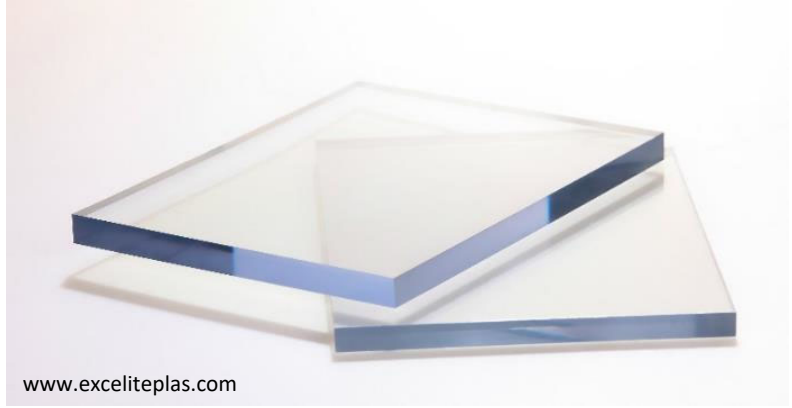
Fatigue and lifetime prediction strategies for polymers

Tom Engels (DSM Research, TU/e), Leon Govaert (TU/e)

amorphous vs. semi-crystalline polymers

polymer glasses



e.g. polycarbonate

semi-crystalline polymers

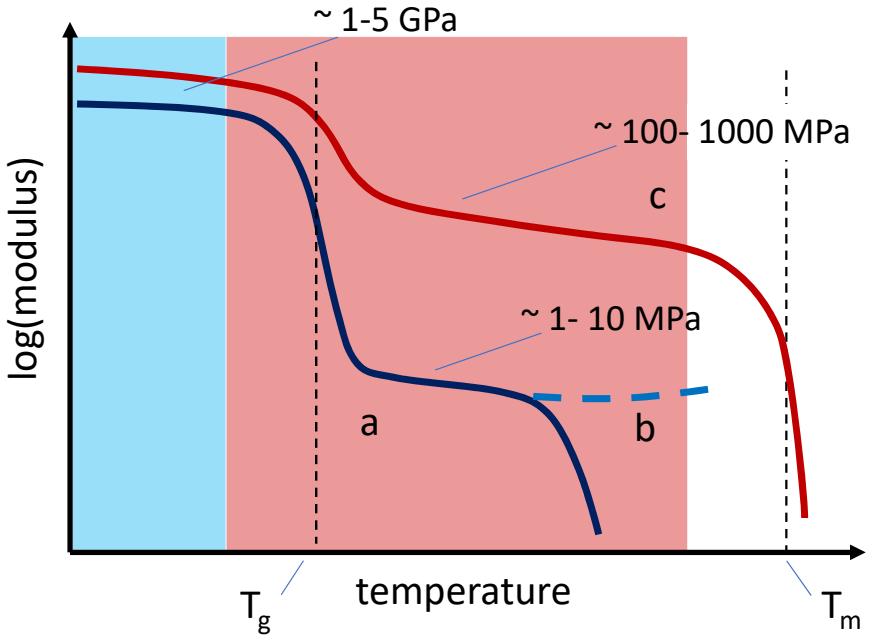
e.g. polyamide-6

application ranges

a. amorphous polymer
(e.g. PS, PC, PMMA)

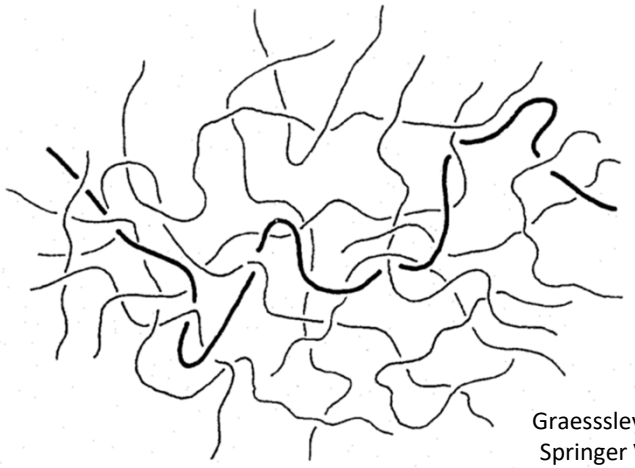
b. crosslinked amorphous polymer
(thermosets)

c. semi-crystalline polymer
(e.g. PE, PP, PA, PET)



- amorphous polymers are used (well) below their T_g
- semi-crystalline polymers are used (well) below their T_m
  typically crystallinities are optimized to achieve maximum modulus

polymer glasses

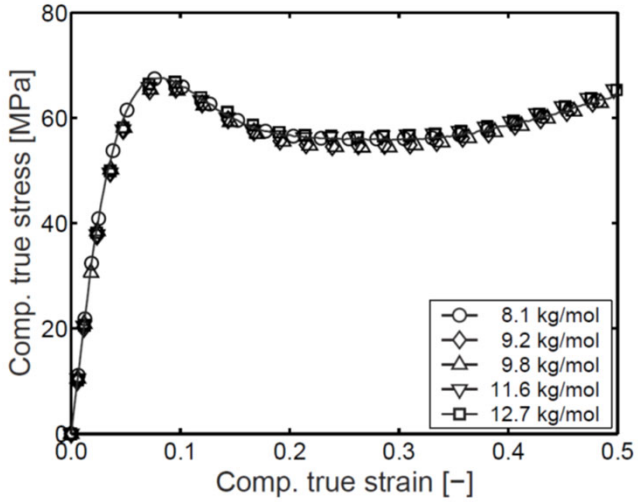


Graesssley, 1982
Springer Verlag

no long range order present in the material;
entanglements (M_e) and chain-ends (M_n) dominate the performance

polymer glasses

intrinsic behavior

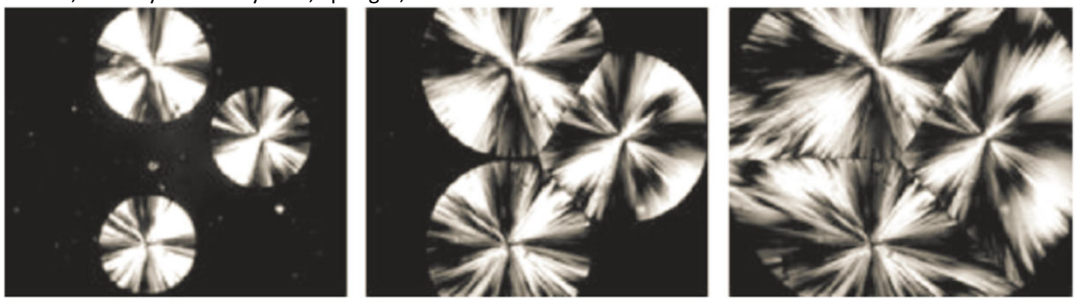


- intrinsic deformation behavior independent of molecular weight; strain hardening ~ M_e
- yield stress level depends on cooling rate, but is independent of molecular weight

Klompen, Mechanical properties of solid polymers, PhD thesis, Eindhoven University of Technology, 2005

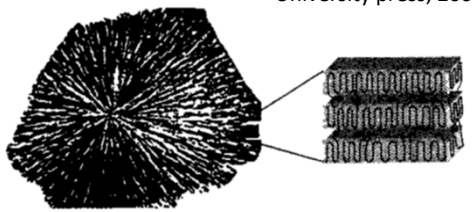
semi-crystalline polymers

Strobl, The Physics of Polymers, Springer, 2007

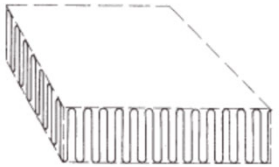


growing spherulites observed during the crystallization of PLLA in an optical microscope (polarized light)

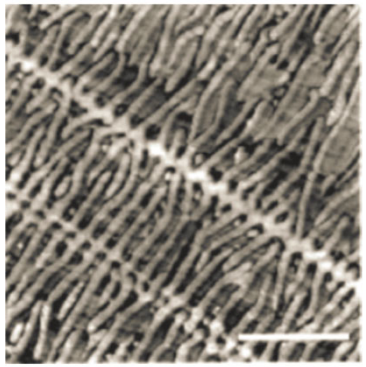
Rubinstein & Colby, Polymer Physics, Oxford University press, 2003



schematic representation of chain folding in polymer crystals



Keller, Rep. Progr. Phys., 31, 623 (1969)



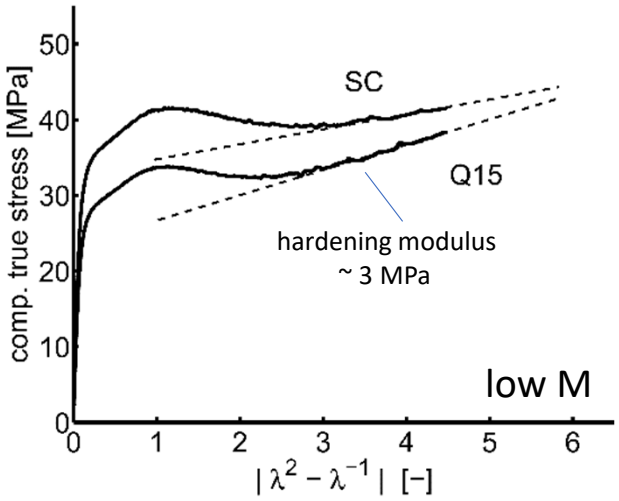
Strobl, The Physics of Polymers, Springer, 2007

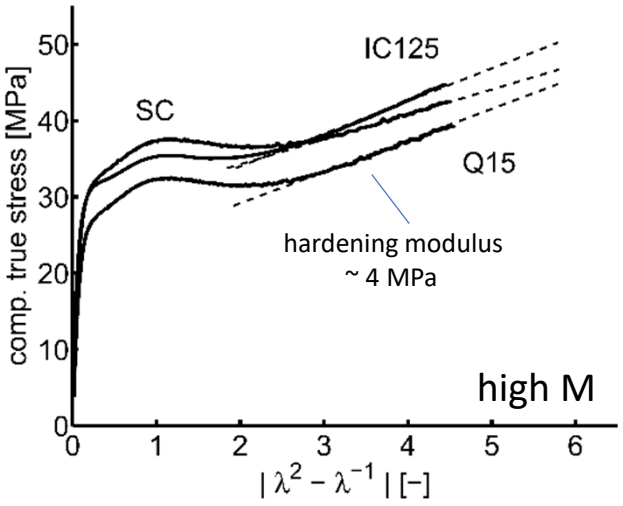
AFM image depicting a PE shish kebab structure (*scale bar*: 300 nm).

crystal morphologies are very rich and dominate the mechanical performance; M_w does influence performance via morphology

semi-crystalline polymers

intrinsic behavior



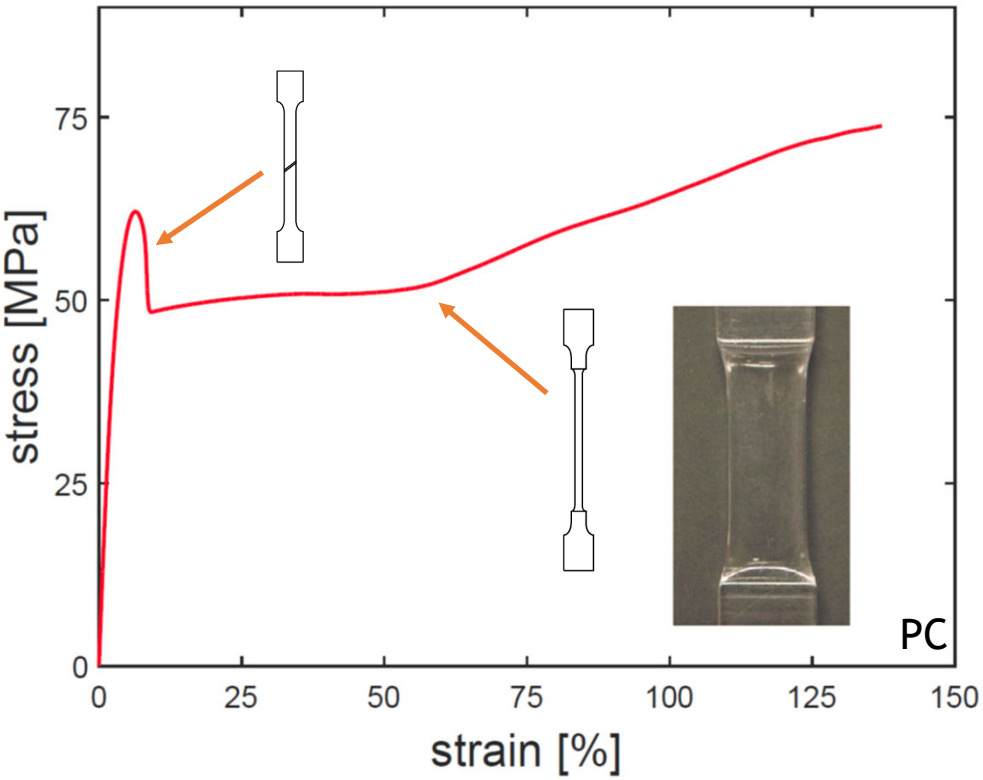


SC = slow cooled
Q15 = quenched at 15°C
IC125 = isothermally crystallized @125°C

- intrinsic deformation behavior depends strongly on molecular weight; strain hardening ~ M_e, ~M_w and crystallization conditions
- yield stress level depends on cooling rate via rate of crystallization (~M_w)

Schrauwen, Deformation and failure of semicrystalline polymer systems, PhD thesis, TU/e, 2003

tensile test / what do we measure ?

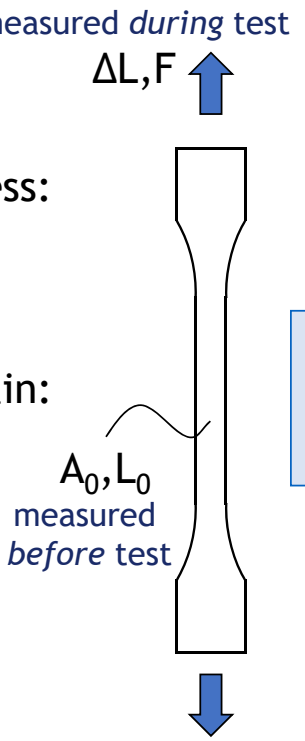


engineering stress:

$$\sigma = \frac{F}{A_0}$$

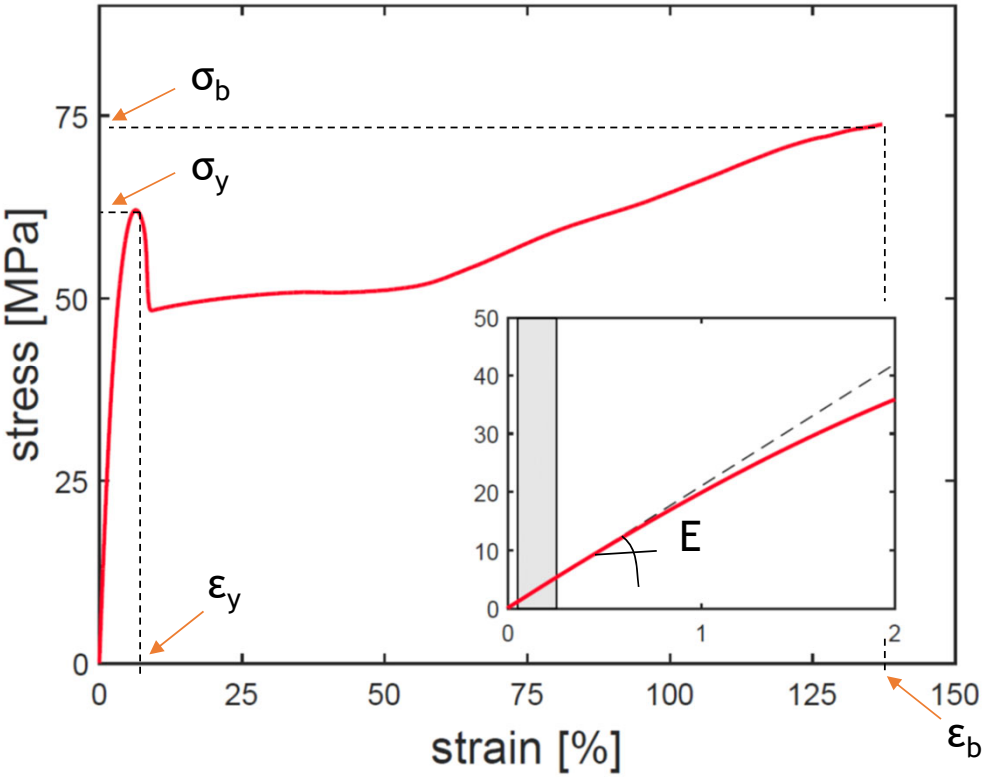
engineering strain:

$$\varepsilon = \frac{\Delta L}{L_0} \cdot 100\%$$



ΔL = elongation [mm]
F = force [N]
A_0 = cross-sectional area [mm^2]
L_0 = initial specimen length [mm]

tensile test / what do we measure ?

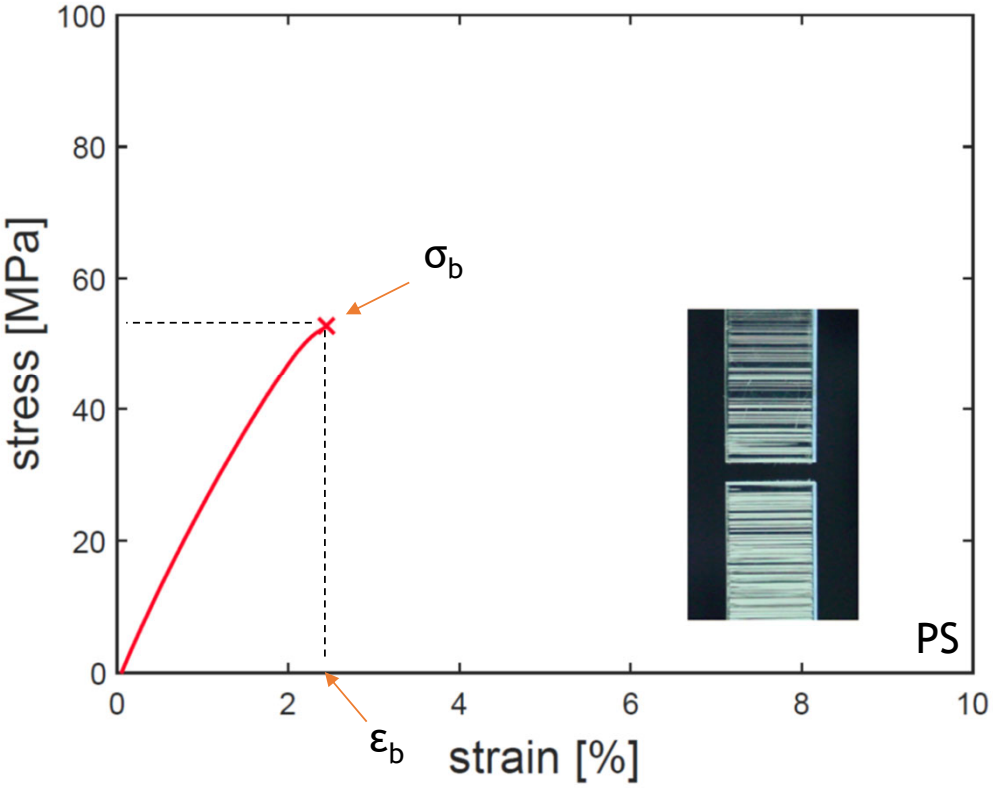


Which material parameters are determined?

