Biomaterials
Is this really a field of research?
Editorial overview
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Synthetic biomaterials

The term 'biomaterial' in itself does not convey to all a specific connotation. Even a perusal of the topics of reviews in this issue of *Current Opinion in Solid State & Materials Science*, or in the issues from the last two years devoted to biomaterials, begs the question of whether or not this really is a field of research in its own right?

To focus the issue further, it is worth reflecting on whether existing biopolymers, or for that matter titanium metal itself, implanted as a successful replacement body part, should be regarded as biomaterials. Probably not, even though they certainly function at the interface between the material and the biological environment. At the other extreme, perhaps, should a study of the crystal formation processes in a shell or bone be regarded as an integral part of this field? Probably not, if the focus of the study is, for example, the hormonal regulation of the process. Probably yes, if the focus is on the strategies developed by the biological system to control, for example, crystal shape. Certainly yes if the aim is to relate structure to mechanical function. The key issue is whether or not new concepts may be derived that could be applied to the development or improvement of synthetic materials.

These examples serve to illustrate that there is a common thread that binds this field together. It focuses on the term 'inspiration'. Synthetic materials of whatever form, soft or hard, molecular scale or macro-scale, whose development is inspired by biology, qualify as bioinspired-materials or simply biomaterials. In particular, when such materials find their use in biomedical applications, we appropriately classify them as true examples of synthetic biomaterials. The converse is that the study of biological materials themselves, with a view to ultimately deriving knowledge that will be useful in the field of materials research, is also certainly an integral part of this field. Research of this type, is the source of the inspiration [1].

This is by no means a new definition. Previous editors of this section have expressed the same opinion [2,3]. This is also certainly not a new concept. In fact it has its roots in the first part of this century, epitomized by the work of D'Arcy Wentworth Thompson.

Thompson wrote a wonderful book entitled 'On Growth and Form' published first in 1917 and then again as a second edition in 1942 by Cambridge University Press [4]. The basic theme of this book is to identify the mathematical and physical principles upon which biological materials are based, and how they dovetail with Darwinian evolution. He uses as examples the whole gamut of materials known to him from the sub-cellular, cellular, extracellular, microscopic and macroscopic levels. As he puts it: "We want to see how, in some cases at least, the forms of living things, and the parts of living things, can be explained by physical and mathematical laws". Thompson's book is also an invaluable source of ideas (inspirations, if you will) for biomaterials. For example, in a discussion on the design of the skeletons of birds in terms of providing a lightweight frame, he draws to the reader's attention the great frigatebird, with its 7-foot wingspan. The bird "weighs a little over a couple of pounds, and all its bones weigh about four ounces. The bones weigh less than the feathers". Perhaps the next design of an ultralight plane may incorporate some of the secrets of the frigate's bones.

Biology as a guide for new materials synthesis and processing

A perusal of the reviews in this issue will readily identify how each subject belongs to the field of biomaterials. The chapters fall into two categories: those that describe biology to 'provide' inspiration as described by Marie-Madeleine Giraud-Guille (pp 221–227) on plywood structures of crustacean cuticle and human bone, Julian FV Vincent (pp 228–231) on wood, David L Kaplan (pp 232–236) on mollusk shells, Lynn W Jelinski (pp 237–245) silk, and those that use biology to design improved materials, as described by Jeffrey A Hubbell (pp 246–251), and Angela K Dillow and Matthew Tirrell (pp 252–259).

With respect to inspiration, three key features of the biological systems stand out [1,5,6]. The first is the organization at the nanometer length scale. Nanoscale building blocks produced through self-assembly yield a nested structure. The nested structures may themselves be formed by self-assembly, often with a lot of help from the cells. As many materials properties (e.g. fracture) do not scale linearly with size, organization at the nanometer scale leads to materials properties fundamentally different from those expected based on simple rules for mixing the bulk properties of the constituents [7].

The second key feature is the hierarchical organization. Many biocomposite systems have at least one distinct structural feature at the molecular, nanoscopic, microscopic, and macroscopic scales. These levels are organized into a hierarchical composite system designed to meet a complex spectrum of functional requirements. Bone, crustacean cuticle (see Marie Madeleine Giraud-Guille [pp 221–227]), and wood (Julian FV Vincent [pp 228–231]) are excellent examples. As synthetic composite systems increase in complexity, they are known to function at higher levels of performance. Intelligent materials and adaptive composite systems may result from this type of complex architectural arrangement. Although it has been shown that certain hierarchical laminates maximize (or minimize) the effective elastic moduli (or dielectric constant or thermal expansion) of a composite material [8], the connection between hierarchical design and properties to facilitate optimization needs to be understood in real products. Further, although the principle of hierarchical design has already been applied to some synthetic composites [9], the smallest level of hierarchy has not yet been reduced to the nanoscale. Here the study of appropriate biological materials could possibly lead the way.

The third key feature is the specific interactions at the interfaces. For example, the pearly nacre of mollusk shells consists of layered plates of $CaCO_3$ ~ 0.5 μm thick held together by a much thinner 'mortar' of organic material. This structurally highly organized matrix functions both as an organic template inducing growth of specifically oriented aragonite crystals epitaxially and contributes significantly to the shell's mechanical properties (see David L Kaplan [pp 232–236]). A key component of this matrix is silk, a protein with remarkable mechanical properties (see Lynn W Jelinski [pp 237–245]). Whatever the nature of the bonding between levels, adequate adhesion is required for the system's structural integrity. Similarly, in the assembly of synthetic products various processing methods may be used simultaneously to assemble units from small to large with desired interfaces and structures.

Fabrication of hierarchical composites

Fabrication of hierarchical composites may involve several techniques. Self-assembly is best justified for building structures in the sub 100 nm length scale [10–12]. However, the use of these nanoscale units in the assembly of larger systems may be best accomplished with the use of existing or emerging methods such as stereolithography where a 2D section is formed by photocuring a thin layer (< 200 μm) and by scanning the 2D pattern with a laser and repeating the process layer by layer [13]. Alternatively, as discussed by Jeffrey A Hubbell (pp 246–251), ink-jet printing technology may be used to build three-dimensional structures of complex morphologies [14], similar to the way in which bees build honey-comb structures. Objects produced by lamination may be infiltrated with self-assembling systems to reduce the structural hierarchy to the nanometer scale. Microcontact printing techniques can also be used to introduce finer scale (10 μm) patterns on surfaces ([15]; see Angela K Dillow and Matthew Tirrell [pp 252–259]).

Biomaterials is, in our opinion, an integral field of research. It is an intimate blend of biology and materials sciences. It covers a wide spectrum of subjects tied together by the common thread of materials research inspired by biology.

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