FEATURE 26 September

2018

Hacking nature's coolest inventions to create the perfect metal

From bamboo stalks to mantis shrimp clubs to teeth, nature marries strength and toughness with spectacular effect. Copying its secrets could usher in a new age of metals

A mantis shrimp's clubs, a stag's antlers and an alligator's armour could hold the key to better metals

Arto Hakola, Monty Rakusen, Mark Bridger, Steve Allen, Martin Pickard, iStock/Getty Images

By **Liz Kalaugher**

WHO'S afraid of the peacock mantis shrimp? Brightly coloured, googly-eyed and with a profusion of weedy legs, it doesn't seem much of a threat. Beneath its ordinary carapace, however, lurks a remarkable weapon. When the mantis shrimp is roused, its clublike appendages punch forward with acceleration greater than a Formula 1 car engine, moving fast enough to make bubbles in the surrounding water and create a force that shatters aquarium glass.

It is an extraordinary feat, especially when you consider the shrimp's deadly appendage is made of nothing more remarkable than the material in our bones or teeth. But it is no isolated example. All across the natural world, plants and animals have developed ways of using nature's simple building blocks to astonishing ends. Using only the meagre items on the menu of raw materials – minerals, proteins, sugars – and without any of the industrial machinery we have at our disposal, they have produced structures that can rival anything we have engineered.

It is a feat we would dearly like to imitate. The trick lies in the way these constituent parts are arranged on the nanoscale, formations that have until recently been impossible to replicate. But as our manufacturing techniques and palette of raw materials improve, some materials scientists have started looking to outdo the natural world. They're using nature's tricks to re-engineer the materials that form the backbone of our world – metals.

A metal's defining qualities – strength and toughness – may seem like different ways of expressing the same thing, but to a materials scientist they are like chalk and cheese. It is an apt comparison. Chalk is stronger than cheese, able to resist loads without bending, but it is not tough – it is brittle, snapping easily. Cheese may be weaker, but its ability to deform before breaking makes it tough.

Metals are generally stronger and tougher than either chalk or cheese. But they are cursed with a weakness: any attempt to increase a metal's natural strength destroys its toughness. We'd love to change that, but it hasn't stopped us using them for thousands of years. "The world is still made of steel," says Robert Ritchie at the University of California, Berkeley, but stronger is always better. "If you have high strength, you don't have to use so much material," says Ritchie. That means your plane, drone or car can weigh less, saving money as well as fuel and cutting the carbon dioxide emissions that are warming the planet. New improved metals could also help make lighter hip replacements, bionic hands, robots, pipelines, reinforcing bars for concrete and coatings to protect spacecraft from impacts.

Over the past 20 years or so, as our control over the nanoscale has improved, we have sought to boost the strength of metals by making their constituent granular crystals smaller. These nanograined metals are super-strong, but so brittle we can't use them in structures. "If you made the Golden Gate Bridge out of a high-strength material, you wouldn't need to use such thick girders, but one day it could just snap and break," says Ritchie. Nature has managed to sidestep this problem.

Taking inspiration from a mussel's byssus threads could lead to metals stronger and tougher than copper
es-cuisine/PhotoAlto/Alamy; Erik Isakson/Getty

Biological materials are generally made up of a mixture of a hard biomineral like calcium carbonate or silica and a soft biopolymer, such as a protein chain or a sugar. The hard part provides the strength and the soft part the toughness; together they are often more than the sum of their parts.

Take a mantis shrimp club. Beneath a thin, hard coating of calcium phosphate like that in our bones, it consists of layers of softer, fibre-like sugar molecules embedded in yet more calcium phosphate. This composite structure already makes for a better combination of strength and toughness than either material could achieve alone. But what really gives the clubs the ability to withstand repeated pummelling is the way those layers change as you go deeper beneath the surface. The further inside the club you go, the less crystalline the calcium phosphate becomes. The layers of aligned sugar molecules also become thinner, and each is rotated relative to the layers above and below, forcing any would-be crack to follow a complicated path.

This gradient is nature's secret sauce, and it is in almost every dish. "It's probably more difficult to think of structures in the natural world that do not have gradients," says Ulrike Wegst of Dartmouth College in New Hampshire.