- Young's modulus, E
  (secant modulus, typically 0.05%<ε<0.25%)
- yield stress, σ_y
  yield strain, ε_y
- strength at break, σ_b
  strain at break, ε_b
  (elongation at break, eab)

Example of ductile behavior

tensile test / what do we measure ?

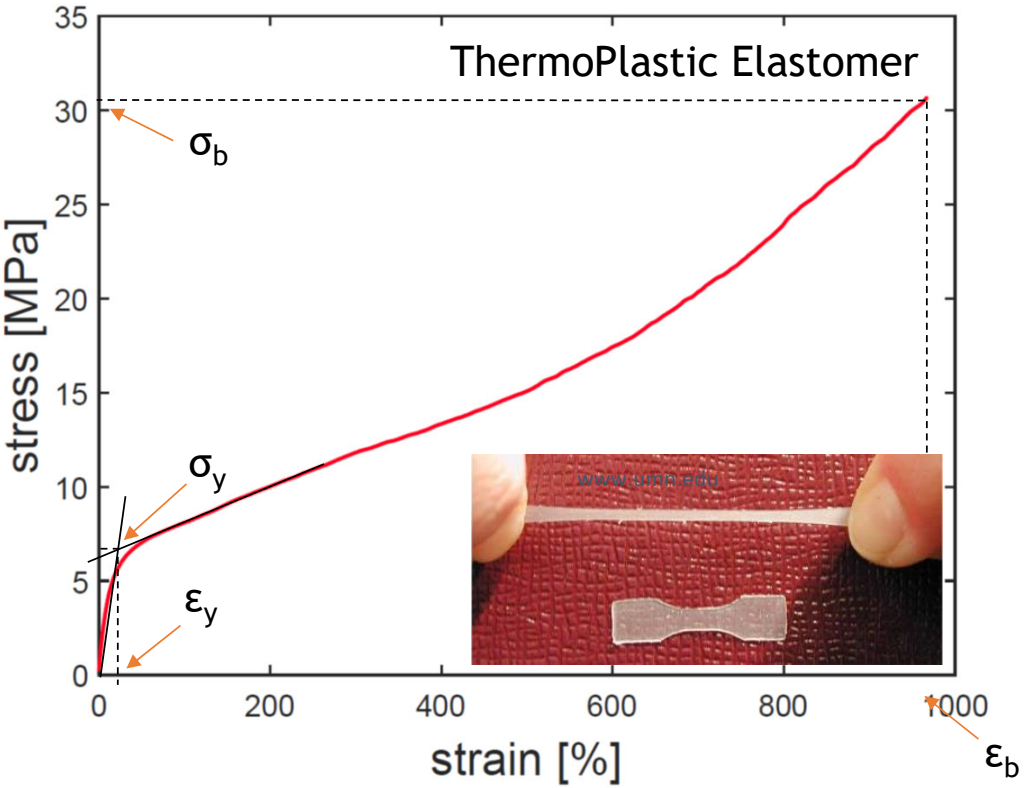


Which material parameters are determined?

- Young's modulus, E
  (secant modulus, typically 0.05%<ε<0.25%)
- yield stress, σ_y
  yield strain, ε_y
- strength at break, σ_b
  strain at break, ε_b
  (elongation at break, eab)

Example of brittle behavior

tensile test / what do we measure ?



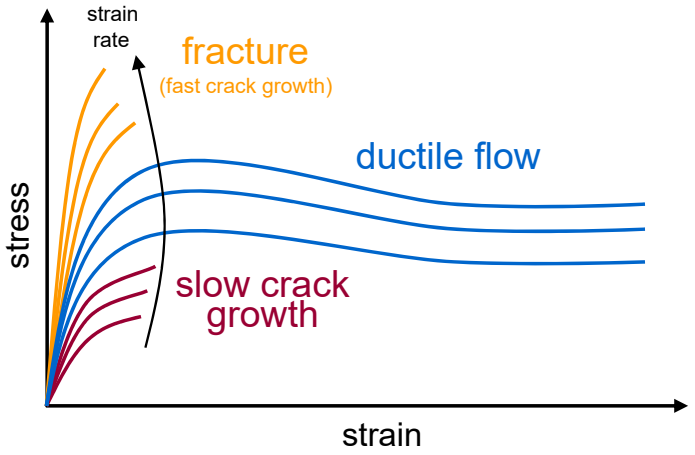
Which material parameters are determined?

- Young's modulus, E
  (secant modulus, typically 0.05%<ε<0.25%)
- yield stress, σ_y
  yield strain, ε_y
- strength at break, σ_b
  strain at break, ε_b
  (elongation at break, eab)

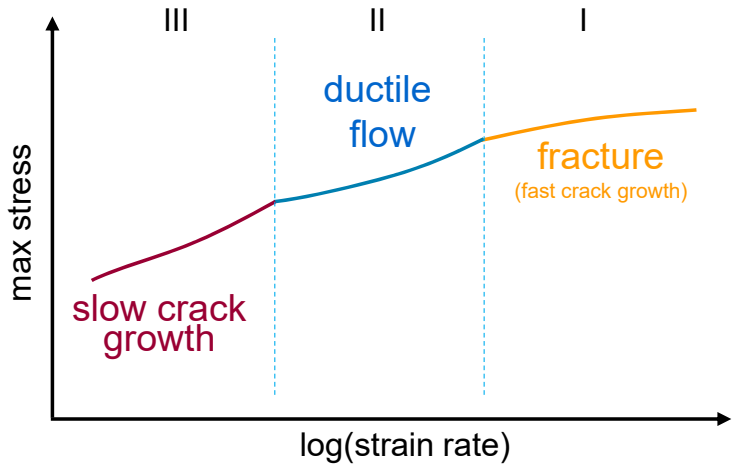
Elastomeric (like) materials typically do not show a distinct yield point / homogeneous deformation

properties depend on testing conditions

stress versus strain



max stress versus strain rate

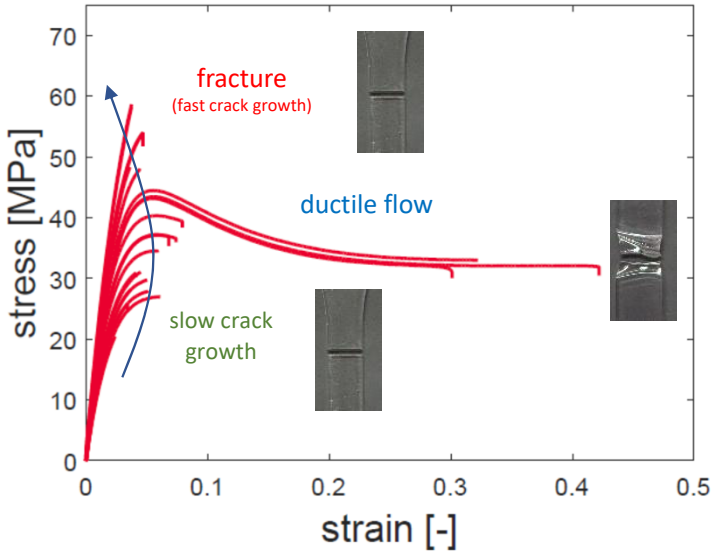


Failure of polymers over broad ranges of strain rate can be assigned to three failure modes:

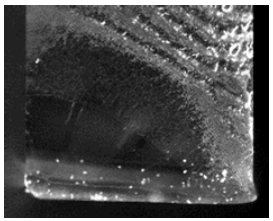
I. high strain rates / short times: fracture (fast crack growth)
II. intermediate strain rates: ductile flow
III. low strain rates / long times: slow crack growth

properties depend on testing conditions

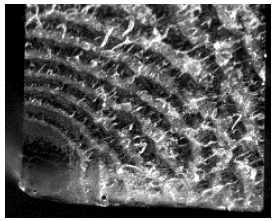
stress versus strain



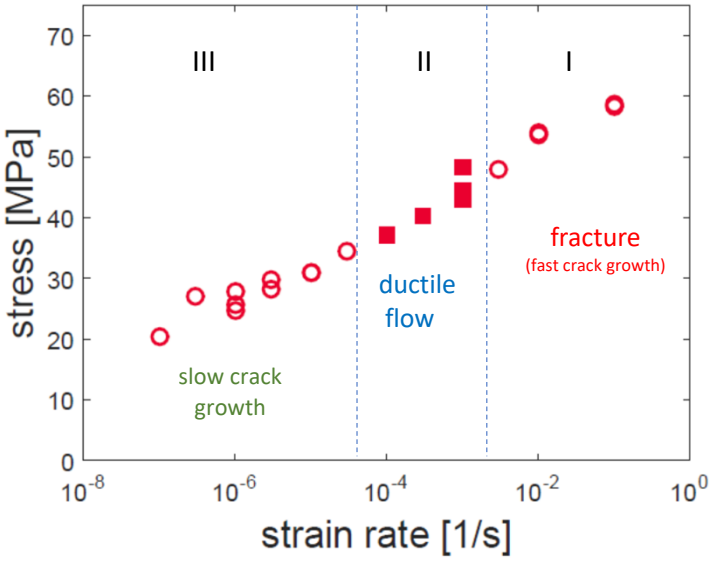
Slow Crack Growth



Fracture



max stress versus strain rate

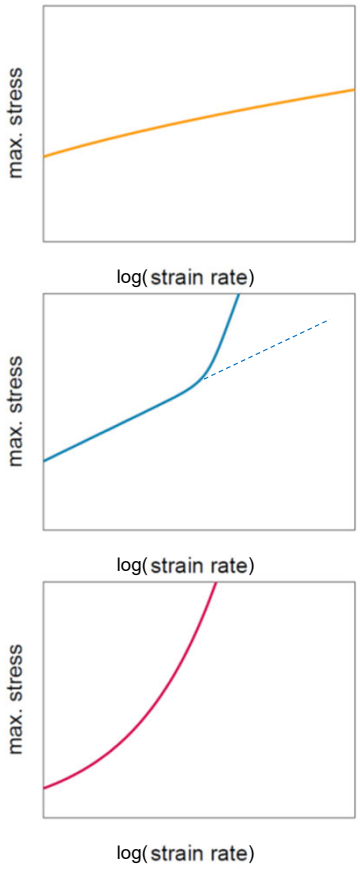


example on commercial PMMA material:

- injection molded tensile bars
- measured @60°C

properties depend on testing conditions

typical response for:



Fracture (Griffith's law)

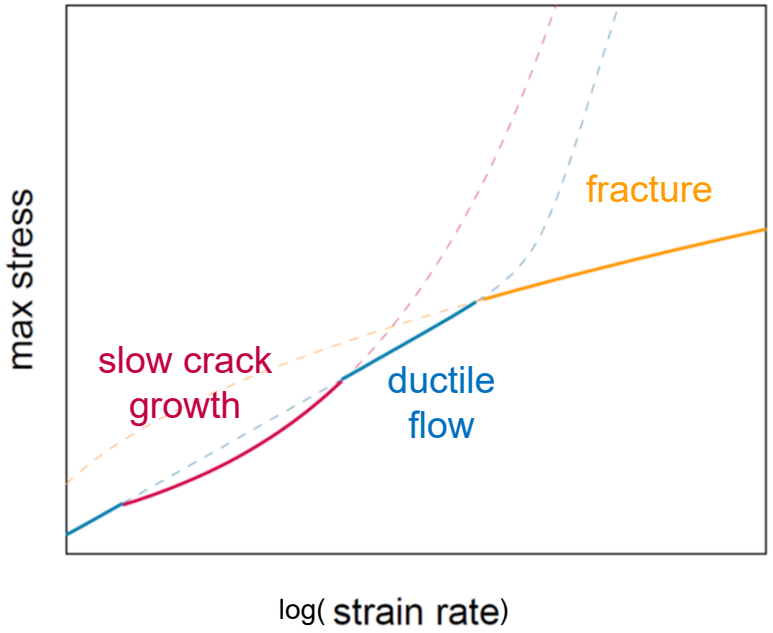
main parameters are energy release rate (=f(mol.weight)) and initial flaw size

ductile flow (Eyring's flow rule)

main influence is the thermal history (≠f(mol.weight))

slow crack growth (Paris' law)

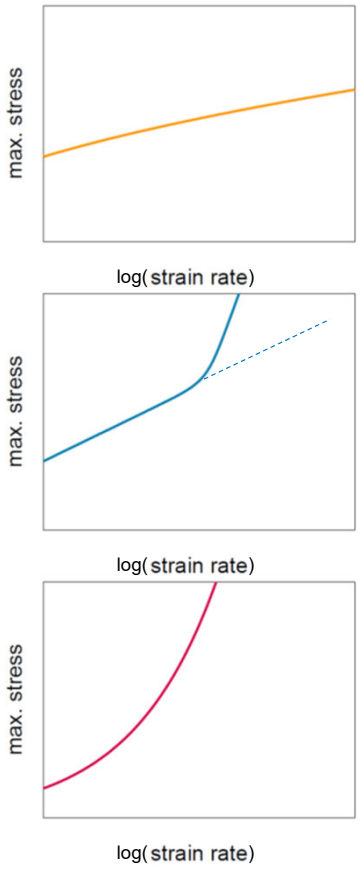
main parameters are the crack growth kinetics (=f(mol.weight)) and initial flaw size



failure mechanisms observed in experiment will depend strongly on temperature and rate

properties depend on testing conditions

typical response for:



Fracture (Griffith's law)

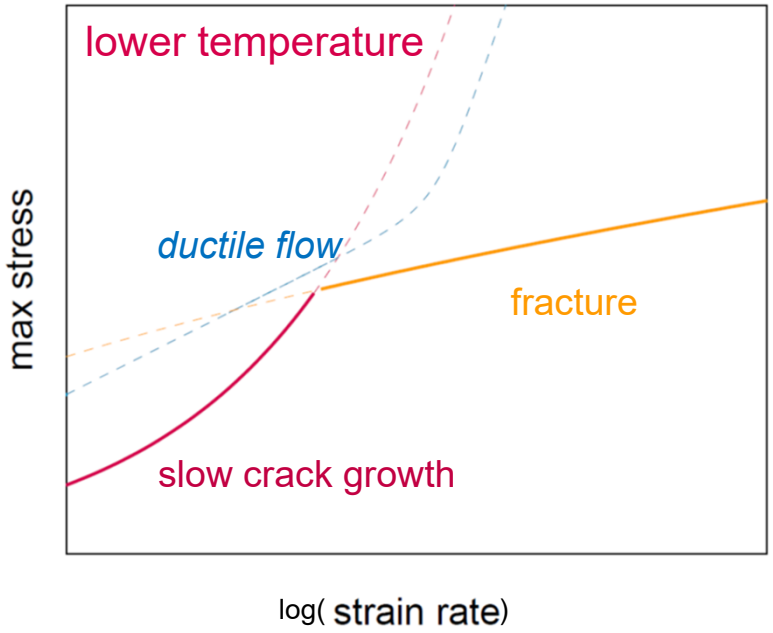
main parameters are energy release rate (=f(mol.weight)) and initial flaw size

ductile flow (Eyring's flow rule)

main influence is the thermal history (≠f(mol.weight))

slow crack growth (Paris' law)

main parameters are the crack growth kinetics (=f(mol.weight)) and initial flaw size

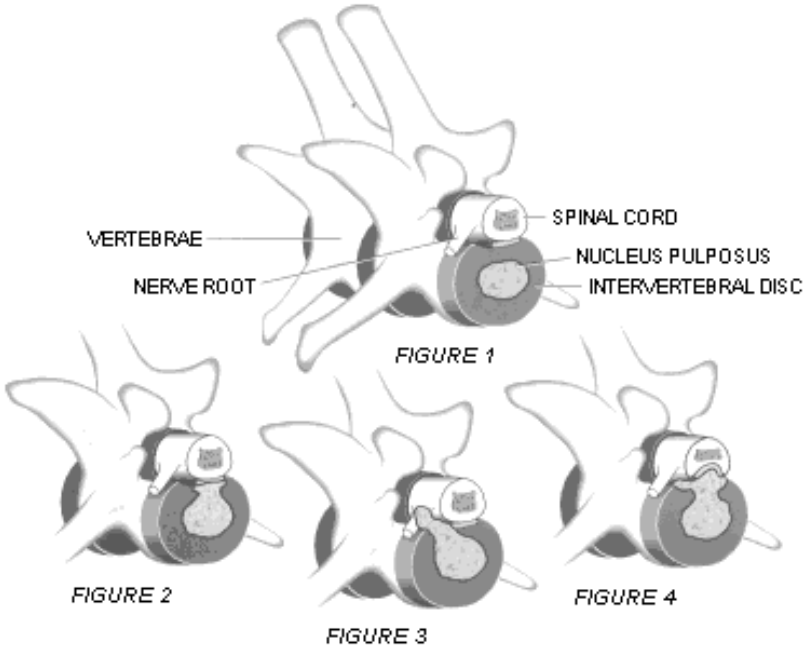


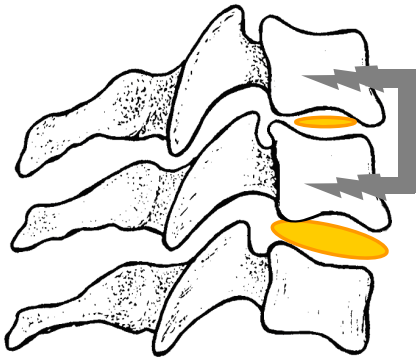
failure mechanisms observed in experiment will depend strongly on temperature and rate

