Polymers

Davide Ruffoni
Mechanics of Biological and
Bio-inspired Materials Research Unit
www.biomat.ulg.ac.be

Introduction

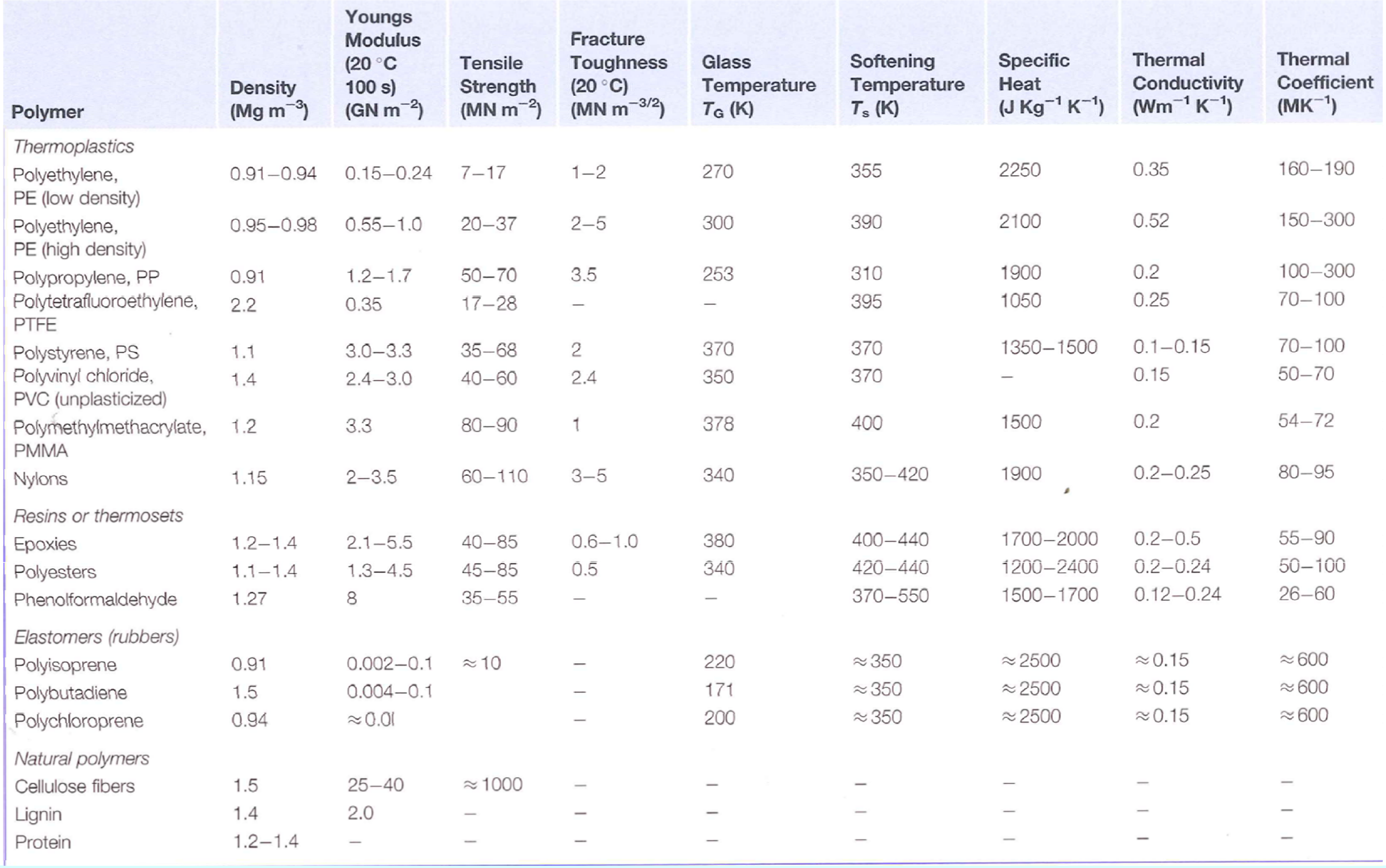
- Many biological materials are built of polymers (e.g., bone, wood) BUT only in the last 100 years we have learned how to make polymers
- Nowadays, industries that make polymers and polymer composites enjoy a faster growth rate than other branches of materials (metals & ceramics)
- Design with polymers requires special strategies as their properties can change substantially with time and temperature (especially around room temperature)

Introduction

- Polymers properties are very diverse, however common features of all polymers include:
  - long molecules (polymer chains) with a covalently bonded backbone of carbon atoms
  - polymer chains are bonded together by weak “secondary bonds” (van der Waals and hydrogen bonds) or by weak bonds + strong covalent cross-links
  - secondary bonds have a melting point close to room temperature (T_{room}) → polymers may show large creep already at T_{room}

→ design and materials selection with polymers involves considerations much different from metals and ceramics

Material Data



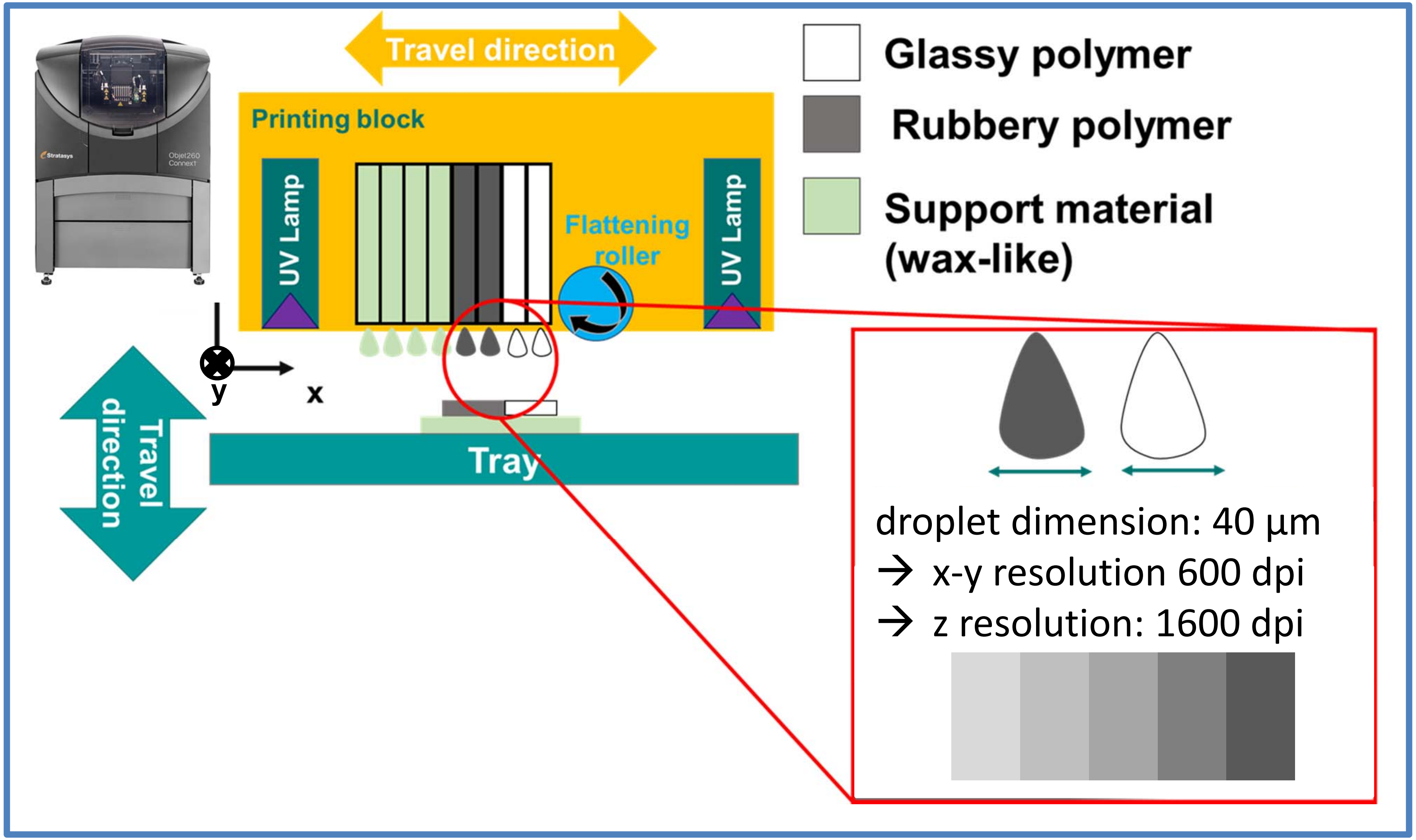
Polymer	Density (Mg m^{-3})	Youngs Modulus (20 °C 100 s) (GN m^{-2})	Tensile Strength (MN m^{-2})	Fracture Toughness (20 °C) (MN m$^{-3/2}$)	Glass Temperature T_G (K)	Softening Temperature T_s (K)	Specific Heat (J Kg^{-1} K^{-1})	Thermal Conductivity (Wm^{-1} K^{-1})	Thermal Coefficient (MK^{-1})
Thermoplastics									
Polyethylene, PE (low density)	0.91–0.94	0.15–0.24	7–17	1–2	270	355	2250	0.35	160–190
Polyethylene, PE (high density)	0.95–0.98	0.55–1.0	20–37	2–5	300	390	2100	0.52	150–300
Polypropylene, PP	0.91	1.2–1.7	50–70	3.5	253	310	1900	0.2	100–300
Polytetrafluoroethylene, PTFE	2.2	0.35	17–28	–	–	395	1050	0.25	70–100
Polystyrene, PS	1.1	3.0–3.3	35–68	2	370	370	1350–1500	0.1–0.15	70–100
Polyvinyl chloride, PVC (unplasticized)	1.4	2.4–3.0	40–60	2.4	350	370	–	0.15	50–70
Polymethylmethacrylate, PMMA	1.2	3.3	80–90	1	378	400	1500	0.2	54–72
Nylons	1.15	2–3.5	60–110	3–5	340	350–420	1900	0.2–0.25	80–95
Resins or thermosets									
Epoxies	1.2–1.4	2.1–5.5	40–85	0.6–1.0	380	400–440	1700–2000	0.2–0.5	55–90
Polyesters	1.1–1.4	1.3–4.5	45–85	0.5	340	420–440	1200–2400	0.2–0.24	50–100
Phenolformaldehyde	1.27	8	35–55	–	–	370–550	1500–1700	0.12–0.24	26–60
Elastomers (rubbers)									
Polyisoprene	0.91	0.002–0.1	≈10	–	220	≈350	≈2500	≈0.15	≈600
Polybutadiene	1.5	0.004–0.1		–	171	≈350	≈2500	≈0.15	≈600
Polychloroprene	0.94	≈0.01		–	200	≈350	≈2500	≈0.15	≈600
Natural polymers									
Cellulose fibers	1.5	25–40	≈1000	–	–	–	–	–	–
Lignin	1.4	2.0	–	–	–	–	–	–	–
Protein	1.2–1.4	–	–	–	–	–	–	–	–

Material Data: **Recommendations**

- If properties of metals (e.g. stainless steel) differ very little from two different manufacturers this is NOT true for polymers (e.g. polyethylene)
- Many factors have a big influence on the behavior of polymers (e.g., distribution of molecular lengths, polymerization, mechanical processing, additives)
- Data from books are only *approximate*

→ accurate data requires to use manufacturer datasheet or (even better) to perform own tests (e.g. 3D polymer printing)

3D Polymer Printer: Objet Connex260 www.stratasys.com



droplet dimension: 40 µm

→ x-y resolution 600 dpi

→ z resolution: 1600 dpi

Material Data: **Recommendations**

- Polymers bonding: "primary" (covalent) bonds + "secondary" (van der Waals and hydrogen) bonds
- At glass temperature T_G the secondary bonds melt → strong decrees in Young's modulus (e.g. from 3 GPa for $T < T_G$ to 3 MPa for $T > T_G$)
- In many polymers T_G is only slightly higher than room temperature T_{room}

  → at T_{room} a large fraction of secondary bonds is already melted and under load the remaining secondary bonds creep

  → decrease in modulus $E_{1000\,h}(20\,°C) = \frac{1}{3} E_{100\,s}(20\,°C)$
- Tensile strength is a large fraction of elastic modulus: $\sigma_y = \frac{E}{20}$ → design based on yield gives large deflections without damage (car bumpers, plastic bottles)

Material Data: **Recommendations**

- For many polymers T_G is near to T_{room}:

  →@ T_{room} polymers are fairly tough, but if $T<T_G$, K_C (fracture toughness) can drop significantly

Material Data: **Recommendations**

Design with polymers requires special attention to:

- **Time-dependent effects**
- **Large elastic deformations**
- **Effects of temperature (even close to room temperature)**

Generic Polymers

Thermoplastics

- Polyethylene is the most common thermoplastics
- They are often linear polymers, i.e. the chains are not cross-linked but may branch
- They soften and flow like a viscous liquid when heated (after the melting of secondary bonds), allowing to be formed
- They are made by adding together (polymerizing) subunits (monomers) to form long chains

