Chapter 11

Mechanical Behavior of Polymers

Contents

Outline (1)

- mechanical property
  - mechanical response of a material to the applied stress (load)

- response of a polymer depends on
  - material (chemical structure)
  - morphology (physical structure)
  - temperature
  - time
  - magnitude of stress
  - state of stress

Outline (2)

- magnitude of stress
  - upon small stresses
    - elastic deformation
    - viscous deformation (flow)
    - viscoelastic deformation
  - upon large stresses
    - plastic deformation
      - yielding → ductile
      - crazing → brittle
    - failure (fracture)

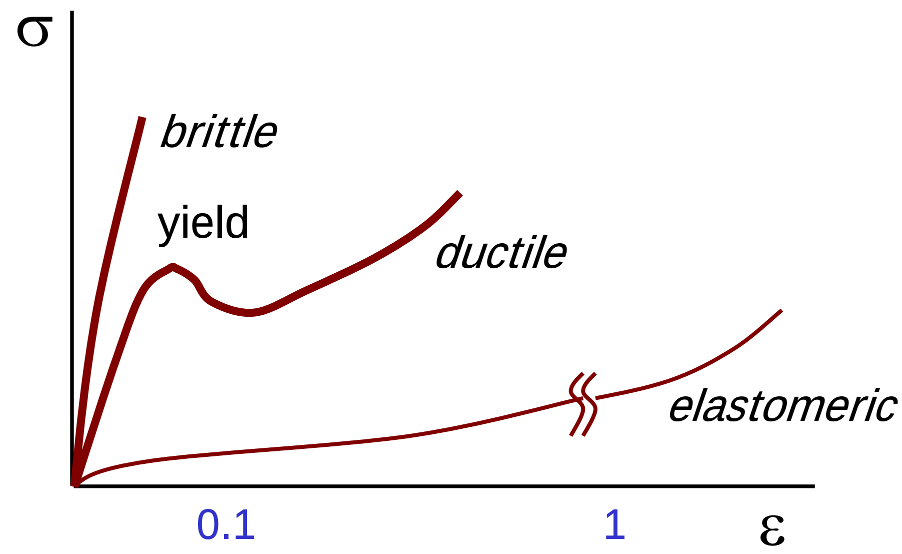


Fig 11.4 p562

tough → ductile

- response of the polymer chains
  - deformations of the bond lengths and angles
  - uncoiling of the chains
  - slippage of the chains
  - scission of the chains

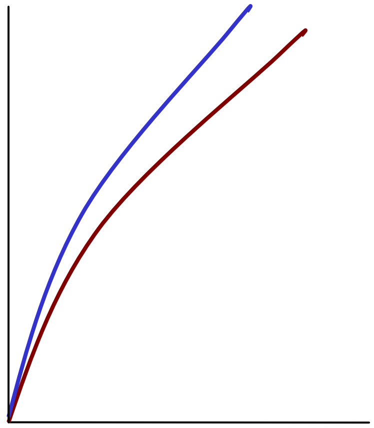
Fig 11.3 p562

Stress and strain

- stress: load (force) per unit area, $\sigma = F/A$ [$N/m^2 = Pa$]
- strain: displacement by load, $\varepsilon = \Delta L/L$ [dimensionless]

- engineering (nominal) stress, $s = F/A_0$
- true (natural) stress, $\sigma = F/A$

- engineering (nominal) strain, $e = \Delta L/L_0$
- true (natural) strain, $d\varepsilon = dL/L$, $\varepsilon = \ln (L/L_0)$
  - $\varepsilon = \ln (L/L_0) = \ln [(L_0+\Delta L)/L_0] = \ln [1+e]$
  - $\varepsilon \sim e$ for small strains only ($e < 0.01$)

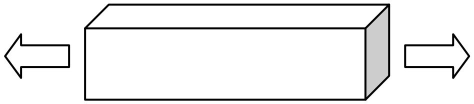


- For UTT, $s < \sigma$ and $\varepsilon < e$

Testing geometry and state of stress (1)

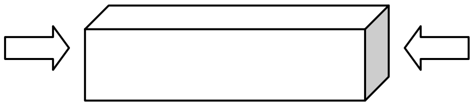
- uniaxial tension

  $\sigma_{xx} = \sigma > 0$, all other stresses = 0



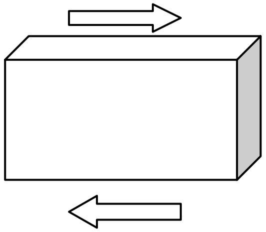
- uniaxial compression

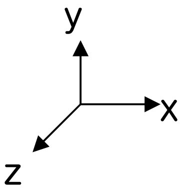
  $\sigma_{xx} = \sigma < 0$, all other stresses = 0



- simple shear ~ torsion

  $\tau_{xy} = \tau$, all other stresses = 0

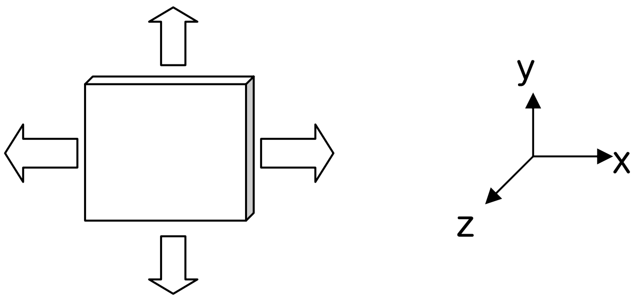




Testing geometry and state of stress (2)

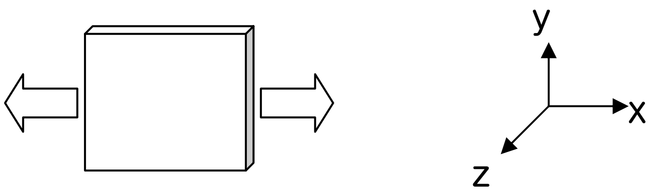
- plane stress

  $\sigma_{zz} = \tau_{zx} = \tau_{yz} = 0$

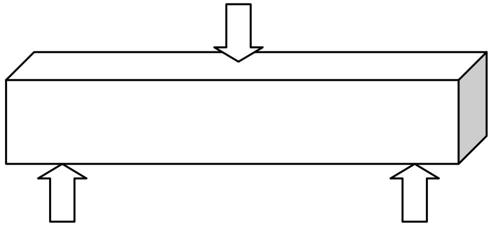


- plane strain

  $\varepsilon_{yy} = 0, \sigma_{yy} = \nu (\sigma_{xx} + \sigma_{zz})$



- bending or flexure



Constitutive equation (1)

- Equations that relate stress to strain (rate)

  $\sigma = c\,\varepsilon$ c : stiffness

  $\varepsilon = s\,\sigma$ s : compliance

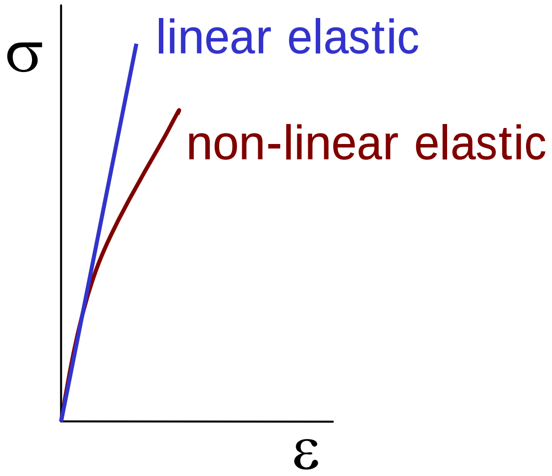
- c, s tensors ~ 81 components (9 x 9)
- by symmetry in σ, ε (equilibrium), 81 → 36 (6 x 6)
- by symmetry in c, s 36 → 21
- by symmetry in material,

  21 → 13 (1 sym pl) → 9 (3 sym pl) → 5 (fiber sym) → 2 (isotropic)

- For isotropic linear elastic solid in UTT

  $\sigma_{(xx)} = E\,\varepsilon_{(xx)}$ (Hooke's law)

  $\varepsilon_{yy} = -\,\nu\,\varepsilon_{xx}$



Constitutive equation (2)

- Stiffness and compliance can be time-dependent (viscoelastic), when stress and/or strain are time dependent. ~ viscoelastic behavior
  - $\sigma(t) = E(t)\, \varepsilon_o$ ~ stress relaxation
  - $\varepsilon(t) = D(t)\, \sigma_o$ ~ creep

- Stiffness and compliance can be strain-level-dependent (nonlinear), when the stress and/or time exceed linear region. ~ nonlinear behavior
  - $\sigma(t) = E(t, \varepsilon_o)\, \varepsilon_o$

- Stiffness and compliance can be orientation-dependent, when the material is anisotropic (fibers, films). ~ anisotropic behavior

  $E_{xx} \neq E_{yy}$; $\nu_{zx} \neq \nu_{xy}$

- It is hard to express the real mechanical response in a constitutive equation.

Viscoelasticity

- Every material is viscoelastic.
- depending on time (strain rate) and temperature
  - elastic, solid-like
  - viscoelastic, polymer-like
  - viscous, liquid-like
  - Deborah Number = material time / experimental time
- VE observation
  - stress relaxation
  - creep
  - recovery
  - time-temperature superposition
  - dynamic mechanical

Application of VE Data to Product Design

- Correspondence principle

  viscoelastic equation → elastic equation

  $\sigma(t) = E(t)\,\varepsilon \rightarrow \sigma = E\,\varepsilon$

- Pseudoelasticity

  From creep, stress relaxation, or isochrone stress-strain curve, estimate long-term stress-strain relation, and design the product.

Creep curves and plots

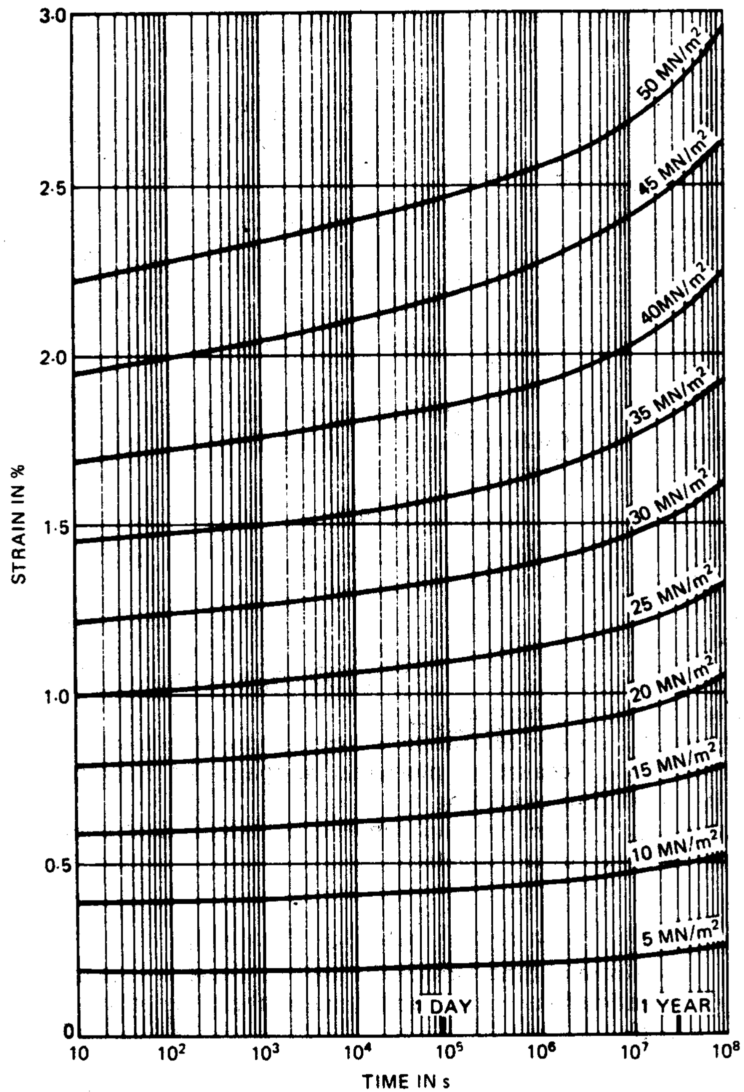
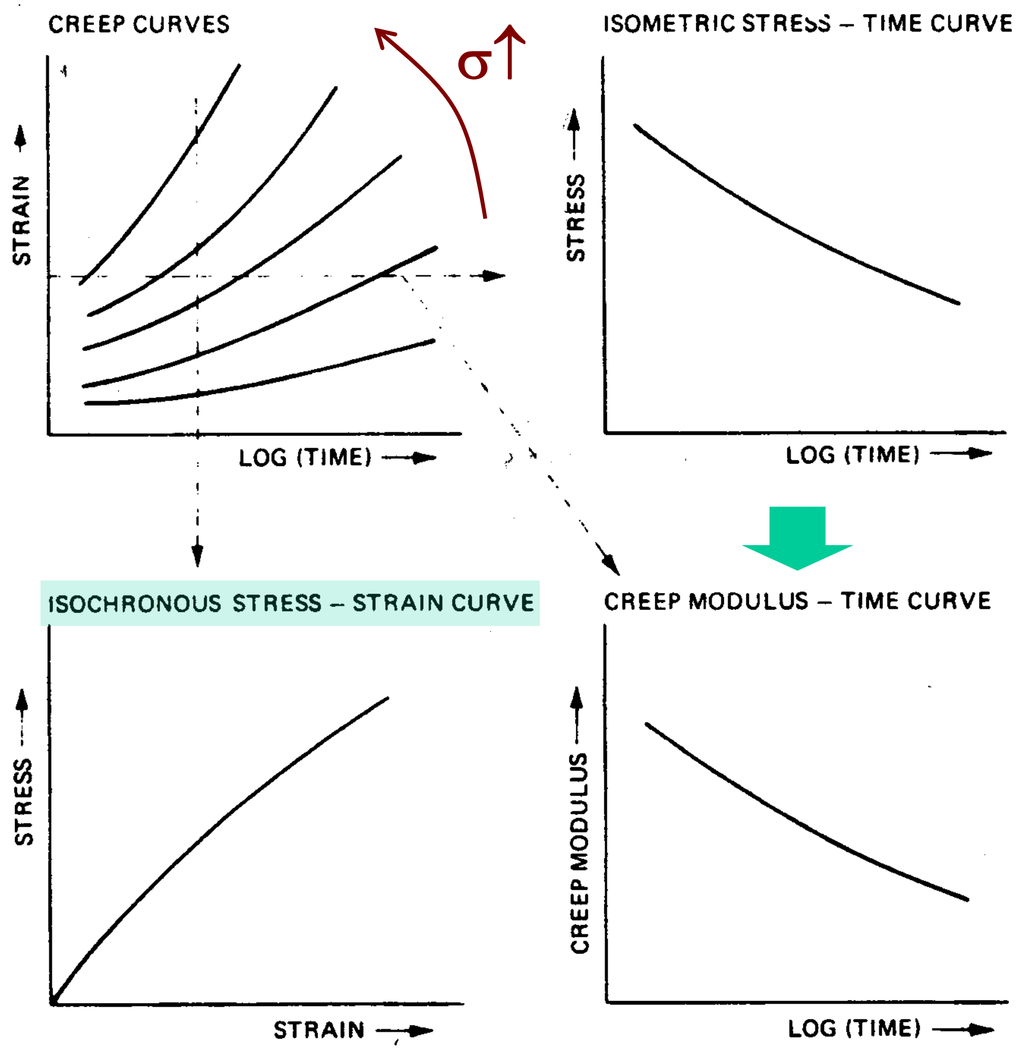


