cm}^{-3}$. These values corresponded to a relative density to the base polymer of 34.7%, 20.4%, and 43.2%, respectively. Due to these density differences, their mechanical properties were normalized against densities. Once different structures were fabricated, three specimens of each were mechanically tested to assess their stiffness and toughness. During these mechanical tests, three distinct deformation behaviors were observed. First, BCC presented a relatively uniform collapse of its structure within itself. Conversely, BFCC exhibited behavior in which an individual layer of unit-cells collapsed before the next layer started to deform. Finally, FCC...
also collapsed uniformly, but the mode of failure observed was buckling of the outer trusses of the structure. No fracture of truss elements was observed after the first mechanical test was completed.

After mechanical testing was performed on the three metamaterial structures fabricated, three distinct behaviors were observed. A stress-strain plot showing the different behaviors is shown in figure 2(b). The lattices during compression testing are shown and deformation at 5%, 10%, and 20% strain have been presented in figure 2(c). FCC structure exhibited the highest stiffness, with an average compressive modulus of 63.5 MPa. The elastic modulus of BCC was 20.7% lower than that observed for FCC. Lastly, the compressive modulus of BFCC was found to be 31 MPa, and with a characteristic sinusoidal behavior. This characteristic behavior is consistent with the collapsing of the individual layers observed during testing. The average specific modulus of the different structures was 123.3 MPa cm$^{-3}$ g$^{-1}$ once normalized by the density of the different geometries. A summary of these results is shown in figure 3(a).

Once the first mechanical test was completed, the different specimens were rapidly unloaded and allowed to shape recover. The shape recovery effect was found to be most apparent during the first few seconds after the test and was characterized for the different geometries. The shape recovery percentage was calculated by measuring the axial length recovered over the initial deformation (10 mm) after the test. A plot showing the shape recovery behavior of the different geometries is shown in figure 2(a). Initially, BCC structure was showing higher percentage of shape recovery than other two structures, however, after 2 min all the structures were showing similar trend of shape recovery and all samples fully recovered after a few days. Upon full shape recovery of the samples, these were subject to a secondary mechanical test using the same parameters as the first test.

From the second compression testing performed on the samples, a significant change in properties was observed. It was found that the compression properties of all geometries were significantly increased. This phenomenon is shown in figure 2(b). A comparison of the specific compressive modulus obtained from the first and second mechanical tests is shown in figure 3(a). From this comparison we can see that significant hardening of the different geometries was achieved. This improvement in specific compressive moduli was more apparent in FCC and BFCC geometries and can be explained by strain hardening on the polymer [30, 31]. While this hardening effect is believed to be due to the material itself, the use of different geometries does play a crucial role in the hardening behavior. The hardening behavior as a function of the geometry of the structure has been shown for other solids in the past [32]. As each geometry has a different deformation mechanism, thus different stress concentration zones, a different strain hardening effect was observed in each geometry.

One of the applications envisioned for these geometries is as energy absorbing layers for mechanical impacts. As such, their toughness was characterized after the completion of the two mechanical tests. This toughness was calculated by measuring the area under the curve of the stress-strain plots shown in figure 2(b). The obtained toughness was then normalized to the density of the different geometries and averaged for the three specimens of each geometry. The average specific toughness of these geometries for both is shown in figure 3(b). Distinct and characteristic toughness levels were observed for the three geometries, contrasting the results obtained for the specific compressive moduli properties. While the specific moduli were found to remain consistent.

Figure 1. Designed and fabricated structures BFCC (a) and (d), FCC (b) and (e), and BCC (c) and (f) are shown.
Figure 2. Recovery performance (a), and stress-strain characteristics (b) of SLA printed BCC, FCC, BFCC prior and after recovery, (c) Optical images of lattices during compression test.
independently of the lattice structure, specific toughness was highly dependent on the geometry. The observed specific toughness for BFCC geometry was 1.07 J kg$^{-1}$, a specific toughness of 2.37 J kg$^{-1}$ was found on the BCC geometry, and 2.72 J kg$^{-1}$ was observed for the FCC geometry. Higher toughness values were observed for all geometries after the second testing.

Figure 3. Specific compressive modulus (a), and specific toughness (b) of BCC, FCC and BFCC structures from first and second compression testing.

Figure 4. Summary of improvements in the specific properties.
As a result of the hardening phenomenon observed in the compressive modulus, specific toughness was also enhanced after the first mechanical test. A summary on the improvement of both properties can be observed in figure 4. BCC geometry exhibited an increase in toughness of 33.57%, in contrast to the 11.94% observed for its compressive modulus; meanwhile, BFCC exhibited an increase in toughness of 67.42%, much higher than the 26.59% observed in its compressive modulus; and FCC exhibited the lowest increase in toughness, only 16.42%, much lower than the increase observed for its compressive modulus. The specific toughness obtained by FCC is almost identical to that observed in BCC after the hardening phenomenon is observed. These geometries reach an average value of 3.167 and 3.16 J kg$^{-1}$, respectively.

Conclusion

In this work, we have studied the shape recovery and mechanical characteristics of 3D printed shape recovery polymers. We have found that the shape recovery efficiency was not influenced using different unit cell geometries and appeared to be only affected by the constituent material. As expected, mechanical properties are dependent on both material properties and geometries utilized to fabricate these metamaterials. While the specific compressive moduli of the three geometries were virtually the same during the first set of tests, significant strain hardening was observed in all specimens after recovery. Once samples were tested for a second time, 11.94%, 26.59%, and 27.55% increase in compressive moduli was observed for BCC, BFCC, and FCC geometries, respectively. Specific toughness was also influenced by the geometries used and was found to be highest for FCC geometry after the second test. After recovery, each geometry exhibited a characteristic increase in this property, and BFCC structure was found to achieve the highest increase, at 67.42%. The findings of this study can be leveraged to achieve an optimal response for repeated load absorption applications.

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Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

ORCID iDs

Md Sahid Hassan https://orcid.org/0000-0003-0466-5395
Luis A Chavez https://orcid.org/0000-0001-5203-6708

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