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Mechanical properties of 3D ceramic nanolattices

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Developments in advanced nanoscale fabrication techniques have allowed for the creation of 3-dimensional hierarchical structural meta-materials that can be designed with arbitrary geometry. These structures can be made on length scales spanning multiple orders of magnitude, from tens of nanometers to hundreds of microns. The smallest features are controllable on length scales where materials have been shown to exhibit size effects in their mechanical properties. Combining novel nanoscale mechanical properties with a 3-dimensional architecture enables the creation of new classes of materials with tunable and unprecedented mechanical properties. We present the fabrication and mechanical deformation of hollow tube alumina nanolattices that were fabricated using two-photon lithography direct laser writing (DLW), atomic layer deposition (ALD), and oxygen plasma etching. Nanolattices were designed in a number of different geometries including octet-truss, octahedron, and 3D Kagome. Additionally, a number of structural parameters were varied including tube wall thickness (t), tube major axis (a), and unit cell size (L). The resulting nanolattices had a range of densities from $\rho = 4$ to 250 mg/cm^3. Uniaxial compression and cyclic loading tests were performed on the nanolattices to obtain the yield strength and modulus. In these tests, a marked change in the deformation response was observed when the wall thickness was reduced below 20nm; thick-walled nanolattices (t>20nm) underwent catastrophic, brittle failure, which transitioned to a gradual, ductile-like deformation as wall thickness was reduced. Thick-walled nanolattices also exhibited no recovery after compression, while thin-walled structures demonstrated notable recovery, with some recovering by 98% after compression to 50% strain and by 80% when compressed to 90% strain. Across all geometries, unit cell sizes, and wall thicknesses, we found a consistent power law relation between strength and modulus with relative density of $E \propto \rho^{1.6}$ and $\sigma_y \propto \rho^{1.75}$. This scaling marks an improvement over other lightweight and ultralight materials, which normally scale as $E \propto \rho^2$ or $E \propto \rho^3$, but does not meet the analytic upper bound of a linear scaling with relative density that is predicted for stretching dominated geometries like the octet-truss.