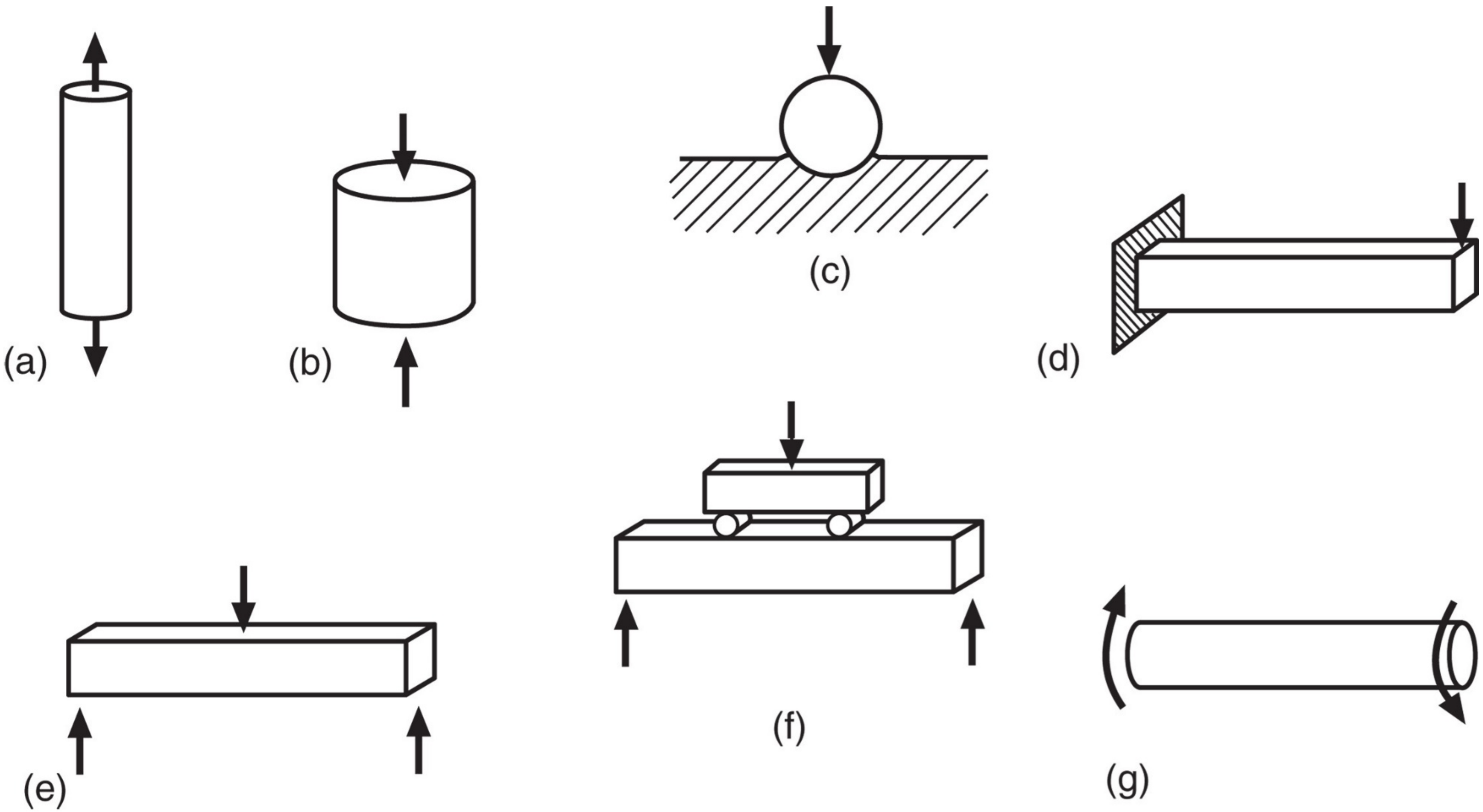
Chapter 4. Mechanical Testing

Mechanical Strengths and Behavior of Solids

Contents

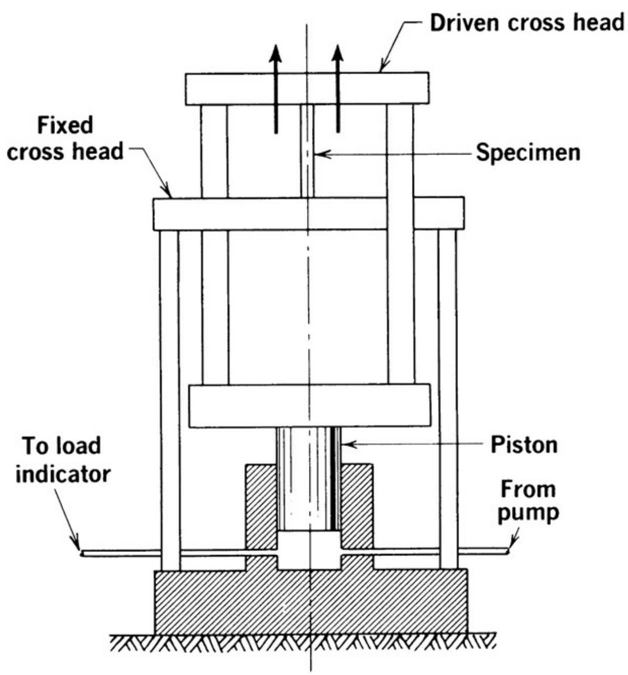
4.1 Introduction

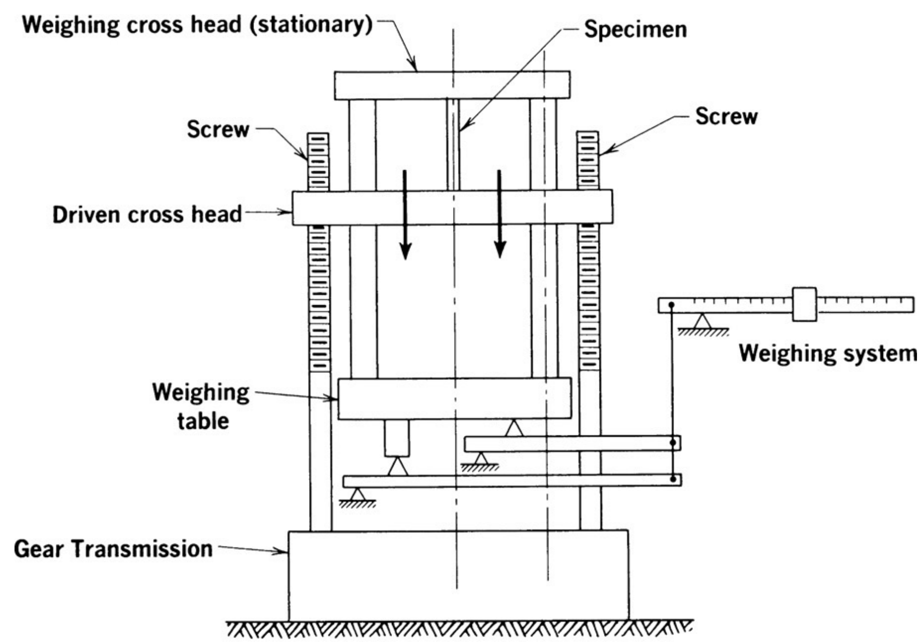
- **Geometry and Loading Commonly Employed in Mechanical Testing**



4.2 Introduction to Tension Test (1)

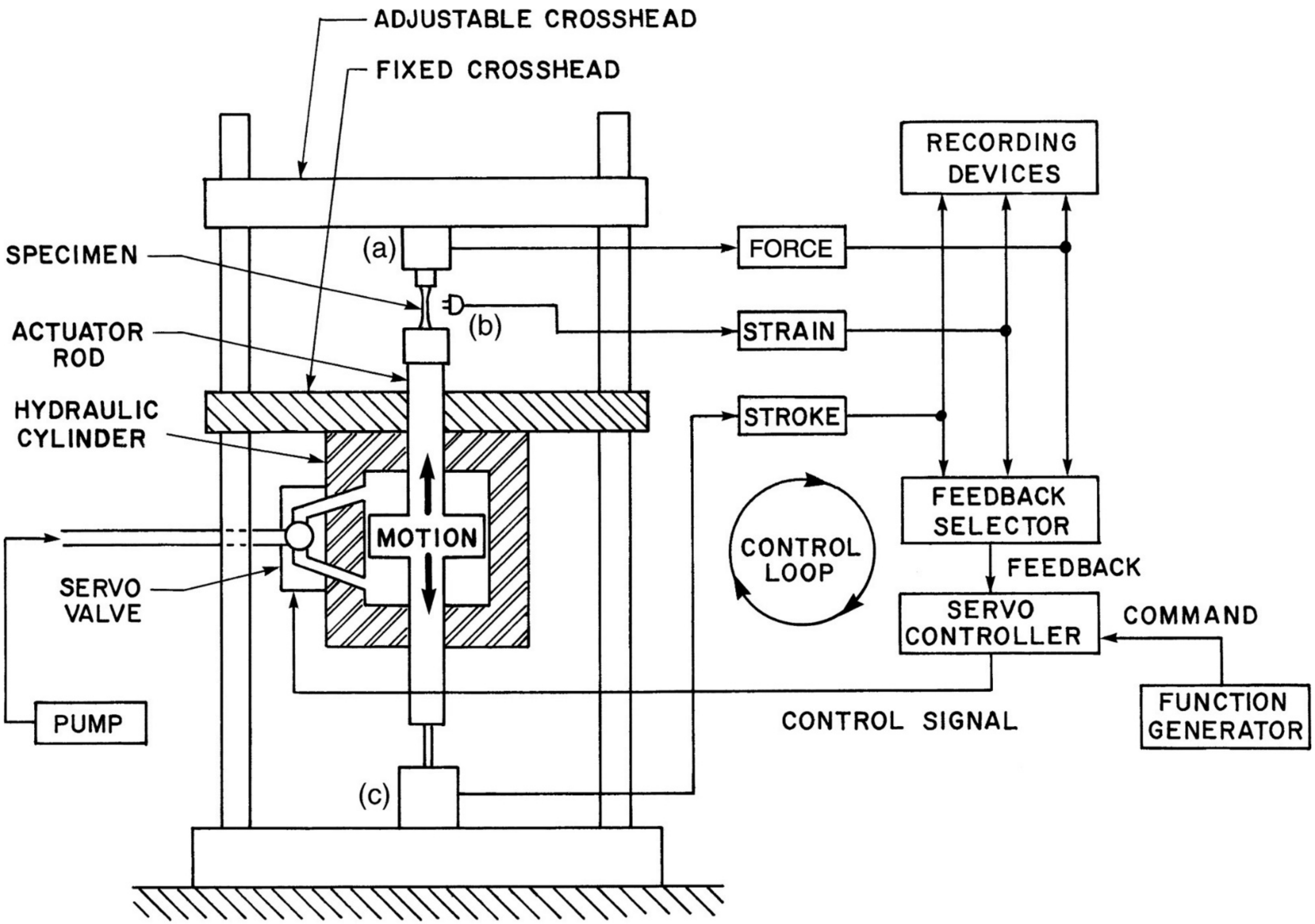
- **Schematics of Simple Testing Machines**





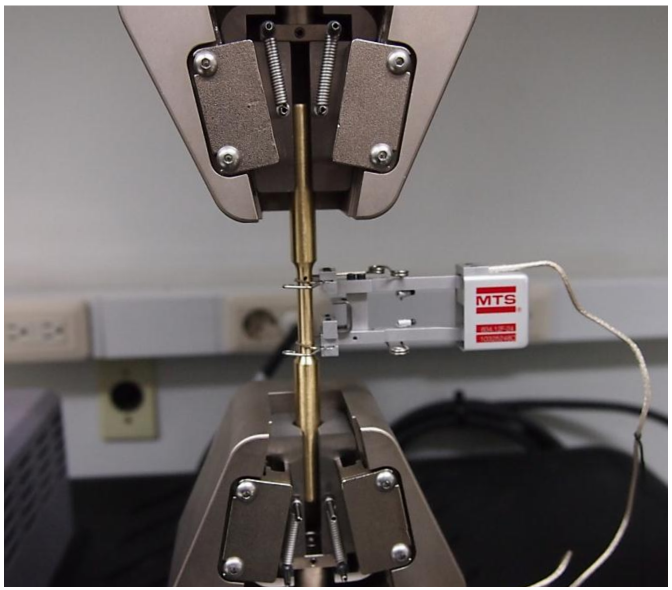
4.2 Introduction to Tension Test (2)

- **Modern Closed-loop Servohydraulic Testing System**



Tension Test (1)

- **Setup for Tension Test**

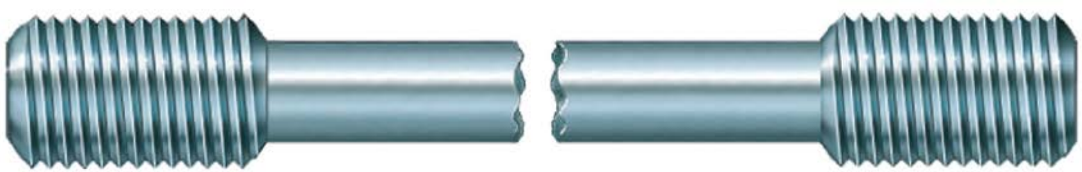


Tension Test (2)

