Chapter 6

Materials Mechanical Properties

Dr. Zhe Cheng

From Rigid Body to Practical Engineering Materials

Statics   Rigid body   No deformation   No failure

There are NO rigid bodies!

Mechanics of Solids
(or Materials, CIVE360)

Practical engineering
materials

w/ deformation
(elastic/reversible or
plastic/irreversible

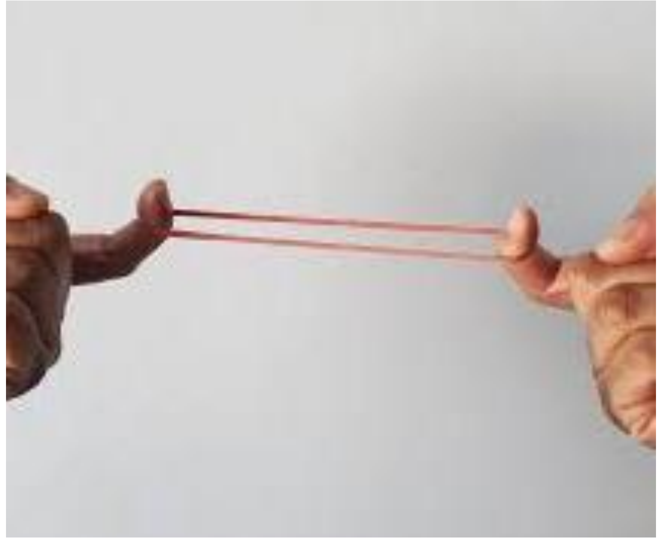
Can (often) failure
(Fracture, Fatigue,
Creep)

Relating & important to other courses such as:

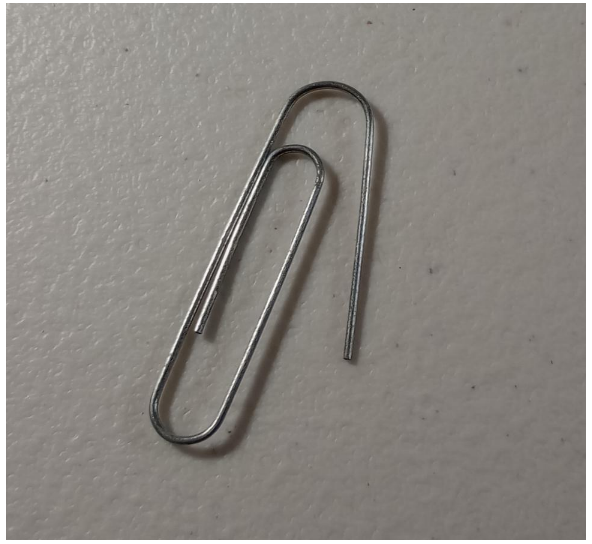
- Machine Design (MECH325)
- Finite Element Analysis (MECH301A)
- Senior Design
- Real world …

Materials Deformation Examples

Rubber band

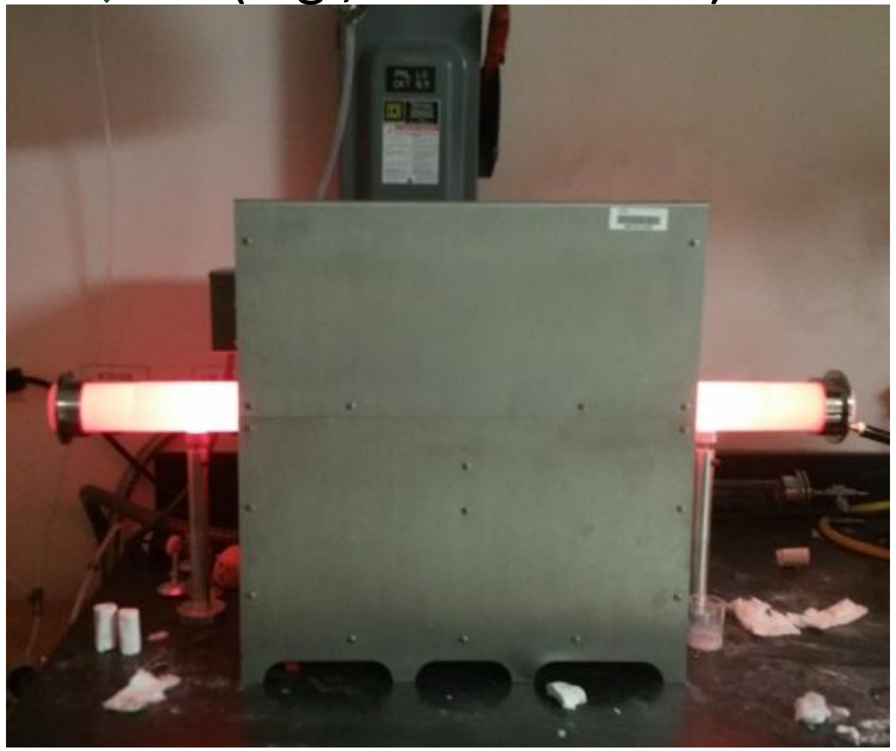


Steel paper clip



Al_2O_3 tube for tube furnace, melting point: Tm = 2025^oC

Use at high temperatures
(e.g., 1300-1600^oC)



Materials Failure Examples

View of the FIU-Sweetwater UniversityCity Bridge which collapsed five days after being installed over SW 8 Street-State Road 41 on March 15, 2018. (Pedro Portal/Miami Herald/TNS via Getty Images

Cracks!

Matt Tranchin
@mtranchin

If this ends up being the opening scene to Final Destination 13, I'm going to be really salty. #Flight1380

9:27 AM - 17 Apr 2018

Engineering Stress

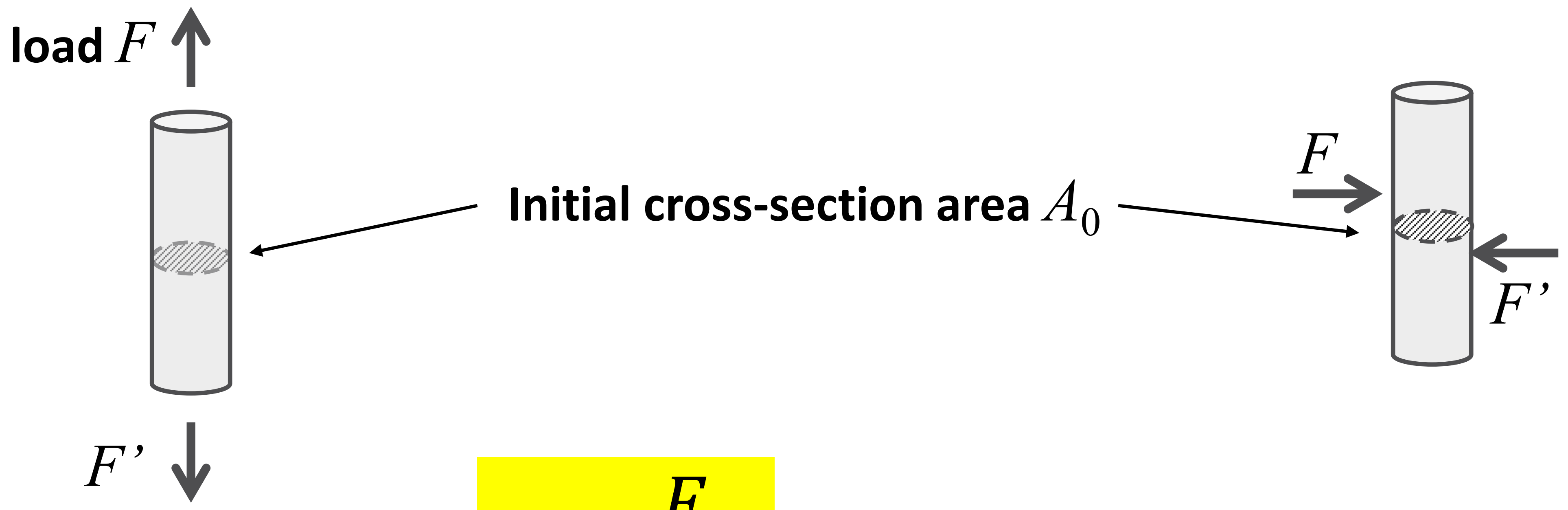
In statics, a “rigid body” can handle ANY force or load, no matter 1 N vs. 10^6 N

In reality, can a design (material or geometry) sustain a given load??

Need to introduce concept of force intensity or STRESS - force per unit area

Axial (tensile or compressive) load

Shearing/cutting load



Normal (Engineering) Stress $\sigma = \dfrac{F}{A_0}$

Shearing (Engineering) Stress $\tau = \dfrac{F}{A_0}$

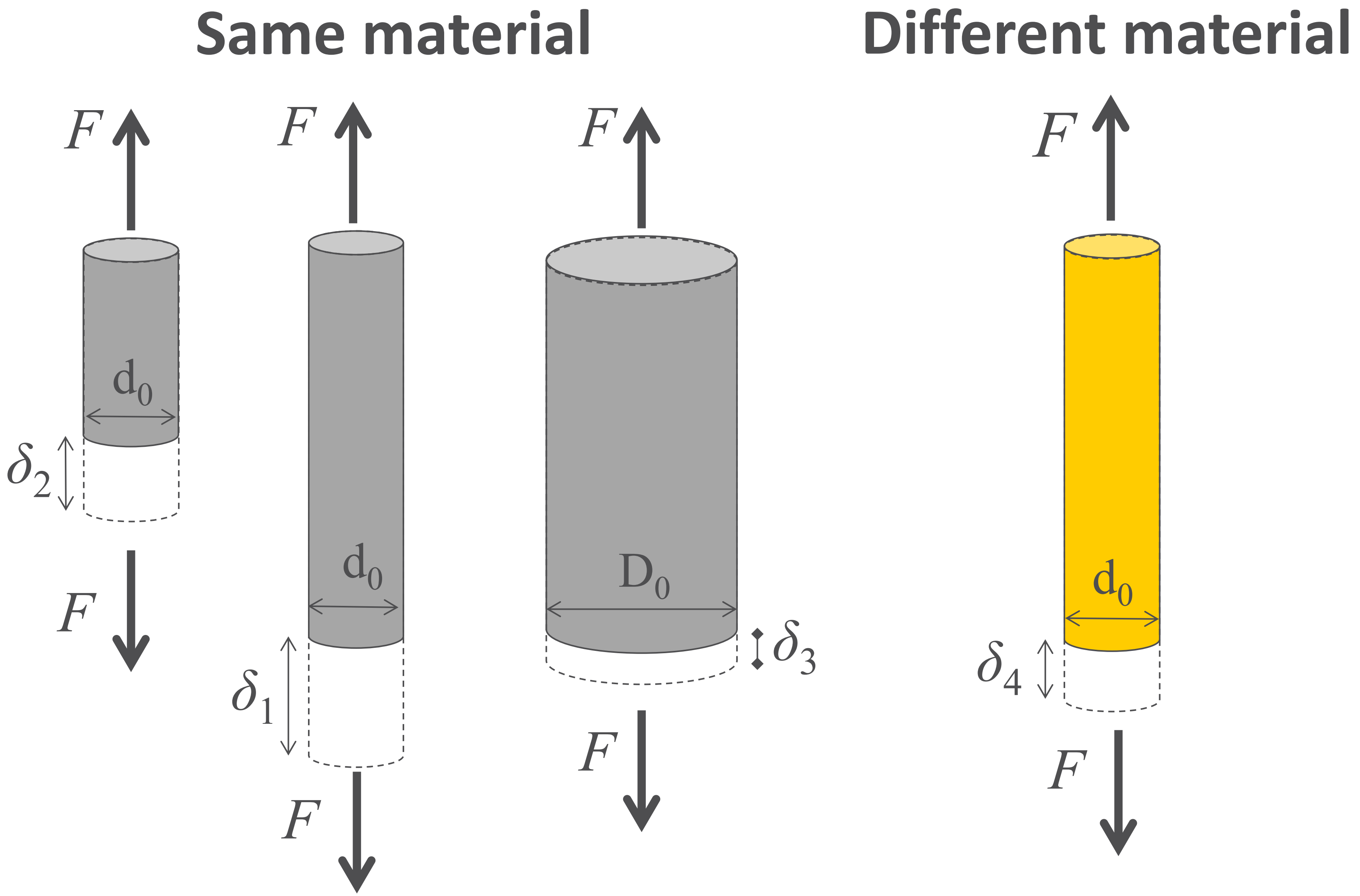
Same Unit: Pa (= N/m^2) or psi (= lb per in^2) or lated

Load F and normal stress σ **perpendicular** to the area of interest A_0

+ for tension, - for compression

Load F and shearing stress τ **parallel** to the area of interest A_0

NO Rigid Body: Load & Stress Lead to Deformation

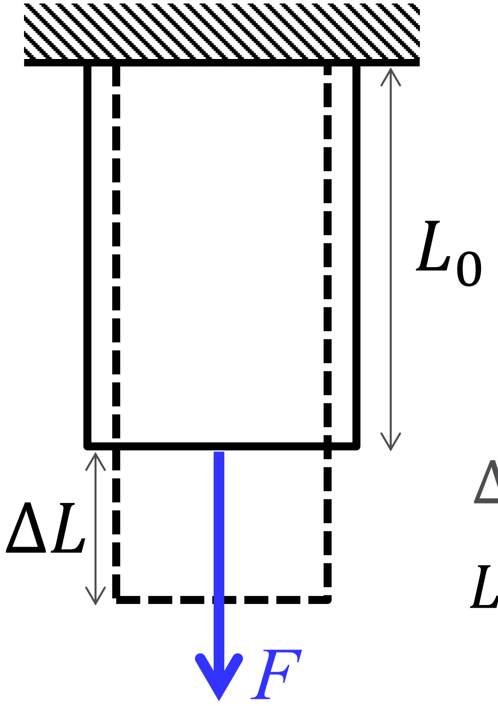


Engineering materials <u>**always**</u> deform or experience shape change under load/stress:

- **Absolute change in length?**
- **Relative change in length** & **angle**? – Need to introduce **STRAIN** or **relative deformation**
- Enable easier comparison between different loading configurations (in dimension or material)

Engineering Strain

Normal (Engineering) Strain ε



$$\varepsilon = \frac{\Delta L}{L_0}$$

ΔL **Absolute change in length**

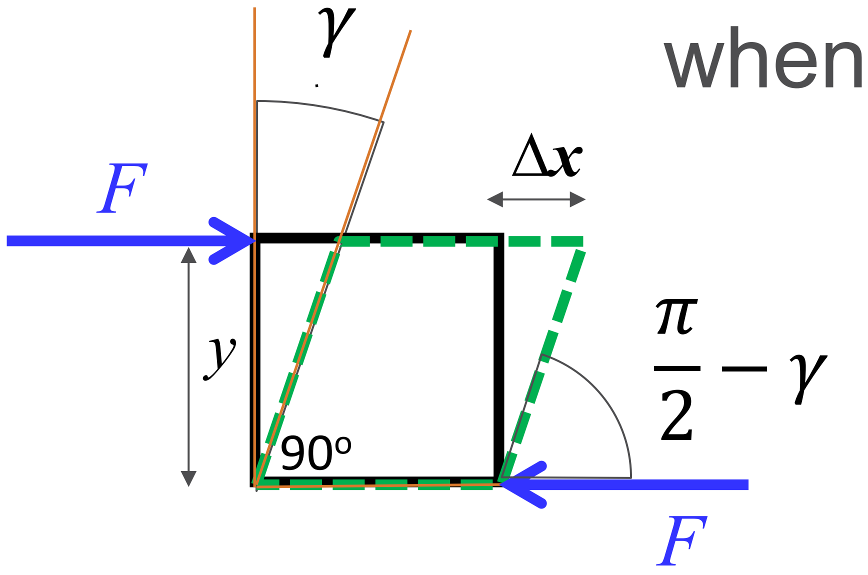
L_0 **Initial length**

Note for tensile test, the sample also experiences contraction/shrinkage in the cross-section area

