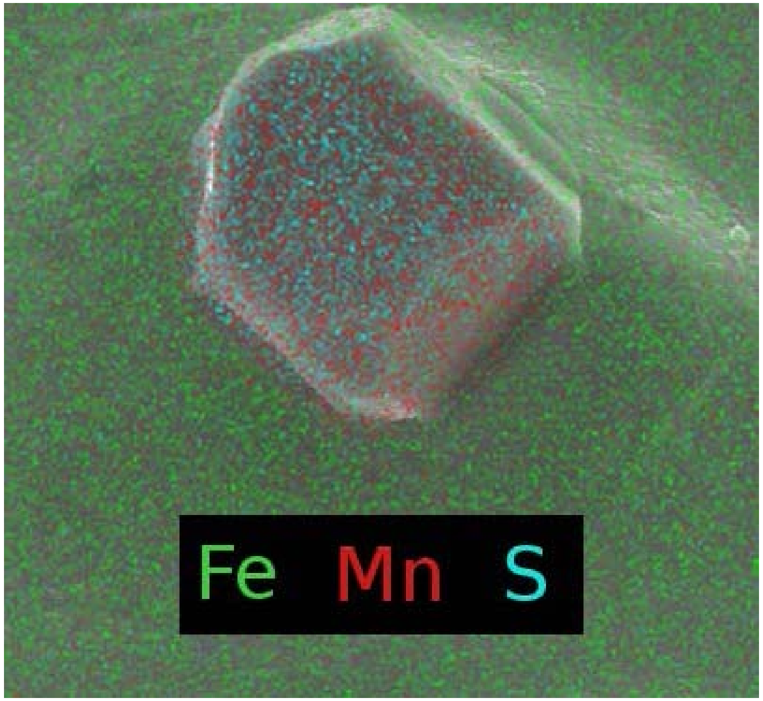
A Survey of Crystalline Defects

Outline – Defects

- 0D Defects
  - Vacancies & Interstitials
- 1D Defects (Dislocations)
- 2D Defects
  - Grain & twin boundaries
- 3D Defects
  - Coherent vs. incoherent inclusions, precipitates

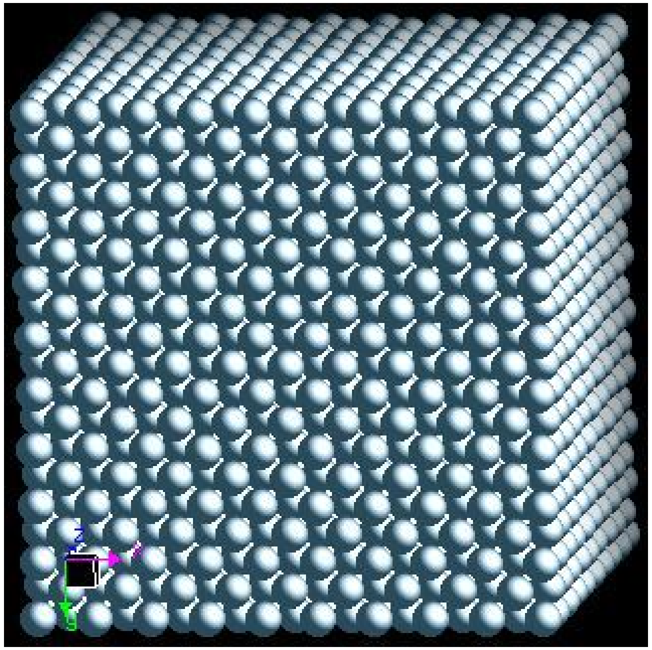


Single crystal of MnS, space group $Fm\bar{3}m$, FCC crystal structure

Crystalline Solids

http://www.webelements.com/calcium/crystal_structure.html

- Periodic, long-range ordered structures

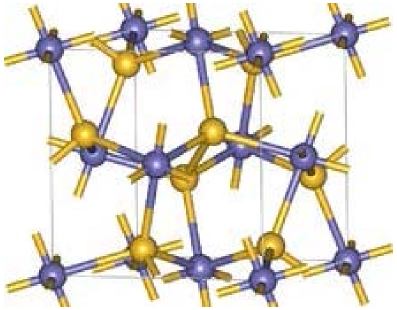


Face centered cubic calcium crystal structure

Single crystals of calcium metal under kerosene

Form Follows Structure

http://www.zkg.de/en/artikel/bildpopup_en_1698578.html?image=5



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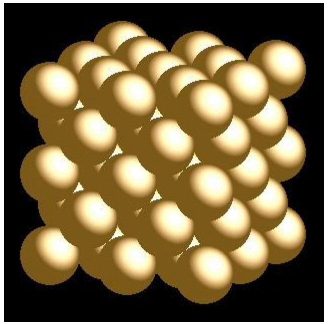

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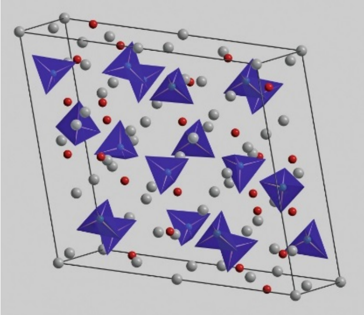

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Pyrite (FeS_2), simple cubic (SC)

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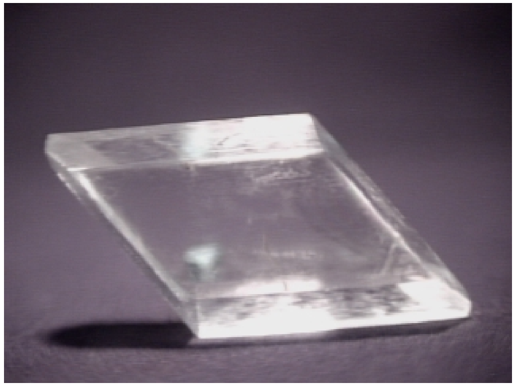
Gold (Au), face centered cubic (FCC)

http://www.palaminerals.com/news_2007_v2.php



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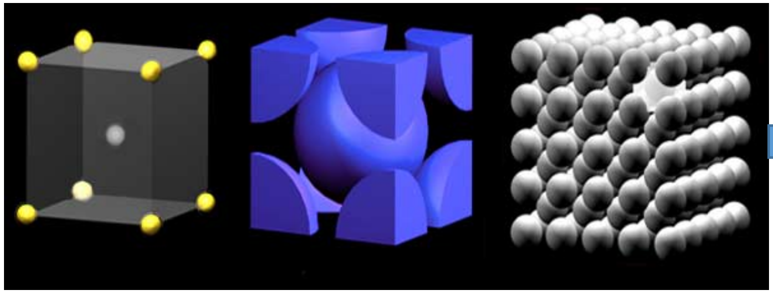
Gypsum, monoclinic

http://www.galleries.com/minerals/symmetry/monoclin.htm

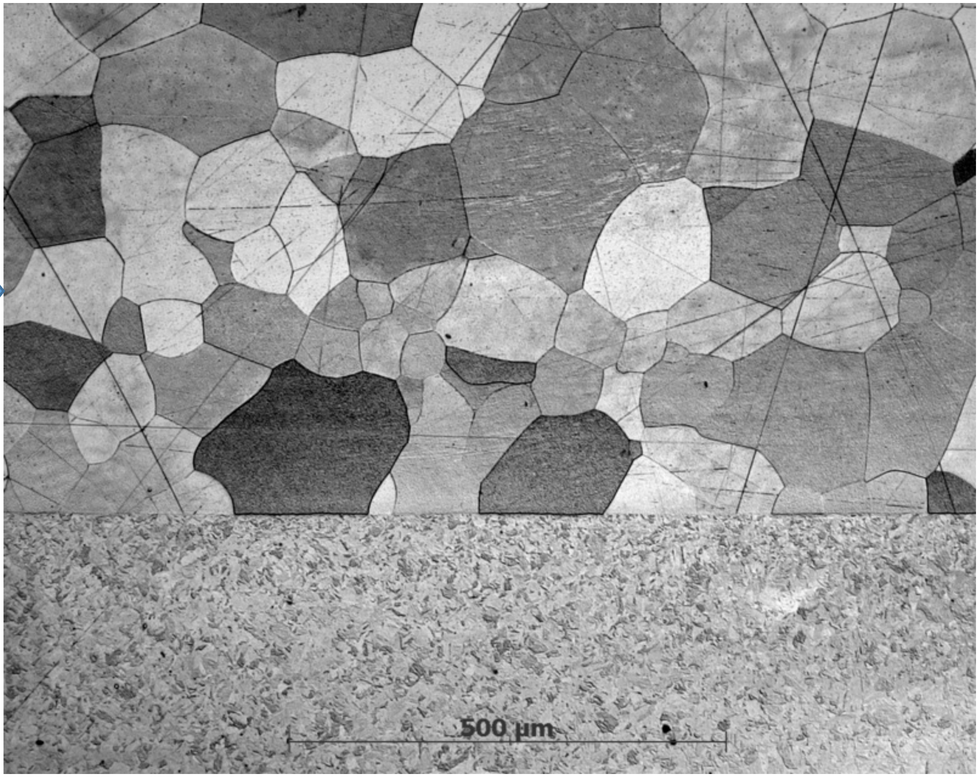
Grain vs. Crystal Structure

- Why do grains look more spherical, when crystal structures are cubic?



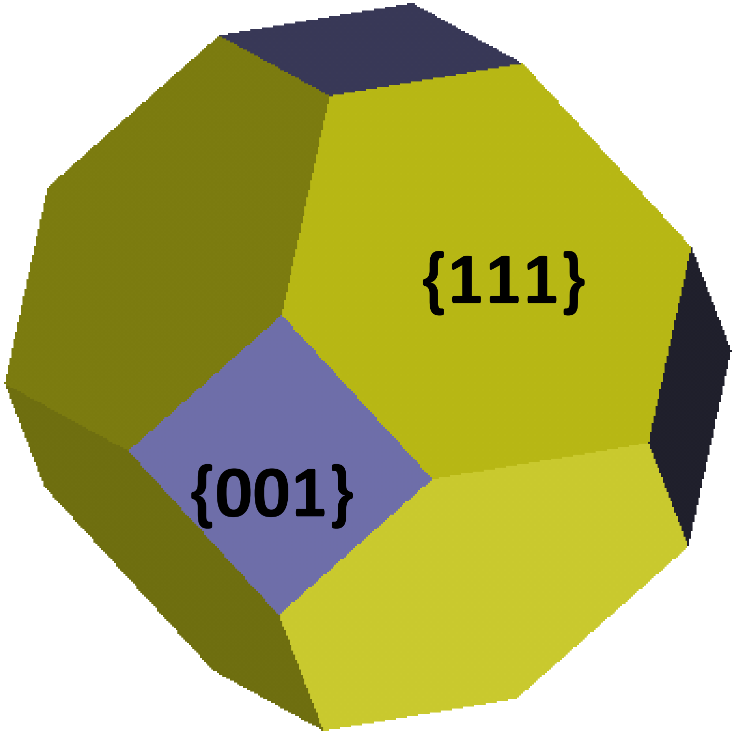
https://www.nde-ed.org/EducationResources/CommunityCollege/Materials/Graphics/CrystalStructure/BCC.jpg

Body centered cubic (BCC) iron crystal structure (left), micrograph of Fe-12Cr-2Si (right)



Grain vs. Crystal Structure

- Wulff crystals describe *lowest energy* surfaces
- Exposing *close packed planes* lowers surface energy

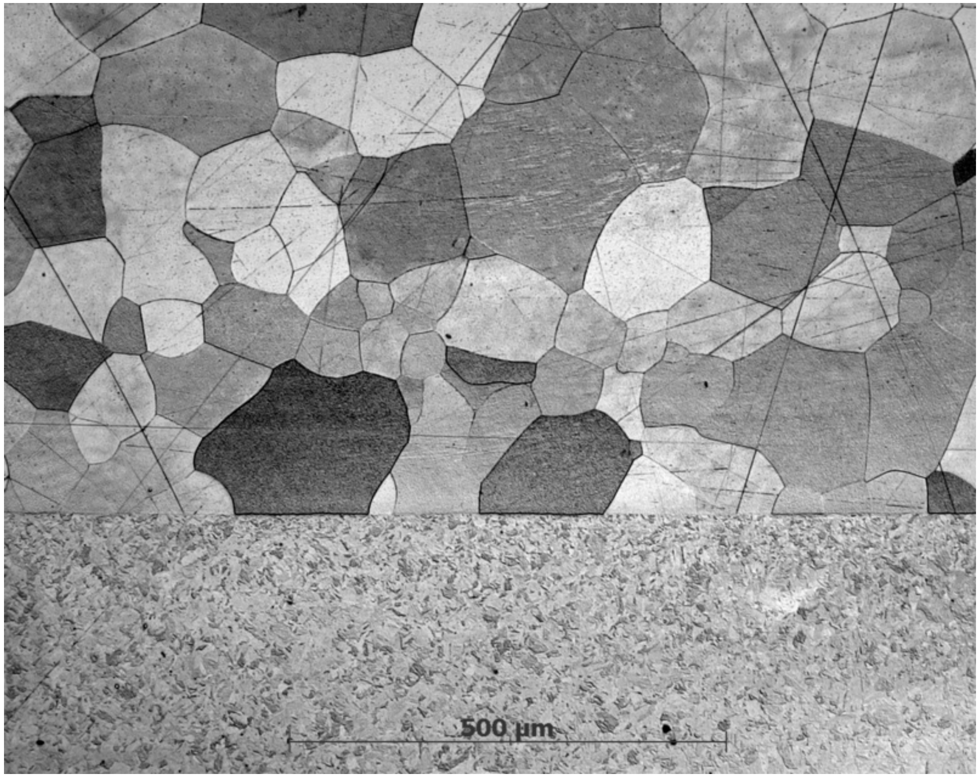


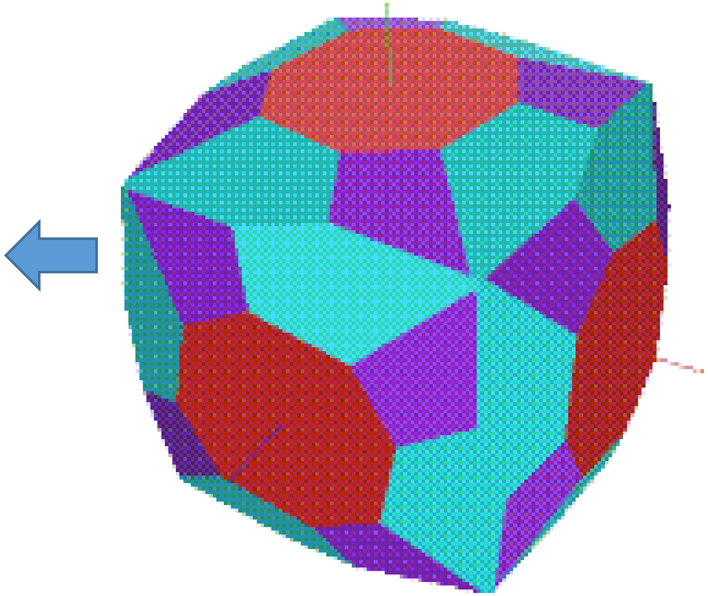
This image is in the public domain.

http://www.ctcms.nist.gov/wulffman/examples.html

Grain vs. Crystal Structure

- We see 2D slices of Wulff crystals as grains!





http://www.ctcms.nist.gov/wulffman/examples.html

Point Defects (0D) – Vacancies

Was, p. 163

[Was, Gary S. *Fundamentals of Radiation Materials Science,* p. 163. ISBN: 9783540494713.] removed due to copyright restrictions.

Point Defects (0D) – Multiple Vacancies

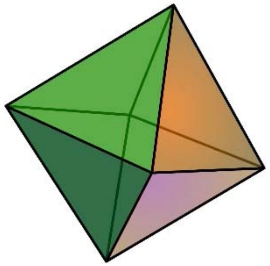
Was, p. 163

[Was, Gary S. *Fundamentals of Radiation Materials Science,* p. 163. ISBN: 9783540494713.] removed due to copyright restrictions.

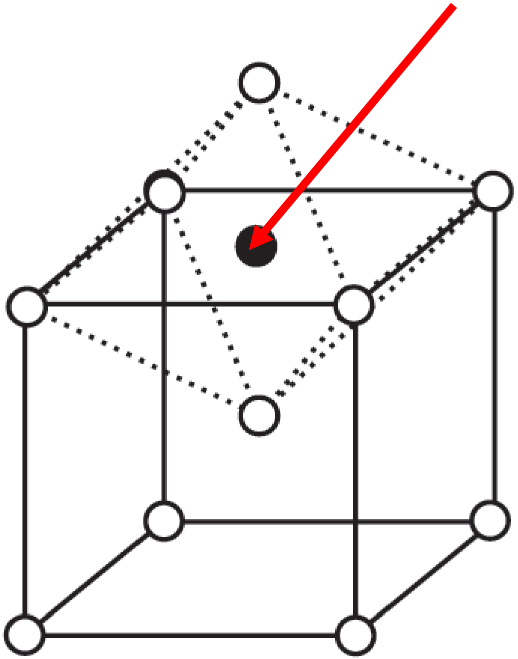
Point Defects (0D) – Interstitials

Was, p. 157

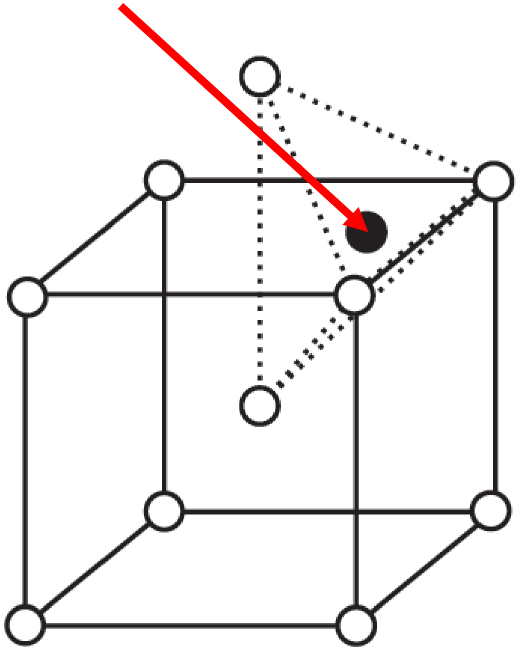
- Extra atoms shoved into the crystal lattice



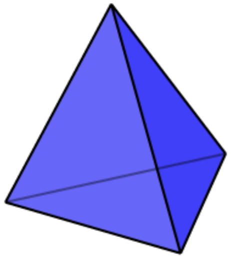
Octahedron



Octahedral interstitial in BCC lattice



Tetrahedral interstitial in BCC lattice

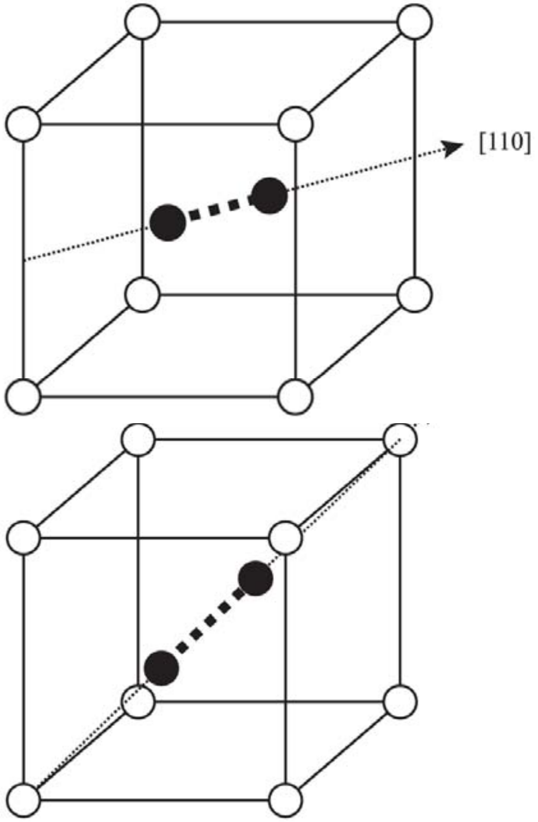


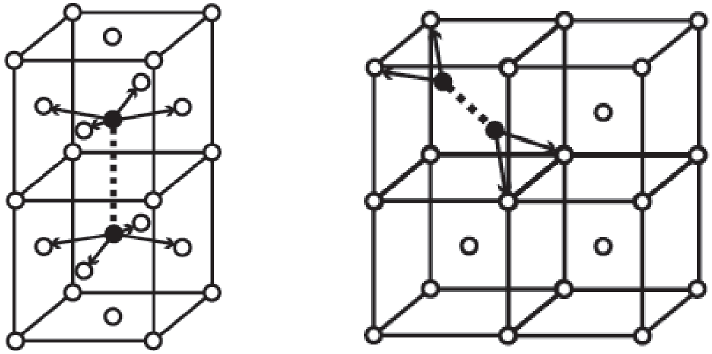
Tetrahedron

Point Defects (0D) – Split Interstitials

Was, p. 159

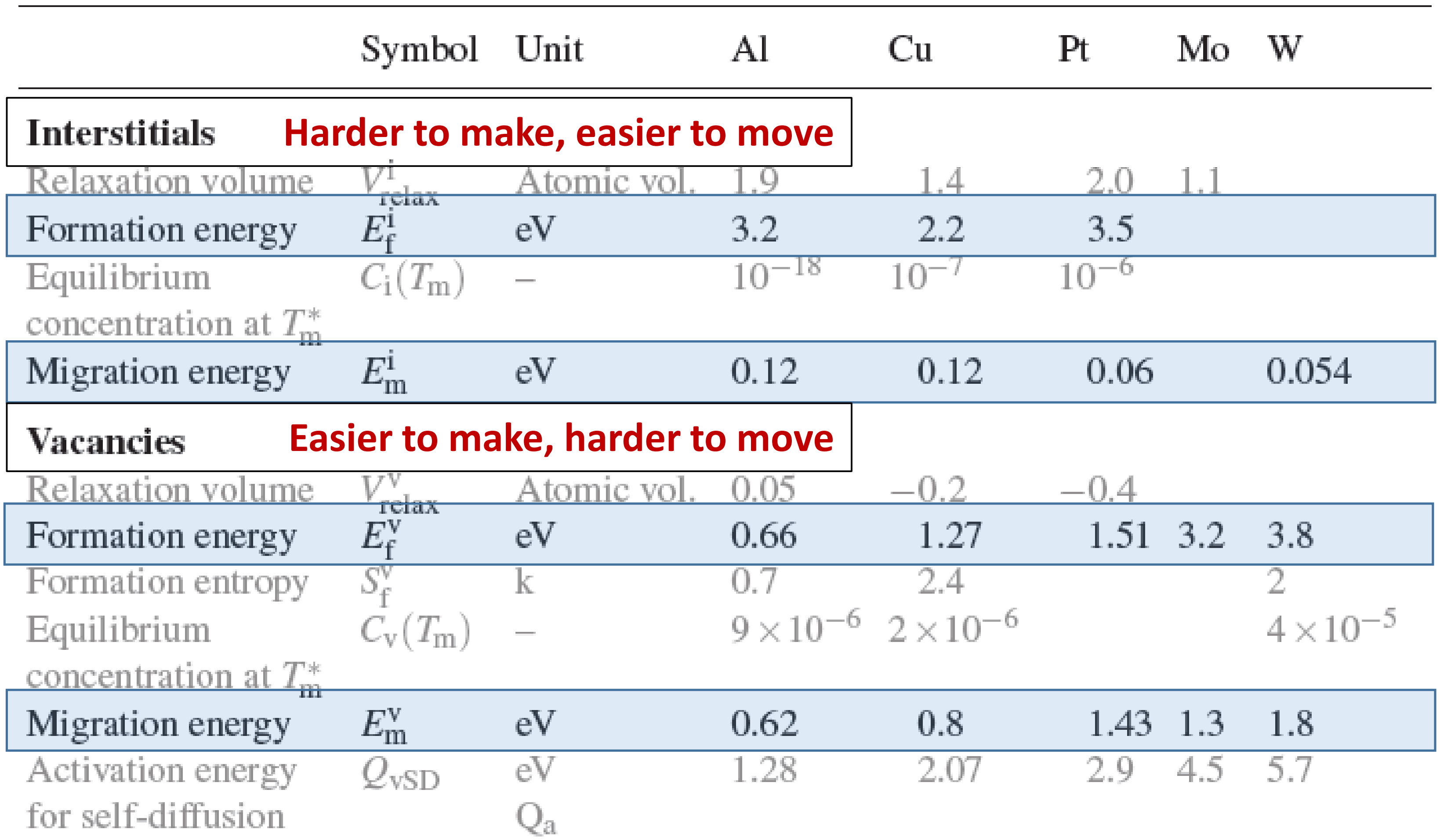
- Dumbbells are often lower energy configurations
- Also much easier to diffuse
  - One interstitial can "knock" the other in their common direction
  - Lower distance to movement





Point Defect Energies

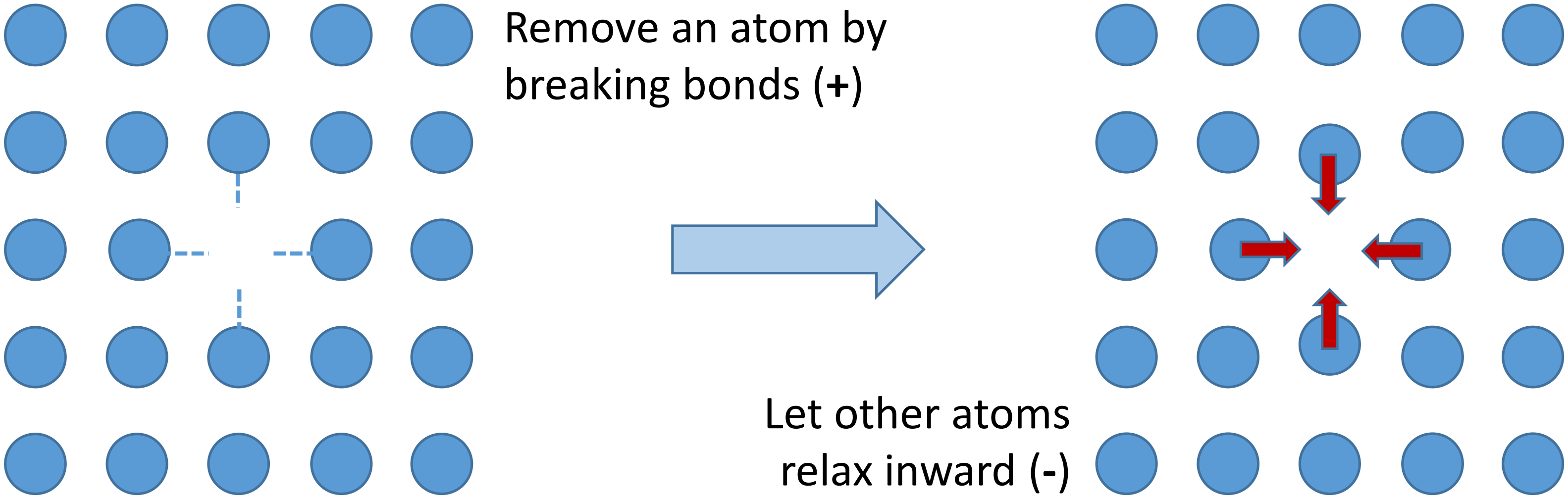
Was, p. 160



	Symbol	Unit	Al	Cu	Pt	Mo	W
Interstitials Harder to make, easier to move							
Relaxation volume	V^{i}_{relax}	Atomic vol.	1.9	1.4	2.0	1.1	
Formation energy	E^{i}_{f}	eV	3.2	2.2	3.5		
Equilibrium concentration at T^{*}_{m}	$C_{i}(T_{m})$	–	10^{-18}	10^{-7}	10^{-6}		
Migration energy	E^{i}_{m}	eV	0.12	0.12	0.06		0.054
Vacancies Easier to make, harder to move							
Relaxation volume	V^{v}_{relax}	Atomic vol.	0.05	−0.2	−0.4		
Formation energy	E^{v}_{f}	eV	0.66	1.27	1.51	3.2	3.8
Formation entropy	S^{v}_{f}	k	0.7	2.4			2
Equilibrium concentration at T^{*}_{m}	$C_{v}(T_{m})$	–	9×10^{-6}	2×10^{-6}			4×10^{-5}
Migration energy	E^{v}_{m}	eV	0.62	0.8	1.43	1.3	1.8
Activation energy for self-diffusion	Q_{vSD}	eV Qa	1.28	2.07	2.9	4.5	5.7

Point Defect Energetics

- How much energy to make a vacancy?



