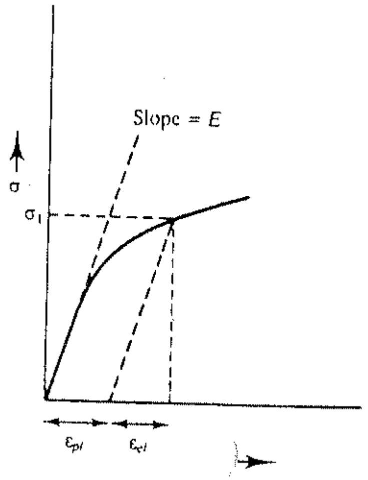
Introduction to Plasticity

- After a high enough stress is reached, the strain is not fully recovered upon unloading
- The remaining permanent strain is the "plastic" strain
- Additional plastic strains may be accumulated upon subsequent loading and unloading

Schematic of Plastic Strain After Unloading



Objectives of This Class

- This class will present an introduction to plasticity in different classes of materials
    - ceramics
    - metals
    - intermetallics
    - polymers
- This will be followed by a detailed description of what happens during a tensile test
- Basic definitions of true stress and true strain will be presented along with σ-ε behavior

Plasticity in Ceramics

- Most ceramics undergo elastic deformation before the onset of catastrophic failure at room temperature
- Most ceramists report flexural properties obtained under 3- or 4-point bending
- Ceramics are stronger in compression than in tension/flexure – why?

Strength Properties of Selected Ceramic Materials

Material	Compressive Strength [MPa (ksi)]	Tensile Strength [MPa (ksi)]	Flexural Strength [MPa (ksi)]	Modulus of Elasticity [GPa (10^6 psi)]
Alumina (85% dense)	1620 (235)	125 (18)	295 (42.5)	220 (32)
Alumina (99.8% dense)	2760 (400)	205 (30)	345 (60)	385 (56)
Alumina silicate	275 (40)	17 (2.5)	62 (9)	55 (8)
Transformation toughened zirconia	1760 (255)	350 (51)	635 (92)	200 (29)
Partially stabilized zirconia + 9% MgO	1860 (270)	—	690 (100)	205 (30)
Cast Si_3N_4	138 (20)	24 (3.5)	69 (10)	115 (17)
Hot-pressed Si_3N_4	3450 (500)	—	860 (125)	—

[a] *Guide to Engineering Materials*, Vol. 1(1), ASM, Metals Park, OH, 1986, pp. 16, 64, 65.

Factors that Control the Strength of Ceramics

- The strength of ceramic materials are controlled by pre-existing defects such as cracks
- Also, ceramics have large slip vectors that are unfavorable for plastic deformation
- Deformation is limited to small strains (typically $< 0.1 - 1\%$) except at high temperatures
- Some fine-grained ceramics may be superplastic ($\varepsilon > 100\text{-}1000\%$) elevated temperature

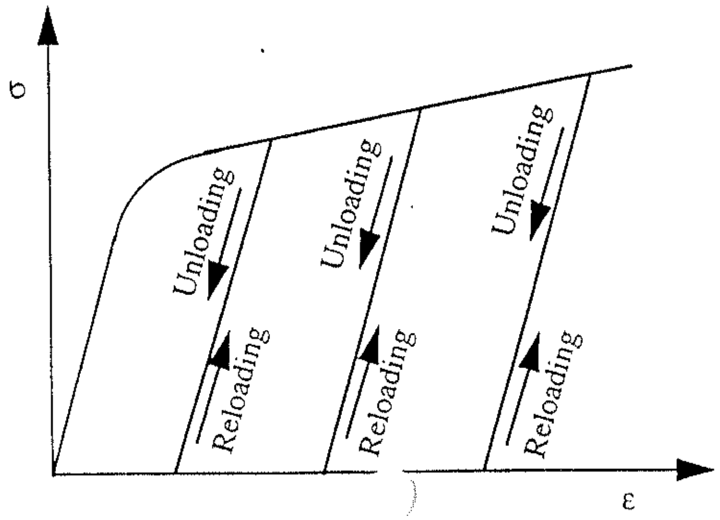
The Effects of Microcracking on Ceramics

