Recent Developments in Understanding the Fatigue Behavior of PEEK Materials

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Kurtz, PEEK Biomaterials Handbook, 2nd Ed.

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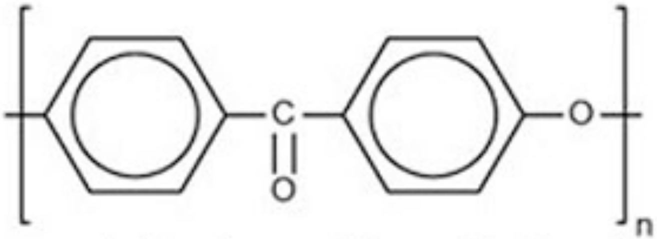
- Thanks to Michael Sobieraj, MD, PhD for co-authoring the related Chapter 5 in the PEEK Biomaterials Handbook, 2nd Edition

PEEK as a substitute for metallic alloys in orthopaedic applications



General properties/characteristics:

- A high performance engineering thermoplastic – good mechanical and wear properties - can be molded into complex shapes - can be reinforced
- Ultimate Stress ~ 100MPa; Elastic modulus about 3 GPa
- Tg ~ 143C
- Semi-crystalline, ~30%-35%
- Resistant to high ionizing radiation and chemical attack
- Stable up to 300C
- Biocompatible; biologically inert

PEEK as a substitute for metallic alloys in medical device applications – mechanical considerations

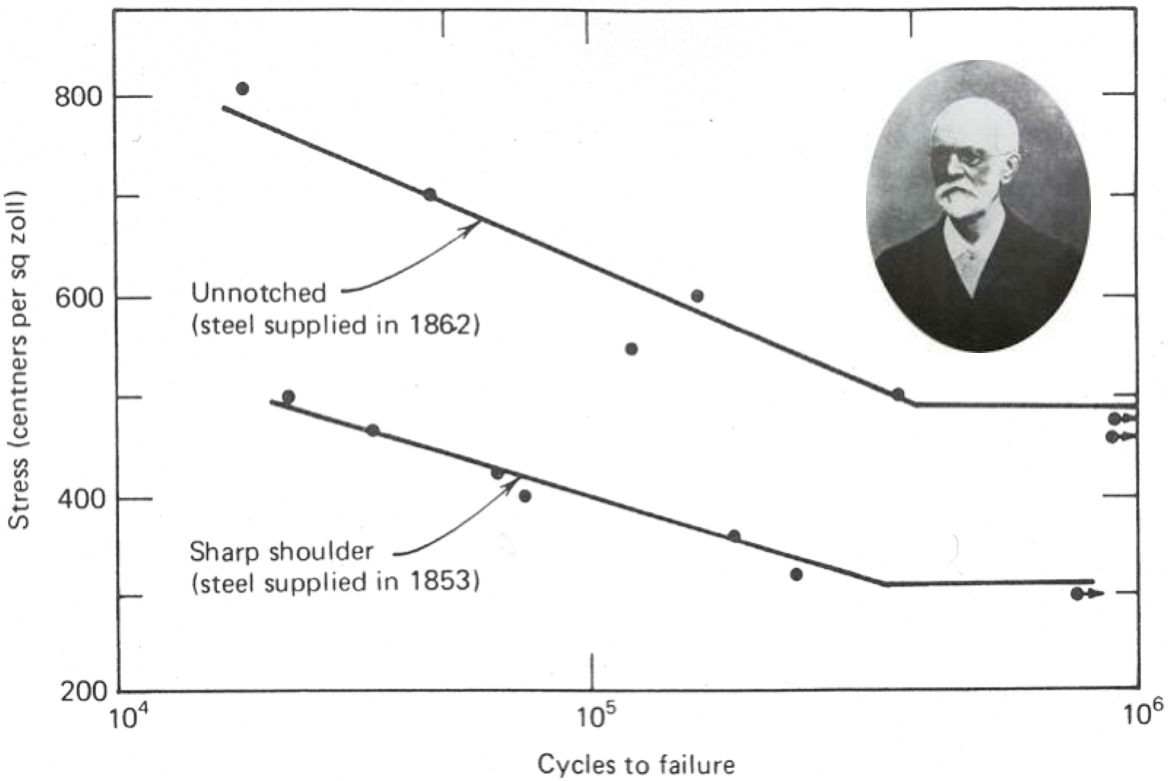
- Are the mechanical properties (deformation, creep, fracture, fatigue) adequate for load-bearing musculoskeletal applications?

- Focus of this overview – recent studies characterizing the fatigue resistance of PEEK and PEEK composites

Brief background - Three approaches to fatigue analyses:

- Stress-Life (S-N)
- Strain-Life (ε-N)
- Fracture mechanics

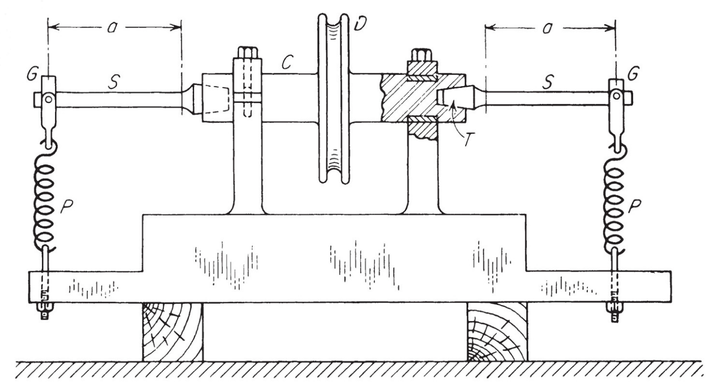
S-N Fatigue Approach (The Wöhler Curve)



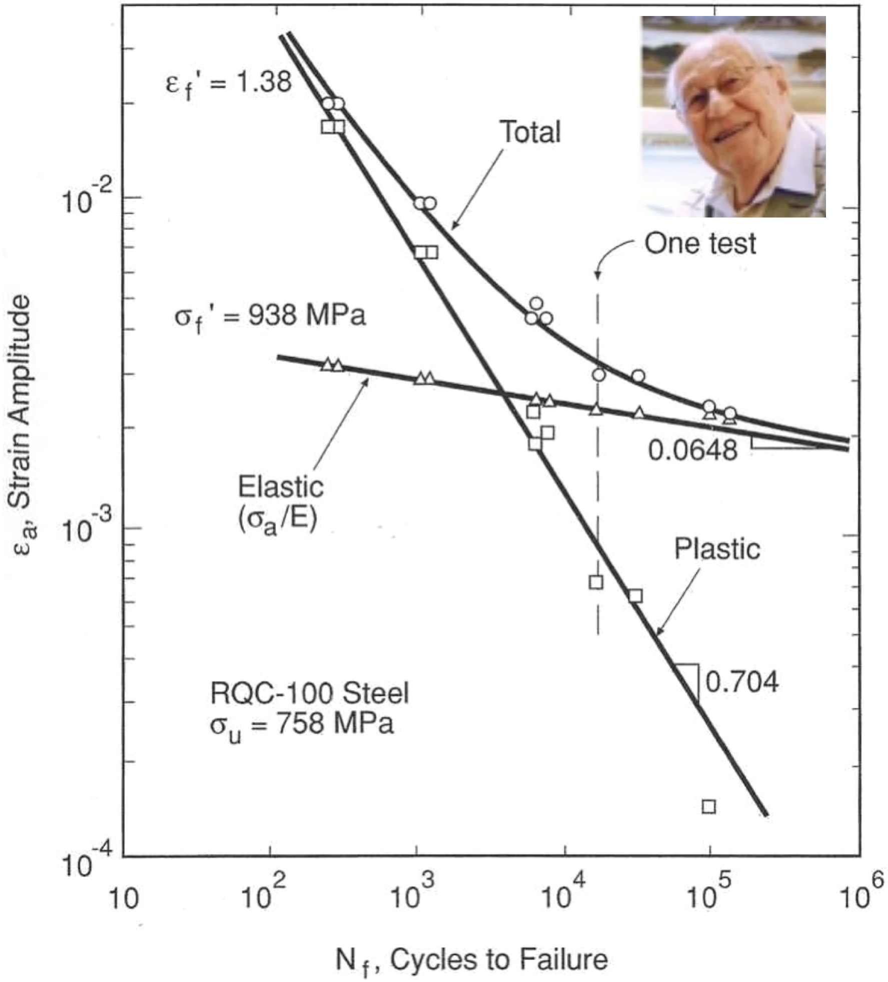
A total life approach:

$N_i + N_p = N_f$

Most useful when plastic strains are small (high-cycle fatigue)



ε-N Fatigue Approach (Manson-Coffin)



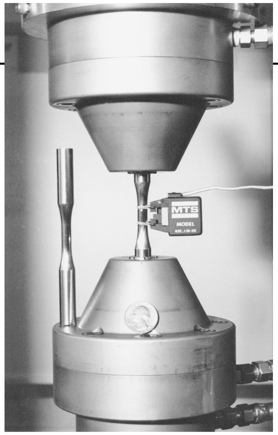
Also a total life approach:

$N_i + N_p = N_f$

$\varepsilon_a = (\sigma'_f/E)(2N_f)^b + \varepsilon'_f(2N_f)^c$

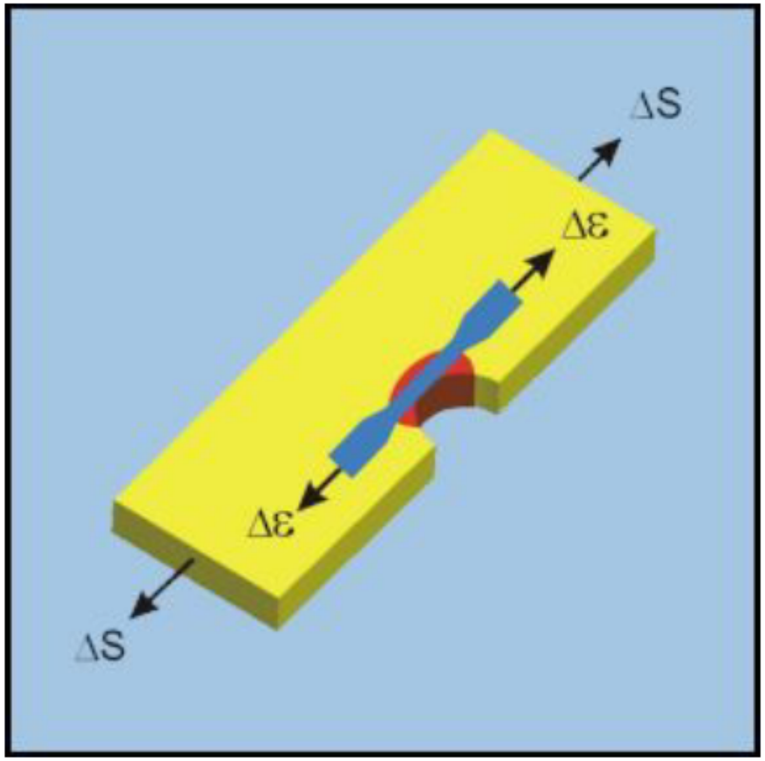
$\varepsilon_a = \sigma_a/E + (\sigma_a/K')^{1/n'}$

Can accommodate large plastic strains
(low- and high-cycle fatigue regimes)

