MATERIAL MARVELS

Second nature

From the invention of Velcro to materials systems that can reshape the way we live our lives, **Andrea Gaini** investigates the past, present and future role of biomimetics in materials science.

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Pictured: The burdock burr flower was the inspiration behind the invention of Velcro in 1955

In 1941, Georges de Mestral, a Swiss engineer, was walking back from a trip to the forest, when he noticed, for the first time, the unique way in which burrs had stuck to his trousers and his dog's hair. By virtue of de Mestral's curious nature, he took it upon himself to analyse the little hooked burrs of the burdock plant and the way they grasped to hair and textile.

De Mestral would spend almost 15 years studying burrs and how to recreate its characteristics and, in 1955, he finally introduced the world to one of the most widely-used products – Velcro.

Velcro is a long proclaimed example of biomimetics, so popular I considered omitting its mention in this article, however, Velcro represents just how impactful the science of biomimicry can be.

According to Dr Marc Desmulliez at Heriot-Watt University, UK, bio-inspired materials play a crucial role in advancing material sciences, providing "a new approach to see the world and utilise what will be useful for humankind".

Often referred to as 'borrowing ideas from nature', biomimetics is defined by Dr Thomas Speck – one of the leading researchers in the field based at Freiburg University in Germany – as a "re-invention inspired by nature".

Despite only being studied as a subject from the 20th Century onwards, Speck says biomimetics has always been around. "Early humans, for example, created sticks and wooden weapons...inspired by the teeth of animals.

"One of the first examples of biomimetic study is Leonardo da Vinci's analysis of flight. Da Vinci quantified nature to re-produce the bird's flight on a machine he had created."

Smartening up

Speck has been researching and studying biomimetics for over 20 years and he finds materials to be one of the most interesting applications of the lessons learnt from nature. He is now working on using biomimetics to "smart-up materials".

"[One of the things] we'd like to create with our research is materials which have embedded energy, embedded intelligence...this is our cue to soft robotics," he offers.

"If you look at robots today, for example, we have a central control unit, which more or less mimics our brain. And this can make things complicated sometimes, because of all the calculations that it requires."

He explains that the venus flytrap is one of the most valuable examples of what bio-inspired, smart materials could do. "[The] venus flytrap has a mechanical memory, it only snaps if it's triggered twice – it senses, it acts." He explains that while one single material might not be able to do all of this, a materials system that has intelligence and reactivity without the complex calculations might.

Speck is currently working on materials systems and structures for plant-inspired growing robots in the European funded project GrowBot. "Here, we use structures and materials systems found in various types of climbing plants as role models for a novel type of climbing robots," he says.

Nature is also inspiring advanced composite materials (ACM) and, specifically, high-performance fibre-reinforced composites (HPFRP).

It is an area explored by Dr Lorenzo Mencattelli, a materials scientist at Imperial College London, UK, in the paper, *Learning from nature: Bio-Inspiration for damage-tolerant high-performance fibre-reinforced composites,* published in *Composites Science and Technology.*

He notes that several biological microstructures present fibrous, hard reinforcements embedded into a soft protein matrix. This closely resembles an advanced fibre-reinforced composite material with high-performance fibres (carbon, glass, aramid, flax, etc.) embedded in a resin system (thermoset and thermoplastic).

He writes, "Despite the obvious similarity, [the] specific microstructural features and distinct traits of biological materials provide unrivalled toughness and damage resistance leading to composite structures capable of surviving in harsh environments and to preserve life and its equilibrium. Such recurrent features include staggered discontinuities, inhomogeneities, hierarchical structures built on multiple length scales and helicoidality."

"The latest evolution towards automated manufacturing signed by the advent of high-rate production 3D printing processes and automated fibre/tape placement technologies opens new avenues for the exploitation of bio-inspired solutions."

Mencattelli tells me that relatively poor damage tolerance and energy dissipation capability have been historical issues of HPFRPs, limiting their use in industry and often leading to overbuilt designs with associated weight penalty.

With the growing request for FRP composite solutions with unprecedented structural efficiency, improvement in performance is necessary to provide competitive composite designs.

"This is where nature can serve as a critical source of inspiration to develop the next generation of advanced composite materials capable of both high-strength and toughness," he notes.

To this end, Mencattelli has worked on the development of Helicoid, a bio-inspired ACM solution that has gone from laboratory to industry.

"The technology...delivers composite structures highly tolerant to impact loading...[using] structures inspired by a recurrent feature found on the protective shells of different creatures (scarbei cuticle, lobster shell, fish scale, mantis shrimp dactyl club) evolved to resist impact," he says.

Planting seeds of inspiration

Dr Mencattelli, Dr Desmulliez and Dr Speck share their favourite bio-elements that have inspired scientific inventions in materials science.

Nacre-like shells

Nacre can be found on mollusc shells (abalone, oyster, etc.) and is composed of a mineralised brick-mortar microstructure, consisting of 95% aragonite ($CaCO_3$) platelets (or tiles) and 5% organic materials.

