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Material Bone: Structure-Mechanical and Function Relations

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ABSTRACT: An assemblage of parts produced up of mineralized collagen fibrils is referred to as "bone." They have very complex organizational structures, with up to seven hierarchical organizational levels. These materials have evolved to perform a broad variety of mechanical functions, and their structures have most likely been fine-tuned to do this. It may be challenging to fit structure to function. In this part, we look at the structure-mechanical connections at each of the organization's hierarchical levels, highlighting both underlying strategies and knowledge gaps when feasible. The knowledge gained from researching these fascinating materials is not only important for human health, but it may also lead to new synthetic material concepts. Bone refers to a family of materials, each with a somewhat distinct structural pattern but all having the same basic building block, the mineralized collagen fibril. There are additional members of this family of minerals that have various names due to historical causes.

KEY WORDS: Bio Mineralization, Biomechanics, Bone Mineral, Lamellar Bone, Mineralized Collagen.

1. INTRODUCTION

The fundamental building block of bone is the mineralized collagen fibril. Dentin, the substance that makes up the inner layers of teeth, cementum, the thin coating that holds the roots of teeth to the jaw, and mineralized tendons are some of the more well-known examples. The structure-mechanical function relationships of various materials are reviewed below, with the fundamental underlying themes highlighted whenever feasible. Although several of these materials have additional purposes, we focus on their mechanical properties. Many bones, for example, serve as significant calcium and phosphate repositories, which are required for a number of metabolic processes[1]. The fine-tuning or adaptation of the structure to its purpose is shown in the variety of structures within this family.

As a result, this variety offers us with a useful study tool that, when compared, may provide important insights into the relationships between form and function[2]. This technique, as effective as it is, must be utilized with care. Although millions of years of fine-tuning this relationship has generated some amazing solutions to difficult structural-mechanical issues, biological structures are not always completely suited to function. Identifying these "new" solutions and potentially applying them to synthetic materials is an intriguing possibility for the study of such biological materials. It's also essential not to presume that each family member performs just one or a few tasks. This may be true, but it's also possible that the opposite is true the general design approach is to create an all-purpose material that will operate sufficiently, if not ideally, in a number of situations. Finally, these biological materials are no different from many synthetic materials that must, for example, operate effectively under compression but also must sometimes resist severe impact and/or bending loads. As a result, the word function in our title is ambiguous; regrettably, the term structure is as well[3].

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The mineralized collagen fibril is the fundamental building component of the bone family of materials. It's made up of a structural version of the fibrous protein collagen, which may also be found in skin, tendons, and other soft tissues. Collagen is the primary component of a three-dimensional matrix into which the mineral develops, and in certain instances onto which it forms. Dahllite, also known as carbonated apatite, is a mineral that belongs to this family of minerals[4]. Water is the third important component. The main components are tightly bound together in the mineralized collagen fibril, which is an organized structure. Their proportions, on the other hand, may vary significantly across family members. The way the building blocks are arranged into higher order structures may also differ, and this is what allows members of the bone family of biological materials to be distinguished. To make things even more complicated, some of these materials are made up of two opposing organizational motifs, and the whole structure may be folded into even bigger superstructures. Thus, the phrase "bone structure" has no meaning; rather, the structures of these materials must be understood both in terms of variations across family members and, more significantly, in terms of hierarchical organizational levels[5].

In land-living vertebrates, one of the primary roles of bone is to provide support for the animal as well as a framework to which muscle may be connected. As a result, one of the most significant characteristics of bone is its mechanical qualities. Because of its complex composite composition, bone offers outstanding mechanical characteristics for load-bearing tasks. The geometrical and topological features of the assemblage, as well as the properties of the component materials, influence the properties of bone. For these reasons, it's critical to comprehend the arrangement of bone's components as well as possible[6].

