SAND2005-7473C

Tribology of Diamond-like Nanocomposite Coatings for Ni-based MEMS: Contact Stress – Deformation Relationships Under Sliding Probes

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2005 MRS Fall Meeting
November 28 – December 2
Boston, MA

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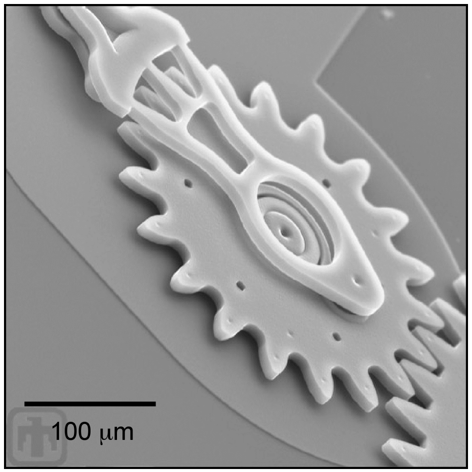
Device Performance and Reliability

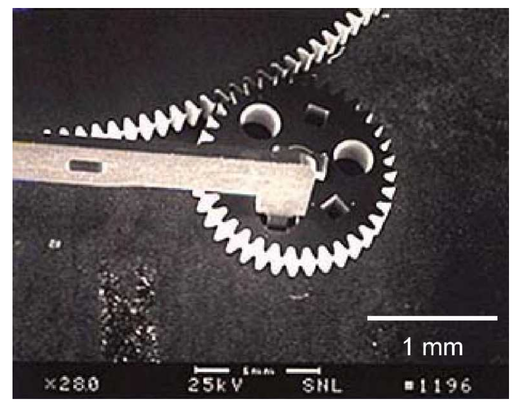
Si Surface Micromachine Technology



- hydrophilic oxides, water adsorption
- adhesion, surface morphology
- friction/wear
- strength

LIGA technology

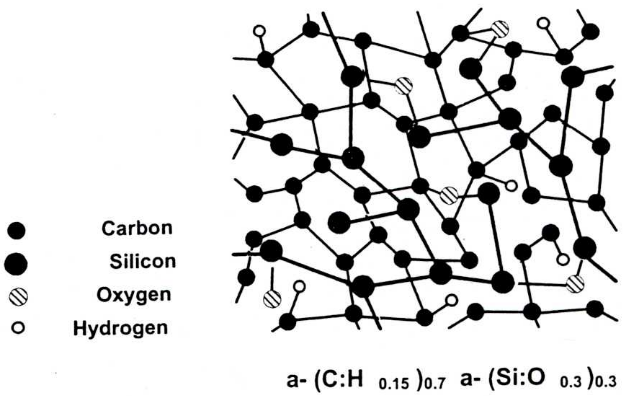
- electroplated Ni alloys
- corrosion
- friction/wear
- strength



Coatings provide a method to enhance performance and reliability.

Diamond-like nanocomposite coatings

DLN coatings were produced by a plasma enhanced CVD process



Schematic of DLN atomic structure.

- Coatings are amorphous
- Conformal coatings could provide coverage of sidewalls
- Substrate temperatures do not typically exceed 150 to 200 ºC

For 1-2 µm thick films on silicon substrates

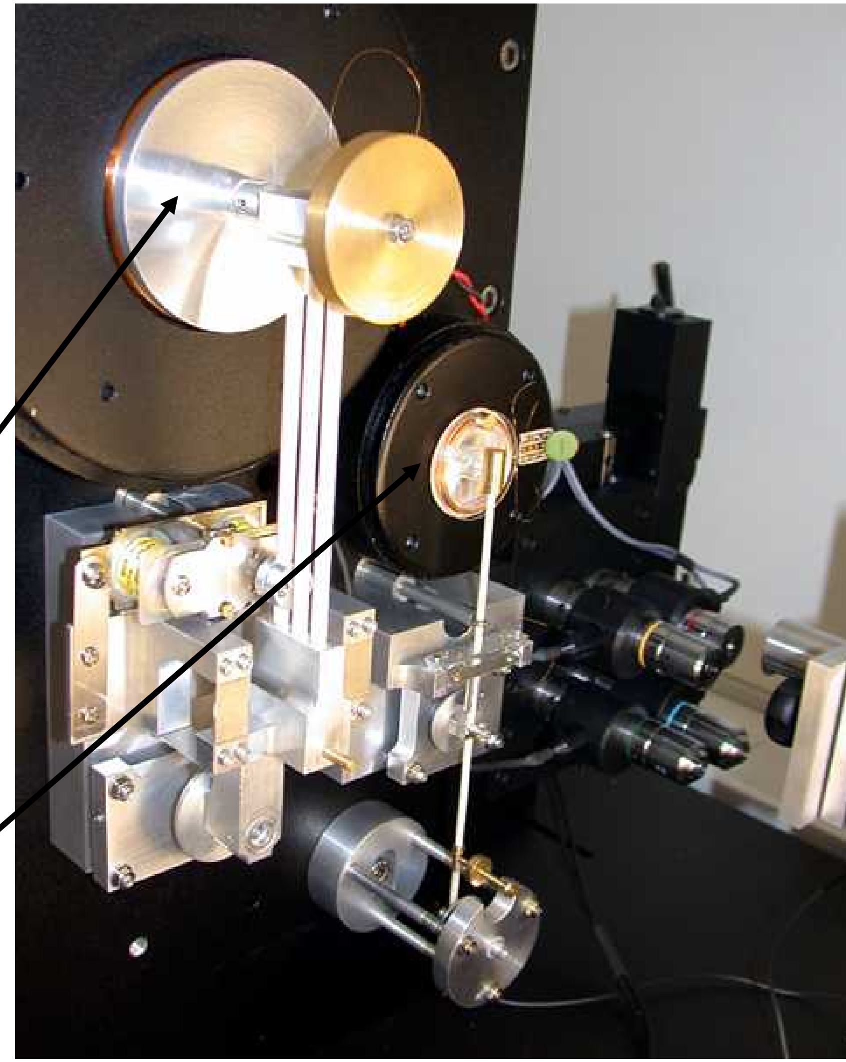
Hardness: 9-17 GPa
Modulus: 90-140 GPa
COF in air: 0.04-0.06

