nanOntario

Centre for Nanomaterials in Manufacturing Innovation

Learning Nanotechnology from Ontario's Great Outdoors

Materials Science & Engineering
UNIVERSITY OF TORONTO

FACULTY OF APPLIED SCIENCE & ENGINEERING

Message from the Publisher

Professor Uwe Erb

Our fourth year research theme is "Bio-inspired strength". Many researchers are turning to nature in search of solutions to our demands for stronger and more lightweight materials. The strength of a material refers to its ability to endure external forces without failure. Diverse strong and lightweight materials have developed over millions of years of natural selection.

To examine strong and lightweight materials, several nanostructures found in nature for strength purposes were explored including spider silk, nacre, and porcupine quills. A scanning electron microscope was used to obtain high magnification images depicting the structures of these materials. The images demonstrate an incredible diversity in the ways strength manifests in lightweight structures.

While these materials all demonstrate lightweight strength, each also offers distinct properties, from the biocompatibility of spider silk to the deformation resistance of nacre. Manufacturing technologies based on these principles are being developed to improve current products as well as design entirely new ones. Future applications may include spider silk inspired parachutes and airbags, nacre-mimetic materials in vehicles and aerospace applications, as well as strong lightweight metal foams and barbed medical bandages inspired by porcupine quills.

If the sun were the size of a chair, then you would only be 5 atoms (~ 1 nm) tall.

1. The Nature

There exist over 40,000 different species of spiders in the world. Instead of actively hunting for food, most spiders take advantage of the strength and sticky nature of webs to capture their prey. When insects become trapped in a web, the spider wraps them up in layers of silk and injects enzymes into their prey, before sucking out the liquefied contents.

Spider

Mussel and its byssus

Depending on the species, mussels are found in both sea and fresh water environments. Capable of growing up to 25 cm in length, they are protected by oval-shaped shells that are rough on the outside but smooth on the inside. The smooth inner iridescent lining, or nacre, protects the mussel shell from harm and predators.

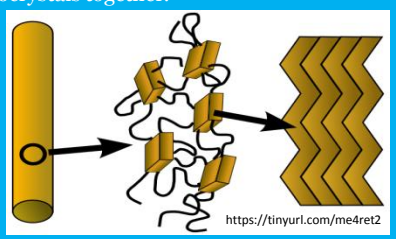
North American porcupines are the second largest rodent in Canada. Their bodies are covered with barbed quills that can easily penetrate skin and are very difficult to extract, helping to cause more damage to assailants. These quills usually lay flat against the body, but are pulled upright when the porcupine is encountered by predators.

Porcupine

2. The Structures

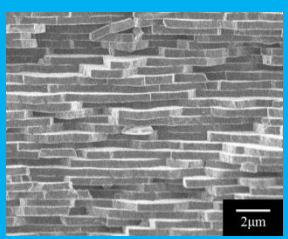
Spider Silk - Protein Polymer

Silk threads are made up of long chains of a protein called spider fibroin. These chains organize into loose networks and tightly packed nanocrystals, the network holding the nanocrystals together.



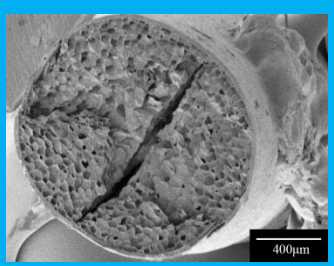
Nacre - Interlocking Tiles

Nacre exhibits a well-ordered brick-and-mortar architecture. The "bricks" are calcium carbonate platelets coated in thin layers of protein analogous to mortar. The proteins contribute to nacre's strength as well as its tile formation.



Porcupine Quill - Thin Cortex, Cellular Foam

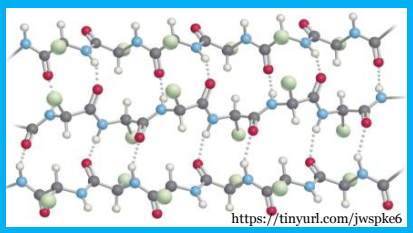
The porcupine quill is composed of cellular foam enclosed in a thin outer shell. The outer shell is made of keratin, the same material that makes up human hair and nails.