Remove an an atom by breaking bonds (**+**)

Let other atoms relax inward (**-**)

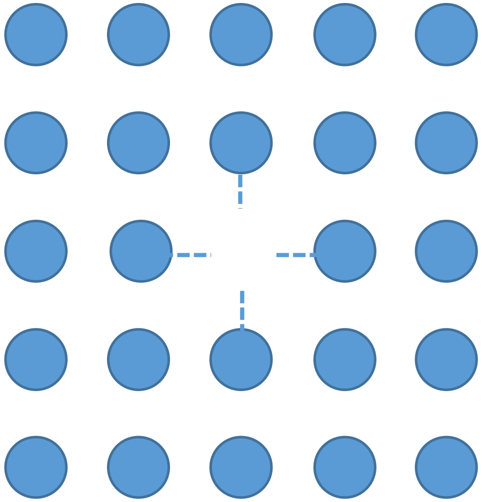
Point Defect Energetics

- How much energy to make a vacancy?
- Fe-Fe bond dissociation energy:

  $118\frac{kJ}{mol} = 1.22eV$ [1]

  - Fe-Fe cluster calculations give 0.64eV [2]
- Z=8 in BCC Fe: $5.12 - 9.76eV$

Remove an atom by breaking bonds (**+**)



[1] Y-R Luo. "Bond Dissociation Energies." CRC Handbook (2009)
[2] T. Nakazawa, T. Igarashi, T. Tsuru, Y. Kaji, *Comp. Mater. Sci.*, 46(2):367-375 (2009)

Point Defect Energetics

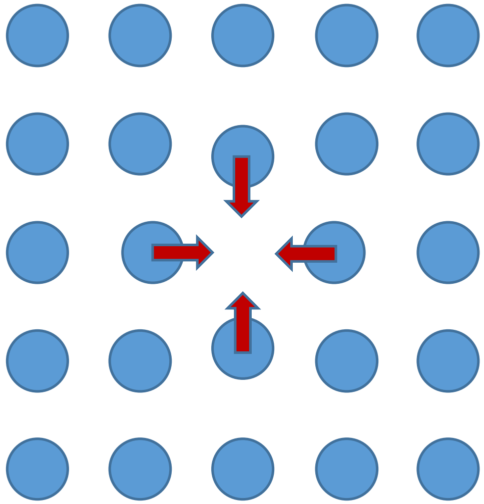
- Z=8 in BCC Fe:

  $5.12\ [2] - 9.76\ [1]\ eV$

- Molecular dynamics (MD) calculations [3] show:

  $$E_{Vacancy} = 1.83eV$$

- Difference due to crystal relaxation



Let other atoms relax inward (-)

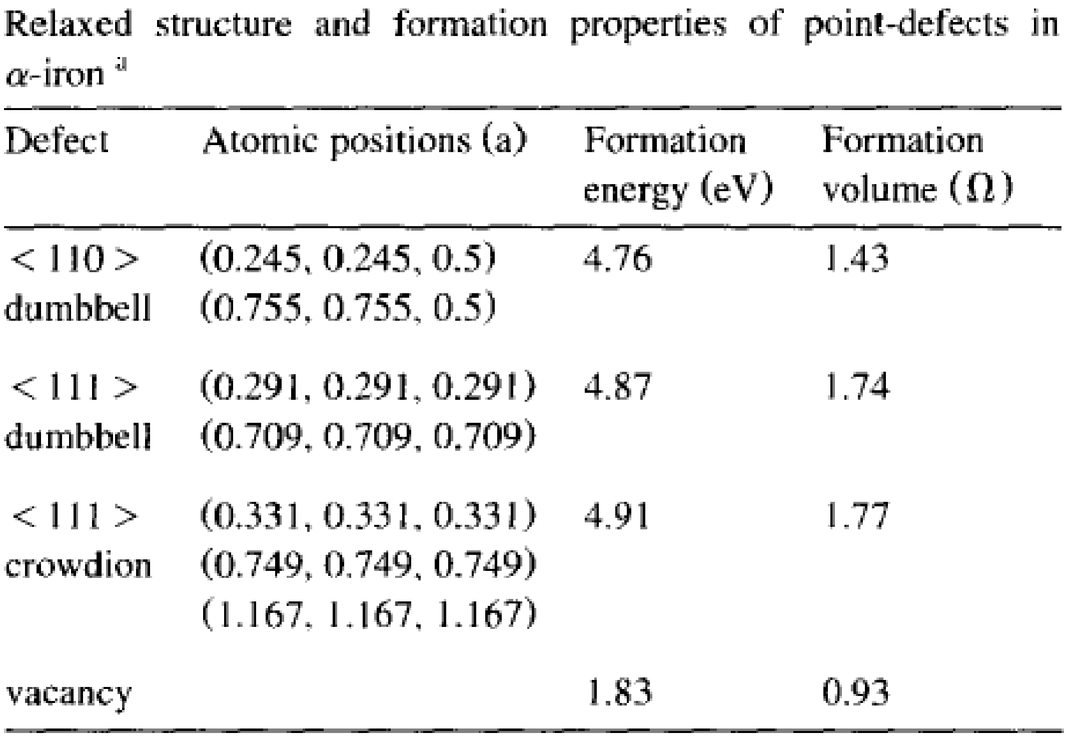
[1] Y-R Luo. "Bond Dissociation Energies." CRC Handbook (2009)

[2] T. Nakazawa, T. Igarashi, T. Tsuru, Y. Kaji, *Comp. Mater. Sci.*, 46(2):367-375 (2009)

[3] B. D. Wirth et al. *J. Nucl. Mater.*, 244:185:194 (1997)

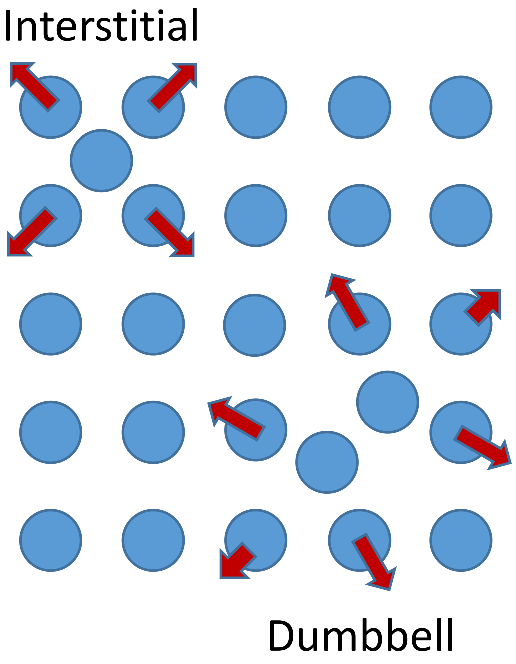
Point Defect Energetics

- Which interstitial is most stable?



Relaxed structure and formation properties of point-defects in α-iron [a]

Defect	Atomic positions (a)	Formation energy (eV)	Formation volume (Ω)
< 110 > dumbbell	(0.245, 0.245, 0.5) (0.755, 0.755, 0.5)	4.76	1.43
< 111 > dumbbell	(0.291, 0.291, 0.291) (0.709, 0.709, 0.709)	4.87	1.74
< 111 > crowdion	(0.331, 0.331, 0.331) (0.749, 0.749, 0.749) (1.167, 1.167, 1.167)	4.91	1.77
vacancy		1.83	0.93



Courtesy of Elsevier, Inc., http://www.sciencedirect.com. Used with permission.
Source: Wirth, B. D., et al. "Energetics of Formation and Migration of Self-interstitials and Self-interstitial Clusters in α-iron." *Journal of Nuclear Materials* 244, no. 3 (1997): 185-94.

B. D. Wirth et al. *J. Nucl. Mater.*, 244:185:194 (1997)

Point Defect Energetics

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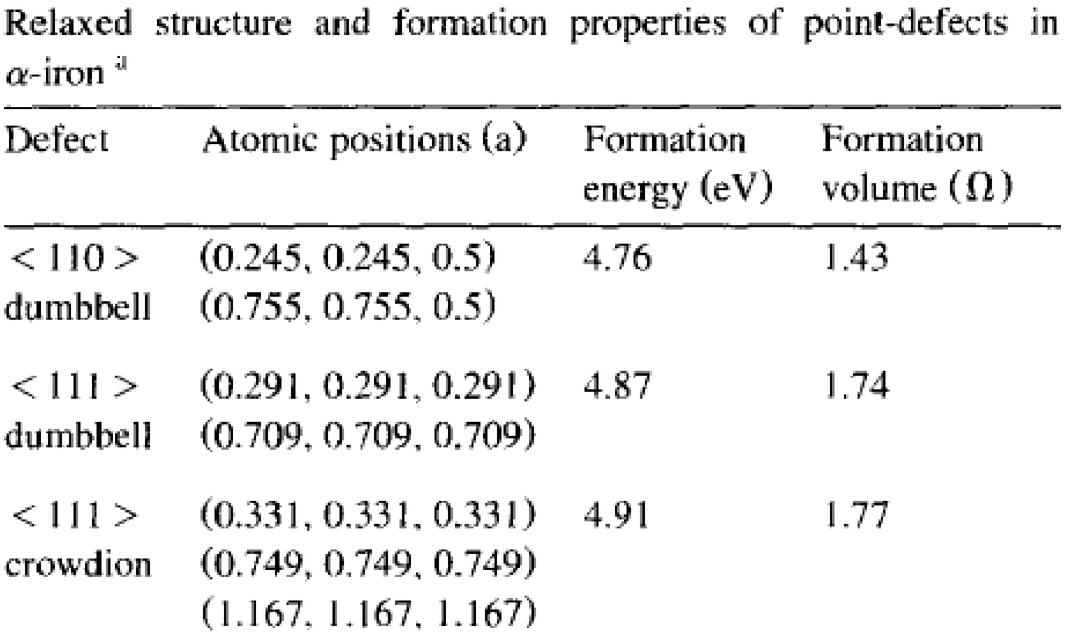

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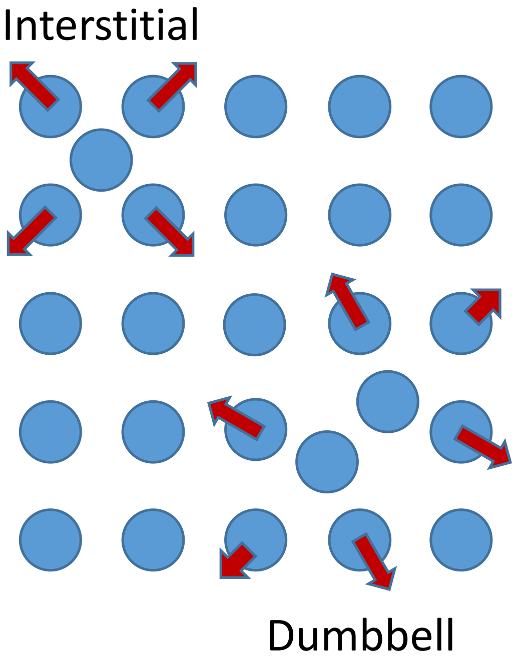
Source: Wirth, B. D., et al. "Energetics of Formation and Migration of Self-interstitials and Self-interstitial Clusters in α-iron." *Journal of Nuclear Materials* 244, no. 3 (1997): 185-94.



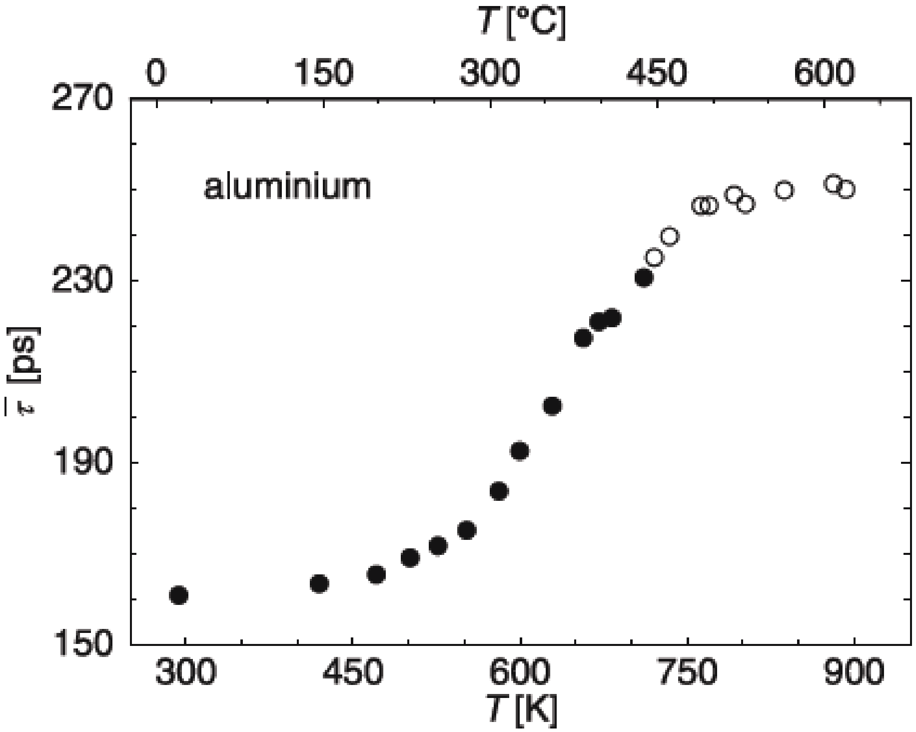
B. D. Wirth et al. *J. Nucl. Mater.*, 244:185:194 (1997)

- Does it matter?

Direct Measurement of C_{1V}^{eq}

Mehrer, p. 78

- Positron annihilation spectroscopy (PAS)
  - Shoot positrons into material, they annihilate very quickly with local electrons
  - Positrons can bind to vacancy, which has a reduced electron cloud
  - Lasts longer!

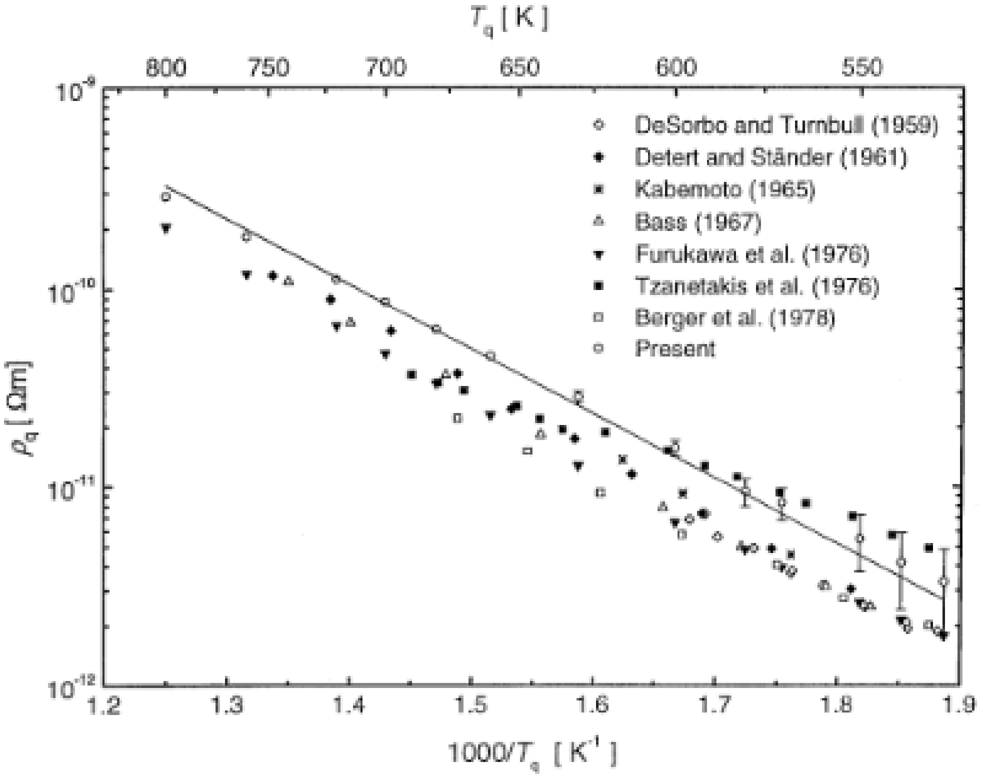


Mean positron lifetime in aluminum

Direct Measurement of C_{1V}^{eq}

A. Khellaf et al., Mater. Trans. 43(2):186 (2002)

- Quenching resistance measurements
  - Heat material to high temperature, quench, measure resistivity
  - Resistivity directly proportional to vacancy concentration
  - Measured at liquid-He temperature



Resistivity of aluminum vs. quenching temperature

Dislocations (1D)

Was, p. 268

- Extra half-plane of atoms shoved into the lattice
- Two types: **Edge** & Screw

[Fig. 7.2 in p. 268 from Was, Gary S. *Fundamentals of Radiation Materials Science*, ISBN: 9783540494713] removed due to copyright restrictions.

Dislocations (1D)

Was, p. 268

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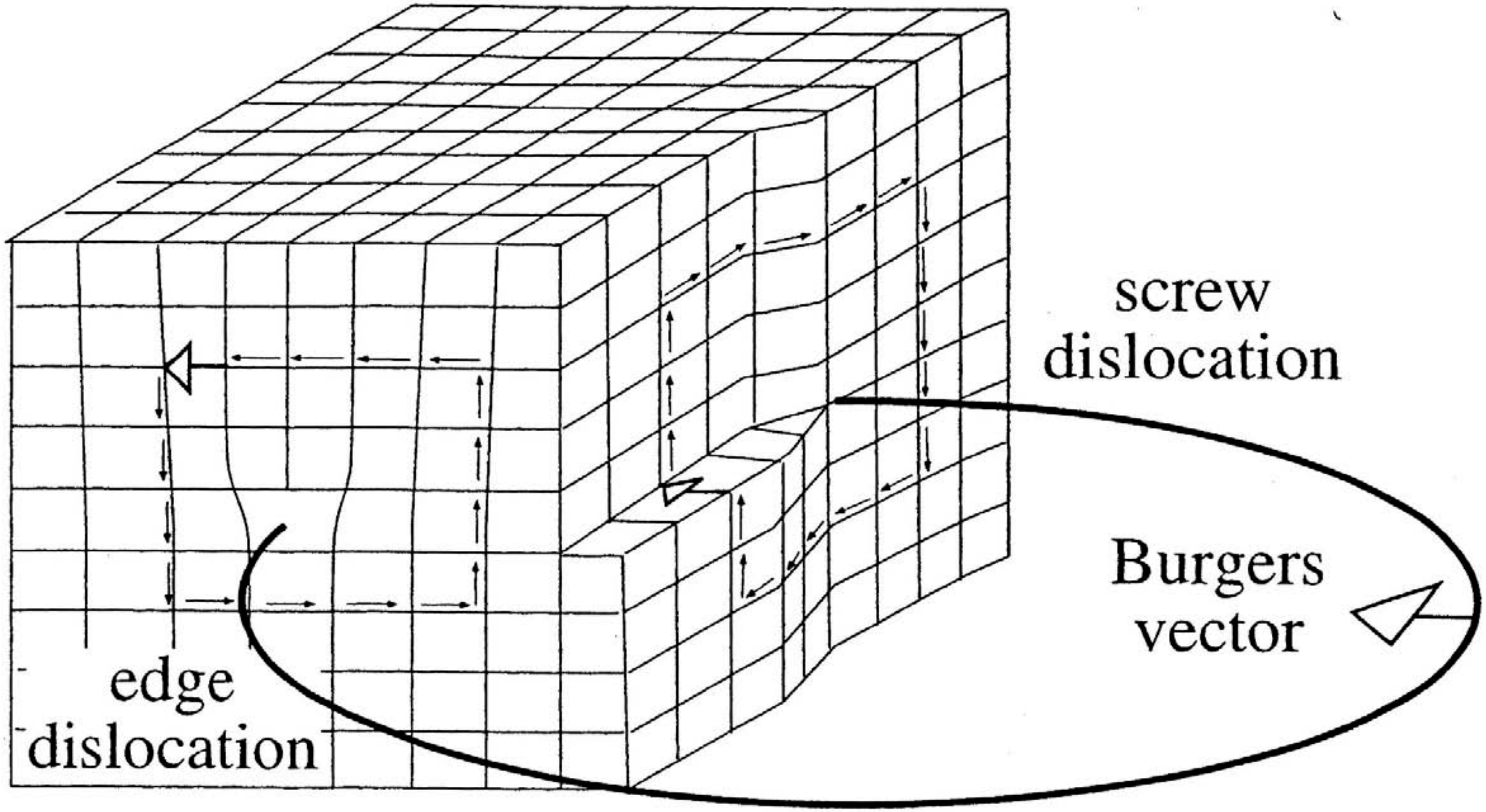
Edge vs. Screw Dislocations

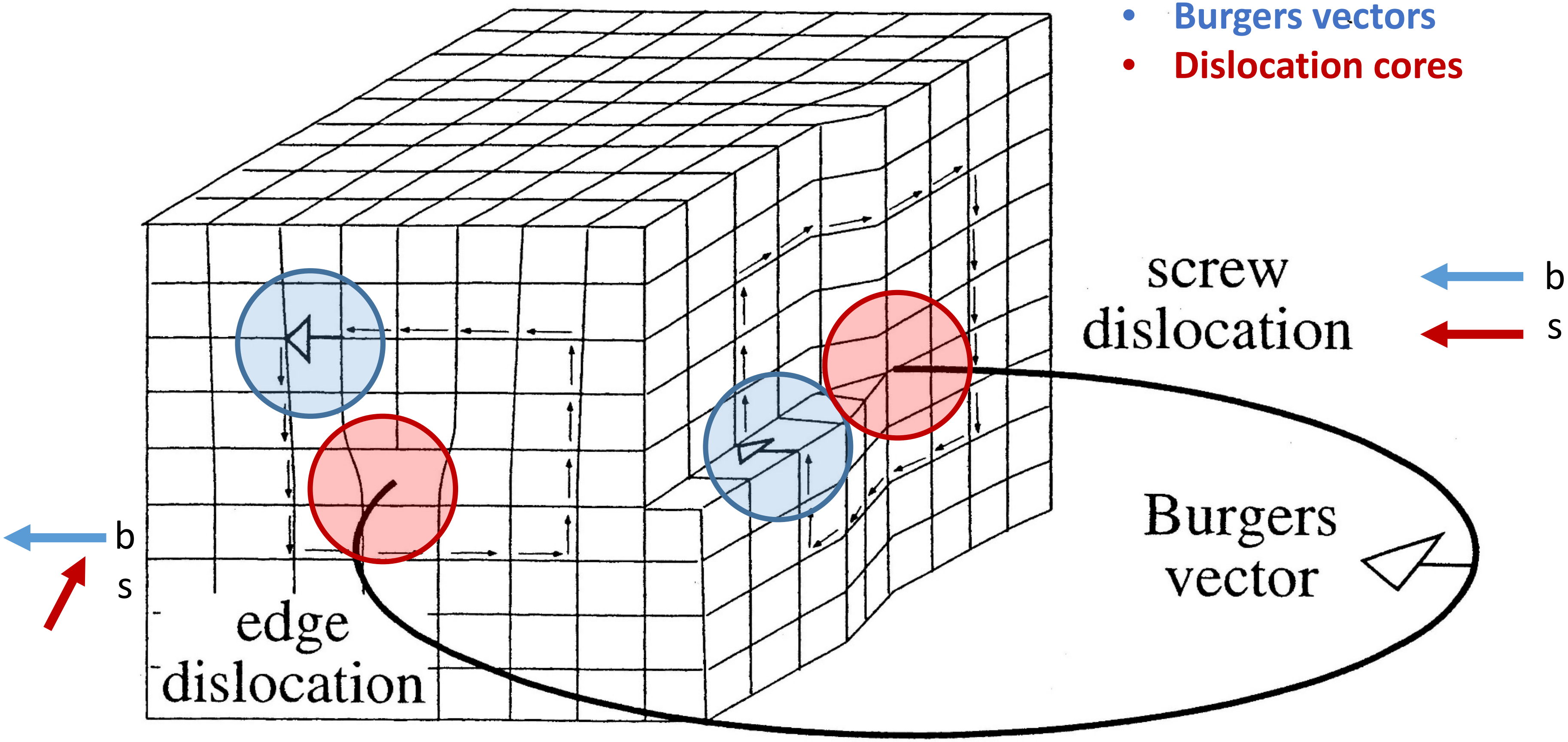
Passchier and Trouw, “Microtectonics,” p. 33 (2005)



Edge vs. Screw Dislocations

Passchier and Trouw, "Microtectonics," p. 33 (2005)

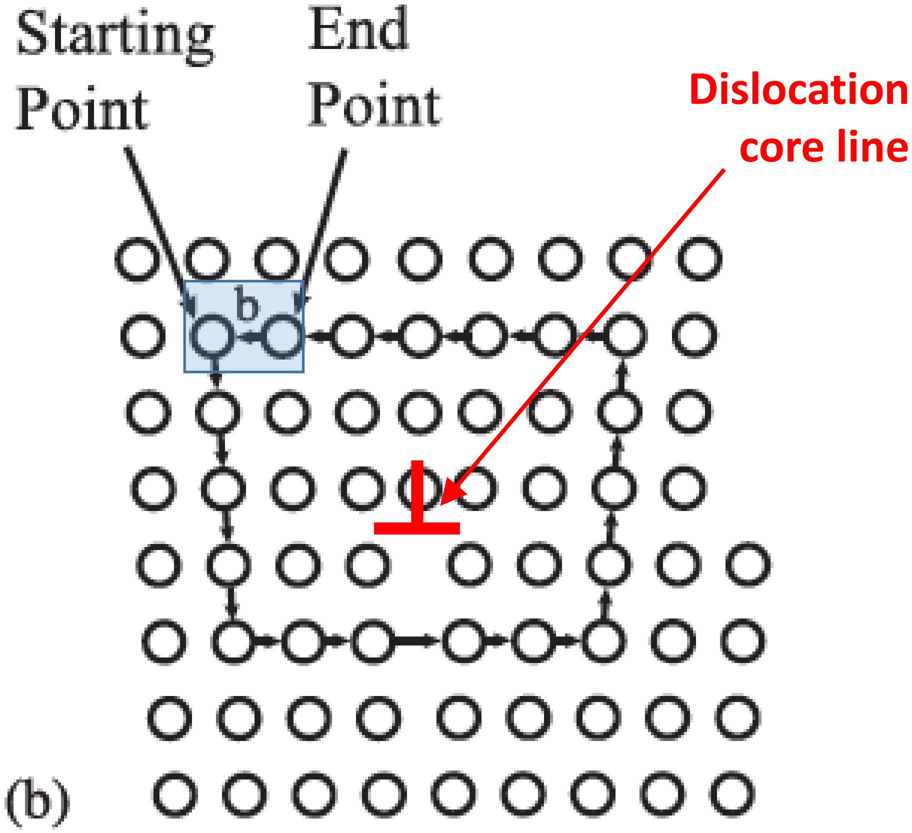
- Burgers vectors
- Dislocation cores



The Burgers Vector

Was, p. 275

- Start at one atom, make a circle around the dislocation core
- The *Burgers Vector* is the direction you move to reach your starting point
- <u>Example:</u> Edge disloc.



