COMPOSITES

- **Principle of combined action-** better combination of properties achieved from combination of 2 or more distinct materials
- New composites- high tech materials, engineered to specific apps
- Old composites- brick/straw composites, paper, known > 5000 yrs
- **Pearlitic steel-** combines hard and brittle cementite with soft, ductile ferrite to get superior material
- Natural composites: wood (polymer-polymer), bones (polymer-ceramic)
- Composites have 2 phases:
    - matrix (continuous)
    - dispersed phase (particulates, fibers)
- Properties depend on:
    - properties of phases
    - geometry of dispersed phase
    - amount of dispersed phase
- Classification of composites:
    - particle reinforced (large particle, dispersion strengthened)
    - Fiber reinforced (continuous (aligned), short fibers (aligned, random)
    - Structural (laminates, sandwich panels)

Particle-reinforced composites

- cheapest, most widely used
- **large particle reinforced-** act by restraining movement of matrix, if matrix is well bonded
- **Dispersion-strengthened composites-** contain 10- 100 nm particles
    - similar to what was discussed under precipitation hardening
    - matrix bears most of load and particles prevent dislocation motion, limiting plastic deformation

Large particle composites

- Properties are combination of components
- **rule of mixtures-** predicts that upper limit of elastic modulus of composite given in terms of elastic modulus of composite in terms of elastic moduli of matrix and particulate phases

Concrete

- Most common large-particle composite is concrete, made of cement matrix that bonds particles of different size (gravel and sand)
- Cement already known to Egyptians and Greek
- Cement is fine mixture of lime, alumina, silica, water
- **Portland Cement-** fine powder, chalk, clay, lime-bearing minerals
- Properties depend on how well mixed and amount of water
    - too little – incomplete bonding
    - too much – porosity
- Cement can be poured in place
    - hardened at room temp even underwater
    - cheap

- Weak and brittle
- water in pores produce cracks when freezes in cold weather

- Concrete = cement strengthened by adding particulates
  - use of different size (stone, sand) allows better packing factor than when using particles of similar size
  - improved by making pores smaller (using finer powder, adding polymeric lubricants, applying pressure during hardening)
- Reinforced Concrete- adding steel rods, wires, mesh
  - Steel has similar thermal expansion coefficient, so reduced danger of cracking due to thermal stresses
  - Pre-stressed concrete obtained by applying tensile stress to steel rods while cement is setting and hardening
    - When TS removed, concrete left under compressive stress, enabling it to sustain tensile loads w/out fracturing
    - Commonly used for railroads, highway bridges

Cermets

- **Cermets-** composites of ceramic particles (strong, brittle) in metal matrix (soft, ductile) that enhances toughness
  - used for cutting hardened steels

Reinforced rubber

- Strengthening rubber with 20-50 nm carbon black particles
  - used in auto tires

Dispersion Strengthened composites

- **Dispersion strengthened composites**- use of hard, small particles to strengthen metals and metal alloys
  - like precipitation hardening but not as strong
  - particles like oxides don't react so strengthening action retained at high temps
- **Precipitation hardening:** changing solid solubility with temp to form fine particles that impede dislocation motion
- **Solid solution hardening –** formation of single phase particles by quenching

Fiber-reinforced composites

- Strength depends on fiber length and orientation with respect to stress direction
- Efficiency of load transfer between matrix and fiber depends on interfacial bond

Influence of Fiber length

- Normally, matrix has much lower modulus than fiber so it strains more
  - Occurs at distance from fiber
  - right next for fiber, strain is limited by fiber
  - For composite under tension, shear stress appears in matrix that pulls from fiber
  - pull is uniform over area of fiber
    - makes force on fiber to be minimum at ends and max in middle

- To achieve effective strengthening and stiffening, fibers must be larger than **critical length**- minimum length at which the center of the fiber reaches ultimate TS when matrix achieves maximum shear strength
- Since is proportional to diameter of fiber d, more unified condition for effective strengthening

Influence of Fiber orientation

- Composite stronger along direction of orientation of fibers and weakest perpendicular to fiber
- For discontinuous, random fibers, properties are isotropic

Polymer Matrix Composites

- Largest, most diverse use of composites due to ease of fabrication, low cost, good properties
- Glass fiber reinforced composites- strong, corrosion resistant, lightweight
    - not stiff, can't be used @ high temps
- Carbon fiber reinforced- use carbon fibers, which have highest specific modulus (module / weight)
    - strong, inert, allow high temp use
- Kevlar, aramid fiber composite used as textile fibers

Laminar Composites

- Sheets (panels) with different orientation of high strength directions stacked and glued together, producing material with more isotropic strength in plane
    - Ex: plywood, modern skis

Sandwich Panels

- Strong, stiff end sheets bonded to lightweight core structure
    - ex: honeycomb
    - provides strength to shear
    - separates faces

Fiber Reinforced Composites

- Most important composites are those in which dispersed phase are fibers
- Design goals of fiber reinforced composites include high strength and/or stiffness on a weight basis
    - **Specific strength-** ratio of TS to specific gravity
    - **Specific modulus**- ratio of E to specific grav
- Fiber reinforced composites with exceptionally high specific strengths and moduli have been produced that utilize low density fiber and matrix materials

Influence of Fiber Length

- Characteristics depend on degree to which applied load is transmitted to fibers by matrix phase
    - Extent, or limit of load transmittance is the magnitude of interfacial bond between fiber and matrix phases
- Under applied load, fiber matrix bond ceases @ fiber ends, so no load transmittance from the matrix at each fiber extremity

- Critical fiber length necessary for effective strengthening and stiffening diameter and ultimate TS, and on fiber matrix bond strength
- **Continuous fibers-** longer than critical length
- **Discontinuous (short) fibers-** shorter than critical length
- Essentially the particulate composites as described above
- To affect a significant improvement in strength of composites, fibers must be continuous

Influence of Fiber Orientation and Concentration

- Arrangement, concentration, and distribution all have significant influence on strength and other properties of fiber reinforced composites
- With respect to orientation, 2 possible extremes:
    - parallel alignment of longitudinal axis of fibers in single direction
    - totally random
- Continuous fibers are normally aligned
- Discontinuous fibers randomly oriented or partly oriented
- better composite props are realized when fiber distribution is uniform

Continuous, Aligned Fiber Composites: Tensile Stress Strain behavior

- Mechanical responses of this type of composite depend on several factors to include stress strain behaviors of fiber and matrix phases, phase volume fractions, and direction in which stress or load is applied
- Properties of a composite having its fibers aligned are anisotropic, dependent on direction in which they are measured
- Continuous fiber reinforced will exhibit uniaxial stress strain response
- In Stage I, both fibers and matrix deform elastically- normally this portion of the curve is linear
- Stage II: Matrix yields and deforms plastically
    - ordinarily nearly linear, but then has diminished slope relative to stage I
- From stage I to II, proportion of applied load onto fibers increases
- Onset of composite failure begins as fibers start to fracture, which corresponds to strain
- Composite failure isn't catastrophic because:
    - not all fibers will fracture at same time, since will always be considerable variations in fracture strength of brittle fiber materials
    - Even after fiber failure, matrix is intact in as much as matrix fracture strain > fiber fracture strain

Elastic Behavior- Longitudinal Loading

- Consider elastic behavior of continuous, oriented fibrous composite loaded n direction of fiber alignment direction
    - assumed that fiber matrix interfacial bond is very good, such that deformation of both matrix and fibers is same (isostrain situation)

Longitudinal Tensile Strength

- Max strength on stress strain curve
- corresponds to fiber fracture
- marks onset of failure

- Failure of this material is complex process, several different failure modes possible
- Mode that operates for specific composite depends on fiber and matrix properties, nature/strength of fiber matrix interfacial bond

Transverse TS

- Strengths of continuous, unidirectional fibrous composites are highly anisotropic, and such composites are normally designed to be loaded along high strength, longitudinal direction
- Premature failure may result inasmuch as transverse strength is usually extremely low
- Sometimes lies below the TS of the matrix
- Variety of factors will have a significant influence on the transverse strength

Discontinuous and Aligned Fiber Composites

- Reinforcement efficiency is lower for discontinuous than for continuous fibers
    - nonetheless, discontinuous composites are becoming more important in commercial market
    - Chopped glass fibers used most extensively
    - Carbon, aramid discontinuous fibers
- Short fiber moduli- strengths approach 90% of continuous reinforced
- Short fiber TS- strengths approach 50% of continuous reinforced

Discontinuous and Randomly Oriented Fiber Composites

- When fiber orientation is random, short and discontinuous fibers are used
- Under these circumstances, rule of mixtures expression for elastic modulus is slightly different than normal one
    - K = fiber efficiency parameter, which depends on Vf and Ef/Em ratio

Summary

- Longitudinal strength = ☺
- Transverse, Perpendicular strength = ☹
- Oblique stress application = meh
- When multidirectional stresses imposed within a single plane, aligned layers that are fastened on top of each other are often utilized
    - use **laminar composites**
- Consideration of orientation and fiber length for particular composite will depend on level, nature of applied stress as well as fabrication cost

Fiber Phase

- Small diameter fiber is much stronger than bulk material
- Probability of presence of critical surface flaw that can lead to fracture diminishes with increasing specimen volume
- On basis of diameter and character, fibers are grouped into 3 different classifications:
    - **Whiskers**- very thin single crystals that have extremely large length to diameter ratios

        - as consequence of small size, have high degree of crystalline perfection and are virtually flaw free, which accounts for exceptionally high strengths
        - Strongest known materials
        - Whiskers not utilized extensively as reinforcement medium because are extremely expensive
        - Difficult and often impractical to incorporate whiskers into a matrix
        - Include graphite, silicon carbide, silicon nitride, aluminum oxide
    - **Fibers**- either polycrystalline or amorphous, have small diameters
        - Fibrous materials generally either polymers or ceramics
    - **Wires-** have relatively large diameters
        - Typical materials include steel, molybdenum, tungsten
        - utilized as radial steel reinforcement in car tires, filament wound rocket castings, wire wound high pressure hoses

Matrix Phase

- **Matrix phase-** metal, polymer or ceramic
- Metals and polymers used as matrix materials because some ductility is desirable
- For ceramic matrix composites, reinforcing component added to improve fracture toughness
- For fiber reinforced composites, matrix phase has many functions:
    - binds fibers together
    - acts as as medium by which externally applied stress is transmitted and distributed to fibers
        - Only a very small proportion of applied load is by matrix phase
        - Is ductile
        - elastic modulus of fiber should be higher than of matrix
    - Protects individual fibers from surface damage as result of mechanical abrasion or chemical reactions with environment
        - May introduce surface flaws capable of forming cracks, which may lead to failure at low TS
    - Separates fibers and by virtue of relative softness and plasticity prevents propagation of brittle cracks from fiber to fiber, which could result in catastrophic failure
        - serves as barrier to crack propagation
        - When fibers have failed, form cluster of critical size

Polymer-Matrix Composites (PMCs)

- Used in greatest diversity of composite applications, as well as in largest quantities

Glass Fiber Reinforced Polymer

- Fiberglass is composite consisting of glass fibers, either continuous or discontinuous, contained within a polymer matrix
- Produced in largest quantities

- Composition of the glass is most commonly drawn into fibers
- fiber diameters range between 3 and 20 micrometers
- Perks!
    - Easily drawn to high strength fibers from molten state
    - Readily available and may be fabricated into glass reinforced plastic
    - As fiber, it's relatively strong, and when embedded in a plastic matrix, produces a composite having a very high specific strength
    - When coupled with various plastics, possess CHEMICAL INERTNESS that renders composite useful in variety of corrosive environments
- Surface characteristics of glass fibers extremely important because even minute surface flaws can negatively affect it
    - like rubbing glass with glass
- Limited to certain temps
    - at high temps, polymers flow

Carbon Fiber reinforced Composites (CFRP)

- High performance fiber material that most commonly used in reinforcement in advanced polymer matrix composites
- Perks!
    - CF has highest specific modulus and specific strength of all reinforcing fiber materials
    - Retain high TS and high strength @ elevated temps
        - high temp oxidation may be a problem
    - @ room temp, CF not affected by moisture, solvents, acids, bases
    - Exhibit diversity of physical, mechanical characteristics, allowing composites incorporating these fibers to have specific engineered properties
    - Fiber, composite manufacturing processes developed that are relatively inexpensive, cost effective
- Carbon fiber have graphitic and crystalline structure
- CF made of rayon, polyacrylonitrile (PAN), and pitch

Aramid Fiber Reinforced Polymer Composites

- Aramid fibers- high strength, high modulus materials
- Introduced in 1970s
- Desirable for outstanding strength to weight ratios- superior to metals
- Trade names: Kevlar, Nomex
- During synthesis, rigid molecules aligned in direction of fiber axis as liquid crystal domains
- Fibers have longitudinal TS and tensile moduli higher than other polymeric fiber materials
- Relatively weak in compression
- Tough, impact resistant, creep resistant, fatigue failure
- Aramids are thermoplasts
    - resistant to combustion
    - stable to relatively high temps

    - Temp range over which they retain their high mechanical properties between -200° C and 200° C
- Susceptible degradation by strong acids and bases
    - relatively inert in other solvents and chemicals
- Aramid fibers most often used in composites having polymer matrices
    - common matrix materials are EPOXIES and POLYESTERS
    - May be processed by most common textile operations
    - Typical applications of these aramid composites are in ballistic products (bullet proof vests), sporting goods, ropes, missile cases, pressure vessels, replacement for asbestos

Other Fiber Reinforcement materials

- Boron- used in military aircraft components, helicopter rotor blades, some sporting goods
- Silicon Carbide- tennis rackets circuit boards, rocket nose cones
- alumina- tennis rackets, circuit boards, rocket nose cones

Polymer matrix Materials

- Matrix determines max service temp, since normally soften, melts, degrades at much lower temp than fiber reinforcement
- Most widely utilized and least expensive polymer resins are polyester and vinyl esters
- these matrix materials used primarily for glass fiber reinforced composites
- large # of resin formulations provide wide range of properties for these polymers
- Epoxies are more expensive and, in addition to commercial apps, are also utilized extensively in PMCs for aerospace apps
- have better mechanical props and resistance to moisture than polymers

Metal Matrix Composites

- Matrix is ductile metal
- Utilized @ higher temps than basal metal counter parts
- Some are higly reactive at elevated temps
    - Complete degradation
- MANUFACTURING
    - Consolidation or synthesis (introduction of reinforcement to matrix) followed by shaping operation
- Automobile manufacturers recently sued MMCs in their products
- Aerospace- advanced aluminum alloy metal matrix composites
- Turbine engines

Ceramic-Matrix Composites

- inherently resilient to oxidation and deterioration at elevated temps were it not for their disposition to brittle fracture
- Fracture toughness of ceramics is low
    - highly improved with addition of metal
- transformation toughening
- Implement ceramic whiskers- inhibit crack propagation by:
    - deflecting crack tips

    - Forming bridges across crack faces
    - Absorbing energy during pull out as whiskers debond from matrix
    - Causing redistribution of stresses in regions adjacent to crack tips

Carbon-Carbon Composites

- New, expensive
- High tensile moduli
- High TS
- High temp influence ability
- Resistance to creep
- large fracture toughness values
- Have low coefficients of thermal expansion
- high thermal conductivities
- low susceptibility to thermal shock
- C-C composites employed in rocket motors, a fraction materials in aircraft and high performance automobiles, for hot pressing molds, turbine engines, ablative shields for re-entry vehicles

Processing of Fiber-Reinforced Composites

- Fibers should be uniformly distributed within the plastic matrix
  - all oriented in same direction

Pultrusion

- Used for manufacture of components having continuous lengths and a constant cross sectional shape (i.e. rods, tubes, beams, etc
- With this technique, continuous fiber **rovings, tows** (loose untwisted bundle of continuous fibers that are draw together as parallel strands) are impregnated with thermosetting resin
  - then pulled through a steel die that preforms to the desired shape and establishes the resin/fiber ratio
  - Stock then passes through a curing die and determines production speed
  - Tubes, hollow sections made possible by using center mandrels or inserted hollow cores
  - Principal reinforcements are glass, C, aramid fibers normally added in concentrations between 40 and 70 vol%
  - Common matrices = polyesters, vinyl esters, epoxy resins
- Continuous process that's easily automated
- Production rates are relatively high, making it very cost effective
- wide variety of shapes are possibly
- no practical limit to length of stock that may be manufactured

Prepreg Production Process

- **Prepeg-** composite industry's term for continuous fiber reinforcement preimpregnated with a polymer resin that's only partially cured (crosslinked)
- Makes tape
- Material is delivered in tape form to the manufacturer, who then directly molds, fully cures the product without having to add any resin
- Composite material form most widely used for structural applications
- Thermoset polymers
- Steps:
  - collimating a series of spool bound continuous fiber tows
    - tows sandwiched, pressed between sheets of release and carrier paper using heated rollers- **calendering**
    - Release paper sheet coated with a thin film of heated resin solution of low viscosity to provide for its thorough impregnation of fibers
    - **Doctor blade-** spreads out resin into film of uniform thickness and width
    - Final prepreg product- thin tape consisting of continuous and aligned fibers embedded in partially cured resin
      - prepared for packaging by winding onto a cardboard core
- At room temp, thermoset matrix undergoes curing reactions