D. J. Kester, C. L. Brodbeck, I. L. Singer and A. Kyriakopoulos, *Surface and Coatings Tech*. 113 (1999) 268-273.

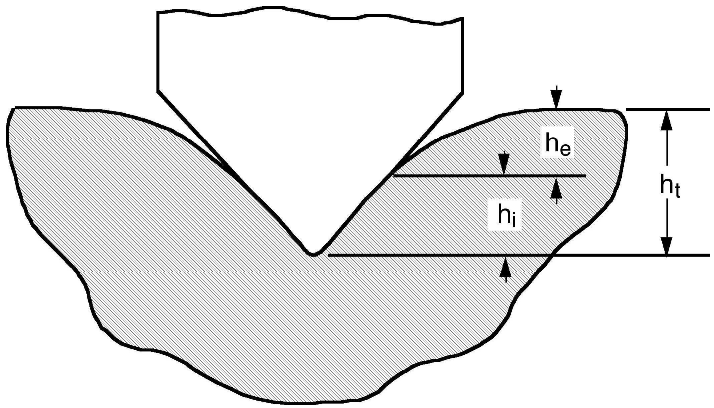
C. Venkatraman, C. Brodbeck and R. Lei, *Surface and Coatings Tech*. 115 (1999) 215-221.

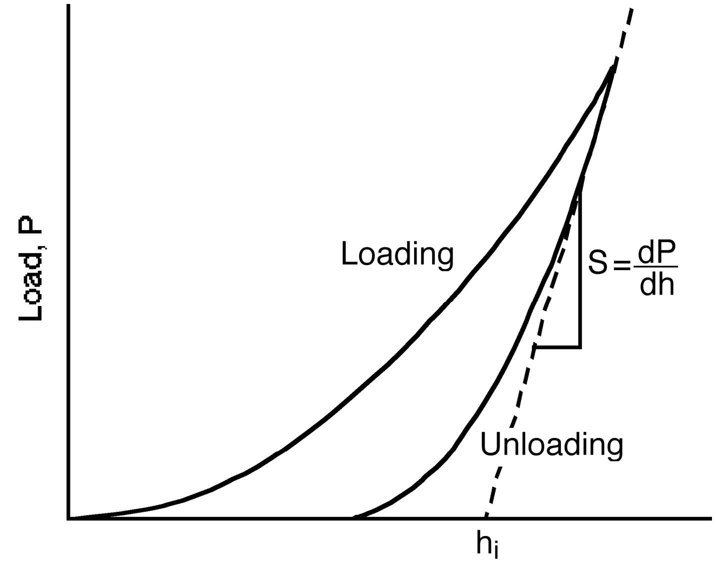
Commercial Nanoindentation Platform

- Instrumented Indentation Testing
  - Record load and displacement
- Directly calibrate load and displacement
- <u>Microtest</u>
  - High load (up to 20 N)
  - Large travel range
    - Up to 30 microns
- <u>Nanotest</u>
  - Peak load of 450 mN
  - Low noise floor



Nanoindentation Technique





Stiffness is calculated from the elastic unloading curve:

$$S = \frac{dP}{dh} = \frac{2E_r\sqrt{A_i}}{\sqrt{\pi}}$$

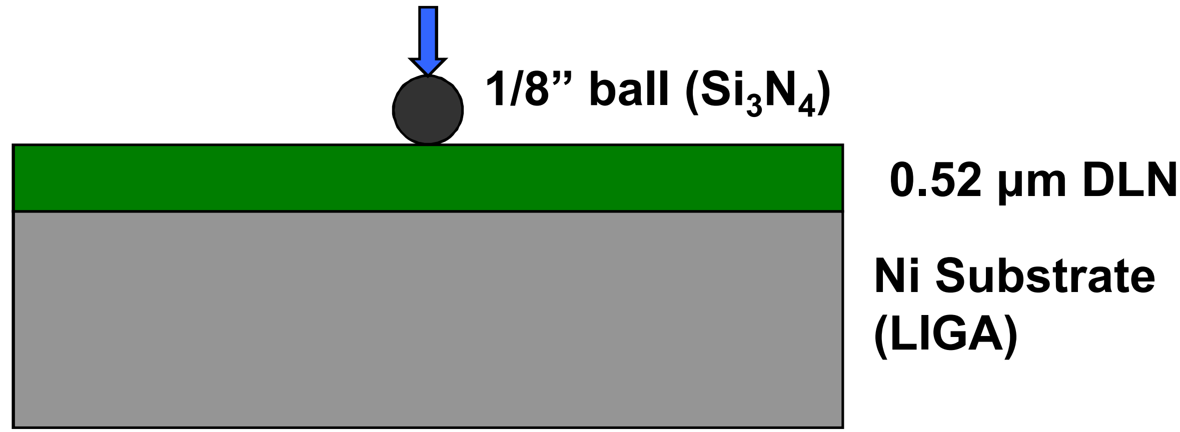
from which the sample elastic modulus can be determined as follows.

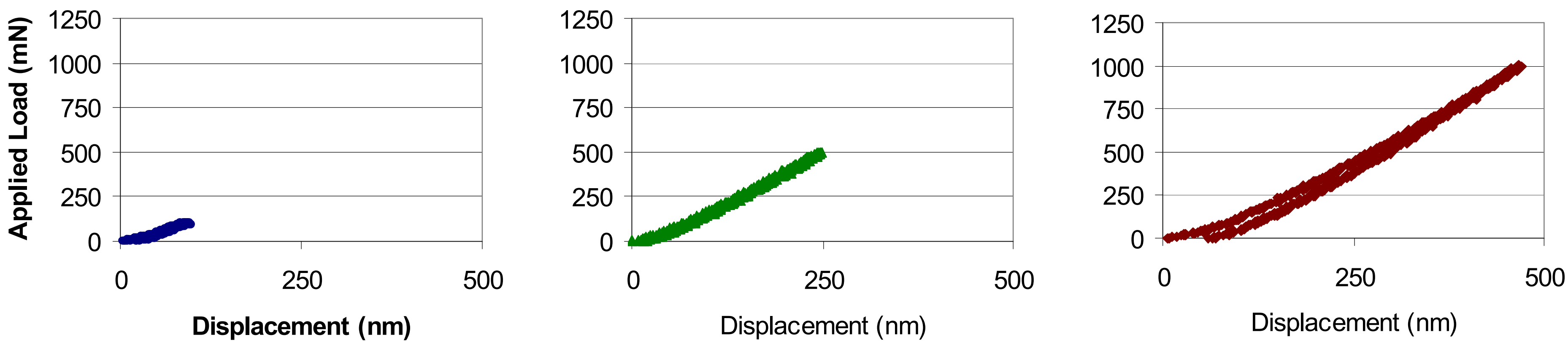
$$\frac{1}{E_r} = \frac{\left(1-\nu_s^2\right)}{E_s} + \frac{\left(1-\nu_i^2\right)}{E_i}$$

