Deformation on the Nanoscale

Tiny Imperfect Crystals Are Still Very Strong

A Berkeley Lab team led by Andrew Minor of the National Center for Electron Microscopy (NCEM), collaborating with researchers at Purdue and the equipment manufacturer Hysitron, have shown that nano-scale materials do not have to be perfect to reach their ultimate strength.

Scientists have long assumed that a crystal needs to be perfect—free of defects such as dislocations, (absence of a partial row of atoms in the crystal)—to sustain stress at its theoretical maximum. This thinking was based on the fact that when a crystal containing a defect is stressed to its limit, it fails through the movement of a dislocation in a nonreversible change of shape called plastic deformation—suggesting that less stress is required here than when no dislocation is present. This hypothesis cannot be confirmed using standard methods however, because materials invariably contain dislocations in their crystalline lattices and thus there are few perfect samples to be tested.

A small crystal, small enough to be perfect, should, it is thought, be capable of achieving strength near its ideal theoretical maximum, which can be calculated based on the electronic structure and the bond strengths between the atoms in a perfect crystal. Once the actual strength of the crystal is determined, by applying very small loads, the result can be compared to theory. Even then, however, the key role of the dislocation cannot be evaluated at the same time.

To enable more definitive studies, a diamond nanoindenter was incorporated inside a transmission electron microscope at NCEM. Using this unique instrument, the researchers were able to image crystals at video rates while simultaneously performing high-resolution load-displacement measurements with the indenter.

The results using perfect crystals revealed the limitations of our current understanding of deformation on the nanoscale. Formerly, jumps in the load-displacement data called "pop-in" events were thought to accompany the onset of plasticity and signify yield at the limit of strength of the crystal. However, the microscopy revealed a more complex multistep process beginning with faint signals of deformation before the pop-in event. In the evolving graph of one such study, displacement is first observed to correspond with video frames that show the sudden appearance of dislocations in the apparently flawless crystal. In the second event, the defects abruptly shift, with dislocations breaking free, gliding over other sections, interacting, and then coming to rest at a new equilibrium position. This event was thought to reduce the load required for further displacement, but in fact, that load builds up again, leading at a greater load than in the first event, and another restructuring of defects. Thus, even though, as the process progressed, this nanocrystal was not perfect, it did withstand loads approaching the theoretical limit. A further increase in displacement requires far less stress.

Future nanomechanical work with the new instrument will involve direct investigation of fundamental parameters that define the stresses required to initiate dislocations and their movement.

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A. M. Minor, S. A. Syed Asif, Z. Shan, E. A. Stach, E. Cyrankowski, T. J. Wyrobek, and O. L. Warren, *Nature Mater*. 5, 697 (2006).

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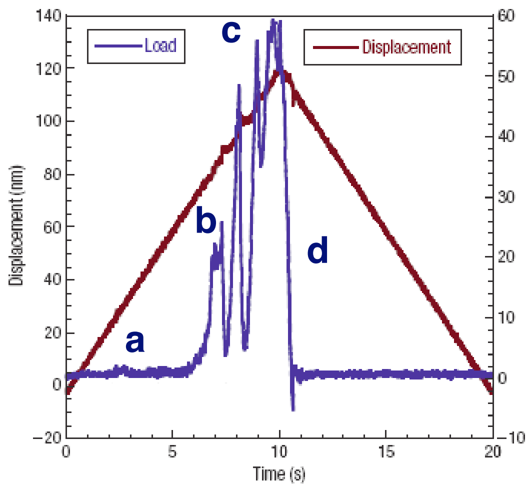

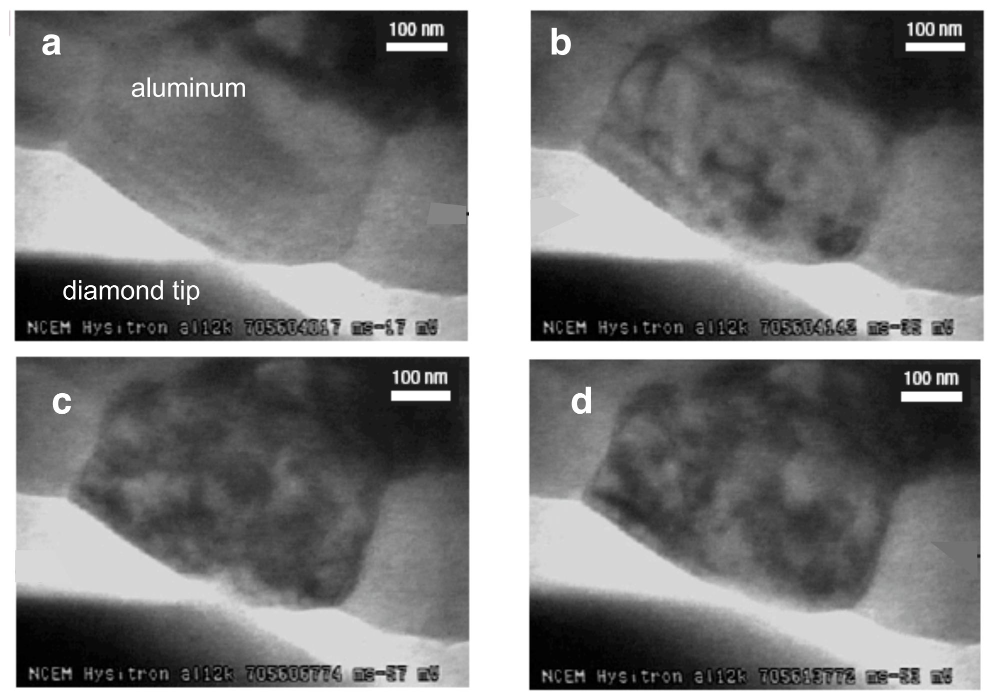

***Load displacement** data and TEM images of a single crystal aluminum sample indented with a diamond tip. As the applied load increases (blue line), the initially perfect crystal (a) first becomes filled with dislocations (b), dark regions. After point (b), the crystal has relaxed. Continued increasing of the load repeats the cycle. At (c) the crystal has even more dislocations, but is sustaining a shear stress near the theoretical limit. Finally, at point (d), the fall in the load data indicates the onset of continuous plastic deformation.*