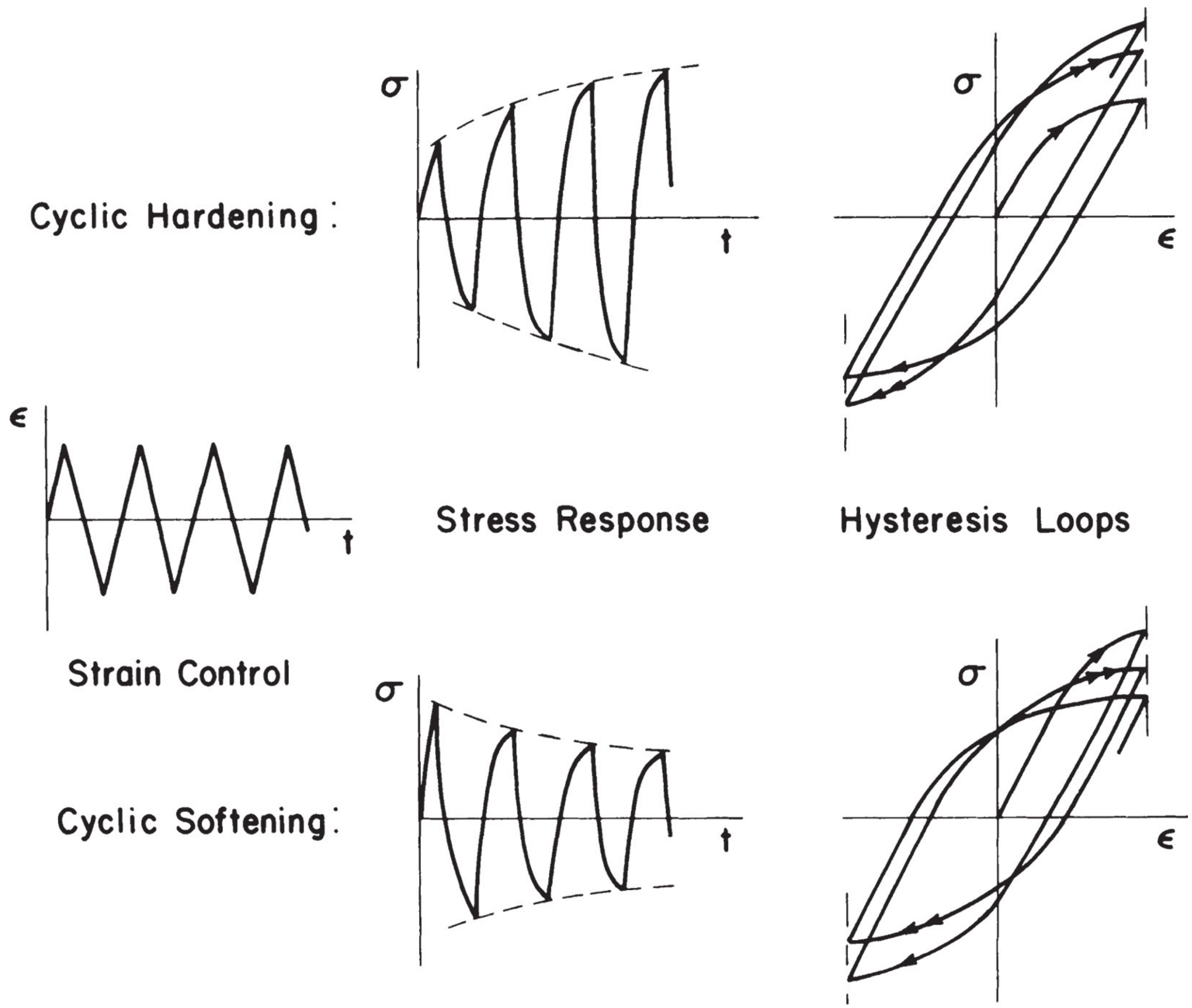


ε-N Fatigue Approach

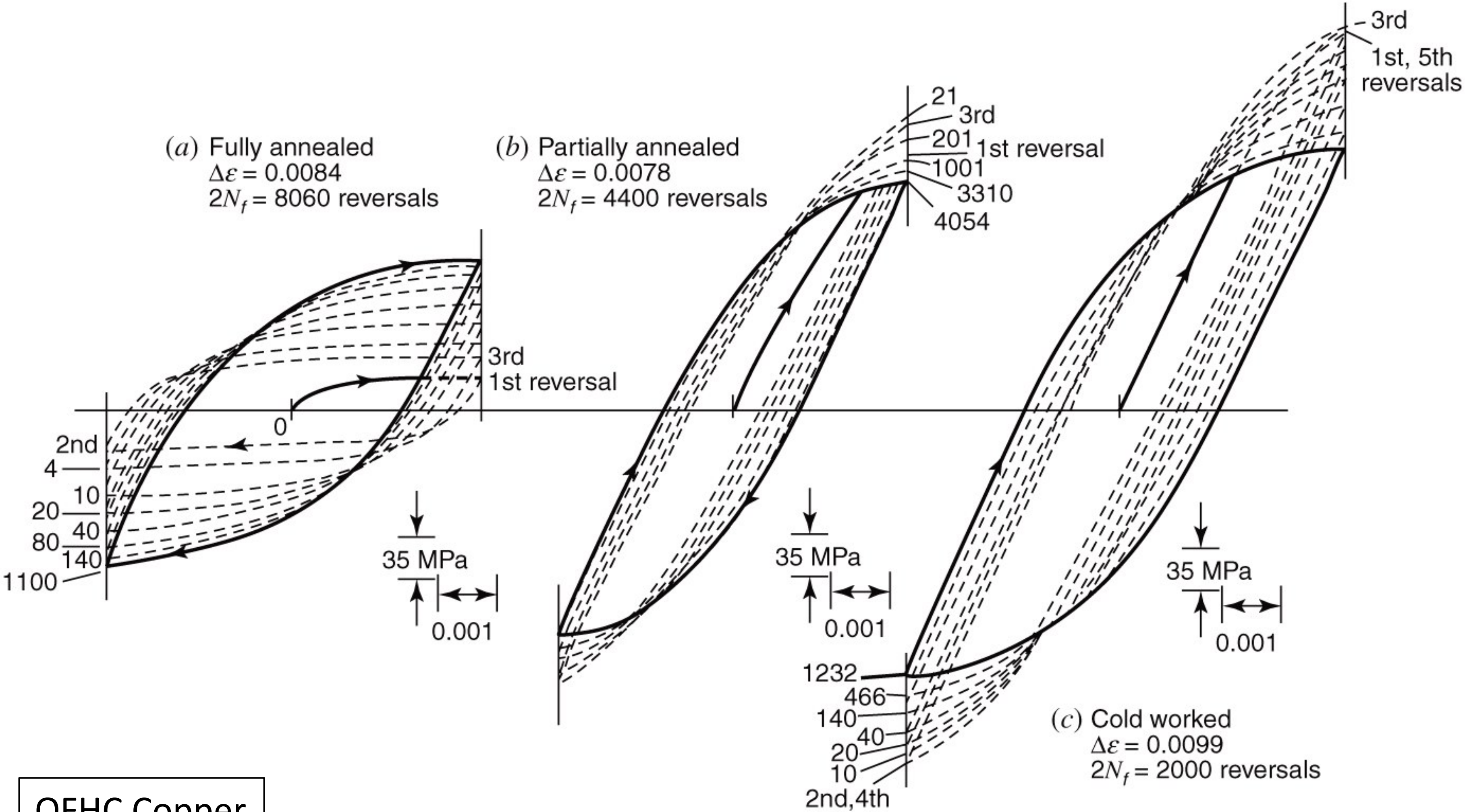
-This approach considers Plastic deformation such as might occur locally at a notch
- That is, *regardless of the external mode of loading* (cyclic stress or strain controlled), the *notch experiences a strain-controlled condition* due to the surrounding mass of elastic material



Cyclic Hardening/Softening seen in ε-N Tests



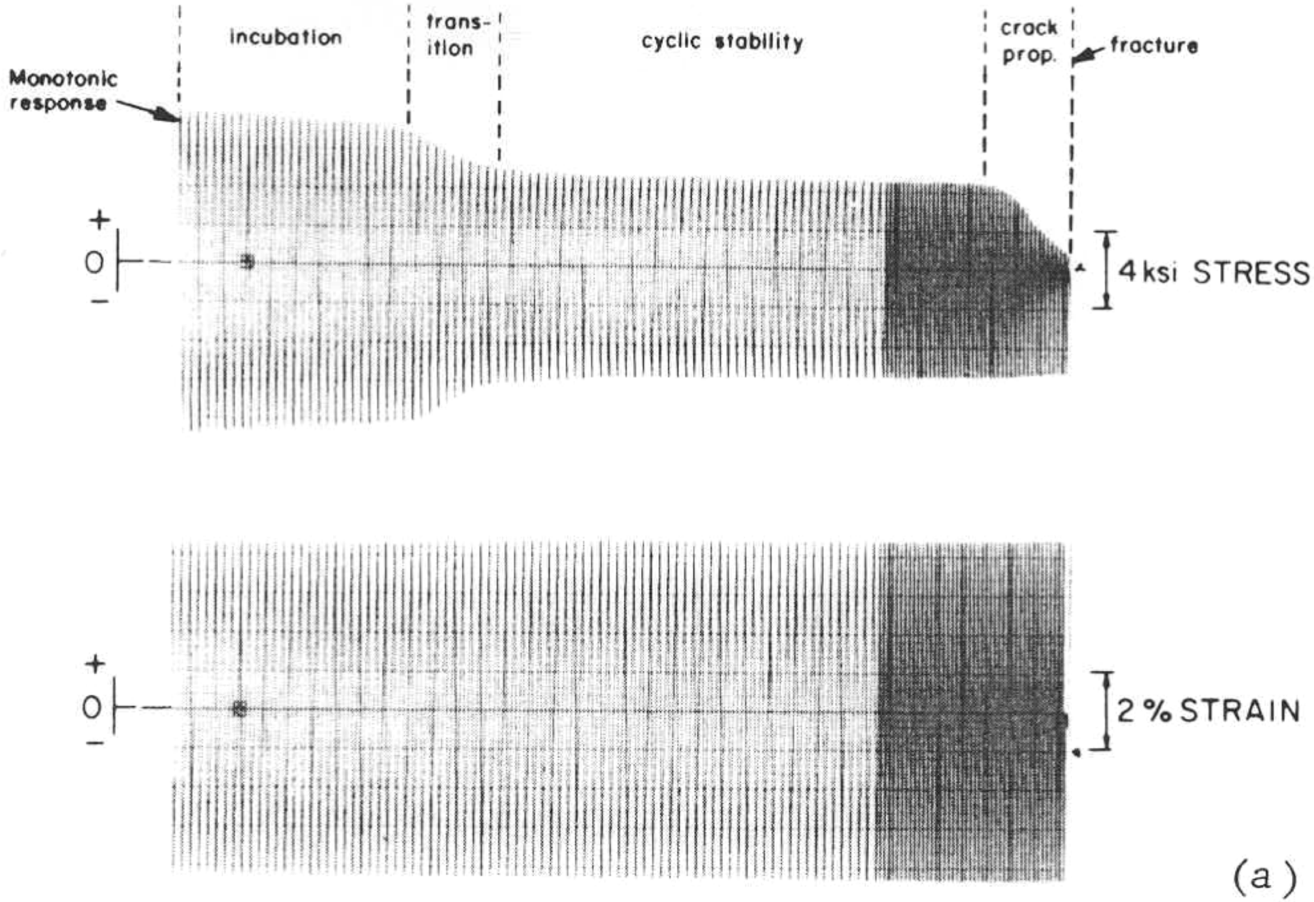
Metals can Cyclic Harden or Soften

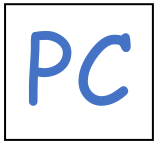


OFHC Copper

Deformation and Fracture Mechanics of Engineering Materials, R.W. Hertzberg et al. 5th Edition

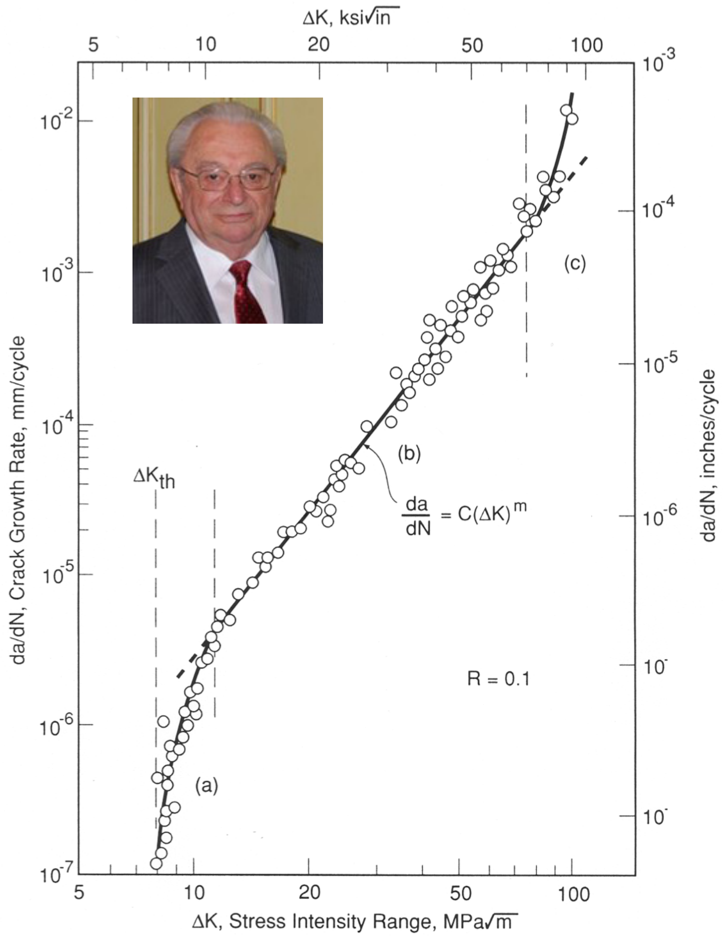
Polymers only Cyclically Soften





Rabinowitz and Beardmore, J Mater Sci 1974

Fatigue Crack Propagation Approach (Paris law)



Focus is on the *kinetics* of fatigue crack growth (N_p)

$da/dN = C\Delta K^m$

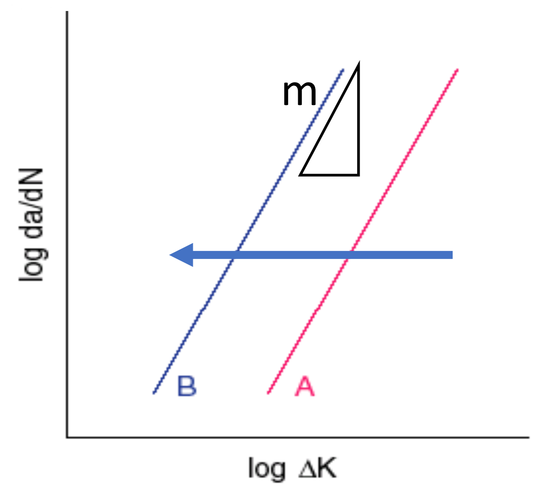
$\Delta K = \Delta\sigma(F)(\pi a)^{0.5}$

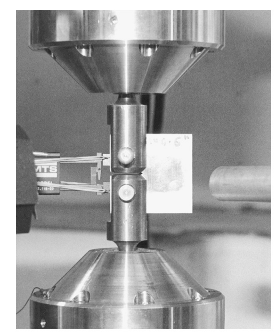
where da/dN = fatigue crack growth rate;

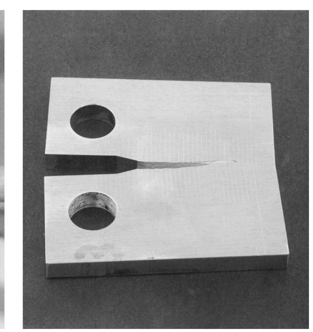
ΔK = stress intensity factor range; and,

C,m = f(material variables, environment, frequency, temperature, stress ratio)

C is the intercept at ΔK = 1; m is the slope

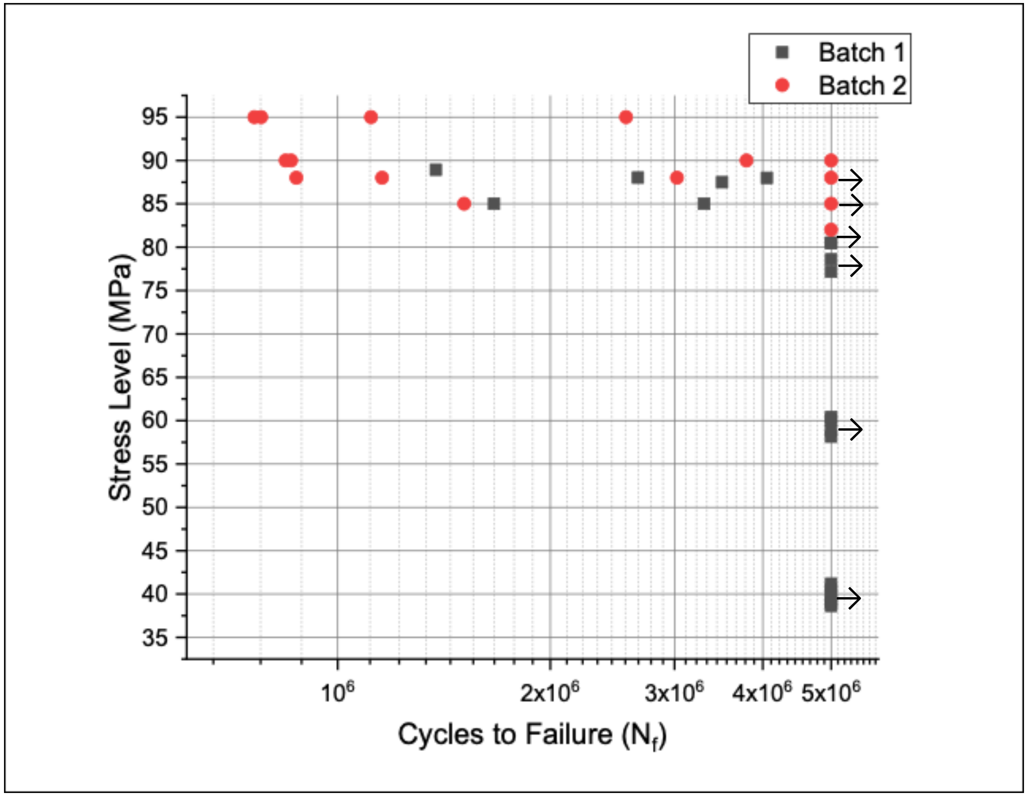


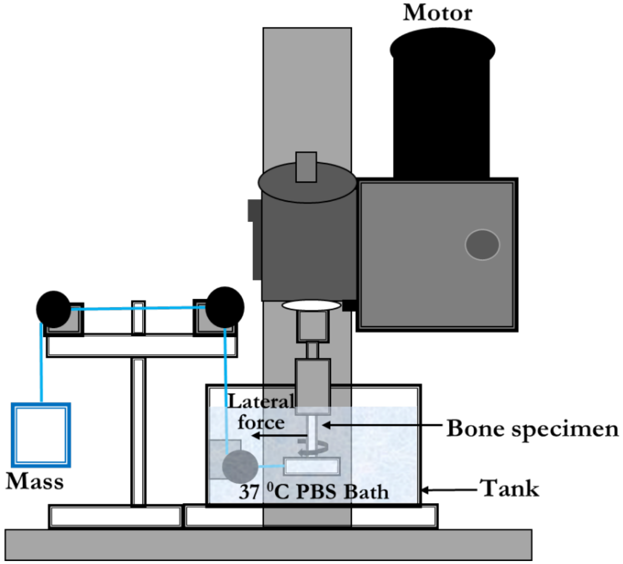




Fatigue Behavior of PEEK Materials
Recent Studies

S-N Fatigue of PEEK

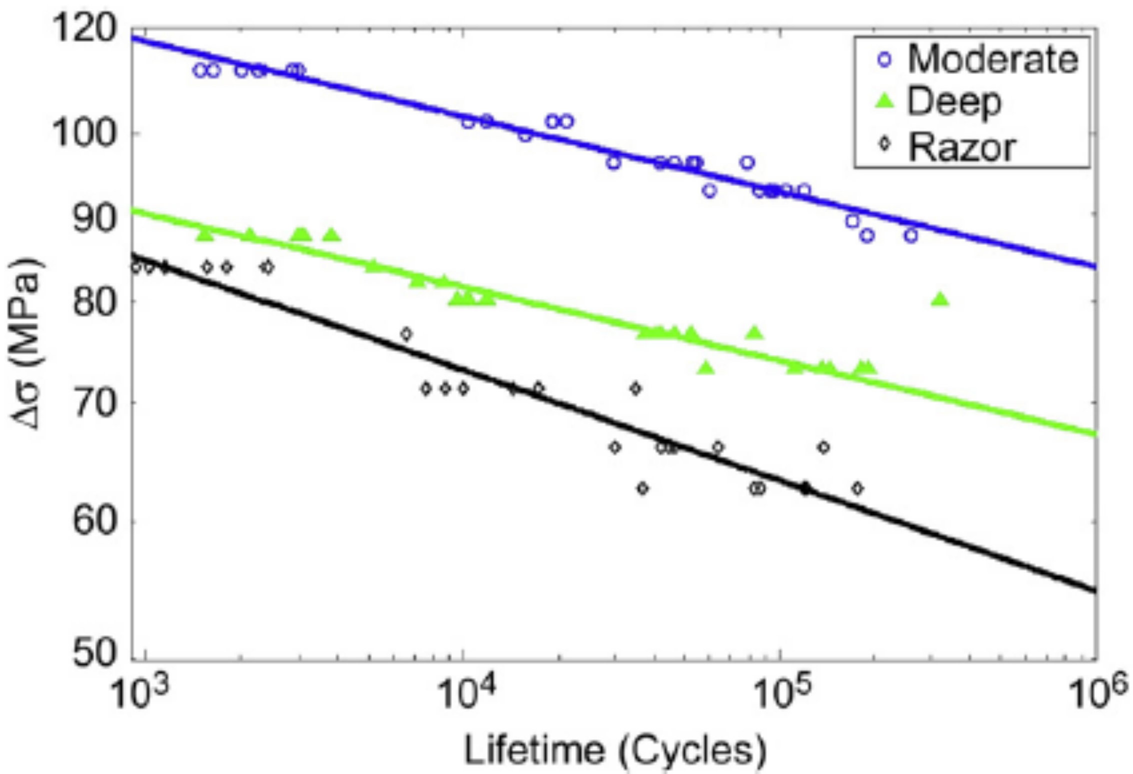


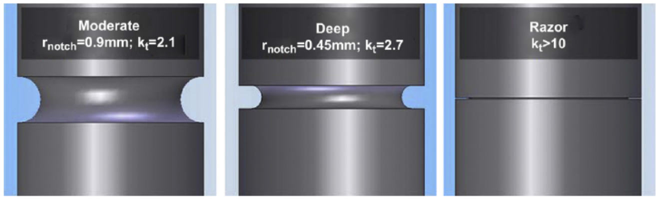


- Very high cyclic stresses (near upper yield point and ultimate stress) required for failure of Injection Molded PEEK
- Unfilled Victrex 450G; rotating cantilever bending, R = -1; 37C PBS solution; 30Hz