- Microcrack generally results in a reduction in Young's modulus, E
- E is a global/scalar measure of damage
- The scalar damage variable is given by

$$D = 1 - E/E_o$$

- Damage tensors may also be used (Lemaitre, 1991)

Schematic of Young's Modulus Reduction Due to Damage

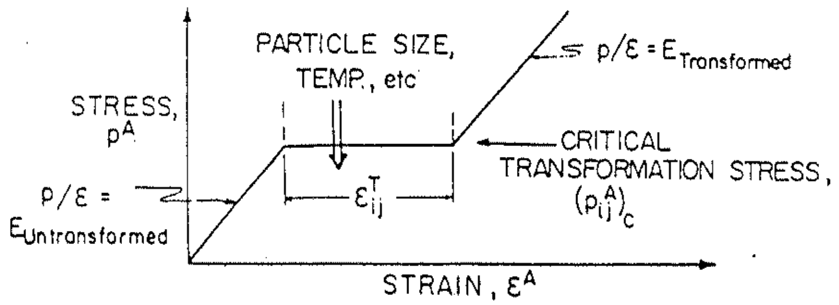


Plasticity in Ceramics: Possible Causes

- Plasticity in ceramics may occur by

  - stress induced phase transformations e.g. in zirconia alloyed with CaO, Y_2O_3 or CeO
  - microcracking mechanisms

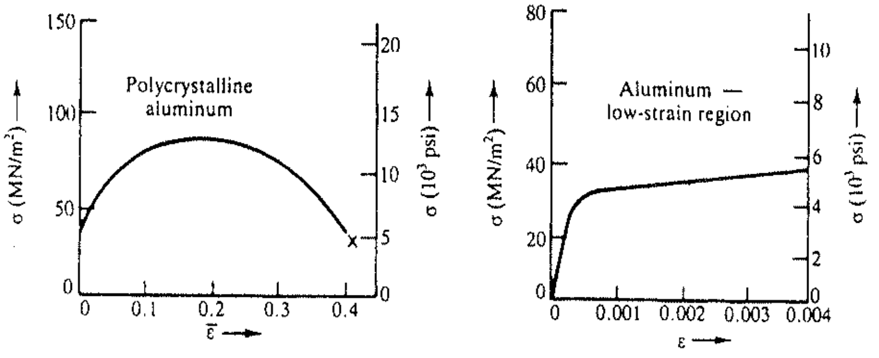
Three Stages of Deformation in Material Undergoing Stress-Induced Phase Transformation



Plasticity in Metals and Their Alloys

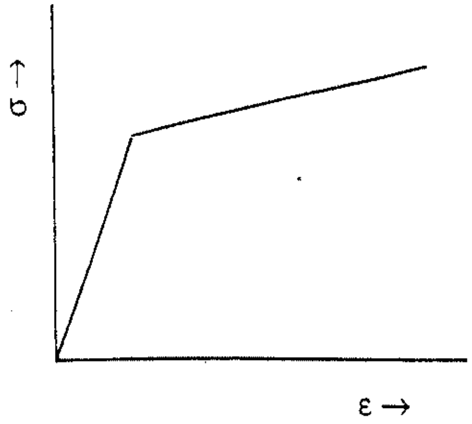
- In contrast to ceramics, plastic deformation in metals/alloys is associated with large strains
- Typical plastic strains to failure can vary between 5 and 100% in ductile metals/alloys
- However, elastic strains are typically less than ~ 0.1 to 1%