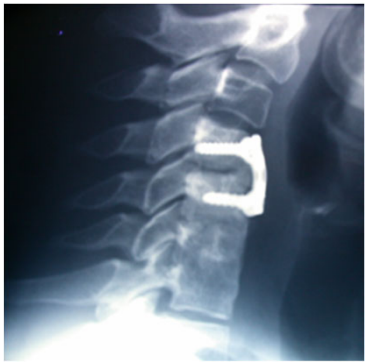
Fatigue and lifetime prediction strategies for polymers

an illustrative example

intervertebral disc degeneration





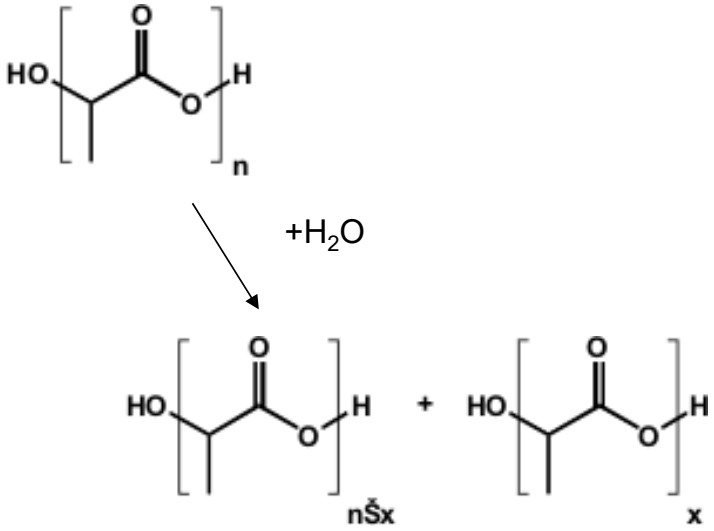


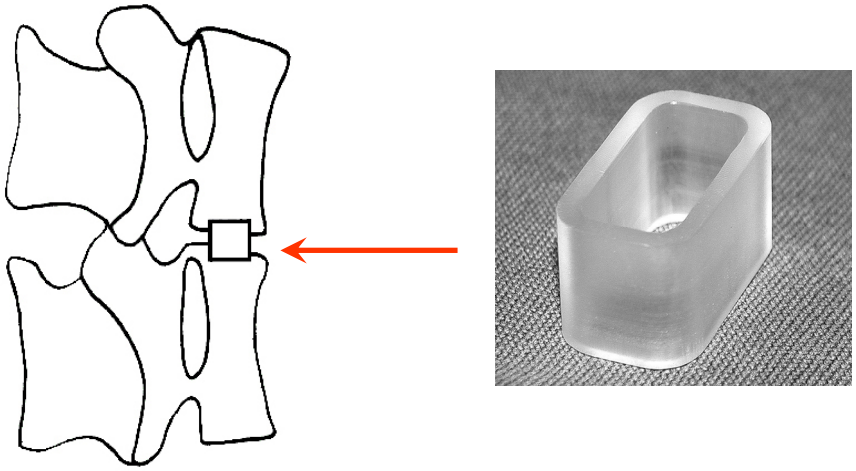
acute case: hernia

fixation of adjacent vertebral bodies

interbody fusion using bioresorbable spinal cages

material degrades over time



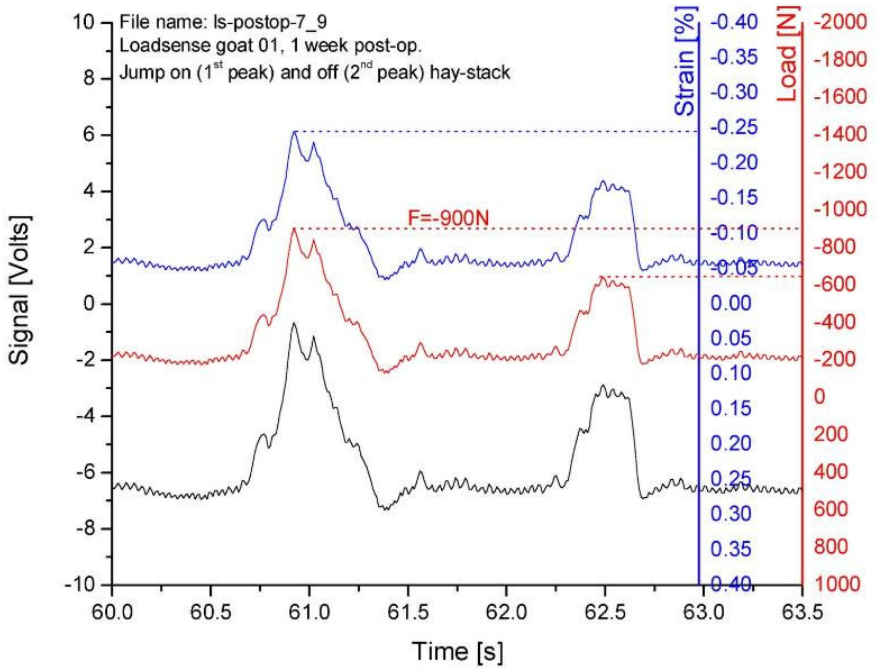


→ loss in molecular weight

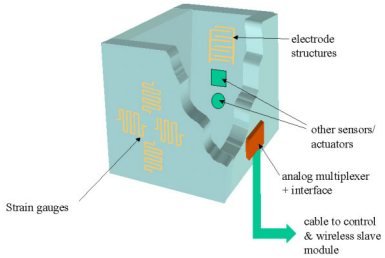
→ loss in strength !!

an illustrative example

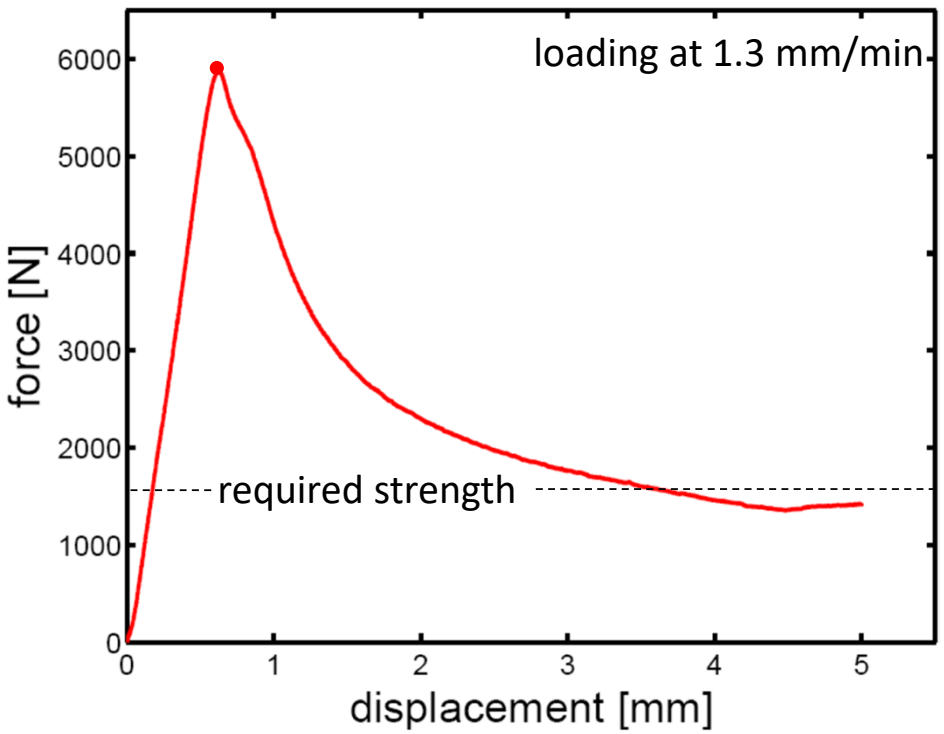
assessment of required strength

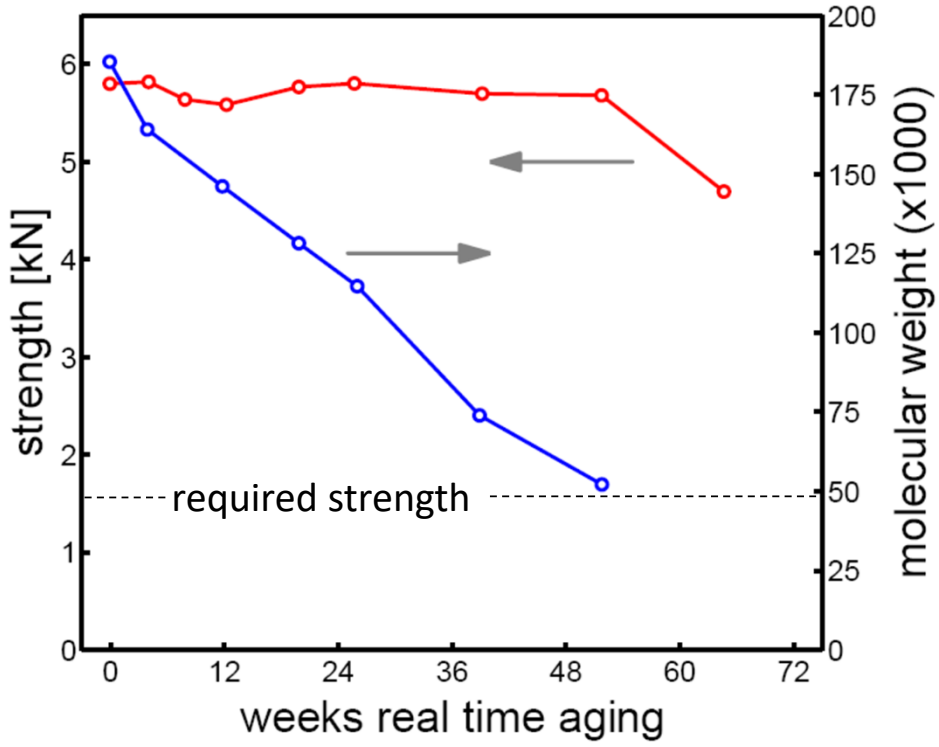


assessment of occurring loads using “instrumented” goat



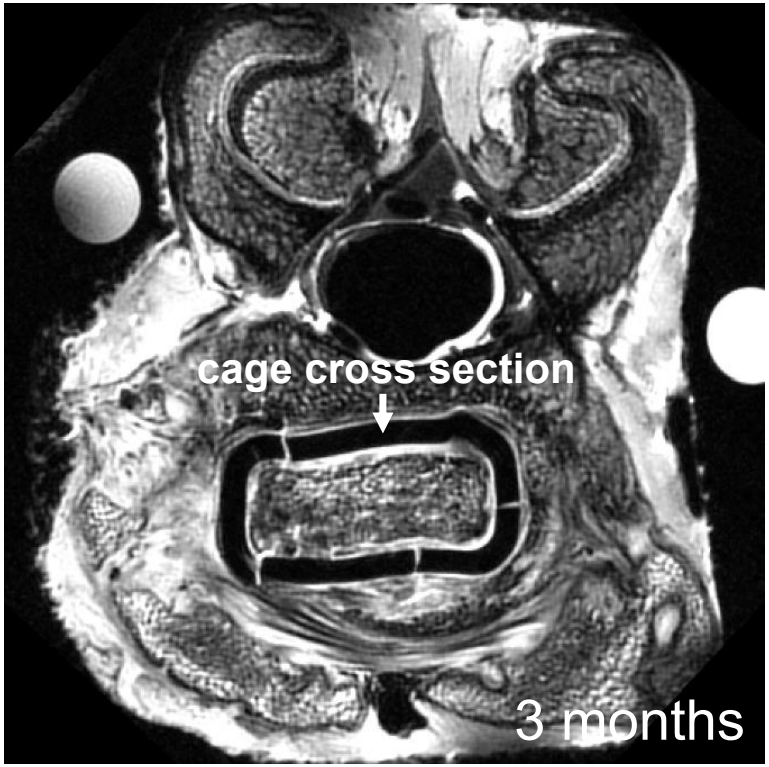
assessment of cage strength

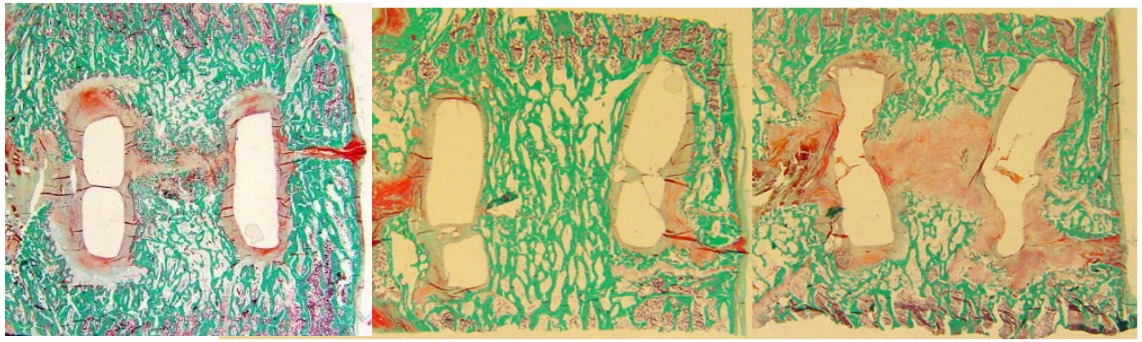




for fusion, cage integrity required for at least 6 months: here achieved with safety factor **6**

actual cage performance (in vivo)





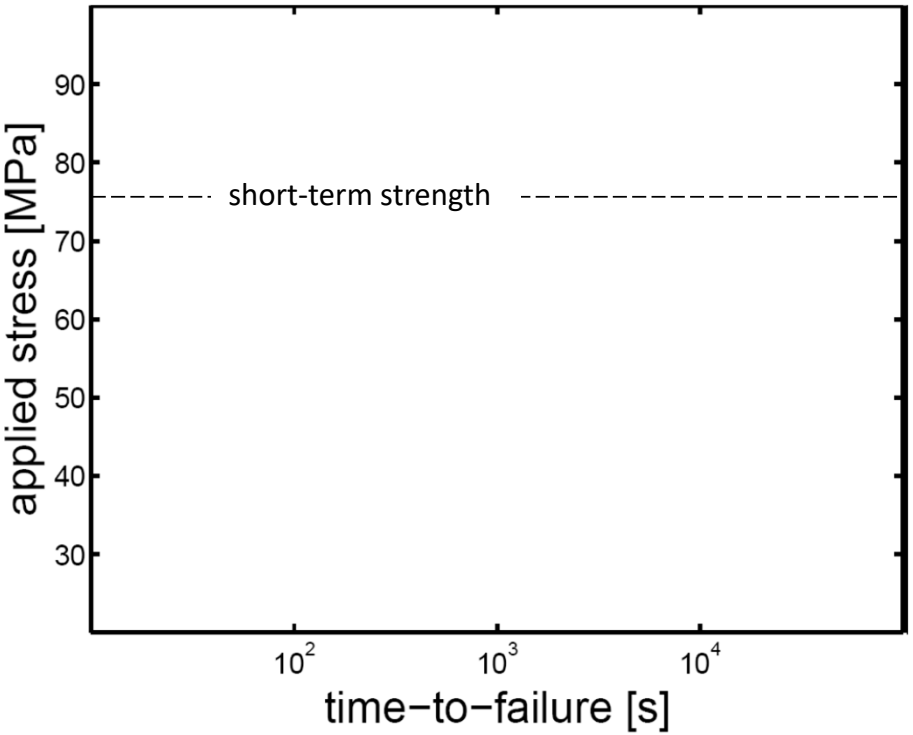
3 months (non-fusion) 6 months (fusion) 6 months (non-fusion)

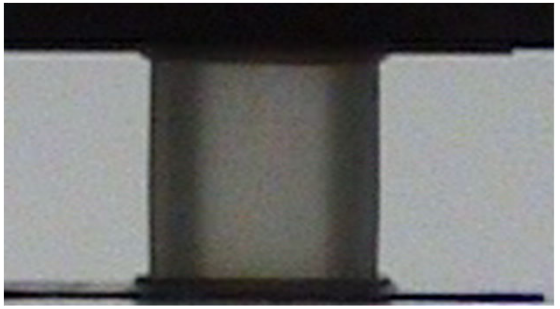
premature cage failure!!!

van Dijk M, Smit TH, Burger EH, Wuisman PI., Spine. 2002;27:2706–14.

failure under constant load: PLA

constant load test / static fatigue





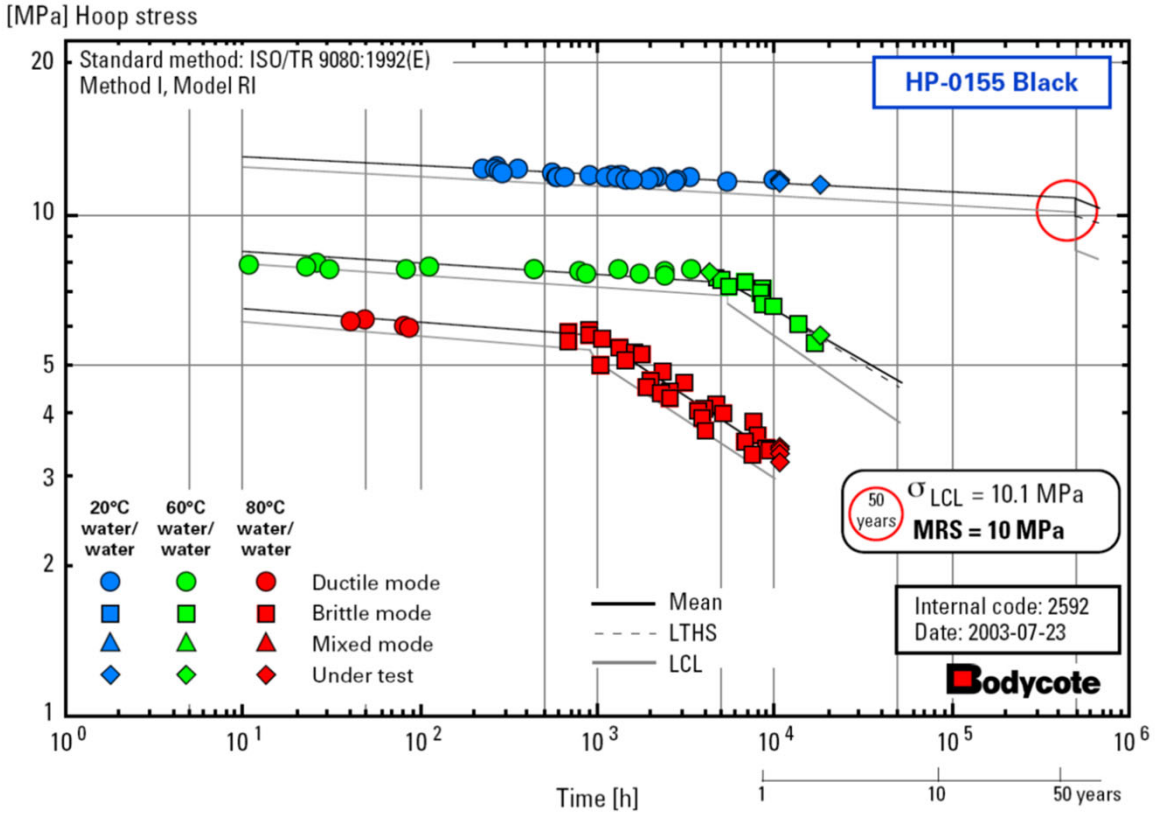
constant load 90% of
short term strength

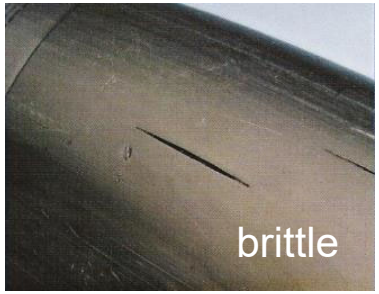
if the actual load is lower than the short-term strength,
this does not imply that the material can sustain this load indefinitely