Generic Polymers: Thermoplastics

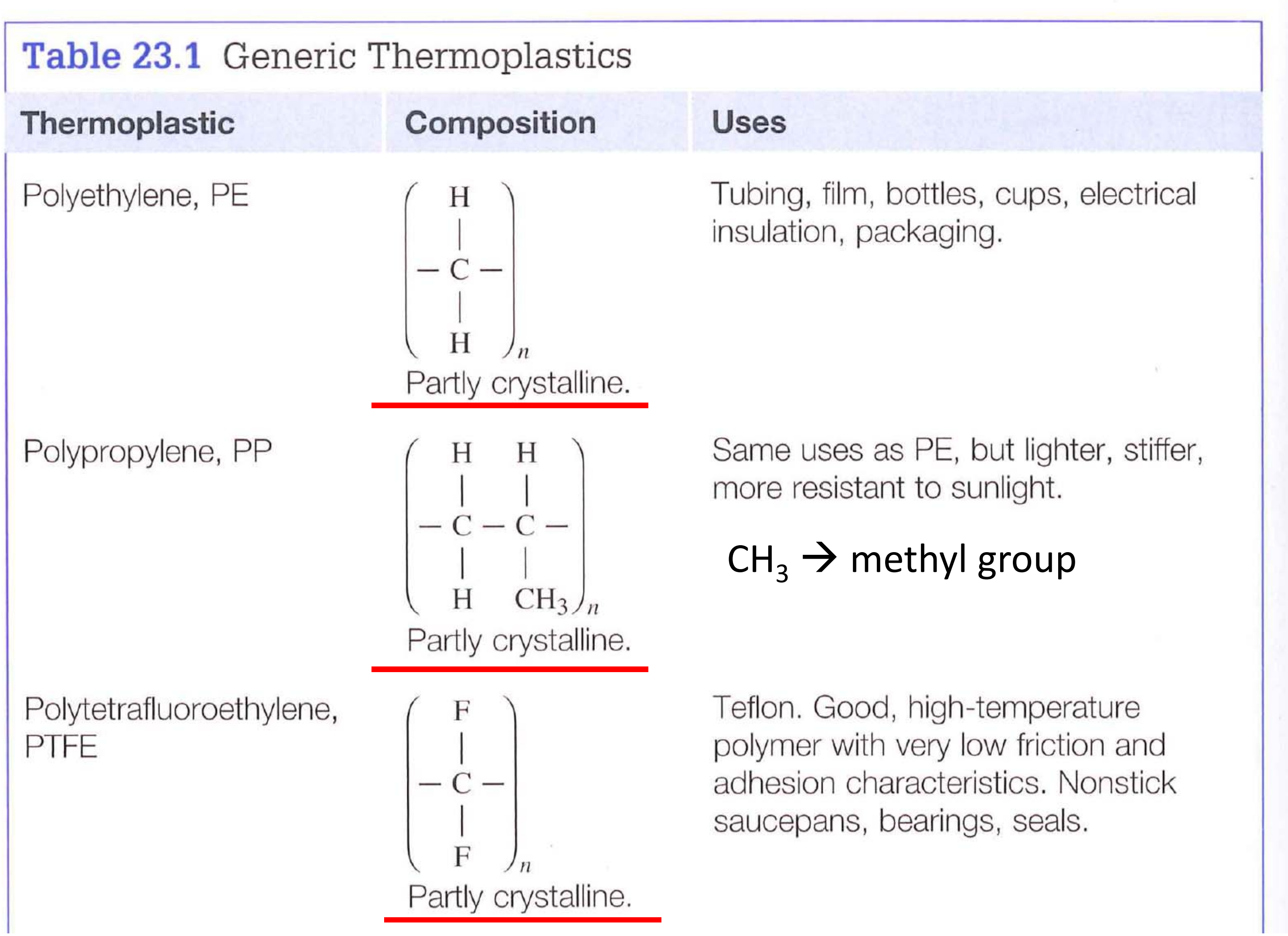


Table 23.1 Generic Thermoplastics

Thermoplastic	**Composition**	**Uses**
Polyethylene, PE	$\left(\begin{array}{c} \mathrm{H} \\ \vert \\ -\mathrm{C}- \\ \vert \\ \mathrm{H} \end{array}\right)_n$ Partly crystalline.	Tubing, film, bottles, cups, electrical insulation, packaging.
Polypropylene, PP	$\left(\begin{array}{cc} \mathrm{H} & \mathrm{H} \\ \vert & \vert \\ -\mathrm{C}- & \mathrm{C}- \\ \vert & \vert \\ \mathrm{H} & \mathrm{CH_3} \end{array}\right)_n$ Partly crystalline.	Same uses as PE, but lighter, stiffer, more resistant to sunlight.
Polytetrafluoroethylene, PTFE	$\left(\begin{array}{c} \mathrm{F} \\ \vert \\ -\mathrm{C}- \\ \vert \\ \mathrm{F} \end{array}\right)_n$ Partly crystalline.	Teflon. Good, high-temperature polymer with very low friction and adhesion characteristics. Nonstick saucepans, bearings, seals.

CH_3 → methyl group

Generic Polymers: Thermoplastics

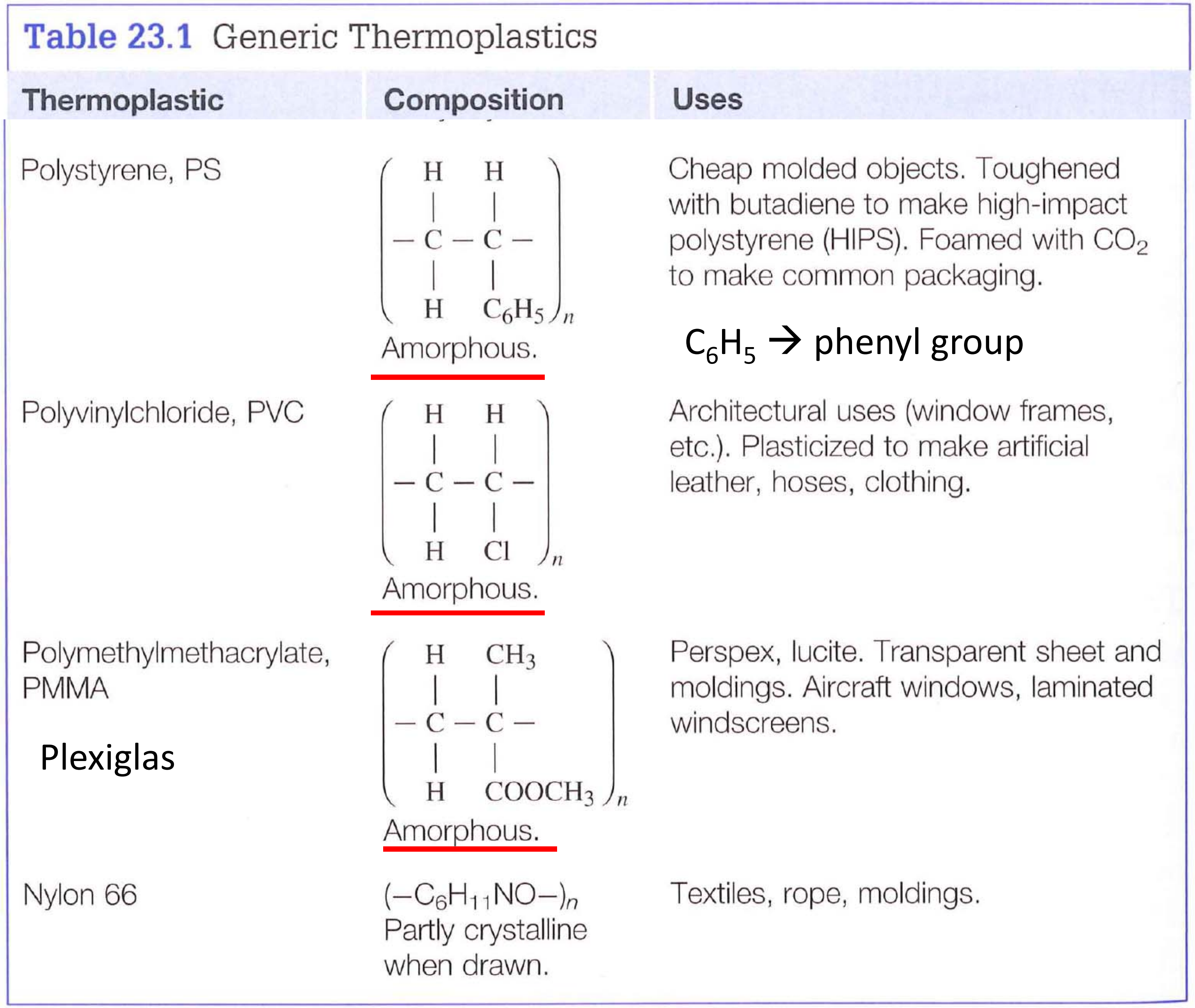


Table 23.1 Generic Thermoplastics

Thermoplastic	Composition	Uses
Polystyrene, PS	$\left(\begin{array}{ccccc} & H & & H & \\ & \vert & & \vert & \\ - & C & - & C & - \\ & \vert & & \vert & \\ & H & & C_6H_5 & \end{array}\right)_n$ Amorphous.	Cheap molded objects. Toughened with butadiene to make high-impact polystyrene (HIPS). Foamed with CO_2 to make common packaging.
Polyvinylchloride, PVC	$\left(\begin{array}{ccccc} & H & & H & \\ & \vert & & \vert & \\ - & C & - & C & - \\ & \vert & & \vert & \\ & H & & Cl & \end{array}\right)_n$ Amorphous.	Architectural uses (window frames, etc.). Plasticized to make artificial leather, hoses, clothing.
Polymethylmethacrylate, PMMA	$\left(\begin{array}{ccccc} & H & & CH_3 & \\ & \vert & & \vert & \\ - & C & - & C & - \\ & \vert & & \vert & \\ & H & & COOCH_3 & \end{array}\right)_n$ Amorphous.	Perspex, lucite. Transparent sheet and moldings. Aircraft windows, laminated windscreens.
Nylon 66	$(-C_6H_{11}NO-)_n$ Partly crystalline when drawn.	Textiles, rope, moldings.

C_6H_5 → phenyl group

Plexiglas

Generic Polymers

Thermosets (or resins)

- Epoxy is the most famous thermosets
- They are made by mixing two components: a resin and a harder (either at room temperature or on heating)
- They are heavily cross-linked (also called network polymers)
- The cross-links form during polymerization so the structure is <u>almost always amorphous</u>
- On re-heating the secondary bonds melt and the modulus drop but the crosslinks prevent viscous flow → no hot-working
- Further heating causes decomposition

Generic Polymers: Thermosets

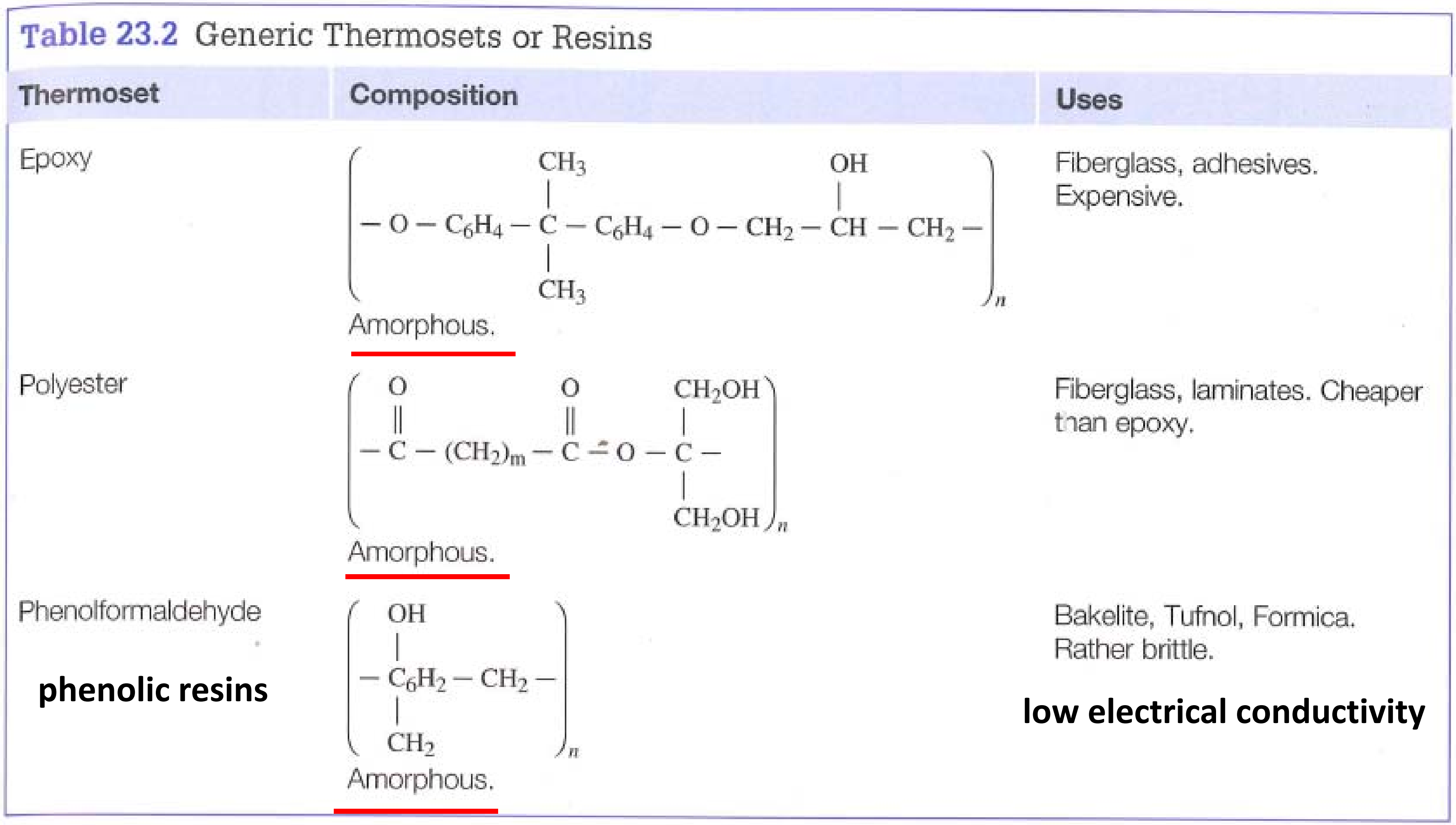


Table 23.2 Generic Thermosets or Resins

Thermoset	Composition	Uses
Epoxy	$\left(-O-C_6H_4-\overset{CH_3}{\underset{CH_3}{C}}-C_6H_4-O-CH_2-\overset{OH}{CH}-CH_2-\right)_n$ Amorphous.	Fiberglass, adhesives. Expensive.
Polyester	$\left(-\overset{O}{\overset{\Vert}{C}}-(CH_2)_m-\overset{O}{\overset{\Vert}{C}}-O-\overset{CH_2OH}{\underset{CH_2OH}{C}}-\right)_n$ Amorphous.	Fiberglass, laminates. Cheaper than epoxy.
Phenolformaldehyde	$\left(-\overset{OH}{\underset{CH_2}{C_6H_2}}-CH_2-\right)_n$ Amorphous.	Bakelite, Tufnol, Formica. Rather brittle.

phenolic resins

low electrical conductivity

Generic Polymers

Elastomers (or rubbers)

- They are almost linear polymers with occasional cross-links
- At room temperature all the secondary bonds have already melted
- The cross-links provide a memory of the material so that it returns to its original shape on unloading

