Mechanical Response of Octahedral and Octet-Truss Lattice Structures Fabricated Using the CLIP Technology

Anil SAIGAL$^{1,*}$, John TUMBLESTON$^2$, Hendric VOGEL$^2$, Courtney FOX$^2$ and Nikolaus MACKAY$^2$

$^1$Department of Mechanical Engineering, Tufts University, 200 College Avenue, Medford, MA 02155, USA
$^2$Carbon, 312 Chestnut Street, Redwood City, CA 94063, USA

*Corresponding Author

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Abstract. In the rapidly growing field of additive manufacturing (AM), the focus in recent years has shifted from prototyping to manufacturing fully functional, ultralight, ultrastiff end-use parts. This research investigates the mechanical behavior of octahedral- and octet-truss lattice structured polyacrylate fabricated using Continuous Liquid Interface Production (CLIP) technology based on 3D printing and additive manufacturing processes. Continuous Liquid Interface Production (CLIP) is a breakthrough technology that grows parts instead of printing them layer by layer. CLIP is a chemical process that carefully balances UV light and oxygen to eliminate additional mechanical steps for part delamination and resin refill. UV light triggers photopolymerization and oxygen inhibits it. By carefully balancing the interaction of light and oxygen, CLIP grows objects from a pool of resin.

Lattice structures such as the octahedral- and octet-truss lattice have recently attracted a lot of attention since they are often structurally more efficient than foams of a similar density made from the same material, and the ease with which these structures can now be produced using 3D printing and additive manufacturing. This research investigates the mechanical response under compression of octahedral- and octet-truss lattice structured polyacrylate fabricated using CLIP technology. It was found that the elastic modulus and strength of the octahedral-truss structured materials are proportional to each other over a relative density range of 0.07 to 0.35. Finally, even though the octet-truss lattice structure is a stretch-dominated unit cell structure, it was found to have a lower stiffness and strength as compared to an octahedral-truss structure of the same relative density. This can be attributed to the smaller diameter and therefore larger l/d of individual struts.

Introduction

Continuous Liquid Interface Production (CLIP) is a breakthrough technology that grows parts instead of printing them layer by layer. CLIP works by projecting light through an oxygen-permeable window into a reservoir of UV curable resin. The build platform lifts continuously as the object is grown. The heart of the clip process is a special window that is transparent to light and permeable to oxygen, much like a contact lens. By controlling the oxygen flux through the window, CLIP creates a “dead zone”—a thin layer of uncured resin between the window and the object. Establishing an oxygen-inhibited dead zone is fundamental to the clip process. This makes it possible to grow without stopping. As a continual sequence of UV images are projected, the object is drawn from the resin bath. Sophisticated software manages the entire process by controlling the variables.

Figure 1 shows the schematic of a CLIP printer. CLIP moves beyond the limitations of 3D printing producing commercial quality parts at game-changing speeds, creating a clear path to 3D manufacturing. Parts printed with clip are much more like injection-molded parts. CLIP produces consistent and predictable mechanical properties, creating parts that are smooth on the outside and solid on the inside. Various resin materials available are designed to meet the specifications of
elongation and resilience expected of a TPE to the strength and temperature resistance of a glass-filled Nylon [1,2]. This is in contrast to the traditional 3D printing process which requires a number of mechanical steps, repeated over and over again in a layer-by-layer approach. In addition, traditionally made 3D printed parts are notoriously inconsistent [3]. The mechanical properties vary depending on the direction the parts are printed due to the layer-by-layer approach.

Background
The mechanical properties of most materials degrade rapidly as the density decreases. This loss in mechanical properties is because most engineered cellular solid materials with random porosity and low densities exhibit a quadratic or stronger relationship between Young’s modulus and density, and strength and density. Namely, $E/E_s \propto (\rho/\rho_s)^n$ and $\sigma_y/\sigma_{ys} \propto (\rho/\rho_s)^n$, where $E$ is Young’s modulus, $\rho$ is density, $\sigma_y$ is yield strength, and $s$ denotes the respective bulk value of the solid constituent material property. The power $n$ of the scaling relationship between relative material density and the relative mechanical property depends on the material’s microarchitecture.

Mechanical metamaterials are man-made materials in which the mechanical properties are mainly defined by their structures instead of the properties of each component. Periodic cellular structures consisting of honeycomb, tetrahedral, 3D Kagome, pyramidal and octet truss arrangement of webs or struts have recently attracted a lot of attention since they have a broad range of applications including structural components, energy absorption, heat exchangers, catalyst support, filters and biomaterials [4-7].

Lattice structures with open cell intermediate face sheets between the layers of inclined struts, such as the octet-truss lattice, have recently attracted a lot of attention since they are structurally more efficient than foams of a similar density made from the same material, and the ease with which these structures can now be produced using 3D printing and additive manufacturing [8,9]. This research investigates the mechanical response of octahedral- and octet-truss lattice structured polyacrylate fabricated using Continuous Liquid Interface Production (CLIP) technology.

Experimental Methods and Materials
Figure 2 shows the a) octahedral and b) octet lattice structures fabricated using the CLIP technology from Prototyping Acrylate PR25. Prototyping Acrylate PR25 is a rapid production material that is used to both quickly iterate through engineering designs and produce parts with remarkable detail that perform well enough to withstand moderate functional testing.
The structures are approximately 25 mm x 25 mm x 25 mm. The fundamental building block for the octahedral structure is a regular octahedron whereas the octet structure has a regular octahedron as its core surrounded by eight regular tetrahedra distributed on its faces. All the strut elements have identical aspect ratios, with 12 solid rods connected at each node. The cubic symmetry of the cell’s FCC structure generates a material with approximately isotropic properties. The minimum diameter of the strut elements is 0.35 mm and increases as the relative density of the structure increases.

**Results and Discussion**

Figure 3 shows the stress strain behavior of the solid, octahedral and octet lattice structures fabricated using the CLIP technology. The compressive mechanical behavior of the lattice structures observed is typical of cellular structures which includes a region of nominally elastic response, yielding, plastic strain hardening to a peak in strength, followed by a drop in flow stress to a plateau region and finally rapid hardening associated with contact of the deformed struts with each other as part of densification.

Table 1 summarizes the measured relative density, compressive modulus and compressive strength of the solid, octahedral and octet structures. Based on ASTM D1621, the yield strength of the solid was determined to be the stress at 10% deformation. It is quite clear that even though these lattice structures are quite light, these structures also have significantly reduced modulus and strength.
In addition, it was found that $E_{\text{octahedral}}/E_{\text{octet}} = (\rho_{\text{octahedral}}/\rho_{\text{octet}})^{1.98}$ and $\sigma_{\text{octahedral}}/\sigma_{\text{octet}} = (\rho_{\text{octahedral}}/\rho_{\text{octet}})^{2.04}$. The value of $n$ that satisfies the equations $E/E_s \propto (\rho/\rho_s)^n$ and $\sigma/\sigma_{ys} \propto (\rho/\rho_s)^n$ is found to be between 2.6 and 2.9. As such, it appears that both these structures at these low relative densities deform predominantly as a result of bending and/or buckling of the struts.

<table>
<thead>
<tr>
<th></th>
<th>Solid</th>
<th>Octahedral</th>
<th>Octet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus (MPa)</td>
<td>520.40</td>
<td>0.398</td>
<td>1.991</td>
</tr>
<tr>
<td>Strength (MPa)</td>
<td>32.94</td>
<td>0.025</td>
<td>0.130</td>
</tr>
<tr>
<td>Relative Density</td>
<td>1.000</td>
<td>0.065</td>
<td>0.148</td>
</tr>
<tr>
<td>Sp. Modulus</td>
<td>444.74</td>
<td>5.20</td>
<td>11.52</td>
</tr>
<tr>
<td>Sp. Strength</td>
<td>28.15</td>
<td>0.33</td>
<td>0.75</td>
</tr>
</tbody>
</table>

Based on the data, it is not clear if the measured increase in strength and stiffness of the octet structure relative to the octahedral structure is due to the increase in relative density of the structure or due the different structures. Hence, five different specimens consisting of octahedral structure with relative densities ranging approximately from 0.07 to 0.35 were fabricated and tested along with an octet structure with a relative density of 0.27.

Figure 4 shows the stiffness and strength of the octahedral and octet structures, respectively, as a function of the relative density of the structure. It was found that the Young’s modulus and strength of the octahedral-truss structured materials are proportional to each other over the relative density range of 0.07 to 0.35. The ratio of elastic modulus to strength was between 16 and 18 over the entire range and about the same as that for the bulk material. Finally, even though the octet-truss lattice structure is a stretch-dominated unit cell structure, it did not behave as such in this investigation and was found to have a lower stiffness and strength as compared to an octahedral-truss structure of the same relative density. This can be attributed to the smaller diameter and therefore larger l/d of individual struts.

**Figure 4.** a) Elastic Modulus and b) Strength of Octahedral and Octet Structures as a function of Relative Density.

**Conclusions**

The compressive stress-strain behavior of the octahedral and octet lattice structures observed is typical of cellular structures. Even though these lattice structures are quite light, these structures also have significantly reduced modulus and strength. It appears that both these structures at low relative densities deform predominantly as a result of bending and or buckling of the struts. It was found that the stiffness and strength of the octet-truss structure is lower as compared to an octahedral-truss structure of the same relative density.
References


