DOI: 10.1017/S1431927606062210
Microsc Microanal 12(Supp 2), 2006

Screw Dislocations and Spiral Growth in Abalone Shell Nacre [1]

Alexander Epstein*, Austin Akey*, and Nan Yao*

*Princeton University, Princeton Institute for the Science and Technology of Materials, 70 Prospect Avenue, Princeton, NJ 08540

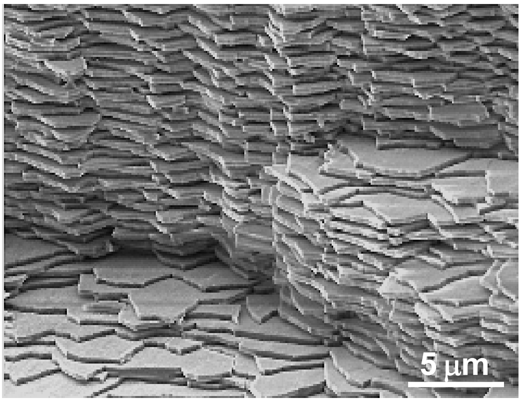
Nacre (mother of pearl), the internal iridescent layer of mollusk shells, is a natural ceramic composite comprised of 95% calcium carbonate in the aragonite polymorph with 5% or less organic macromolecules sandwiched in between. Yet its work of fracture is about 3000 times greater than monolithic ceramics, and its capability for substantial inelastic strain, in contrast to most ceramics, renders it notch insensitive and can eliminate stress concentrations and catastrophic failure [2]. These extraordinary physical properties have attracted much interest from many disciplines.

Mature nacre consists of pseudo-hexagonal aragonite platelets of 5-8 μm diameter and 0.5 μm height that generally are stacked vertically and form horizontal sheets of lamellae, as shown in Fig. 1. A range of often conflicting theories, including the heteroepitaxial growth and mineral bridge models, have attempted to explain nacre's strength and highly ordered nature with limited success [3].

In this paper we present a previously unreported structural feature of nacre: micrometer-scale screw dislocations in the aragonite layers and resultant spiral growth. Compared to typical ionic or covalent crystals (dislocation density 10^3 cm^{-2}), nacre contains 1 x 10^6 screw dislocations per cm^2 [4]. The fact that these screw dislocations—larger scale analogues of atomic lattice defects—are so ubiquitous indicates they are structurally significant. Using scanning electron microscopy (SEM), focused ion beam (FIB), and transmission electron microscopy (TEM), the spiral arrangement of the platelets was studied in plan and cross-section views, as shown in Fig. 2. The SEM/FIB was also used with a nano-manipulator in situ to remove individual platelets and to explore the structure of the screw dislocation cores, at which the surrounding spiral growth domains originate. Tessellated cores at the centers of these domains were observed both in cross-section and also at multiple depths in excavated plan views following nano-manipulation. A geometric model of the core platelets was derived from these observations. In addition to the proposal that these screw dislocations are a fundamental strengthening mechanism of nacre, this work suggests that the lamellar layers of aragonite propagate *via* a large number of continuous spiral growth domains, not through planar growth as previously thought. This new model, by explaining in concert with earlier theories the mechanical strength of abalone nacre, may provide a basis for creating new comparable ceramic composites through synthetic or biomineralization means.

References

[1] We acknowledge partial support of this work from the National Science Foundation (MRSEC-REU program) and the New Jersey Center for Science and Technology (NJCST).
[2] A. P. Jackson, J. F. V. Vincent, and R. M. Turner, *Proc. R. Soc. London, Ser. B* **1988**, *234*, 415.
[3] S. Blank, et al, *J. Microscopy* **2003**, *212*, 280.
[4] O. H. Wyatt and D. Dew-Hughes in *Metals, Ceramics, and Polymers*, Cambridge University Press, Cambridge, United Kingdom, **1974**, 347.



