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Deformation & failure behaviour of semi-crystalline polymers: role of crystallinity and strain hardening

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Introduction
Deformation and failure behaviour of polymers is important for engineering applications. For semi-crystalline polymers, temperature and flow history of processing can influence the type of deformation/failure behaviour. A qualitative distinction in deformation types:

\[ \sigma \rightarrow I: \text{Homogeneous deformation} \]
\[ \sigma \rightarrow II: \text{Stable neck drawing} \]
\[ \sigma \rightarrow III: \text{Brittle failure} \]

Figure 1: 3 types of deformation/failure of polyethylene.

Objective: Rationalize the observed influence of processing conditions on the deformation/failure behaviour.

Analytical approach
Simple neo-Hookean approach for true stress [1]:

\[
\sigma_{t} = \sigma_{y} + G R \left[ \lambda^2 - \frac{1}{\lambda} \right]
\]

gives an engineering stress:

\[
\sigma_{\text{eng}} = \frac{\sigma_{y}}{\lambda} + G R \left[ \lambda^2 - \frac{1}{\lambda} \right]
\]

Considerè’s analysis
Considerè’s condition for necking is met when at yield \( \frac{d\sigma_{\text{true}}}{d\varepsilon_{\text{true}}} < 0 \). Figure 3 visualizes a transition from homogeneous deformation to necking for \( \sigma_{y}/GR > 3 \).

Figure 3: Engineering stress: necking is induced by an increase in \( \sigma_{y} \) (left) or a decrease in \( GR \) (right).

Neck stability
Minimum value of \( \lambda_{n} \) in the neck to meet 2\textsuperscript{nd} considerè’s condition for stable necking [2]:

\[
\sigma_{y} = \frac{\lambda_{n}^2 + 2}{\lambda_{n}}
\]

Stress equilibrium (defining: \( \sigma_{\text{break}} = \kappa_{2} \sigma_{y} \)) gives a draw ratio at break, \( \lambda_{0} \):

\[
\sigma_{y} = \frac{\lambda_{0}^2 - \frac{1}{\kappa_{2}}}{\kappa_{2}}
\]

/department of mechanical engineering

Experimental results

Influence of thermal history:
- Quenched (Q)
- Slowly cooled (SC)
- Annealing of quenched samples (A)

Figures 5: Compressive true stress-strain behaviour.

Influence on intrinsic behaviour:
- Annealing: crystallinity & lamellae thickness \( \uparrow = \text{yield stress} \uparrow \)
- Cooling rate \( \downarrow = \text{disentanglement of (short) chains upon crystallization} \rightarrow \text{strain hardening} \downarrow \)

Figures 6: Macroscopic tensile behaviour (PET, PE1, PE2)

Influence on macroscopic deformation/failure:
Transition region II \( \rightarrow III \):
- PET: due to increase in yield stress
- PE1: due to decrease in strain hardening
- PE2: no transition due to less disentanglement and higher strenght of molecular weight

Figures 7: Deformation PE2.

Conclusions
- Strain hardening depends on chain entanglement density and orientation
- Yield stress depends on crystallinity/lamellae thickness
- Both can influence the deformation/failure behaviour

References: