

# MATERIALS ENGINEERING

MT30001

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Offered by:

Metallurgical & Materials Engineering Dept.

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# Ceramics, polymers & composites

# Content of this course

- Ceramic materials
- Polymers
- Composite materials

## Textbooks referred to:

- Materials Science and Engineering: An Introduction – W. D. Callister

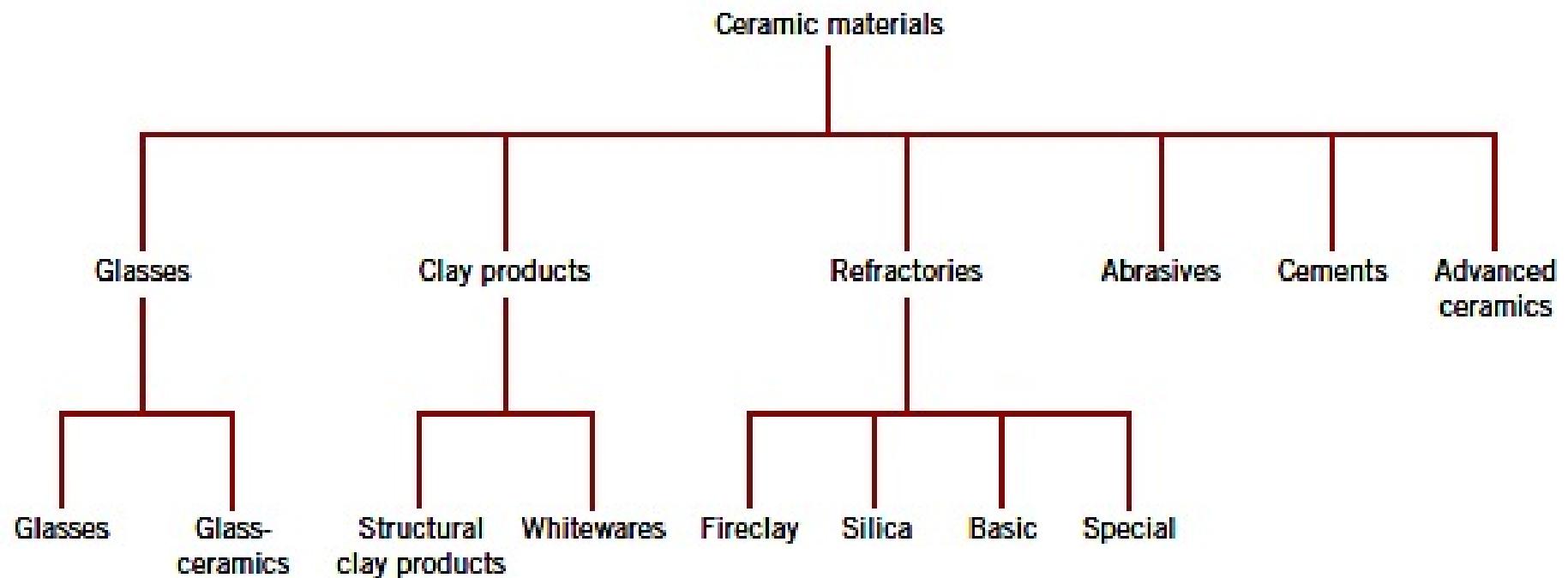
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# Ceramics

- Ceramics are composed of at least two elements and often more. Hence, the crystal structure of ceramics is generally more complex than metals
- The atomic bonding in ceramics range from pure ionic to totally covalent. Many ceramics have a combination of ionic and covalent bonding. The degree of ionic bonding depends upon the electronegativities of the atoms

<i>Material</i>	<i>Percent Ionic Character</i>
CaF <sub>2</sub>	89
MgO	73
NaCl	67
Al <sub>2</sub> O <sub>3</sub>	63
SiO <sub>2</sub>	51
Si <sub>3</sub> N <sub>4</sub>	30
ZnS	18
SiC	12

# Application of ceramics



# Application of ceramics



# Application of ceramics

- Glasses are used as laboratory ware and ovenware, reinforcements in glass-resin composites, optical lenses etc.
- Clay products are used as building bricks, tiles, pottery, tableware, plumbing fixtures etc.
- Refractories are used as furnace linings for metal refining, glass manufacturing, metallurgical heat treatments etc.
- Abrasive ceramics are used to wear, ground or cut away other materials
- Advanced ceramics are used in optical fibre communication, microelectromechanical systems, ball bearings, piezoelectric components etc.

# Structure of ceramics

- For the ceramic materials with predominantly ionic bonding, the crystal structure consists of positively charged metallic ions or cations and negatively charged nonmetallic ions or anions
- The crystal structure of ceramics are determined by two factors:
  - The magnitude of the electrical charge on each of the component ions
  - The relative sizes of the cation and anion

# Structure of ceramics

With regard to the first factor:

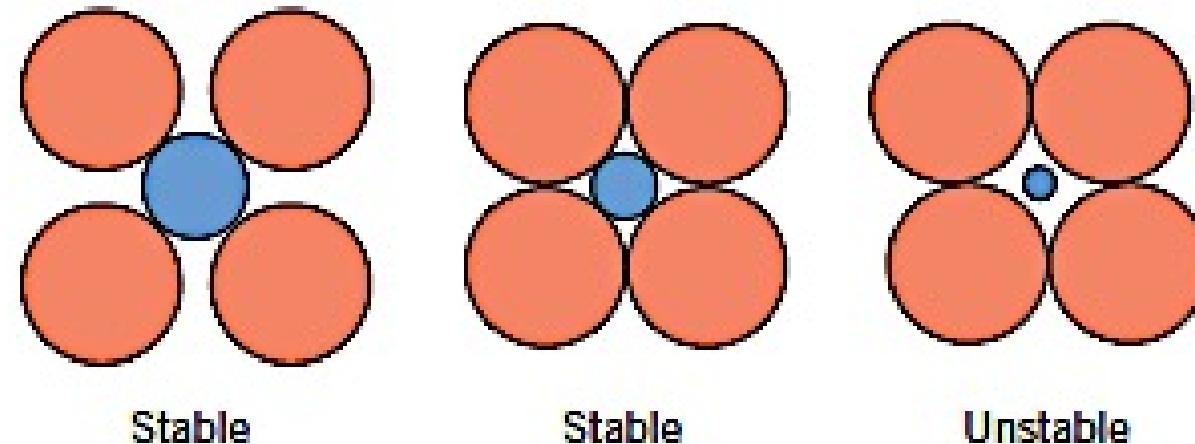
- The crystal must be electrically neutral
- All the cation positive charges must be balanced by an equal number of anion negative charges
- The chemical formula of a ceramic compound indicates the ratio of the cations to anions
- Consider  $\text{CaF}_2$  for example. As each Ca has +2 charge ( $\text{Ca}^{2+}$ ) and each F has -1 charge ( $\text{F}^-$ ), To attain charge balance, the number of  $\text{F}^-$  ions in should be double the number of  $\text{Ca}^{2+}$  ions, denoted by the formula  $\text{CaF}_2$ .

# Structure of ceramics

With regard to the second factor:

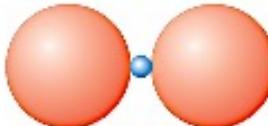
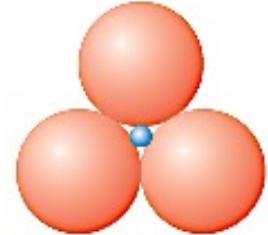
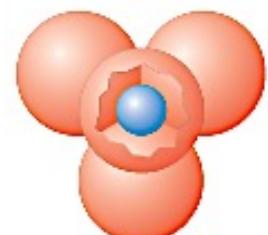
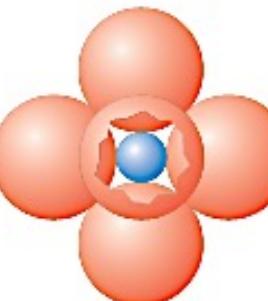
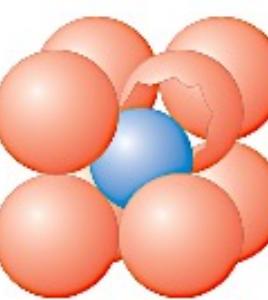
- It involves the ionic radii of the cations and anions,  $r_C$  and  $r_A$  respectively
- The cations are usually smaller than the anions and hence the ratio  $r_C/r_A < 1.0$
- Each cation prefers to have as many nearest neighbour anions as possible and vice versa
- **Stable ceramic configurations form when the anions surrounding a cation are all in touch with the cation**
- The co-ordination number is related to the cation/anion radius ratio. For a specific co-ordination number, there is a minimum  $r_C/r_A$  ratio for which this contact is made

# Structure of ceramics



Schematic of stable and unstable anion-cation coordination configurations. Red circles denote anions and blue circles denote cations

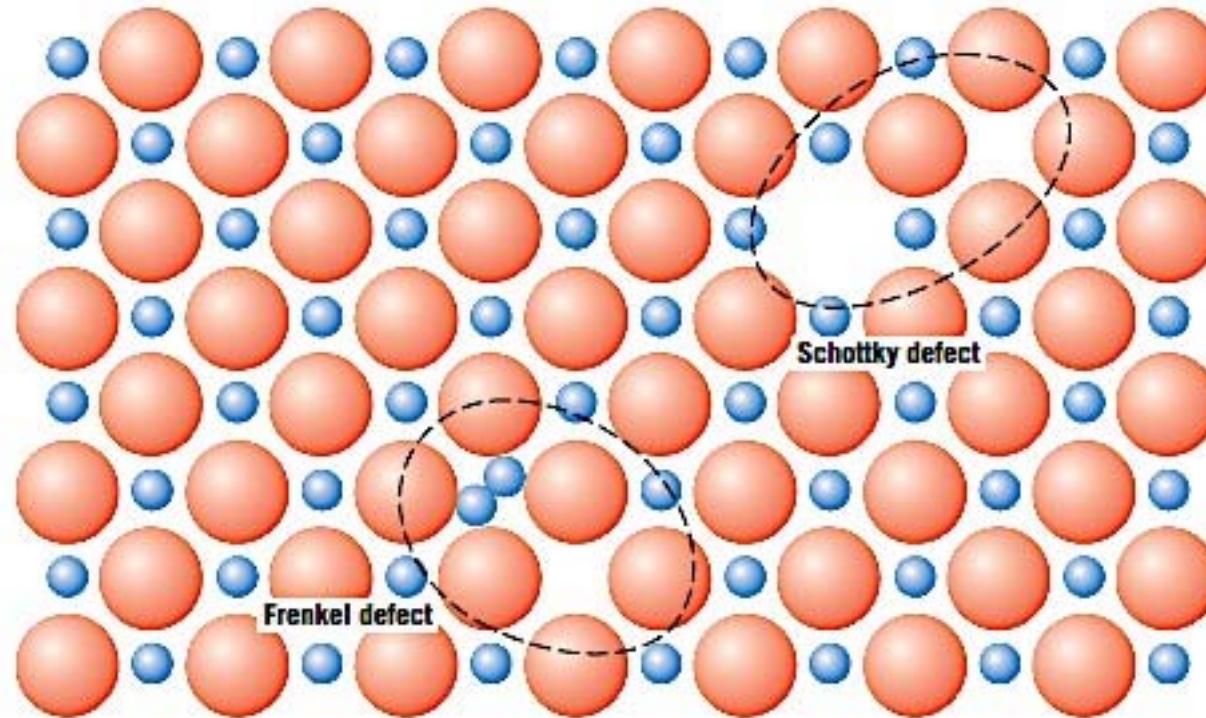
# Structure

<i>Coordination Number</i>	<i>Cation–Anion Radius Ratio</i>	<i>Coordination Geometry</i>
2	<0.155	
3	0.155–0.225	
4	0.225–0.414	
6	0.414–0.732	
8	0.732–1.0	

# Imperfections in ceramics

- As with metals, both vacancies and interstitials are possible in ceramics. As ceramics contain ions of at least two types, defects for each ion type may occur
- The term **defect structure** is often used to designate the types and concentrations of atomic defects in ceramics. The condition of electroneutrality must be maintained also while considering defect structures
- Two principal imperfections in ceramics are:
  - **Frenkel defect:** It is formed when a cation leaves its normal position and moves into an interstitial site
  - **Schottky defect:** In AX type ceramic, this can be thought of as removing one cation and one anion together from the interior of the structure

# Imperfections in ceramics

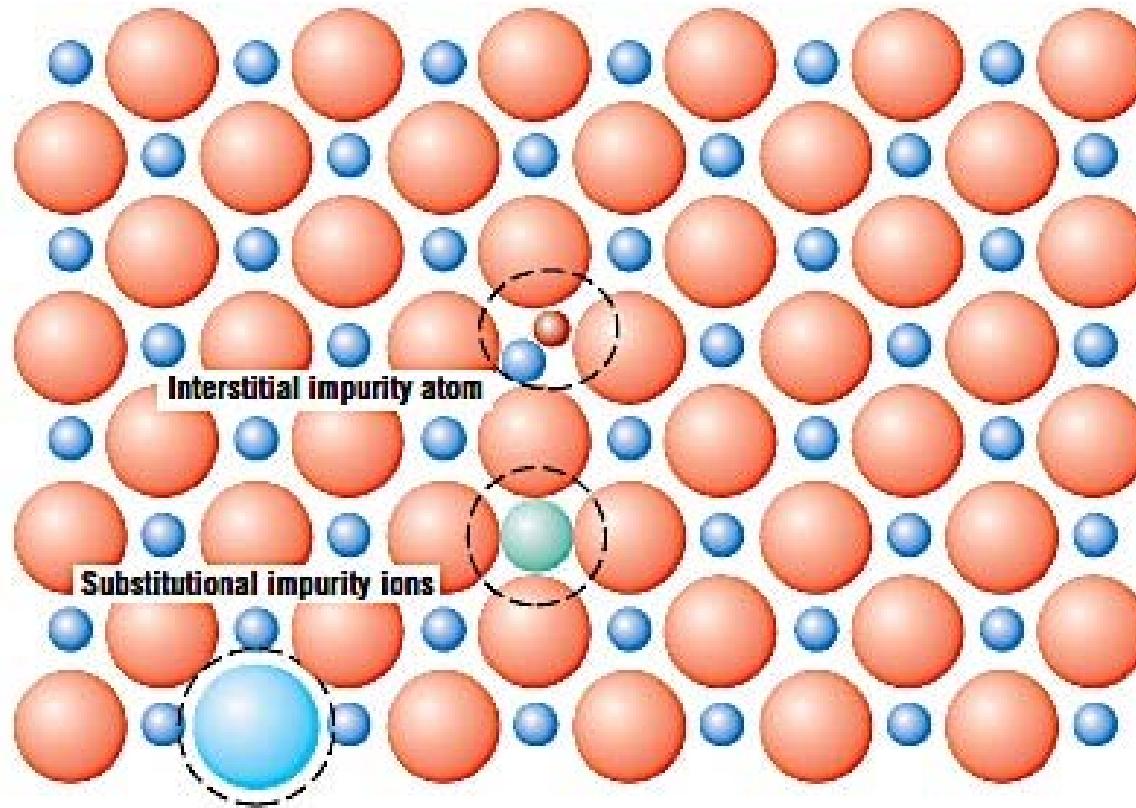


Schematic representation of Frenkel and  
Schottky defects

# Impurities in ceramics

- Impurity atoms can form solid solutions in ceramics just like in metals. Both substitutional and interstitial solid solutions are possible
- For an interstitial, the ionic radius of the impurity must be relatively small in comparison to the anion
- A substitutional impurity will substitute for the host ion to which it is most similar in electrical sense
- To achieve any appreciable solid solubility of the substitutional impurity ions, its ionic size and charge must be nearly the same as those of one of the host ions
- For different charge of the impurity, the difference must be compensated so that charge neutrality is maintained.

# Impurities in ceramics



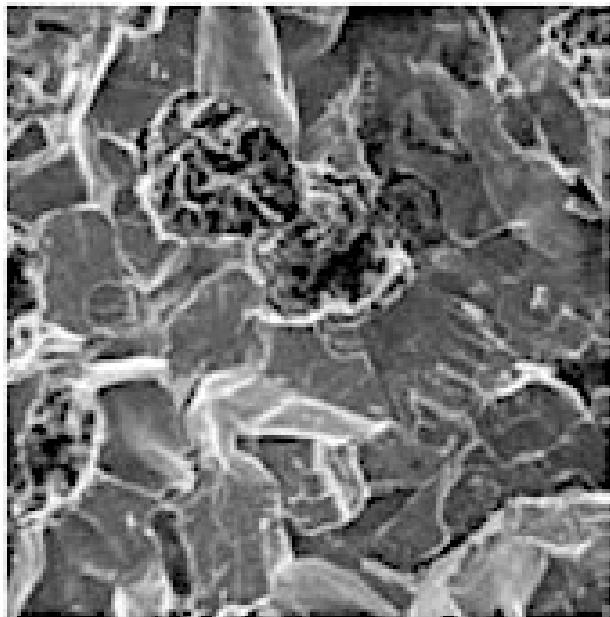
Schematic representation of interstitial, anion and cation substitutional impurity ions

# Mechanical properties of ceramics

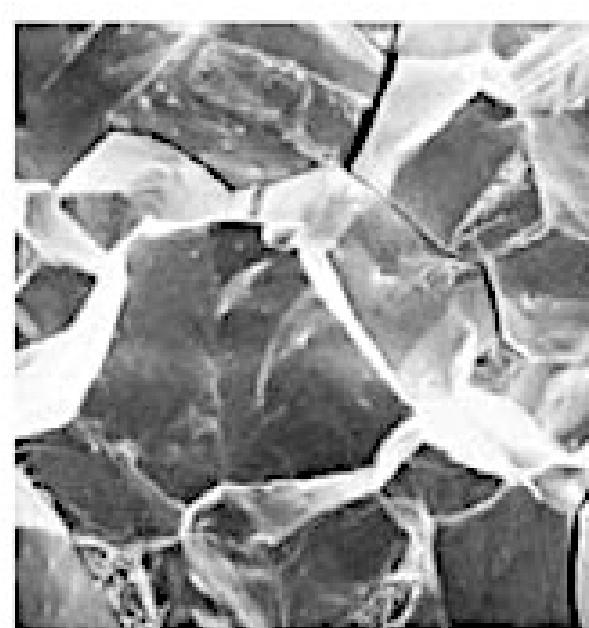
## Fracture

- At room temperature, both crystalline and non-crystalline ceramics under an applied tensile load almost always fracture without any plastic deformation
- The brittle fracture process consists of the formation and propagation of cracks through the material cross-section along a direction normal to the applied load
- Crack growth in crystalline ceramics may be either transgranular (i.e. through the grains) or intergranular (i.e. along grain boundaries)
- When fracture is transgranular, cracks propagate along specific crystallographic cleavage planes

# Mechanical properties of ceramics



A



B

A: Transgranular fracture

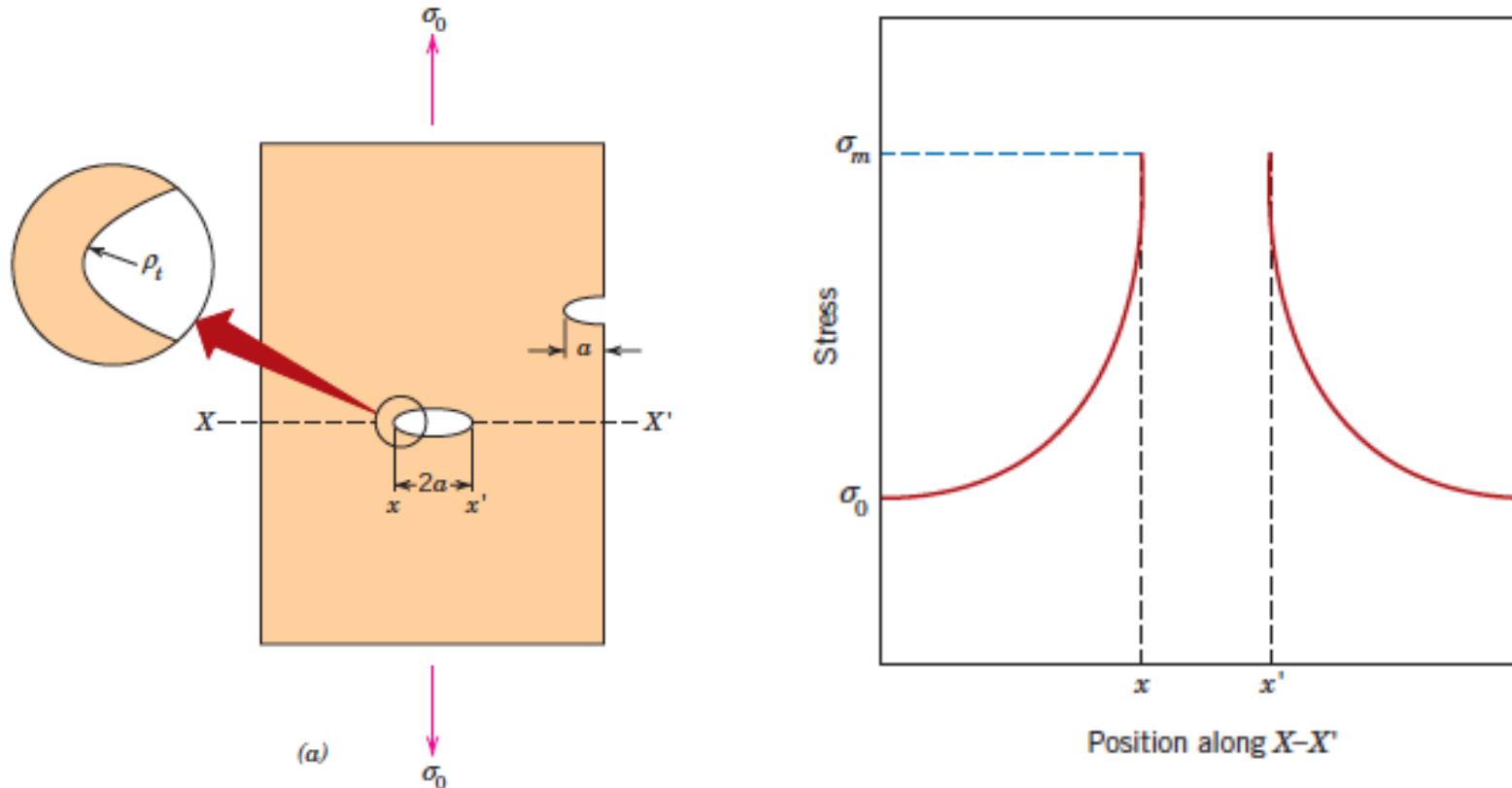
B: Intergranular fracture

# Mechanical properties of ceramics

## Fracture

- The substantially lower measured fracture strength of ceramics in comparison to the predicted theoretical strength is due to the very small omnipresent flaws in the material, which act as stress raisers
- These stress raisers may be minute surface or interior cracks, interior pores, inclusions etc.
- Stress concentration at the tip of a flaw may cause a crack to grow , until eventual failure
- Plane strain fracture toughness ( $K_{IC}$ ) of a ceramic is its resistance against propagation of a crack. The  $K_{IC}$  values for ceramics are typically low, typically  $< 10 \text{ MPa}\sqrt{\text{m}}$

# Stress concentration at crack tip



For an elliptical internal *crack of length  $2a$ , tip radius of curvature  $\rho_t$* , oriented normal to the *applied stress  $\sigma_0$*

$$\sigma_m = 2\sigma_0 \cdot \left( \frac{a}{\rho} \right)^{1/2}$$

$\sigma_m$  = Maximum stress at the crack tip

# Stress concentration at crack tip

$$K_t = \frac{\sigma_m}{\sigma_0} = 2 \cdot \left( \frac{a}{\rho_t} \right)^{1/2}$$

- The quantity  $K_t$  is known as – stress concentration factor
- Stress concentration factor increases with increasing crack length and decreasing crack tip radius
- The maximum stress at the crack tip for an internal crack with length  $2a$  is identical to that of a surface crack of length  $a$ 
  - ➔ Surface cracks are more deleterious than internal cracks

# Mechanical properties of ceramics

## Fracture

- When several specimens of a specific brittle ceramic material is tested, there is generally considerable scatter in the measured fracture strength
- This large scatter may be explained by the dependence of fracture strength on the probability of the existence of a critical flow capable of initiating fracture
- This probability varies from specimen to specimen and depends upon the fabrication route and subsequent treatment
- Normally, the larger the specimen size, the greater is the probability of existence of a critical flaw and the lower the fracture strength

# Mechanical properties of ceramics

## Fracture

- For applied compressive stresses, there is no stress amplification associated with pre-existent flaws
- Hence, brittle ceramics display much higher strengths in compression than in tension. Compressive strength of such ceramics is typically 10 times or even higher than their tensile strength
- Fracture strength of a brittle ceramic may also be significantly improved by imposing residual compressive stresses at the surface.

