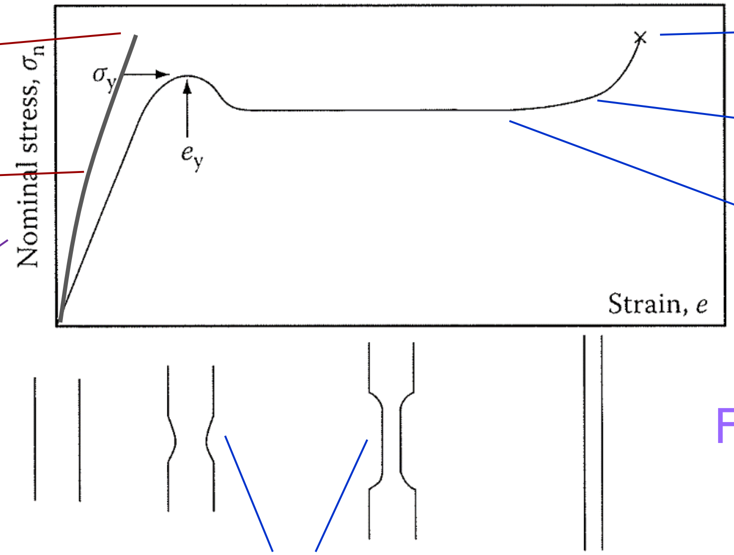
Chapter 22

Yield and Crazing

Large deformation behavior
Ductile and brittle behavior

Large deformation behavior

- Upon large stress beyond (visco)elastic limit, a polymer experience either
  - yielding or crazing, the two competing plastic deformation processes.
  - yielding limits strength; helps necking to ductile failure
  - crazing to brittle fracture



brittle fracture

brittle

nominal σ
= engineering σ

ductile failure

ductile

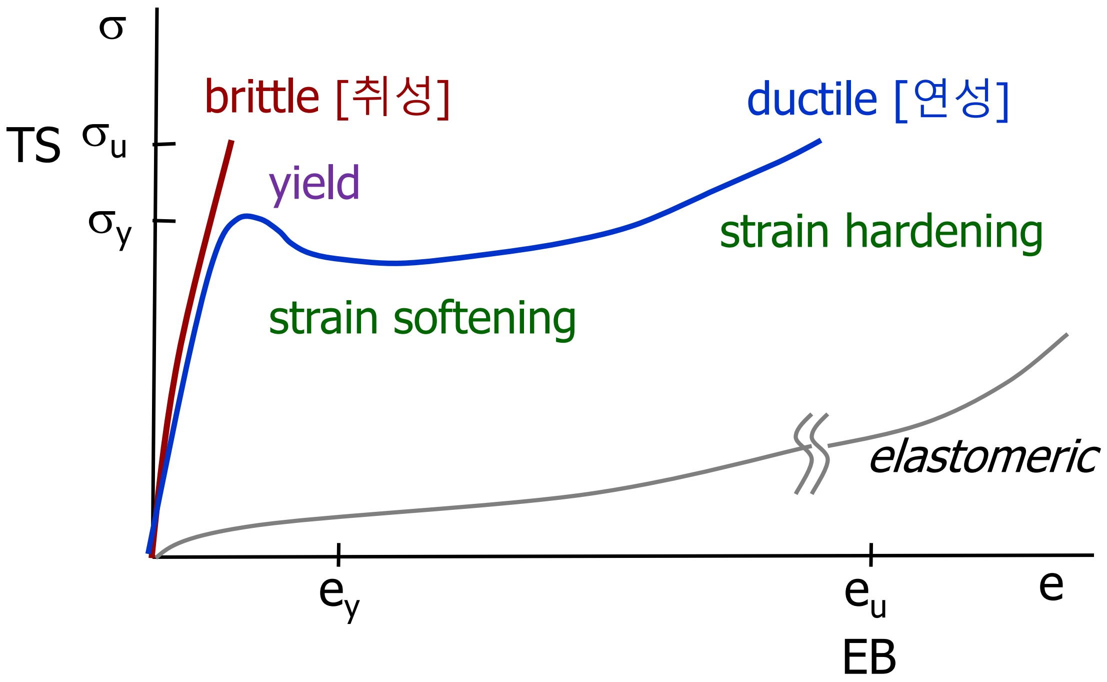
cold-drawing

neck

Fig 22.1

yield and tensile strength

- upon uniaxial tension test [UTT]

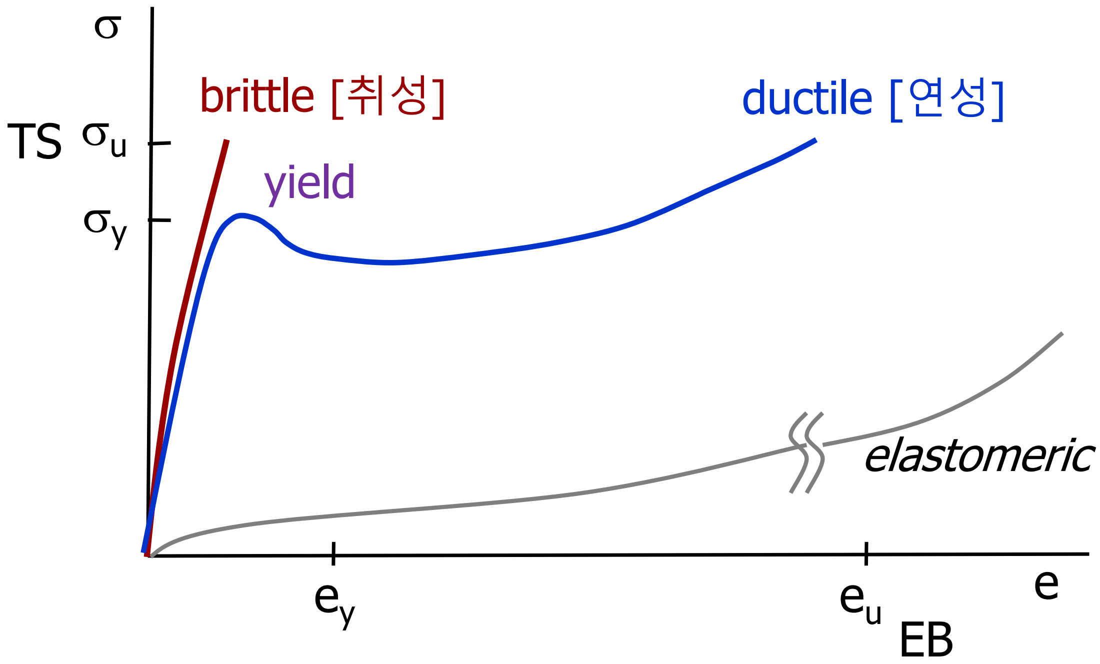


p513 yield point by Considere construction?
useful for metals
for polymers? just σ_{max}

cold-drawing = SS + SH

- yield strength [항복강도] ~ stress at yield σ_y
- tensile strength [TS, 인장강도] or ultimate stress σ_u
- elongation at break [EB, 파단신장률] or ultimate strain e_u

