Materials by Design: 3-Dimensional Architected Structural Meta-Materials

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~$245 million
970,000 pounds
$2.97 /gallon
5 gallons /mile
$107,000 LA → Zurich

Heavy and Unsafe

Expensive

Non durable
Correlation between material properties and density

Achieving high toughness and strength in BMGs involves preventing single shear-band formation, which is inherently unstable. The key is to promote crack advance and extrinsic crack-tip-shielding mechanisms, which act primarily behind the tip to impede crack advance. Intrinsic toughening, associated with crack extension, results essentially from plasticity and enhances a material’s inherent damage resistance; as such it increases both the crack-initiation and crack-growth toughnesses. Extrinsic toughening acts to lower the local stress and strain fields at the crack tip; as it depends on the presence of a crack, it affects only the crack-tip shielding.

Figure 2 | Strength and toughness strategies for BMG alloys.

Figure 1 | Conflicts of strength versus toughness.


Creating ultra-light, strong, and fracture tolerant materials

*Architectured structures with nanometer-sized solids merge structural and material properties into a single “meta-material”*
Multiple Length Scales in Hierarchical Architected Materials

⇒ Smallest feature size defines material properties
⇒ Structural and material effects are no longer independent
⇒ CRITICAL to study MECHANICAL PROPERTIES at each RELEVANT SCALE

Fabrication of 3D Architected Nanoscale Meta-Materials

Movie created by post-doc Seok-Woo Lee

Size Effects in Nanomaterials

**SINGLE CRYSTALS**

*Smaller is Stronger*

- J.R. Greer, J. de Hosson *Prog Mat Sci* (2011)


**NANOCRYSTALLINE METALS**

*Smaller is Weaker*


Nanomechanical experiments can help understand size-induced behavior of materials.


In-situ Nanomechanical Experiments

A smorgasbord of research pursuits for relevant technologies

**LIGHTWEIGHT ELECTRODES FOR (Li-ion) and (Li-air) BATTERIES**

Damage-resistant nanostructured electrodes (no cracking!) by designing proper architecture

Work of Wendy Gu, Chen Xu
Collaboration w/ M. Ortiz, W.A. Goddard (Caltech)
⇒ Bosch, LiOx

**3-D SCAFFOLDS for Cell Growth**

Work of Alessandro Maggi, Zach Aitken, Ottman Tertuliano
Collaboration w/Drs. Hetts and Han (UCSF)
⇒ Medtronic, ARL

**PHOTONIC CRYSTALS**

Photonic Crystals

- Nanotruss Antireflective Coating
- N-type Semiconductor
- P-N Junction
- P-type Semiconductor

Work of Viki Chernow
Collaboration w/ J. Dionne (Stanford)
⇒ Resnick Institute

**BIO-MIMICKING and MECHANICS**

Work of Lucas Meza, Lauren Montemayor, Seok-Woo Lee
⇒ Google <X>, HRL
Strong and Recoverable Ceramic ($\text{Al}_2\text{O}_3$) Nanolattices

⇒ **Architecture** can control mechanical properties like **toughness** and **recoverability**

⇒ **Possible to use DESIGN to create of entirely NEW CLASSES of MATERIALS**
Strong and Damage-Tolerant Hollow TiN Nano-Trusses

80nm-thick TiN (ceramic) attains Mises stresses of \(~2.5\text{GPa} (~E/30)\) (tensile stresses of \(~1.75\text{GPa}\)) without failure!

=> Insensitivity of Strength to External Flaws?

Hierarchical Design of Lightweight, Damage-Tolerant Nano-Metamaterials

**Scientific Objectives**
- To design and create metallic and ceramic nano-lattices with optimized geometries and nano-scale thicknesses hierarchically arranged into 3-dimensional architectures

**Technical Approach**
- 2-Photon Lithography to Create Structures with any geometry (dimensions: from several hundred nm to several hundred microns)
- Deposition of wide variety of materials in thin conformal coatings (can be layered)
- In-situ Micro- and Nano-Mechanical Testing

Hierarchical distribution of length scales and functionalities resembles design principles in hard biomaterials

=> Nano-metamaterials offer enhanced energy absorption and damage tolerance, harnessing extremely lightweight and superior toughness in a single material

For details/publications: http://jrgreer.caltech.edu/
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