Furthermore, hardness can be determined as

$$H = \frac{P_{max}}{A_i}$$

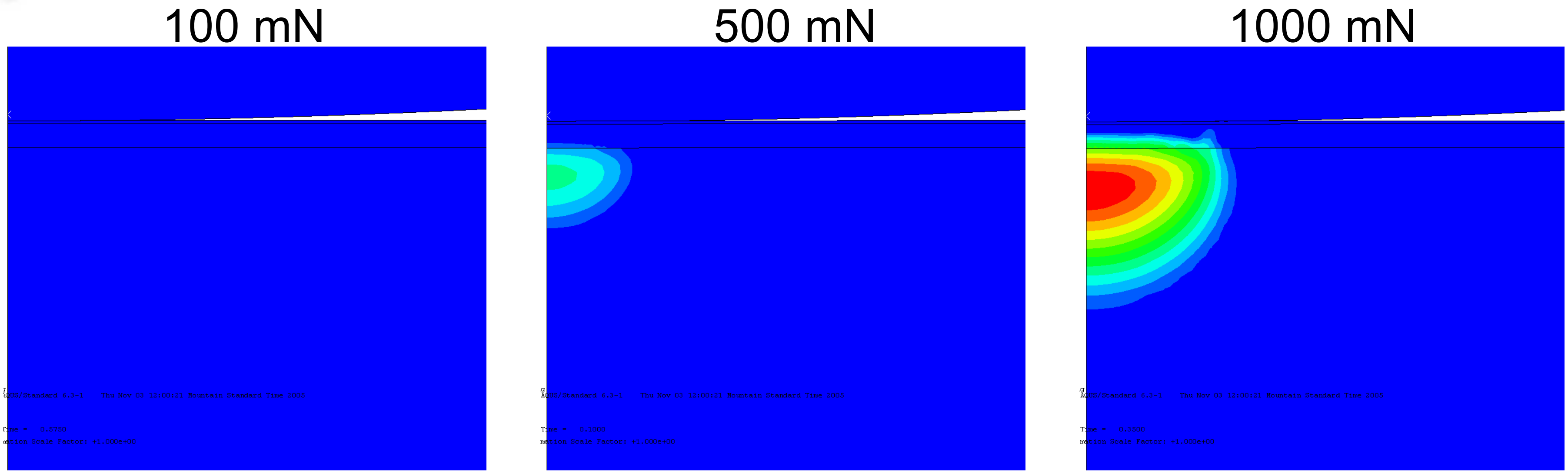
Nanoindentation Results

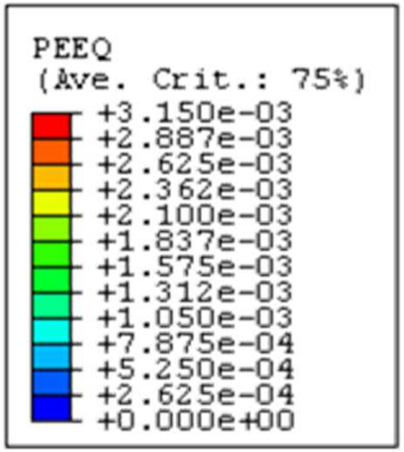




- Nanoindentation shows elastic deformation at low loads
- Permanent deformation occurs at loads around 500 mN