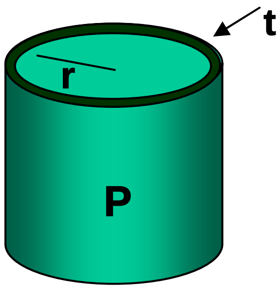
Figure 9.9. Curves for creep in tension of a commercial polysulphone (Polyethersulphone 300P–ICI) at 20°C. (From ICI Technical Service Note PES 101, reproduced by permission of ICI Plastics Division)



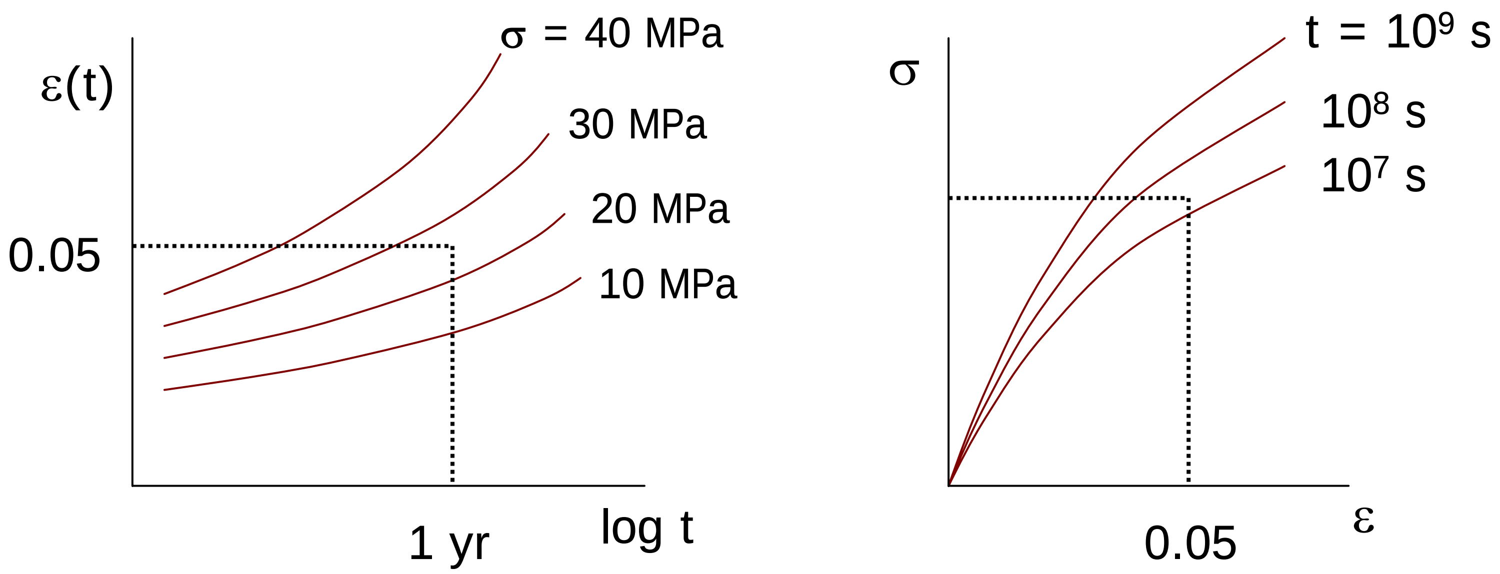
different from transient σ–ε curve

An example of product design

- To design a pressure vessel that is required to be used for 1 year without yielding or fracture (say 5% maximum allowable strain),

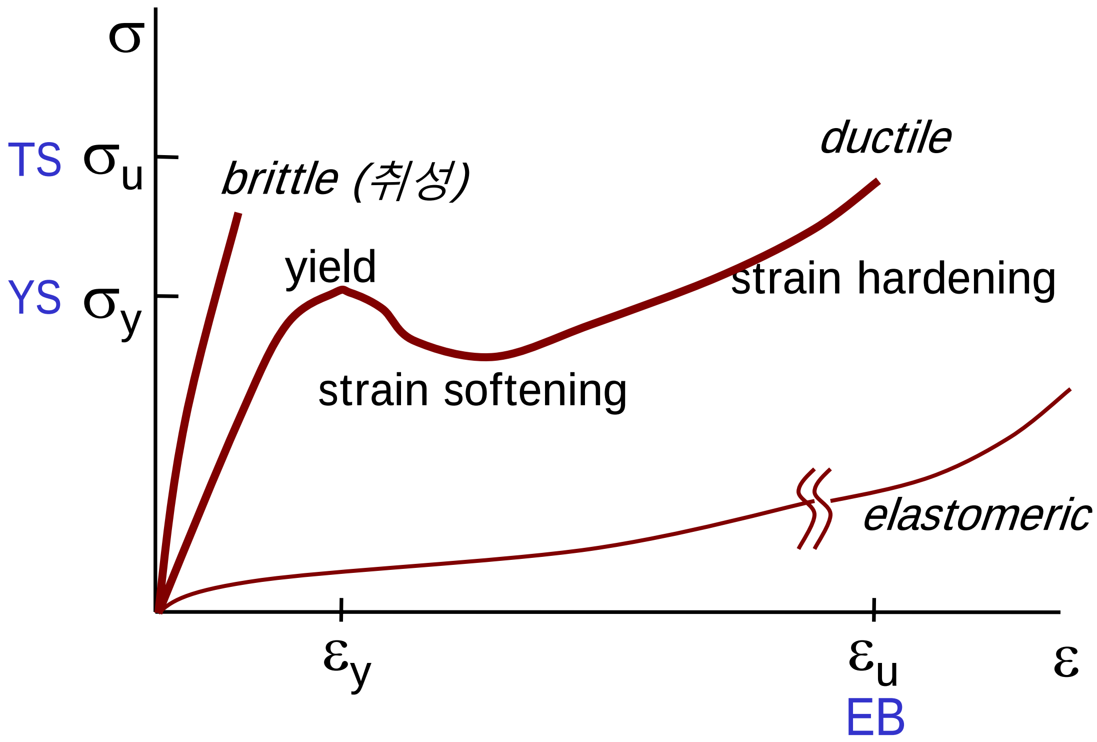


$$\sigma = P\, r\, /\, t$$



Large deformation behavior

- Upon large stress beyond (visco)elastic limit, a polymer experience either yielding or crazing, the two competing processes.
  - Yielding precedes ductile failure; crazing precedes brittle failure.



- yield strength (항복강도)
  ~ stress at yield
- tensile strength (인장강도)
  ~ stress at failure
- elongation at break (파단신장률)

- stiff ~ high E
- strong ~ high TS
- ductile ~ high EB after yield
- tough ~ high energy before fracture

- ductility (연성) ~ ability to yield and be cold-drawn
- toughness (강인성) ~ resistance to crack propagation

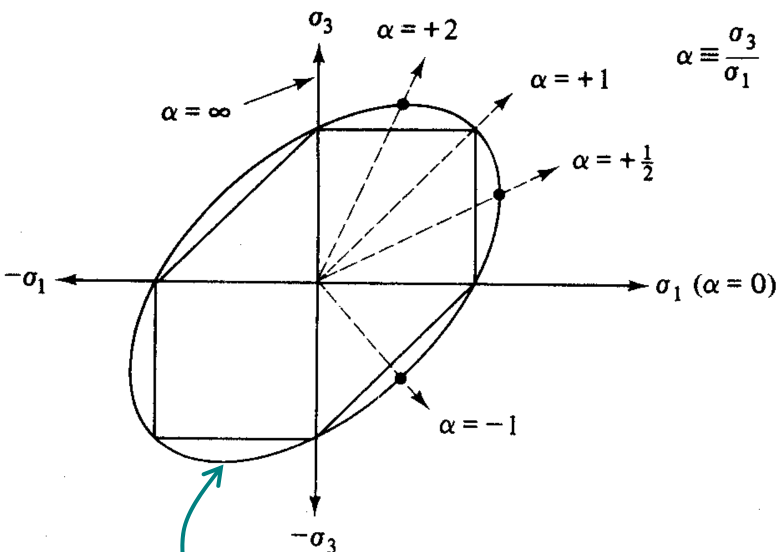
Yield criteria

- yield = start of plastic deformation
- yield by <u>shear only</u>

$$\tau_{max} = \sigma_1 - \sigma_3 = 2C = 2\tau_y = \sigma_y$$

- pressure-independent YC

  ~ metals



Eqn (11.18) p572

- pressure-dependent YC

  ~ polymers

$$\sigma_y(\text{comp}) = (1.1 - 1.3)\ \sigma_y(\text{tension})$$

$$\sigma_y = \sigma_y^0 - \mu\ (\sigma_1 + \sigma_2 + \sigma_3)/3$$

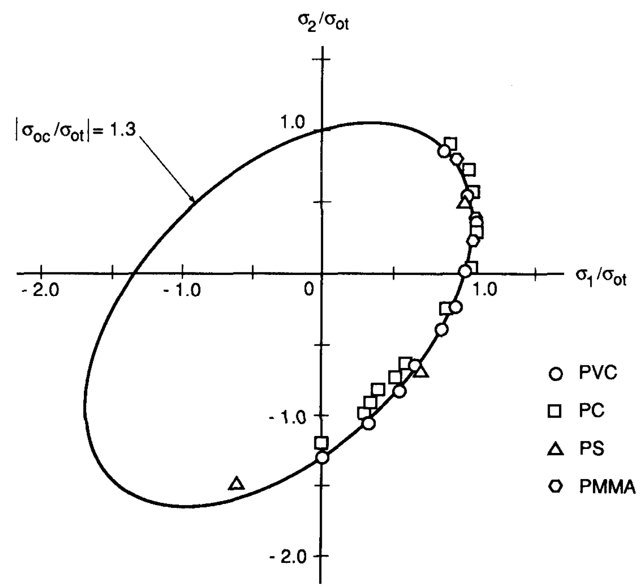
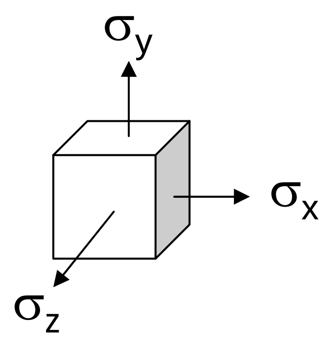


Fig 11.10 p572

When all τ's = 0, then x, y, z are principal axes and σ_x, σ_y, σ_z are principal stresses (σ_1, σ_2, σ_3).

