Nano-mechanics: From Material Fabrication to In-Operando Characterization

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The mechanical properties of nanostructured materials can significantly deviate from their conventional bulk counterparts due to the contribution of surface effects, grains and the effect of nanoscale architecture. To understand those aspects of nanoscale materials a broad spectrum of characterization methods is required. The workshop dedicated to this topic took place at Brookhaven National Laboratory on May 17, 2017. It brought together scientists with expertise in nanomechanics, material fabrication and structural probing. Such significant interest in mechanical properties of nanoscale materials is due to their enhanced and highly tailored performance. For example, the specifically designed nanomaterials can be strong yet light, be hard but not brittle, and respond to stress and temperature in a prescribed way.

Designing and creating these 3D materials to satisfy various criteria is challenging. Conventional fabrication methods are not well positioned for fabricating of 3D structures with the desired mechanical response. On the other hand, chemical synthesis and self-assembly methods offer only limited control over material architecture, which is critical to achieve desired mechanical properties. Thus, as realized by the scientific community, new approaches are needed for fabrication of material with prescribed mechanical responses. A number of talks focused on methods to regulate mechanical characteristics of soft materials. Bryan D. Vogt (University of Akron) discussed various hydrogel systems, which have a double network architecture allowing for the enhancement of energy dissipation and results in a formation of tougher polymers. Lawrence F. Drummy (Air Force Research Laboratories) demonstrated that assemblies of polymer-grafted “hairy” nanoparticles represent an interesting class of materials where polymer entanglement can affect materiamechanical properties. The hierarchical nature of mineral-organic hybrids that can operate on two length scales to strengthen the system was discussed by Elaine DiMasi (Brookhaven National Laboratory). Recent advances in additive manufacturing inspired by biological systems have permitted a highly tailored material fabrication, as described by James C. Weaver (Harvard University). For example, he presented a range of approaches to build materials mimicking biological systems, including laminated composites, photonic architectures, and low drag surface coatings. New aspects of hard nanomaterials were discussed by Seok-Woo Lee (University of Connecticut). He showed that intermetallic compounds exhibit a reversible phase transition and that a unique reversible phase transformation process allows using them as a superelastic and shape memory material.

Such a broad range of systems---with spatial and temporal scales relevant to mechanic responses---impose significant challenges on unraveling the origin of material strength and elasticity, as discussed by Jeffrey Kysar (Columbia University). He stressed that the gap in experimental analysis of the mechanical behavior of materials across multiple length scales---from 10s of nanometers to 10s of micrometers---limits our ability to predict the mechanical response. Indeed, as discussed by many workshop participants, experimental characterization of nanoscale and nanostructured materials is challenging due to the need to measure nm-scale displacements and nN-scale forces. Nanoindentation and MEMS actuators provide the most versatile experimental platform for this purpose. Performing the experiments in-operando a scanning electron microscope provides the opportunity to observe failure mechanisms and to measure heterogeneous deformation fields. In this regard, many efforts to bridge the gap between modelling and material testing are being actively developed. The speakers stressed the use of new characterization methods that combine mechanical testing with direct in-situ structural probing. Warren Oliver (Nanomechanics Inc.) discussed new indentation techniques for high temperature, high strain rate and two dimensional testing. The presentation from Douglas Stauffer (Bruker Nano Surfaces) emphasized that fatigue behavior of material at extreme temperatures can be studied using in-situ by combining a high-rate mechanical testing and electron microcopy. The fast progress of in-situ micromechanical testing methods allows for establishing discovery platforms through combinatorial methods, as discussed by Jeffrey M. Wheeler (ETH Zurich). He showed that new geometries for measuring uniaxial strength and fracture toughness at very small length scales over a wide range of strain rates provide unique tools to reveal micromechanical properties over a broad range of temperatures and strain rates, thus, allowing for mapping of plastic deformation mechanism. In area of two-dimensional (2D) materials, Elisa Riedo **(**City University of New York) presented a new method to perform sub-Å-resolution indentations to measure the perpendicular-to-the-plane elasticity in promising 2D materials, such as graphene and MoS_2, are a few-atomic-layer thick films with strong in-plane bonds and weak interactions between the layers.

The coupling of mechanical testing and a structural characterization in-operando, during testing, is crucial for revealing the mechanisms governing mechanical response and failure mechanisms. The workshop speakers discussed that electron microscopy and x-ray methods can provide significant insight into structural response to stresses on different scales. X-ray methods offer unpreceded opportunities for 3D structural probing over a broad range of scales. Yu-chen Karen Chen-Wiegart (Stony Brook University and BNL) discussed X-ray tomography to probe nano-mechanical properties of materials under stress. Talks by Elane DiMassi (BNL) and Bryan D. Vogt (University of Akron) emphasized x-ray scattering as an effective tool to probe structure evolution over multiple scales in real time under the condition of mechanical stress. These talks triggered discussions about developing new capabilities for micromechanical testing at NSLS II that will allow correlating mechanical responses with chemical and structural 3D characterization provided by tomographic and scattering techniques. Also, a significant interest was expressed towards establishing micromechanical testing capabilities coupled with transmission and scanning electron microscopes at the Center for Functional Nanomaterials, with potential coupling of these capabilities with x-ray methods, where the characterization can be performed for the same sample at the microscale and nanoscale. The need for the establishment of comprehensive portfolio of 3D fabrication methods that will use additive manufacturing, 3D processing, and self-assembly was recognized by workshop participants, since such methods will enable new materials with exquisite mechanical properties.