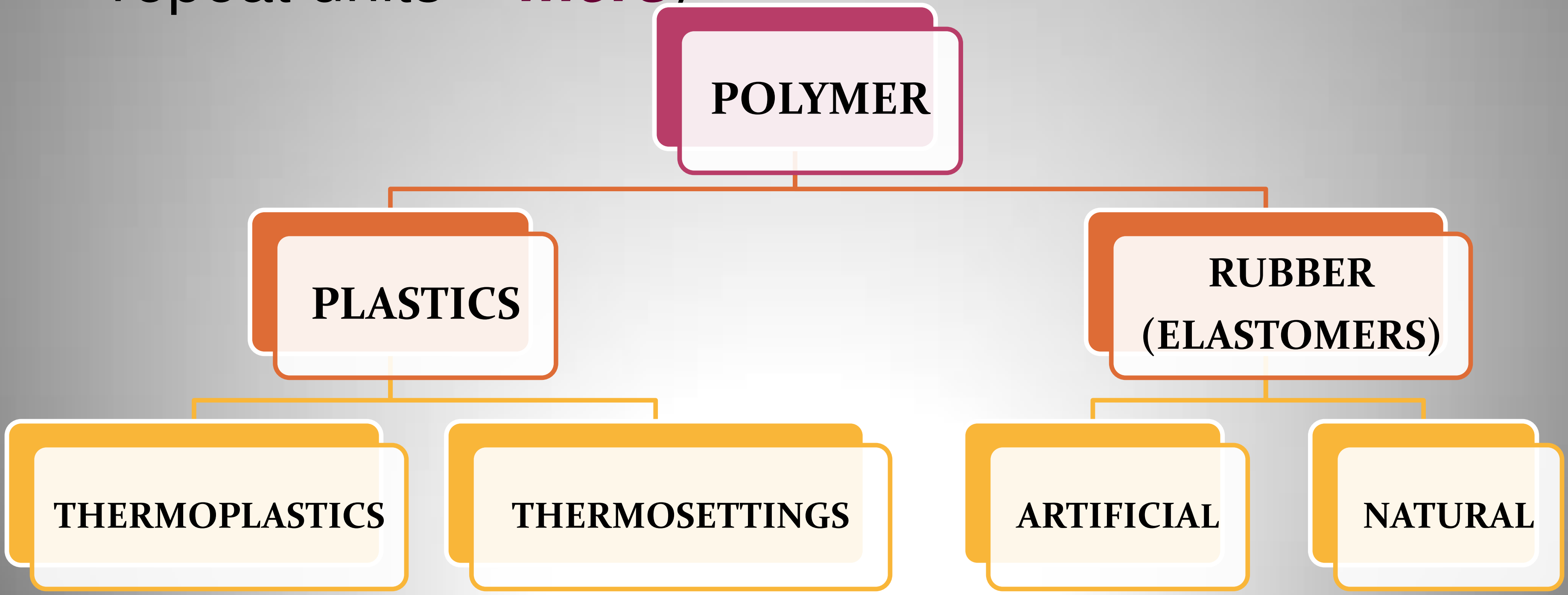
11

Non-Metallic Materials

1. POLYMER
2. CERAMIC
3. COMPOSITE

1. POLYMER

- Polymer means “many parts”. Contains many chemically bonded units that themselves are bonded together to form a solid (chains of small repeat units ~ ***mers***)



- POLYMER
  - PLASTICS
    - THERMOPLASTICS
    - THERMOSETTINGS
  - RUBBER (ELASTOMERS)
    - ARTIFICIAL
    - NATURAL

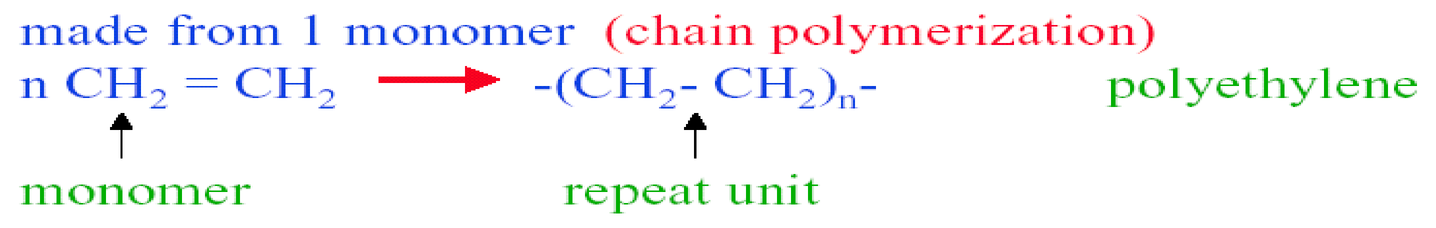
- Polymers are characterized by:
  - Low density materials (replace metals such as steel, aluminium etc)
  - Versatility in synthesis – processing – properties relationship
  - Raw materials and processing are cost-effective
  - Recycling is possible and practical
- Characteristics of Polymers when compared to metals and ceramics

Characteristic	Advantage / disadvantage
Low melting point	Ease of processing/ lower useful temperature range
High elongation	Low brittleness/ high creep and lower strength
Low density	Lightweight products/ low structural strength
Low thermal conductivity	Good thermal insulation/ dissipates heat poorly
Electrical resistance	Good electrical insulation/ do not conduct electricity
Easily colored	Use without painting/ difficult to match colors
Flammable	Waste can be burned/ may cause fume or fire hazard

- Polymers are organic (hydrocarbons) materials

- **Monomers/Mers** : small molecule from which a polymer is synthesized

- **Homopolymer** : Polymers synthesized from one type of Monomer, eg. *Polyethylene (PE), Polypropelene (PP), Ploystyrene (PS)*



made from 1 monomer (chain polymerization)

$n\ CH_2 = CH_2 \rightarrow -(CH_2\text{-}\ CH_2)_n\text{-}$ polyethylene

monomer

repeat unit

- **Copolymer** : Polymers synthesized from more than one type of monomers,
  eg. *Hexamethylene Diamine + Adipic Acid = Nylon 6,6 + Water ,*
  Phenol + Formaldehide = Phenol Formaldehide + Water

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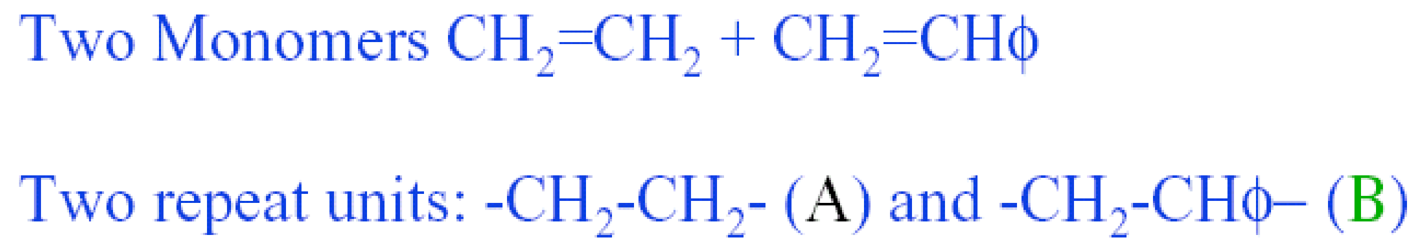
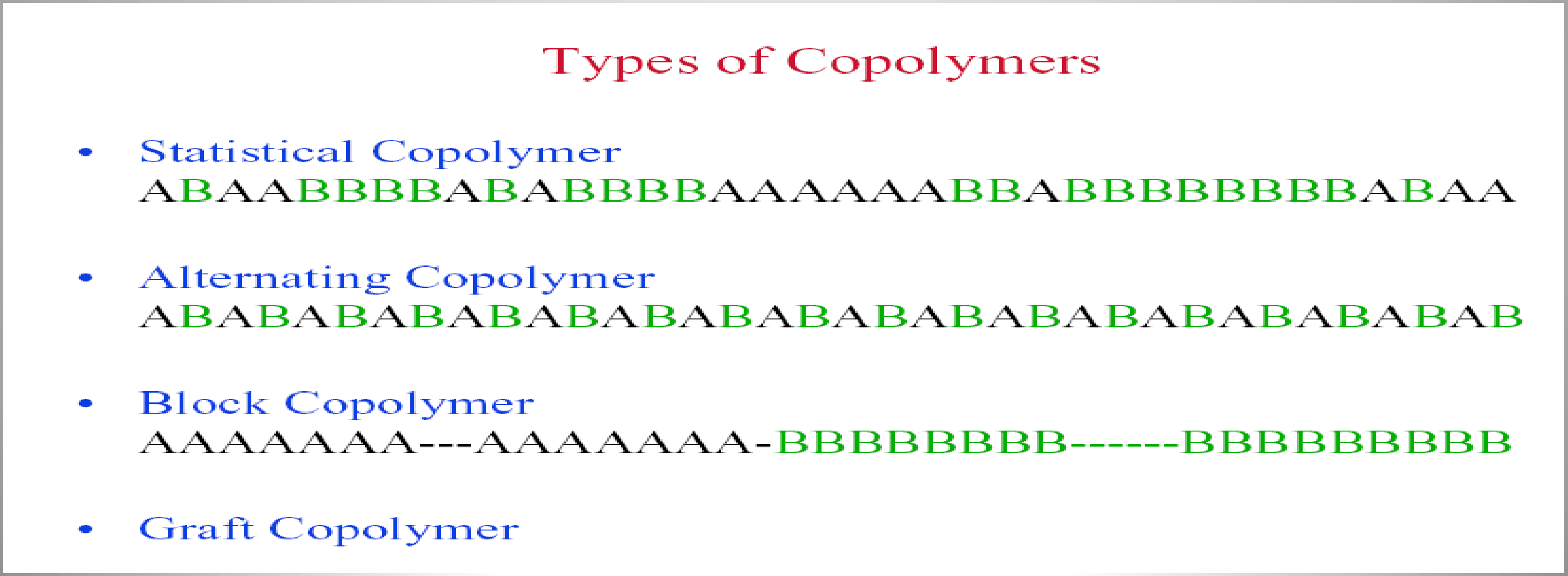


Two Monomers $CH_2{=}CH_2 + CH_2{=}CH\phi$

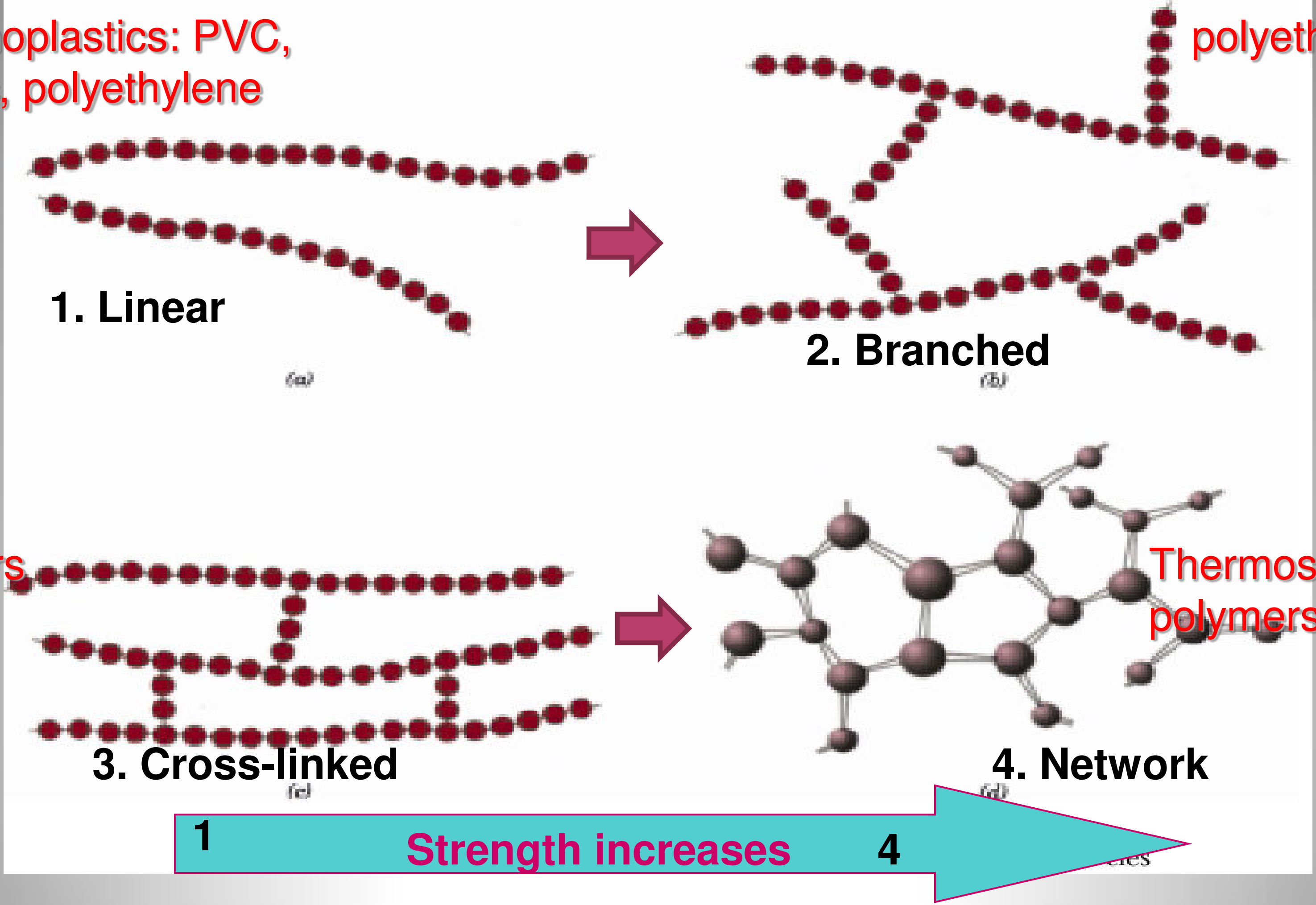
Two repeat units: $-CH_2-CH_2-$ (A) and $-CH_2-CH\phi-$ (B)



Types of Copolymers

- Statistical Copolymer
  ABAABBBBABABBBBAAAAAAABBABBBBBBBABAA
- Alternating Copolymer
  ABABABABABABABABABABABABABABABABABAB
- Block Copolymer
  AAAAAAA---AAAAAAAA-BBBBBBBB------BBBBBBBBB
- Graft Copolymer

Polymer Architecture



Thermoplastics: PVC, acrylic, polyethylene

1. Linear

polyethylene

2. Branched

Rubbers

3. Cross-linked

Thermosetting polymers

4. Network

1 **Strength increases** **4**

PLASTICS

- A large and varied group of synthetic materials that are processed by forming or moulding into shape
- Can be devided into two : THERMOPLASTICS and THERMOSETTING plastics

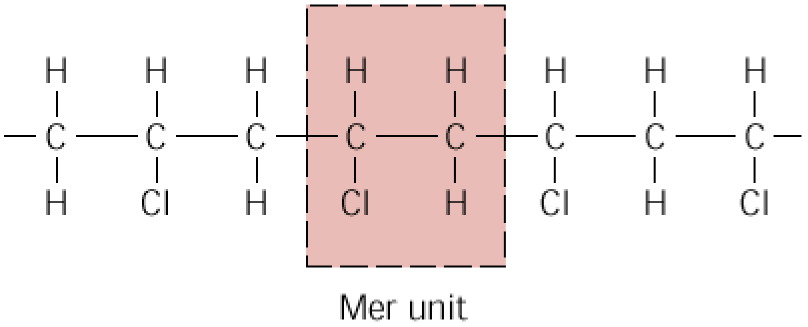
Thermosetting components

Thermoplastics component

THERMOPLASTICS

- Require heat to form and after cooling, retain the shape they were formed into.
- Can be reheated and reform a number of time (can be recycled)
- Consist of very long main chains of carbon atoms covalently bonded together (Mostly homopolymers)
- Synthesized by additional polymerization
- Easy to colour using colour pigments

PVC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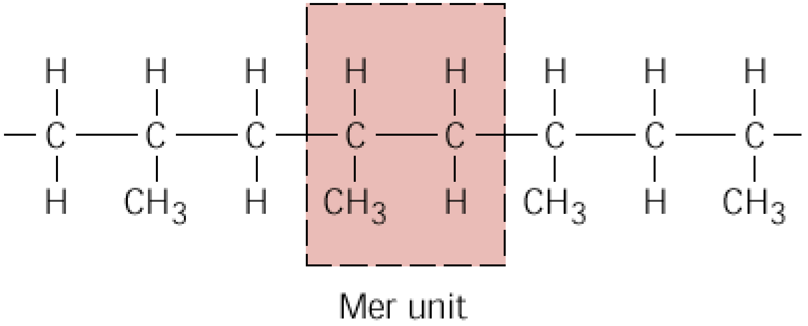
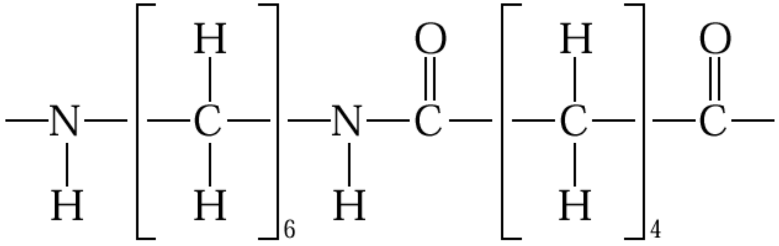
(b)

Polypropylene

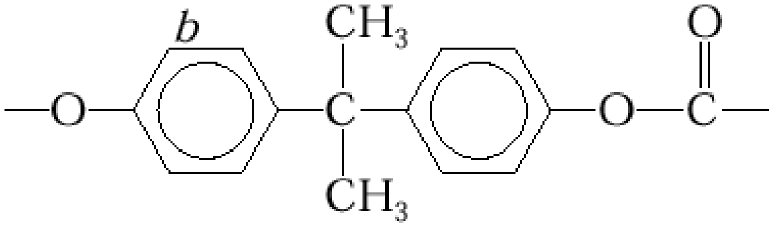

$$-\overset{\mathrm{H}}{\underset{\mathrm{H}}{\mathrm{C}}}-\overset{\mathrm{H}}{\underset{\mathrm{CH_3}}{\mathrm{C}}}-\overset{\mathrm{H}}{\underset{\mathrm{H}}{\mathrm{C}}}-\overset{\mathrm{H}}{\underset{\mathrm{CH_3}}{\mathrm{C}}}-\overset{\mathrm{H}}{\underset{\mathrm{H}}{\mathrm{C}}}-\overset{\mathrm{H}}{\underset{\mathrm{CH_3}}{\mathrm{C}}}-\overset{\mathrm{H}}{\underset{\mathrm{H}}{\mathrm{C}}}-\overset{\mathrm{H}}{\underset{\mathrm{CH_3}}{\mathrm{C}}}-$$