    - prepreg stored at 0° C or lower
- Both thermoplastic and thermosetting resins are utilized: carbon, glass, aramid fibers are most common reinforcements
- actual fabrication begins with the lay up- laying of prepreg tape onto a tooled surface
- Final curing accomplished by simultaneous application of heat and pressure
- Lay up carried out entirely by hand, where in operator both cuts the lengths of tape and then positions them in the desired orientation on the tooled surface
- Cost reduced if use automated lay up

Filament winding

- Process by which continuous reinforcing fibers accurately positioned in a predetermined pattern to form a hollow (usually cylindrical) shape
    - fiber are 1st fed through a resin bath and then wound onto a mandrel, usually using automated winding equipment
- Once the proper thickness has been achieved, curing occurs in an oven or at room temp, and then mandrel is removed
- Various winding patterns are possible
    - ex: circumferential, helical, polar
- Filament wound parts have very high strength to weight ratios
- High degree of control over winding uniformity and orientation is afforded with this technique
- Most economically attractive

CERAMICS APPLICATIONS

Glasses and Glass Ceramics

- Glasses are primarily oxides, silicates
- optical transparency, ease of fabrication
- **Devitrification-** transforming amorphous ceramics to crystalline ceramics
    - Result: **glass ceramic**
    - Nucleating agent added to induce crystallization/devitrification process
- Glass ceramic properties:
    - Low coefficient of thermal expansion
    - Doesn't experience thermal shock
    - high mechanical strengths and thermal conductivities achieved
    - Some made optically transparent, some opaque
    - pore free
    - very easily manipulated
    - strength
- Glass ceramic apps:
    - ovenware/tableware
    - electrical insulators
    - substrates for printed circuit boards
    - architectural cladding
    - heat exchangers, regenerators

Clay Products

- 2 Classifications: Structural clay products, whitewares
- **Structural clay products**
    - Including building bricks, tiles, sewer pipes
    - apps where structural integrity is important
- **Whiteware ceramics**
    - Become white after high temp firing
    - Includes porcelain, china, tableware, pottery, plumbing fixures (sanity ware)
    - Many include nonplastic ingredients, which influence the changes that take place during the drying and firing processes and characteristics of finished piece

Refractories

- **Refractory ceramics-** capacity to withstand high temps without melting or decomposing
    - remain unreactive, inert when exposed to sever environments
    - provide THERMAL INSULATION
    - bricks are most common examples
- Applications:
    - furnace linings for metal refining
    - Glass manufacturing

    - metallurgical heat treatment
    - power generation
- Performance depends on composition
    - Large particles = **grog**
    - small particles= fine
        - involved information of a bonding phase upon firing
        - This is responsibly for increasing strength of brick
        - predominantly glassy or crystalline
- Service temp normally below that at which refractory piece was fired
- Porosity= microstructural variable controlled to produce a suitable refractory brick
    - strength, load-bearing capacity, resistance to attack by corrosive materials increase with porosity reduction
    - However, thermal shock, thermal insulation, conductivity diminished

Fireclay refractories

- high purity fireclays with alumina and silica mixture are primary ingredients for fireclay refractories
- Upgrading alumina content will increase max service temp, allowing for formation of small amount of liquid
- Fireclay ricks used principally in furnace construction, to confine hot atmospheres and to thermally insulate structural members from excessive temps
- For fireclay brick, strength no ordinarily important consideration because support of structural loads not usually required
- OVEN BRICK PIZZAS!

Silica Refractories

- "Acid refractories"
- Presence of small concentrations of alumina has adverse influence on performance of refractories
- high temp, load bearing capacity
- used in arched roofs of steel and glass making furnaces
- small portions of brick exist as liquid
- Resistant to slags rich in silica

Basic Refractories

- rich in periclase, magnesia (MgO)
- contain Ca, Cr
- Steel making open hearth furnaces

Abrasive Ceramics

- **Abrasive ceramics-** wear, grind, cut away other material which is softer
- Properties:
    - hardness, wear resistance
    - High degree of toughness to ensue that abrasive particles don't easily fracture
    - refractories → friction results in high temp

- Ceramic abrasives:
    - Tungsten Carbide (WC)
    - Diamond
    - Aluminum oxide (alumina)
    - silica sand
- Applications
    - bonded to grinding wheels
        - coated abrasives
        - loose grains
    - bonded to wheel by means of glassy ceramic, organic resin
    - surface should contain porosity
        - continual flow of air currents, liquid coolants within the pores that surround the refractory grains prevents excessive heating
    - coated abrasives those in which abrasive powder coated on some type of paper or clothed material

Cements

- **cements-** inorganic, plaster of paris and lime which are produced in extremely large quantities
- when mixed with water, form a paste that sets and hardens
- Solid and rigid structures with any shape formed
- act as bonding phase that chemically binds particulate aggregates into single cohesive structure
- similar to glassy bonding phase in clay products, refractory bricks
- **Portland cement** is most common
    - **Calcination-** grinding, mixing clay and lime bearing minerals in proper proportions, heating mixture to 1400° C in a kiln
        - Process by which portland cement is produced
        - produces chemical and physical changes in raw materials
        - product ground into very fine powder to which is added small amount of gypsum
    - "hydraulic cement" because hardens when reacts with water

Piezoelectric ceramics

- **Piezoelectricity-** electrical polarity induced upon mechanical strain
- used as transduces between electrical and mechanical energies
- used in sonar!
    - Electrical signal causes piezoelectric material to oscillate and transforms it into mechanical energy
    - A second piezoelectric material receives the mechanical energy that bounces off of nearby object, which is then reverted back to electrical energy

Microelectromechanical (MEMS) systems

- **MEMS-** mini "smart" systems consisting of multitude of mechanical devices integrated with large numbers of electrical elements on substrate of Si
- Mechanical components are microsensors and microactuators

    - microsensors collect environmental info by measuring mechanical, thermal, chemical, optical, magnetic phenomena
    - like little gears that transfer info and energy
- Applications:
    - accelerometer in air bag systems
    - electronic displays
    - data storage units
    - energy conversion devices
    - chem detectors
    - DNA amplification
- Will probably take over integrated circuits

Optical fibers

- **Optical fiber-** made of extremely high purity silica
- Free of even minute levels of contaminants, defects that absorb, scatter, attenuate a light beam
- Used in COMMUNICATIONS

Ceramic Ball Bearings

- Races of bearings still often made of steel because of higher TS than ceramic ball bearings
- **hybrid bearings-** steel races, ceramic (Si Nitride) balls
- Properties:
    - higher reduction of noise and vibrations when in use
    - can operate at much high speed
    - higher hardness
    - less heat generated
    - coefficient of friction is MUCH lower than of steel (30% of steel)
    - lower lubrication levels required than for all steel bearings
- Manufacturing challenges:
    - difficult to yield pore free material
    - hard to make smoother surface finish that steels

CERAMICS FABRICATION AND PROCESSING

Fabrication and Processing of Glass

- Upon cooling, glass becomes more and more viscous in continuous manner with decreasing temp
    - no definite temp at which liquid transforms to solid was with crystalline materials
- Past melting pt, no definite volume (turns into liquid)
- **Glass transition temp (fictive temp)**- below this temp the material is considered a glass
    - above this temp its considered a liquid
    - slight decrease in slope
- Viscosity temp diagram:
    1. **melting pt-** glass is fluid enough to be considered liquid
    2. **working pt**- glass easily deformed at this viscosity
    3. **Softening pt**- max temp at which glass piece can be handed without causing significant dimensional alterations
    4. **Annealing pt-** atomic diffusion sufficiently rapid that any residual stress removed within 15 mins
    5. **Strain pt-** temps below strain pt, fracture occurs before onset of plastic deformation
        a. has plastic deformation
- Most glass forming operations carried out within working (/softening) range

Glass forming

- Glass is produced by heating raw materials to elevated temp above which melting occurs
- Most glasses are silica-soda-lime
    - Silica is usually quartz sand
    - Calcium and sodium oxide added as soda ash and limestone
- ESSENTIAL that glass is pore free for most applications
    - needs to be homogeneous
    - Homogeneity reached by complete melting and mixing of constituents
    - Porosity results from small gas bubbles produced
- Processing: (4 methods)
    - Pressing- used in fabrication of thick walled pieces, such as plates and dishes
        - glass piece formed by pressure application in a graphite coated cast iron mold having desired shape
            - mold heated to ensure even surface
    - Blowing- automated for glass jars, bottles, etc