Du and Rimnac, Unpublished Data, 2018

S-N Fatigue of PEEK is Notch Sensitive

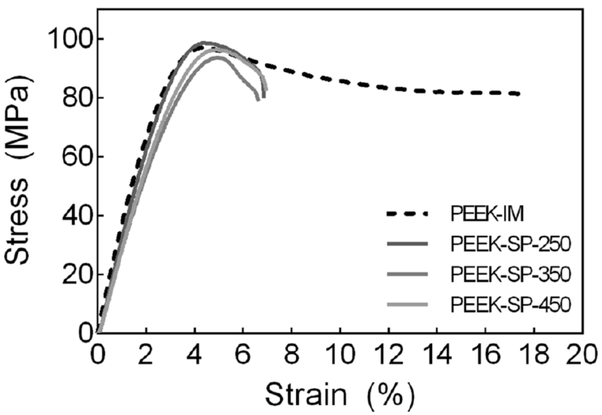


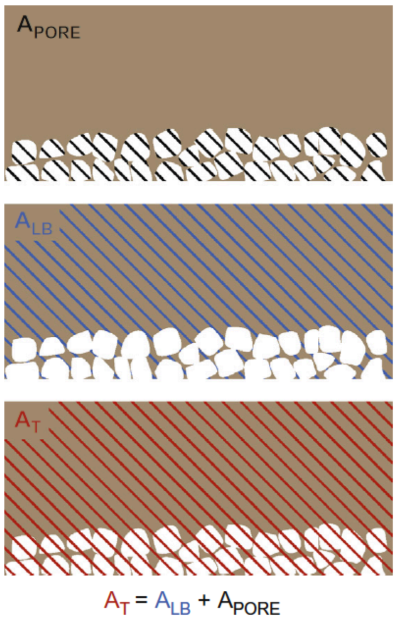


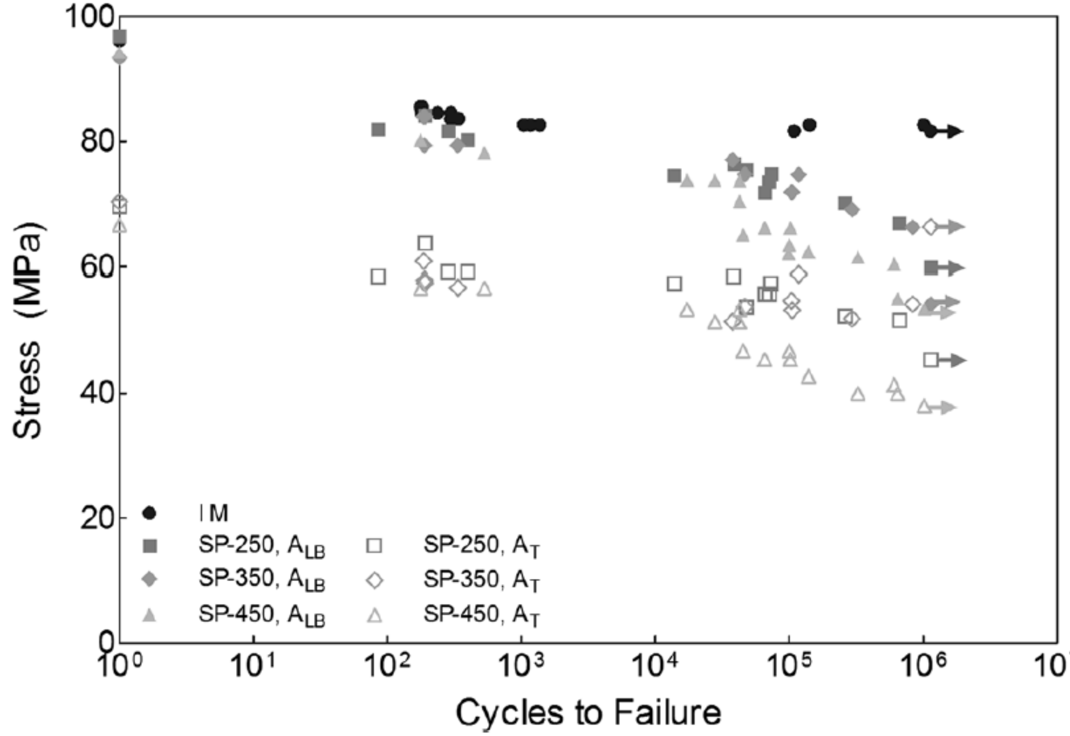
- N_i shortened with increase in notch severity
- Optima LT1, Invibio; R~0; Preconditioned and tested in 37C PBS solution; 2 Hz

Sobieraj et al, Biomaterials, 2010

S-N Fatigue of PEEK is Notch Sensitive

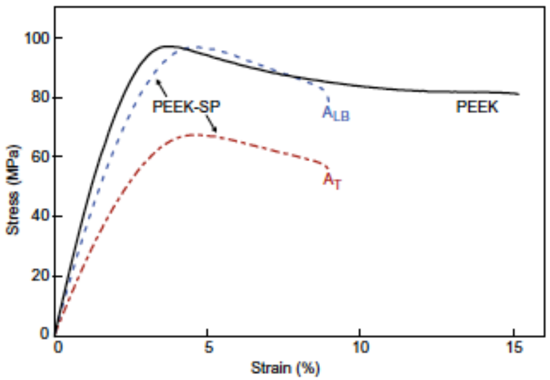


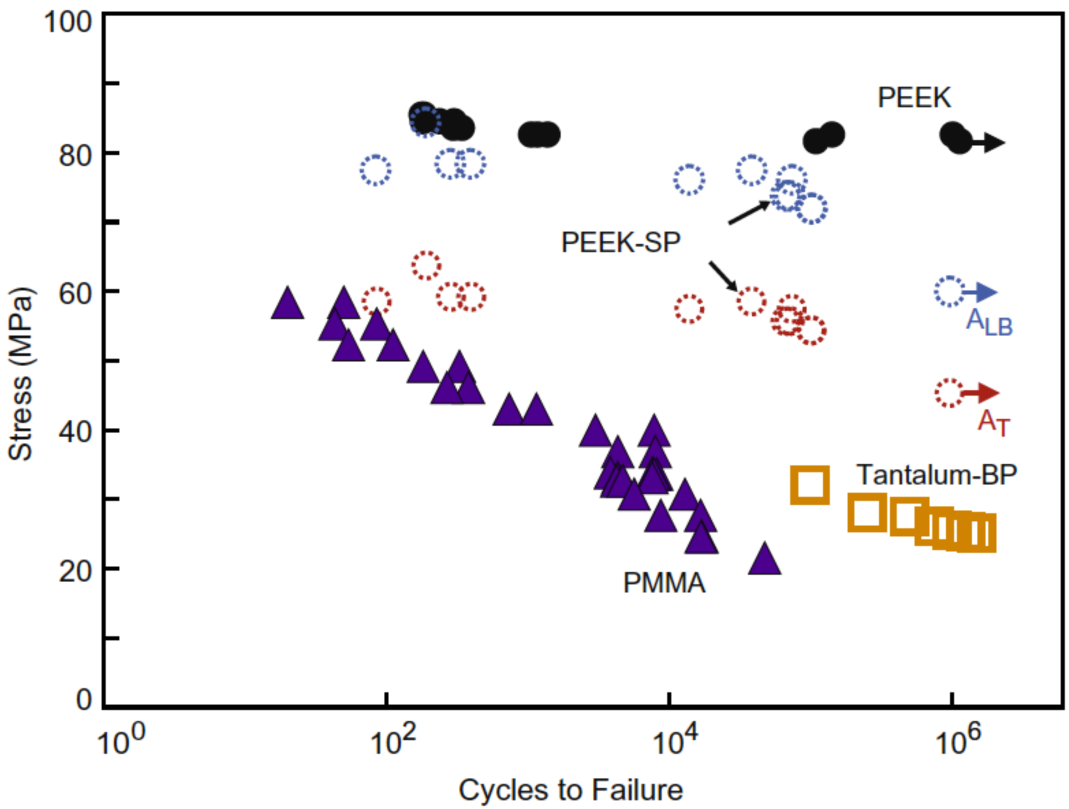




- Again, very high cyclic stresses required for failure of IM PEEK
- Surface porosity negatively affects S-N fatigue life
- Zeniva™ 500, Solvay Specialty Polymers; R = 0.05; RT; 1 Hz

Surface porous PEEK S-N Fatigue Compares Favorably with PMMA and Porous Tantalum





Evans et al., Acta Biomaterialia 2015

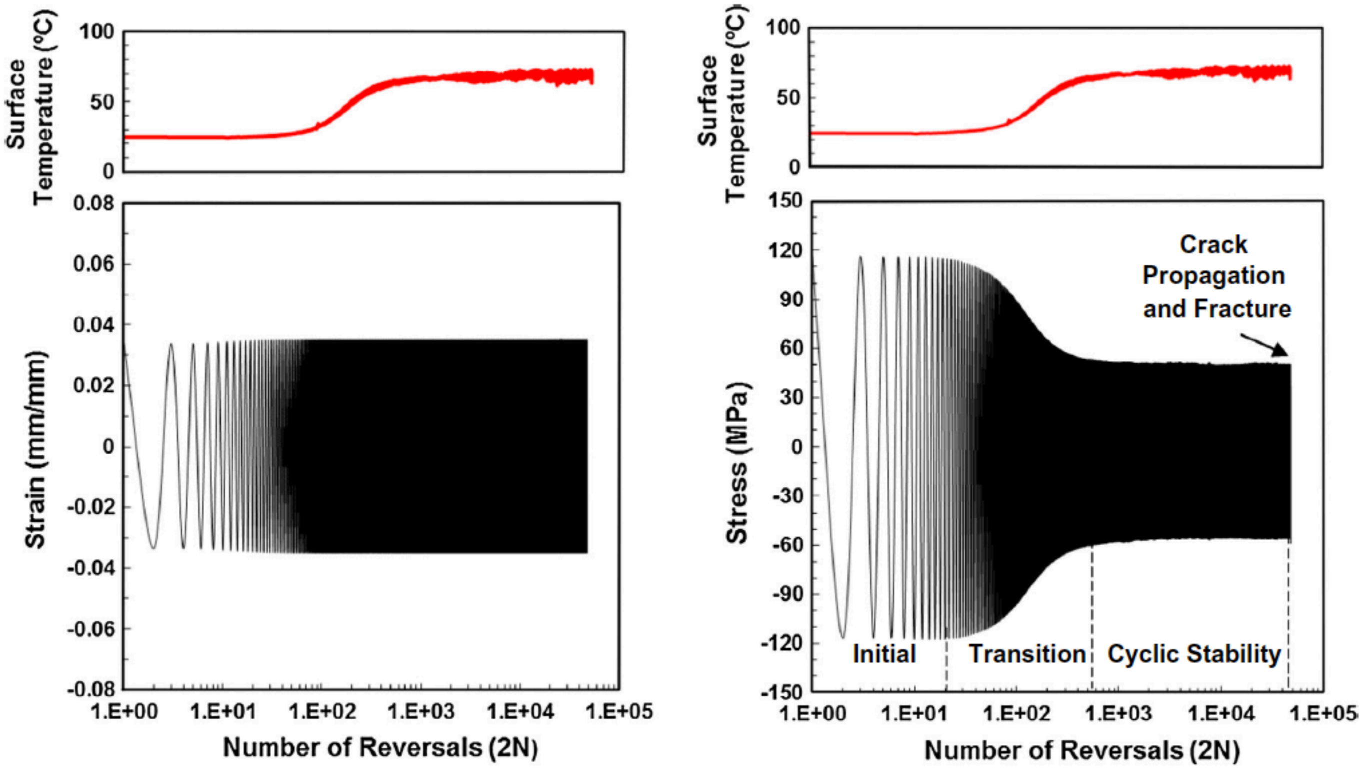
S-N Fatigue of PEEK - Observations

- Unfilled PEEK demonstrates quite good S-N fatigue behavior, at RT and PBS 37C

- Maintains reasonable S-N life with surface porosity

- Notching and severe stress concentrations will reduce life via truncation of N_i

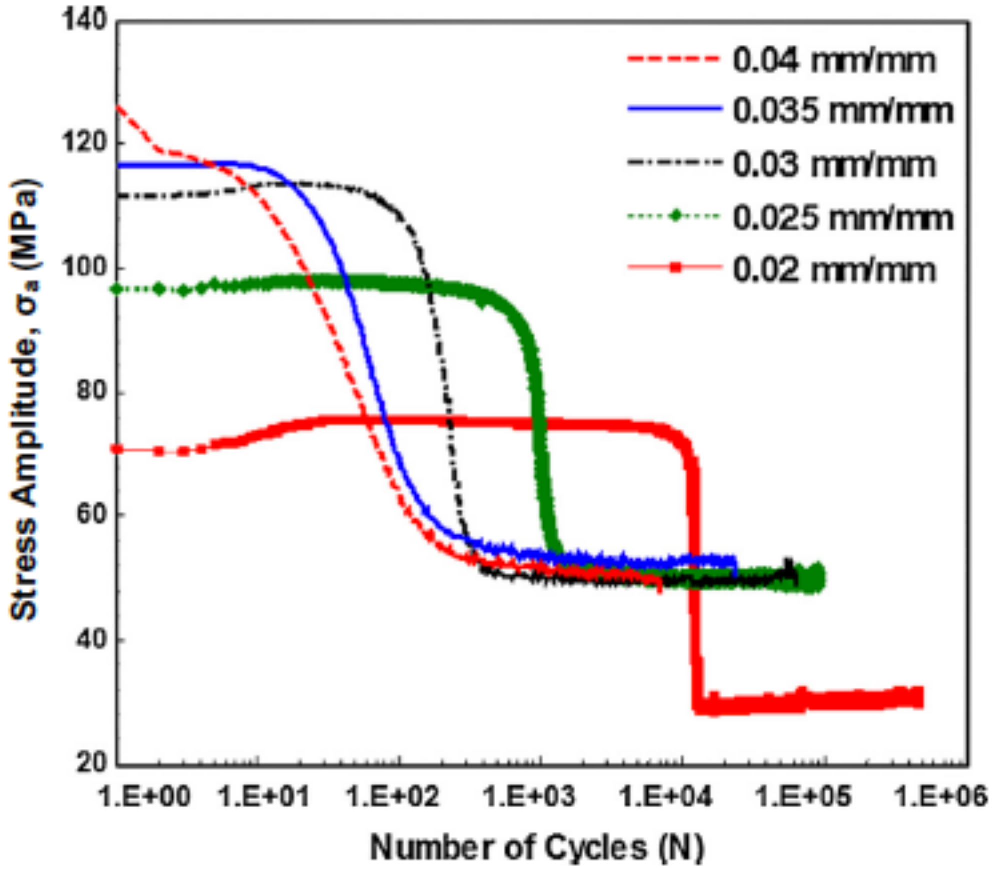
ε-N Fatigue of PEEK



- PEEK exhibits cyclic softening, consistent with other polymers
- Note the surface temperature rise to 50-60C (T_g = 143C); there appears to be a thermal component contribution in these tests (reduction in elastic modulus)
- The presence of a transition is consistent with other thermoplastic polymers
- TECA PEEK™, Ensinger; R= -1 (strain); RT; 0.5 Hz