- **Fracture in Tension Test**

Necking

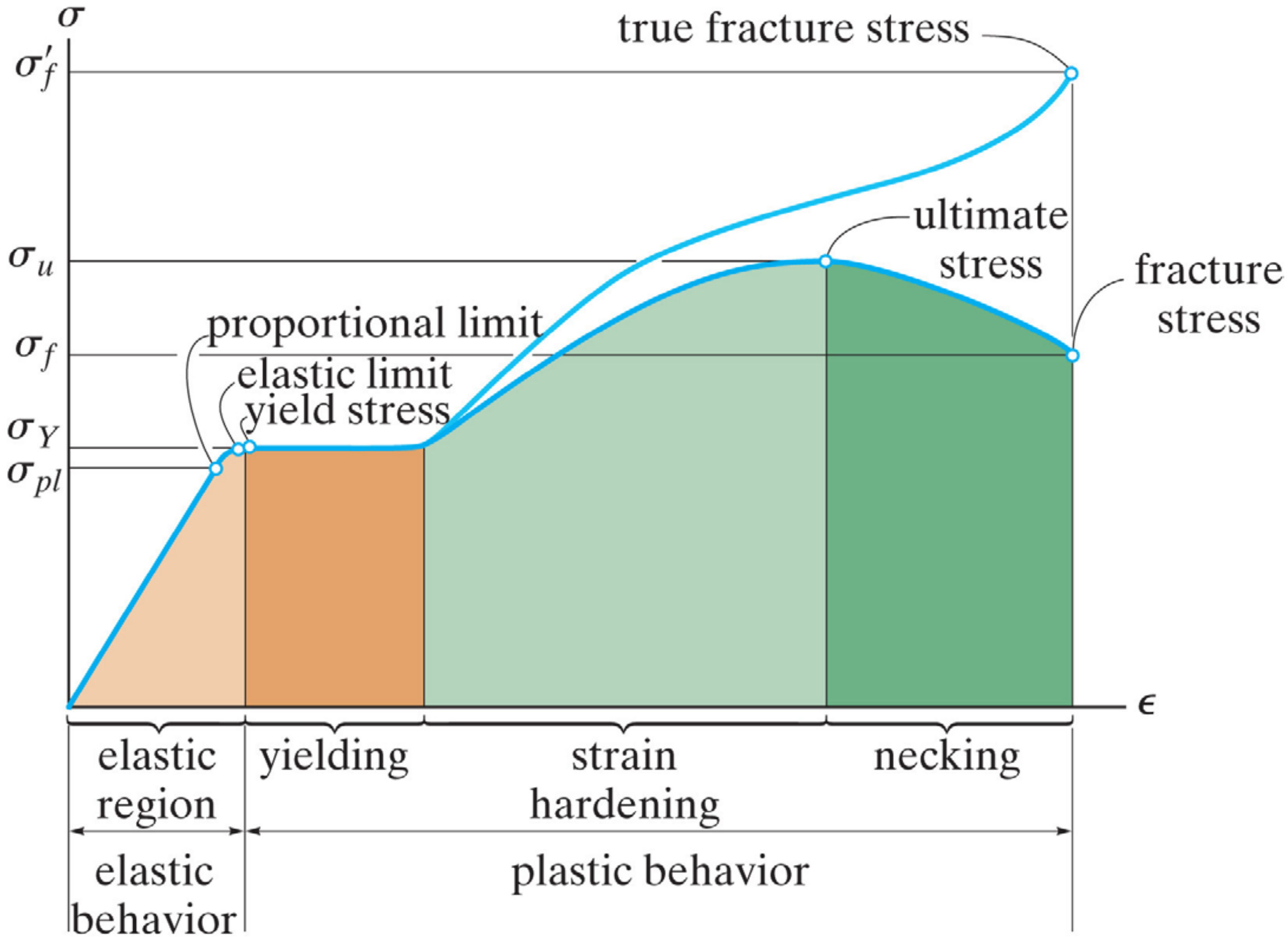
Failure of a
ductile material



Tension failure of
a brittle material

4.3 Engineering Stress-Strain Properties (1)

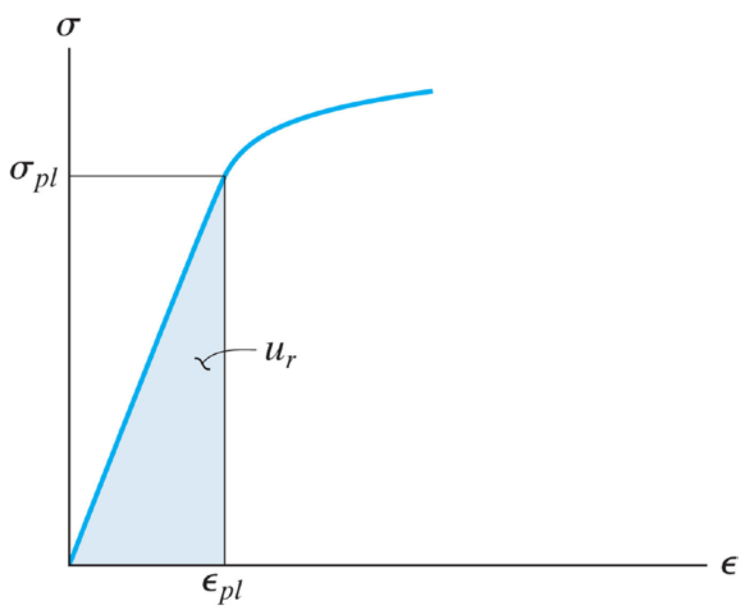
- **Stress-strain curve**



4.3 Engineering Stress-Strain Properties (2)

- **Resilience**
  – The ability of a material to absorb energy when deformed elastically and to return it when unloaded.

$$u_r = \frac{1}{2}\sigma_{pl}\varepsilon_{pl} = \frac{1}{2}\frac{\sigma_{pl}^2}{E}$$



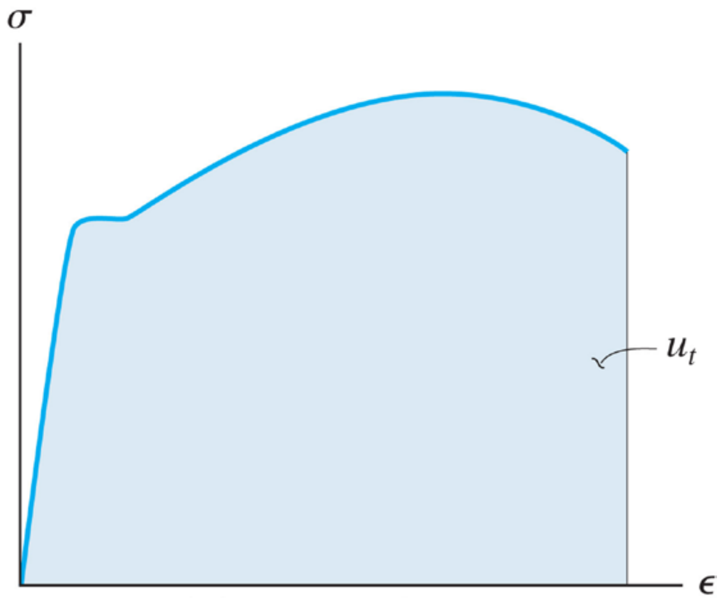
Modulus of resilience u_r

4.3 Engineering Stress-Strain Properties (3)

- **Toughness**
  - The ability of a material to absorb energy without fracture.

Ductile: $$u_t = \frac{1}{2}\left(\sigma_y + \sigma_u\right)\varepsilon_f$$

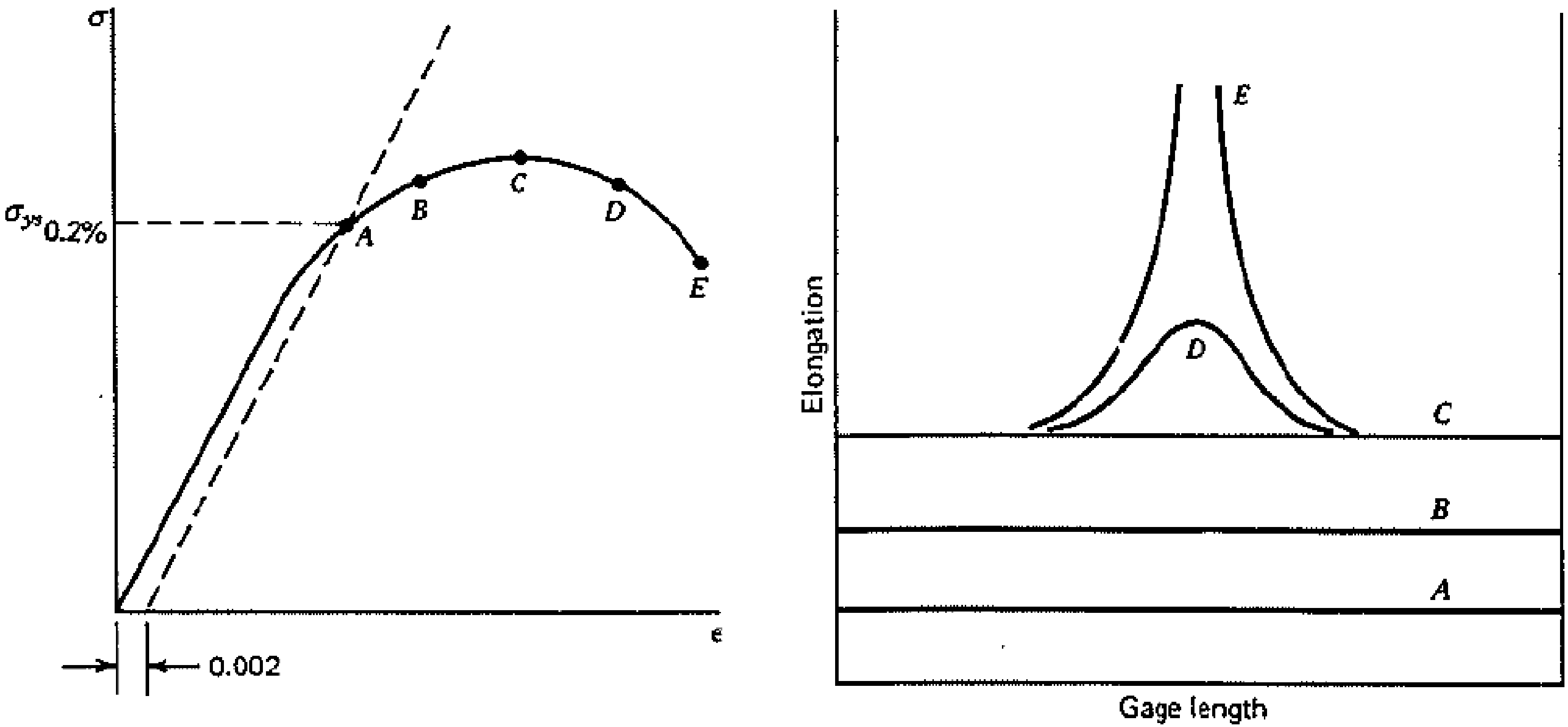
Brittle: $$u_t = \frac{2}{3}\sigma_f \varepsilon_f$$



Modulus of toughness u_t

Necking (1)

- **Extent of Uniform Strain**
  – It is desirable to maximize the extent of uniform elongation prior to the onset of localized necking.



Necking (2)

- **Extent of Uniform Strain**
  - The amount of uniform strain is related to the magnitude of the strain-hardening exponent.

$$P = \sigma A$$

$$dP = \sigma dA + A d\sigma$$

$$dP = 0$$ -> Necking point

$$\sigma dA + A d\sigma = 0 \quad \text{->} \quad \frac{d\sigma}{\sigma} = -\frac{dA}{A}$$

$$Al = constant \quad \text{->} \quad Adl + ldA = 0 \quad \text{->} \quad \frac{dl}{l} = -\frac{dA}{A}$$

$$\frac{dl}{l} = d\epsilon = -\frac{dA}{A} = \frac{d\sigma}{\sigma} \quad \text{->} \quad \sigma = \frac{d\sigma}{d\epsilon}$$

Necking (3)

- **Extent of Uniform Strain**
  - The true plastic strain at necking instability is numerically equal to the strain-hardening coefficient.