Generic Polymers: Rubbers

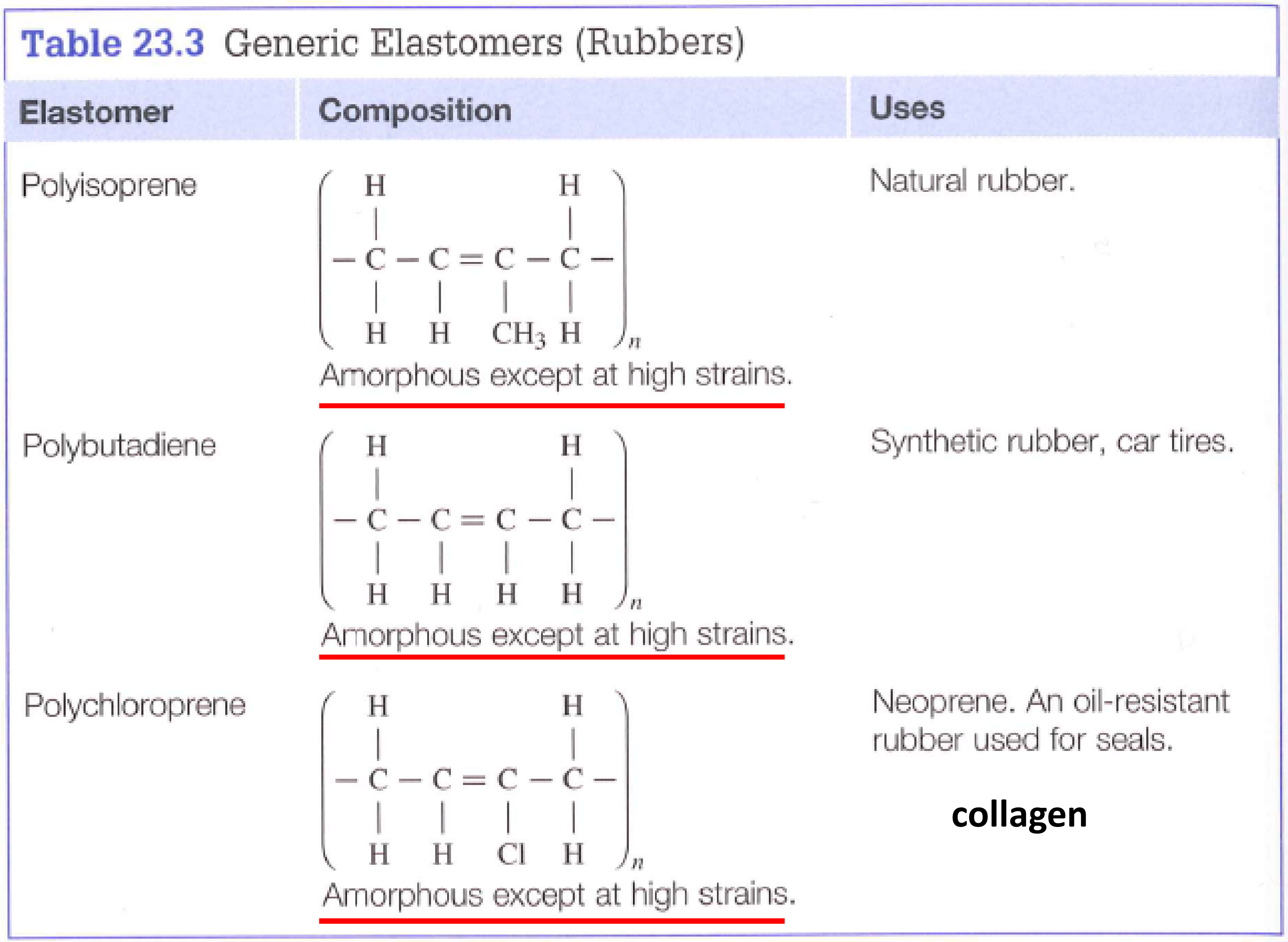


Table 23.3 Generic Elastomers (Rubbers)

Elastomer	Composition	Uses
Polyisoprene	$\left(-\overset{\mathrm{H}}{\underset{\mathrm{H}}{\mathrm{C}}} - \underset{\mathrm{H}}{\mathrm{C}} = \underset{\mathrm{CH_3}}{\mathrm{C}} - \overset{\mathrm{H}}{\underset{\mathrm{H}}{\mathrm{C}}} - \right)_n$ Amorphous except at high strains.	Natural rubber.
Polybutadiene	$\left(-\overset{\mathrm{H}}{\underset{\mathrm{H}}{\mathrm{C}}} - \underset{\mathrm{H}}{\mathrm{C}} = \underset{\mathrm{H}}{\mathrm{C}} - \overset{\mathrm{H}}{\underset{\mathrm{H}}{\mathrm{C}}} - \right)_n$ Amorphous except at high strains.	Synthetic rubber, car tires.
Polychloroprene	$\left(-\overset{\mathrm{H}}{\underset{\mathrm{H}}{\mathrm{C}}} - \underset{\mathrm{H}}{\mathrm{C}} = \underset{\mathrm{Cl}}{\mathrm{C}} - \overset{\mathrm{H}}{\underset{\mathrm{H}}{\mathrm{C}}} - \right)_n$ Amorphous except at high strains.	Neoprene. An oil-resistant rubber used for seals.

collagen

Generic Polymers: Natural Polymers

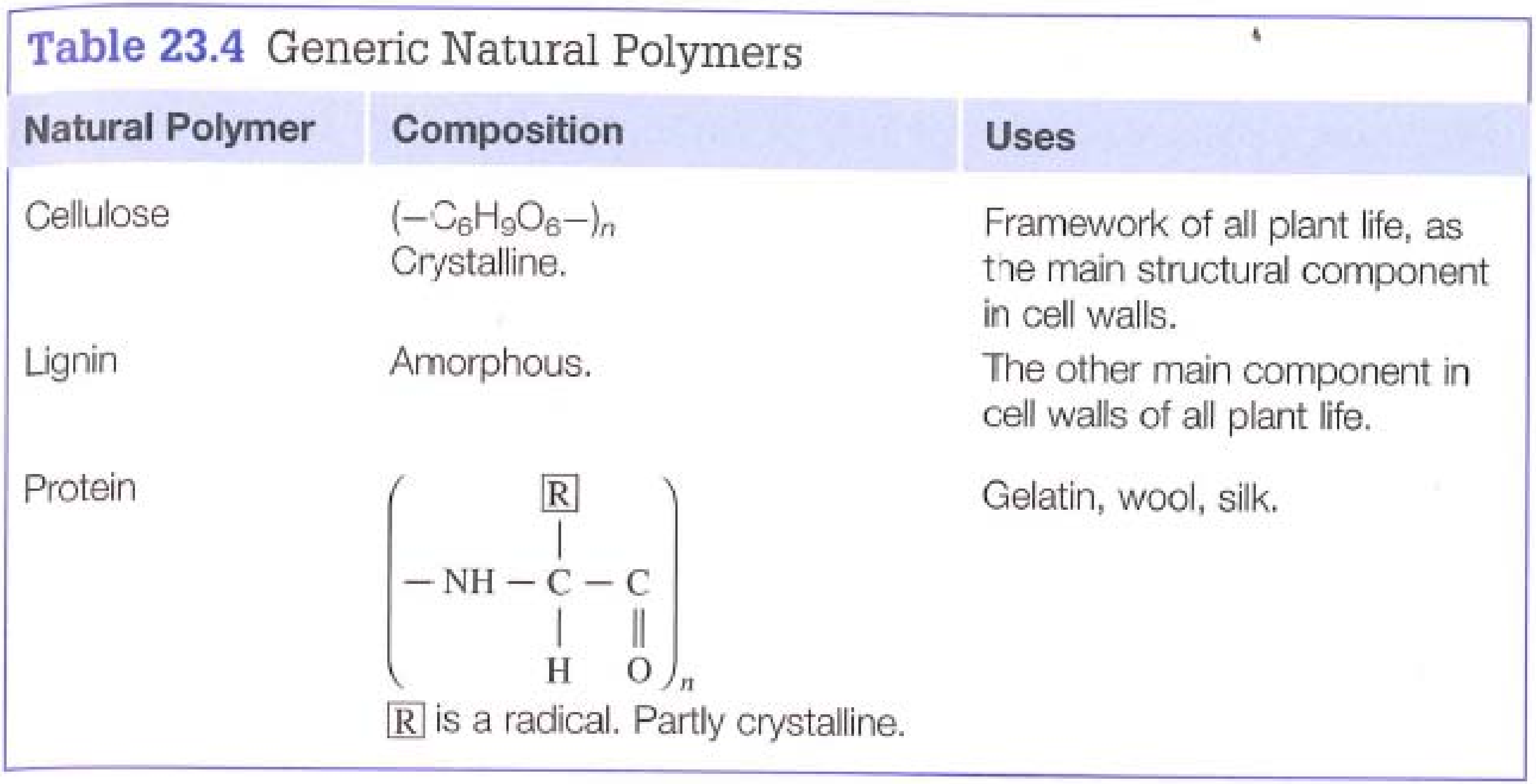
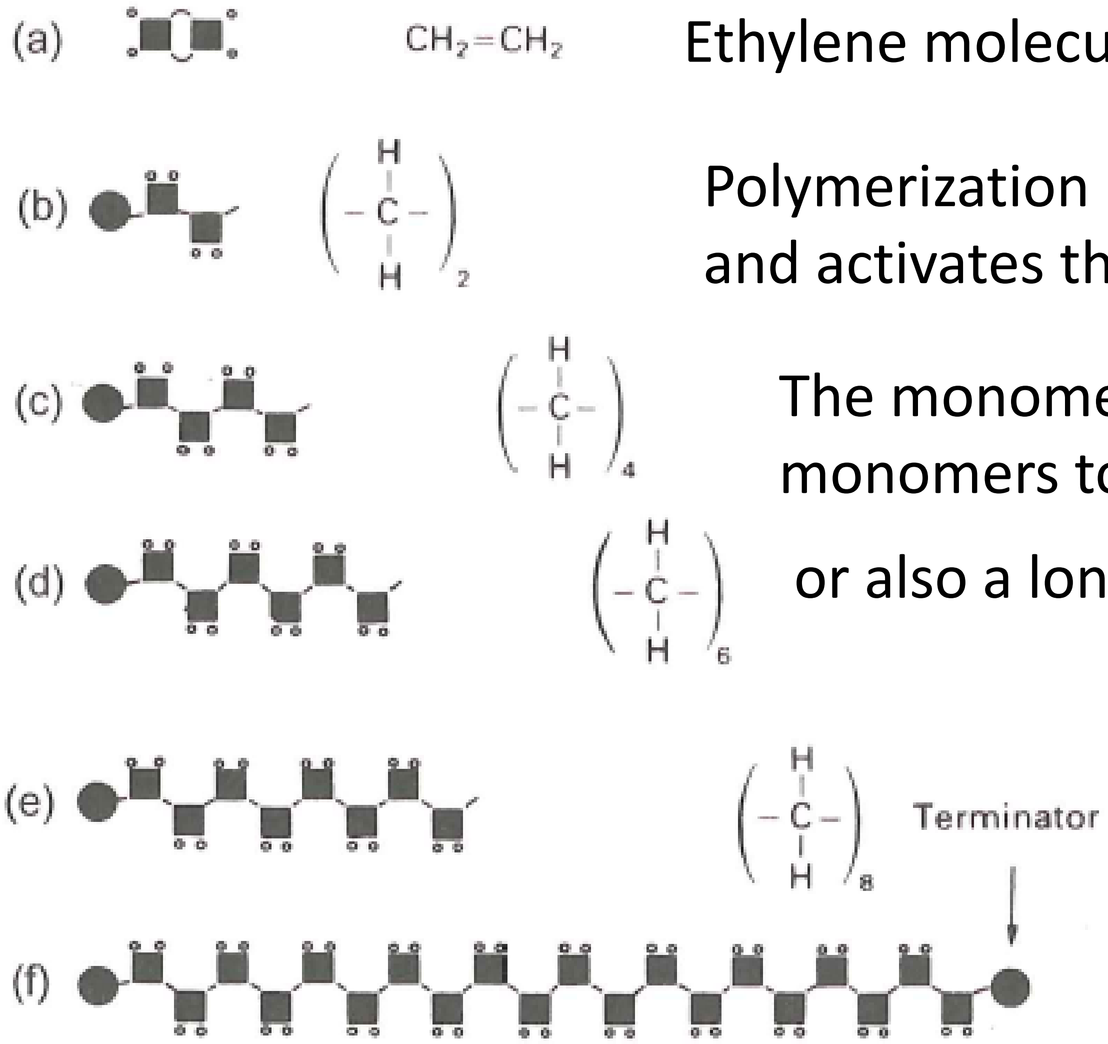


Table 23.4 Generic Natural Polymers

Natural Polymer	Composition	Uses
Cellulose	$(-C_6H_9O_6-)_n$ Crystalline.	Framework of all plant life, as the main structural component in cell walls.
Lignin	Amorphous.	The other main component in cell walls of all plant life.
Protein	$\left(-\mathrm{NH}-\underset{\underset{\mathrm{H}}{\vert}}{\overset{\overset{\boxed{\mathrm{R}}}{\vert}}{\mathrm{C}}}-\underset{\underset{\mathrm{O}}{\Vert}}{\mathrm{C}}\right)_n$ $\boxed{\mathrm{R}}$ is a radical. Partly crystalline.	Gelatin, wool, silk.

Molecular Length



Ethylene molecule (or monomer)

Polymerization breaks the double bond and activates the monomer

The monomer can link to other monomers to form a dimer …

or also a long chain

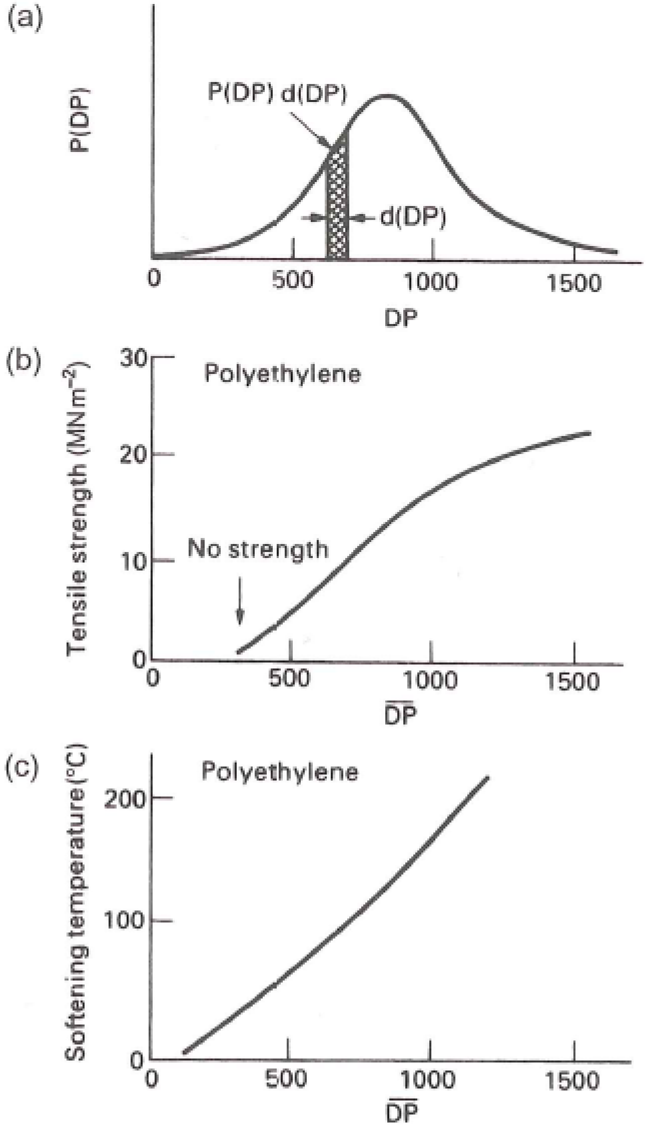
The ends of the chains either link to other macromolecules or end with a terminator (OH)

Molecular Length & Weight

- Degree of Polymerization (DP): number of monomer units in the chain
- To have a solid polymer with “useful” mechanical properties the DP must be at least 500
- Commercial polymers have DP: 10^3-10^5
- Molecular Weight (MW):

  → DP x molecular weight of the monomer (ethylene monomer C_2H_4 has molecular weight of 28; average DP of polyethylene is 10^4 → average MW=280.000)
- In all commercial polymers there is a range of DP and thus of molecular length and weight

Molecular Length & Weight



$$\overline{DP} = \int_0^{\infty} DP\,P(DP)\,d(DP)$$

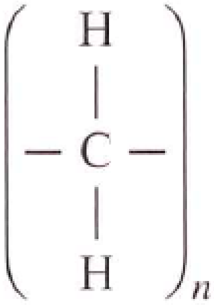
Polymeric materials based on the same repeating monomer <u>do not have a unique set of properties</u>:

→ there are many polyethylene and their properties strongly depend on the average DP