        - from **parison** (raw glob of glass, temporary shape) formed by mechanical pressing in a mold
            - inserted into a blow mold, forced to conform the mold contours by pressure created from blast of air
    - Drawing-used to form long glass pieces like sheets, rods, tubing, fibers, which have CONSTANT CROSS SECTION
        - sheet glass also fabricated by hot rolling
        - flatness and surface finish improved significantly by floating sheet on bath of molten tin at elevated temp
            - piece slowly cooled, heat treated by annealing
        - continuous glass fibers formed in drawing operations
    - Fiber forming

Heat Treating Glasses

- Annealing
    - When ceramic material cooled from elevated temp, internal stress (**thermal stresses**) introduced as result of difference in cooling rate and thermal contraction between surface and interior regions
    - Thermal stresses important in brittle ceramics, especially glasses, since weaken material or, in extreme cases, lead to fracture, termed **thermal shock**
    - To avoid thermal stresses, cool material at slow rate
    - Once stresses introduced, elimination/ reduction of thermal stresses in their magnitude is possibly by annealing heat treatment in which glassware is heated to annealing point then slowly cooled to room temp
- Glass Tempering
    - Strength of glass piece enhanced by inducing compressive residual surface stresses
    - **Thermal tempering**- glass heated to temp above glass transition region yet below softening point (is a liquid)
        - Then cooled to room temp in jet of air or oil bath
        - Residual stresses arise from differences in cooling rates for surface and interior regions
        - Initially, surface cools more rapidly and, once dropped to temp below strain pt, becomes rigid
            - at same time interior cools slower
            - is at higher temp, above strain pt
            - is till PLASTIC
        - With continued cooling, interior attempts to contract to degree than rigid exterior allows
            - interior IMPOSES RADIAL INWARD STRESSES
            - compressive stresses on surface with tensile stresses at interior regions
        - Failure of ceramic materials *almost always* results from CRACK INITIATED BY TENSILE STRESS

        - to cause fracture of a TEMPERED glass, tension needs to overcome residual compressive surface forces
    - Applications:
        - large doors
        - windshields
        - eyeglass lenses

Fabrication and Processing of Clay Products

- includes structural clay products and white wares
- also contain other ingredients
- have to be subjected to firing and drying operations
- each of ingredients influence the changes that take place during these process and the characteristics of the finished pieces

Characteristics of Clay

- **hydroplasticity-** When water is added to clay, become very plastic
- Important property in forming operations
- Flay fuses/melts over range of temps
- dense and strong ceramic piece produced during firing without complete melting
- fusion temp range depends on composition of clay
- Clays are **aluminosilicates** (composed of alumina and silica) + chemically bonded water
- Broad range of physical characteristics, chem compositions and structures
- Common impurities include compounds of Ba, Ca, Na, K, and Fe and organic matter
- Complicated crystal structures
- **KAOLINITE- most clay has kaolinite structure**

Compositions of Clay

- Also contain nonplastic ingredients
- nonclay minerals include flint/finely ground quartz, flux (feldspar)
- quartz is primarily filler materials- inexpensive, hard, chemically unreactive
- When mixed with clay, flux forms a glass

Fabrication techniques

- Raw materials have to go through milling, grinding operations in which particle size is reduced
    - followed by screening or sizing to yield powdered product having a desired range of particle sizes

Hydroplastic forming

- when mixed with water have extremely low yield strengths
- water-clay ratio of hydroplastic mass must give yield strength sufficient to permit formed ware to maintain its shape during handling and drying

- Most common hydroplastic forming technique is extrusion, in which a stiff plastic ceramic mass forced through a die orifice having the desired cross sectional geometry
  - similar to extrusion of metals
- Applications:
  - formation of blocks
  - tiles
  - pipes
  - bricks

Slip casting

- **Slip-** suspension of clay, nonplastic materials in water
- When poured into porous mold (made of plastic of paris), water from slip is absorbed into mold, leaving behind a solid layer on the mold wall
  - may be continued until entire mold cavity becomes solid
  - **Drain slip casting-** terminated when shell wall reaches desired thickness by inverting mold and pouring out excess slip
- Slip has to have high specific gravity and has to be fluid, pourable
  - low drying shrinkage
  - high strength
- Properties of mold influences quality of casting

Drying and Firing

- Retains significant porosity, insufficient strength for practical apps
- May still contain liquid
- Liquid removed in a drying process
- Density and strength enhanced as a result of high temp heat treatment or firing procedure
- **Green-** formed and dried but not fired

Drying

- Experiences shrinkage
- as water removed and drying occurs, interparticle separation decreases
  - aka, shrinkage
- Draying at interior regions of body accomplished by diffusion of water to surface where evaporation occurs
- If rate of evaporation > rate of diffusion, surface dries more rapidly than interior and shrinks
  - High probability formation of defects
- Rate of surface evaporation diminished to rate of water diffusion
- Evaporation controlled by temp, humidity, rate of airflow
- Water content of formed body is also critical
- Clay particle size has influence- shrinkage enhanced as particle size decreases

Firing

- After firing, density increased
- **Vitrification-** gradual formation of liquid glass that flows into and fills some of pore volume

- Degree of vitrification depends on firing temp and time, + comp of body
- adding feldspar and other fluxing agents lowers temp at which liquid glass forms

Powder Pressing

- Analogous to powder metallurgy
- used to fabricate both clay and nonclay compositions
- powdered mass compacted into desired shape by pressure
- Degree of compaction maximized and fraction of void space minimized by using coarse and fine particles
- No plastic deformation of particles during compaction, as may be with metal powders
- 3 Powder Pressing techniques:
    1. **Uniaxial-** powder compacted into metal die by pressure applied in a single direction
        a. formed piece takes on configuration of die and platens through which pressure is applied
        b. Confined to simple shapes
        c. Production rates high and inexpensive
        d. Firing required afterwards
    2. **Isostatic** (Hydrostatic)- powdered material contained in rubber envelope and pressure applied by fluid **isotactically** (same magnitude in all directions)
        a. More time consuming and expensive
        b. Firing operation required afterwards
    3. Hot pressing
        a. With hot pressing, powder pressing, heat treatment performed simultaneously
            i. powder aggregate compacted at elevated temp
        b. used for materials that don't form liquid phase except at high and impractical temps
        c. utilized when high densities w/out appreciable grain growth desired
        d. inexpensive, with some limitations
        e. costly in terms of time, since both mold and die must be heated, cooled during each cycle
- During firing, formed piece shrinks, experiences reduction of porosity and improvement in mechanical integrity
    - occurs by coalescence of powder particles in more dense mass
- **Sintering-** necks form along contact regions between adjacent particles
    - grain boundary forms within each neck
    - every interstice between particles= pore
    - As this progresses, pores become smaller, more spherical in shape
    - Carried out below melting temp so that liquid phase normally not present
    - Mass transport necessary to effect changes shown

Tape Casting

- HOW TAPE IS PRODUCED!
- Sheets prepared from slips, similar to slips from slip casting
- consists of suspension of ceramic particles in organic liquid that also contains binders, plasticizers incorporated to impart strength and flexibility to cast tape
- De-airing a vacuum necessary to remove entrapped air, solvent vapor bubbles
- *Formation*: Tape formed by pouring slip onto flat surface
    - Doctor blade spreads out slip into thin tape of uniform thickness
    - In drying process, volatile slip components removed by evaporation
    - green product is flexible tape cut into which holes punched prior to firing
- *Apps:*
    - used in production of ceramic substrates used for integrated circuits, multilayered capacitors

Metal Alloys: Applications and Processing

Ferrous Alloys

- **Ferrous Alloys**- iron is prime constituent
- Produced in larger quantities than any other type of metal
- Very important engineering construction material
- Reasons for widespread use (Pros):
    1. Abundance: Iron containing compounds exist in abundant quantities within Earth's crust
    2. Money: Metallic iron, steel alloys produced using economical extraction, refining, alloying, fabrication techniques (fairly cheap)
    3. Applicable: Very versatile, can be tailored to have a wide range of mechanical and physical properties
- Cons: susceptible to corrosion

Steels

- Iron-carbon alloys that *contain appreciable concentrations* of other alloying elements
- Mechanical properties sensitive to content of carbon, which is normally <1.0 wt%
- **Plain carbon steels-** contain only residual concentrations of impurities other than carbon and a little manganese
- **Alloy steels-** more alloying elements intentionally added in specific concentrations