❑ upon uniaxial tension test [UTT]



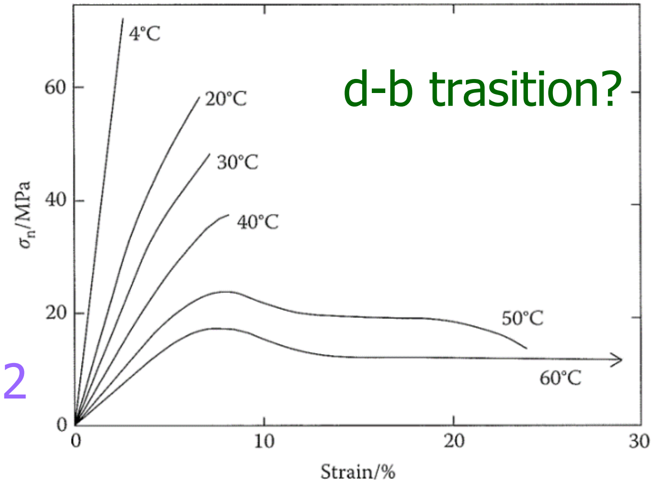
- ➢ ductility = ability to yield and be cold-drawn
- ➢ toughness [강인성] = resistance to crack propagation
- ➢ tensile toughness = area under s-s curve

- ➢ stiff/flexible ~ E
- ➢ strong/weak ~ TS
- ➢ ductile/brittle ~ yield or not, EB
- ➢ tough/fragile ~ stress K_{Ic} or energy G_{Ic} before fracture
- ➢ hard/soft ~ surface hardness [경도]

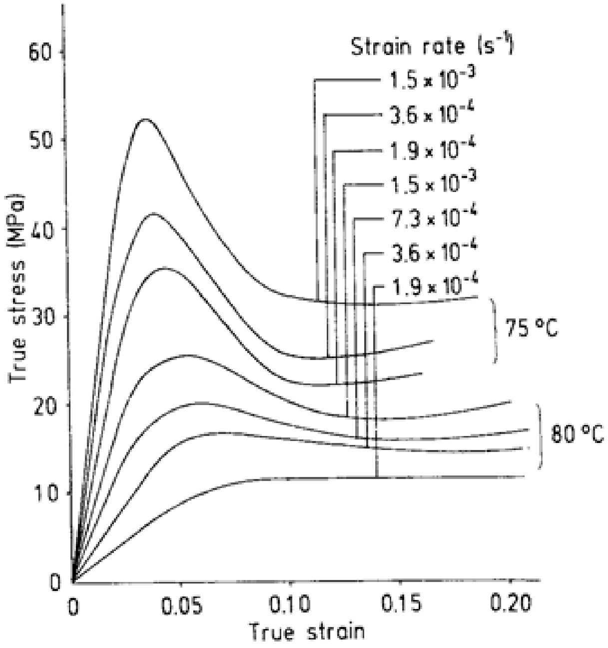
Yield

- yield = start of plastic [塑性] deformation
  - elastic/plastic ~ recoverable/permanent
- yield strength [yield stress, σ_y]
  - depends on temperature
  - depends on strain rate de/dt

Fig 22.2



d-b trasition?



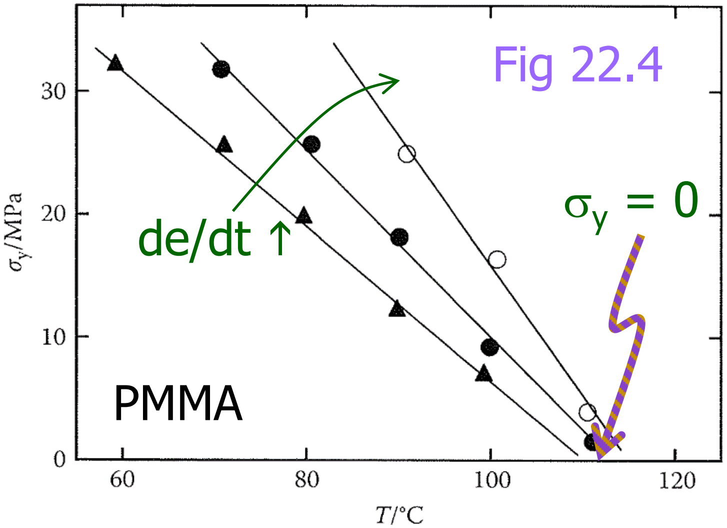


Fig 22.4

de/dt ↑

$\sigma_y = 0$

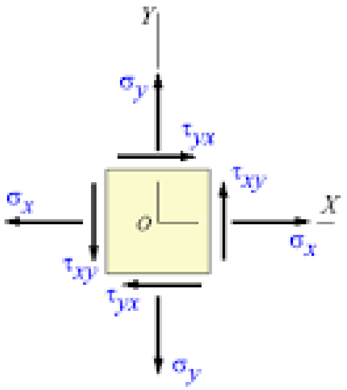
PMMA

Yield criteria

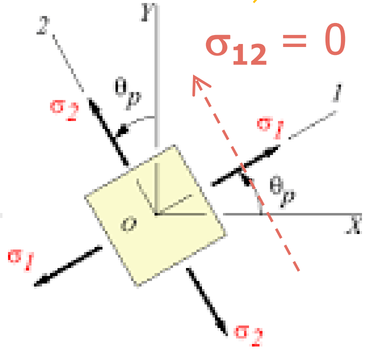
- yield criterion = stress conditions where yield can occur
- Yield occurs only by shear deformation.
  - max shear stress $\sigma_{s,max} = \sigma_1 - \sigma_3$
    - max shear in UTT? σ_1 (in 45° to 1-axis)
  - if $\sigma_1 = \sigma_2 = \sigma_3$
    - diagonal in σ_1-σ_2-σ_3 space
    - purely hydrostatic
    - $\sigma_{s,max} = \sigma_1 - \sigma_3 = 0$
    - no shear → no yield

$$\begin{pmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \sigma_3 \end{pmatrix}$$

all shear stresses = 0
principal axes 1, 2, 3
principal stresses
$\sigma_1, \sigma_2, \sigma_3$ ($\sigma_1 > \sigma_2 > \sigma_3$)