Bone is a hierarchically organized material with many organizational levels. Bone is made up of two types of bone: cortical bone, which forms the outer shell, and trabecular bone, which is a spongy bone found inside or at the ends of the bone. Lamellar or fibro-lamellar bone makes up newly produced bone. The majority of the cortical bone is later rebuilt by osteons, which spread in roughly straight pathways along the axis of long bones. A single osteon is composed of lamellar bone as well, but it is shaped like a ring around a central. Osteocytes are cells found in both lamellar and osteonal bones, and one of their roles is to serve as a stress sensor. Laminar bone is arranged into a pattern termed twisted plywood at the next lower hierarchical level, in which the orientation of the collagen fibrils progressively or discretely rotates from one layer to the next. The nanoscale scale, which includes collagen fibrils and crystals, is the next hierarchical level[2]. This study focuses on the nanoscale level, which is the least known yet crucial since the collagen-crystal arrangement at the nanoscale is a key component of bone formation. The mineralized collagen fibril, also known as the collagen-crystal unit, has a significant impact on the overall mechanical properties of bone and is required as an input for multiscale models of bone. As a consequence, it's critical to understand its design and anticipate the mechanical characteristics that follow and also shown in Figure 1[7].

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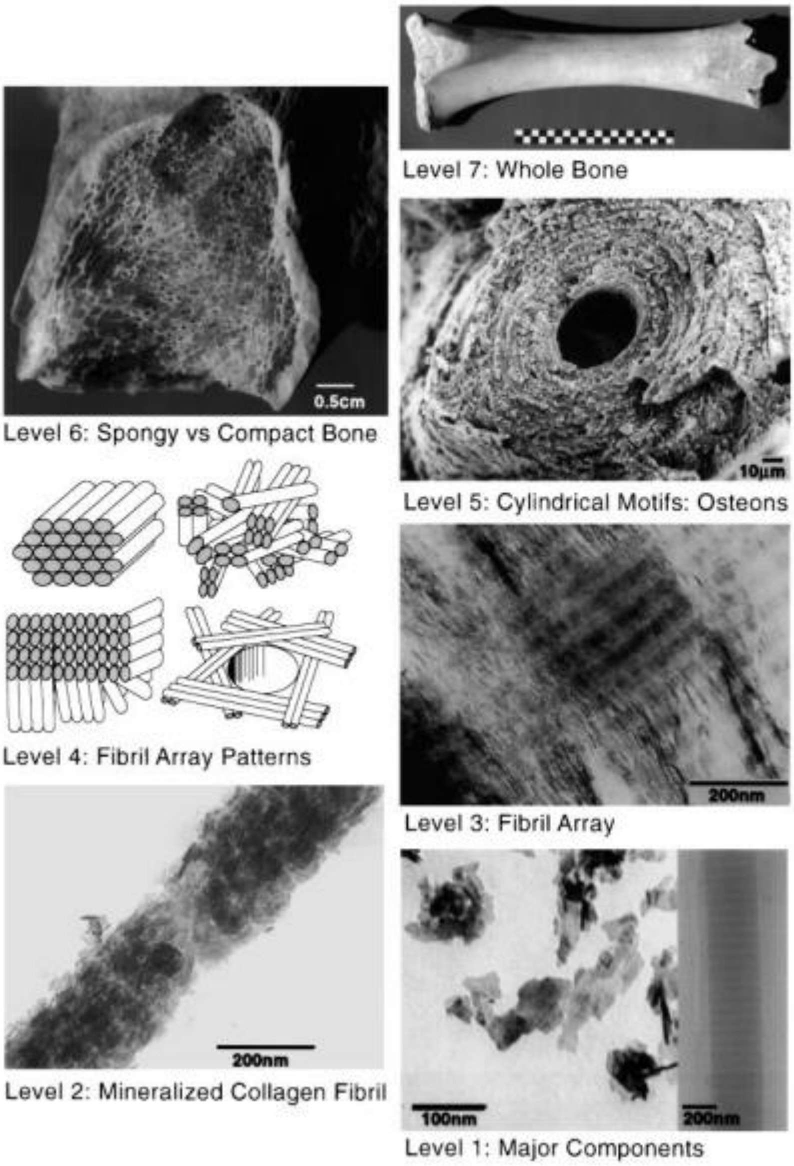

Figure 1: The 7 hierarchical levels of organization of the bone family of materials.

