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ABSTRACT:

Thermal Strain Propagation in Architected Polymer Metamaterials and Composites

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Temperature-dependent behavior of polymers across phases, such as variations in the coefficient of thermal expansion and mechanical properties, is often used to design polymer metamaterials with unusual properties, including negative thermal expansion [1]. However, the same mismatches are also hypothesized to give rise to small local deformations and defects that can eventually lead to the early formation of pores in composites, even before high-temperature processes such as pyrolysis [2]. These pores can act as stress concentration sites, thereby promoting damage initiation and premature mechanical failure. Despite the importance of these phenomena, the mechanisms governing the propagation of thermal strains during manufacturing and across interfaces of two material systems remain difficult to isolate experimentally. This limitation reduces the ability to predict the behavior of complex polymer systems.

In this study, fused filament-fabricated architected structures were used as model systems to investigate thermally induced deformation propagation in polymer metamaterials and composites. Bend-dominated auxetic structures were first used to demonstrate apparent negative thermal expansion (NTE) resulting from thermally induced buckling rather than intrinsically negative material expansion. Variation in printing parameters further showed that the NTE behavior was strongly influenced by the resulting microstructure and sample geometry. An analytical unit-cell model that coupled temperature-dependent expansion with geometry-dependent instability successfully captured the observed NTE behavior during testing.

Building on this framework, fused filament-fabricated composite material were used to examine how thermal strains propagated across surfaces and interfaces. Controlled thermal loading was applied while full-field surface deformation was measured using three-dimensional digital image correlation. These measurements enabled simultaneous tracking of surface displacement and temperature fields. X-ray computed tomography was used to observe the evolution of inclusions and internal defects during thermal loading. Together, these experimental approaches revealed how thermally dependent material properties and manufacturing-induced defects translated into surface strain patterns in architected and composite polymer systems.

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