PERIODIC STRUCTURAL SOLIDS AND COMPOSITES: MECHANCIS AND MUTIFUNCTIONAL APPLICATIONS

Lifeng Wang*[a)]
*Department of Civil & Environmental Engineering, Clarkson University, Potsdam, NY 13699, USA

Summary We demonstrate the potential to design and fabricate two-component periodically ordered polymer structures which are shown to have a unique combination of stiffness, strength, and energy absorption, as well as damage tolerance. The results provide guidelines for engineering and tailoring the nonlinear mechanical behavior and energy absorption of cocontinuous composites and further creating multifunctional materials, such as 3D shape memory polymers and mechanically tunable band gap (phononic or photonic) materials.

Natural and synthetic composite materials consisting of two or more different materials are a major avenue for achieving materials with enhanced properties and combination of properties. The combination of hard and soft materials enables outstanding combination of mechanical performance properties including stiffness, strength, impact resistance, toughness, and energy dissipation. In this work, we demonstrate the potential to achieve materials with enhancements in stiffness, strength and energy dissipation.

Triply periodic minimal surfaces have been of great interest to physical scientists, material scientists and biologists; these co-continuous structures have been observed in block copolymers, micellar materials, nanocomposites, cell membranes, and biological exoskeletons. Here we consider periodic co-continuous structures with simple cubic (SC), body-centered-cubic (BCC), and face-centered cubic (FCC) Bravais lattices, which correspond to the level set structures associated with triply periodic minimal surfaces known as the tubular P, I-WP, and F-RD respectively (see Figure 1). Prior works have found: (1) these level set structures to exhibit better elastic properties than their rod-connected model counterparts; 2) these structures to provide multifunctional optimization, such as simultaneous optimization of transport of heat and electricity; (3) these structures can be scaled down and fabricated at submicron length scales that enables the coupling of mechanical deformation with photonic or phononic properties. Herein, we explore the linear and nonlinear mechanical behavior of these structures including their elastic stiffness, yield, post-yield, and dissipative behaviors, as well as shape memory effects.

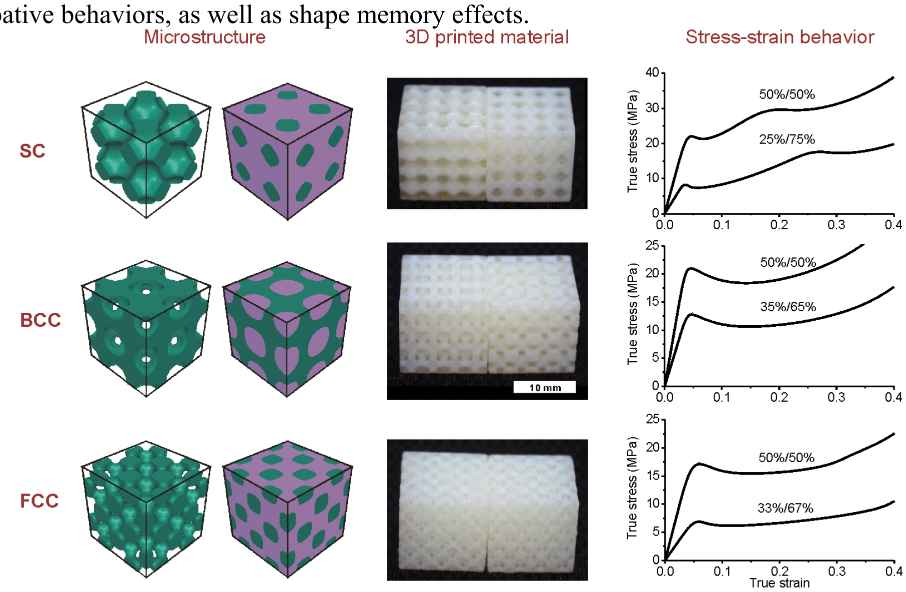

Figure 1. 3D periodic co-continuous composites consisting of 2×2×2 unit cells with SC, FCC and BCC lattice. These certain structures are fabricated using a 3D printing process where the volume fraction of each phase can be tailored (50% for current figures). Their mechanical behavior can be studied experimentally and numerically. The stress-strain curves show typical elastic-plastic response and strongly depending on the volume fraction of each phase.

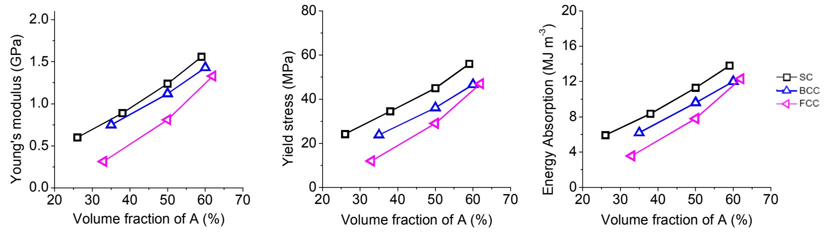

Figure 2. Young's modulus, yield stress, and energy absorption dissipation at 25% strain of co-continuous composites with varying volume fraction.

a) Corresponding author. Email: lifwang@clarkson.edu.