3. The Theory

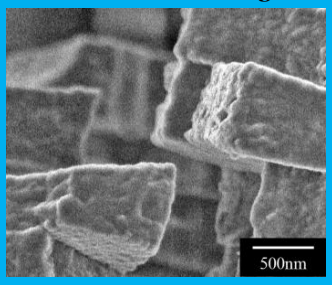
Strong and Lightweight Materials

1) Spider Silk's Numerous Bonds



The chains of spider fibroin have side groups that cause them to form hydrogen bonds between each other. Although the individual bonds are quite weak, the fibroin chains allow for many bonds to occur in a short length. By their sheer numbers, these bonds give the silk its strength.

2) Nacre's Tiles and Nanograins



The mechanical interlocks between the mineral tiles makes nacre strong. Each tile is also composed of numerous nanograins that further improves strength by the Hall-Petch effect.

3) Energy-Absorbing Foam Structure

The foam helps absorb energy when the structure is in compression. Since foam is a lightweight material, it gives the structure a higher compressive strength without too much additional weight. This is part of what enables porcupines to defend themselves against attackers effectively.

4. The Applications

1) Spider Silk Infused Bullet-Proof Skin

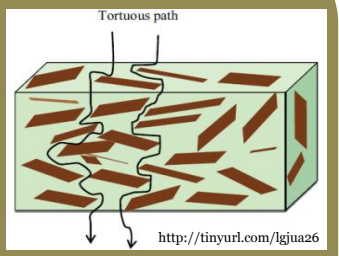
Spider silk's combination of high strength and rupture elongation makes it a promising material for engineering applications requiring high energy absorption (e.g. bullet-proof vests).

Dutch artist Jalila Essaidi worked alongside Forensic Genomics Consortium Netherlands in an effort to create "bullet-proof skin".

By embedding a bullet-proof matrix of spider silk between the dermis and epidermis of an in vitro human skin, Essaidi's team created a bio-engineered skin capable of stopping a .22 calibre long rifle bullet traveling at 165 m/s.

2) Nacre-mimetic Polymer/Clay Nanocomposites

Scientists have discovered that polymer mixed with long and thin nanolayers of clay improved properties compared to pure clay and pure polymer. Roughly mimicking nacre's brick-and-mortar structure, the more ordered the clay nanolayers are, the stronger the material becomes.



For example, montmorillonite (MMT) is a clay that has been shown to form structures similar to nacre. It mixes well with various polymers to make polymer nanocomposites such as polystyrene/MMT, epoxy/MMT, and poly(vinyl alcohol)/MMT.

3) Metal Foam

Using foam structures, ERG Materials and Aerospace Corp. has been able to manufacture metal foam materials, which are lightweight and impact-resistant.

This is important in aerospace engineering, where weight of the aircraft is one of the most important factors to be minimized.

The metal foams are produced at 8% density, which means about 92% of the total volume is nothing but air!

4) Sports Equipment

Nanotechnology offers improved sports equipment, allowing athletes to take their game to the next level. Grafalloy's Epic golf shaft by Combat uses a nano-nickel coating, developed by Integran Technologies Inc., Toronto, to enhance strength and durability.

This phenomenon, called the Hall-Petch effect, allows the shaft to have both the light weight of graphite and the strength of steel.

Collaborators and Sponsors

ERG AEROSPACE CORPORATION

ROM

INTEGRAN TECHNOLOGIES INC.

CelluForce

IMAGE X-PRESS Printing Friendly Excellence Service

Hitachi High-Tech

Special Thanks

Kelly Snow
Jeffrey Karp

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nanOntario, Volume 4

Publisher
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T: 416.978.3012

September 2013

www.mse.utoronto.ca