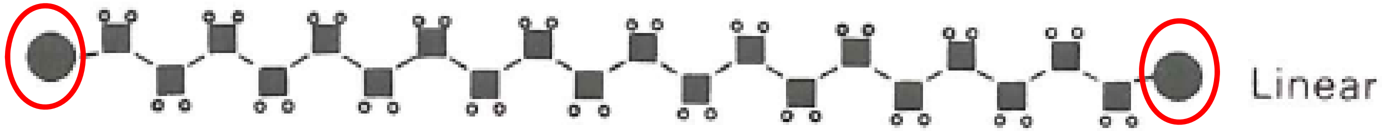
Molecular Architecture

Thermoplastics

- Largest class of engineering polymers
- Linear molecules **not cross-linked** → soften when heated
- The simplest linear-chain polymer is polyethylene



$$\left(\begin{array}{c} H \\ | \\ -C- \\ | \\ H \end{array} \right)_n$$



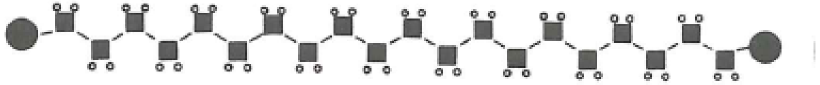
Molecular Architecture

Thermoplastics

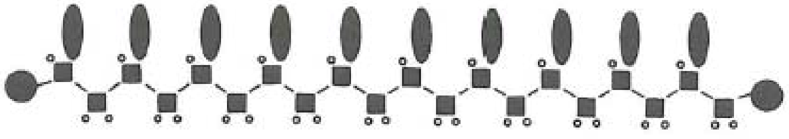
- By replacing one H with a side-group R (radical) we have the *vinyl* group of polymers [-C-H=CH_2]:
  - R = Cl → polyvinyl chloride
  - R = CH_3 → polypropylene
  - R = C_6H_5 → polystyrene
- The radical gives **asymmetry** to the chain → different ways the monomers can be attached to form a chain

Molecular Architecture

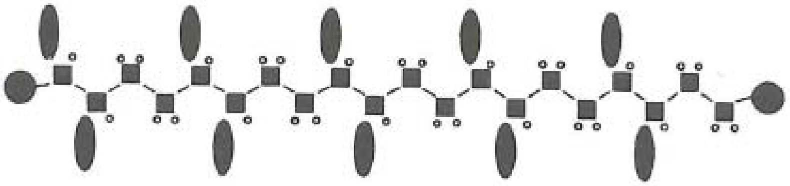
Thermoplastics



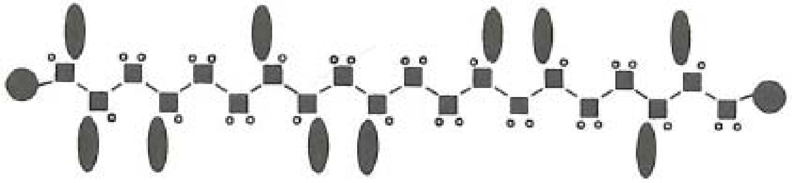
Linear (PE)



Isotactic: the side-groups are all on the same side



Sindiotactic: the side-groups alternate regularly

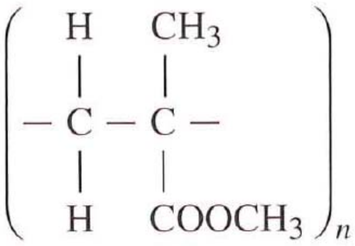


Atactic: the side-groups alternate irregularly

Molecular Architecture

Thermoplastics

- Tacticity influences properties:
  - regular molecules can form crystals whereas irregular molecules (atactic) cannot
  - isotactic molecules carry a net electric dipole and can be electroactive (e.g. piezoelectric effects)
- If two H are replaced → *vinylidene* group



$$\left(-\overset{\displaystyle H}{\underset{\displaystyle H}{\overset{|}{\underset{|}{C}}}} - \overset{\displaystyle CH_3}{\underset{\displaystyle COOCH_3}{\overset{|}{\underset{|}{C}}}} - \right)_n$$

Amorphous.

- ▪ R1 = CH_3 (methyl) & R2= $COOCH_3$ (ester)

→ PMMA or Plexiglass

- ▪ increased difficulty to get regular arrangements

→ most of them are amorphous

Molecular Architecture

Thermosets

- Based on large poylfunctional monomers
- Form random three-dimensional networks with several (covalent) cross-links
- Do not melt when heated
- Do not easily dissolve in solvents
- Cannot be formed after polymerization
- Chemical more stable and mechanically stiffer than thermoplastics
- Used as adhesive, coating and matrix for composites

Molecular Architecture

Elastomers

- Linear polymers with a few cross-links

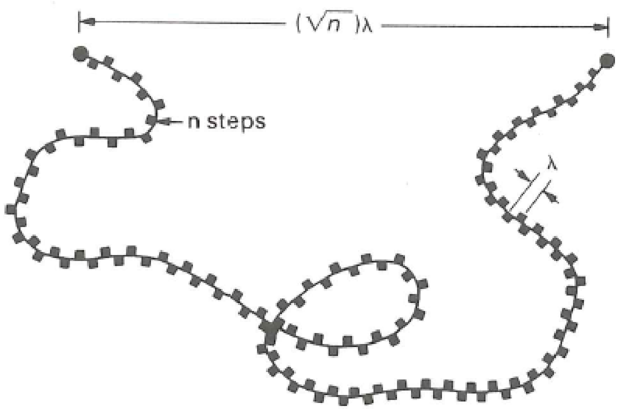
  (**1 every 100 or more monomers**)

  e.g., DP 500 → less than 5 cross links !!!
- Glass temperature (T_g) well below room temperature (at room temperature the secondary bonds have melted)

Molecular Packing and Glass Transition

- Due to the rotational degrees of freedom of the C-C backbone, a free polymer molecule is never straight but it can spiral, twist, ...
- This is particularly the case when a linear polymer melts (e.g. during forming)

→ spaghetti-like tangle

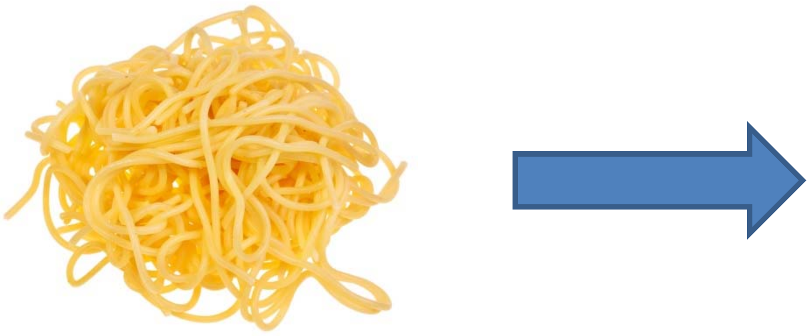


The average end-to-end distance is described by the random walk model of a polymer with n units of length λ: $\sqrt{\boldsymbol{n}}\boldsymbol{\lambda}$

Large strain (400%) are needed to straighten out the molecule

Molecular Packing and Glass Transition

- When the polymer melt is cooled the spaghetti-tangle may freeze without rearranging:



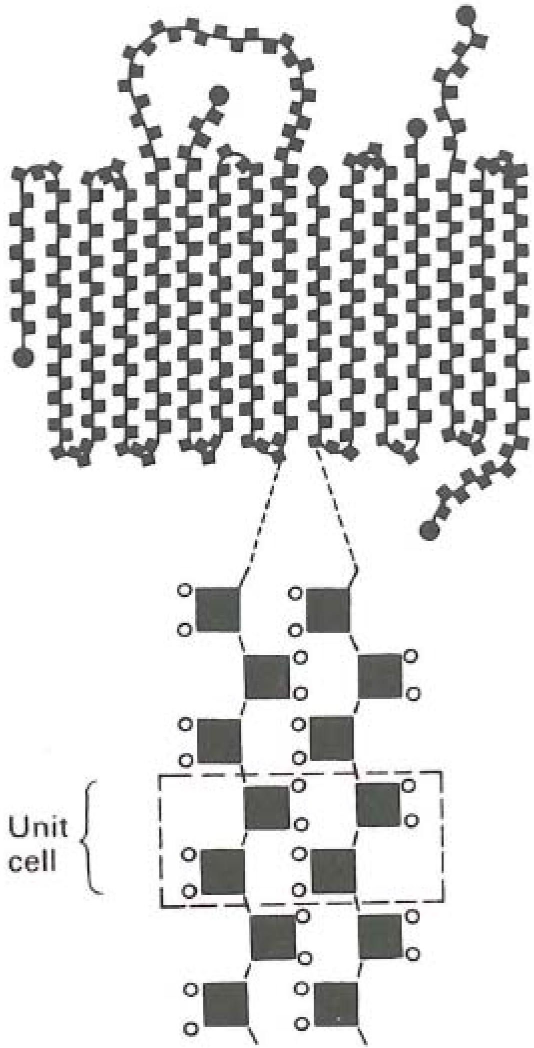
Amorphous structure

- During cooling molecules can move and may line-up (depending on their architecture and secondary bonds) → they can form *crystallites*

Molecular Packing and Glass Transition

Polymer crystals

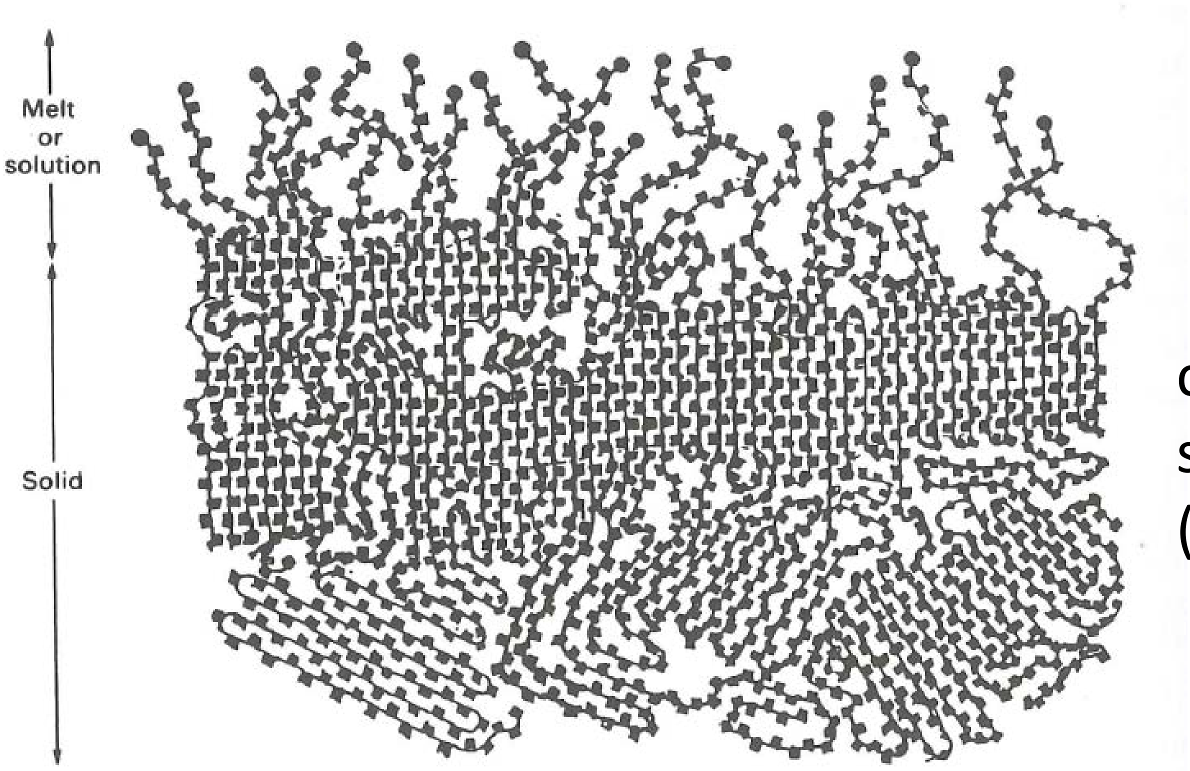
- Linear chain molecules with no side-groups or branches can crystallize (e.g. high density polyethylene)
- On cooling secondary bonds tend to pull the molecules together into parallel bundles → *chain folded* crystals
- In general, crystallinity is not as high as in metals but it is high enough to diffract X-rays and to allow the definition of a unit cell



Molecular Packing and Glass Transition

Polymer crystals

- Even the most crystalline molecules (high density PE) is only **80% crystal**



crystalline parts separated by amorphous (or glassy) regions

Mechanical Properties

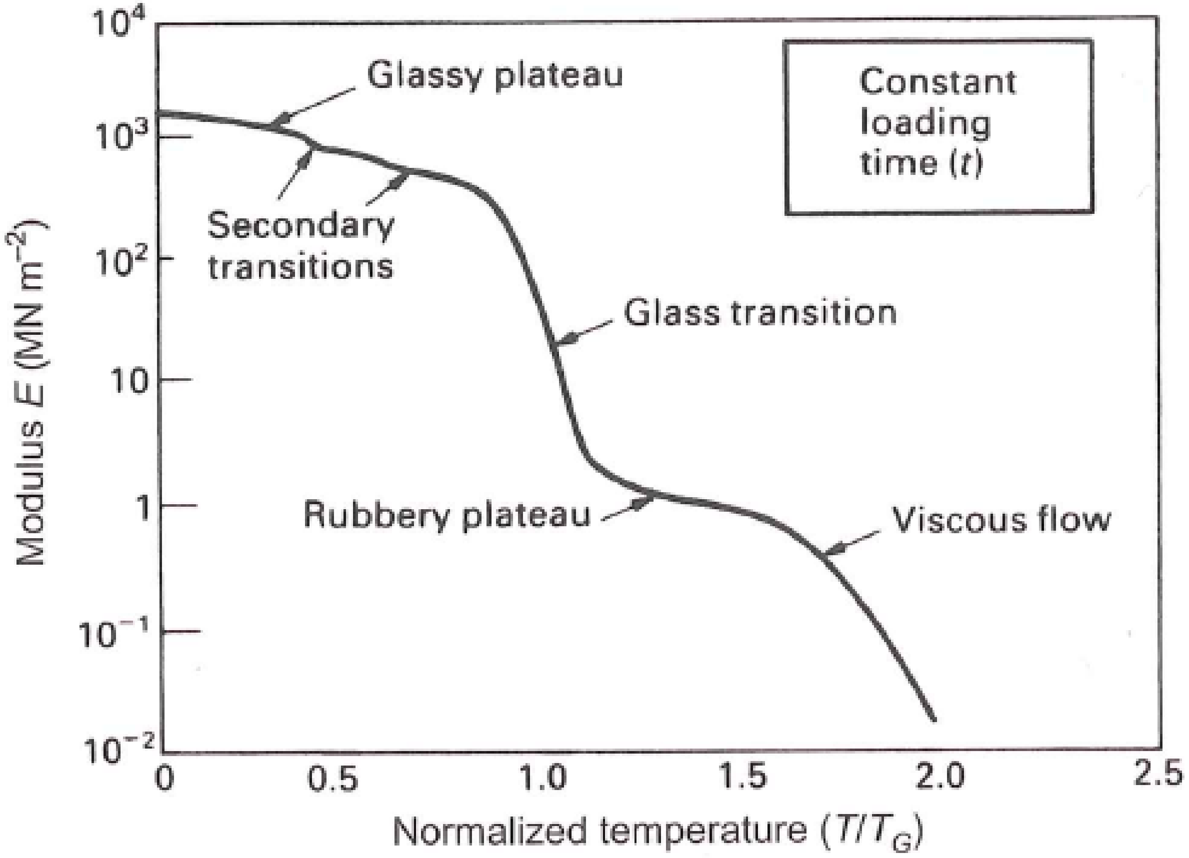
Introduction

- Large spectrum of mechanical properties (brittle-elastic, plastic, viscoelastic, rubbery and viscous) within a quite “small” temperature range:

  [**-20** °C → **+200** °C]

- While metals and ceramics have a constant stiffness and strength at room temperature, this is **not true** for polymers
- Mechanical state of a polymer mainly depends on **molecular weight** and **temperature** - how close is T to T_G
- Polymer mechanical properties are often plotted against **T/T_G**

Introduction



PMMA: $T_{room} = 0.75\ T_G$
polyethylene: $T_{room} = 1\ T_G$
polyisoprene: $T_{room} = 1.5\ T_G$

general behavior of Young's modulus as a function of temperature for a linear (amorphous) polymer for a fixed loading time

Time and Temperature Dependent Stiffness

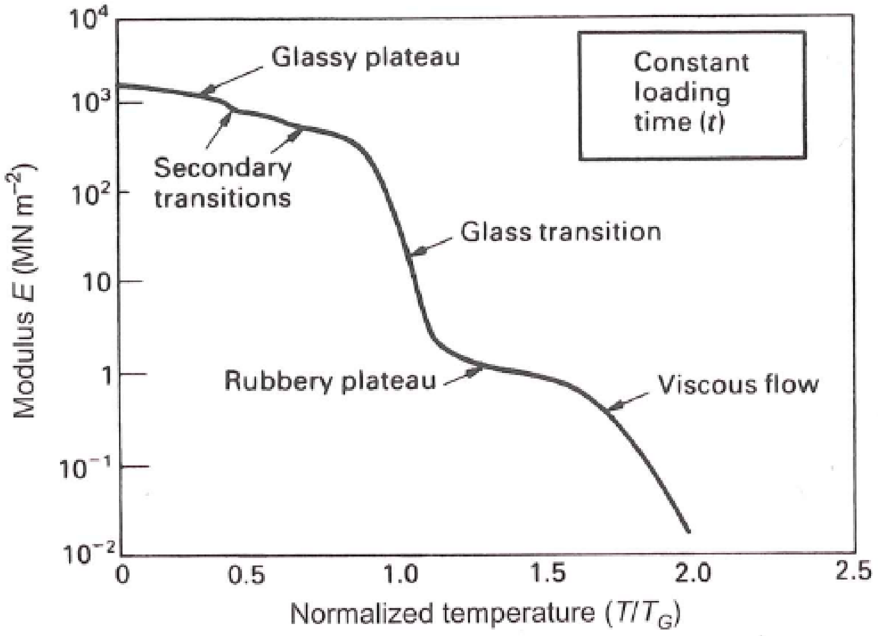
- When a polymer is loaded by a constant force, it deflects by an amount that increases with **time** t and **temperature** T

$$\boxed{E(t,T) = \frac{\sigma}{\varepsilon(t,T)}}$$

- The Young's modulus of a polymer can change up to a factor of 10^3 when the temperature is changed, even around room temperature

Time and Temperature Dependent Stiffness

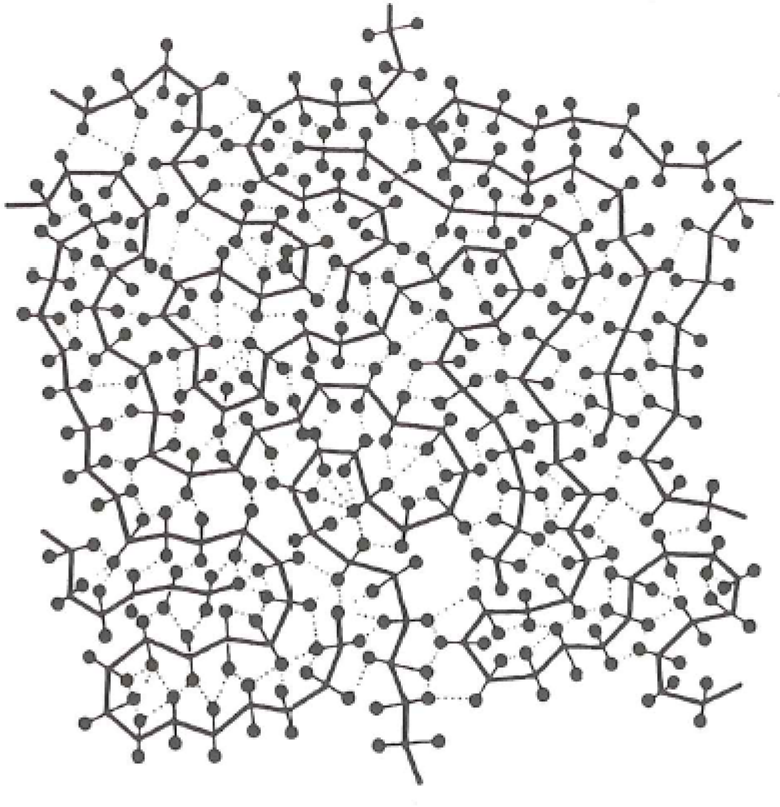
- Behaviour of linear amorphous polymer (PMMA)



a) Glassy regime: large modulus (3 GPa)
b) Glass-transition regime: steep drop in modulus (3 GPa → 3 MPa)
c) Rubbery regime: low modulus (3 MPa)
d) Viscous regime: the polymer starts to flow
e) Decomposition regime: chemical breakdown starts

Time and Temperature Dependent Stiffness

Glassy regime and secondary relaxation



linear amorphous polymer with strong covalent bonds and weak secondary bonds

Glassy modulus is due to bond stretching and the modulus of the polymer is an "average" of the stiffness of its bonds:

$$E = \left\{\frac{f}{E_1} + \frac{(1-f)}{E_2}\right\}^{-1}$$

f: fraction of covalent bonds

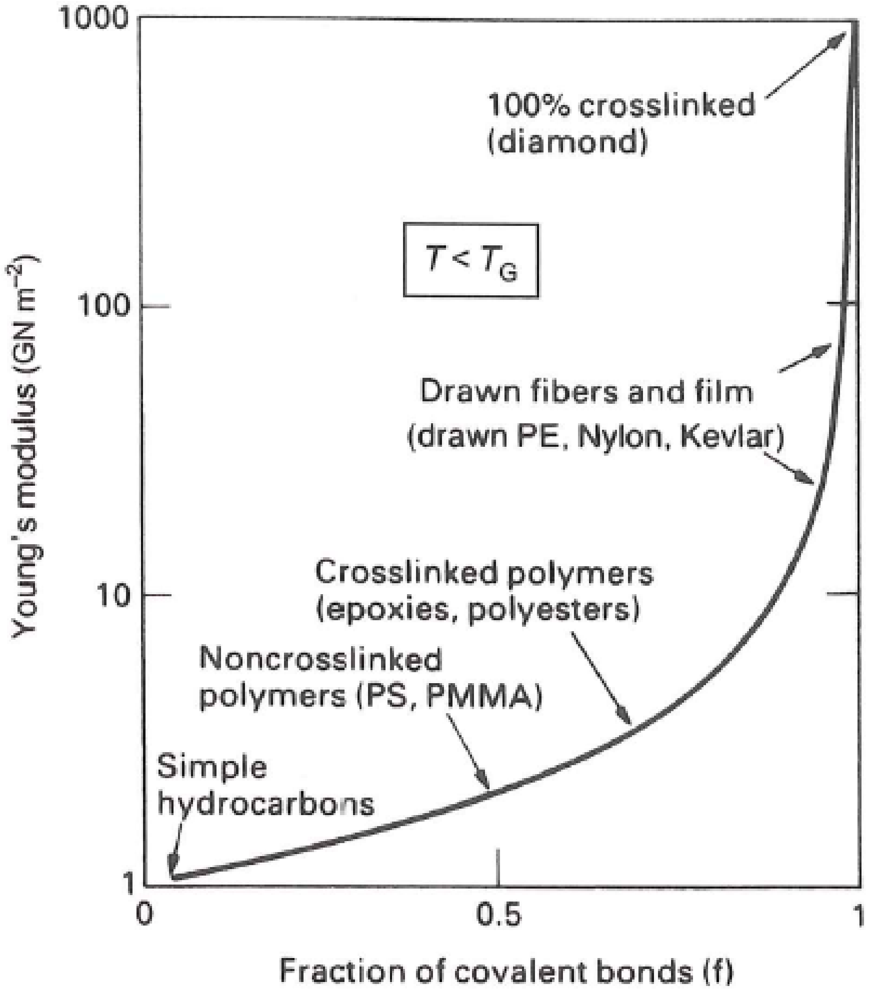
$f = 1$ (polymer is completely cross-linked) → E~ 10^3 GPa (diamond)

$f = 0$ (no cross-links) → E~ 1 GPa (simple hydrocarbon like paraffin)

$$E = \left\{\frac{f}{10^3} + \frac{(1-f)}{1}\right\}^{-1}$$

Time and Temperature Dependent Stiffness

Glassy regime and secondary relaxation



$$E = \left\{ \frac{f}{10^3} + \frac{(1-f)}{1} \right\}^{-1}$$

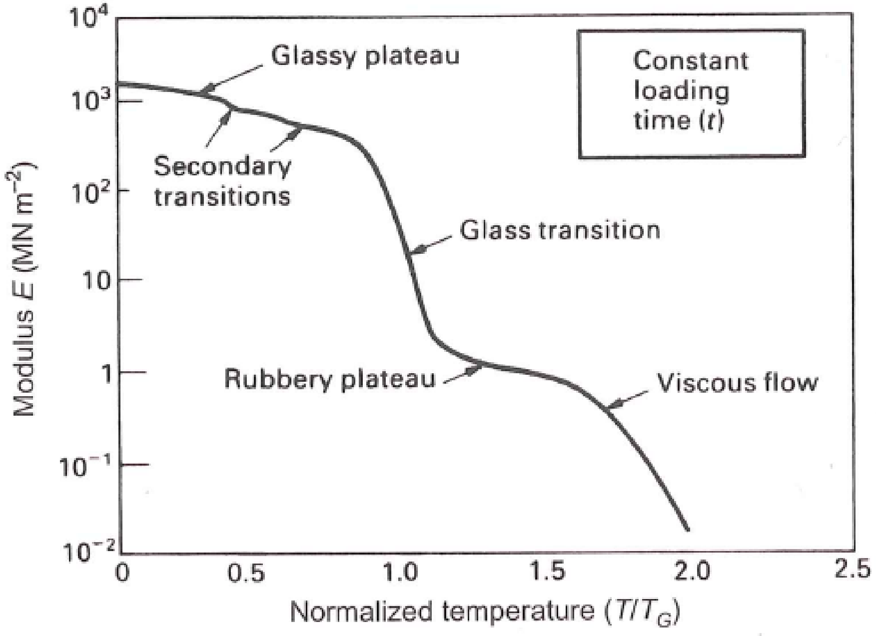
Non-crosslinked random linear polymer ($f = 0.5$) → glassy modulus of 3 GPa

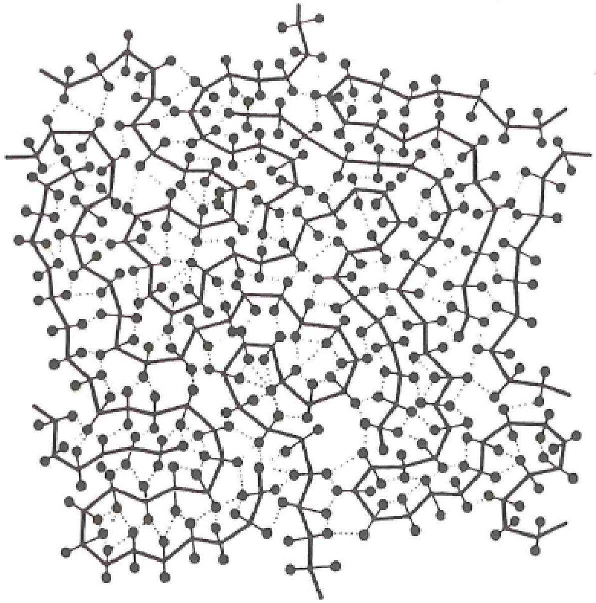
heavy cross-linked polymers ($f = 0.75$) → glassy modulus of 8 GPa

drawn polymers have chains lined-up along the drawning direction (i.e. anisotropic) → $f = 0.98$ in drawing direction → glassy modulus of **100 GPa** (<u>only in drawing direction</u>!)
ORIENTATION STRENGHTENING

Time and Temperature Dependent Stiffness

Glassy regime and secondary relaxation

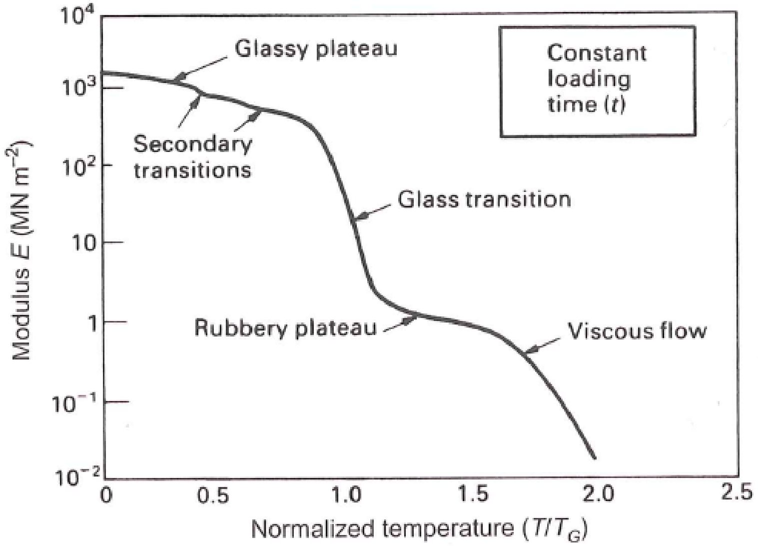


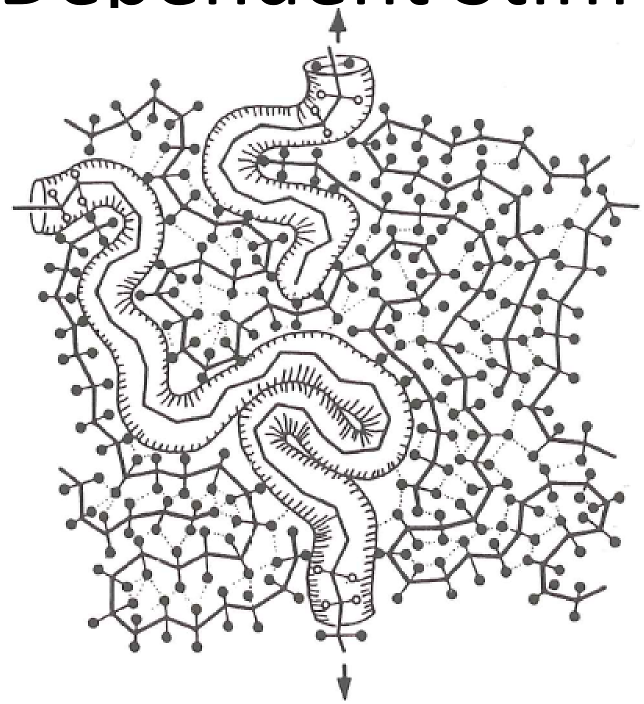


Secondary relaxation: in principle, the glassy modulus (due to bond-stretching) should not depend too much on temperature; however due to the packing of molecules, there are some "loose site" in the structure that can be occupied by side groups or chain segments by increasing temperature. Such rearrangements may cause an "extra" strain which can decrease the glassy modulus by a factor of 2