Dislocation Glide

Was, p. 272

- Movement one plane at a time along the slip direction

[Fig. 7.8 in p. 272 from Was, Gary S. *Fundamentals of Radiation Materials Science*, ISBN: 9783540494713] removed due to copyright restrictions.

Edge Dislocation Glide

A video is played in class to demonstrate the concept.

http://youtu.be/kk2oOxSDQ7U

Dislocation Glide

- Movement one plane at a time along the slip direction

[Fig. 7.9 from Was, Gary S. *Fundamentals of Radiation Materials Science.* ISBN: 9783540494713] removed due to copyright restrictions.

Dislocation Climb

Was, p. 273

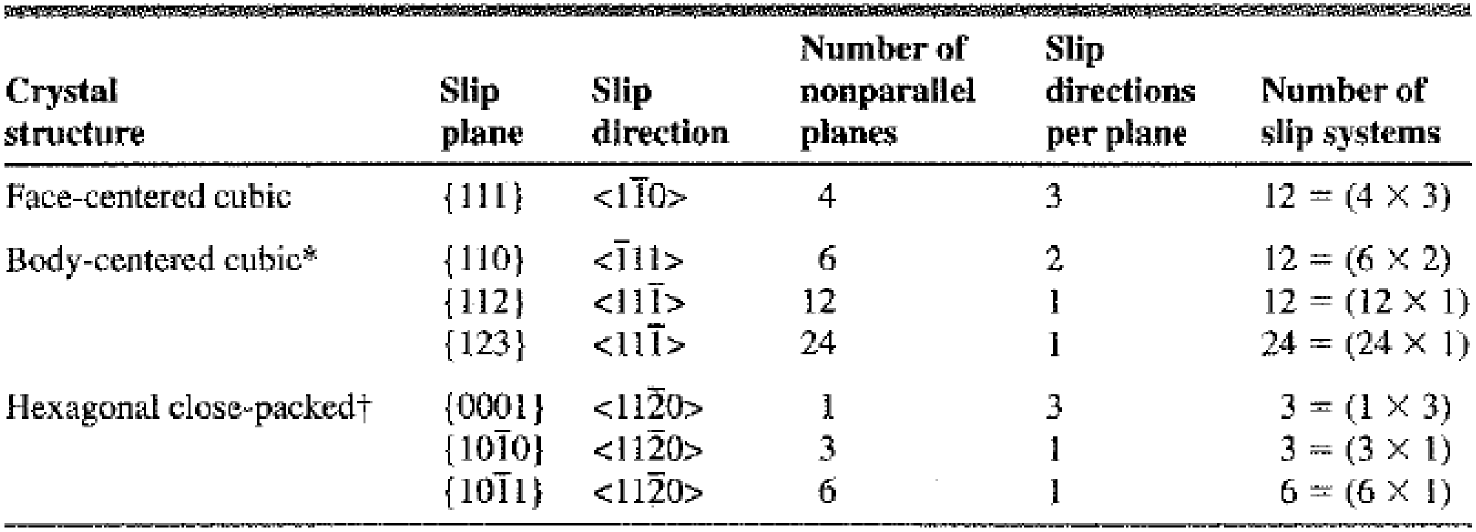
- Vacancy diffusion to dislocation core
  - Vacancies are attracted to the compressive stress at core

[Fig. 7.12 in p. 273 from Was, Gary S. *Fundamentals of Radiation Materials Science*, ISBN: 9783540494713] removed due to copyright restrictions.

Dislocation Kinks, Jogs

Allen, “Kinetics of Materials,” p. 116

- Dislocations preferentially move on slip systems
  - Certain directions of easier movement
  - Close packed planes slip in close packed directions



Crystal structure	Slip plane	Slip direction	Number of nonparallel planes	Slip directions per plane	Number of slip systems
Face-centered cubic	$\{111\}$	$\langle 1\bar{1}0\rangle$	4	3	12 = (4 × 3)
Body-centered cubic*	$\{110\}$	$\langle \bar{1}11\rangle$	6	2	12 = (6 × 2)
	$\{112\}$	$\langle 11\bar{1}\rangle$	12	1	12 = (12 × 1)
	$\{123\}$	$\langle 11\bar{1}\rangle$	24	1	24 = (24 × 1)
Hexagonal close-packed†	$\{0001\}$	$\langle 11\bar{2}0\rangle$	1	3	3 = (1 × 3)
	$\{10\bar{1}0\}$	$\langle 11\bar{2}0\rangle$	3	1	3 = (3 × 1)
	$\{10\bar{1}1\}$	$\langle 11\bar{2}0\rangle$	6	1	6 = (6 × 1)

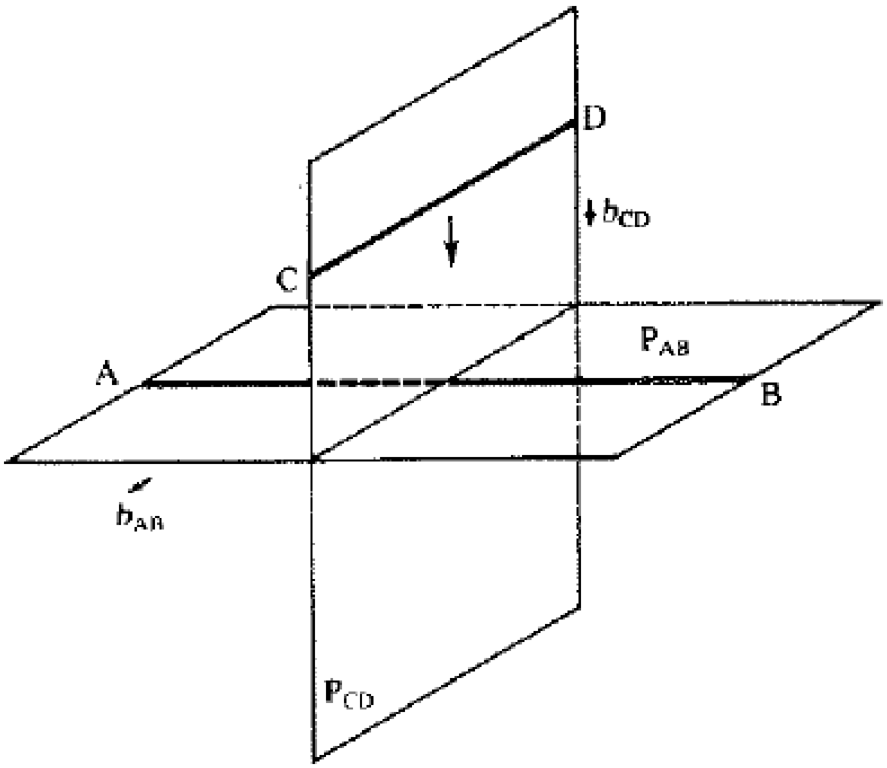
Dislocation Motion

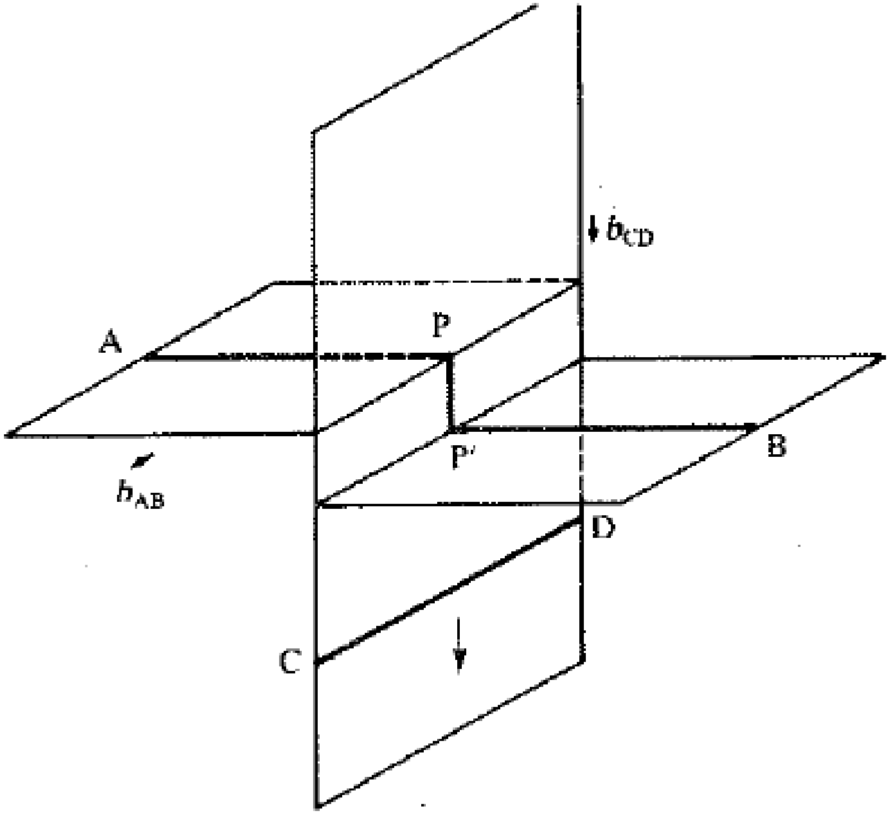
Was, p. 277

[Fig. 7.18 in p. 277 from Was, Gary S. *Fundamentals of Radiation Materials Science*, ISBN: 9783540494713] removed due to copyright restrictions.

Glissile vs. Sessile Sections

Allen, "Kinetics of Materials," p. 124

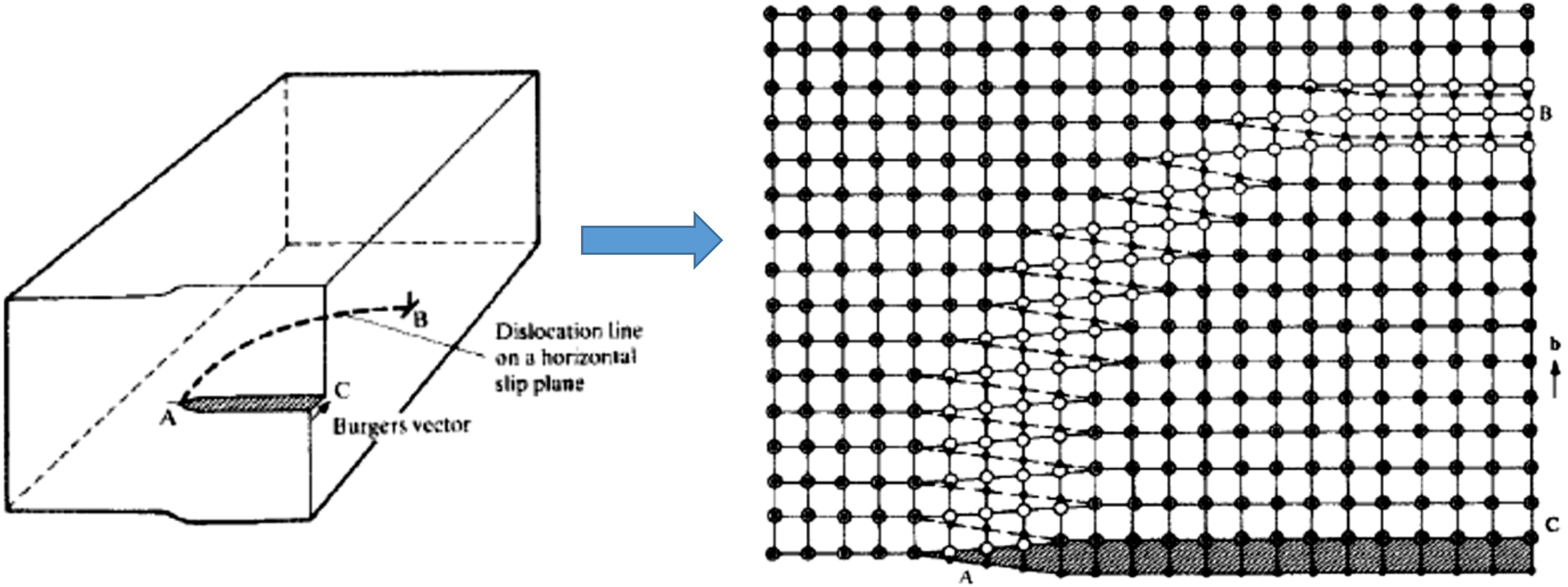




Two edge dislocations moving towards each other form a *sessile* jog

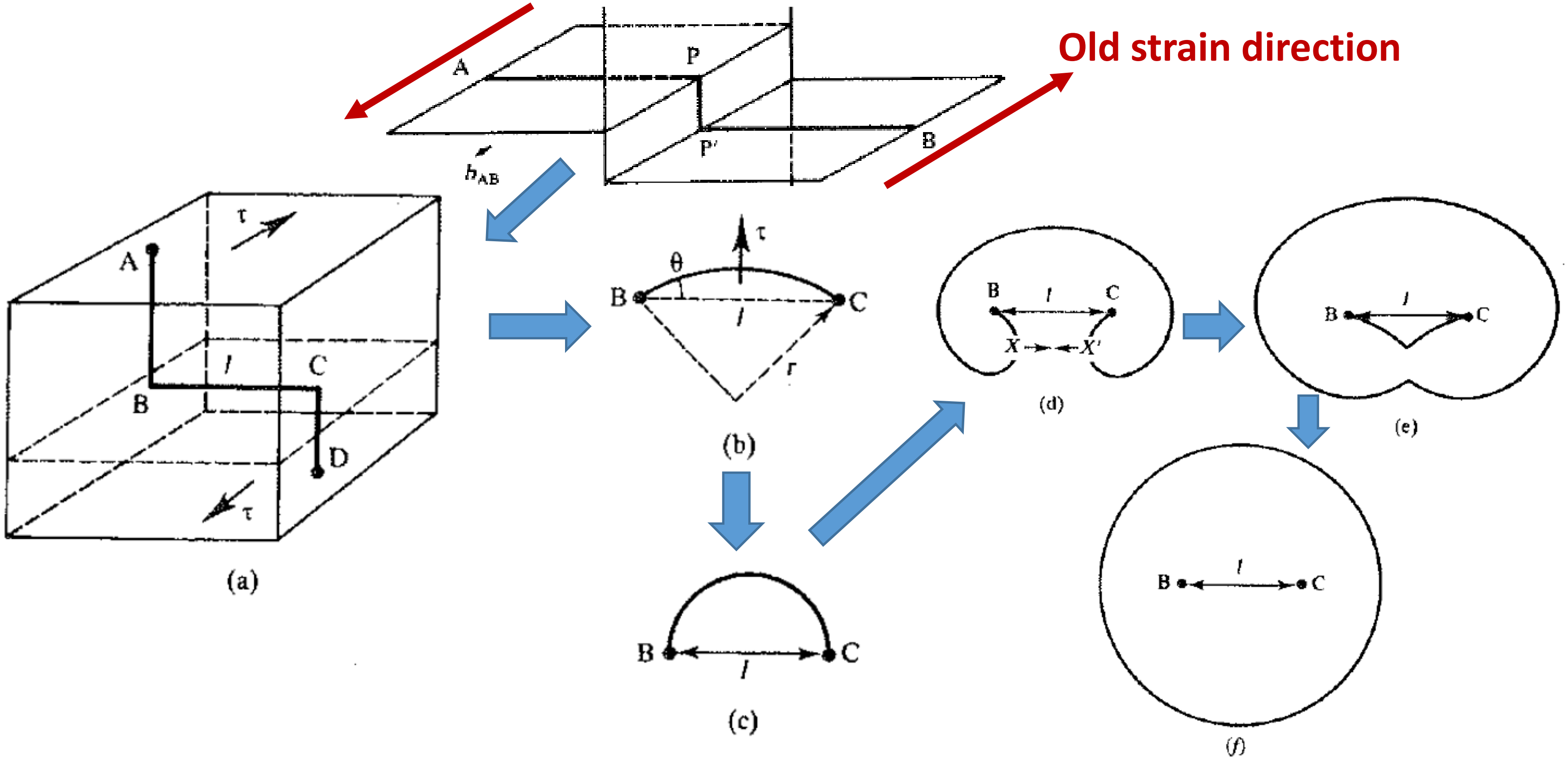
Dislocation Loops

- Loops have mixed edge/screw character
  - May be circular planes of atoms between two planes



Dislocation Loop Sources

- Come from sessile sections of dislocations



Dislocation Videos!

http://www.numodis.fr/tridis/TEM/mechanisms/multiplication.html

Dislocation sources in Mo-5Nb

A video is played in class to demonstrate the concept.

Dislocation Videos!

http://www.numodis.fr/tridis/TEM/mechanisms/multiplication.html

A Frank-Read Source in Silicon A video is played in class to demonstrate the concept.

Dislocation Videos!

http://www.numodis.fr/tridis/TEM/mechanisms/multiplication.html

Dislocation source in Ge at high temperature

A video is played in class to demonstrate the concept.

Dislocation Videos!

http://www.numodis.fr/tridis/TEM/mechanisms/multiplication.html

Dislocation sources and pileup in Ge

A video is played in class to demonstrate the concept.

Dislocation Videos!

http://www.numodis.fr/tridis/TEM/mechanisms/multiplication.html

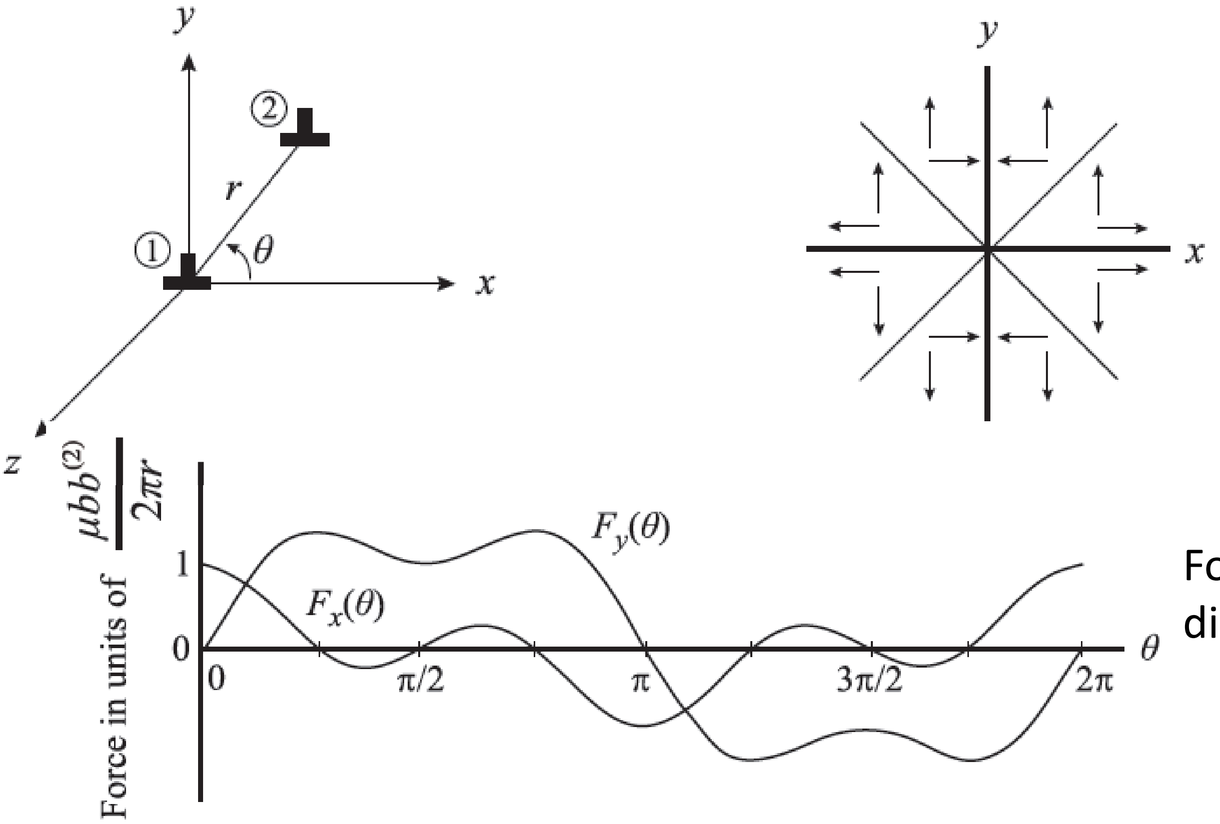
Dislocation sources in Si

A video is played in class to demonstrate the concept.

Forces Between Edge Dislocations

Was, p. 289-290

- X & Y forces, no Z-force



Peach-Kohler Equation

Burgers vector of dislocation (2) transposed

Line vector of dislocation (2) transposed

$$f = \underset{(2)}{\underline{b}}^{T} \underset{(1)}{\underline{\underline{\sigma}}} \times \underset{(2)}{\underline{s}}$$

Force vector on dislocation (2)

Stress tensor induced by dislocation (1)

All Together: Loops, Movement, Pileup

Dislocations moving & piling up in Inconel 617 (Ni-based alloy) under *in-situ* straining in the TEM

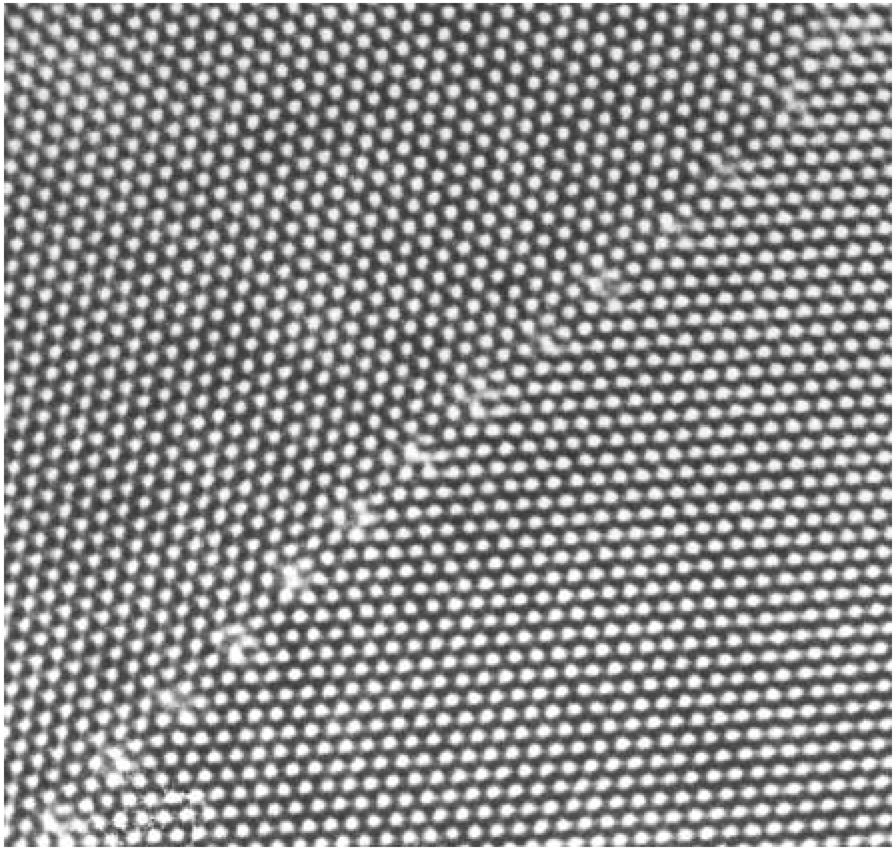
http://youtu.be/r-geDwE8Z5Y

A video is played in class to demonstrate the concept.

Grain Boundaries (2D)

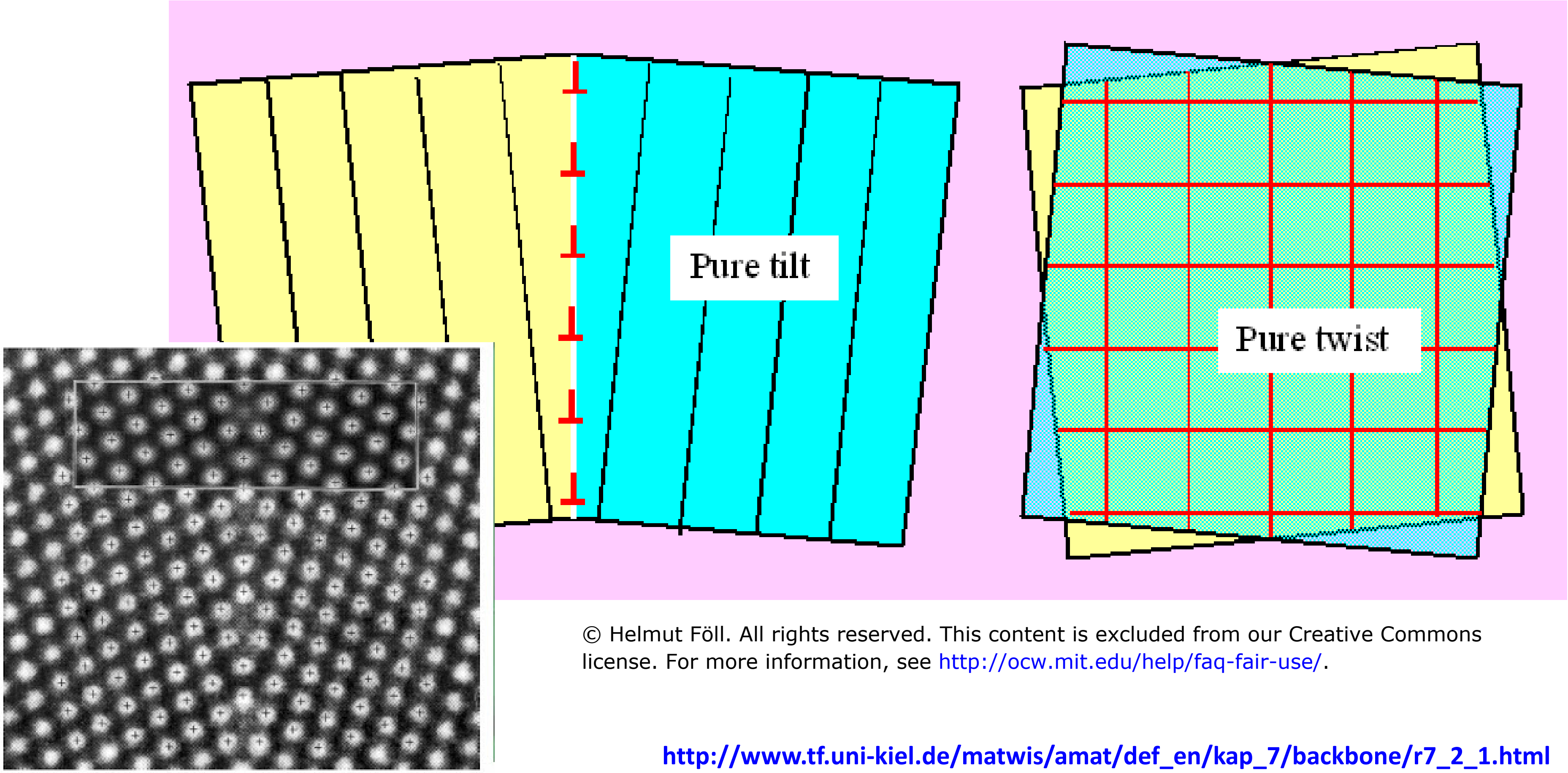
http://www-hrem.msm.cam.ac.uk/gallery/

- Regions of different orientation
  - May also be different crystal structure



TEM image of a grain boundary in pure Al

GBs can be Lines of Dislocations



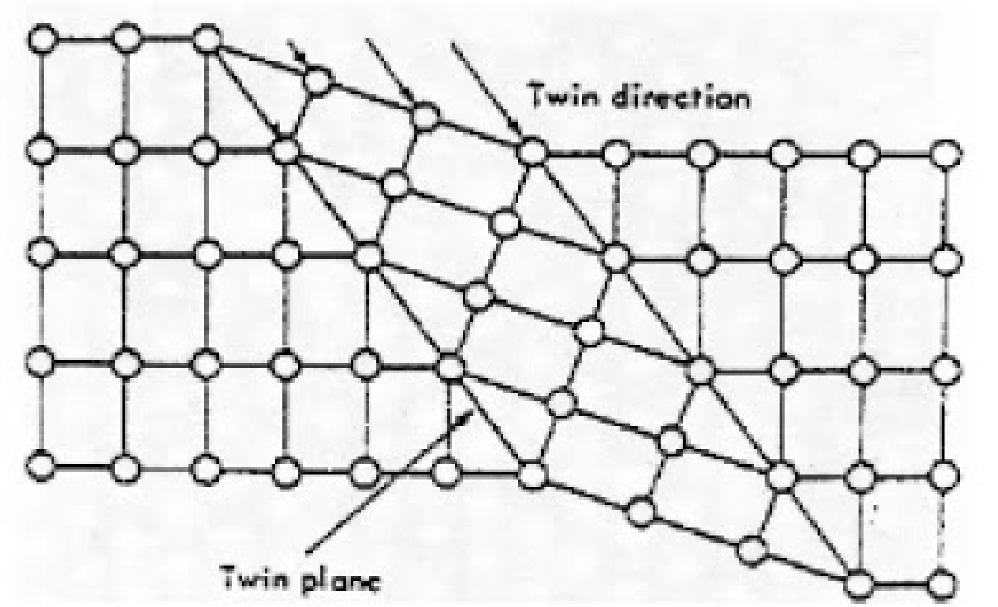
Tilt grain boundary in Al

http://www.tf.uni-kiel.de/matwis/amat/def_en/kap_7/backbone/r7_2_1.html

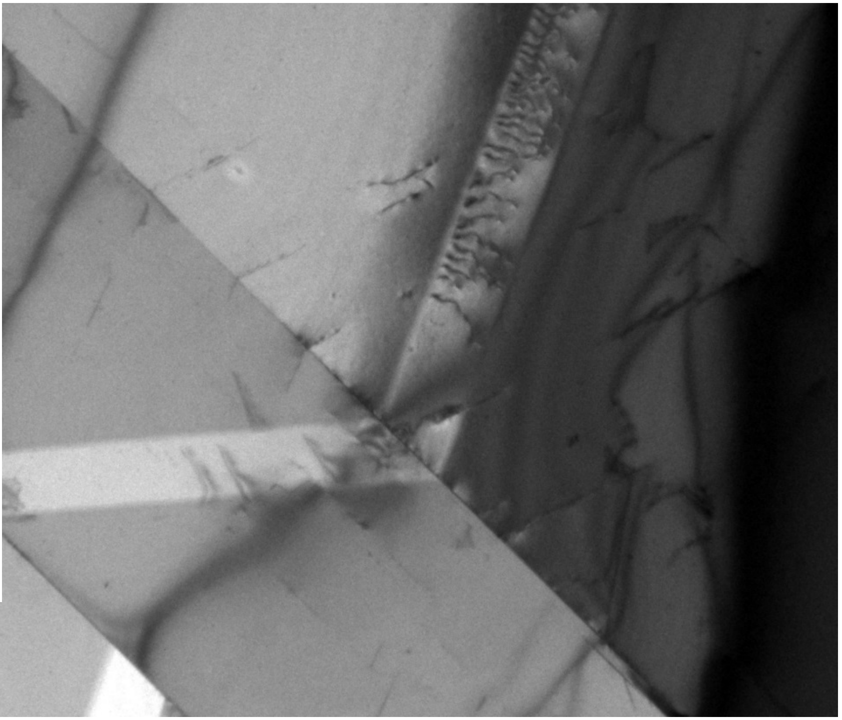
http://moisespinedacaf.blogspot.com/

Twinning

- Alternate plastic deformation mechanism



http://dcg.materials.drexel.edu/?page_id=14#nuclear

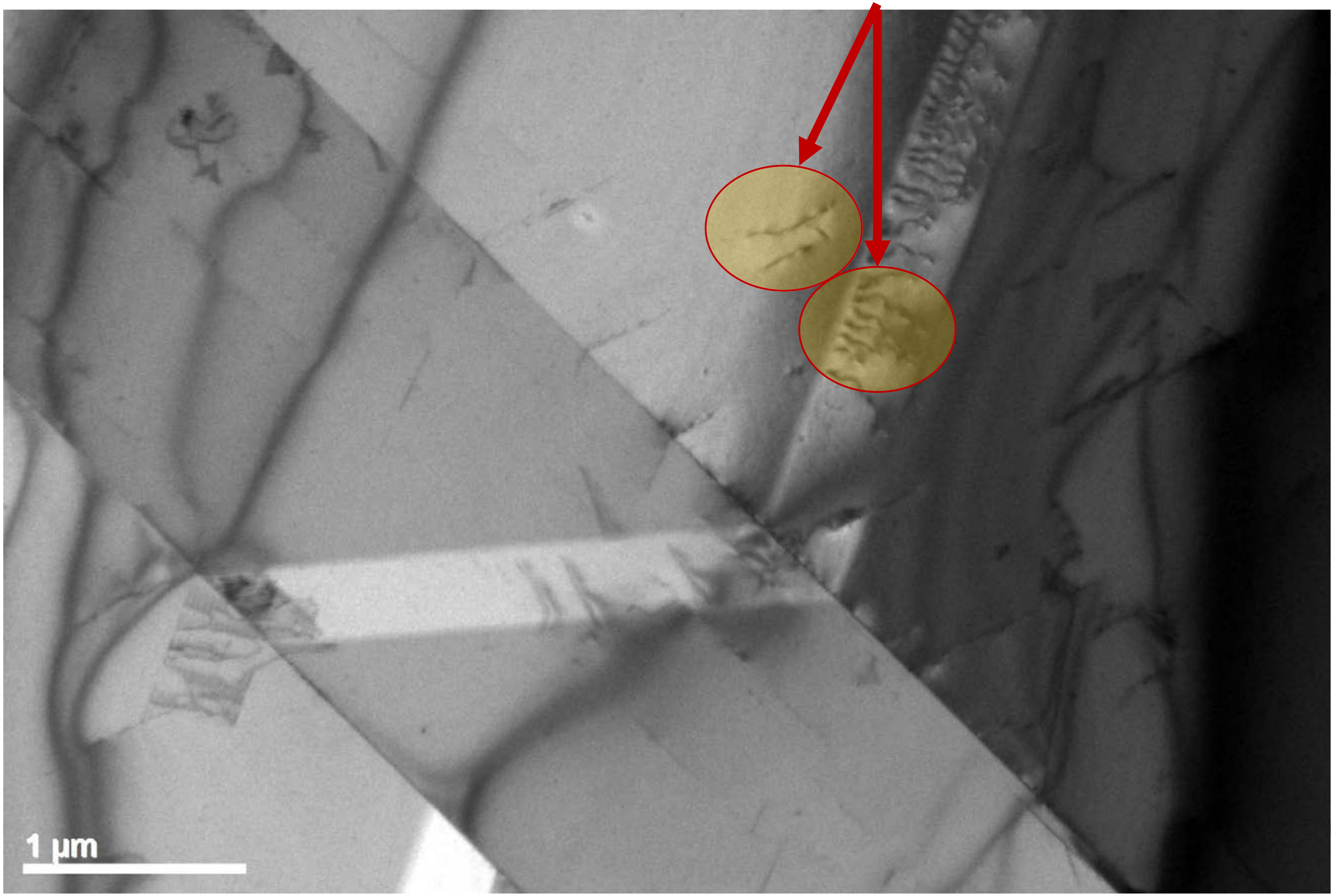


Twinning observed in irradiated reactor pressure vessel steel

Courtesy of Dynamic Characterization Group, property of Drexel University. Used with permission.

Twinning

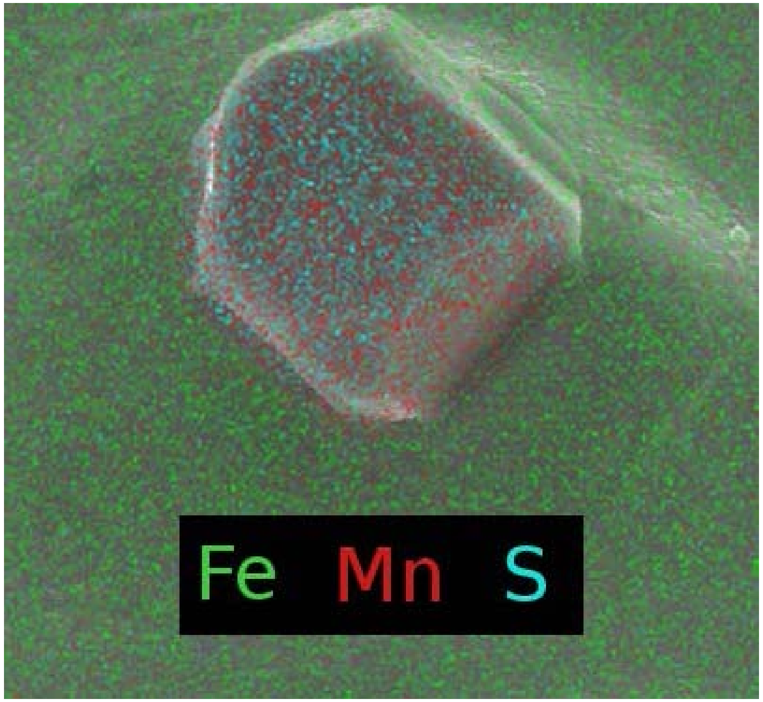
Differently oriented dislocations inside/outside twin boundary!



Courtesy of Dynamic Characterization Group, property of Drexel University. Used with permission.

Inclusions (3D)

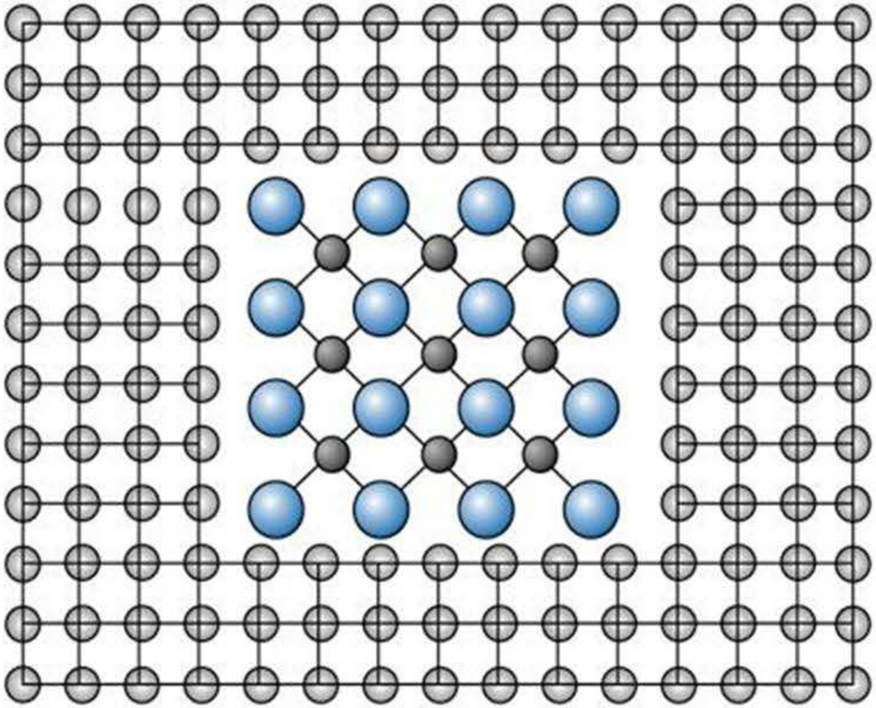
- Other phases trapped within base material
- Examples:
  - Secondary particle precipitates in Zircaloys
  - Carbides in steels
  - Y_2O_3 particles in Oxide Dispersion Strengthened (ODS) steels



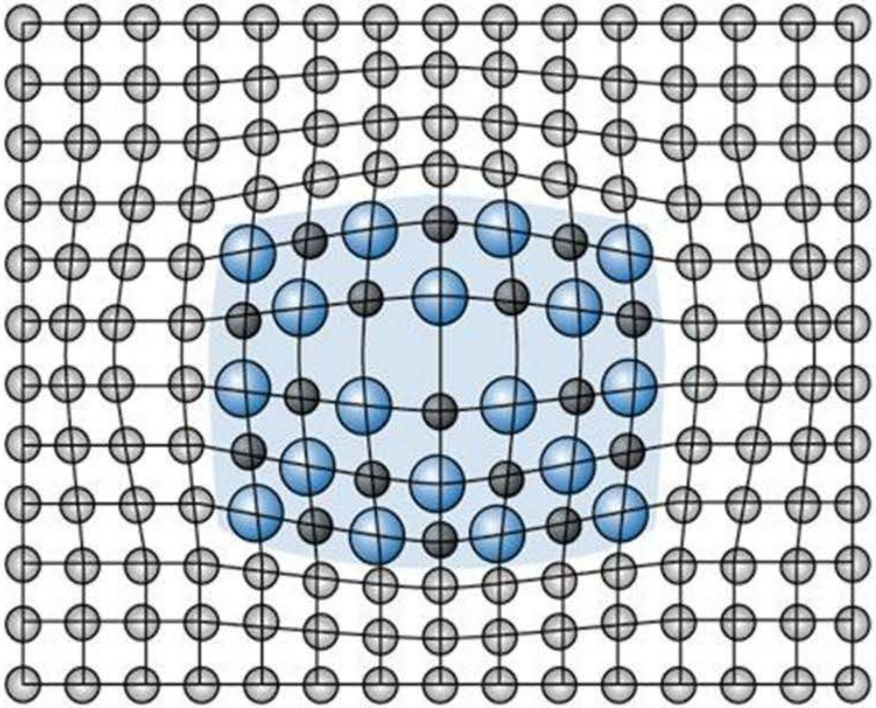
Single crystal of MnS, space group $Fm\bar{3}m$, FCC crystal structure embedded in Alcator rotor steel

Coherent vs. Incoherent

- Which do you think would be better at sinking defects? Stopping dislocations?



Incoherent inclusion



Coherent inclusion

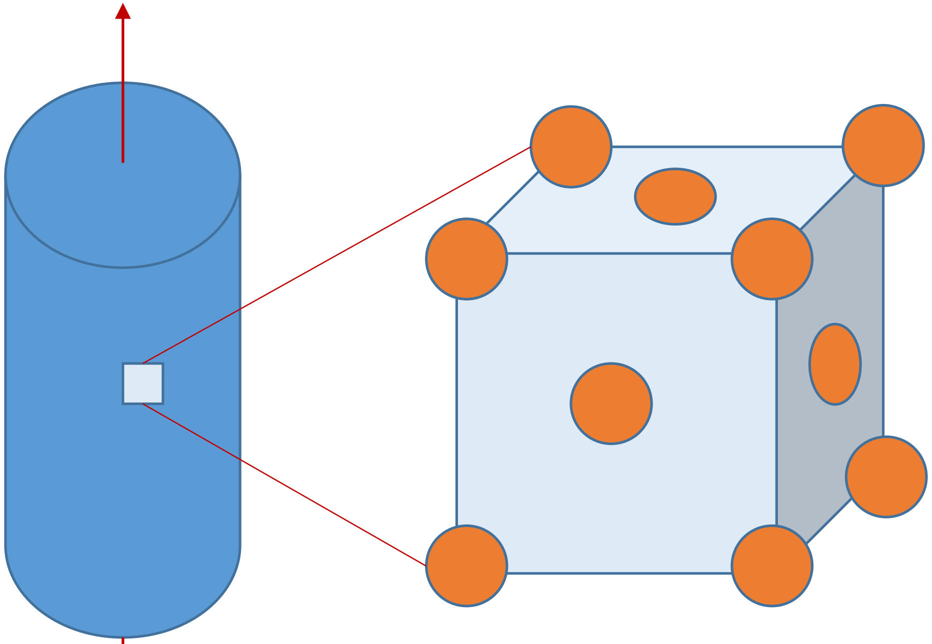
Switching Gears: Structural Material Properties

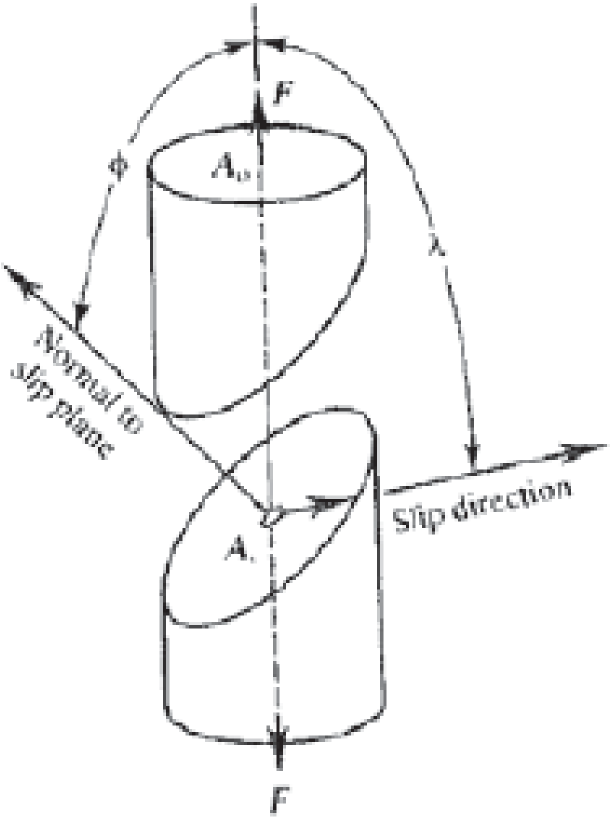
- Goals:
  - Understand true vs. engineering stress & strain
  - Quantify and differentiate between hardness, toughness, strength, ductility, stiffness
  - Know how to measure these properties
  - Resolve stresses onto slip systems
  - Predict the differences in mechanical response between single, dual, and polycrystalline materials

Images from now on are from T. H. Courtney, *Mechanical Behavior of Materials* unless otherwise noted

Resolved Shear Stress

- Consider a single crystal bar of FCC material, tensioned in the [001] direction:





How much shear does the slip syster

Resolved Shear Stress

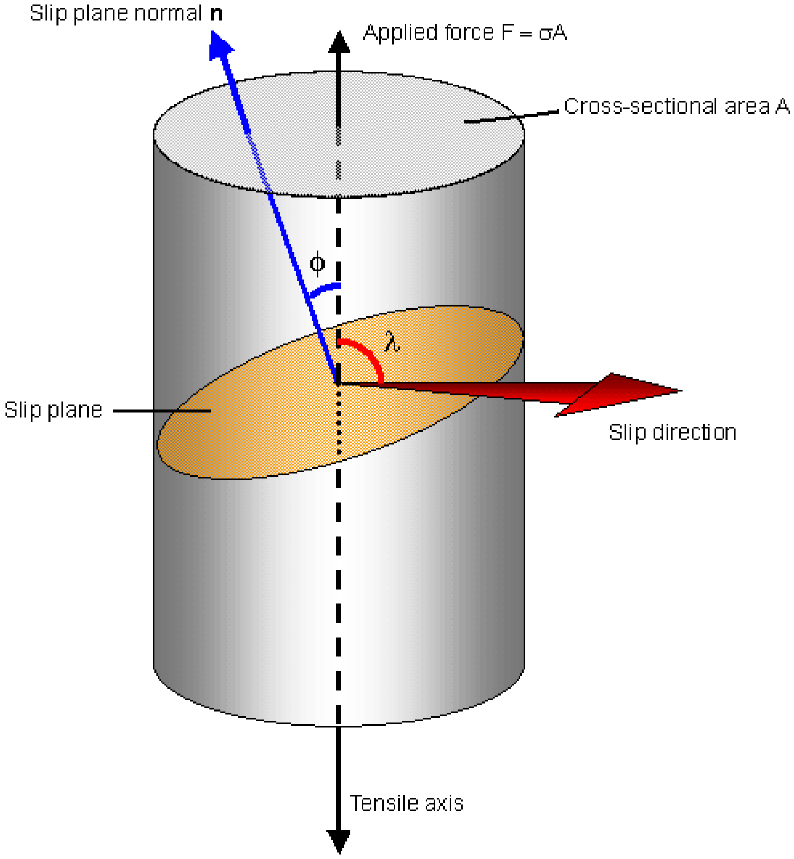
http://www.doitpoms.ac.uk/tplib/slip/printall.php

- Project force onto the tilted plane containing the slip system, to get the stress

$$\sigma_{slip} = \frac{F}{A_{slip}} = \frac{F}{\frac{A_0}{\cos\theta}} = \sigma \cos\theta$$

- Also project shear movement in direction of slip

$$\tau = \sigma \cos\lambda$$



Courtesy of University of Cambridge. Used with permission.

Resolved Shear Stress

- The total shear stress becomes:

$$\tau = \sigma \cos\lambda \cos\theta = \frac{\sigma}{m}$$

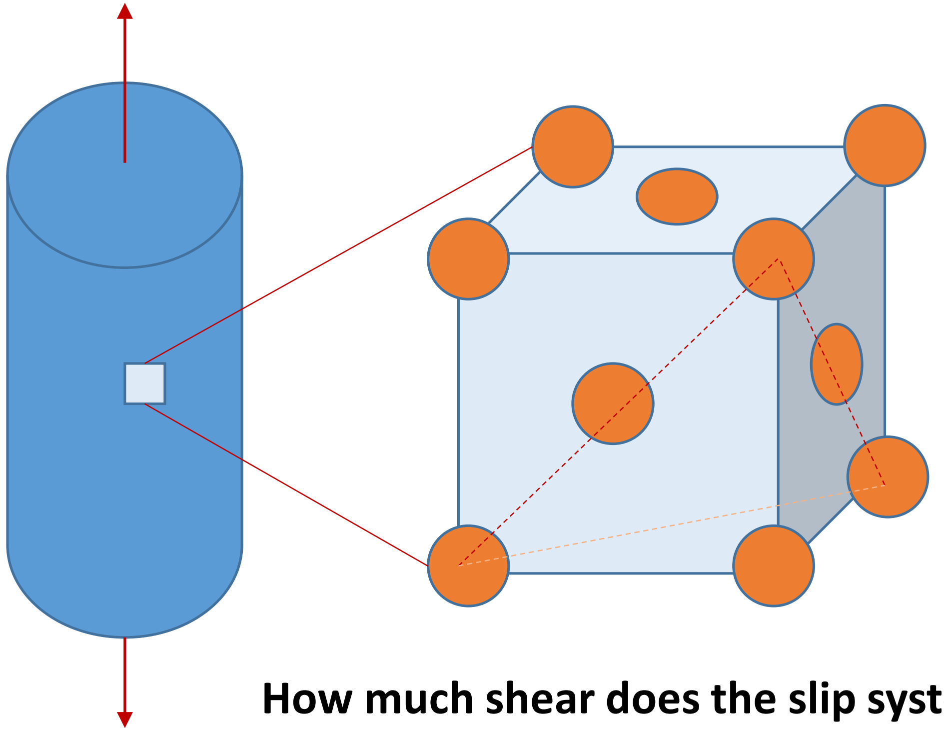
$$m = \frac{1}{\cos\lambda \cos\theta}$$

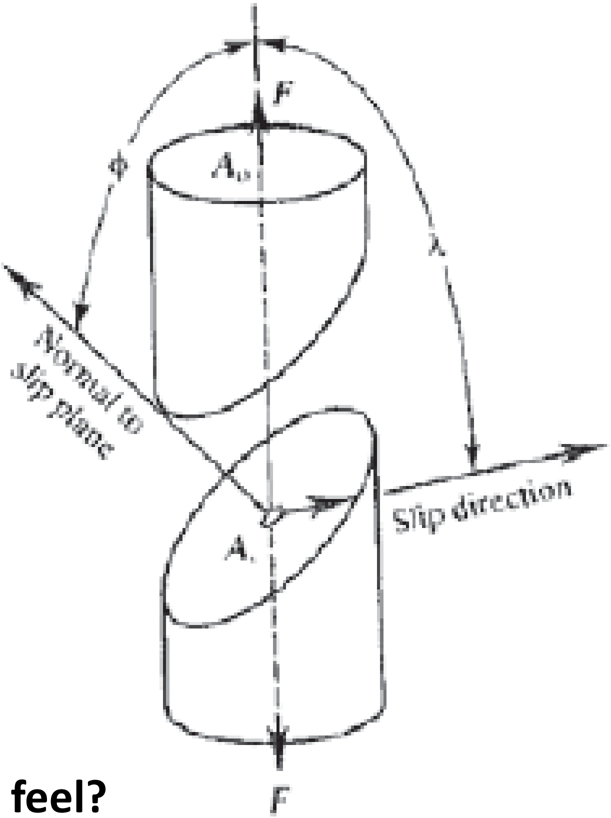
Schmid factor

- Effectively reduces applies stress felt on a slip plane

Resolved Shear Stress

- Consider a single crystal bar of FCC material, tensioned in the [001] direction:

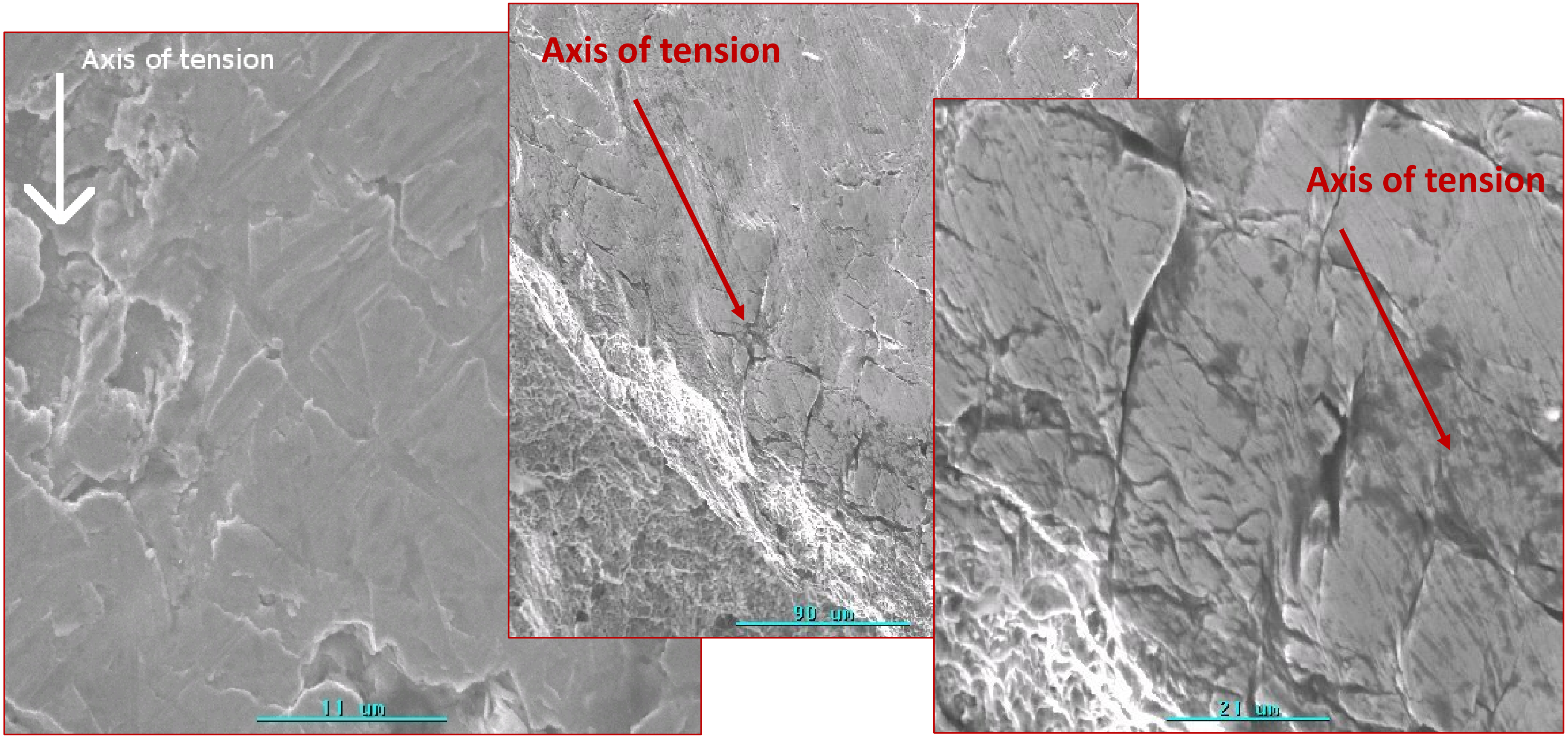




How much shear does the slip system feel?