Stress-Strain Behavior in Al Alloy

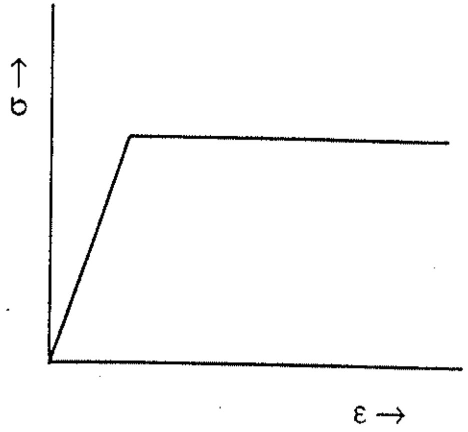


The Three Types of Stress-Strain Response

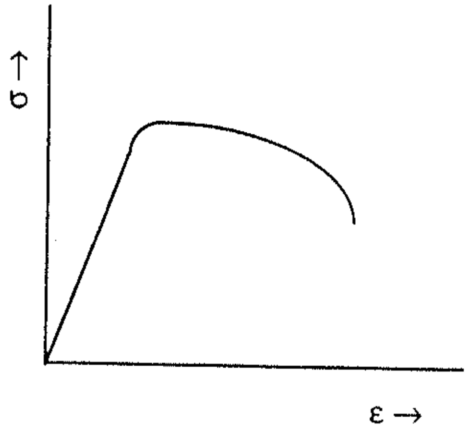
Strain Hardening



Elastic-Perfectly Plastic



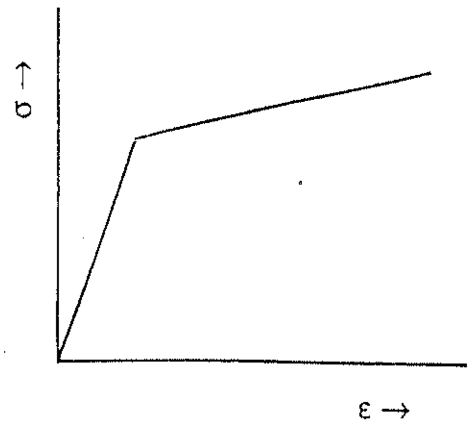
Strain Softening



Reasons for Strain Hardening in Metals/Alloys

- Strain hardening occurs largely as a result of dislocation interactions with defects
    - point defects (vaccencies, solutes, interstitials)
    - line defects (dislocations)
    - surface defects (grain boundaries & stacking faults)
    - volume defects (precipitates)

Strain Hardening



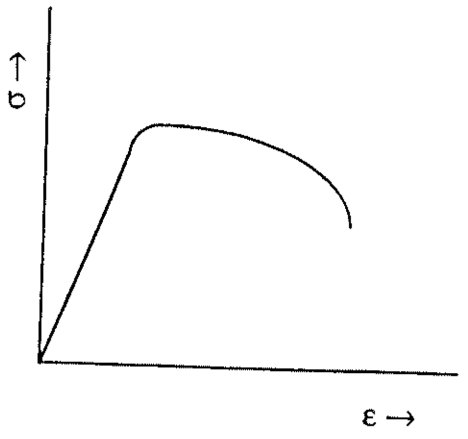
Reasons for Strain Softening

- Strain localization on a particular microstructural feature such as a precipitate

- Once the initial shear stress is overcome

  - material may offer decreasing resistance to increasing displacement
  - this may give rise ultimately to strain softening

Strain Softening



Portevin Le Chatelier Effect

- Since dislocations interact with solute clouds, serrated yielding phenomena may be observed in stress-strain behavior

- Different types of stress-strain behavior associated with possible dislocation/solute interactions

- Phenomenon referred to as Portevin Le Chatelier effect (Portevin and Le Chatelier, 1923)