Shrestha et al, Int J Fat 2016

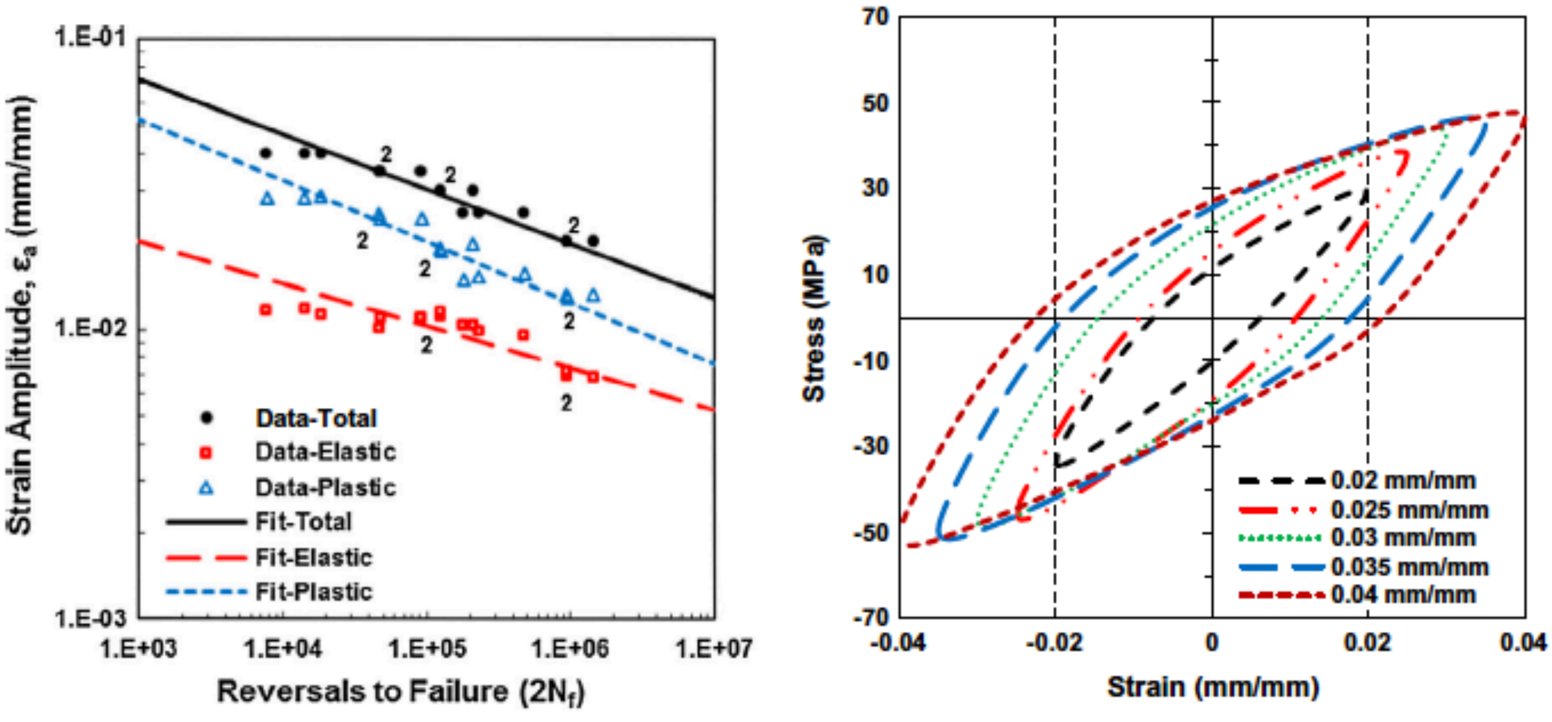
ε-N Fatigue of PEEK



Cyclic softening occurs more rapidly at higher strain rates
At all strain rates, there is an initial phase, followed by transition, followed by steady-state

Shrestha et al, Int J Fat 2016

ε-N Fatigue of PEEK



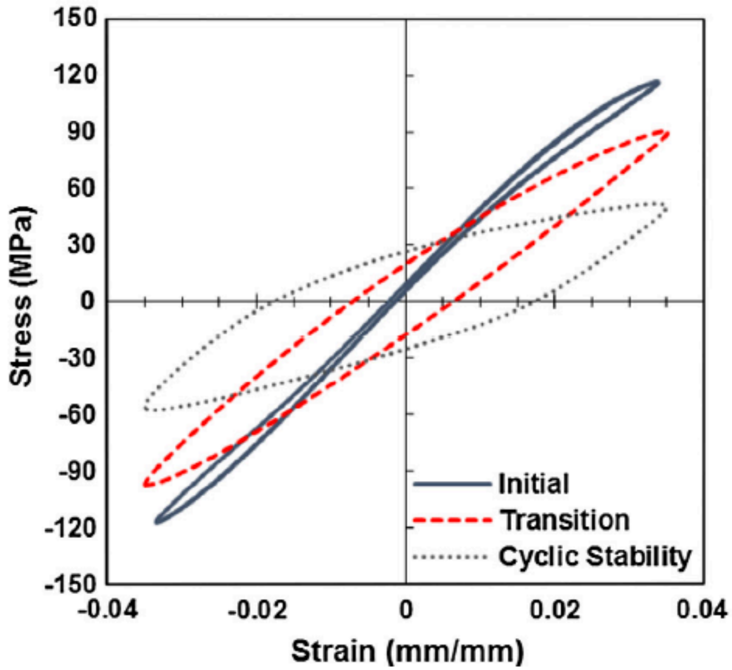
ε-N life can be decomposed into elastic and plastic strains per Manson-Coffin relationship

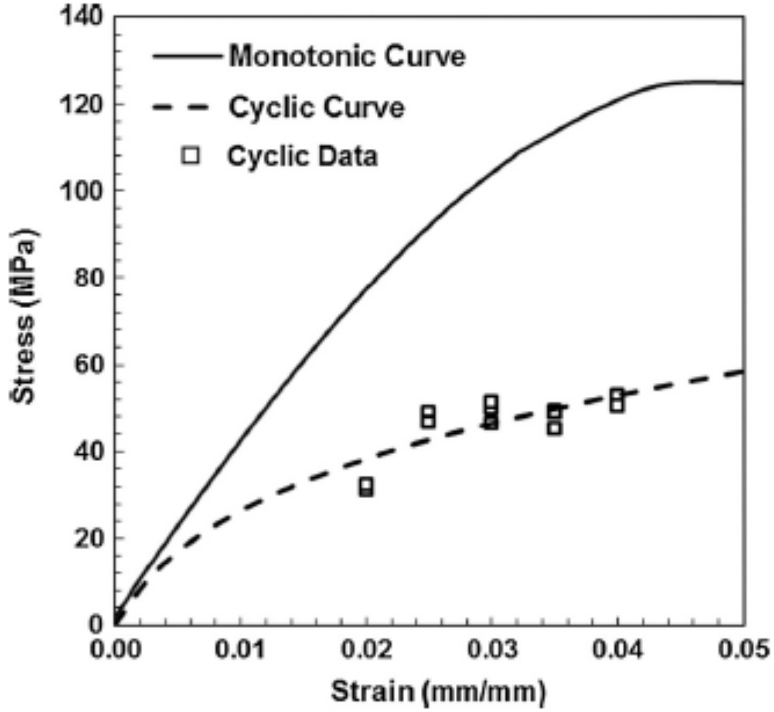
Plastic strains dominate, even in the high cycle fatigue regime

$\varepsilon_a = (\sigma'_f/E)(2N_f)^b + \varepsilon'_f(2N_f)^c$

Shrestha et al, Int J Fat 2016

ε-N Fatigue of PEEK





- With softening, the hysteresis loop is enlarged
- A cyclically-stabilized σ-ε curve can be compared to the monotonic
- Model using a Ramberg-Osgood approach: $\varepsilon_e = \sigma/E \quad \varepsilon_p = (\sigma/K')^{1/n'}$

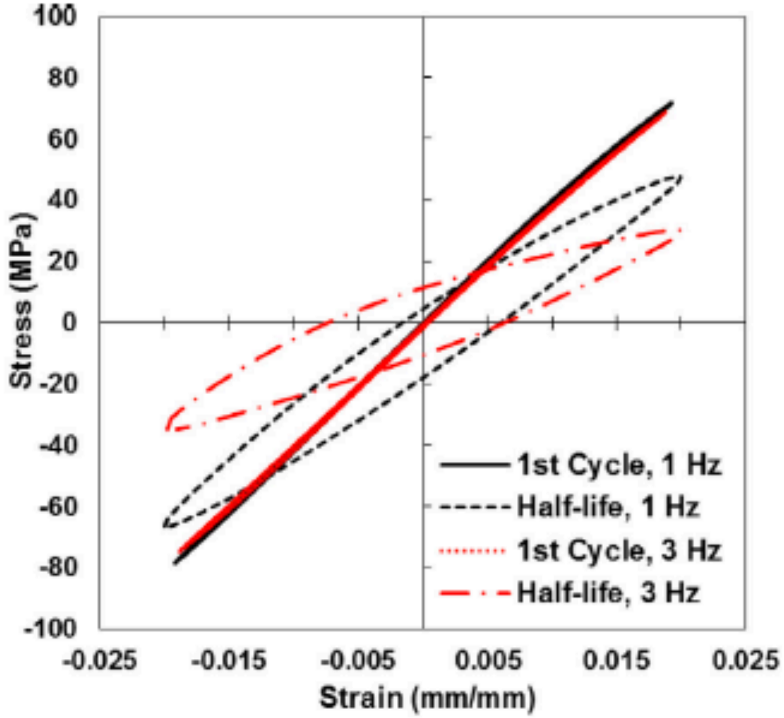
$(\varepsilon_p \rightarrow \sigma = K'\varepsilon^{n'}_p)$

Where K' is the cycle strength coefficient and n' is the cyclic strain hardening exponent

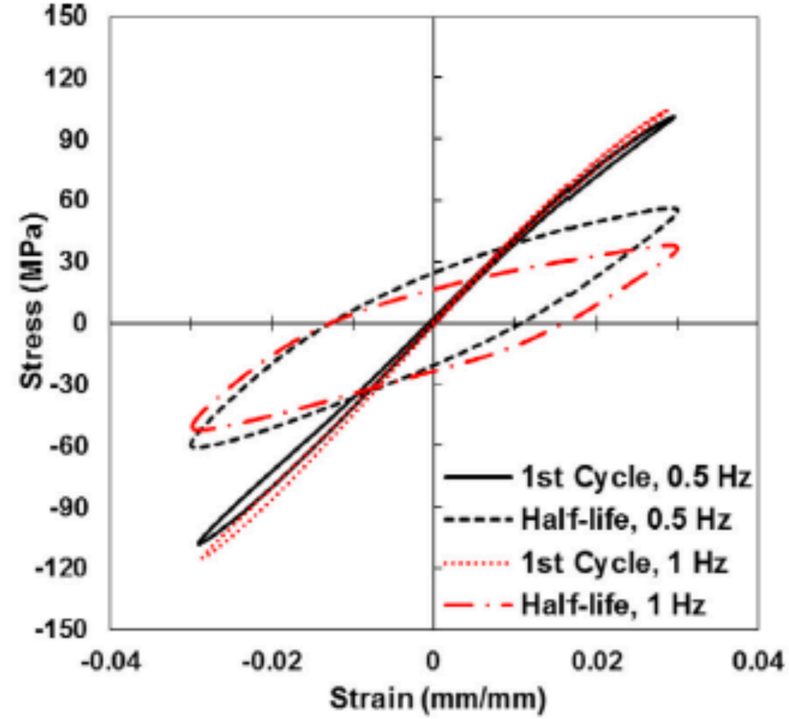
$\varepsilon_a = \varepsilon_e + \varepsilon_p$