- Level 1: Isolated crystals from human bone and part of an un-mineralized and unstained collagen fibril from turkey tendon observed in vitreous ice in the TEM.
- Level 2: TEM micrograph of a mineralized collagen fibril from turkey tendon.
- Level 3: TEM micrograph of a thin section of mineralized turkey tendon.
- Level 4: Four fibril array patterns of organization found in the bone family of materials.
- Level 5: SEM micrograph of a single osteon from human bone.
- Level 6: Light micrograph of a fractured section through a fossilized (about 5500 years old) human femur.
- Level 7: Whole bovine bone (scale: 10 cm).

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The dynamics of bond formation between polymer filaments with thermal analysis and sintering experiments under different conditions have been reported. The cooling conditions play an important role in the bond formation. This work demonstrated that the FDM parts are basically composites of partially bonded parent thermoset, with the natural implication that predictive mechanical properties simply based on void fraction and orientation is not sufficient. The same group performed a more in-depth study on the mechanisms that control the bond formation under different process conditions. Creep deformation was found to be a dominant factor in bond formation in addition to small time scale sintering temperature. Using ANSYS FEM program, numerical model to simulate the FDM extrusion process by considering the coupled heat and mass transfer phenomena was performed to identify factors affecting part distortions and layer thickness values[8].

There have been many measurements of the bulk elastic, plastic, and ultimate characteristics of various members of the bone family of materials. The wide range of these values reflects a variety of factors, including structural diversity, specimen orientation, mineralization extent and porosity changes, specimen exact locations, and, not least, differences in the methods employed to make the measurements. It's obvious that sorting out the contributions of all of these variables to the bulk mechanical properties, which is the focus of this review, is critical.

As a result, understanding the structure-function relationships in these materials is difficult. Sorting out the bulk mechanical behaviour in terms of the contributions of the sub-structures at each hierarchical level is excellent for gaining a thorough knowledge of this topic. Unfortunately, even if we were able to fully characterize these materials in this manner, it would still not be a sufficient study since many of these materials change with time. The mechanical characteristics are affected as a result of this. Some of these changes are thermodynamic in nature, such as the growth of crystal sizes, while others are biological in nature, such as the determination of the average proportions of collagen, mineral, and water in a particular substance. Furthermore, specialized bone cells actively remove older bone and replace it with younger bone, which may have a somewhat different structure than older bone and is therefore likely tuned to operate in the prevailing stress field at the time of creation. These materials are really "smart" in this regard[9].

The research on the structure-function relationships of the bone family of materials has so far been unable to offer a comprehensive picture of the topic. Despite this insufficiency, we have decided to arrange this evaluation according to organizational hierarchies. We look at the architectures and mechanical characteristics of five of the seven hierarchical levels, which vary in size from nanometers to millimetres. These relationships in macroscopic structures have been widely studied elsewhere[10].

Understanding the structure-mechanical function relationships in the bone family of materials is progressing. Although there are numerous gaps in our knowledge, particularly when considering the structure in terms of its seven hierarchical levels, our theoretical grasp of these relationships and our ability to anticipate them is gradually increasing. Bone models of different degrees of complexity have been suggested throughout the years, mainly based on composite materials ideas. Only a handful of these models, however, include platelet- or ribbon-shaped reinforcement and account for some of the intricate geometrical and structural details. Additional rigorous experimental work with extremely tiny specimens with well-

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defined features is definitely needed. Due of the technological challenges of examining extremely tiny specimens, experimental findings are currently scarce at these levels. The mineralized collagen-based materials family has a wide range of structures that may be used to meet a wide range of mechanical needs. This may happen when vast arrays of single fibre-based plies or lamellae are assembled at different orientations into layered or laminated structures.

