

MATSCI 104 Review Sheet

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1 Mechanical Properties of Metals

1.1 Stress-Strain Behavior

- On an atomic scale, macroscopic elastic strain is manifested as small changes in the inter-atomic spacing and the stretching of inter-atomic bonds.
- Magnitude of the modulus of elasticity is a measure of the resistance to separation of adjacent atoms, inter-atomic bonding forces

1.2 Elastic Properties of Materials

- The maximum value of Poisson's ratio is 0.5
- Plastic Deformation: the breaking of bonds with original atom neighbors and then the re-forming of bonds with new neighbors as large numbers of atoms or molecules move relative to one another; deformation is accomplished by slip

1.3 Tensile Properties

- The magnitude of the yield strength for a metal is a measure of its resistance to plastic deformation.
- At TS, a small constriction or neck begins to form at some point and all subsequent deformation is confined at the neck (necking); fracture occurs at the neck.
- The magnitude of both yield and tensile strengths decline with increasing temperature
- Importance of ductility:
 - Indicates to a designer the degree to which a structure will deform plastically before fracture.
 - Specifies the degree of allowable deformation during fabrication operations
- Resilience: the capacity of a material to absorb energy when it is deformed elastically and the capacity, upon unloading, to have this energy recovered.
 - Modulus of resilience: strain energy per unit volume required to stress a material from an unloaded state up to the point of yielding.
 - Resilient materials are those having high yield strengths and low moduli of elasticity.
- Toughness: material's resistance to fracture when a crack is present.; the ability of a material to absorb energy and plastically deform before fracturing.
 - If the metal is tough, it must display both strength and ductility.

1.4 True Stress and Strain

- True stress and strain valid only to the onset of necking.
- The correct stresses within the neck is slightly lower than the stress computed from the applied load and neck cross-sectional area
- For compression, there is no maximum because necking does not occur.

1.5 Hardness

- Hardness is proportional to tensile strength
- Hardness tests are performed more frequently (simple, inexpensive, nondestructive, other mechanical properties often may be estimated from hardness data)

2 Dislocations and Strengthening Mechanisms

Macroscopic plastic deformation corresponds to permanent deformation from the movement of dislocations.

2.1 Characteristics of Dislocations

- Atoms may be thought of as experiencing a compressive strain relative to atoms positioned in the perfect crystal and far removed from the dislocation
- For a screw dislocations, lattice strains are pure shear only

2.2 Slip Systems

- The slip plane is the plane that has the densest atomic packing
- FCC & BCC are quite ductile because extensive plastic deformation is normally possible along the various system; HCP have few active slip systems, normally quite brittle.

2.3 Strengthening by Grain Size Reduction

- During the plastic deformation, slip or dislocation motion must take place across common boundary.
- Grain boundary acts as a barrier to dislocation motion for
 - A dislocation passing into another grain must change its direction of motion because the two grains are of different orientations.
 - The atomic disorder within a grain boundary region results in a discontinuity of slip planes from one grain into the other.
- A small grained material is harder and stronger because the smaller one has a greater total grain boundary area to impede dislocation motion
- Grain size reduction improves not only the strength, but also the toughness.
- Small-angle grain boundaries are not effective in interfering with the slip process because of the slight crystallographic misalignment across the boundary
- Twin boundaries effectively block slip and increase the strength of the material.

2.4 Solid-Solution Strengthening

- Alloying with impurity atoms that go into either substitutional or interstitial solid solution
- Alloys are stronger than pure metals because impurity atoms that go into solid solution typically impose lattice strains on the surrounding host atoms.
- Solute atoms tend to diffuse to and segregate around dislocations in such a way as to reduce the overall strain energy.
- The resistance to slip is greater when impurity atoms are present because the overall lattice strain must increase if a dislocation is torn away from them (for edge disl.)

2.5 Strain Hardening (Cold Work)

- A ductile metal becomes harder and stronger as it is plastically deformed.
- The dislocation density in a metal increases with deformation or cold work because of dislocation multiplication or the formation of new dislocations. (the average of distance of separation between dislocations decreases.) As the dislocation density increases, the resistance to dislocation motion by other dislocations becomes more pronounced

3 Failure

3.1 Fundamentals of Fracture

- Ductile metals typically exhibit substantial plastic deformation with high energy absorption before fracture; For brittle, little or no plastic deformation with low energy absorption
- Ductility is a function of temperature of the material, the strain rate, and the stress state.
- Fracture process – 1) Crack formation 2) Propagation
- Stable crack: it resists any further extension unless there is an increase in the applied stress
- Unstable crack: crack may spread rapidly, with very little accompanying plastic deformation and continues spontaneously without an increase in magnitude of the applied stress. (brittle)
- The reasons that ductile fracture is preferred:
 - Brittle fracture occurs suddenly and catastrophically without any warning.
 - More strain energy is required to induce ductile fracture since these materials are generally tougher.
- Fracture ensues around perimeter of the neck by shear deformation at an angle of about 45 with the tensile axis (the angle at which the shear stress is a maximum)