> **“A mantis shrimp’s punch accelerates faster than a Formula 1 car”**

Gradients come in a variety of flavours. The remarkable flexibility of bamboo stalks, for example, arises from a distribution gradient, with more cellulose found on the outside of the stems to ensure they don’t break. The bony plates that protect alligators have a gradient in their structural arrangement, with four different types of bone, varying in the way their collagen fibres align, creating a hard upper surface, a porous core and a softer base. Fish scales, which are also made of collagen, have a gradient in composition. They are more mineralised at the surface, where hardness is needed to defend against the teeth of bigger fish, and less so beneath, providing toughness. Even our own teeth have a gradient between two different materials, dentin and enamel, creating a smooth interface rather than a sudden change that concentrates stress and may initiate breakage.

“Nature has to play these games because it’s not dealing with particularly good materials – collagen and chitin and minerals,” says Ritchie. “We would never use them as structural materials, but nature has the ability to craft them into these ingenious structures.”

Testing our metal

It has taken a while, but we’re just starting to master the same ability. Back in 2011, Ke Lu at the Shenyang National Laboratory for Materials Science in China and his colleagues made a gradient structure in copper, one with nanoscale-sized grains at the surface that gradually increased in size into the bulk of the material. They did this by repeatedly grinding the surface, keeping the inner structure untouched but causing the outer layer to subdivide into smaller grains. This outer skin, which Lu compares to the layer of enamel coating our teeth, provided a gradient that made the copper twice as strong without reducing its toughness. This was a breakthrough, says Ramathasan Thevamaran at the University of Wisconsin-Madison. "It showed a pathway to improve both strength and toughness in metals that are often found to be mutually exclusive."

Ritchie has taken the concept of gradient nanograins a step further. He was inspired by byssus, the material in the threads produced by mussels to help them cling to rocky surfaces. Byssus is strong and tough. It also has a huge gradient – while the rock-facing end is strong and stiff, the mussel end is stretchier and 10 times less stiff. To create this dramatic difference, the form of collagen making up the threads changes along their length.

But there is a snag. To replicate the remarkable properties of byssus, Ritchie needed something more complicated than copper. That is because the outer coating of the fibres consists of a hard layer that contains even harder granules – a structure impossible to reproduce in a pure metal.

Instead, Ritchie focused on steel, an alloy of iron, carbon and other elements. As Lu had done before, he battered the surface of the metal, this time with hundreds of small steel balls. As well as creating a gradient in grain size, this also made some pockets of steel shift their structure into a hard phase known as martensite. The result was alternating stripes of hard martensite and a softer phase, austenite, inside each grain: a gradient in grain size paired with a two-phase structure.

This combination gives the steel a higher strength than other steels while stopping it from becoming brittle. "The hard and soft phases help you with the strength and ductility and the gradient gives you a harder, stronger outer surface and a tougher underbelly," says Ritchie. That being said, he adds, "it's still very primitive compared to nature".

It's a start, but it only scratches the surface – quite literally. For Thevamaran, the key to making the perfect metal lies in reaching deep into the material. In 2016, he fired microcubes of silver at a rigid silicon surface faster than the speed of sound. The microcubes hit the silicon so hard that they deformed, causing the changes in grain size he was looking to create. "With a shock process, you'll propagate through the material," says Thevamaran. "You're likely to get a continuous gradient. That could be one advantage."

"Nature can craft poor materials into ingenious structures"

For all of these laboratory successes, scaling up such processes is a challenge. "One of the problems with emulating nature is nature does it from the bottom up; it takes the atoms or the molecules and it builds up from there," says Ritchie. "We go the other way – we take a big chunk of metal and try to generate it down."

The solution might be the emerging technology of 3D printing, which allows you to build up a material layer by layer. This makes small-scale construction possible, says Ritchie, although making larger products is more challenging. "The problem with 3D printing, despite all the hype you hear, is at present it's good for making the right shape but it's very difficult to make the right properties," he says. Ritchie thinks it needs another decade or so to improve.

That said, gradient nanograined steels could start to be seen in structures in just five years, says Ritchie. And other super-metals could perhaps be available even sooner for Formula 1 cars or biomedical uses.

Even then, nature will still be able to do things we can't. The peacock mantis shrimp moults and grows a new shell every three or four months, removing all the damage done to its club from tens of thousands of impacts. That ability packs quite a punch.

This article appeared in print under the headline "Natural born metals"

Liz Kalaugher is a science writer based in Bristol, UK, and co-author of *Furry Logic: The physics of animal life*

Magazine issue 3197, published 29 September 2018