Low-Carbon Steels

- Produced in greatest quantities
- < 0.25 wt% carbon
- Unresponsive to heat treatments intended to form martensite
    - Cold work strengthening
- Microstructures consist of ferrite, pearlite constituents
- Mechanical properties:
    - Soft
    - weak
    - ductile
    - tough
    - *Yield Strength*: 275 MPa
    - *TS:* 425-550 MPa
    - *Ductility:* 25% elongation
- Machinability
    - Machinable, weldable
    - LEAST EXPENSIVE TO PRODUCE OF ALL STEELS
- Applications:
    - Automobile body components
    - structural shapes (I beams, channel, angle-iron)
    - sheets used in pipelines, buildings, bridges, tin cans

- **High strength low alloy (HSLA)**- other alloying elements like Cu, V, Ni, Mb
    - Low concentration of carbon but high concentration of other alloying elements
    - Because of other alloying elements, less susceptible to corrosion
    - Mechanical properties:
        - Ductile
        - Formable
        - Machinable
        - More resistant to corrosion
        - *Tensile Strength*: ≥ 480 MPa
    - Applications:
        - Since less corrosive, used for structural importance applications

Medium Carbon Steels

- Carbon concentrations between 0.25 wt% and 0.60 wt%
- Heat treated by austenitizing, quenching, then tempering to improve mechanical properties
- Most often used when fully tempered → microstructures of tempered martensite
- Plain medium hardened steels have low hardenabilities
- Successfully heat treated in only thin sections with rapid quenching rates because of such low hardness
    - Additions of alloying elements like chromium, Ni, molybdenum improve capacity of these alloys to be heat treated
        - give rise to a bunch of different strength-ductility combinations
- Heat treated medium carbons steels are stronger than low carbon steels, but less ductility and toughness
- Applications:
    - Railway wheels and tracks
    - gears
    - crankshafts
    - other machine parts
    - high strength structural components calling for combo of high strength wear resistance, toughness

High-Carbon Steels

- Carbon contents between 0.60 and 1.4 wt%
- Mechanical Properties:
    - Hardest, strongest, least ductile of carbon steels
    - Almost exclusively used in hardened, tempered conditions
    - Especially wear resistant
        - Capable of holding a sharp cutting edge
- Tool and die steels are high-carbon alloys
    - usually contain Cr, V, W, Mb

        - Combing with carbon to create very hard, wear-resistant carbide compounds

Stainless Steels

- **stainless steels**- highly resistant to corrosion (rusting) in a variety of environments, especially in ambient atmosphere
- Predominant alloying element: Cr
- At least 11 wt% Cr is required (<< that's a LOT of chromium!)
- Corrosion resistance may be enhanced by addition of Ni and Molybdenum

METAL WORKING AND PROCESSES

Annealing

- Heat above upper critical temp, maintain suitable temp, then cool
- Increases ductility and makes more workable
- Soften metal, relieve internal stresses
- MAKE HOMOGENEOUS STRUCTURE
- improve cold working conditions
- Copper, silver, Brass, steel- heat metal until glowing then cool in still air
  - can be quenched, but these doesn't need to be cooled quickly, unlike ferrous material
- Metal is softened, prepared for work, such as stamping, shaping, forming
- Reduces risk of deformation

Thermodynamics

- Diffusion of atoms within a solid
  - Material progresses toward equilibrium
  - Heat increases process by providing energy to break bonds
- Movement of atoms destroys dislocations in metals, not as strongly in ceramics
- Alteration in dislocations allows metals to deform more easily
- **stress relief-** release Gibbs free energy
  - Relief of internal stresses is a spontaneous process
  - At room temp, is very slow
  - Annealing's high temps help speed up stress relief
  - Many reaction pathways → *reduces **lattice vacancy gradients***
    - creation of lattice vacancy gradients is governed by Arrhenius equation and diffusion of lattice vacancy gradients is governed by Fick's Law.
- Hardness is reduced as ductility increases

Stages

1. **Recovery**- remove (linear) dislocations and their internal stresses
   a. occur at lower temp stage of all annealing (diffusion)
   b. Before new strain free grains
   c. *grain size and shape not altered*
   d. recovery is sped up as increase temp
2. **Recrystallization**-New strain free grains grow
   a. Grains replace strained grains
3. **Growth**- material coarsens, grains grow bigger, lose STRENGTH
   a. regain through hardening

Environments

- High temp annealing CAN RESULT IN OXIDATION
- If need to avoid oxidation, use an endothermic gas or forming gas
  - **endothermic gas**- Combo of CO, H2, N2
  - **Forming gas-** Combo of H2 and N2

- Magnetic properties of mu-metal are introduced in an H atmosphere

Set up and Equipment

- Use large ovens
    - Inside have enough space to place work piece in position to receive maximum exposure to circulating heated air
- high volume- gas fire conveyer furnaces
- high quantity- car bottom furnaces used
- Once annealing is completed, work pieces left in oven so parts cool in controllable manner
    - some leave and cooled off through quenching
- Quenching used for some ferrous alloys, but not copper

Semiconductor Diffusion Annealing

- Si wafers are annealed so dopant atoms (B, P, Ar) can substitute evenly throughout crystal lattice
    - results in changes in electrical properties

Normalization- uniformly decreases grain size

- Improves ductility and toughness
- Annealing process
- apply to ferrous alloys
- Gives material uniform FINE grained structure, makes less brittle
- Transform from austenite to ferrite, pearlite, sorbite
- Heat steel 20-50 K above upper critical point
- Smaller grains form, produces TOUGHER AND MORE DUCTILE material
- Improves machinability of component, provides dimensional stability if subjected to further heat treatment processes

Process Annealing

- Aka "intermediate annealing, subcritical annealing, in process annealing
- ***NOT FULL ANNEALING-** apply this process in between *work-hardening*
    - Work harden, then anneal, and then harden more
- Improves ductility in the middle of work hardening
- Important in shaping, creating more refined work through processes of rolling, drawing, forging, spinning, extruding, heading
- Heated to temp below austenizing temp, held to relieve stresses
    - then placed in furnace to cool
- **** reduces risk of DISTORTION
- Temp range: 260°C (500°F) to 760°C (1400°F)

Full Anneal

- Produces 2ND MOST DUCTILE STATE an alloy can have
- Creates ENTIRELY NEW UNIFORM microstructures with good dynamic properties
- For steel, heat 50°C above austenic temp and held for sufficient time to allow material to fully form austenite or austenite-cementite grain structure
- Exact process depends on type of metal
- LOWER YIELD AND TENSILE STRENGTH

- **lamellar pearlite annealing** (LP annealing)- specific microstructure
- **process anneal-** only goal is to soften material

Short cycle anneal- turn normal ferrite to malleable ferrite

- Heat, cool, and heat again for 4-8 hours

Resistive Heating

- **Resistive heating**- anneal copper wire
- Employs electrical short circuit
- Doesn't require temp-regulated furnace like other methods of annealing
- USE TO HEAT UP WIRE
  - Use friction of turning and drawing of copper wire in a wheel.

Quenching

- **Quenching-** rapid cooling of workpiece to obtain certain material properties
- PREVENTS low temp processes, such as phase transformations → provide only a NARROW window of time in which reaction is thermodynamically stable and accessible
- *Reduces* crystallinity, increases *toughness* of alloys and plastics
- steel and ferrous alloys are hardened and strengthened
- Produces harder material by surface or through-hardening varying on rate at which is cooled
- Then material is **tempered-** reduces brittleness that increase due to quenching
- includes cooling AND heating, although often secedes annealing
  - quench gears, shafts, and wear blocks

Quenching Process

1. Heating to required temp (annealing)
   a. Most materials heated to 815-900°C
2. Soaking- by air, bath, or vacuum
   a. Soaking in air furnaces (1-2 minutes) is a little shorter than for vacuum, bath
3. Cooling- 1 of most efficient quenching media where max hardness is acquired
   a. chance that causes distortion or cracking
   b. Much slower quenching velocity of oil than of water.
   c. Can use inert gases

- Hard to control

Effect of Quenching

- Before hardening, microstructure = pearlite grain (uniform, lamellar)
  - **Pearlite-** mix of ferrite and cementite formed when steel, cast iron manufacture and cooled at slow rate
- After hardening, microstructure = martensite (fine, needle-like)
- Before quenching, need to look up quenching constants
- Steel with high carbon content reaches a much harder state that steel with low carbon content