$\sigma_1 > \sigma_2 > \sigma_3$



If $\sigma_x = \sigma_y = \sigma_z$ and τ's = 0,

$\sigma_1 = \sigma_2 = \sigma_3$ (purely hydrostatic)

$\sigma_1 - \sigma_3 = 0$ → no yield

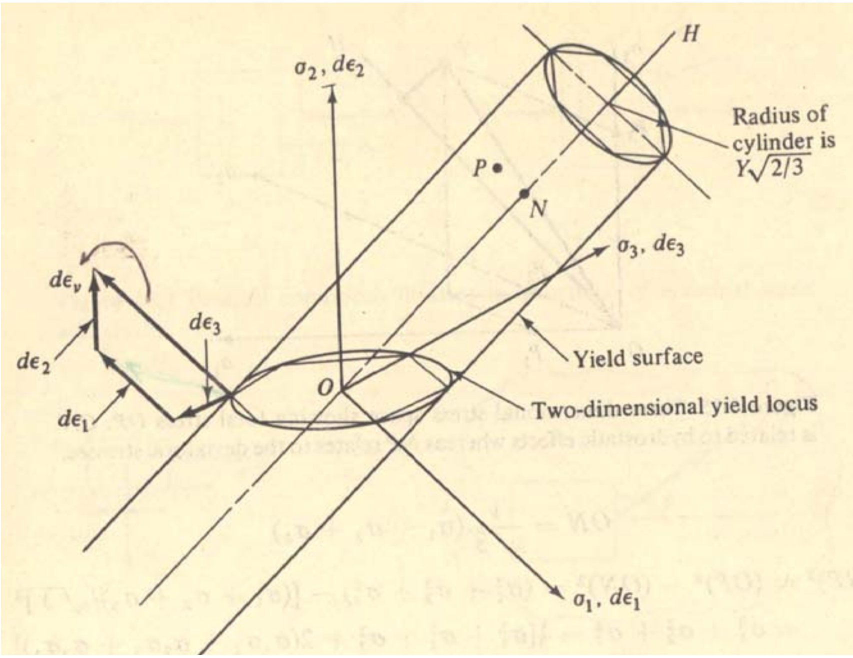
If $\sigma_x > 0$, and other σ's & τ's = 0,

$\sigma_1 - \sigma_3 = \sigma_y$ → yield at $\sigma_1 = \sigma_y$

If $\sigma_1 = -\sigma_3$ and $\sigma_2 = 0$,

$\sigma_1 - \sigma_3 = 2\sigma_1 = \sigma_y$

→ yield at $\sigma_1 = \tau_y = \sigma_y/2$



Yield behavior

- strain rate ↑ → YS ↑
- Temp ↑ → YS ↓

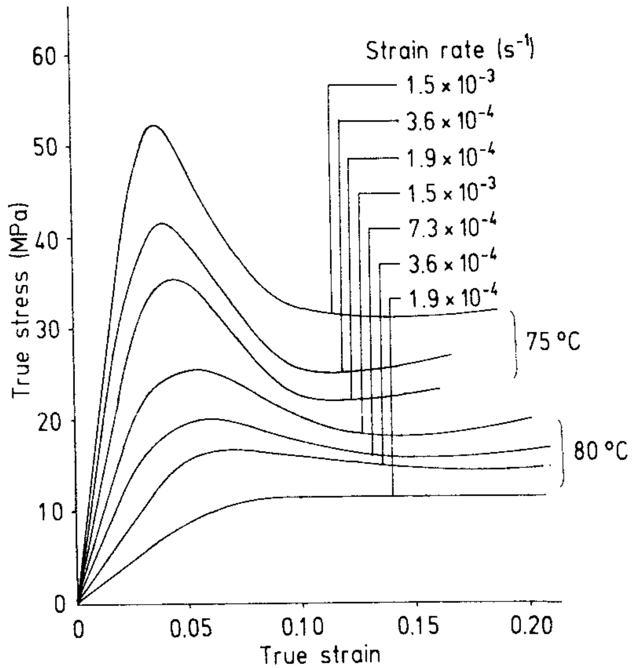


Figure 10-10. True stress–true strain curves for polystyrene determined in plane strain compression. From Bowden and Raha (1970); reproduced with permission of Taylor and Francis Ltd.

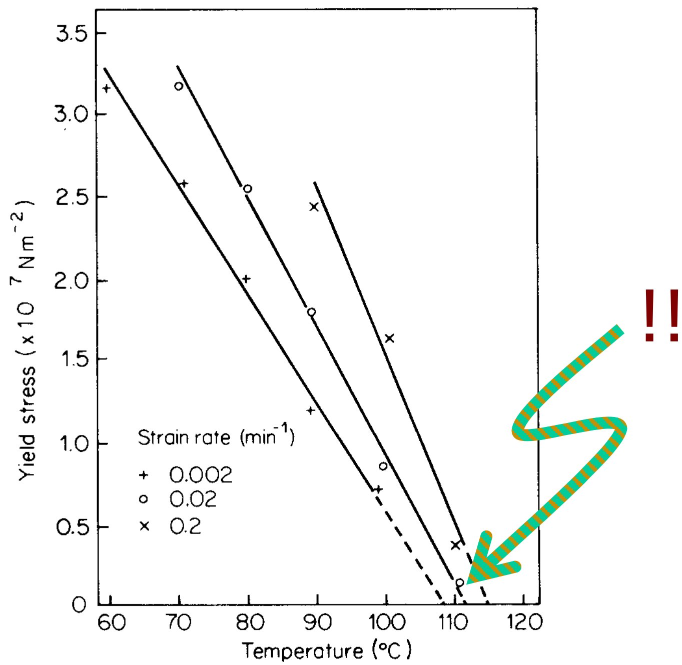


Figure 11.36. Variation in the yield stress with temperature at various strain rates for polymethyl methacrylate. [Redrawn with permission from Langford, Whitney and Andrews. *Mater. Res. Lab. Res. Rept. No. R63-49,* MIT School of Engineering, Cambridge, Mass., 1963.]

📖Fig 11.5 p566

📖Fig 11.6 & 7

Post-yield behavior (1)

- strian softening
  - load drop
  - state of T_g at yield point

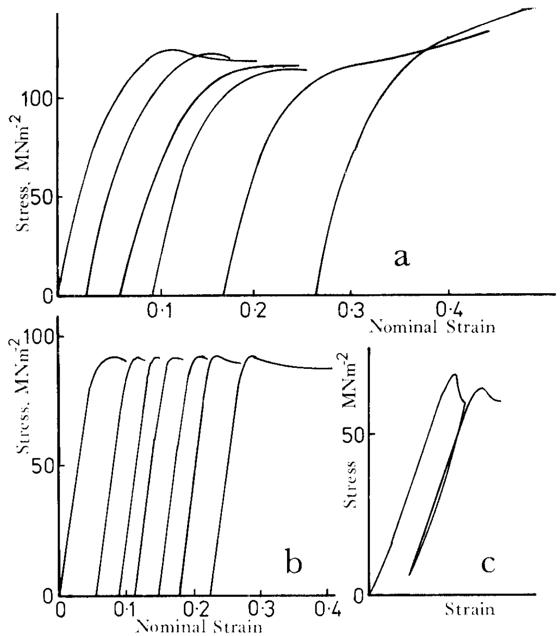
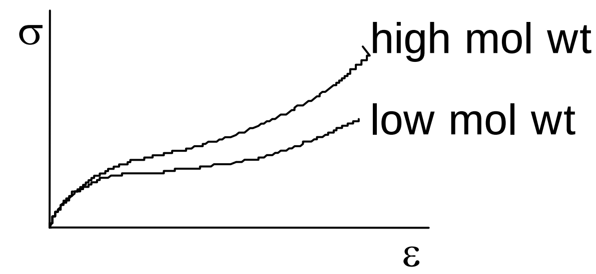


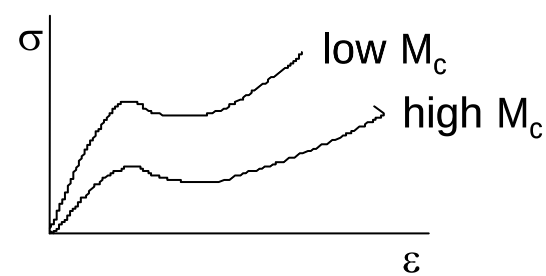
Fig. 6. (a) *Stress–strain curves obtained on a sample of PMMA in plane-strain compression. The test has been interrupted and the load reduced to zero five times during the test. The unloading paths are not plotted.* (*Reproduced from reference* 9 *by permission of the Editor of* Polymer.) (b) *Similar test on polystyrene at room temperature.*[10] (c) *Test on polyethylene terepthalate in uniaxial compression.* (*Reproduced from reference* 8 *by permission of John Wiley and Sons Inc.*)

- strain hardening
  - rise in stress
  - orientation of chains

Polyethylene

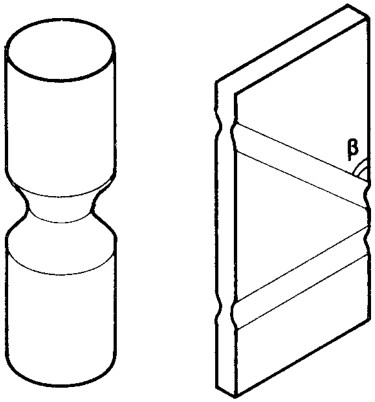


Epoxy

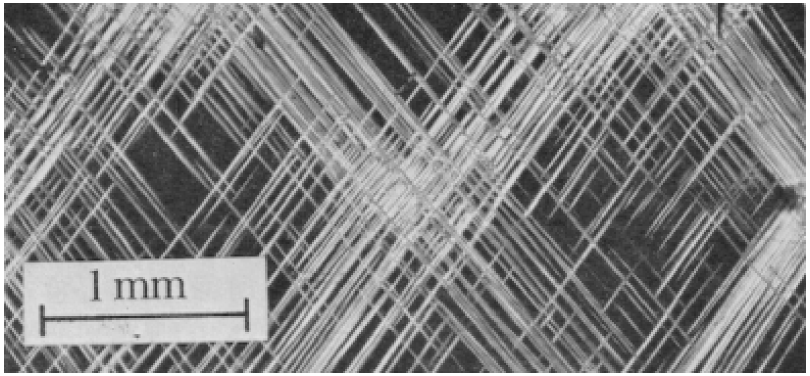


Post-yield behavior (2)

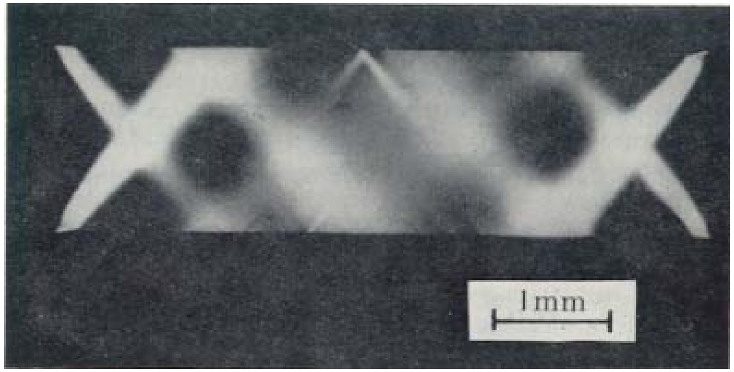
- inhomogeneous deformation
  - localized instability due to softening, which interacts with restraints
  - with no restraint ~ necking
  - with restraint in 1 direction ~ inclined necking
  - with restrainst in 2 directions ~ shear band



PS



PMMA



📖Fig 11.9(b) p571

Deformation of semicrystalline polymers

- semicrystalline = amorphous + crystal (lamellae)
  - $T < T_g < T_m$ (e.g. PET at RT)
    - Glass and crystals have comparable mechanical properties.
    - Yield behavior is similar to amorphous polymers.
  - $T_g < T < T_m$ (e.g. PE at RT)
    - crystals in liquid (rubber)
    - initial deformation (modulus) at rubber.
    - Only crystals yield: As crystallinity increases, σ_y increases.