Linear polymers

Nylon


$$-\underset{\mathrm{H}}{\mathrm{N}}-\left[\overset{\mathrm{H}}{\underset{\mathrm{H}}{\mathrm{C}}}\right]_6-\underset{\mathrm{H}}{\mathrm{N}}-\overset{\mathrm{O}}{\mathrm{C}}-\left[\overset{\mathrm{H}}{\underset{\mathrm{H}}{\mathrm{C}}}\right]_4-\overset{\mathrm{O}}{\mathrm{C}}-$$

Polycarbonate (PC)



Complex polymers

MATERIAL TYPE	CHARACTERIZATION	APPLICATIONS
POLYETHYLENES (PE)	Chemically resistants, electrically insulating, tough, low strength, poor resistance to weathering	Flexible bottles, toys, ice trays, film wrapping materials, battery parts
POLYSTYRENE (PS)	Excellent electrical properties, good thermal and dimensional stabilities, inexpensive	Wall tiles, toys, indoor lighting panels, food containers
POLYPROPYLENES (PP)	Resistant to heat distortion, excellent electrical properties and fatigue strength, chemically inert	Sterilizable bottles, packaging films, TV cabinets, luggage
VINYLS ***Eg. PVC***	Low cost, general purpose materials, rigid, heat distortionable	Floor covering, pipe, electrical wire insulation, garden hose

ACRYLONITRILE – BUTADIENE – STYRENE (ABS)	Outstanding strength and toughness, resistant to heat distortion, good electrical properties, flammable	Refrigerator linings, lawn and garden equipment, toys, highway safety devices
ACRYLICS ***Eg. Plexiglass***	Outstanding light transmission, resistance to weathering, fair mechanical properties	Lenses, transparent aircraft enclosures, outdoor signs
POLYAMIDES ***Eg. Nylons***	Good mechanical strength, abrasion resistance and toughness, low coefficient of friction, absorbs water	Bearings, gears, cams, handles, jacketing for wires and cables

THERMOSETTING PLASTICS

- Form into a permanent shape and cured by a chemical reaction
- Cannot be remelted and reformed into another shape (cannot be recycled)
- Consist of a network of carbon atoms covalently bonded to form a rigid solid.
- High strength and hardness compare to thermoplastics
- Normally synthesized by condensation polymerization

MATERIAL TYPE	CHARACTERISTICS	APPLICATIONS
EPOXIES ***Eg. Araldite***	Excellent mechanical properties, corrosion resistance, good adhesion, inexpensive, good electrical properties	Electrical moulding, sinks, adhesive, protective coatings, used with ribre glass laminates
PHENOLICS ***Eg. Bakelite***	Excellent thermal stability, can be compounded with resins, fillers, inexpensive	Motor housings, telephones, auto distributors, electrical fixtures
POLYESTERS ***Eg. Laminac***	Excellent electrical properties, low cost, can be formulated for room or high temperature	Helmets, fibreglass boats, auto body components, chair, fans

POLYMER FORMATION

- The properties and processing of polymers depend on their structure and chemical composition

- Polymers are formed by causing small units (monomers) to chemically bond together and form very long molecules (polymers)

- The process used to cause this bonding is called “polymerisation”

- Polymerisation reactions can be:

  1. Chain- Growth Polymerisation (addition polymerisation)
     - No by-product formation

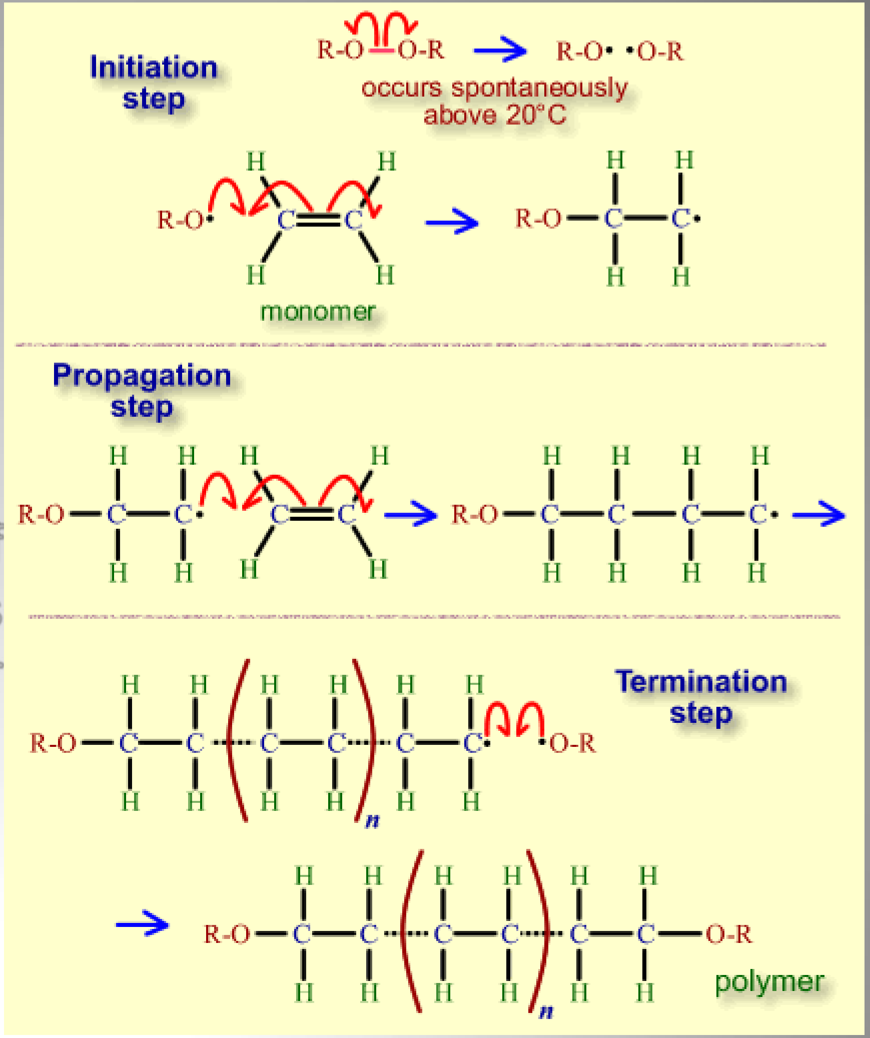
  2. Step-Growth Polymerisation (condensation polymerisation)
     - Formation of a by-product

