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Biomimetics: Science Mimicking Nature

Biomimetic materials or devices are those whose design, organization, and functional properties are modeled on biological systems. This field of research can be described as a sort of biological "reverse engineering" in which scientists seek to discover the basic mechanisms through which natural materials are formed in order to develop new technologies. Examples of current biomimetic studies reveal some of nature's secrets and their potential influence on practical aspects of everyday human life, from human tissue repair to industrial materials.

Fig. 1 The mother-of-pearl growth surface of abalone shell is colored due to the way light refracts as it strikes tiny terraces of calcium carbonate. Photo courtesy of UCSD Jacobs School of Engineering

Abalone Body Armor

Engineering researchers at the University of California, San Diego are using the shell of a seaweed-eating snail as a guide in the development of a new generation of bullet-stopping armor. The colorful oval shell of the red abalone is highly prized as a source of nacre, or mother-of-pearl, jewelry, but the researchers are most impressed by the ability of the shell to absorb heavy blows without breaking.

In a paper published in the January 15, 2005 issue of *Materials Science and Engineering A,* Marc A. Meyers, a professor in UCSD's Jacobs School of Engineering, and engineering graduate student Albert Lin explain in detail for the first time the steps taken by the abalone to produce a helmetlike home made with 95% calcium carbonate "tiles" and 5% protein adhesive. Teachers who write on blackboards know that calcium carbonate, or chalk, is weak and brittle, but Meyers and Lin have demonstrated that a highly ordered bricklike tiled structure created by the mollusk is the toughest arrangement of tiles theoretically possible.

Abalone shell can't stop an AK47 bullet. However, laminates of aluminum and other materials have been disappointing as armors. Meyers argues that a careful examination of the steps taken by abalone to make their shells may help materials scientists develop similarly lightweight and effective body armor for soldiers, police, and others. "In our search for a new generation of armors, we have exhausted the conventional possibilities, so we've turned to biology-inspired, or biomimetic, structures," said Meyers, a former scientist with the U.S. Army Research Office. "The laminate structure of abalone shell has stimulated our group to develop a new synthetic material using this lowly mollusk as a guide."

Biomimetic researchers interested in tough materials have discovered that mollusk shells, bird bills, deer antler, animal tendon, and other biocomposite materials have recurring building plans that yield a hierarchy of structures from the molecular level to the macroscale. For example, at the nanoscale, abalone shell is made of thousands of layers of calcium carbonate tiles, approximately 10 µm across and 0.5 µm thick, or approximately one one-hundredth the thickness of a strand of human hair. (The irregular stacks of thin tiles refract light to yield the characteristic luster of mother-of-pearl, shown in Fig. 1.)

Meyers said a key to the strength of the shell is a positively charged protein adhesive that binds to the negatively charged top and bottom surfaces of the calcium carbonate tiles. The glue is strong enough to hold layers of tiles firmly together, but weak enough to permit the layers to slip apart, absorbing the energy of a heavy blow in the process (Fig. 2). Abalones quickly fill in fissures within their shells that form due to impacts, and they also deposit "growth bands" of organic material during seasonal lulls in shell growth. The growth bands further strengthen the shells. The precise way that building blocks of shells are assembled determines their strength, and many of those details have been unknown. Meyers explains:

Contrary to what others have thought, the tiles abutting each other in each layer are not glued on their sides, rather they are only glued on the top and bottom, which is why adjacent tiles can separate from one another and slide when a strong force is applied. The adhesive properties of the protein glue, together with the size and shape of the calcium carbonate tiles, explain how the shell interior gives a little without breaking. On the contrary, when a conventional laminate material breaks, the whole structure is weakened.