Tempering

- **Tempering-** increases TOUGHNESS of iron based alloys
  - Performed after hardening, reducing some of excess hardness
    - heats metal to much lower temp than used for hardening
    - Exact temp determines amount of hardness removed
      - depends on composition of alloy and desired properties in finished product
  - Hard tools tempered to very low temps while springs tempered at higher temps
  - ****Glass tempering- heat up and then quickly cool surface
    - increases toughness
- DECREASES HARDNESS, INCREASE TOUGNESS AND DUCTILITY
- Applied to ferrous alloys, steel/ cast iron
- Controlled heating of quench work piece to temp below lower critical temp
- Temp at which crystalline phases of alloy (ferrite and cementite) combine into austenite
  - don't heat above because still WANT martensite structure
- Low temp tempering only relieves internal stress and decreases brittleness while maintaining majority of hardness
- Carbon steels- tempering alters size and distribution of carbides in martensite

Terminology

- **Toughness** is measured by Charpy Izod test
- **Plasticity-** ability to mold, bend, deform in manner that doesn't spontaneously return to original shape
  - proportional to ductility, malleability

Tempering in Carbon Steel

- Steel softened to malleable state through annealing, or can be hardened to state as rigid and brittle as glass by quenching
- Hardened state is to brittle
  - lacks structural integrity useful for applications
- Tempering- decreases hardness, increases ductility of quenched steel
  - imparts springiness, malleability to steel
  - Allows metal to bend before breaking
- Depending on degree of tempering, can either be elastic or plastic
  - elastic → SPRING APPLICATION!
- Tempering- balances mechanical properties of metal:
  - shear strength
  - yield strength
  - hardness
  - ductility
  - TS
- Achieves any combo of properties
  - makes useful for variety of applications

- Springs don't require much rigidity, but must deform elastically before breaking
- Quenched steel ALWAYS tempered
- Steel is sometimes annealed through normalization—partly softened
- Tempering sometimes used on normalized steels to further soften, increasing malleability and machinability for easier metalworking
- Tempering also used on welded steel → relieve some of stresses and excess hardness created in heat affected zone around weld

Quenched-Steel

- Steel heated above upper critical temp and then quickly cooled (quenching)
- After quenched steel near hardest possible state (martensite), is then tempered to incrementally decrease hardness to more suitable point for application
    - Hardness of quenched steel depends on COOLING RATE AND COMPOSITION
- Steel with high carbon content reaches a much harder state that steel with low carbon content
- Tempering high C steel to certain temp makes harden than heating low C steel to same temp
- Amount of time @ tempering temp also has effect
- TEMPERING DEPENDS ON TIME AND TEMP
    - heating at high temp for short time = heating @ low temp for long time
- Temp range:
    - Tempering @ low temp, between 66-148 °C (151-298°F)
        - doesn't have effect other than slight relief of some of internal stresses
    - Tempering @ higher temps: 148-205°C (298-401°F)
        - Produces slight reduction in hardness, but relieves much of internal stresses, improves ductility
    - Tempering @ very high temps: 260-340°C (500-644°F)
        - Decrease in ductility, increase in brittleness
        - ******Tempered Martensite Embrittlement range**
    - Tempering @ 600°C
        - **Temper embrittlement stage**
        - occurs if steel is held in TE temp too long

Normalized Steel

- **Normalized steel-** heated above upper critical temp and then cooled in standing air
- Consist of pearlite, bainite, martensite grains mixed together in the microstructure
- Produces steel much stronger than fully annealed steel, tougher than temper-quenched steel

Blacksmithing

- Old version of blacksmithing
  - "forgers of iron"
- Temp was judged by watching tempering colors of metal
- Tempering consisted of heating above a charcoal, coal forge or by fire
  - hold work at right temp for correct amount of time NOT POSSIBLE
- Tempering performed by slowly, evenly overheating metal (judged by color) and watching it cool immediately
  - cooled in air or immerse in water
  - Same effect as heating at right temp
- Easier to blacksmith thicker irons, specimens because heat only surface to right temp
  - however, might not heat all the way through

Tempering Colors

- If steel freshly ground, sanded, polished, will form oxide layer on surface when heated
  - as temp of steel increased, thickness of iron oxide also increases
- Thin layers of FeO allows some transparency, called **thin film interference**
- **Thin film interference-** produces colors on surface
- As thickness of oxide layer increases with temp, causes colors to change from light yellow to brown to purple to blue
- Colors
  - Faint-yellow – 176 °C (349 °F) – engravers, razors, scrapers
  - Light-straw – 205 °C (401 °F) – rock drills, reamers, metal-cutting saws
  - Dark-straw – 226 °C (439 °F) – scribers, planer blades
  - Brown – 260 °C (500 °F) – taps, dies, drill bits, hammers, cold chisels
  - Purple – 282 °C (540 °F) – surgical tools, punches, stone carving tools
  - Dark blue – 310 °C (590 °F) – screwdrivers, wrenches
  - Light blue – 337 °C (639 °F) – springs, wood-cutting saws
  - Grey-blue – 371 °C (700 °F) and higher – structural steel
- As increase temp, oxide loses transparency
- Layer increases with thickness over time
- Oxidizing, carburizing heat sources affects final result
- Oxide layer protects steel from corrosion through passivation
- **Differential tempering-** temper different parts of piece differently, have a gradient
  - used for knives, swords, etc.

FAILURE

Creep

- Deformation under elevated temps, exposed to static stresses is **creep**
- Significant @ 40% melting temp
- Deformation, strain measured and plotted as function of elapsed time
- Typical creep test has constant load under constant temp
- Primary creep = transient creep
    - continuously decreasing creep rate
    - material is experiencing an increase in creep resistance or strain hardening
    - instantaneous deformation
- Secondary creep- longest duration
    - BALANCE BETWEEN RECOVERY AND STRAIN HARDENING
- Tertiary creep- acceleration of rate and ultimate failure
    - "rupture"
    - Results from microstructural, metallurgical changes
        - grain boundary separation
        - formation of internal cracks
- Decrease in effective cross sectional area and increase in strain rate
- For tensile loads, a neck may form at some point within the deformation region
    - lead to decrease in cross sectional area and increase in strain rate
- **Steady state creep = minimum creep rate**
- **Rupture lifetime**= time to rupture
- Increased temp means:
    - instantaneous strain at time of rupture increases
    - Steady state creep rate increases
    - Rupture lifetime diminished
- Creep graph is *creep strain/time*
- Factors about materials that affect creep:
    - melting temp
    - elastic modulus
    - grain size
        - if these are higher, then there is greater resistance to creep
- Smaller grains permit more grain boundary sliding
    - results in higher creep rates
- Refractory metals are extremely resilient to creep

Fatigue

- **Dynamic, fluctuating stresses**
- Responsible for 90% of all metallic failures
  - polymers, ceramics also susceptible (except for glasses)
- Catastrophic, insidious, occurs without warning
- Brittle like failure
  - very little plastic deformation
  - even in ductile metals
- Fracture surface is perpendicular to direction of an applied tensile stress
- Applied stress may be axial, flexural, or torsional
- **Reversed stress cycle**- equal magnitude of tensile stress to compressive stress (max to min)
- **Mean stress** = middle stress
  - average of max and min stresses
- **Range of stress-** difference between max stress and min stress
- **Stress amplitude =** ½ of stress range
- **Stress ratio-** ratio of minimum to maximum stress amplitudes
  - Reversed stress cycle value is -1 because compression (minimum) is negative
- Random stress cycle
- Axes: x axis = stress, y axis = lo g N
  - N = number of cycles
- Higher the magnitude of stress, the smaller number of cycles
- **Fatigue limit**- limiting stress level- below which fatigue failure won't occur
  - For some ferrous and titanium alloys, SN curve becomes horizontal
- Fatigue limits range between 35% and 60%
- **Fatigue strength**- stress level at which failure will occur for some specified number of cycles
- **Fatigue life-** corresponding number of fatigue cycles for a specific fatigue strength
- In reality, will be a scatter plot due to the following factors:
  - specimen fabrication
  - surface preparation
  - metallurgical variables
  - specimen alignment in the apparatus
  - mean stress
  - test frequency
- Low cycle fatigue: less than 10^4 to 10^5 cycles
- High cycle fatigue: > E4 to E5 cycles

Crack Initiation and Propagation

- 3 steps:
  - Crack initiation- small crack forms at some point of high stress concentration

    - Crack propagation- crack advances incrementally with each stress cycle
    - Final failure-occurs very rapidly once the advancing crack has reached a critical size
- Cracks associated with fatigue failure initiate on the **surface** of a component at some point of stress concentration
- Crack nucleation sites include:
    - surface scratches
    - sharp fillets
    - keyways
    - threads
    - dents
- Cyclic loading can produce microscopic surface discontinuities resulting from dislocation slip steps
    - also act as stress raisers and crack initiation sites
- 2 types of markings from cycling loading:
    - beachmarks
    - striations
        - Indicate the position of the crack tip at some point in time
        - appear as concentric ridges that expand away from the crack initiation sites
            - circular or semicircular patterns
- **Beachmarks** (clam shell marks) are of MACROSCOPIC dimensions
    - observed with unaided eye
    - occur for components that experienced INTERUPTIONS
        - ex: machines that only work during workshift hours
    - Each beach mark band represents period of time over which crack growth occurred
- **Striations**- microscopic in size
    - subject to observation with TEM or SEM microscope
    - Each striation represents advance distance of a crack front during a single load cycle
- Beach marks and striations are different in both ORIGIN AND SIZE
- There may be 1000s of striations in 1 beackmark
- IF THERE ARE BEACKMARKS OR STRIATIONS, THEN THERE WAS FATIGUE
    - but even if there aren't doesn't mean that it wasn't fatigue

