Biological materials sciences

Biological materials science is a new field at the interface of materials science and biology. Historically, the fields of structural biology and physiology have tended to overlook materials-science approaches when investigating biological matter. However, including studies of the physical (mechanical, optical and/or magnetic) properties of materials, and how they respond to changing environmental factors, provides opportunities to improve understanding of biological processes such as tissue growth, self-repair, sensing and cell motility.

The emergence of biological materials science is due, in part, to the advent of regenerative medicine, as this discipline needs biomaterials that interact with the body in a specific, predictable manner. In parallel, the development of new technologies means that researchers now have the tools to study, in greater detail, the structure and physical properties of biological materials, whether cells, tissue samples or complete organs. This knowledge can be used to engineer new 'smart' materials that can, for example, self-assemble, self-repair and/or evolve, and to investigate how these biomaterials interact with biological systems. Drawing inspiration from natural processes, the search is on to find alternative, more efficient ways of synthesizing organic materials.

BIOMIMETICS

The creation of new material families based on biological systems — biomimetic materials synthesis — involves much more than simply copying structures observed in nature[1]. Researchers also need to appreciate the building principles used in their construction. This, in turn, requires a thorough understanding of the relationship between structure and function[2].

One area where this approach has already been successful is biomimetic mineralization. Biominerals, such as mother-of-pearl, generally have superior properties to artificially created materials with similar composition. Materials scientists have discovered that biominerals are not formed via the classical crystallization process but instead start with organized nanoparticle building units coupled with amorphous or even liquid precursors. By drawing on elements of this alternative pathway, it is possible to make a range of complex synthetic crystalline structures[3,4]. Using this strategy to engineer mother of pearl in the laboratory resulted in a synthetic material that was practically indistinguishable from the genuine biomineral.

MULTI-SCALE MODELLING AND STRUCTURE

In many cases, the extraordinary mechanical properties of biological materials are related to their highly layered or hierarchical structure[5]. The high fracture resistance of deep-sea glass sponges is a good example: the glass-fibre bundles are woven as in a basket, providing mechanical strength; whereas, on a smaller scale, each individual fibre is composed of concentric layers of silica and an organic matrix, which dramatically reduces the brittleness[6].

The relationship between a material's hierarchical structure and properties can be explored in multi-scale models (Fig. 1). These powerful tools allow a material's behaviour to be modelled over a range of length scales and time periods. The models can be validated by comparing predicted results with experimental data at each scale of interest, providing insight into the overall principles of material design. A multi-scale approach is also useful when simulating the formation of certain biological materials that self-organize at many different levels. Membrane proteins, for example, rely on this complex self-assembly process for their high flexibility.

Biomimetic science promises to be of considerable value to future material design challenges, whether for biomaterials or other mechanical applications. The development of high-performance electrodes for modern lithium batteries is a good example. Materials chosen as battery electrodes are often porous. This type of structure is favoured because it provides a large surface area for electron-exchange reactions. However, the pattern of porosity in these materials is typically regular or sometimes random — arrangements that can limit electron movement. The hierarchical pore structure of biological systems offers a similarly large surface area but minimal resistance to transport. In the lung, for instance, a few litres of air can be exchanged in a matter of seconds.

New synthetic materials designed according to this principal of hierarchical porosity are showing considerable promise as battery electrodes, in terms of their storage capacity and charge/discharge rate. This could have important implications for the development of rechargeable batteries for laptop computers or other mobile electronic devices.

TOWARDS NEW CLASSES OF BIOMATERIALS

Unlike natural materials, biomaterials can include high-performance synthetic composites. Inorganic functional materials can be combined with organic elements, for example polyelectrolytes and self-assembled

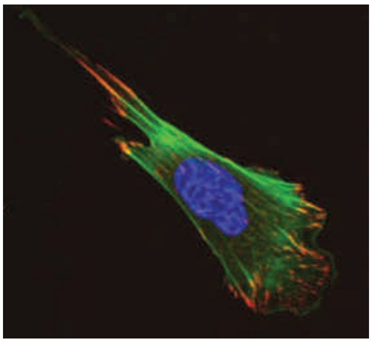
Marine mussels use byssal threads for attaching to rocks in wave-swept habitats. Researchers at the Max Planck Institute of Colloids and Interfaces together with colleagues from the University of California at Santa Barbara have shown that an inhomogeneous distribution of cross-links in the cuticle of these threads provides both extensibility and abrasion resistance. This finding might assist in developing new concepts for polymeric coatings (Harrington, M. J. *et al*. *Science* **328**, 216–220, 2010).

