Mechanical Properties of Nanoparticles

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Materials 265

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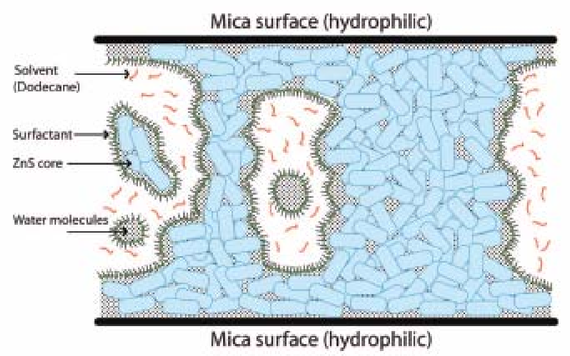
Overview

- Measuring single nanoparticles
  - Why isn't it done more often?
  - Compression of single nanoparticles
  - Some applied theories

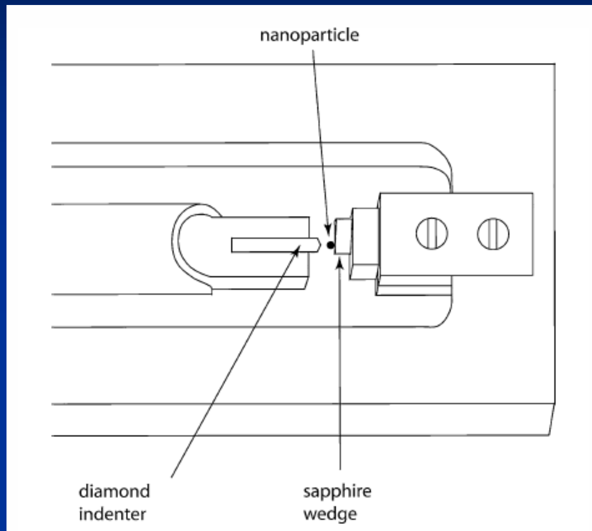
Why Not Test a Nanoparticle?

- Nanostructured Materials
  - Hall-Petch (GB dominate dislocation behavior)
- Nanoparticle Composites
  - Often clay or CNT in polymer
  - Matrix softer, interface limited
- Nanoparticles in Solution
  - Jamming, lubrication, aggregation dominate

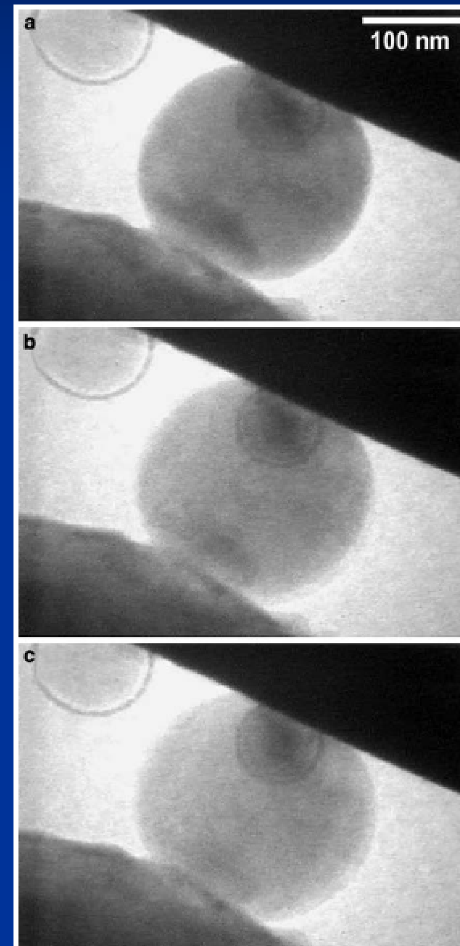


Y. Min, M. Akbulut, R.K. Prud'homme, Y. Golan, and J. Israelachvili
J. Phys. Chem. B, **2008**, 112 (46), 14395-14401

Fracturing a Nanoparticle



- STM in TEM
  - 300 nm radius tip Berkovich Geometry
- Si Nanoparticle
  - HPPD

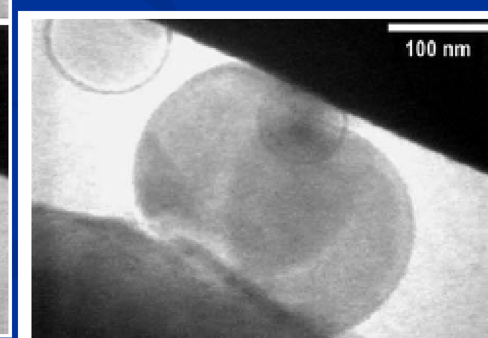


a. Strain (dark)

b. starts to relax

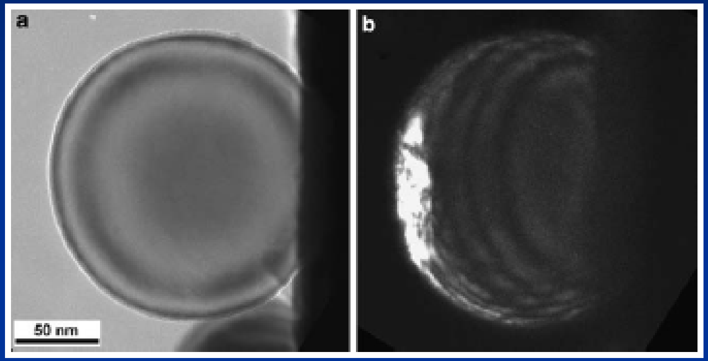
c. relaxes further as particle has gotten wider

