Introduction to Instrumented Indentation Testing: Data Analysis

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President

W.C. Oliver and G.M. Pharr, J. Mater. Res. 7, 1564 (1992)

So why do we need instrumented indentation?

- *Because we don't have enough material*
- *Material behaves differently at small scales*
- *Testing simplicity*

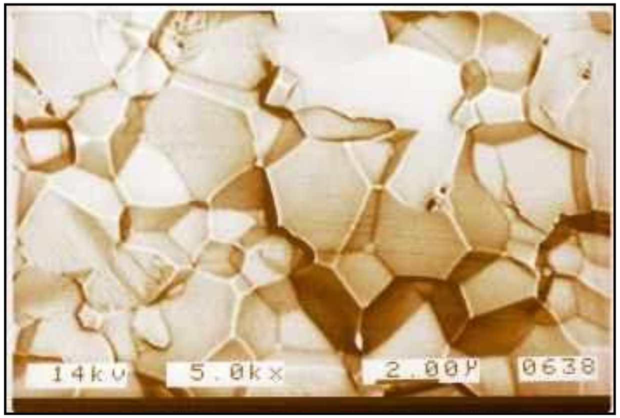
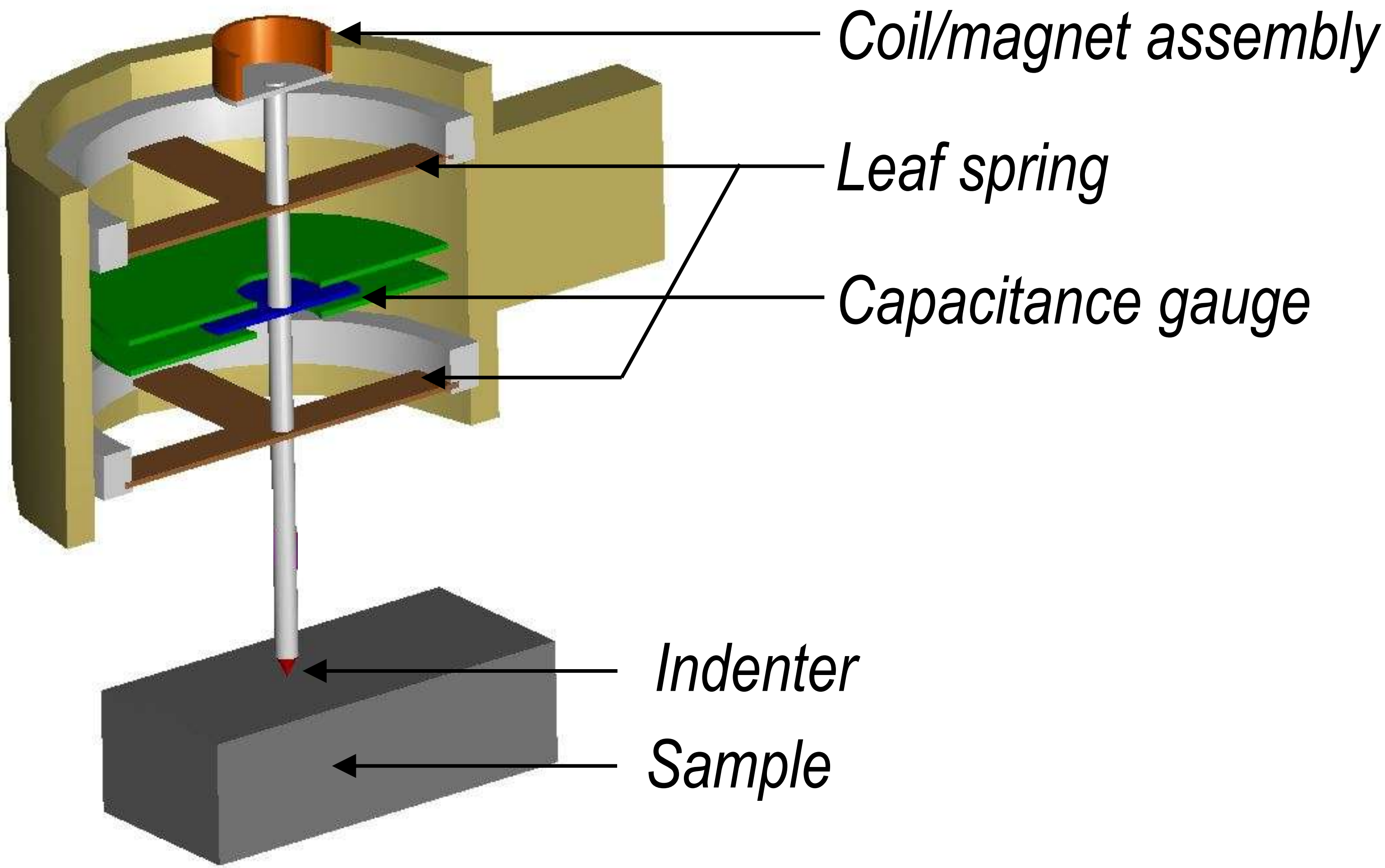


Figure 3. Grain structure in a metal.