3.2 Brittle Fracture

- The direction of crack motion is nearly perpendicular to the direction of the applied tensile stress and yields a relatively flat fracture surface
- V-shaped, lines or ridges that radiate from the origin of the crack
- Cleavage: crack propagation corresponds to the successive and repeated breaking of atomic bonds along specific crystallographic planes. (Transgranular)
- Intergranular: crack propagation is along grain boundaries.

3.3 Principles of Fracture Mechanics

- The measured fracture strengths are significantly lower than those predicted by theoretical calculations based on atomic bonding energies because of the presence of microscopic flaws or cracks that always exist under normal conditions at the surface and within the interior of a body of material.
- The magnitude of this localized stress decreases with distance away from the crack tip.
- For ductile metal, plastic deformation ensues when the max stress exceeds the yield strength. This leads to a more uniform distribution of stress near the stress raiser and to the development of a maximum stress concentration factor less than the theoretical value.
- Fracture toughness: a measure of a material's resistance to brittle fracture when a crack is present.
- Y depends on both crack and specimen sizes and geometries
- K_{Ic} depends on specimen thickness. (If thickness is much greater than the crack, K_{Ic} is independent)
- K_{Ic} values are relatively large for ductile materials. (depends on temp, strain rate, microstructure)
- The magnitude of K_{Ic} decreases with increasing strain rate and decreasing temperature.
- An enhancement in yield strength wrought by solid solution or dispersion additions or by strain hardening generally produces a corresponding decrease in K_{Ic} .
- K_{Ic} normally increases with reduction in grain size as composition.

3.4 Fracture Toughness Testing

- The ductile-to-brittle transition is related to the temperature dependence of the measured impact energy absorption
- As the temperature is lowered, the impact energy drops suddenly over a relatively narrow temperature range, below which the energy has a constant but small value. (the mode of fracture is brittle)
- Ductile fracture surface: fibrous or dull; Brittle fracture surface: granular (shiny) texture
- Ship example: each fracture crack originated at some point of stress concentration (sharp corner or defect) and then propagated around the entire girth of the ship

- Low-strength FCC metals and most HCP metals do not experience a d-to-b transition
- For high-strength materials, the impact energy is also relatively insensitive to temperature; however, these materials are also very brittle, as reflected by their low impact energies. This behavior is typically found in low-strength steels that have the BCC crystal structure.
- For these steels, decreasing the average grain size results in a lowering of the transition temperature.
- Fatigue occurs after a lengthy period of repeated stress or strain cycling and is catastrophic and insidious, occurring very suddenly and without warning

3.5 S-N Curve

- The lower surface of the specimen is subjected to a tensile stress, whereas the upper surface experiences compression stress.
- S: stress, N: number of cycles to failure
- The higher the magnitude of the stress, the smaller the number of cycles the material is capable of sustaining before failure.
- For some ferrous (iron-based) and titanium alloys, fatigue failure does not occur below fatigue limit
- Most nonferrous alloys (aluminum, copper, brass) do not have a fatigue limit.
- The fatigue limit represents the largest value of fluctuating stress that will not cause for essentially an infinite number of cycles.
- Low-cycle fatigue: associated with relatively the high load that produce not only elastic strain but also some plastic strain during each cycle.
- High-cycle fatigue: for lower stress levels wherein deformations are totally elastic, longer lives result.

3.6 Crack Initiation and Propagation

- Crack associated with fatigue failure almost always initiate on the surface of a component at some point of stress concentration.
- Cyclic loading can produce microscopic surface discontinuities resulting from dislocation slip steps that may also act as stress raisers and therefore as crack initiation sites.
- There is very localized plastic deformation at crack tips, even though the maximum applied stress to which the object is exposed in each stress cycle lies below the yield strength of the metal
- The presence of beachmarks(macroscopic) or striations(microscopic) on a fracture surface confirms that the cause of failures was fatigue; the absence of either or both does not exclude fatigue failure.
- Beachmarks and striations do not appear on the region over which the rapid failure occurs.
- Evidence of plastic deformation will be present for ductile failure and absent for brittle failure.