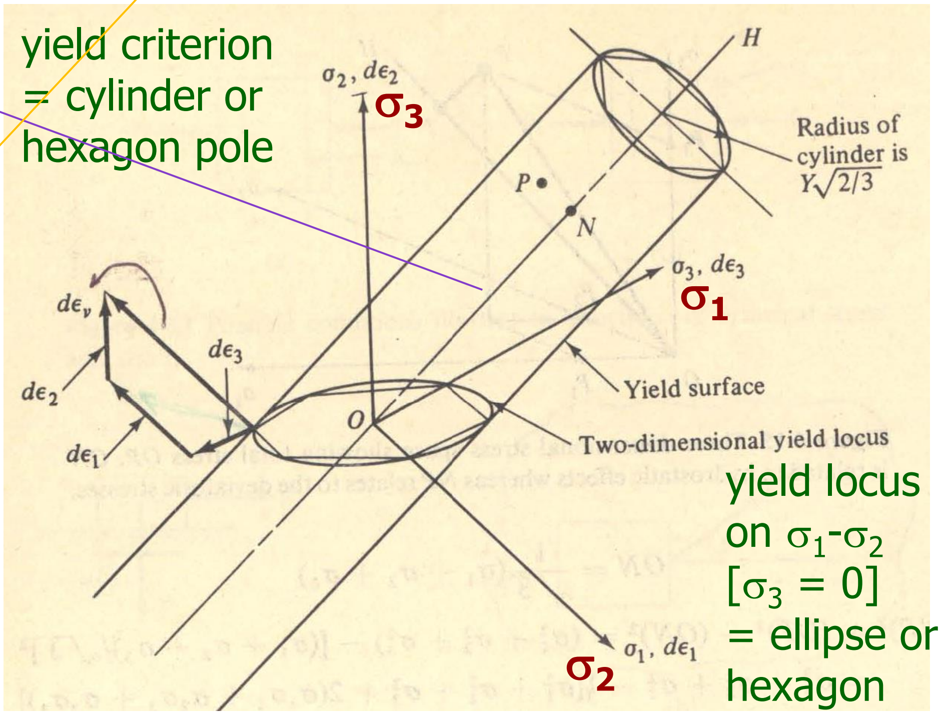


Stresses in given coordinate system



$\sigma_{12} = 0$

Principal stresses



yield criterion = cylinder or hexagon pole

σ_3

σ_1

σ_2

yield locus on σ_1-σ_2 [$\sigma_3 = 0$] = ellipse or hexagon

- Tresca yield criterion
  - UTT [σ_1 or σ_2 (> 0) only]
    - $\sigma_{s,max} = \sigma_1 - \sigma_3 = \sigma_1 = \sigma_y$
    - yield at $\sigma_1 = \sigma_y$
  - UCT [σ_1 or σ_2 (< 0) only]
    - $\sigma_1 - \sigma_3 = \sigma_1 = \sigma_y$
  - pure shear [$\sigma_1 = -\sigma_2$]
    - $\sigma_1 - \sigma_2 = 2\sigma_1 = \sigma_y$
    - yield at $\sigma_1 = \sigma_y/2$
- von Mises criterion