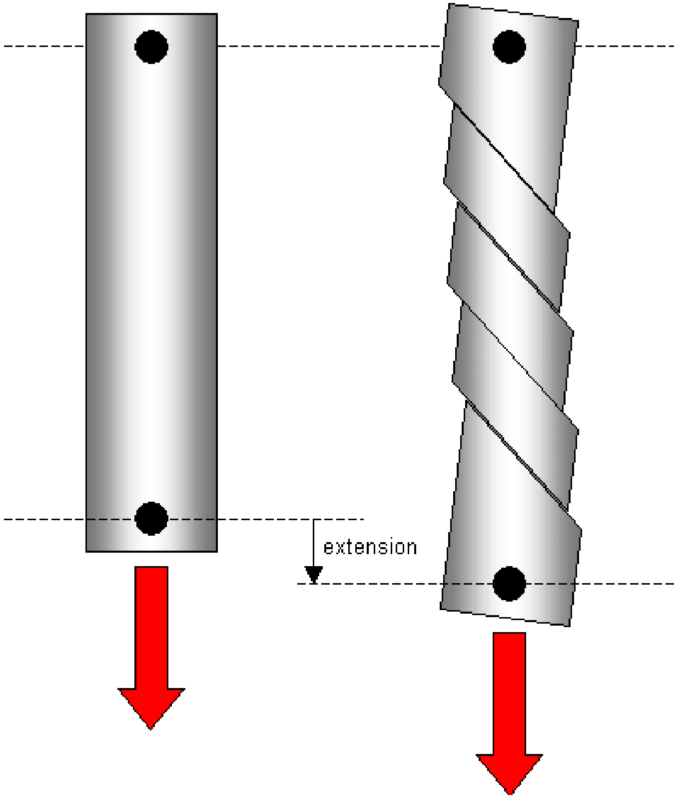
Examples of Shear & Slip

- Alcator C-Mod rotor steel in uniaxial tension:



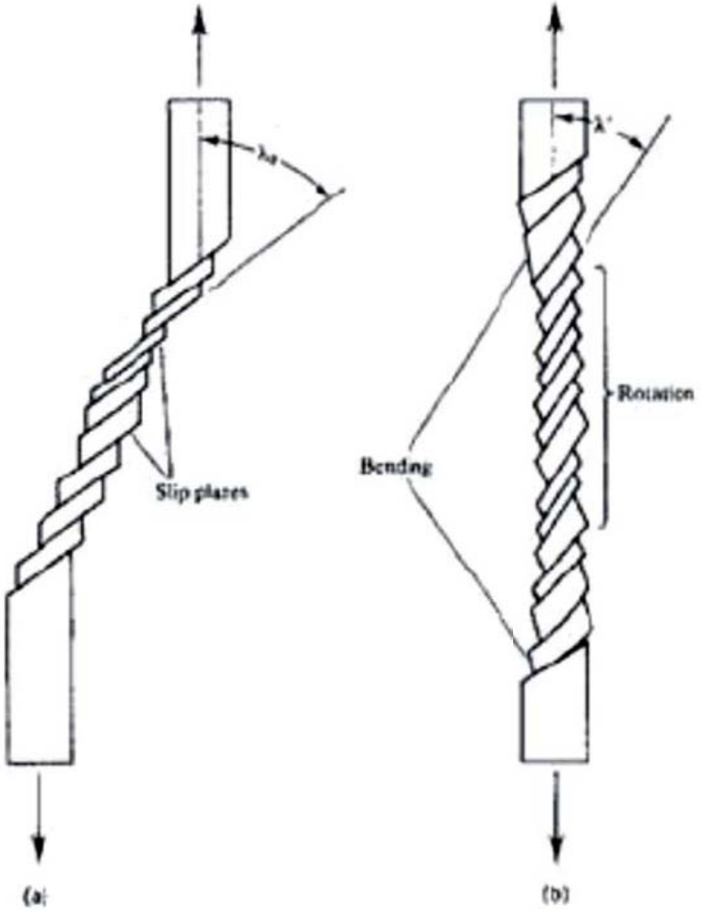
Evidence of Slip Systems

http://www.doitpoms.ac.uk/tlplib/slip/printall.php



Unslipped single crystal fixed at top end.

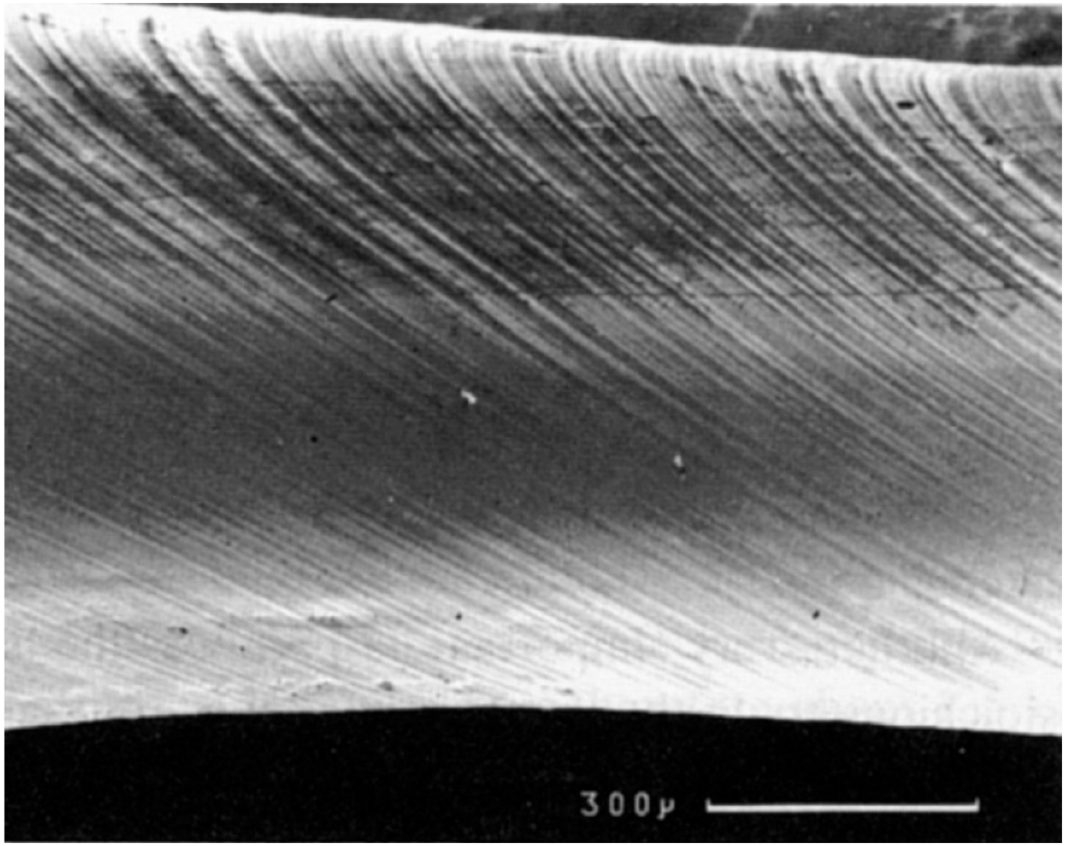
Single crystal after plastic deformation by tensile stress in the direction of the arrow. Slip occurs on distinct parallel planes.



Courtesy of University of Cambridge. Used with permission.

Evidence of Slip Systems

http://www.doitpoms.ac.uk/tlplib/miller_indices/printall.php

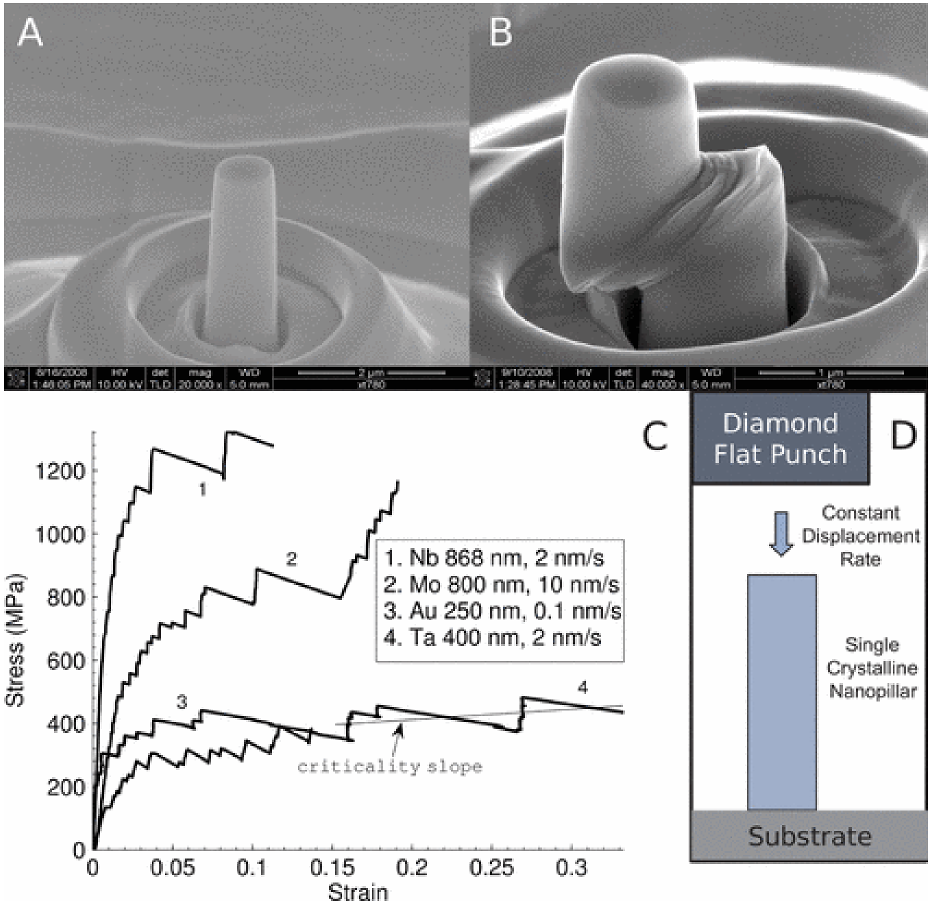


Courtesy of University of Cambridge. Used with permission.

A scanning electron micrograph of a single crystal of cadmium deforming by dislocation slip on 100 planes, forming steps on the surface

Evidence of Slip Systems

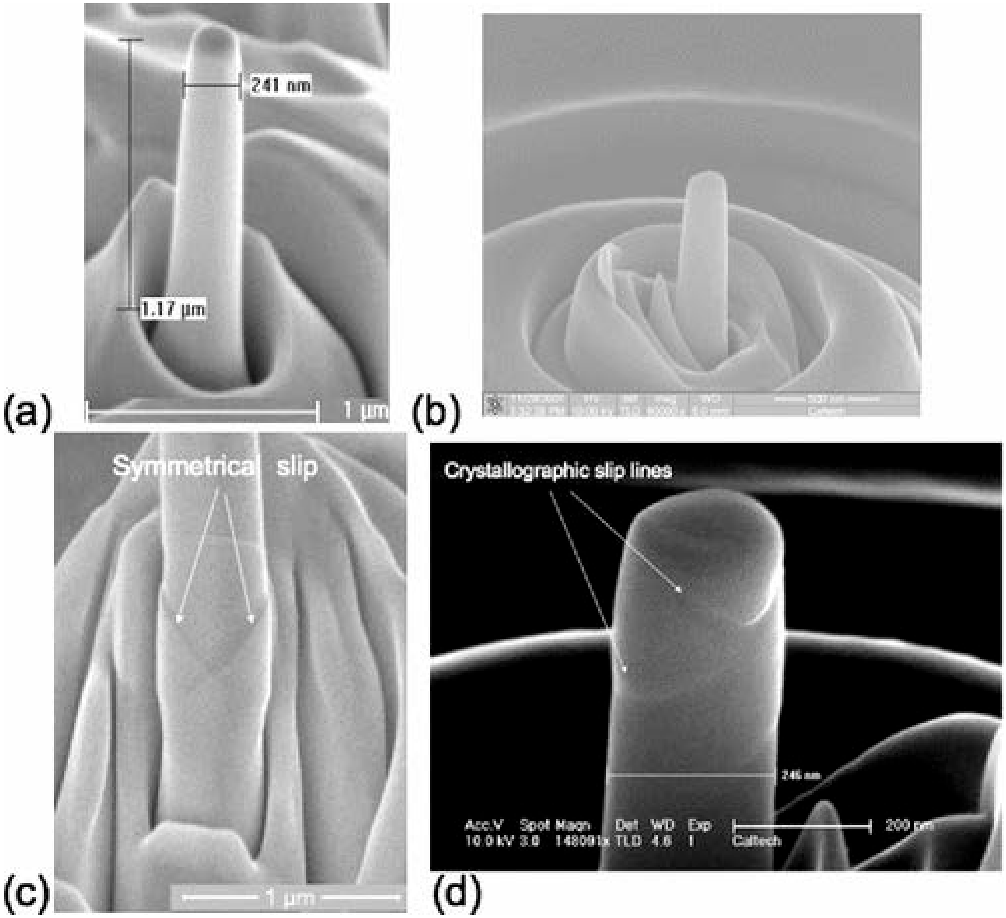
N. Friedman et al. Phys. Rev. Lett. 109, 095507 (2012)



- Nanopillar compression tests using a diamond flat punch
- Clear 45 degree angles observed
    - Slip systems activated by *shear*

Evidence of Slip Systems

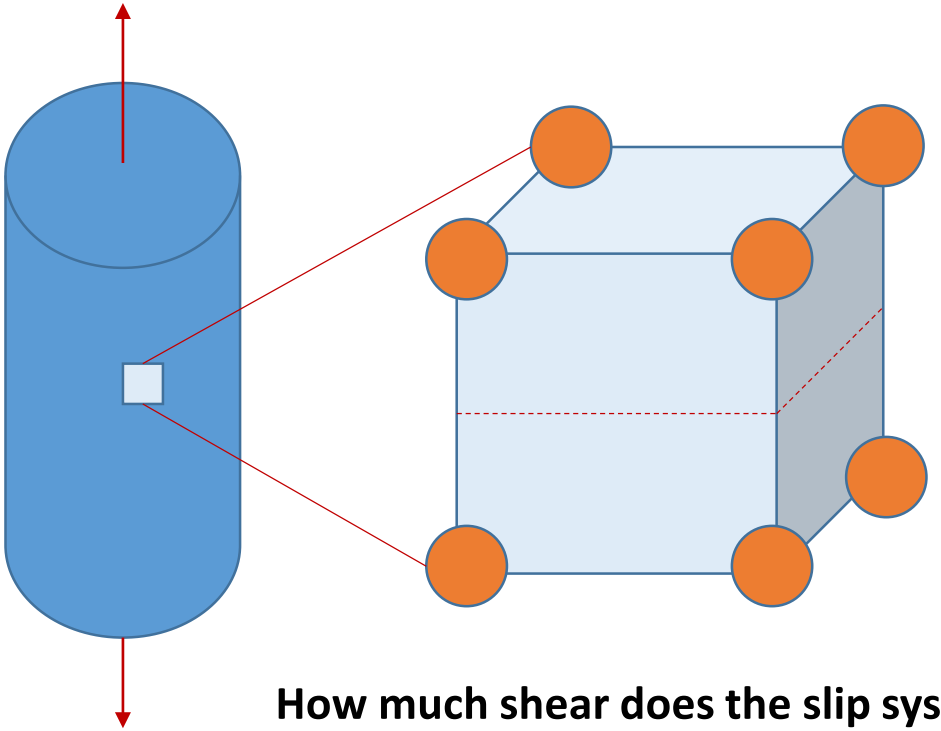
S. Brinckmann et al. Phys. Rev. Lett. 100, 155502 (2008)

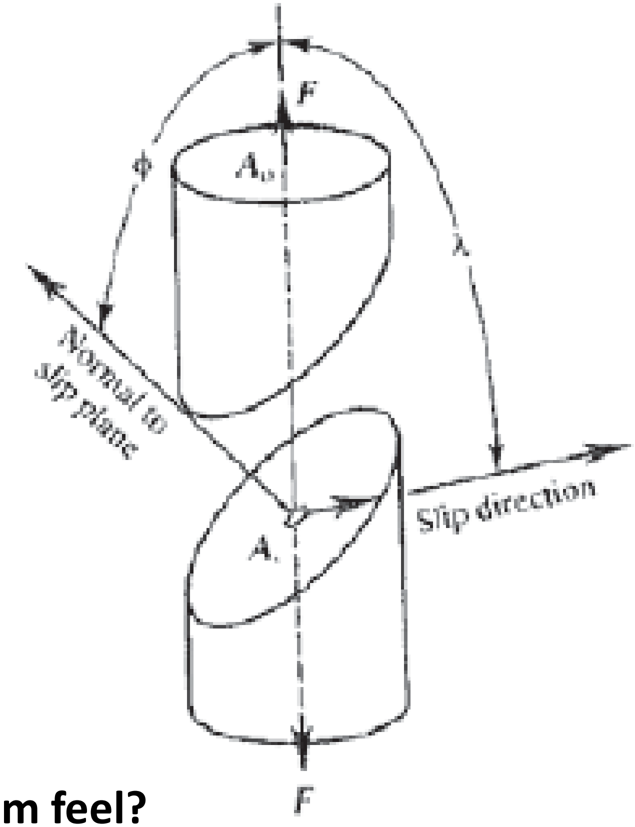


- Nanopillar compression tests using a diamond flat punch
- Clear 45 degree angles observed
  - Slip systems activated by *shear*

Resolved Shear Stress

- Consider a single crystal bar of SC material, tensioned in the [001] direction:

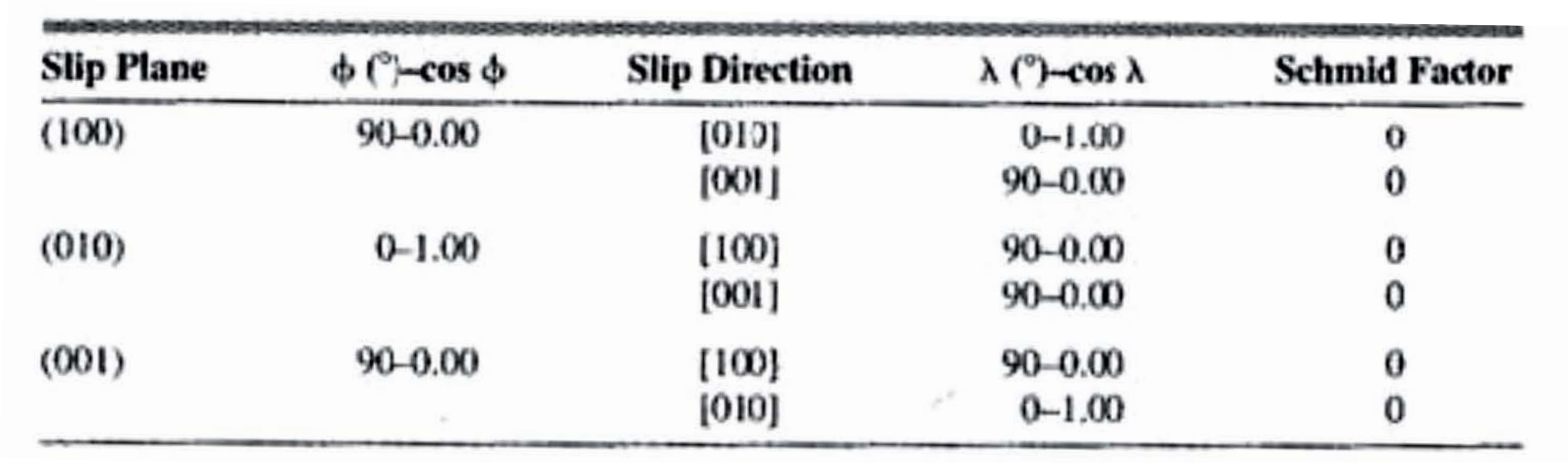




How much shear does the slip system feel?

Resolved Shear Stress

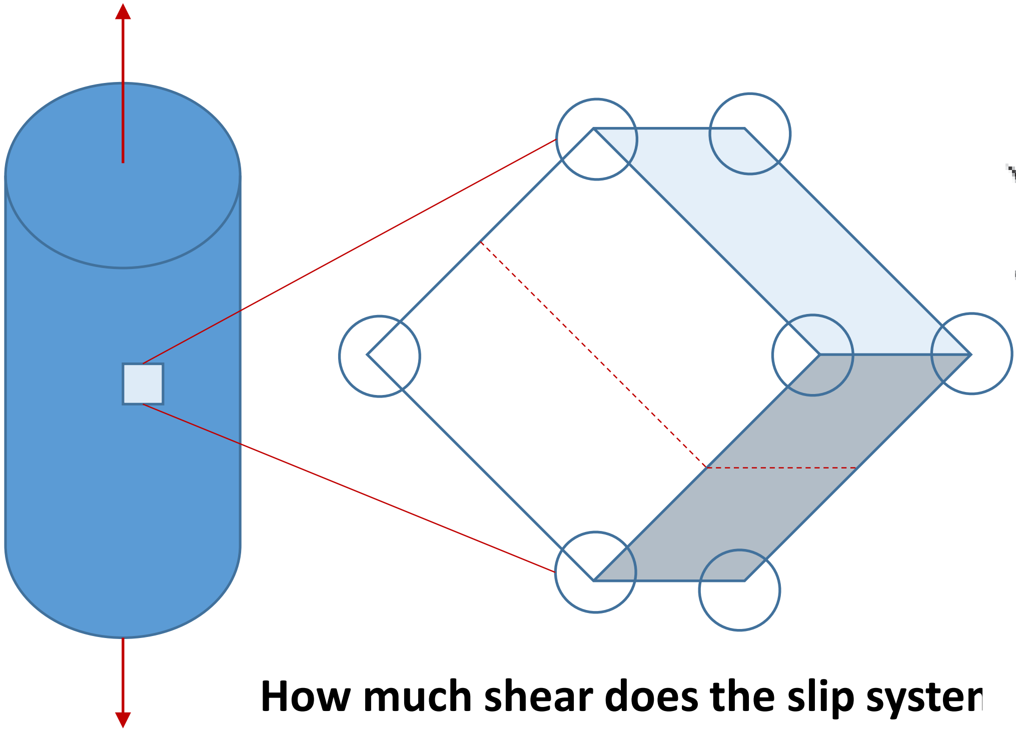
- Consider a single crystal bar of SC material, tensioned in the [001] direction:

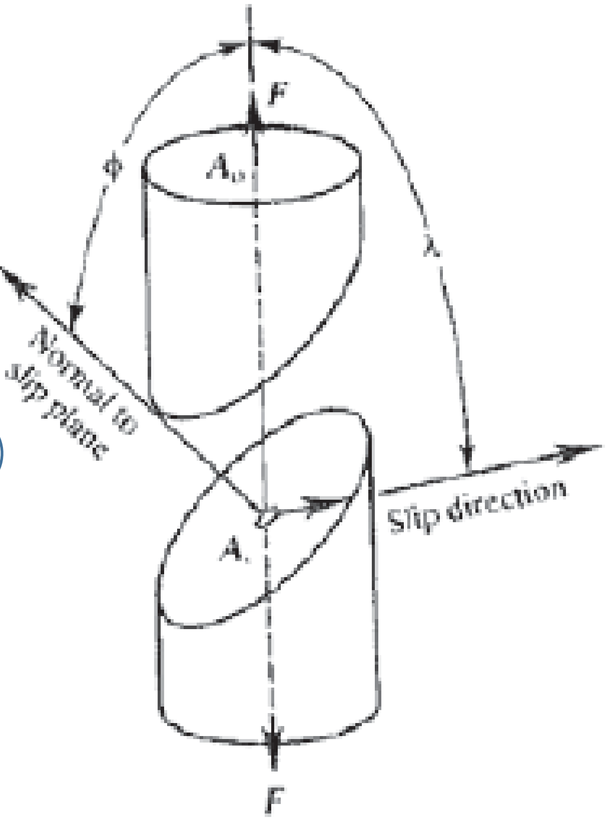


Slip Plane	ϕ (°)–cos ϕ	Slip Direction	λ (°)–cos λ	Schmid Factor
(100)	90–0.00	[010]	0–1.00	0
		[001]	90–0.00	0
(010)	0–1.00	[100]	90–0.00	0
		[001]	90–0.00	0
(001)	90–0.00	[100]	90–0.00	0
		[010]	0–1.00	0

Resolved Shear Stress

- Consider a single crystal bar of SC material, tensioned in the [011] direction:



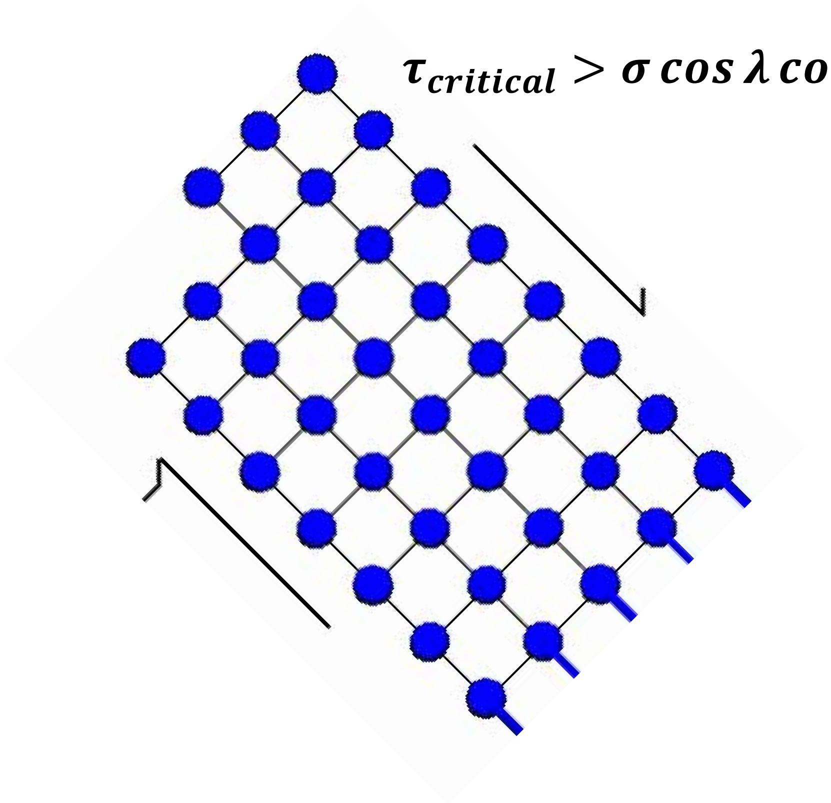


How much shear does the slip syster

Will It Slip or Break?