Shearing Strain γ

$$\gamma = \operatorname{atan}\frac{\Delta x}{y} \approx \frac{\Delta x}{y}$$

when $\frac{\Delta x}{y} \ll 1$

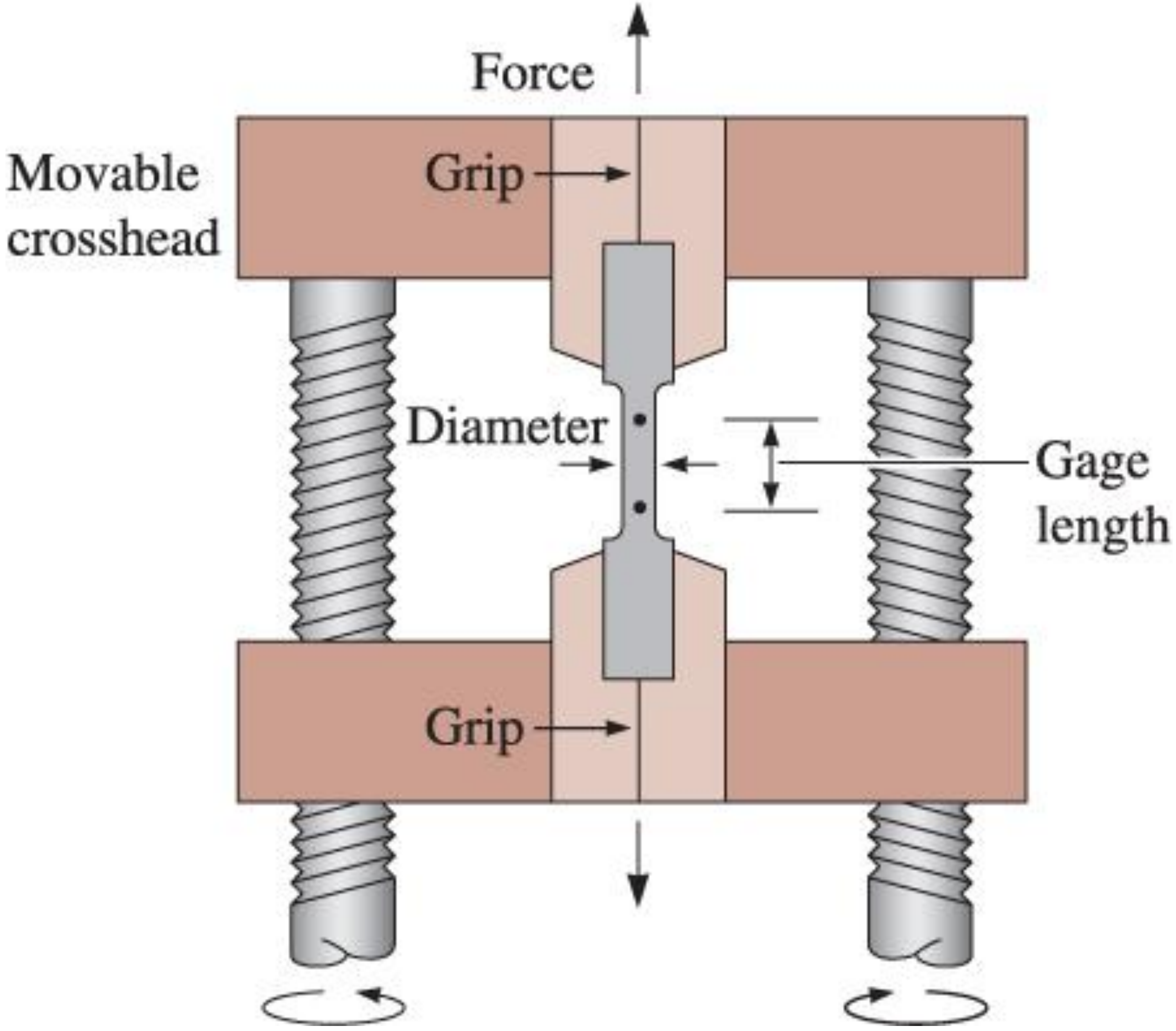


For shearing, sample shape or dimension change is primarily in the **angle**!

Strain, no matter normal or shearing, is always dimensionless.

Tensile Test & Stress-Strain Curve

A material's mechanical behavior, often represented by engineering stress-strain curve, is usually obtained from tensile tests



Tensile test machine

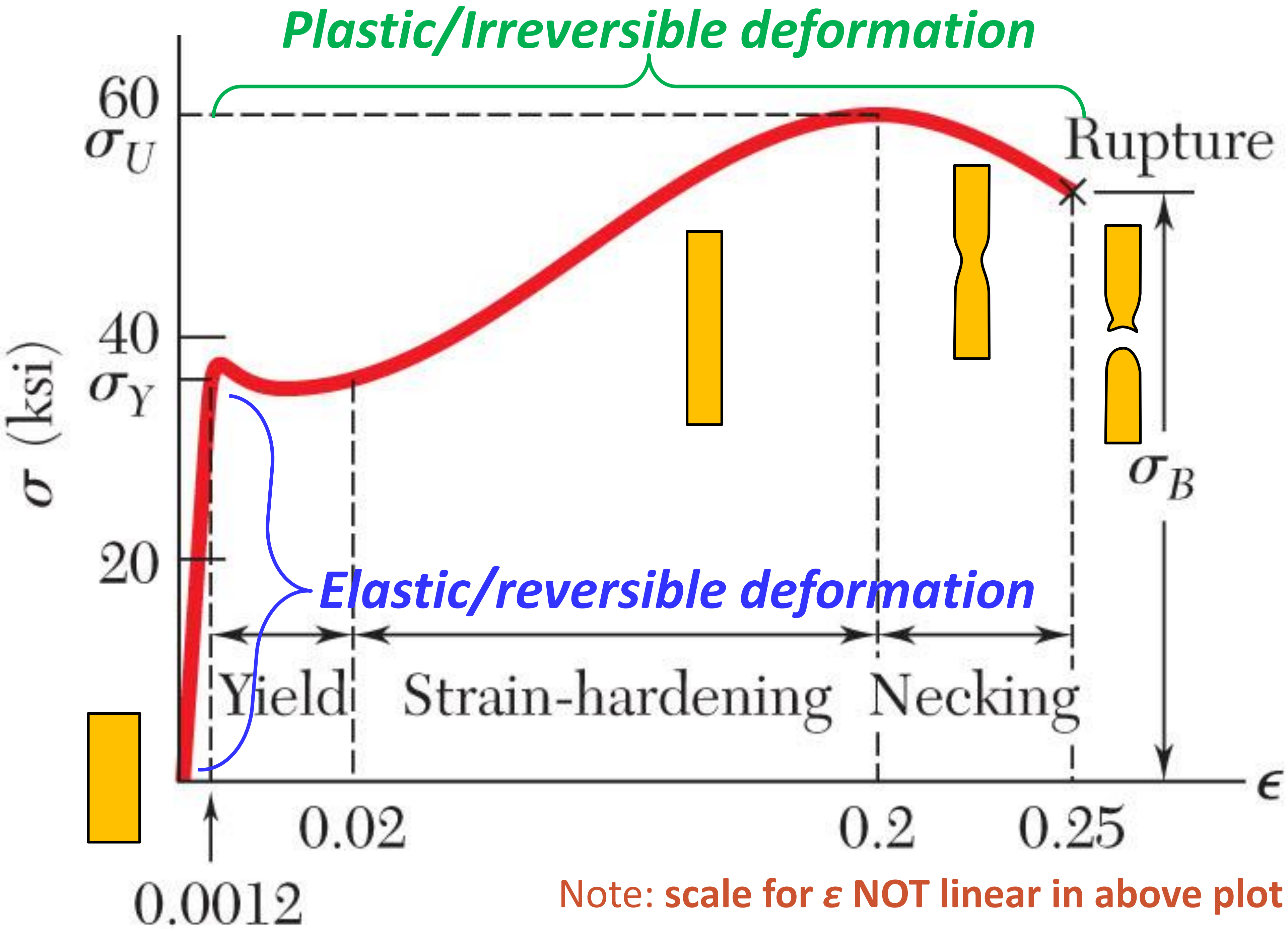
"Dog-bone" shaped samples for tensile test

Usually for metals, polymer, composites, but NOT for ceramics

https://www.instron.com/en/resources/test-types/tensile-test
https://hill-engineering.com/general-interest/tensile-test/

Stress – Strain Curves for Ductile Materials

- Initial **linear, elastic/reversible** behavior at low stress
- Afterwards, significant ***non-linear, plastic/irreversible*** deformation,
- Eventual fracture or failure, often with **NECKING** before fracture or rupture, that help predict failure
- For most metals (and plastics, with changes)

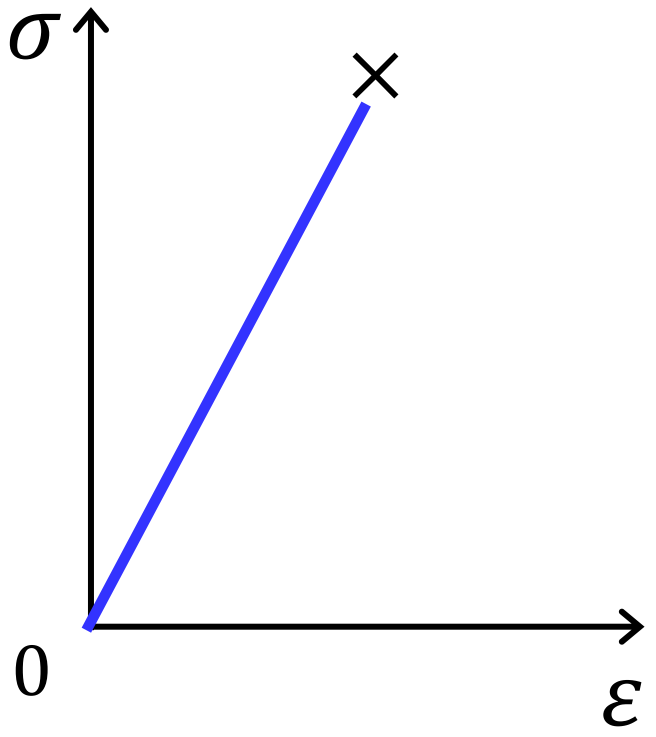


Note: **scale for ε NOT linear in above plot** (to better show initial, low stress region)

(*a*) Low-carbon steel

Stress – Strain Curves for Brittle Materials

- Only has linear, elastic/reversible section under low stress,
- NO non-linear/plastic/irreversible section, as it would fail/fracture/break
- NO necking



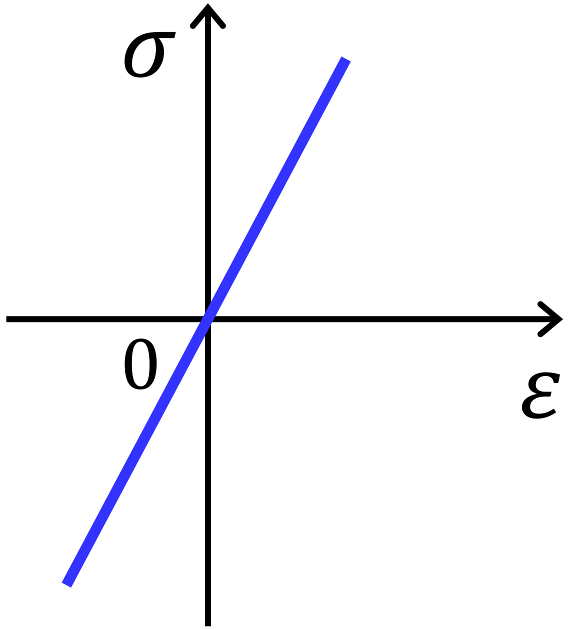
1st Stage: Linear Elastic/Reversible Deformation & Hooke's Law

- Ductile or brittle, when **stress is (very) low**, a material's deformation is **reversible** or **elastic**, and there is **linear relationship between engineering stress σ & strain ε**

Hooke's Law

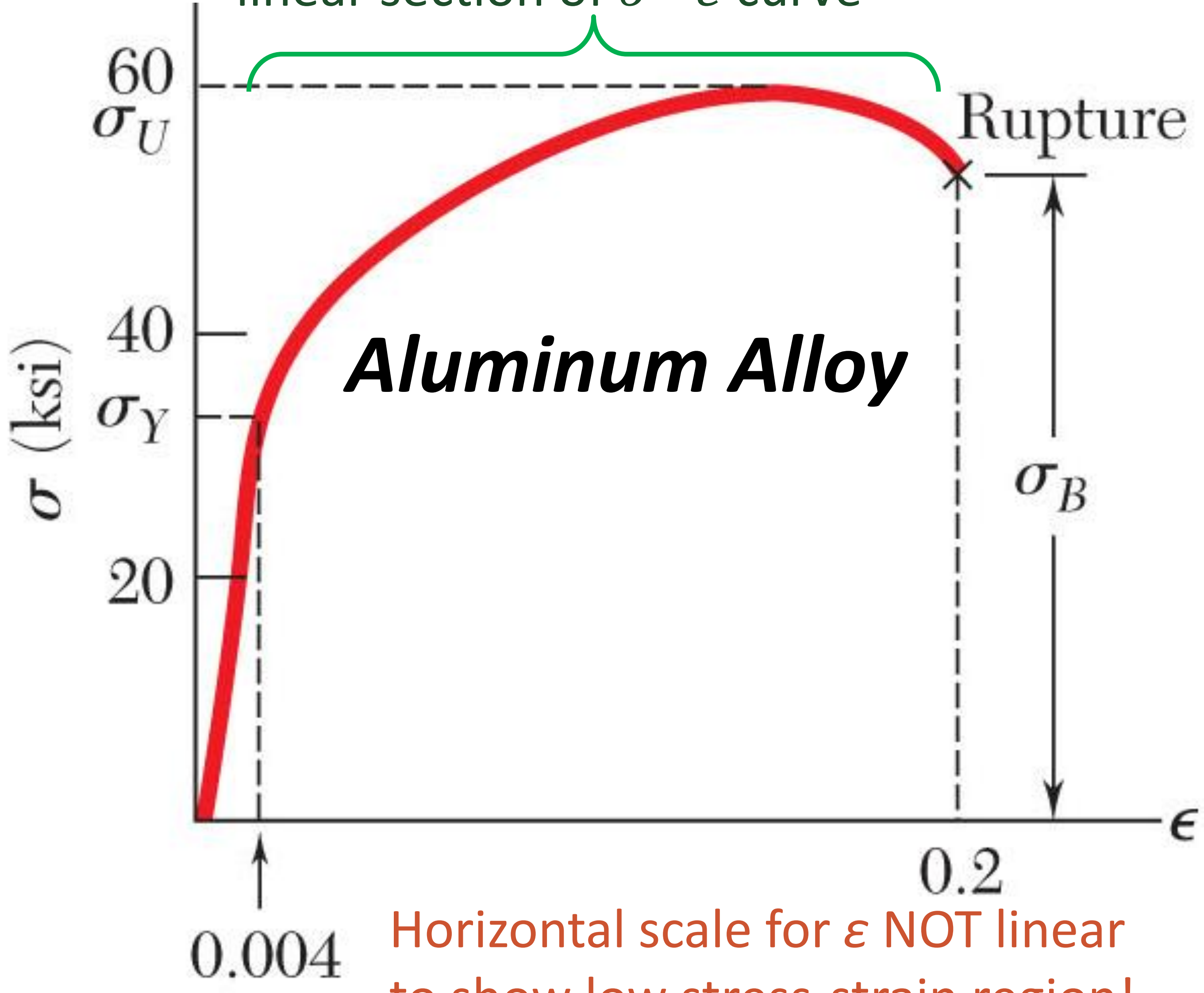
$$\sigma = E\varepsilon$$

$$\varepsilon = \frac{\sigma}{E}$$



E Elasticity Modulus

- Also known as **Young's modulus**
- Slope of the beginning, linear section of the stress-strain curve
- Small E → materials easily elongates upon tensile stress (i.e., not strong or stiff)



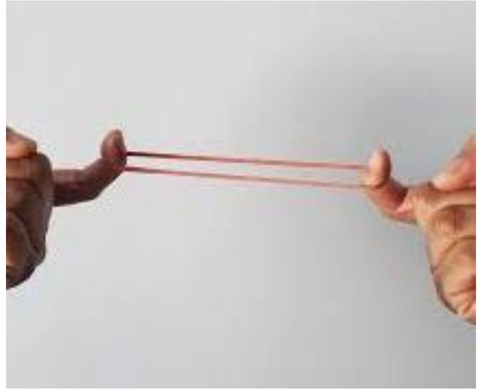
Do NOT use Hooke's law on later, non-linear section of σ - ε curve

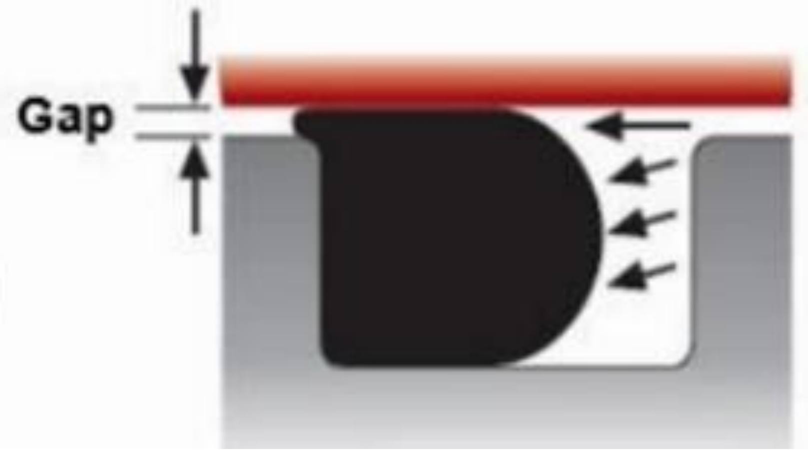
Horizontal scale for ε NOT linear to show low stress-strain region!