- post-yield ~ reorientation of crystals

📖Fig 11.8 p570

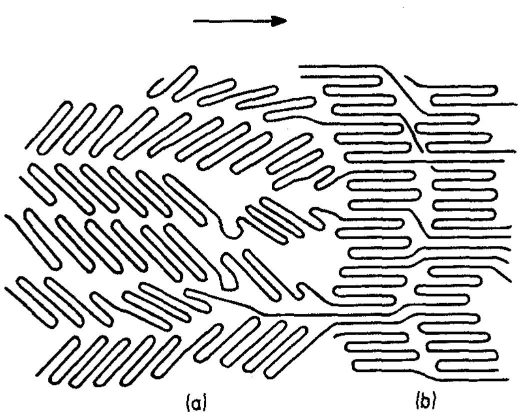
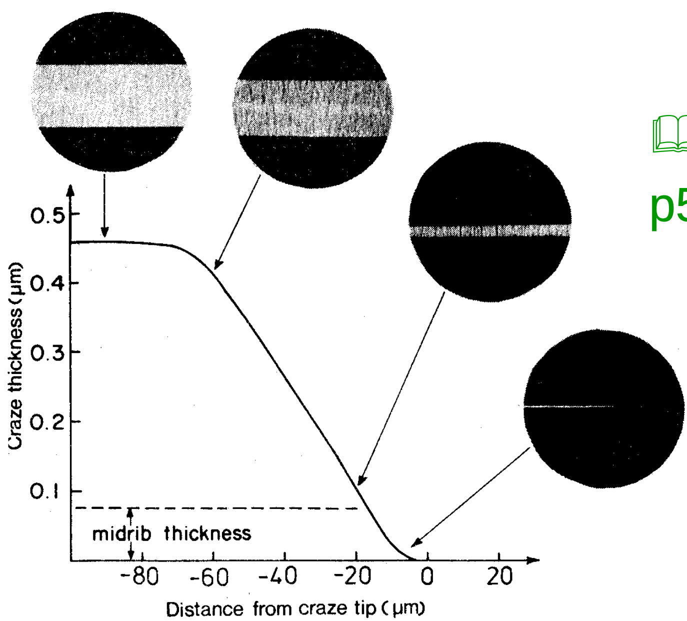


Figure 10-19. Model for transformation from lamellar (a) to fibrillar (b) morphology on drawing a semicrystalline polymer. From Peterlin (1965); reproduced with permission. © John Wiley & Sons, Inc.

Crazing

- localized inhomogeneous plastic deformation by dilatational stress
  - normal yielding ↔ (shear) yielding
  - compete with shear yield
- structure of craze
  - long, thin wedge of deformed polymer (microfibrils)



📖Fig 11.9(a) p571

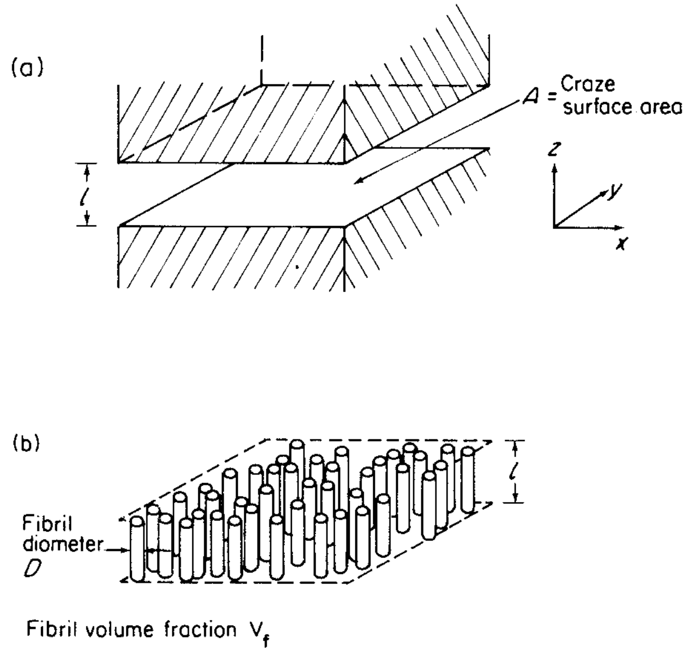


Figure 12.12. Schematic diagram of the forest of cylindrical fibrils oriented normal to the craze surface. [Redrawn with permission from Brown and Kramer, *J. Macromol. Sci. B*, **19**, 487 (1981) by courtesy of Marcel Dekker Inc.]

Formation and growth of craze

- Craze initiation criteria

📖Fig 11.10 p572

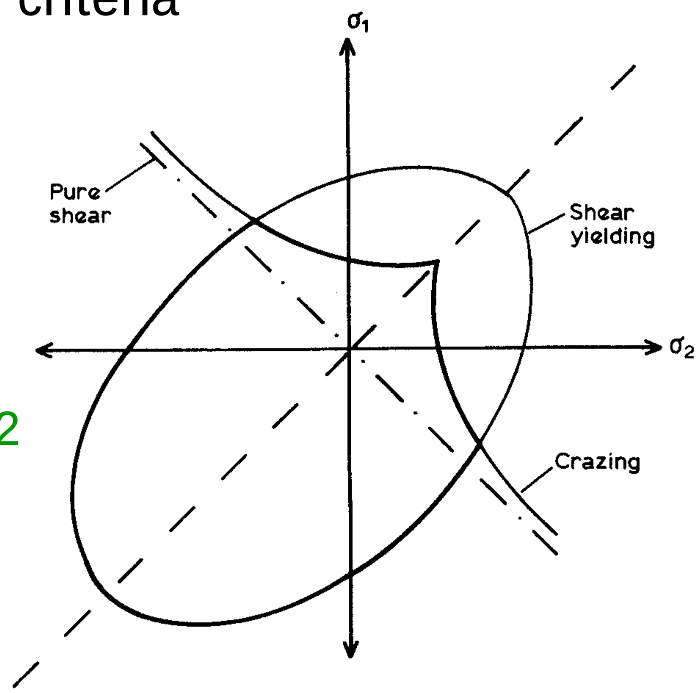


Fig. 5.8. Comparison of envelopes for the initiation of craze yielding (eqn. (5.5)) and shear yielding (eqn. (4.14)) in PMMA. Heavy continuous line indicates failure envelope (after Sternstein & Ongchin[64]).

No crazing by compression

Both craze and yield criteria are dependent on Temp and dε/dt.

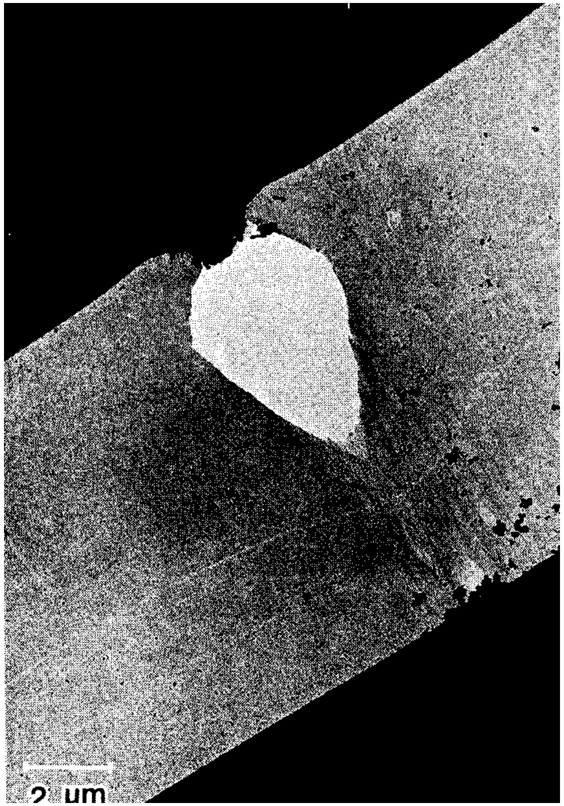
→ ductile-brittle transition

- Craze propagation
  - thicken by drawing new materials from bulk
  - lengthen by meniscus instability 📖Fig 11.30 p598

Craze failure

- At very slow strain rates,
  - fibril breakdown at interface between craze and bulk → void
  - void grows → impinge to other voids → crack
  - connecting cracks from other crazes → fracture

- At high strain rates,
  - craze fracture
  - craze fibrils found in fracture surface



Environmental stress cracking (ESC)

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

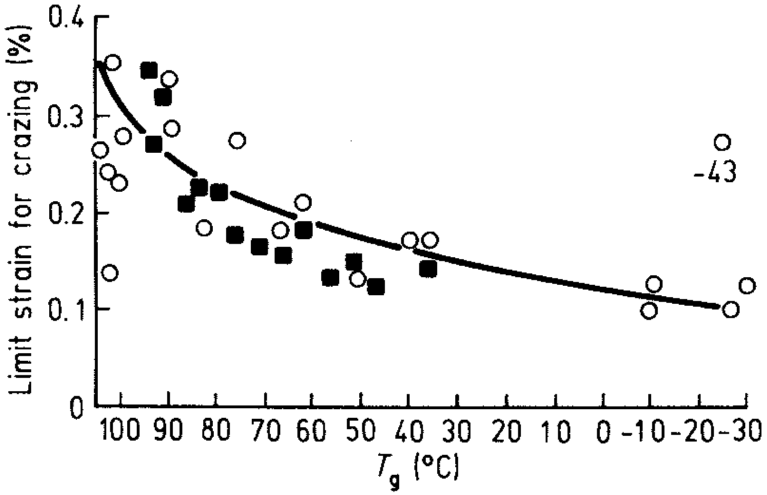


Figure 15-17. Decrease in T_g of PS due to solvent absorption, and its effect on the critical strain for crazing (Kambour et al., 1973). (○) Swollen samples in various chemical solvents; (■) extended in air mixed with PS-dichlorobenzene.

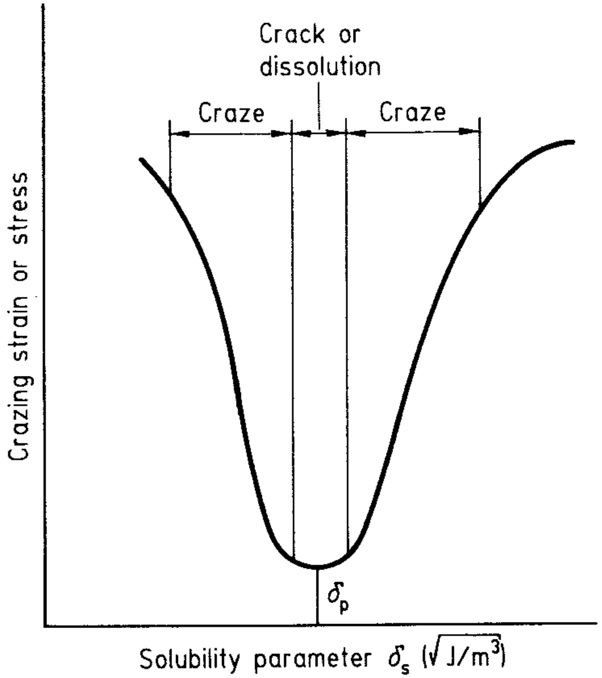


Figure 15-18. Schematic relationship between the critical crazing strain of a polymer and the solubility parameter SP of solvents.

Fracture

✓ failure (파쇄, 파단) ~ rupture by exceedingly large stress

✓ fracture (파괴) ~ failure by crack propagation

- micromechanism of fracture
  - Chain scission or slip? 🕮Fig 11.3 p562, Fig 11.29 p 595
  - Upon stress,

    i) chain slip (against crystal, crosslinking, entanglement)

    iiA) crazing/yielding or

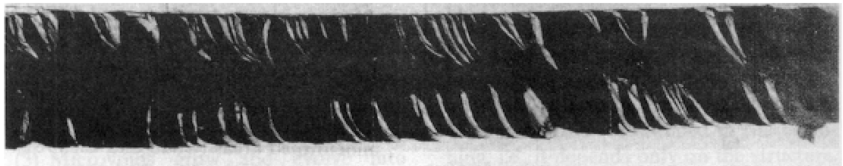
    iiB) chain scission (with high X_c, low M_c, low M_e)

    iii) chain scission as stress increases

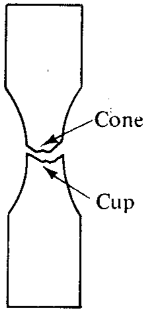
    iv) voiding → crack → fracture

Ductile fracture (1)