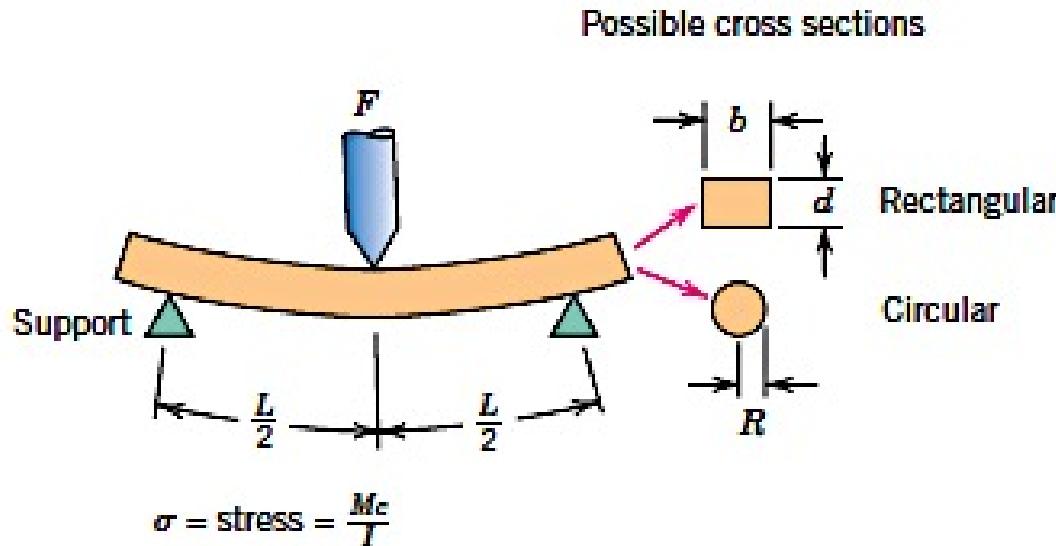
# Mechanical properties of ceramics

## Stress-strain behavior

- The stress-strain behavior of brittle ceramics is not usually determined by a tensile test because
  - It is rather difficult to prepare and test specimens having the required geometry
  - It is difficult to grip brittle materials for a tensile test without fracturing them
  - Ceramics fail at only about 0.1% strain. Hence, for the tensile test the specimens must be perfectly aligned to avoid bending
- Hence, either 3- or 4-point bending tests on rod specimens with circular or rectangular cross-sections are employed for ceramics

# Mechanical properties of ceramics

## Stress-strain behavior



where  $M$  = maximum bending moment

$c$  = distance from center of specimen  
to outer fibers

$I$  = moment of inertia of cross section

$F$  = applied load

	$\underline{M}$	$\underline{c}$	$\underline{I}$	$\underline{\sigma}$
Rectangular	$\frac{FL}{4}$	$\frac{d}{2}$	$\frac{bd^3}{12}$	$\frac{3FL}{2bd^2}$
Circular	$\frac{FL}{4}$	$R$	$\frac{\pi R^4}{4}$	$\frac{FL}{\pi R^3}$

# Mechanical properties of ceramics

## Stress-strain behavior

- At the point of loading, the top surface of the specimen is placed in a state of compression, while the bottom surface is in tension
- Stress is computed from the specimen thickness, the bending moment and the moment of inertia
- Stress at fracture from bending test is known as flexural strength, modulus of rupture or bending strength
- For a specimen with rectangular cross-section, the three point bedning strength is denoted as

$$\sigma_{fs} = \frac{3F_f L}{2bd^2}$$

Where  $F_f$  is the applied load at the point of fracture

# Mechanical properties of ceramics

## Stress-strain behavior

- The flexural strength depends upon the specimen size. With increasing specimen volume, there is an increase in the probability of the existence of a critical flaw → flexural strength decreases as specimen size increases
- The flexural strength of a ceramic body is also higher than its tensile strength
- In tensile test, the entire specimen is under tensile stress; whereas in bending test, only the elements close to the outer surface of the test-part is under tensile stress. Due to the lesser area under tensile stress in bending test, the flexural strength is higher

# Mechanical properties of ceramics

## Creep

- Ceramic materials often experience creep deformation as a result of stresses at elevated temperatures
- Generally, the time-deformation creep behavior of ceramics is similar to metals
- Creep in ceramics takes place however at higher temperatures
- To study the creep behavior of ceramics, high temperature compressive creep tests of ceramics are carried out

# Mechanical properties of ceramics

## Mechanism of plastic deformation – crystalline ceramics

- Plastic deformation occurs in crystalline ceramics by the movement of dislocations
- The high hardness and brittleness of ceramics are due to the difficulty against slip deformation
- In crystalline ceramics with predominantly ionic structure, very few slip systems are available for dislocation motion to occur → this is a direct consequence of the electrically charged nature of ions
- Crystalline ceramics with covalent structure are also hard and brittle as: a) the covalent bonds are strong, b) slip systems are limited and c) dislocation structure is complex

# Mechanical properties of ceramics

## Mechanism of plastic deformation – noncrystalline ceramics

- Plastic deformation does not occur by dislocation motion; rather it occurs by viscous flow – the same manner in which liquids deform
- The rate of deformation is proportional to applied stress
- Viscosity is the characteristic property for viscous flow and it is a measure of the noncrystalline material's resistance to deformation
- Noncrystalline ceramics have extremely high viscosities at ambient temperatures. The viscosity decreases, as the temperature increases

# Glass and glass ceramics

- Glasses are a familiar group of ceramics. They are noncrystalline silicates containing other oxides such as  $\text{Na}_2\text{O}$ ,  $\text{CaO}$ ,  $\text{K}_2\text{O}$ ,  $\text{Al}_2\text{O}_3$  that influence the glass properties
- The two main characteristics of glasses are:
  - Their optical transparency
  - The relative ease with which they may be fabricated
- Compositions, characteristics and applications of some common glass materials are mentioned in the next slide

# Glass and glass ceramics

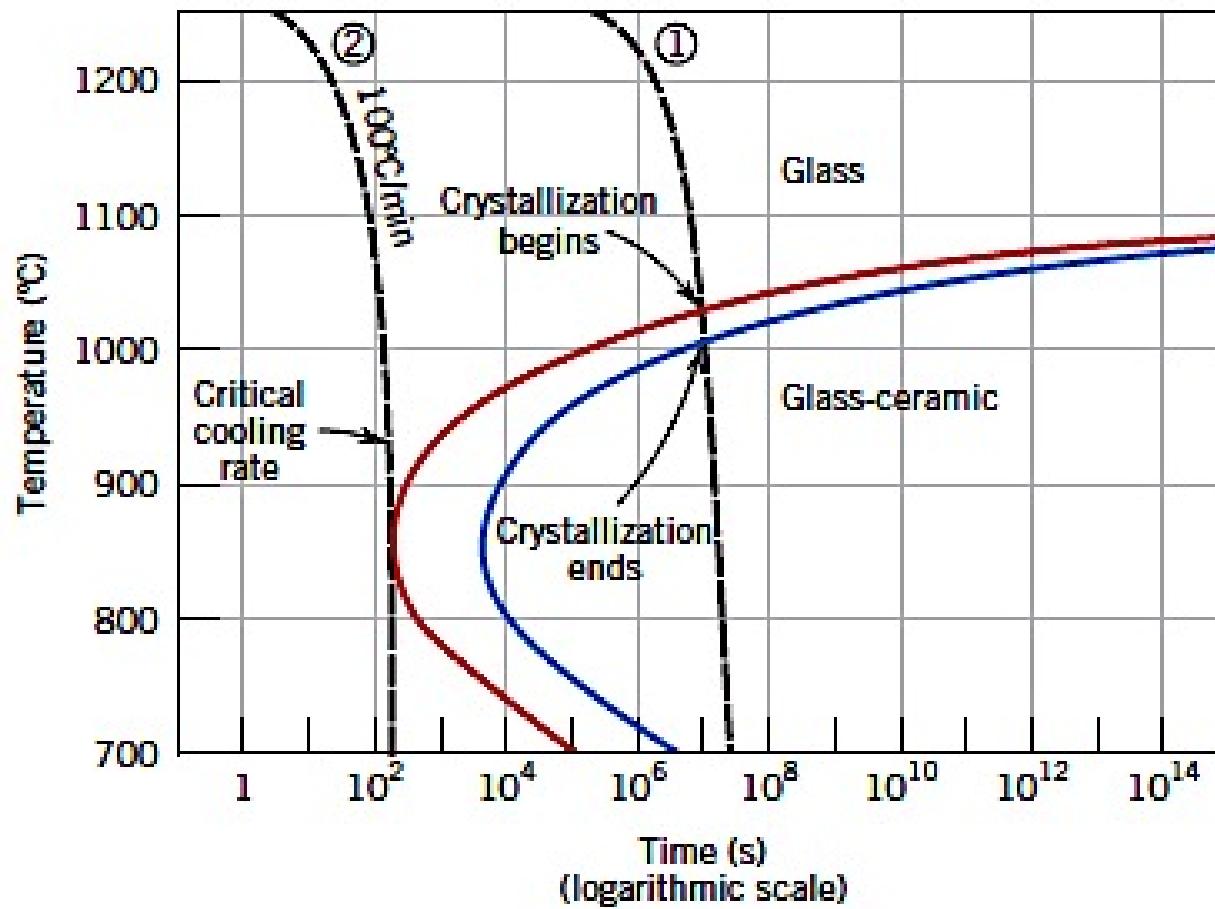
**Table 13.1 Compositions and Characteristics of Some of the Common Commercial Glasses**

Glass Type	Composition (wt%)						Characteristics and Applications
	$SiO_2$	$Na_2O$	$CaO$	$Al_2O_3$	$B_2O_3$	Other	
Fused silica	>99.5						High melting temperature, very low coefficient of expansion (thermally shock resistant)
96% Silica (Vycor)	96				4		Thermally shock and chemically resistant—laboratory ware
Borosilicate (Pyrex)	81	3.5		2.5	13		Thermally shock and chemically resistant—ovenware
Container (soda-lime)	74	16	5	1		4 MgO	Low melting temperature, easily worked, also durable
Fiberglass	55		16	15	10	4 MgO	Easily drawn into fibers—glass-resin composites
Optical flint	54	1				37 PbO, 8 K <sub>2</sub> O	High density and high index of refraction—optical lenses
Glass-ceramic (Pyroceram)	43.5	14		30	5.5	6.5 TiO <sub>2</sub> , 0.5 As <sub>2</sub> O <sub>3</sub>	Easily fabricated; strong; resists thermal shock—ovenware

# Glass and glass ceramics

- Most inorganic glasses can be transformed from a non-crystalline state to a crystalline state by proper high temperature heat treatment
- This heat treatment process is called crystallization and the formed fine grained polycrystalline material is called glass-ceramic
- The formation of these glass-ceramics is a process of phase transformation involving the stages of nucleation and growth.
- The dependence of the degree of transformation on temperature and time can be expressed via isothermal transformation and continuous cooling diagrams

# Glass and glass ceramics



Continuous cooling transformation diagram for the crystallization of a lunar glass

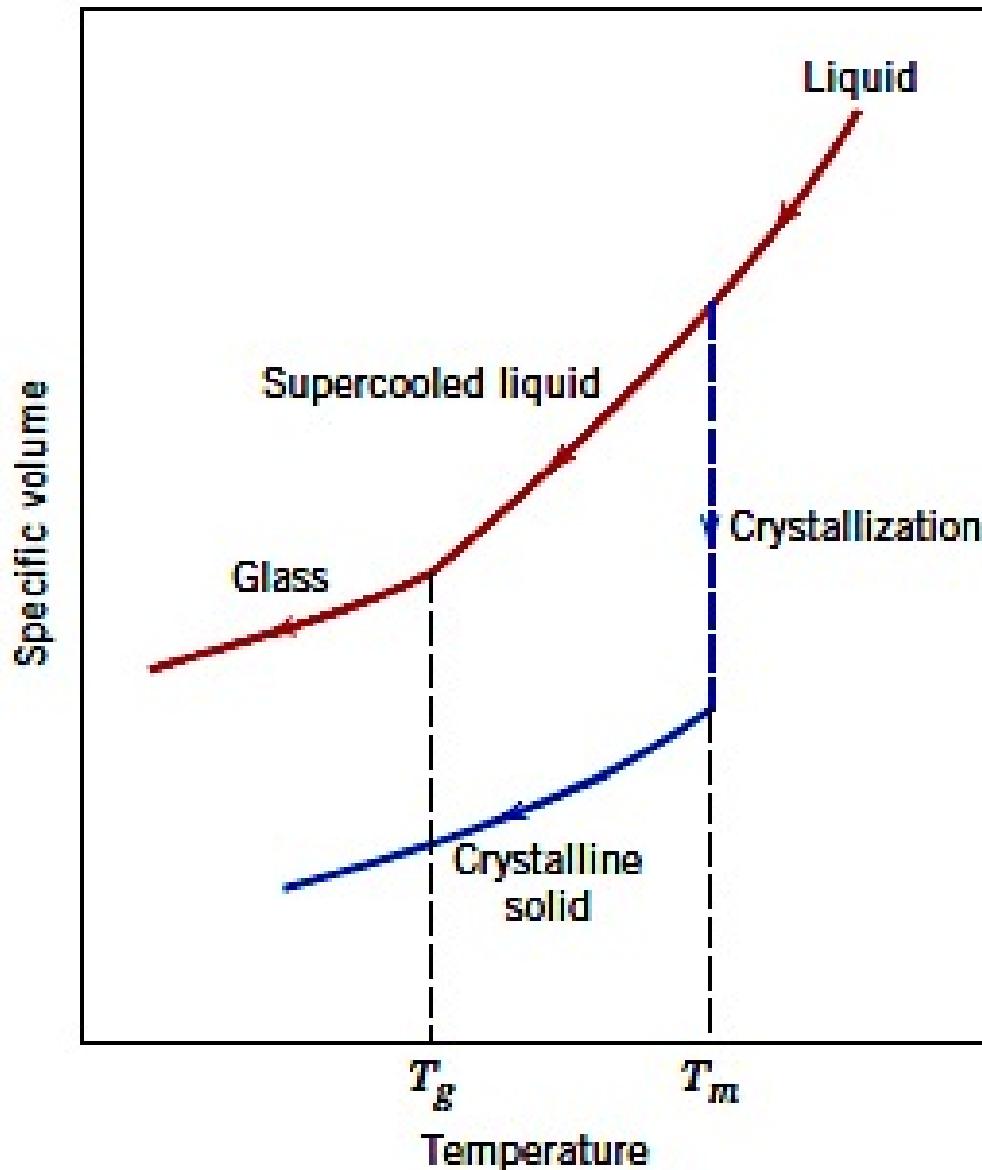
# Glass and glass ceramics

- The begin and end of transformation curves have the same general shape as for eutectoid steel
- Two cooling curves marked as 1 & 2 are shown
- The cooling rate for the curve 2 is >> for curve 1
- For curve 1, crystallization begins at the intersection with the upper curve, progresses with time and decreasing temperature. Finally upon crossing the lower curve, all of the glass crystallizes
- The curve 2 just misses the nose of the crystallization start curve. It is the critical minimum cooling rate for 100% glass formation. For slower cooling rates, some glass ceramic will form.

# Glass – temperature dependence

- Non-crystalline materials like glass do not solidify in the same manner like the crystalline solids
- Upon cooling, a glass becomes more and more viscous continuously with decreasing temperature
- There is no definite temperature at which a liquid transforms to solid, as with melting point of crystalline materials
- The dependence of the specific volume on temperature can be considered as one example to distinguish between crystalline and non-crystalline solids

# Glass – temperature dependence



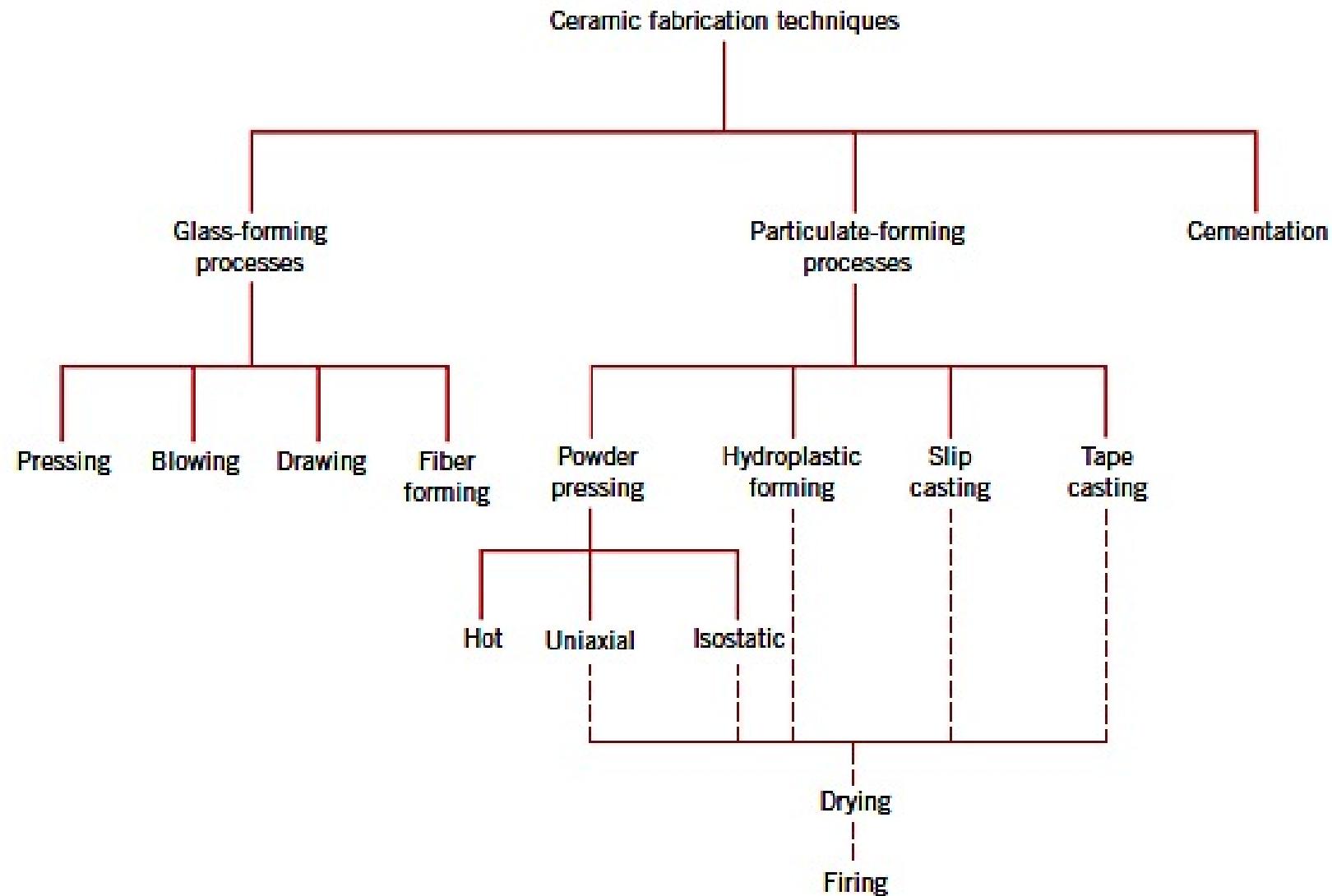
# Glass – temperature dependence

- For crystalline materials, there is a discontinuous decrease of specific volume at the melting temperature  $T_m$
- For glassy materials, the specific volume decreases continuously with a decrease in temperature
- At a temperature known as the **glass transition temperature ( $T_g$ )**, a slight decrease in the slope of the specific volume vs. Temperature curve occurs
- Below this temperature the material is considered to be a glass. Above this temperature, it is first a supercooled liquid and finally a liquid

# Fabrication & processing of ceramics

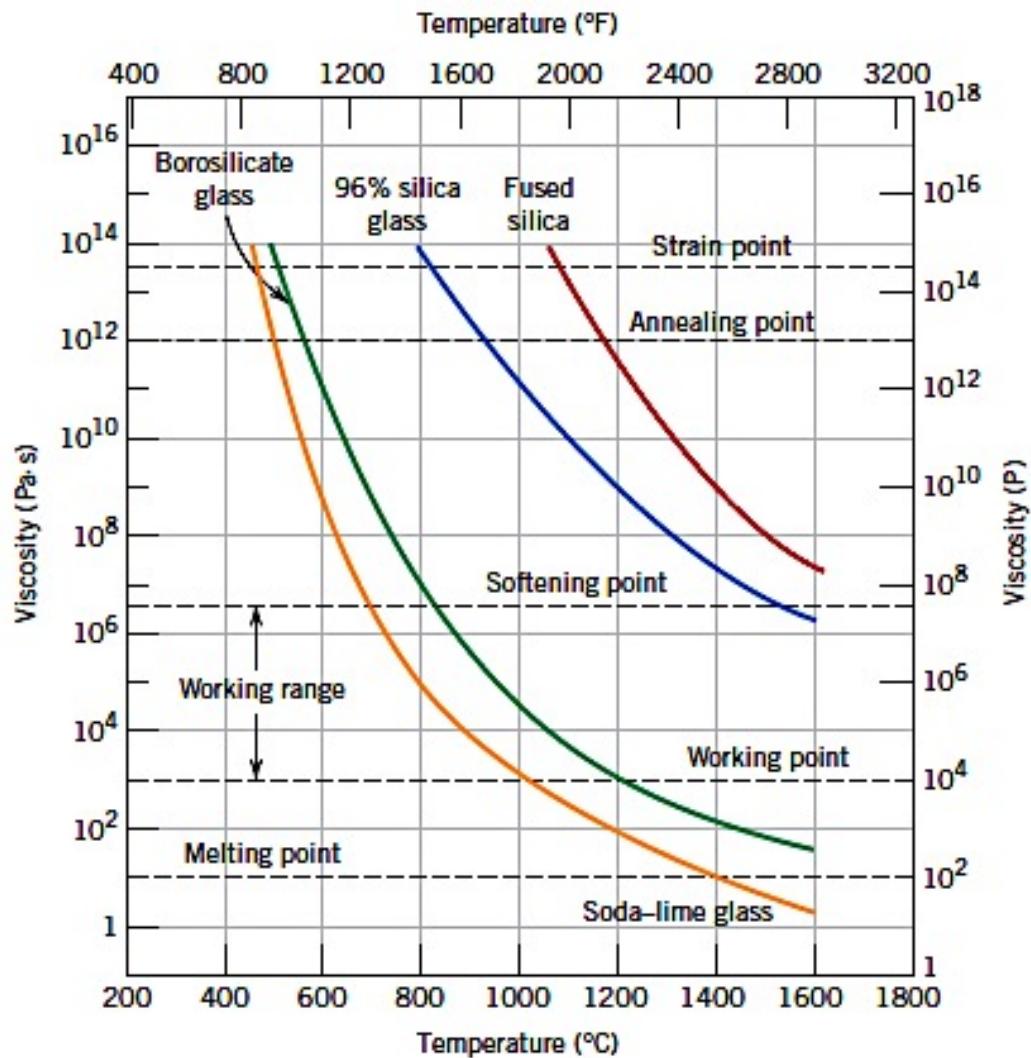
- As the melting points of ceramics are relatively high, casting of ceramics is normally impractical
- Additionally, due to their brittleness, forming operations are also not applicable to ceramics
- Hence, special forming techniques for ceramics are needed
- Powder forming by drying and firing of ceramics particulates is a common technique
- Glasses are formed at elevated temperatures from a fluid mass that becomes very viscous upon cooling

# Fabrication & processing of ceramics



# Glass forming – effect of temperature

Viscosity-temperature characteristics of the glass are important in glass forming operations



Plot of logarithm of viscosity vs. temperature for four different glasses

# Glass forming – effect of temperature

In relation to glass forming operation, several viscosity ranges are of importance:

**Melting point:** It corresponds to the temperature at which the viscosity is 10 Pa.s. The glass is fluid enough to be considered as a liquid

**Working point:** It corresponds to the temperature at which the viscosity is  $10^3$  Pa.s. The glass is easily deformed at this point

**Softening point:** It corresponds to the temperature at which the viscosity is  $4 \times 10^6$  Pa.s. This is the maximum temperature at which the glass piece may be handled without causing significant dimensional alterations

# Glass forming – effect of temperature

**Annealing point:** It corresponds to the temperature at which the viscosity is  $10^{12}$  Pa.s. Atomic diffusion is sufficiently rapid at this temperature so that any residual stresses may be removed within 15 minutes

**Strain point:** It corresponds to the temperature at which the viscosity is  $3 \times 10^{13}$  Pa.s. At temperatures below the strain point, fracture will occur before the onset of plastic deformation

Most glass forming operations are carried out between the working and the softening temperatures

# Powder processing

- Powder processing is used to fabricate both clay and non-clay products, including electronic and magnetic ceramics as well as some refractory brick products
- A powdered mass, usually containing a small amount of water or binder, is first compacted into the desired shape by pressure.
- Coarse and fine powders are mixed in different proportions in order to maximize the degree of compaction and minimize the fraction of void space
- One function of the binder is to lubricate the powder particles as they move past one another in the compaction process

# Powder processing

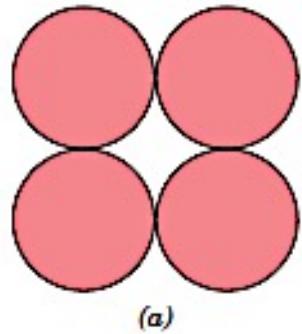
Three basic powder pressing procedures are available:

- 1) **Uni-axial pressing:** The powder is compacted in a metal die by pressure applied along one single direction. The formed piece takes on the shape of the die and the platens. The method is confined to shapes that are simple; however the production rate is high and the process is inexpensive
- 2) **Isostatic pressing:** The powder is contained in a rubber envelope and the pressure is applied isostatically by a fluid. More complicated shapes are possible; however, the process is more time consuming and expensive
- 3) **Hot pressing:** will be discussed later

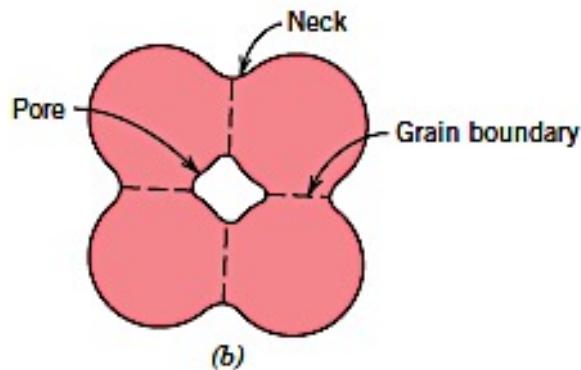
# Powder processing

- For both uni-axial and isostatic procedures, a firing operation is required after the pressing step
- During firing the formed part shrinks and experiences a reduction in porosity and an improvement in mechanical properties
- It occurs by the coalescence of the powder particles into a more dense mass → **sintering**

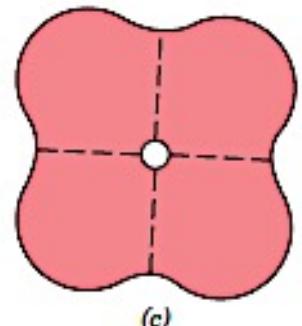
# Powder processing



Schematic representation of powder particles after pressing



Particle coalescence and pore formation as sintering begins



As sintering proceeds, the pores change size and shape and become smaller

# Powder processing

- Powder particles touch each other after powder pressing
- Sintering is carried out below the melting point of the species. Mass transport necessary for sintering takes place via atomic diffusion
- During the initial sintering stage, necks begin to form along the contact regions between adjacent particles and the interstices between the particles become pores
- As sintering progresses, the pores continuously become smaller and more spherical in shape
- The driving force for sintering is the reduction in total particle surface area. As sintering progresses, the total particle surface area decreases

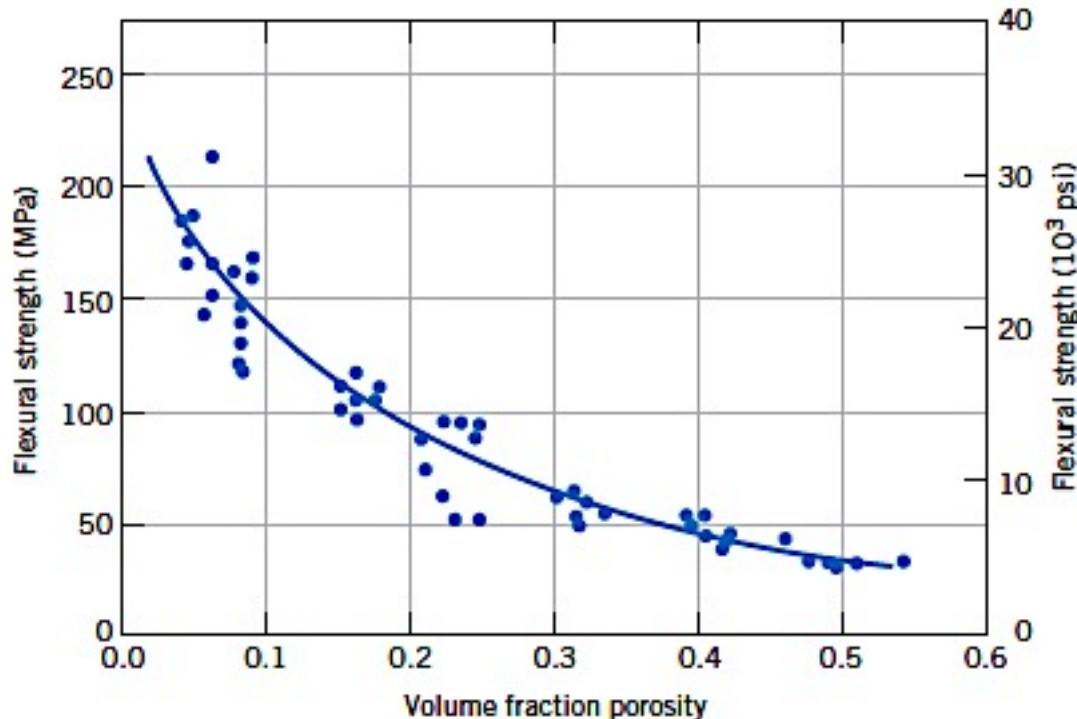
# Powder processing

## Hot pressing

- In hot pressing the powder aggregate is compacted at elevated temperatures – it is a combination of powder pressing and heat treatment in one step
- Hot pressing is employed when high part density without appreciable grain growth is aimed for
- The main drawbacks of the process are its high cost and due to the challenging process parameters (high pressure at high temperatures) the mold normally has a short lifetime

# Effect of porosity on properties

- For the ceramic parts fabricated via powder processing route, some residual porosity will always remain in the parts after sintering
- Any residual porosity will have a deleterious effect on the elastic properties and strength of the ceramic part

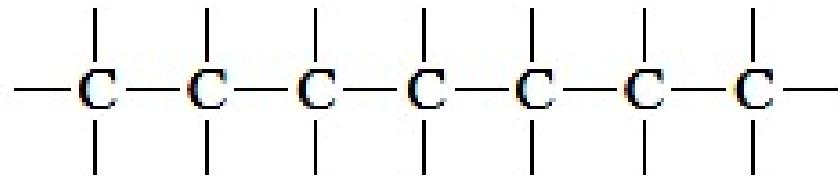


Pores reduce the flexural strength by acting as stress raisers and reducing the total load bearing area

# Lecture 2

# Polymer

- Polymers are organic materials. The molecules in polymers are gigantic and because of their size they are often referred to as macromolecules.
- Within each molecule, the atoms are bound together by covalent interatomic bonds
- For carbon chain polymers, the backbone of each chain is a string of carbon atoms as shown below



- Each of the two remaining valence electrons for each carbon atom may be involved with atoms or radicals

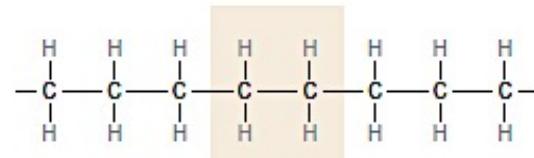
# Polymer

## Repeat units

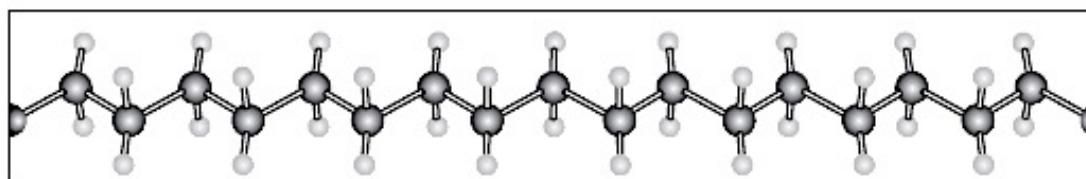
The macromolecules of polymers are composed of structural elements which are successively repeated along the chain. They are known as repeat units.

## Monomer

Monomer refers to the small molecule from which a polymer is synthesized



(a)



(b)

Schematic  
representation of the  
structure of  
polyethylene

# Polymer

<i>Polymer</i>	<i>Repeat Unit</i>	
Polyethylene (PE)	$\begin{array}{c} \text{H} & \text{H} \\   &   \\ -\text{C} & -\text{C}- \\   &   \\ \text{H} & \text{H} \end{array}$	
Poly(vinyl chloride) (PVC)	$\begin{array}{c} \text{H} & \text{H} \\   &   \\ -\text{C} & -\text{C}- \\   &   \\ \text{H} & \text{Cl} \end{array}$	
Polytetrafluoroethylene (PTFE)	$\begin{array}{c} \text{F} & \text{F} \\   &   \\ -\text{C} & -\text{C}- \\   &   \\ \text{F} & \text{F} \end{array}$	
Polypropylene (PP)	$\begin{array}{c} \text{H} & \text{H} \\   &   \\ -\text{C} & -\text{C}- \\   &   \\ \text{H} & \text{CH}_3 \end{array}$	
Polystyrene (PS)	$\begin{array}{c} \text{H} & \text{H} \\   &   \\ -\text{C} & -\text{C}- \\   &   \\ \text{H} & \text{C}_6\text{H}_5 \end{array}$	Repeat units for some common polymers

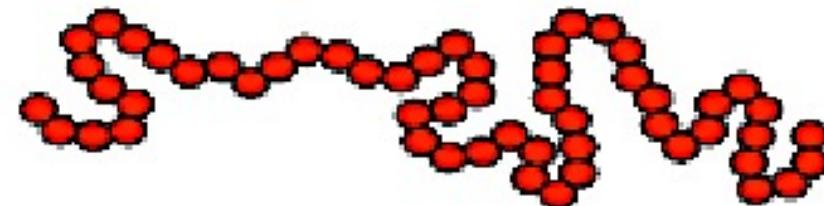
# Polymer

- When all of the repeating units along a polymer chain are of the same type, the resulting polymer is called a **homopolymer**
- If the polymer chains are composed of two or more different repeat units, they are known as **copolymers**.  
Copolymers are further classified as:
  - In **random copolymers** the two different units are dispersed randomly along the chain
  - In **alternate copolymers**, the two repeat units alternate chain positions
  - A **block copolymer** is one in which the identical repeat units are clustered in blocks along the chain

# Polymer

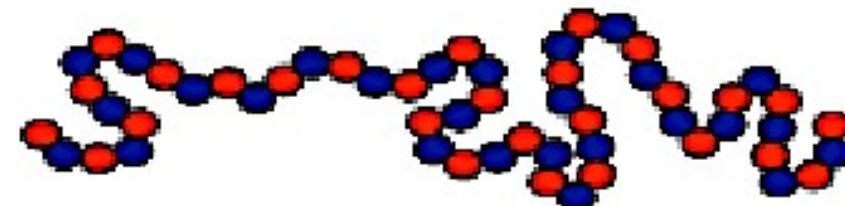
Homopolymer

Linear

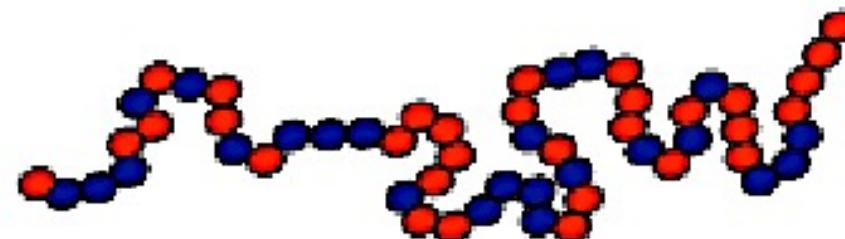


Copolymer

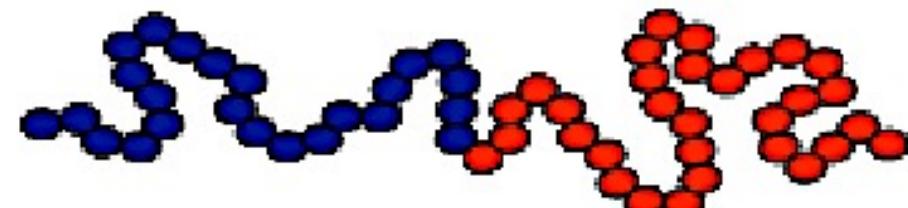
Alternating



Random or  
statistical



Block



# Polymer

## Molecular weight of polymers

- Extremely large molecular weights are observed in polymers with very long chains
- The **degree of polymerization (DP)** represents the average number of repeat units in a polymer chain. It is the ratio of the number average molecular weight of the polymer to the repeat unit molecular weight of the polymer

# Polymer

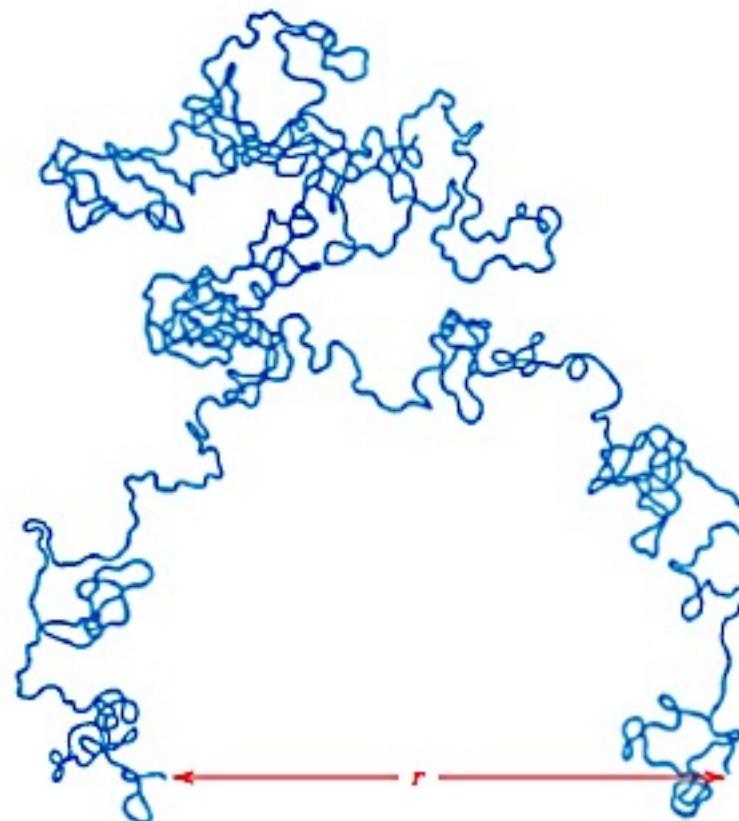
## Molecular weight of polymers

- Many polymer properties are affected by the length of the polymer chain
- The melting or softening temperature increases with increasing molecular weight of the polymer
- At room temperature, polymers with very short chains with molecular weights in the range of 100 g/mol generally exist as liquids
- Polymers with molecular weights of approx. 1000 g/mol are waxy solids, while solid polymers have molecular weights > 10000 g/mol
- Thus, the same polymer material can have very different properties depending upon its molecular weight

# Polymer

## Molecular shape

- Polymers consist of large numbers of molecular chains, each of which may bend, coil or kink in the manner shown below



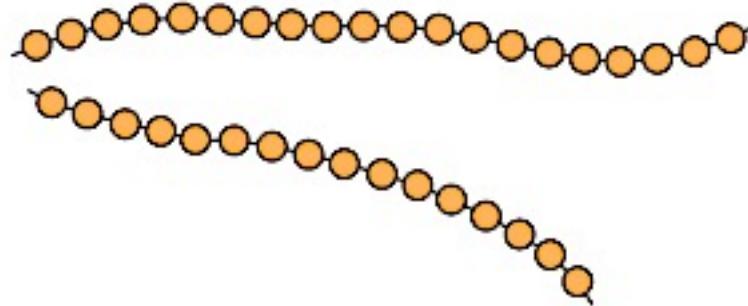
# Polymer

## Molecular shape

- This leads to extensive intertwining and entanglement of neighboring chain molecules
- These random coils and molecular entanglements are responsible for a number of important polymer characteristics
- Some mechanical and thermal properties of polymers are a function of the chain segments to experience rotation in response of applied stress or thermal energy
- Regions of chain segment with double bond or presence of bulky or large side group of atoms restricts rotational movement

# Polymer molecular structure

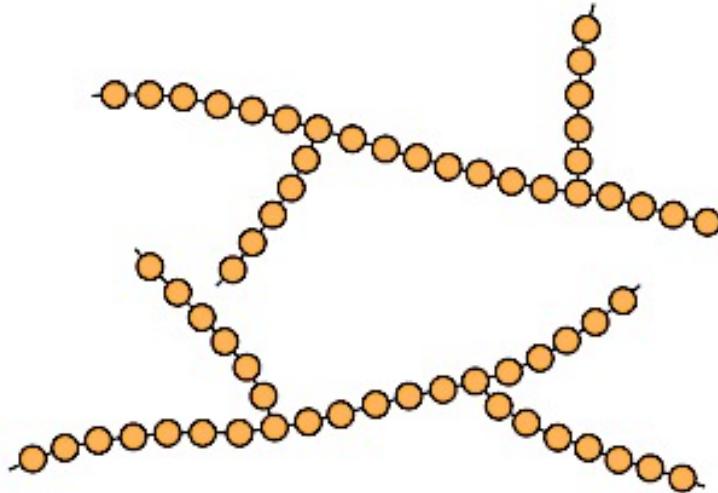
## Linear polymers



- In linear polymers the repeat units are joined together end to end in single chains
- The long chains are flexible and may be thought of as a mass of spaghetti
- There may be extensive van der Waals and hydrogen bonding between the chains
- Examples of polymers with linear structure are polyethylene, nylon, poly vinyl chloride etc.

# Polymer molecular structure

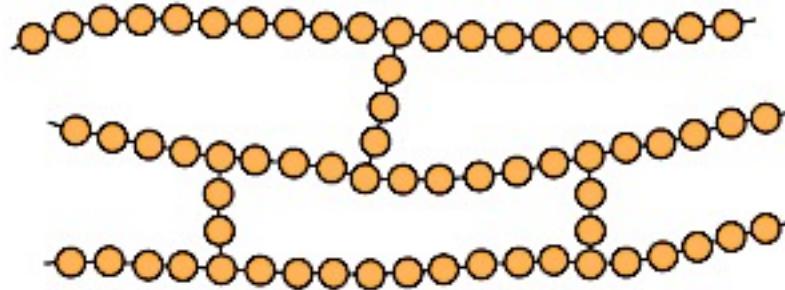
## Branched polymers



- Branched polymers are polymers in which side-branch chains are connected to the main ones
- The chain packing efficiency is reduced with the formation of side branches, which results in a lowering of polymer density
- Polymers with linear structures may also be branched
- High density polyethylene is a linear polymer while low density polyethylene has a branched structure

# Polymer molecular structure

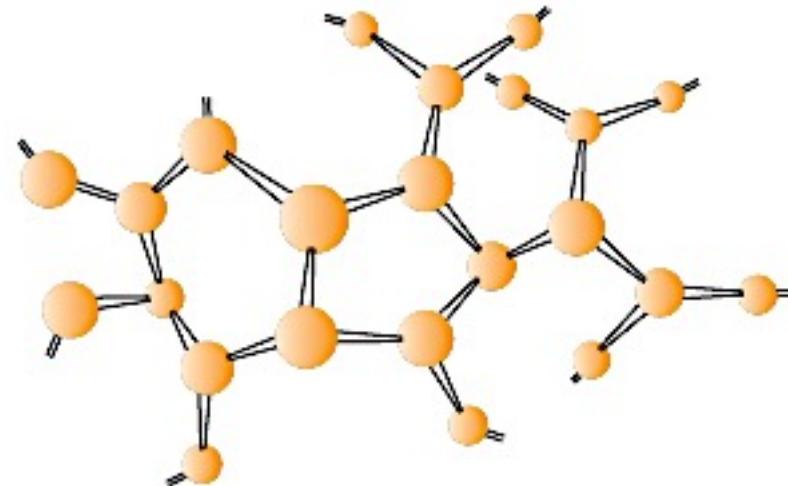
## Crosslinked polymers



- In crosslinked polymers the adjacent linear chains are joined to one another at various points by covalent bonds
- The process of crosslinking is achieved either during synthesis or by a nonreversible chemical reaction
- Many of the rubber elastic materials are crosslinked

# Polymer molecular structure

## Network polymers

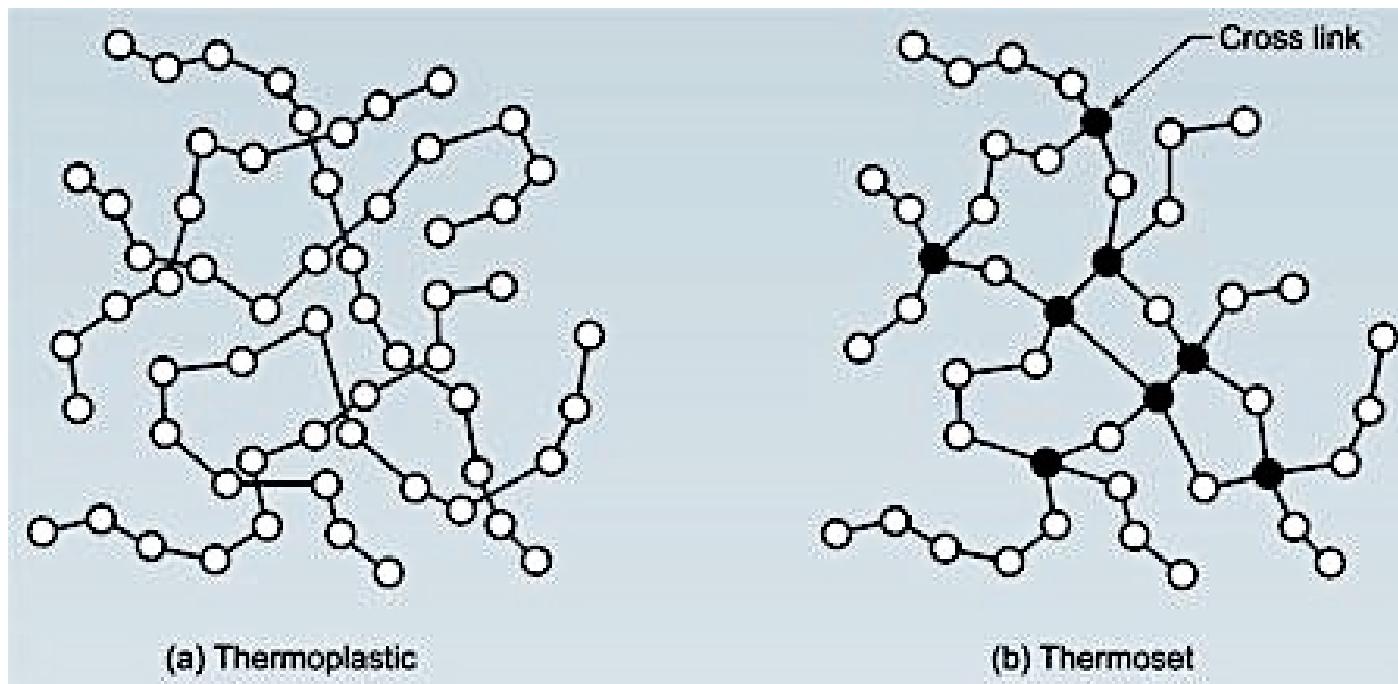


- Multifunctional monomers forming three or more active covalent bonds make 3-dimensional networks and are called network polymers
- A highly crosslinked polymer may also be called a network polymer
- Epoxies, polyurethanes and phenol-formaldehyde belong to this class

# Thermoplastic & thermosetting polymers

In terms of their behavior with an increase in temperature, polymers are classified in two groups:

- Thermoplastic polymers
- Thermosetting polymers



# Thermoplastic polymers

- Thermoplastics soften and eventually liquify when heated and harden when cooled – these processes are totally reversible and may be repeated
- Most linear polymers and those having some branched structures with flexible chains are thermoplastics
- Irreversible degradation occurs when a thermoplast is heated to too high a temperature
- Thermoplasts are relatively soft
- They are normally fabricated by the simultaneous application of heat and pressure
- Examples of common thermoplastic polymers are polyethylene, polystyrene, poly vinyl chloride etc.

# Thermoplastic polymers

Plastic Name	Products	Properties
Polyamide (Nylon)		Bearings, gear wheels, casings for power tools, hinges for small cupboards, curtain rail fittings and clothing Creamy colour, <i>tough</i> , fairly <i>hard</i> , resists wear, <i>self-lubricating</i> , good resistance to chemicals and machines
Polymethyl methacrylate (Acrylic)		Signs, covers of storage boxes, aircraft canopies and windows, covers for car lights, wash basins and baths Stiff, hard but scratches easily, durable, <i>brittle</i> in small sections, good electrical insulator, machines and polishes well
Polypropylene		Medical equipment, laboratory equipment, containers with built-in hinges, 'plastic' seats, string, rope, kitchen equipment Light, hard but scratches easily, tough, good resistance to chemicals, resists <i>work fatigue</i>
Polystyrene		Toys, especially model kits, packaging, 'plastic' boxes and containers Light, hard, stiff, transparent, brittle, with good water resistance
Low density polythene (LDPE)		Packaging, especially bottles, toys, packaging film and bags Tough, good resistance to chemicals, flexible, fairly soft, good electrical insulator
High density polythene (HDPE)		Plastic bottles, tubing, household equipment Hard, stiff, able to be sterilised

# Thermosetting polymers

- Thermosetting polymers are network polymers
- They become permanently hard during their formation and do not soften upon heating
- They have covalent crosslinks between adjacent molecular chains. During heating these bonds anchor the chains together & resist the motion
- Cross-linking is extensive in that 10 – 50% of the chain repeat units are crosslinked
- Heating to excessive temperatures cause severance of these crosslinked bonds and polymer degradation
- Thermosets are harder and stronger than thermoplasts and have better dimensional stability
- Vulcanized rubbers, epoxies, resins are typical examples

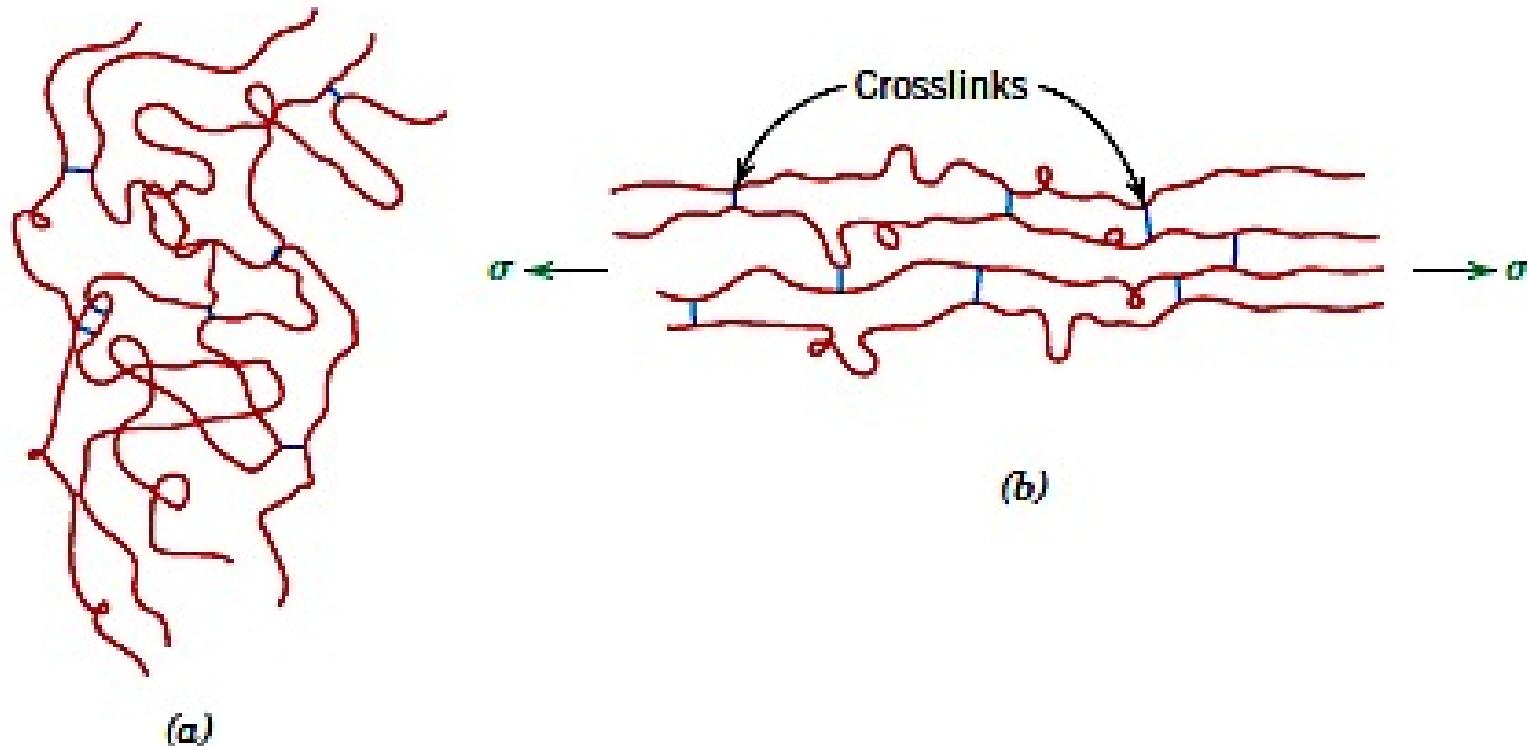
# Thermosetting polymers

Plastic Name	Products	Properties	
Epoxy resin		Casting and encapsulation, adhesives, bonding of other materials	Good electrical insulator, hard, brittle unless reinforced, resists chemicals well
Melamine formaldehyde		Laminates for work surfaces, electrical insulation, tableware	Stiff, hard, strong, resists some chemicals and stains
Polyester resin		Casting and encapsulation, bonding of other materials	Stiff, hard, brittle unless laminated, good electrical insulator, resists chemicals well
Urea formaldehyde		Electrical fittings, handles and control knobs, adhesives	Stiff, hard, strong, brittle, good electrical insulator

# Elastomers

- One of the fascinating properties of elastomers is their rubberlike elasticity → ability to be deformed to quite large deformations and then elastically spring back to original form
- This results from the crosslinks in the polymer that provide a force to restore the chains to their undeformed configuration
- In an unstressed condition, an elastomer is amorphous and composed of crosslinked molecular chains that are highly twisted, kinked and coiled
- Elastic deformation upon application of tensile stress partially uncoils and straightens the chains along the loading direction

# Elastomers



- Upon release of the stress, the chains springback to their prestressed configurations, and the macroscopic piece retains its original shape

# Elastomers

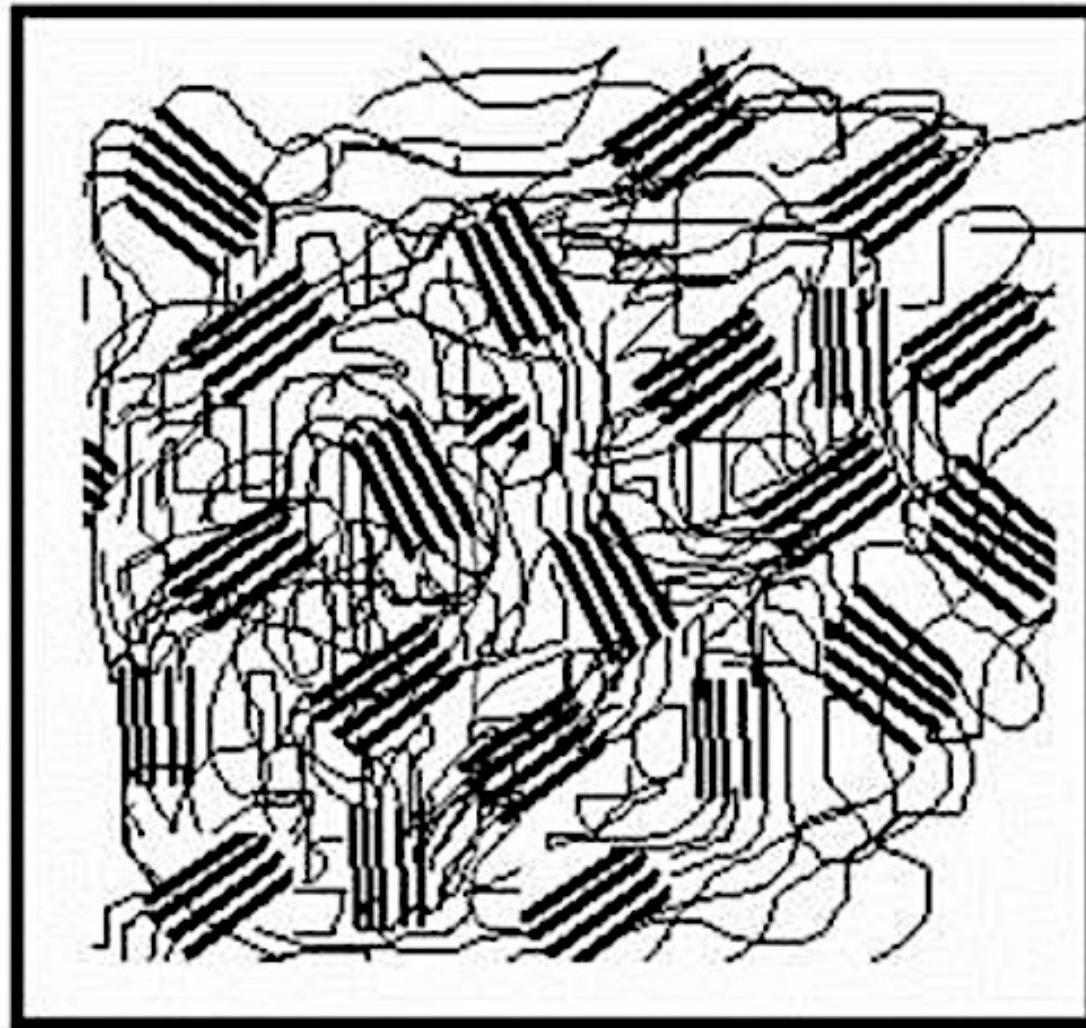
Several criteria must be met for a polymer to be elastomer:

- It must not easily crystallize, elastomeric materials are amorphous materials having chains that are naturally kinked and coiled
- Chain bond rotations must be relatively free for the coiled chains to readily respond to an applied stress
- For elastomers to achieve relatively large elastic deformation, onset of plastic deformation must be avoided. Restricting the motion of the chains via crosslinking achieves this
- The elastomer must be above its glass transition temperature. Below this temperatures elastomers become brittle

# Polymer crystallinity

- Polymer crystallinity can be thought of as the packing of molecular chains to produce an ordered array
- As a consequence of their size and complicated structure, polymer molecules are often only partially crystalline (or semicrystalline), with crystalline regions dispersed within the remaining amorphous material
- Any chain disorder or misalignment caused by twisting, kinking and coiling of the chains will result in an amorphous region.
- Due to its prevalent structure, a polymer is never 100% crystalline. The degree of crystallinity may range from completely amorphous to almost entirely crystalline (up to about 95%)

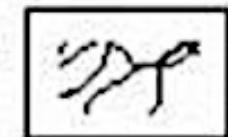
# Polymer crystallinity



Crystalline region



Amorphous Region



# Polymer crystallinity

- The density of a crystalline polymer is greater than an amorphous structure of the same material and molecular weight, as in a crystalline structure the chains are more closely packed together
- The degree of crystallinity is defined as:

$$\%crystallinity = \frac{\rho_c(\rho_s - \rho_a)}{\rho_s(\rho_c - \rho_a)} \times 100$$

$\rho_s$  = Density of the polymer sample

$\rho_c$  = Density of the perfectly crystalline polymer

$\rho_a$  = Density of the totally amorphous polymer

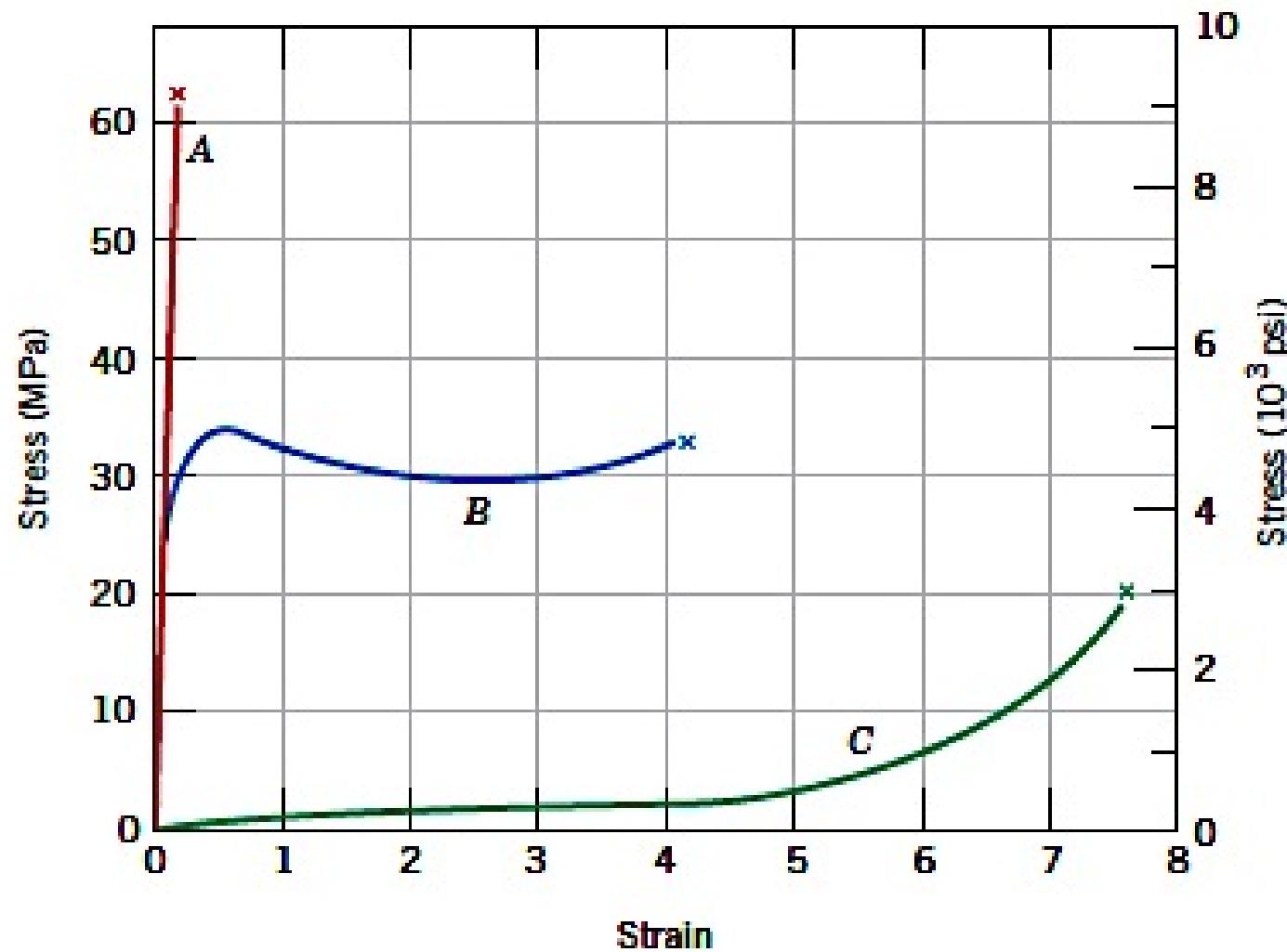
# Polymer crystallinity

- The degree of crystallinity of a polymer depends upon the rate of cooling during solidification and the chain configuration
- The chains are in a highly random and disordered state in the viscous liquid and for them to attain an ordered state, sufficient time needs to be allowed
- Crystallization is not favored in polymers that are composed of chemically complex repeat units
- On the other hand, in chemically simple polymers such as polyethylene, crystallization is not prevented even for very rapid cooling rates

# Polymer crystallinity

- Crystallinity is easily accomplished in linear polymers as there are very few restrictions to stop chain alignment
- Presence of side branches interferes with crystallization and so branched polymers are never highly crystalline.
- Most network and crosslinked polymers are almost totally amorphous as the crosslinks prevent the polymer chains from rearranging
- For co-polymers, the more random and irregular the arrangement of the repeat units, the lesser is the tendency to develop crystallinity
- The higher the crystallinity, the stronger the polymer and the lesser is its tendency to softening by heat

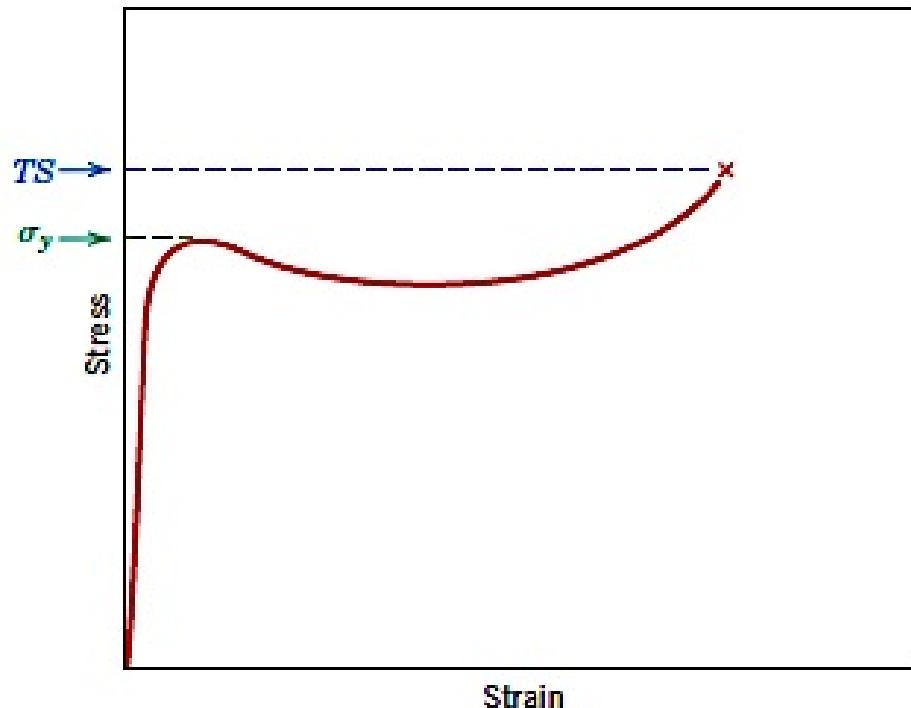
# Stress-strain behavior of polymers



# Stress-strain behavior of polymers

- The mechanical properties of polymers are highly sensitive to the rate of deformation, the temperature and the chemical nature of the environment
- Three typically different stress-strain curve variants are observed for polymers
- **Curve A** illustrates the stress-strain behavior of a brittle polymer – it fractures while deforming elastically
- **Curve B** illustrates the stress-strain behavior of a plastic polymer – the initial deformation is elastic, followed by yielding and a region of plastic deformation
- **Curve C** illustrates the totally elastic rubber like stress-strain behavior (large recoverable strains at low stress levels)

# Stress-strain behavior of polymers



Schematic stress-strain plot for a plastic polymer showing the determination of yield and tensile strength

- **Yield strength** is the maximum on the curve, occurring just beyond the termination of the linear elastic region
- **Tensile strength** is the stress at which fracture occurs
- For plastic polymers, tensile strength may be lower than yield strength

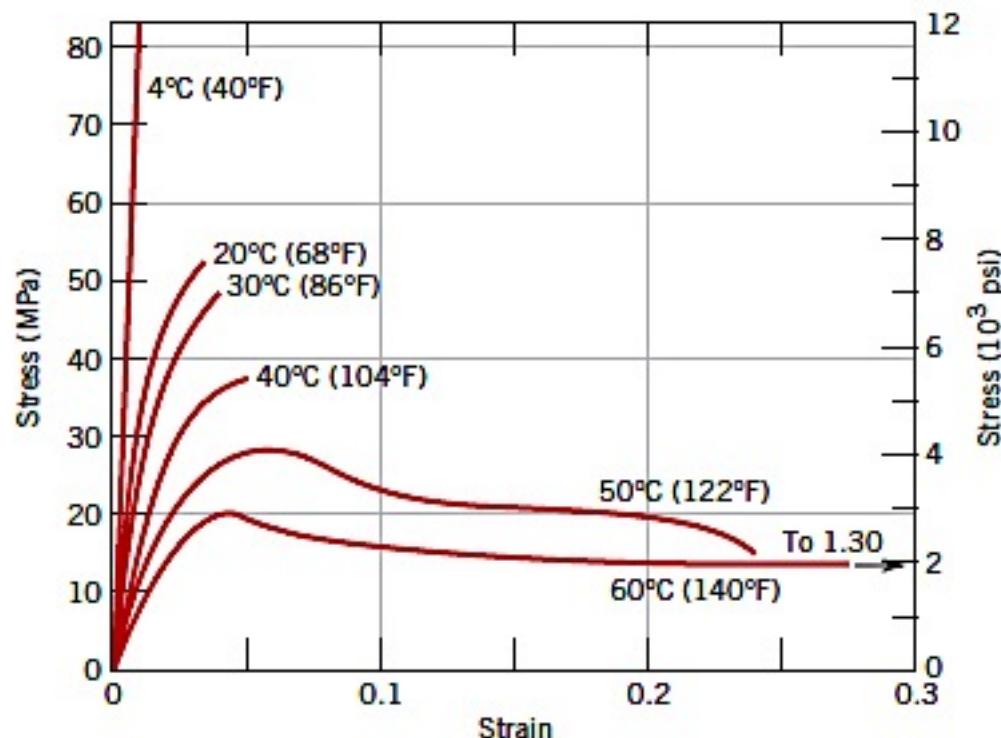
# Stress-strain behavior of polymers

**Table 15.1 Room-Temperature Mechanical Characteristics of Some of the More Common Polymers**

<i>Material</i>	<i>Specific Gravity</i>	<i>Tensile Modulus [GPa (ksi)]</i>	<i>Tensile Strength [MPa (ksi)]</i>	<i>Yield Strength [MPa (ksi)]</i>	<i>Elongation at Break (%)</i>
Polyethylene (low density)	0.917–0.932	0.17–0.28 (25–41)	8.3–31.4 (1.2–4.55)	9.0–14.5 (1.3–2.1)	100–650
Polyethylene (high density)	0.952–0.965	1.06–1.09 (155–158)	22.1–31.0 (3.2–4.5)	26.2–33.1 (3.8–4.8)	10–1200
Poly(vinyl chloride)	1.30–1.58	2.4–4.1 (350–600)	40.7–51.7 (5.9–7.5)	40.7–44.8 (5.9–6.5)	40–80
Polytetrafluoroethylene	2.14–2.20	0.40–0.55 (58–80)	20.7–34.5 (3.0–5.0)	13.8–15.2 (2.0–2.2)	200–400
Polypropylene	0.90–0.91	1.14–1.55 (165–225)	31–41.4 (4.5–6.0)	31.0–37.2 (4.5–5.4)	100–600
Polystyrene	1.04–1.05	2.28–3.28 (330–475)	35.9–51.7 (5.2–7.5)	25.0–69.0 (3.63–10.0)	1.2–2.5
Poly(methyl methacrylate)	1.17–1.20	2.24–3.24 (325–470)	48.3–72.4 (7.0–10.5)	53.8–73.1 (7.8–10.6)	2.0–5.5
Phenol-formaldehyde	1.24–1.32	2.76–4.83 (400–700)	34.5–62.1 (5.0–9.0)	—	1.5–2.0
Nylon 6,6	1.13–1.15	1.58–3.80 (230–550)	75.9–94.5 (11.0–13.7)	44.8–82.8 (6.5–12)	15–300
Polyester (PET)	1.29–1.40	2.8–4.1 (400–600)	48.3–72.4 (7.0–10.5)	59.3 (8.6)	30–300
Polycarbonate	1.20	2.38 (345)	62.8–72.4 (9.1–10.5)	62.1 (9.0)	110–150

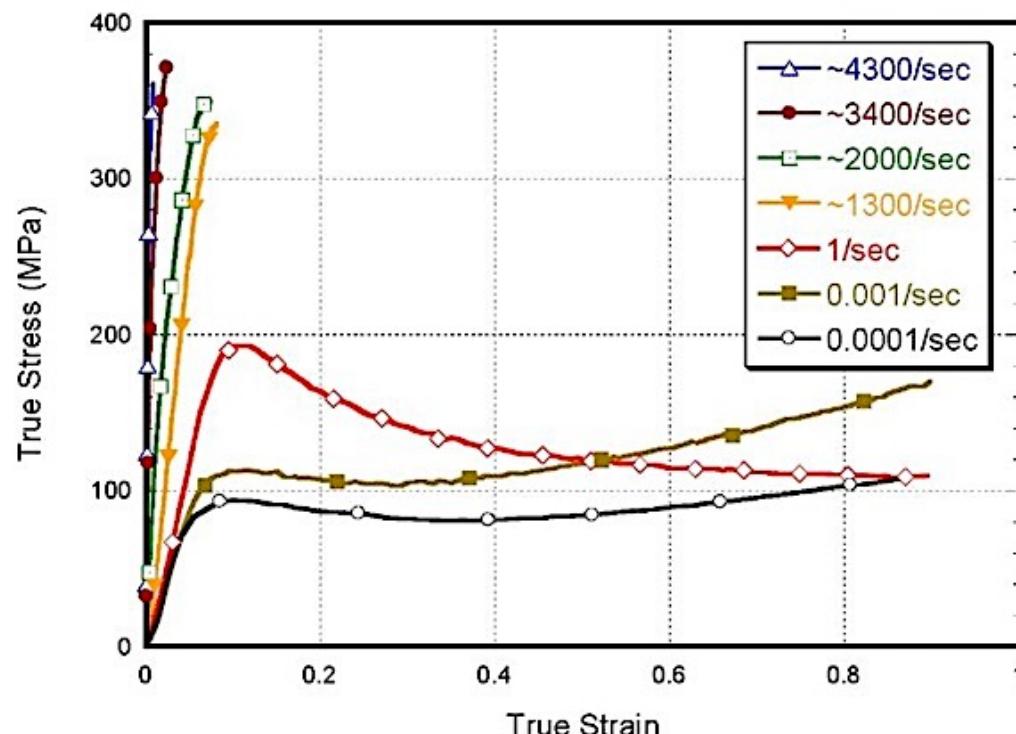
# Stress-strain behavior of polymers

- The mechanical characteristics of polymers are very sensitive to temperature changes near room temperatures
- An increase in temperature causes a decrease in elastic modulus, a reduction in tensile strength and an increase in ductility

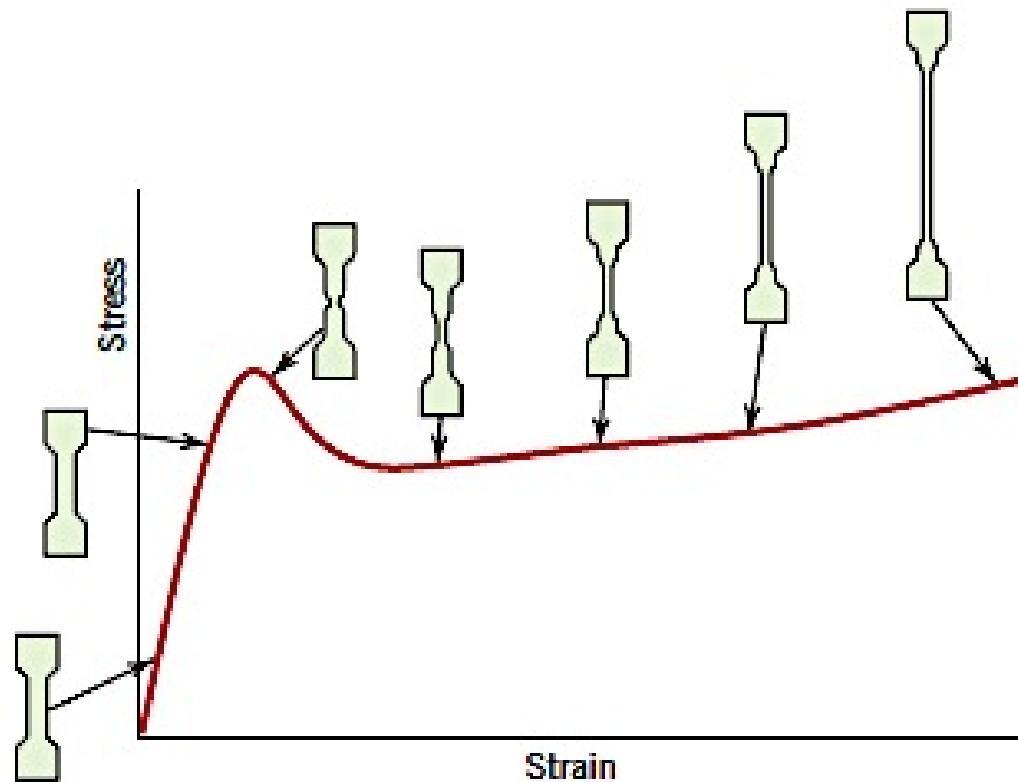


# Stress-strain behavior of polymers

- Strain rate has a very strong influence on the mechanical properties
- Decreasing the strain rate has the same influence on the stress-strain behavior as an increase in temperature – the material becomes softer and more ductile



# Stress-strain behavior of polymers



Schematic representation of the shape change occurring in a plastic polymer sample during tensile test

# Stress-strain behavior of polymers

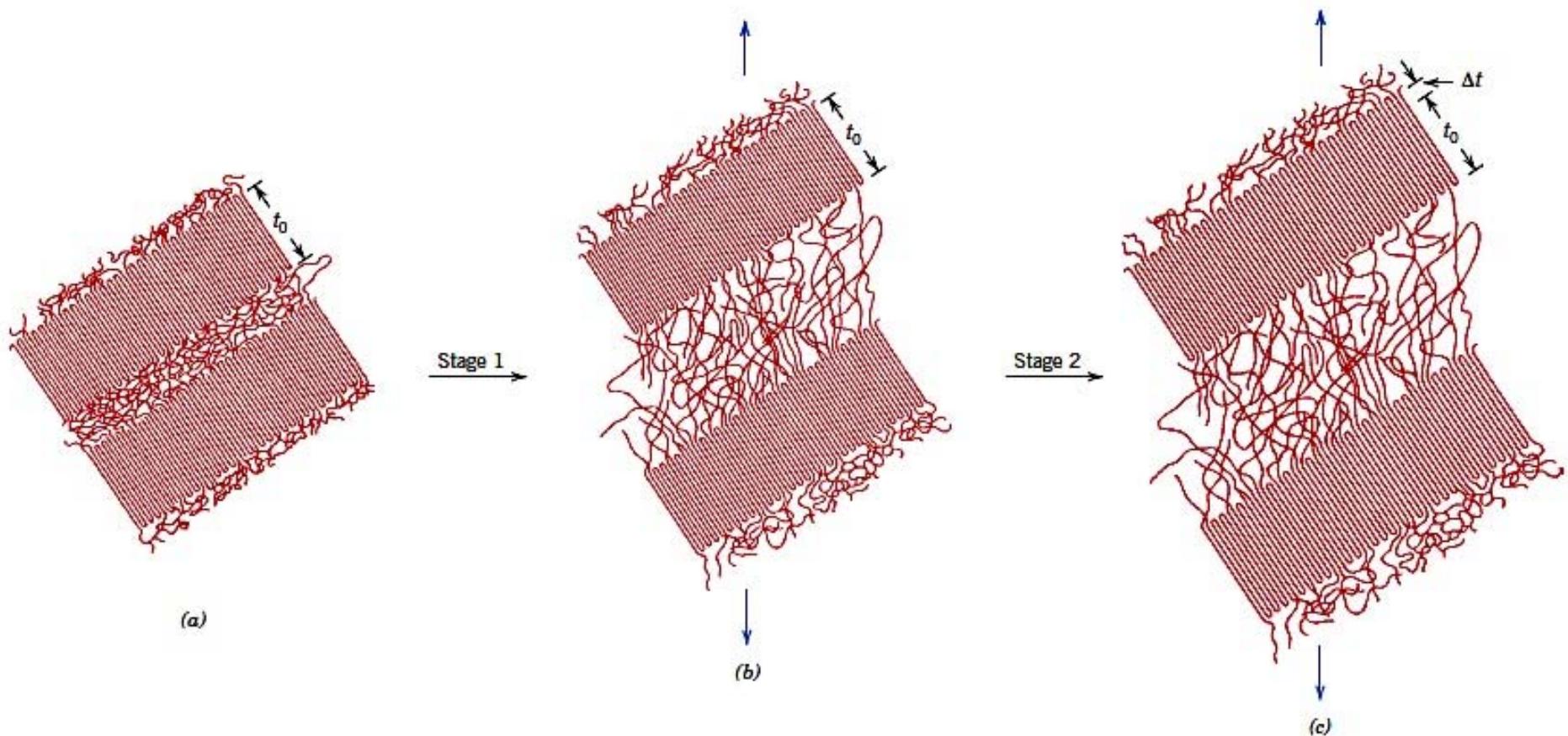
- At the upper yield point, a small neck forms within the gauge section of the specimen
- Within this neck, the chains become oriented; i.e. the chain axex become aligned parallel to the direction of tensile test
- Consequently, there is a resistance against further deformation at this point and specimen eleongation proceeds by the propagation of this neck region along the gauge length of the sample
- As the neck elongates further, the chain orientation phenomenon further continues

# Stress-strain behavior of polymers

The deformation mechanism during tensile test in a semi-crystalline polymer is briefly described. The complete deformation mechanism is subdivided into two parts:

- Mechanism of elastic deformation
- Mechanism of plastic deformation

# Mechanism of elastic deformation

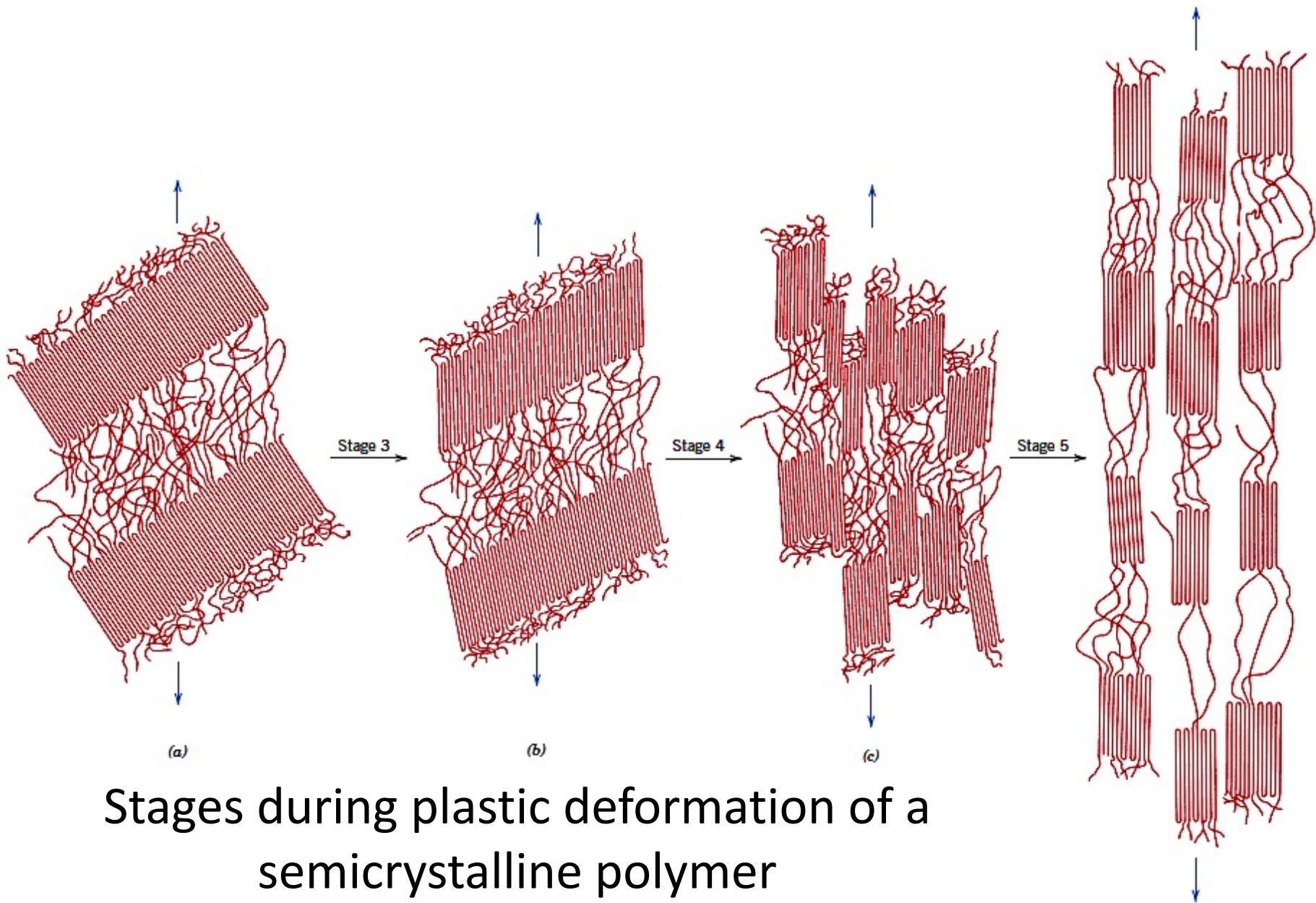


Stages during elastic deformation of a semicrystalline polymer

# Mechanism of elastic deformation

- The onset of elastic deformation in semicrystalline polymers occurs from chain molecules in amorphous regions elongating along the direction of the applied tensile stress
- Continued deformation in the second stage occurs by changes in both amorphous and lamellar crystalline regions
- Amorphous chains continue to align and become elongated. Additionally there is bending and stretching of the strong chain covalent bonds within the crystalline lamella