Elastic Modulus: High & Low

- Examples when a material’s elastic modulus *E* needs to be **high**:
  - Wheels for trains
  - Cables for suspending bridges
  - Auto frame
  - …

- Examples when elastic modulus E needs to be **low**:
  - Rubber band (e.g., for hair)
  - O-ring for sealing
  - …

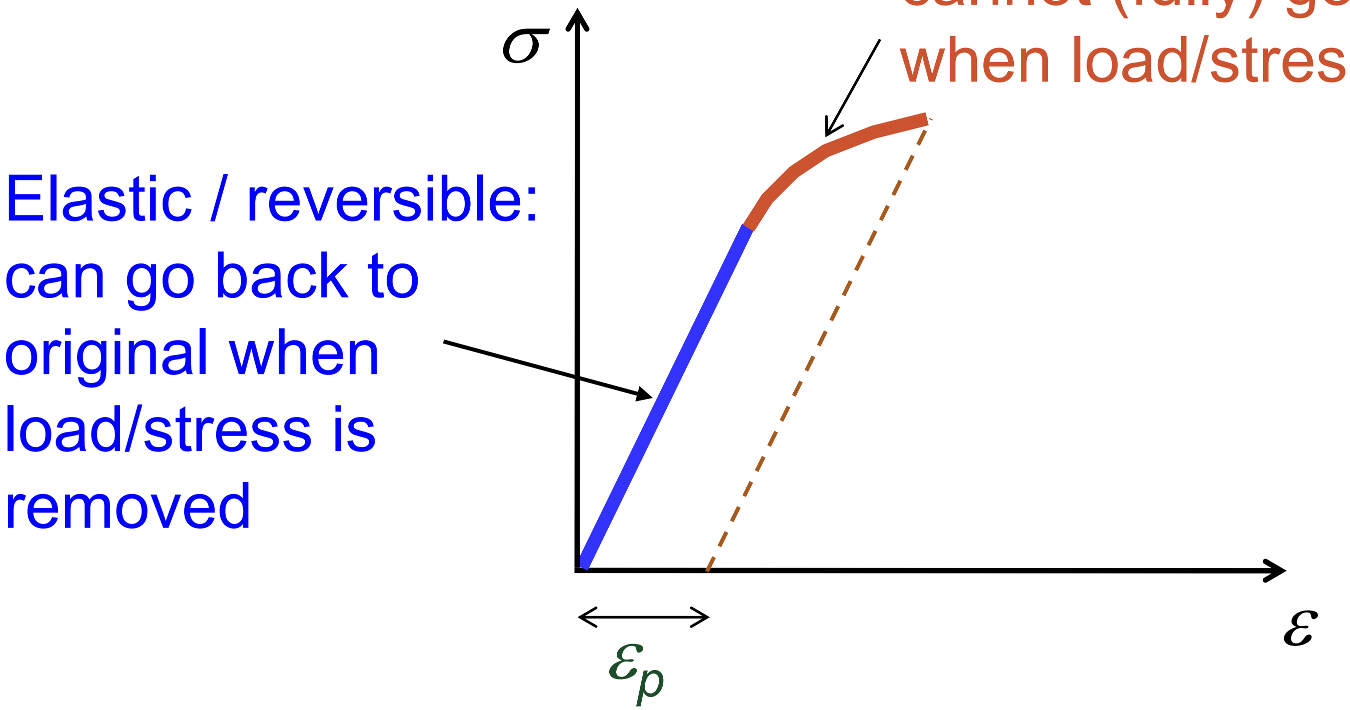




2nd Stage – Plastic (Permanent/Irreversible) Deformation

In tensile test for most metals & polymers:

- When load/stress is low – elastic, reversible deformation (1st stage)
- When load/stress increases further – ***plastic, irreversible (or permanent)*** deformation occurs, and the stress-strain behavior is typically ***non-linear***



Plastic, irreversible:
cannot (fully) go back to original when load/stress is removed

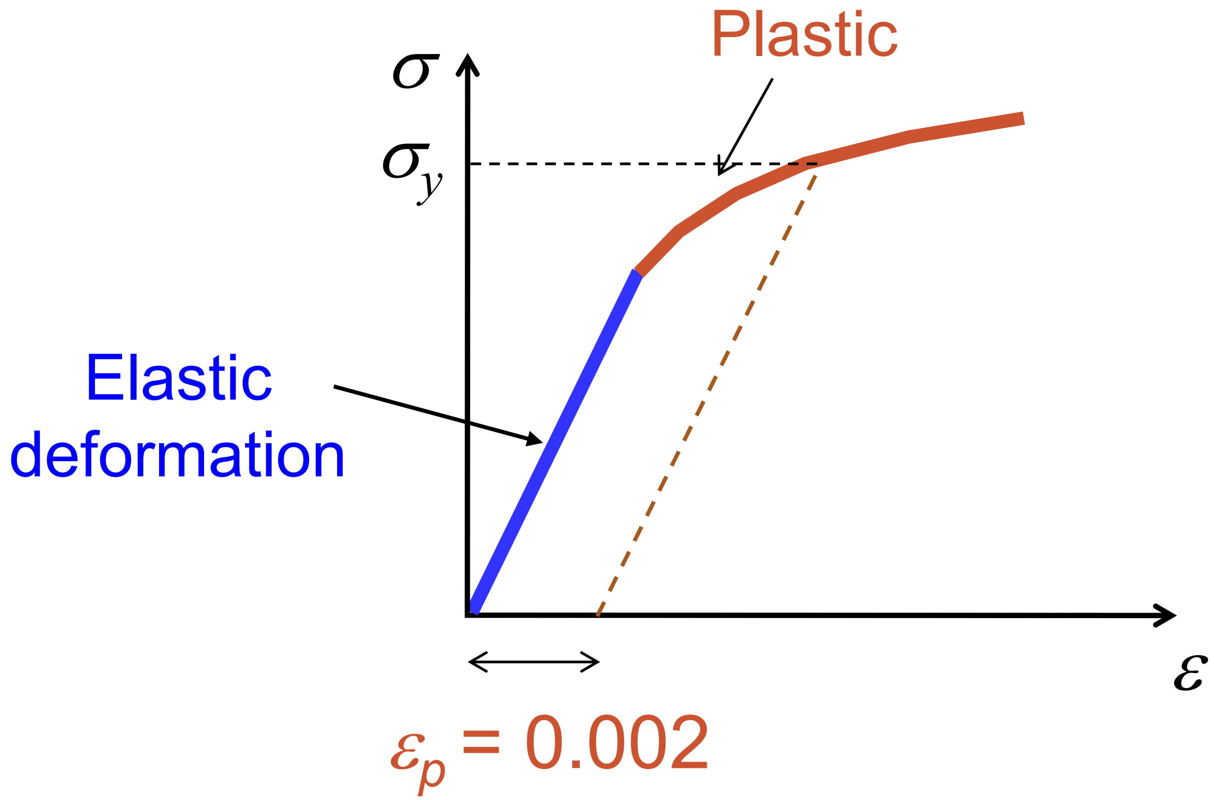
Elastic / reversible:
can go back to original when load/stress is removed

plastic or residual strain

Features in Plastic Region - Yield Strength

Yield strength σ_y - Stress at which level plastic (irreversible or permanent) deformation starts to occur

- Difficult to pinpoint due to gradual transition
- In practice, often use **"offset" yield strength** for a given strain ε, and for metals, mostly tensile strain of 0.002 or **0.2% - a very small value!**



Determine Yield Strength from Tensile Curves

Yield strength for A514 steel:

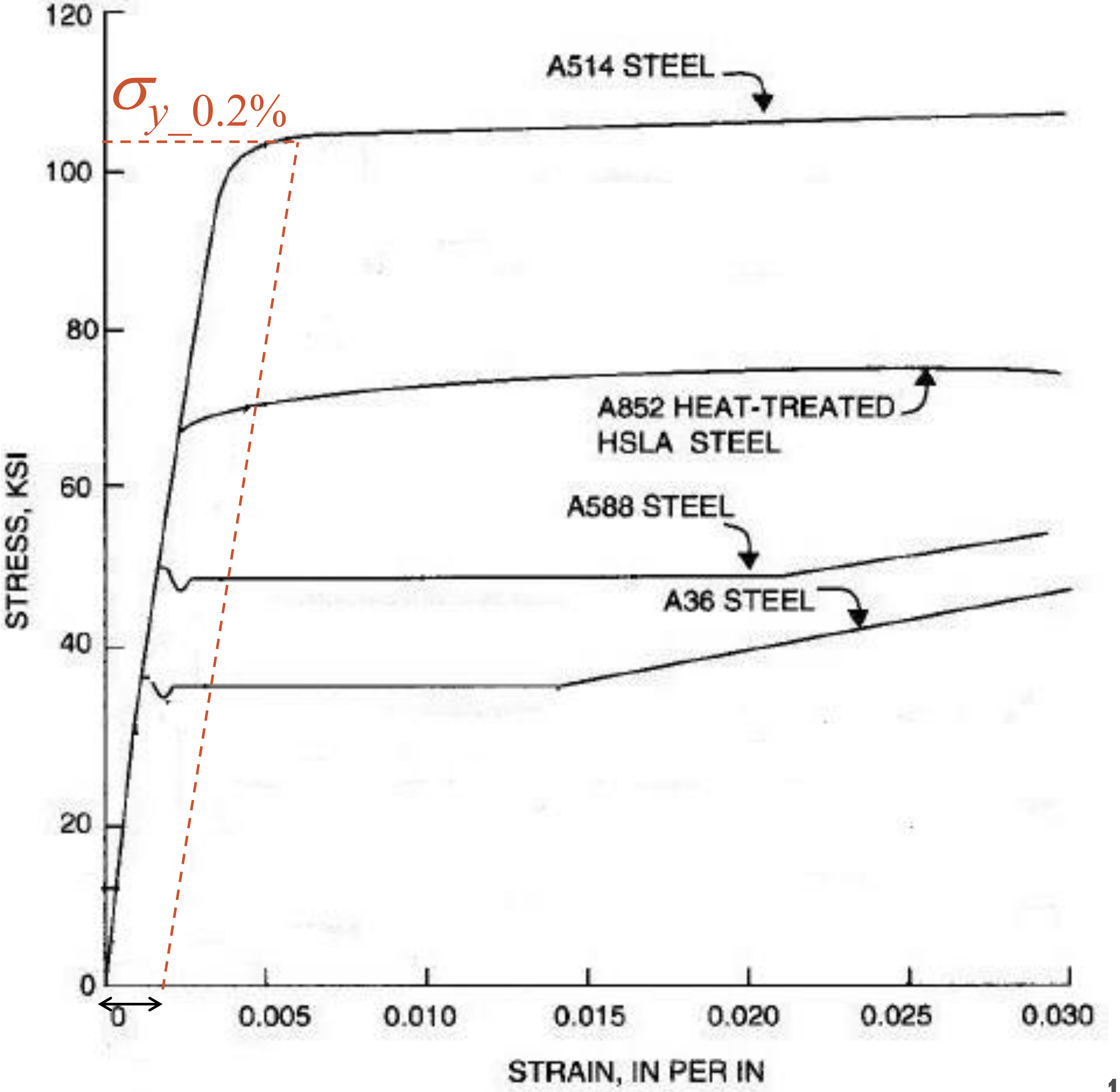
- **Estimation/“eye-ball” method:**

Stress when plastic (non-linear) deformation starts →
Look for the transition between linear (elastic) to non-linear (plastic) → **~ 95 ksi**

Or, by convention, metals mostly use:

- **0.2% “off-set” method:**

From 0.2% strain/0 stress point, draw a line parallel to linear section of tensile curve → intercept with tensile curve → **~105 ksi**



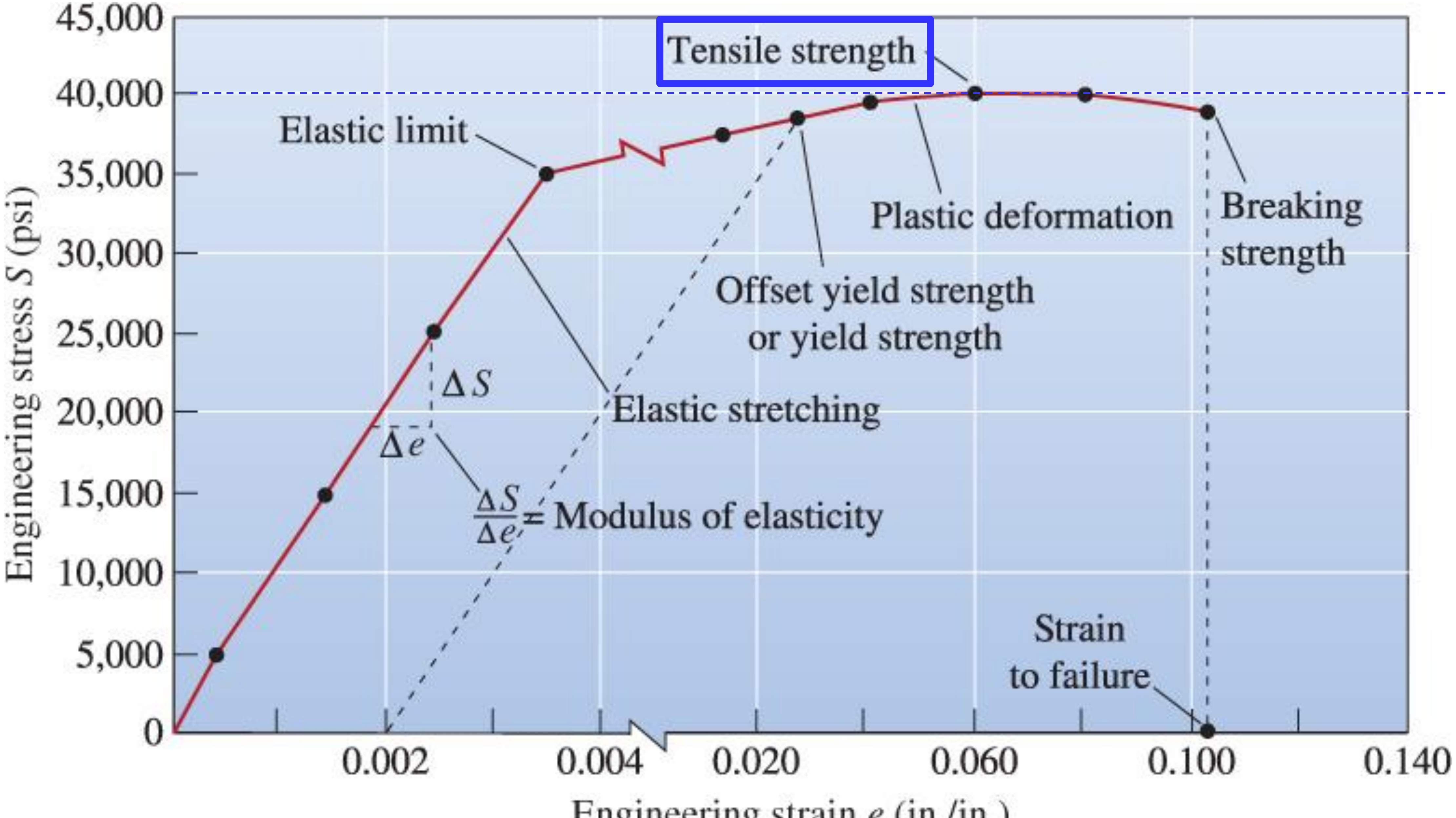
Materials' Yield Strength – High & Low

- When high yield strength is desirable
  - iPhone frame
  - Bicycle wheel spoke

- When low yield strength is desirable
  - Aluminum food wrap
  - Metal for twist ties