- failure of shear band



- thermal fracture
  - necking, not stabilized
  - cone-and-cup failure



- diamond cavity
  - craze blunted by shear band

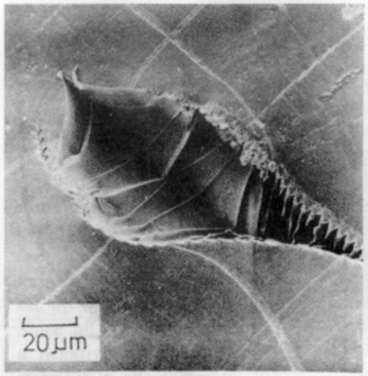
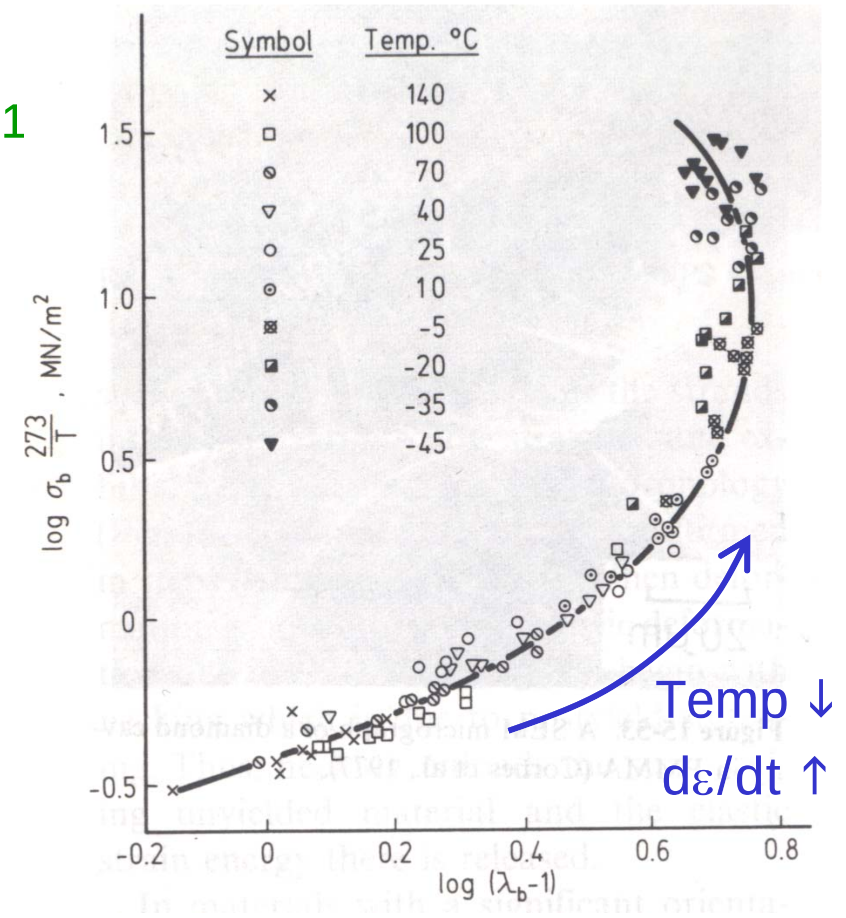


Figure 15-53. A SEM micrograph of a diamond cavity in PMMA (Cornes et al., 1977).

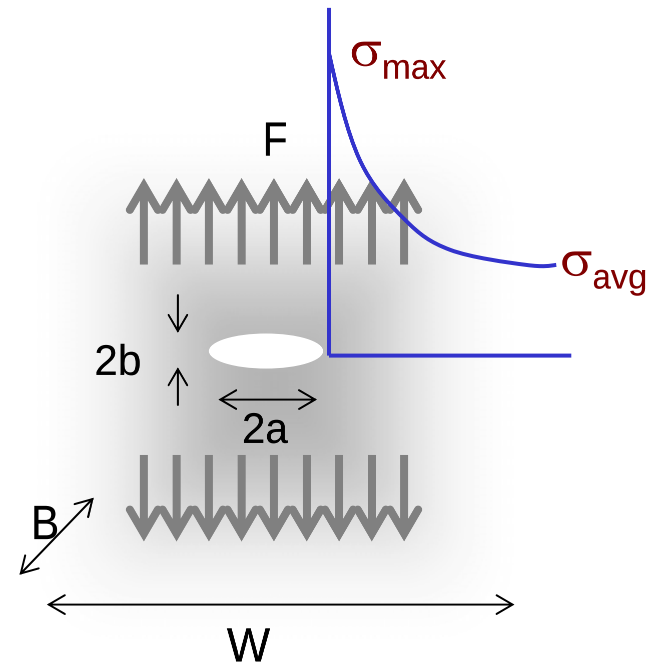
Ductile fracture (2)

- tensile rupture of elastomers
  - elastomerixc up to failure
  - 'failure envelope' 📖Fig 11.17 p581
    - TS vs EB
      - at different Temp and $d\varepsilon/dt$
    - time – Temp superposition
      - time to break, $t_b = \varepsilon_b/(d\varepsilon/dt)$



Brittle fracture (1)

- theoretical strength of solids
  - σ_{theo} = E/10 ← for interatomic separation
  - For whiskers, $\sigma_f \sim E/10$
  - For isotropic glassy polymers,
    - $\sigma_f \sim E/100 < \sigma_{theo}$ (E ~ 3 GPa, σ_f < 100 MPa)
    - due to flaw (crack, notch, inclusion).
      - stress concentration
      - plastic constraint



- stress concentration
  - ahead of crack tip
  - stress concentration factor,

    $k = \sigma_{max}/\sigma_{avg} = 1 + (2a/b) = 1 + 2(a/\rho)^{1/2}$

Brittle fracture (2)

- plastic constraint
  - ahead of crack tip
  - triaxial stress state
    - $\sigma_1 > 0$ (applied), σ_2 & $\sigma_3 > 0$ (due to crack)
  - triaxiality → yield at higher stress ~ plastic deformation constrained
  - yield at a stress higher than σ_c → brittle

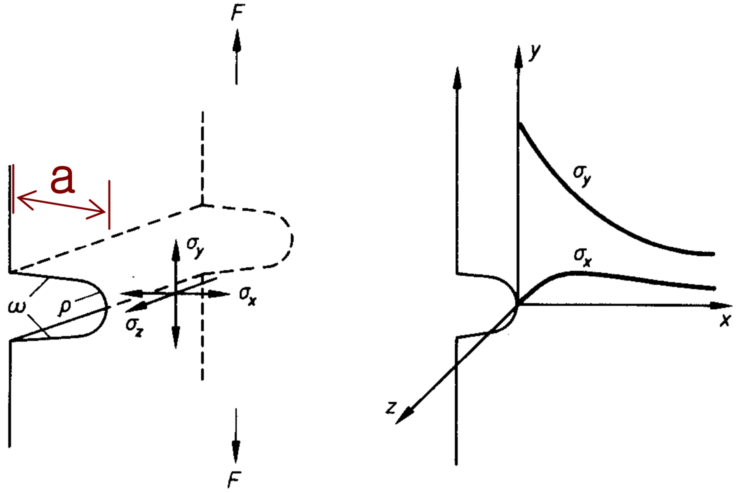


Figure 15-57. Elastic stress distribution in the interior of a thick plate with a notch whose radius is ϱ.

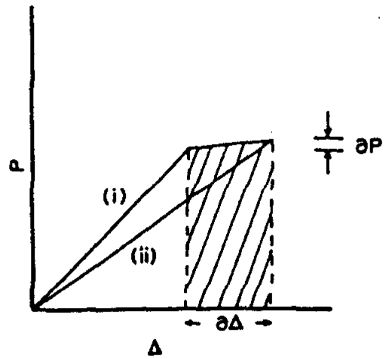
Fracture mechanics (1)

- Energy balance approach
  - specimen with crack length 2a
  - Crack grows when released strain energy by stress ($\sigma^2 \pi a/E$) is greater than created surface energy (2γ)
  - $\sigma_f = [2E\gamma/\pi a]^{1/2}$: Griffith fracture criterion 📖eqn (11.20) p586
  - for polymers; $2\gamma \sim 1$ J/m^2, fracture energy (G_c) ~ 100 - 1,000 J/m^2
    - Fracture energy higher by other process: plastic deformation at crack tip
  - replacing 2γ with G_c

    $\sigma_f = [EG_c/\pi a]^{1/2}$ for plane stress

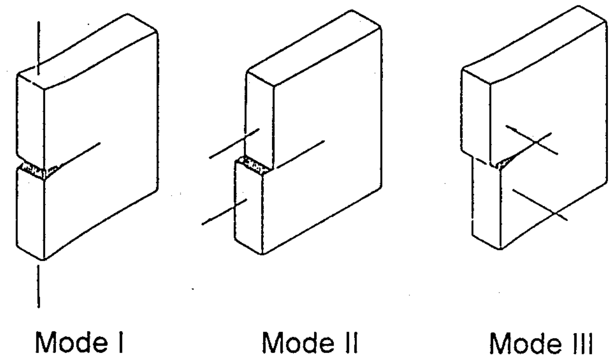
    $\sigma_f = [(EG_c/\pi (1-\nu^2)a]^{1/2}$ for plane strain
  - G_c: critical strain energy release rate; 'fracture energy' [J/m^2]
  - measurement of G_c

    $G_c = (P^2/2B)\,(dC/da)$

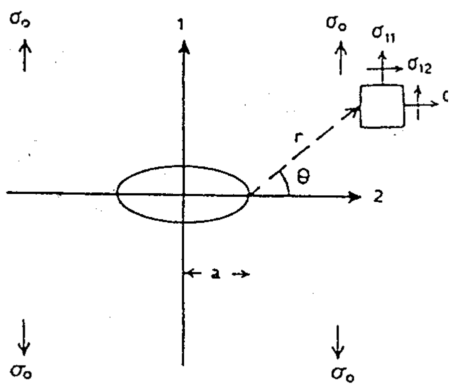


Fracture mechanics (2-1)

- Stress intensity factor approach
  - linear elastic fracture mechanics (LEFM)
  - 3 modes of fracture



  - stress at a point



$$\begin{Bmatrix}\sigma_{11}\\ \sigma_{12}\\ \sigma_{22}\end{Bmatrix} = \frac{K_I}{(2\pi r)^{1/2}} \cos(\theta/2) \begin{Bmatrix} 1+\sin(\theta/2)\sin(3\theta/2) \\ \sin(\theta/2)\cos(3\theta/2) \\ 1-\sin(\theta/2)\sin(3\theta/2) \end{Bmatrix}$$

$\sigma_{33} = 0$ (Plane stress), or

$\sigma_{33} = \nu(\sigma_{11} + \sigma_{22})$ (Plane strain), and

$\sigma_{23} = \sigma_{13} = 0$

  - Crack grows when $K_I > K_{Ic}$
  - K_{Ic}: critical stress intensity factor; 'fracture toughness' [MPa $m^{1/2}$]

(파괴강인성)

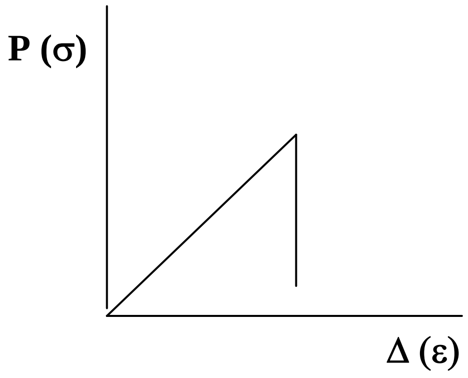
Fracture mechanics (2-2)

- measurement of K_{Ic}

  $K_{Ic} = \sigma_f \, a^{1/2} \, Q$

  Q ~ geometry factor

  📖Fig 11.25 p587



📖Fig 11.22 p586

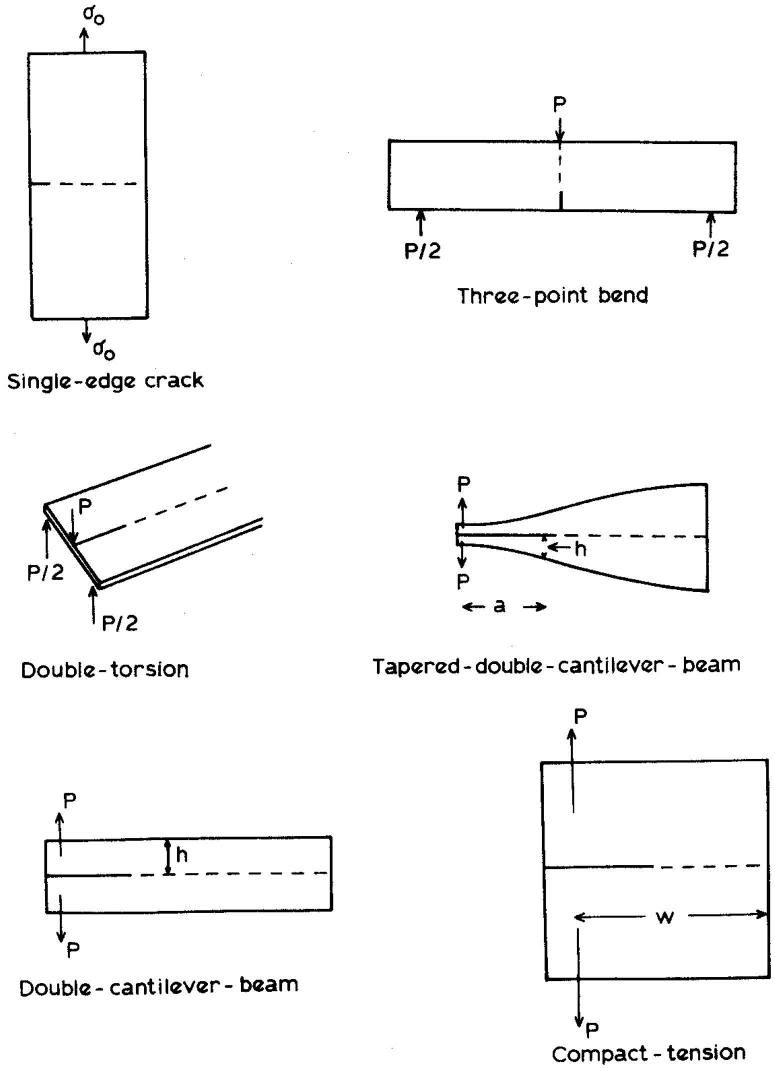


Fig. 3.13. Sketches of various fracture mechanics specimens employed with rigid polymers.