Properties (mechanical)

- **Young's modulus**
- **Yield stress / Hardness**
- Storage and loss modulus (polymers)
- Fracture toughness
- Stress exponent for creep

NANO Indenter ® G200 (XP or DCM) schematic



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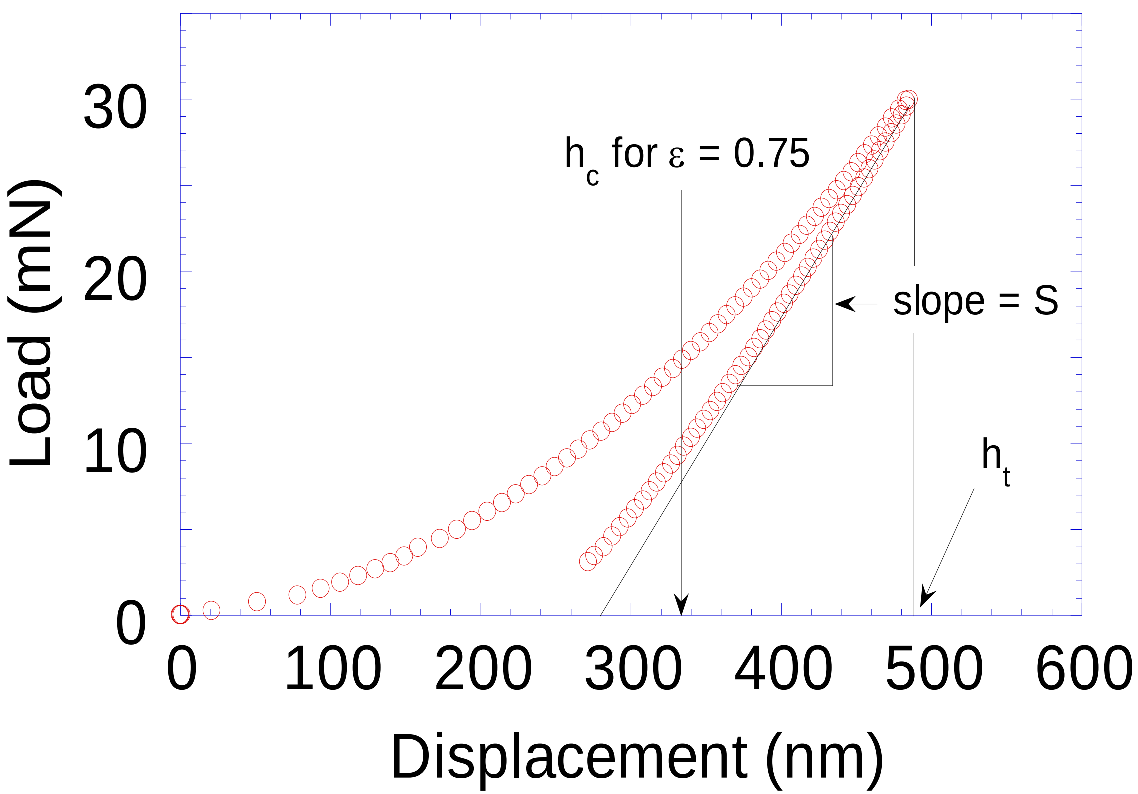
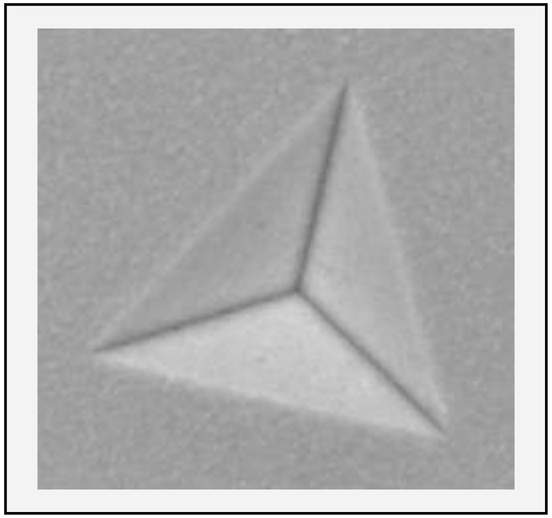
Instrumented indentation testing (IIT)