Shrestha et al, Int J Fat 2016

ε-N Fatigue of PEEK



(a)

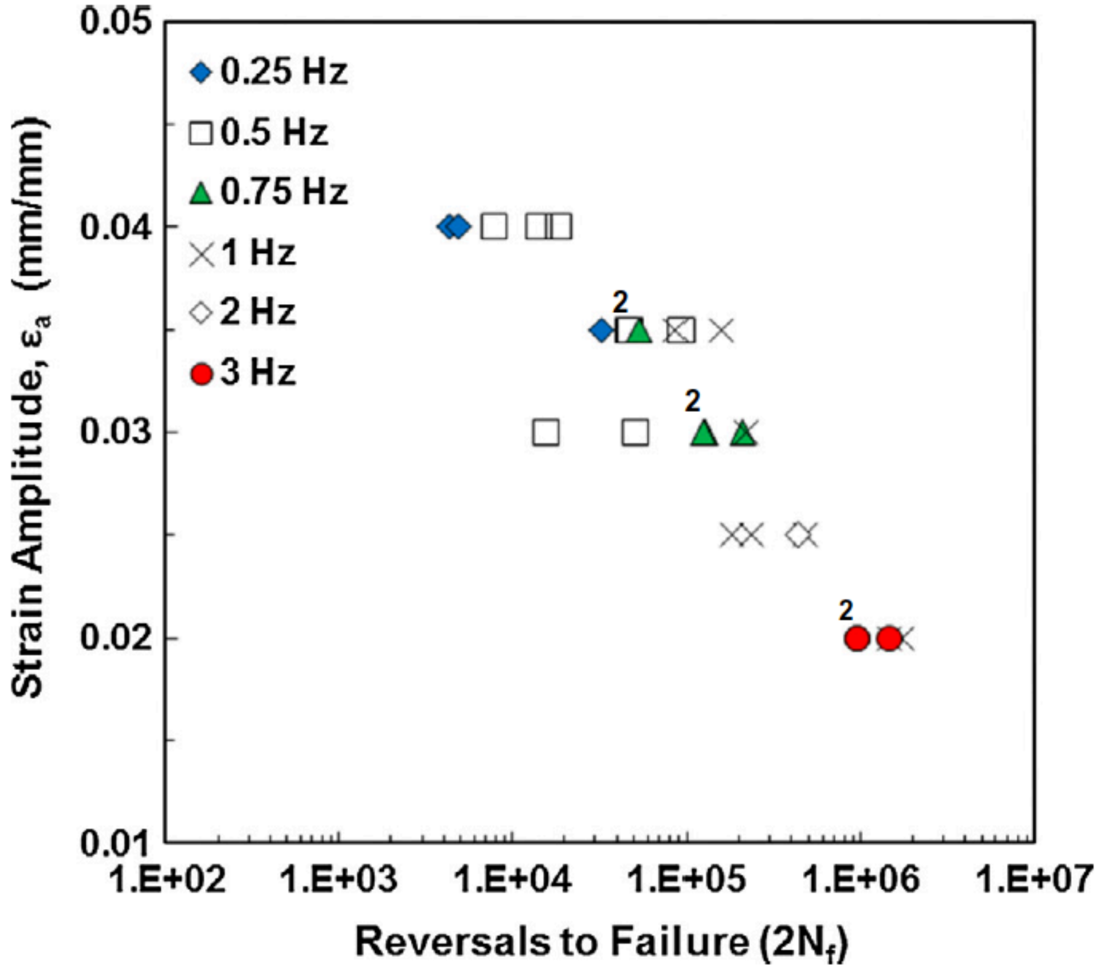


(a)

- Cyclic behavior is affected by test frequency
- Note the hysteresis expansion with increase in test frequency
- Specimen temperature increased somewhat with increase in test frequency
- Degradation in modulus was observed

Shrestha et al, Int J Fat 2016

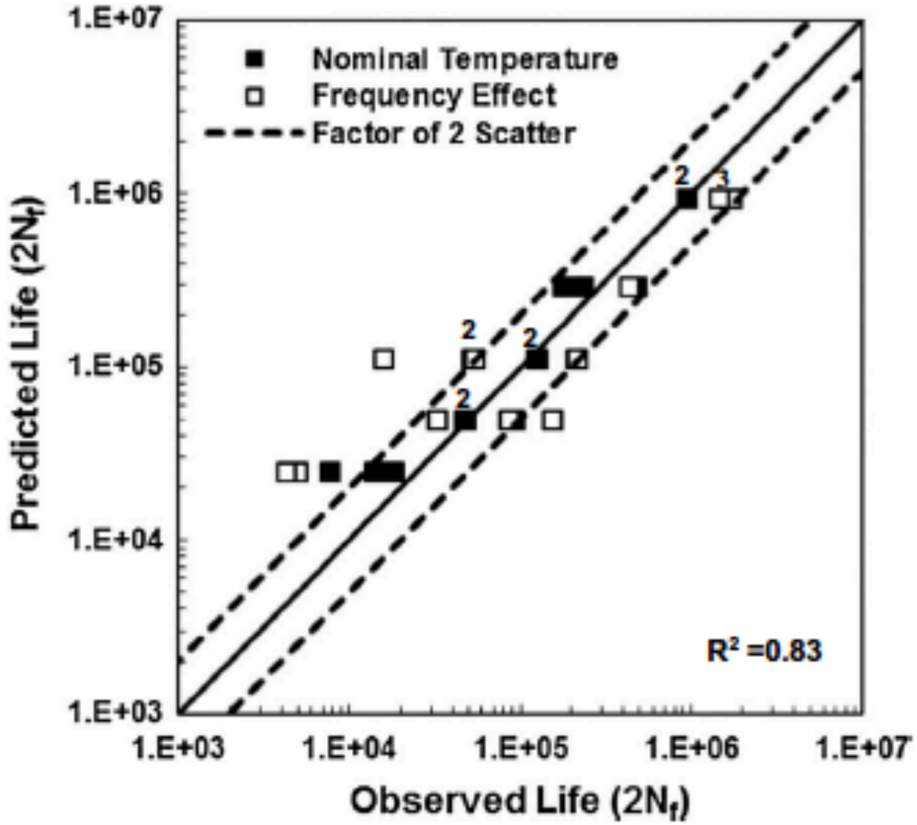
ε-N Fatigue of PEEK



- Cyclic lifetime may increase with an increase in test frequency

Shrestha et al, Int J Fat 2016

ε-N Fatigue of PEEK



ε-N N_f can be reasonably predicted using the Manson-Coffin relationship

Shrestha et al, Int J Fat 2016

ε-N Fatigue of PEEK – crack initiation

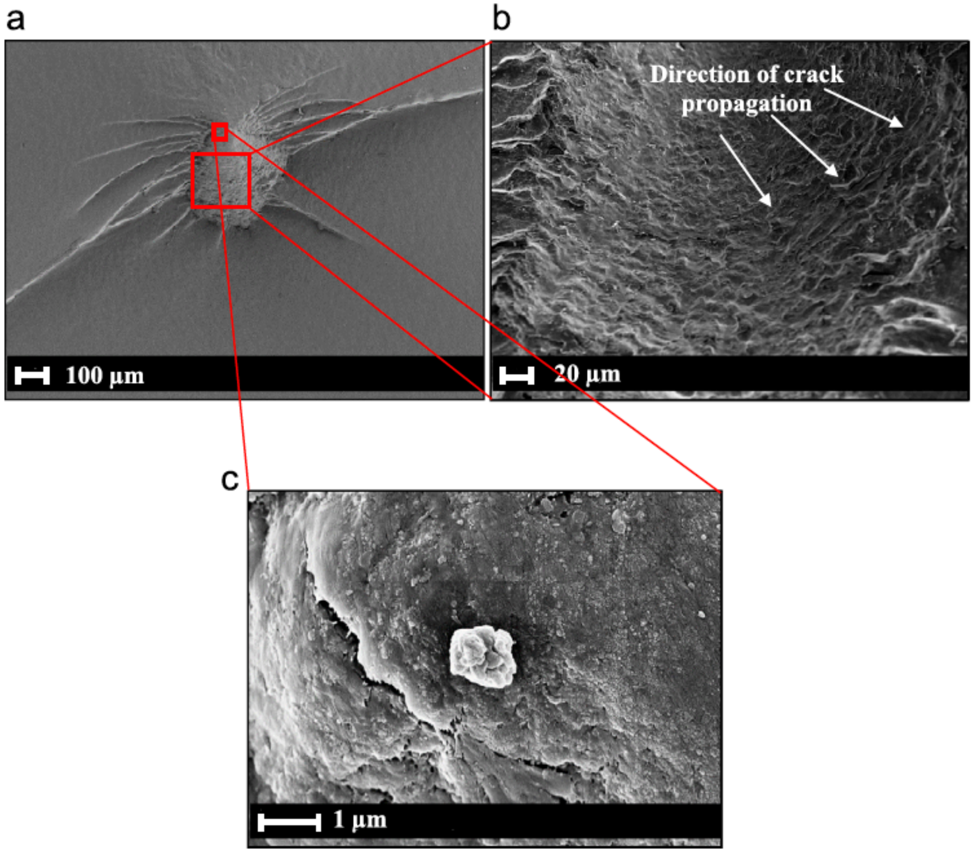


Fig. 7 – (a) Fracture surface of a fatigued specimen at 0.025 mm/mm strain amplitude showing the incubation and crack propagation region, (b) the direction of crack propagation, and (c) incubating particle.

Cracks initiate at micro-inclusions, pores, microcracks; fatigue striations can be identified in stable crack propagation regime

Simsiriwong et al, JMBBM 2015

ε-N Fatigue of PEEK

$$N_{total} = N_{inc} + N_{MSC/PSC} + N_{LC}$$

Where

N_{inc} = cycles to incubate a crack

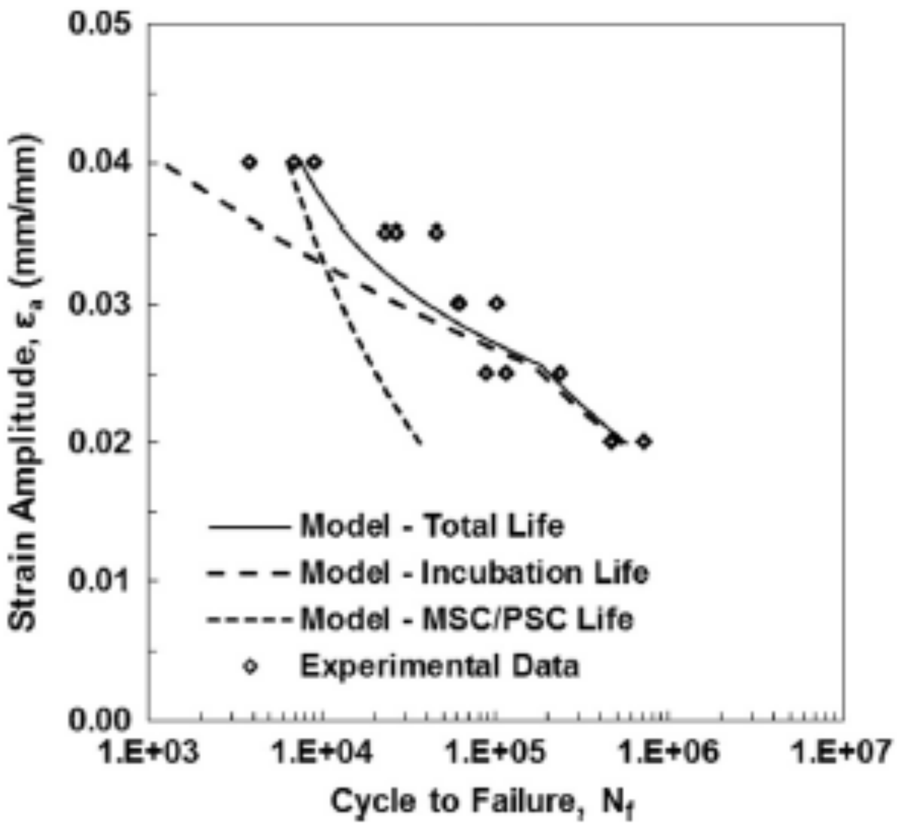
N_{MSC} = cycles, propagation of a microstructurally small crack

N_{PSC} = cycles, propagation of a physically small crack

N_{LC} = cycles for long crack propagation (LEFM regime)