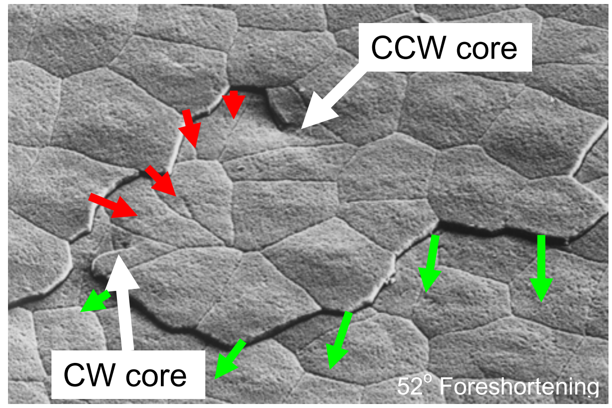
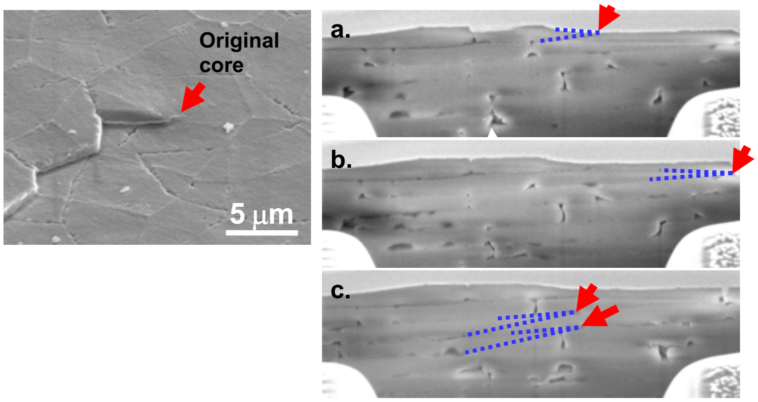


Fig. 1. Left: the tessellated column structure of abalone shell nacre is comprised of stacked aragonite platelets about 8 μm wide and 0.5 μm tall separated by an organic matrix. Right: Screw dislocations and spiral growth in nacre. The top core and corresponding spiral growth domain are oriented CCW; the bottom core and corresponding domain are CW.



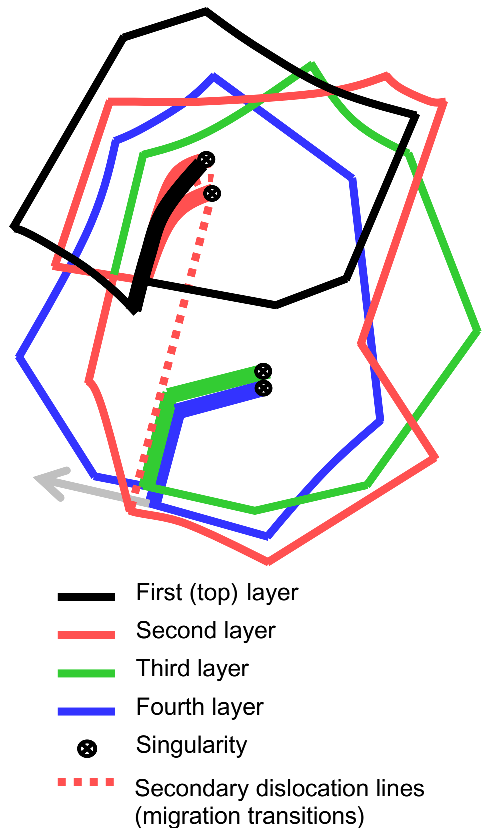


Fig. 2. Left: FIB was used to mill slices through about six layers of a core (above left) with thickness intervals from 0.1 to 0.3 μm. In these subsequent SEM images, the arrows and dashed lines indicate four different core singularities discovered through close inspection. Note that the singularity migrates right between (a) and (b), and then migrates left of the original for two layers in (c). Since the core does not display a visible column, it is not immediately recognizable, and was likely dismissed as a one-layer defect in prior studies. The depths of the three cross-sections are in increasing order from (a) to (c). Right: A composite diagram of screw dislocation core platelets examined in a four-layer nanoprobe excavation. The core is tessellated and exhibits a migrating singularity that can move up to the width of a platelet from layer to layer. Secondary dislocation lines and irregular plate geometry facilitate the singularity migrations. As seen in the diagram, the sizes and boundaries of successive platelets are thus rarely identical.

https://doi.org/10.1017/S1431927606062210 Published online by Cambridge University Press