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2\sigma_y^2$$

$$\sigma_1 = \frac{\sigma_y}{\sqrt{3}}$$

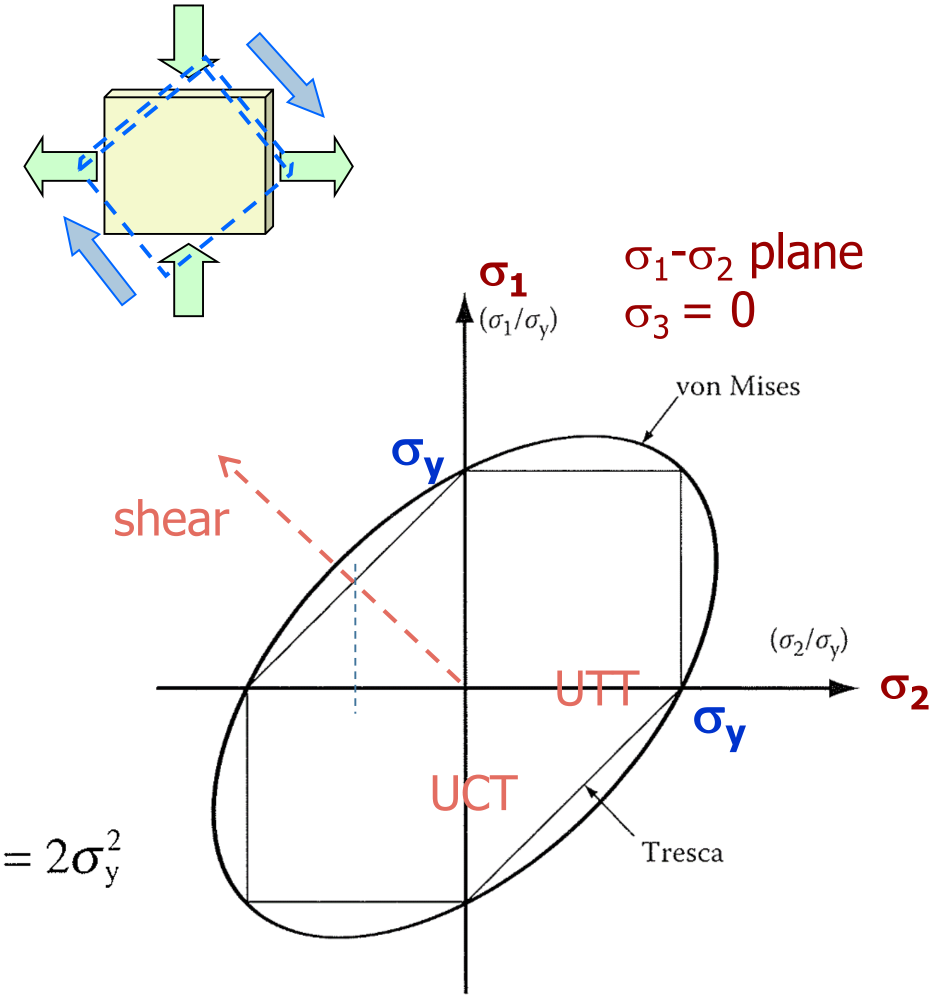


Fig 22.5

Pressure-dependent yield criteria

- σ_y of polymer affected by hydrostatic pressure p
  - $\sigma_s = \sigma_s^o - \mu p$
  - σ_y(comp) = (1.1 – 1.3) σ_y(tension)

$$p = \frac{1}{3}\left(\sigma_1 + \sigma_2 + \sigma_3\right)$$

$$\begin{pmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \sigma_3 \end{pmatrix}$$

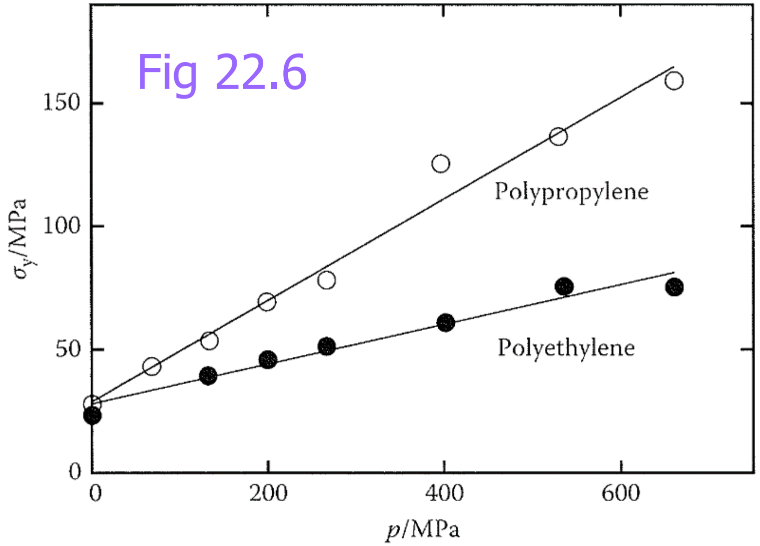
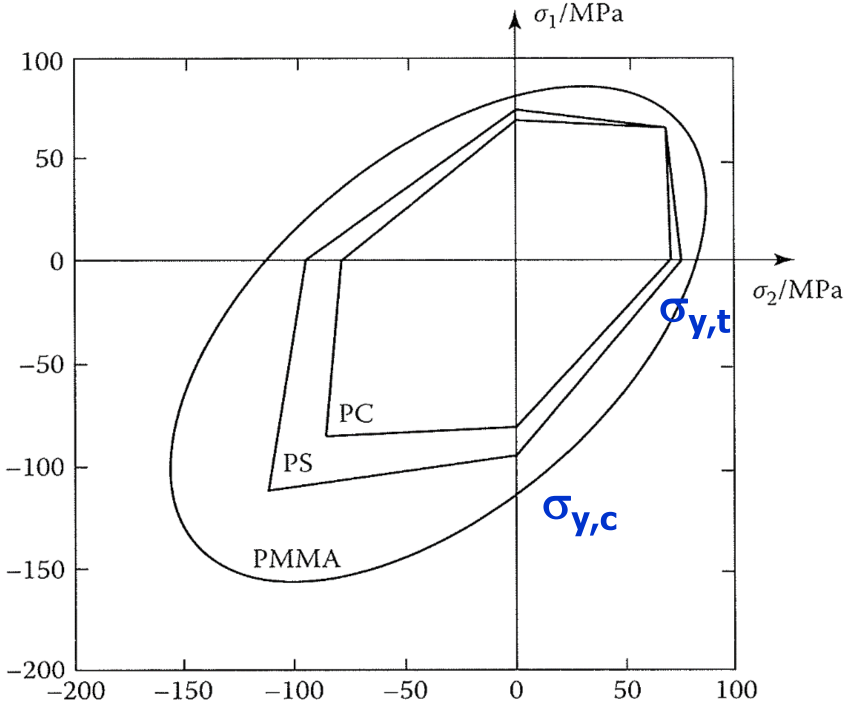


Fig 22.6



yield criteria = cone or hexagonal horn

Theories for yield (of glassy polymers)

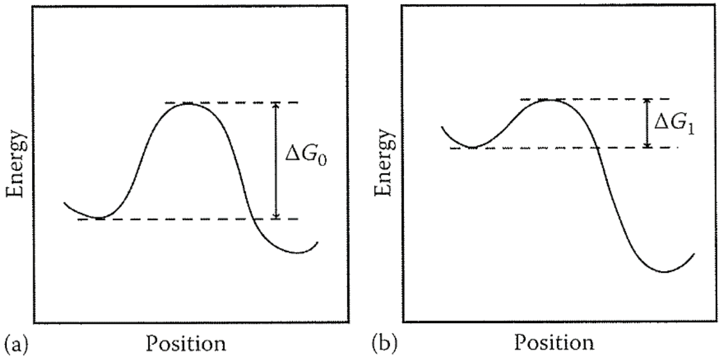
- adiabatic heating (to T_g)
- reduction of T_g by strain (through free volume up)
  - what about yield by compression?
- rate theory (by Eyring)
  - jump [motion or flow] frequency ν

$$\nu_0 = B\exp\left(\frac{-\Delta G_0}{\mathbf{k}T}\right)$$

  - bias of potential well by stress σ

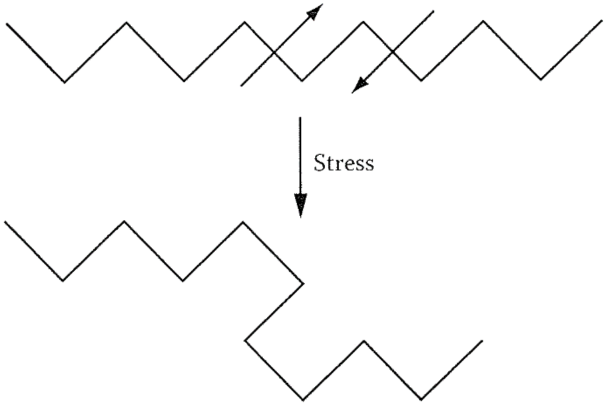
$$\nu_f = B\exp\left[\frac{-(\Delta G_0 - (1/2)\sigma A x)}{\mathbf{R}T}\right]$$

