Polymer Materials Science

BMEGEPT9107, 2+0+0, 3 Credits

6. Strength and Fracture Behavior of Polymers

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Books, textbooks, lecture notes, guides

- L.M. Vas: Lecture notes, ppt slides, [http://pt.bme.hu/~vas](http://pt.bme.hu/~vas)
Strength and failure 1

- Defects and strength of materials

**Strength**: Resistance of materials against irreversible deformation and crack propagation

**Cause of fracture** in general:
Propagation of existing cracks as an effect of loads (mechanical, thermal, chemical)

![Real distribution of defects](image)

- Defects and strength of materials – Size effects

1. **Paradox of solid body**: The tensile strength ($\sigma_B$) of materials is greater in fiber form than in the usual bulk form but less than the theoretical maximum:
   \[ \sigma_{B,\text{bulk}} < \sigma_{B,\text{fiber}} < \sigma_{B,\text{theoretical}} \]

2. **Paradox of fiber form**: While the tensile breaking force ($F_B$) of fibers increases the tensile strength ($\sigma_B$) decreases with the fiber diameter ($d$)

3. **Paradox of fiber length**: The mean tensile breaking force ($F_B$) of fibers decreases with gauge length ($l_o$) of fibers
Strength and failure 1

- Defects and strength of materials – Size effects

Ad. (3) Paradox of fiber form – Measurement on glass fibers

Quelle: Flachsfasern; Dr. S. Odenwald, TU Clausthal

Strength and failure 1

- Defects and strength of materials – Size effects

Ad. (3) Paradox of fiber length – Measurement on flax fibers

Quelle: Flachsfasern; Dr. S. Odenwald, TU Clausthal

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Strength and failure 1

- Defects and strength of materials – Size effects

(4) Paradox of fiber bundle:
Since the breakages of fibers (number of fibers: n) in a fiber bundle subjected to tensile load do not take place simultaneously but sequentially therefore the bundle breaking force related to one fiber ($F_{n,\text{max}} / n$) is less than the mean fiber breaking force obtained by single fiber tests ($F_S$). Accordingly the fiber strength utilization factor of the fiber bundle ($\eta_n$) can be defined:

\[
0 < \eta_n = \frac{F_{n,\text{max}}}{nF_S} < 1
\]

Strength and failure 2

- Failure, fracture

Ductile fracture of PE

Extended breaking pits/holes at S-B balls of ABS copolymer
Strength and failure 2

- **Tensile and shear zones** (inhomogeneous zones) as irreversible deformation processes in (particularly amorphous) polymers

![Scheme](image1)

Normal stress induced → NFZ

![Scheme](image2)

Shear stress induced → SFZ

- **Tensile flow zones (crazes)** (NFZ): density and orientation inhomogeneities – kind of structurized microcracks
  - Occur mainly in amorphous thermoplastics (ATP: PS, SAN, PMMA, PC);
  - May occur in the amorphous parts of semicrystalline thermoplastics (RTP: PE, PP, PA, PET) as well,
  - More rarely they can also be found in strongly crosslinked polymer resins (STH: UP, EP, VE).

- **Shear flow zones** (SSZ): orientation inhomogeneities that occur more rarely; conditions of their rise:
  - Activizable relaxation mechanism (secondary dispersion range),
  - Suitable temperature and low loading rate to the activation.
Strength and failure 2

- Tensile and shear zones (inhomogeneous zones)

Tensile and shear zones (NFZ) in PS


Strength and failure 2

- Tensile zones (crazes, NSZs) in ATP polymers

Effect of time and load level on the deformation of polymer (creep curves) and the formation of tensile (flow) zones ($\varepsilon_F$ is the limit flow deformation belonging to the first NFZ, $\varepsilon_B$ is the creep failure strain)

Strain dependency of the rise of flow zones

Strength and failure 2

- Tensile zones (crazes) in STP polymers

At tensile testing of PP the range of micro-crack formation (NFZ, crazy) (see whitening) accompanying the inhomogeneous spherulite-deformations reaches from the necking far into the parts without necking.

Strength and failure 2

- Failure and damage modes in composites

- Matrix cracks
- Fiber-matrix debonding
- Fiber slippage
- Fiber breakage

**Strength and failure 2**

- Failure modes in composites and their conditions

  ![Diagram of composite failure modes](image)

- Matrix cracks
- Fiber-matrix debonding
- Fiber slippage
- Fiber breakage


**Fracture mechanics of polymers**

- Modes of crack propagation and fracture

  ![Diagram of crack propagation](image)

- Start of cracking
- Structural element (sample) containing a crack
- Start of crack propagation (rate of decrease)
- Crack propagation
  - Instable
  - Stable
  - Slow crack growth
- Crack stopping
- Rigid fracture
- Ductile fracture
- Fatigue or creep fracture, Stress corrosion

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Fracture mechanics of polymers

METHODS OF FRACTURE MECHANICS

- Methods of linear elastic fracture mechanics (LEFM)
  - Stress-intensity theory ($K_{I_{crit}}$)
  - Linear elastic behavior
  - Small plastic range behavior
  - Energy hypothesis ($G_{I_{crit}}$)

- Methods of nonlinear elastic fracture mechanics (NLEFM)
  - Crack opening displacement (COD) theory ($\delta_{I_{crit}}$)
  - J-integral ($J_{I_{crit}}$) (and J-point integral)
  - Essential work of fracture (FWF)

Neuber-type elliptical notch/void and the crack

In the case of a crack tip infinitesimally small radius:

$$\sigma_0 \rightarrow \sigma_{max} \rightarrow 0, \ k \rho \rightarrow 0$$

Value of notch induced stress peak by Neuber:

$$\sigma_{max} = \alpha_k \sigma_N, \quad \alpha_k = 1 + 2\sqrt{\frac{\alpha}{\rho}}$$
Fracture mechanics of polymers