Factors that Affect Fatigue Life

- fatigue behavior of engineering materials is sensitive to a number of variables
- These factors include mean stress level, geometrical design, surface effects, metallurgical variables, environment
- Mean stress decreases fatigue life
- Especially sensitive to condition and configuration of component surface

Surface Treatments

- During machining operations, small scratches/grooves are invariably introduced into workpiece surface by cutting tool action
- By already having surface tensile stress, impose residual compressive stresses within a thin outer surface layer
- Residual compressive stresses commonly introduced into ductile metals mechanically by localized plastic deformation within the outer surface region
- **Shot peening**- localized plastic deformation within the outer surface region
    - Shoot little bibi gun balls at a surface
    - high velocities
- **Case hardening**
    - surface hardness, fatigue life enhanced for steel alloys
    - accomplished by a carburizing or nitriding process whereby a component is exposed to carbonaceious or nitrogenous atmosphere at elevated temp
    - introduced by atomic diffusion from the gaseous phase
    - hardens surface
    - introduces compressive residual stresses

Environmental Fatigues

- **Thermal fatigue**-induced at elevated temps by fluctuating thermal stresses
    - mechanical stresses from external source need not be present
    - origin of thermal stresses is the resistance for structural component to expand or contract
- **Corrosion fatigue-** simultaneous action of cycle stress and chemical attack
    - corrosive environment has deleterious influence, produces shorter fatigue lives
    - normal ambient atmosphere will affect fatigue behavior of some materials
    - Small pits form as a result of chem reactions→ serve as points of stress concentration and crack nucleation sites
    - Crack propagation rate is enhanced as a result of the corrosive environment
    - Nature of stress cycles influence the fatigue behavior
    - Lowering the load application frequency leads to longer periods during which open crack in contact with environment
        - reduces fatigue life

IRON ALLOTROPES

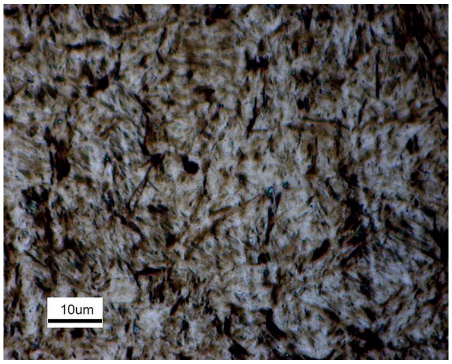
Iron Allotropes

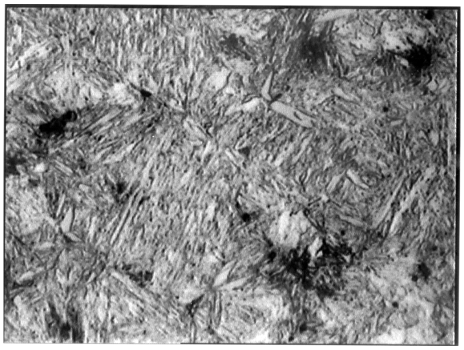
- Martensite transformation when cooled quickly
  - insoluble atoms can't diffuse in time
- Composition has big effect on results of heat treating
  - if percent correct, alloy forms single, continuous micro structure upon cooling (pearlite)
  - Perfect mixture = eutectoid
  - Hypoeutectoid- solution contains less of solute than eutectoid
  - Hypereutectoid- solution contains more of solute
- Eutectic alloy- single melting point
  - when molten eutectic alloy cooled, all constituents crystallize into respective phases at same temp
- eutectoid alloy- phase change occurs not from liquid but from solid solution
  - when cool eutectoid alloy from solution temp, constituents separate into different crystal phases, forming single crystal structure
  - eutectoid steel has .77% carbon
- Slow cooling- austenite separates into platelets of phases ferrite and cementite. Forms layered pearlite
- Hypoeutectic- when cooled, is solid
  - 2 melting pts above eutectic melting pt
  - between 2 melting pts, is part solid and part liquid
  - constituent with lower melting pt solidifies first
- **Hypoeutectoid**
  - 2 critical temps called arrests
  - between arrests is part solution, part crystallizing phase
- Ferrite softer than pearlite
- **Hyper eutectic**
  - Constituents have higher melting pts than solidifying temp
- **Hyper eutectoid-** > .77% C
  - When cooling from upper transformation alloy
- Large grains means large grain boundaries
- Austenite exists above upper critical temp
- Martensite transformation is independent
  - if cool below marteniste temp before other microstructures can form, will develop under speed of sound
- When austenite cooled extremely slow, will form large ferrite crystals

Martensite

- Hard form of steel
- not a DIFFUSION transformation
  - displacive transformation
- Hard minerals occurs as lath or plate shaped
- NOT ACICULAR (spiky flakes-shaped)- ONLY LENTICULAR (lens shaped)

- Formed in steels by quenching of austenite at such high rate that NO TIME TO DIFFUSE
    - Too fast to form cementite
- Result: Supersaturated ferrite that's BCC and is highly strained
- Shear deformations produce large numbers of dislocations
    - MORE DISLOCATIONS MEANS > STRENGTH
- VERY strong- pearlitic steel has 400 HB @ most where as martensitic steel can reach up to 700 HB
- Martensitic reaction begins during cooling when austenite reaches **martensitic start temp,** parent austenite becomes unstable
- As sample is quenched, large % of austenite transforms to martensite until reach **lower martensitic temp,** where displacive transformation abortion
- Rapid quench essential to create martensite
- Big increase in dislocation density
- Combo of big # of dislocations, precipitates that originate and pin dislocations in place
- If cool @ critical cooling rate, only martensite forms
- If cool slower than critical cooling rate, then some pearlite will form
    - this is because has more time for diffusion
- THERMALLY INDUCED OR STRESS INDUCED
- Crystal structure: BODY CENTERED TETRAGONAL
    - Austenite is FCC
- IS NOT AN EQUILIBRIUM PHASE
- **Displacive Transformation-** very little thermal energy requirement, is only a very fast shift of atomic positions
    - Can even occur at **cryogenic** (Production of very low temp, like at -150°C or 123K) temps
- Attainment of equilibrium is accelerated @ high temps, so tempering reverses martensitic formation
- Can add tungsten to interfere with cementite nucleation
- Metastable state

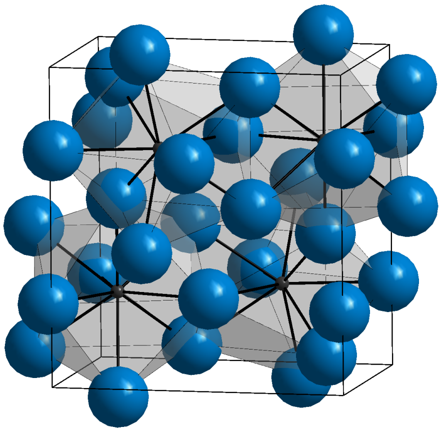




<u>Cementite</u>

- Orthorhombic crystal structure
- Hard, brittle

- CERAMIC IN PURE FORM
- Cementite + ferrite = pearlite
- Forms form austenite during cooling and martensite during tempering
    - forms lamellar structure
    - SLOWLY cooling
- Would form martensite if more quickly cooled
- IS FERROMAGNETIC
    - @ Curie temp, changes from ferromagnetic to paramagnetic



Austenite

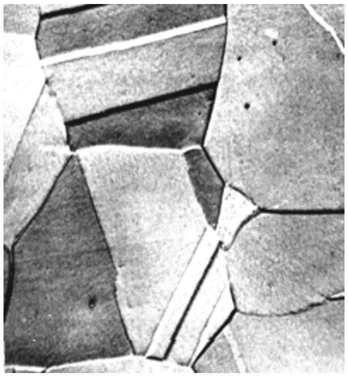
- Gamma phase iron
- Metallic, NON MAGNETIC
- Exists above critical eutectoid temp
- FCC crystal structure
- Alpha ferrite undergoes phase transition from BCC to FCC configuration of gamma iron
- Soft and ductile but can dissolve more carbon
    - GREATER % OF CARBON
- Most commonly used type of carbon steel

Austenitization

- Heat iron, iron-based metal, steel to temp at which it changes crystal structure from ferrite to austenite (from BCC to FCC)
- Incomplete initial austenitization can leave undissolved carbides in matrix

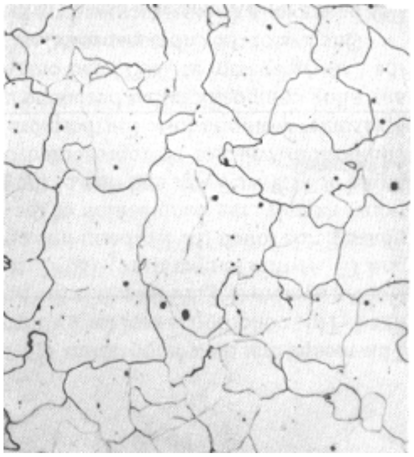
Austempering

- Hardening process used on iron-based metals to promote better mechanical properties



Alpha ferrite

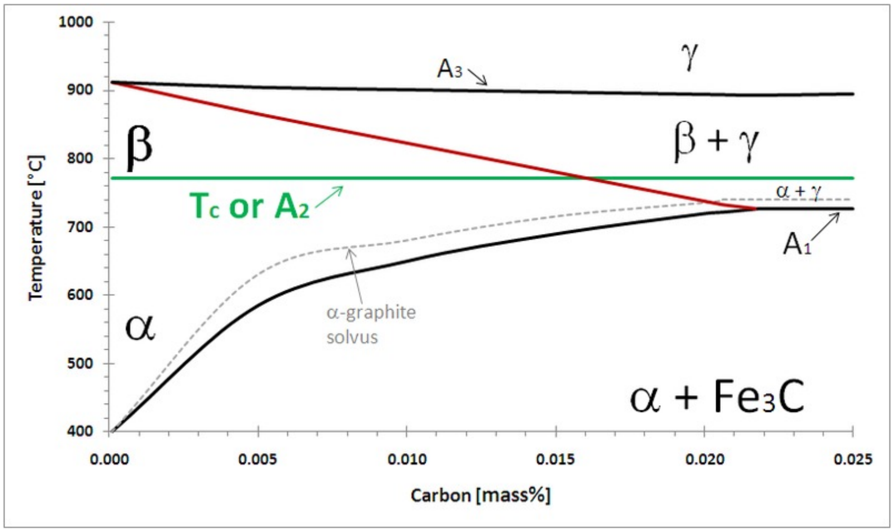
- Pure iron with BCC
- BCC gives steel and cast iron magnetic properties
- is a ferromagnet
- Strength: 280 N/mm^2
- Hardness: 80 Brinell
- Mild steel- ferrite with increasing amounts of pearlite (fine lamellar structure of ferrite and cementite)
- If allowed to reach equilibrium at room temp, any iron carbon alloy will have some ferrite
- Exact amount of ferrite depends on cooling processes the iron-carbon alloy undergoes as is cooled from liquid state
- Mild steel- up to 0.2 wt% C
- In pure iron, Ferrite is stable below 910°C
    - above this temp, FCC austenite is stable
- From 1390 to 1539 °C (melting pt), becomes BCC delta ferrite
- Ferrite above Curie temp becomes paramagnetic and is called **beta ferrite**
- Only small amnt of C can be dissolved in ferrite
    - max solubility is 0.02 wt% at 723 and 0.005% at 0°C
    - Because C dissolves in iron interstitially, with C atoms 2 times the diameter of the interstitial holes
    - Each C atom surrounded by strong local strain field
        - Enthalpy of mixing is positive, since is surrounded by local strain field
        - Contribution of entropy to free energy of solution stabilizes structure for low C content
        - 723 = minimum temp at which Fe C austenite is stable
            - eutectoid reaction between ferrite, austenite, cementite



Beta Ferrite

- Beta ferrite, beta iron = obsolete terms for paramagnetic form of alpha ferrite

- Primary phase of low carbon, mild steel, most cast irons @ room temp = ferromagnetic ferrite
- As Ferrite heated above curie temp, thermal agitation of atoms exceed oriented magnetic moment of unpaired electron spins in 3d shell
- Curie temp forms low temp boundary of beta iron field in phase diagram below:



  - is crystallography identical to alpha ferrite, except for magnetic domains
  - EXPANDED BCC lattice parameter as function of temp
  - Only of minor importance in heat treating of steel
  - Considered as the high temp end of alpha ferrite
  - Curie temp is minor compared to eutectoid pt and critical temps of where austenite is in equilibrium with cementite and gamma iron
  - Beta ferrite and critical temp are very important in the induction heating of steel
    - **induction heating-** heating through electromag induction, where *eddy currents* (circular currents propagating) are generated within the metal and resistance leads to Joule heating of metal
  - Steel is typically austenitized before quenching and tempering
    - high frequency alternating magnetic field of induction heating heats steel by 2 mechanisms below the Curie temp

Graphite

- conductor
- semimetal
- most stable form of carbon under STP
- Can be considered as highest grade of coal
- Crystalline flake graphite

3 types of ores

- **Crystalline flake graphite-** flat, isolated, plate-like particles with hexagonal edges if unbroken and when broken edges can be irregular or angular

- **Amorphous graphite**- fine particles, result of thermal metamorphism of coal
  - fine flake graphite called amorphous sometimes
- **Lump graphite** (vein graphite)- occurs in fissure veins, fractures
  - appears as massive platy intergrowths of fibrous, acicular crystalline aggregates

NANOMATERIALS

(I hope this is part of the rules next year)

- **Nanomaterials**- field of mat sci approach on nanotech
- **Nanomaterial**- material with nanoscale dimensions (usually 1 tenth of a micrometer, but could be up to a micrometer)
- **Quantum size effect**- electronic properties of solids are altered with great reductions in particle size
- Nanoparticles take advantage of increased surface area to volume ratio
    - Optical properties like fluorescence become function of particle diameter
    - DOES NOT occur when go from macro to *micro* dimensions, only if go from macro to *nano*
- When introduced to a bulk material, nanoparticles strongly influence the mechanical properties of the material
    - Ex: polymers can be reinforced by nanoparticles resulting in new materials that can be lightweight replace metals in certain apps

Classification

- **Fullerenes-** class of allotropes of carbon which are grapheme sheets rolled into tubes/spheres
    - Includes carbon nanotubes/silicon nanotubes, which have a strong mechanical strength and interesting electrical properties
    - Medical applications:
        - Binding specific antibiotics to the structure of resistant bacteria
        - Target types of cancer cells like melanoma
        - Light activated antimicrobial agents
        - Heat resistance, superconductivity are properties that are attracting research
    - Creation:
        - Send a large electric current between 2 graphite electrodes in an inert atmosphere
        - The carbon plasma arc between the electrodes cools into sooty residue form which many fullerenes can be isolated
- **Nanoparticles (nanocrystals)-** made of metals, semiconductors, oxides
    - In particular interest for mechanical, electrical, magnetic, optical, chemical properties
    - Used as quantum dots and chemical catalysts such as nanomaterial-based catalysts
    - Bridget between bulk materials and atomic/molecular structures
        - Bulk materials have constant physical properties regardless of size, but not true at the nano-scale
        - Size dependent properties include: quantum confinement in semiconductor particles, surface plasmon resonance in some metals and superparamagnetism in magnetic materials
    - Nanoparticles exhibit special properties relative to bulk material

        - Ex: bending of bulk copper wire, ribbon, etc. occurs with movement of copper atoms and clusters at the 50 nm scale
        - Copper nanoparticles smaller than 50 nm are considered super hard materials that don't exhibit the same malleability and ductility as bulk copper
        - Change in props not always desirable- ferroelectric materials < 10 nm can switch magnetization direction using room temp thermal energy, making useless for memory storage
    - Suspension of nanoparticles are possible b/c of interaction of particle surface with solvent is strong enough to overcome differences in density
    - Nanoparticles often have unexpected visual properties because they're small enough to confine electrons and produce quantum effects
        - Ex: gold appears deep red and black in solution at nano size
    - Really high surface area to volume ratio of nanoparticles provides a *huge* drive for diffusion, esp at elevated temps
    - Sintering is possible at low temps and over shorter durations than for larger particles
    - Surface effects of nanoparticles *reduces* incipient melting temp
- **Sol gel**- method for producing solid materials from small molecules
    - Used for fabrication of metal oxides, especially the oxides of Si and Ti
    - Involves conversion of monomers into a colloidal solution (sol) that acts as precursor for integrated network (gel) of discrete particles of network polymers