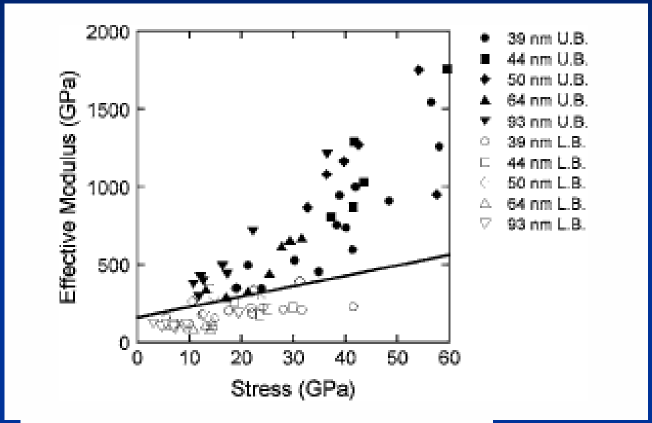
d. and particle is fractured

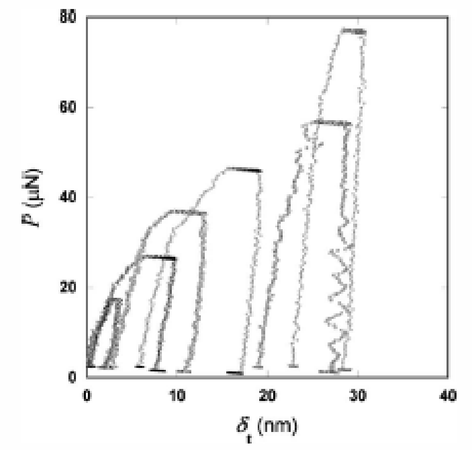


Nowak, J.D.; Mook, W.M.; Minor, A.M.; Geberich, W.W.; Carter, C.B.; *J Mater. Res.* 2006, 41, 4477

Plastic Deformation







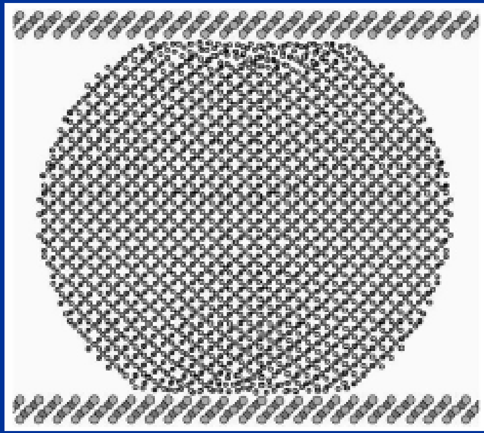
- Si particle deforms plastically leaving residual stress
  - Shows on repeated compression

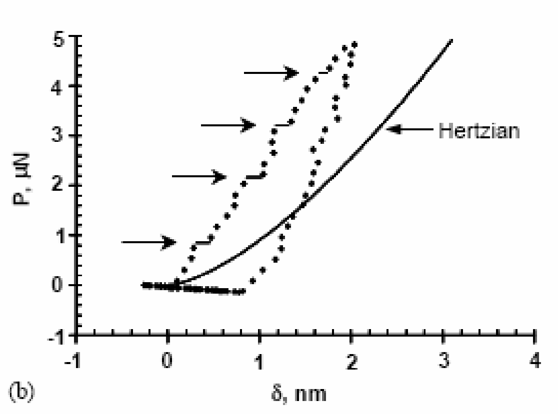
Mook, W.M.; Nowak, J.D.; Perrey, C.R.; Carter, C.B.; Mukherjee, R.; Girshick, S.L.; McMurry, P.H.; Geberich, W.W.; *Phys Rev B* 2007, 75, 214112.