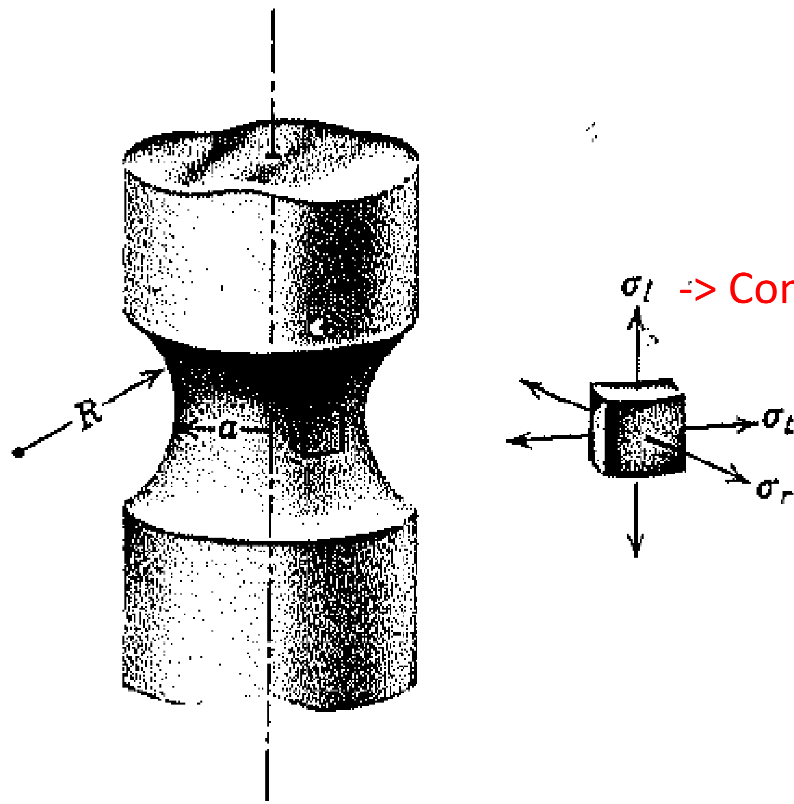
$$\sigma = K\epsilon^n$$

$$\sigma = \frac{d\sigma}{d\epsilon} \quad \text{->} \quad K\epsilon^n = Kn\epsilon^{n-1}$$

$$n = \epsilon$$

Necking (4)

- **Triaxial Tension Stress Distribution**
  - A triaxial stress state exists in the vicinity of the neck.
  - Triaxial stress -> hard to yield -> more stress is needed to yield -> more strength -> more brittle - > fracture



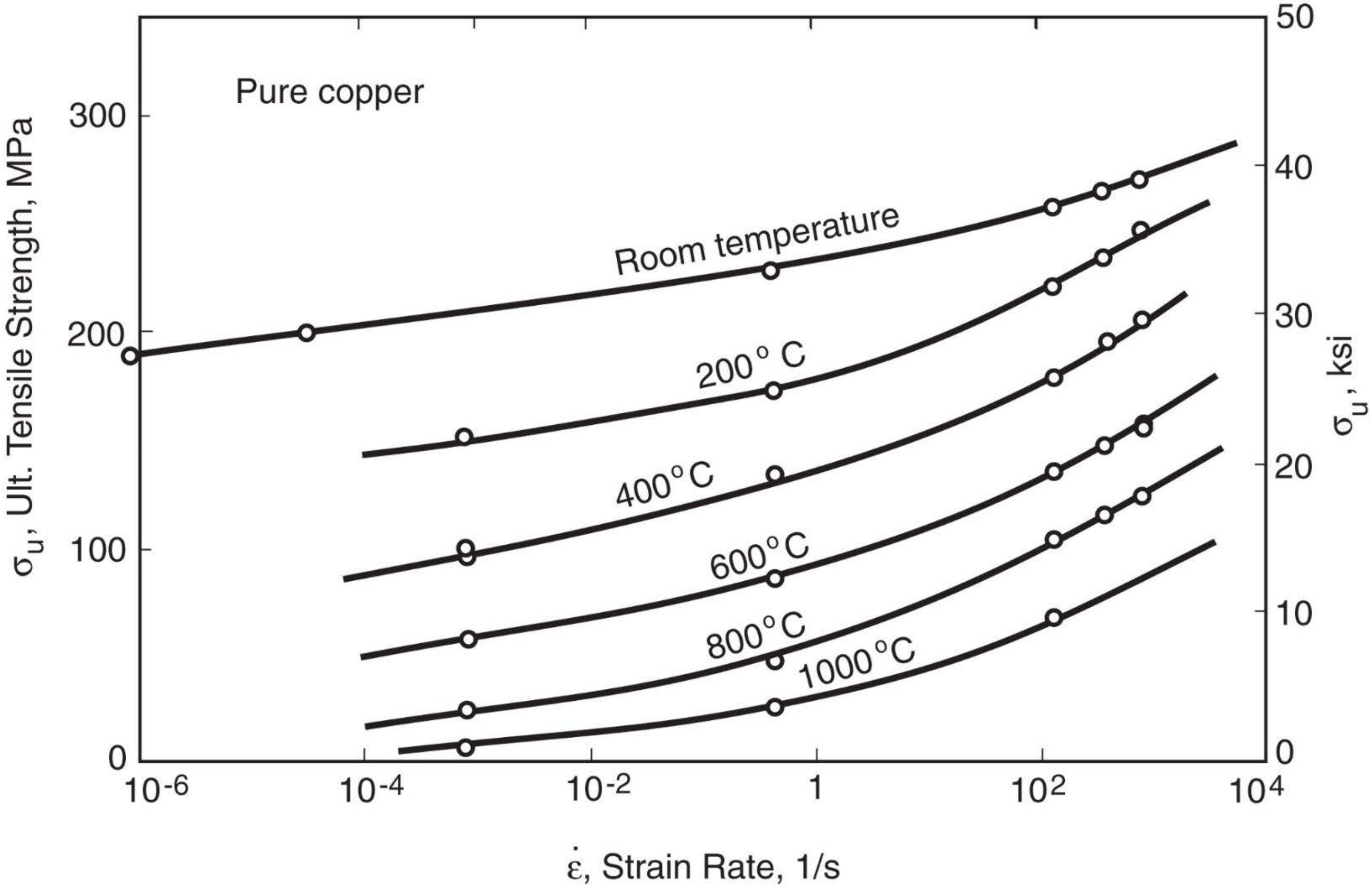
σ_l -> Compression

σ_t -> Tension

σ_r -> Tension

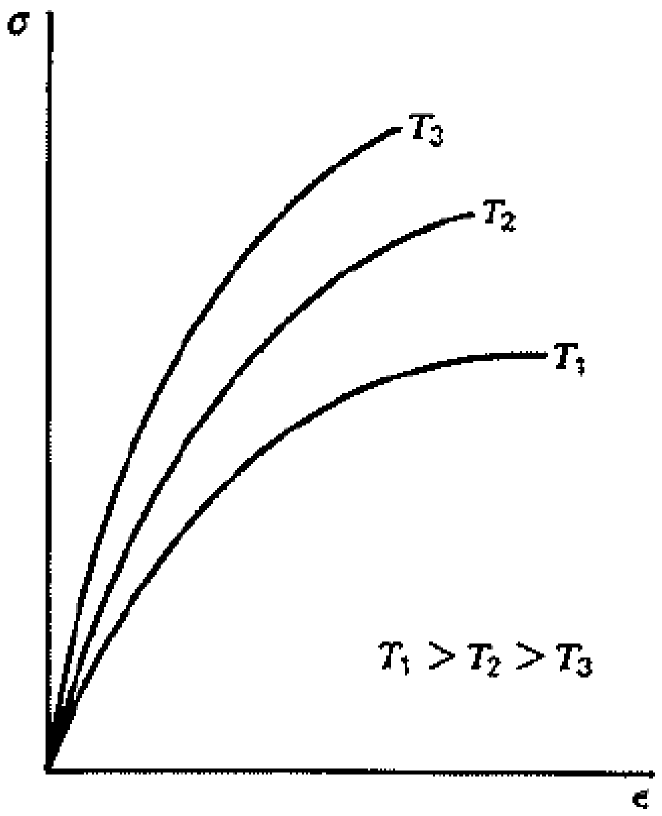
4.4 Trends in Tensile Behavior (1)

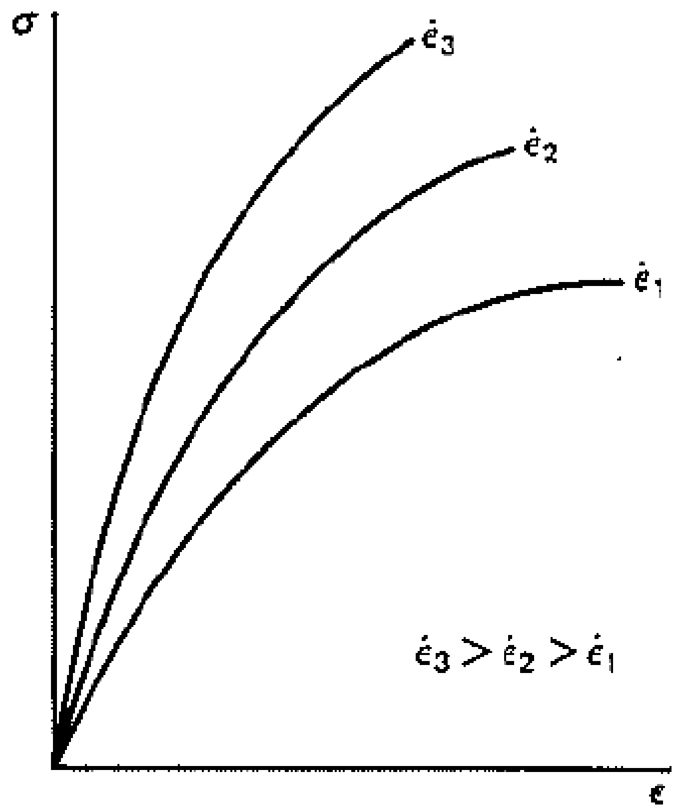
- **Effect of Strain Rate at Various Temperatures**
  - At a given temperature, increasing the strain rate increases the strength.
  - For a given strain rate, decreasing the temperature increases the strength.



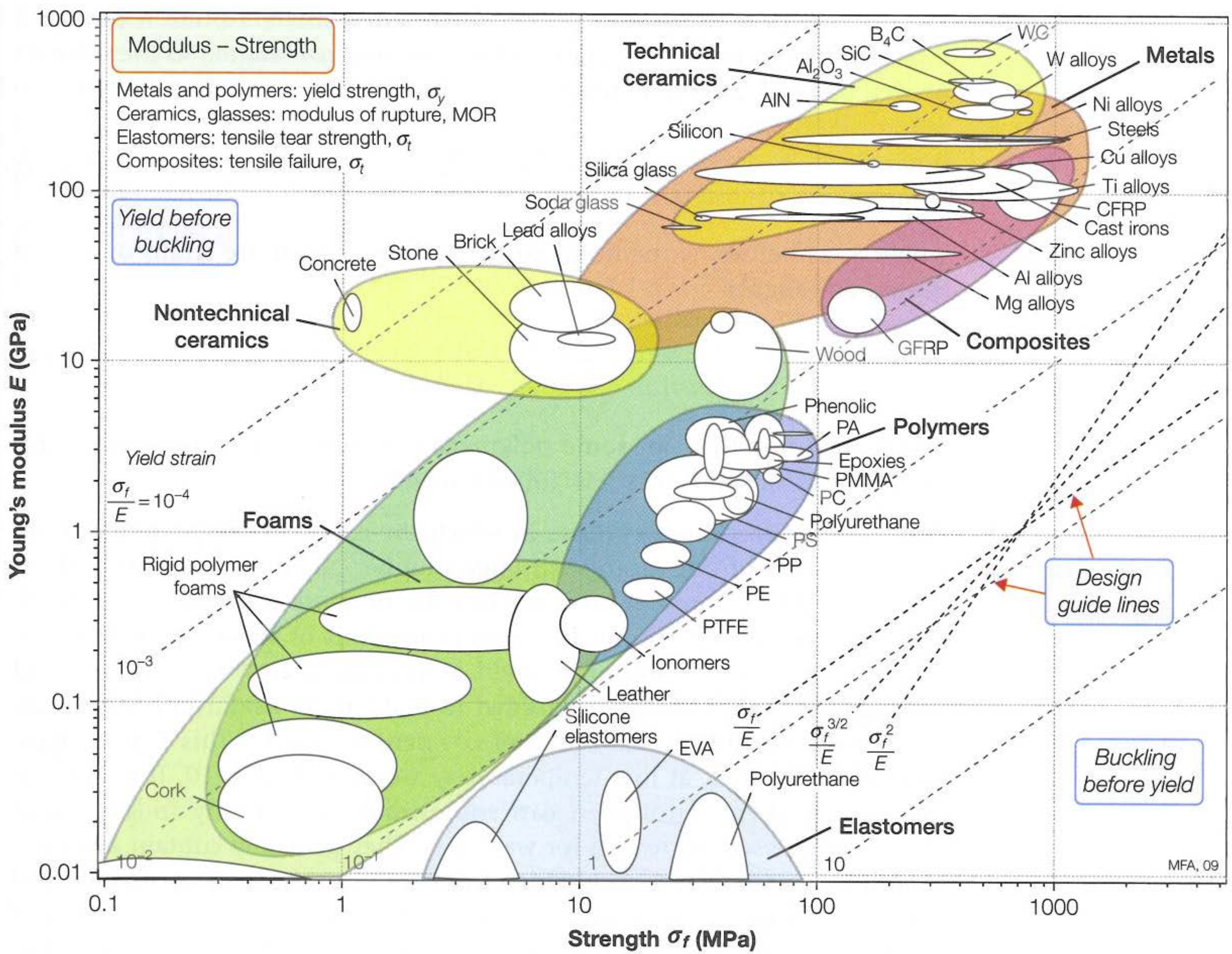
4.4 Trends in Tensile Behavior (2)

- **Effect of Strain Rate at Various Temperatures**
  - At a given temperature, increasing the strain rate increases the strength.
  - For a given strain rate, decreasing the temperature increases the strength.