Fracture mechanics (3)

- relationship between G and K
  - $G_{Ic} = K_{Ic}^2 / E$ plane stress 📖eqn 11.24 p587
  - $G_{Ic} = K_{Ic}^2 / E(1-\nu^2)$ plane strain

📖Table 11.3 p575

TYPICAL VALUES OF G_{Ic} AND K_{Ic} FOR VARIOUS MATERIALS

Material	*Young's modulus, E (GPa)*	G_{Ic} ($kJ\,m^{-2}$)	K_{Ic} ($MN\,m^{-\frac{3}{2}}$)
Rubber	0·001	13	—
Polyethylene	0·15	20 (J_{Ic})	—
Polystyrene	3	0·4	1·1
High-impact polystyrene	2·1	15·8 (J_{Ic})	—
PMMA	2·5	0·5	1·1
Epoxy	2·8	0·1	0·5
Rubber-toughened epoxy	2·4	2	2·2
Glass-reinforced thermoset	7	7	7
Glass	70	0·007	0·7
Wood	2·1	0·12	0·5
Aluminium—alloy	69	20	37
Steel—mild	210	12	50
Steel—alloy	210	107	150

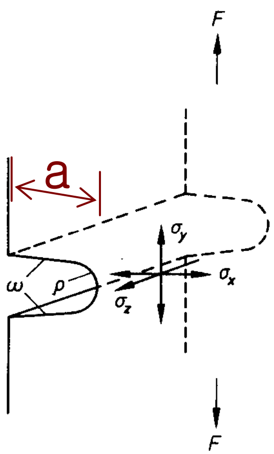
Fracture mechanics (4)

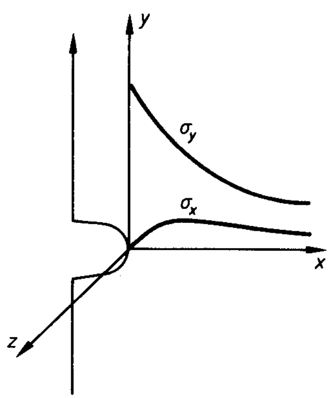
- plastic deformation in front of crack tip → higher G_c and K_c
- plastic zone size
  - From stress analysis by LEFM
  - In front of crack tip ($\theta = 0$), as $r \rightarrow 0$, $\sigma \rightarrow$ infinity ~ impractical
  - σ is cut off by yield strength (σ_y)
  - $\sigma_1 = K_I/(2\pi r)^{½}$ at $\theta = 0$ 📖eqn 11.23
  - When $\sigma_1 = \sigma_y$, plastic zone radius $r_p = (1/2\pi)(K_I/\sigma_y)^2$
  - By plastic constraint, $r_p = (1/2\pi)(K_I/m_p\sigma_y)^2$

    plastic constraint factor $m_p = \sigma_{y,effective}/\sigma_y \geq 1$

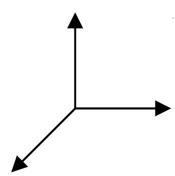
$\sigma_y = \sigma_1 - \sigma_3$
$\sigma_1 = \sigma_y + \sigma_3 = \boldsymbol{\sigma_{y,eff}}$

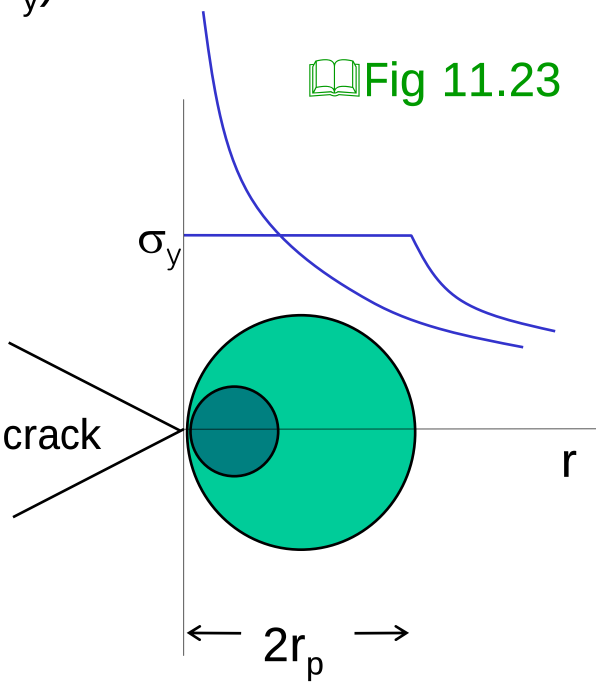
📖Fig 11.23





notch whose radius is ρ.





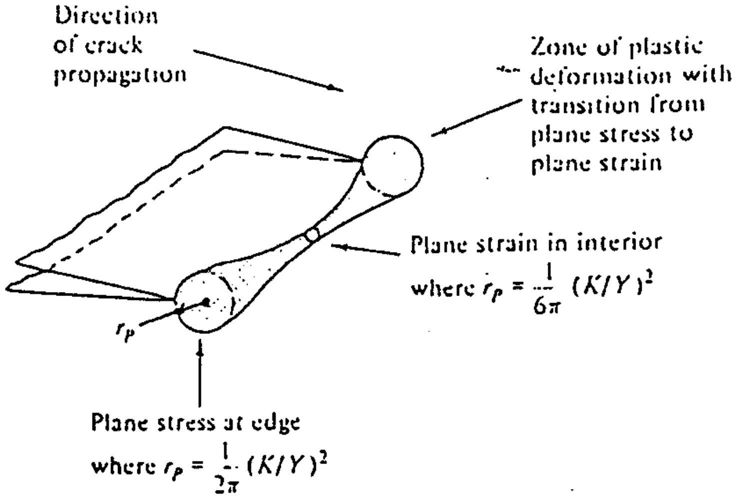
Fracture mechanics (5)

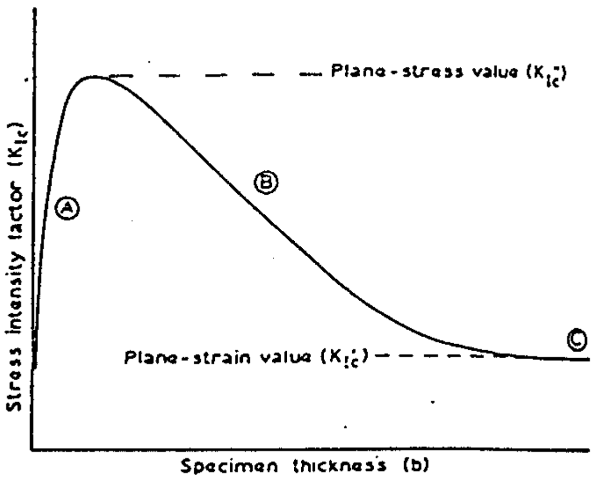
- effect of specimen thickness
  - edge; plane stress condition; $\sigma_3 = 0$

    $$r_p'' = (1/2\pi)\,[K_I/\sigma_y]^2$$

  - inside; plane strain condition; $\varepsilon_3 = 0$, $\sigma_3 = \nu(\sigma_1 + \sigma_2)$

    $$r_p' = (1/6\pi)\,[K_I/\sigma_y]^2$$





  - $B < 2\,r_p''$; plane stress condition
  - $B > 2.5\,[K_I/\sigma_y]^2 \approx 15.7\,r_p''$; plane strain condition ~ ASTM

Impact strength (1)

- testing methods
  - flexed-beam impact test: Izod, Charpy; ASTM D256
  - falling-weight impact test
  - tensile impact test

¶11.2.4 p573

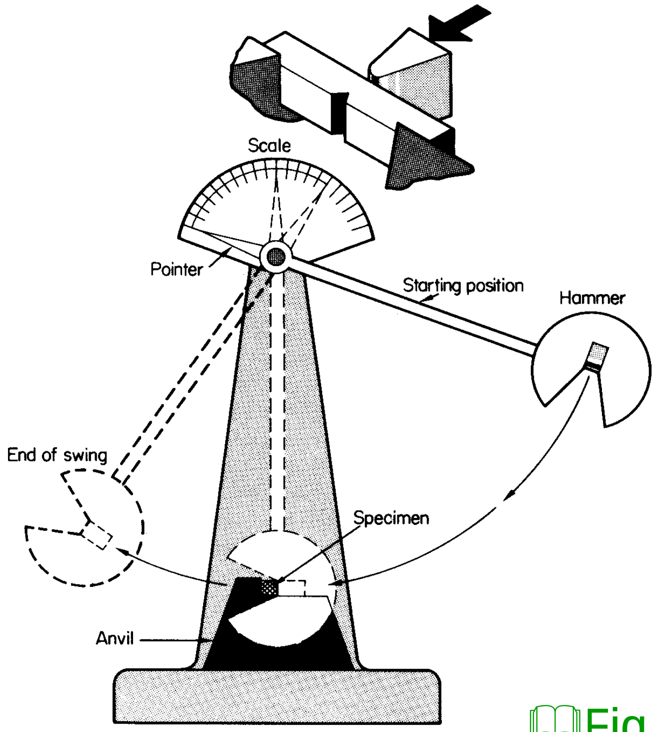


Fig 11.11 p574

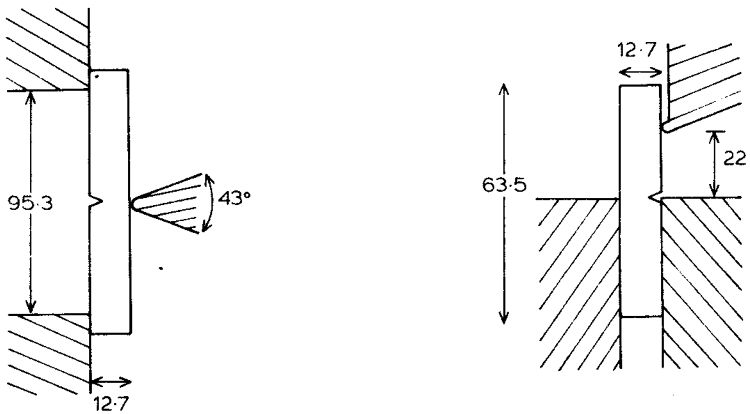


Fig. 6.1. Geometry of testing and specimen support arrangement for (a) Charpy and (b) Izod tests specified in ASTM-D 256 (all dimensions in mm).

Impact strength (2)

- impact strength (IS, 충격강도)
  - energy absorbed per unit area (J/m^2) or unit length (J/m)
    - energy rather than strength
  - not a material property ← depends on many factors
    - Temp ↑ → IS ↑
    - thickness of specimen ↑ → IS ↓ (pl. σ to pl. ε)
    - with notch (notched IS) vs without notch (unnotched IS)
    - notch tip radius ↑ → IS ↑
      - * notch sensitivity
  - Relation betw IS, G_{Ic}, and K_{Ic}

Table 11.3 p575

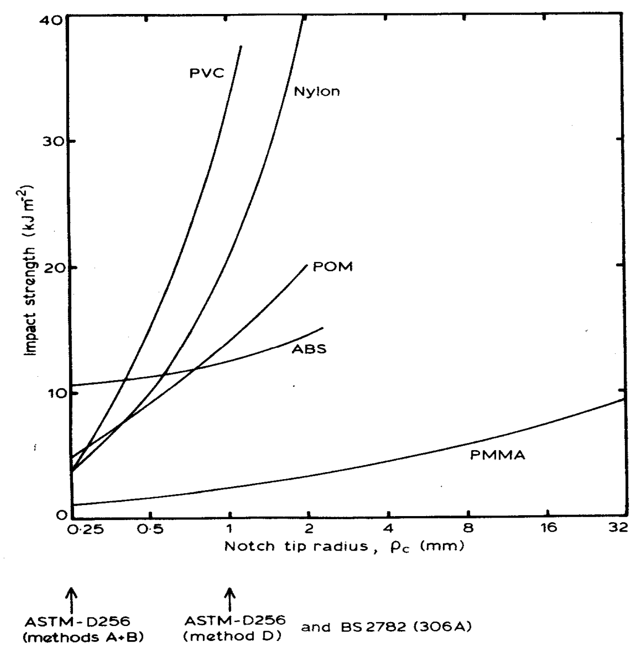


Fig. 6.2. Impact strength as a function of notch tip radius for different polymers (after Vincent[1]).