- Effective at certain strain rate/temperature ranges

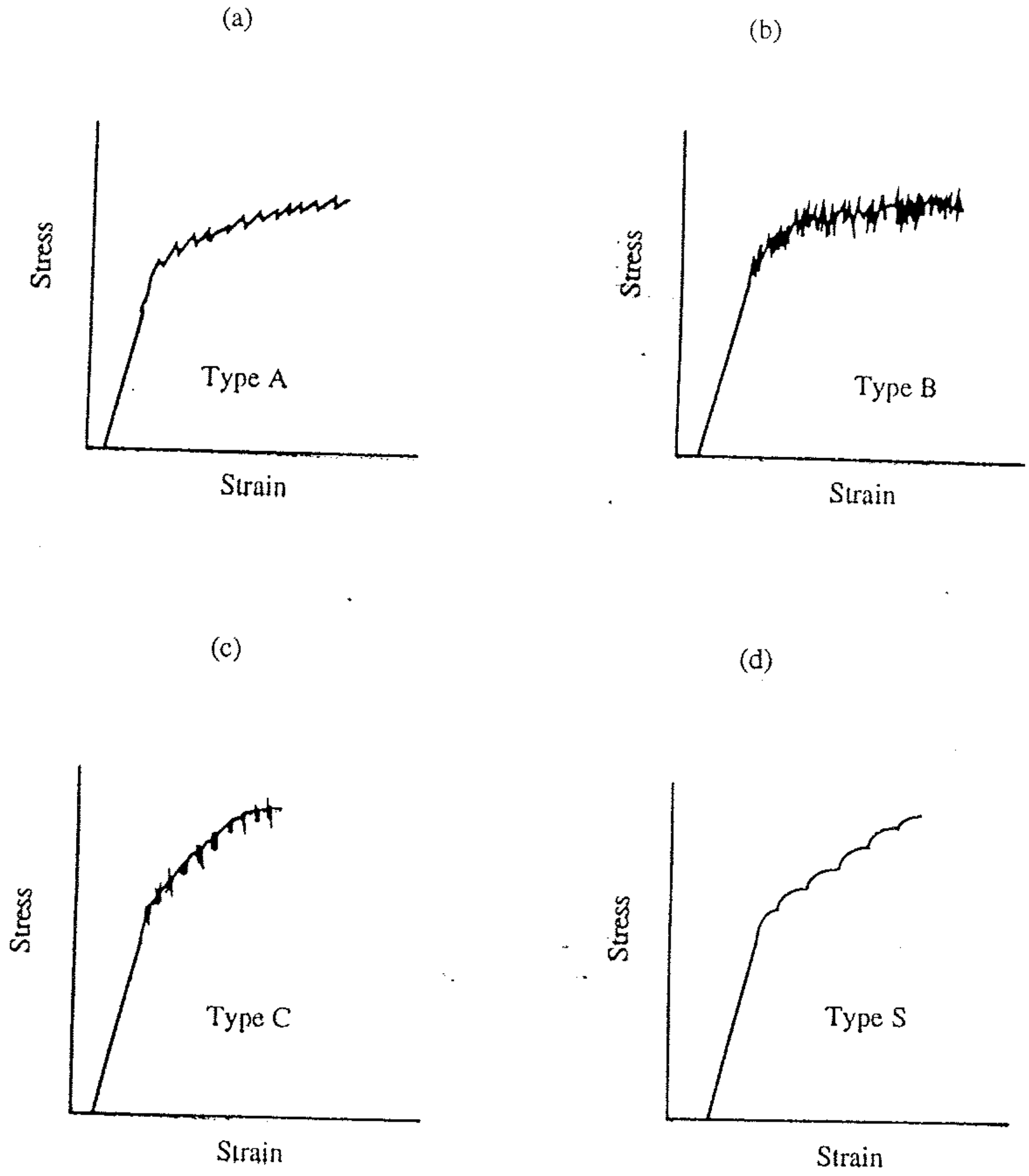
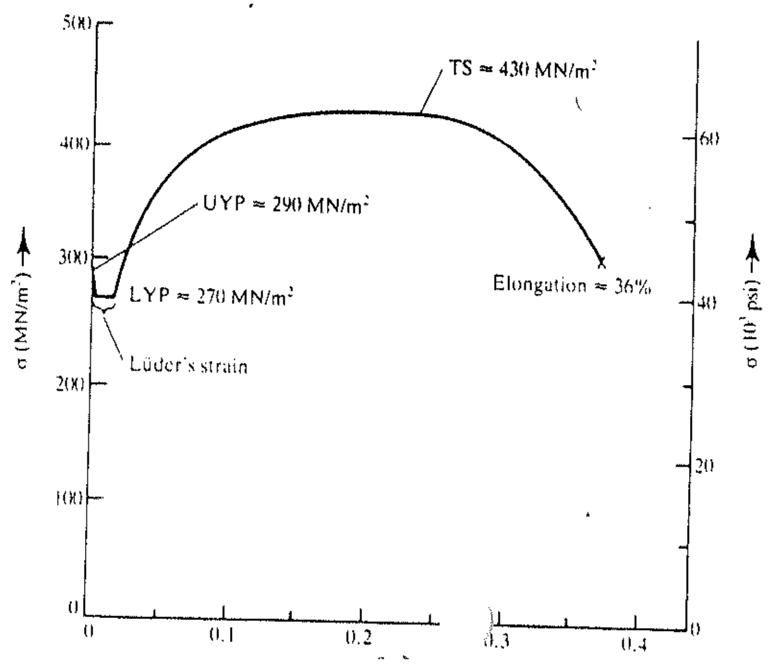


Figure 5.6 - Types of Serrated Yielding Phenomena: (a) Type A; (b) Type B; (c) Type C, and (d) Type S (Types A-C After Brindley and Worthington, 1970 - Reprinted with permission from Metall. Rev.; Type S After Pink, 1994 - Reprinted with permission from Scripta Met.).

Anomalous Yielding Phenomena

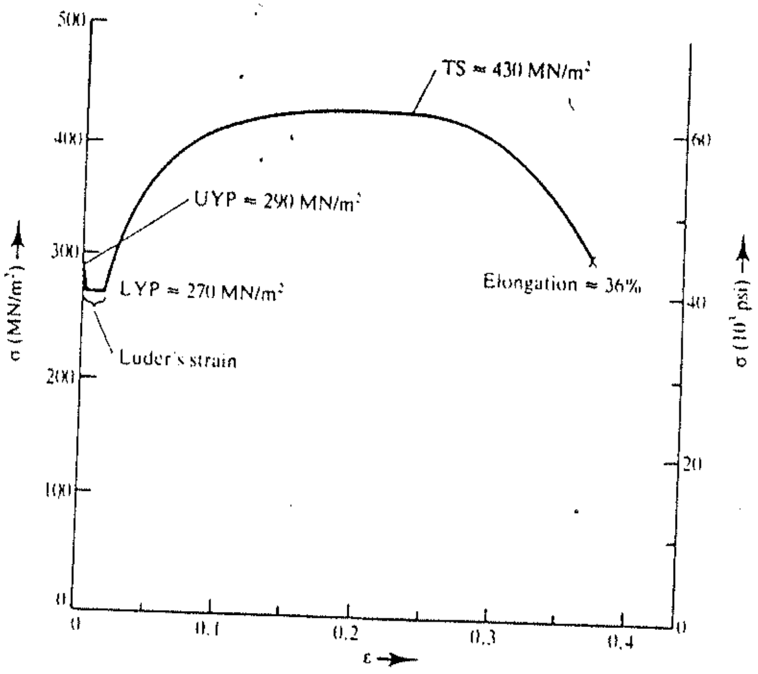
- Anomalous double yield point phenomena observed in some plain carbon steels
- Upper yield point (UYP) corresponds to the unpinning of dislocations for interstitials
- Load drops to lower yield point (LYP) upon unpinning
- Luders bands (shear bands inclined at ~ 45° to loading axes) then observed to propagate across gauge section

Anomalous Yielding in 1018 Plain Carbon Steel



Some Note on Lűder's Band

- Strain is relatively constant in the Luder's strain regime
- Serrations may be observed with sensitive instrumentation
- The strain at the end of this regime is known at the Lűder's strain
- Slip bands have spread completely across the gauge at the Lűder's strain – which is followed by conventional stress-strain behavior