Time and Temperature Dependent Stiffness

Glass or viscoelastic transition





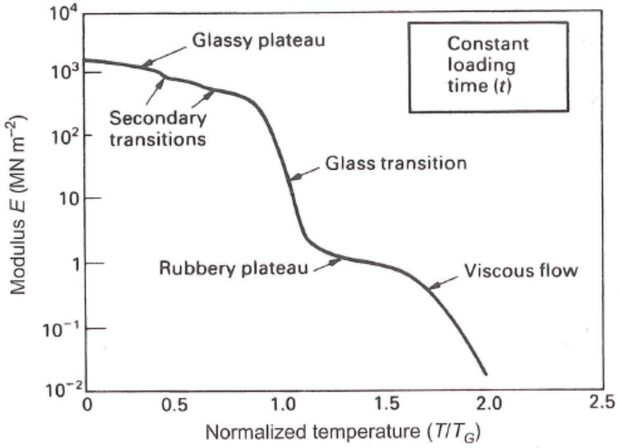
T ↑: secondary bonds melt and modulus drop considerably

Consider each polymer chain as contained in a "tube" made up by the surrounding molecules: when loaded at T_G each molecule can move in a snake-like manner (reptate) in the tube. Further increasing T, polymer expand giving extra free volume and allowing more regions to slide

As there are still non-sliding parts, on unloading the elastic regions pull the polymer back to its original shape (contrasted by reverse viscous sliding → it takes time!)

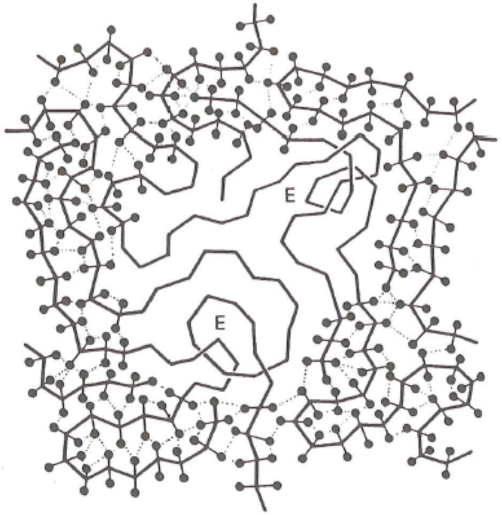
Time and Temperature Dependent Stiffness

Rubbery behavior and elastomers



For T > T_G (up to $1.5xT_G$) there can be two different behaviors for amorphous polymers depending on the average degree of polymerization ($\overline{DP}$):

- $\overline{DP} < 10^3$ (polymer with short chains) → molecular flow is easier and easier, elastic modulus decreases → viscous flow
- $\overline{DP} > 10^4$ (polymer with longer chains) → there is a rubbery state before viscous flow



long molecules form entanglements (E): points where the molecules become knotted together

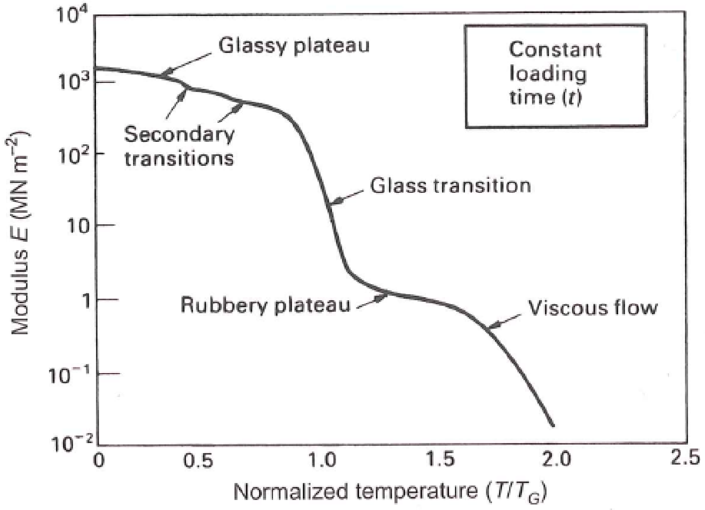
on loading the molecules reptate except at entanglements (gives a shape memory)

rubbery modulus is 1/1000 of glassy modulus

strong rubbery behavior (ε>300% completely recoverable) can be obtained by replacing entanglements with cross-links (1 every few hundreds monomer) as they do not melt

Time and Temperature Dependent Stiffness

Viscous flow



At higher T (>1.5 T_G) the secondary bonds are melt completely and there is slip event at entanglements → linear polymers become viscous liquids (<u>this is the regime in which thermoplastics are molded</u>)

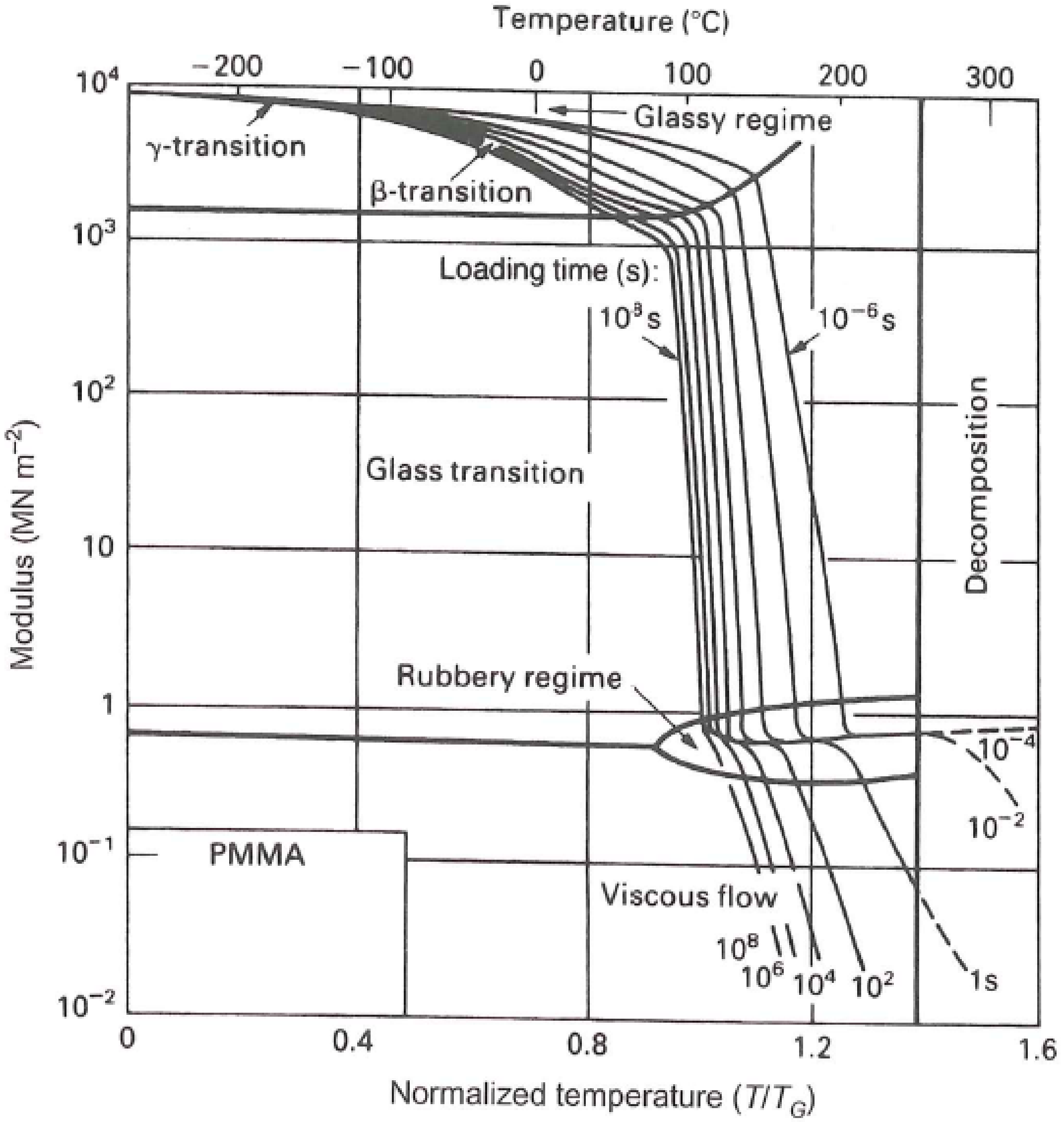
Viscosity is defined (and usually measured) in shear (shear stress σ_s which produces a shear rate $\dot{\gamma}$):

$$\eta = \frac{\sigma_s}{\dot{\gamma}}$$

Poise= 10 Pa x s

Polymers are formed at a viscosity: 10^4 -10^6 poise (they can be blown and molded)

Time and Temperature Dependent Stiffness



modulus diagram

for PMMA (**typical linear amorphous polymer**)

→ summarizes temperature and time dependence of Young's modulus for "small-strain" behavior of an amorphous polymer

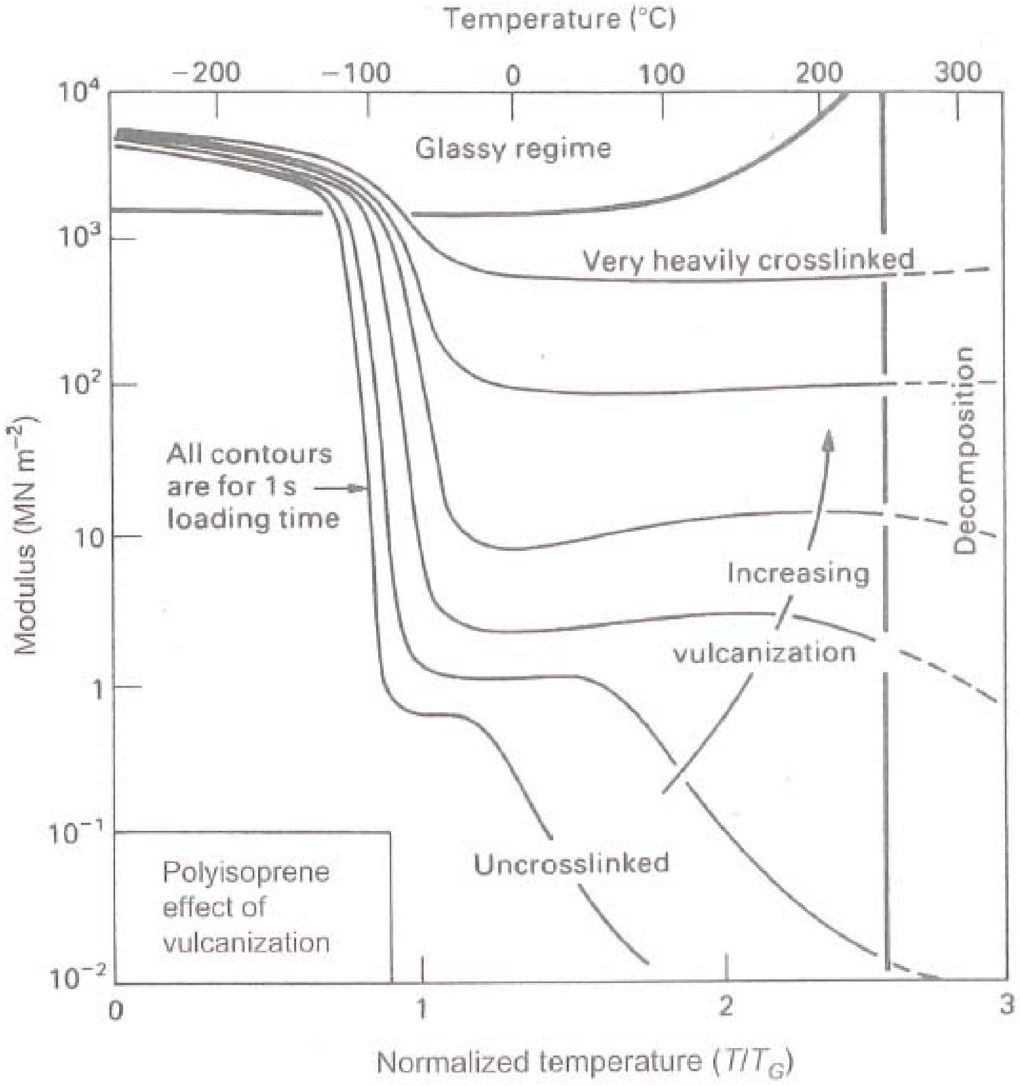
T range: 0 K up to 1.6 T_G

time range: 10^{-6} s to 10^8 s

5 regions

drop in modulus (/2 glassy and /100 rubbery) for longer loading time

Time and Temperature Dependent Stiffness



modulus diagram

influence of cross-links

modulus diagram for polyisoprene (rubber)

Increase crosslink density:

- → contours of the modulus diagram are pushed up (decrease modulus drop)
- → rubbery plateau is extended.