Fatigue and lifetime prediction strategies for polymers

phenomenology & modelling

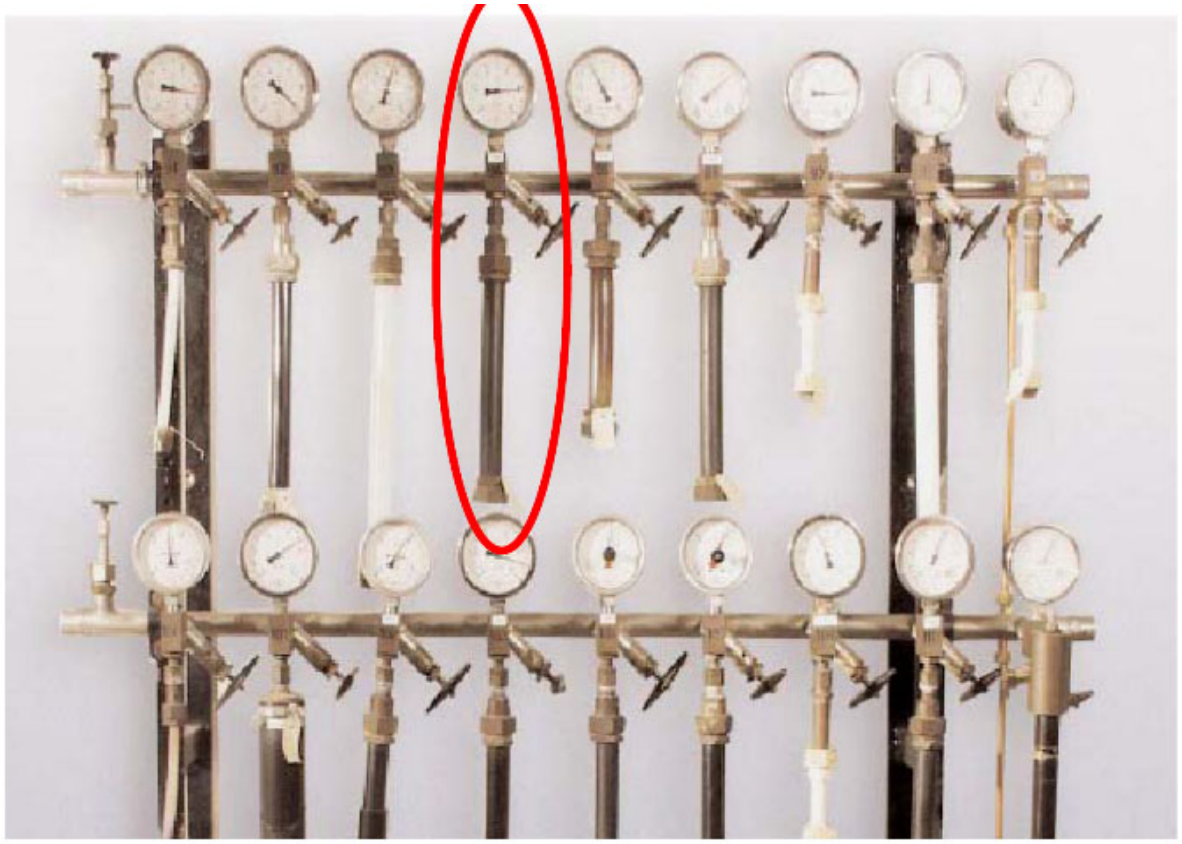
long-term hydrostatic testing





example: PE100 (HP-0155) (www.bodycotepolymer.com)
extrapolation using ISO 9080

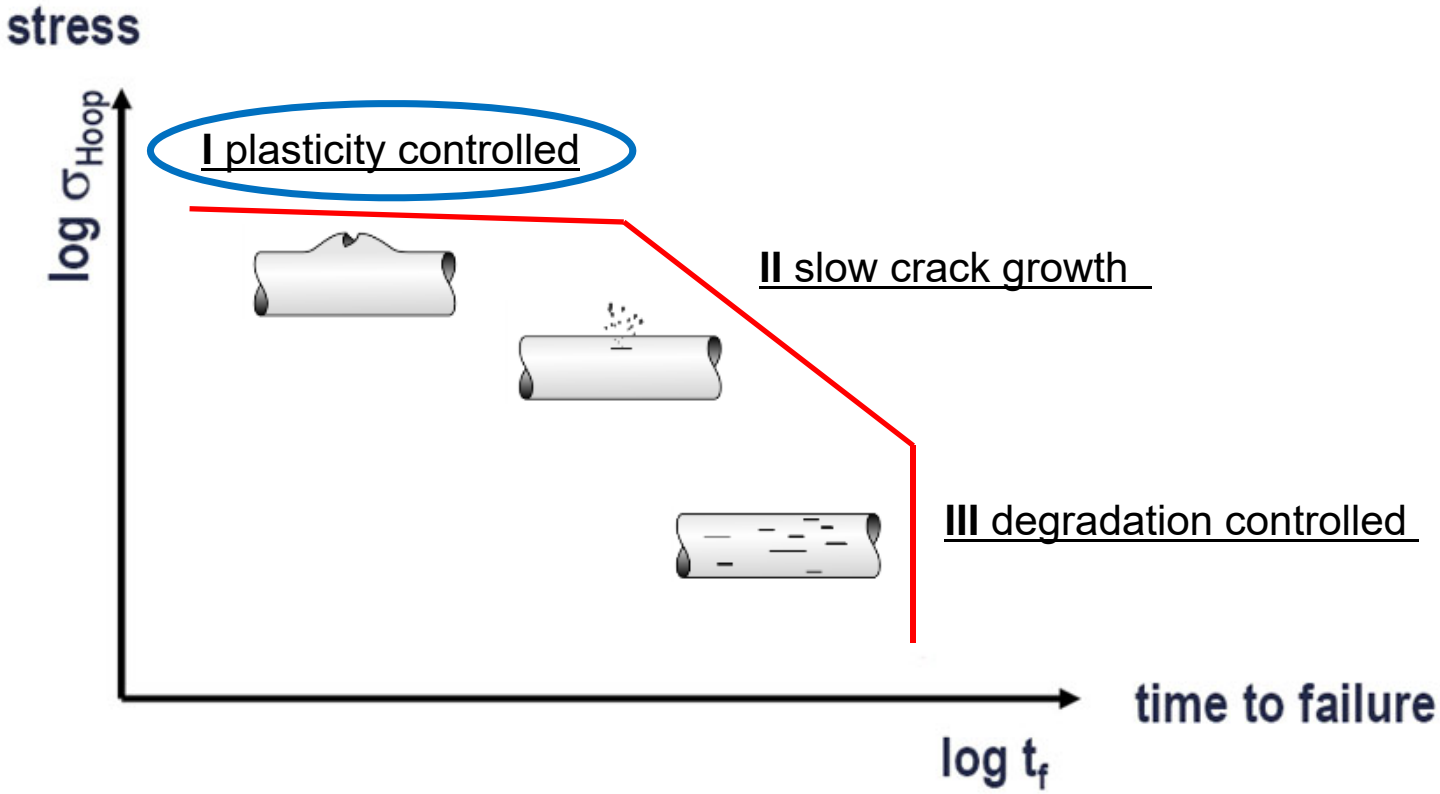
long-term testing: real-time loading?



Hostalen **GM 5010** under constant pressure since 1956

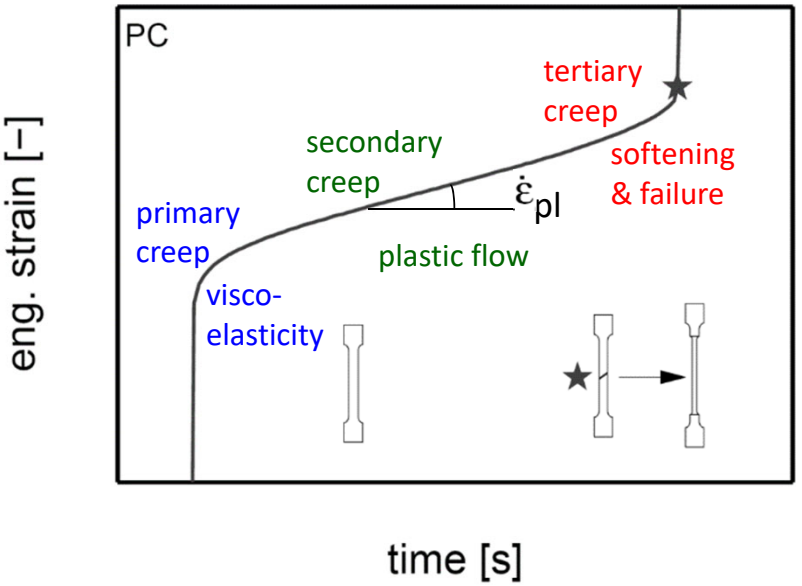
courtesy D. Lilge, Basell

long-term hydrostatic testing: failure modes

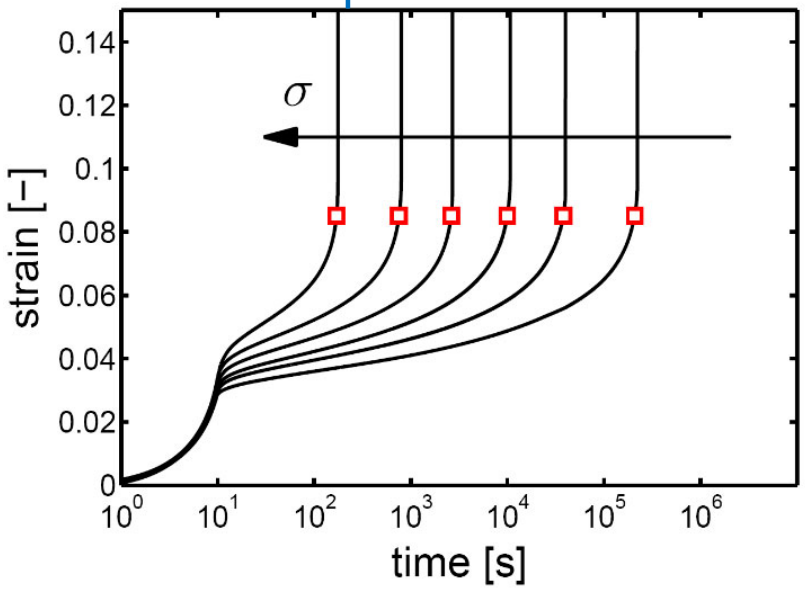


plasticity controlled failure: kinetics

constant stress



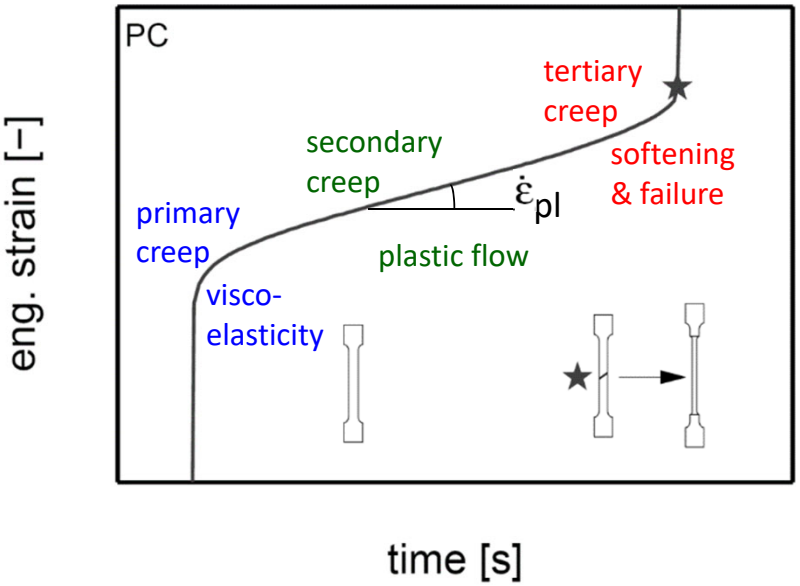
stress dependence



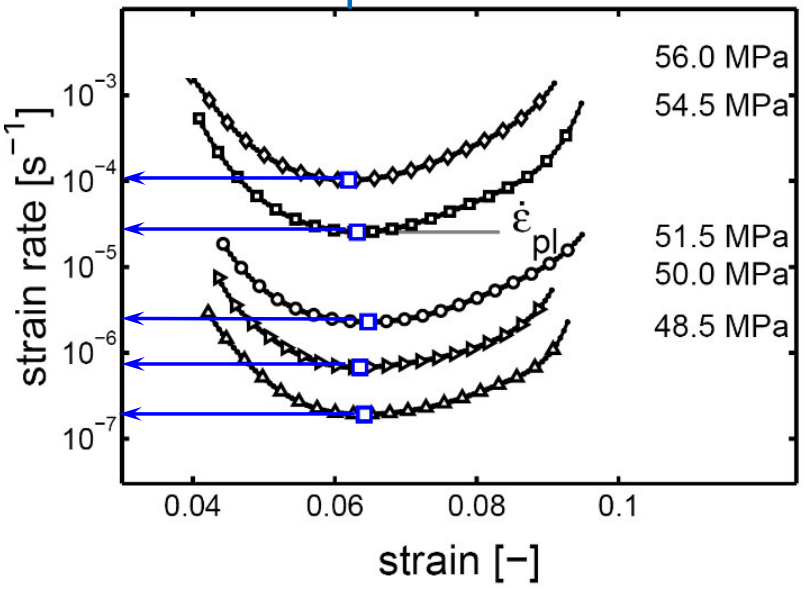
failure originates from accumulation of plastic strain

plasticity controlled failure: kinetics

constant stress



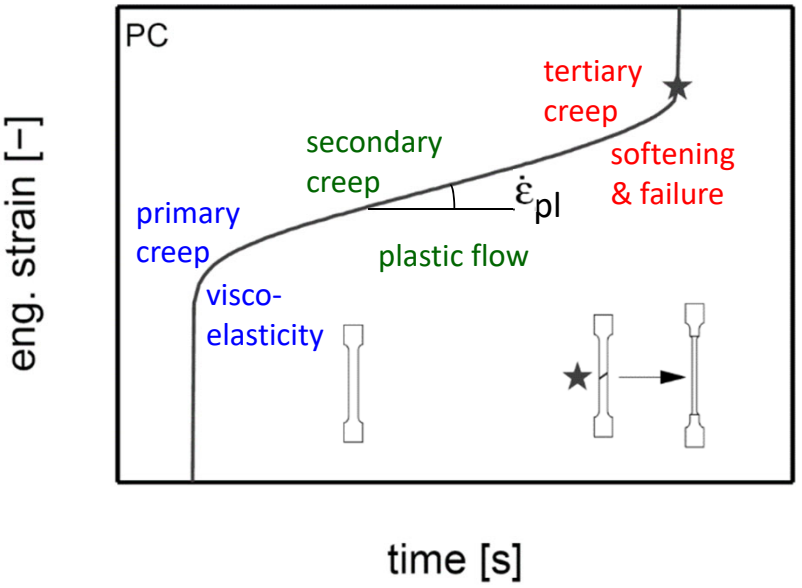
stress dependence



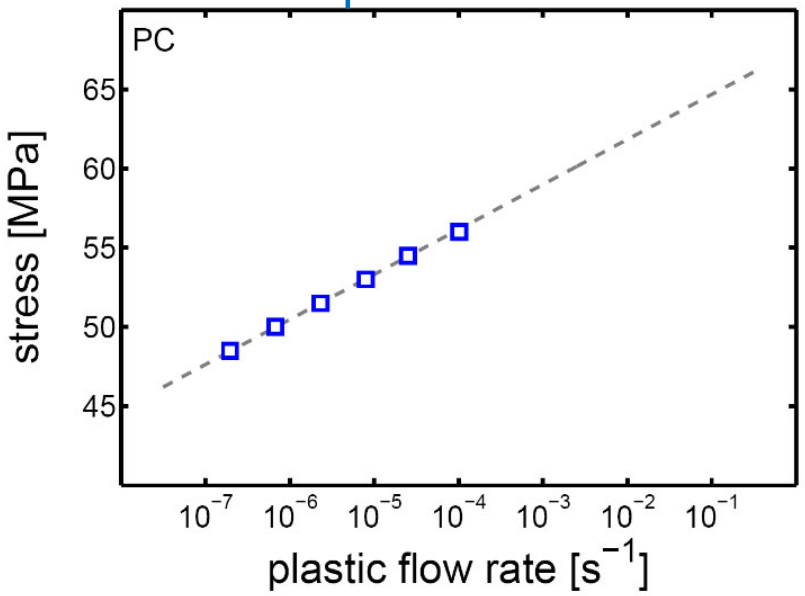
failure originates from accumulation of plastic strain

plasticity controlled failure: kinetics

constant stress



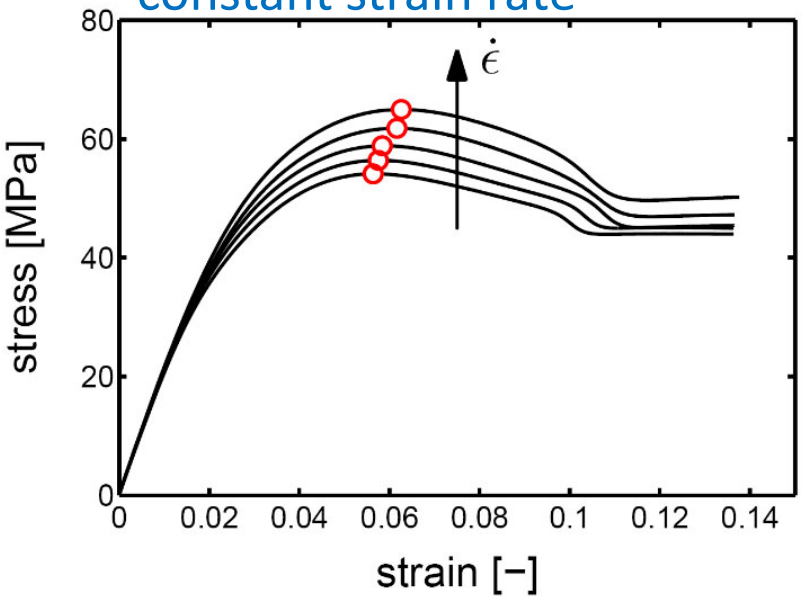
stress dependence



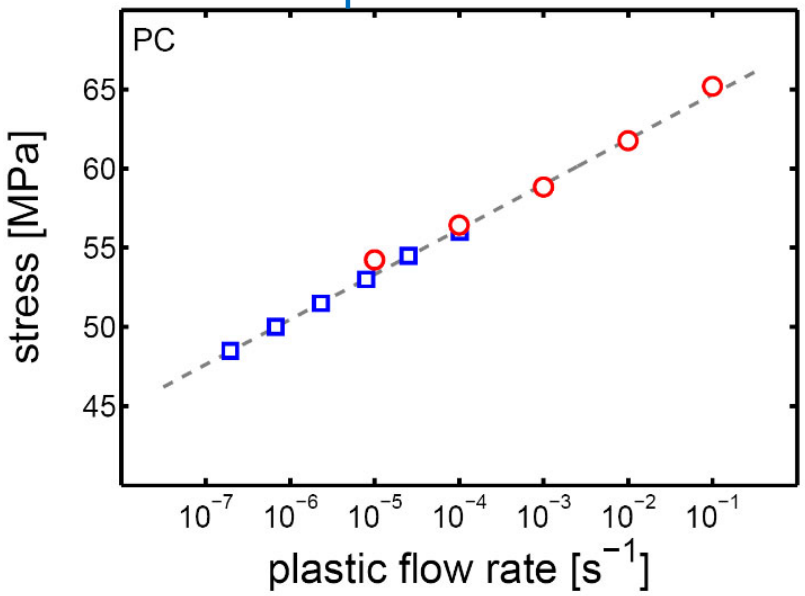
failure originates from accumulation of plastic strain

plasticity controlled failure: kinetics

constant strain rate



stress dependence



steady state reached in constant strain rate identical
to that reached in constant stress

Bauwens-Crowet et.al., 1974

plasticity controlled failure: kinetics

$$\dot{\varepsilon}_{pl}(T,\sigma) = \dot{\varepsilon}_0(S) \cdot \exp\left(-\frac{\Delta U}{RT}\right) \cdot \sinh\left(\frac{\sigma V^*}{kT}\right)$$

changes in state

- prior thermal history
- progressive aging

deformation kinetics

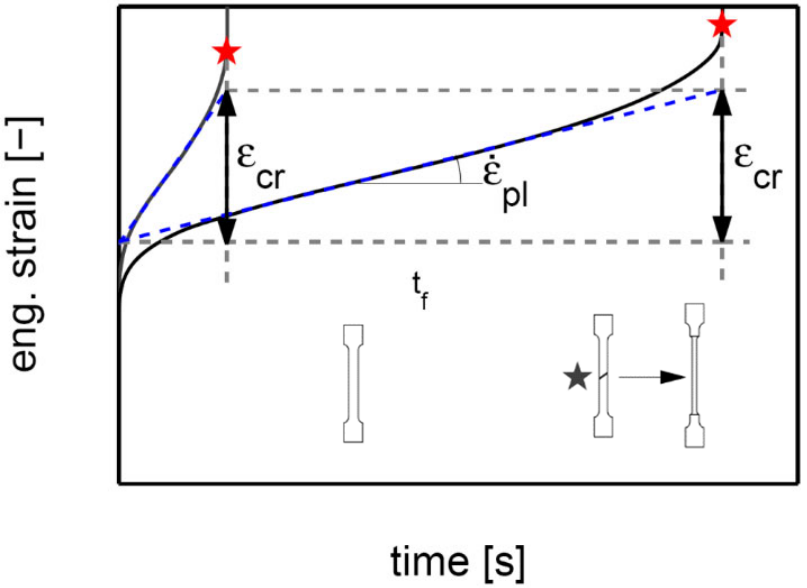
- stress-dependence
- temperature dependence

$\Delta U, V^*$ independent of thermodynamic state

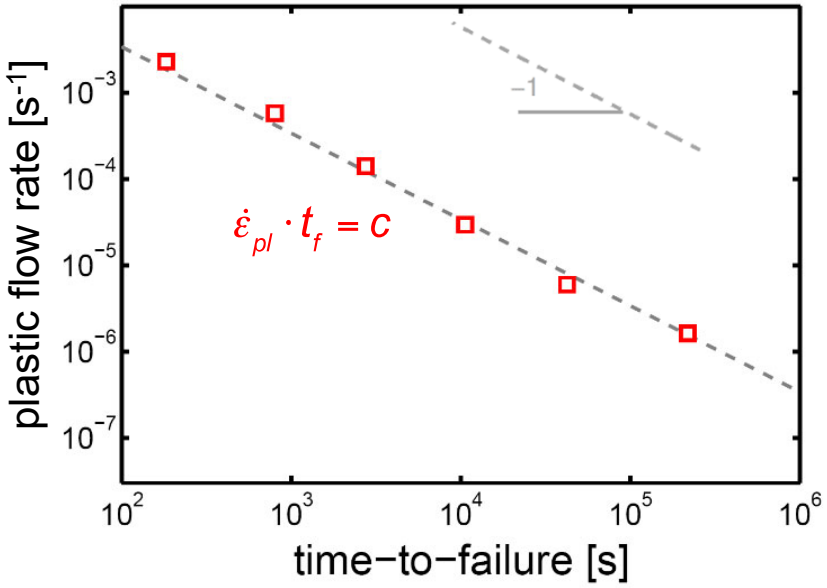
Henry Eyring

life time prediction: concept of critical strain

constant stress



flow rate vs. time-to-failure

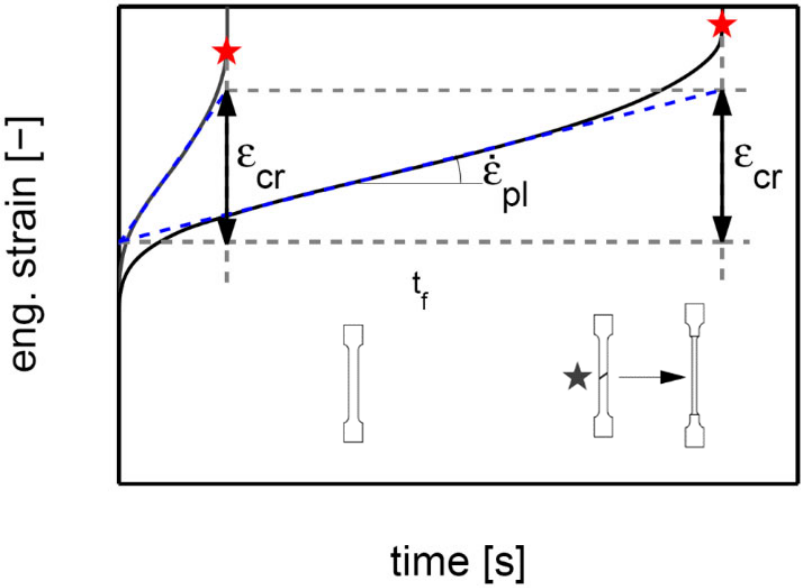


$$t_f(\sigma) = \frac{\varepsilon_{cr}}{\dot{\varepsilon}_{pl}(\sigma)}$$

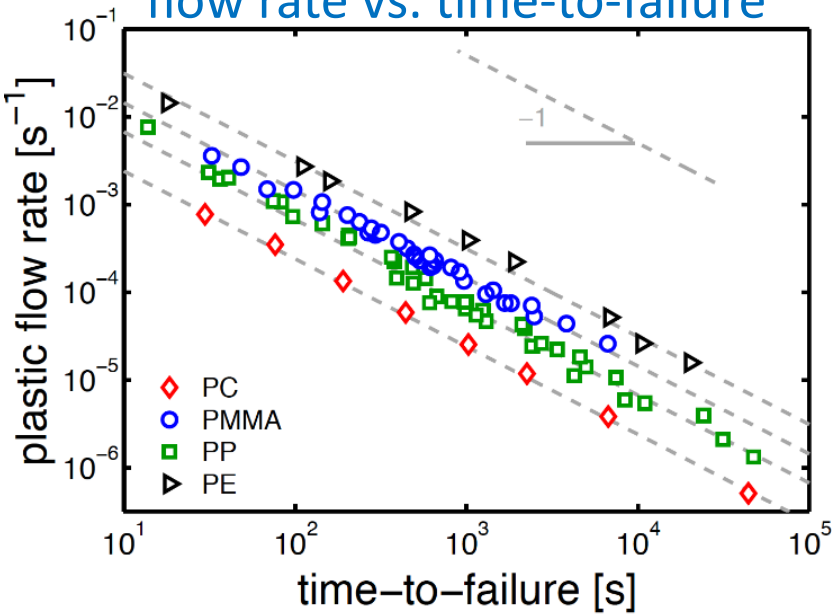
"

life time prediction: concept of critical strain

constant stress



flow rate vs. time-to-failure

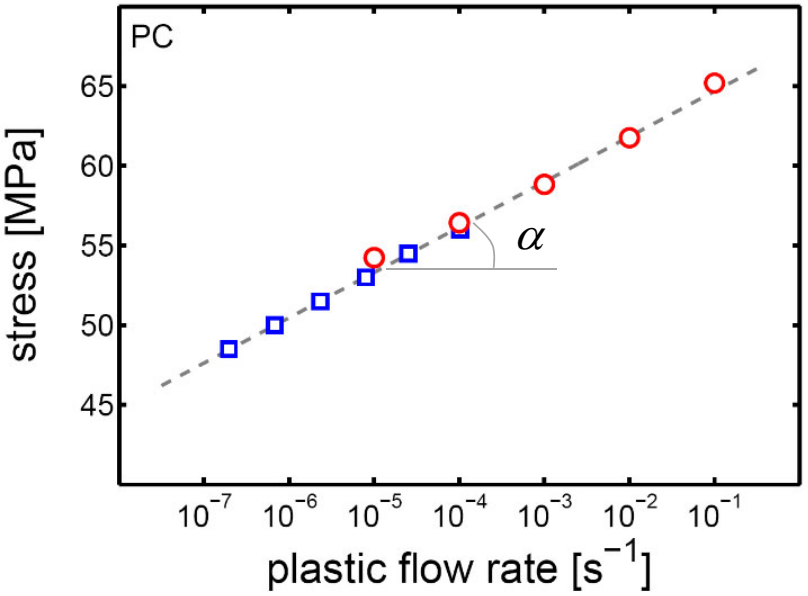


$$t_f(\sigma) = \frac{\varepsilon_{cr}}{\dot{\varepsilon}_{pl}(\sigma)}$$

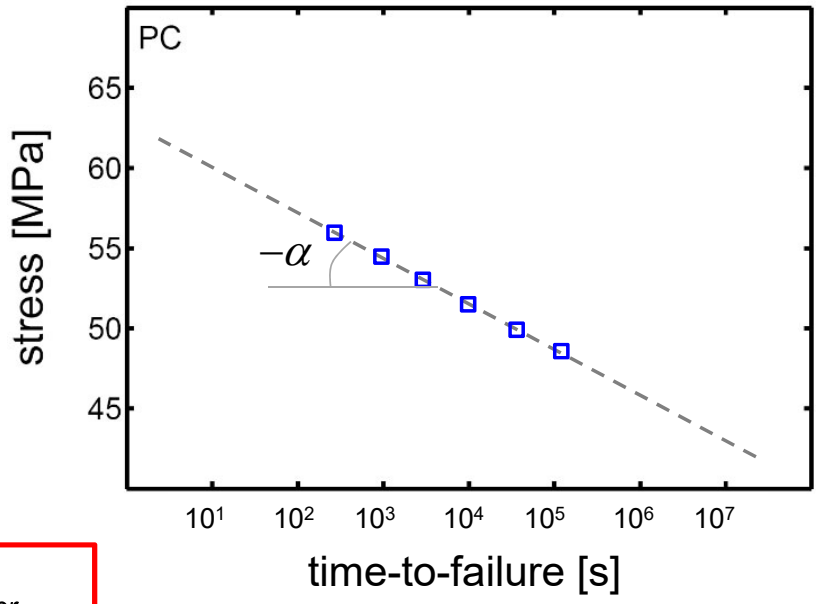
"

time-dependent failure: concept of critical strain

flow kinetics



failure kinetics



$$t_{fail} = \frac{\varepsilon_{cr}}{\dot{\varepsilon}_{pl}\left(T,\sigma\right)}$$

kinetics identical for both loading histories

time-dependent failure: concept of critical strain

accumulation of plastic strain proceeds at:

$$\dot{\varepsilon}_{pl}\left(T,\sigma\right) = \dot{\varepsilon}_0(S)\cdot\exp\left(-\frac{\Delta G}{RT}\right)\cdot\sinh\left(\frac{\sigma v^*}{kT}\right)$$

strain localization (failure) is triggered when a critical level of plastic strain has accumulated

$$\varepsilon_{pl,acc} = \int_0^t \dot{\varepsilon}_{pl}\left(T,\sigma\right)dt'$$

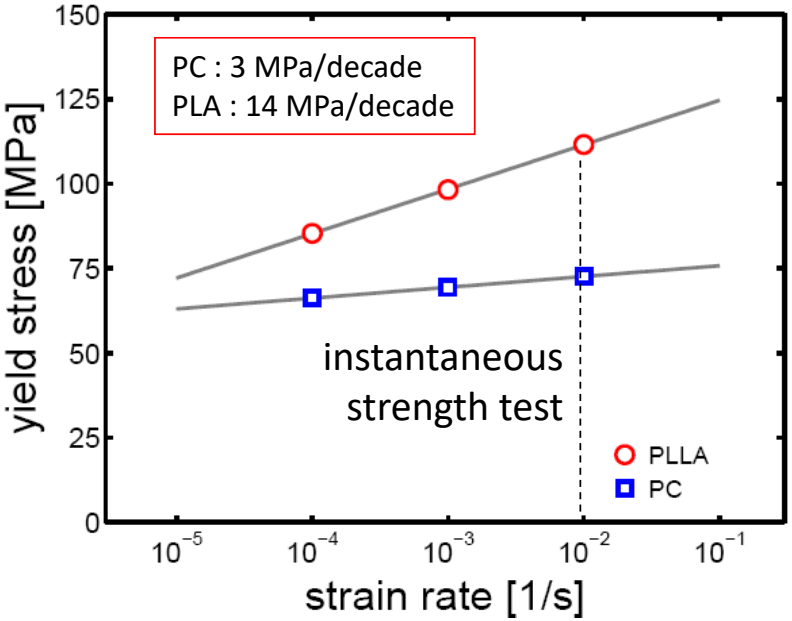
failure if: $\varepsilon_{pl,acc} \geq \varepsilon_{cr}$

constant loading:

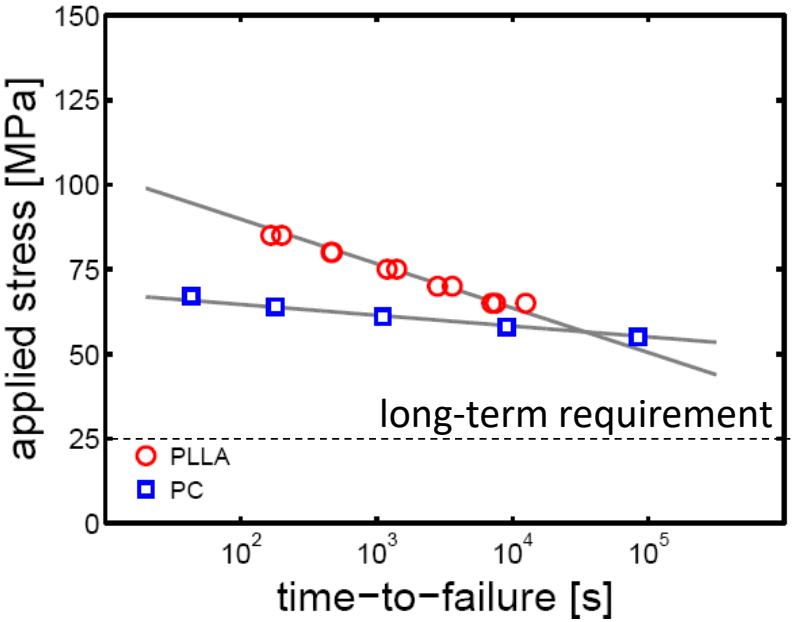
$$t_{fail} = \frac{\varepsilon_{cr}}{\dot{\varepsilon}_{pl}\left(T,\sigma\right)}$$

time-dependent failure: importance of kinetics

strain rate dependence of yield stress

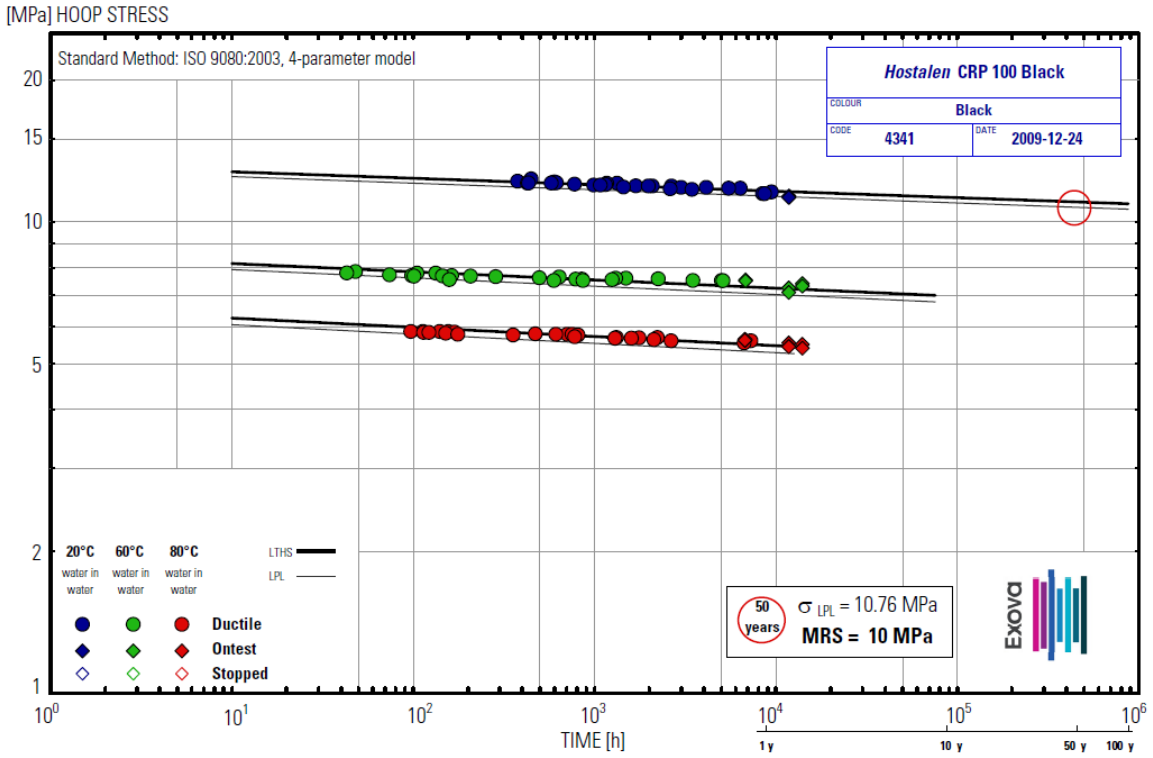


stress dependence of time-to-failure



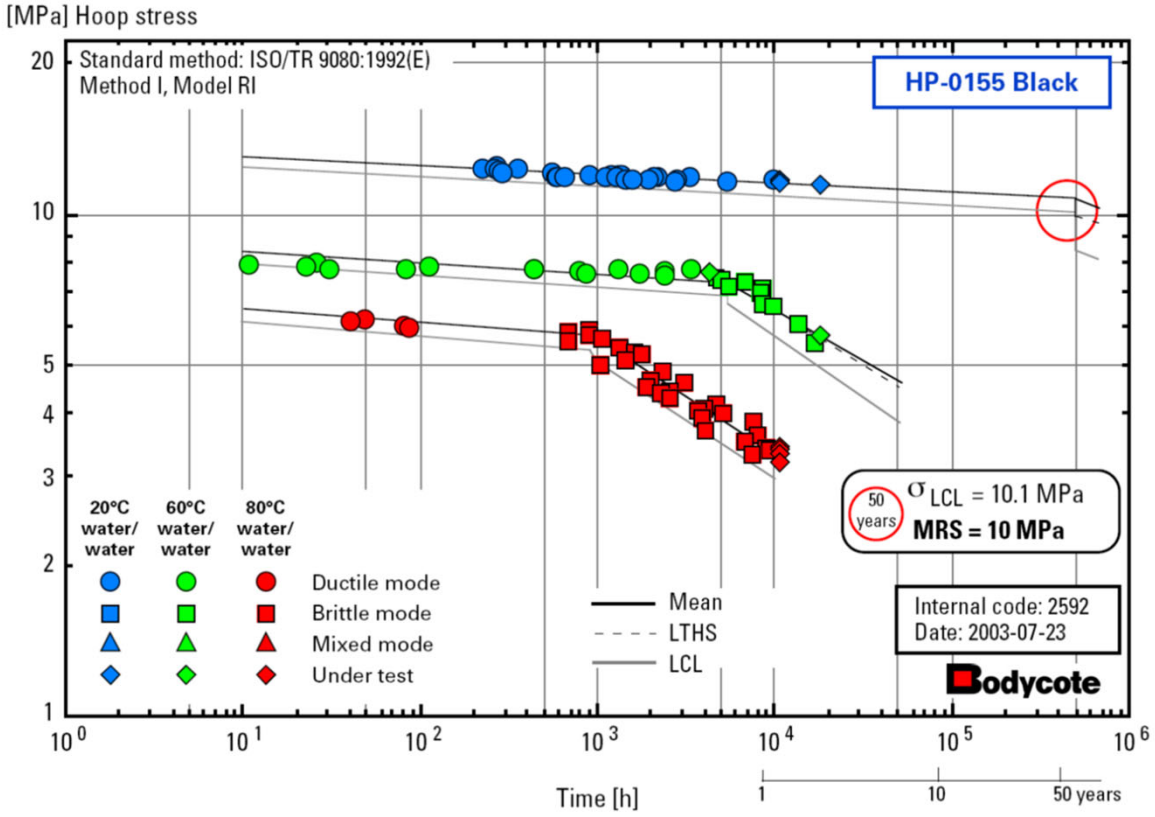
- PLA appears significantly stronger than e.g. PC when tested under constant strain rates
- under constant stress, however, PC outperforms PLA already within a day!

