

3. Mechanical Properties of Materials

- 3.1 Stress-Strain Relationships
- 3.2 Hardness
- 3.3 Effect of Temperature on Properties
- 3.4 Fluid Properties
- 3.5 Viscoelastic Properties

1

Mechanical Properties

- A material's behavior when subjected to mechanical stresses (load)
 - Properties include elastic modulus, ductility, hardness, and various measures of strength
- Mechanical properties desirable to the designer, such as high strength, usually make manufacturing more difficult
- Integration of design and manufacturing
- Tension, Compression and Shear tests

2

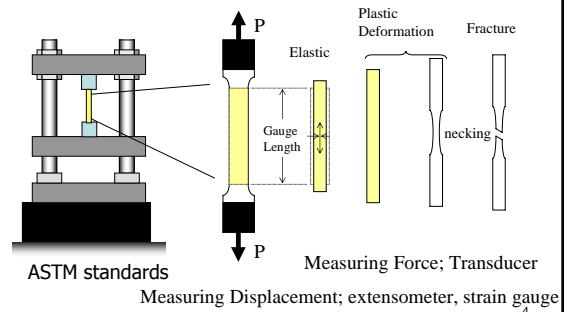
3.1 Stress-Strain Relationships

- Tensile Properties
 - Elastic modulus
 - ductility
 - hardness
 - various measures of strength
 - Proportional limit
 - Elastic limit
 - Yield strength
 - Offset yield strength
 - Ultimate Tensile strength, $TS = \frac{F_{max}}{A_0}$
 - Failure Strength

- Elongation (EL) = $(L_f - L_0) / L_0$
- Area Reduction (AR) = $(A_0 - A_f) / A_0$

3

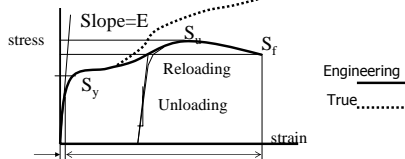
Tensile Test



4

Stress and Strain Diagram

- **Engineering Stress & Strain** $\sigma_e = \frac{F}{A_0}$, $e = \frac{\delta}{L_0}$
 - Original Area, A_0
- **True Stress and Strain** $\sigma = \frac{F}{A}$, $\epsilon = \ln \frac{L_0}{L}$
 - Instantaneous Current Area, A



5

Flow Curve

- The straight line in a log-log plot shows the relationship between true stress and true strain in the plastic region as

$$\sigma = K\epsilon^n$$
 where K = strength coefficient; and n = strain hardening exponent
- **strain hardening** - true stress increases continuously in the plastic region until necking.

6

Ultimate Point

At Maximum load (necking),

$$P = \sigma A$$

$$dP = \sigma dA + A d\sigma = 0$$

$$\frac{d\sigma}{\sigma} = -\frac{dA}{A} \quad (1)$$

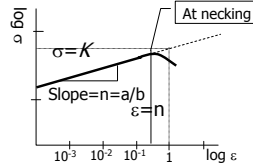
For a constant volume process

$$Al = \text{constant}$$

$$A dl + l dA = 0$$

$$\frac{dA}{A} = -\frac{dl}{l} = -d\varepsilon$$

$$\text{Flow Curve: } \sigma = K \varepsilon^n$$



Eq. (1) can be manipulated

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

With the flow curve,

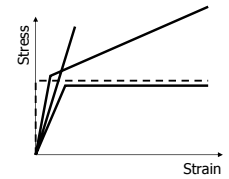
$$K \varepsilon^n = K n \varepsilon^{n-1}$$

$$\therefore \varepsilon = n$$

7

Characteristics

- Ductile and Brittle
- Perfectly elastic: $\sigma = E\varepsilon$
- Perfectly plastic: $\sigma = Y$
- Elastic and Perfectly Plastic
 - Flow curve: $K = Y, n = 0$
- Elastic and Strain hardening
 - Flow curve: $K > Y, n > 0$
- Nonlinear
- Temperature-dependent



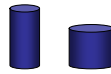
8

Compression Properties

- Engineering stress,
- Engineering strain,

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

$$e = \frac{h - h_0}{h_0}$$



Barreling due to the friction
At the contact surfaces.

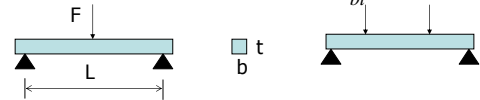
Typically Use K and n from tensile tests

$$\sigma = K \varepsilon^n$$

9

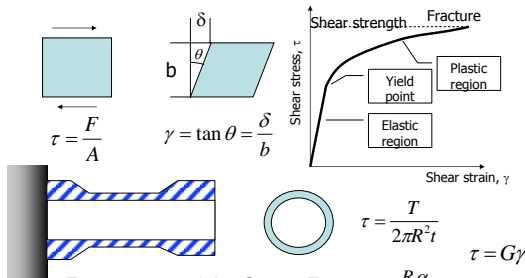
Bending and Testing of Brittle Materials

- Brittle Materials deform elastically until fracture
 - Failure occurs at the outer fibers of specimen when tensile strength are exceeded.
 - *Cleavage* - separation rather than slip occurs along certain crystallographic planes
- Three Point Bend Test
- Four Point Bend Test
- Transverse Rupture Strength, $TRS = \frac{1.5 FL}{bt^2}$



10

Shear Properties



• For most materials, $G \cong 0.4E$

11

Hardness

- Brinell Hardness Test: 10mm diameter ball
with a load of 500, 1000 or 3000kg

$$HB = \frac{2F}{(\pi D_b) \left(D_b - \sqrt{D_b^2 - D_i^2} \right)}$$

- Rockwell Hardness Test: A cone shape indenter; the depth of penetration is measured.
- Vickers Hardness Test: Pyramid shape indenter

$$HV = \frac{1.854F}{D^2}$$

12

Shear Plastic Stress-Strain Relationship

- Relationship similar to flow curve
- Shear stress at fracture = *shear strength* S
 - Shear strength can be estimated from tensile strength: $S \cong 0.7(TS)$
 - Where did 0.7 come from?
- Since cross-sectional area of test specimen in torsion test does not change, the engineering stress-strain curve for shear is similar to true stress-strain curve

13

Hardness

- Knoop hardness Test: Pyramid shape indenter

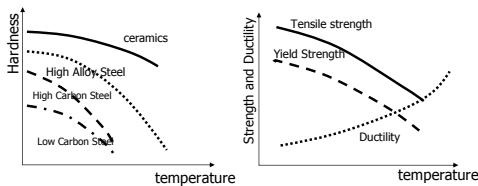
$$HK = \frac{14.2F}{D^2}$$
- Scleroscope: rebound height
- Durometer: The resistance to penetration (elastic deformation)
- Relationship between Hardness and Strength

$$TS = K_h(HB) \quad \text{where } K_h = 500 \text{ in lb/in}^2 = 3.45 \text{ in MPa}$$

14

Temperature Effect

- Affect the all properties
- Hot hardness
- Recrystallization ($0.5T_m$)



15


Recrystallization

- Most metals strain harden at room temperature
- Upon heating to sufficiently high temperature, strain hardening does not occur
 - Recrystallization* - Formation of new strain-free grains
 - Recrystallization temperature* of a given metal = $0.5 T_m$ measured on an absolute scale
- Recrystallization above the recrystallization temperature takes time.
- In manufacturing - recrystallization reduces forces and power. *Hot working* - Forming metals above recrystallization temperature

16

Fluid Flow in Manufacturing

- In many processes, materials (metals, Glass and Polymers) converted from solid to liquid by heating.
- Flow is a defining characteristic of fluids
 - Viscosity (the resistance to flow) is a measure of the internal friction on fluid with velocity gradients
 - Fluidity* (Reciprocal of viscosity) is the easiness of a fluid flows
- Viscosity can be defined using two parallel plates separated by a distance d
 - Shear viscosity is the fluid property that defines the relationship between F/A and dv/dy (*shear rate*);

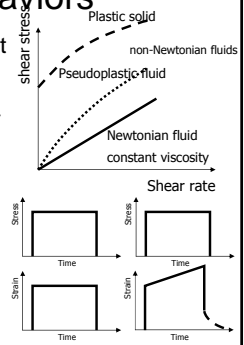
$$\tau = \frac{F}{A} = \eta \frac{dv}{dy} = \eta \dot{\gamma} \quad \text{or} \quad \tau = \eta \dot{\gamma}$$

 - where η = a constant of proportionality called the *coefficient of viscosity*, (Pa-s)

17

Viscous behaviors

- A thermoplastic polymer melt is non-Newtonian
 - A fluid exhibiting decreasing viscosity with increasing shear rate is called *pseudoplastic*
- Complicates analysis of polymer processes such as injection molding
- The material property that determines the strain subjected to combination of stress and temperature over time.

