Experimental Mechanics (2019) 59:277–278
https://doi.org/10.1007/s11340-019-00497-0

Recent Advances in Micro, Nano, and Cell Mechanics

Y. Zhu [1] · T. Saif [2] · F.W. DelRio [3]

Published online: 9 March 2019

The field of micro- and nano-mechanics for both solid-state and biological materials continues to attract tremendous interest. At these length scales, innovative experimental methods are continually being developed, including in-situ electron microscopy, super-resolution florescence microscopy, scanning probe microscopy and spectroscopy, and traction force microscopy. Novel micro- and nano-materials are also emerging, from thin films to nanowires, nanotubes, and two-dimensional (2D) materials to micro- and nano-lattice structures to active soft materials, all of which can exhibit size effects in elastic and inelastic properties as well as size-dependent deformation and fracture mechanisms. Conversely, fundamental studies at the micro- and nano-scale can be critical to the design of large-scale materials. The overall goal of this special issue in Experimental Mechanics is to highlight some recent advances in this exciting field of research.

In this special issue, we present fourteen papers, which include one review paper and thirteen research papers. It starts with the review paper by Liechti that summarizes recent progress in characterizing the interfacial mechanical behavior of 2D materials. 2D materials, crystalline materials consisting of a single or few layer(s) of atoms, have received significant attention recently. Interfacial mechanics (adhesion and friction) is essential for integrated device applications of 2D materials. Future research needs and opportunities on interfacial mechanics of 2D materials are discussed. The issue then moves to the thirteen research papers, which are grouped into three categories – micromechanics, nanomechanics, and cell mechanics.

The section on micromechanics includes several papers on the mechanical behavior of materials at the microscale. Digital image correlation (DIC) is a powerful technique to provide full-field displacement and strain maps, which has been extended recently to the microscale. In *A high resolution digital image correlation study under multiaxial loading*, Polatidis et al. apply DIC to high-resolution images from electron backscatter diffraction in a scanning electron microscope (SEM). The quantitative strain maps provide valuable insights into slip systems under equibiaxial and uniaxial loading. In another article using in-situ SEM testing, *In situ micromechanical characterization of metallic glass microwires under torsional loading*, Fan et al. report the torsional behavior of Fe-Co-based metallic glass microwires. Both spiral stripes and shear bands are found to contribute to the fracture mechanisms. X-ray computed tomography (CT) has also been used to obtain high-resolution three-dimensional descriptions of samples. In *A multi-loading, climate-controlled, stationary ROI device for in-situ X-ray CT hygro-thermo-mechanical testing*, Vonk et al. develop an in-situ CT device to enable advanced hygro-thermal-mechanical tests on specimens subjected to multiple loading modes while controlling and measuring force, displacement, temperature, and relative humidity in real time. The potential for the new CT device is demonstrated by investigating the creasing, folding, and relaxation processes of cardboard within a climate-controlled environment. X-ray methods have also shown utility for assessing residual stresses in multilayer thin films. In *Residual stresses in Cu/Ni multilayer thin films measured using the sin2ψ method*, McDonald et al. use X-ray diffraction and the sin2ψ method to investigate residual stresses in magnetron-sputtered Cu/Ni multilayer thin films. The findings not only show that residual stress in metal multilayers is strongly dependent on film thickness, but more generally, demonstrate the efficacy of the method when peak broadening and overlapping issues are addressed. Finally, it is important to quantitatively understand the relationship between the population of critical flaws and the distribution of strength in a component. In *Material flaw populations and component strength distributions in the context of the Weibull function*, Cook and DelRio derive a model linking the parameters describing the flaw population and those describing the strength distribution of components. The model is applied to three sets of micro- and nano-scale silicon

✉ Y. Zhu
yzhu7@ncsu.edu

[1] North Carolina State University, Raleigh, NC, USA

[2] University of Illinois at Urbana-Champaign, Champaign, IL, USA

[3] National Institute of Standards and Technology, Boulder, CO, USA

components and validated using atomic force microscopy (AFM) topographic data.