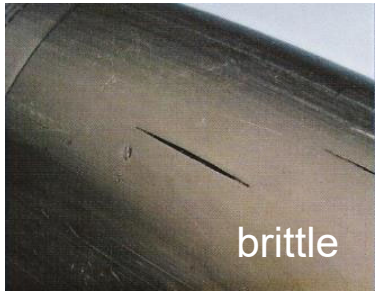
long-term hydrostatic testing



example: PE100 (HP-0155) (www.bodycotepolymer.com)
extrapolation using ISO 9080

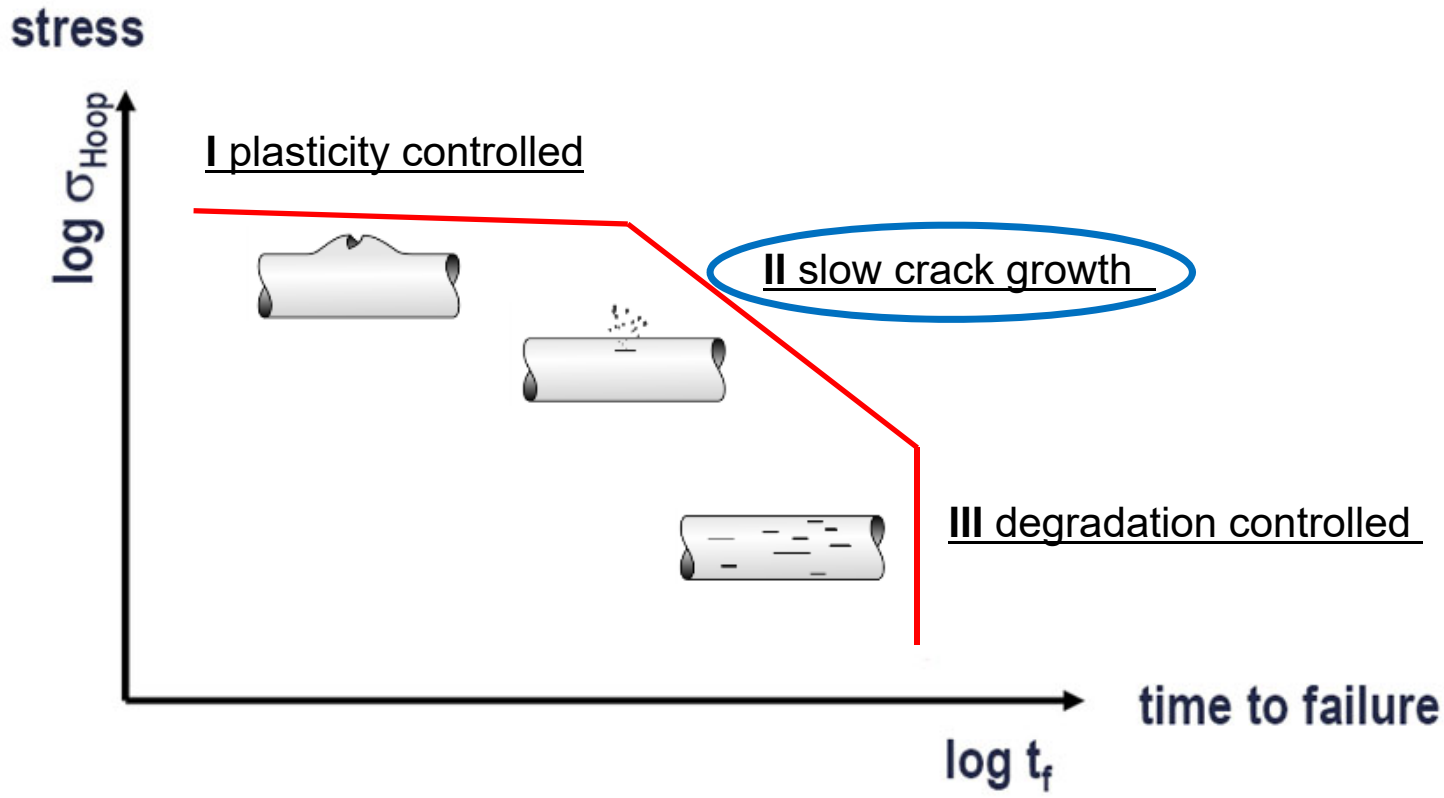
long-term hydrostatic testing





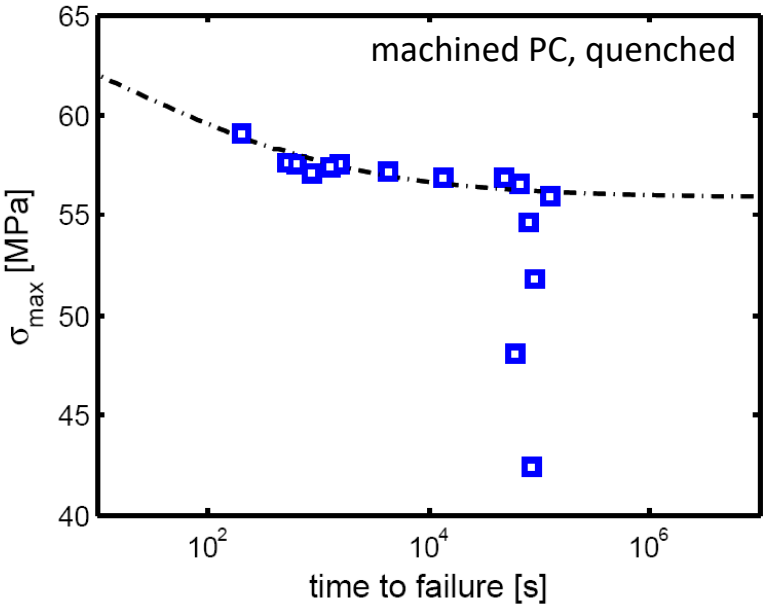
example: PE100 (CRP-100) (www.bodycotepolymer.com)
extrapolation using ISO 1167

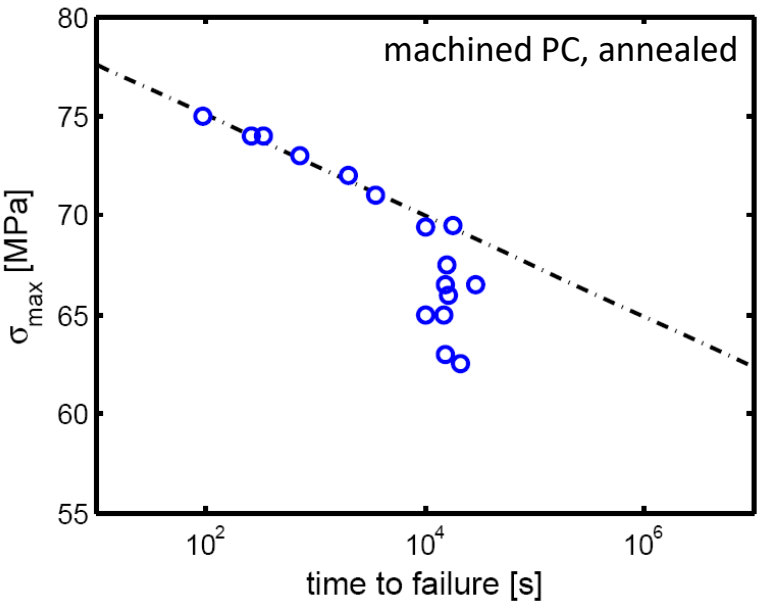
long-term hydrostatic testing: failure modes



brittle failure: crack growth!

fatigue loading, 0.1 Hz, σ_{min} = 2 MPa





change in failure mode and kinetics!

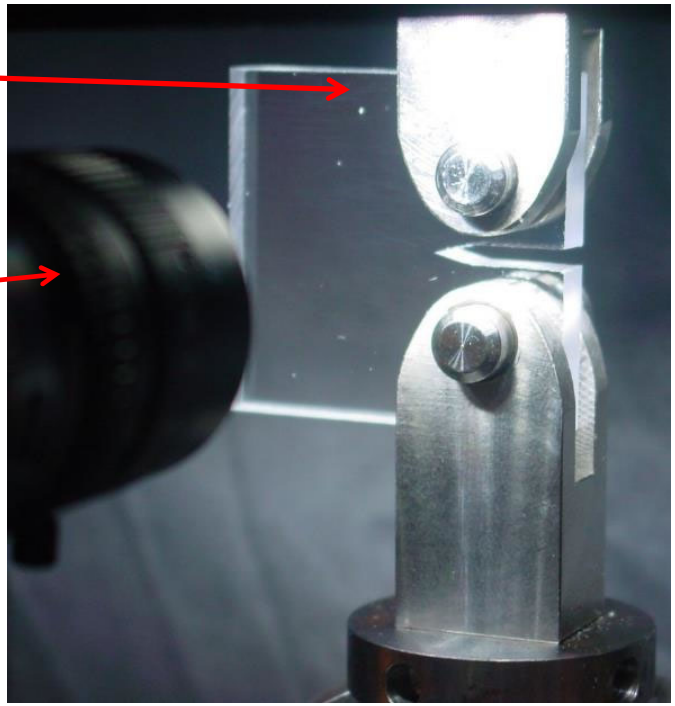
growth and failure of a crack that is initially present

brittle failure: crack growth measurement

servo-hydraulic tensile tester in force control

pre-cracked
CT specimen

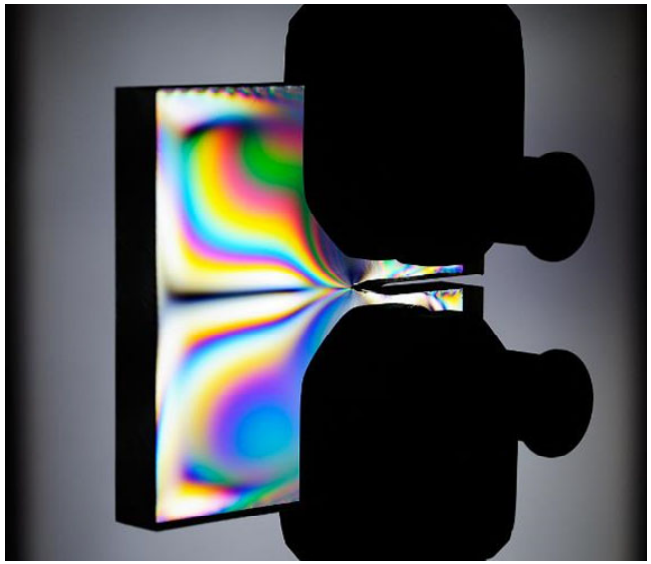
camera

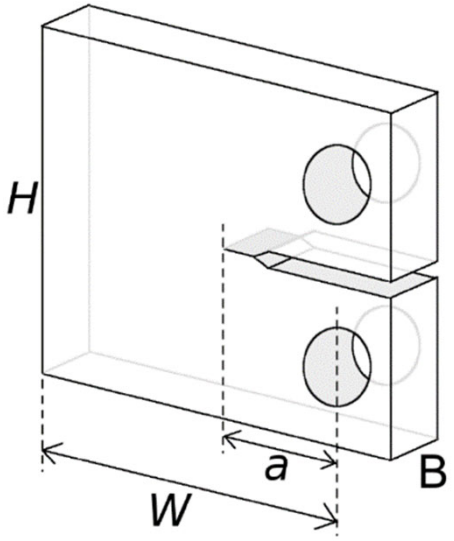


crack length determined by image processing.

brittle failure: crack growth measurement

Compact Tension (CT-)specimen

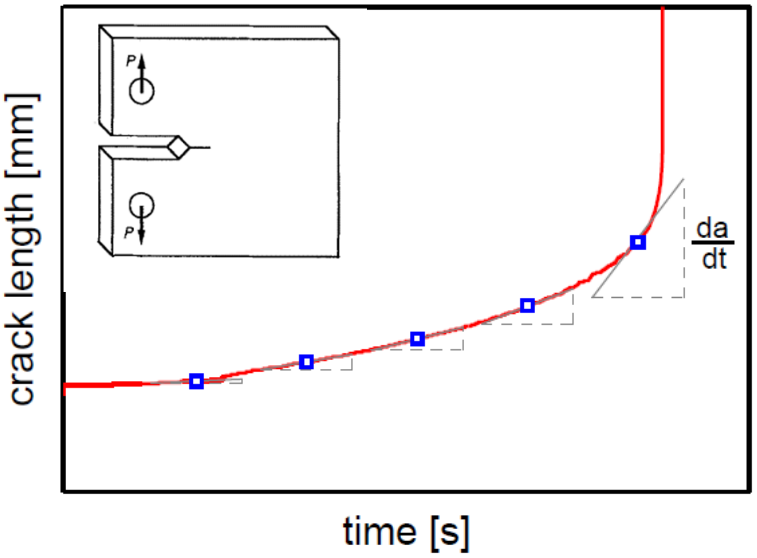


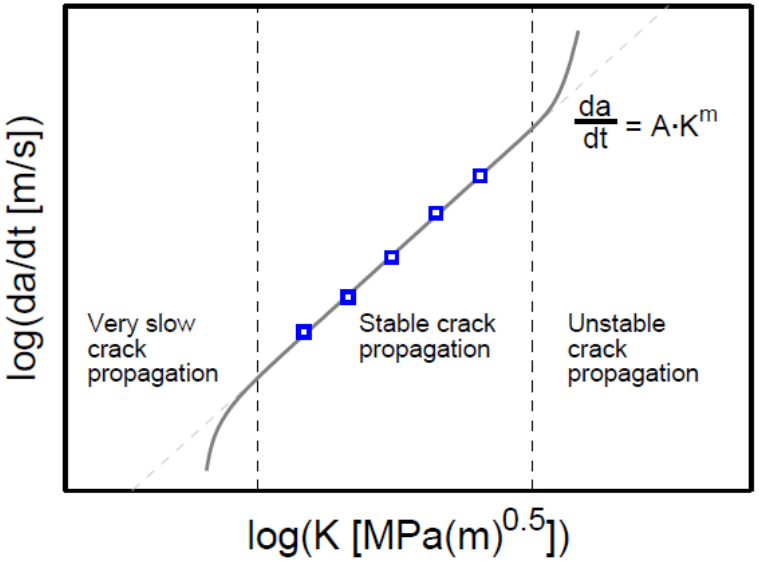


$$K_I = \frac{F}{B\sqrt{W}}\left[0.886 + 4.64\left(\frac{a}{W}\right) - 13.32\left(\frac{a}{W}\right)^2 + 14.72\left(\frac{a}{W}\right)^3 - 5.6\left(\frac{a}{W}\right)^4\right]$$

mode I slow crack growth

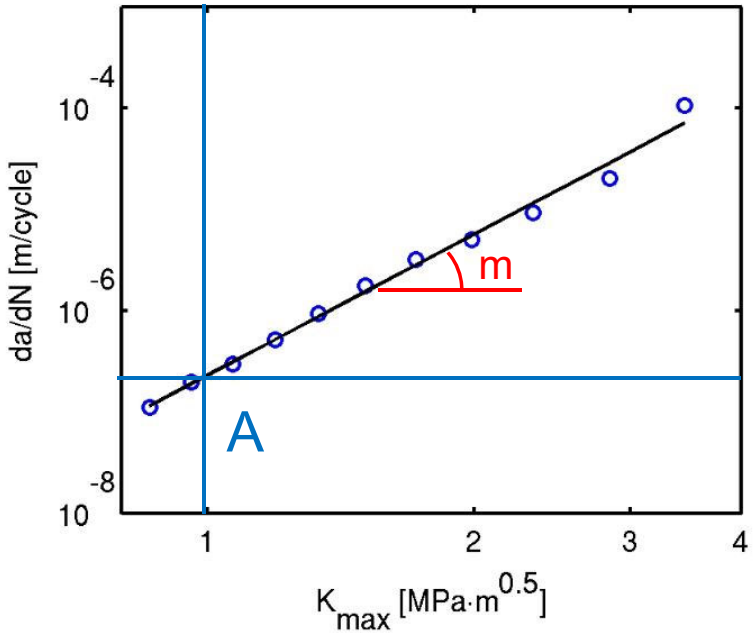
crack growth monitored under static load





"Paris Law": $\frac{da}{dt} = AK^m$

crack propagation rate



Paris law:

$$\frac{da}{dN} = AK_{max}^{m}$$

slope

value at $K_{max} = 1$

slow crack growth: lifetime prediction

Paris law:

$$\frac{da}{dt} = AK^m = A\left(Y\sigma\sqrt{\pi a}\right)^m$$

integrate over crack length:

$$t_f = \int_0^{t_f} dt = \int_{a_i}^{a_f} \frac{1}{A\left(Y\sigma\sqrt{\pi a}\right)^m} da$$

lifetime versus stress:

$$t_f = \left(\frac{1}{A}\int_{a_i}^{a_f} \frac{1}{\left(Y\sqrt{\pi a}\right)^m} da\right) \cdot \sigma^{-m}$$

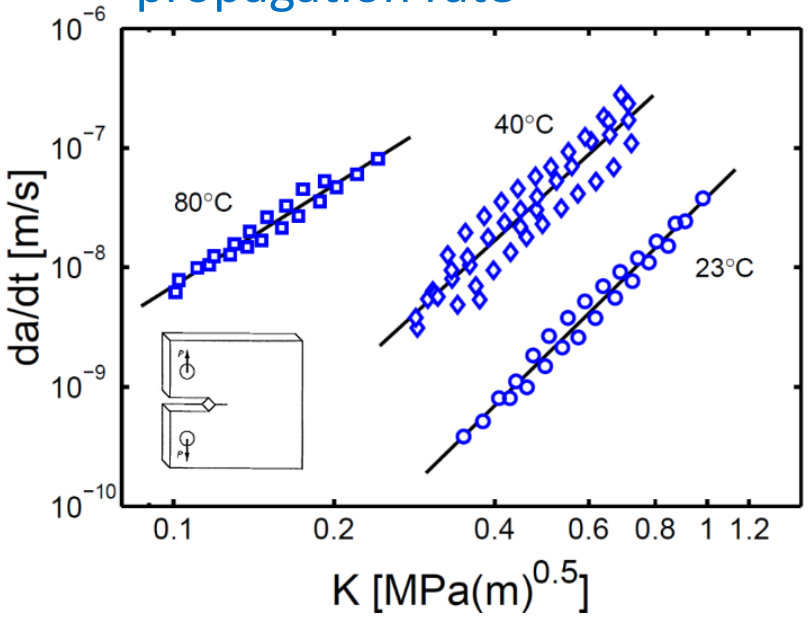
stress versus lifetime:

$$\sigma = \left(\frac{1}{A}\int_{a_i}^{a_f} \frac{1}{\left(Y\sqrt{\pi a}\right)^m} da\right)^{\frac{1}{m}} \cdot t_f^{-\frac{1}{m}}$$

$$\sigma = c_f \cdot t_f^{-\frac{1}{m}}$$

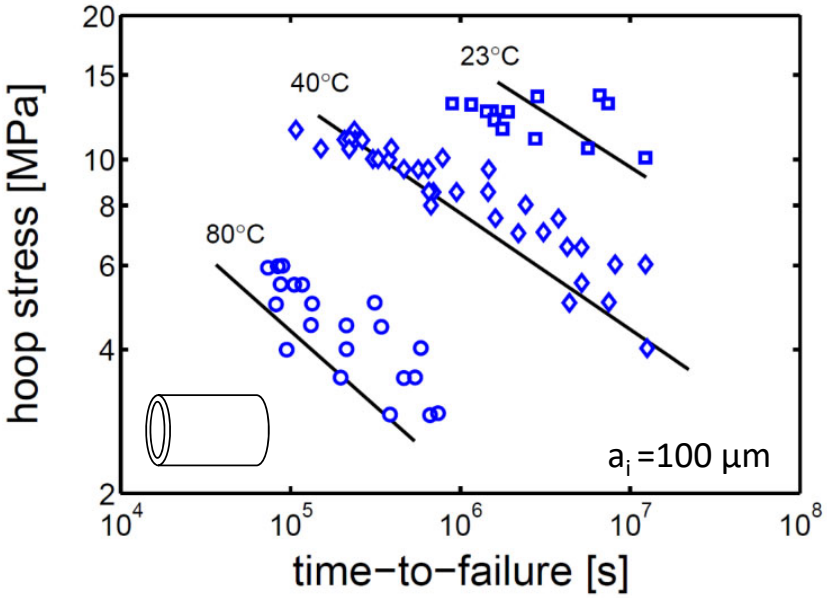
slow crack growth: lifetime prediction

propagation rate



$$\frac{da}{dt} = AK^m$$

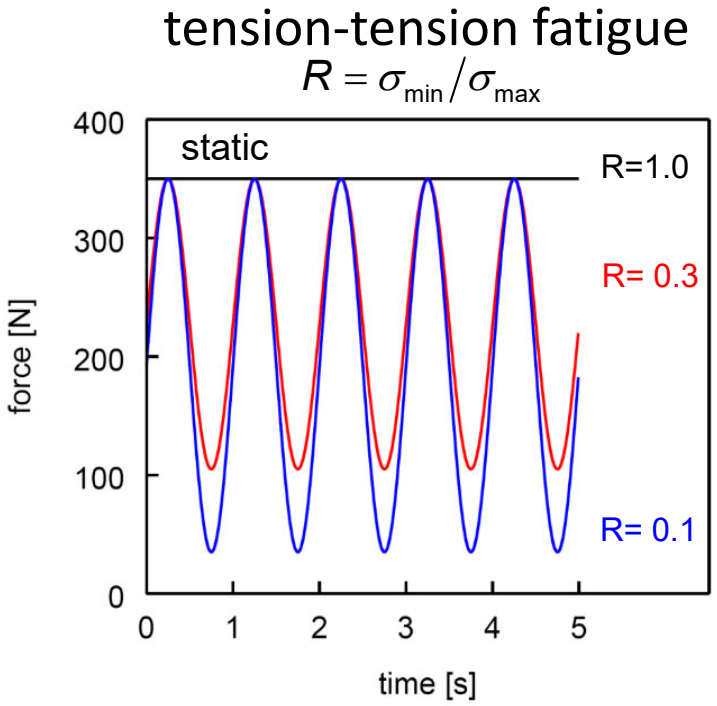
lifetime



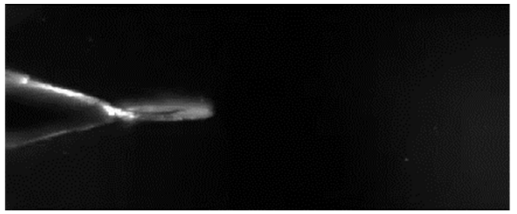
$$\sigma = c_f \cdot t_f^{-1/m}$$

Gray et al., Plast. Rub. Proc. Appl. 1981

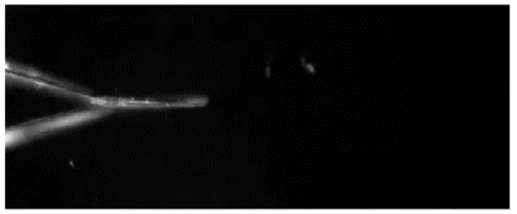
slow crack growth: static versus cyclic loading



R=1.0



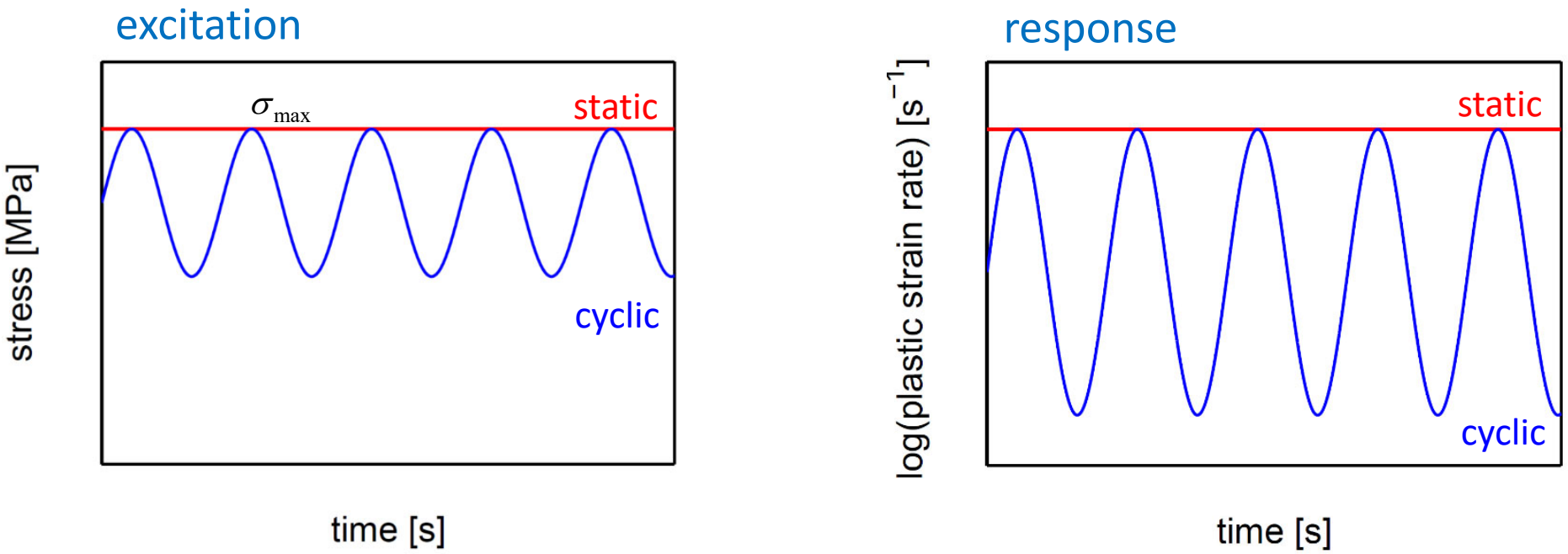
R= 0.3



R= 0.1

strong acceleration of crack growth in cyclic loading!

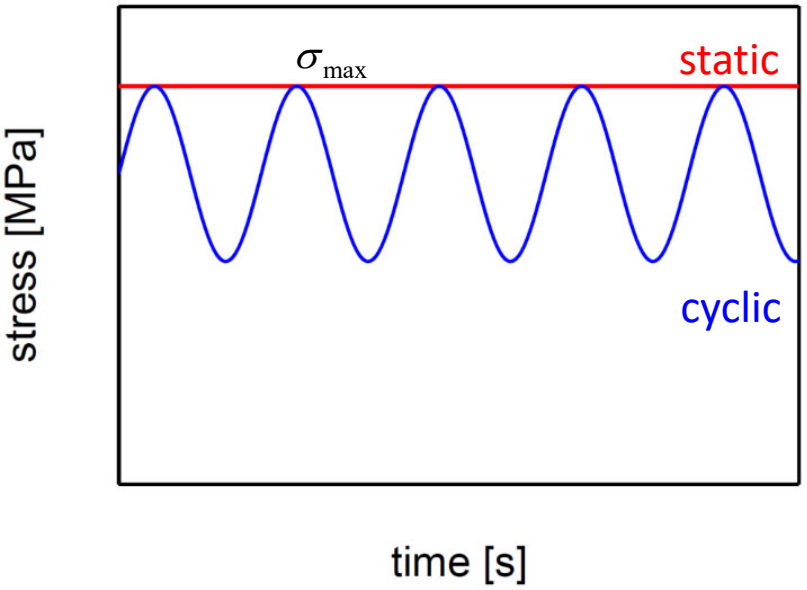
plasticity-controlled failure: cyclic loading



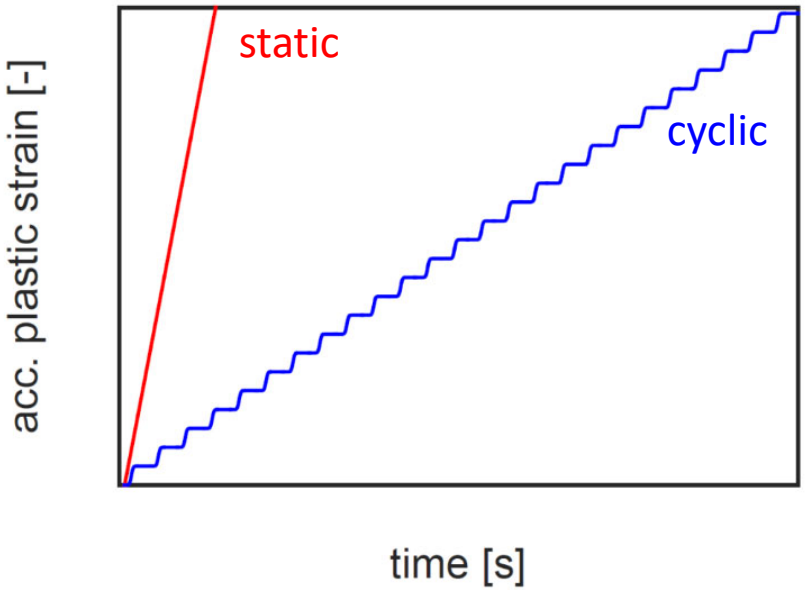
$$\varepsilon_{pl,acc} = \int_0^t \dot{\varepsilon}_{pl}(T,\sigma)\,dt' \qquad \text{failure occurs when:} \qquad \varepsilon_{pl,acc} \geq \varepsilon_{cr}$$

plasticity-controlled failure: cyclic loading

excitation



response

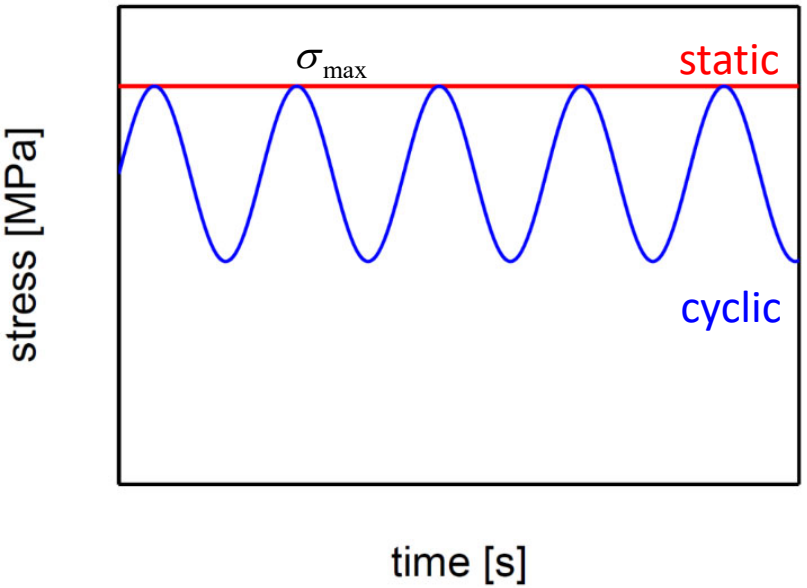


$$\varepsilon_{pl,acc} = \int_0^t \dot{\varepsilon}_{pl}(T,\sigma)\,dt'$$

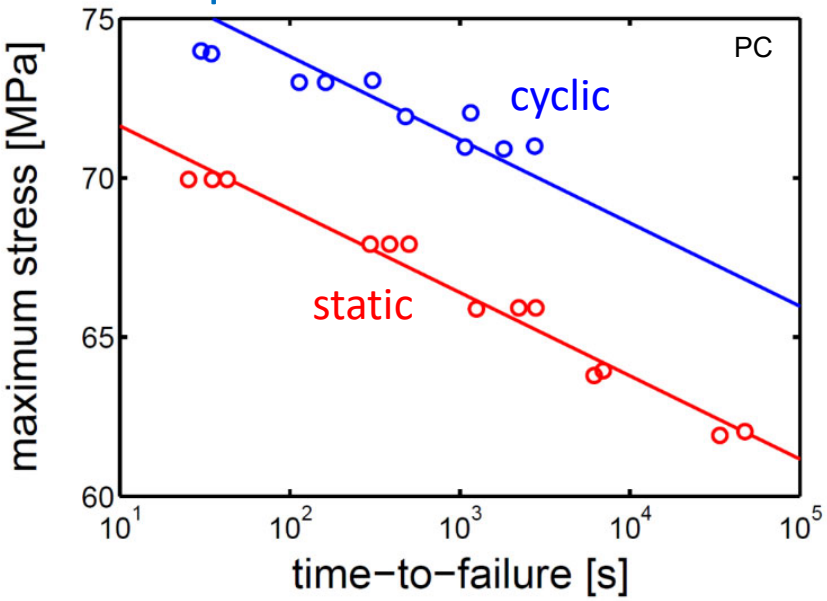
failure occurs when: $\varepsilon_{pl,acc} \geq \varepsilon_{cr}$

plasticity-controlled failure: cyclic loading

excitation



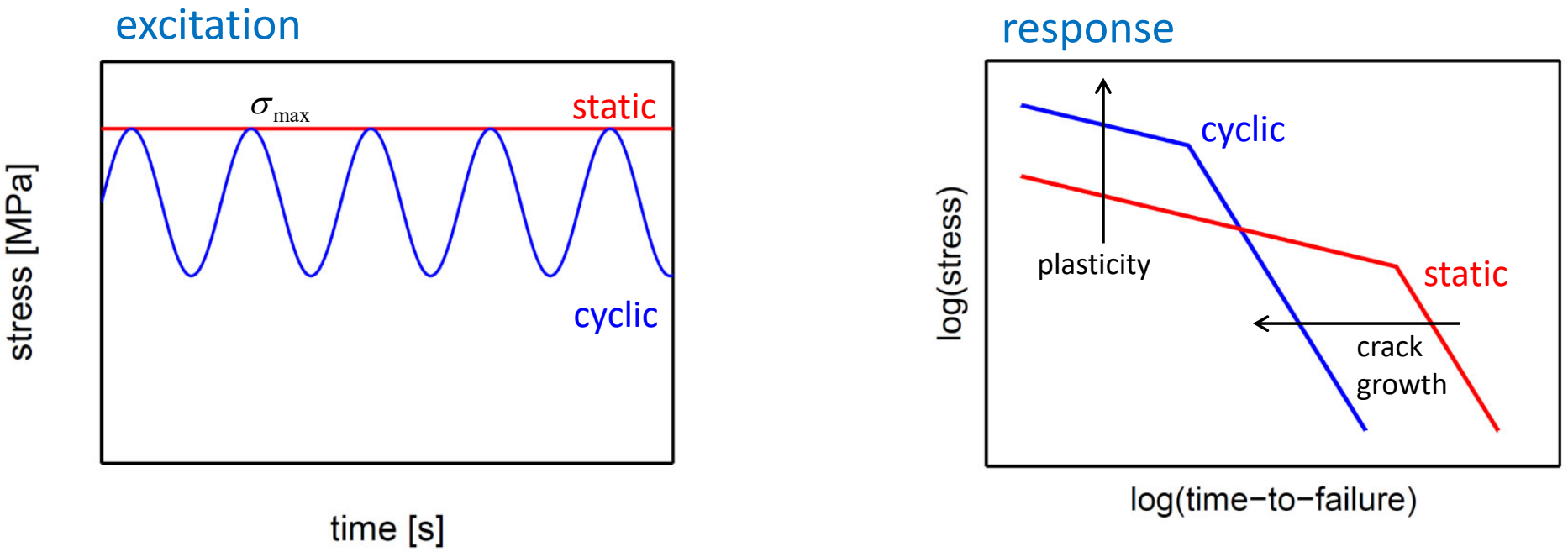
response



lifetime improves as a result of decreasing rate of plastic strain accumulation

cyclic load has longest time-to-failure

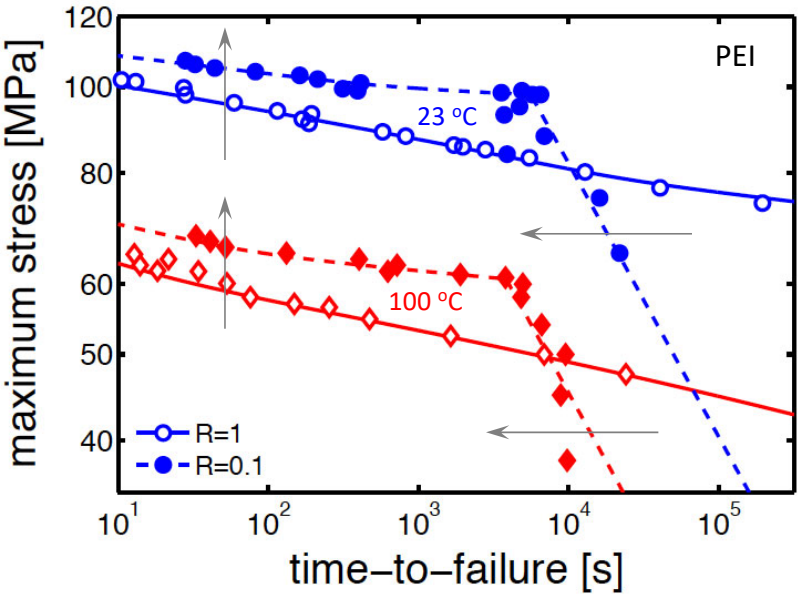
cyclic vs. static loading: time-to-failure

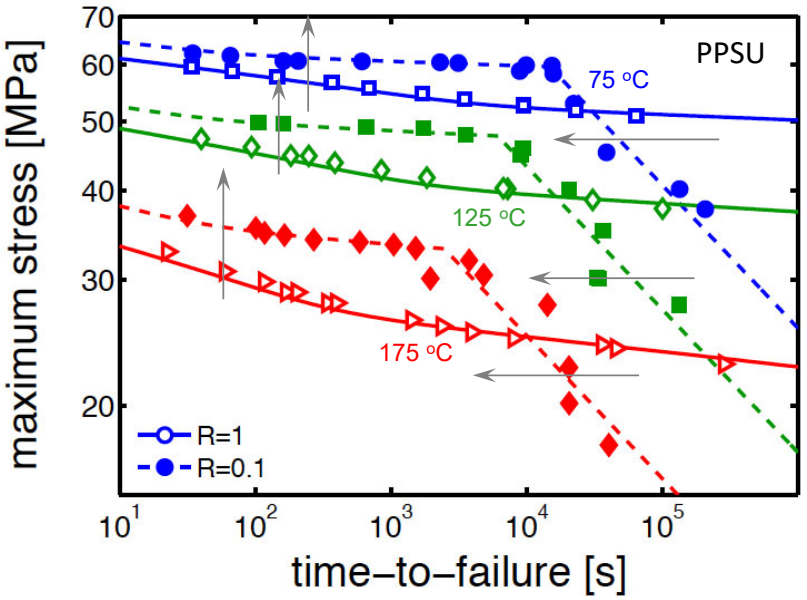


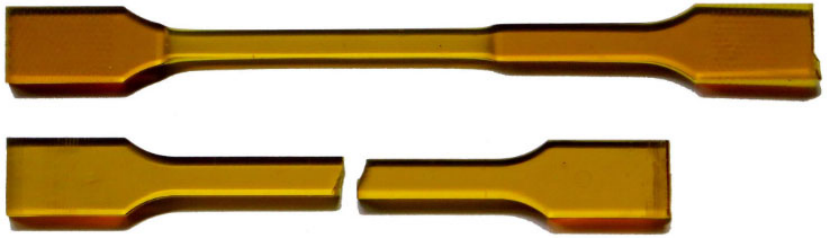
cyclic loading has a different effect on both failure modes!