Features in Plastic Region - (Ultimate) Tensile Strength

σ_{TS} or σ_U - **Maximum** stress on engineering stress-strain curve - highest stress level beyond which a material will fracture



σ_{TS} = 40,000 psi

To be safe, actual stress should be designed to be much lower than σ_{TS} (half or even 1/3)

Features in Plastic Region - Ductility

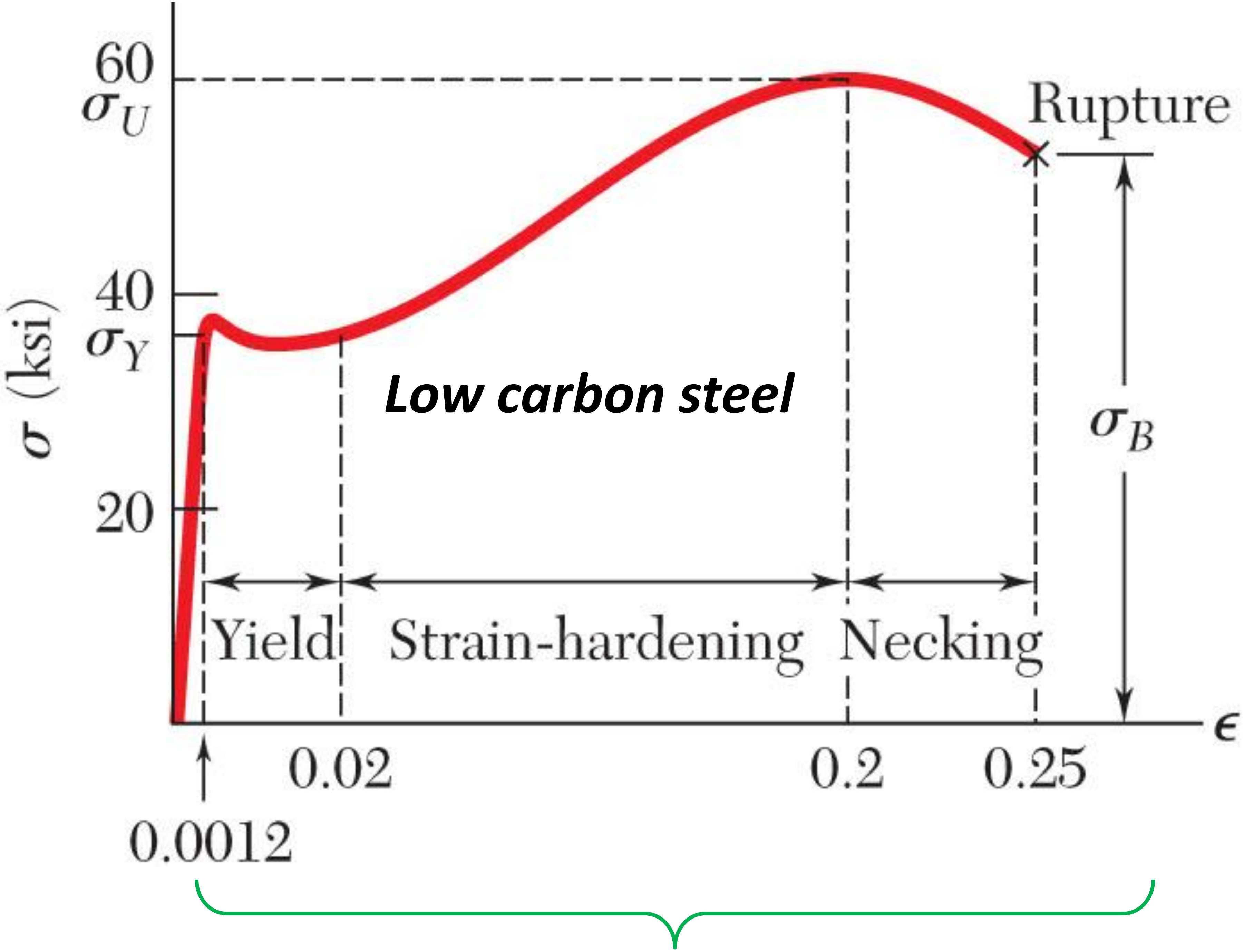
For materials that show plastic deformation, one measure of ductility is **percentage elongation (EL)**, i.e., the total plastic strain at failure (fracture or break):

$$\%EL = \frac{L_f - L_0}{L_0} \times 100\%$$

Strictly speaking, elastic strain should be excluded. But for practical metals, often not much difference:

Low carbon steel example:

$\%EL$ = 0.25 - 0.0012 ≈ 0.25 or 25%



Note: horizontal scale for ε NOT linear!

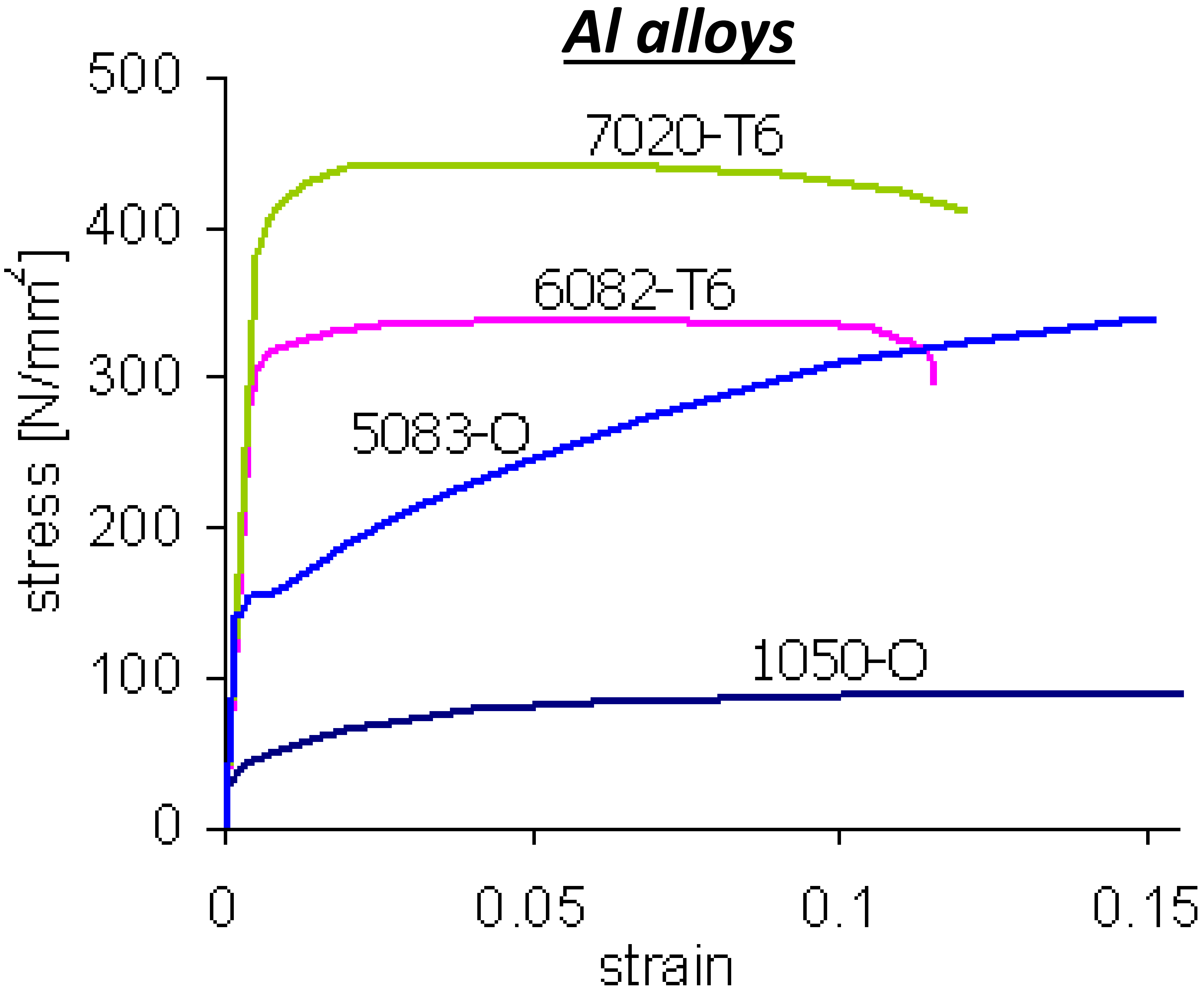
Ductility from Area of Reduction

In tensile test of many metals and polymer, sample cross-section shrink/reduce, which provides another way to represent ductility

$$\%Redution\ in\ Area = \frac{A_0 - A_f}{A_0} \times 100\%$$

Brittle materials show very little reduction of cross-section area

Tensile (σ- ε) Curves for Different Aluminum Alloys



http://aluminium.matter.org.uk/content/html/eng/default.asp?catid=217&pageid=2144417131

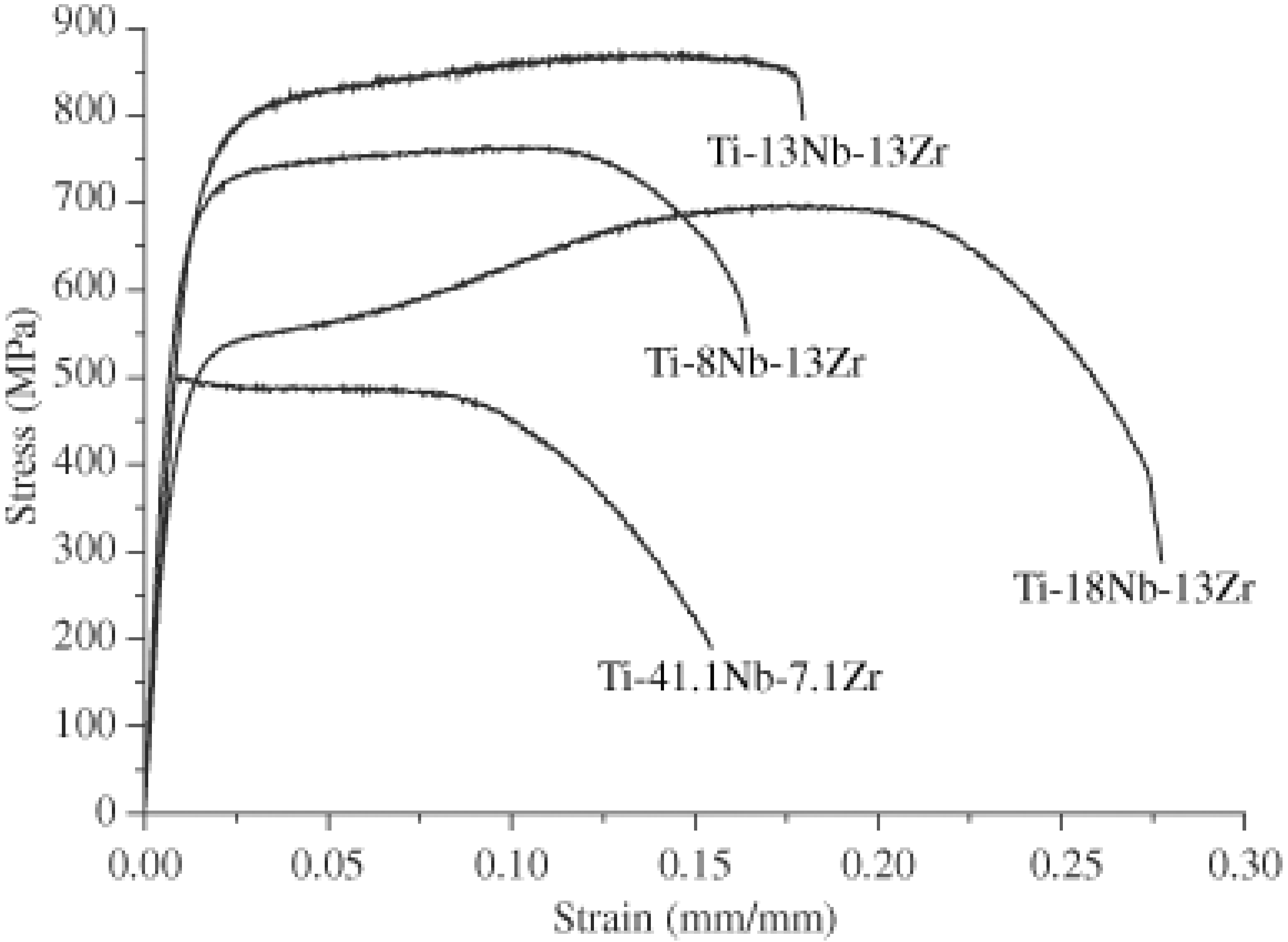
Four Al alloys have:

- Roughly **same elastic modulus** E (slope of initial linear section)

- ***Different***
  - **Yield strength** σ_y (transition from initial linear, elastic to non-linear, plastic deformation)
  - **Tensile strength** σ_{TS} (max stress point)
  - **Percentage elongation** $\%EL$ (roughly strain at fracture)

E Depends on Bonding; σ_y , σ_{TS} , $\%EL$ Influenced by Microstructure

Ti alloys



http://www.scielo.br/scielo.php?pid=s1516-14392005000400013&script=sci_arttext

Different Ti alloys have:

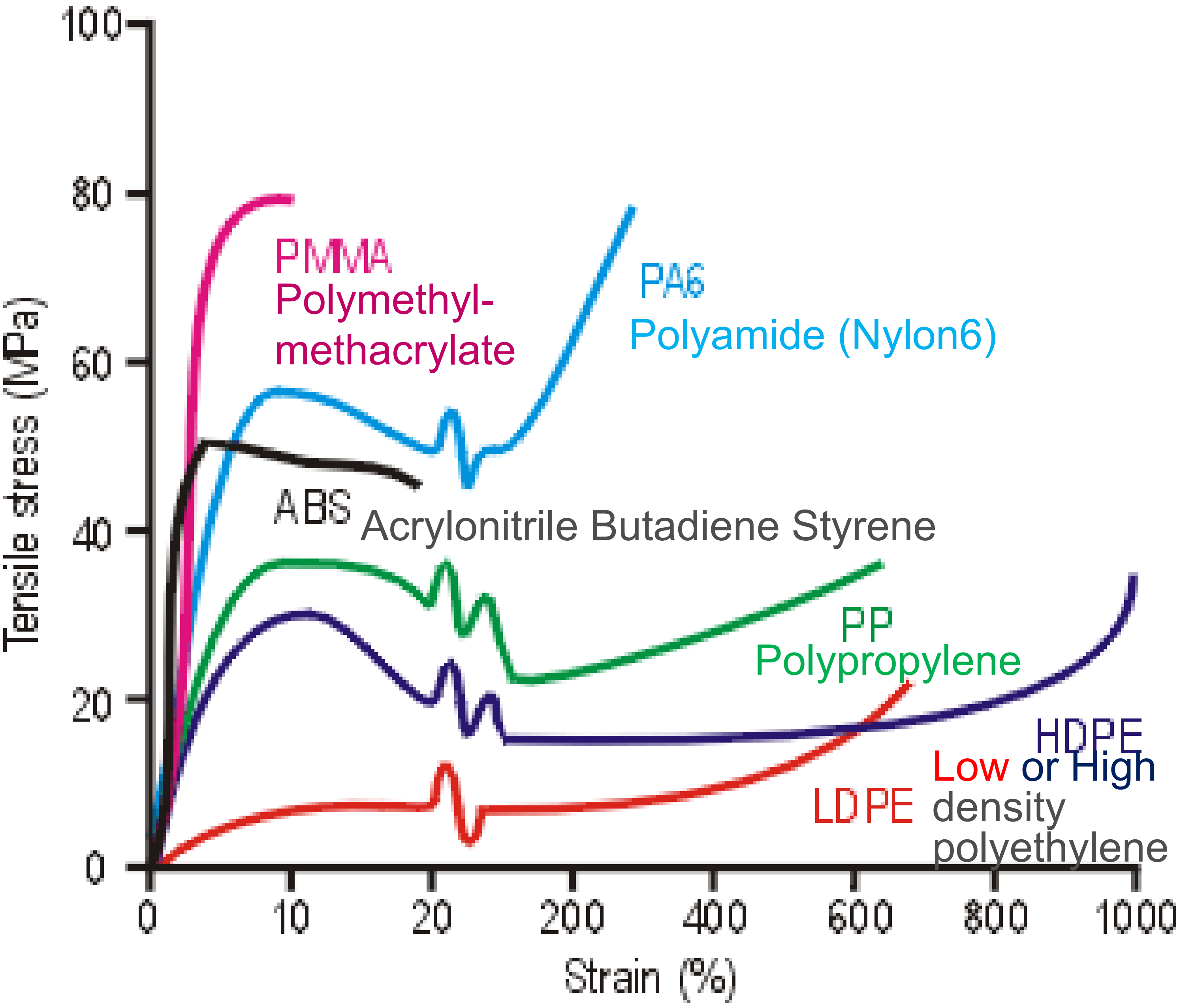
- Roughly **same** elastic modulus E
- Different σ_y, σ_{TS} , $\%EL$

For metals, higher melting point indicates stronger bonding & higher E

Metal	T_m (°C)	*E* (GPa)
Pb	327	14
Mg	650	44
Al	660	70
Cu	1085	120
Fe	1538	200
W	3410	400

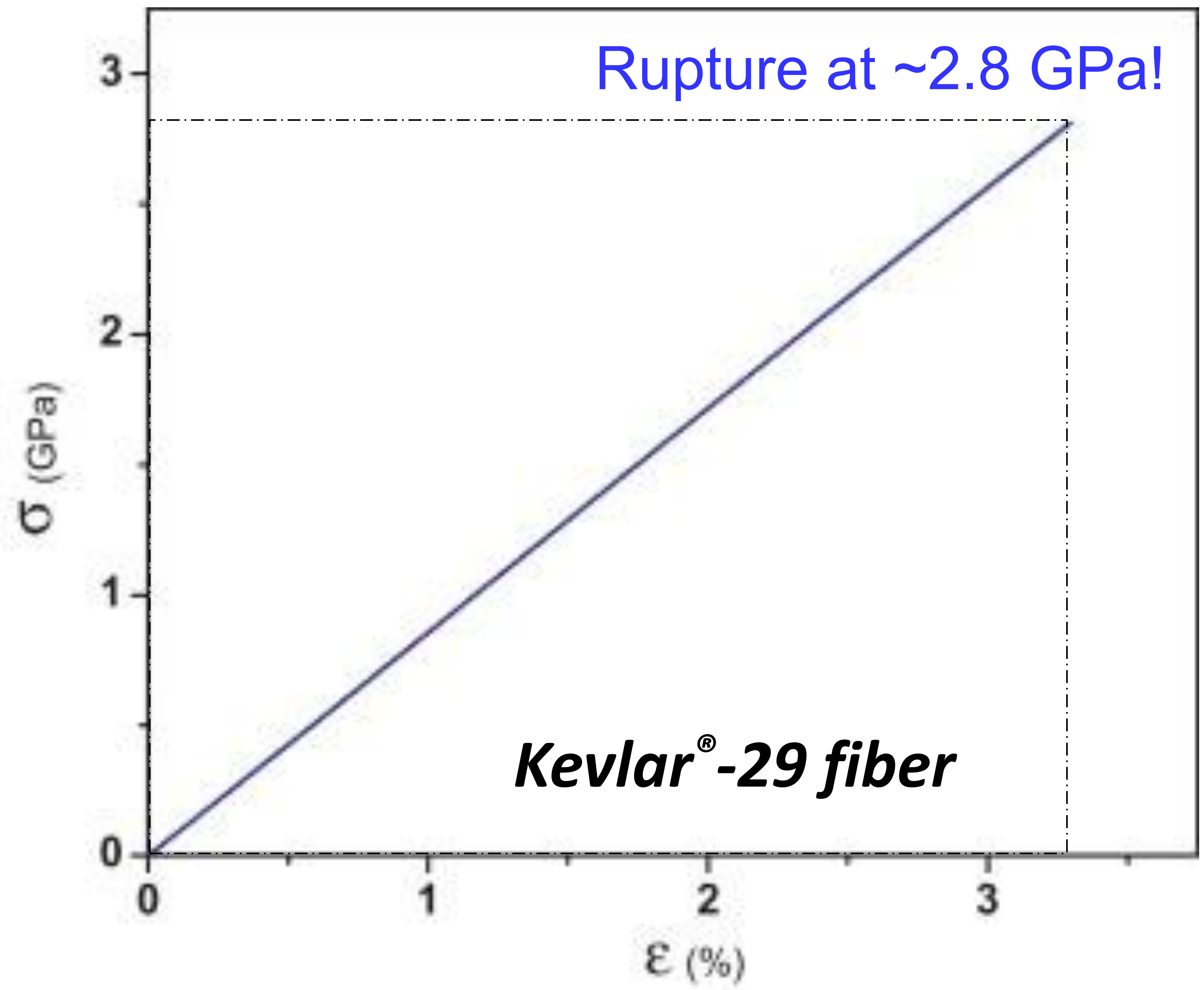
σ_y, σ_{TS} , $\%EL$ strongly influenced by **microstructure**/defects (e.g., dislocations, second phases), as explained in Chapter 7.

Tensile Curves for Polymers



http://www.azom.com/article.aspx?ArticleID=510

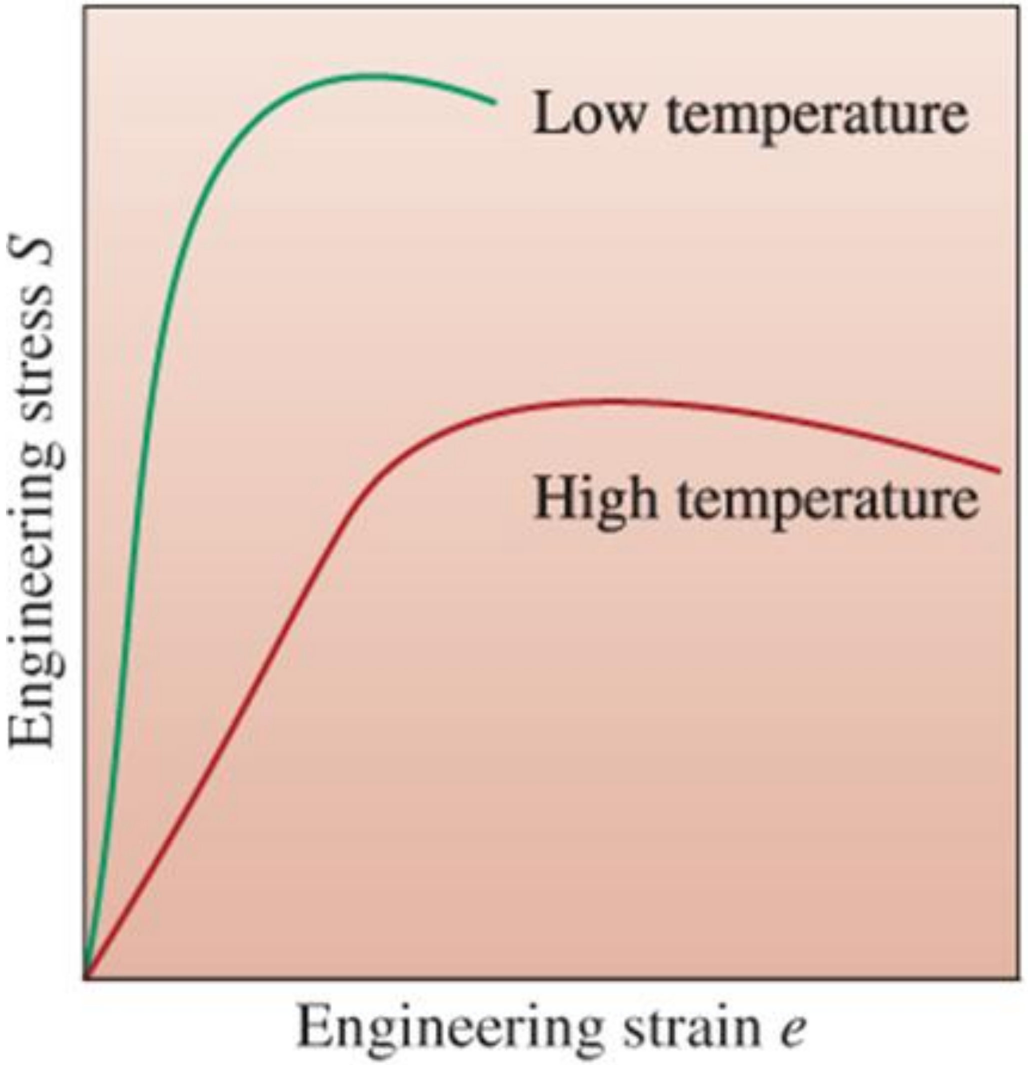
Many polymers have low modulus E, low yield strength σ_y, & tensile strength σ_{TS}

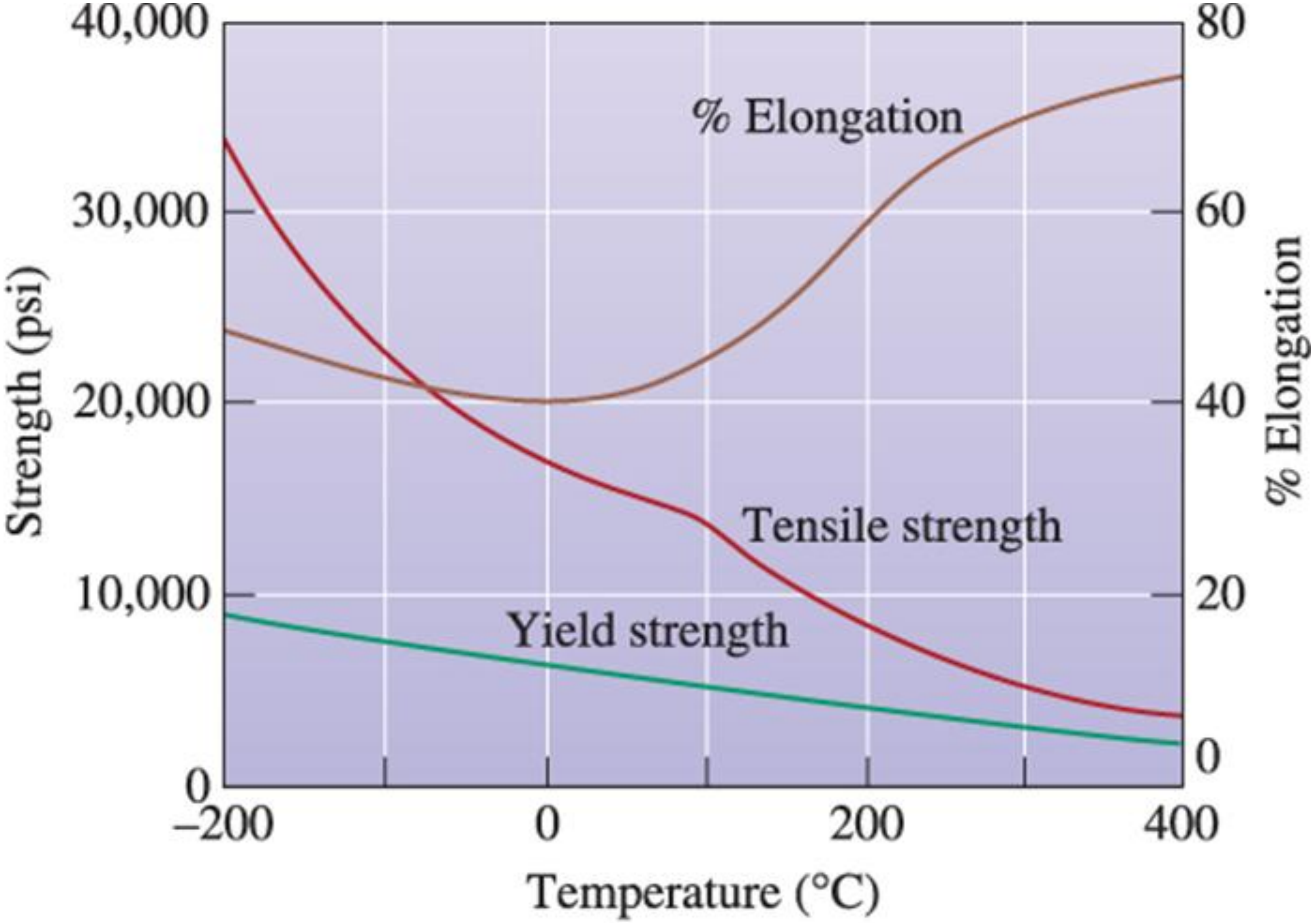


https://www.sciencedirect.com/science/article/pii/S0925838811021153

But some, e.g., para-aramid or Kevlar® give σ_{TS} higher than many metals!