Nowak, J.D.; Mook, W.M.; Minor, A.M.; Geberich, W.W.; Carter, C.B.; *J Mater. Res.* 2006, 41, 4477

Hertzian Approximation

- Model of a deformable sphere between hard surfaces
- Hertzian curve underestimates modulus





$$P = \frac{4}{3}E^{*}R^{1/2}\delta^{3/2}, \quad E^{*} = \left(\frac{1-\nu_i^2}{E_i} + \frac{1-\nu_{\mathrm{Si}}^2}{E_{\mathrm{Si}}}\right)^{-1}$$

W.W. Gerberich et al. *J. Mech. Phys. Solids,* 51, (2003) 979 – 992

Dislocations in Nanoparticles

- Crystal structure dependent
  - fcc hardens by dislocation starvation
  - bcc hardens by "traditional" work hardening

Attached to a Surface

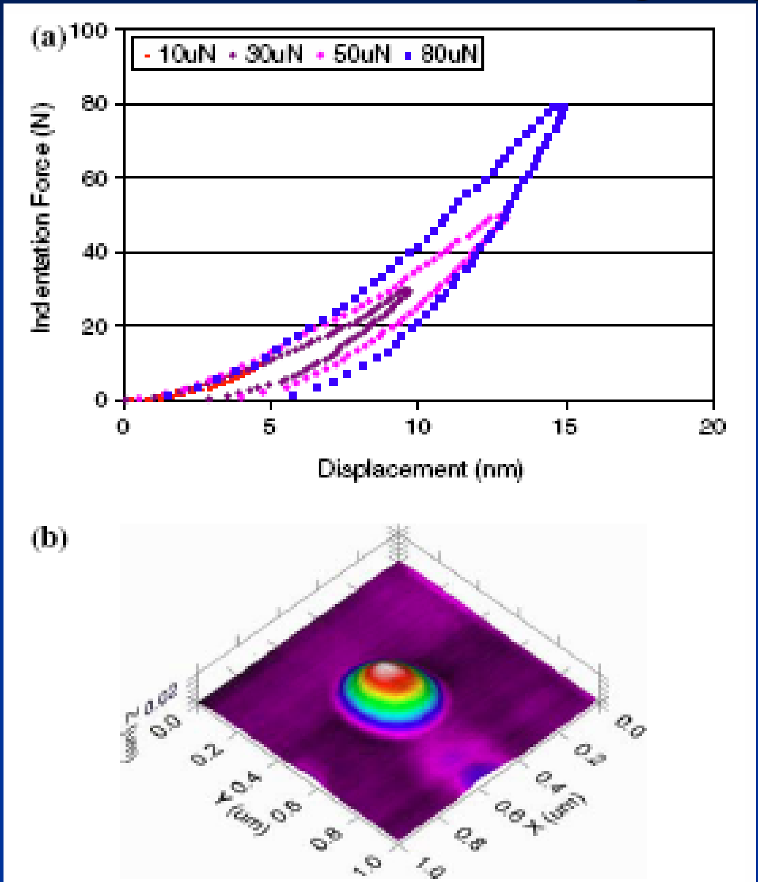


Figure 6. (a) Loading–unloading curves under repeated indentations on a silica nanoparticle starting from 10 μN indentation forces and progressively increased the indentation force at 10 μN steps. Only four curves are shown for clarity. The nanoparticle strain hardened with progressively increased indentation loads. (b) The nanoparticle deformed without obvious fracture.

Table 1.
Experimental results of nanoindentation on 10 randomly selected silica nanoparticles attached to single crystal silicon (100) substrate using 10 μN indentation forces.

P_{max} (μN)	$H_{particle}$ (nm)	h_{max} (nm)	h_c (nm)	R_C (nm)	E_r (GPa)	H (GPa)	$E_{particle}$ (GPa)	H by Linear Increase in Contact Area with Indentation Depth (GPa)	H by Geometric Contact Area (GPa)
10	42.0	4.6	2.6	30.6	73.7	3.5	76.5	4.0	9.1
10	43.4	4.1	2.5	29.8	78.0	3.5	81.3	3.9	9.0
10	48.0	5.4	2.9	32.4	55.3	3.0	56.4	2.9	6.5
10	49.9	5.4	3.3	34.7	55.9	2.6	57.0	2.7	6.1
10	52.6	5.3	3.4	35.4	63.0	2.5	64.7	2.6	5.9
10	54.4	4.6	3.1	33.6	78.4	2.8	81.8	2.8	6.5
10	59.8	5.1	3.1	33.3	59.5	2.8	61.0	2.3	5.4
10	60.0	5.7	3.9	38.1	62.6	2.2	64.3	2.1	4.8
10	63.0	5.1	3.4	35.0	73.8	2.6	76.5	2.2	5.1
10	75.0	4.8	3.0	33	67.2	2.8	69.4	1.9	4.4
Average	54.8 ± 10.0	5.0 ± 0.5	3.1 ± 0.4	33.6 ± 2.4	66.7 ± 8.8	2.8 ± 0.4	68.9 ± 9.6	2.8 ± 0.7	6.3 ± 1.6

$H_{particle}$ is the nanoparticle height before indentation, h_{max} is the maximum indentation displacement, h_c is the contact depth, and R_c is the contact radius.

- Silica on silicon
- Nanoindenter, image from SPM

M. Zou, D Yang *Trib. Lett.*, **2006**, 22 (2), 189.

Other Considerations

- Fraction of surface atoms
- Curvature
- Defect density
- Allowed mechanical modes
  - Compression
  - Tension, torsion,