Crystallization increases the modulus too:

- → crystalline regions are stiffer than amorphous because of the highly dense packing
- → does not suppress melting. Crystalline polymers (high density PE) can still be molded (cross-linked polymers cannot)

Strength & Failure

- Strength: stress at which "something" starts to happen giving a permanent shape change (plastic flow or propagation of a brittle crack)
- There are at least 5 processes that can induce **failure** (i.e. limit strength) in polymers
  1) **Brittle fracture** (like in ordinary glass)
  2) **Cold drawing**: the drawing-out of molecules in solid-state, giving large shape changes
  3) **Shear banding**: giving slip bands like in metals
  4) **Crazing**: a kind of microcracking associated with local cold drawing
  5) **Viscous flow**: when the secondary bonds have melted ($T>1.5\ T_G$)

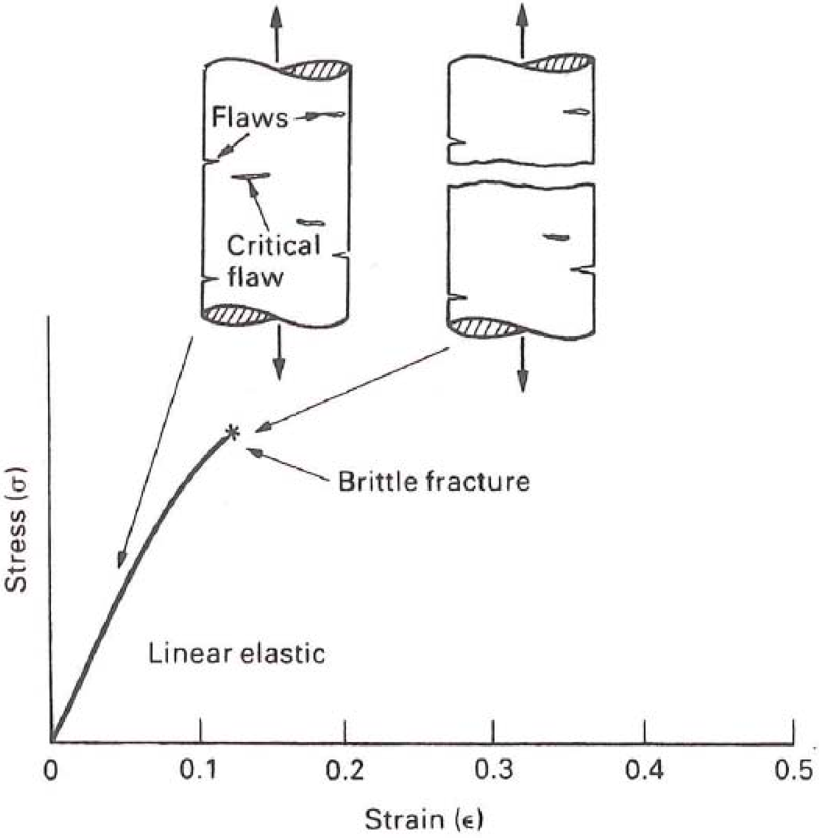
Strength & Failure: Tension

Brittle Fracture

- T < **0.75** T_G → polymers are brittle
- In the presence of a small defect (size c)

$$\sigma \sim \frac{K_C}{\sqrt{\pi c}}$$

- K_C: fracture toughness (1 $MNm^{-3/2}$)



Below 0.75 T_G polymers are low-toughness materials and anything that concentrate stresses (e.g., cracks, notches, sharp changes of section) is **dangerous**

Strength & Failure: Tension

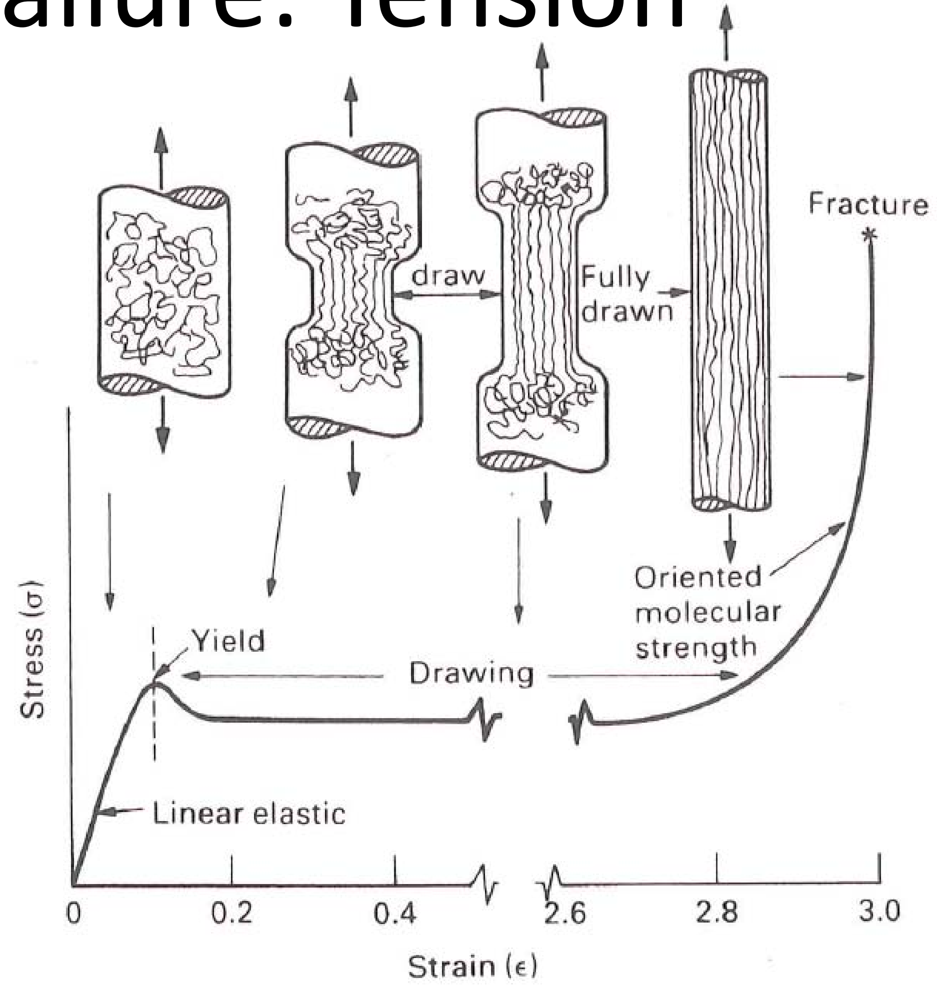
Cold drawing

- T ~ T_G
- $\varepsilon < 0.1$ linear elastic
- $\varepsilon = 0.1$ yield
- $0.1 < \varepsilon < 2.8$ drawing:

→ chains unfold, draw out from the amorphous tangle, straighten and align

→ formation of a neck which spreads in the entire sample

- $\varepsilon > 2.8$ drawing is complete and rapid rise of σ till fracture



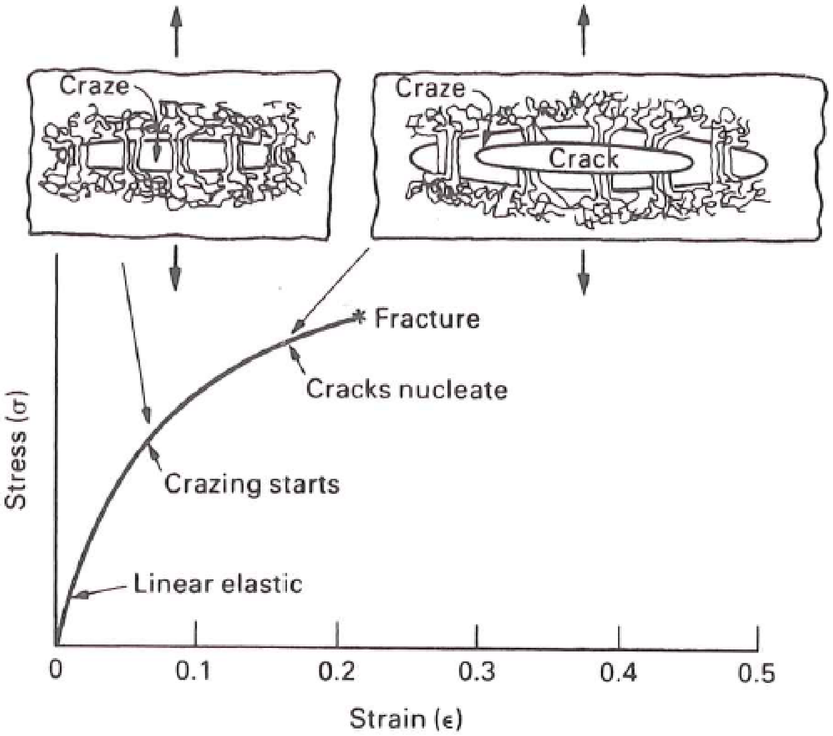
Example of polyethylene (typical behavior of a linear polymer)

Drawing gives a material which is much stiffer and stronger in drawing direction

Strength & Failure: Tension

Crazing

- T ~[0.75 T_G - T_G]
- Crazing is a combination of localized cracking and drawing
- Molecules are drawn out but on a much smaller scale
- Small damaged regions appears (craze) and the drawn material forms ligaments bridging the crazes (stabilizing the microcracks)
- Before drawing becomes general a crack forms at a center of a craze and propagates to give final fracture

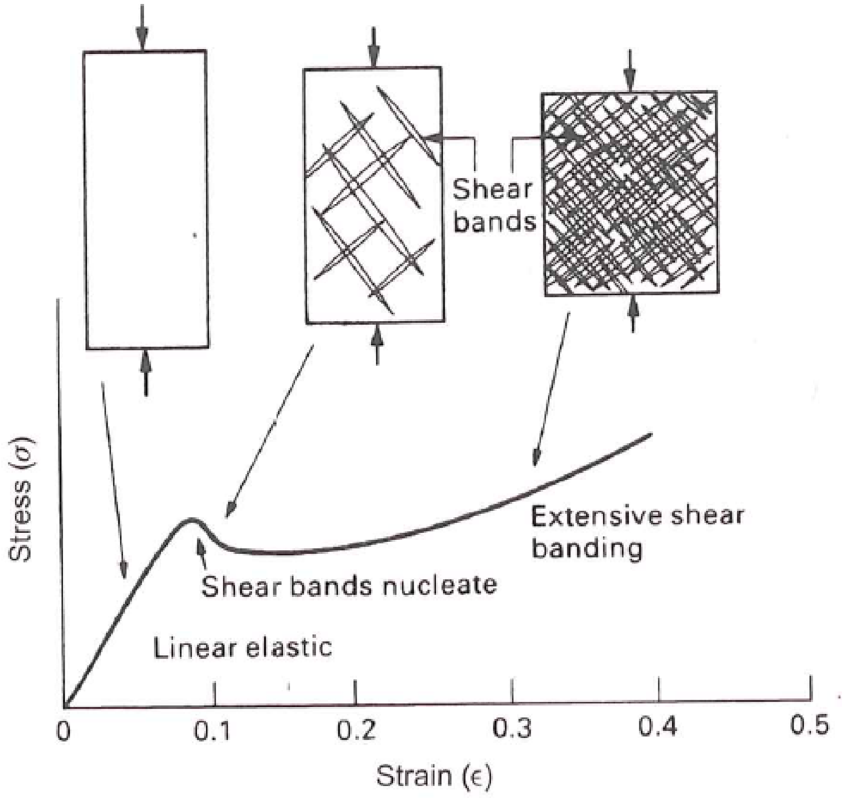


Example of polystyrene at room temperature (typical behavior of a linear polymer)

Strength & Failure: Compression

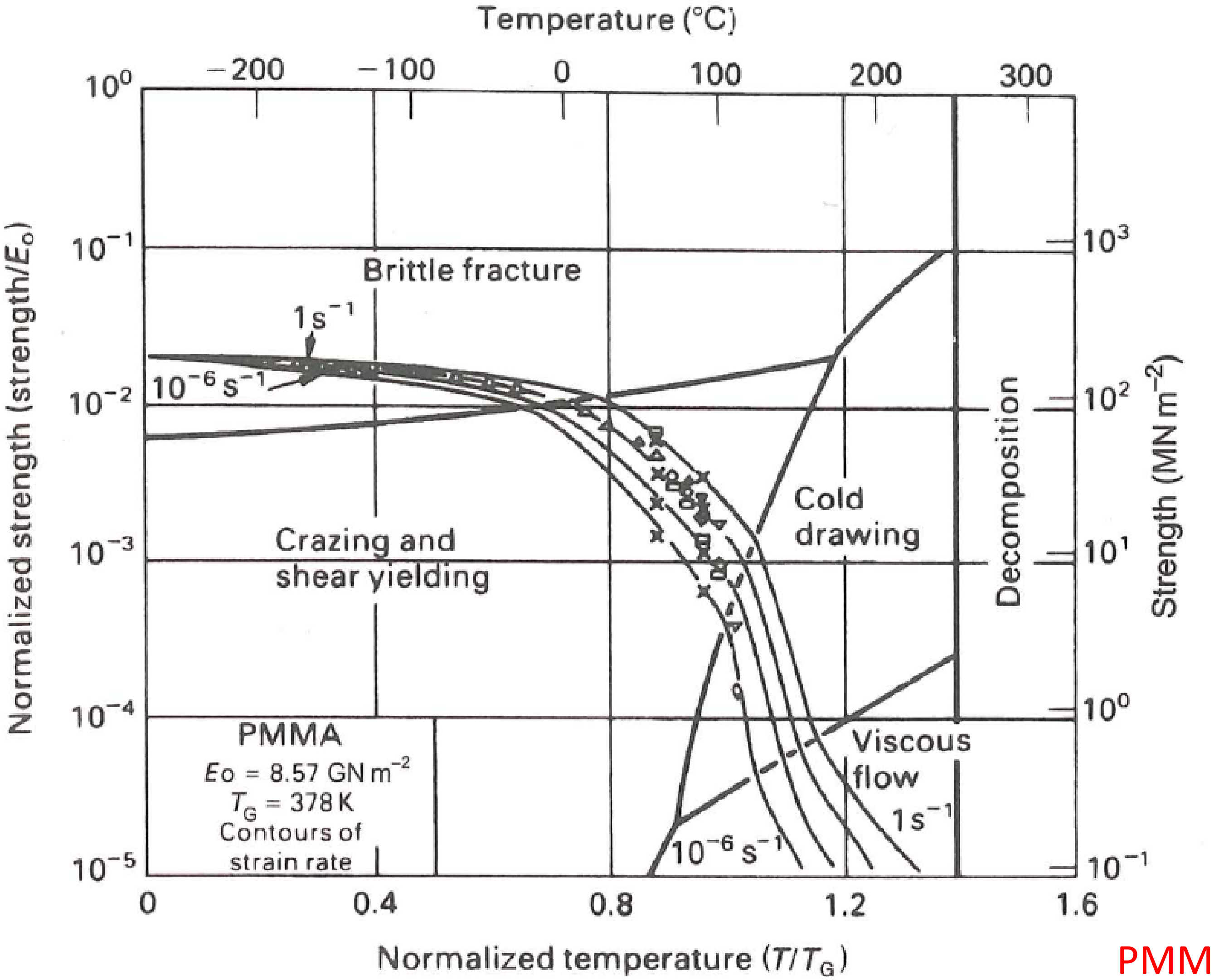
Shear banding

- T ~[0.75 T_G - T_G]
- Shear banding is a form of polymer plasticity which appears in compression
- Within each band a finite shear takes place
- As the number of bands increases the total overall strain accumulates