# Mechanism of plastic deformation

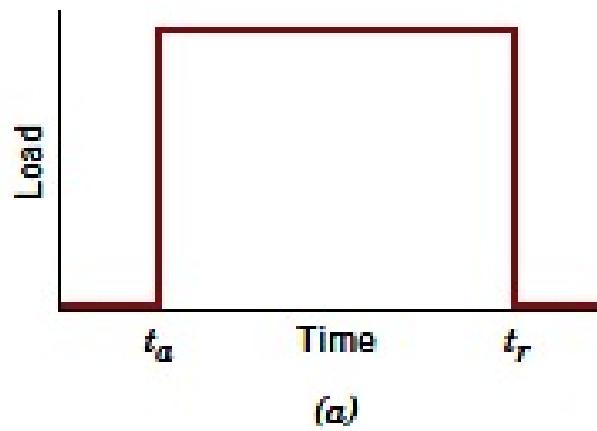


Stages during plastic deformation of a  
semicrystalline polymer

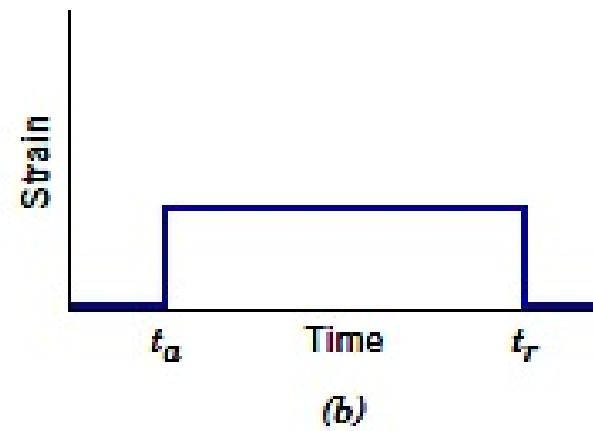
# Mechanism of plastic deformation

- The transition from elastic to plastic deformation occurs in stage 3. Adjacent chains in the lamellae slide past one another. Tilting of the lamella occurs so that chain folds become more aligned with the tensile axis.
- In the next stage, crystalline block segments separate from the lamella, while the segments are attached to one another by tie chains
- In the final stage the blocks and tie chains become oriented in the direction of the tensile axis. Hence, the appreciable tensile deformation of semicrystalline polymers produces a highly oriented structure.

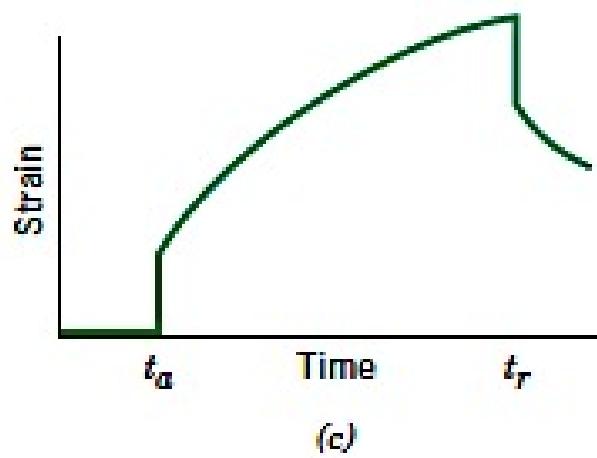
# Viscoelastic deformation of polymers



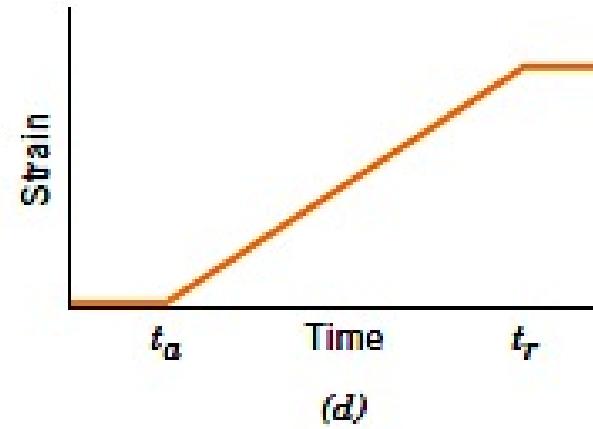
(a)



(b)



(c)



(d)

Totally elastic a) load-time and b) strain-time behavior.  
Viscoelastic behavior is shown in (c) and viscous behavior (d)

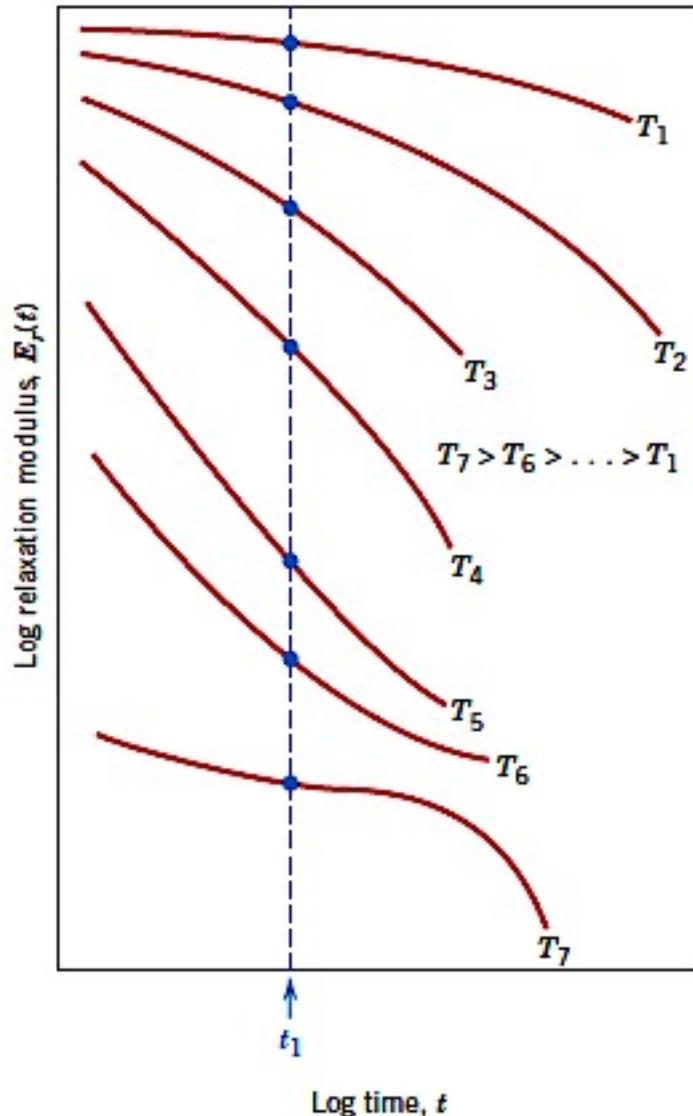
# Viscoelastic deformation of polymers

- **Elastic deformation** is instantaneous, i.e. total deformation occurs the instant the stress is applied. Upon release of the external stress, the deformation is completely recovered instantly
- For **totally viscous** behavior, deformation is not instantaneous. In response to an applied stress, the deformation is time dependent. After stress release, the deformation is not completely recovered
- **Viscoelastic behavior** is the intermediate scenario – the application of stress results in an instantaneous elastic strain, followed by a viscous time-dependent strain

# Viscoelastic deformation of polymers

- The viscoelastic behavior of polymeric materials is dependent on both time and temperature
- Stress relaxation measurement is one method to measure and quantify this behavior
- A specimen is initially strained rapidly in tension to a predetermined low strain level. At a constant temperature, the stress necessary to maintain this strain is measured as a function of time
- The time dependent elastic modulus for viscoelastic materials is known as **relaxation modulus ( $E_r(t)$ )**

# Viscoelastic deformation of polymers

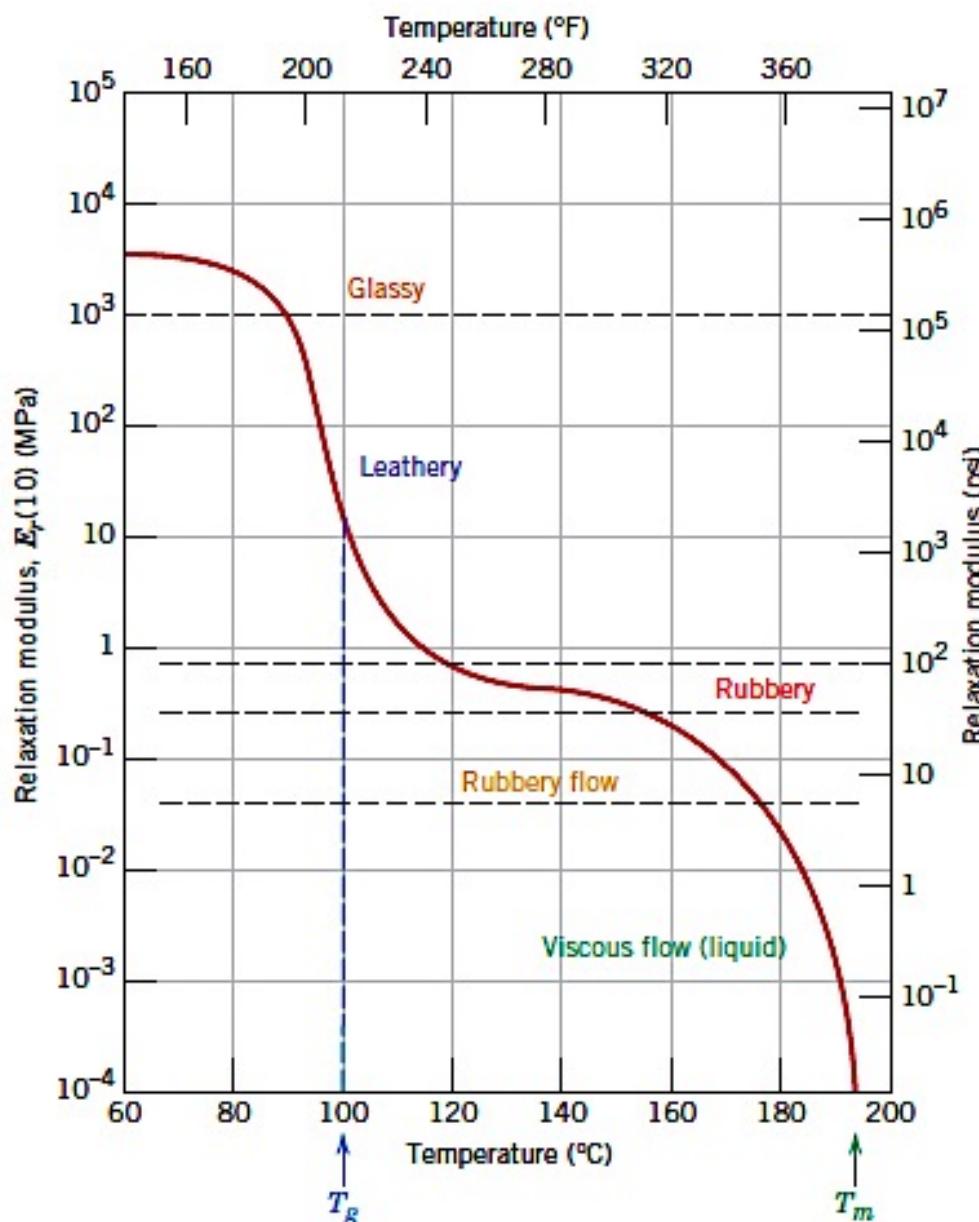


- Schematic plot for logarithm of relaxation modulus vs. Logarithm of time is shown
- The magnitude of the relaxation modulus is a function of temperature
- With an increase in time, the magnitude of the relaxation modulus decreases
- Curves are displaced to lower modulus level with increasing temperature

# Viscoelastic deformation of polymers

- To show the influence of temperature on relaxation modulus, data points are collected at a specific time and then cross-plotted vs. Temperature
- When logarithm of relaxation modulus is plotted against temperature, typically five different regions are obtained in a curve for a viscoelastic material ➔ refer to the next slide

# Viscoelastic deformation of polymers



# Viscoelastic deformation of polymers

- The lowest temperature range is denoted as the **glassy region**
  - The material is rigid and brittle
  - The value of the relaxation modulus is that of the elastic modulus, which initially is virtually independent of temperature
  - At this stage the long polymer molecular chains are essentially frozen

# Viscoelastic deformation of polymers

- The temperature range following the glassy region is denoted as the **leathery or glass transition region**
  - With increasing temperature after glassy region, in the glass transition region the relaxation modulus abruptly drops by a factor of about  $10^3$  within a span of approx.  $20\text{ }^\circ\text{C}$
  - The glass transition temperature ( $T_g$ ) lies near the upper limit of this region
  - In this region a polymer sample is leathery; i.e. the deformation is time dependent and not completely recoverable after load release

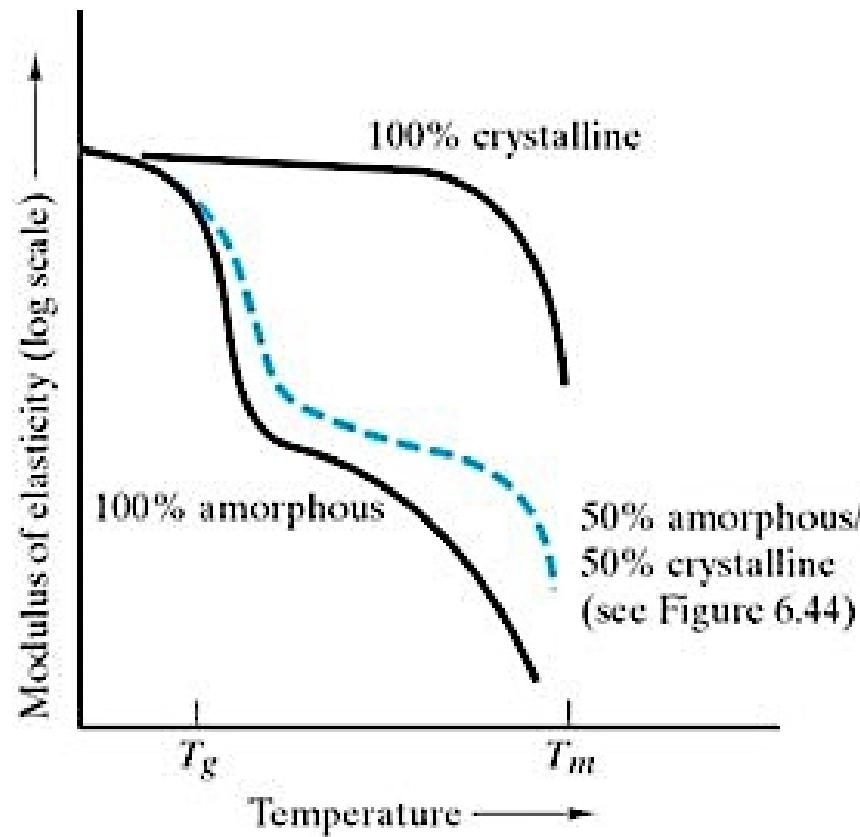
# Viscoelastic deformation of polymers

- The temperature range following the glass transition region is denoted as the **rubbery region**
  - In this region the material deforms in a rubbery manner
  - Both elastic and viscous components of deformation are present
  - It is easy to produce deformation in this region as the relaxation modulus is relatively low

# Viscoelastic deformation of polymers

- The final two high temperature regions are denoted as the **rubbery flow and viscous flow regions**
  - Upon heating through these regions, the material experiences a gradual transition to a soft rubbery state and finally to a viscous liquid
  - The polymer is a very viscous liquid within the rubbery flow region
  - Within the viscous flow region the modulus decreases dramatically with increasing temperature. Any deformation at these temperatures is entirely viscous with no elastic deformation

# Viscoelastic deformation of polymers



Influence of the polymer molecular configuration on the temperature dependence of relaxation modulus

# Viscoelastic deformation of polymers

- The temperature dependence of the relaxation modulus is a strong function of the molecular configuration of the polymer
- In an almost completely crystalline polymer the drop of relaxation modulus at the glass transition temperature is very less
- In crystalline polymers, the relaxation modulus is maintained at a relatively high value with increasing temperature until the melting point
- At the melting point the relaxation modulus drops abruptly

# Viscoelastic creep of polymers

- Many polymeric materials are susceptible to time-dependent deformation when the stress level is maintained constant. Such deformation is termed **viscoelastic creep**
- Viscoelastic creep may be significant even at room temperature and at modest stress levels below the yield stress
- Creep modulus of a polymer, defined as the ratio of the applied constant stress and the time dependent strain, is temperature sensitive and decreases with increasing temperature
- The susceptibility to creep decreases as the degree of crystallinity in a polymer increases

# Fracture of polymers

- The fracture strength of polymers is low relative to the metals and ceramics
- As a general rule, the mode of fracture in thermosetting polymers (i.e. polymers with heavily crosslinked networks) is brittle
- Cracks form in regions of stress concentrations (i.e. scratches, notches, sharp flaws etc.). At the tips of these cracks there is a stress concentration, which leads to crack propagation and fracture
- Both ductile and brittle fracture modes are possible in thermoplastics and many thermoplastics are capable of a ductile to brittle transition

# Fracture of polymers

- Factors that favor brittle fracture of thermoplasts are:
  - A reduction in temperature
  - An increase in strain rate
  - Presence of a sharp notch
  - Increased specimen thickness
  - Any modification of the polymer structure that raises the glass transition temperature
- Thermoplasts are brittle below their glass transition temperature; as the temperature is raised however, they become ductile above  $T_g$  and undergo plastic deformation prior to fracture (refer to stress-strain plots in slide 79)

# Factors affecting mechanical property

Apart from temperature and rate of deformation, several factors strongly influence the mechanical properties of semicrystalline polymers. Four such factors are discussed here briefly:

## Molecular weight

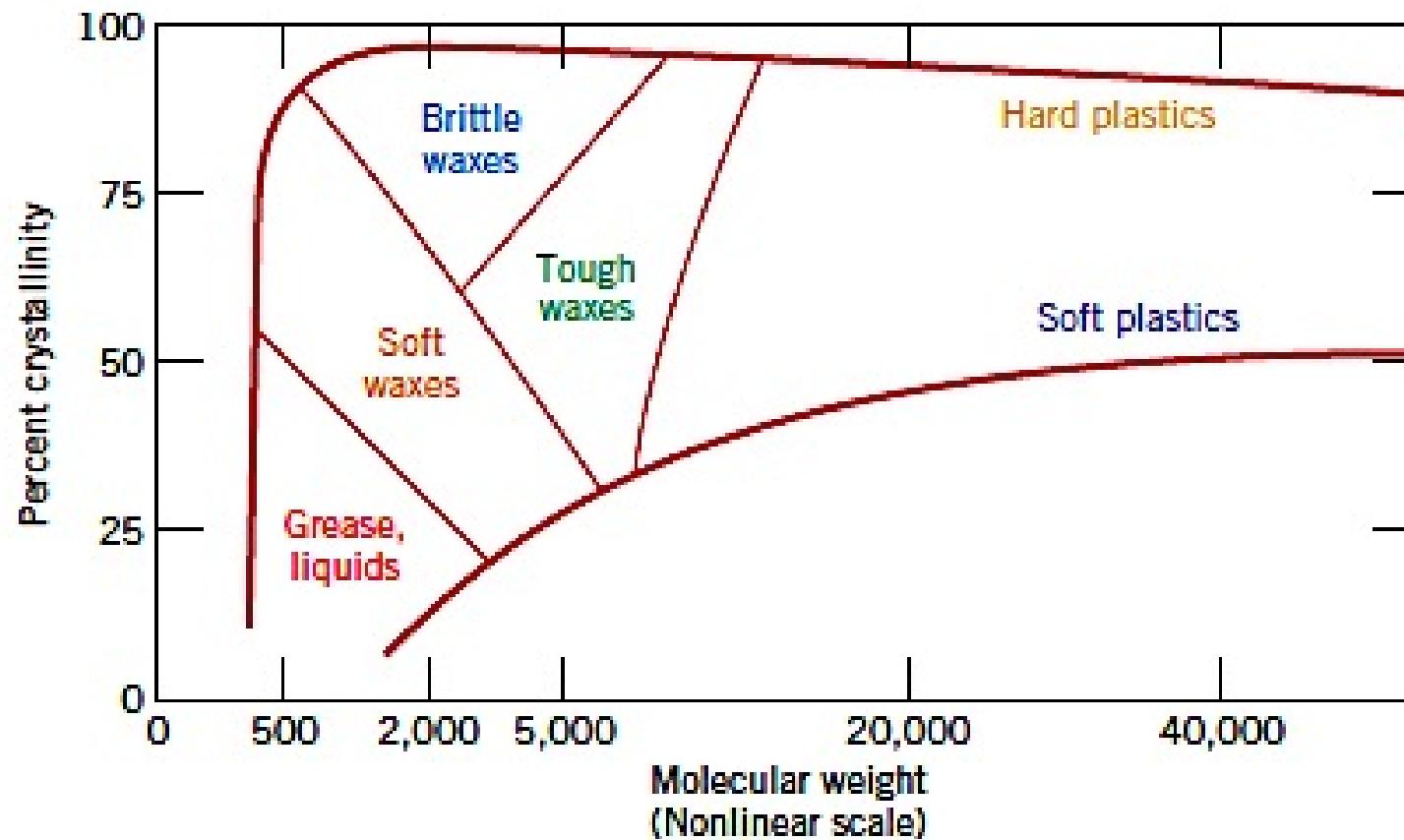
- Although there seems to be no direct influence of molecular weight on tensile modulus, for many polymers the tensile strength increase with increasing molecular weight
- This can be attributed to an increase of chain entanglement with an increase in the molecular weight