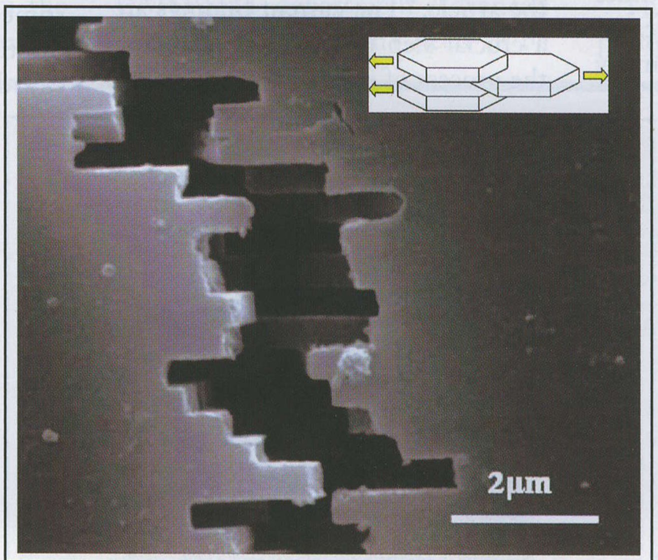

Fig. 2 *Under stress, tiles of calcium carbonate can slide, absorbing energy. Because of this microstructure, the abalone shell can absorb a great deal of energy without failing. The mollusk can repair these imperfections. Photo courtesy of UCSD Jacobs School of Engineering*

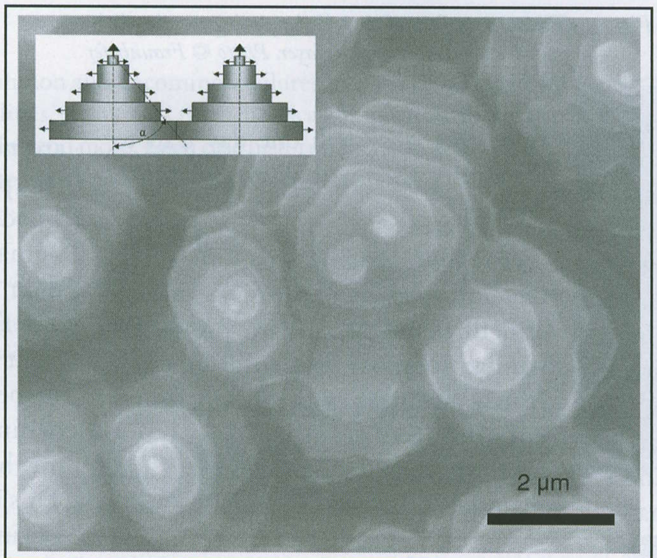

Fig. 3 *The terraced, Christmas-tree-like surface of abalone shell has evenly spaced nucleation sites from which stacks of hexagonal "tiles" of calcium carbonate grow. The top and bottom surfaces of each layer of tiles are separated by a protein adhesive, but the adhesive does not bind the edges of tiles to adjoining tiles. Photo courtesy of UCSD Jacobs School of Engineering*

Meyers and Lin closely measured shell growth by coaxing abalone grown in a laboratory aquarium at UCSD's Scripps Institution of Oceanography. They gently pushed back a section of the mantle from the shell of individual abalones, glued 15 mm glass slides to the shell, and later withdrew the slides at various time intervals and examined the growth of "flat pearl" with a transmission electron microscope. The flat pearl samples revealed that approximately every 10 µm, the abalone mantle initiated calcium carbonate precipitation. At those points, tiles began to form, growing 0.5 µm thick and slowly outward and assuming a hexagonal shape as individual tiles in each layer gradually grew to abut a neighboring tile. Photographed from above by a microscope, the growth surface of the shells has a Christmas tree appearance (Fig. 3) because abalones add layers of tile faster than each layer is filled in.

Meyers and Lin plan to complete their analysis of the abalone shell and generate a mathematical description that can be used by others to construct body armor based on the abalone.

Biologic Tooth Repair

Scientists at The Forsyth Institute in Boston have found and replicated a key aspect of the mechanism by which dental enamel is formed. The findings, published in the February 14, 2005 *Journal of Structural Biology*, may one day lead to new biological methods for repairing teeth and other mineralized tissues as well as to new very hard ceramic materials.

