EDITORIAL

Fatigue-resistant deformable biomineral hard tissues

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As we know from brick walls and the construction of houses: the constituents and architecture of materials play a crucial role in determining their final performance. In early societies, people used raw materials such as stones and sticks to fabricate tools, and every part brought its specific advantages to the tool. However, with the rapid development of technology and the introduction of new types of raw materials in modern society, the

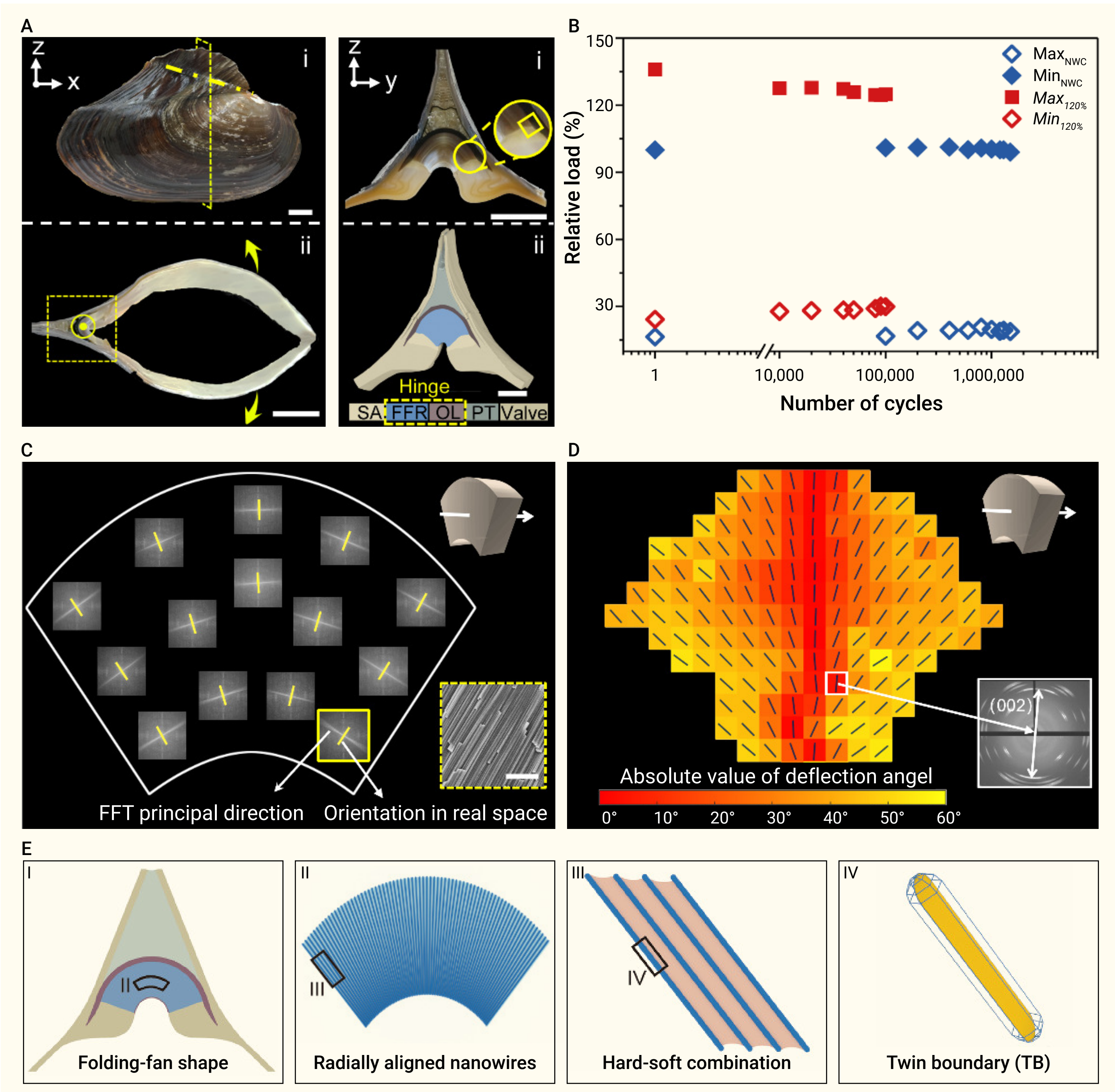

Figure 1. Multi-scale structural characteristics and fatigue-resistant performance of the FFR in the hinge.[5] (A) Photos of the bivalve, *Cristaria plicata* and the hinge sections. (B) Anti-fatigue performance of the hinge at natural working condition (NWC) and overloading condition. Microstructural (C) and crystallographic (D) characteristics in the whole FFR. (E) Anti-fatigue design of the FFR. Copyright 2023, AAAS.

architecture and materials interfaces become hard to see, but the relative importance of the interface just increased. We have to be honest: there is a source of inspiration! Scientists turned their attention to nature, which has evolved over millions of years, to explore the secrets of biomaterials with exceptional properties.[1] Such materials include nacre, bone, tooth enamel, spider silk and wood.