# Factors affecting mechanical property

## Degree of crystallinity

- Degree of crystallinity has a strong influence on polymer mechanical properties as it affects the intermolecular secondary bonding
- For semicrystalline polymers, the tensile modulus increases significantly with the degree of crystallinity
- Additionally, increasing the degree of crystallinity of a polymer generally increases its strength
- However, with increasing degree of crystallinity the polymer tends to become more brittle

# Factors affecting mechanical property



Influence of the molecular weight and degree of crystallinity on physical properties of polymer

# Factors affecting mechanical property

## Predeformation by drawing

- On a commercial basis, one of the most important techniques to increase the strength and modulus of a polymer is to permanently deform it in tension. This process is called drawing
- In terms of property alterations, drawing of polymers is analogous to strain hardening of metals
- During drawing the molecular chains slip past one another and become highly oriented
- The properties of drawn polymers are highly anisotropic – tensile modulus and strength along the drawing direction are significantly improved

# Factors affecting mechanical property

## Heat treatment

- Heat treating or annealing of a semicrystalline polymer can lead to an increase in % crystallinity, crystallite size and perfection
- For undrawn polymers that are subjected to constant time heat treatment, increasing the annealing time has the following effect:
  - An increase in tensile modulus
  - An increase in yield strength
  - A reduction in ductility
- Hence, the effects of annealing on polymers are opposite to those observed in metals

# Lecture 3

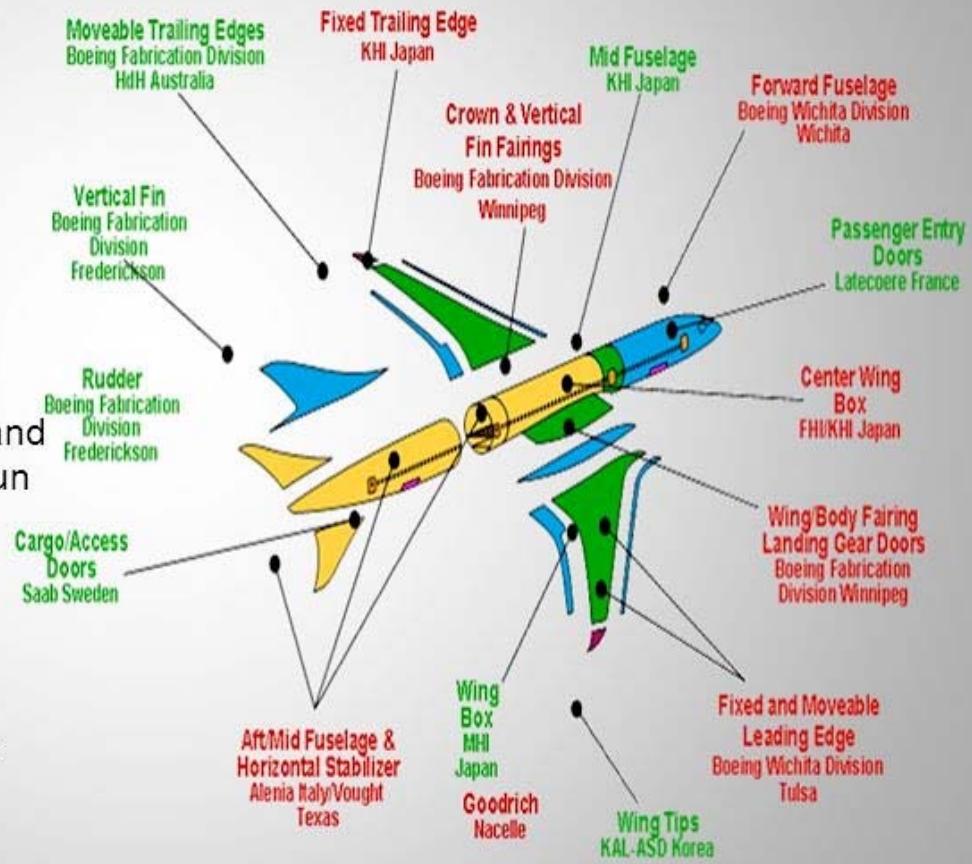
# Composites

- A composite is considered to be any multiphase material that exhibits a significant proportion of the properties of both constituent phases such that a better combination of properties is realized. The constituent phases must be chemically dissimilar & separated by a distinct interface.
- Better property combinations are fashioned by the judicious combination of two or more distinct materials
- Very often in two phase composites, one phase is discontinuous (known as dispersed phase) in another phase which is continuous (named as matrix)
- Composite properties are function of the properties of the constituent phases, their relative amounts, shape & distribution

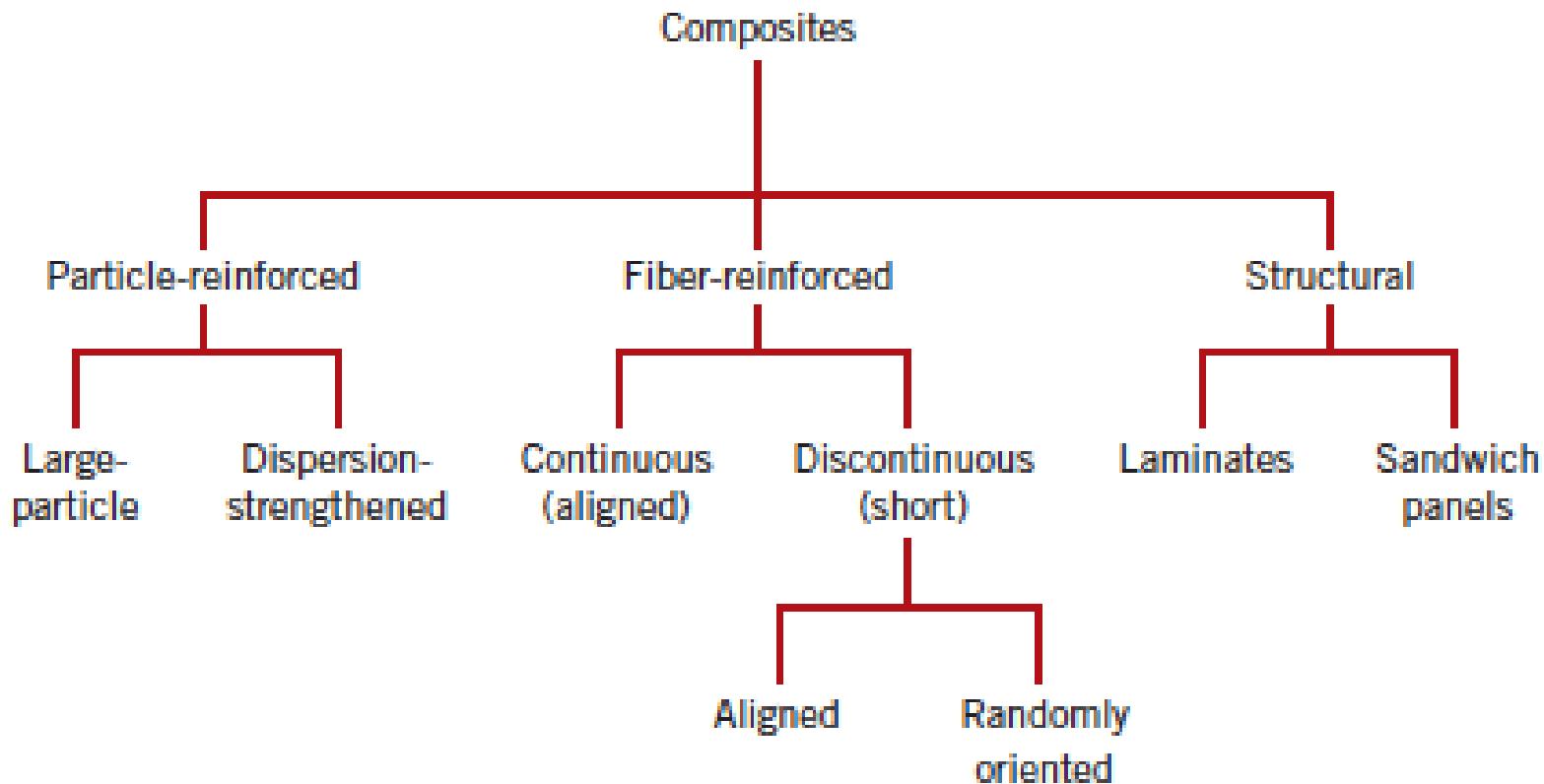
# Composites

## Composite applications

- Transportation
  - Ground, air, marine, space
- Military
  - armor, weapons, containers
- Sporting goods
  - golf, tennis, fishing, helmets, wheels, skis/snow boards, kite and wind surfing, snow machines, gun components
- Building materials
  - pipes, beams, panels, bridges, roofing, decking, signs, furniture
- Medical
  - prosthetic devices, braces, enclosures, body moving aids



# Composites



One classification scheme of composite materials based  
on the shape of the dispersed phase

# Particle reinforced composites

- Particles can have quite a few variety of geometries; but they should be of approximately the same dimension in all directions → aspect ratio close to unity
- For effective reinforcement, the particles should be small and evenly distributed throughout the matrix
- Two rule of mixtures mathematical expressions have been formulated for the dependence of the elastic modulus of the composite on the volume fraction of the constituent phases
- These expressions are known as the upper bound and lower bound, respectively. The elastic modulus of the composite lies between these two bounds

# Particle reinforced composites

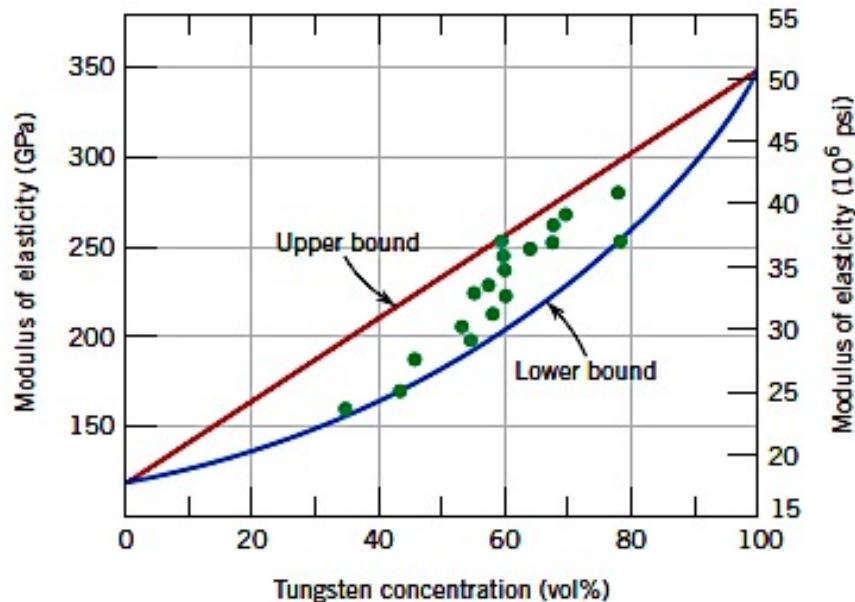
## Upper bound

$$E_c(u) = E_m V_m + E_p V_p$$

## Lower bound

$$E_c(l) = \frac{E_m E_p}{V_m E_p + V_p E_m}$$

E and V denote the elastic modulus and volume fraction while the subscripts m, p and c denote matrix, reinforcement & composite, respectively



Elastic modulus vs. Vol.% tungsten for a composite of copper reinforced with tungsten particles

# Particle reinforced composites

- Particle reinforced composites are used with all three material types – metals, ceramics and polymers
- Cermets are examples of ceramic/metal composites. Cemented carbides, a composite of extremely hard particles of tungsten carbide in a cobalt metal matrix are extensively used as cutting tools for hardened steels
- Hard carbides in cemented carbides provide the cutting surface & the ductile metallic matrix provides toughness
- Both elastomers and plastics are frequently reinforced with various particulates. Carbon black is rather inexpensive and when added to vulcanized rubber, it enhances tensile strength, toughness and tear resistance

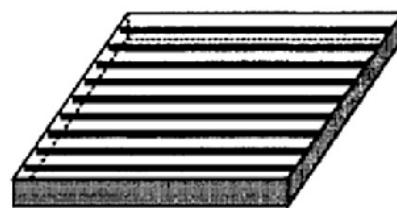
# Particle reinforced composites



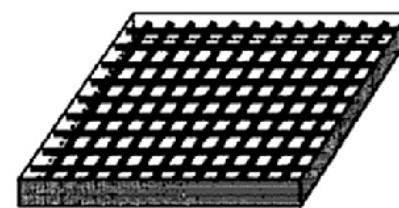
Photomicrograph of tungsten carbide-cobalt cemented carbide. Light areas are the cobalt matrix

# Fiber reinforced composites

- Technologically, the most important composites are those in which the dispersed phase is in the form of a fiber
- Design goals of fiber reinforced composites often include high strength/stiffness on a weight basis (properties known as **specific strength** and **specific stiffness**, respectively)



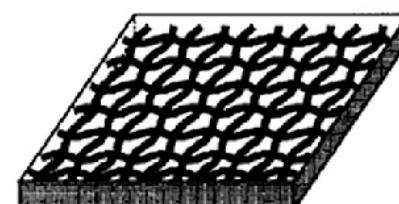
(a) Unidirectional



(b) Bi-directional



(c) Discontinuous fiber



(d) Woven

# Fiber reinforced composites

## Influence of fiber length

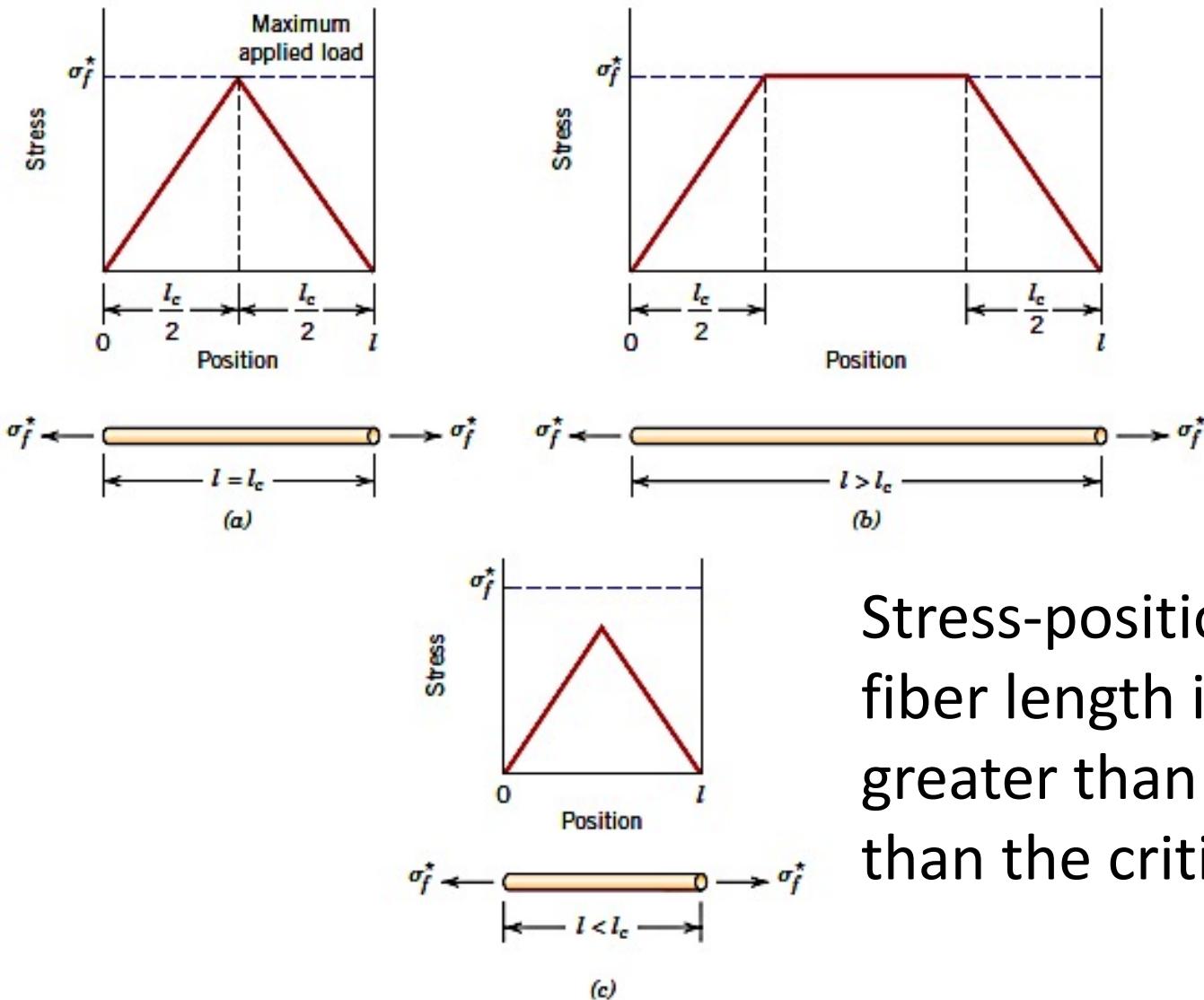
- Apart from the properties of the fiber and the matrix, the mechanical characteristics of a fiber reinforced composites also depend upon the load transfer to the fiber from the matrix via the interface
- Some critical minimum fiber length is necessary for effective strengthening and stiffening of the composite material
- If  $l_c$  is the critical fiber length then

$$l_c = \frac{\sigma_f \cdot d}{2\tau_c}$$

$\sigma_f$  = ultimate tensile strength of fiber  
 $d$  = fiber diameter  
 $\tau_c$  = shear yield strength of matrix

# Fiber reinforced composites

## Influence of fiber length



Stress-position profiles when fiber length is a) equal to b) greater than and c) lower than the critical length

# Fiber reinforced composites

## Fiber length and orientation

- For a fiber length exactly equal to this critical length, the maximum strength is achieved only at the axial midpoint of the fiber (refer to Fig. a)
- As fiber length increases, the reinforcement caused by the fiber becomes more effective as the maximum strength is attained over an extended fiber length (refer to Fig. b)
- Finally, if the fiber length is  $< l_c$ , the maximum strength is attained at no point of the fiber (refer to Fig. c)
- Fibers for which  $l >> l_c$  (normally  $l > 15l_c$ ), are known as continuous fibers

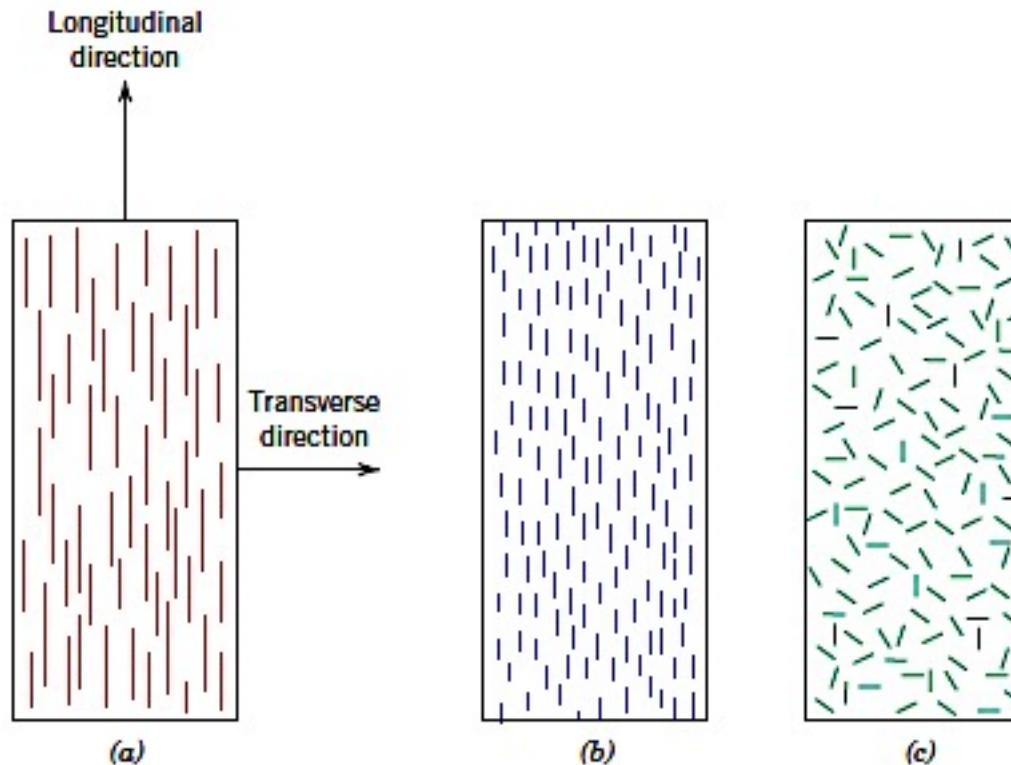
# Fiber reinforced composites

## Fiber length and orientation

- Apart from fiber length, the fiber orientation with respect to the loading axis also significantly influences the properties of the composite
- With respect to fiber orientation, fibers can be classified as:
  - A parallel alignment of the longitudinal axis of the fibers along a single direction. Continuous fibers are generally aligned
  - A totally random alignment. Discontinuous fibers are normally randomly distributed