Temperature Effect on Tensile Properties





Increasing T generally makes materials weaker and more ductile, by:

- Decreasing elastic modulus E, yield strength σ_y, and tensile strength σ_U
- Increasing percentage elongation $\%EL$

True Stress vs. Engineering Stress

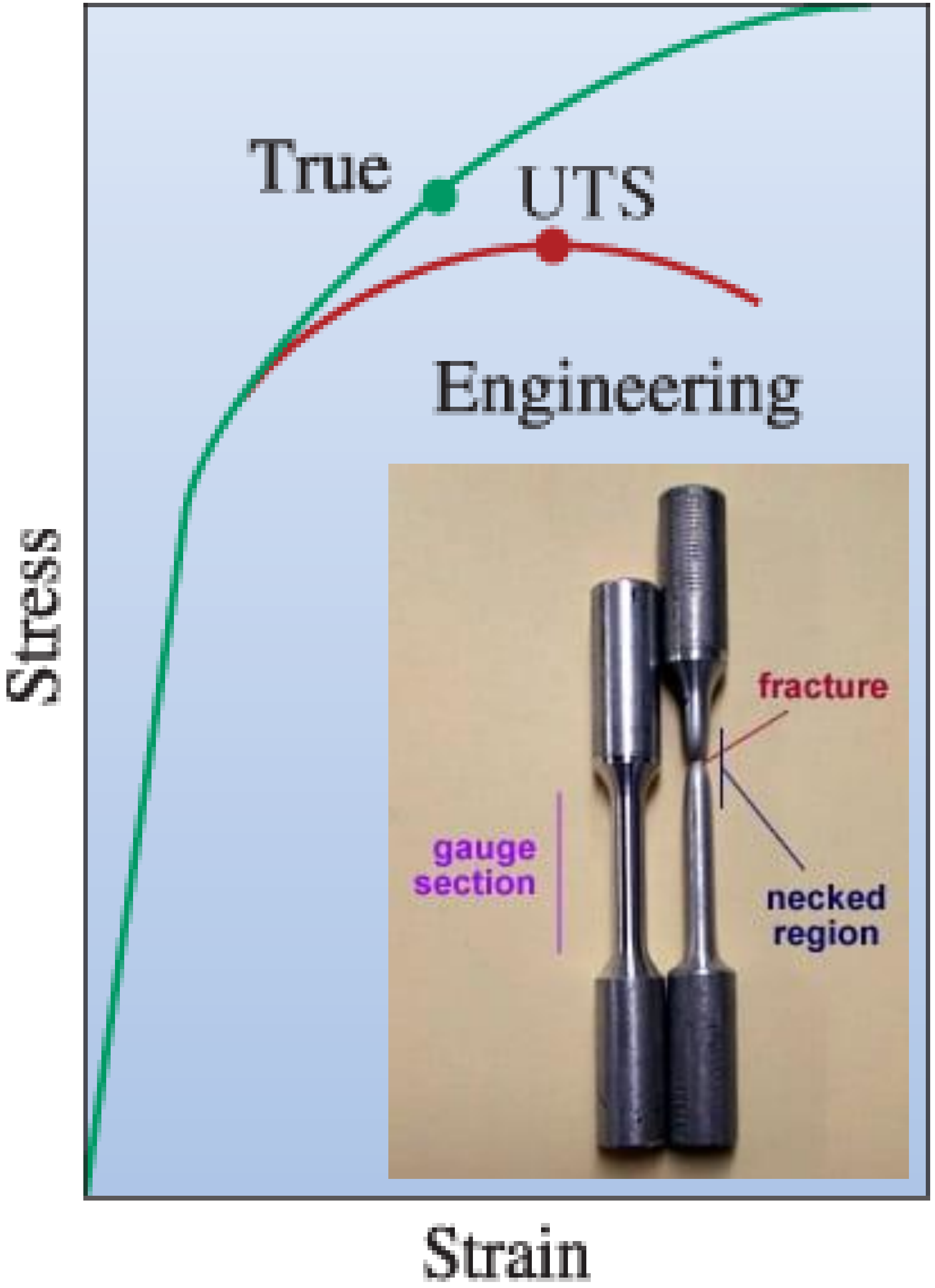
Because sample cross-section area reduces when sample is under tensile load, engineering stress actually underestimates the stress

If actual or true cross-section area A_T is known, true stress

$$\sigma_T = \frac{F}{A_T}$$

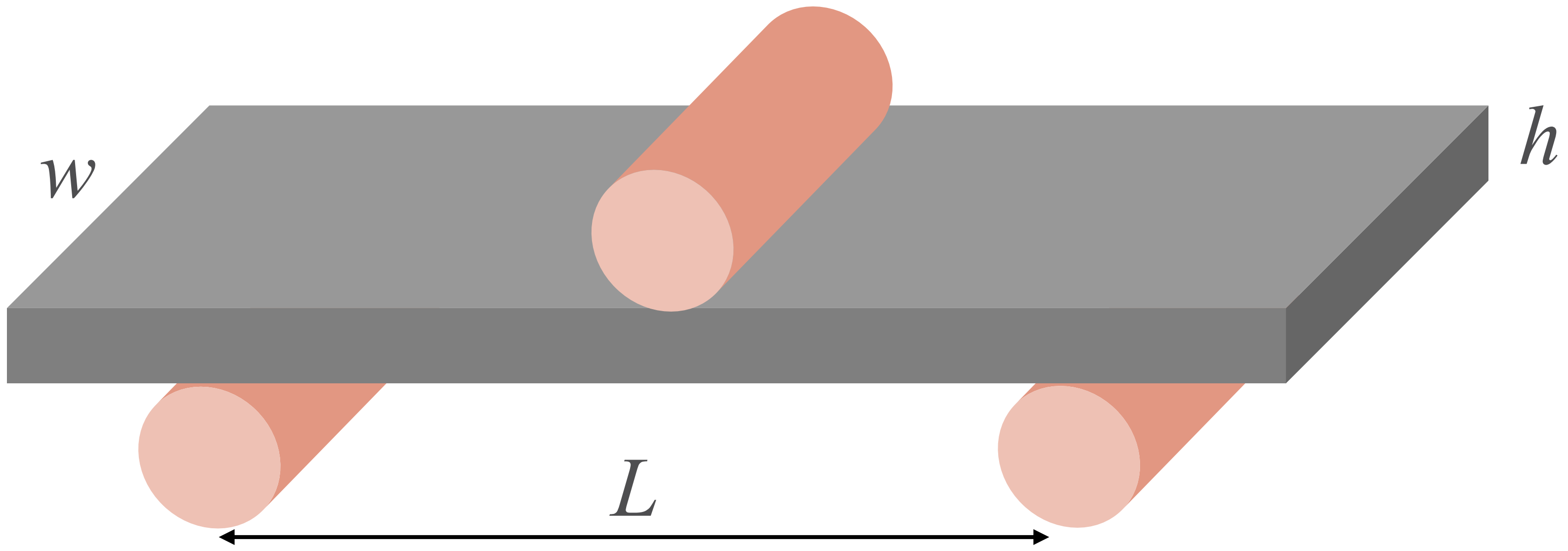
True stress is usually higher than **engineering stress**

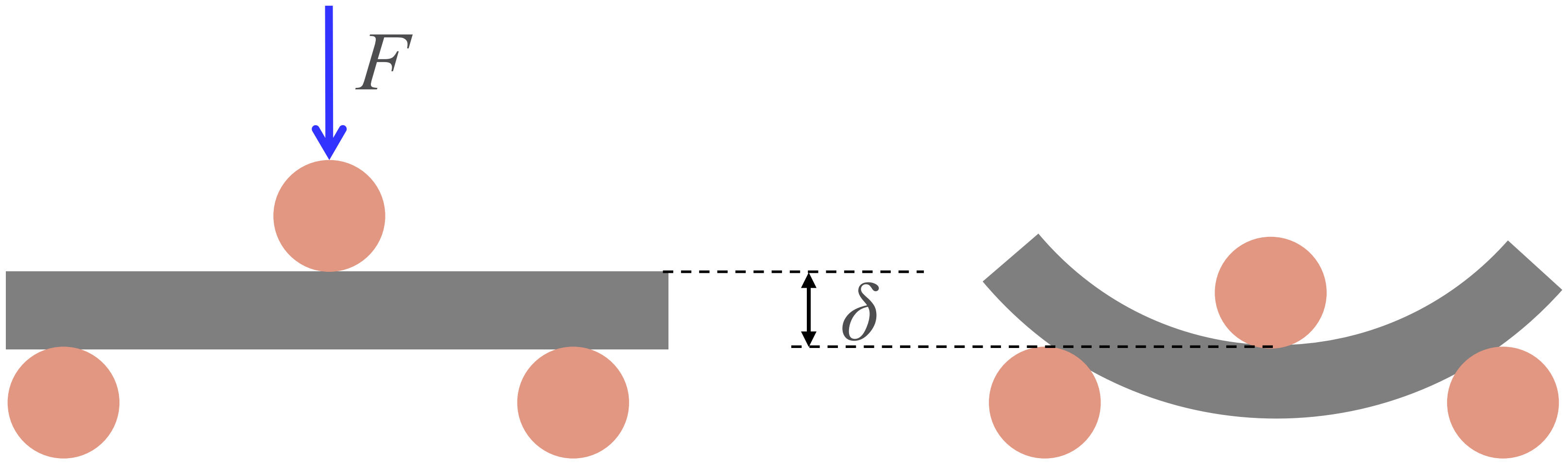
True stress is NOT widely used, due to difficulty w/ measuring actual cross-section area, especially after necking.



Bending Test for Measuring Modulus & Strength of Brittle Materials

- NO tensile tests for hard, brittle materials due to difficulties in machining clamping
- Bending tests, often 3-point or 4 point*, are carried out to get properties such as elastic modulus and **flexural strength**





Bending modulus

$$E_{Bend} = \frac{L^3 F}{4wh^3\delta}$$

Flexural strength

$$\sigma_{Bend} = \frac{3FL}{4wh^2}$$

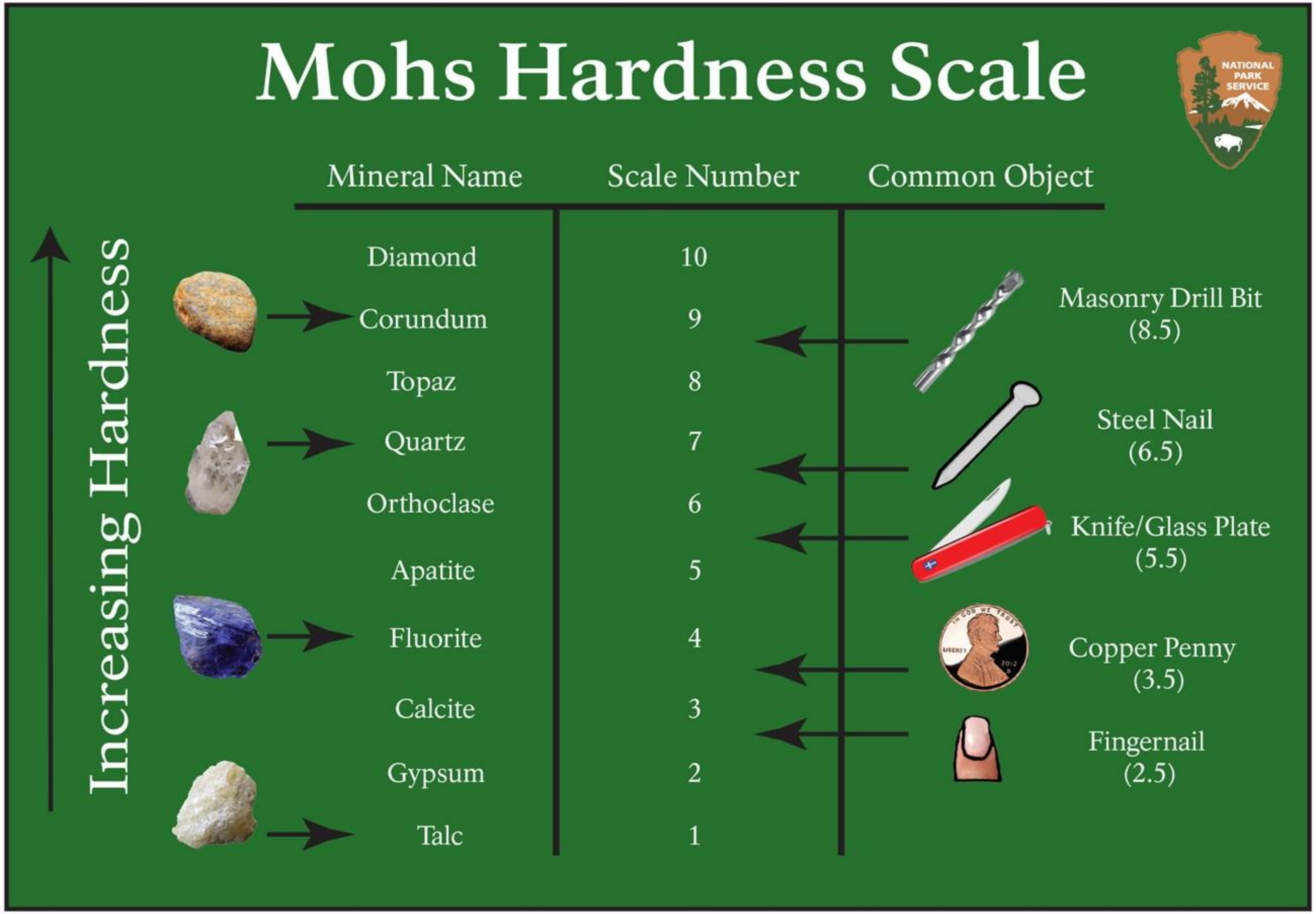
* 4-point bending suitable for samples containing flaws due constant momentum (pure bending)

Hardness (1)

- Ability of a materials to **resist scratch** or highly **localized (plastic) deformation**

- High hardness means:
  - Better resistance to local plastic deformation or cracking in compression
  - Better capability to scratch/grind other materials
  - Better wear resistance

Scratch Test for Determining Hardness



Mohs Hardness Scale

Mineral Name	Scale Number
Diamond	10
Corundum	9
Topaz	8
Quartz	7
Orthoclase	6
Apatite	5
Fluorite	4
Calcite	3
Gypsum	2
Talc	1

Common Object

Masonry Drill Bit (8.5)

Steel Nail (6.5)

Knife/Glass Plate (5.5)

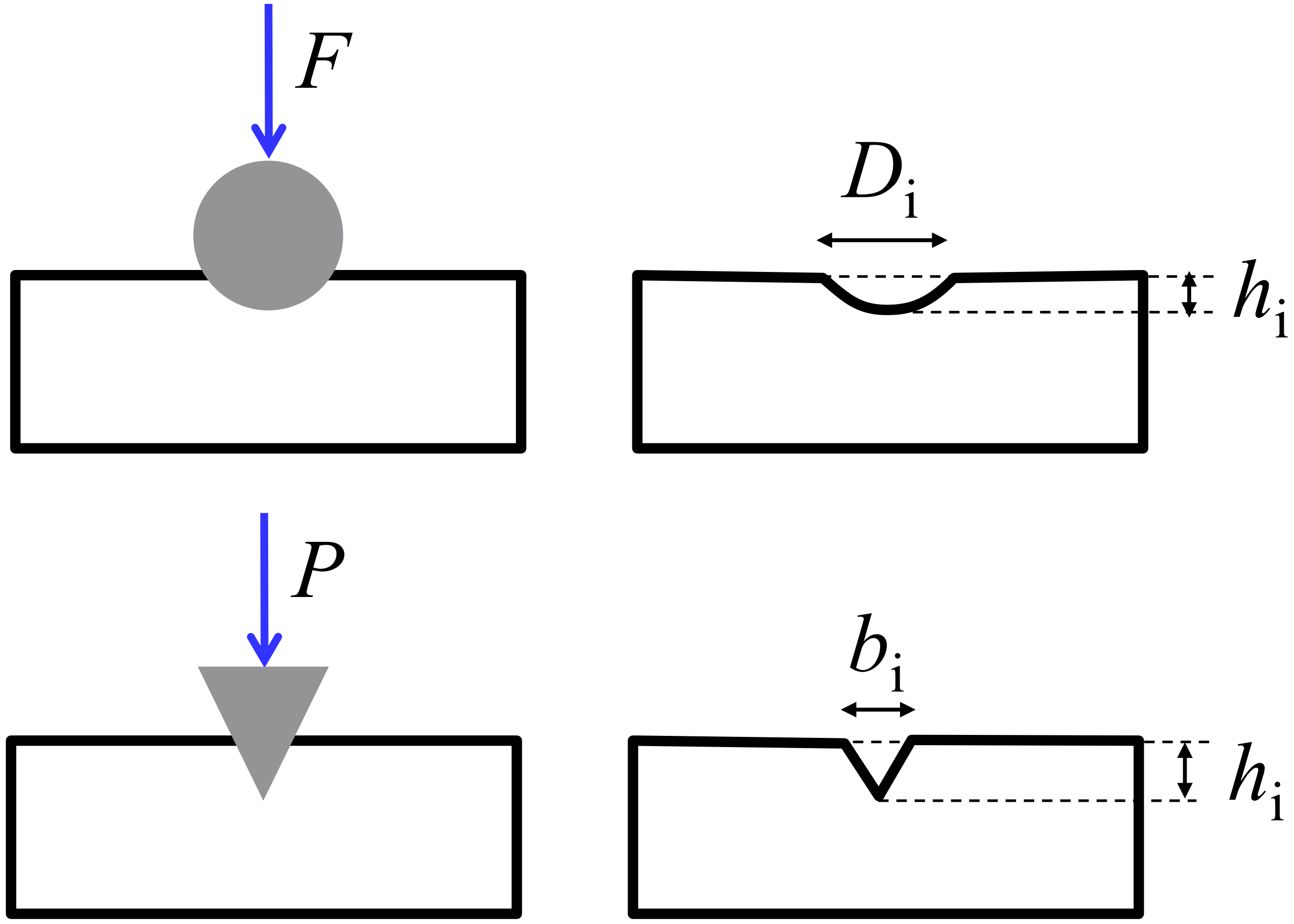
Copper Penny (3.5)

