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Bone and bone-inspired materials

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ABSTRACT

Bone is a biological material, optimized by nature, to perform its structural and biochemical functions. Bone has a complex composite structure that contributes to its excellent mechanical performance. In this paper, we first describe the structure, composition, and properties of bone. Then, we discuss the bone-inspired materials and structures for medical and engineering applications.

INTRODUCTION

Bone is a multifunctional biological material (Olszta et al., 2007). As a structural material, it provides a frame, protects organs, and contributes to the movement. Bone also manufactures blood cells, stores useful minerals, maintains pH in the blood, and detoxifies. Structurally, bone is a biological nanocomposite material consisting of an organic phase (collagen, non-collagenous proteins, and other organics), minerals (nanoscale apatite crystals), and fluids. The organic and mineral phases are roughly 1:1 ratio by volume in mature human bone. The mineral gives bone its high stiffness and strength while the organic phase contributes to its ductility and time-dependent behavior. These components in synergy lead to a stiff, strong, tough, impact-resistant, and lightweight material.

Bone has a complex hierarchical structure, due to self-assembly, spanning from an atomic scale to macroscale as shown in Figure 1 (Rho et al., 1997, Olszta et al., 2007). At the macroscale, bone consists of cortical and trabecular bone types. The cortical bone (5-30 vol% porosity) forms an outer stiff shell of long bones; such design allows the bone to optimally withstand axial, bending, and torsional loads while being lightweight. The trabecular bone (30-95 vol% porosity), fills the ends of long bones to distribute loads and absorb impacts. At the mesoscale, trabecular bone is a highly porous random open-celled foam (with pores under 1 mm in dimensions). In contrast, the cortical bone is dense and consists of aligned hollow cylinders called osteons (~200 μm in diameter). These foam-like and tubular structures, respectively, have high energy absorption capacity. At the microscale, both cortical and trabecular bone have lamellar structures. These layered

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systems at the sub-microscale consist of lamellae (3-7 μm in thickness) made of aligned mineralized collagen fibrils, with orientations changing from ply to ply. Multiple interfaces and slip of fibrils provide toughness and energy absorption. At the nanoscale, tropocollagen molecules, ~ 1 nm in diameter, in the form of a triple helix, align to form a collagen fibril (~50 nm in diameter), which serves as a template for the deposition of nanoscale minerals. The minerals fill the space around collagen fibrils, giving bone its high stiffness and strength.

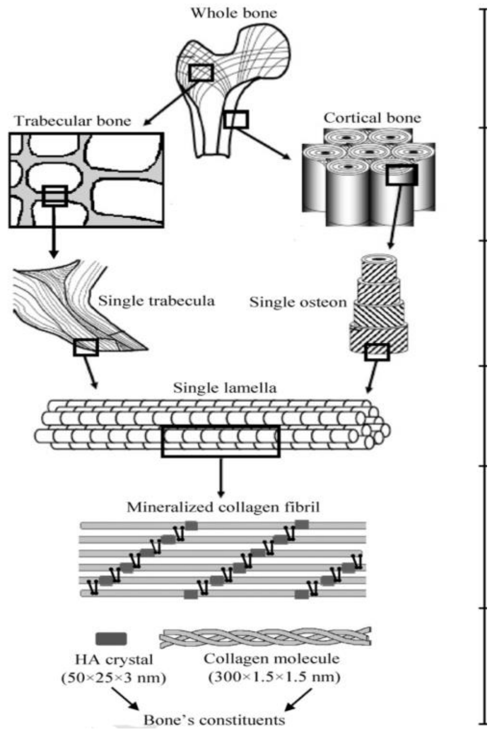

Figure 1 Hierarchical structure of bone (Hamed and Jasiuk, 2012)

Thus, bone is a highly complex nanocomposite material with hierarchical structure, which gives bone to its excellent mechanical properties. Bone is of high interest to researchers and clinicians. Research on bone has been focused on the bone's structure, composition, and properties at different structural scales in health and disease. From mechanics perspective, bone offers multiple challenges due to its structural and material complexity, which makes it a fruitful subject for research, see Jasiuk (2018) for literature review. Bone is spatially heterogeneous and anisotropic material. Other features include helical structures (tropocollagen molecules and osteons) and functionally graded (spatially changing) properties. Bone has been generally modeled as a linear elastic material or elastoplastic anisotropic material, while fewer models account for the time-dependence using viscoelastic and viscoplastic constitutive models. Bone has also been modeled as a poroelastic material to account for fluids in bone and as a piezoelectric material, in particular in models of bone adaptation. Bone, as living tissue, can remodel and regenerate; it grows larger under loading (such as exercise) and can self-heal when fractured. Finally, bone has been modeled as a couple-stress or Cosserat material to account for bone response under gradients in stress and strain fields, i.e., under bending, torsion, and fracture. Thus, bone offers plentiful opportunities for scientific exploration. The knowledge of bone's structure-property relations in bone is needed to understand and assess bone's health. Such knowledge can also be utilized to design new bone-inspired materials for medical and technological applications.