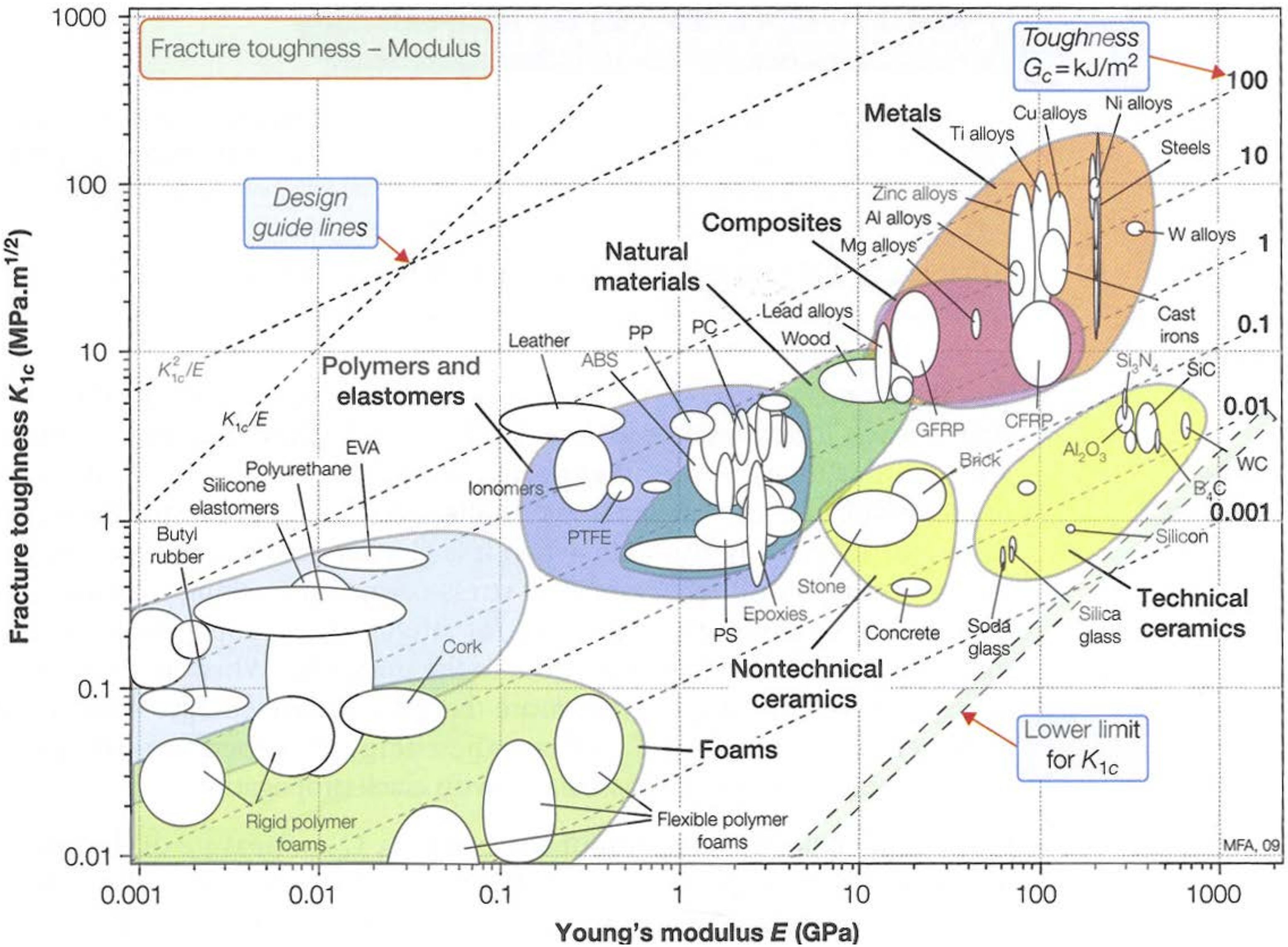




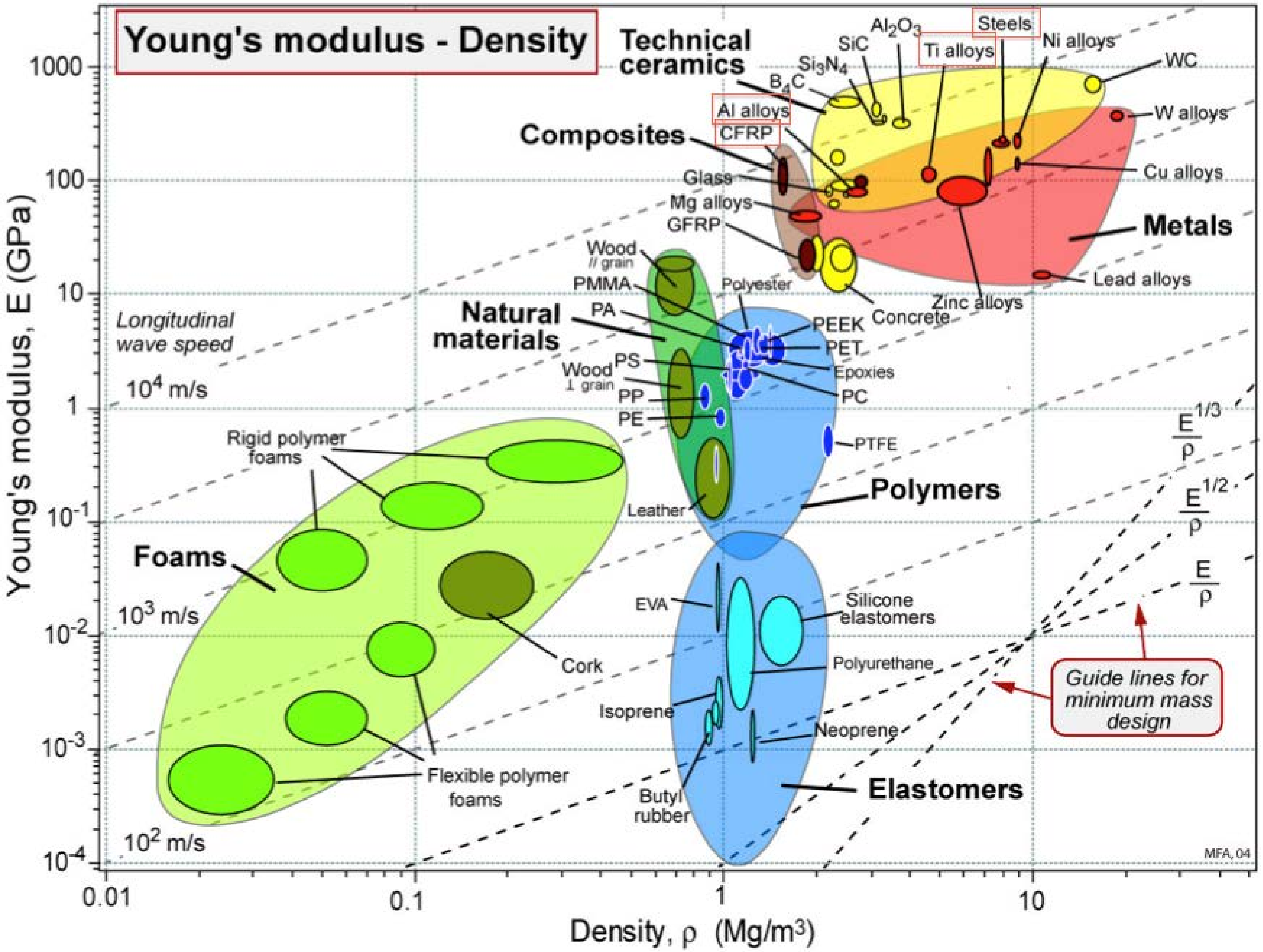
Material Selection in Design (1)



Material Selection in Design (2)

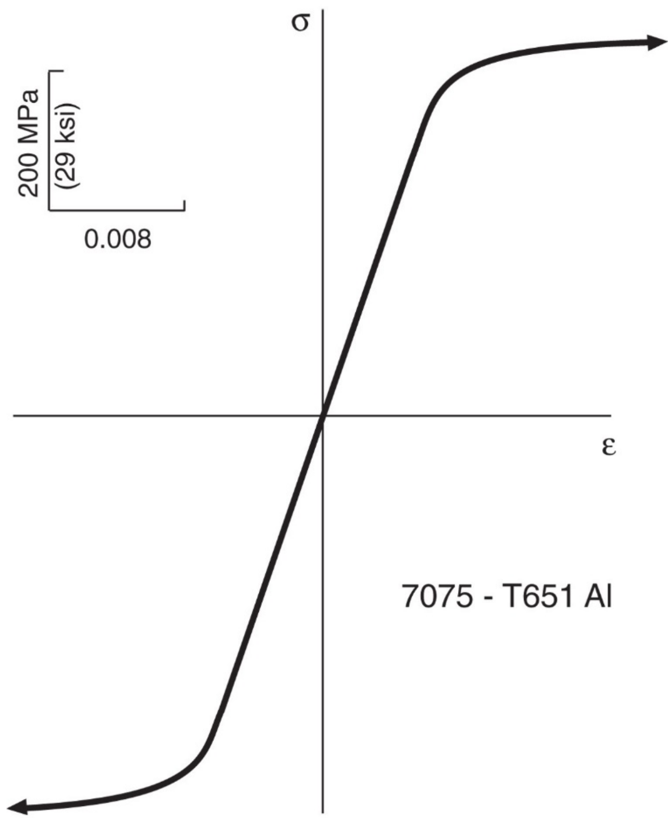


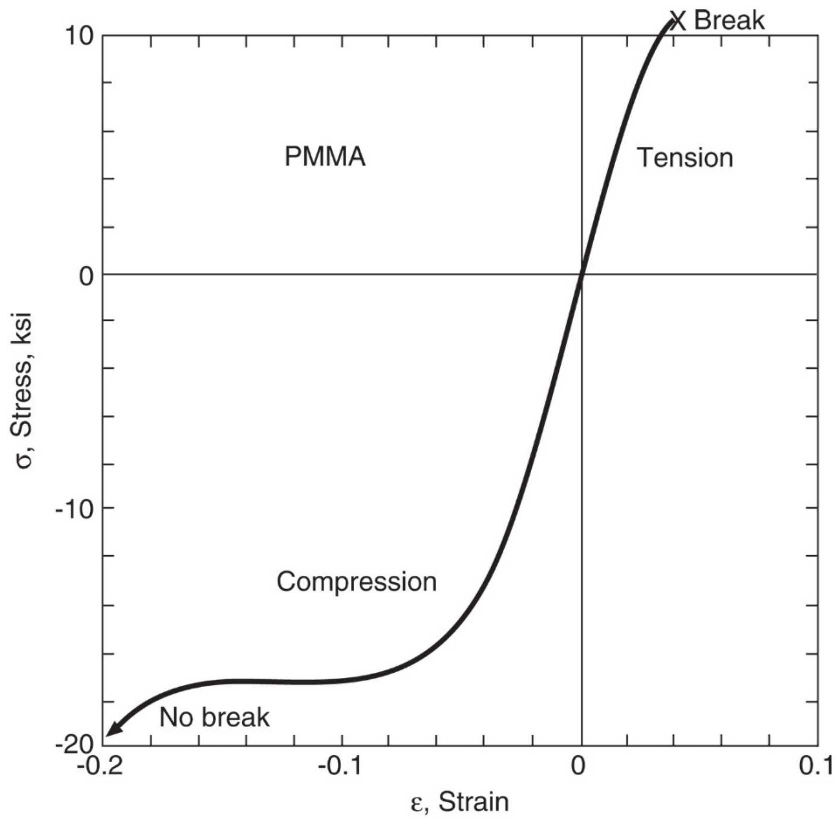
Material Selection in Design (3)



4.5 Compression Test (1)

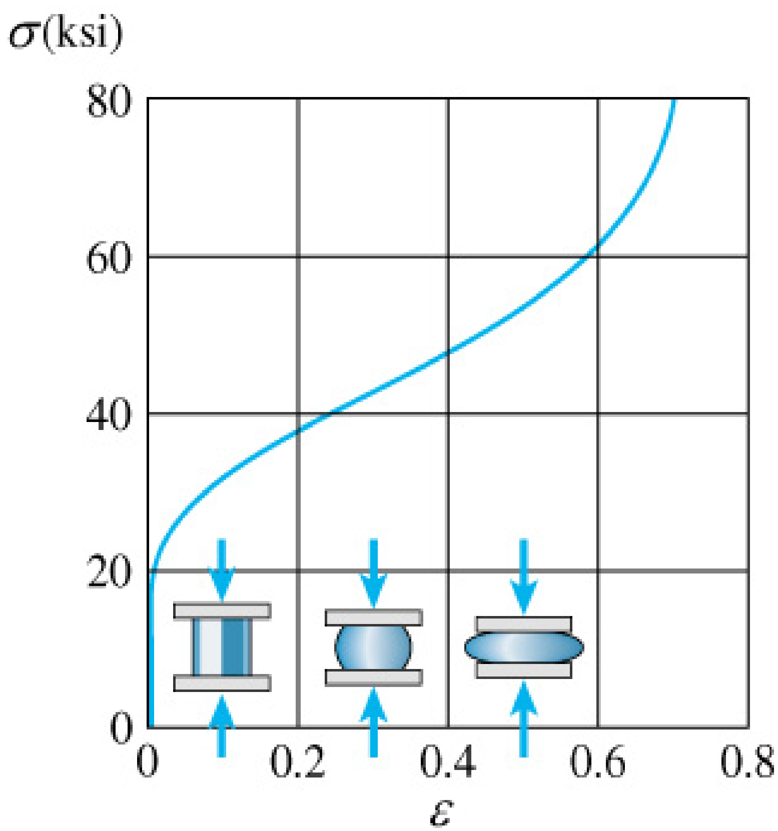
- **Compressive Behavior**
  - There is no maximum force in compression prior to fracture, and the engineering ultimate strength is the same as the engineering fracture strength.