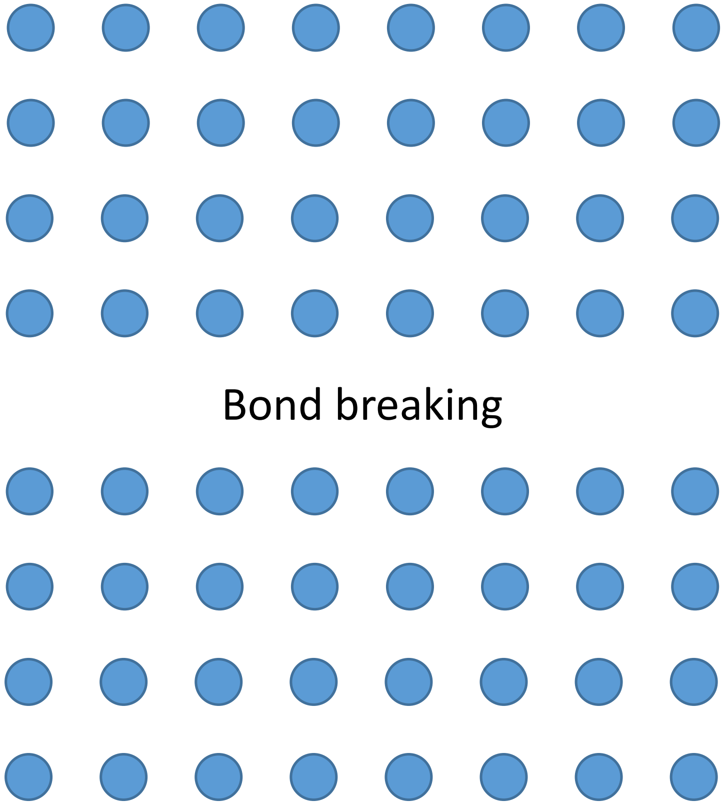
- Balance between two mechanisms:

$$\tau_{critical} > \sigma \cos\lambda \cos\theta$$



vs.

$$\sigma > \sigma_{UTS}$$



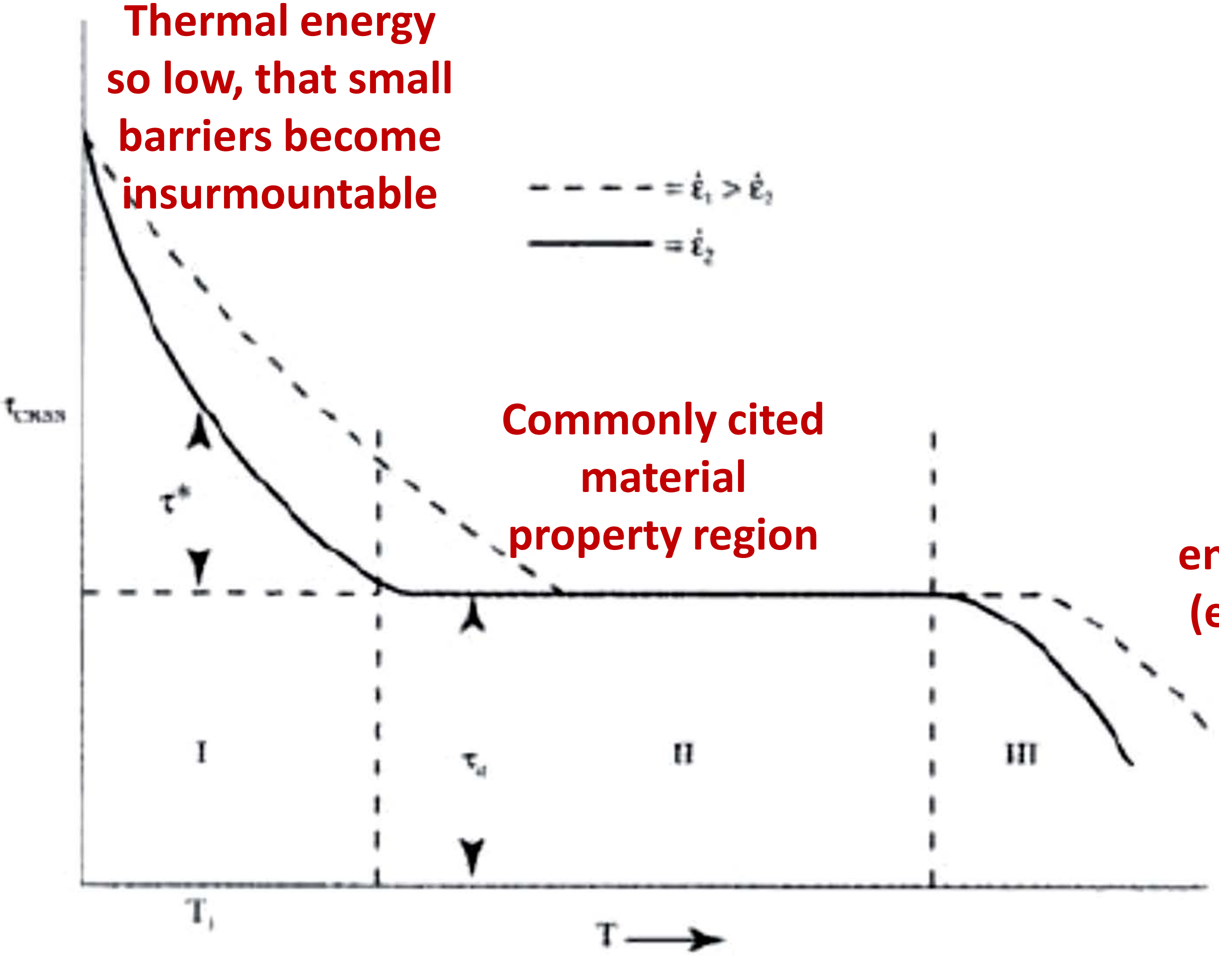
Critical Resolved Shear Stress (τ_{CRSS})

- Shear stress that is enough to get dislocations moving (plastic deformation)
- Related to the *yield stress* (σ_y), the stress where plastic deformation starts:

$$\sigma_y = m\tau_{CRSS}$$

- NOTE: σ_y has crystallographic dependence in single crystals! What about polycrystals?

τ_{CRSS} vs. Temperature



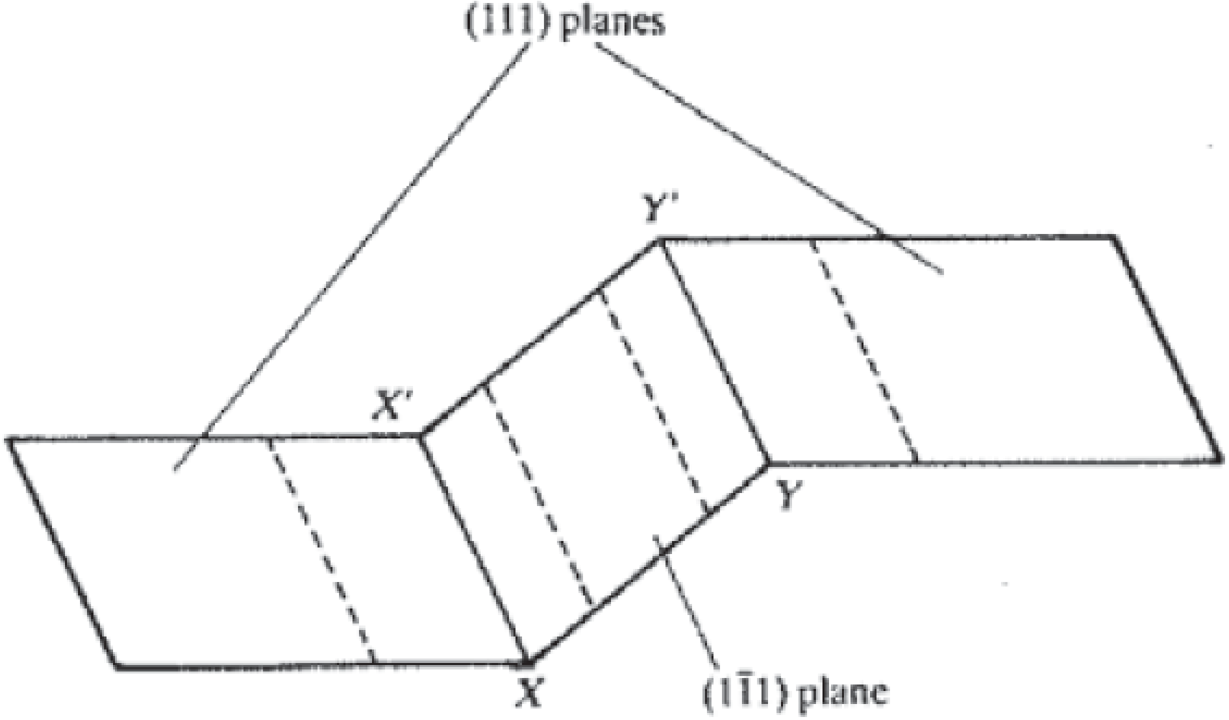
Thermal energy so low, that small barriers become insurmountable

Commonly cited material property region

Diffusion-enhanced region (easier to move dislocations)

What Happens When Dislocations Get Stuck?

- <u>Cross slip:</u> switching to other slip planes



- Resolved shear stress must be high enough!

Stress vs. Strain

- Stress: Force over area
- Engineering stress: Force divided by *original* area
- True stress: Force divided by *actual* area as it *changes*

$$\sigma = \frac{F}{A_0} \qquad \sigma_t = \frac{F}{A(t)} = \frac{F}{A_0}\frac{A_0}{A(t)} = \sigma\frac{A_0}{A(t)}$$

- Conserve volume during stretching: $V_0 = V(t)$

Stress vs. Strain

$$\sigma = \frac{F}{A_0} \qquad \sigma_t = \frac{F}{A(t)} = \frac{F}{A_0}\frac{A_0}{A(t)} = \sigma\frac{A_0}{A(t)}$$

- Conserve volume during stretching: $V_0 = V(t)$

$$V_0 = A_0 L_0 = V(t) = A(t)L(t); \quad \frac{A(t)}{A_0} = \frac{L_0}{L(t)}$$

$$\sigma_t = \sigma\frac{A_0}{A(t)} = \sigma\frac{L(T)}{L_0} = \sigma\frac{L_0 + \delta L}{L_0} = \sigma\left(1 + \frac{\delta L}{L_0}\right)$$

Engineering strain (ε)

True vs. Engineering Strain

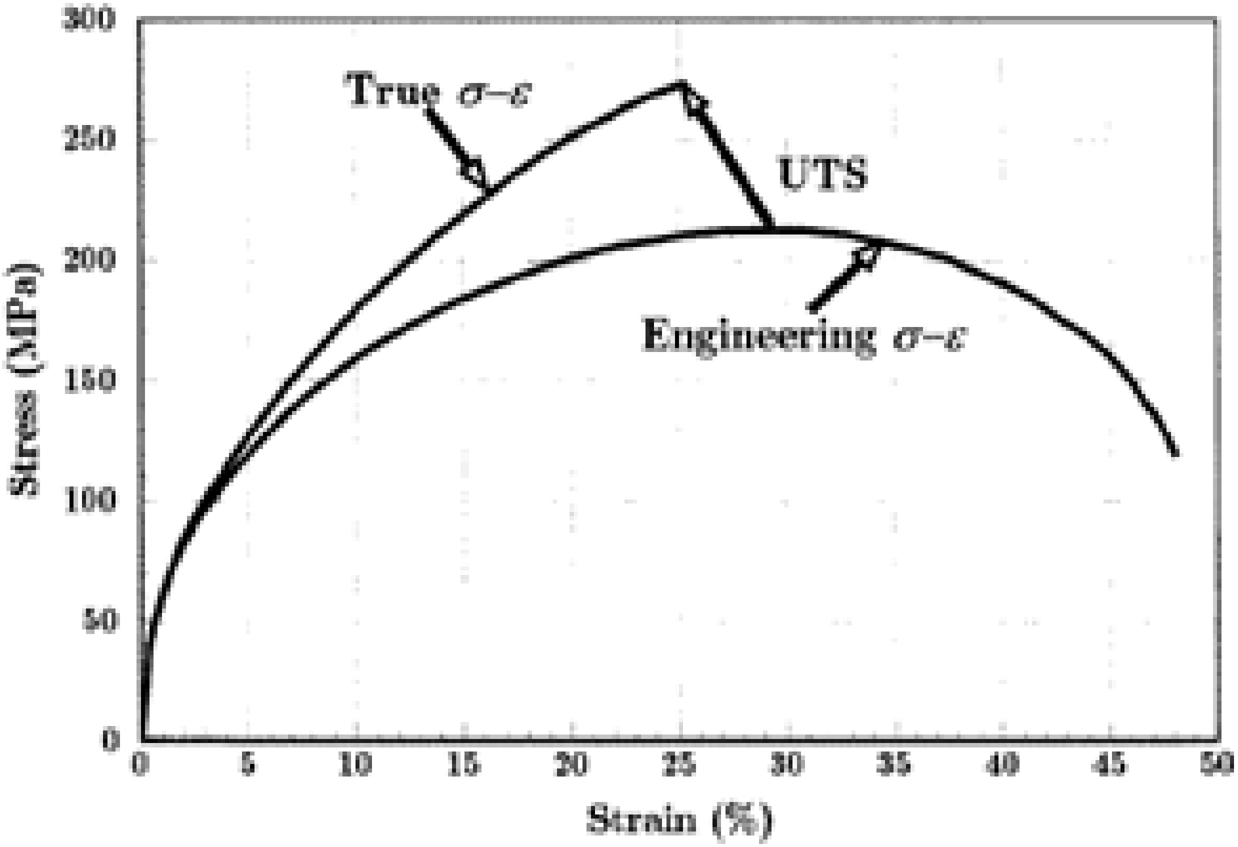
- Engineering strain (ε): $\frac{\delta L}{L_0}$ (from *original* length)
- True strain (ε_T): Instantaneous increase in length:

$$\varepsilon_T = \int_{L_0}^{L(t)} \frac{dL}{L} = \ln L(t) - \ln L_0 = \ln\left[\frac{L(t)}{L_0}\right]$$

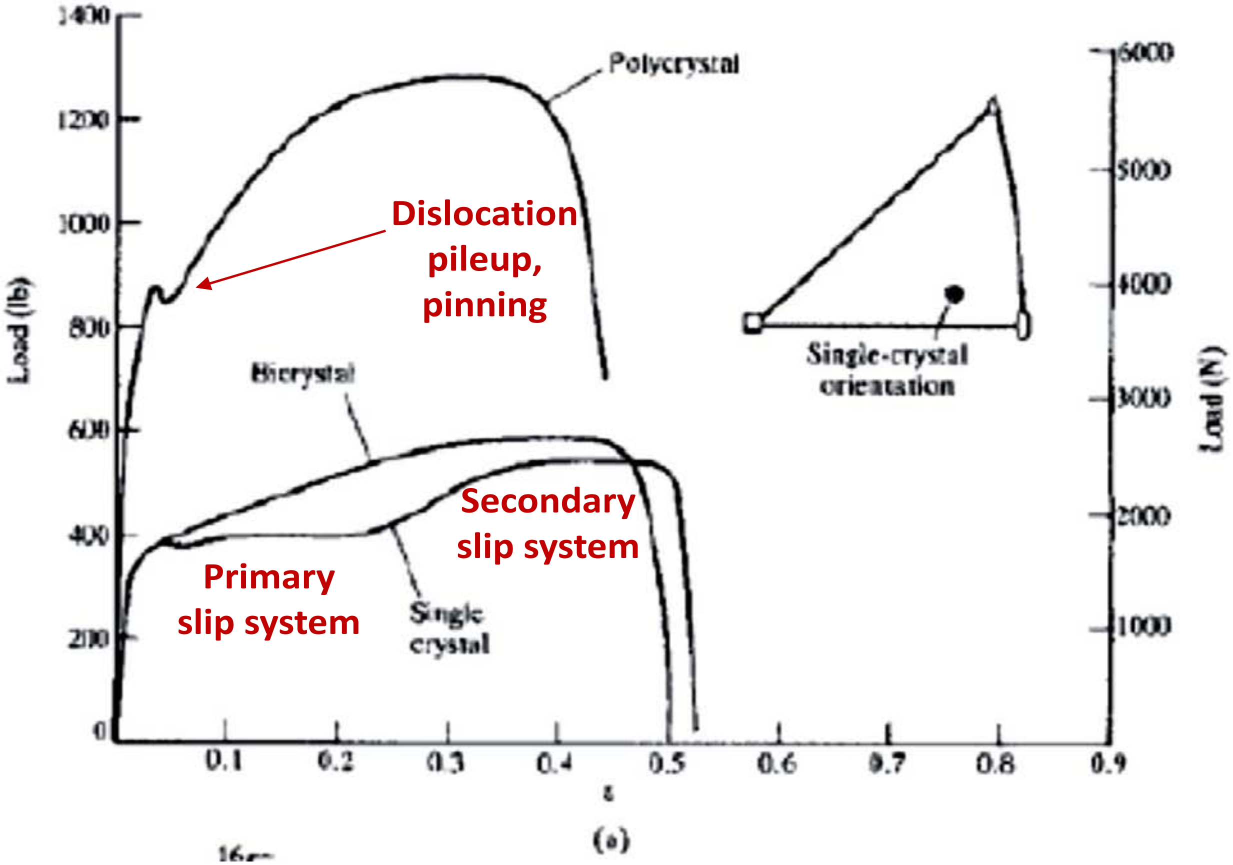
$$\varepsilon_T = \ln\left[\frac{L_0 + \delta L}{L_0}\right] = \ln[1 + \varepsilon]$$

Stress-Strain Curves

http://keytometals.com/page.aspx?ID=CheckArticle&site=kts&NM=42

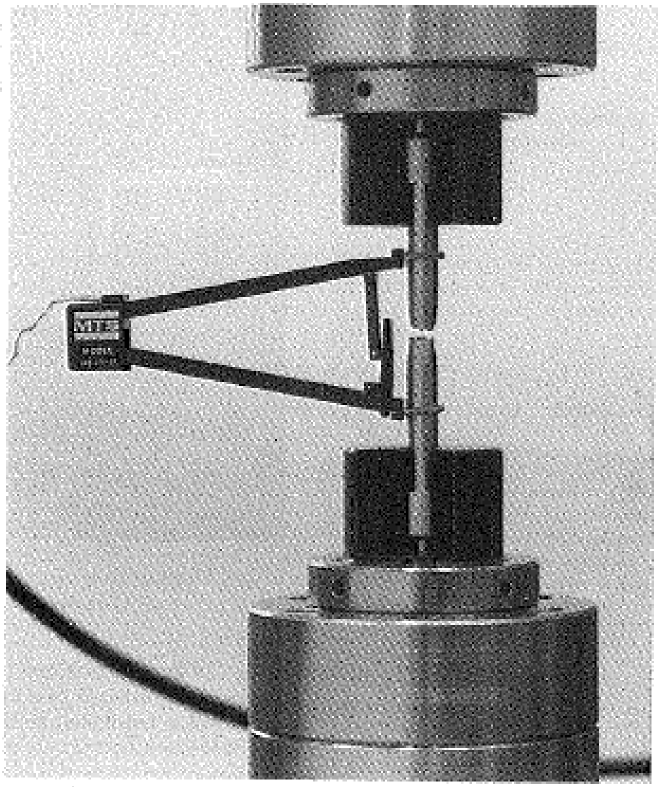


Single, Dual, and Polycrystals

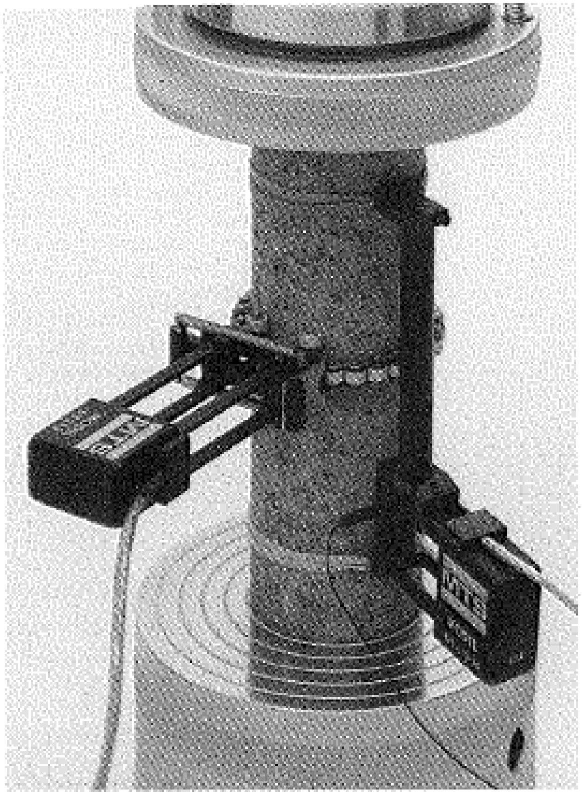


Measuring Stress-Strain

J. M. Gere, "Mechanics of Materials," pp. 12, 14



Uniaxial tensile tester, with extensometer for measuring strain



Uniaxial compression tester, with extensometer and diameter measurement

Dislocations and Defects

E. Bitzek and P. Gumbsch, Dynamic aspects of dislocation motion: atomistic simulations, Materials Science and Engineering A, 400-401 (2005), pp. 40-44

- Defects can slow down (pin) dislocations

A video is played in class to demonstrate the concept.