Nickel



First Problem: Finding the surface

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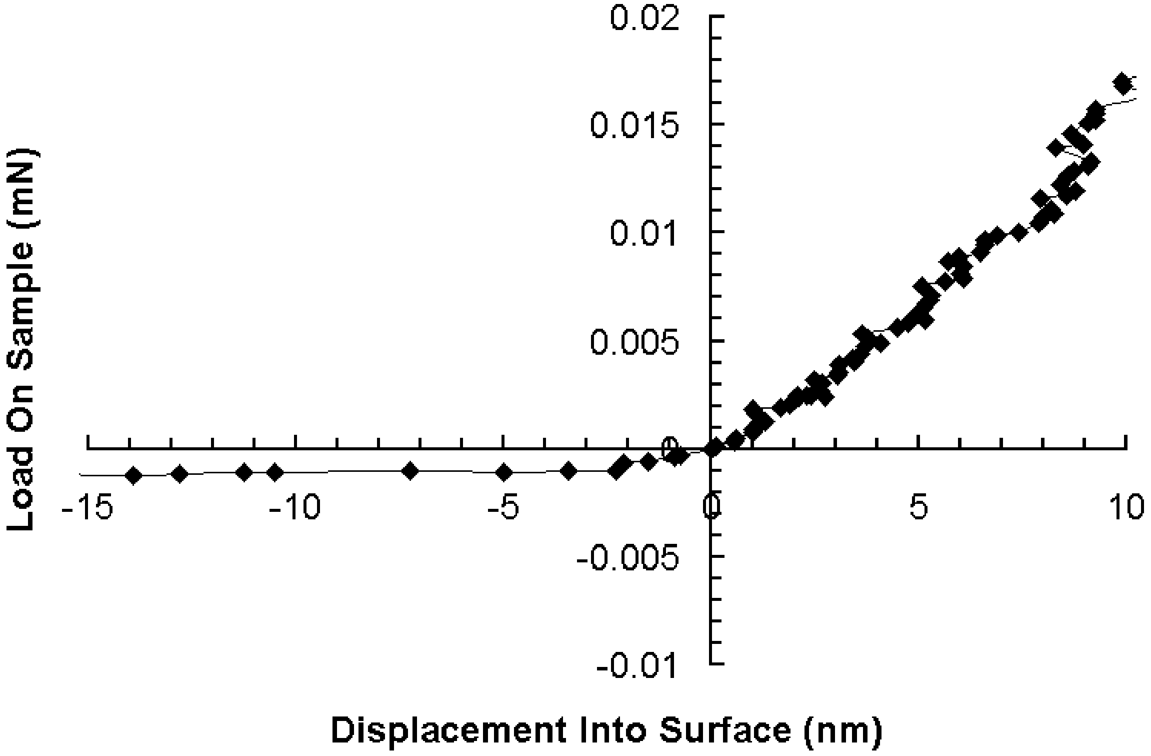
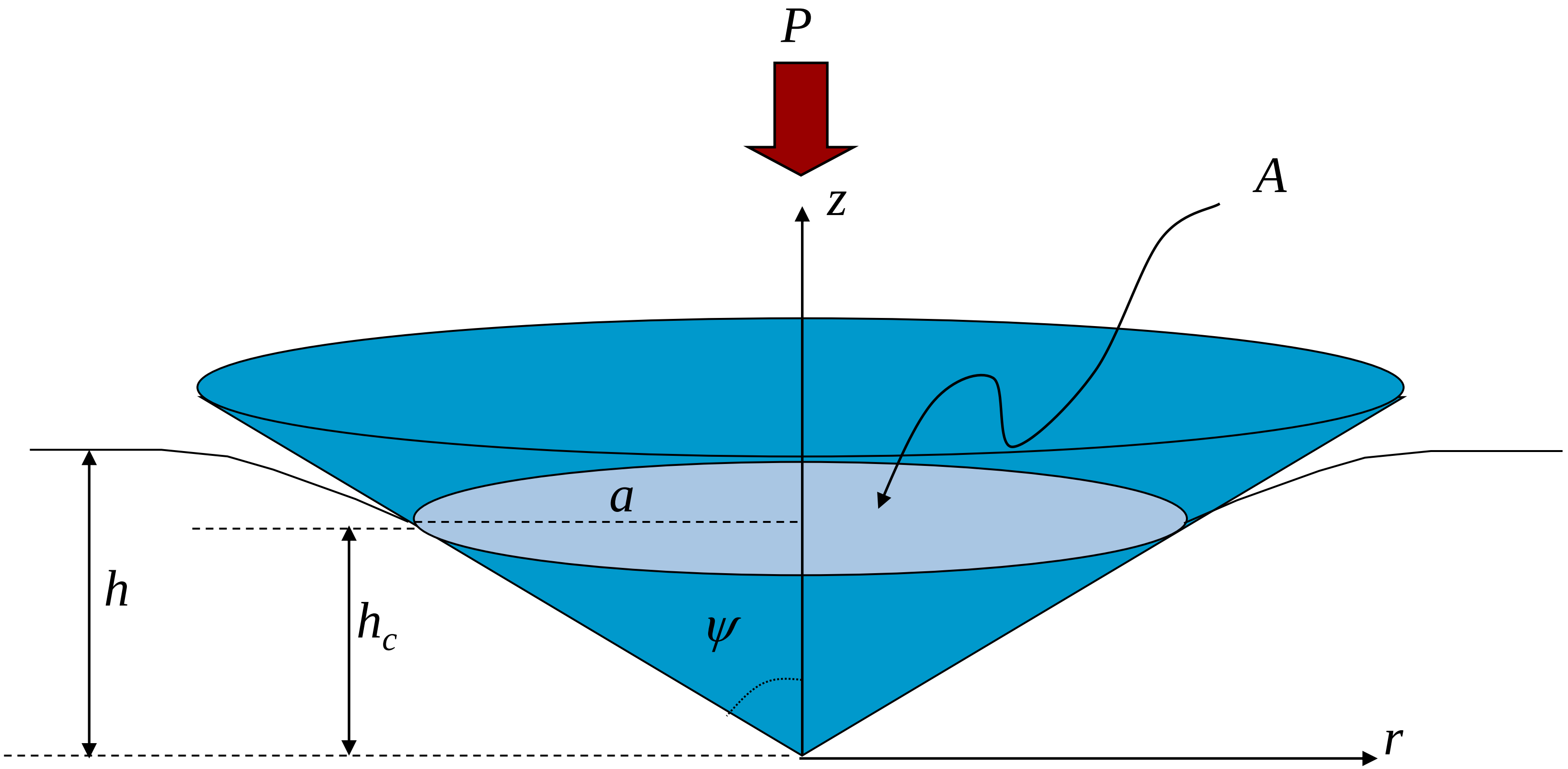
Determining the point of contact