The section on nanomechanics includes several papers on the mechanical behavior of materials at the nanoscale. In the last two decades, a variety of new nanoscale mechanical testing techniques have been developed, including AFM-based techniques, instrumented indentation, and cavity interferometry. In *The effect of edge compliance on the contact between a spherical indenter and a high-aspect-ratio rectangular fin*, Stan et al. present an interesting analysis on the adhesive contact between a rigid spherical indenter and a high-aspect ratio fin. The analysis is applied to a nanomechanical measurement using intermittent contact resonance AFM on low-k dielectric fins. AFM has also shown the ability to go beyond material characterization and to be equally as useful for the manipulation of 2D materials. In *Nanomechanical unfolding of self-folded graphene on flat substrate*, Yi et al. demonstrate nanomechanical unfolding of self-folded graphene sheets on flat substrates using AFM-based techniques. The AFM measurements and molecular dynamics simulations highlight the unfolding processes that take place in going from a z-shaped self-folded graphene sheet to a flat sheet, with an emphasis on the reversible sliding phenomenon in the adhered region and the effects of number of layers and stacking interactions. Instrumented indentation, or nanoindentation, has become a standard technique for quasi-static and dynamic mechanical testing in dry and wet environments. In *Nanoindentation of fused quartz at loads near the cracking threshold*, Mound and Pharr explore crack formation and development in brittle materials during sharp indentation contact. Together with SEM images, the results show that there is a distinct threshold load below which no cracking is observed, and that this threshold value increases with indenter angle. Moreover, the first cracks to form emanate outward from the corners of the indentation and terminate at what appears to be the elastic-plastic boundary. In In-situ *nanoindentation measurement of local mechanical behavior of a Li-ion battery*, Vasconcelos et al. use nanoindentation to measure the in-situ mechanical behavior of individual phases in a Li-ion battery cathode. The modulus, hardness, and fracture strength of agglomerated particles and sintered pellets are measured in dry and wet states, which resulted in a mechanistic understanding of the complex behavior in Li-ion batteries. Finally, in *An experimental setup for combined in-vacuo Raman spectroscopy and cavity-interferometry measurements on TMDC nano-resonators*, Nathamgari et al. demonstrate an experimental setup that facilitates both Raman spectroscopy and interferometric measurements on few-layered WS_2 resonators. The combination of the two techniques in-vacuo prevents sample degradation, enables thickness measurements, and allows for high-responsivity cavity interferometers.

The section on cell mechanics highlights the increasing attention that the area is receiving from the experimental mechanics community. It is now well recognized that living cells not only respond to biochemical stimuli, but also to their mechanical microenvironment, as well as, intra- and extracellular forces and deformations. Cells transduce these mechanical cues to functions that determine their fates, including differentiation and disease state. In *Phase dependent mechanosensitivity in cardiomyocytes*, Williams and Saif present new methods to study contraction of cardiomyocytes in response to stretching of the substrate on which they are seeded. The results show that spontaneously contractile cardiomyocytes can synchronize within 1 min to a cyclic mechanical perturbation of limited frequency difference with stable phase differential. In *Faster sickling kinetics and sickle cell shape evolution during repeated deoxygenation and oxygenation cycles*, Du and Dao present a method where red blood cells (RBCs) from sickle cell disease patients are subjected to cycles of oxygenation (normoxia) and deoxygenetaion (hypoxia). During deoxygenation, sickled hemoglobin undergoes polymerization and corresponding RBC stiffening, a key signature of sickled-cell disease. The results reveal that the disease progresses faster with the prior history of hypoxia-normoxia cycles. In *Probing endothelial cell mechanics through Connexin43 disruption*, Islam and Steward assess the effect of cell-cell junctions on cell forces by disrupting the junctional proteins, Connexin 43 (CX43). The endothelial cells used for the study form the linings of blood vessels. The study offers insights on the role of CX43 on cell mechanics, endothelial permeability, and barrier strength. Such experimental methods are increasingly being developed for fundamental mechanistic studies, disease diagnostics, and prognostics.

"There is plenty of room at the bottom", which is especially valid in small-scale mechanics. This collection of one review paper and thirteen research papers highlights just a small sampling of recent advances in the broad and active fields of micro, nano, and cell mechanics. This special issue was made possible by the invitation and support of the Experimental Mechanics Editor-in-Chief, Professor Ioannis Chasiotis, and by the technical assistance of the editorial team. Last but not least, the guest editors would like to thank all the authors and reviewers for their excellent work.