Deformation Mechanisms of Geological Materials at the Nanoscale

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Understanding the fundamental deformation mechanisms of geological materials is critical when considering designs for CO_2 sequestration, waste storage, geothermal heat pumps, and hydraulic fracking, for example. Minerals in the mica group are abundant, comprising almost 15% of the upper continental crust [1]. These minerals have a layered sheet-like structure, and shear along the basal plane with relative ease. Mica greatly influences the mechanical properties of its host rock, to the point where it will singly determine the strength of the rock if it is preferentially orientated and contiguous [2]. Thus, understanding the deformation mechanisms of this constituent mineral is essential in predicting mechanical behavior of geological materials. Ex-situ [3–5] and qualitative in-situ Transmission Electron Microscopy (TEM) [6] straining experiments have so far determined that dislocation glide is confined to the basal plane, as well as the slip systems and dislocations present. However, there are multiple locations in the unit cell where dislocation glide could occur, and thus far no work has satisfactorily determined where these dislocations responsible for deformation are [7], nor which deformation mechanisms control the shear strength. By quantitatively investigating deformation and fracture in mica minerals at the nanoscale, this research aims to form a fundamental understanding of geological materials behavior, needed for predictive models.

Here we have begun experiments that probe the mechanical behavior of biotite mica, with the aim of establishing deformation mechanisms as a function of shear stress and loading direction, as well as quantitatively measure activation and interaction energies of participating defects. Tensile samples are cut, using a gallium (Ga^+) Focused Ion Beam (FIB) from exfoliated sheets, or ultramicrotome- or Plasma-FIB- prepared thin slices. These are then transferred to a Hysitron Push-to-Pull (PTP) device in the Scanning Electron Microscope (SEM) with a micromanipulator, and affixed with electron-beam-deposited platinum. To minimize surface amorphization and other Ga^+ FIB-induced effects, all cuts are made blind, such that damage is confined to the sample edges. In-situ TEM quantitative tensile testing is done with the Hysitron PI-95 at ~1 nm/s while under direct observation in the I^3TEM, a JEOL 2100 operated at 200 keV. Initial results, Figure 1, show samples loaded in tension parallel to the basal plane show nominally elastic behavior until brittle failure, reaching near-ideal strengths.

These are the very first quantitative in-situ TEM mechanical tests of mica. The measured mechanical properties compare well to those of bulk-scale mica, and thus slip-oriented samples are expected to yield a quantitative understanding of unit deformation mechanisms in this geological material [8].

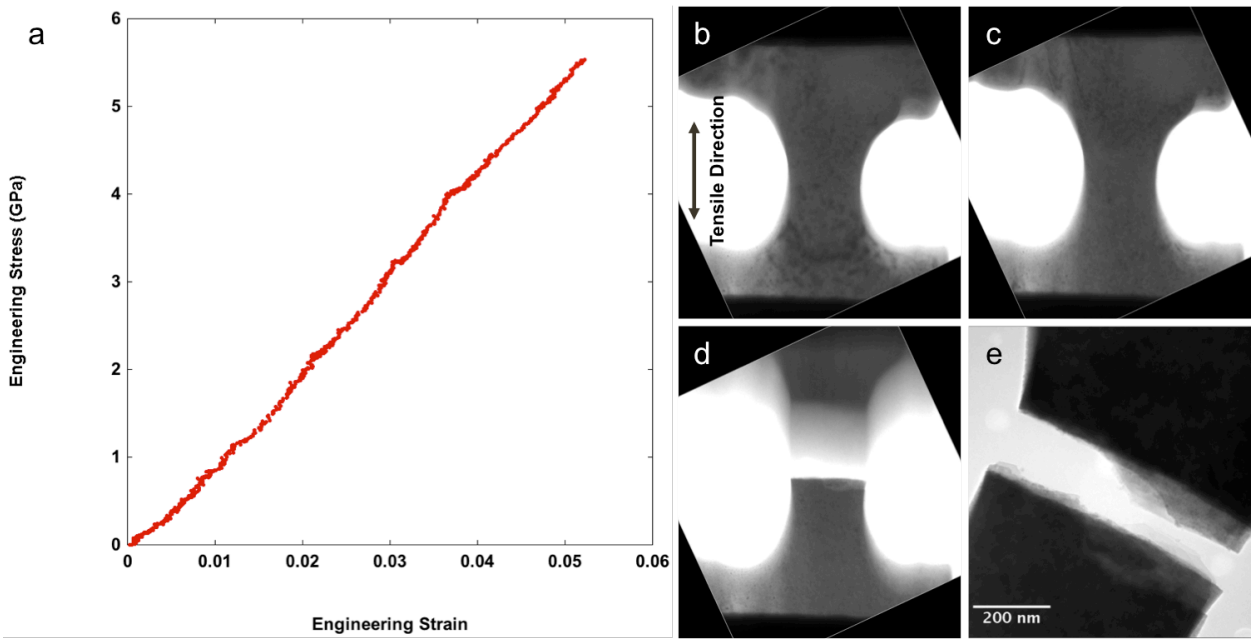

Figure 1. Quantitative in-situ TEM tensile test of biotite mica. Loading direction parallel to [010](001). (a) Engineering stress-strain curve showing nominally elastic behavior and brittle fracture. (b-d) Still frame images from in-situ video acquired during straining. (b) Sample before loading. (c) Frame before failure, σ = 5.5 GPa. (d) Frame after failure. (e) Bright-field TEM micrograph of fracture surface.

References:

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[8] This work was performed, in part, at the Center for Integrated Nanotechnologies, an Office of Science User Facility operated for the U.S. Department of Energy (DOE) Office of Science. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND Number: SAND2016-5762 A. The authors gratefully acknowledge Dr. Khalid Hattar for the use of his equipment and facilities: the I^3TEM and Hysitron PI-95.