Developing multifunctional composite materials for aerospace applications

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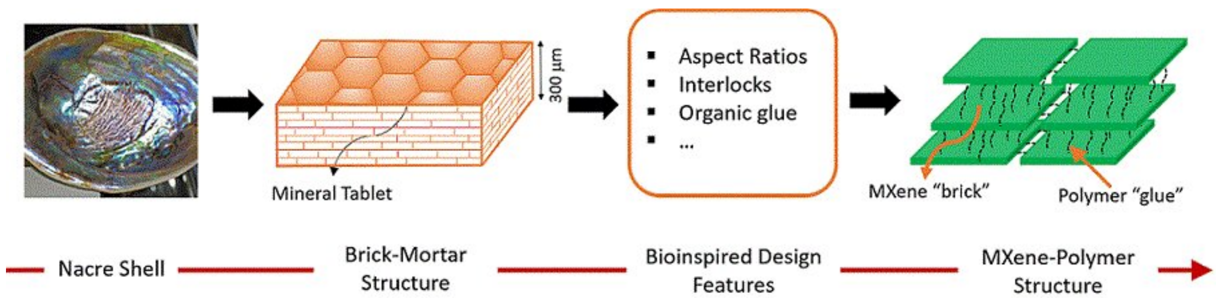

An oyster shell's inside is lined with nacre or mother-of-pearl, which can provide an inspiration for the design of MXene-based composites. Credit: South Dakota State University

Materials for aerospace applications face many challenges. The structure of an aircraft must be light yet strong. Structural components such as the wings or fuselage must resist damage while at the same time in some areas be able to handle high temperatures from engine exhaust. An aircraft's electronic components must also be shielded from electrical surges due to lightning strikes or other interference.

Developing new materials that meet these multiple demands is what assistant professor Anamika Prasad of South Dakota State University's Department of Mechanical Engineering has been working on in collaboration with the materials research group at Wright-Patterson Air

Force Base.

Prasad received an eight-week U.S. Air Force Research Laboratory fellowship last summer to work with the materials and manufacturing directorate and is continuing her research on MXene-based composites through a second fellowship this summer. The fellowship program, sponsored by the Air Force Office of Scientific Research, builds relationships with full-time science, mathematics and engineering faculty at U.S. colleges and universities by giving them an opportunity to perform research at an Air Force Research Lab.

"It was an amazing collaborative experience working alongside AFRL scientists and summer fellows (faculty and students)," said Prasad, whose research at SDSU focuses on using plant-inspired structures to design and manufacture composite materials.

Faculty normally perform research on-site, but the COVID-19 pandemic led to Prasad working remotely and shifted the focus to computational analysis of MXenes, a new class of two-dimensional engineering materials. A paper that describes the results of their summer 2020 research is under review by the MRS Bulletin Impact.

AFRL research materials engineer Dhriti Nepal said, "It is a great pleasure working with professor Prasad. Her insights on bioinspired structures for mechanics and multiscale modeling has been exceptionally valuable for designing next-generation composites."

Focusing on multifunctionality

Engineering materials typically fall into individual buckets, Prasad said. "If we want materials that are tough, we choose a metal; if we want a material designed for flexibility and low density, we choose a polymer or plastics; if we want high strength and heat resistance, we choose a ceramic." However, for aerospace applications, the emphasis is on multifunctional materials.

"Multifunctionality is built into natural systems," Prasad said. Fast-growing plants must be flexible yet maintain optimum strength and provide a resilient path for water and thermal management as the structure grows. Shells and exoskeletons are examples of materials with a good balance of toughness and strength while maintaining properties, such as surface smoothness for defense against parasites.

MXene—pronounced like the name Maxine, discovered in 2011 at Drexel University, has unique property combinations. It can be made into highly conductive and strong thin films in layers of only a few atoms, similar to graphene. "This new two-dimensional material has very high strength in a plane when you pull it and is very conductive and heat resistant," Prasad said.

Unlike the single-atom (carbon) of graphene, MXene's 2D layer structure can have a wide range of compositions, where M stands for early transition metal, such as titanium or chromium, and X stands for carbon and/or nitrogen. "Because the compounds are not just a single element, we can play around with them, functionalizing the surface layers for different applications," Prasad said. Other researchers estimate more than a million MXene alloy compounds are yet to be discovered.

However, pure MXene films have a thin, flaky structure that makes it difficult to create a composite combination that retains the unique properties while providing structural durability. "If you add polymer to MXenes to form a composite, it provides structural stability, but the composites may lose their main functionality of conductivity. To make them useful, we must find pathways of composite design that do not alter their unique properties," Prasad said.

AFRL research chemist Vikas Varshney said, "Combining multifunctionality with structural viability in such composites is crucial for a number of Air Force structural applications. Working with Dr. Prasad, we plan to model and explore as much of a phase space as possible towards understanding the role of different composite parameters in governing their structural properties, eventually guiding experimentalists towards developing structurally sound multifunctional composite materials."

Analyzing MXene structures

Prasad compared the structure of the thin, flaky individual tablets of MXene-polymer composites to the layered bricks and the mortar structure present in some natural systems as a means of gaining inspiration for the composite design.

"Many shells, for example, internally have a brick-mortar structure in which brick or tiles are polygons and are rigid. All the tiles are dispersed within a polymeric mortar, which binds the tiles and allows them to give or flex," she said.

The tiles themselves have a wavy, rough structure, Prasad continued. This unevenness makes the tiles interlock. "When a crack occurs, it travels the zigzag path through the mortar-like polymer, which provides sacrificial joints that break to give it (the piece) further strength and fracture toughness."

Last summer, she and her AFRL teams analyzed natural composites to understand how their unique design features could be applied to MXenes. This summer, she continued tasks to develop simulations to model MXene-based composites and surface interactions.

"We want to predict their macroscale response from what's happening at an atomic level of material design," Prasad. Beginning this fall, senior mechanical engineering major Jordan VonSeggern of Elk Point, South Dakota, will join her research group to continue developing the model through an AFRL-supported internship.

Through her collaboration with AFRL researchers, Prasad has "found a group of people who are really supportive and have helped me explore new ideas." She plans to continue to apply what she has learned about MXene-based composites to her research at SDSU.

"I can create MXene-based composite materials and functionalize the layers to provide the capability to sense the growth of plants or to see what is flowing inside the xylem tissues," she said. Tough, flexible films made using MXenes can be used to create biomedical sensors that measure electrical conductivity as different nutrients flow through plant tissues.

This spring, Prasad received an SDSU Research, Scholarship and Creative Activities Challenge Fund grant to begin developing simulation tools to predict the properties of MXene-based composites and bring machine learning capabilities in her materials research. SDSU's RSCA Challenge Fund helps faculty generate preliminary data to increase their ability to compete for external funding.

Provided by South Dakota State University