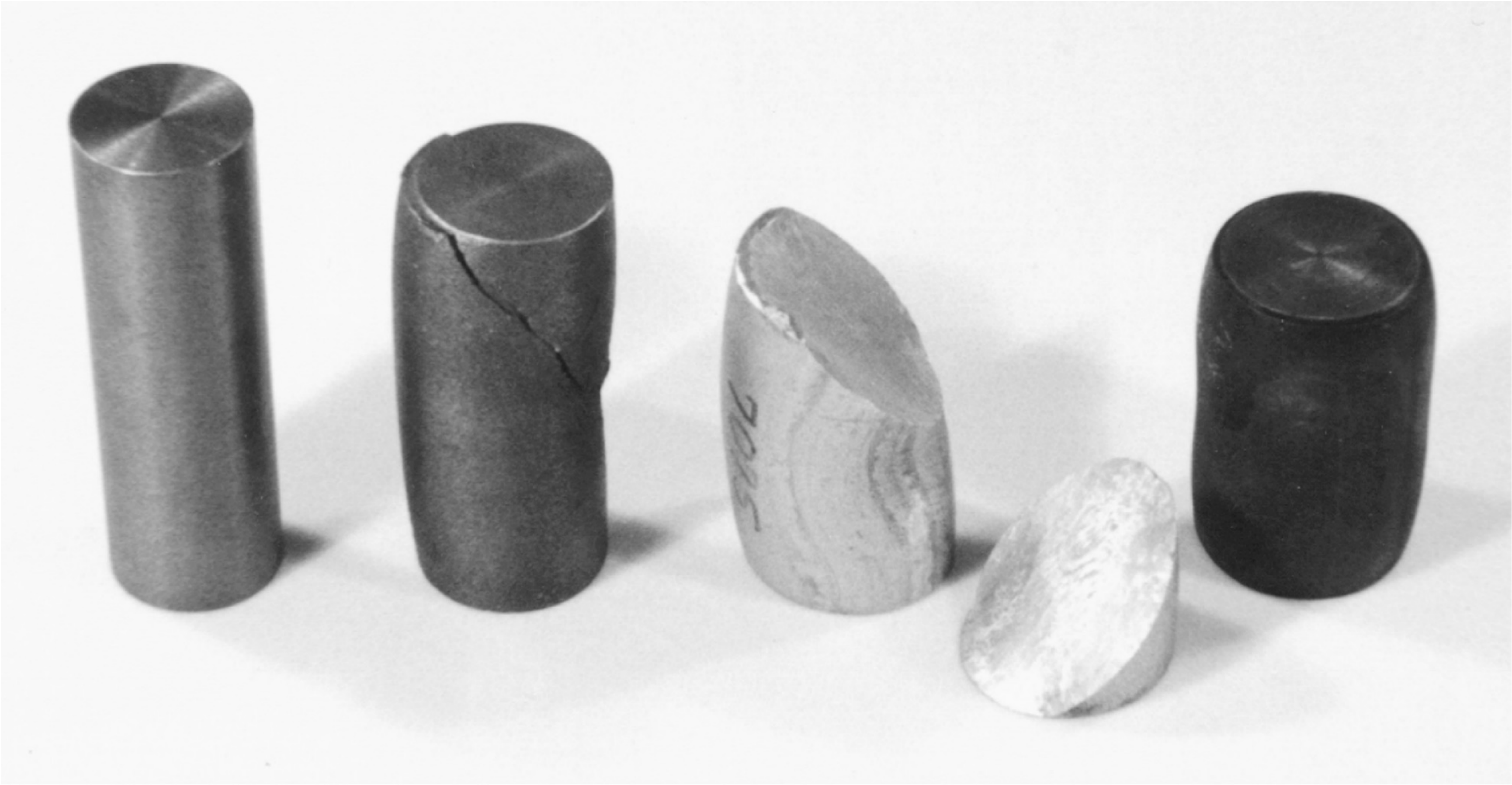
4.5 Compression Test (2)

- **Barreling Effect**
  - Considering both the desirability of small L/d to avoid buckling and large L/d to avoid barrel shape, a reasonable compromise is L/d = 3 for ductile and 2 for brittle materials



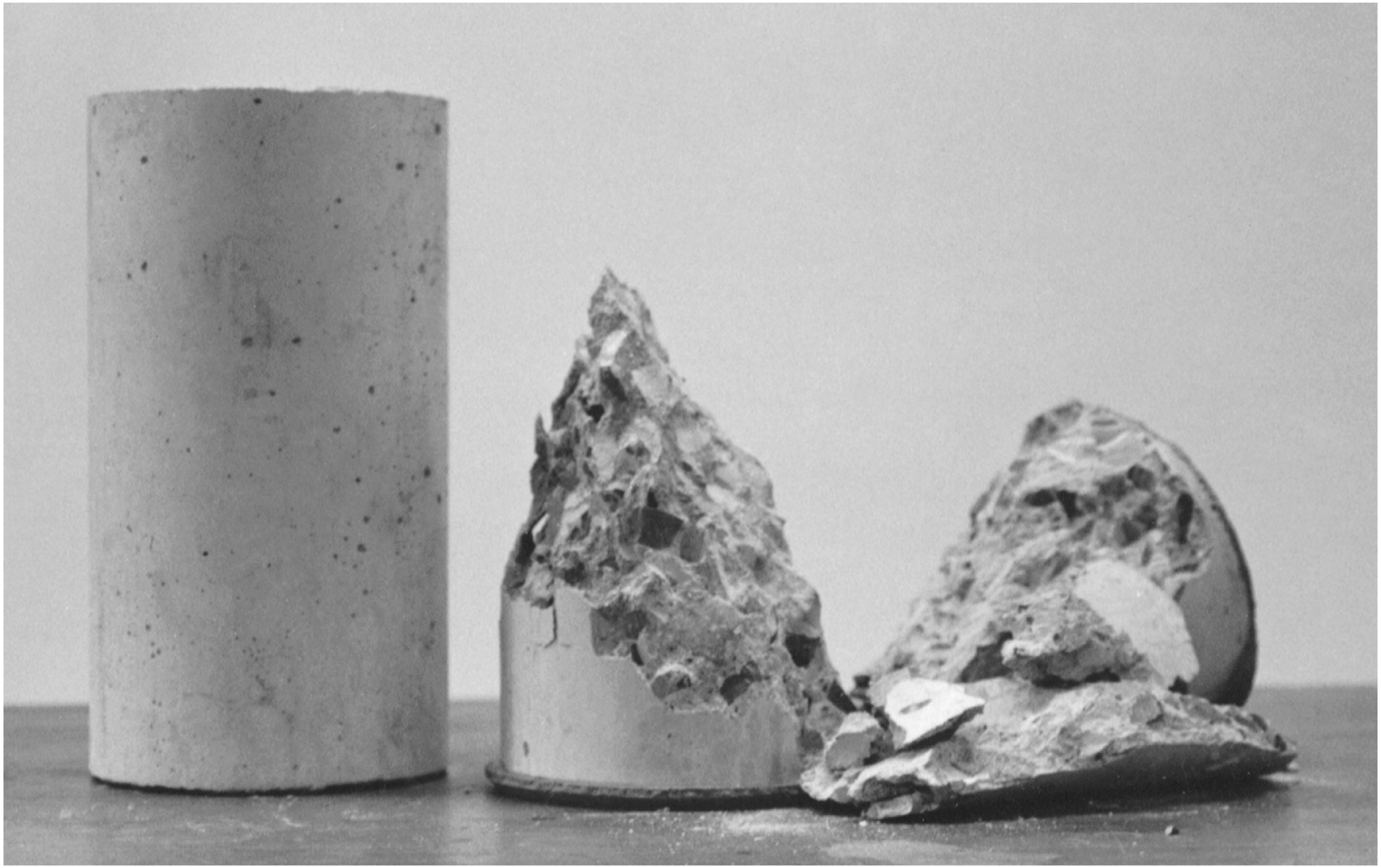
4.5 Compression Test (3)

- **Fracture on the Inclined Surface due to Shear Stress (Ductile)**

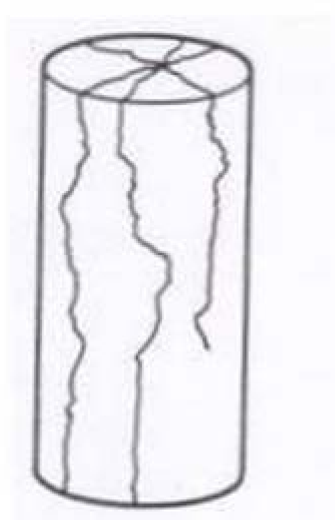


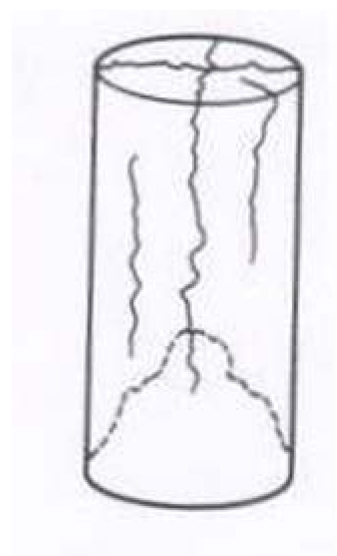
4.5 Compression Test (4)

- **Fracture on the Inclined Surface due to Shear Stress (Brittle)**



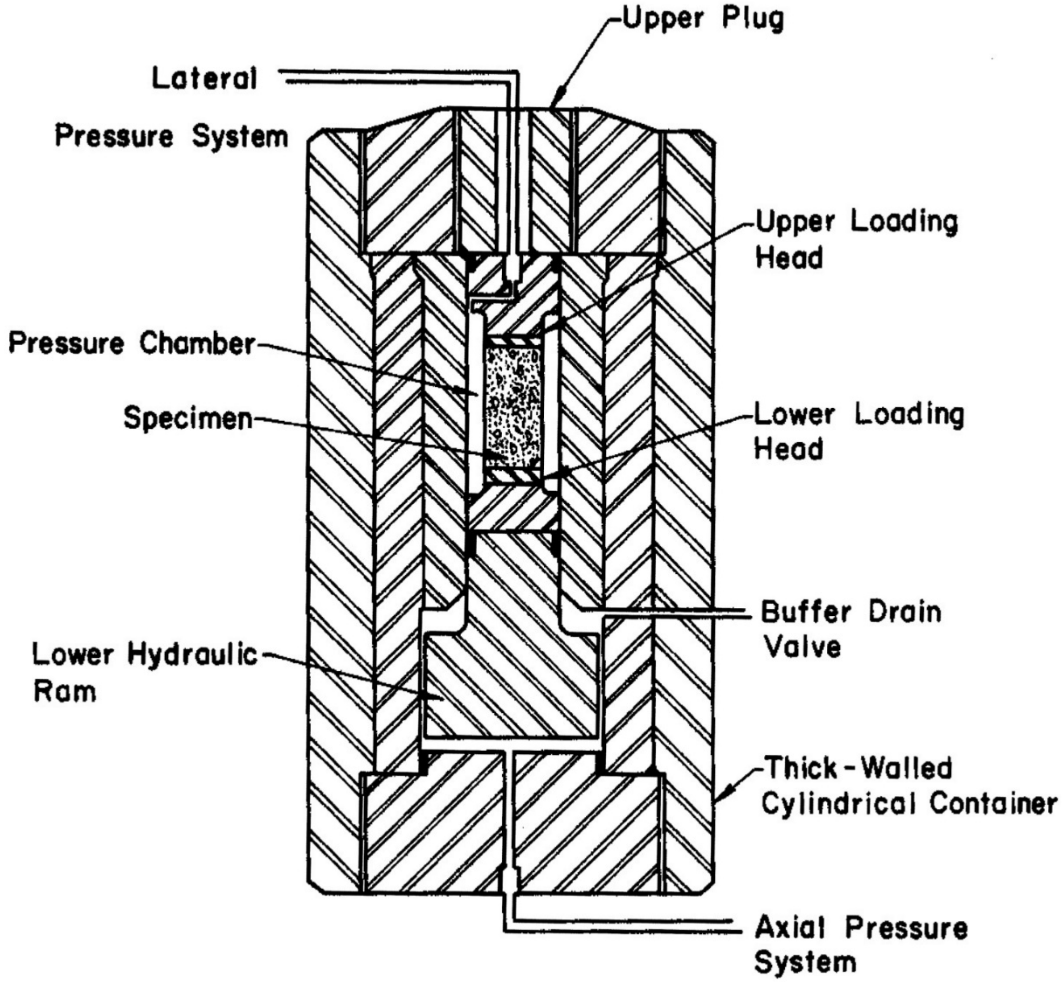
4.5 Compression Test (5)