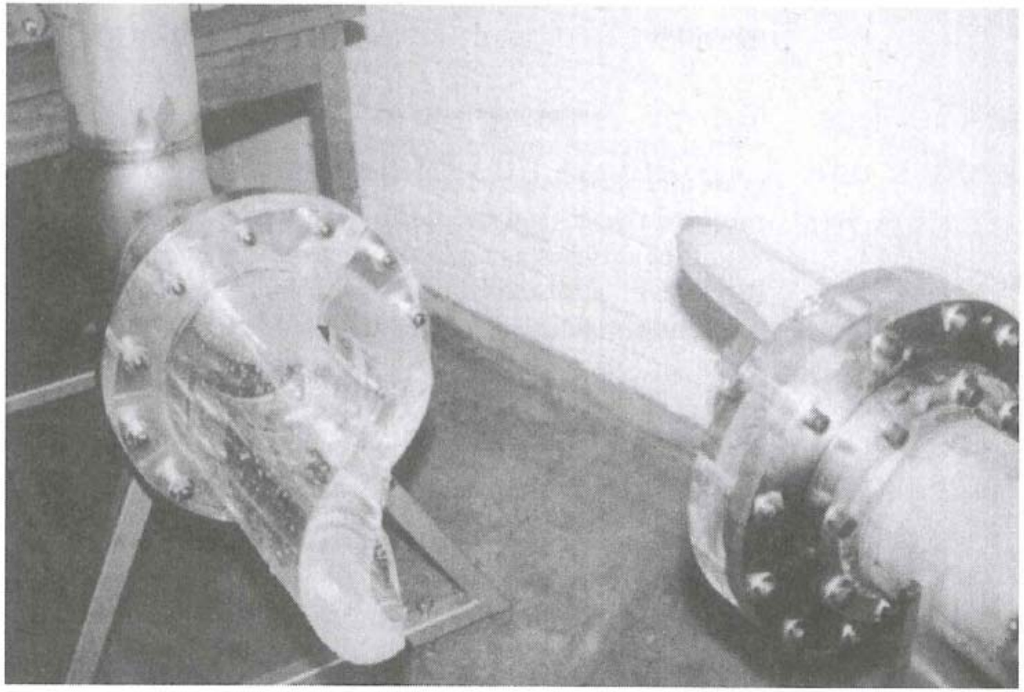
Strength & Failure

Strength diagrams for polymers



PMMA in tension

Example: Explosion of a Pressure Window

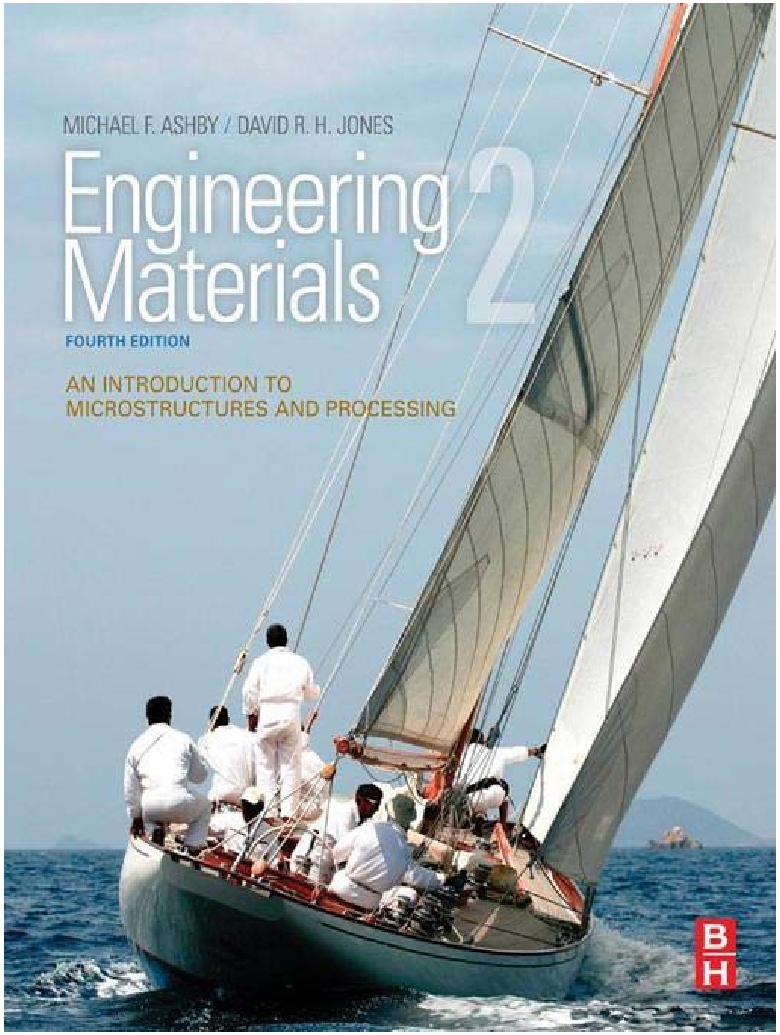


Flange connector in an internally pressurized piping system

The connector is made up of PMMA and failed catastrophically during the testing phase at a pressure much lower than expected.

Investigate the possible reason for failure…

Reference Book



Chapters:
23, 24

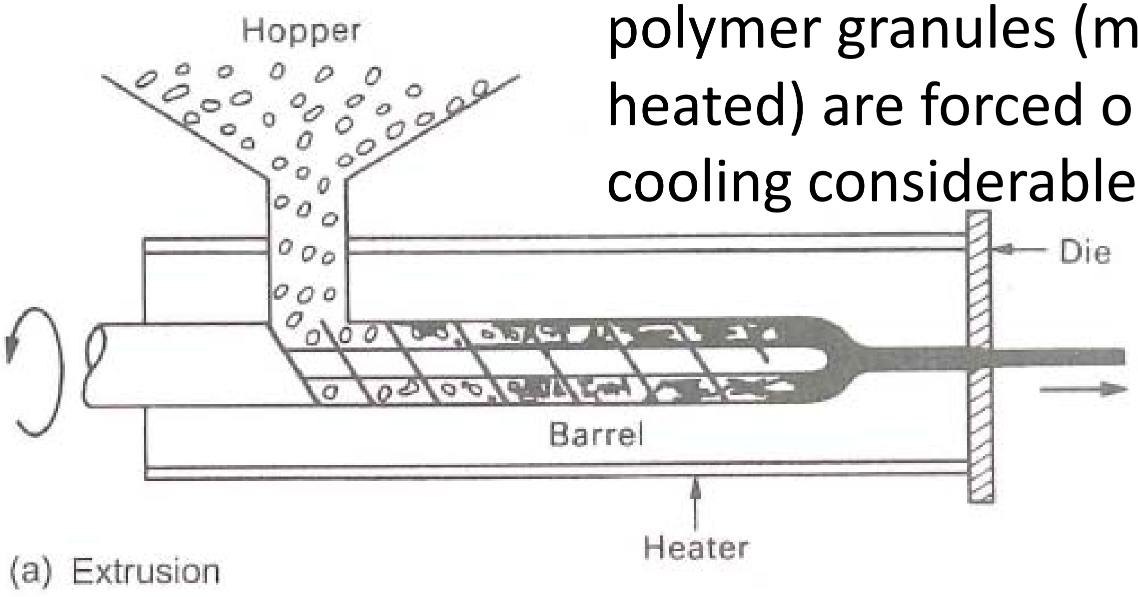
Forming of Polymers

Forming Polymers

- **Thermoplastic:**
  - soften when heated → injection molding, vacuum forming, blow molding, compression molding
- **Thermosets:**
  - heated, formed and cured simultaneously by compression molding
- **Rubbers:**
  - formed like thermosets by pressing and heating a mix of elastomers and vulcanizing agent

Forming Polymers: **Extrusion**

- cheap continuous process to produce shapes of constant section (→ semi finished products)



(a) Extrusion

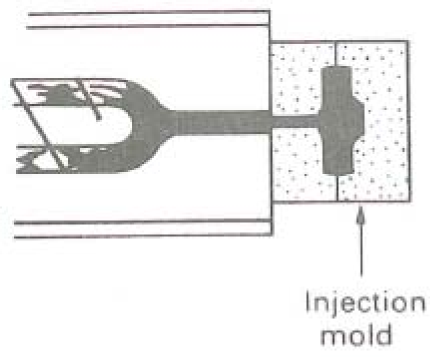
polymer granules (mixed, compressed and heated) are forced out through a die → upon cooling considerable contraction

tubes, sheets, ribbons, rods

- shear flow in the die orients the polymer chains in the extrusion direction → increase strength and anisotropy
- 60 % of thermoplastics

Forming Polymers: **Injection Molding**

- slower and more expensive than extrusion

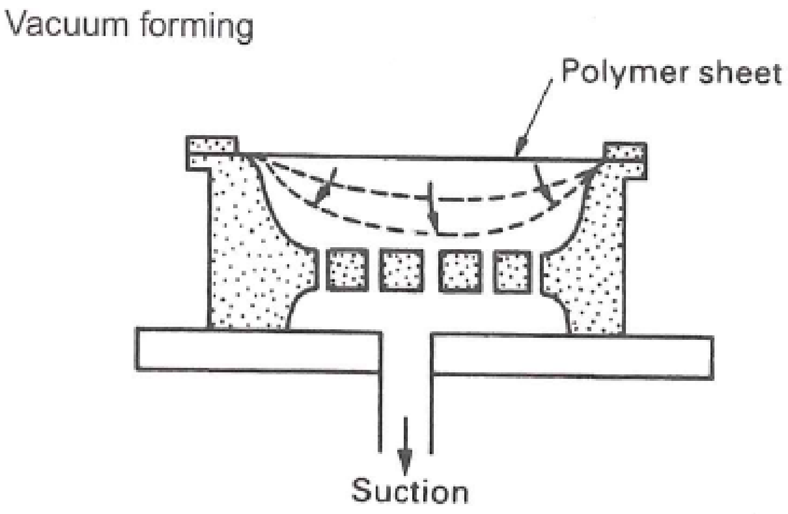


molded polymer is forced into a mold which is cooled below T_G
excess polymer is injected to compensate for contraction

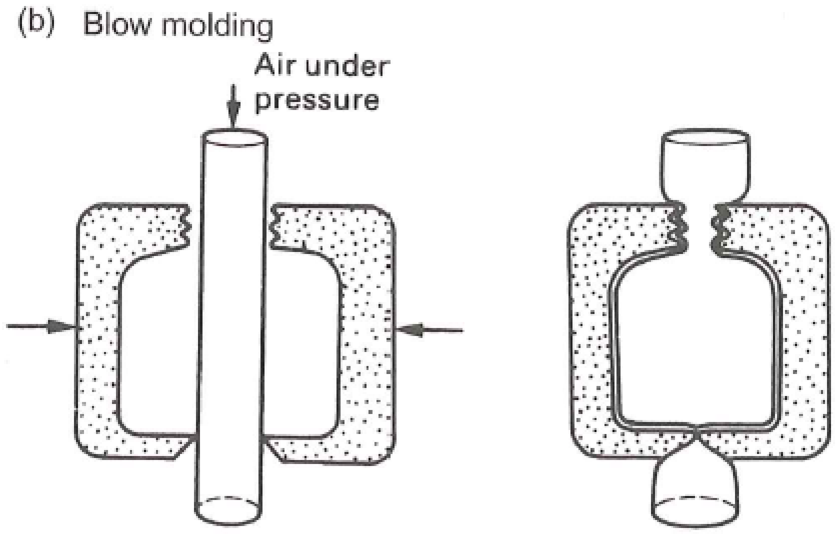
- again shear flow in the die orients the polymer chains in the extrusion direction → increase strength and anisotropy
- high precision as the polymers cool under applied pressure
- Molding parameters: T [150 – 350 °C], P[30 – 120 MPa]

Forming Polymers: **Vacuum & Blow**

- In vacuum and blow forming, sheets produced by extrusion are shaped by vacuum or pressure forming



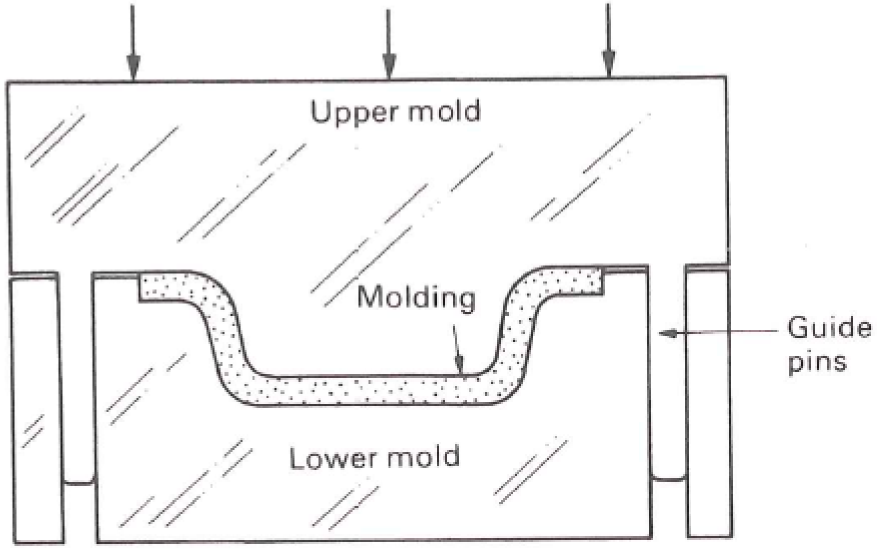
Heat softened is pressed into a mold



Heated tube is clamped in a split mold and expanded (plastic bottles)

Forming Polymers: **Compression Molding**

- Used both for thermoplastics and thermosets



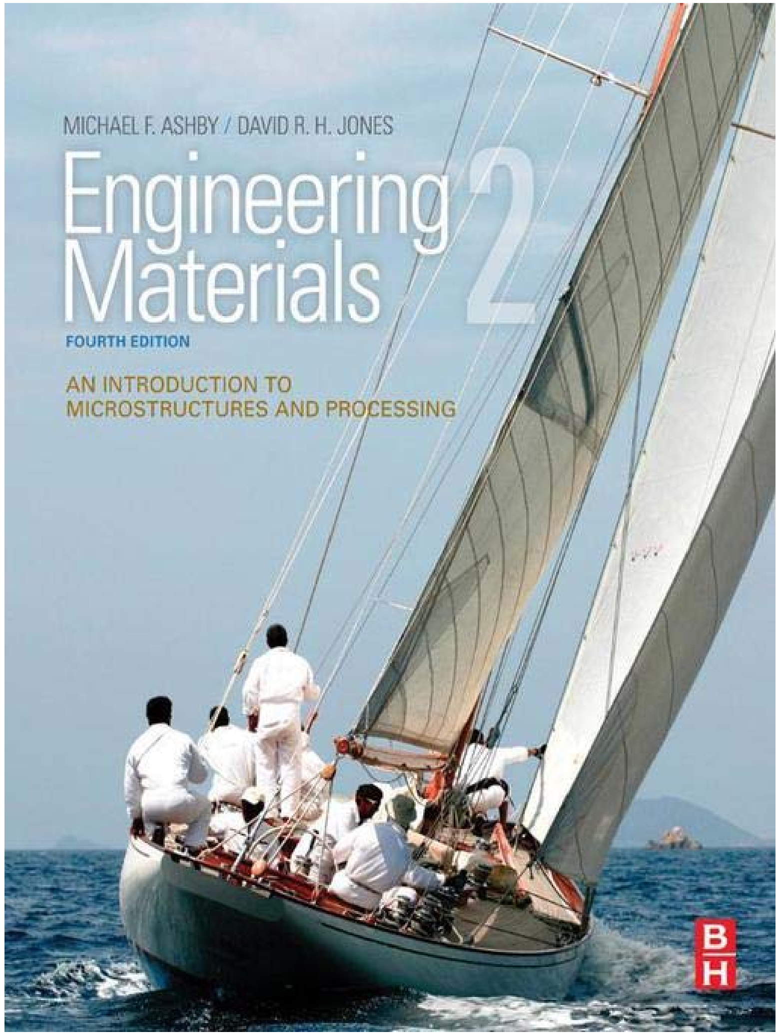
Compression molding

the polymer or resin is heated and compressed between dies

used to make car bumpers

- since a thermoset can be removed while still hot → forming time ranges from 10 seconds (small parts) to 10 minutes
- pressure is lower than for injection molding

Reference Book



Chapter:
25