# Fiber reinforced composites

## Fiber length and orientation



Schematic representation of a) continuous and aligned b)  
discontinuous and aligned and c) discontinuous and  
randomly oriented fiber reinforced composites

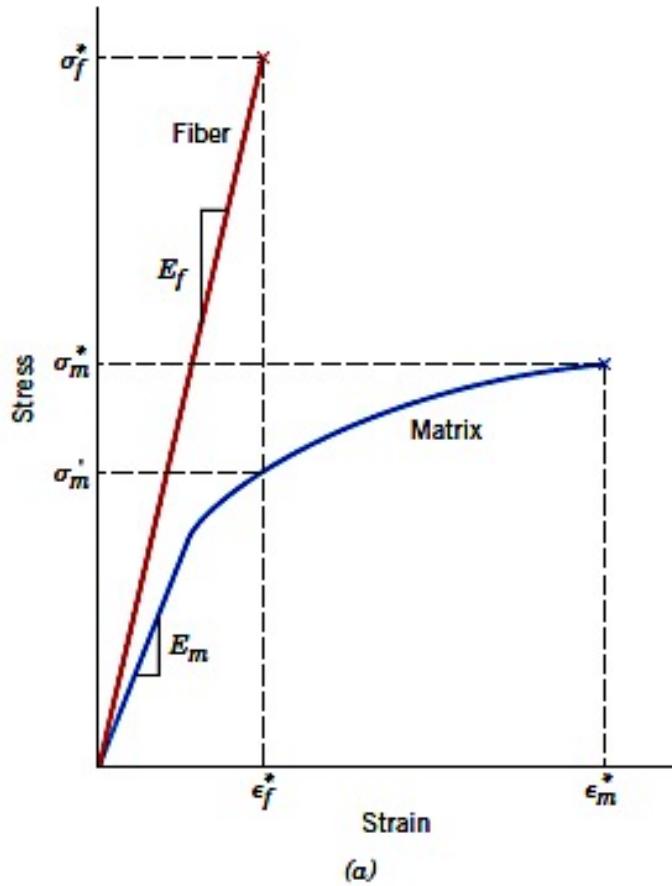
# Fiber reinforced composites

## Tensile stress-strain behavior

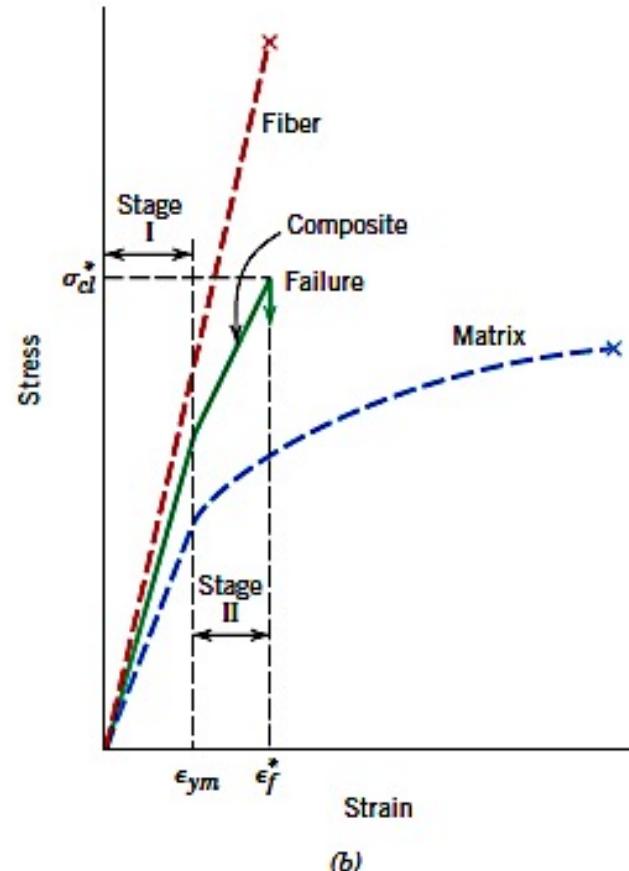
- Tensile stress-strain behavior of continuous fiber reinforced composites depends on several factors:
  - The stress-strain behavior of the fiber and the matrix phases
  - Individual phase volume fractions
  - Direction of the stress application with respect to the fiber long axis
  - The characteristics of the fiber-matrix interface
- Properties of composites with aligned fibers are highly anisotropic ➔ highest property enhancement along fiber direction with poor properties transverse to fibers

# Fiber reinforced composites

## Tensile stress-strain behavior along fiber direction



(a)



(b)

Schematic tensile stress-strain behavior for a) brittle fiber and ductile matrix and b) composite made from the two

# Fiber reinforced composites

## Tensile stress-strain behavior along fiber direction

- Assume that the fibers are brittle and the matrix is ductile with respective tensile stress-strain plots and material parameters shown in Figure (a)
- A composite made from the fiber and matrix combination under tensile loading along fiber direction will have a stress-strain plot similar to the **green curve** in Figure (b)
- In the initial stage I region, both matrix and the fibers deform elastically. The composite is macroscopically elastic at this stage and the stress-strain plot is linear

# Fiber reinforced composites

## Tensile stress-strain behavior along fiber direction

- Assuming a very strong interfacial bond between fiber and matrix, the strain in both fiber and matrix is the same (**isostrain condition**)

$$\varepsilon_c = \varepsilon_m = \varepsilon_f$$

- The total load carried by the composite is the sum of the loads carried by the matrix and the fiber phase

$$F_c = F_m + F_f$$

- Further expansion of the ideas of uni-axial stress and strain yields the expression for composite elastic modulus in stage I (**refer to ch. 16.5 of Callister book**)

$$E_c = E_m \cdot V_m + E_f \cdot V_f$$

# Fiber reinforced composites

## Tensile stress-strain behavior along fiber direction

- Stage I ends and stage II begins at the point when the matrix starts deforming plastically
- Normally the tensile strength of the fibers is much higher than the matrix and hence in stage II the matrix deforms plastically while the fibers are still elastic
- Stage II of the composite tensile stress-strain curve is also ordinarily linear, however with respect to stage I, the slope is diminished
- As the matrix starts deforming plastically, it transfers load to the fibers and hence in stage II the load fraction carried by the fibers increases

# Fiber reinforced composites

## Tensile stress-strain behavior along fiber direction

- Onset of composite failure begins as the fibers start to fracture
- Although the fibers are brittle the fracture of composites is not an catastrophic event because:
  - Not all fibers fracture at the same time, because there will always be significant variation in the fracture strength of fibers
  - Even after fiber failure the matrix is still intact (their failure strain is larger than the fiber) and is capable of sustaining a diminished load as the matrix deforms plastically

# Fiber reinforced composites

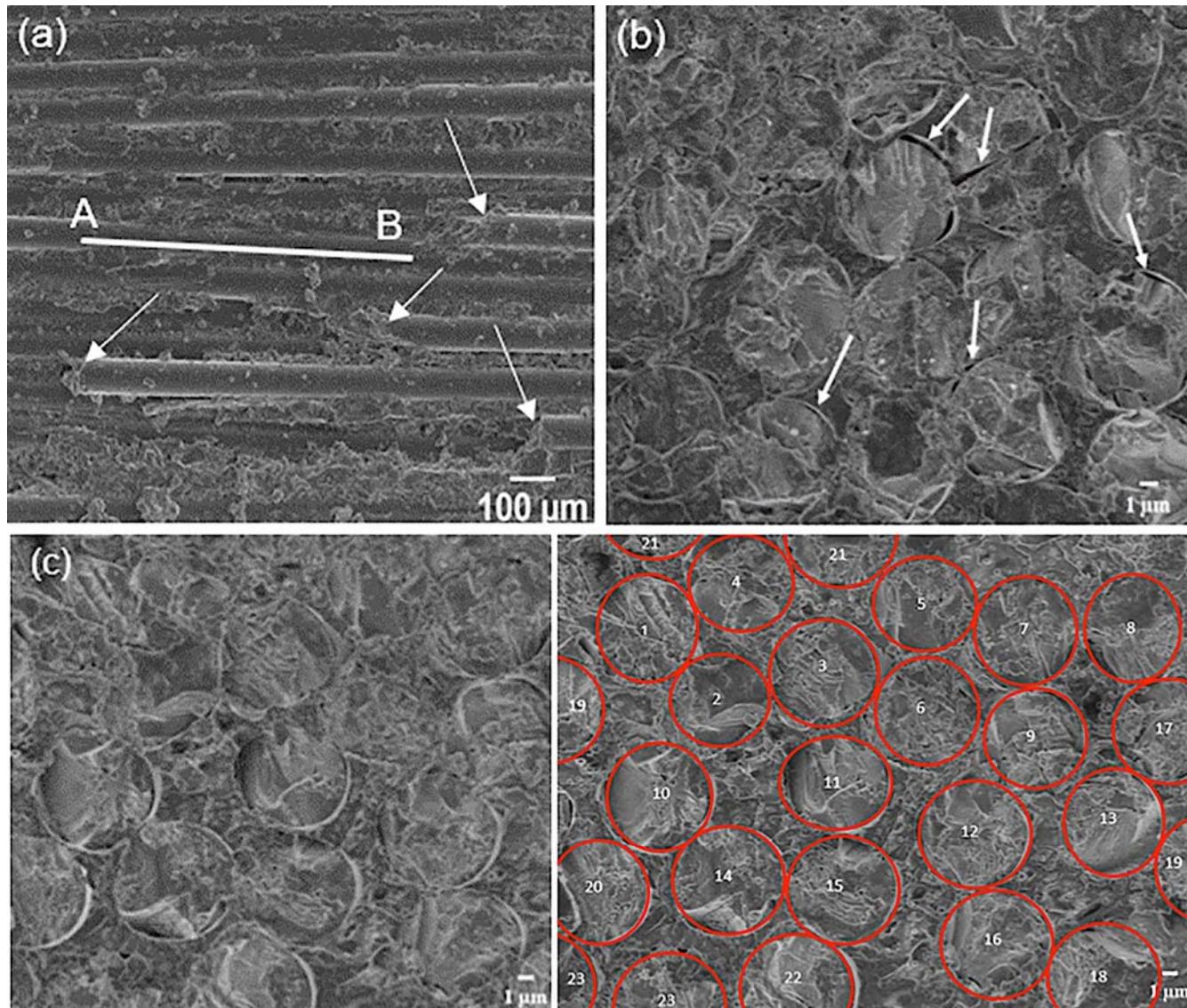
## Tensile stress-strain behavior along fiber direction

- The tensile strength of fiber reinforced composites is taken as the maximum point on the stress-strain curve and often this point corresponds to the onset of fiber fracture
- Assuming the fracture strain of fibers to be less than the metal, the longitudinal tensile strength of fiber reinforced composites is estimated as

$$\sigma_c^* = \sigma_m^* (1 - V_f) + \sigma_f V_f$$

where  $\sigma_m^*$  is the matrix strength at the strain corresponding to onset of fiber failure

# Fiber reinforced composites – typical fractographs



# Fiber reinforced composites

## Tensile modulus and strength along transverse direction

- In transverse loading the tensile load is applied along 90° angle to the direction of continuous fibers
- For this loading condition, the stress in all three phases (matrix, fiber and composite) is assumed to be same (**isostress condition**)

$$\sigma_c = \sigma_m = \sigma_f$$

- Total strain in the composite is then the sum of the strains in the fiber and matrix and from elementary elasticity analysis, the modulus of the composite is (**refer to ch. 16.5 of Callister book**)

$$\frac{1}{E_c} = \frac{V_m}{E_m} + \frac{V_f}{E_f}$$

# Fiber reinforced composites

## Tensile modulus and strength along transverse direction

- The strengths of continuous and unidirectional fibrous composites are highly anisotropic.
- When loaded along transverse direction, premature failure may occur as the transverse strength is usually extremely low – sometimes lying below the matrix tensile strength
- Factors affecting transverse strength are – properties of both the fiber and matrix, the fiber-matrix interfacial bond strength and the presence of any void
- Measures to improve transverse strength include strengthening the matrix and improving the interfacial bonding

# Discontinuous fiber reinforced composites

- Short-fiber composites can be produced having elastic modulus and tensile strength that approach 90% and 50% respectively, of their continuous fiber counterpart
- For a discontinuous and aligned fiber composite in which  $l > l_c$ , the longitudinal tensile strength is given by:

$$\sigma_c' = \sigma_f V_f \left( 1 - \frac{l_c}{2l} \right) + \sigma_m' (1 - V_f)$$

where  $\sigma_f$  is the failure strength of the fiber and  $\sigma_m'$  is the instantaneous strength of the matrix at the point of composite failure

# Fiber reinforced composites

**Table 16.3 Reinforcement Efficiency of Fiber-Reinforced Composites for Several Fiber Orientations and at Various Directions of Stress Application**

<i>Fiber Orientation</i>	<i>Stress Direction</i>	<i>Reinforcement Efficiency</i>
All fibers parallel	Parallel to fibers	1
	Perpendicular to fibers	0
Fibers randomly and uniformly distributed within a specific plane	Any direction in the plane of the fibers	$\frac{3}{8}$
	Any direction	$\frac{1}{5}$
Fibers randomly and uniformly distributed within three dimensions in space		

# Fiber reinforced composites: fibers

- An important characteristic of most materials, especially brittle ones, is that a small diameter fiber is much stronger than the bulk material
- The probability of the presence of a critical surface flaw that can lead to fracture diminishes as the volume decreases and this feature leads to the high strength of fibers
- Normally, the materials used for reinforcing fibers have high stiffness and tensile strength
- On the basis of diameter and character, fibers are generally classified into three groups: whiskers, fibers and wires

# Fiber reinforced composites: fibers

**Table 16.4 Characteristics of Several Fiber-Reinforcement Materials**

<i>Material</i>	<i>Specific Gravity</i>	<i>Tensile Strength</i> [GPa ( $10^6$ psi)]	<i>Specific Strength</i> (GPa)	<i>Modulus of Elasticity</i> [GPa ( $10^6$ psi)]	<i>Specific Modulus</i> (GPa)
<i>Whiskers</i>					
Graphite	2.2	20 (3)	9.1	700 (100)	318
Silicon nitride	3.2	5–7 (0.75–1.0)	1.56–2.2	350–380 (50–55)	109–118
Aluminum oxide	4.0	10–20 (1–3)	2.5–5.0	700–1500 (100–220)	175–375
Silicon carbide	3.2	20 (3)	6.25	480 (70)	150
<i>Fibers</i>					
Aluminum oxide	3.95	1.38 (0.2)	0.35	379 (55)	96
Aramid (Kevlar 49)	1.44	3.6–4.1 (0.525–0.600)	2.5–2.85	131 (19)	91
Carbon <sup>a</sup>	1.78–2.15	1.5–4.8 (0.22–0.70)	0.70–2.70	228–724 (32–100)	106–407
E-glass	2.58	3.45 (0.5)	1.34	72.5 (10.5)	28.1
Boron	2.57	3.6 (0.52)	1.40	400 (60)	156
Silicon carbide	3.0	3.9 (0.57)	1.30	400 (60)	133
UHMWPE (Spectra 900)	0.97	2.6 (0.38)	2.68	117 (17)	121
<i>Metallic Wires</i>					
High-strength steel	7.9	2.39 (0.35)	0.30	210 (30)	26.6
Molybdenum	10.2	2.2 (0.32)	0.22	324 (47)	31.8
Tungsten	19.3	2.89 (0.42)	0.15	407 (59)	21.1
					140

# Fiber reinforced composites: matrix

- The matrix phase of fiber reinforced composites can be a metal, polymer or ceramic
- Metals and polymers are used as matrix materials because some ductility is necessary.
- For ceramic matrix composites, the dispersed phase is added to improve the fracture toughness
- The matrix phase serves several functions in a fiber reinforced composite
  - It binds the fibers together and it acts as a medium by which an externally applied stress is transmitted to the fibers

# Fiber reinforced composites: matrix

- The matrix material should be ductile and the elastic modulus of the fibers should be much higher
- The matrix protects the individual fibers from surface damage as a result of mechanical abrasion or chemical reactions with the environment
- The matrix separates the fibers and by virtue of its relative softness and plasticity, prevents the propagation of brittle cracks from fiber to fiber

# Polymer matrix composites (PMC)

- PMCs consist of a polymer resin as the matrix with fibers as the reinforcing medium
- In light of their room temperature properties, light weight and cost, they are used in the greatest diversity of composite applications
- Two of the most common PMCs are
  - Glass fiber reinforced polymer composites (GFRP)
  - Carbon fiber reinforced polymer composites (CFRP)

# Polymer matrix composites (PMC)

## Glass fiber reinforced polymer composites (GFRP)

- Fiberglass is a composite consisting of glass fibers, either continuous or discontinuous, contained within a polymer matrix
- Glass is popular reinforcement for several reasons:
  - It is easily drawn into high strength fibers from molten state
  - It is readily available and may be formed into a composite economically
  - As a fiber it is relatively strong and when embedded in a plastic matrix the composite has very high specific stiffness
  - It is chemically inert in many corrosive environments

# Polymer matrix composites (PMC)

## Glass fiber reinforced polymer composites (GFRP)

Applications

# Polymer matrix composites (PMC)

## Carbon fiber reinforced polymer composites (CFRP)

- Carbon in a high performance fiber material that is the most commonly used reinforcement in advanced PMCs
- The main reasons behind the extensive use of carbon fibers as reinforcement are:
  - Carbon fibers have the highest specific stiffness and strength of all reinforcing materials
  - They retain their properties at elevated temperature
  - At room temperature, carbon fibers are not affected by moisture, acids and bases
  - Relatively inexpensive fiber and composite manufacturing processes have been developed

# Polymer matrix composites (PMC)

## Carbon fiber reinforced polymer composites (CFRP)

Applications

# Polymer matrix composites (PMC)

**Table 16.5 Properties of Continuous and Aligned Glass, Carbon, and Aramid Fiber-Reinforced Epoxy-Matrix Composites in Longitudinal and Transverse Directions. In All Cases the Fiber Volume Fraction Is 0.60**

<i>Property</i>	<i>Glass (E-glass)</i>	<i>Carbon (High Strength)</i>	<i>Aramid (Kevlar 49)</i>
Specific gravity	2.1	1.6	1.4
Tensile modulus			
Longitudinal [GPa ( $10^6$ psi)]	45 (6.5)	145 (21)	76 (11)
Transverse [GPa ( $10^6$ psi)]	12 (1.8)	10 (1.5)	5.5 (0.8)
Tensile strength			
Longitudinal [MPa (ksi)]	1020 (150)	1240 (180)	1380 (200)
Transverse [MPa (ksi)]	40 (5.8)	41 (6)	30 (4.3)
Ultimate tensile strain			
Longitudinal	2.3	0.9	1.8
Transverse	0.4	0.4	0.5

# Metal matrix composites (MMC)

- In MMCs the matrix is a soft and ductile metal or its alloy
- The reinforcement in MMCs improves specific stiffness, specific strength, abrasion resistance, creep resistance and dimensional stability
- Some advantages of MMCs over PMCs include higher operating temperatures, nonflammability and greater resistance to degradation by organic fluids
- MMCs are however significantly more expensive than PMCs and this restricts their operation

# Metal matrix composites (MMC)

- As matrix material in MMCs superalloys, as well as alloys of Al, Mg, Ti and Cu are employed
- The reinforcement may be in the form of particulates, both continuous and discontinuous fibers and whiskers; concentrations normally range between 10 and 60 vol%
- Typical applications include:
  - In automobile industry as engineer components (due to light weight, wear resistance and thermal stability), driveshafts, forged suspension and transmission components etc.
  - In aerospace industry – in space shuttle Orbiter, in Hubble Space Telescope etc.

# Metal matrix composites (MMC)

**Table 16.9 Properties of Several Metal-Matrix Composites Reinforced with Continuous and Aligned Fibers**

<i>Fiber</i>	<i>Matrix</i>	<i>Fiber Content (vol%)</i>	<i>Density (g/cm<sup>3</sup>)</i>	<i>Longitudinal Tensile Modulus (GPa)</i>	<i>Longitudinal Tensile Strength (MPa)</i>
Carbon	6061 Al	41	2.44	320	620
Boron	6061 Al	48	—	207	1515
SiC	6061 Al	50	2.93	230	1480
Alumina	380.0 Al	24	—	120	340
Carbon	AZ31 Mg	38	1.83	300	510
Borsic	Ti	45	3.68	220	1270

# Ceramic matrix composites (CMC)

- In spite of their resistance to oxidation and deterioration at elevated temperatures, the application of ceramic materials are limited due to their brittleness
- Fracture toughness of ceramic materials is inherently low and typically lie in the range of 1 – 5 MPa $\sqrt{m}$
- The fracture toughness of ceramics is improved significantly by the development of a new generation of ceramic matrix composites (CMC) - particulates, fibers or whiskers of one ceramic phase is embedded into the matrix of another ceramic phase
- Improvement in fracture toughness results from the interaction between a crack and the dispersed phase → this interaction impedes the crack propagation

# Ceramic matrix composites (CMC)

- CMCs display an improved fracture toughness which lie in the range of 6-20 MPa $\sqrt{\text{m}}$
- In general, increasing the reinforcement content improves both strength and toughness
- Furthermore, a considerable reduction in the scatter for fracture strengths of CMCs with respect to their unreinforced ceramics is observed
- CMCs also display better high temperature creep behavior and resistance to thermal shock

# Ceramic matrix composites (CMC)

Application of CMCs