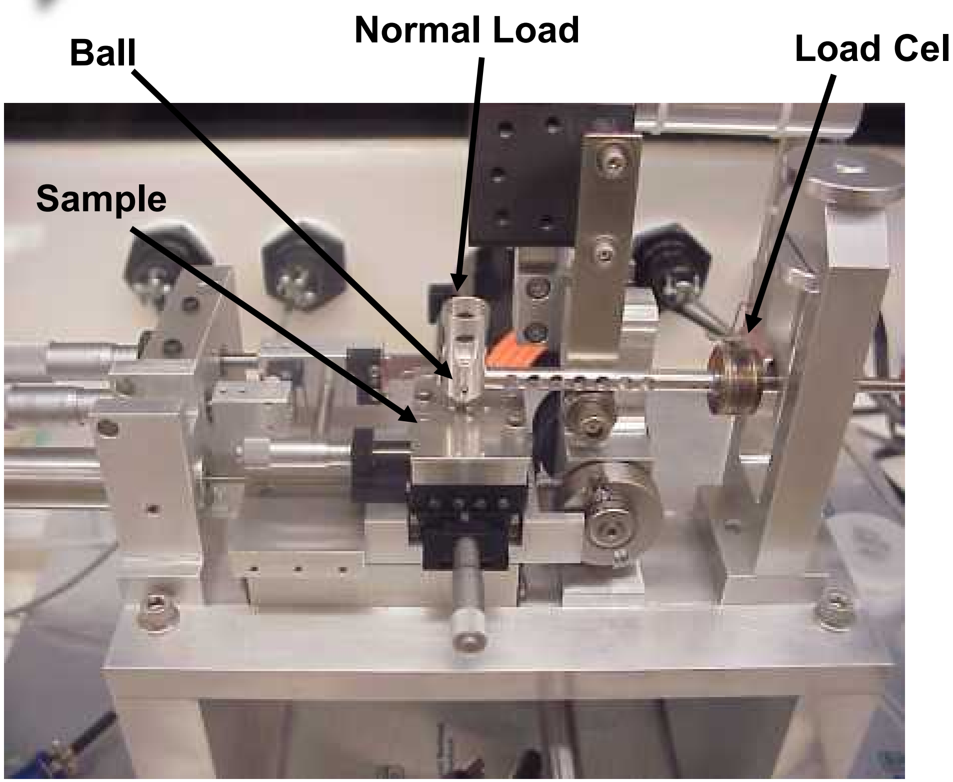
FEM Indentation

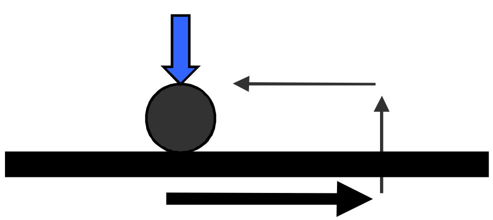


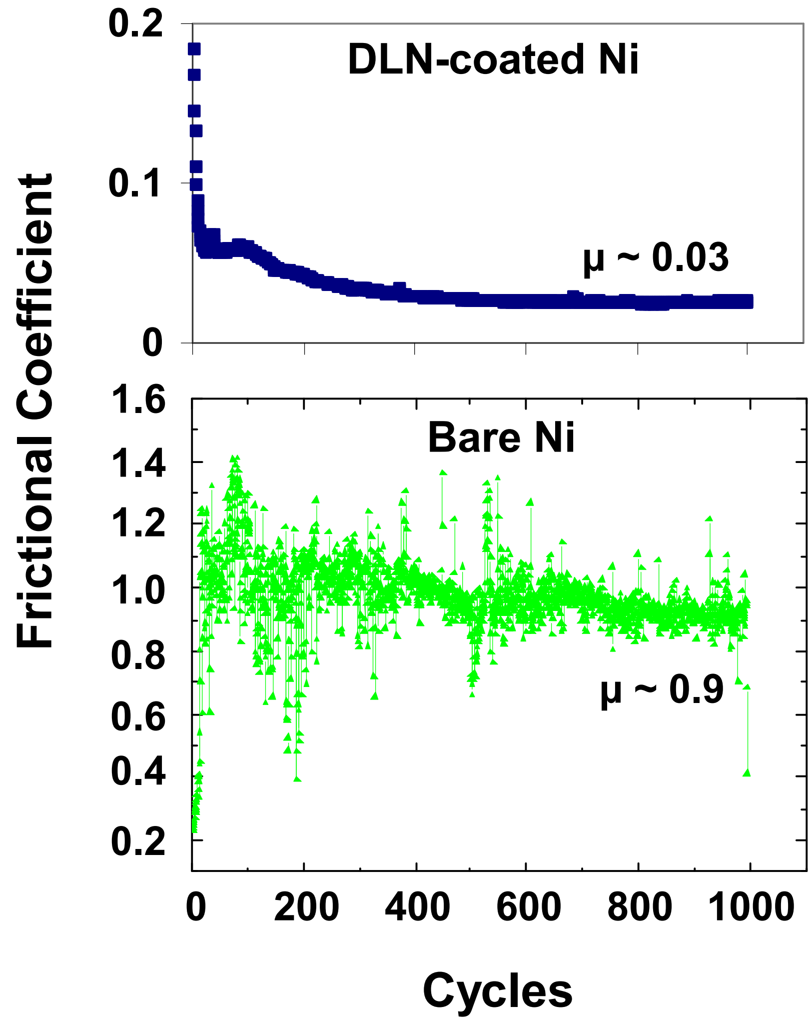


- FEM simulations imply that deformation will be elastic at 100 mN normal load
  - Plasticity initiates around 280 mN
- Increasing loads generate significant plasticity beneath the tip

Linear Wear Testing

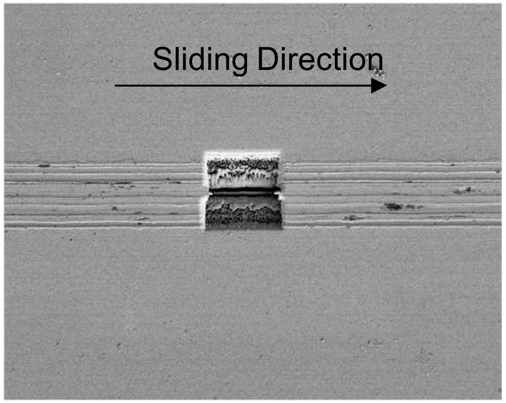


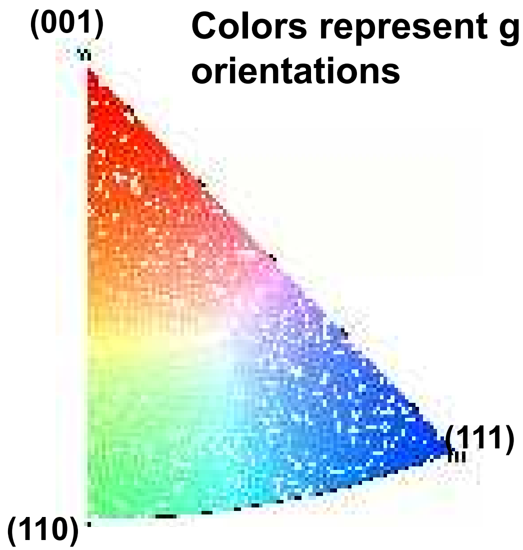




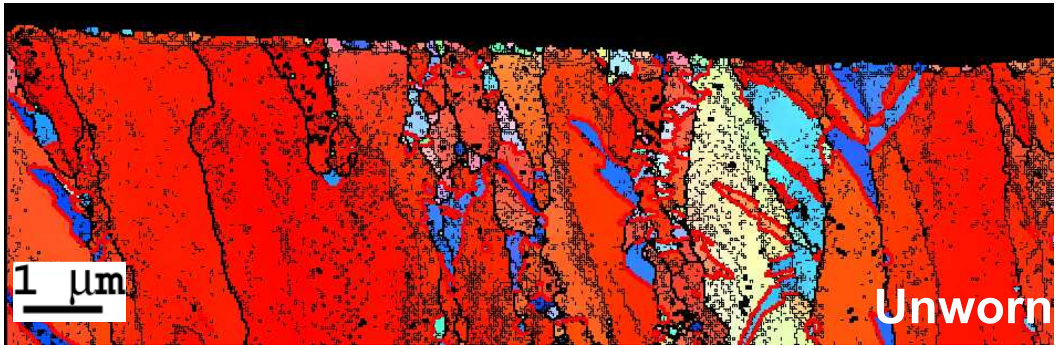
- DLN coating reduces frictional coefficient by factor of 30