$$\sigma(t) = f(t)\epsilon$$



18

Viscoelastic Behavior of Polymers

- Viscoelastic - Combination of viscosity and elasticity
- *Die swell* - In extrusion of polymers, the profile of extruded material grows in size after being squeezed through the smaller die opening
 - It “remembers” (Shape memory)

Materials	Viscosity (Pa-s)	Materials	Viscosity (Pa-s)
Glass @540C	10^{12}	Polymer@151C	115
Glass @815C	10^5	Polymer@205C	55
Glass @1095C	10^3	Water@20C	0.001
Machine Oil	0.1	Water@100C	0.0003

19

4. Physical (Non-mechanical) Properties of Materials

- 4.1 Volumetric and Melting Properties
- 4.2 Thermal Properties
- 4.3 Mass Diffusion
- 4.4 Electric Properties
- 4.5 Electrochemical Processes

20

Physical Properties

- Non-mechanical properties that define the behavior of materials in response to any non-physical stimuli such as volumetric, thermal, electrical, and electrochemical properties
- Components in a product must do more than withstand mechanical stresses. For example, they must conduct electricity (or not), allow heat to transfer (or not), transmit light and satisfy many other functions.
- Physical properties often influence process performance as in machining & microelectronics.

21

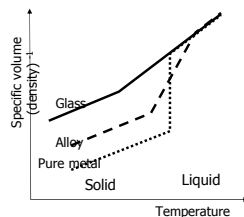
4.1 Volumetric Properties

- Density (ρ) – lb/in³ or g/cm³
 - Specific gravity (ρ/ρ_{water})
 - Specific volume ($1/\rho$)
 - Strength-to-weight ratio – T.S./density
- Thermal expansion
 - Length ratio - Coefficient of Thermal Expansion (CTE or α) - /°F or /°C.
 - As T increases, CTE can either increase or decrease
 - Phase transformation
 - used in *shrink fit* and *expansion fit* assemblies

22

4.1 Melting Characteristic

- Melting point is the temperature at the materials transforms from solid to liquid.
 - Freezing point - from liquid to solid
 - Heat of Fusion – An amount of Heat Energy to accomplish transformation.
- Supercooled – Below the freezing point the nucleation of crystals has not been initiated.
- Implication in casting



23

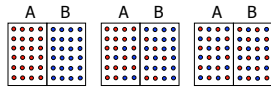
4.2 Thermal Properties

- Specific Heat, C
 - The quantity of Heat Energy required to increase the temperature of a unit mass of a material by 1 degree.
 - $H=CW(T_2-T_1)$ where H = amount of heat energy; C = specific heat of the material W = its weight
 - Volumetric heat storage capacity, ρC
 - Thermal conductivity, k
 - Thermal diffusivity, $K = \frac{k}{\rho C}$

24

4.3 Mass Diffusion

- Mass Diffusion
 - the movement of atoms within a material (liquid, gas and solid).

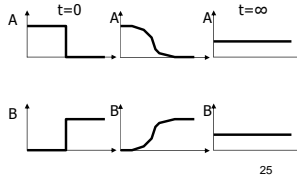


- Fick's First Law:

$$\frac{dm}{dt} = -D \frac{dc}{dx} A \quad \text{or} \quad J = -D \frac{dc}{dx}$$
 where $D = D_0 \exp\left(-\frac{Q}{RT}\right)$

- Fick's Second Law

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x} \left(D \frac{\partial c}{\partial x} \right) = -\frac{\partial J}{\partial x}$$



- Applications:
 - Surface Hardening
 - Diffusion
 - Welding

25

4.4 Electrical Properties

- Resistivity (in $\Omega\text{-m}$) and Conductivity ($1/r$):

$$r = R \frac{A}{L} \quad \text{Ohm's Law: } I = \frac{E}{R}$$

- Classes of Materials
 - Conductor
 - Insulator (dielectric)
 - Arc if a high enough voltage is applied
 - Superconductor
 - Semiconductor – a material whose resistivity is between conductor and insulator. (Si)
- Implication in Electric Discharge Machine(EDM)

26

4.5 Electrochemical Processes

- Electrochemistry – A field of science concerned with the relationship between electricity and chemical changes
- Electrolytic cell
 - Electrolyte
 - Electrodes – anode and cathode
- Electrolysis if any chemical change occurs
- Farady's Law
 - Volume removed, $V=CIt$, p. 660
- Implications in electroplating and electrochemical machining

27