1. Chain - Growth Polymerisation

☐ Applies to monomers that have double bonds

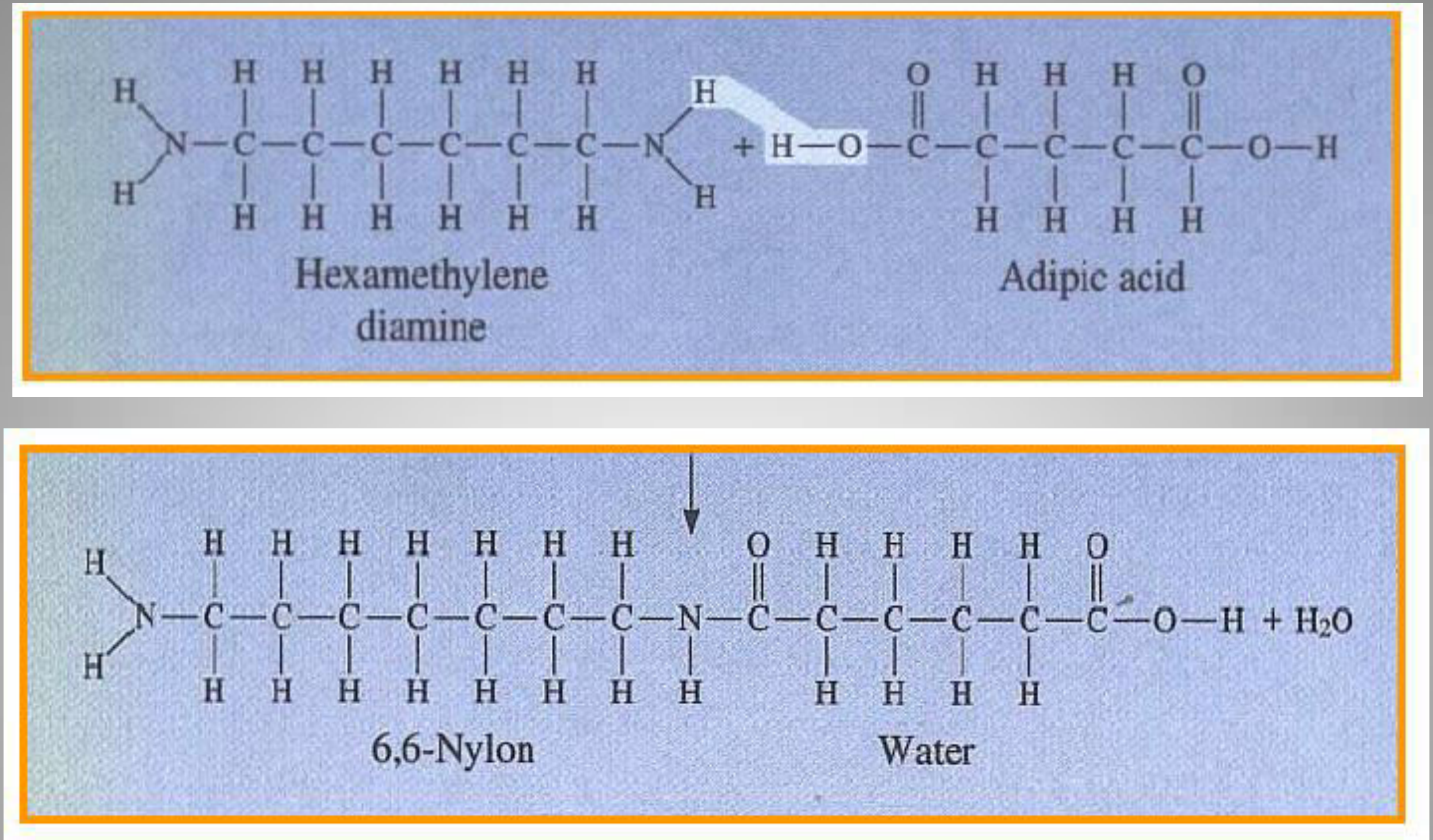
☐ Proceeds by several sequential steps

1. *Initiation step*: active initiator (peroxide) interact with monomer double bond
2. *Propagation step*: linear growth of molecule as monomer units become attached to one another producing chain molecule
3. *Termination step*: chain will eventually stop when the active end of two propagating chains react or link together to form a non-reactive molecule



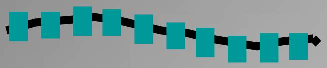
Chain polymerisation of polyethylene

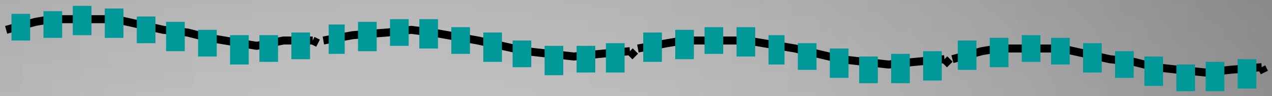
Step – Growth Polymerisation of 6,6 nylon



MOLECULAR WEIGHT

- Molecular weight, M_i: Mass of a mole of chains.

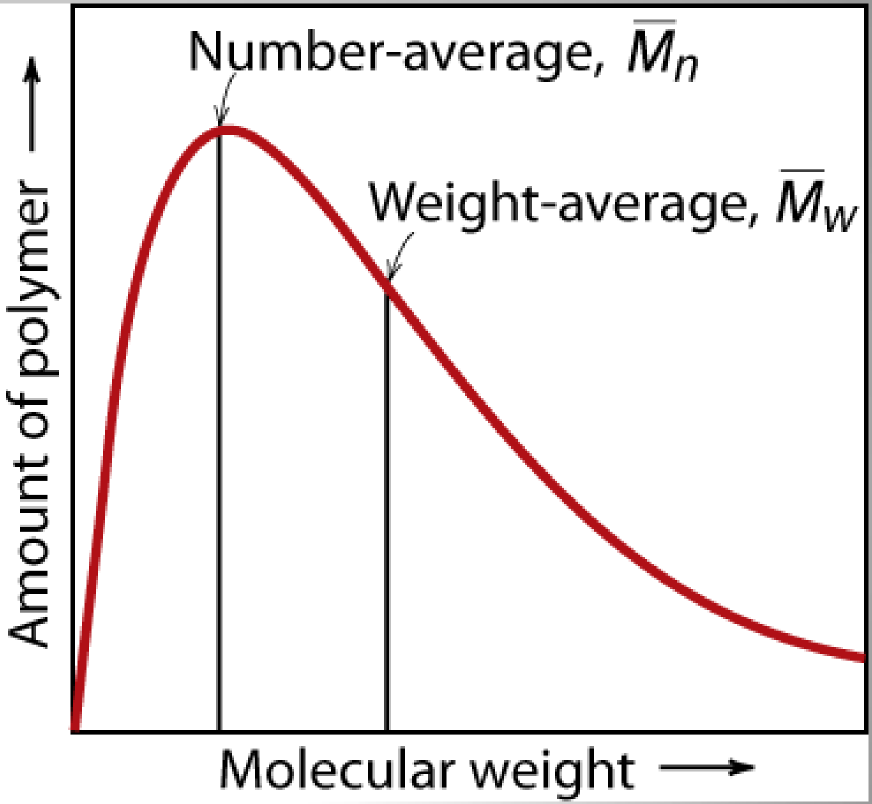




$$\overline{M}_n = \frac{\text{total wt of polymer}}{\text{total \# of molecules}}$$

$$\overline{M}_n = \Sigma x_i M_i$$
$$\overline{M}_w = \Sigma w_i M_i$$

$\overline{M}_w$ is more sensitive to higher molecular weights



Adapted from Fig. 14.4, *Callister 7e.*

Molecular Weight Calculation

Example: average mass of a class

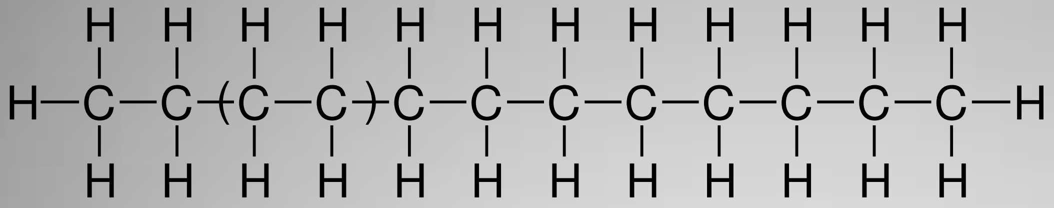
N_i	M_i	x_i	w_i
# of students	mass (lb)		
1	100	0.1	0.054
1	120	0.1	0.065
2	140	0.2	0.151
3	180	0.3	0.290
2	220	0.2	0.237
1	380	0.1	0.204
		$\overline{M}_n$	$\overline{M}_w$
		186 lb	216 lb

$$\overline{M}_n = \sum x_i M_i$$

$$\overline{M}_w = \sum w_i M_i$$

Degree of Polymerization, *n*

n = number of repeat units per chain



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$n_i = 6$

$$n_n = \sum x_i n_i = \frac{\overline{M}_n}{\overline{m}} \qquad n_w = \sum w_i n_i = \frac{\overline{M}_w}{\overline{m}}$$

where $\overline{m} =$ average molecular weight of repeat unit

$$\overline{m} = \Sigma f_i m_i$$

Chain fraction — f_i

mol. wt of repeat unit i — m_i

Elastomeric (Rubber) Material

- Elastomers are a group of polymers that have very large elastic elongation
- Elastomers are materials that can be repeatedly stretched to over twice their length and then immediately return to their original length when released.
- Elastomers can be either thermoplastics or thermosets
- Elastomers can also be natural or synthetic

***Natural Rubber**:*

- This is obtained by a suspension of a non-soluble component in water called, *latex*.

- Natural rubber has the tendency to soften and creep at elevated temperatures

- However, this problem was solved by *Goodyear* when he accidentally discovered that cooking natural rubber with sulfur would increase high temperature stability of the material.

- The use of heat and **sulfur (S)** led to the name of the process, ***vulcanisation***. This process is used to cross-link or cure elastomeric materials.

Polymer Additives

Improve mechanical properties, processability, durability, etc.

- Fillers
  - Added to improve tensile strength & abrasion resistance, toughness & decrease cost
  - ex: carbon black, silica gel, wood flour, glass, limestone, talc, etc.

- Plasticizers
  - **Plasticizers** are additives that increase the plasticity or fluidity of the material to which they are added
  - Added to reduce the glass transition temperature T_g
  - commonly added to PVC - otherwise it is brittle

e.g. phthalates add to PVC

Ester plasticizers serve as plasticizers, softeners, extenders, and lubricants, esters play a significant role in rubber manufacturing.

Other plasticizers
Benzoates
Epoxidized vegetable oils
Sulfonamides

- Stabilizers

Stabilizers for polymers are used directly or by combinations to prevent the various effects such as oxidation, chain scission and uncontrolled recombinations and cross-linking reactions that are caused by photo-oxidation of polymers.

  - Antioxidants
  - UV protectants

The effectiveness of the stabilizers against weathering depends on solubility, ability to stabilize in different polymer matrix, the distribution in matrix, evaporation loss during processing and use.

Polymer Additives

- Lubricants
  - Added to allow easier processing
  - "slides" through dies easier – ex: Na stearate

- Colorants
  - Dyes or pigments

- Flame Retardants

Flame retardants are materials that inhibit or resist the spread of fire.