Indentation schematic: Accounting for sink in



$$h_c < h$$

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Summary of IIT (nanoindentation) analysis

$$\frac{1}{E_r} = \frac{(1-\nu^2)}{E} + \frac{(1-\nu_i^2)}{E_i}$$

$$\sigma_y \approx H/3$$

$$H = P/A$$

$$E_r = \frac{\sqrt{\pi}}{2}\frac{S}{\sqrt{A}}$$

$$A = f(h_c)$$

$$h_c = h - 0.75P/S$$

$$S = \left.\frac{dP}{dh}\right|_{h_{max}}$$

Nomenclature:

E	Young's modulus
H	hardness
σ_y	Yield stress
E_r	reduced modulus
ν	Poisson's ratio
i	(as subscript) indenter
S	contact stiffness
A	projected contact area
h_c	contact depth
h	displacement
P	applied force (load)

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Determining contact stiffness, *S*

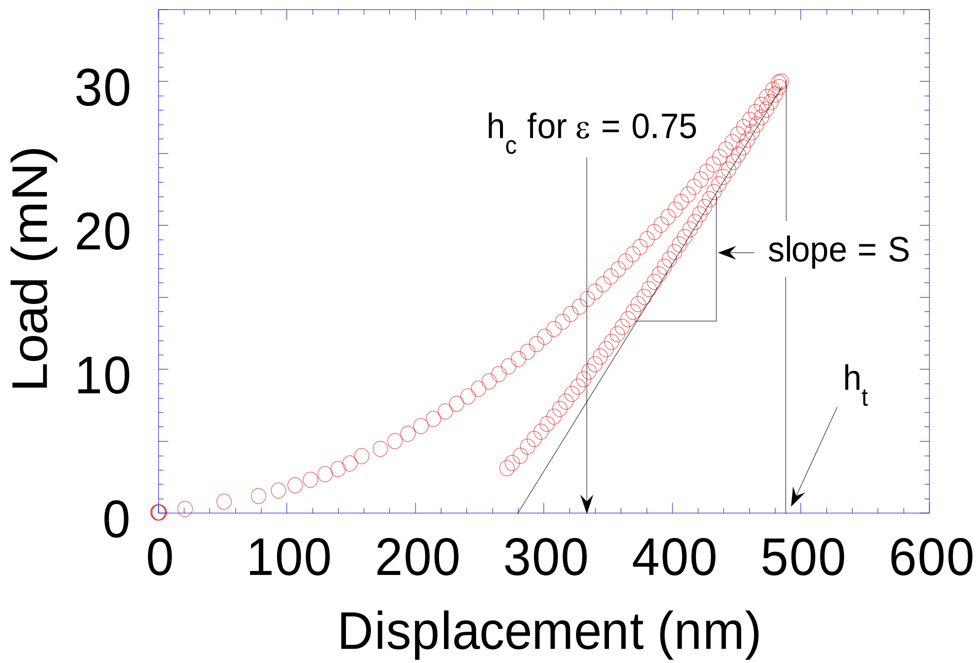
- Fit all unloading data for which $P > 0.5P_{max}$ (i.e. top half of unloading curve)