  - yield when
    - $\sigma = \sigma_y$ and
    - $V^‡$ = vol for plastic deformation [yield]



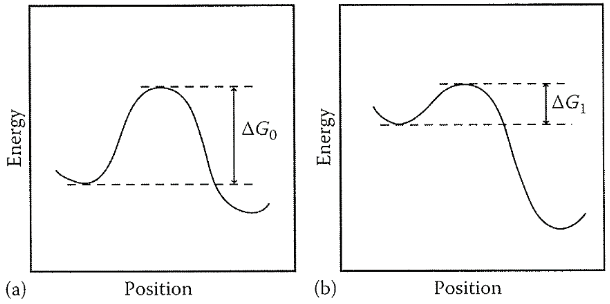
A = cross-sectional area of flow
x = distance of flow
A x = $V^‡$ = activation [Eyring] volume
$V^‡$ is not real like V_f.

- molecular theory (by Robertson)
  - conformational change by stress
  - from low-energy ‘trans’ to high-energy ‘cis’
  - ‘cis’ population reaching T_g at yield



- connection of rate and molecular theories
  - $\dot{e} \propto (v_f - v_b) = v_0 \exp\left(\frac{\sigma A x}{2\mathbf{k}T}\right) - v_0 \exp\left(\frac{-\sigma A x}{2\mathbf{k}T}\right)$

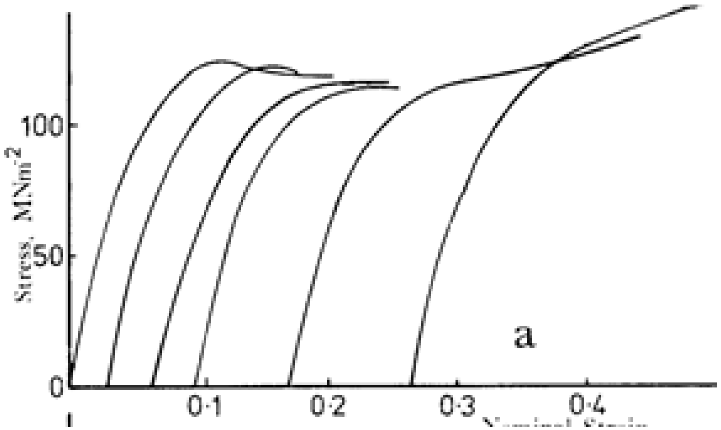
    → strain-rate sensitivity of σ_y
    → estimation of $V^‡$ and ΔG

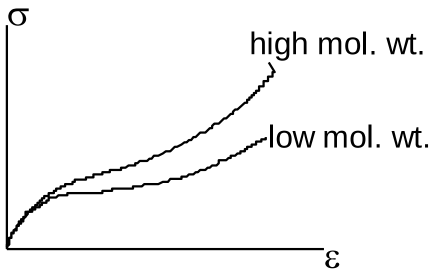


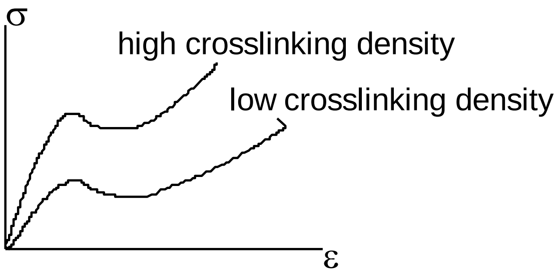
  - energy difference trans and cis → # of bonds for yield and T_g

Post-yield behavior

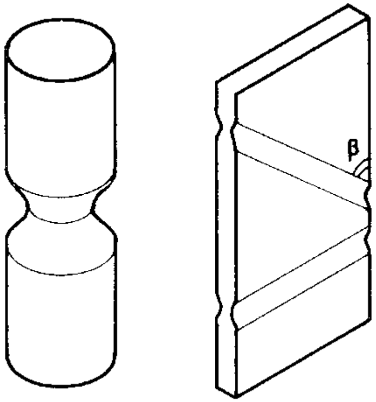
- strain-softening
  - drop in true stress
    - not for metals
  - intrinsic softening
    - state of T_g at yield point
- strain-hardening
  - rise in stress
  - due to orientation of the chains
    - by stretching between entanglements




Polyethylene


Epoxy

- inhomogeneous deformation
  - localized instability due to softening, which interacts with restraints
  - with no restraint ~ necking
  - with restraint in 1 direction ~ inclined necking
  - with restraint in 2 directions ~ shear band