The microstructure is organised on various length scales, from nano- to the macroscale. The key toughening mechanisms are based on tile pull-out, with one tile sliding against another, dissipating large quantities of energy through friction. This mechanism creates stable crack growth in the material, which would otherwise be extremely brittle and subject to damage localisation and catastrophic failure.

The nacre structure has been used in materials science to toughen glass, where square or hexagonal borosilicate glass sheets were bonded together using ethylene-vinyl acetate interlayers, generating a structure that allows glass plates to slide past each other. This produces a five-layered glass composite that is deformable and impact resistant, while maintaining high stiffness, flexural strength, surface hardness and transparency.

Geckos

Geckos have the ability to walk up walls thanks to small rows of hairs, known as setae, which generate several attractions between molecules on the surfaces and create a solid foothold. Engineers have been able recreate a similar effect using silicones, plastics, carbon nanotubes and other materials.

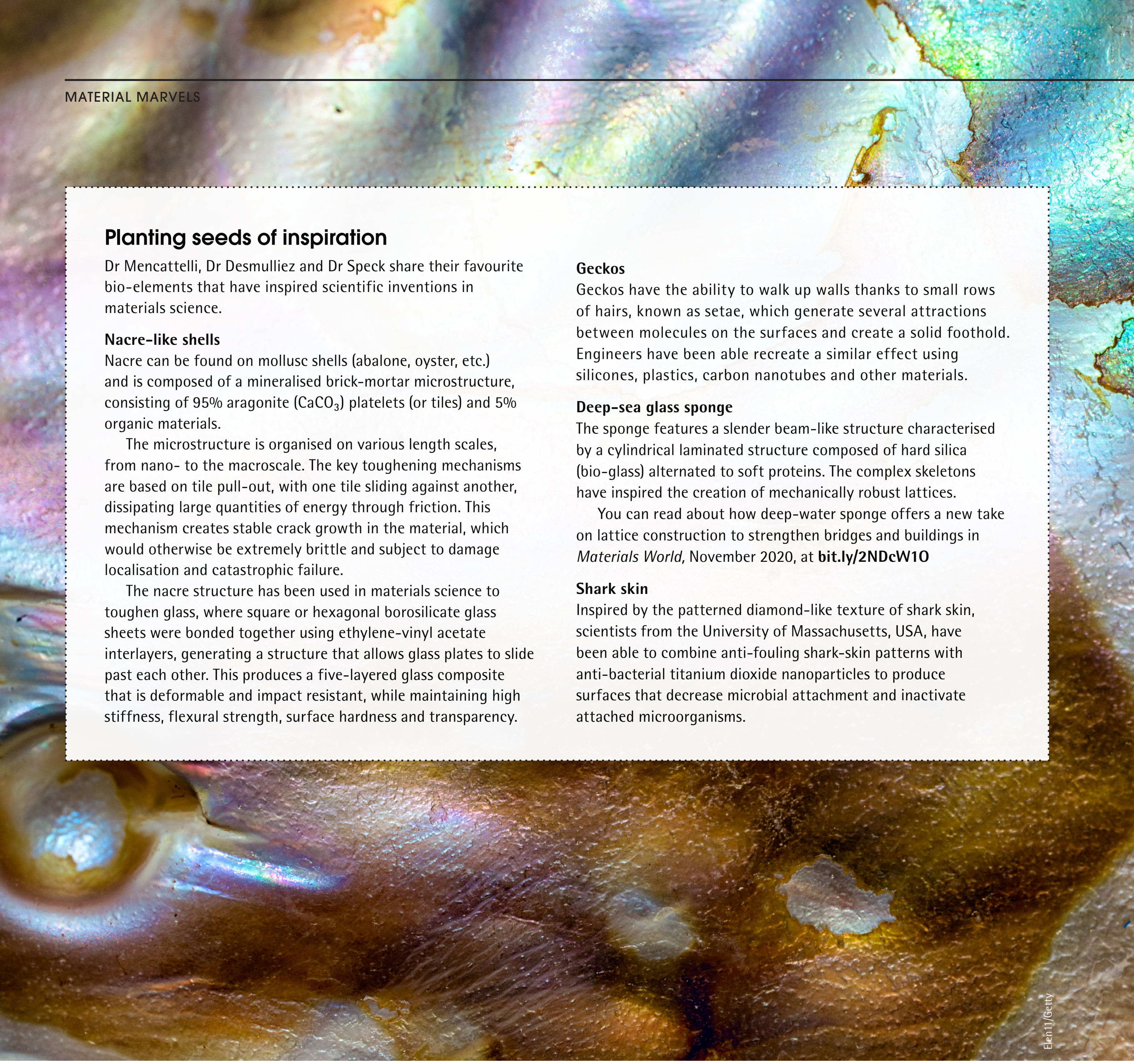
Deep-sea glass sponge

The sponge features a slender beam-like structure characterised by a cylindrical laminated structure composed of hard silica (bio-glass) alternated to soft proteins. The complex skeletons have inspired the creation of mechanically robust lattices.