- Fit to the functional form

$$P = B(h-h_f)^m$$

- Analytically differentiate and evaluate at $h = h_{max}$:

$$S = \mathrm{d}P/\mathrm{d}h = Bm(h_{max} - h_f)^{m-1}$$



Problem at large depths: load frame stiffness

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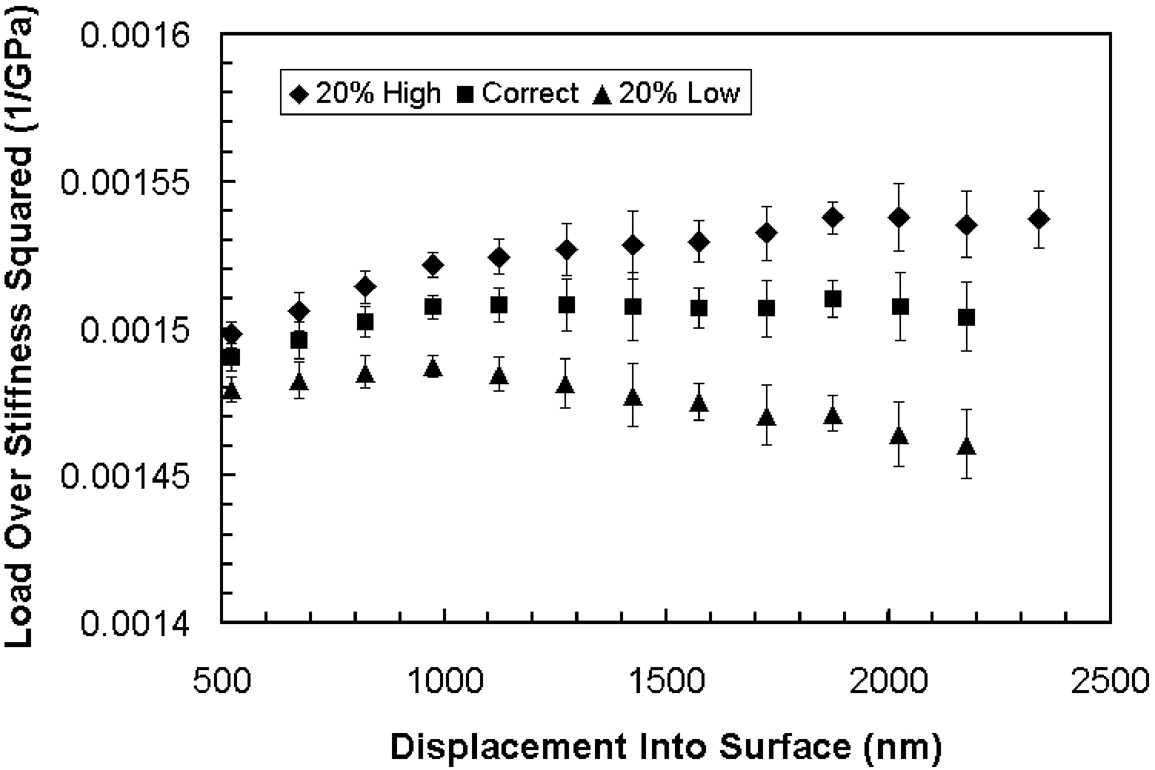
Correcting for load frame stiffness

