Elastic and Plastic Properties

- Elastic deformation: non-permanent and reversible deformation
- Young's modulus: stiffness of a material
  - $\sigma = E\varepsilon$
  - $\sigma = \sigma_{eng} = \frac{F}{A_o}$
  - $\varepsilon = \varepsilon_{eng} = \frac{\Delta L}{L_o}$
  - Within the same class of materials, higher E means higher melting point
- Modulus of resilience: energy absorbed during elastic deformation - area under stress-strain curve
  - $\text{MOR} = \frac{\sigma_y^2}{2E}$
- Poisson's ratio: applicable for isotropic materials
  - $\nu = -\frac{\varepsilon_x}{\varepsilon_z} = -\frac{\varepsilon_y}{\varepsilon_z}$
- Bond length: r_o is the interatomic distance that minimizes potential energy

$$E \propto \left(\frac{dF}{dr}\right)_{r_o}$$

- Yield strength: σ_y
- Ultimate tensile strength: σ_{UTS}
- Fracture (tensile) strength: σ_f
- Ductility: amount of deformation before failure (% elongation or % area reduction)
- Toughness: energy absorbed before failure
- Hardness: resistance to localized plastic deformation

9. Crystal Strengthening

1. Grain size reduction - smaller grain size means more area at grain boundaries, which impede dislocation motion
   - Hall-Petch equation: $\sigma_y = \sigma_o + k_y d^{-1/2}$
2. Solid-Solution - substitutional and interstitial atoms cause stresses in lattice, which impede dislocation motion
3. Work hardening - plastic deformation (work hardening) strengthens metals by increasing dislocation density and dislocation-dislocation interaction, which impedes dislocation motion
   - $\sigma_T = K\varepsilon_T^n$
   - $\%CW = \frac{A_o - A_d}{A_o} \cdot 100$

10. Recrystallization and Grain Growth

- Homologous temperature: $T_H = \frac{T_{\text{deformation}}}{T_{\text{melting point}}}$ (in Kelvin)
  - Pure metals: $T_H < 0.4$ cold work, $T_H > 0.4$ hot work

- Alloys: $T_H < 0.6$ cold work, $T_H > 0.6$ hot work
- Rolling (work hardening) increases strength but decreases ductility. Grains are elongated
- Annealing: reverse effects of work hardening by releasing energy stored during work hardening, which drives recovery and recrystallization
    - Results in smaller grains

1. Recovery
    - Restoration of electrical and thermal properties. Dislocations reconfigure to have lower strain energy
2. Recrystallization
    - New strain-free equiaxed grains with low dislocation densities are formed
    - Recrystallization temperature: temperature at which recrystallization completes in one hour
    - Recrystallization temperature decreases with increased cold work
    - With more cold work, activation energy Q decreases so the rate of recrystallization at a given temperature increases
    - Recrystallization occurs more rapidly in pure metals than alloys because solute atoms reduce mobility of grain boundaries
3. Grain growth
    - Grains grow to reduce grain boundaries and energy within material
    - $d^n - d_0^n = Kt$

11. Fracture

Ductile versus brittle fracture

- fracture toughness K_c: material's resistance to brittle fracture under presence of crack. Describes stress situation around crack tip
- K_t: stress concentration factor

Griffith equation: calculates critical stress for crack propagation

12. Fatigue

Fatigue failure requires tensile stresses

- Shot-Peening: stores residual compressive stresses
- Case-Hardening: carbon or nitrogen rich surface created through atomic diffusion

S-N curve: relates fatigue strength and fatigue life (number of cycles until failure)

13. Ductile-Brittle Transition

- Drastic reduction in ductility as temperature is decreased
    - Ductile failure: due to dislocation movement
    - Brittle failure: due to cracks
- Higher strain rate increases the DBT temperature
- Higher carbon % of steel increases DBT temperature

Charpy impact test

- Simulates severe conditions. Difference in potential energy is the absorbed energy

14. Creep Failure

- Time dependent permanent deformation of materials subjected a constant load at elevated temperatures
- Occurs at above $0.4T_m$ for metals

1. Primary creep: due to work hardening
2. Secondary creep: constant creep rate due to balancing of work hardening and recovery. 90% of creep time
3. Tertiary creep: acceleration of creep until rupture

- Higher temperature and higher stress increase creep rate
- Creep resistant: high melting temperature, high elastic modulus, and large grain size
- Larson-Miller parameter: relates temperature and time to rupture

15. Corrosion

- Corrosion: chemical attack, resulting in oxidation (loss of electrons)
  - Driving force is reduction of energy
- Ingredients
  - Reduction in energy
  - Water or moisture to act as medium for ion conduction and ionic transport
  - Source of oxidant (normally O2, sometimes sulfur)
  - Mass transport of oxidant to the metal
- Stress corrosion: occurs at regions of high stress
- Galvanic corrosion:
  - More reactive metal (anode) is oxidized - it corrodes
  - Less reactive metal (cathode) is reduced - it is protected
  - Galvanic series: ranks reactivity of metals and alloys in seawater at $25^\circ\mathrm{C}$
  - EMF series: pure metals
- Corrosion protection
  - Protective oxide - impedes oxygen transfer to metal interior. For example, chromium forms an oxide layer
  - Physical barriers - uses less chemically active metal layer, which inhibits contact with water and oxygen. For example, nickel, tin, chromium
  - Sacrificial (cathodic) protection - uses more chemically active metal layer, which corrodes while main metal stays intact

16. Phase Diagrams

- Phase: homogeneous portion of system that has uniform physical and chemical characteristics
  - Equilibrium conditions

Binary Isomorphous Systems: two elements, liquid and solid regions each contain one phase

- Liquidus line: boundary between all liquid and liquid/solid two phase region

- Solidus line: boundary between all solid and liquid/solid two phase region
- Phase composition: use tie line intersection with liquidus and solidus to find composition of liquid and solid phases
- Lever rule: gives mass fraction of liquid and α-solid. Assumes infinite diffusion, so mass is distributed instantaneously
- Non-equilibrium cooling: cored structures, where center of solid particles have higher concentration

17. Phase Diagrams II

Binary Eutectic Systems: two elements, and there is a single chemical composition that solidifies at a lower temperature than any of its constituents

- Cooling at eutectic temperature: lamellae (alternating layers) of α and β form
- If cooling crosses eutectic isotherm, then lamellae will form, in addition to primary regions. There will be primary α, eutectic α, and β