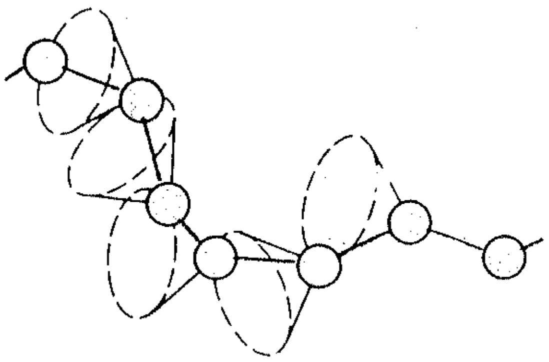
Plasticity in Intermetallics

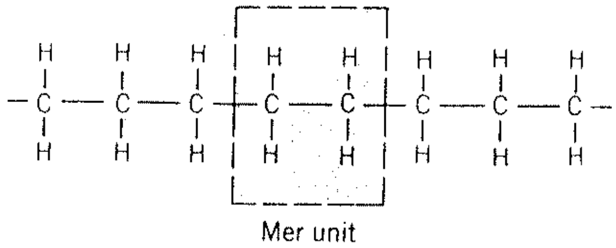
- Intermetallics are compounds between metals and non-metals
- They generally have ordered or partially ordered crystal structures
- They also tend to have partially ionic or covalently bonded structures
- Usually exhibit limited ductility at room-temperature
    - iron aluminides (Fe_3Al-xB) – 10-20% ductility
    - gamma titanium aluminides (TiAl) – 1-2 % ductility
    - nickel aluminides (N_3Al-xB) – 10-50 ductility
    - nickel aluminides (NiAl) < 1%
    - niobium aluminides (Nb_3Al-xTi) – 1-30% ductility

Plasticity in Polymeric Materials

- Plasticity in polymers is not associated with dislocation motion
- Instead, plasticity in polymers associated with sliding of polymer chains
- Chain sliding occurs readily in linear polymers
- Chain sliding is hindered by side groups and other steric hindrances

Chain Structure of Polymeric Materials

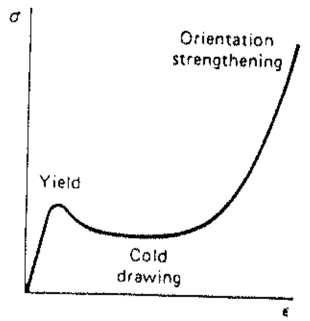




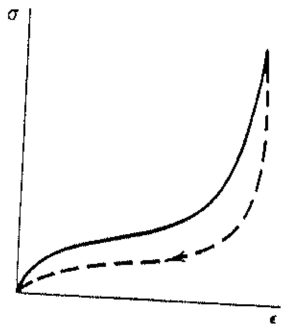
Plasticity in Polymeric Materials

- Plasticity in Polymeric Materials
- Plasticity in polymers can result in strain levels between 10 and 1000%
- Such large strains associated with sliding, unkinking and uncoiling
- Unloading may be time-dependent (viscoelastic or viscoplastic)