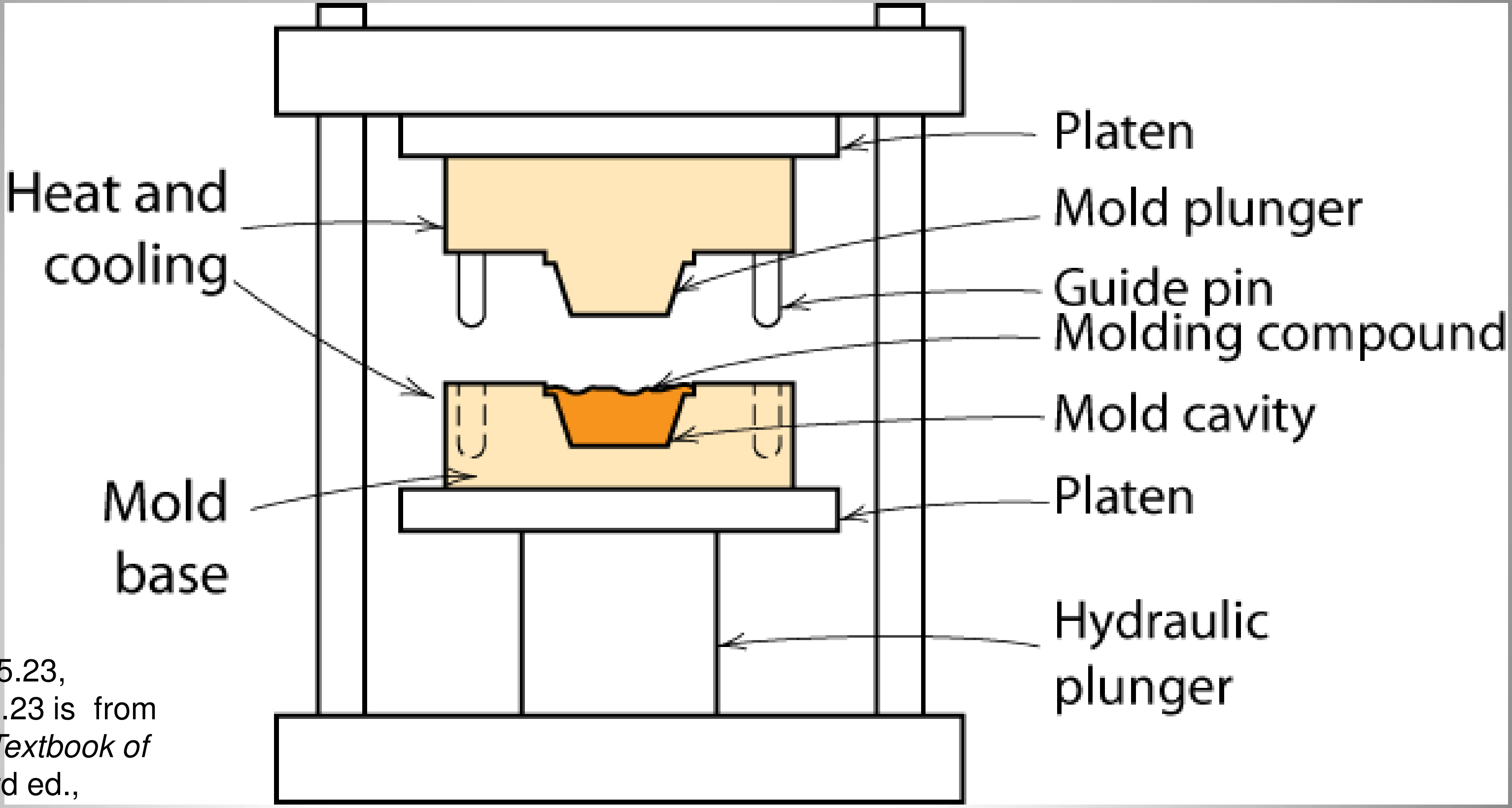
  - Cl/F & B

Processing of Plastics

- Thermoplastic –
  - can be reversibly cooled & reheated, i.e. recycled
  - heat till soft, shape as desired, then cool
  - ex: polyethylene, polypropylene, polystyrene, etc.
- Thermoset
  - when heated forms a network
  - degrades (not melts) when heated
  - mold the prepolymer then allow further reaction
  - ex: urethane, epoxy

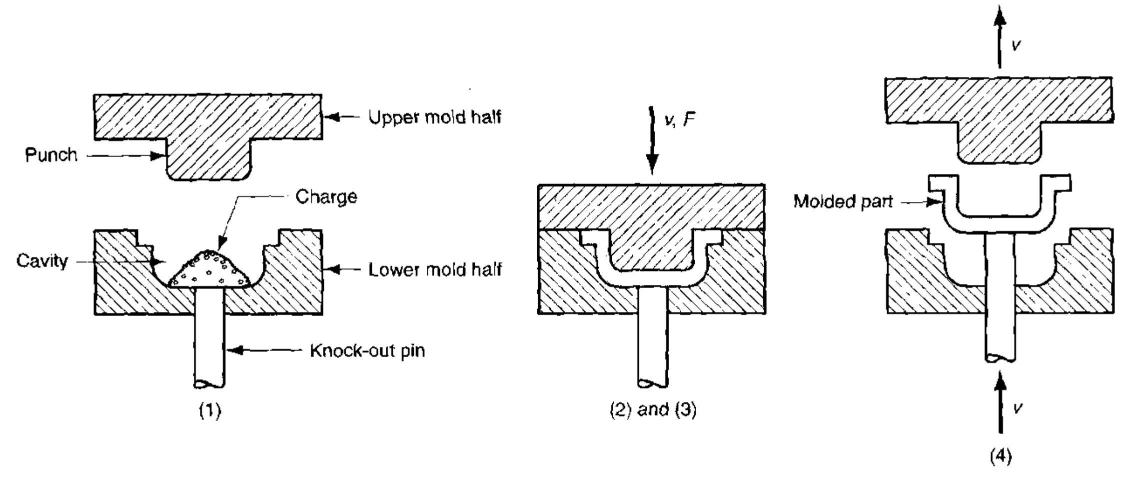
Processing Plastics - Molding

- Compression and transfer molding
  - thermoplastic or thermoset



Adapted from Fig. 15.23, *Callister 7e*. (Fig. 15.23 is from F.W. Billmeyer, Jr., *Textbook of Polymer Science,* 3rd ed., John Wiley & Sons, 1984.)

Compression Moulding



- This process was the first to be used to form plastics. It involves four steps:

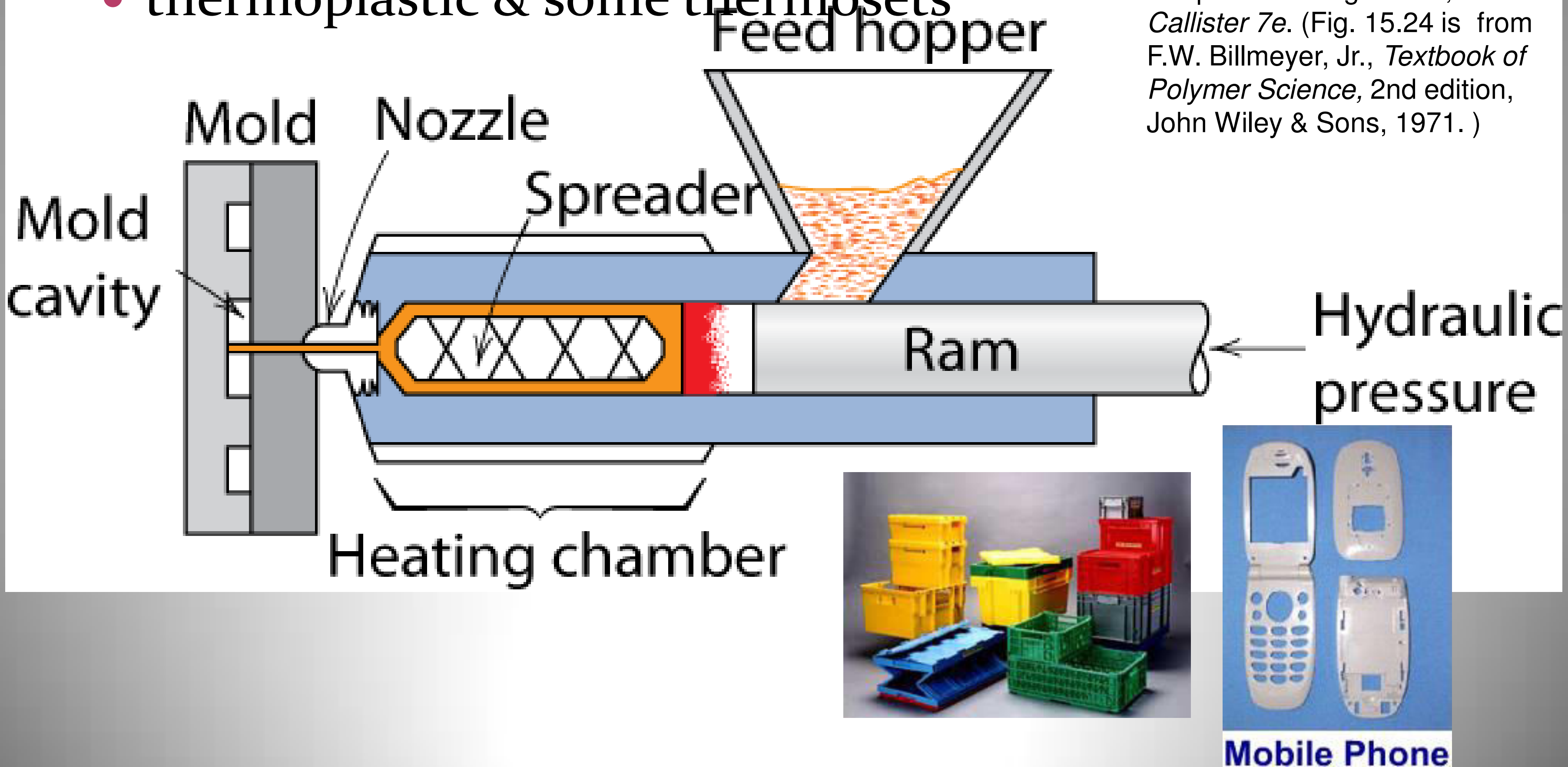
1. Pre-formed blanks, powders or pellets are placed in the bottom section of a heated mould or die.
2. The other half of the mould is lowered and is pressure applied.
3. The material softens under heat and pressure, flowing to fill the mould. Excess is squeezed from the mould. If a thermoset, cross-linking occurs in the mould.
4. The mould is opened and the part is removed.