$$E_r = \frac{\sqrt{\pi}}{2}\frac{S}{\sqrt{A}}$$

$$H = P/A$$

$$\frac{H}{E^2} \propto \frac{P}{S^2}$$



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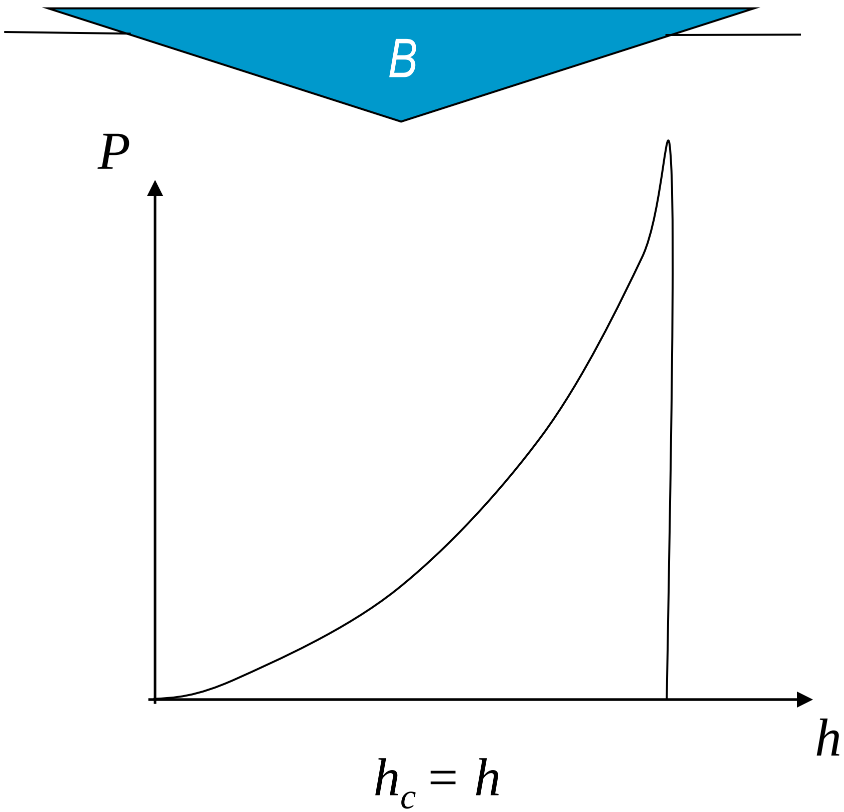
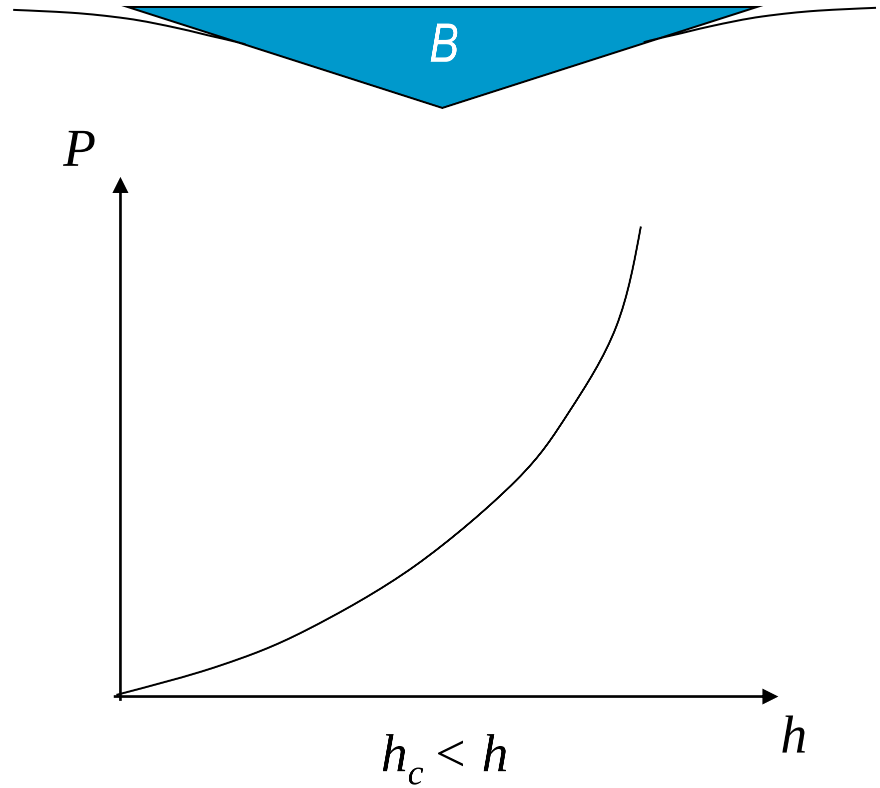
Intuitive "rightness" of $h_c = h - 0.75P/S$





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Problem at small depths: area function

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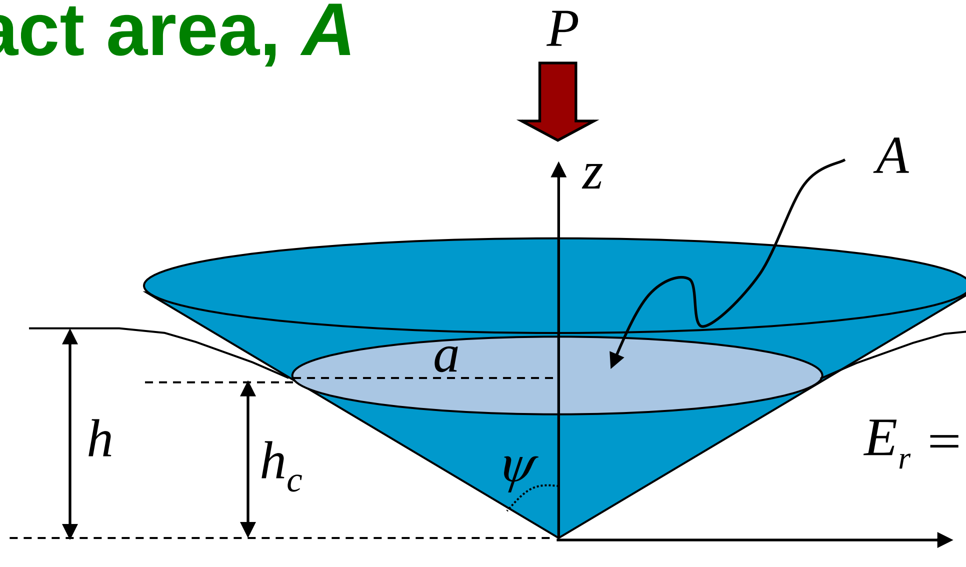
Determining contact area, *A*



$$E_r = \frac{\sqrt{\pi}}{2}\frac{S}{\sqrt{A}}$$

Generally:

$$A = \mathbf{f}(h_c)$$

Specifically:

Tip type	Area function	Comments
Perfect Berkovich	$A = 24.56h_c^2$	Used when h_c > 2 microns
Real Berkovich	$A = 24.56h_c^2 + Ch_c + B$	C is determined by indenting a known material and is about 150nm.
Sphere	$A = 2\pi Rh_c^2$	R is tip radius; value may be determined by indenting a known material.
Real cube-corner	$A = 2.60h_c^2 + Ch_c + B$	C is determined by indenting a known material and is about 150nm.
Flat-ended cylinder	$A = \pi a^2$	a is the punch radius; A is constant (independent of indentation depth)

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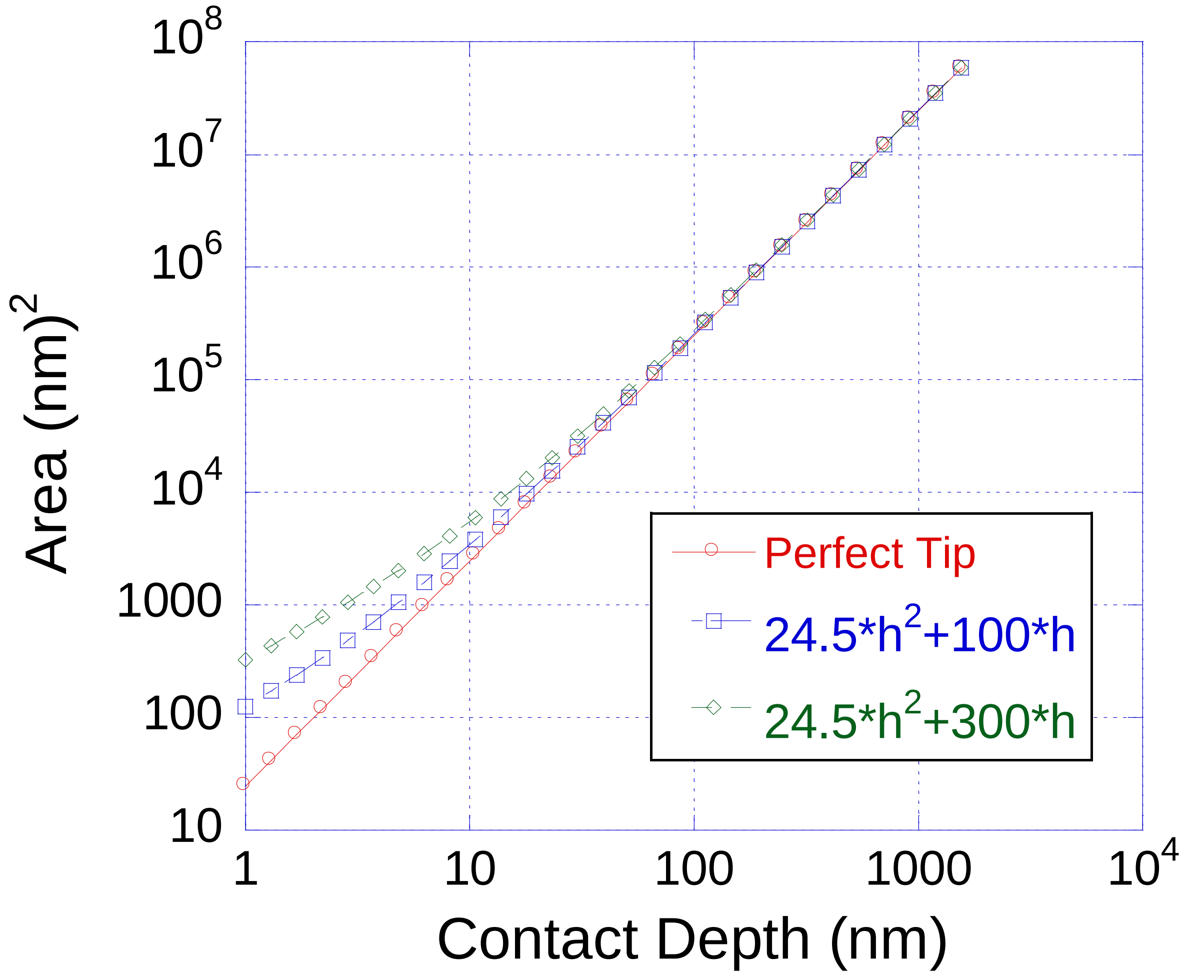
The problem at small depths: The effect of tip rounding on the contact area calculation



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Calculating yield stress from IIT

$$\sigma_y \approx H/3$$

- This relationship holds when testing metals with a Berkovich indenter.
- For many applications, it is sufficient to know the hardness; yield stress is not often calculated. When comparing similar materials, the material with the higher hardness will have the higher yield stress.

