View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by Purdue E-Pubs

Purdue University
Purdue e-Pubs

IUTAM Symposium Architectured Materials Mechanics

Symposium Contributions

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

Mechanics of Three-Dimensional Nano-Architected Meta-Materials

Julia Greer
Caltech, jrgreer@caltech.edu

Lucas Meza

Arturo Mateos

Carlos Portela

Follow this and additional works at: https://docs.lib.purdue.edu/iutam


Part of the Engineering Commons

Recommended Citation

Greer, J., Meza, L., Mateos, A., & Portela, C. (2018). Mechanics of Three-Dimensional Nano-Architected Meta-Materials. In T. Siegmund & F. Barthelat (Eds.) *Proceedings of the IUTAM Symposium Architectured Materials Mechanics, September 17-19, 2018* , Chicago, IL: Purdue University Libraries Scholarly Publishing Services, 2018. https://docs.lib.purdue.edu/iutam/presentations/abstracts/28

This document has been made available through Purdue e-Pubs, a service of the Purdue University Libraries. Please contact epubs@purdue.edu for additional information.

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

Mechanics of Three-Dimensional Nano-Architected Meta-Materials

Julia R. Greer[1], Lucas Meza [2], Arturo Mateos[1], Carlos Portela[1], Dennis Kochmann[1,3], and Yong-Wei Zhang[4]

[(1)]California Institute of Technology (Caltech), 1200 E. California Blvd. Pasadena, CA 91125, jrgreer@caltech.edu

[(2)] University of Cambridge, Engineering Department, Trumpington Street, Cambridge, CB2 1PZ, UK, lrm41@eng.cam.ac.uk

[(3)] Department of Mechanical and Process Engineering, ETH Zurich, 8092 Zurich, Switzerland

[(4)] IHPC Institute of High Performance Computing, A*STAR, Singapore 138632

Keywords: nanolattices, nano-architected materials, nanomechanics, stress-strain response

Lightweight materials that are simultaneously strong and stiff are desirable for a range of applications: from transportation to energy storage to defense. Recent developments in micro- and nanoscale 3D fabrication techniques have enabled the creation of materials with controllable, multi-scale nanoarchitectures whose features span five orders of magnitude from nanometers to millimeters. These fabrication methods and nanomaterial processing techniques permit a nearly unbounded design space through which new combinations of nanomaterials and architecture can be realized.

We designed, fabricated, and mechanically analyzed a wide range of nanoarchitected materials in the form of nanolattices, made from different materials systems, using a combination of two-photon lithography and various thin film deposition techniques. These nano-architected materials have periodic and hierarchical architectures that span over 4 orders of magnitude in density, $\rho = 0.3 - 300\ kg/m^3$, with features as small as 5nm. In-situ uniaxial compression and cyclic loading experiments performed on different nanolattice topologies revealed a range of novel mechanical properties: resilience of hollow aluminum oxide (Al_2O_3) nanolattices which recovered nearly completely after compression to >50% strains when their wall thicknesses were 20nm and below, enabled by shell buckling; nanolattices with fractal-like hierarchical geometries exhibited enhanced recoverability and a near-theoretical scaling of strength and stiffness with relative density: $E \propto \rho^{1.04}$ and $\sigma_y \propto \rho^{1.17}$ [1,2].

Systematic nanomechanical experiments on four distinct geometries of solid polymer and hollow ceramic (Al_2O_3) revealed a nearly identical scaling of strength (σ_y) and Young's modulus (E) with relative density ($\bar{\rho}$), ranging from $\sigma_y \propto \bar{\rho}^{1.45}$ to $\bar{\rho}^{1.92}$ and $E \propto \bar{\rho}^{1.41}$ to $\bar{\rho}^{1.83}$, which implies that solely changing the topology does not necessarily have a significant impact on nanolattice mechanical properties. We provide an in-depth exploration of the parameter space of solid- and hollow-beam nanolattices using experiments, finite element analysis, and beam-based numerical simulations and models. This work establishes that the strength and stiffness of solid- and hollow-beam nanolattices does not correlate with topology alone, but is instead governed by an intricate combination of geometry and structural parameters. Nanolattices with widely different topologies can have nearly identical strength and stiffness at the same relative density, and hollow nanolattices with the same topology and relative density can have widely different stiffness. We postulate that the convergence of strength and stiffness in solid lattices at higher densities is caused by the increased influence of beam

intersections at the nodes. These results suggest that the existing classification of nanolattice topologies as stretching- or bending-dominated is insufficient, and new theories must be developed to accurately capture the effect of both nodal interferences in solid-beam lattices and empty nodes in hollow-beam lattices on the mechanical properties [3].

A remaining question about these nano-architected materials is whether they can be characterized as a continuum solid. Extensive research has shown that these ultralight and strong structural metamaterials are particularly attractive for mechanically-demanding applications; yet their susceptibility to flaws, fracture behavior, and discrete-continuum duality remains virtually unexplored. We fabricated 3D nanolattices with octet architecture and 5um unit cells, comprised of 50nm-thick alumina tubes with pre-fabricated center through-notches oriented at different angles to the loading direction and investigated their tensile-to-failure response. We discovered that failure always initiated at the notch, where tube walls fractured first, and that discrete lattice architecture enabled instantaneous crack propagation to occur along nodal planes orthogonal to the loading direction, regardless of notch orientations and microstructural material flaws. This is in contrast to classical theory, which predicts an initial crack deflection as a function of notch orientation in monolithic materials. Experiments revealed that tensile strength of 27.4MPa was highest for unnotched samples and decreased systematically with notch orientation to 7.2MPa in orthogonally-notched samples. These failure stresses are consistent with predictions of linear elastic fracture mechanics for self-similar monolithic tensile samples of ideally-brittle solids. Experiments also revealed the specific tensile strength to be a factor of 4 higher than what has been reported for architected materials and bulk materials at similar low densities. These findings imply that the continuum nature of nano-architected materials offers predictability of failure stresses, and their discreteness provides control of fracture trajectory, both of which enable developing advanced new materials through informed architectural design [4].

These experimental, computational and theoretical results uncover how architecture can be used to access unique lattice mechanical property spaces while demonstrating the practical limits of existing beam-based models in characterizing their behavior.

Acknowledgments

JRG and her group gratefully acknowledge the financial support of the Vannevar-Bush Faculty Fellowship through the US Department of Defense. DMK acknowledges support from the Office of Naval Research through grant N00014-16-1-2431. YWZ acknowledges the financial support from A*STAR, Singapore and the use of computing resources at A*STAR Computational Resource Centre, Singapore

References

[1] L. R. Meza, S. Das, J. R. Greer "Strong, Lightweight and Recoverable Three-Dimensional Ceramic Nanolattices" ***Science*** 345, 1322-1326 (2014)

[2] L. Meza, A.J. Zelhofer, N. Clarke, A.J. Mateos, D.M. Kochmann, and J.R. Greer "Hierarchy in 3-D Architected Meta-Materials Brings Resilience" ***Proc of the Nat'l Academy of Sciences*** 112 (37), 11502 (2015)

[3] L. R. Meza, G. Phlipot, C. M. Portela, A. Maggi, L. C. Montemayor, A. Comella, D.M. Kochmann, and J. R. Greer "Reexamining the Mechanical Property Space of Three-Dimensional Lattice Architectures" ***Acta Mater***. 140**,** 424-432 (2017)

[4] A. J. Mateos, W. Huang, Y.-W. Zhang, and J.R. Greer "Predicting failure in flaw-containing hollow ceramic nanolattices" *(submitted, 2017)*