Deformation of Rubber



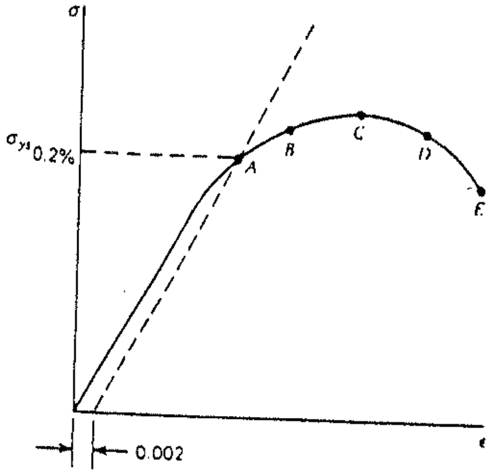
Viscoelasticity of Rubbery Polymer



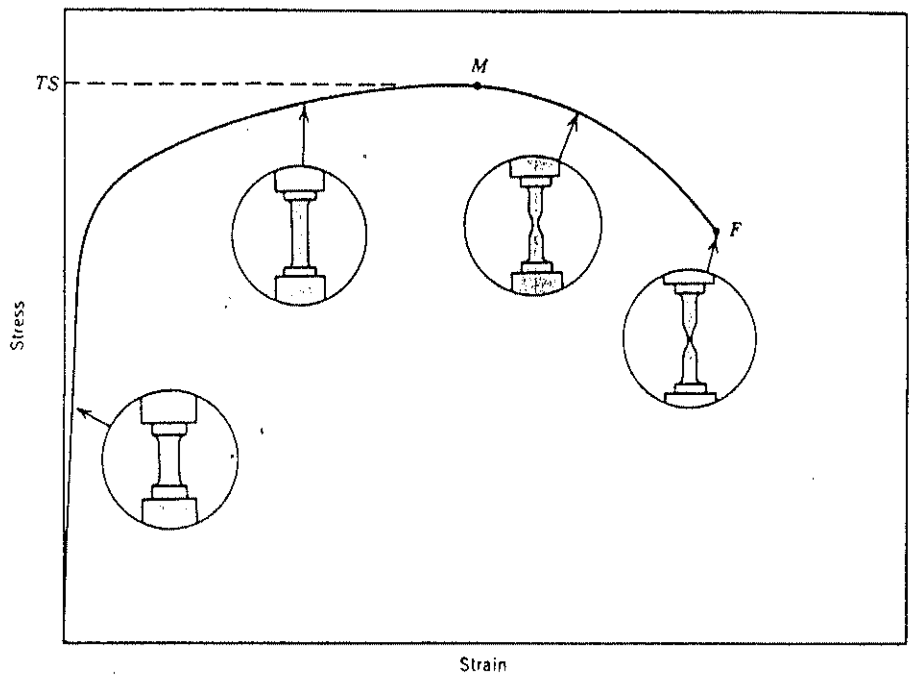
Elastic-Plastic Behavior in Materials

- Generic stress-strain behavior shows "elastic" and "plastic" regimes
- Linear behavior occurs up to the proportional limit
- Linear elasticity persists up to the elastic limit
- 0.2% offset yield stress defined (corresponds to 0.002 strain)
- Specifications for tensile testing in the ASTM E-8 code