Fatigue fracture (1)

- Upon stress fluctuation (oscillation), materials fail (fracture) at stress level well below they can withstand under monotonic loading (usually YS or TS).
- fatigue strength
  - S-N curve
  - stress (σ_a or σ_{mean}) vs # of cycles to fracture
  - endurance limit

📖Fig 11.25 p590

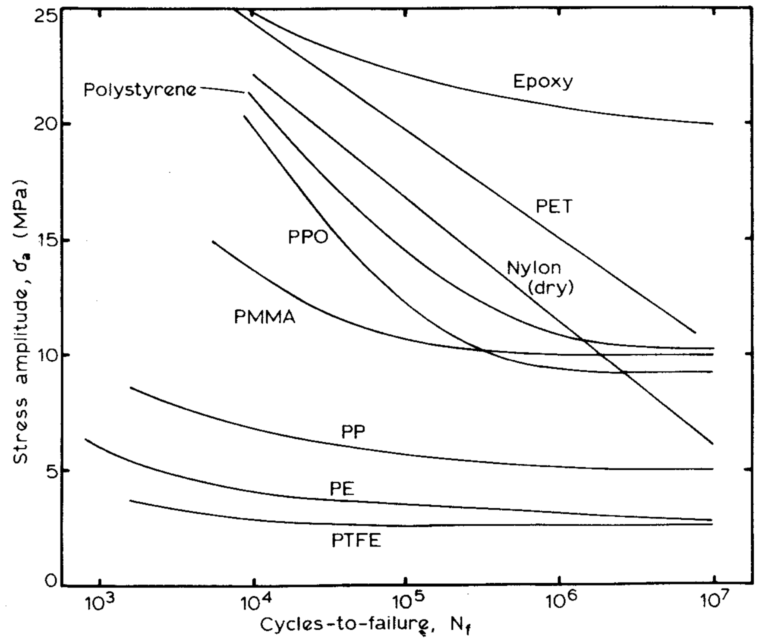


Fig. 6.5. Representative stress amplitude, σ_a, versus logarithm cycles-to-failure, N_f, curves for several polymers tested at a frequency, ν_d, of 30 Hz (after Riddell[62]).

Fatigue fracture (2)

- fatigue crack propagation
  - $da/dN = A\,\Delta K_I^m$ (Paris equation) Fig 11.26 p591

    $\Delta K = K_{max} - K_{min}$
  - continuous craze propagation
  - discontinuous crack propagation

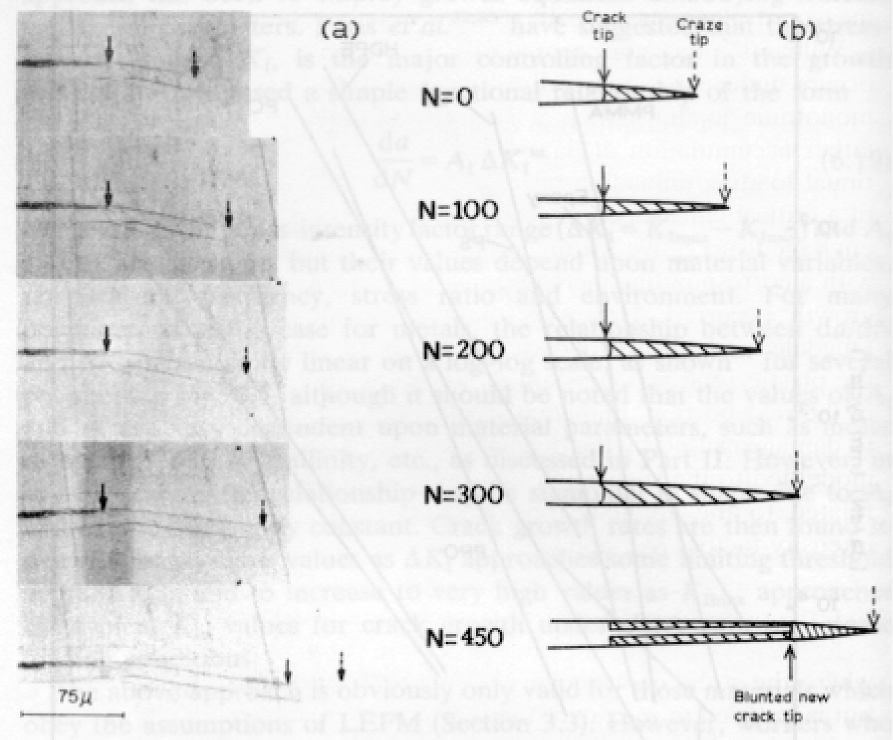
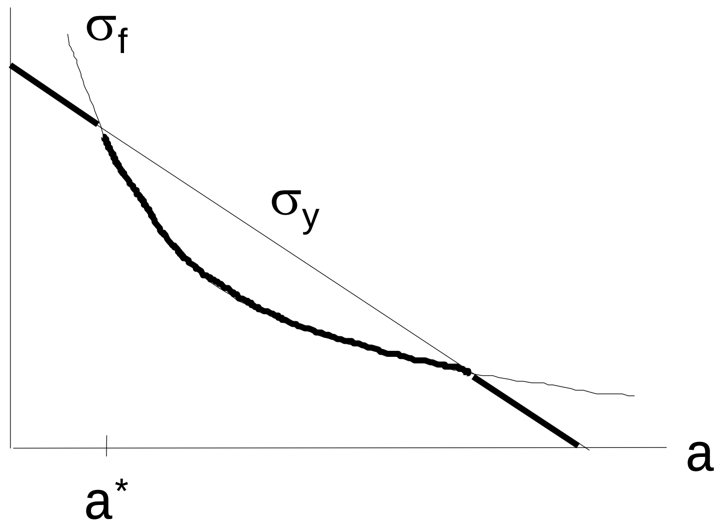
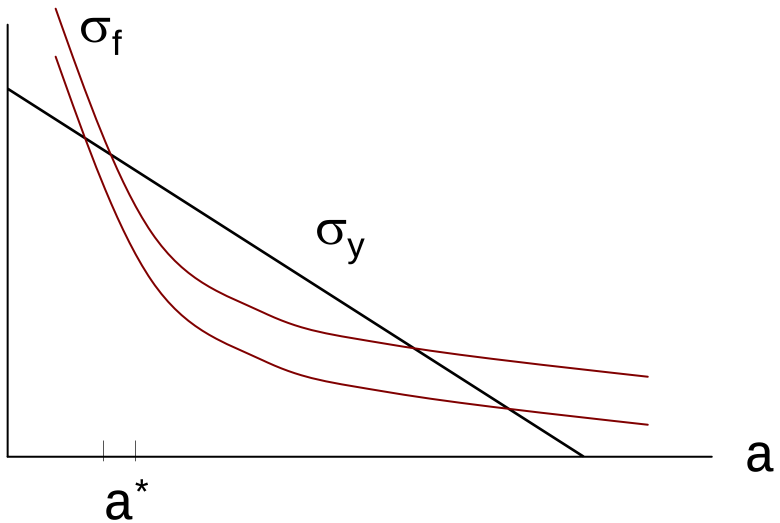


Fig. 6.8. Discontinuous crack growth process. (a) Composite optical micrograph of PVC showing position of crack (↓) and craze (⇣) tip at given cyclic intervals; (b) Model of discontinuous crack propagation mechanism (after Skibo et al.[95]).

Ductile-brittle transition (1)

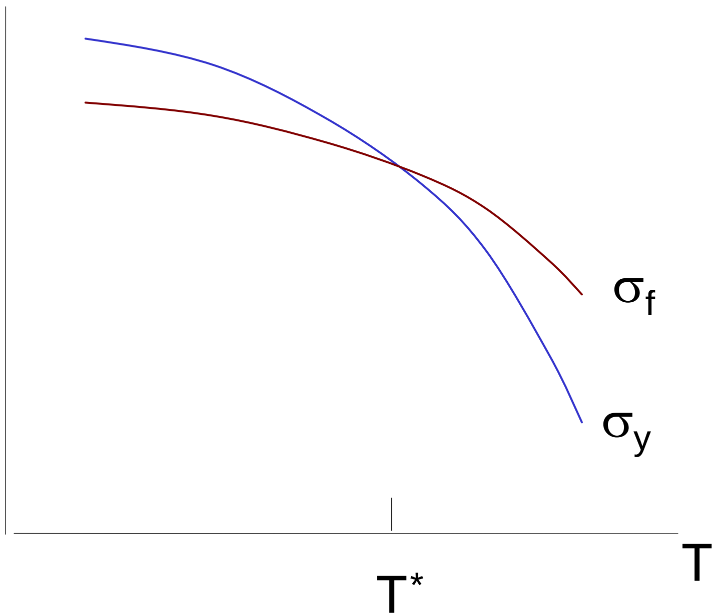
- crack length
  - $\sigma_f \propto K_{Ic}/a^{0.5}$
  - $\sigma_y \propto$ loaded area (1/a)
  - D/B transition at a*
- thickness of specimen
  - B ↑ → K_{Ic} ↓ → a^* ↓
  - Plane stress (ductile) to plane strain (brittle) transition



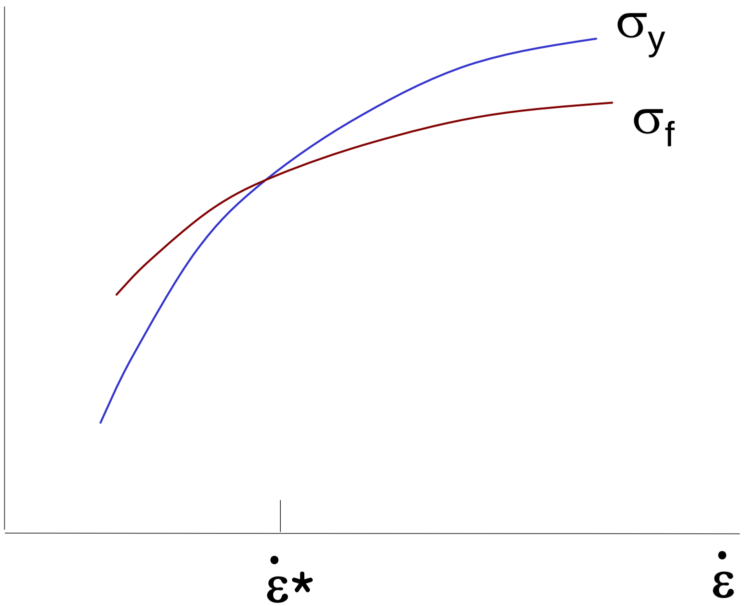


Ductile-brittle transition (2)

- temperature
  - T ↑ → K_{Ic} ↓
  - T ↑ → σ_y ↓ (faster)
- strain rate
  - $(d\varepsilon/dt)$ ↑ → K_{Ic} ↑
  - $(d\varepsilon/dt)$ ↑ → σ_y ↑(faster)



D/B transition Temp



Toughening (1)

- dream: modulus of steel with resilience of rubber
- goal: enhancing the ability to resist crack propagation
- ideas
  - enlarging the volume in which energy dissipation (absorption) occurs
  - limiting the growth of crack
- approaches
  - plasticization by liquid (plasticizer)
    - lowering YS → ductile
    - lowering modulus and T_g also
  - multiple deformation by 2nd phase

📖Table 11.3 p575

    - increasing # of site of crazing or yielding
    - increasing volume of energy absorption
- methods

📖 ¶11.2.4.2 p573

  - rubber toughening
    - large energy absorption, modulus drop
    - HIPS, ABS, toughened epoxy, etc
  - thermoplastic toughening
    - small energy absorption, no modulus drop
    - PC/ABS, PC/PBT, Nylon/PPO, etc

Toughening (2)

- toughening mechanisms

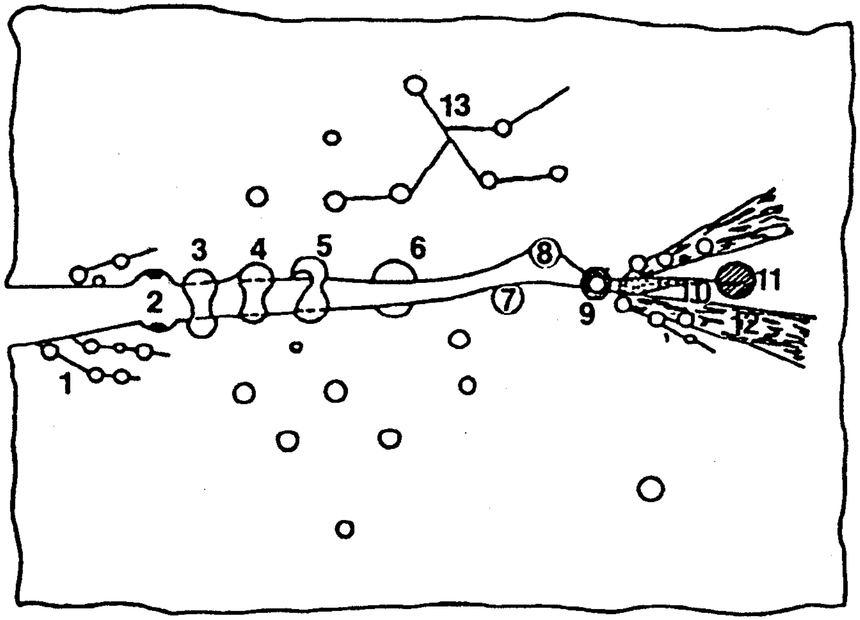


FIGURE 1. Toughening mechanisms in rubber-modified epoxies:
(1) shear-band formation near rubber particles;
(2) fracture of rubber particles after cavitation;
(3) stretching, (4) debonding and (5) tearing of rubber particles;
(6) transparticle fracture; (7) debonding of hard particles;
(8) crack deflection by hard particles;
(9) voided/cavitated rubber particles;
(10) crazing; (11) plastic zone at craze tip;
(12) diffuse shear-yielding; (13) shear band/craze interaction.

