Biological Blueprints For Architected Impact Resistant Materials

Kisailus D[1]*.
*lead presenter: david.k@uci.edu
1 University of California at Irvine, USA

There is a growing need for the development of low cost light-weight materials with high strength and durability. Nature has evolved efficient strategies, exemplified in the crystallized tissues of numerous species, to synthesize materials that often exhibit exceptional mechanical properties. These biological systems demonstrate the ability to control nano- and microstructural features that significantly improve the mechanical performance of otherwise brittle materials by the multiscale assembly of organic templates [1-3].

In this work, we investigate a number of impact resistant organisms, one of which provides insight towards new multiscale architectural designs. This is revealed in the hyper-mineralized combative and fast striking dactyl club of the stomatopods, highly aggressive marine crustaceans [4-6]. The primary toughening structure within this club as well as in other structures we studied [7,8] is the helicoid, consisting of unidirectional fibers surrounded by a matrix and stacked on top of each other with each subsequent layer rotated in plane at a small angle. In addition, within the outermost surface of the clubs is the impact surface, where we uncover a novel and previously unobserved architectural design that provides the capability to localize damage and avoid catastrophic failure from high-speed collisions during its feeding activities [9]. This coating consists of a biomineralized composite of densely packed ~ 65 nm nanoparticles within an organic matrix. Closer analysis of these particles reveals a bi-continuous network of hydroxyapatite (HAP) mineral integrated within an organic matrix. The mesocrystalline HAP nanoparticles are assembled from small highly aligned nanocrystals guided by the biomineral templating proteins. Under high strain rate (~10^4 s-1) impacts, particles rotate and translate, while the nanocrystalline networks fracture at low angle grain boundaries, form dislocations, and undergo amorphization. The interpenetrating organic network provides additional toughening, as well as significant damping, with loss coefficient ~0.02. A rare combination of stiffness and damping is therefore achieved, outperforming many engineered materials. Based on these findings, we are now engineering composites [10] and biomimetic coatings that integrate the design features found in the mantis shrimp and demonstrating their use in automotive, aerospace and personal protective equipment.

References

[1] Huang W et al. Multiscale toughening mechanisms in biological materials and bioinspired designs. Advanced Materials. 2019;31:1901561.
[2] Yaraghi N and Kisailus D. Biomimetic Structural Materials: Inspiration from Design and Assembly. Annual Reviews of Physical Chemistry. 2018;69:23-57.
[3] Huang W et al. Nano-Architected Tough Biological Composites from Assembled Chitinous Scaffolds. Accounts of Chemical Research. 2022;55:1360-1371.
[4] Weaver J et al. The Stomatopod Dactyl Club: A Formidable Damage-Tolerant Biological Hammer. Science. 2012;336:1275-1280.
[5] Yaraghi N et al. A Sinusoidally-Architected Helicoidal Biocomposite. Adv. Materials. 2016; 28: 6835–6844.
[6] Grunenfelder L et al. Ecologically driven ultrastructural and hydrodynamic designs in stomatopod cuticles. Advanced Materials. 2018;30:1705295.
[7] Rivera J et al. Structural Design Variations in Beetle Elytra. Advanced Functional Materials. 2021;2106468.
[8] Yaraghi N et al. The Stomatopod Telson: Convergent Evolution in the Development of a Biological Shield. Advanced Functional Materials. 2019;29:1902238.
[9] Huang W et al. A natural impact resistant bi-continuous composite nanoparticle coating. Nature Materials. 2020; 9:1236-1243.
[10] Rivera J et al. Modulation of impact energy dissipation in biomimetic helicoidal composites. J. Materials Research and Technology. 2020;9:14619-14629.