- Loading and crack propagation modes by Irwin

![Mode I](Opening)

![Mode II](Parallel slippage)

![Mode III](Transverse slippage)


Fracture mechanics of polymers

- Griffith-type crack model and the stress intensity theory by Erwin – LE material

Based on Westergaard’s results Irwin introduced the stress intensity factors (K):

\[ \sigma_y = \frac{1}{\sqrt{2\pi r}} \left[ K_I f_I^i \theta + K_{II} f_{II}^i \theta + K_{III} f_{III}^i \theta \right] \]

For the \( f_i(\theta) \) Williams-Irwin equations:

\[ f_i(\theta) = \begin{cases} 1 & \text{if } i = j \\ 0 & \text{if } i \neq j \end{cases} \]

\[ B = \text{breadth} \]

\[ K_c = \text{critical stress int. factor} \]

Condition of instable crack propagation in plane deformation state:

\[ K_I = \frac{1}{B} \sigma_0 \sqrt{\pi a}, \quad r = x < a \]

\[ K_I \geq K_c = 1.0 \sigma_c \sqrt{\pi a}; \quad \sigma_c = \sigma_B \]
Fracture mechanics of polymers

- Irwin-type crack model of small plastic range – ~LE material

\[ K_I = \left( \frac{a + p_l}{B} \right) \sigma_c \sqrt{a + p_l}, \quad r = x \]

\[ p_l = \frac{K_I}{\sigma_c}, \quad B = \text{breadth} \]

Shape of the plastic range

Condition of instable crack propagation in plane deformation state:

\[ K_I \geq K_{IC} = Y \sigma_c \sqrt{a + p_l} \quad \sigma_c = \sigma_B \]

Fracture mechanics of polymers

- Energy hypothesis by Griffith – LE material

\[ \frac{\partial W}{\partial c} - \frac{\partial U}{\partial c} \geq \gamma_s \frac{da}{dc} = 2 \gamma_s t \]

\[ da = 2 \delta r, \quad \epsilon = \alpha, \quad c, \quad \text{surface crack} \]

\[ \gamma_s = \text{surface stress} \]

Energy release rate (G):

\[ G_I = 2 \gamma_s, \quad G_{IC} = \frac{K_I^2}{Y^2 E_s} \]

\[ E^* = \frac{E}{1 - \nu^2}, \quad \text{plane deformation state} \]

Condition of instable crack propagation in plane deformation state:

\[ G_I \geq G_{IC}, \quad \sigma_c = \sigma_B \]
Fracture mechanics of polymers

- Dugdale-type crack model and the crack opening displacement (COD) method by Wells – NLE or plastic materials

\[
\text{Conditions:}
\begin{align*}
\bullet & \text{Elastic deformation outside of } 2a; \\
\bullet & \sigma_F \text{ stress in the plastic range and at the crack tips}
\end{align*}
\]

Condition of crack opening and fracture:

\[
\delta \approx \frac{\pi \sigma_F^2}{E \epsilon_F} \geq \delta_c
\]

In case of LE.

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Fracture mechanics of polymers

- J-integral method by Cherepanov and Rice – NLE or plastic materials

\[
J = \int_{\Gamma} W_{e} dy - \sigma \frac{\partial u}{\partial x} ds
\]

\[
W_{e} = \sum_{l,j} \sigma_{ij} \delta \epsilon_{ij}
\]

\[
\sigma \text{ and } u \text{ are the stress and displacement vectors}
\]

In case of LE behavior:

\[
J_{l} = \frac{k_{l}^{2}}{y^{2}E}
\]

Condition of stable crack propagation in plane deformation state:

\[
J_{I} \geq J_{IC} = m \sigma_{F} \delta_{c}
\]

For viscoelastic creep J-point integral

\[
J = \int_{\Gamma} W_{e} dy - \sigma \frac{\partial u}{\partial x} ds
\]

\[
W_{e} = \int \sigma_{ij} d\epsilon_{ij}
\]

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Fracture mechanics of polymers

- Essential Work of Fracture (EWF): $W_e$

**Conditions:**
- Tensile test of DEN sample at low rate
- Plastic deformation in the range before the crack tip (ligament)

$$W = U_e + U_p = \theta w_e + \theta^2 w_p$$

$$W / tl = w_e + \beta w_p$$

Elliptical zone: $\beta = \frac{2b}{4l}$

$w_e$ and $w_p$ = elastic and plastic specific work

![Graph showing work of deformation](image)

PP blend modified with elastomers

Before fracture the micro-cracks, micro-slippages, micro-breakages cause pulse-like vibration packages propagating with sound speed.

Testing of fracture behavior of polymers

- Measuring methods of crack propagation
  - Optical video-camera measurement and image analysis
  - Measurement of acoustic emission
  - Measurement of compliance on tensile tester
  - Measurement of electric potential difference
  - Measurement of ultrasound propagation speed

- Measurement of acoustic emission
Testing of fracture behavior of polymers

Measurement of acoustic emission — failure dependent amplitude and cumulative event number ($\Sigma AE$)

- Continuous
- Burst-like

- Threshold
- Ring-down count
- Event at elapsed time
- Rise time
- Peak amplitude
- Duration or width of AE event

Testing of fracture behavior of polymers

Crack size based designing and checking

Leak before-break condition in the limit case of the leak:

$$a = t$$

E.g. The size of a crack on the internal surface of a container of wall thickness $t$ is known.

The container may be used at load $\sigma_0$ further on if the next inequality stands:

$$nK_I = n\sigma_0 \sqrt{\pi t} < K_{Ic}$$

where $n>1$ is the safety factor.