cyclic vs. static loading: smooth bars

glassy polymers





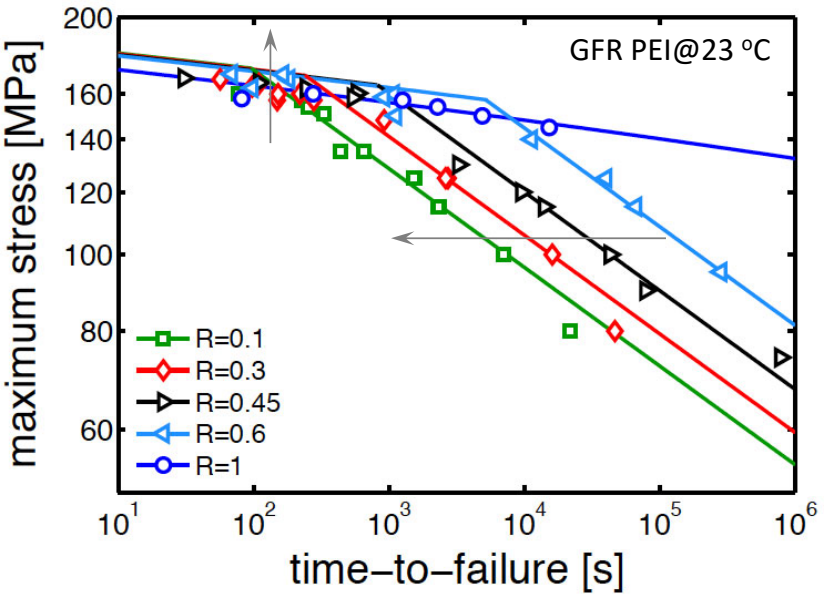


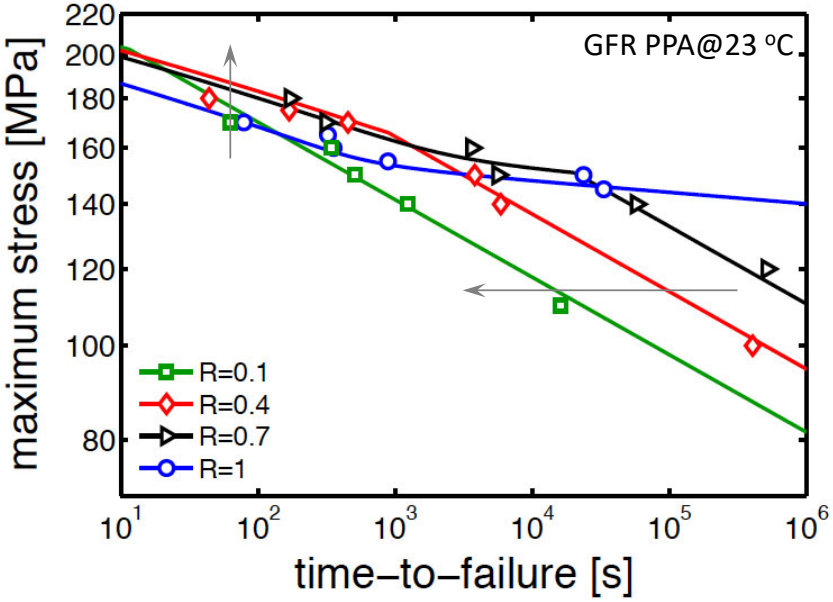
plasticity-controlled failure

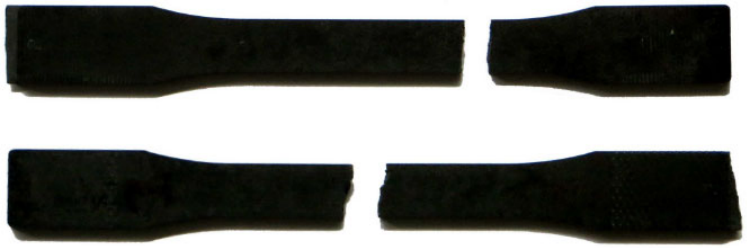
slow crack growth

cyclic vs. static loading: smooth bars

fibre-reinforced systems



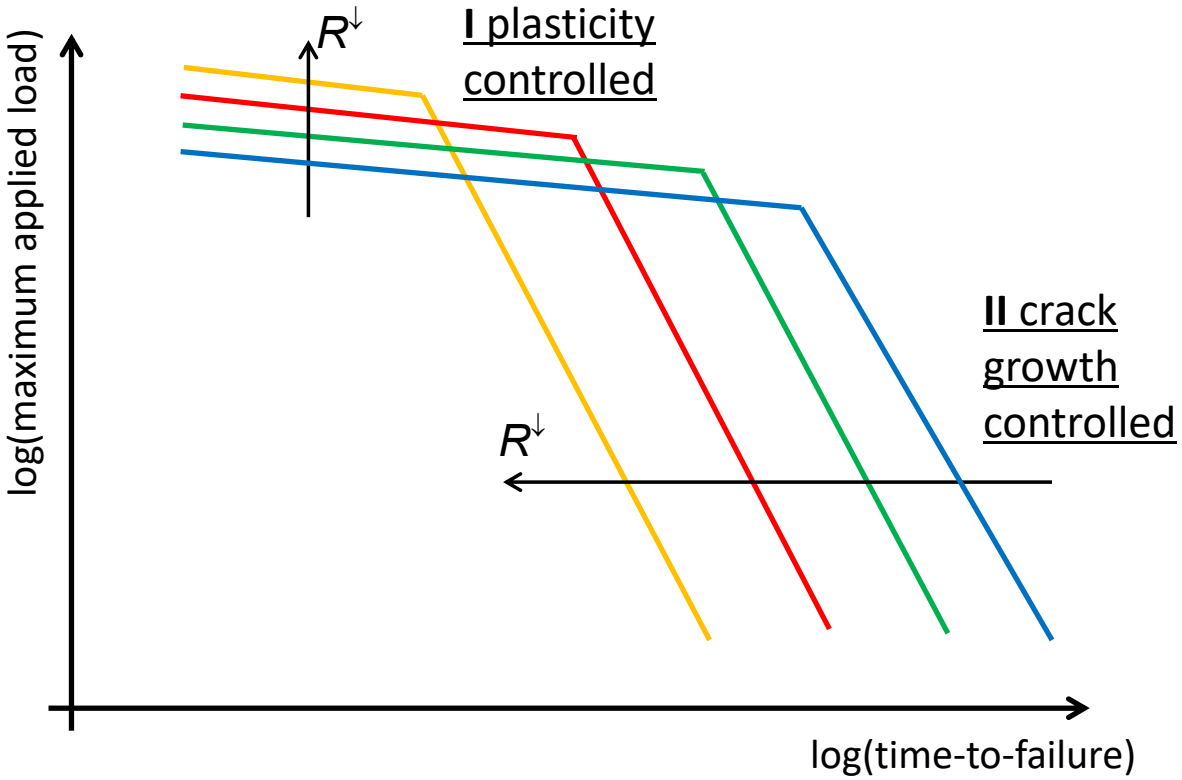




plasticity-controlled failure

slow crack growth

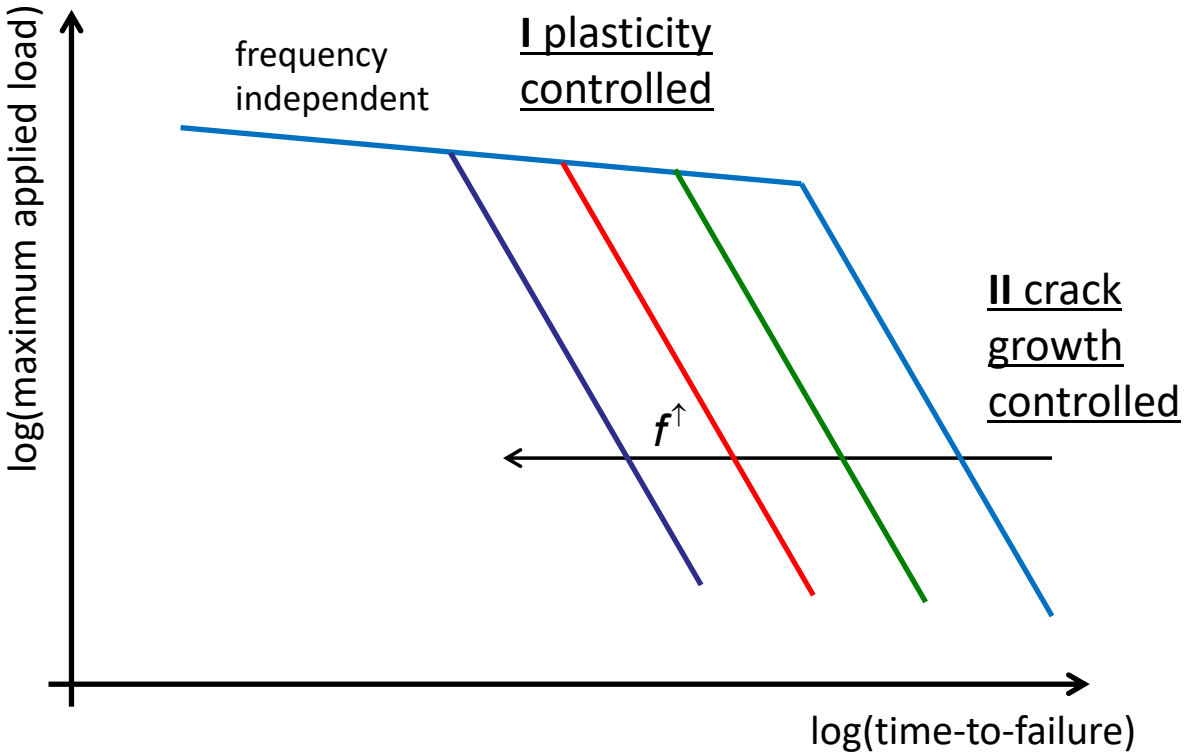
trends time-to-failure: amplitude ratio R



plasticity controlled failure: lifetime increases with decreasing R

slow crack growth: lifetime decreases with decreasing R

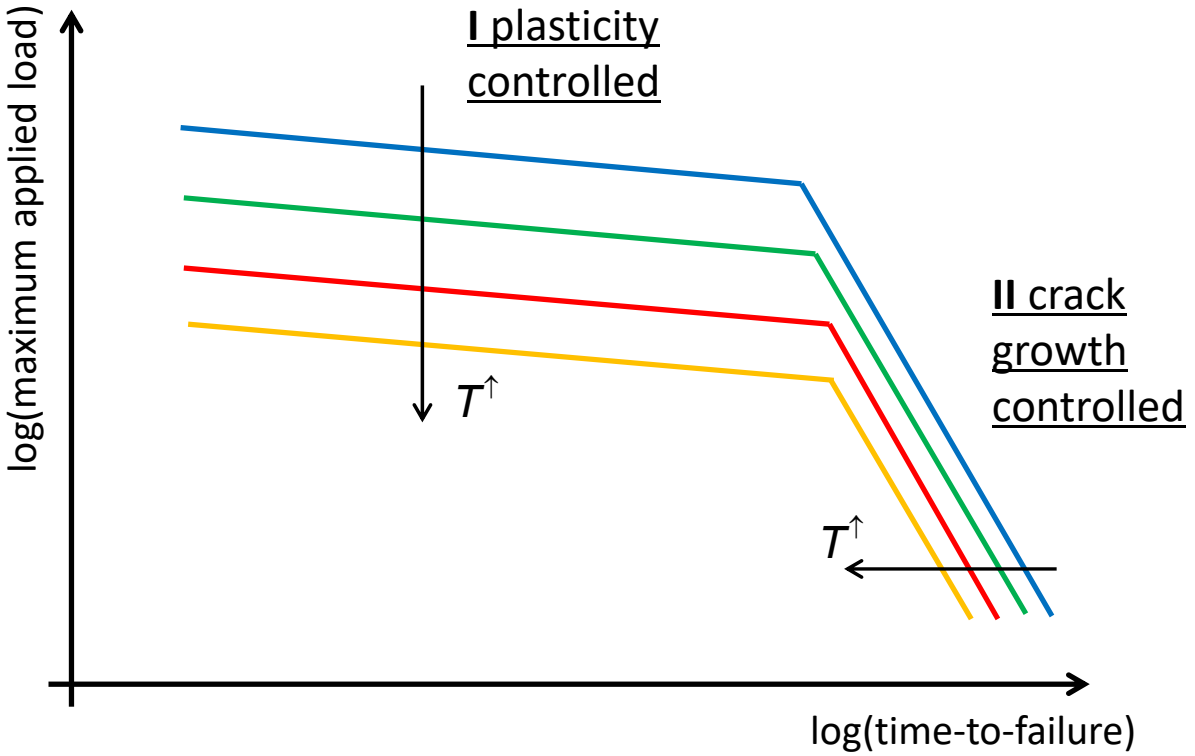
trends time-to-failure: frequency



plasticity controlled failure: lifetime independent of frequency

slow crack growth: lifetime decreases with increasing frequency

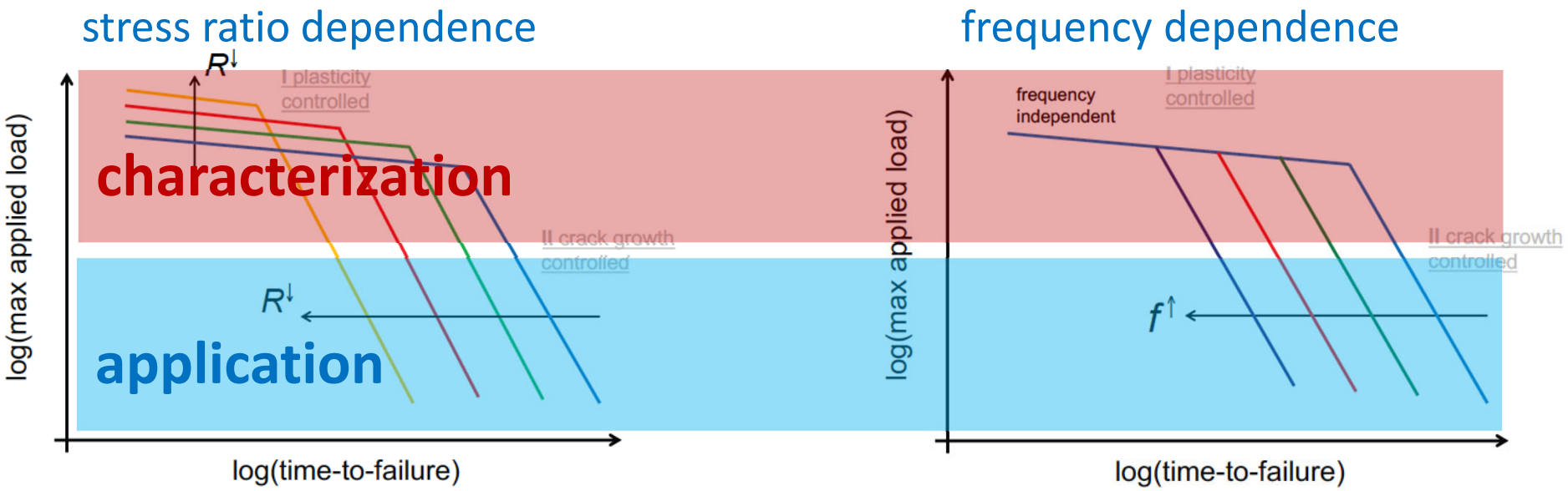
trends time-to-failure: temperature



plasticity controlled failure: strong temperature dependence

slow crack growth : weak temperature dependence

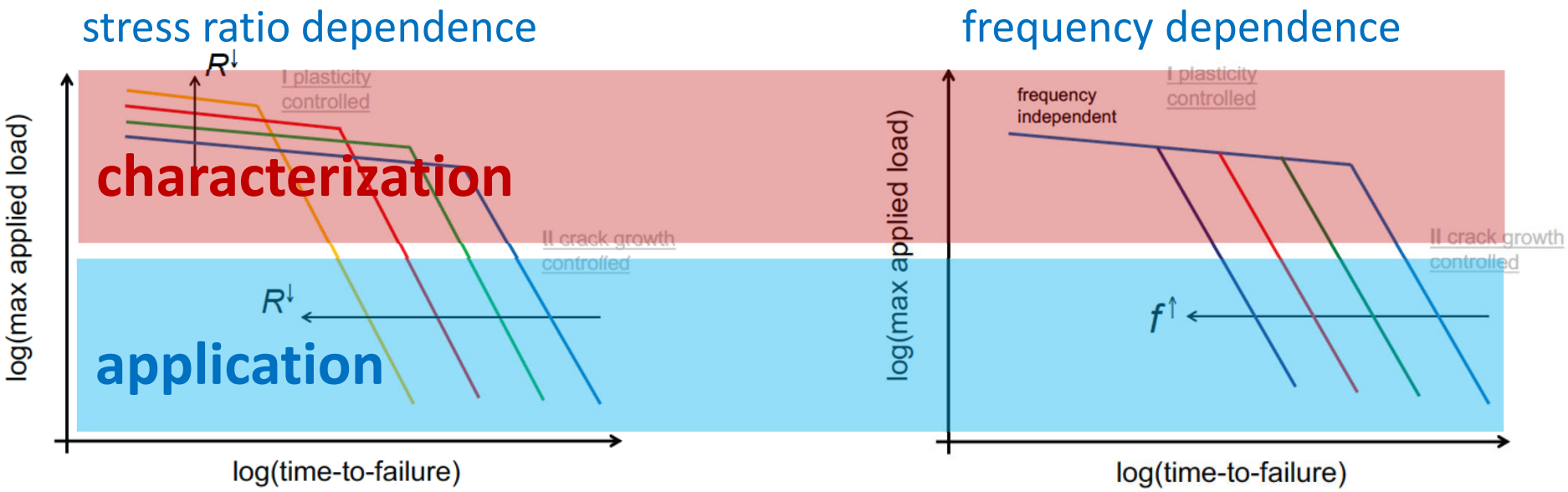
fatigue and lifetime prediction strategies for polymers



in practical applications, lifetime is likely controlled by slow crack growth

in fatigue characterization, other mechanisms may contribute !!!

fatigue and lifetime prediction strategies for polymers



correct extrapolation of “short-term” characterization data
requires identification of underlying mechanisms

Fatigue and lifetime prediction strategies for polymers

Take home messages:

- mechanical properties depend on testing conditions and molecular details
- three failure mechanism are typically identified:
  - fracture (Griffith's law) =f(mol.weight)
  - ductile flow (Eyring's flow rule) ≠f(mol.weight)
  - slow crack growth (Paris' law) =f(mol.weight)
- under "long-term" dynamic loading conditions ductile flow and slow crack growth are the dominant failure modes:
  - ductile flow is a time-dependent failure mode
  - slow crack growth is a (strongly) frequency depend failure mode

- correct extrapolation of "short-term" characterization data requires identification of underlying mechanisms