Carmichael's Concise Review

Microscopic Architecture Protects Against Piranhas

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One of the largest freshwater fish (2 to 2.5 meters long, over 150 kg) lives in the Amazonian rivers and lakes. It is well known that these waters are populated with piranhas that swarm and devour almost anything that moves. The lungfish *Arapaima gigas* coexists with piranhas by virtue of an armor-like plating of scales. Y.S. Lin, C.T. Wei, E.A. Olevsky, and Marc Meyers examined the microscopic structure and mechanical properties of these scales to discover what provided this protection [1].

Light microscopy reveals an irregular pattern of veins within the scale and a circular pattern of ridges on the surface. Interestingly, *Arapaima* scales are commonly used as nail files by people in the Amazon basin because of these ridges. Two main sections of the scale could be observed by light microscopy: an embedded part (overlapped by an adjacent scale) with a thickness of about 1 mm and an exposed section about 2 mm thick. The scale has a laminate structure composed of an external layer (that is highly mineralized) with ridges and internal layers. The main building block of the scale is collagen Type I fibers forming a plywood structure (known to engineers as Bouligand stacking). Collagen fibrils, with a diameter of about 100 nm, form collagen fibers with a diameter of about 1 micron. The collagen fibers, in turn, assemble into lamellae with a thickness of about 50 microns. Light microscopy of cross sections of a scale reveals external and internal layers. The corrugated surface of the external layer corresponds to the ridge structure of the surface, whereas the internal layers are characterized by lamellae.

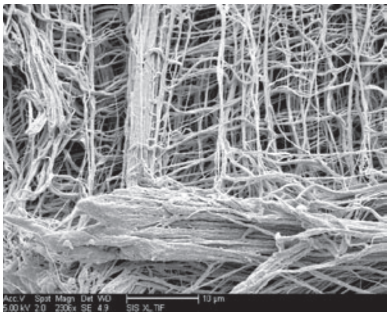

Figure 1: Scanning electron micrograph of the fracture surface of collagen fibers showing the change in orientation of collagen fibrils in adjacent lamellae.

Examination of fractured surfaces with a field emission scanning electron microscope clearly showed the different collagen fibril orientations in adjacent lamellae (Figure 1). The angle of fibril orientation in adjacent lamellae appeared to be close to 90°, thus forming a plywood structure. However, orientations closer to 60° could not be ruled out. This would impart a "twisted" plywood structure.

Energy-dispersive X-ray spectroscopy was used for analysis on cross sections of scales to verify the elemental content and differentiate between the external and internal layers. One finding was that the calcium content of the external layer was about twice that of the internal layer. The surface was also rich in phosphorus, which together with the higher calcium accounts for the hardness.

Many other tests of mechanical properties (tensile strength, indentation tests, etc.) were performed. It was determined that the tough but springy internal layer of collagen covered by a rock-hard layer of collagen fibers cemented with calcium and phosphorus created a double-layered hard-on-soft pattern that prevents cracks from growing. The scales were so tough that piranha teeth can actually shatter when colliding with these scales! In addition to protecting *Arapaima* in its hostile environment, mimicking this microarchitecture has applications in designing protective structures, such as body armor.

References

[1] YS Lin, CT Wei, EA Olevsky, and MA Meyers, *J Mech Behav Biomed Mater* 4 (2011) 1145–56.

[2] The author gratefully acknowledges Dr. Marc Meyers for reviewing this article.

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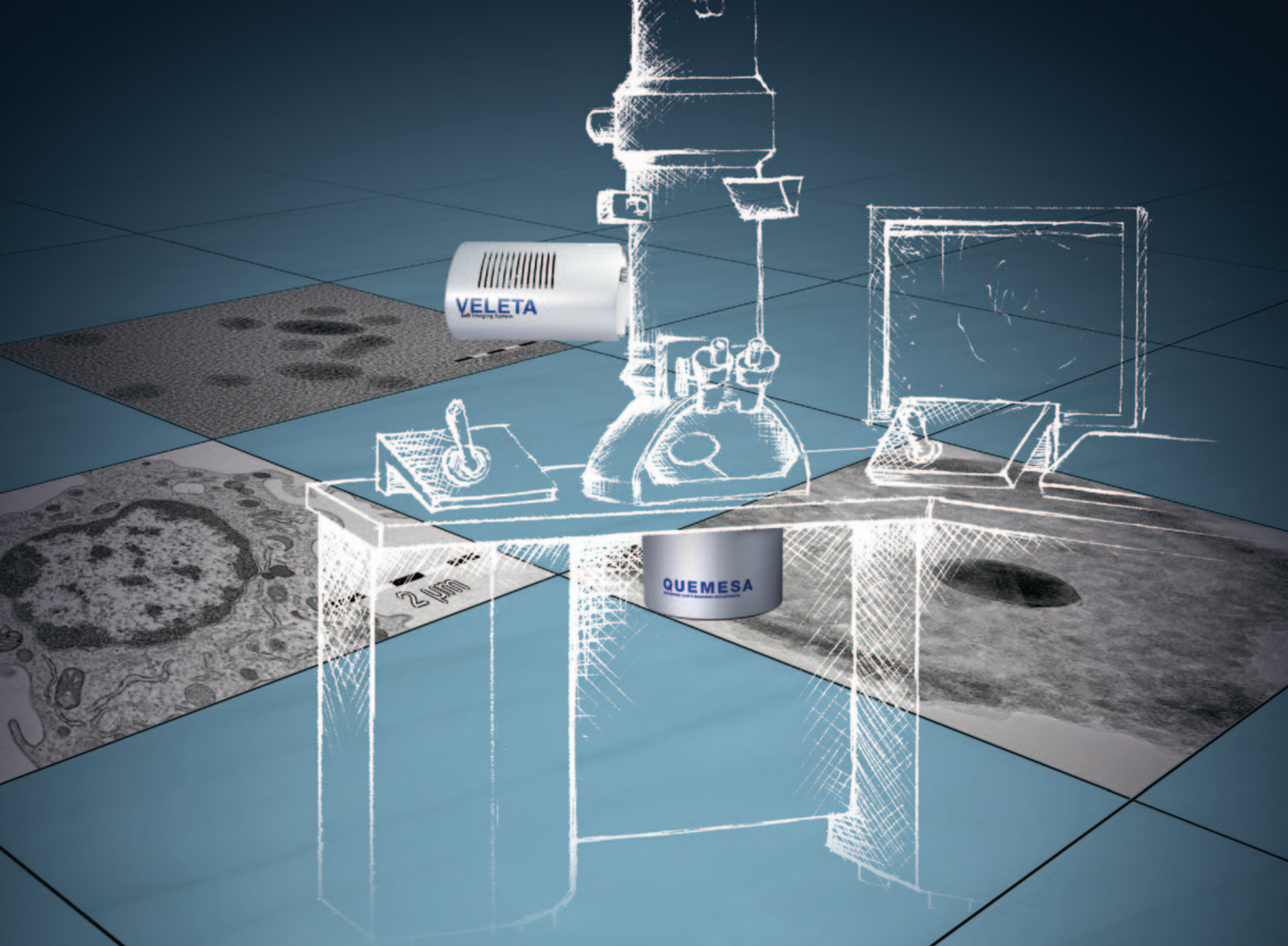

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