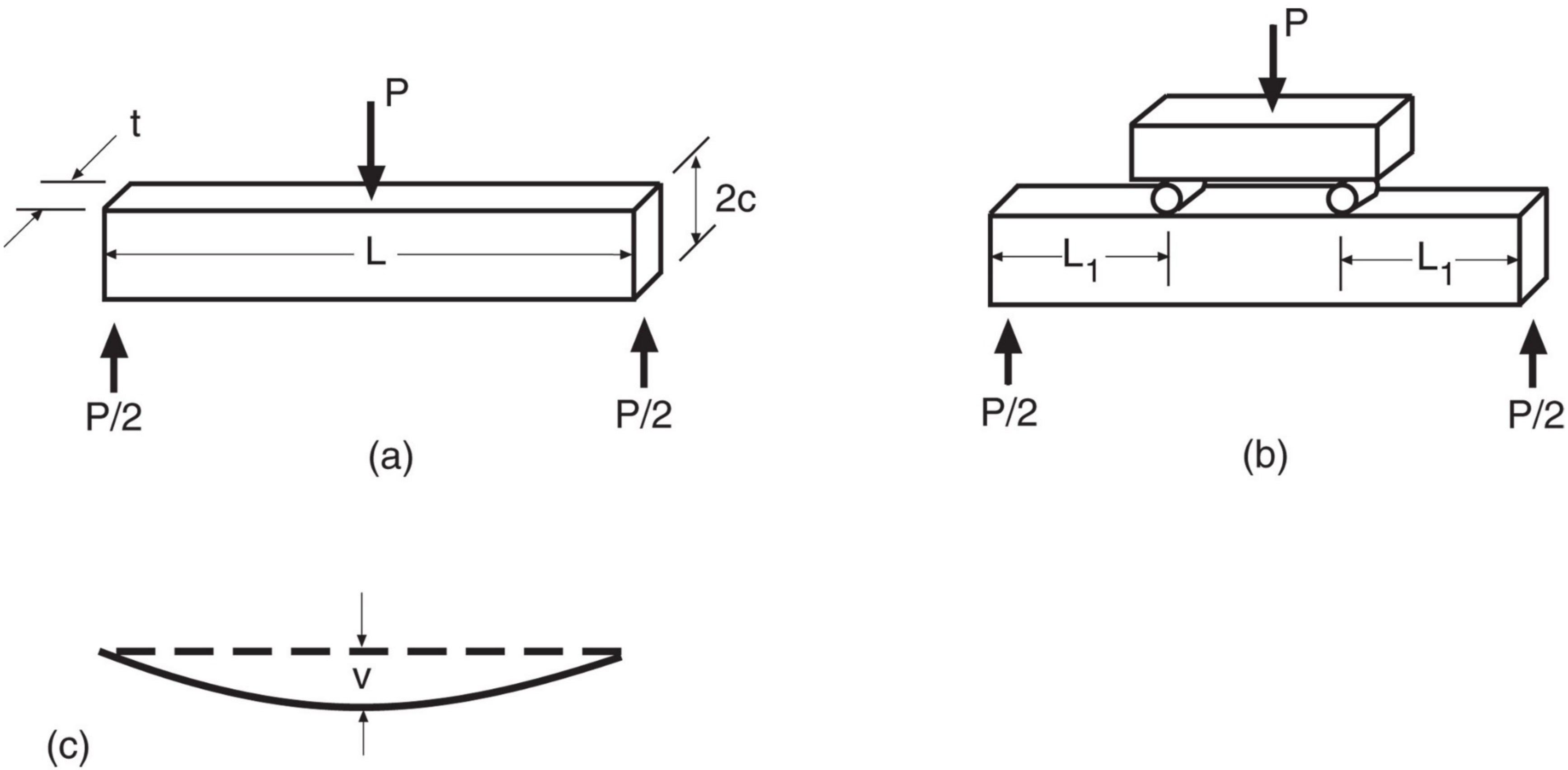
4.5 Compression Test (5)

- **Hydraulic Pressure for Multiaxial Compression Test**



4.6 Bending Test (1)

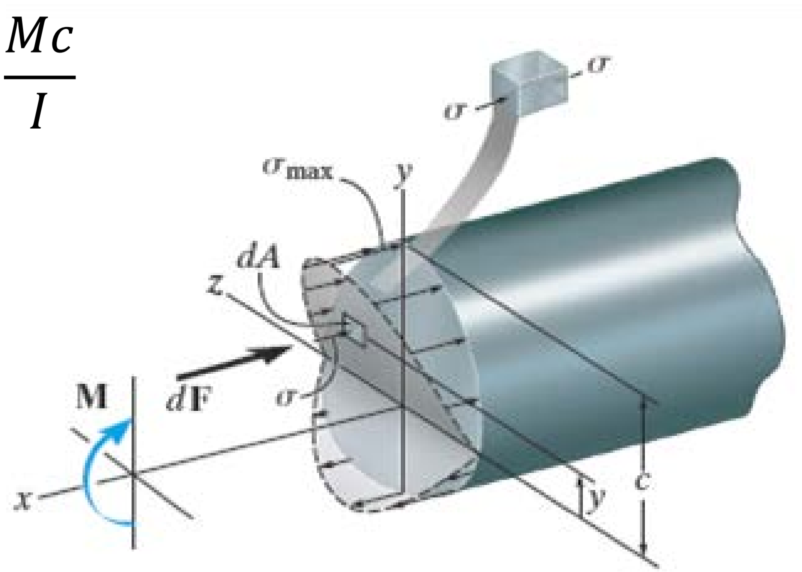
- **Loading Configuration**

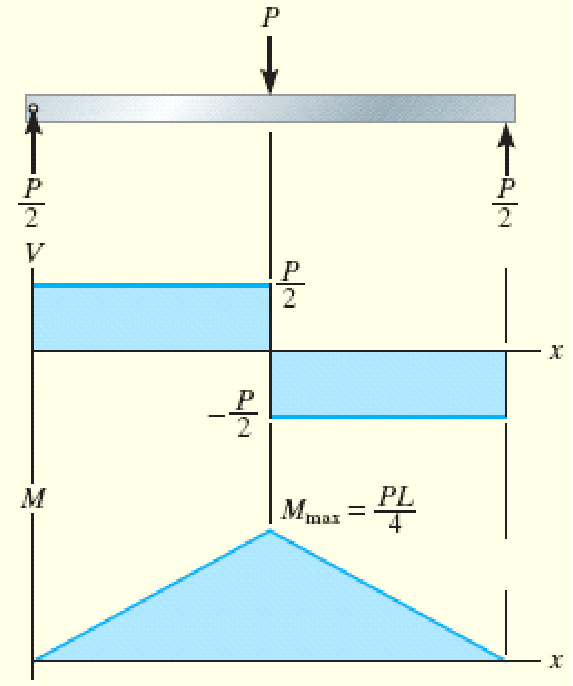


4.6 Bending Test (2)

- **Basic Theory**
  - Bending tests are especially needed to evaluate tensile strengths of brittle materials.
  - Brittle materials are usually stronger in compression than in tension, so the maximum tension stress (modulus of rupture) cause the failure in the beam.
  - For materials that exhibit linear behavior, the fracture stress may be estimated by simple linear elastic beam analysis.

$$\sigma = \frac{Mc}{I}$$





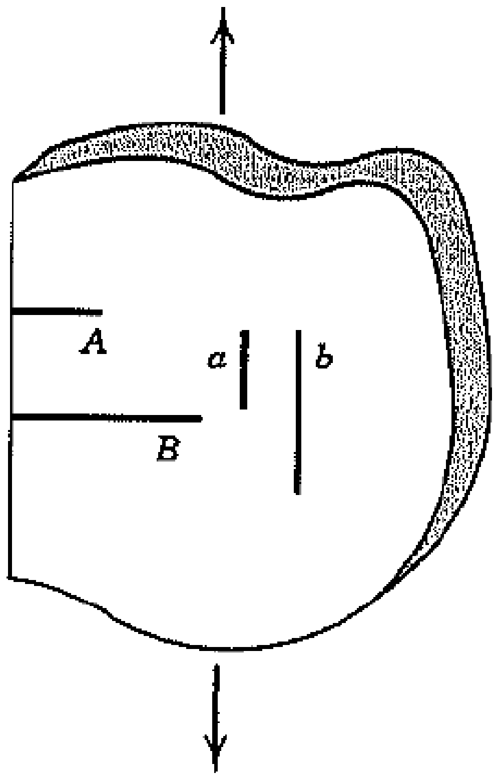
4.6 Bending Test (3)

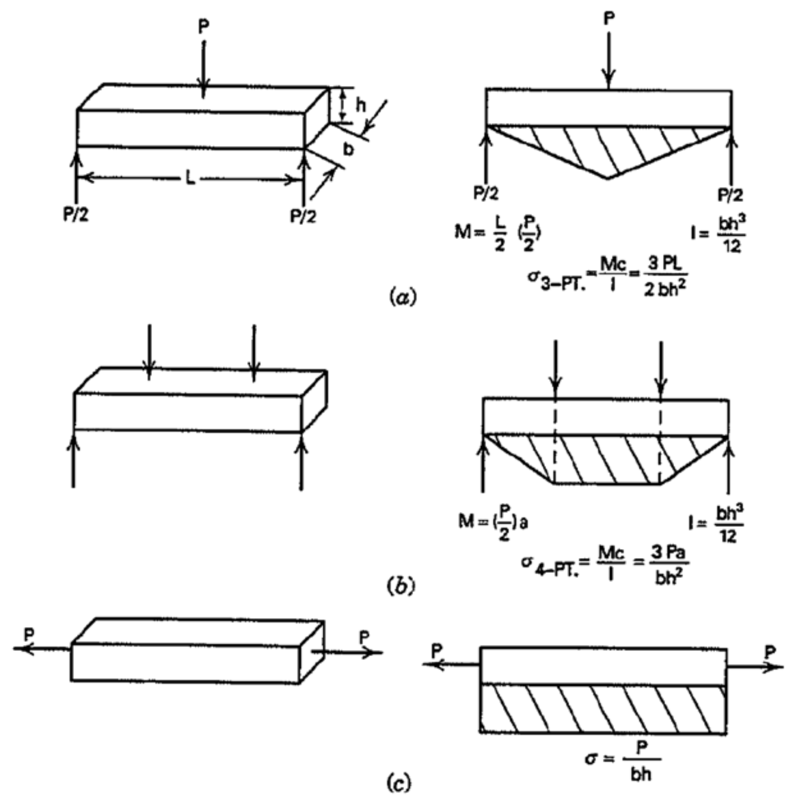
- **Possible Causes of Discrepancy between Tension and Bending Test**
  - Local elastic or plastic deformations at the supports and/or points of load application may not be small compared with the beam deflection.
  - In relatively short beams, significant deformations due to shear stress may occur that are not considered by the ideal beam theory used
  - The material may have different elastic moduli in tension and compression, so that an intermediate value is obtained from the bending test.
  - Modulus of rupture referred to as flexural strength or bending strength.

Material	Modulus of Rupture* MPa (ksi)	Tensile Strength MPa (ksi)
Al_2O_3 (0-2% porosity)	350–580 (50–80)	200–310 (30–45)
Sintered BeO (3.5% porosity)	172–275 (25–40)	90–133 (13–20)
Sintered stabilized ZrO_2(<5% porosity)	138–240 (20–35)	138 (20)
Hot-pressed Si_3N_4 (<1% porosity)	620–965 (90–140)	350–580 (50–80)
Fused SiO_2	110 (16)	69 (10)
Hot-pressed TiC (<2% porosity)	275–450 (40–65)	240–275 (35–40)

4.6 Bending Test (4)

- **Statistical Nature of Fracture**
  - The failure event depends on the probability that a flaw of a certain size and orientation is present when specific stress is applied.
  - The longer the wire, the greater the likelihood that a critical defect is present to cause failure.





4.7 Torsion Test (1)

- **Basic Theory**
  - The state of tress and strain in a torsion test on a round bar corresponds to pure shear.
  - For brittle behaviors, fracture on planes of maximum tension stress, 45^{o} to the specimen axis.
  - For ductile behaviors, fracture occurs on a plane of maximum shear stress transverse to the bar axis .
  - The shear stress at fracture can be related to the torque.

