IUTAM Symposium Architectured Materials Mechanics | Symposium Contributions

Sep 17th, 12:00 AM - Sep 19th, 12:00 AM

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Howon Lee

Chen Yang
Rutgers University, chen.yang@rutgers.edu

Manish Boorugu

IUTAM Symposium Architectured Material Mechanics,
T. Siegmund, F. Barthelat, eds
September 17-19, 2018, Chicago, IL, USA, , Chicago, IL, USA

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Howon Lee[1], Chen Yang[1], and Manish Boorugu[1]
[(1)]Rutgers University – New Brunswick, 98 Brett Rd, Piscataway, NJ USA,
howon.lee@rutgers.edu

KEYWORDS:
Microlattice, shape memory polymer, 3D printing

The mechanical properties of microlattices are determined from the properties of their constituent material, relative density and structural design. Much effort has been focused on additive manufacturing of microlattices with different structural design with governing relationship between stiffness and relative density. A commonly used scaling relationship between stiffness and relative density of microlattice is $E/E_s \sim (\rho/\rho_s)^n$, where the exponent n is 1 for stretching-dominated lattices and n is 2 for bending-dominated lattices [1]. Regardless of constituent materials used and the scaling laws between stiffness and density, mechanical properties of the microlattices are irreversibly fixed when the microstructural design is physically realized through manufacturing. In this work, we achieved reversibly tunable mechanical properties in lightweight microlattices by employing a stimuli-responsive constituent material. By actively tuning the properties of the constituent material, desired mechanical property of the microlattice can be achieved simply by controlling environmental conditions.

Here we use a photo-crosslinkable and temperature-responsive shape memory polymer (SMP) as the constituent material. Not only does this SMP exhibit thermally triggered shape recovery from large deformation and shape fixing, it also shows a remarkable property transition between rigid and elastic states around its glass transition temperature (T_g). At temperature lower than the glass transition temperature, SMP is glassy and rigid. It deforms plastically and stay at the temporary shape. At temperature higher than the transition temperature, SMP is rubbery and soft. It deforms elastically and generates restoring force to recover to its original fabricated shape. It has been shown that a large span of material properties of SMPs, such as glass transition temperature, glassy and rubbery moduli, failure strain, and toughness can be achieved from different combinations of monomer and crosslinker [2]. This variety in mechanical properties of SMP allows the SMP microlattices to be tailored for a wide range of applications. In addition, SME permits full shape recovery of the microlattices to its original shape even after large deformation. Although several 3D printed structures using SMP have been reported demonstrating shape transformation from 2D to 3D or from one configuration to another in 3D space [3][4], utilizing mechanical property modulation to achieve tunable functions has not been reported.

We used projection micro-stereolithography (PμSL) to additively fabricate SMP microlattices in this work. PμSL is a rapid and high resolution photo-polymerization based additive manufacturing technique [5]. UV light from a light emitting diode (LED) is spatially modulated by a digital micro-mirror device (DMD™) which displays a computer controlled pattern generated from a 3D CAD model. UV light reflected off the DMD™ passes through a projection lens and is focused on the surface of photo-curable resin. Resin in the illuminated area solidifies and form a layer of the projected pattern. After completing the layer, the sample holder drops down to fabricate the next layer. By repeating the cycles iteratively, PμSL creates a solid micro object layer-by-layer. In this manner, a PμSL system can rapidly manufacture complex 3D micro-structures at a microscale resolution.

In this work, TBA 80% + PEGDA 250 20% was used as the constituent SMP. It has a glass transition temperature of 63 °C and its elastic modulus changes by more than two orders of magnitude from 2.9 GPa at 30 °C to 7.8 MPa at 90 °C (Fig. 1a). We used tetradecahedron microlattice (Kelvin foam microlattice), which is a bending-dominated open-cell foam, as a model microlattice. We printed four different samples with various relative densities (Fig. 1b) to demonstrate the scaling law between mechanical stiffness and relative density. Unlike widely reported microlattices whose stiffness is fixed once manufactured, our microlattices inherit the thermally responsive stiffness from the constituent SMP. They show a stiffness change by more two orders of magnitude with a temperature span of 60 °C. For a Kelvin foam with a relative density of 9.7 %, its stiffness of 5.6 MPa at 30 °C decreases to 0.14 MPa at 90 °C. From all four samples having different relative densities, we observed that stiffness still depended on its structural design at each temperature and the scaling law with the exponent of 2 for bending-dominated lattices was preserved as shown in Fig. 1c. Furthermore, shape fixing at low temperature and shape recovery at high temperature were successfully demonstrated from 3D printed SMP microlattices (Fig. 1d). The mechanical metamaterials with lightweight, tunable properties and recoverability can potentially lead to new smart structural systems that can effectively react and adapt to varying environments or unpredicted loads.

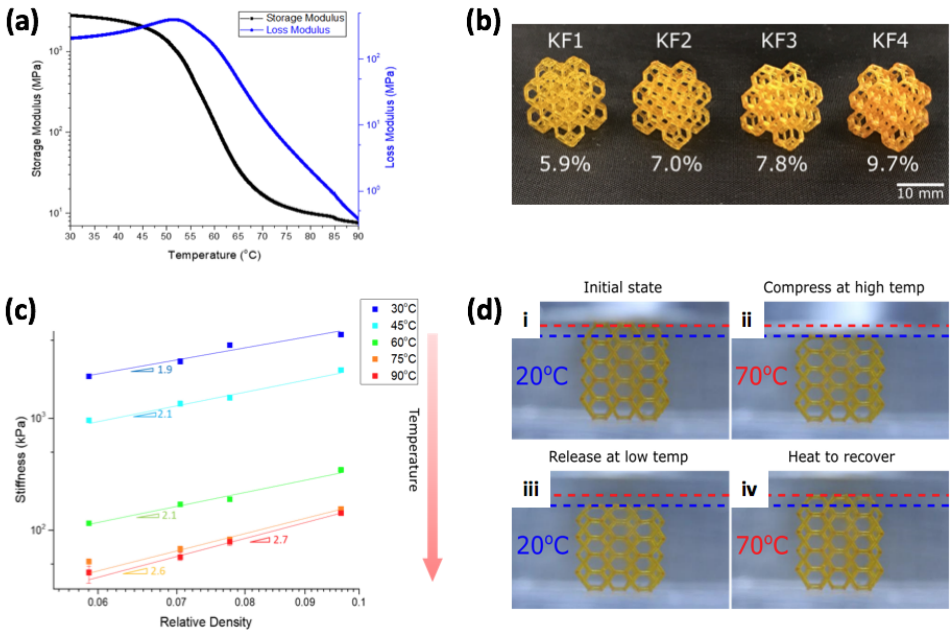

Figure 1. 3D printed microlattices with tunable stiffness and shape memory capability (a) temperature dependent modulus of shape memory polymer (b) 3D printed shape memory microlattices (c) tunable mechanical performance with temperature (d) shape recovery of the microlattices.

Acknowledgments

The authors gratefully acknowledge the support provided by Defense Acquisition Program Administration and Agency for Defense Development under the contract UD150032GD. This work was also partly supported by Rutgers School of Engineering Startup Fund and Rutgers University Research Council Grant.

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