Analysis of these biomaterials reveals that they all have sophisticated multi-level structures, often combining the opposite, a yin and yang on molecular scale. For example, nacre, which is both strong and tough, shows a typical brick-and-mortar structure consisting of brittle and hard aragonite plates and a protein glue in between, stacked regularly.[2] At the nanoscale, the organic inclusions in the aragonite plates enhance the tensile fracture resistance of the plate. The protein matrix between the plates can deform plastically before the plates start sliding. At the same time, both mineral bridge connections between aragonite plates and nano asperities on the plates provide load transfer between the layers. All the nanostructures significantly dissipate the energy of mechanical load and diminish crack extension. This multi-level structure from nano to macroscopic of the nacre endows nacres with superior mechanical properties, or in simple words although made of a waste materials or side product, chalk, it is very hard to crack a seashell in the fight for food. The design strategy has inspired to design artificial materials by mimicking the structure of the nacre to improve the damage tolerance capacity of the native brittle materials.

Brittle materials are widely used as structural or functional components in fields such as aerospace, electronics and tissue engineering. Artificial brittle materials are sensitive to microcracks and imperceptible defects, so that the materials are prone to accumulate damage to produce fatigue cracks and consequent failure under prolonged cyclic loading.[3] With the development of foldable and wearable devices, there is an increasing demand for deformable functional materials with low fatigue. The fatigue resistance of brittle materials could now be enhanced by mimicking the structures of nacre and bone.[4] However, there the anti-fatigue performance relies on the toughening behavior during fatigue crack propagation, which means that the materials start to work when the crack starts to expand, but this might have irreversible effects on the functional performance of the device, say electric conductivity. Thus, finding and developing new fatigue-resistant structural models from biomaterials is essential for the future design and fabrication of deformable functional materials.

Recently, Yu and his research team have found and explored a previously ignored design model for fatigue resistance in the folding fan-shaped deformable hard tissue (FFR) of the hinge in the bivalve, *Cristaria plicata* .[5] They investigated the multiscale mechanical behaviors and multilevel structures of the FFR through quantified modeling and multiscale mechanics analysis by using advanced characterization techniques (Figure 1). Finally, a new biomimetic design strategy could be presented for enhancing material fatigue resistance by integrating the multiscale structural characteristics with the intrinsic properties of the components.

Unraveling the correlation between structures and performances of biomaterials at different scales is challenging. In addition to observing the properties exhibited by the materials, numerical simulations have been applied to the material characterization work. The obtained results are used to establish structure-performance relationships at different scales. This however requires a deep understanding of the nature of the material to bridge the differences between models at different scales.

In the study of the FFR in the bivalve hinge, Yu et al. analyzed the stress distribution state of each region of the hinge from a macroscopic perspective, and then clarify the mechanical roles played by different regions. With an in-depth structural dissection, further abstraction of representative volume units was performed to understand the contribution of the microstructure and crystallographic orientation of radially oriented aragonite nanowires in the tissue to the mechanical properties. At the same time, comparative models on the nanoscale were established to reveal the contributions of the soft and hard structures in the tissue. As a result, a full-scale understanding of the structure-performance relationships embedded in the FFR was established through this stepwise in-depth observations and simulation interplay.

Compared with typical hard biomineral materials (e.g., bone, tooth enamel), the FFR within the hinge integrates multiple mechanical properties including high stiffness, deformability, and fatigue resistance. Yu et al. thereby shed light on an often-overlooked interrelation in the design process of bioinspired materials. When researchers focus excessively on the structure design of materials, they may neglect the utilization of the properties of the material elements themselves in the assembly process, but these are crucial for the final performance of the materials, often in a highly indirect and thereby unpredictable way.

The present unraveled multi-scale design principle combines deformability and fatigue resistance already in the intact, non-cracked material and is expected to be useful for the future design and fabrication of functional materials from brittle components. I seriously hope to see soon a foldable mobile phone where not only the material design is delicate, but the screen is persistent.

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DECLARATION OF INTERESTS

The author declares no competing interests.