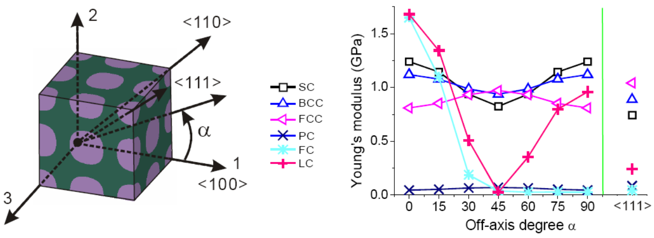

Figure 3. Simulated modulus of the particle-reinforced, fiber-reinforced, lamellar composites, SC, BCC, and FCC co-continuous composites under uniaxial compression as a function of off-axis loading angle.

First, we investigate the elastic-plastic mechanical response of these composites using finite element based micromechanical modelling. We explored the linear and nonlinear mechanical behavior of these structures including their elastic stiffness, yield, post-yield, and dissipative behaviors as a function of volume fraction of each phase (see Figure 2). The properties obtained for these co-continuous structures are compared with conventional particle-reinforced composites, fiber-reinforced composites, and lamellar composites. We show that the co-continuous composites can be tailored to provide dissipation mechanisms that engage more of the material in plastic deformation and have outstanding mechanical performance achieving a unique combination of stiffness, strength and energy absorption. FEA simulations are also conducted to investigate the anisotropy of different set of co-continuous composites subjected to systematic off-axis loadings. Our work has shown the co-continuous composites are 3D multi-directionally reinforced, are less dependent on material distribution (see Figure 3).
Second, we explore the mechanical behavior of these composites at sub-millimeter scale experimentally. The polymer/elastomer co-continuous composites are fabricated by Connex500 3D printer (Objet, MA) which allows the simultaneous printing of two different materials. The compression tests are conducted to characterize large deformation behavior of these co-continuous composites. Interestingly, due to the co-continuous structural arrangement, cracks occurring in the glassy polymer phase are easily arrested by the elastomer and thus no continuous cracking pathway is generated to very large strain. Cracking is contained and distributed in co-continuous structures and enables these composites to continuously provide the energy absorption to a larger failure strain before complete failure. This also indicates damage tolerance of these co-continuous composites due to the mutual constraints between two phases. The result suggests the tailoring of microstructure to achieve different failure mechanisms to enhance the energy dissipation under large deformation.
Moreover, a thermo-mechanical loading-unloading-shape recovery cycle is designed to explore the shape memory effects of the composites (see Figure 4). We find these composites have interesting shape memory features that enable the recovery of not only shape but also mechanical property. We demonstrate that the elastomer phase provides great mechanical enhancement and additional recovery force to the composites.
These results provide avenues for design of lightweight, strong, and stiff shape memory polymer-based structures and composites that have a wide range of multifunctional applications. Examples include shape-change polymeric materials, materials that respond to external stimuli (temperature, electric field, etc.), tunable sensors for tissue engineering, tunable band-gap materials for photonic applications, etc. Polymer co-continuous composites may also be applied to obtain 3D shape memory or tailored viscoelastic behavior where two phases are selected to tune the shape memory or the viscoelastic behavior in order to be activated at multiple temperatures and/or multiple time scales.

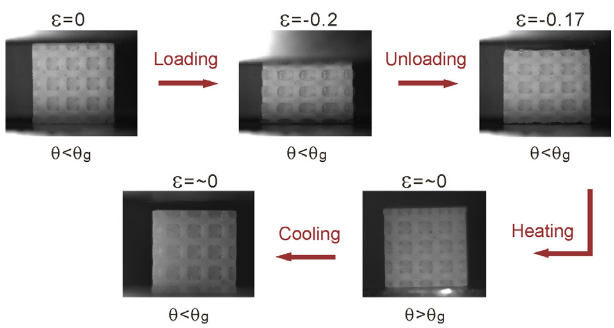

Figure 4. Shape memory effect of BCC co-continuous composites showing a thermo-mechanical loading-unloading-shape recovery cycle.

References

[1] L. F. Wang, M. C. Boyce, C. Y. Wen, and E. L. Thomas, "Plastic Dissipation Mechanisms in Periodic Microframe-Structured Polymers", Advanced Functional Materials 19, 1343-1350 (2009).

[2] J. H. Lee, L. F. Wang, S. Kooi, M. C. Boyce and E. L. Thomas, "Enhanced Energy Dissipation in Periodic Epoxy Nanoframes", Nano Letters 10, 2592-2597 (2010).

[3] L. F. Wang, J. Lau, E. L. Thomas, and M. C. Boyce, "Co-Continuous Composite Materials for Stiffness, Strength and Energy Dissipation", Advanced Materials 23, 1524-1529 (2011).