CHARACTERISTICS OF BIOLOGICAL MATERIALS

Plants and animals have evolved over billions of years to become very efficient in utilizing materials for their desired functions (Meyers et al. 2008). Bone and other biological materials have hierarchical structures with porous, layered, helical, gradient, tubular, cellular, and sutured features. Such characteristics provide multiple toughening mechanisms (crack deflection, fiber bridging, ligament bridging, phase transformations, constrained microcracking) and high energy absorption via viscoelasticity, porosity, and various deformation modes. All biological materials are composites made of biopolymers and often biominerals, such as bone, which results in outstanding mechanical properties.

The general characteristics of biological materials are

- Hierarchical (atomic to macro levels)
- Composite (several constituents)
- Cellular, porous
- Sometimes mineralized (nano, micro reinforcement)
- Functionally graded (spatially changing properties)
- Viscoelastic (time dependent behavior)
- Anisotropic (properties differ depending on direction)
- Fluid-filled
- Multifunctional
- Adaptive, self-healing
- Self-organized, self-assembled

Imitating natural materials (biomimetics) or taking ideas from nature (bioinspiration) is a new and exciting research area where elucidating the biological structure is followed by the invention of new human-made materials (Wegst et al., 2014). Yet, biological materials are made from a limited number of elements, and they usually serve more than one function. Thus, engineering materials designs can have a much broader spectrum of possibilities: wider selection of elements and more focused functionalities, which could lead to superior performance compared to biological materials.

BONE-INSPIRED MATERIALS

Many engineering materials and structures have characteristics resembling biological materials, including bone. Cellular materials such as honeycomb-like materials or foams with irregular geometries are used for insulation, cushioning, and energy absorption. They facilitate the designs light and stiff components such as sandwich panels, portable structures and floating devices. Their low thermal conductivity yield cheap thermal insulators, low stiffness makes them ideal for cushioning, low strengths and large compressive strains give energy absorption.

Laminated composite materials used in aerospace and other industries closely resemble lamellar structures in bone and other biological materials. Functionally graded materials, which have spatially changing properties, have been utilized to reduce stress concentrations, thus increasing load-bearing capacity of structures. One application is as thermal barriers (e.g., tiles on space shuttles). Lattices with graded porosity have shown to have superior energy absorption characteristics. Functionally graded structures are found in various biological materials, including bone.

Interfaces play an important role in tailoring properties of composite materials. Nature is employing interfaces in multiple ways to provide toughness and energy absorption. Interfaces in bone are utilized at every scale to arrest, deflect, and diffuse cracks, to resist fractures. Nanocomposite materials, which contain nano-sized fillers, can have superior properties to composites with micro-sized fillers. Nanocomposites have a much larger interface area which may provide multiple benefits, including higher stiffness, strength, and enhanced energy-absorbing mechanisms in the form of interfacial slipping and debonding. Bone is a polymer-ceramic nanocomposite.

Bone and other biological materials can self-heal and adapt to environment. There have been developments on self-healing engineering materials. Ideas include infusing into a composite glass spheres containing polymer or creating composites with vasculatures. Other ideas include tailored thermoplastics which can anneal upon heating. These developments are still at their early stages and provide limited repair mechanisms as compared with what is possible in natural materials. Active area of research is also on adaptive (smart) materials.

Advancements in additive manufacturing provide design freedom. 3D printing and 4D printing offer nearly unlimited possibilities for manufacture new complex bioinspired materials. For example, we have explored bone-inspired material designs by considering composites with two interpenetrating phases (Sabet et al, 2018).

The challenge to design synthetic materials with superior properties, based on lessons learned from nature, is still an open one. Bioinspiration, along with advancements in materials synthesis, manufacturing techniques, and modeling (topology optimization, machine learning), opens numerous opportunities for new materials discovery.

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