Cylinder: $\tau_f = \dfrac{T_f r_2}{J}$ Hollow bar: $\tau_f = \dfrac{2T_f r_2}{\pi(r_2^4 - r_1^4)}$

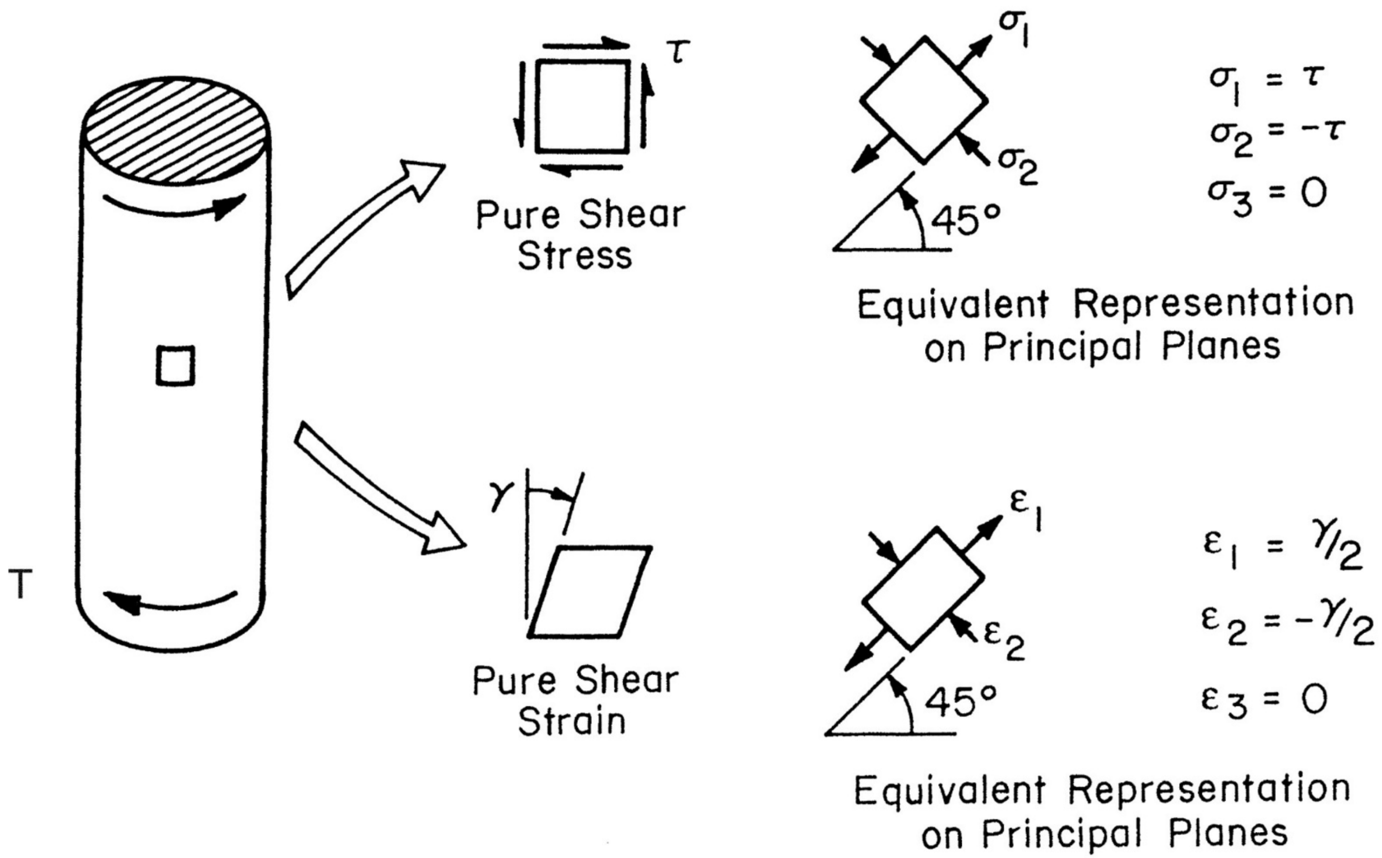
  - The shear modulus can be evaluated as below.

Cylinder: $G = \dfrac{L}{J}\left(\dfrac{dT}{d\theta}\right)$ Hollow bar: $G = \dfrac{2L}{\pi(r_2^4 - r_1^4)}\left(\dfrac{dT}{d\theta}\right)$

where $\theta = \frac{TL}{GJ}$

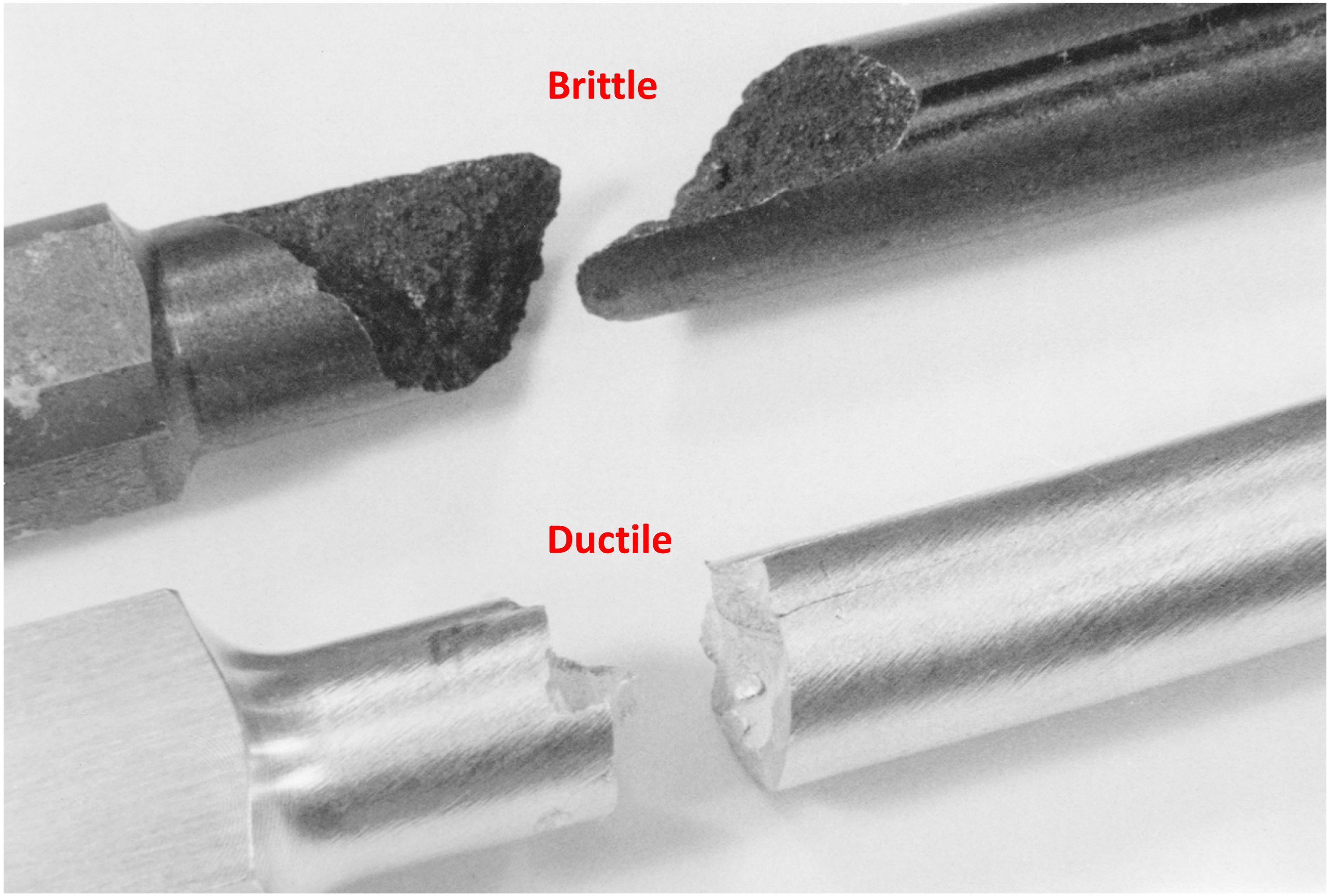
4.7 Torsion Test (2)

- **Resulting State of Pure Shear Stress and Strain**



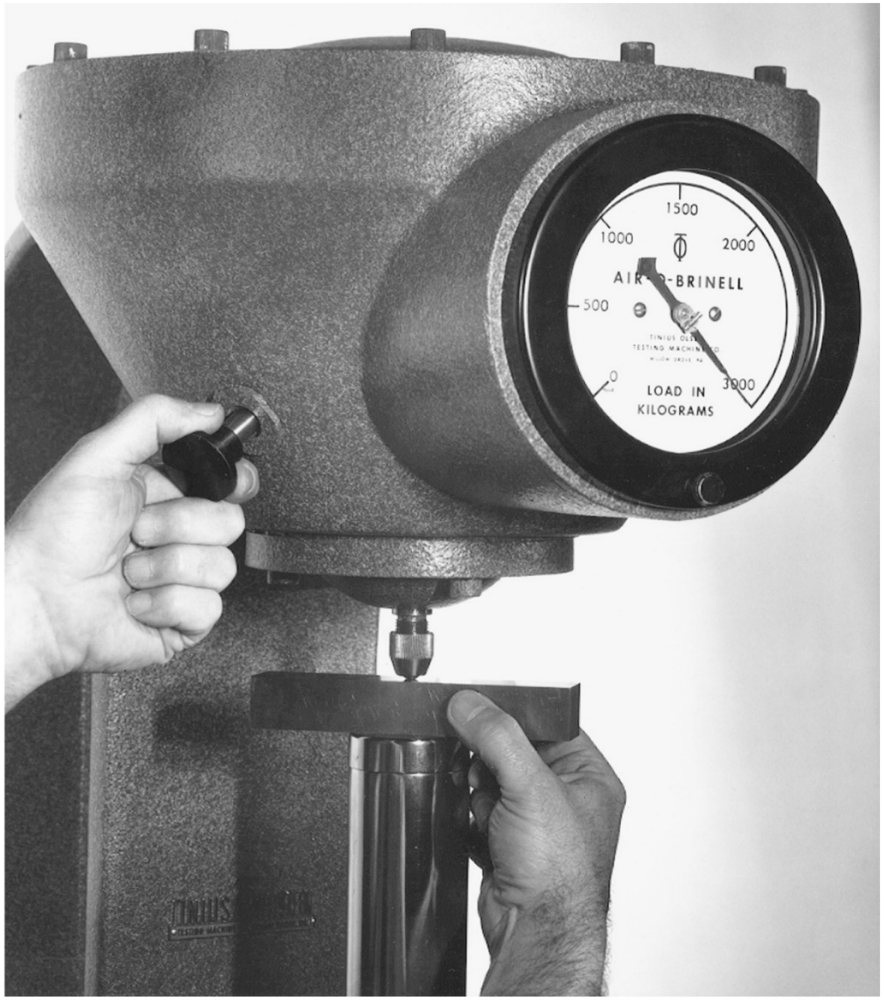
4.7 Torsion Test (3)

- **Typical Torsion Failures**



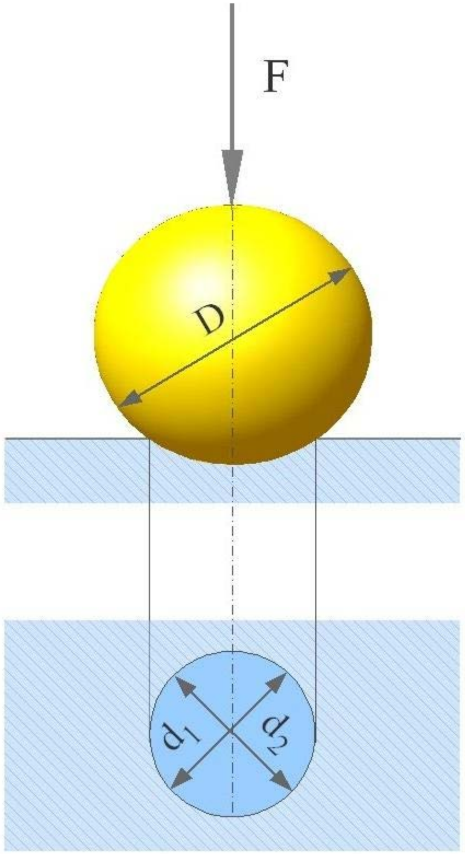
4.8 Brinell Hardness Test (1)

- **Brinell Hardness Tester**



4.8 Brinell Hardness Test (2)

- **Test Configuration**
  - A large **steel ball** (10 mm in diameter) is used with a relatively high force.
  - For fairly hard materials (steels and cast irons) -> 3000 kgf
  - For soft materials (copper and aluminum alloys) -> 500 kgf
  - For very hard materials -> **tungsten carbide ball** is used.