You can read about how deep-water sponge offers a new take on lattice construction to strengthen bridges and buildings in *Materials World*, November 2020, at **bit.ly/2NDcW1O**

Shark skin

Inspired by the patterned diamond-like texture of shark skin, scientists from the University of Massachusetts, USA, have been able to combine anti-fouling shark-skin patterns with anti-bacterial titanium dioxide nanoparticles to produce surfaces that decrease microbial attachment and inactivate attached microorganisms.



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Above: The nacre shell, the source of inspiration of many techniques to develop stronger materials

The damage resistance of the club depends on the highly expanded helicoidal lay-up made of thin fibrous layers. This is reconstructed by slightly rotating adjacent plies by a small angle, leading to a helicoidal distribution of fibre orientations.

"Since the applicability of Helicoid technology isn't constrained to any specific material constituents and manufacturing processes (it works with most manufacturing technologies), the technology holds the potential to bring benefits to a wide range of markets where crashworthiness, light-weighting and high performances are key design drivers," Mencattelli explains.

This could include sporting goods, aerospace, automotive, renewable energy, electric vehicles, fuel cell vehicles, rail, defence and consumer goods, he says.

Manufacturing an advantage

Biomimicry UK, a company helping to fund research in biomimetics, has found that there are over 100 institutions in the UK researching the area and its different applications. However, despite this, Speck admits that when it comes to actual impact in terms of new material production, this still floats around a shallow 1%.

"On an intellectual level, biomimetics helps us to start thinking of new materials and materials systems…On the other hand, if we look at the materials which are produced for public use, I would say this is much less."

Both Speck and Mencattelli acknowledge that the majority of the breakthroughs will come through manufacturing technologies that can reproduce naturally occurring features.

"Scalability and cost-effective manufacturing are…the key limitations for the implementation and exploitation of bio-inspired solutions into industrial materials," Mencattelli suggests.

"In my view, it all hinges on how to make sure that we harvest the information from natural products that will help fight the very large societal challenges that we are facing."

"These often require the realisation of complex structures, with limited spatial resolution. In this context…the latest evolution towards automated manufacturing signed by the advent of high-rate production 3D printing processes and automated fibre/tape placement technologies opens new avenues for the exploitation of bio-inspired solutions."

Dr Julian Vincent, Professor at the Nature Inspired Manufacturing Centre at Heriot-Watt University, UK, agrees. "It seems to me that a breakthrough necessitates the introduction of a new technique (i.e. new to the topic area) that allows phenomena to be seen in a new light.

"Unfortunately, we run into the same problem of transdisciplinary studies. Studies on hydrophobic surfaces led to a number of interesting devices, but I don't know how many products, if any, have resulted."

He says that future advances in the field will depend on the integration of biologists and technologists.

"Revolution and advantage is more likely to result from proper integration rather than technical advances. Biologists have to realise that technology is, on the whole, not particularly interested in the beauty of nature, and that the input of biology is to add another design tool for use by technology.

"In turn, technology has to realise that the comfort and convenience of reaching out for a standard answer, well tried and tested, may not be the best solution in the long run."

The future calls

Desmulliez, like many others in the field, identifies 'animated materials' as one way forward. "Animated (also called life-like) materials are the first step towards embedding information and local control without the need of a central intelligence. It is the first step towards a deeper understanding of biomaterials." he explains.

Mencattelli adds that "animated materials are really an exciting area that hold the potential for revolutionary inventions".

But terminology will have to change to adapt to the idea of creating materials systems rather than simply materials, suggests Speck. "I think there's a lot of potential in material systems [with] embedded energy and embedded intelligence."

He stresses that soft machine will be a new revolution – like the Internet – in the next 10 to 15 years. "I think [soon], everybody will have some kind of soft machine at home, perhaps they might not be called machines, but they will do stuff, interact with us...And we will [move] away [a bit] from this kind of one-central-control unit into smart materials."

Many advances are on the horizon for a field that has never stopped feeding ideas and inspiration to the world of science. Desmulliez concludes, "In my view, it all hinges on how to make sure that we harvest the information from natural products that will help fight the very large societal challenges that we are facing."

Can offshore wind farms mimic mussels' anchoring technique?

Researchers at the University of Nottingham, UK, are investigating how sea mussels stick to wet and wave-hit rocks using collagen-rich sticky threads, ending in adhesive pads known as plaques. They hope to unlock novel engineering solutions to anchor the floating foundations of an offshore wind farm to the seabed, by learning exactly how mussel plaques adapt their grip to different surfaces.

The team notes that engineers are yet to find a reliable way to fix cables from the foundation into the ground, in a system that can withstand the weight of the turbines and the forces of rough oceans and high winds.

The adhesive structure of a mussel plaque is made up of an outer, dense and protective cuticle layer and a low-density, porous plaque core consisting of a foamy network of pores at different length scales and reinforced by fibre bundles. The outer and core layers work in a cooperative way.

Existing research has demonstrated that the plaque core has good load-bearing capacity and strength under tension and shear. In contrast, man-made porous materials, such as foams or honeycombs, have very limited load-bearing capacity and strength under the same forces.

The three-year project aims to mimic the unique structural characteristics of sea mussel plaques to inform the design of new, ultra light-weight, porous, yet durable, materials. These could also find use in aerospace and transportation manufacturing.


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