Simsiriwong et al, JMBBM 2015

ε-N Fatigue of PEEK

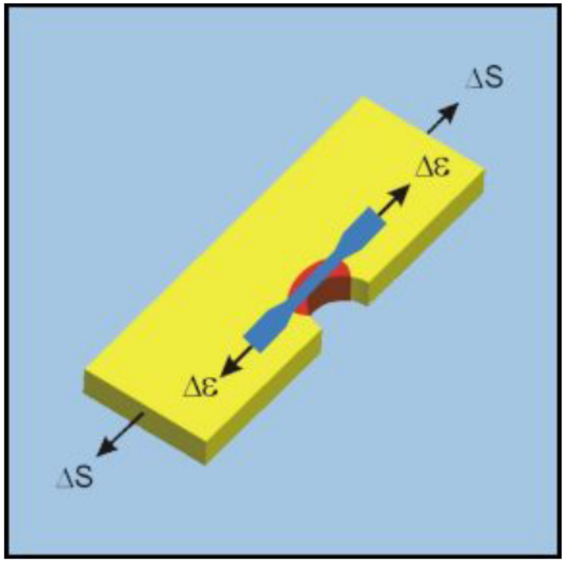


Model appears to be predictive of fatigue life – incubation life dominates at low cyclic strains

Simsiriwong et al, JMBBM 2015

ε-N Fatigue of PEEK - observations

- May be a useful approach to evaluate and predict incubation and initiation of cracks from blunt notches in components where the local conditions are under strain control
- Even low frequency cyclic straining can potentially lead to thermal variations that affect fatigue life; may need to be accounted for unless adiabatic conditions are assured



Fatigue Crack Propagation Behavior of PEEK

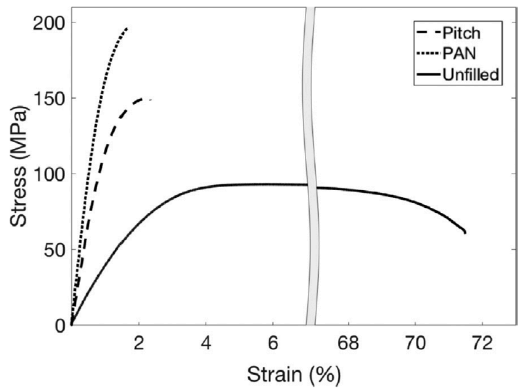
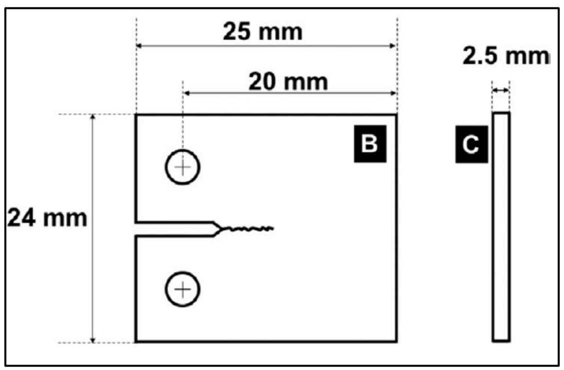
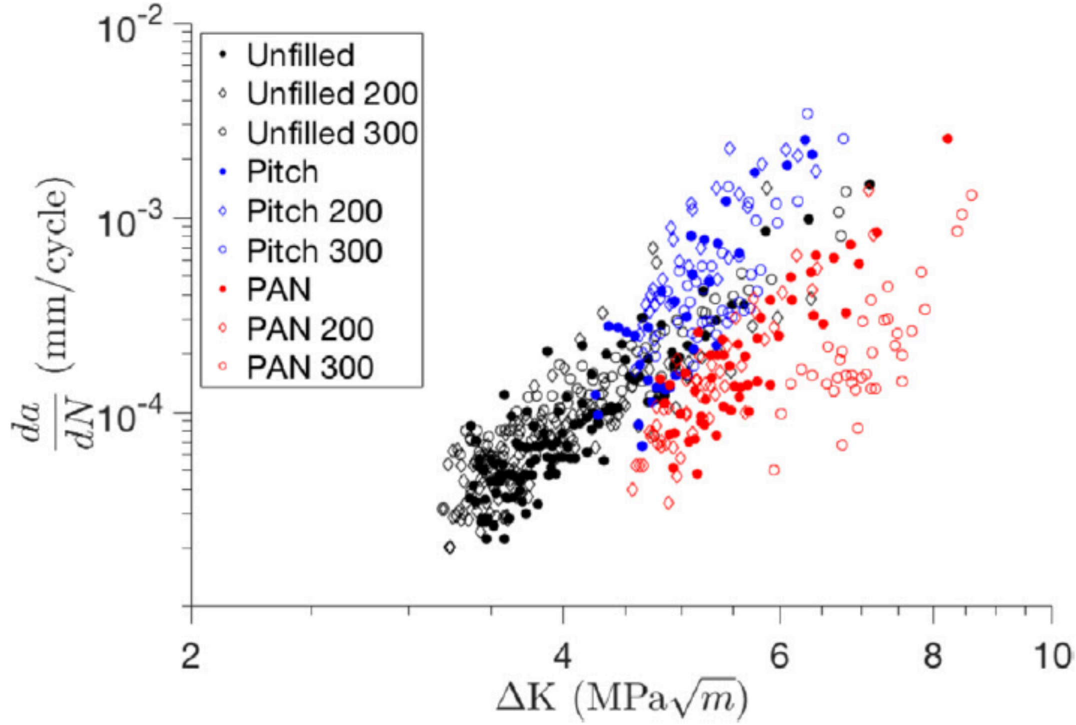


Fig. 2. Representative stress-strain plots for Pitch CFR PEEK, PAN CFR PEEK, and unfilled PEEK (non heat-treated formulations).

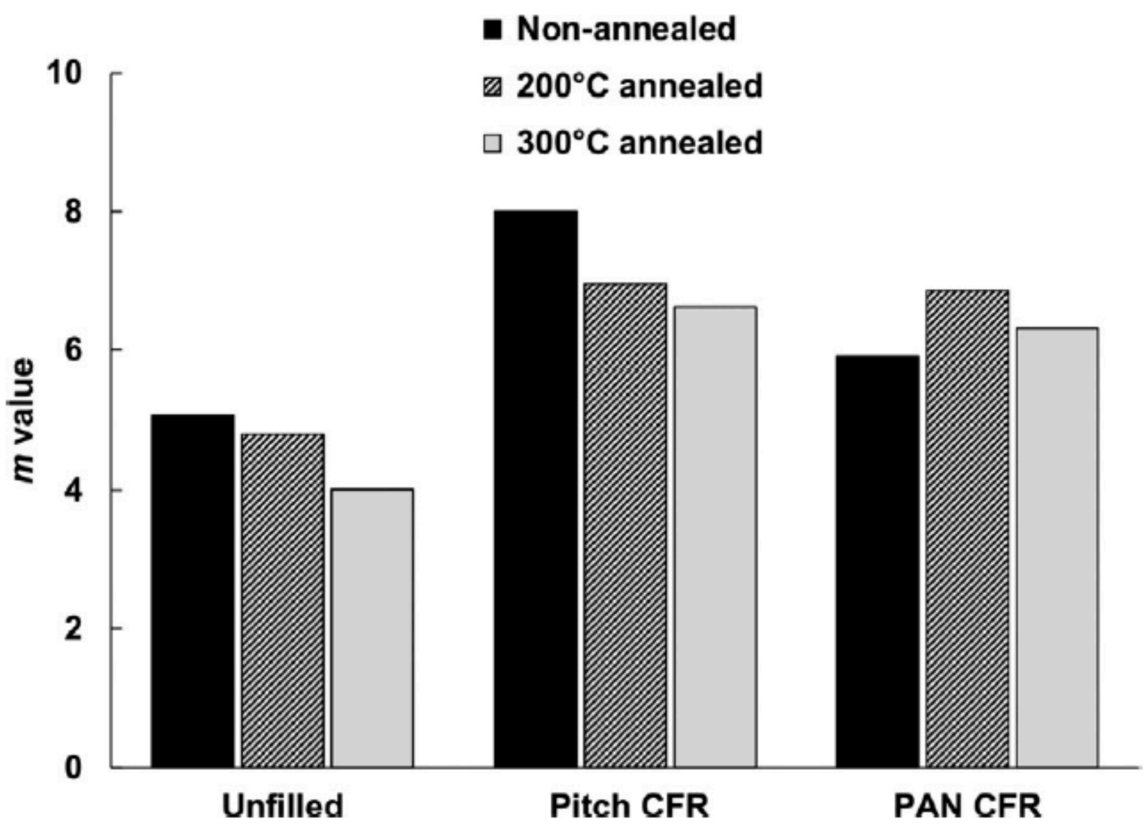




- Carbon fiber reinforcement (PAN) can improve FCP resistance
- PEEK-OPTIMA™ LT1, Invibio; Pitch CFR (PEEK-OPTIMA Wear Performance™); PAN CFR (PEEK-OPTIMA Reinforced™); R= 0.1; RT (air cooled); 5 Hz

Bonnheim et al., JMBBM, 2019

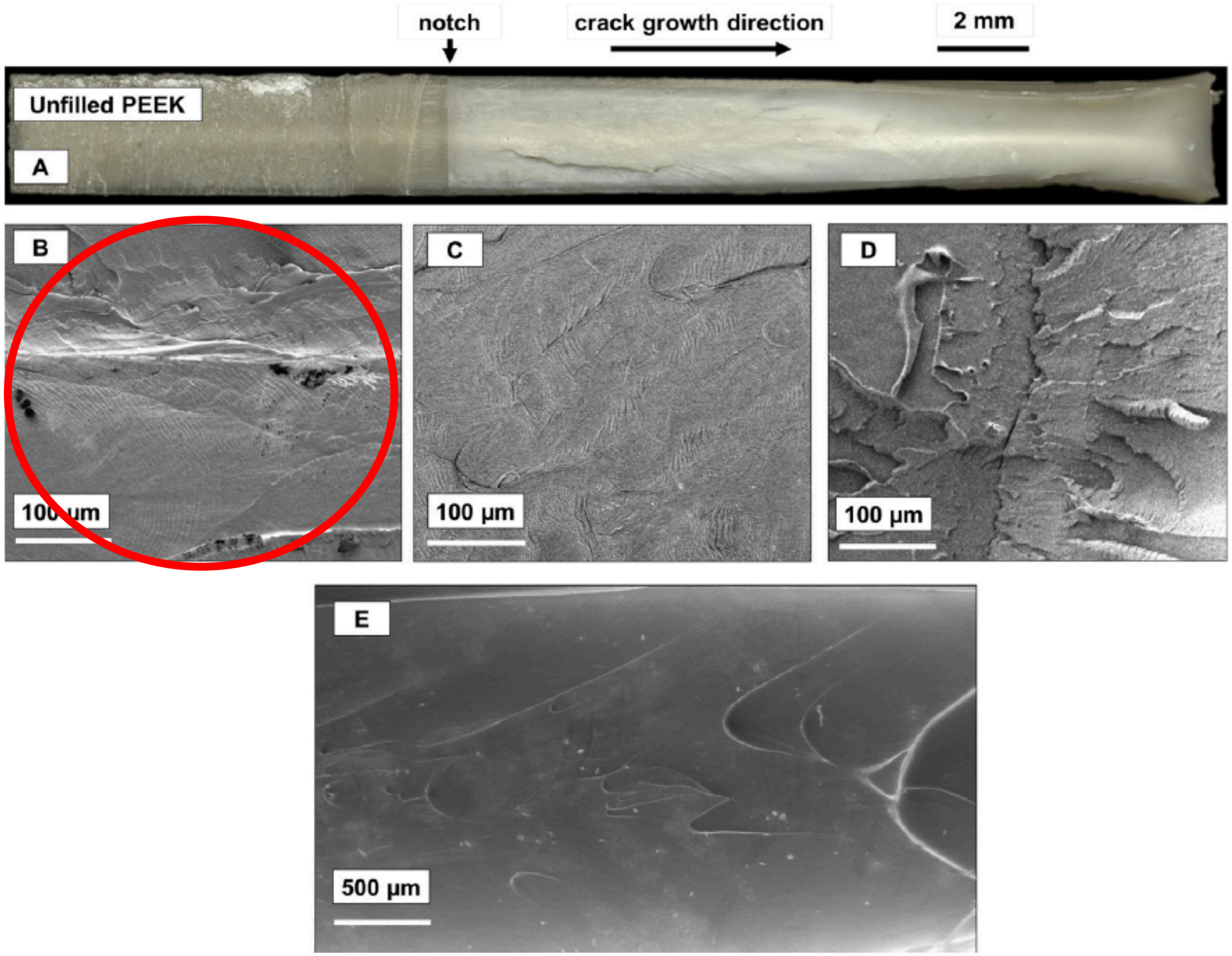
Fatigue Crack Propagation Behavior of PEEK