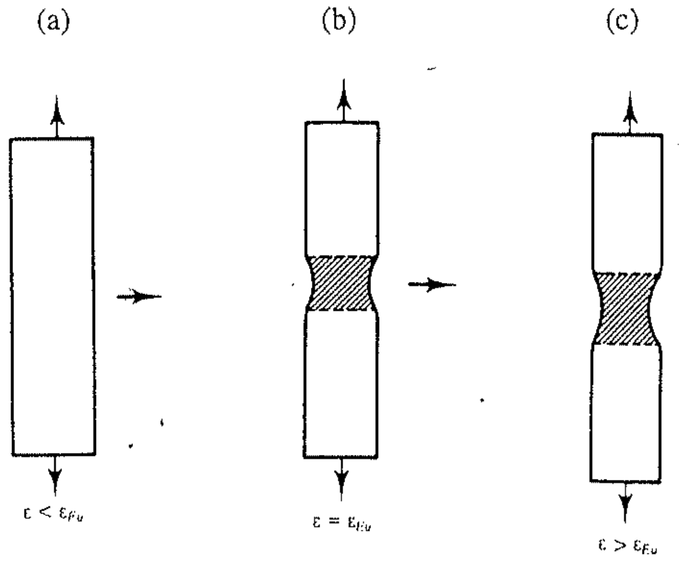
Schematic of Stress-Strain Behavior



Stages of Elastic-Plastic Deformation

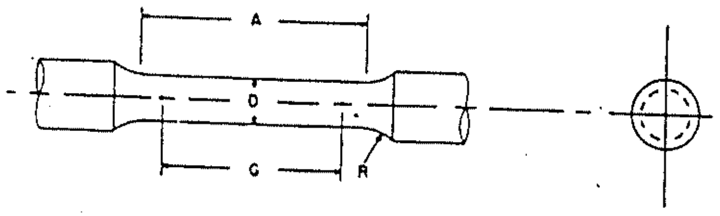


Hardening Versus Geometric Instability

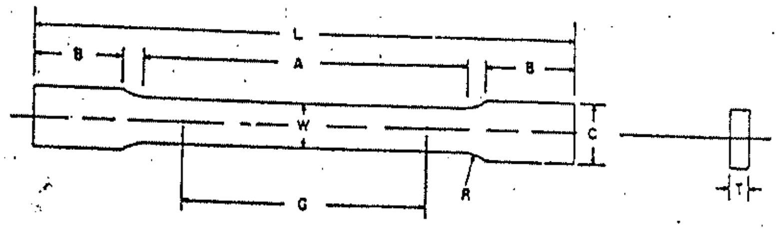


Types of Tensile Specimen Geometries

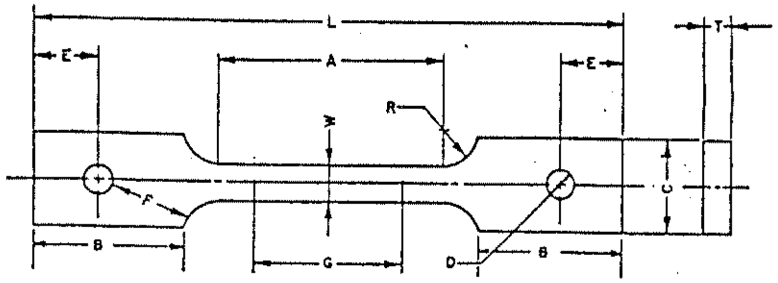
Cylindrical



Dog-Bone (Wedge Grips)



Dog-Bone (Pin-Loaded)



Basic Definitions of Stress and Strain

- The engineering stress is given by:

$$\sigma_E = \text{Engineering Stress} = \frac{\text{Applied load}}{\text{Original Cross} - \text{Sectional Area}} = \frac{P}{A_0}$$

The true stress is given by

$$\sigma_T = \text{True Stress} = \frac{\text{Applied load}}{\text{Actual Cross} - \text{Sectional Area}} = \frac{P}{A}$$

- The engineering strain is given by

$$\varepsilon_E = \frac{\delta \ell}{\ell_0} = \frac{\ell - \ell_0}{\ell_0}$$

- The true strain is given by

$$\varepsilon_T = \int_{\ell_0}^{\ell} \frac{d\ell}{\ell} = \ln\left(\frac{\ell}{\ell_0}\right)$$

Relationships Between Stress and Strain

- The engineering and true strains are given by

$$\varepsilon_E = \frac{\ell}{\ell_0} - \ell = \frac{A_0}{A} - \ell$$

and

$$\varepsilon_T = \ln\left(\frac{\ell}{\ell_0}\right) = \ln\left(\frac{A_0}{A}\right) = \ln(\ell + \varepsilon_E)$$

- Similarly, the true stress may be expressed in terms of the engineering stress, since

$$\sigma_T = \frac{P}{A} = \frac{P}{A_0} \cdot \frac{A_0}{A} = \sigma_E \frac{A_0}{A} = \sigma_E \frac{1}{l_0} = \sigma_E (1 + \varepsilon_E)$$

Comparison of Engineering and True Stress-Strain Behavior

A schema showing the relationship between tensile true stress–true strain (dotted line) and engineering stress–engineering strain (solid line). For engineering strains less than ε_{Eu}, $\sigma_T > \sigma_E$ and $\varepsilon_T < \varepsilon_E$. The necking point ($\sigma_E = \text{T.S.}$) has no particular significance in the true stress–true strain curve. At some strain greater than ε_{Eu}, ε_T (when calculated on the basis of neck area) becomes greater than ε_E, although σ_T remains greater than σ_E.