Toughening (3)

- rubber particle deformation
  - bridging
  - effect on toughness not large

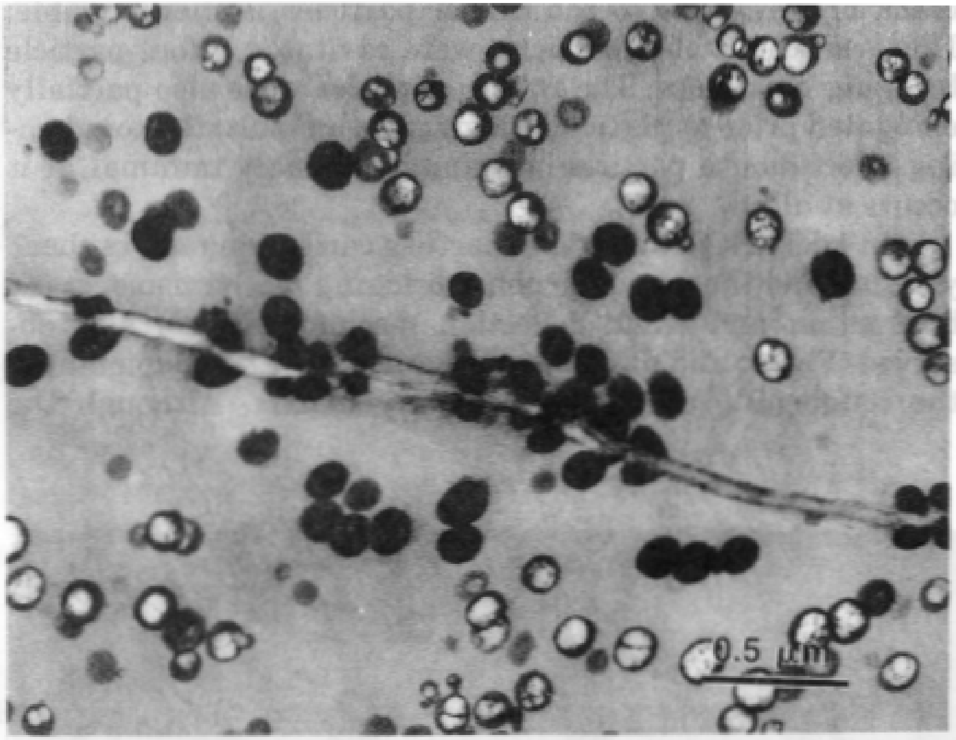


Figure 6 A TEM micrograph taken at the damaged crack wake of the CSR-B–modified epoxy system. The crack propagates through the rubber particles, instead of propagating around the rubber particles. The rubber particles appear to have deflected the crack path. The crack propagates from left to right.

Toughening (4)

- ▷ multiple crazing
  - particles initiate and stop crazes
  - stress-whitening observed
    - HIPS

📖Fig 11.2 p561

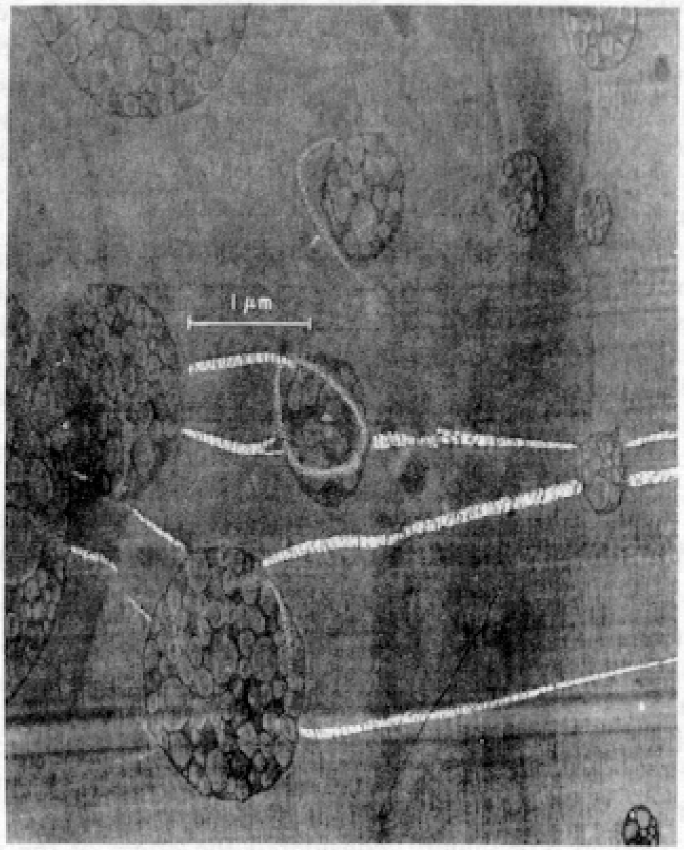


Fig. 11.1. Transmission electron micrograph of a microtomed section of HIPS, stained with osmium tetroxide (after Kambour & Russell[33]).

Toughening (5)

- cavitation and shear yielding
  - particles debond or cavitate
  - removing triaxiality
    - removing hydrostatic component
  - inducing yielding of matrix
  - necking observed
    - toughened PVC

- crazing and shear yielding
  - whitening and necking
    - ABS

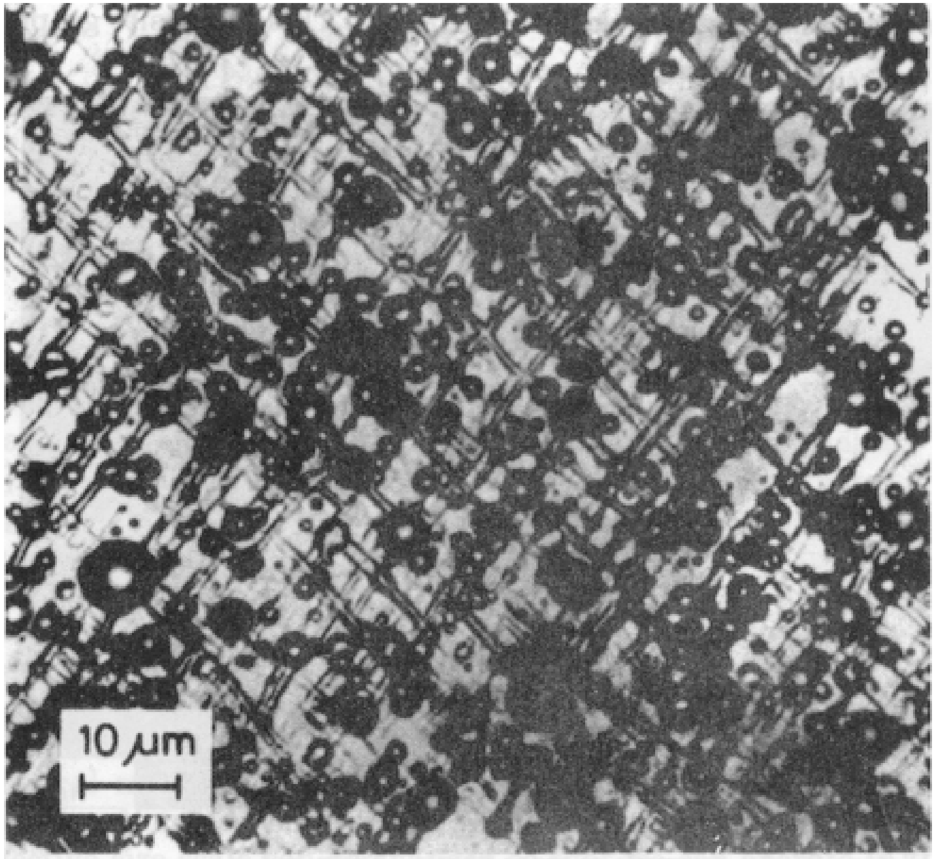
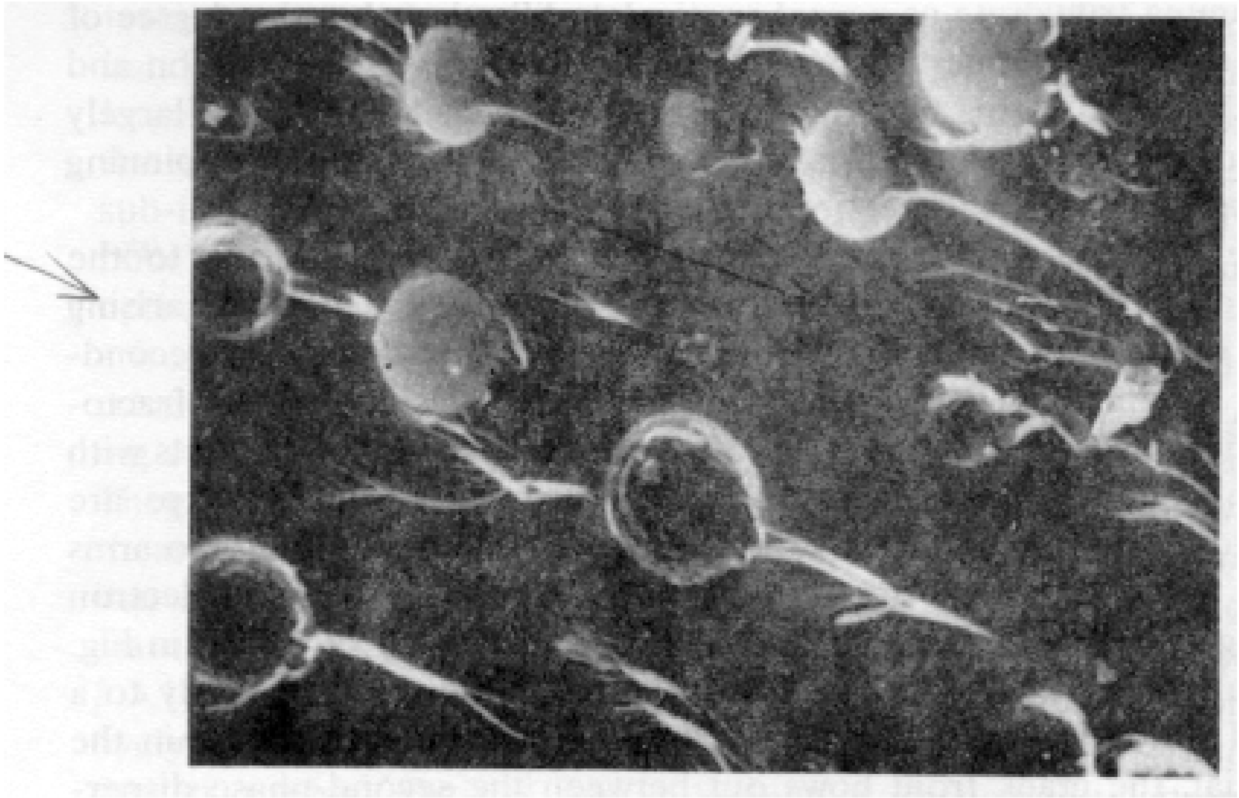


Figure 1 An example of shear banding. (From Ref. 7.)

Toughening (6)

- crack pinning
  - increasing surface area
  - tortuous path



Toughening (7)

- factors governing toughness of toughened plastics
  - matrix
    - degree of crosslinking
    - entanglement density
    - T_g
    - yield strength
  - particle
    - content (volume fraction)
    - size
    - size distribution
    - T_g
    - adhesion to matrix