Metamaterials with extreme stiffness and strength

Metamaterials have mechanical properties that are a function of their geometry on the mesoscale, the intermediate scale between microstructural features of the constituent material(s) and the macroscale on which loads and parts are described. These materials can fill an otherwise unpopulated region of property space in terms of low density and high stiffness and strength. A material geometry has been identified that achieves theoretical bounds for isotropic stiffness, over a wide range of relative densities, giving it nearly ideal properties, and is capable of filling this hole in property space. This closed cell geometry, while being relatively simple, presents challenges in terms of fabricability when compared to open cell geometries which allow for fluid transport, facilitating infiltration and exfiltration of materials during and after processing. A second disparate material system has been measured to have the highest specific stiffness and strength for its density. This material is formed by self-assembly on the nanoscale to produce an inverse FCC geometry. These opaline structures are then coated with TiO$_2$ by atomic layer deposition. The addition of this second stiff phase greatly increases the ultimate performance, while having a mixed influence on structural efficiency. While this material has been measure to have extremal properties its performance is poor compared to an ideal geometry. We investigate the morphological features associated with high performance by comparing these two material systems. Finite element homogenization is used to compute the properties and resolve strain energy distributions. Uniform strain energy distributions in stiff networks of members aligned with principle stresses are key to high performance. Two and three phase theoretical bounds are used as metrics for performance, with three phase systems having a significant advantage in ultimate performance when compared to the Voight bound. Compromises between constituent properties, fabrication techniques, mesoscale geometry, scale, and other factors are currently necessary in realizing materials that can achieve extremal properties beyond current possibilities.