Although the progress made in establishing an empirical relationship between the process parameters and mechanical properties of the FDM part has practical significance in improving and optimising the FDM process, a fundamental understanding of the process–property relationship has been elusive. In addition, no direct experimental evidence of spatially resolved deformations has been undertaken to probe the process–property relationship which is inherently heterogeneous for FDM process. This paper focuses on the influence of the filament scale structure on the macroscopic property of the FDM part considering planar geometry, so that the lamina analogy for laminate can be studied carefully first. A simplified elastic finite element model of a FDM part was considered and the distribution of strain energy in the FDM part under mechanical load was evaluated. FDM dog bone samples were made with various raster angles and air gaps with the dimensions identical to those used in FE model.

FE model

To investigate the relationship between the filament scale structure and the macroscopic property, the following simplifying assumptions were made:

(i) The extruded filaments have homogeneous and isotropic properties with no defects
(ii) The extruded filaments are uniform and have the same constant cross-section profile that is determined by the extrusion parameters
(iii) The bonds between filaments are perfect and have the same mechanical properties as the filament
(iv) The FDM part is loaded in the elastic regime of the materials and the applied mechanical load did not lead to plastic deformations
(v) The FDM part is assumed to be under plain stress condition.

Several research groups have looked at simulations of the change in effective Young's modulus in the past. Although the numerical model cannot be statistically verified by the tests because of the simplifying assumptions employed in modeling to portray the material state as homogenous, qualitative comparisons may be made at this point. As the air gap decreases from positive to negative, the effective Young's modulus increases, and the improvement is most noticeable when the raster angle is 90u, which qualitatively agrees with our simulation findings.

We can account for imperfect filament bonds in future work by treating the filament bond as an artificial material with experimentally calibrated material properties, allowing us to study the multiscale relationship between the inhomogeneous material property at the filament scale and the macroscale property of the FDM part as a function of key manufacturing procedures. Furthermore, flexibility and failure criteria must be considered in order to allow the development of progressive failure based on strain localizations clearly seen utilizing the whole field strain mapping method presented for the first time in the current research for additively produced material. Furthermore, by combining high resolution and non-invasive damage diagnostics utilizing X-ray computed tomography, the stochastically distributed flaws may be integrated for investigating the impact of the stochastic features of the FDM process.

2. DISCUSSION

This is an important characteristic of structural design in nature and synthetically by humans, which is motivated in both cases by the fact that complex macroscopic structures are typically designed to withstand a variety of stresses applied in various directions, rather than a single type of stress. As a result, rather of being single-valued, the design requirements are diversified, and structural complexity is inevitable. At higher and higher organizational levels, this tendency also results in the progressive loss of a formal connection between the different physical characteristics. For example, a scaled-up model may be able to predict the stiffness of a fibril based on the stiffness of a single molecule, but predicting the stiffness of a macroscopic composite structure from the stiffness of a molecule is considerably more challenging. Because of the greater sensitivity of strength to the existence of flaws, predicting it is much more challenging. In theory, Lekhnitskii's work on completely orthotropic materials may be used to solve more difficult problems like predicting the elastic constants of osteons or arrays of osteons.

3. CONCLUSION

High-molecular-weight organic fibres like aramids and polyethylene are simple examples. From the molecular level up, they are structurally structured like tendons. The structural and mechanical anisotropies are greatest at the molecular size in both biological and synthetic materials, but they gradually decrease as the scale rises via sub-fibrillary and fibrillary arrays, up to the micrometre level. Both bone and man-made composites have structures and physical characteristics that exhibit less anisotropy as they move up the scale. However, because of the inherent variability of material and geometrical properties, aging effects, and our current lack of detailed information of the structures and properties at smaller scales, models can only lead to simplified results, especially in the case of biological materials and structures. In the case of bone, structural complexity manifests itself in a variety of subtle ways. The interaction of fibrils and laminates at all levels is a good example. The potential of theoretical models to bridge gaps in our understanding is perhaps greatest at the level of single lamellas or parallel fibrillar arrays, and it is exactly at this level that they are most useful. The study of structure-mechanical function relationships in such materials is a fascinating topic in and of itself, and it may provide new ideas for improving synthetic materials.

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