- When thermoplastics are used, the mould is cooled before removal so the part will not lose its shape.

- When thermosets are used, they may be ejected while they are hot and after curing is complete. This process is slow, but the material moves only a short distance to the mold, and does not flow through gates or runners. Only one part is made from each mold.

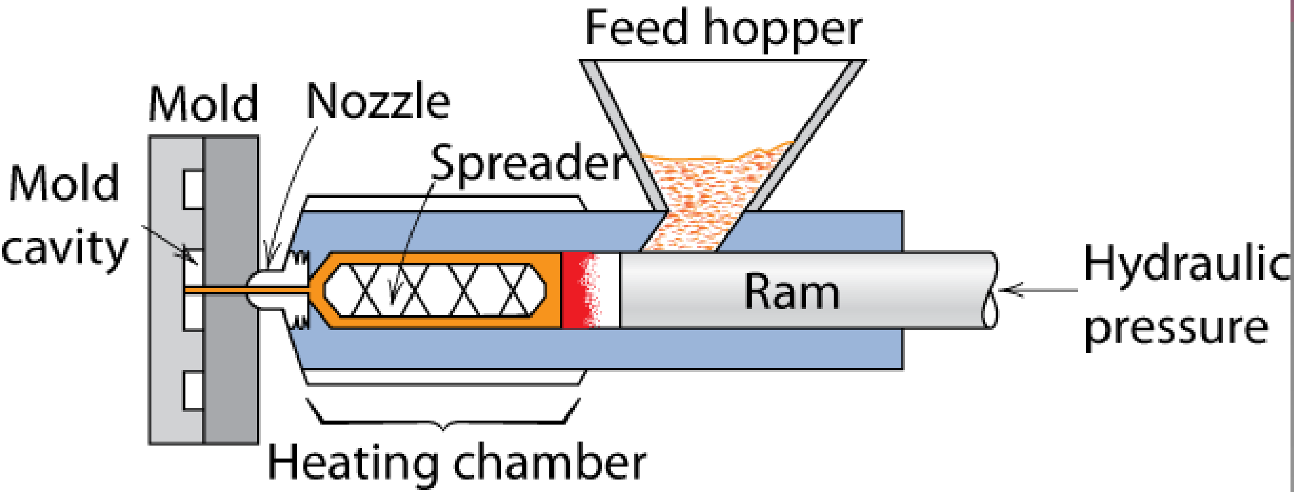
Processing Plastics - Molding

- Injection molding
  - thermoplastic & some thermosets



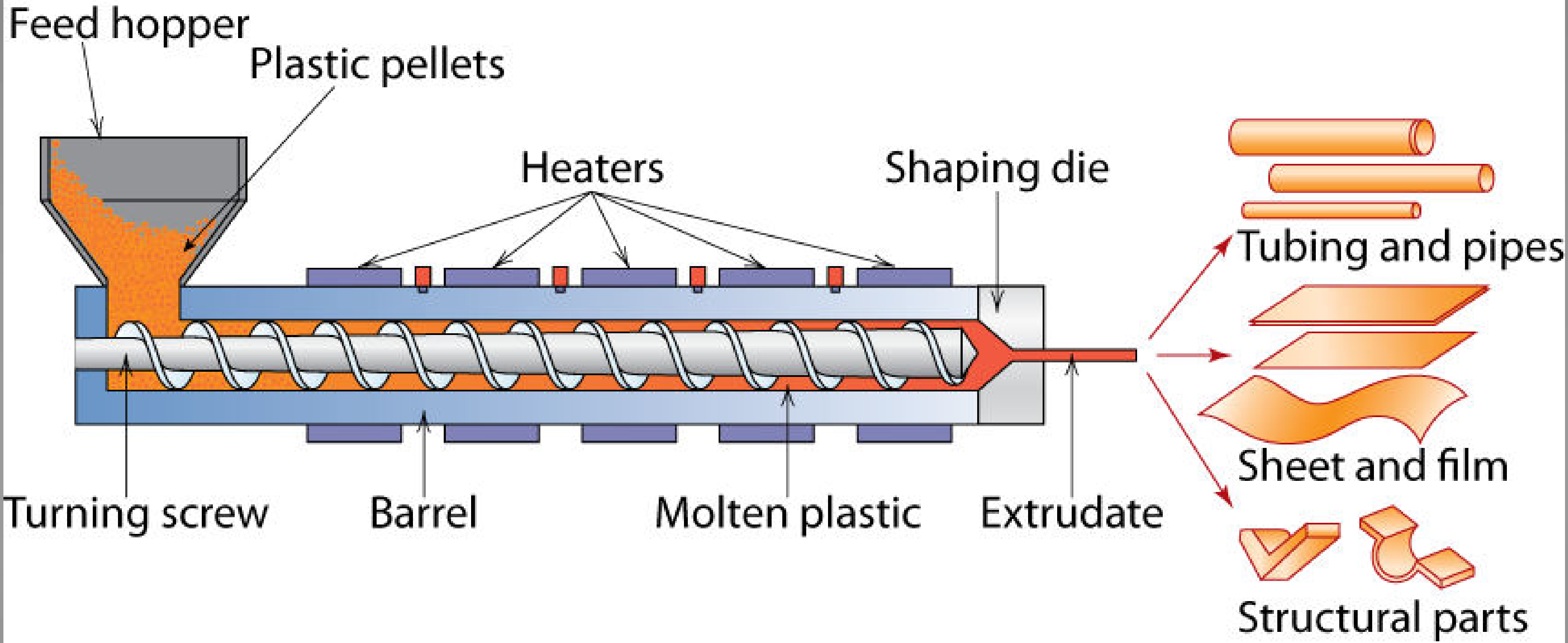
Adapted from Fig. 15.24, *Callister 7e*. (Fig. 15.24 is from F.W. Billmeyer, Jr., *Textbook of Polymer Science,* 2nd edition, John Wiley & Sons, 1971.)

