Application of Fracture Mechanics Concepts to Nanostructures of Biological Systems

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ABSTRACT

Bone-like biological materials have achieved superior stiffness and toughness through hierarchical composite structures of mineral and protein. Gecko and many insects have evolved hierarchical surface structures to achieve extraordinary adhesion capabilities. We use fracture mechanics concepts to show that the nanometer scale plays a key role in allowing these biological systems to achieve their superior properties [1, 2]. We suggest that the principle of flaw tolerance may have had an overarching influence on the evolution of the bulk nanostructure of bone-like materials and the surface nanostructure of gecko-like animal species. We demonstrate that the nanoscale sizes allow the mineral nanoparticles in bone to achieve optimum fracture strength and the spatula nanoprotrusions in Gecko to achieve optimum adhesion strength. In both systems, strength optimization is achieved by restricting the characteristic dimension of the basic structure components to nanometer scale so that crack-like flaws do not propagate to break the desired structural link. Continuum modeling and atomistic simulations have been conducted to verify the concept of flaw tolerance at nanoscale.

A simple tension-shear chain model has been developed to model the stiffness and fracture energy of biocomposites. It is found that, while the problem of low toughness of mineral crystals is alleviated by restricting the crystal size to nanoscale, the problem of low modulus of protein has been solved by adopting a large aspect ratio for the mineral platelets. Using a Barenblatt-Dugdale type model, the fracture energy of biocomposites is found to be proportional to the effective shear strain and the effective shear stress in protein along its path of deformation to fracture. The bioengineered mineral-protein composites are ideally suited for fracture energy dissipation as the winding paths of protein domain unfolding and slipping along protein-mineral interfaces lead to very large effective strain before fracture. Cross-linking mechanisms can increase the shear stress in protein and along the protein-mineral interface. Optimization of mineral platelets near theoretical strength is found to be crucial for allowing a large effective stress to be built up in protein. Similarly, for gecko adhesion, the strength optimization of individual spatulas is found to play a critical role in enhancing adhesion energy at the higher hierarchical level.

Reference:

[1] H. Gao, B. Ji, I.L. Jaeger, E. Arzt and P. Fratzl, “Materials Become Insensitive to Flaws at Nanoscale: Lessons from Nature,” 2003, *Proceedings of the National Academy of Sciences of USA*, Vol. **100**, pp. 5597–5600.

[2] H. Gao, B. Ji, M.J. Buehler and H. Yao, “Flaw tolerant bulk and surface nanostructures of biological systems,” 2004, *Mechanics and Chemistry of Biosystems*, Vol. **1**, No. 1, pp. 37-52.