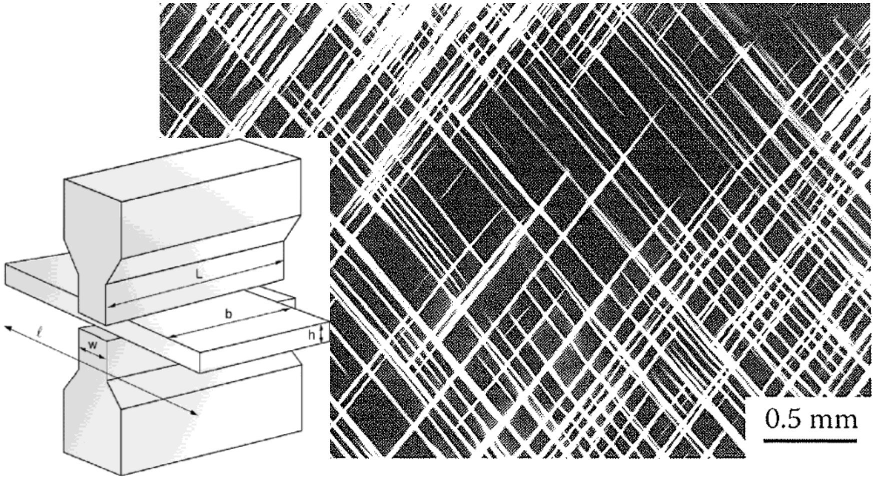
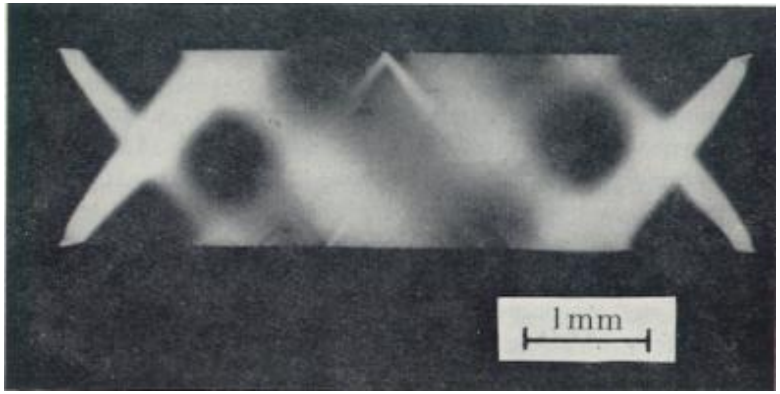


Fig 22.10 p542
PS under plane-strain compression



PMMA
more ductile than PS (with larger $V^{\ddagger}$ and lower strain rate sensitivity)

Yielding of semicrystalline polymers

- yield of crystal
  - combination of slip, dislocation, twinning, matensitic transform’n
  - sliding of chains
- plastic deformation of semicrystalline polymers
  - spherulite deforms, crystal intact
  - crystal yields
  - crystals reoriented
  - drawing of fiber

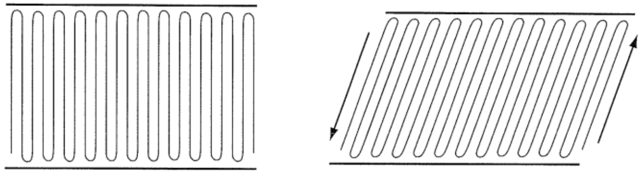


Fig 22.13

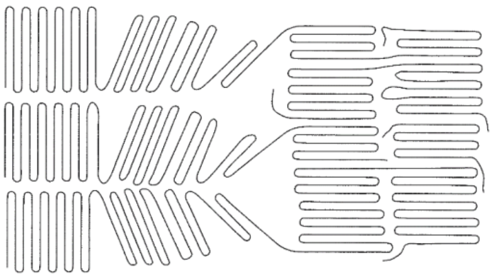


Fig 22.18

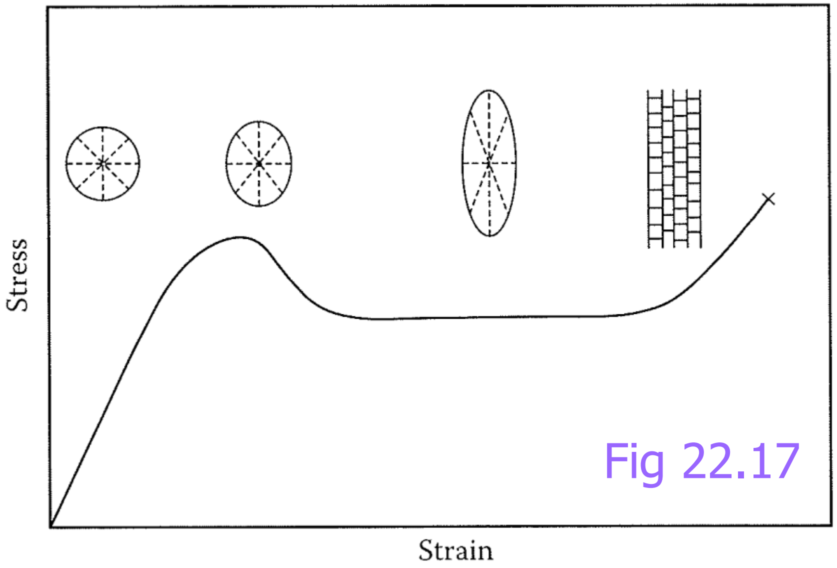


Fig 22.17

Craze/crazing

- craze = long thin wedge of deformed polymer microfibrils

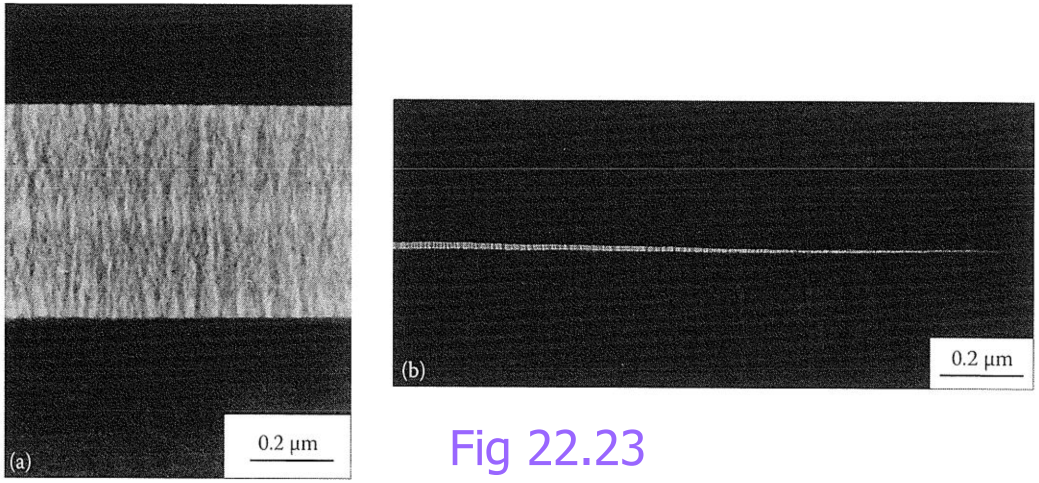
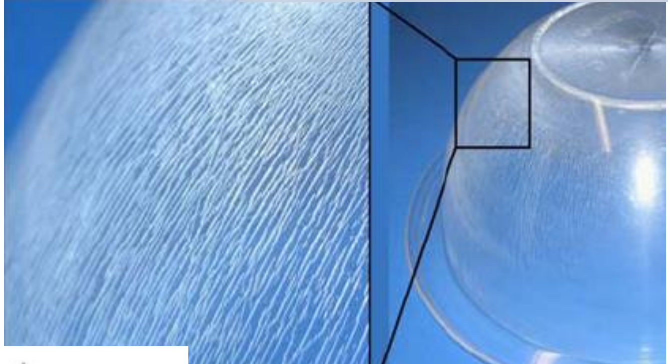
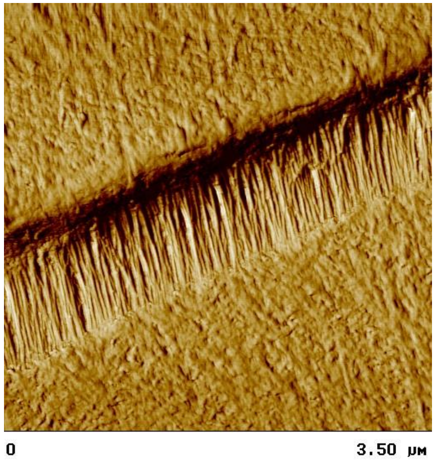