3.7 Factors that Affect Fatigue Life

- Increasing the mean stress level leads to a decrease in fatigue life.
- Fatigue life is especially sensitive to the condition and configuration of the component surface.
- Any notch or geometrical discontinuity can act as a stress raiser and fatigue crack initiation site
- The sharper the discontinuity, the more severe the stress concentration.
- Improving the surface finish by polishing enhances fatigue life significantly. (surface marking limits F.L)
- Imposing residual compressive stresses within this outer surface layer to enhance the fatigue life. A surface tensile stress of external origin is partially nullified and reduced in magnitude by the residual compressive stress. (shot peening)
- Case hardening: both surface hardness and fatigue life are enhanced for steel alloys/ by a carburizing or nitriding process
- The improvement of fatigue properties results from increased hardness within the case.
- Creep: deformation under the condition at elevated temp. and exposed to static mechanical stresses/ time dependent and permanent deformation of materials/ $0.4T_m$

3.8 Generalized Creep Behavior

- Primary creep: decreasing creep rate - material is experiencing an increase in creep resistance or strain hardening
- Secondary creep: rate is constant – a balance between competing processes of strain gardening and recovery
- Recovery: the process by which a material becomes softer and retains its ability to experience deform.
- Tertiary creep: acceleration of the rate and ultimate failure (rupture)
- At rupture, microstructural changes (grain boundary separation, internal cracks formation) – decrease in the effective cross-sectional area and an increase in strain rate.

3.9 Stress and Temperature Effects

- Both temp., level of stress, T_m , grain size and E influence the creep characteristics
- At a temperature, substantially below $0.4T_m$ and after the initial deformation, the strain is virtually independent of time.
- If either increasing stress or temperature 1) The instantaneous strain at the time of stress application increases. 2) The steady-state creep rate increases 3) The rupture lifetime decreases.
- Stress-induced vacancy diffusion, grain boundary diffusion, dislocation motion and grain boundary sliding affect creep behavior

3.10 Alloys for High-Temperature Use

- The larger the grain size, the better a material's resistance to creep
- Smaller grains permit more grain boundary sliding, which results in higher creep rates. (contrast to influence of grain size on the mechanical behavior at low temp)
- Directional solidification: produces either highly elongated grains or single-crystal components.
- The creep resistance of the superalloys is enhanced by solid-solution alloying and also by the formation of precipitate phases.

4 Phase Diagram

4.1 Phases

- Across a boundary, there will be a discontinuous change in physical or chemical characteristics
- When a substance can exist in two or more polymorphic forms (FCC & BCC), each of these structures is a separate phase because their respective physical characteristics differ.

4.2 Microstructure

- The mechanical behaviors of a material often depend on the microstructure
- Microstructure is characterized by the number of phases present, their proportions, and the way they are distributed or arranged.
- Microstructure depends on such variables as the alloying elements present, their concentrations, and the heat treatment of the alloy.

4.3 Phase Equilibria

- Free energy: a function of the internal energy of a system and the randomness or disorder of the atoms or molecules
- A system is at equilibrium if its free energy is at a minimum.
- The characteristics of system do not change with time (stable)
- Phase equilibrium is reflected by a constancy with time in the phase characteristics of a system
- Metastable: a state of equilibrium is never completely achieved because the rate of approach to equilibrium is extremely low.

4.4 Binary System

- For a binary isomorphous system, the solid-to-liquid transformation takes place at T_m , and no further heating is possible until this transformation has been completed
- For a binary eutectic system, the eutectic reaction is similar to solidification for pure components in that the reaction proceeds to completion at a constant temperature. Low T_m alloys are prepared having near-eutectic compositions; makes material especially attractive as a low temperature solder because it is easily melted.

4.5 Development of Microstructure in Isomorphous Alloys

- Because diffusion is a time-dependent phenomenon, to maintain equilibrium during cooling, sufficient time must be allowed at each temperature for the appropriate compositional readjustments.
- Nonequilibrium; the slower the cooling rate, the smaller this displacement; if the diffusion rate in the solid phase increases, this displacement decreases.
- Coring may be eliminated by a homogenization heat treatment

4.6 Mechanical Properties of Isomorphous Alloys

- All temp and compositions below T_m , only a single solid phase exists. Therefore, each component experiences solid-solution strengthening or an increase in strength and hardness by additions of the other component.
- Ductility (%EL) decreases with additions of the second component; Tensile strength is opposite.

4.7 Development of Microstructure in Eutectic Alloys

- The eutectic structure forms in specific layers because, for lamellar configuration, atomic diffusion of lead and tin need only occur over relatively short distances.

- Macroconstituent: an element of the microstructure having an identifiable and characteristic structure
- Consequences upon crossing the eutectic isotherm:
 - Grains of the primary macroconstituent will be cored, that is, have a nonuniform distribution of solute across the grains.
 - The fraction of the eutectic macroconstituent formed will be greater than for the equilibrium situation.