Fingernail (2.5)

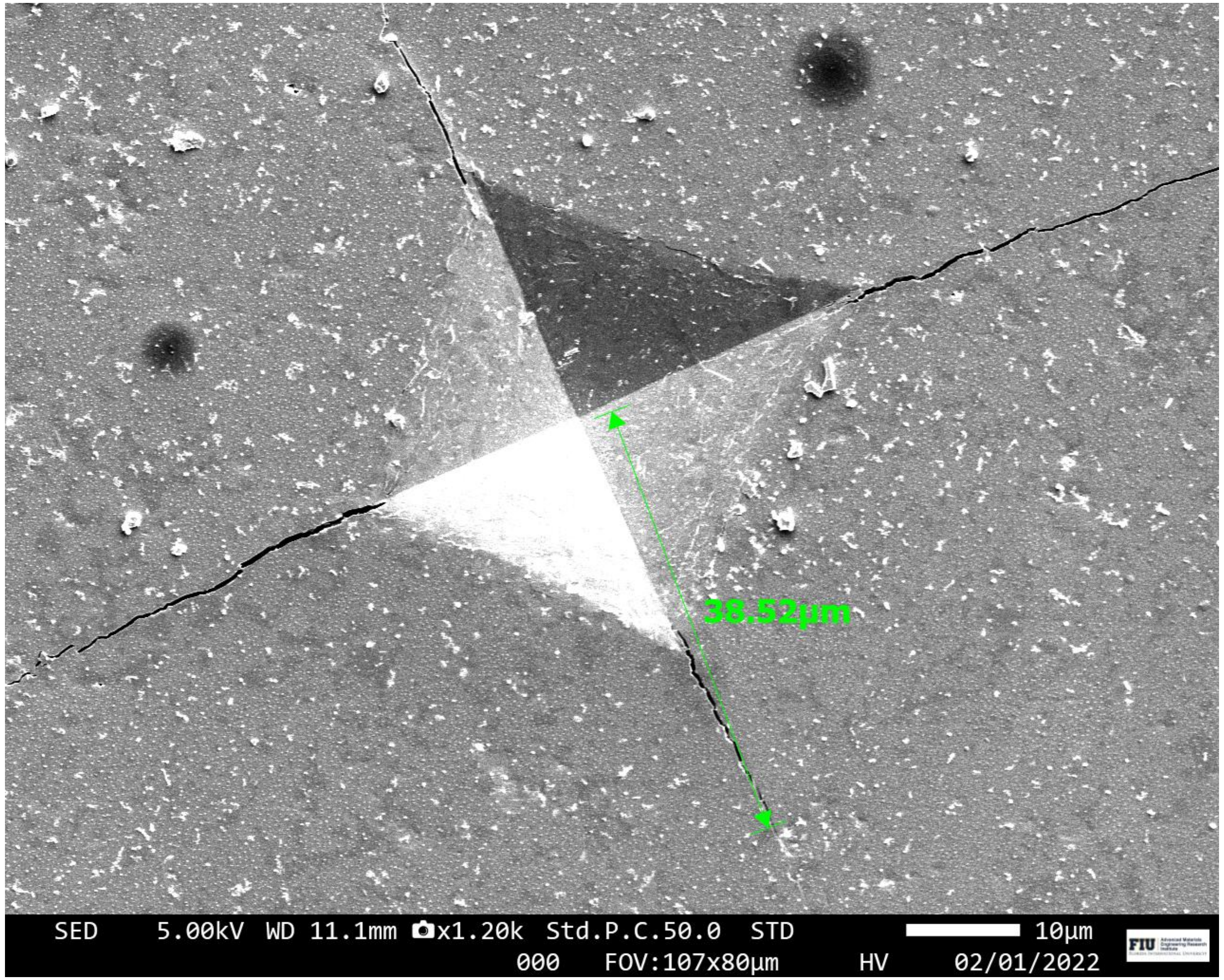
https://www.nps.gov/articles/mohs-hardness-scale.htm

Hardness (2)

- Indentation for determining hardness
  - Using a hard steel ball or diamond tip
  - Press into sample at a given load
  - Measure indent size (diameter, area, depth…)

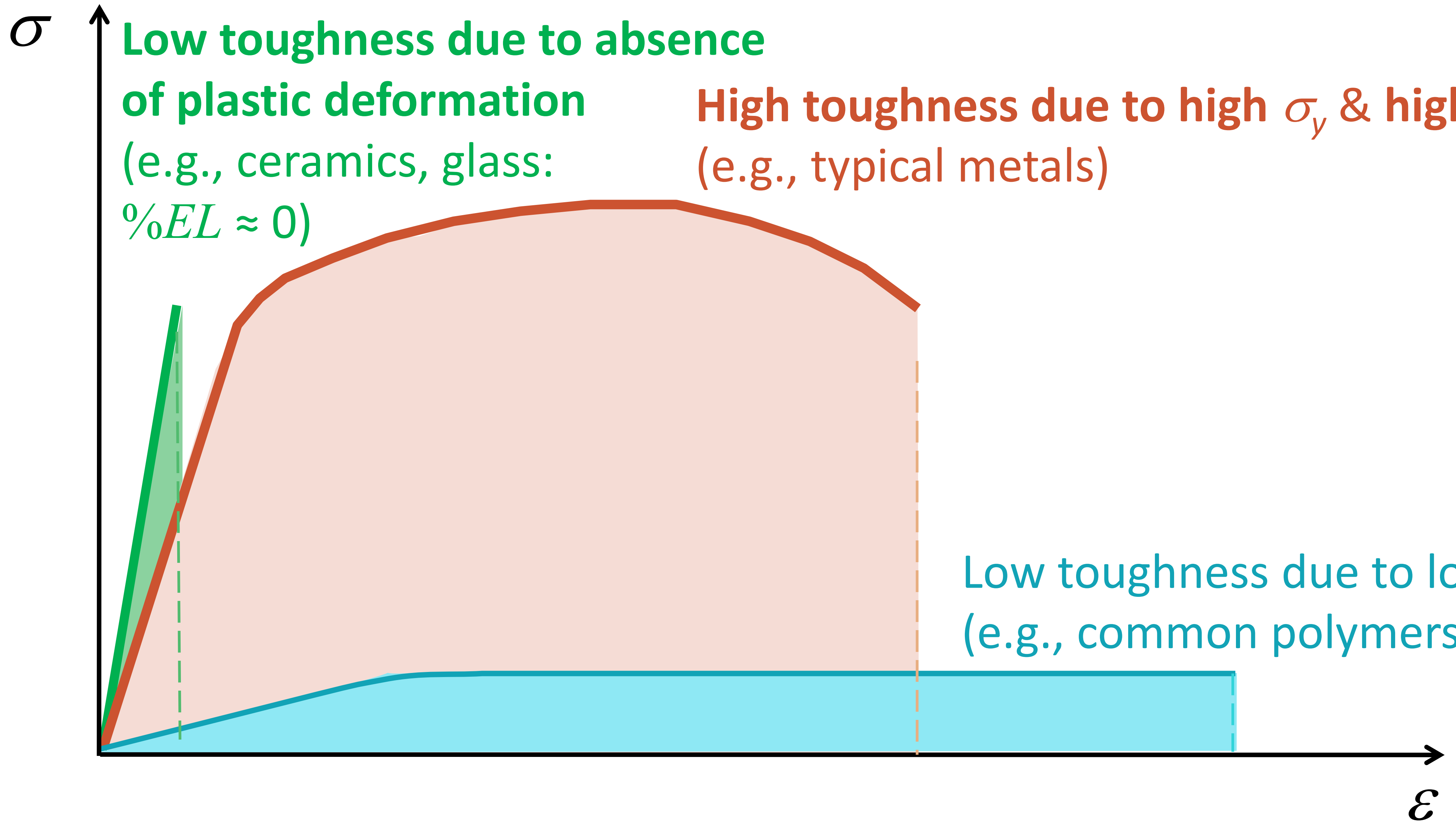


Example: Vickers Indentation Mark for $(Al_{0.17}Nb_{0.17}Ta_{0.17}Ti_{0.32}Zr_{0.17})N$



Toughness in Tension

- **Tensile toughness** - energy, per unit volume, needed to fracture an engineering material in tensile test (low strain rate ~10^{-3} s^{-1})
- Approximate by the total **area** under the tensile (stress-strain) curve



Low toughness due to absence of plastic deformation

(e.g., ceramics, glass: $\%EL \approx 0$)

High toughness due to high σ_y & high $\%EL$

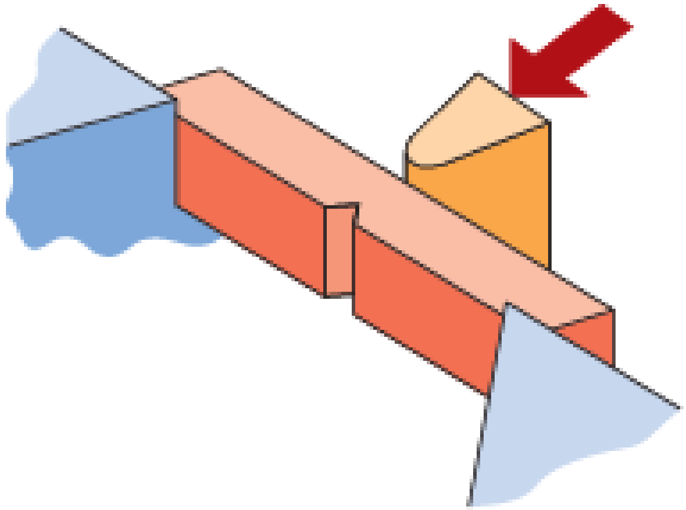
(e.g., typical metals)

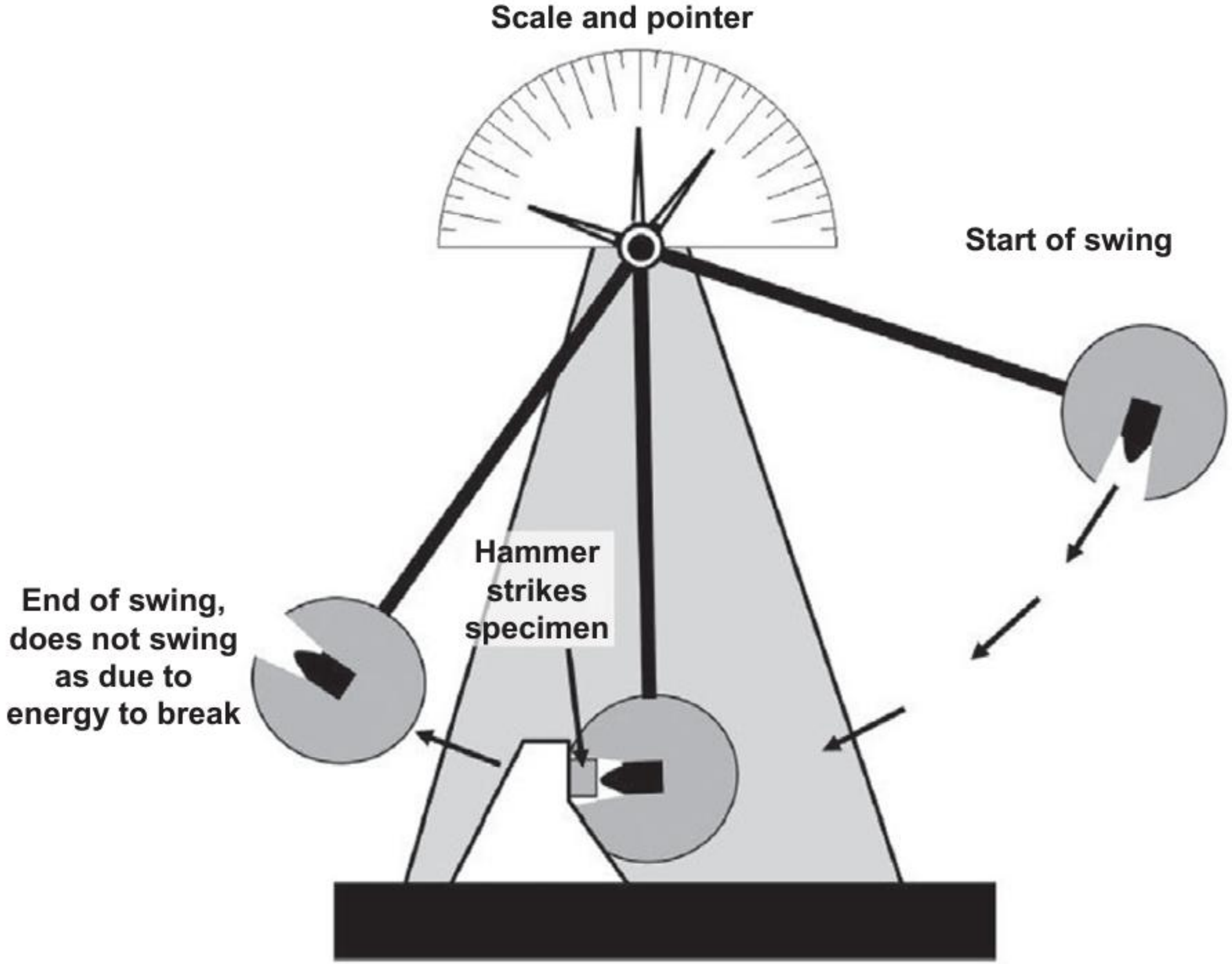
Low toughness due to low σ_y

(e.g., common polymers)

Toughness upon Impact

- **Impact toughness**: energy (per volume) a material absorbs upon impact, especially under **high strain rate** (e.g., ~10^3 s^{-1})