Fig 22.23

- crazing
  - localized plastic deformation
  - by dilatational stress
    - normal yielding vs (shear) yielding
  - compete with shear yielding
    - brittle vs ductile





Craze criteria

- craze initiation
  - no crazing by compression
  - critical-strain craze criterion

$$\sigma_1 - \nu\sigma_2 = X + \frac{Y}{(\sigma_1 + \sigma_2)}$$

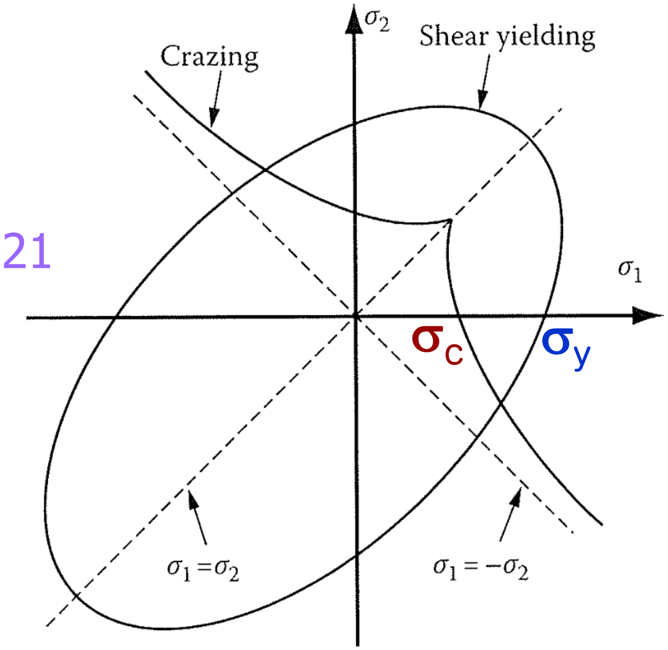


Fig 22.21

- ductile-brittle transition
  - Both craze and yield criteria are dependent on temperature and strain rate.
    - σ_c, σ_y ↑ with T ↓ or de/dt ↑
  - ductile-brittle transition by relative σ_c and σ_y

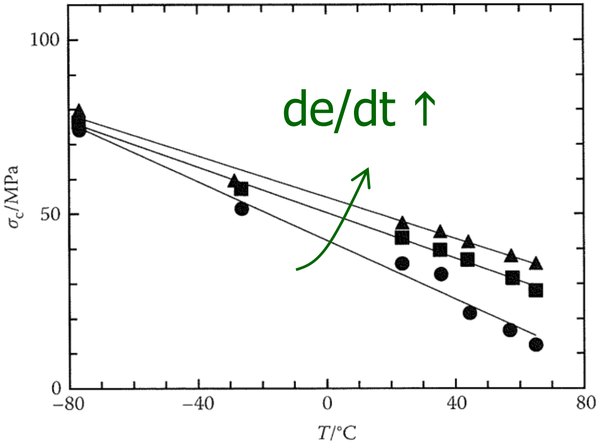
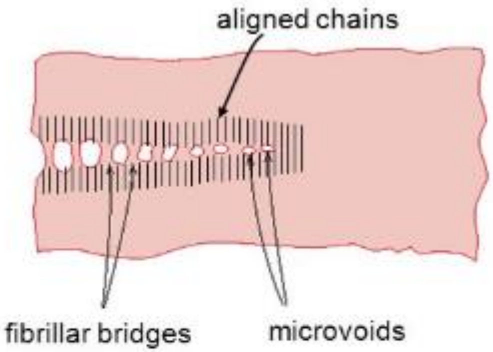
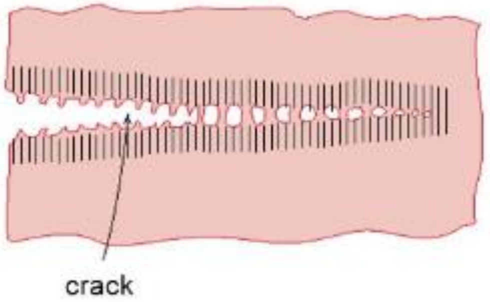


Fig 22.20

Craze propagation

- craze propagation
  - thicken by drawing new materials from bulk
  - lengthen by meniscus instability