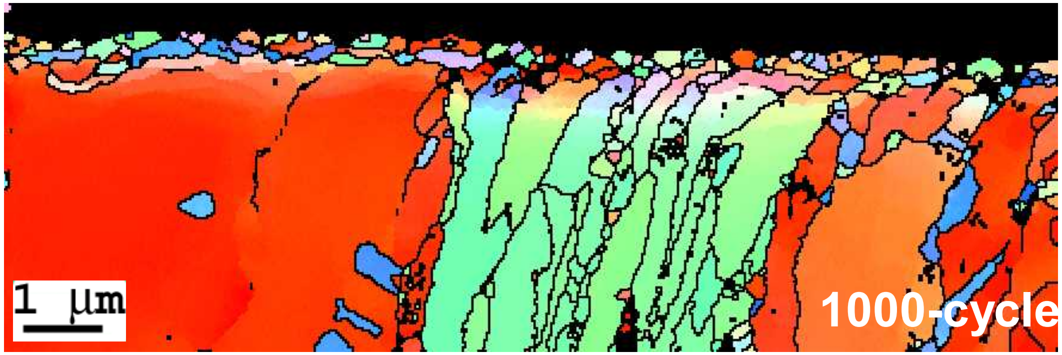
EBSD analysis of wear scars





Colors represent grain orientations





Cross section through wear scar

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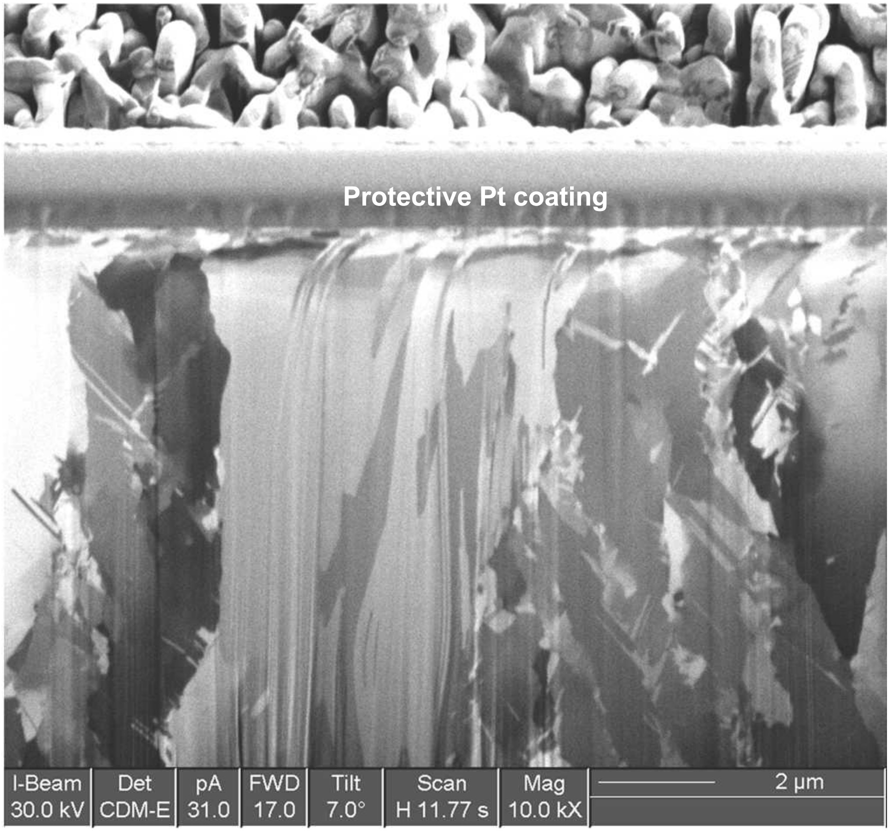
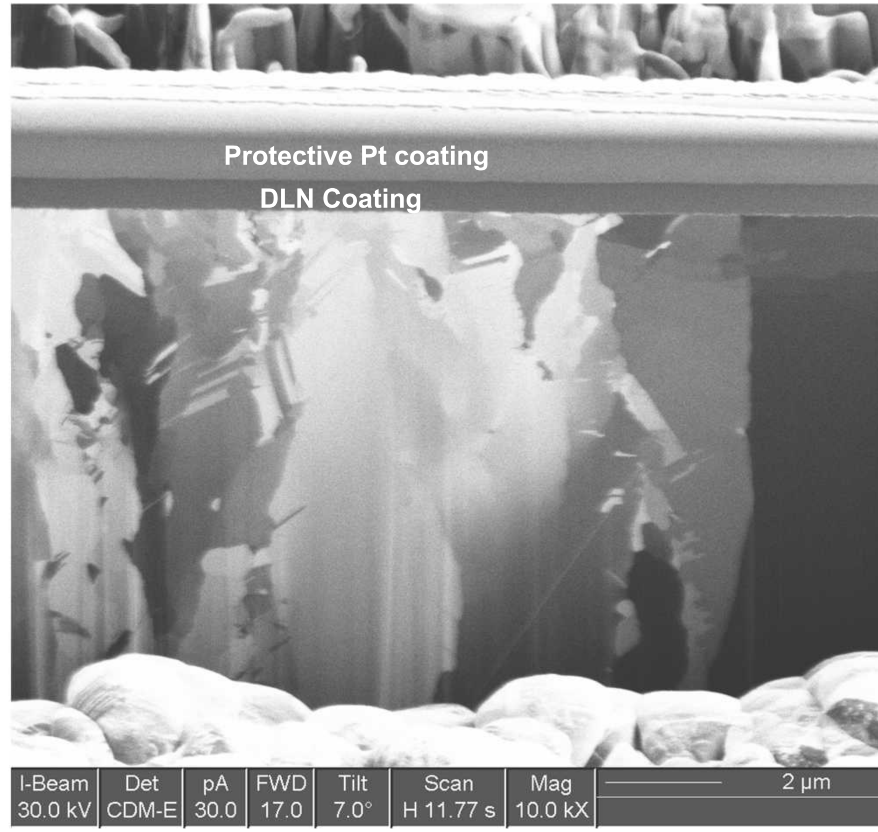
Linear wear results at 100 mN