- Biomimetic materials science draws inspiration from natural structures to synthesize new materials with improved functionality.
- Multi-scale models and characterization techniques are powerful tools for studying hierarchical structures and processes in biological materials at a range of length and time scales.
- New biomaterials concepts will emerge by understanding the interaction between materials and biological systems at the cellular level.

monolayers can serve as templates for proteins, peptides, amino acids, DNA and polysaccharides to create oxide-based biomaterials with superior mechanical properties[7].

Knowing how these biomaterials interact with biological systems is another important line of research. A subtle change to a material's physical or chemical properties can make an enormous difference to the growth of cells it has contact with. This is especially significant if the material is to be used in clinical applications, biomedical engineering or even the control of biofouling. The likelihood of cells adhering to a material's surface can, for example, depend on nanoscale spacings between possible binding sites or the presence of additional factors such as integrin receptors, which play a critical role in adhesion to an extracellular matrix by generating force, translating mechanical cues into biochemical signals and communicating with growth factor receptors (Fig. 2).

Fig. 2 | Interactions between biomaterials and living systems at the cellular level.



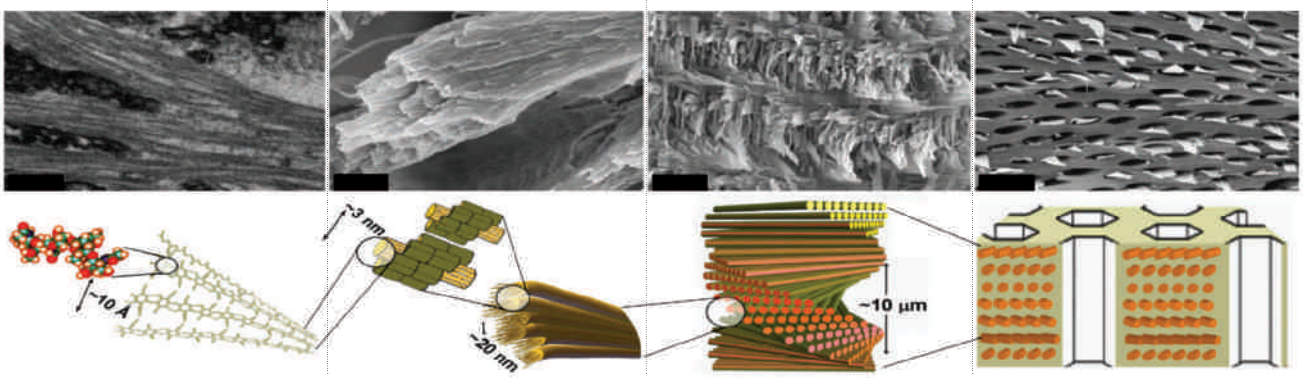
This image of a migrating fibroblast cell demonstrates the areas responsible for adhesion (red staining) and motility (green staining).

Biomimetic science is inspired not only by natural materials but also by natural processes. Active molecular systems, such as intracellular transport and the response to mechanical stimuli, might provide inspiration for micromechanical devices for energy conversion, actuation and/or lab-on-a-chip applications[2,8]. Similarly, bio-geological processes stimulate novel research, including the laboratory-based formation of coal or carbon-derived materials from waste biomass. Such reactions are performed at high temperatures and rely on catalysts to produce yields that would be impossible in nature. Many uses have been proposed for the resulting man-made carbon structures, ranging from soil conditioners and water filters to high-end hybrid materials for lithium batteries[9]. A bio-geo-mimetic approach is, in addition, being used to identify carbon capture and storage solutions, as well as fuel cells that do not emit carbon dioxide.

There is potential to develop multi-functional biological materials with more complex hierarchical structures using a materials perspective. Understanding how materials and cells interact will allow greater control over tissue engineering, and contribute to new regenerative therapies and energy-storage solutions.

Fig. 1 | Hierarchical structure of the lobster shell. Different features of the chitin structure are shown at size scales from nanometres to millimetres.

0.1 nm – 10 nm	10 nm – 100 nm	100 nm – 10 µm	10 µm – 10 mm
a-chitin (H-bonded anti-parallel N-acetyl-glucosamine molecular chains).	Mineralized chitin-protein nanofibres in a planer array.	Twisted plywood stack of mineralized chitin-protein planes without pore canals.	Twisted plywood stack of mineralized chitin-protein planes with pore canals.
Transmission electron microscope	Field emission scanning electron microscope	Field emission scanning electron microscope	Field emission scanning electron microscope



(adapted from ref 10).

Fig 2: R. Fässler, MPI Biochemistry.

For references see pages 70 and 71