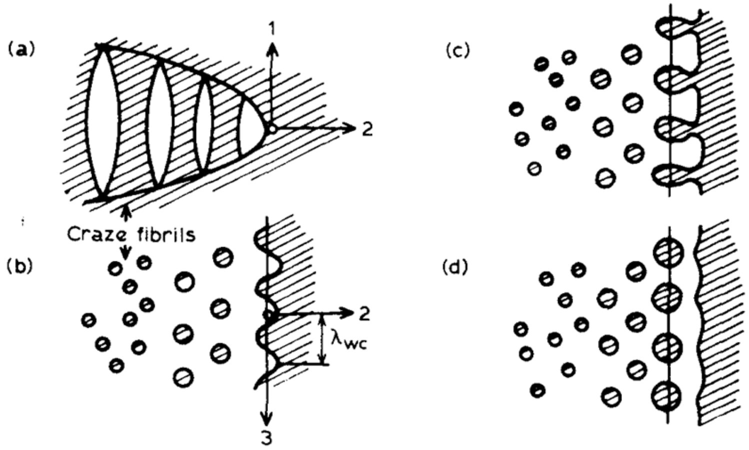
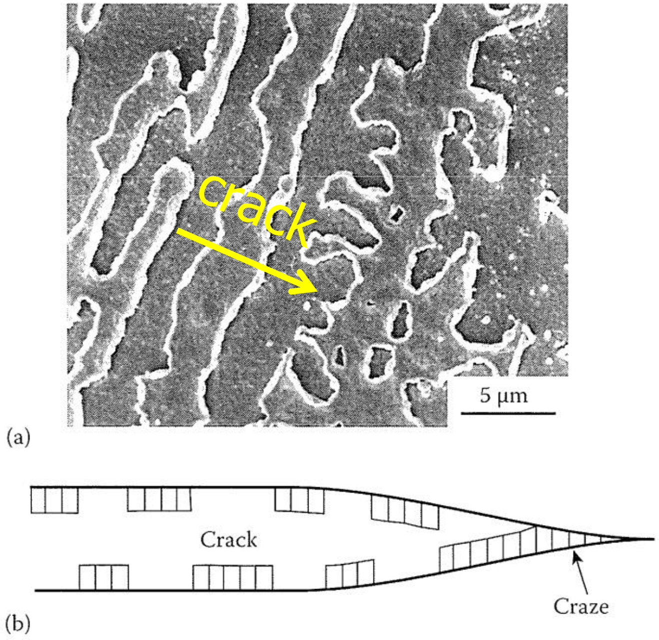


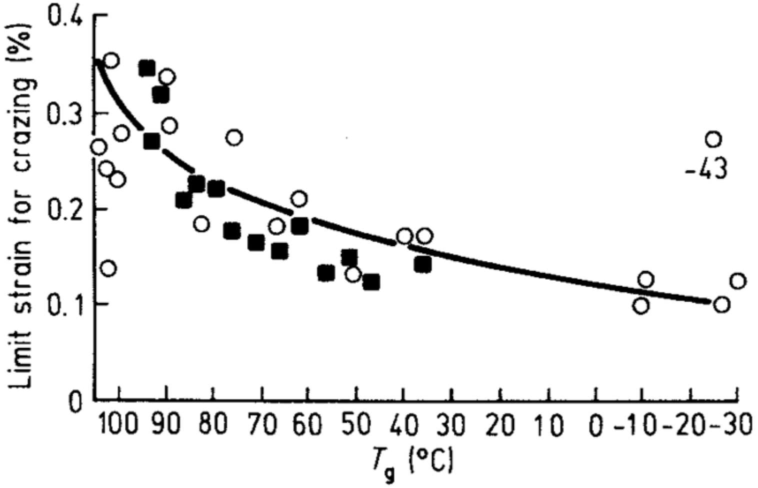
Fig 23.10 p570

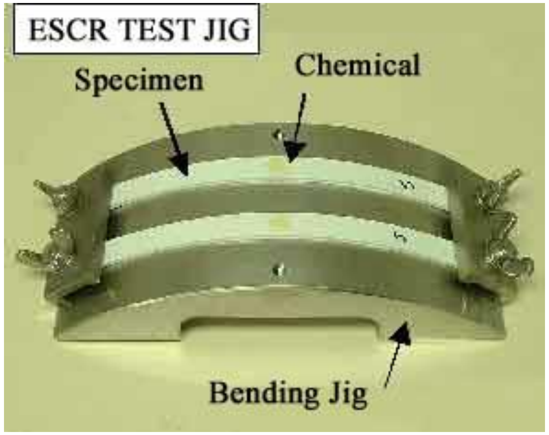


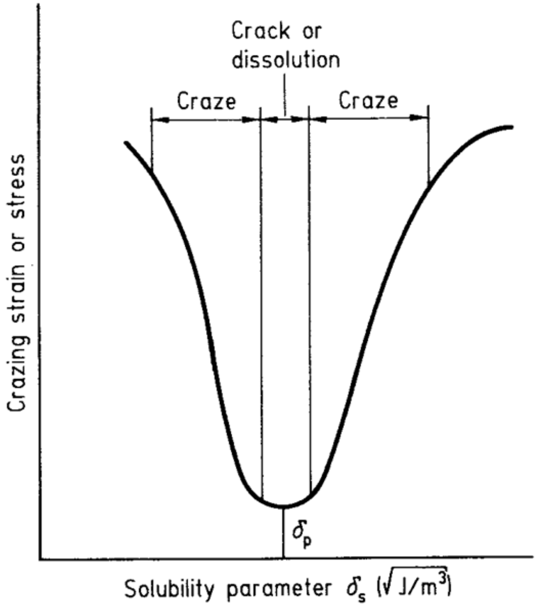
Environmental stress cracking [ESC]

= environmental stress crazing
= environmental fracture §23.4.4 p582

- ❑ Absorbed liquid or gas
  - ❑ plasticizes polymer → soften
  - ❑ craze at a lower stress → fracture
  - ❑ effective when solubility parameter difference is small







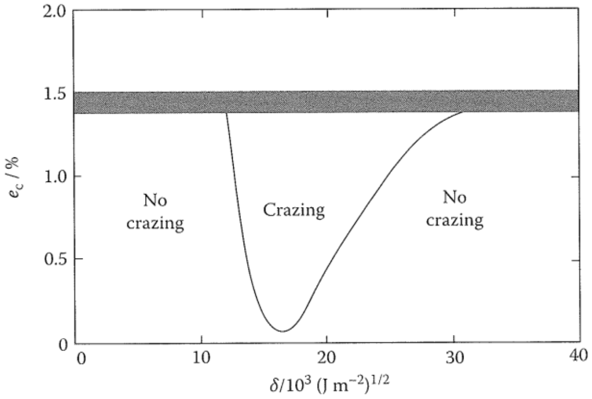


Fig 23.24 p583