Sliding Direction



Uncoated Ni Surface

μ ~ 0.9



DLN Coated Ni surface

μ ~ 0.03

- 1000-cycle wear scar at 100 mN load in dry nitrogen atmosphere

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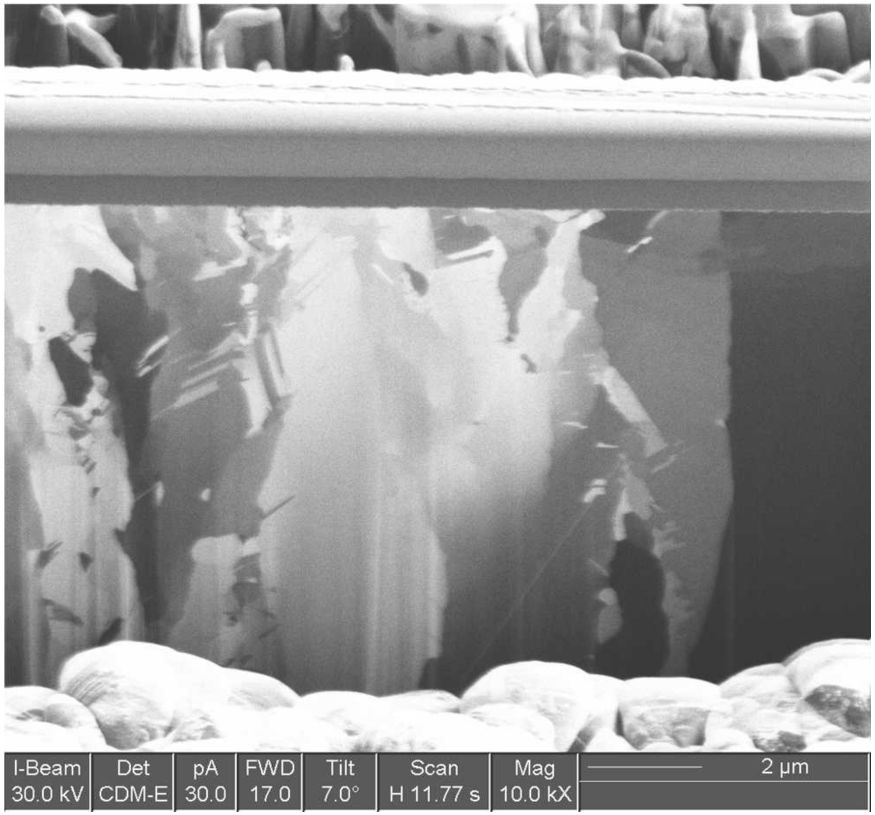
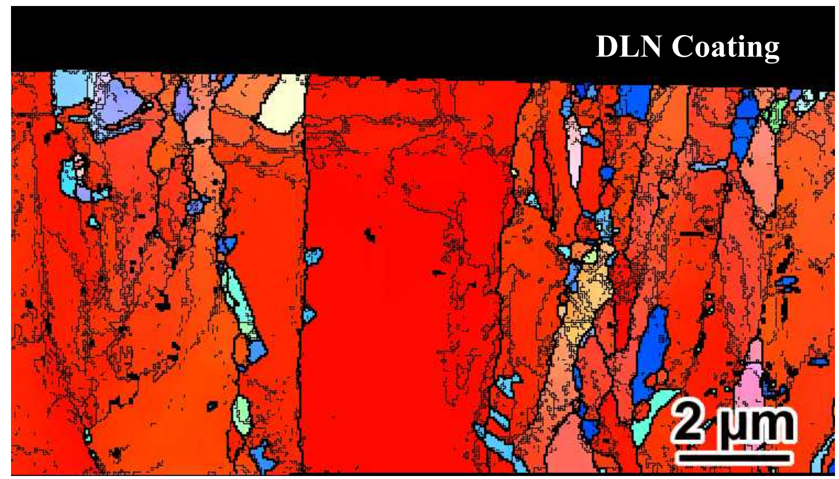
DLN-coated Ni at 100 mN