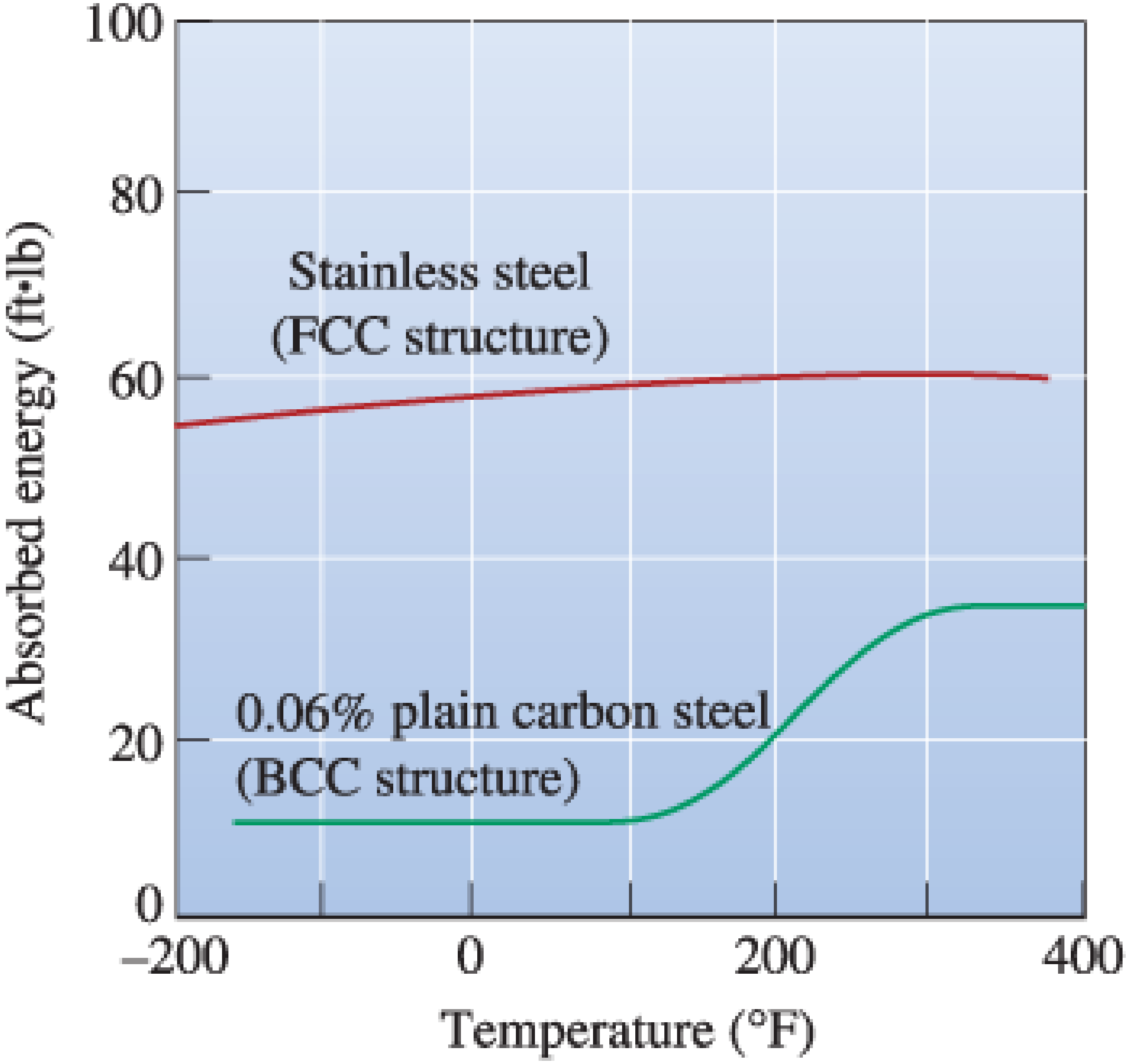


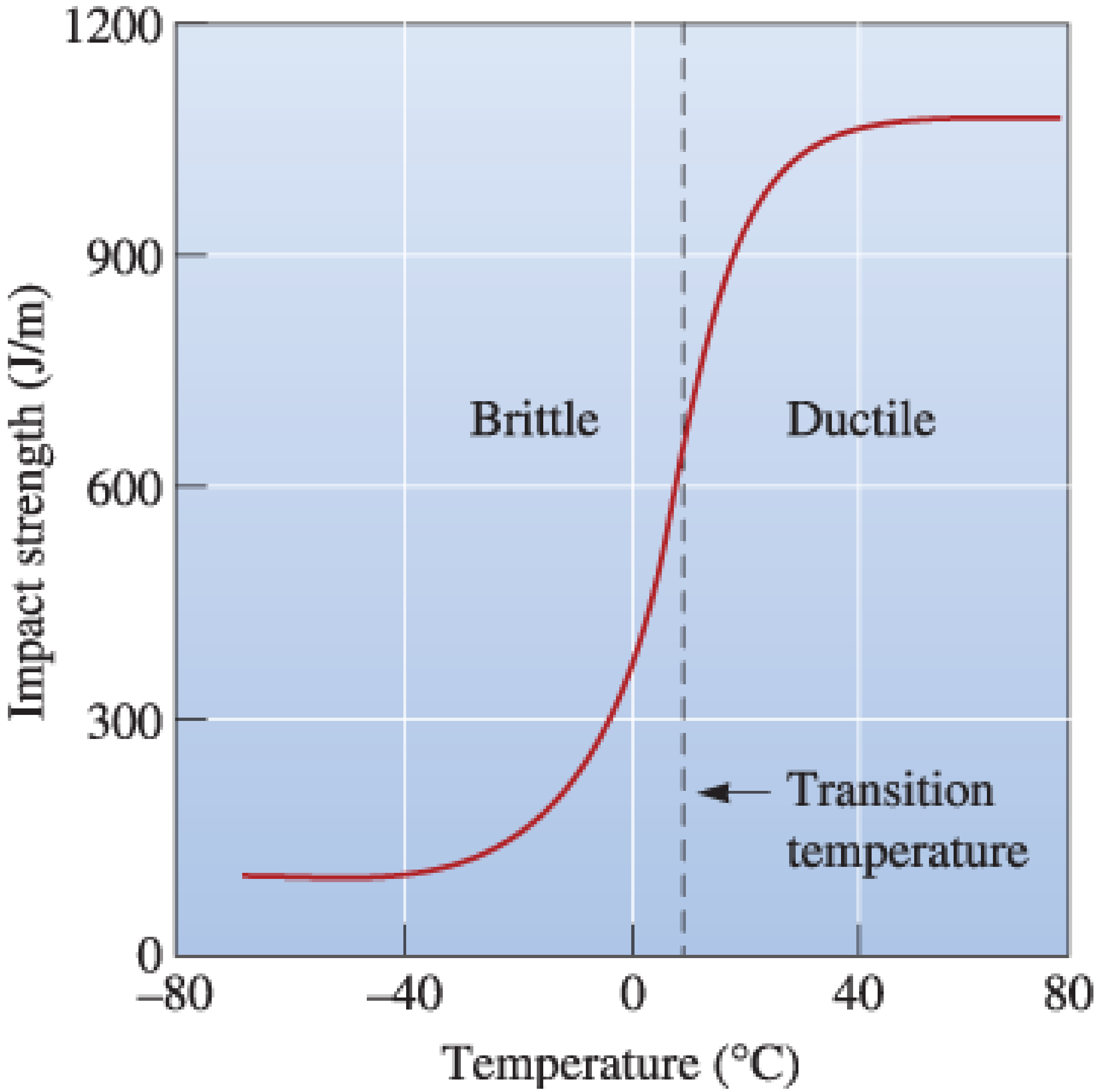


Anshuman Shrivastava, in Introduction to Plastics Engineering, 2018

Ductile to Brittle Transition Temperature (DBTT)

- Impact tests help give qualitative info such as DBTT.
  - Some materials are ductile over wide temperature (some stainless steel, Al, Cu)
  - Others show large drop in ductility at lower temperature (e.g., polymer, C-steel)

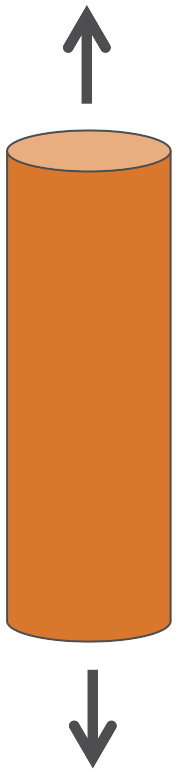




Class Exercise
(if time allows)

Class Exercise on Normal/Tensile Stress

For a cylindrical sample with tensile force of 10,000 N loaded along its long axis, if the initial cross-section area is 10 cm^2, please calculate the normal engineering stress σ.

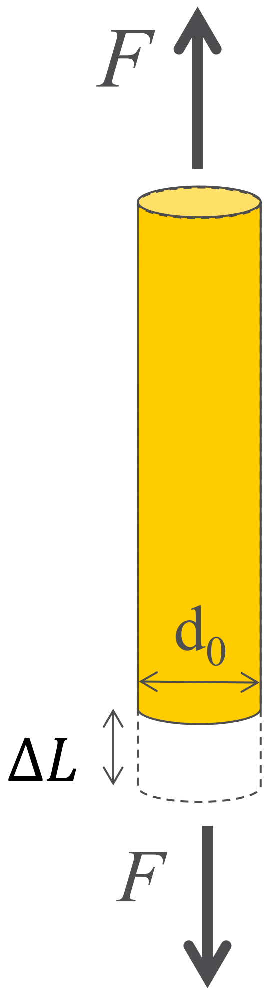


$$\sigma = \frac{F}{A_0}$$

$$\sigma = \frac{F}{A_0} = \frac{10{,}000N}{10cm^2} = \frac{10^4 N}{10 \times 10^{-4} m^2} = 10^7 \frac{N}{m^2} = 10^7 Pa = 10MPa$$

Class Exercise on Tensile/Normal Strain

A cylindrical sample is subject to tensile force along its long axis. Its original length is 50 mm. After the tensile force is applied, its length become 50.05 mm. Please calculate the normal or tensile strain along its long axis



$$\varepsilon = \frac{\Delta L}{L_0}$$

$$\varepsilon = \frac{\Delta L}{L_0} = \frac{L - L_0}{L_0} = \frac{50.05mm - 50.00mm}{50mm} = \frac{0.05mm}{50mm} = 0.1\%$$

Hooke’s Law Class Exercise

A steel bar 100 mm long and having a square cross section area of 4 cm^2 is pulled in tension with a load of 80,000 N, and experiences an elongation of 0.10 mm. Assuming that the deformation is entirely elastic, calculate the elastic modulus of the steel *E*.

Hooke’s law $\sigma = E\varepsilon$ $\qquad E = \frac{\sigma}{\varepsilon}$

$$E = \frac{\sigma}{\varepsilon} = \frac{F/A_0}{\Delta L/L_0} = \frac{F \cdot L_0}{\Delta L \cdot A_0} = \frac{80{,}000N \times 100mm}{0.10mm \times 4cm^2}$$

$$E = \frac{80{,}000N \times 100 \times 10^{-3}m}{0.10 \times 10^{-3}m \times 4 \times 10^{-4}m^2} = 2 \times 10^{11}\,\frac{N}{m^2} = 2 \times 10^{11}\ Pa\ = 200\ GPa$$

Homework 6.0

Carefully review chapter 6 lecture slides and, if time allows, read textbook sections (Askeland 6.1-6.7, 6.9-6.10) and give an honor statement confirming the reading

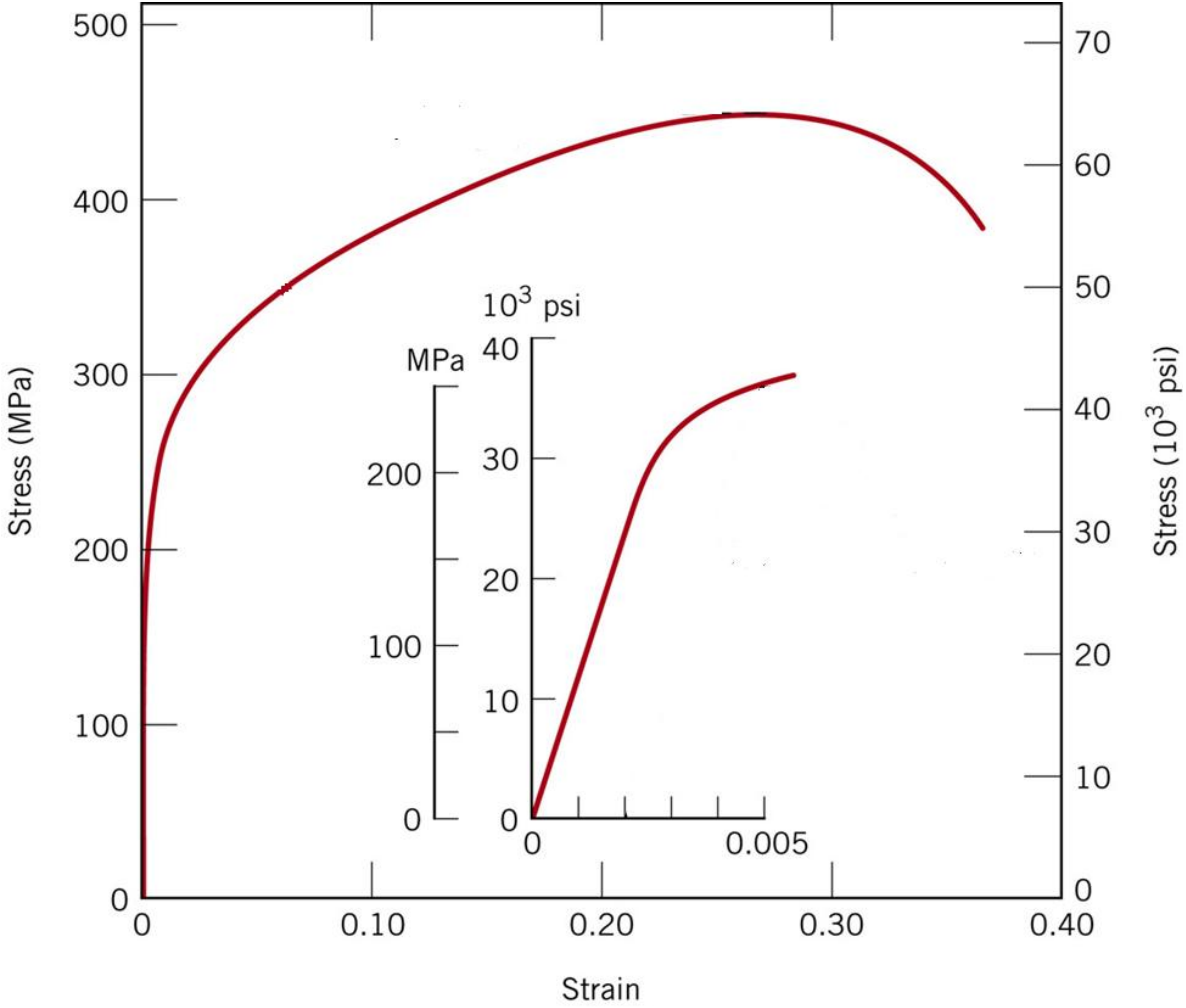
Homework 6.1

A cylindrical alloy sample having an elastic modulus of 100 GPa and an original diameter of 4 mm will experience only elastic deformation when a tensile force of 2000 N is applied. If the maximum allowable elongation is 0.4 mm, compute the maximum length of the specimen before deformation (i.e., application of the tensile force)

Homework 6.2

A tensile load of 25000N is applied to a cylindrical rod of 400 mm long and a radius of 5 mm. If the rod should not experience plastic deformation and the absolute elongation should not be more than 1 mm, which of the material below are possible candidates and why?

Material	E **(10^9 Pa)**	σ_y **(10^6 Pa)**	σ_U **(10^6 Pa)**
Aluminum alloy	70	255	420
Copper alloy	100	345	420
Pure copper	100	250	290
Steel alloy	207	450	550



Homework 6.4

Based on the tensile engineering stress – strain curve for copper alloy (insert is zoom-in for the low stress region), determine (i) Elastic modulus; (ii) Offset yield strength and ultimate tensile strength; (iii) Maximum load by a cylinder specimen with original diameter of 10 mm; (d) Change in length for a 200 mm sample subject to 400 MPa

Homework 6.3

A cylindrical specimen with a diameter of 12.8 mm and a gauge length of 50.800 mm is pulled in tension. `Use the tensile data below to complete below:

1. Plot the tensile curve (i.e., engineering stress vs. engineering strain)
2. Compute the modulus of elasticity
3. Determine the yield strength at a strain offset of 0.002
4. Determine the tensile strength of this alloy
5. What is the approximate ductility, in percent elongation?

Force (kN)	Guage Length (mm)
0.00	50.80
7.33	50.85
15.10	50.90
23.10	50.95
30.40	51.00
34.40	51.05
38.40	51.31
41.30	51.82
44.80	52.83
46.20	53.85
47.30	54.86
47.50	55.88
46.10	56.90
44.80	57.66
42.60	58.42
36.40	59.18