Reviewing Material Properties

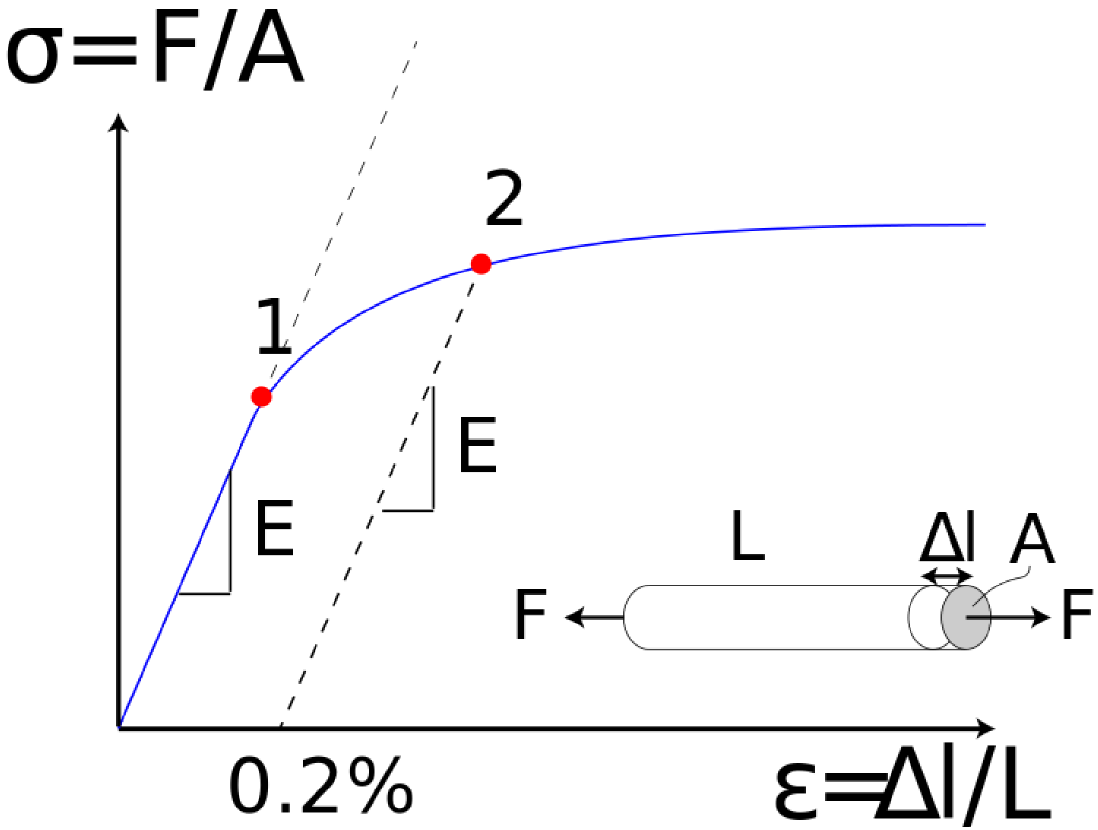
- Find the following on a stress-strain diagram:

- Toughness
- Strength
- Ductility
- Stiffness

- Perhaps define them first…

Young's Modulus (Stiffness, E)

Measures elastic deformation vs. stress

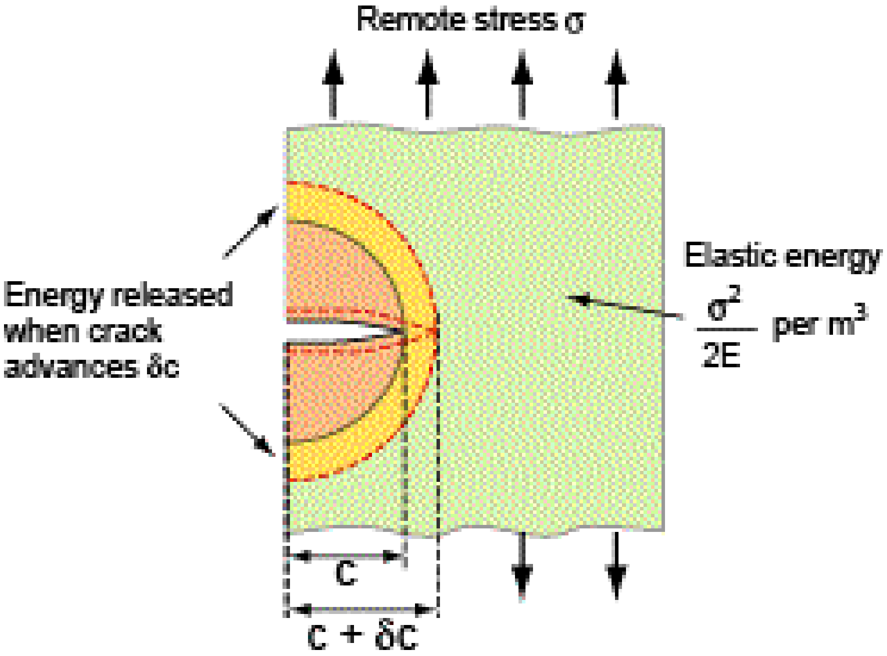


Source: Wikimedia Commons

Toughness (G_c)

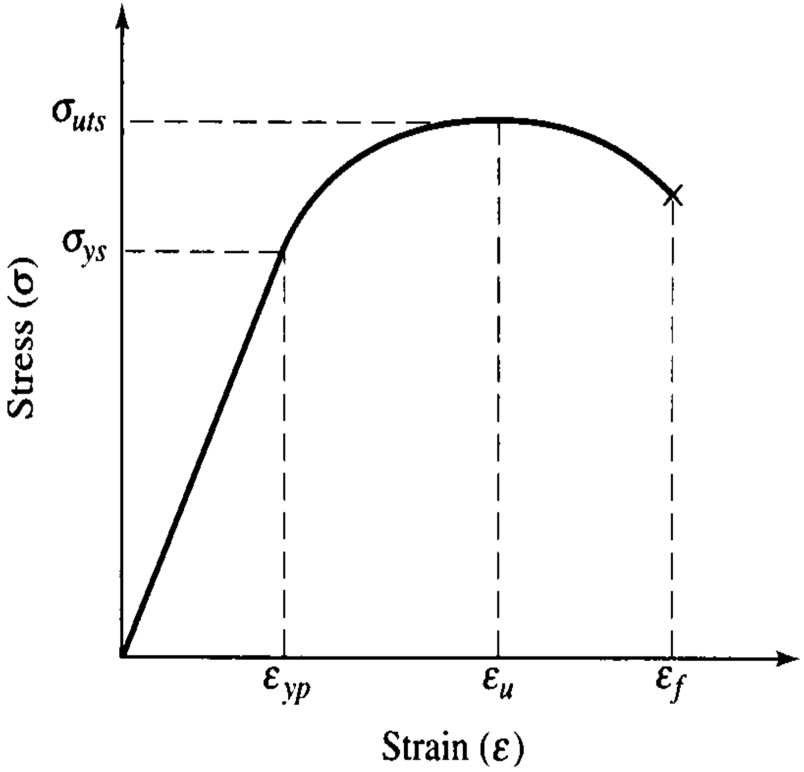
- Measures the energy it takes to separate a material

$$K_{Ic} = \sqrt{EG_c}$$



Source: inventor.grantadesign.com

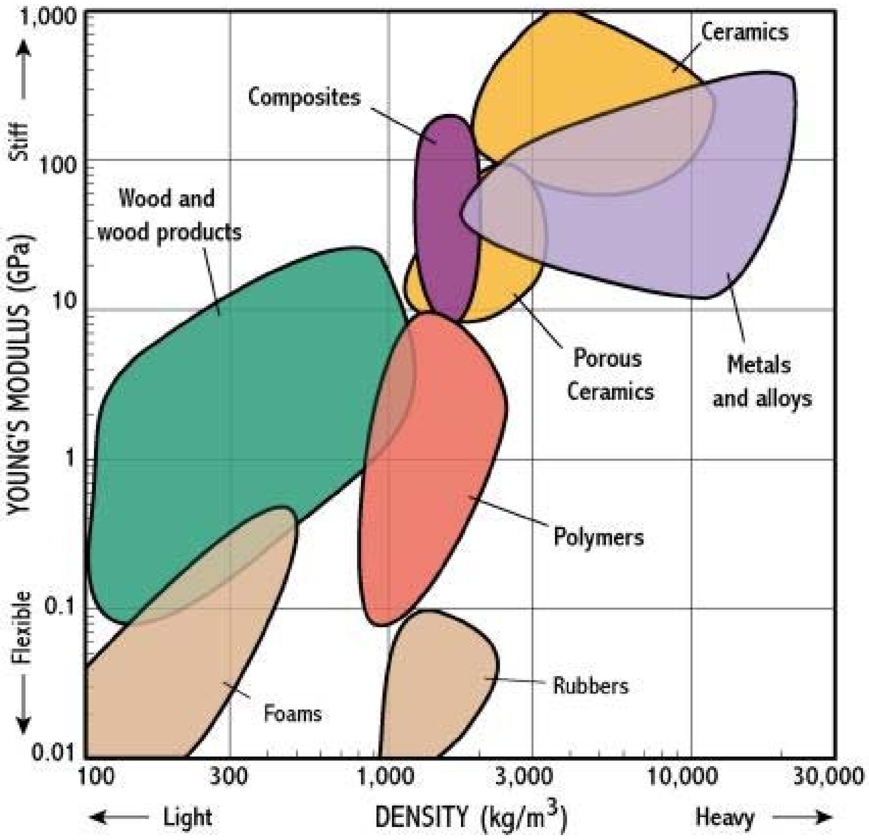
Material Properties on Stress-Strain Diagram

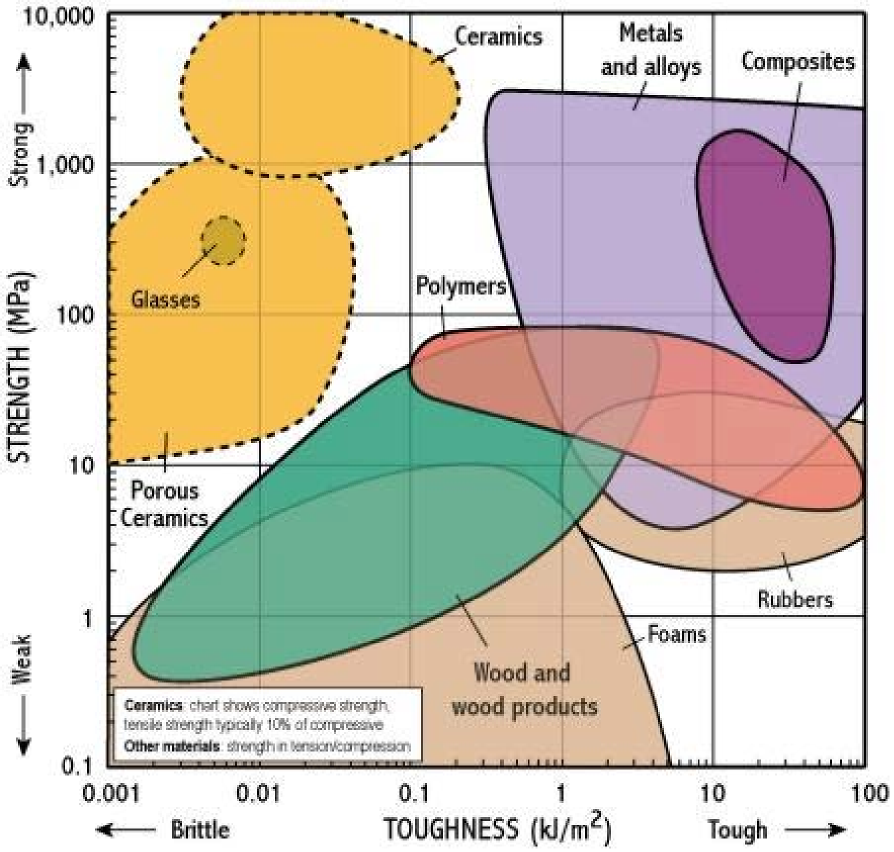


Courtesy of Ben Best. Used with permission.

http://www.benbest.com/cryonics/lessons.html

Materials Selection Charts





http://www-g.eng.cam.ac.uk/125/now/mfs/tutorial/non_IE/charts.html

Failure Criteria – Crack Propagation

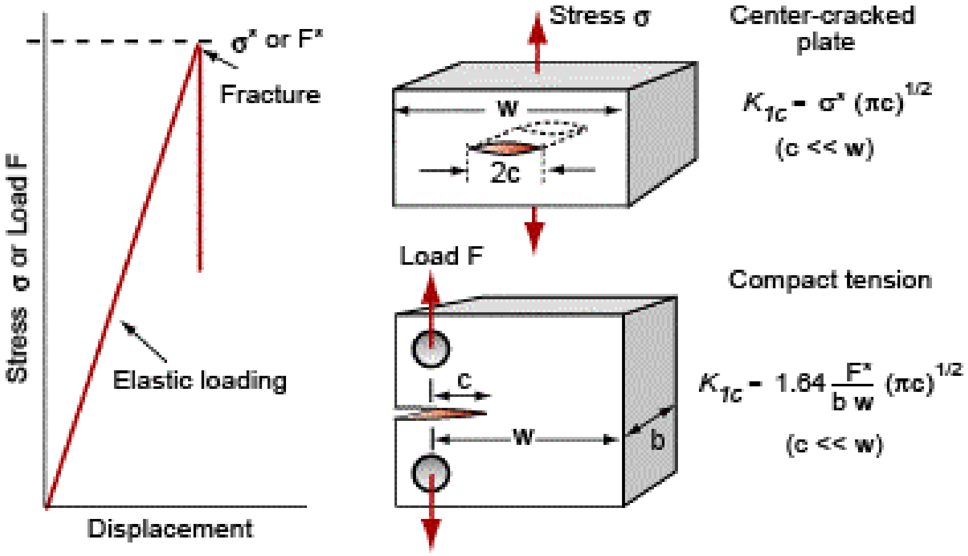
$$K_{Ic} = Y_1 \sigma^* \sqrt{\pi c} \text{ or } K_{Ic} = Y_2 \frac{F^*}{bw} \sqrt{\pi c}$$

Resistance to crack propagation

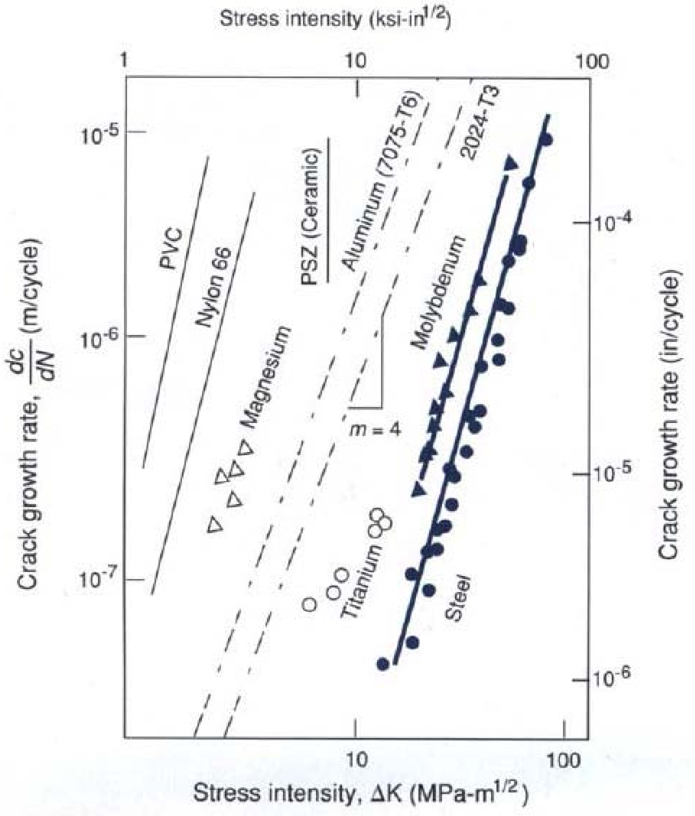
-Y_1, Y_2 are geometric factors near 1

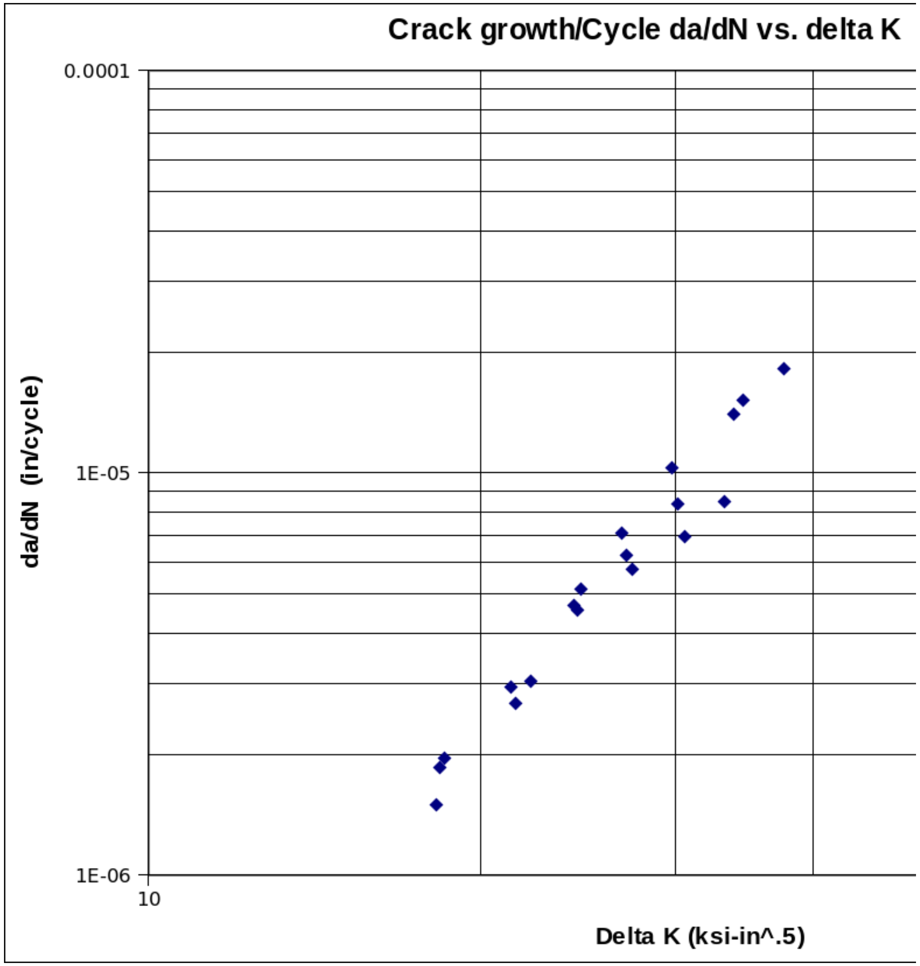
-σ^*, F^* are critical stress and force, respectively

Source: inventor.grantadesign.com



Fracture Toughness – Real Data from Alcator C-Mod





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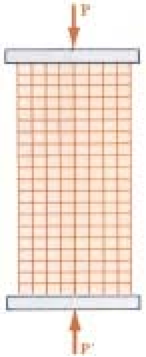
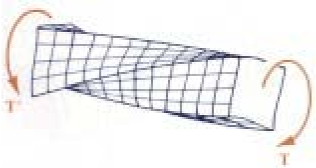
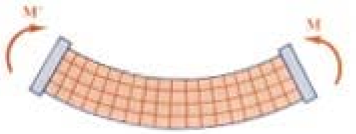
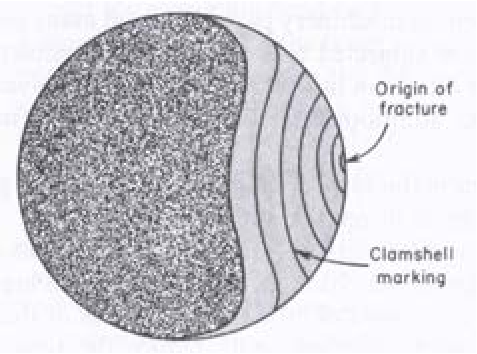
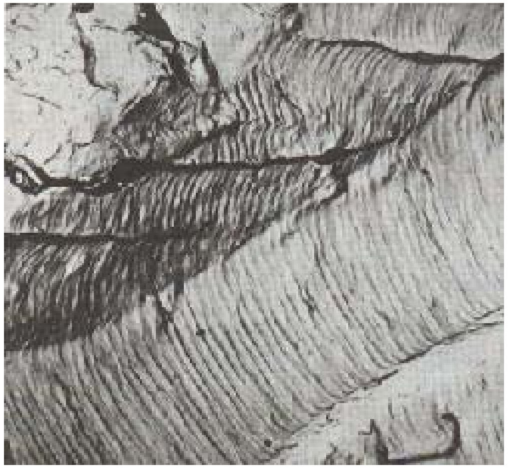
Failure Criteria – Fatigue







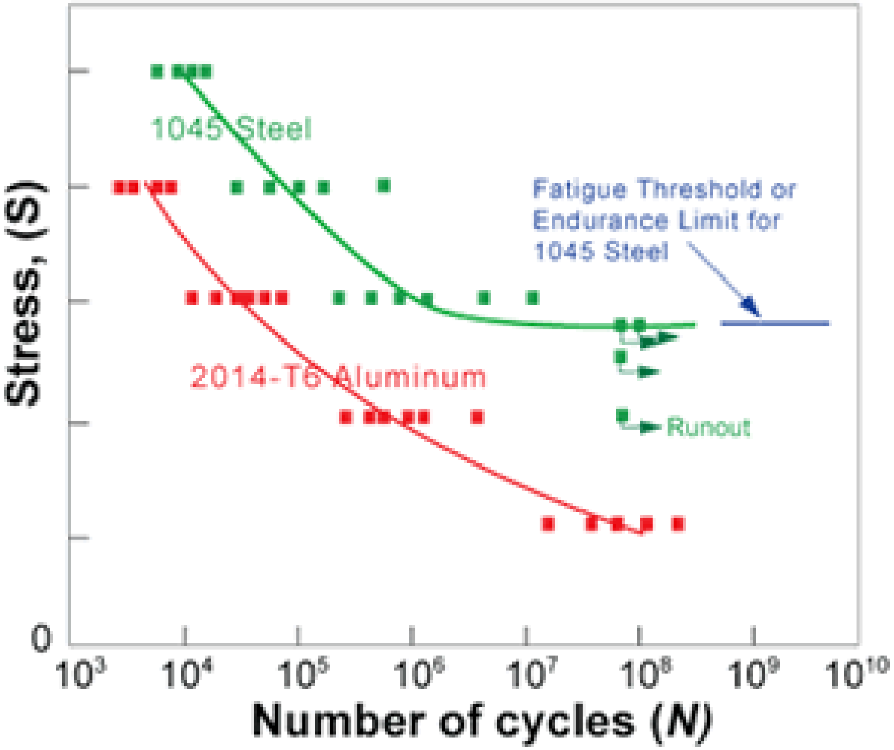




Source: www.sv.vt.edu/classes/MSE2094_NoteBook/97ClassProj/anal/kelly/fatigue.html

- Repeated application of stress can cause cracks to grow
- Induced by vibrations, mechanical loading
- Telltale “fatigue striations”
- **Where do these come from?**

Failure Criteria – Fatigue

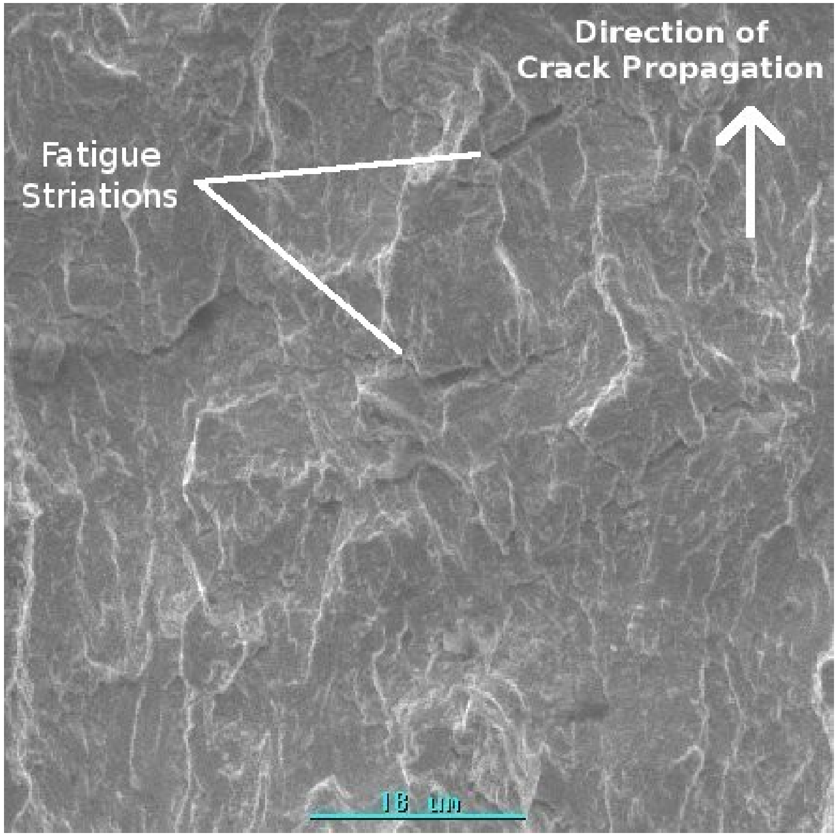


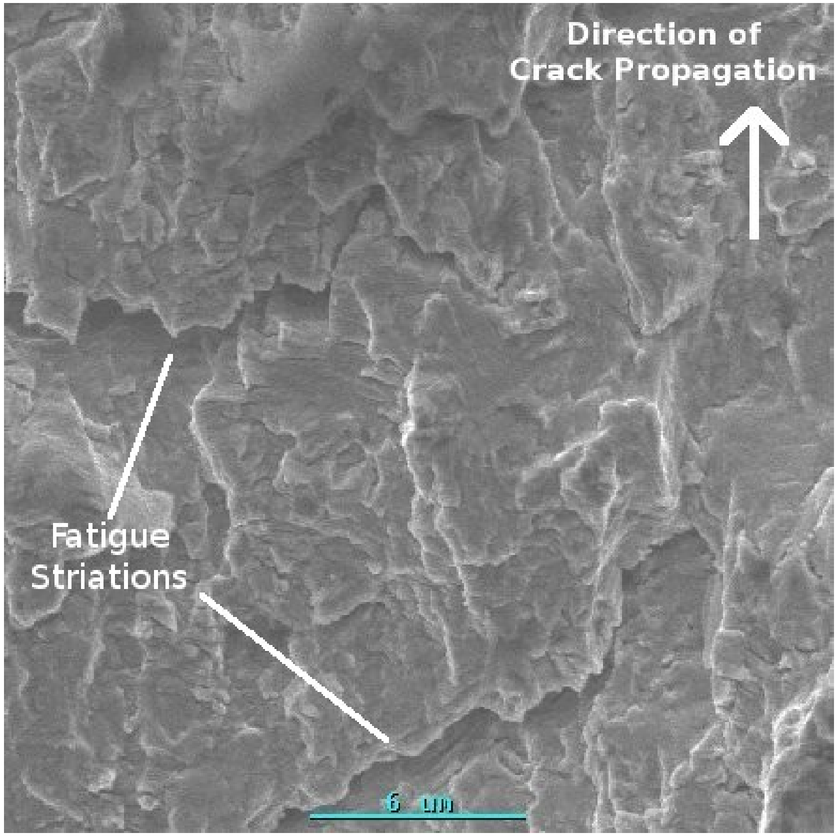
This image is in the public domain.