Sliding Direction

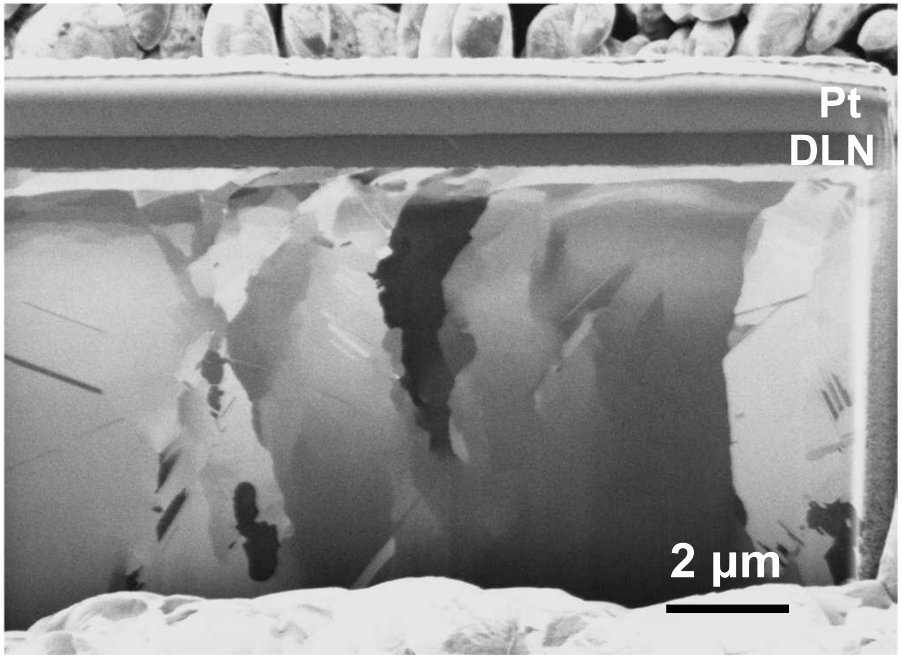


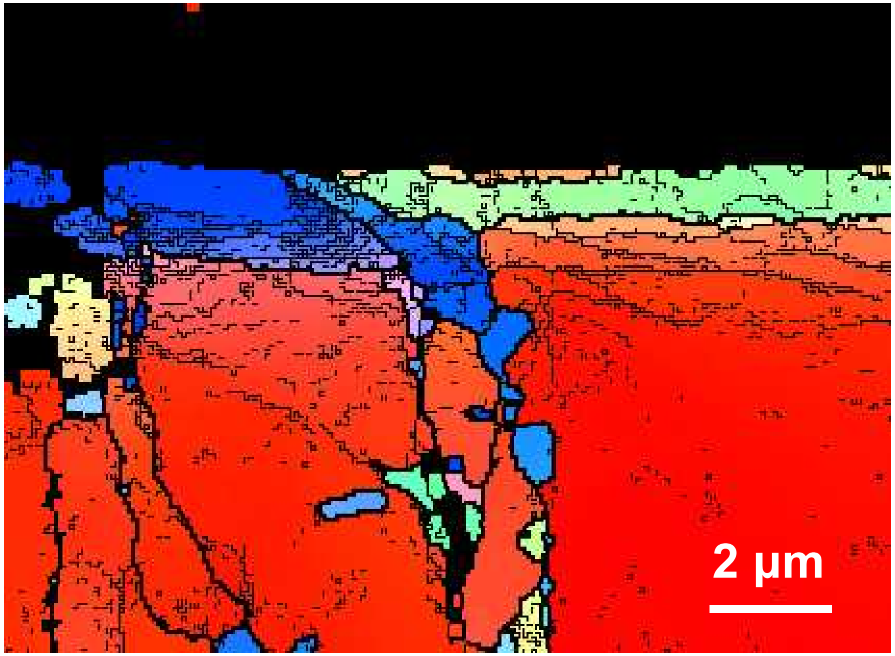


- Elastic deformation only in DLN and nickel at normal load of 100 mN

DLN-coated Ni at 500 mN

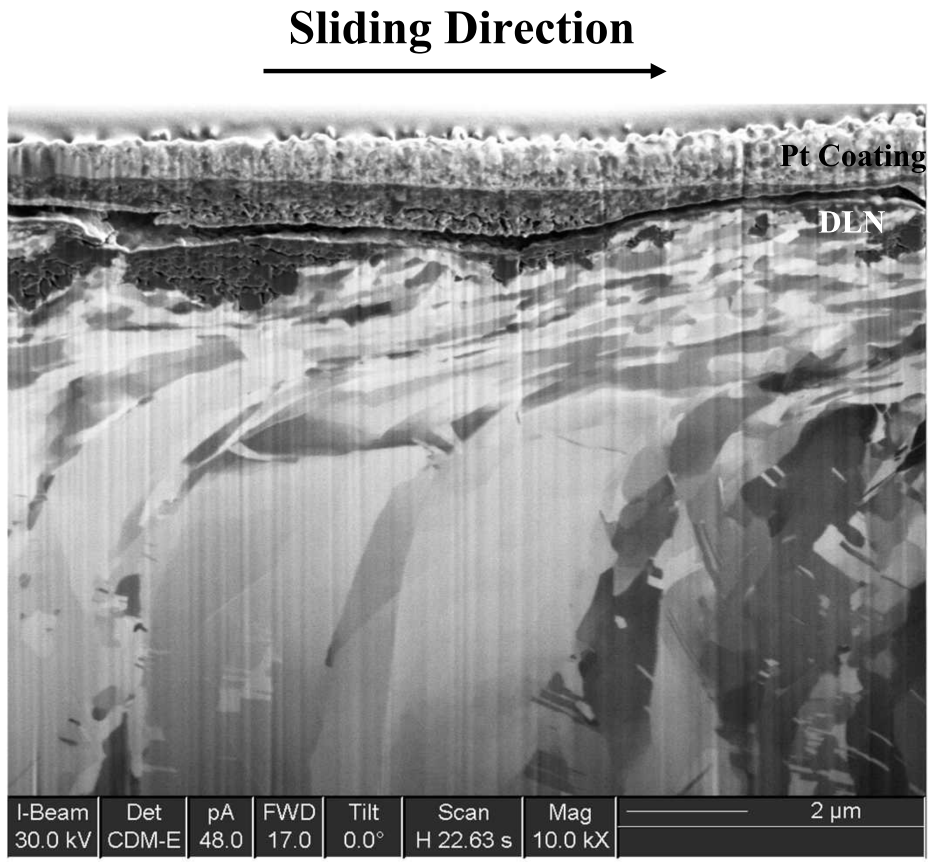
Sliding Direction





- Nickel underneath the DLN coating deforms at higher loads, 500 mN, but the coating remains intact

DLN-coated Ni at 1000 mN



- At high loads (1000 mN) significant plastic deformation in the Ni substrate occurs, along with breakdown and fracture of the DLN layer

Results and Conclusions

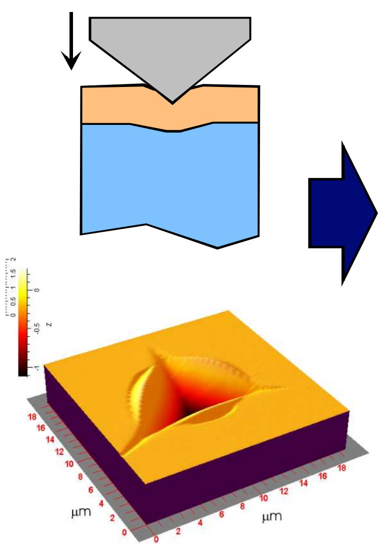
- DLN coatings reduce the frictional coefficient from 0.8 to 0.03
- With increasing normal load above 100 mN, plastic strains are generated in the Ni substrate
  - Quasi-static indentation FEM simulations predict plasticity above 280 mN
  - Observed in quasi-static indentation, FEM, and EBSD of wear scars

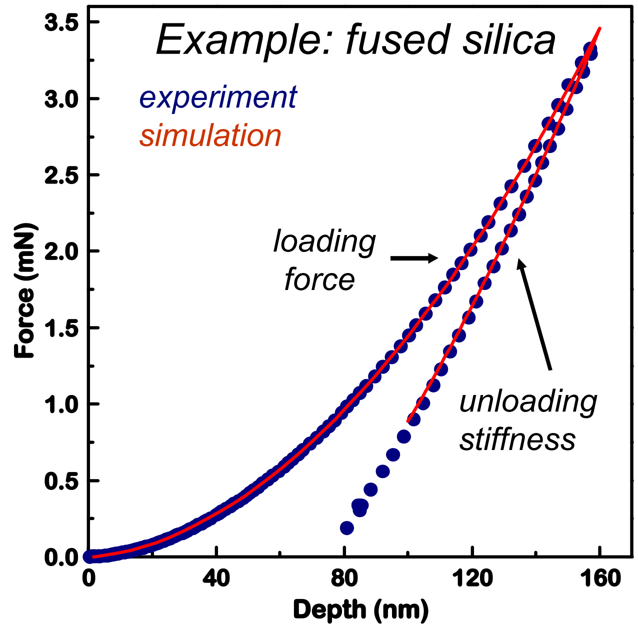
Acknowledgements

- Bekaert Advanced Coatings Technologies
  - Cyndi Brodbeck and Chandra Venkatraman for providing the DLN coatings
- Bonnie McKenzie for scanning electron microscopy
- James Knapp for FEM assistance