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Determining Young's modulus

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

(For diamond tip, ν_i = 0.07, E_i = 1141 GPa)

What? I have to know one elastic property (ν_s) in order to get the other (E_s)? Not fair! Actually, this is not as bad as it sounds.

$$E_s = E_r(1-\nu_s^{\ 2})$$

$$\delta E_s = \frac{\mathrm{d}\,E_s}{\mathrm{d}\,\nu}\delta\nu = 2E_r\nu\delta\nu$$

$$\frac{\delta E_s}{E_s} = \frac{2\nu}{\left(1-\nu^2\right)}\delta\nu$$

So, for a generous uncertainty of ν = 0.25±0.1

$$\frac{\delta E}{E} = \frac{2(0.25)}{\left(1-0.25^2\right)}(0.1) = 5.3\%$$

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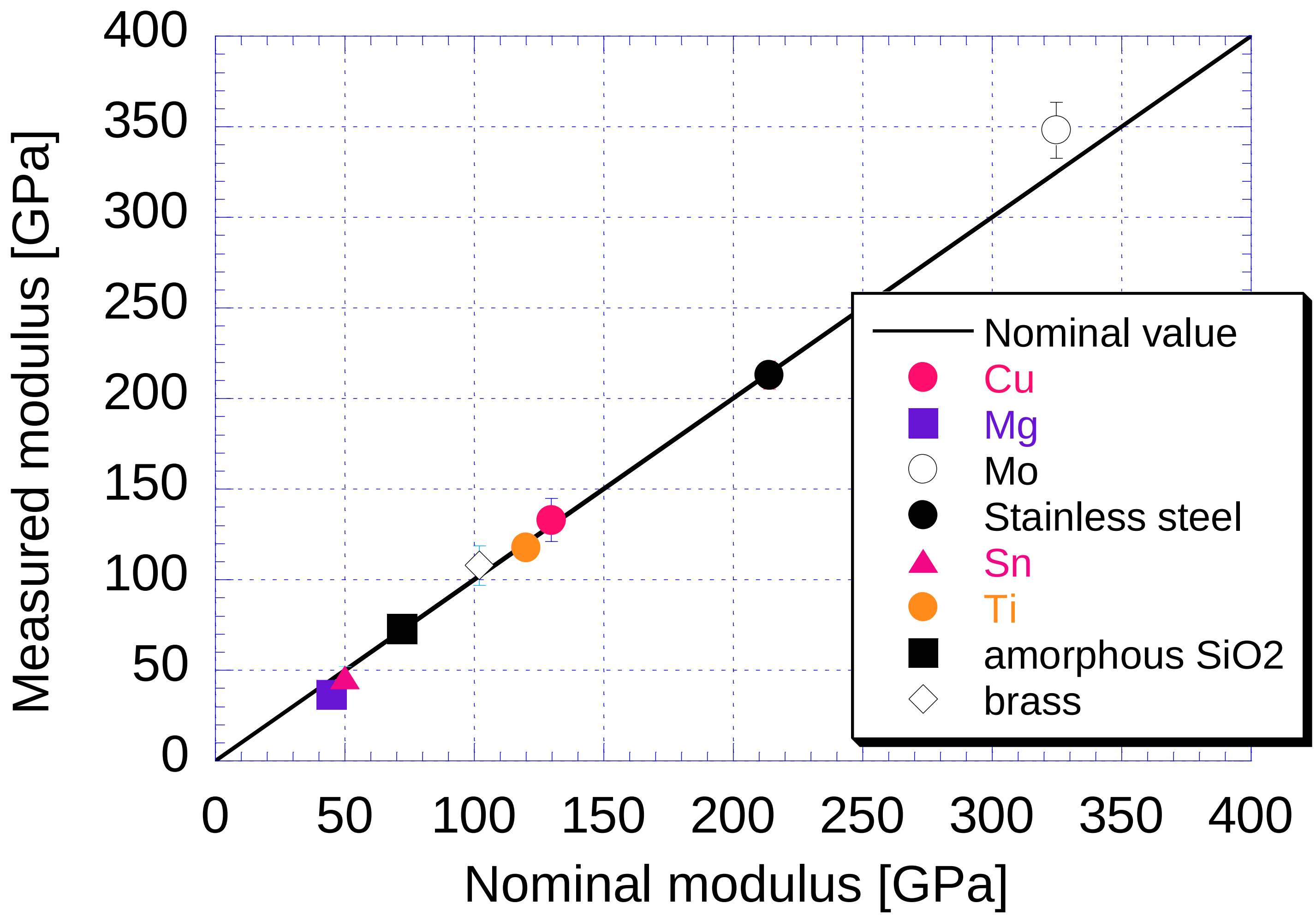
Getting Young's modulus by indentation



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QUESTIONS?

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