Carbon fiber reinforced increased m of Paris relationship versus Unfilled, indicating faster fatigue crack growth

Bonnheim et al., JMBBM, 2019

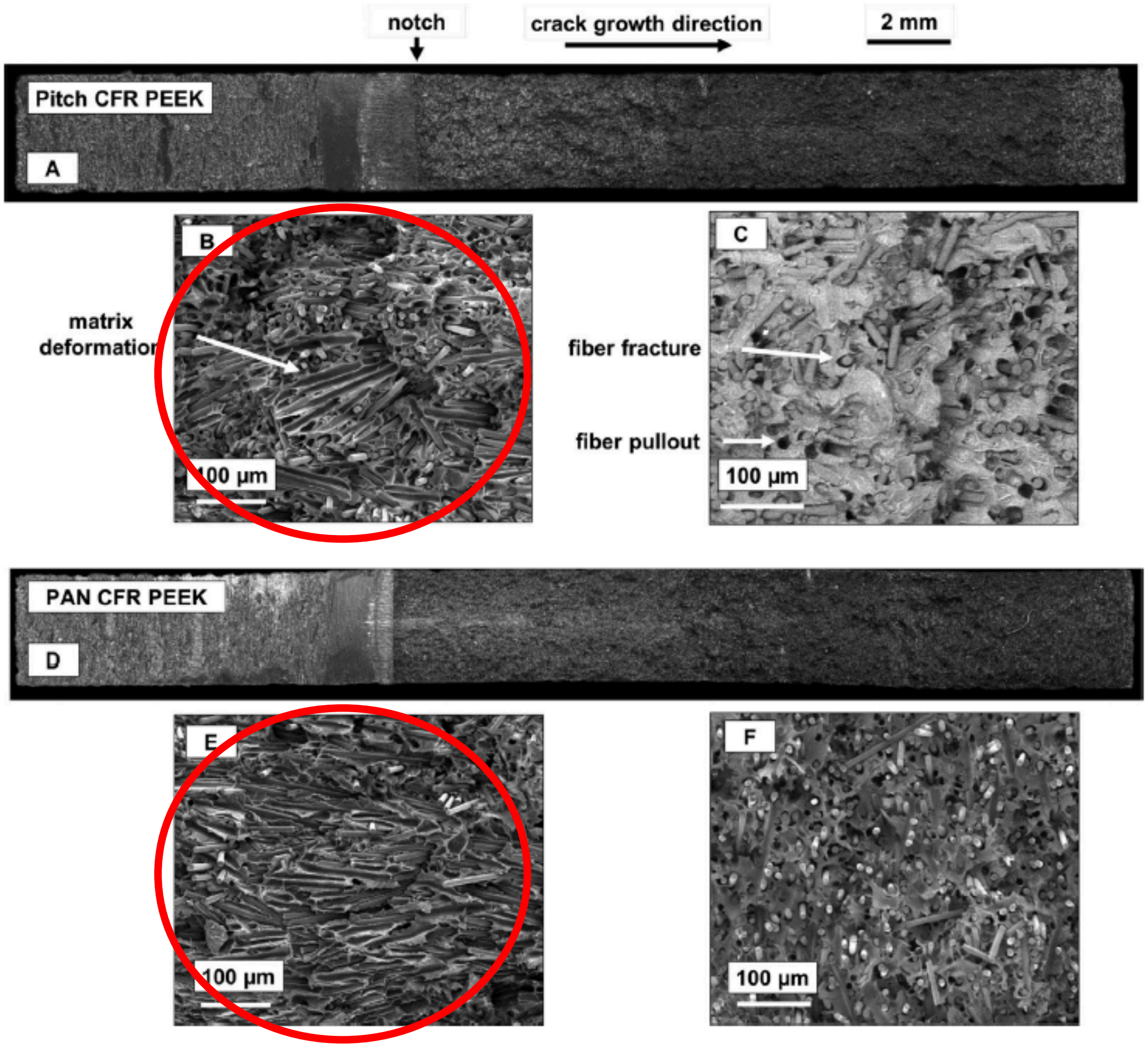
Fracture Appearance



Unfilled PEEK: fatigue striations are evident in stable crack growth regime, transitioning to parabolic markings

Bonnheim et al., JMBBM, 2019

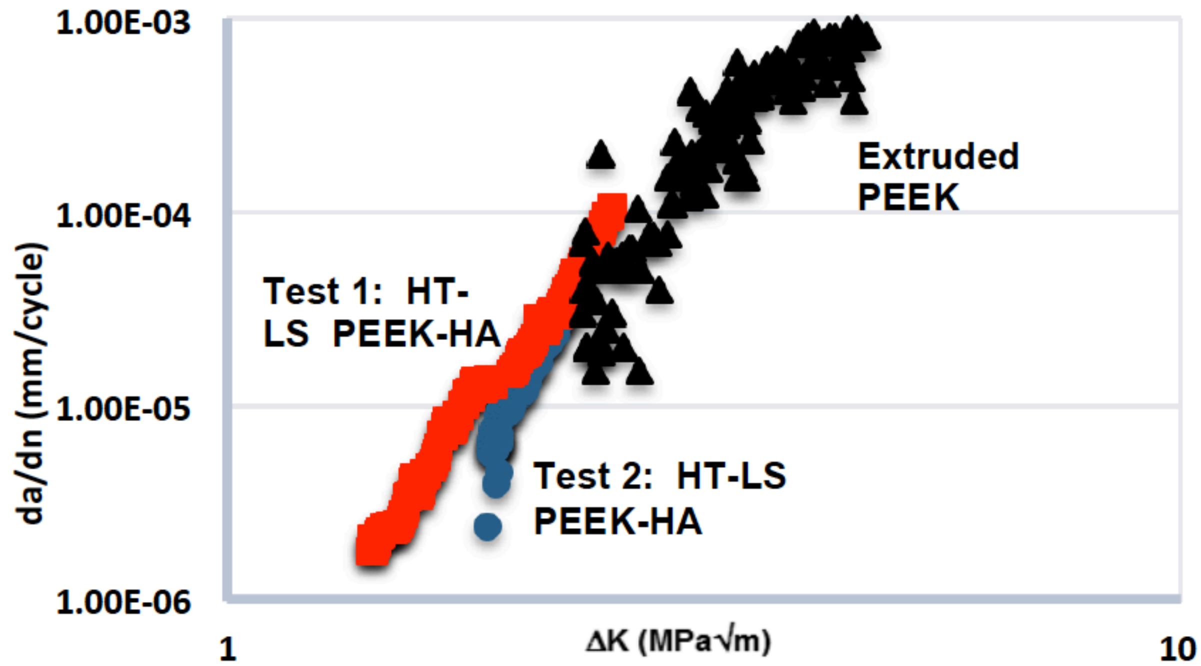
Fracture Appearance

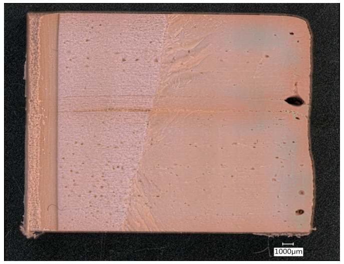


CFR PEEK:
Matrix deformation; fiber pull-out; fiber fracture

Bonnheim et al., JMBBM, 2019

Fatigue Crack Propagation Behavior of PEEK/HA

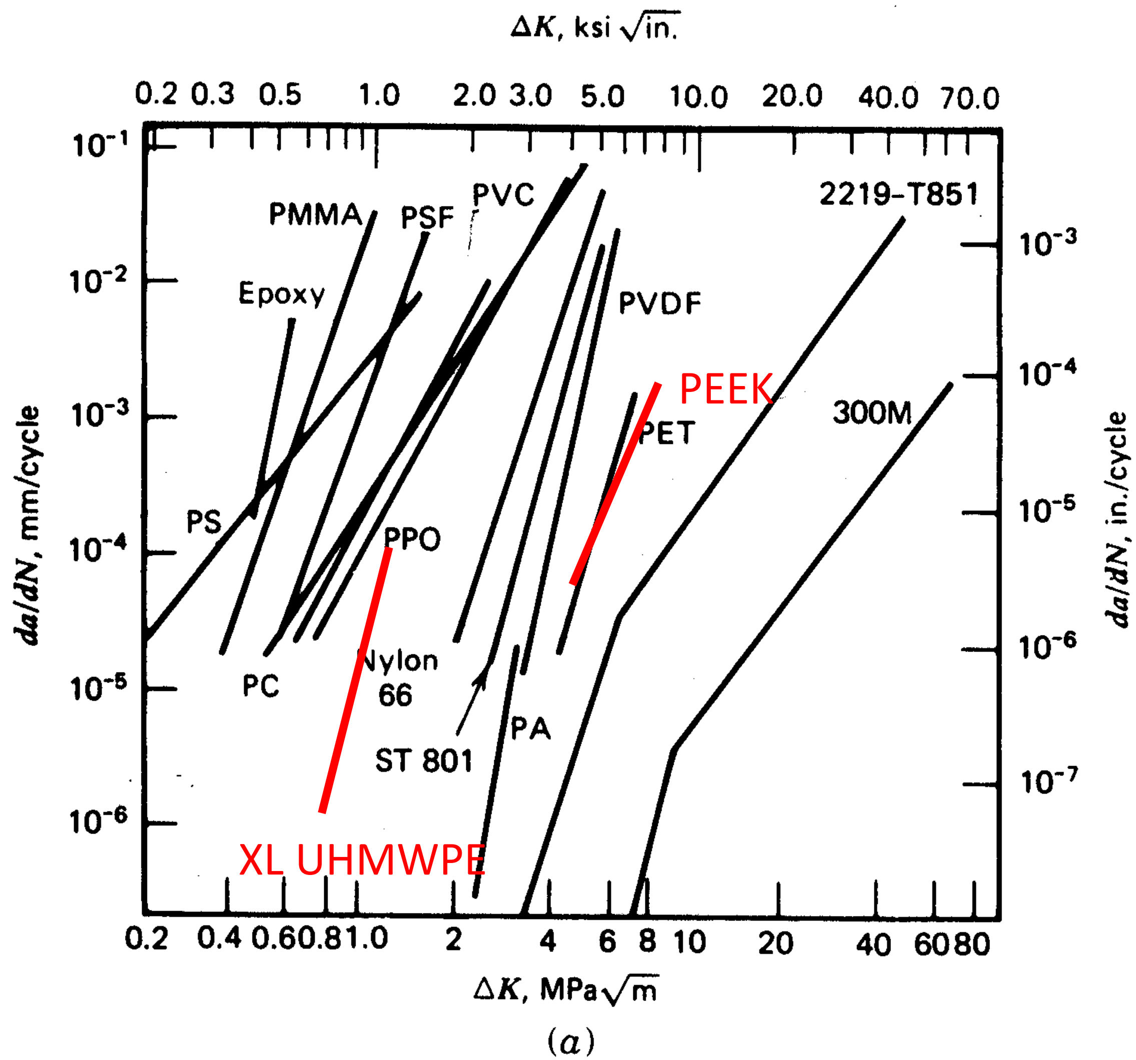




- HT-LS AM PEEK/HA; R = 0.1; RT; 3 Hz
- Achieved stable fatigue crack growth
- Fracture toughness ~
- PEEK OPTIMA® LT1 Invibio, 2% HA; Commercial: Quadrant EPP Ketron 1000

Flanagan et al., Poster 1266, ORS 2018

FCP Behavior of PEEK versus Other Materials



Summary/ Directions for Future Studies

- S-N, ε-N, and fatigue crack propagation resistance of PEEK is generally high and compares favorably with other structural polymers
- S-N is subject to surface conditions; notching
- ε-N is subject to specimen heating arising from cycling
- FCP can be enhanced with CFR (with attention paid to the processing conditions)
- Stable FCP can be achieved in HT-LS PEEK/HA (promising for additively manufactured constructs)

- Still little information on fatigue and fracture performance of medical grade PEEK, particularly for modified and additively manufactured formulations and under physiologically-relevant conditions

Thank you!