Injection Moulding

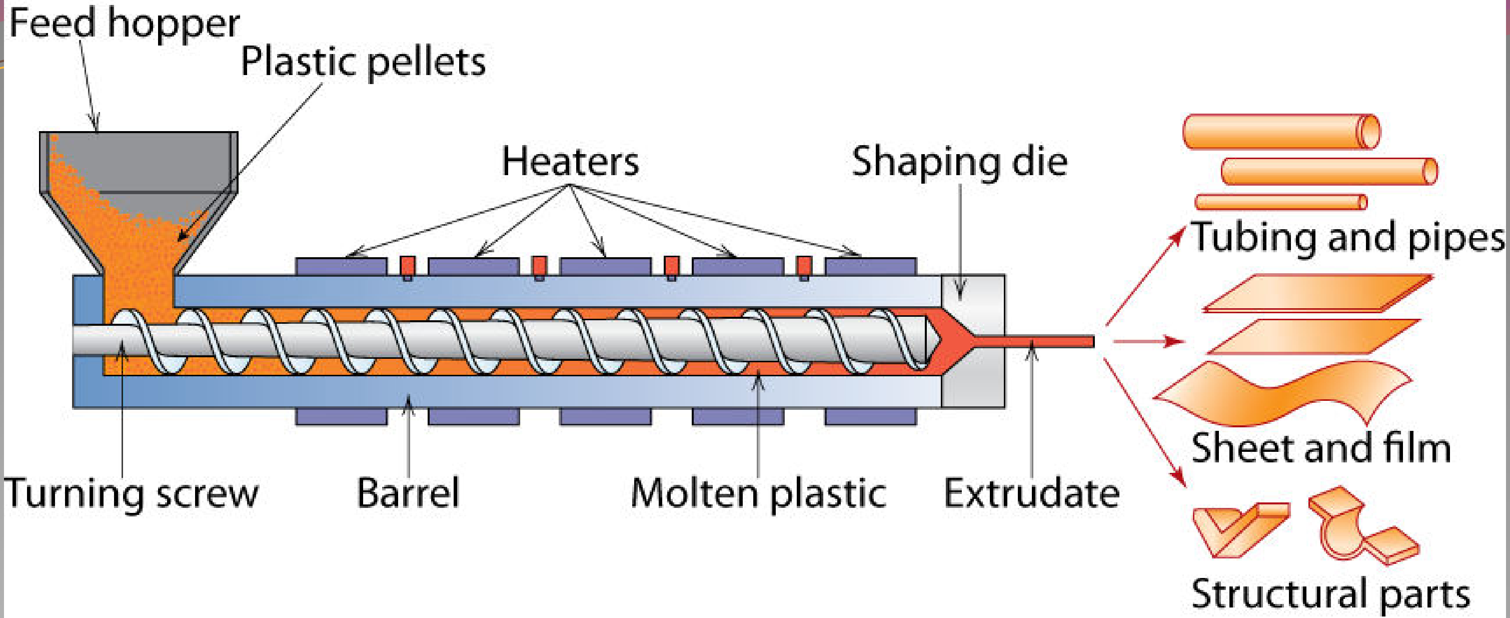


- A common process for forming plastics and involves four steps:
  1. Powder or pelletized polymer is heated to the liquid state.
  2. Under pressure, the liquid polymer is forced into a mould through an opening, called a sprue. Gates control the flow of material.
  3. The pressurized material is held in the mould until it solidifies.
  4. The mould is opened and the part removed by ejector pins.
- Advantages of injection molding include rapid processing, little waste, and easy automation. Molded parts include combs, toothbrush bases, pails, pipe fittings, and model airplane parts.

Processing Plastics – Extrusion



Adapted from Fig. 15.25,
Callister 7e. (Fig. 15.25 is from
Encyclopædia Britannica, 1997.)



Extrusion

- ☐ This process makes parts of constant cross section like pipes and rods. liquid polymer goes through a die to produce a final shape. It involves four steps:

  1. Pellets of the polymer are mixed with colouring and additives.
  2. The material is heated to its proper plasticity.
  3. The material is forced through a die.
  4. The material is cooled.

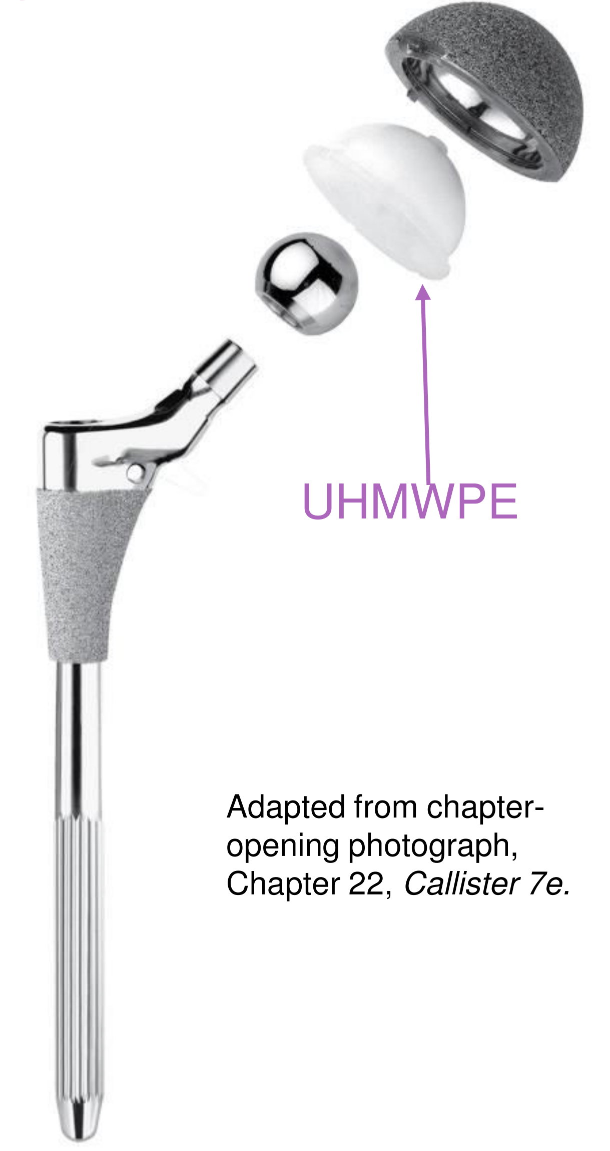
- ☐ An extruder has a hopper to feed the polymer and additives, a barrel with a continuous feed screw, a heating element, and a die holder. An adapter at the end of an extruder blowing air through an orifice into the hot polymer extruded through a ring die produces plastic bags and films.

PROCESS	TP or TS	Advantages	Disadvantages
INJECTION MOULDING	TS, TP	Most precise control of shape and dimensions. Highly automatic process and has fast cycle time. Widest choice of materials.	High capital cost and is only good for large batch size. Has large pressures in mould (20,000 psi).
COMPRESSION MOULDING	TS	Has lower mould pressures (1000 psi). Does minimum damage to reinforcing fibers (in composites), and large parts are possible.	Requires more labour, longer cycle than injection moulding. Has less shape flexibility than injection moulding, and each charge is loaded by hand.
BLOW MOULDING	TP	Can make hollow parts (especially bottles). Stretching action improves mechanical properties. Has a fast cycle, and is low labour.	Has no direct control over wall thickness. Cannot mould small details with high precision, and requires a polymer with high melt strength.
EXTRUSION	TP	Used for films, wraps, or long continuous parts (e.g; pipes).	Must be cooled below its glass transition temperature to maintain stability.

TP: thermoplastic, TS: thermoset

Advanced Polymers

- Ultrahigh molecular weight polyethylene (UHMWPE)
  - Molecular weight
    ca. 4x10^{6} g/mol
  - Excellent properties for variety of applications
    - bullet-proof vest, golf ball covers, hip joints, etc.



Adapted from chapter-opening photograph, Chapter 22, *Callister 7e.*

2. CERAMICS

- An inorganic , non metallic materials that consist of metallic and metallic elements bonded together primarily by ionic and/or covalent bonds such as oxides, carbides and nitrides.

- Can be divided into two types :

  Engineering ceramics, eg. aluminium oxide (Al_2O_3), silicon dioxide (SiO_2), silicon carbide (SiC), silicon nitride (Si_3N_4)

  Traditional ceramics, eg. clay minerals (porcelain), cement, glass)

- Very hard and strong but extremely brittle (low ductility), high melting temperature, very good thermal and electrical insulator, good chemical inertness

- In terms of fabrication :

  Casting process is normally impractical : due to high melting temperature of ceramics

  Metal forming process (rolling, forging, extrusion, drawing etc) which involved plastic deformation cannot be applied to ceramics : due to extreme brittleness, can cause fracture

- Normally fabricated from powders through powder metallurgy slip casting processes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Applications:

- Glass-ceramics :
  ovenware, tableware, oven windows (Pyrex, Vision, Corning Ware)
  ~ Due to high mechanical strength, low coefficient of thermal expansion (to avoid thermal shock), high temperature capabilities

- Clay :
  i) structural applications ~ building bricks, tiles and sewer pipes
  ~ Applications where structural integrity is important

  ii) whitewares ~ porcelain, pottery, tableware, chinaware, sanitary ware

- Abrasive Ceramics

  ~ Used to wear, grind or cut away other softer materials
  eg. Silicon carbide (SiC), tungsten carbide (WC),
  aluminium oxide (Al_2O_3) and silica (SiO_2) sand

  ~ Bonded grinding wheels, grinding papers (sand paper)

3. COMPOSITES

- Materials made from two or more constituent materials with significantly different physical or chemical properties which remain separate and distinct at the macroscopic or microscopic scale within the finished structure.

- Composed of normally two phases:

1) Dispersed or reinforcement phase :

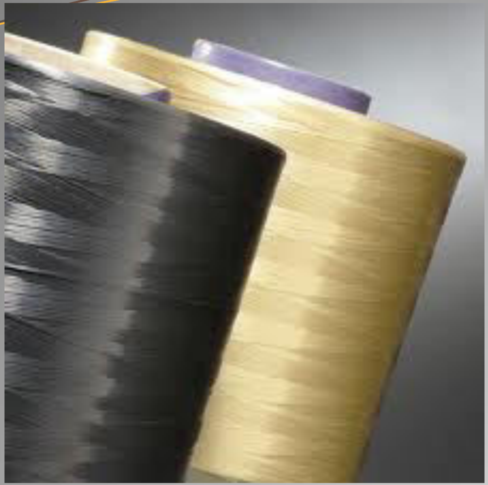
Purpose: enhance matrix properties.

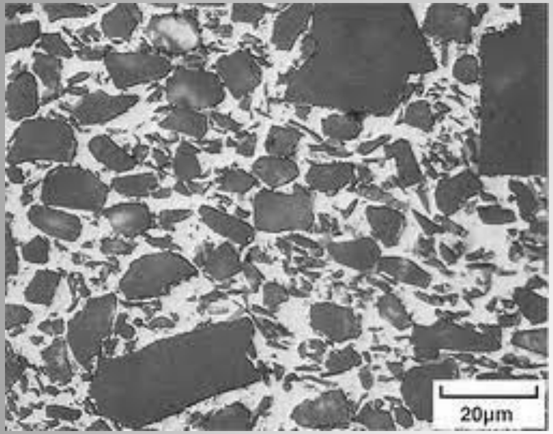
MMC: increase σ_y, *TS*, creep resist.