- **Brinell Hardness Number**
  - Brinell hardness number (*HB)* is obtained by dividing the applied force by the curved surface area of the indentation.

$$HB = \frac{2F}{\pi D[D - (D^2 - d^2)^{0.5}]}$$

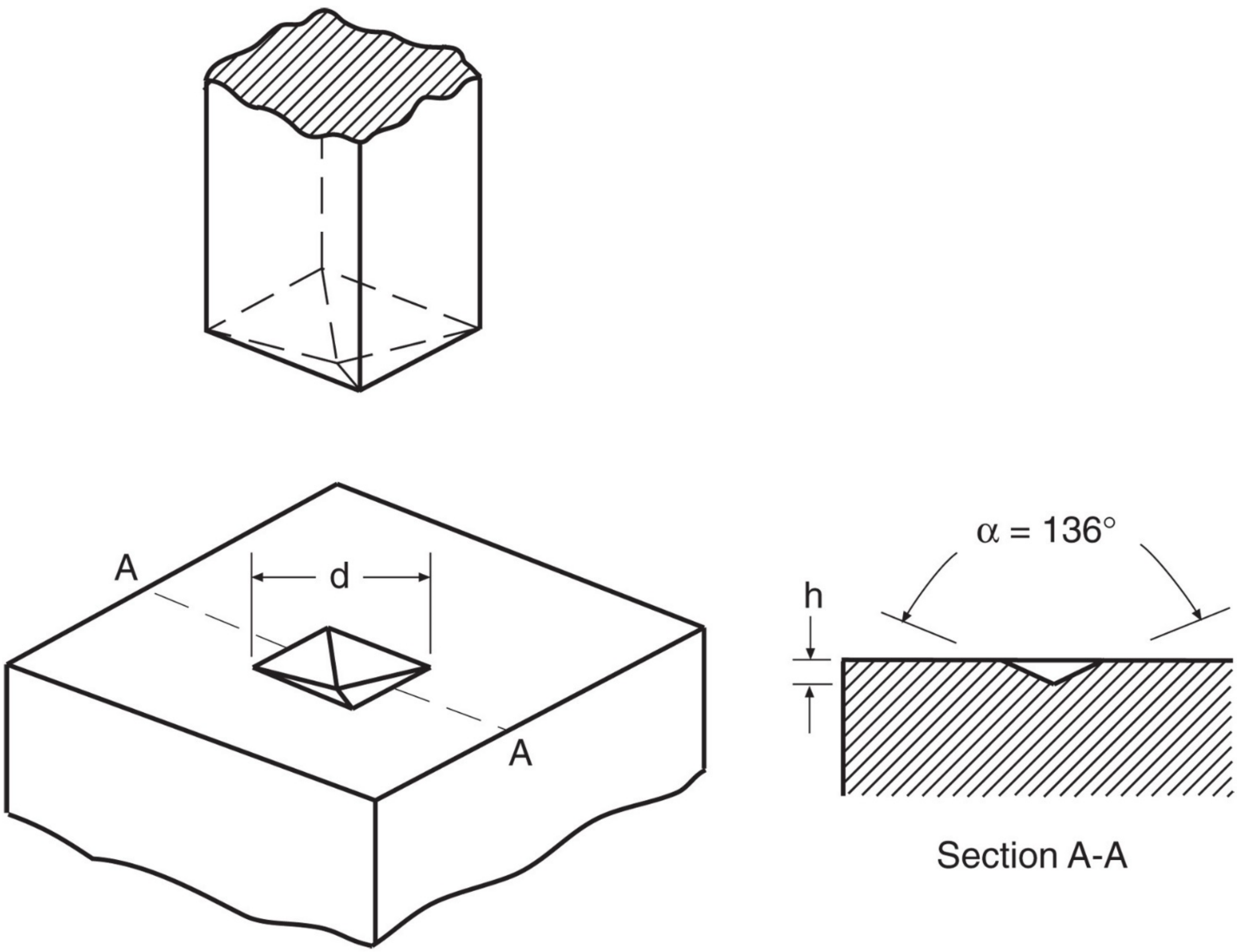
4.8 Brinell Hardness Test (3)

Brinell hardness numbers

Material	Hardness
Softwood (e.g., pine)	1.6 HBS 10/100
Hardwood	2.6–7.0 HBS 1.6 10/100
Lead	5.0 HB (pure lead; alloyed lead typically can range from 5.0 HB to values in excess of 22.0 HB)
Pure Aluminium	15 HB
Copper	35 HB
Hardened AW-6060 Aluminium	75 HB
Mild steel	120 HB
18–8 (304) stainless steel annealed	200 HB[4]
Glass	1550 HB
Hardened tool steel	600–900 HB (HBW 10/3000)
Rhenium diboride	4600 HB
Note: Standard test conditions unless otherwise stated	

4.8 Vickers Hardness Test (1)

- **Vickers Hardness Indentation**



4.8 Vickers Hardness Test (2)

- **Test Configuration**
  - Vickers hardness test is based on the same general principles as the Brinell test.
  - It differs primarily in that the indenter is a diamond point in the shape of a pyramid with a square base.

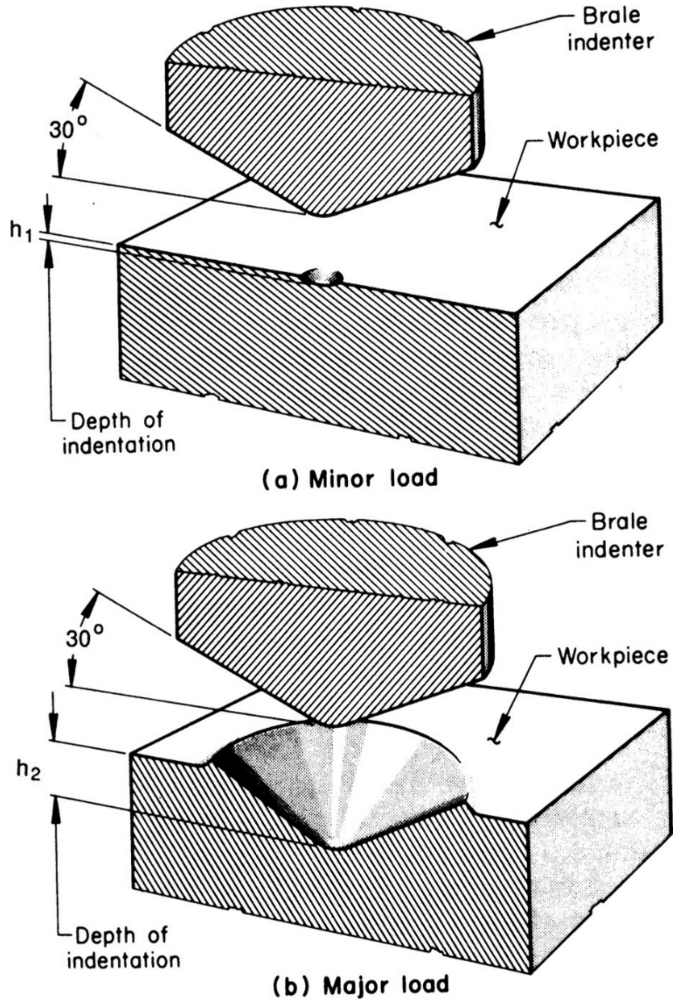
- **Vickers Hardness Number**
  - Vickers hardness number (*HV)* is obtained by dividing the applied force by the surface area of the pyramidal depression.

$$HV = \frac{2P}{d^2} sin \frac{\alpha}{2}$$

  - A Vickers hardness value is nearly independent of the magnitude of the force used.
  - 1-120kgf used for all solid materials

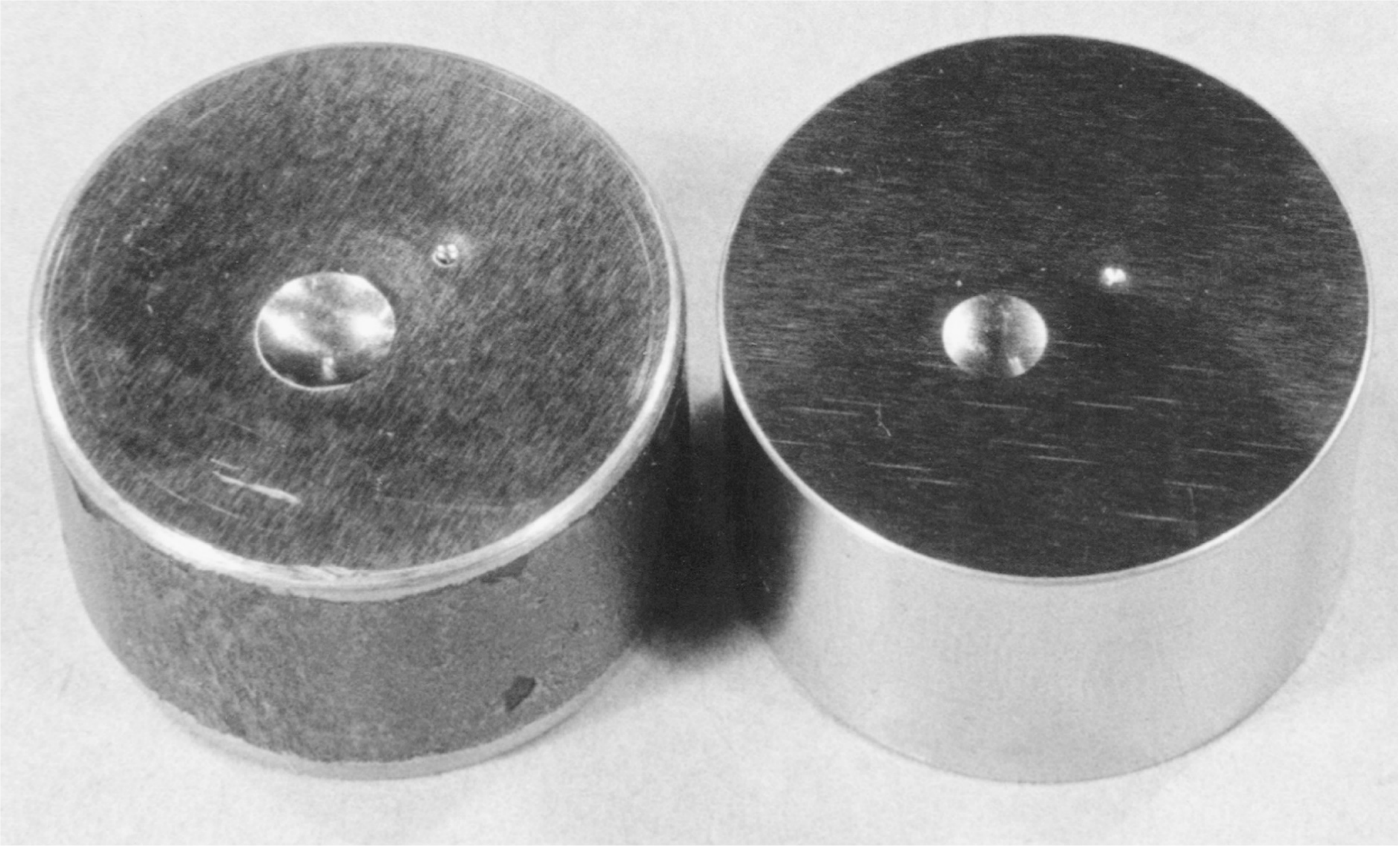
4.8 Rockwell Hardness Test (1)

- **Rockwell Hardness Indentation**



4.8 Rockwell Hardness Test (2)

- **Brinell and Rockwell Hardness Indentations**



4.9 Notch-Impact Test

- **Charpy V-notch Tester (Standardized high strain rate tester)**
  - The energy required to break the sample is determined from an indicator that measures how high the pendulum swings after breaking the sample.
  - The energies depend on the details of the specimen size and geometry, including the notch-tip radius.
  - The support and loading configuration are also important, as are the mass and velocity of the pendulum or weight.

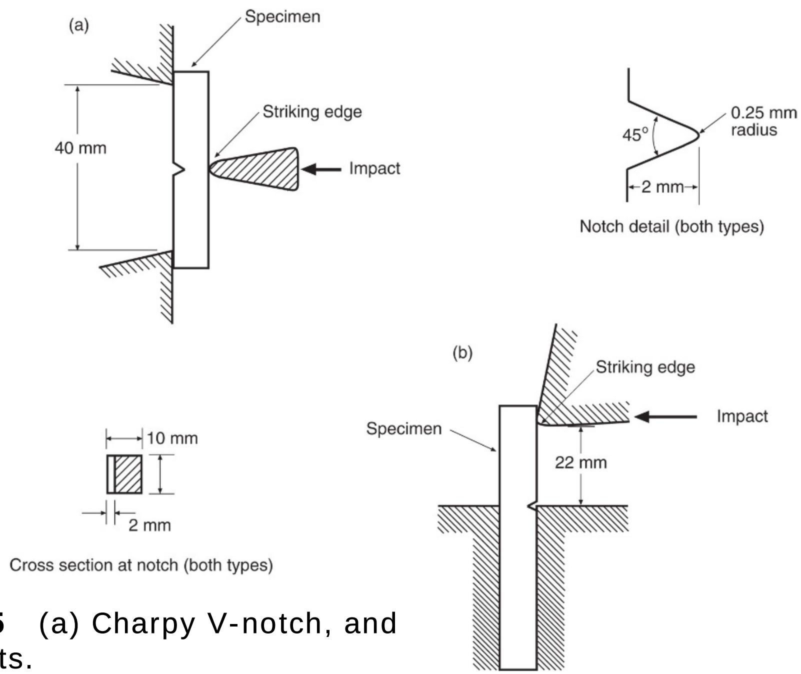


Figure 4.35 (a) Charpy V-notch, and (b) Lzod tests.