Modeling of Nanoindentation

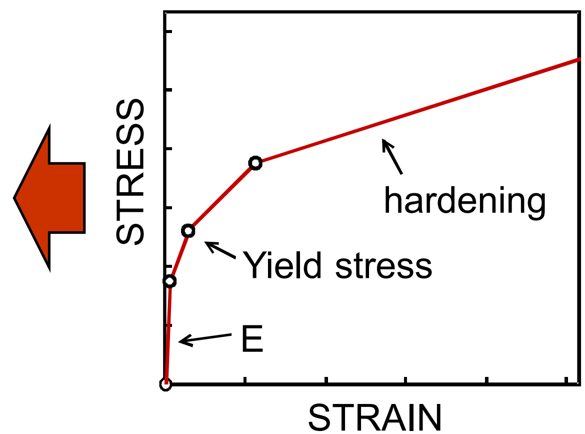
EXPERIMENT





SIMULATION

Film stress-strain curve



$\sigma = E\varepsilon$ ***for*** $\varepsilon < Y_0 / E$

$\sigma = K\varepsilon^n$ ***for*** $\varepsilon \geq Y_0 / E$

- ***Experiment***: triangular tip pressed into specimen – force required depends on the mechanical properties of both film and substrate.
- ***Simulation***: finite element modeling – vary yield and elasticity for just the film until a good fit to experiment is obtained.

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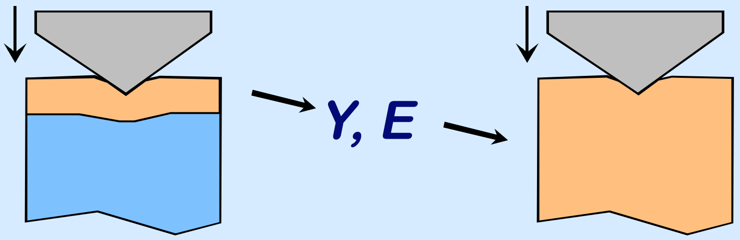
Finite-element simulations

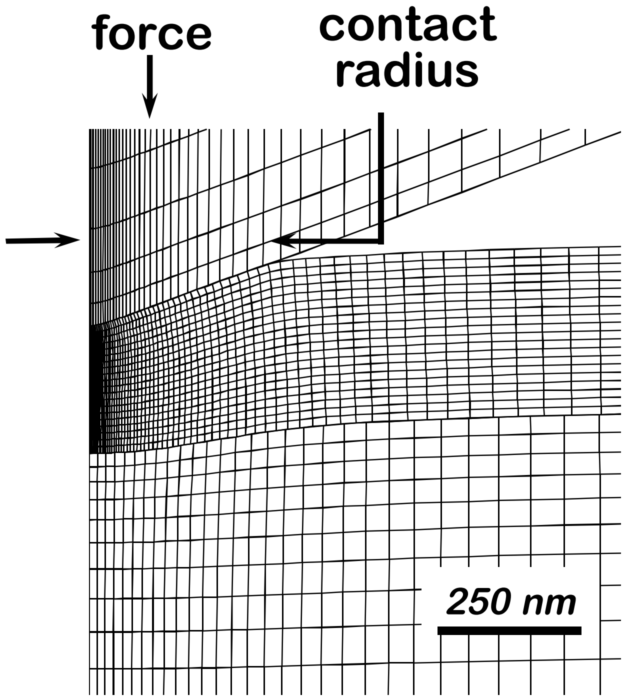
- Simulations use ABAQUS/Standard 6.3 on a 600 MHz Octane2 workstation
  - 2D: 30-60 mins
- Properties of the substrate and indenter are fixed at calibrated values
- Y and E for the layer are varied until a good fit to experiment is obtained
  - Tip yielding, residual stress, and friction can be modeled
- Two primary simplifications:
  - 2-dimensional axisymetric meshes
  - isotropic elastic-plastic materials with Mises yield criteria

- Hardness of the layer material is determined by an additional simulation of a “bulk” sample of just the layer material:

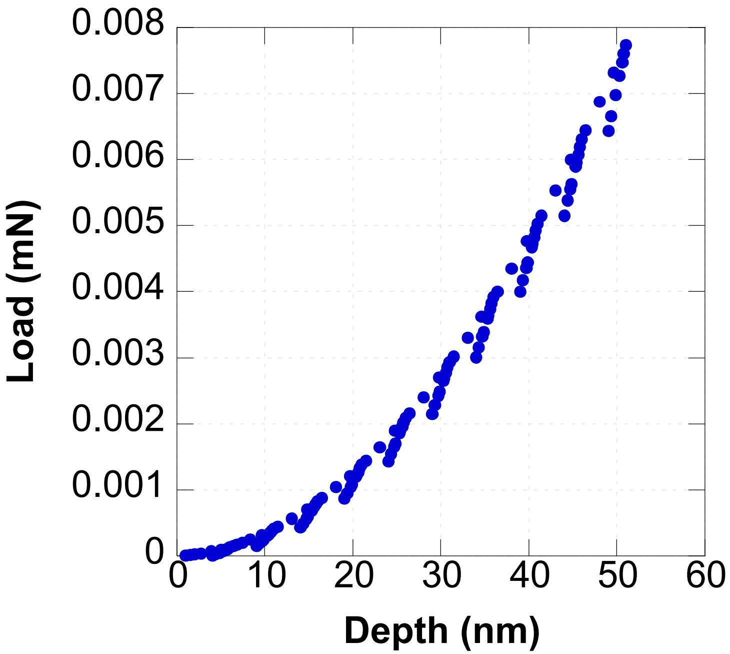


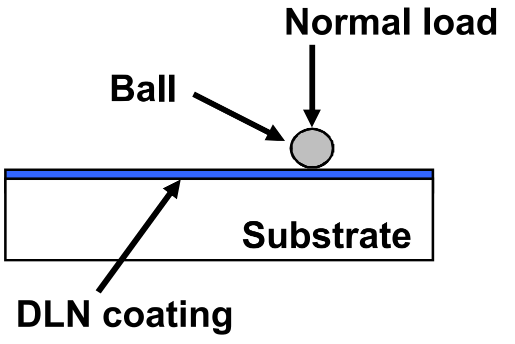
Simulation Inputs

- Meshes are generated specific to each sample, including layer thickness and tip shape (blunting).
- Indentation profiles include multiple unloading segments to determine contact stiffness as a function of tip displacement.



2D axisymetric mesh




Normal load
Ball
Substrate
DLN coating

Motivation

- Note the contacting sliding surfaces
- Surface interactions dominate as machine scale is reduced
- Basic understanding of tribology is required for design of reliable micromachines