Mechanics and Physics of Nano-solids in Designing 3-D Hierarchical Meta-Materials

J.R. Greer,
[1]*California Institute of Technology*

Creation of extremely strong yet ultra-light materials can be achieved by capitalizing on the hierarchical design of 3-dimensional nano-lattices. Such structural meta-materials exhibit superior thermomechanical properties at extremely low mass densities (lighter than aerogels), making these solid foams ideal for many scientific and technological applications. The dominant deformation mechanisms in such “meta-materials”, where individual constituent size (nanometers to microns) is comparable to the characteristic microstructural length scale of the constituent solid, are essentially unknown. To harness the lucrative properties of 3-dimensional hierarchical structures, it is critical to assess mechanical properties at each relevant scale while capturing the overall structural complexity.

We present the fabrication of 3-dimensional nano-lattices whose constituents vary in size from nanometers to tens of microns to millimeters. We discuss the mechanical properties of a range of nano-sized solids with different microstructures, subjected to mechanical deformation in a custom-made *in-situ* nanomechanical instrument, SEMentor. Attention is focused on the interplay between the internal critical microstructural length scale of materials and their external limitations in revealing the physical mechanisms governing the mechanical deformation, where *competing material- and structure-induced size effects* drive overall properties. We discuss SMALLER is STRONGER phenomenon in (1) **single crystalline metals** in the framework of dislocation nucleation driven plasticity. Beyond single crystals, several intriguing phenomena arise in boundary-containing samples: (2a) **nano-twinned** nano-samples exhibit twin-spacing-dependent ductile vs brittle transition; (2b) a **single grain boundary** in a nano-crystal can serve as a dislocation sink, a source, or a preferred pathway for frictional sliding and shear-off depending on orientation, and (2c) multiple grain boundaries within **nanocrystalline** metallic nano-pillars exhibit SMALLER is WEAKER trend and flaw-driven fracture. (3) Amorphous metallic alloys, **metallic glasses** were found to exhibit strength increase, brittle-to-ductile transition, and unprecedented fatigue resistance when reduced to nano-scale. Unlike in bulk, all of these nano-structured nano-sized samples exhibit highly stochastic, intermittent stress-strain relationships. We attribute these dissimilarities from bulk to the nano volume-induced unique deformation mechanisms, whose role is critical in defining the overall structural response of meta-materials.