Elia Beniash, Staff Scientist at Forsyth, explains that enamel, the hardest tissue in the human body, is composed mainly of calcium phosphate mineral crystals:

> It is well known that enamel's strength and durability derive from the unique way in which those crystals are organized into parallel bundles called 'rods.' In the current research, carried out in test tubes, we demonstrated that the protein amelogenin plays a key role in regulating the organization and growth of these crystals and how it works. We also determined that newly-forming enamel structure emerges as a result of cooperative interactions between forming crystals and assembling proteins, rather than sequentially, as in the formation of other mineralized tissues such as bone and dentin (the bony material found under enamel, in teeth).

The study was conducted with mouse amelogenin, which is very similar to the form of the protein found in human teeth.

In the words of Henry Margolis, chair of the Forsyth Department of Biomineralization and co-author of the article, "The current findings are a crucial step toward understanding the process of enamel formation. We hope this work will one day lead to an ability to repair damaged tooth enamel."

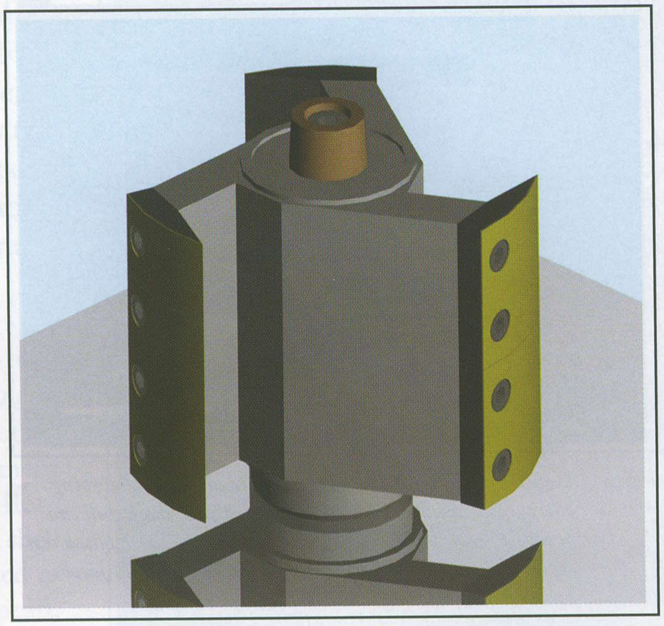

Fig. 4 The outer surfaces of the self-sharpening rotating knives are coated with a hard ceramic layer. Photo © Fraunhofer UMSICHT

Another long-term goal is the development of biomimetic nanostructured materials with properties similar to those of dental enamel. "Such advances will rely on future collaborative studies involving chemists, biophysicists, biologists, and materials scientists," Margolis said.

Knives Sharp As Rodent Teeth

Blades grow blunt after cutting for a while. New knives that can sharpen themselves have been modeled on the incisors of rodents, enabling plastics and elastic materials to be ground faster and more effectively without changing blades.

A plastic park bench, shopping bag, or toy building block—they all have something in common with most plastic articles: They are manufactured from granulates. Making granulate or powder requires a lot of grinding, and a problem with grinding mills has always been that their blades grow blunt within a few hours. This means halting production to remove, sharpen, replace, and adjust the knives. The mills stop turning and valuable time is lost.

Researchers at the Fraunhofer Institute for Environmental, Safety, and Energy Technology UMSICHT (Oberhausen, Germany) are collaborating with Kennametal Widia (Bangalore, India) to develop permanently sharp blades for grinding mills, inspired by the self-sharpening incisors of rats. These creatures are notorious for their permanently sharp teeth that can bite through wood, metal, or even concrete. Unlike humans and most other mammals, their perpetually growing teeth are not fully coated with enamel. The front surface has a hard, horseshoe-shaped, ultrathin enamel coat, but behind it is the softer dentin that mechanically stabilizes the tooth. This is worn down through gnawing, leaving a sharp knife-edge of enamel protruding beyond it.

The new cutting blades (Fig. 4) work in exactly the same way. Their tough body is made of hard metal, an alloy of tungsten carbide and