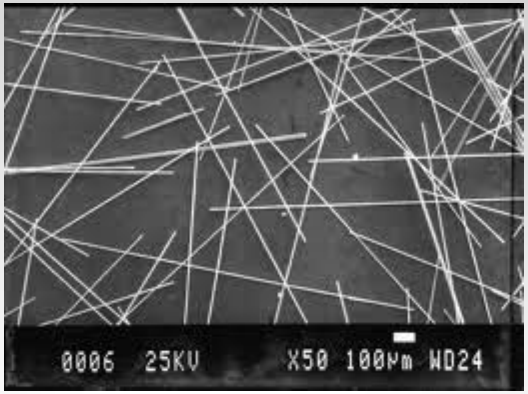
CMC: increase t*oughness,*

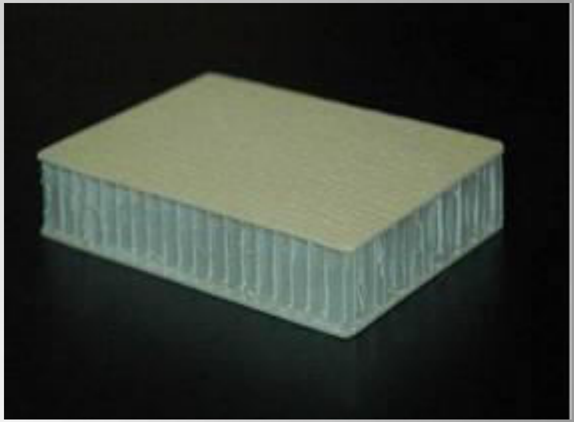
PMC: increase *E*, σ_y, *TS*, creep resist.

Classification: Particle, fiber, structural




20µm


0006 25KV X50 100µm WD24



2) Matrix : The continuous phase

Purpose: transfer stress to other phases, protect phases from environment,

Classification: Metal Matrix Composite (MMC)
Ceramic Matrix Composite (CMC)
Polymer Matrix Composite (PMC)

- Benefits from composite materials :

Improve stiffness, strength, toughness, wear resistance, thermal properties, low coefficient of thermal expansion


M Z 8800
LN
777
BOEING 777

Metal Matrix Composites

- MMC’s consist of a low density metal reinforced with a ceramic material

- The most common metal alloys used as matrix are:
  - Aluminium (Al), Magnesium (Mg), and Titanium (Ti)

- The ceramic reinforcement can be
  - Continuous: long fibres (Boron, SiC)
  - Discontinuous: particulates or whiskers (SiC)

MMC offer:

- Higher specific stiffness
- Higher operating temperatures
- Greater wear resistance
- Possibility to tailor the properties for a specific application.

MMC disadvantages include:

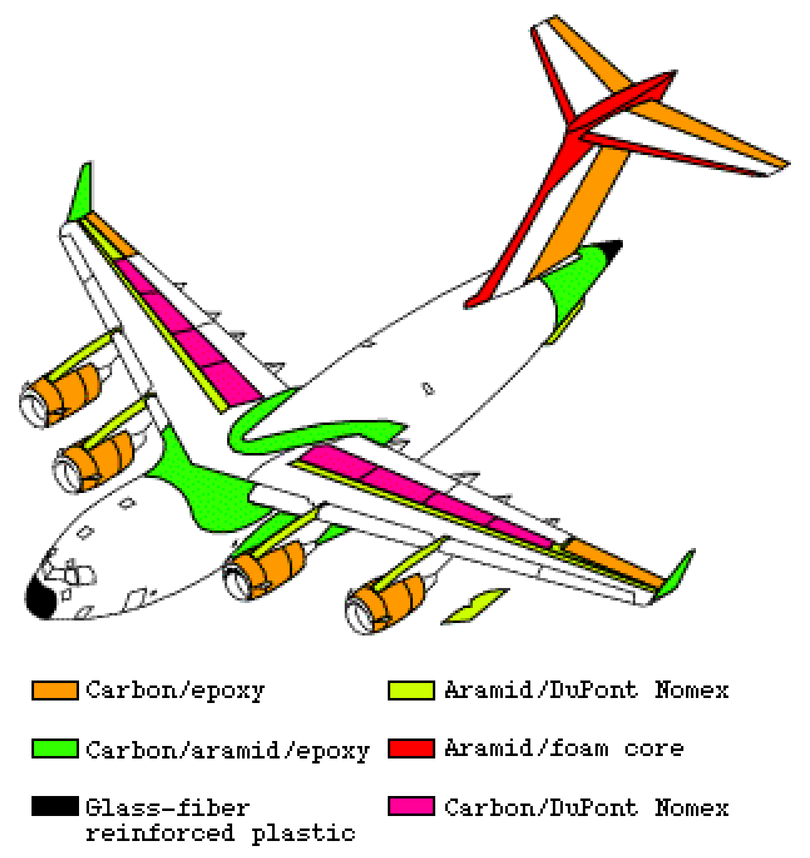
- Higher cost of materials and processing
- Lower ductility and toughness

Reinforcement	Aerospace	Automotive	Advantage
Continuous Fibres	Fins, compressor blades, aircraft structure, engine components		High thrust to weight ratio, high stiffness, low density, controlled CTE
Discontinuous Reinforcement Particulate and whiskers	Wing panels, precision components, engine components	Piston, connecting rods, bearings, cylinder liners, brake parts, drive shafts,	Wear resistance, low cost, elevated temperature properties, fatigue strength

Polymer Matrix Composites (PMC’s)

- Polymeric matrix composites are materials which contain polymers as matrix materials surrounding very small reinforcing fibers and/or fillers

- The technology of PMC’s has been driven to a large extent by aerospace and military applications



- Advantages of PMCs
  - Light weight
  - High strength-to-weight ratio
  - Directional strength
  - Corrosion resistance
  - Weather resistance
  - Dimensional stability
  - Low thermal conductivity (low thermal conductivity and low CTE)

- Among the three types of composites, PMC's have gained significant market penetration
- PMC's are used in:
  - **Aerospace components**
  - **Automotive parts**
  - **Biomedical**
  - **Sport (golf club shafts, tennis rackets)**

	Aerospace/DOD	Automotive
Major Fibers	Carbon	Glass
	Aramid	Polyester
	Boron	Nylon
Major Matrices	P.E.E.K.	Epoxy
	Epoxy	Vinyl Ester
	Carbon	Polyester
Major Processes	Prepreg	SMC Molding
	Tape Lay	Injection Molding
	Filament Winding	Filament Winding
	Autoclaving	Pultrusion
	Vacuum Bagging	Transfer Molding

Ceramic matrix composites (CMC's)

- Ceramic matrix composites (CMC's) combine reinforcing ceramic phases with a ceramic matrix to create materials with new and superior properties

- The primary function of the ceramic reinforcement is to provide toughness to the brittle ceramic matrix

- CMC's are specifically designed to overcome the brittleness of ceramics

- The desirable characteristics of CMC’s are:

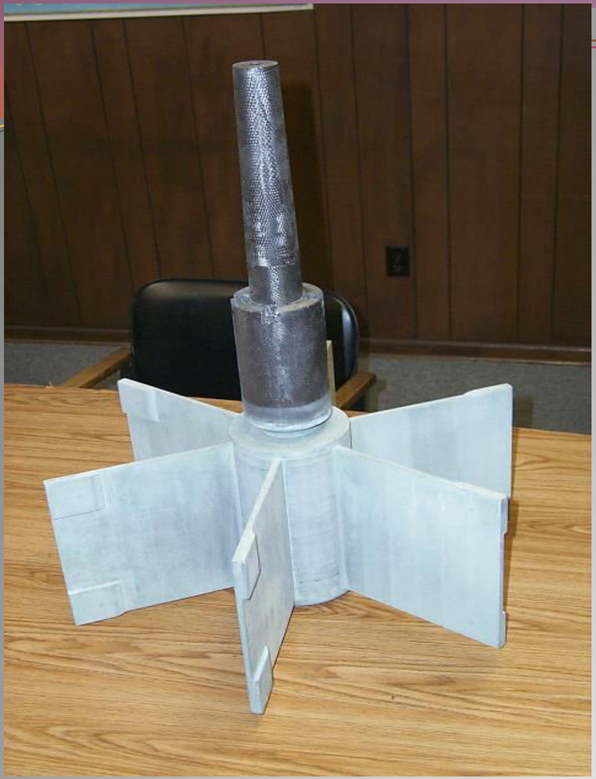
  - High temperature stability
  - High thermal shock resistance
  - High hardness
  - High corrosion resistance
  - Light weight
  - Versatility in providing unique engineering solutions

- Ceramic matrices can be categorised as either:
  - **Oxides:** **(alumina, silica, mullite)**
  - **Non-oxides:** **(SiC, Si_3N_4, BC, AlN)**

- Common discontinuous reinforcements are:
  - SiC, BC, BN, **Si_3N_4**

- Recent advanced CMC's use continuous fibers to achieve superior properties, but they are expensive to manufacture

- Common continuous reinforcements are:
  - SiC, mullite, Carbon, alumina, glass

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COATED PISTON TOP
2600 F CAPABLE
HEAT TREATED SKIRT
1000 F CAPABLE