4.8 The Iron-Iron Carbide (Fe-Fe₃C) Phase Diagram

- Cementite (Fe₃C); Carbon is an interstitial impurity in iron and forms a solid solution
- In BCC α -ferrite, the limited solubility is explained by the shape and size of the BCC interstitial positions, which make it difficult to accommodate the carbon atoms.
- The γ phase of iron, when alloyed with carbon alone, is not stable below 727°C; The solubility is greater than BCC ferrite because the FCC octahedral sites are larger than BCC tetrahedral sites -; the strains imposed on the surrounding iron atoms are much lower.
- Cementite is very hard, brittle and only metastable.

4.9 Development of Microstructure in Iron-Carbon Alloys

- The pearlite exists as grains, often termed colonies; within each colony the layers are oriented in essentially the same direction, which varies from one colony to another.
- The layered pearlite forms because carbon atoms need diffuse only minimal distances with the formation of this structure.
- The cementite phase begins to form along the initial γ grain boundaries, similar to α phase.
- Non-equilibrium affects the occurrence of phase changes or transformations at temperatures other than those predicted by phase boundary lines on the phase diagram. Non-equilibrium phases at room temperature do not appear on the phase diagram

5 Precipitation Hardening

- Precipitation hardening: the strength and hardness of some metal alloys may be enhanced by the formation of extremely small, uniformly dispersed particles of a second phase within the original phase matrix by appropriate heat treatments.
- Two requisite features for precipitation hardening: Maximum solubility of one component in the other, on the order of several percent; and a solubility limit that rapidly decreases in concentration of the major component with temperature reduction.
- The composition of a precipitation-hardenable alloy must be less than the max solubility.
- Solution heat treatment: all solute atoms are dissolved to form a single phase solid solution
- Any diffusion and the accompanying formation of any of the β phase are prevented by quenching
- Precipitation heat treatment; The character of these β particles, and subsequently the strength and hardness of the alloy, depend on both the precipitation temperature T_2 and the aging time at this temp.
- With increasing aging time, the strength or hardness increases, reaches a maximum, and finally diminishes.
- The strengthening and hardening effects result from the innumerable particles of these transition and metastable phases.
- Strengthening process is accelerated as the temperature is increased.
- Associated with an increase in strength is a reduction in ductility.
- During plastic deformation, dislocation motions are effectively impeded as a result of distortions, and, consequently, the alloy becomes harder and stronger.
- In the final treatment, little strength loss is sustained as a result of recrystallization.
- If the alloy is precipitation hardened before cold working, more energy must be expended in its deform.
- Cracking may result because of the reduction in ductility that accompanies the precipitation hardening.

6 Crystal Structures

6.1 Crystal Structures

- The magnitude of the electrical charge on each of the component ion and the relative sizes of the cations and anions influence the crystal structure.
- The crystal must be electrically neutral; the ratio of cation and anion is less than unity.
- Stable ceramic crystal structures form when those anions surrounding a cation are all in contact with that cation
- Ionic radius tends to increase as the number of nearest-neighbor ions of opposite charge increases.
- When an electron is removed from an atom or ion, the remaining valence electrons become more tightly bound to the nucleus, which results in a decrease in ionic radius.
- The close-packed planes are composed of the large anions.
- Ceramic crystal structures of this type depend on two factors: the stacking of the close-packed anion layers; the manner in which the interstitial sites are filled with cations.

6.2 Silicate Ceramics

- Often the silicates are not considered to be ionic because there is a significant covalent character to the interatomic Si-O bonds.
- Low density: the bonding is covalent, which is directional, also atoms have specific angle to form tetrahedron, so the atoms are not closely packed together.
- Silica Glasses: the addition of these modifiers and intermediates lowers the T_m and viscosity of a glass and makes it easier to form at lower temperatures.
- Electroneutrality is ordinarily established by a second planar sheet structure having an excess of cations, which bond to these unbonded oxygen atoms from the Si_2O_5 sheet.

6.3 Imperfections in Ceramics

- It is highly improbable that there would be appreciable concentrations of anion interstitials; the anion is relatively large, and to fit into a small interstitial position, substantial strains on the surrounding ions must be introduced.
- Defects in ceramics do not occur alone.
- Frenkel defect: a cation-vacancy and a cation-interstitial pair.
- Schottky defect: a cation vacancy- anion vacancy
- Q_{fr} is the energy required for the formation of each Frenkel defect.
- Q_s represents the Schottky defect energy of formation
- To achieve any appreciable solid solubility of substituting impurity atoms, the ionic size and charge must be very nearly the same as those of one of the host ions.
- For an impurity ion having a charge different from that of the host ion for which it substitutes, the crystal must compensate for this difference in charge so that electroneutrality is maintained with the solid. One way this is accomplished is by the formation of lattice defects (vacancy or interstitials)