- Stress (S) vs. number of cycles (N)
- Lower limit of stress (where N is infinite) is the "safe zone"
- **Why do these limits exist?**

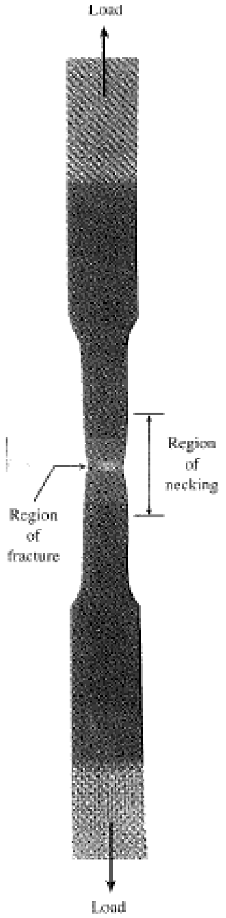
Source: www.nde-ed.org/EducationResources/CommunityCollege/Materials/Mechanical/S-NFatigue.htm

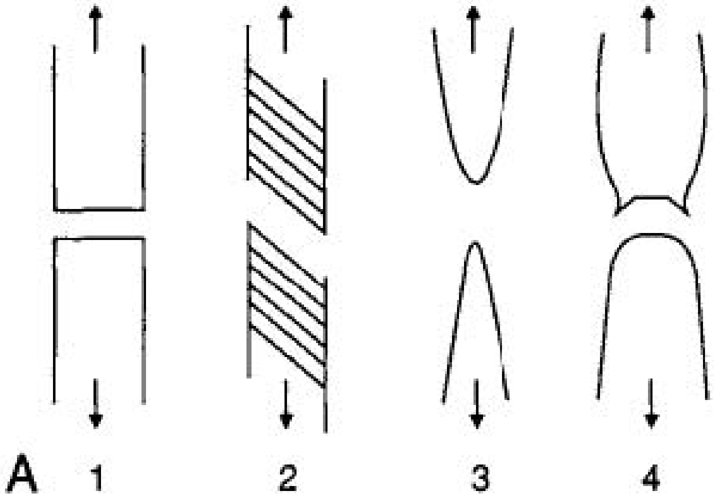
Fatigue Striations in Alcator C-Mod Rotor



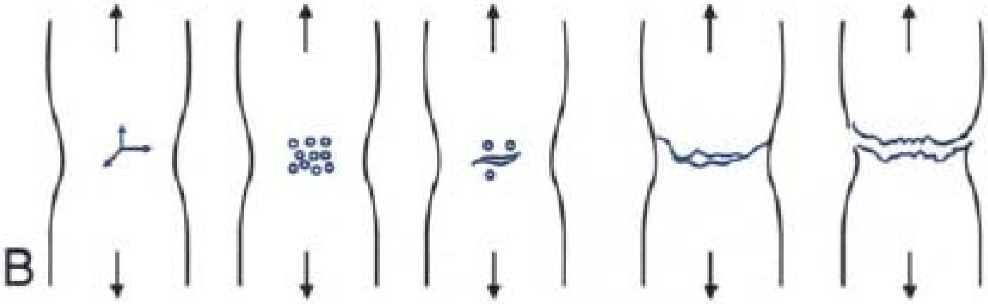


Failure Mechanisms in Tension





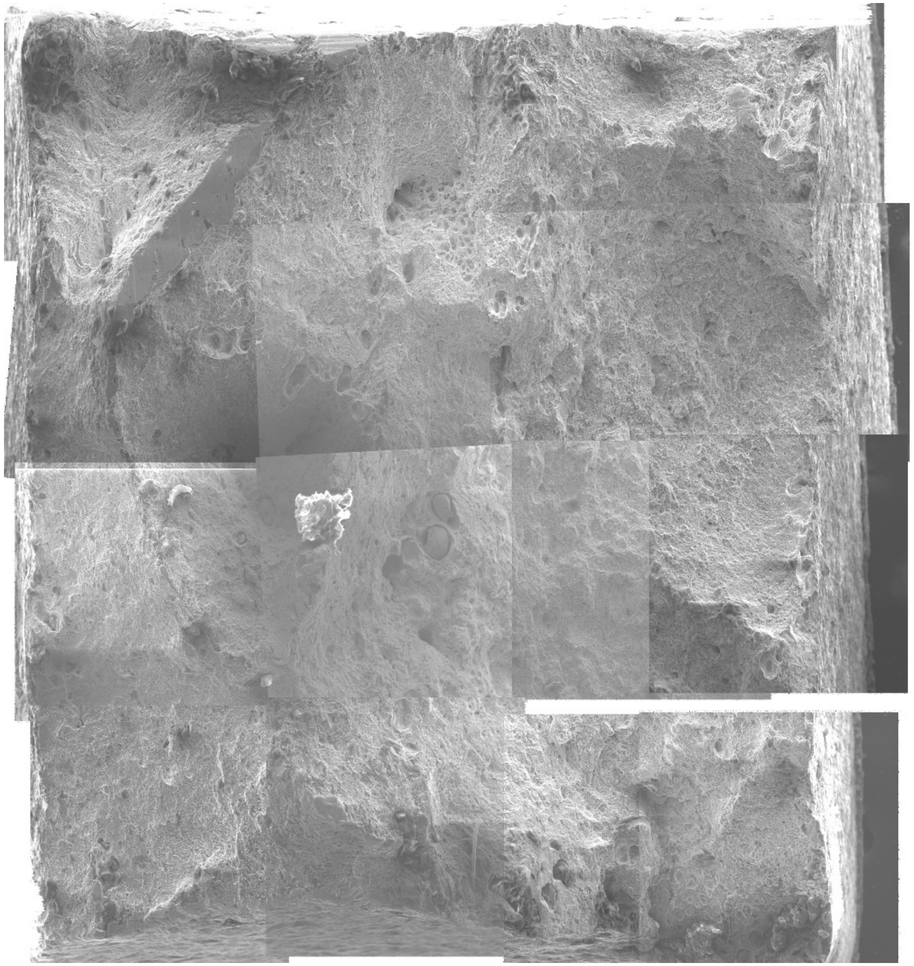
1. **Brittle fracture**
2. **Single crystal slip bands**
3. **Ideal ductile fracture (full elongation)**
4. **Realistic cup-and-cone fracture**

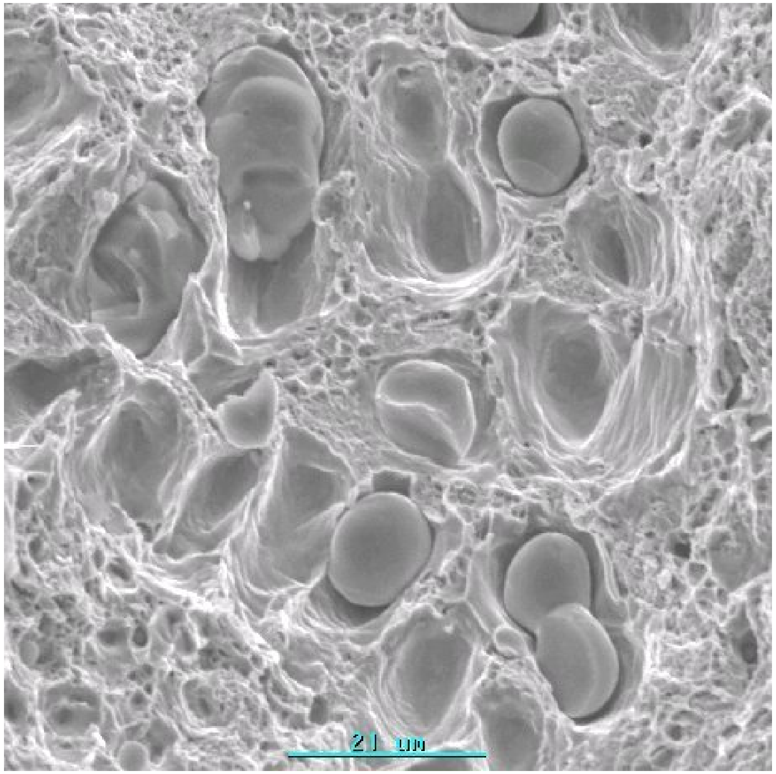


Stages of cup-and-cone fracture formation in ductile materials

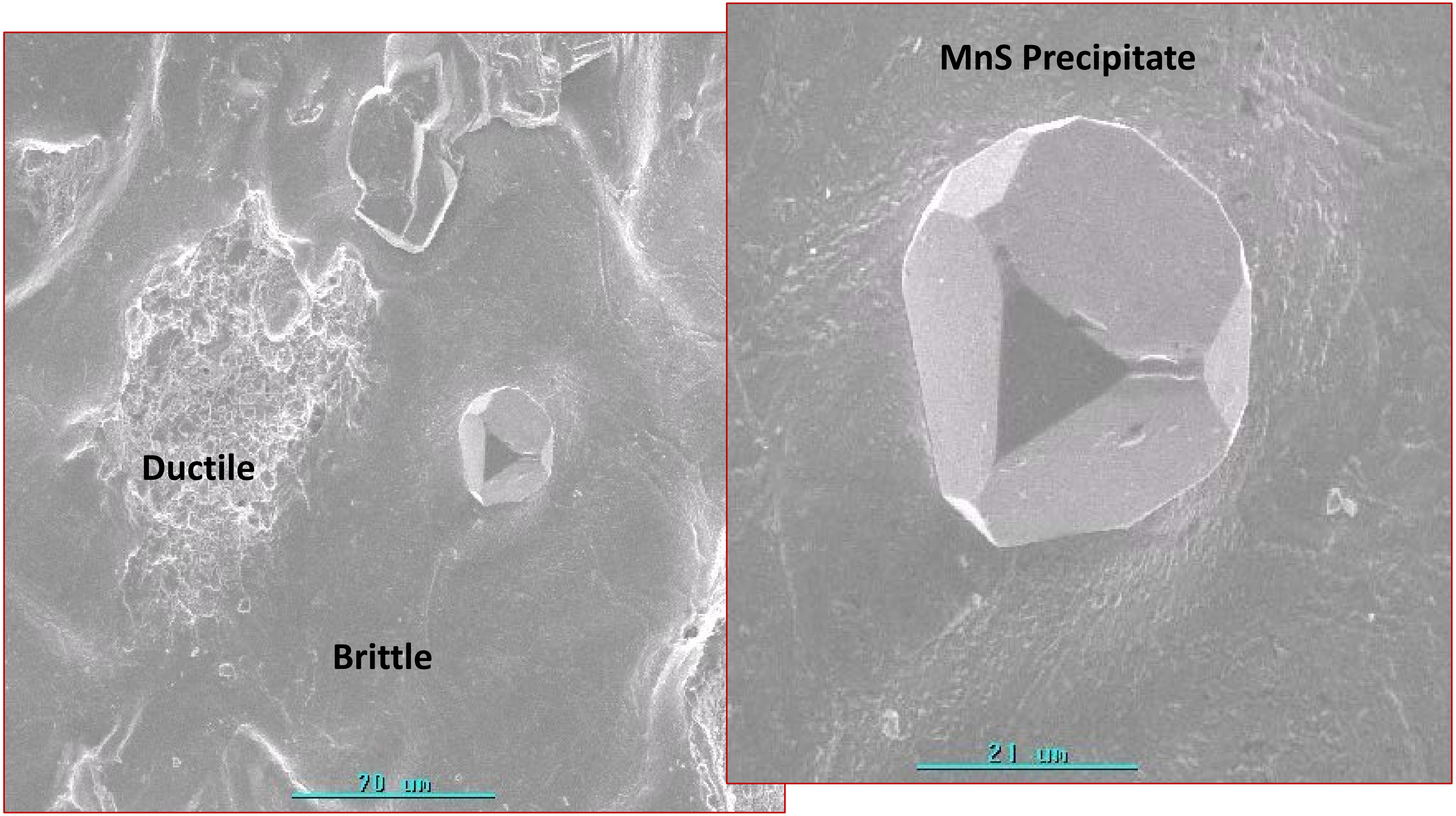
Engineering Materials Science, *Milton Ohring* , Ch. 10

Examples of Cup-and-Cone Fracture in Alcator C-Mod



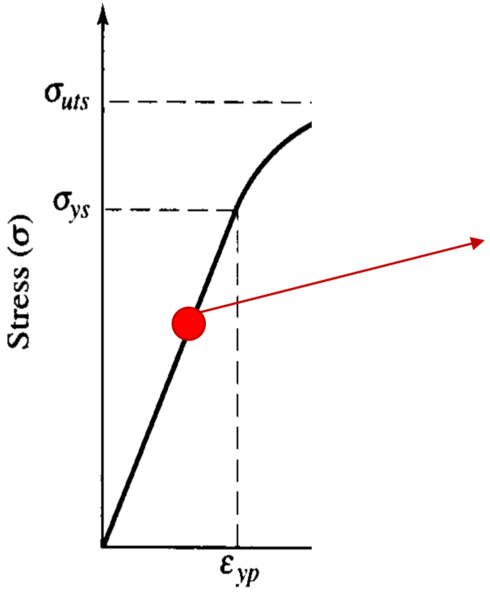


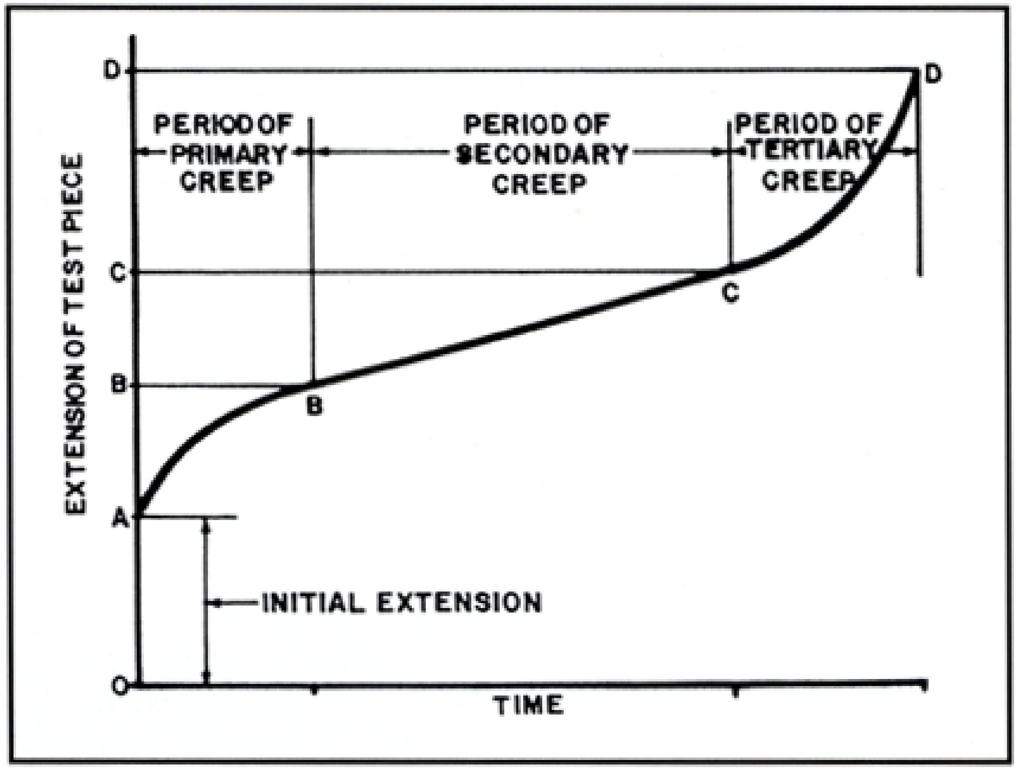
Brittle & Ductile Fracture, Side by Side



Creep – Plastic Deformation Below Yield Stress

- Imagine stretching a bar of metal within the elastic region



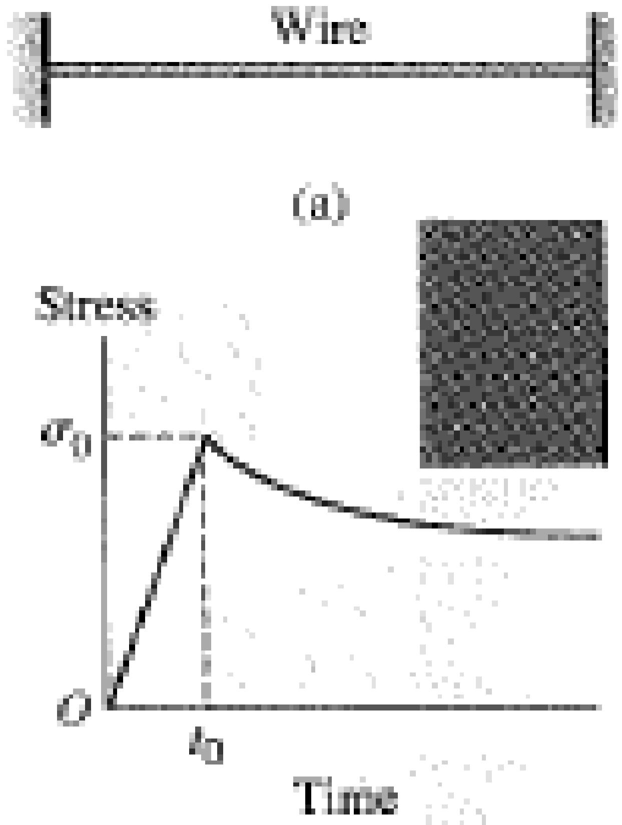


http://www.nationalboard.org/Index.aspx?pageID=181

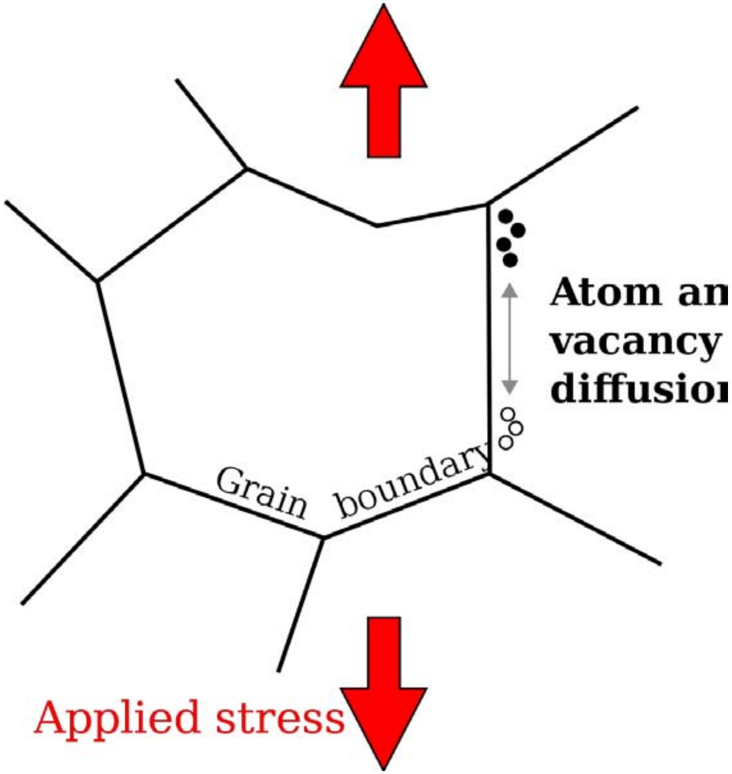
Creep – Stress vs. Time

J. M. Gere, “Mechanics of Materials,” pp. 22

- Stress increased elastically to σ_0
- Held for long time
- Stress at constant strain decreases due to *creep*



Creep Mechanisms



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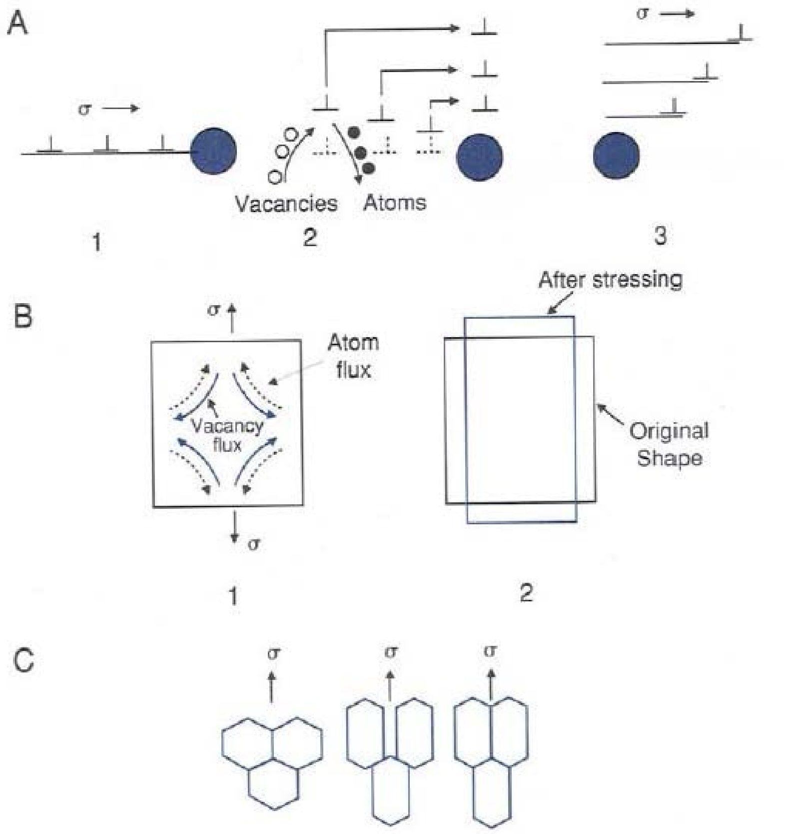
Source: Wikimedia Commons

- Plastic flow under constant stress
- Tension, gravity...
- Happens well below yield stress
- Multiple modes (Coble, Nabarro-Herring...)

Creep Mechanisms

- Dislocation climb
  - Follows power law
- Nabarro-Herring (diffusional)
  - Vacancy movement
- Coble
  - Grain boundary movement



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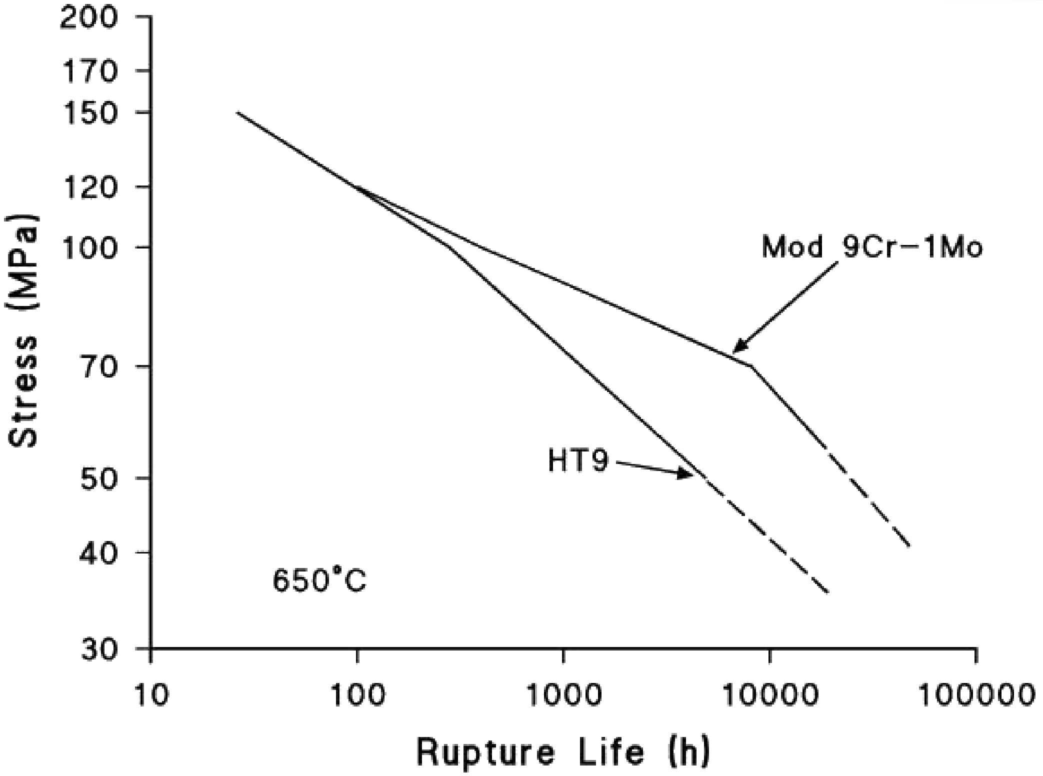
Failure Criterion – Creep Lifetime

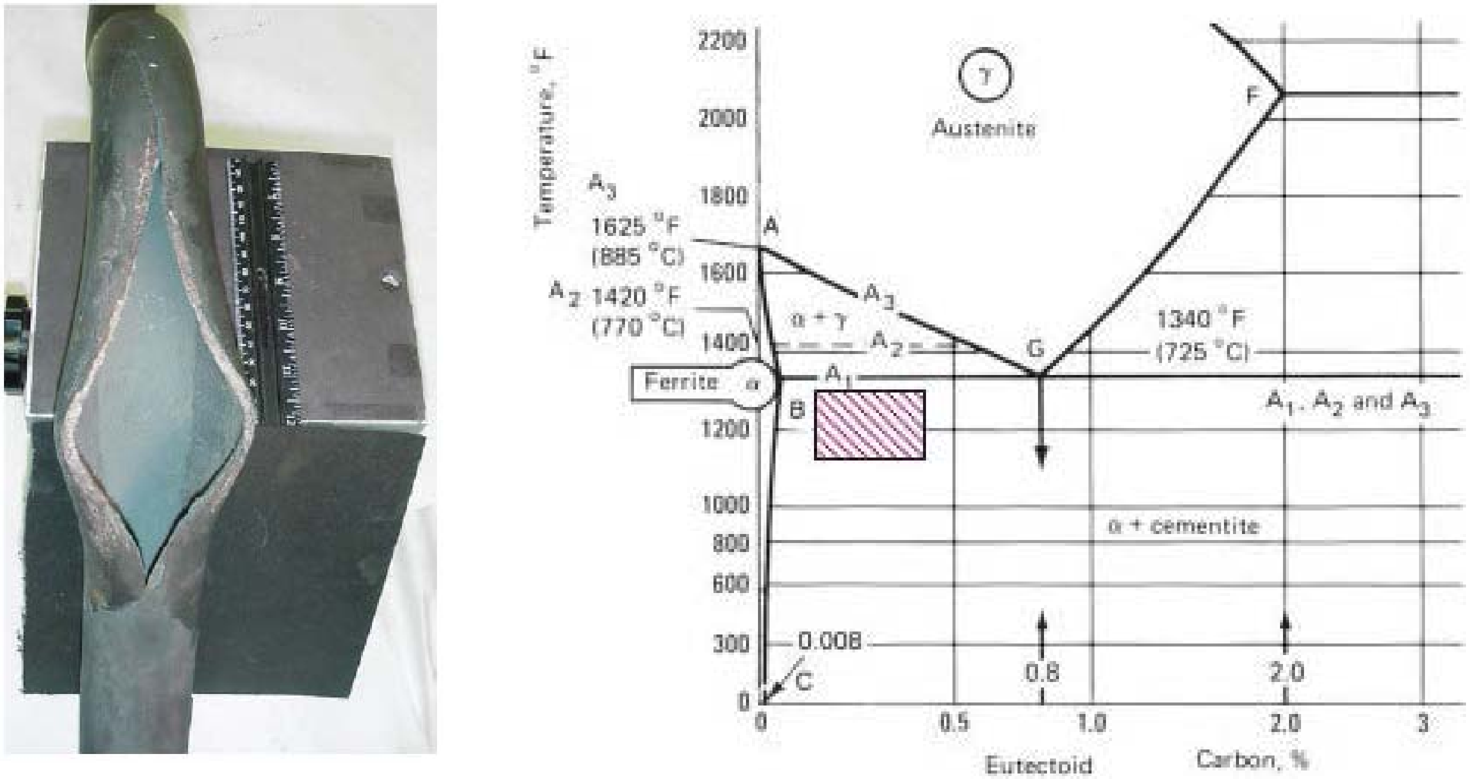


Courtesy of Elsevier, Inc., http://www.sciencedirect.com. Used with permission.
Source: Klueh, R. L., and A. T. Nelson. "Ferritic / Martensitic Steels for Next-generation Reactors." *Journal of Nuclear Materials* 371, no. 1-3 (2007): 37-52.

- Creep rupture lifetime can limit usefulness of part
- Example: Alloys HT9, T91 in high temperature service conditions

Source: R.L. Klueh, A.T. Nelson. *J. Nucl. Mater.*, 371(1-3):37-52 (2007).

Creep Failure by Time at Temperature and Pressure



Creep failure of alloy T91 due to improper heat treatment, heated above A1 temperature. In T. Totenmeier, "Experience with Grade 91 Steel in the Fossil Power Industry." Presentation, ALSTOM, Feb. 2009.

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