Mechanical Properties

- Elastic deformation
- Plastic deformation

- Fracture
  - Fatigue
  - Environmental crack growth
Crack Instability

• The critical crack length for given $\sigma_a$

\[ a_c = Q^{-2} \left[ \frac{K_{lc}}{\sigma_a} \right]^2 \]

• Sources of the critical crack
  – Manufacturing defects
  – Crack growth in service
    • Fatigue
    • Corrosion (H-embrittlement)
Crack Growth to Failure

- Crack growth mechanisms
  - Fatigue (cyclic load)
  - Corrosive crack growth (hydrogen)

- Characteristic pattern:
  - Initiating flaw
    - Defect or corrosion pit
    - Nucleated defect (fatigue)
  - Crack growth to critical size
    - Identify by characteristic fracture mode
      - Corrosion: often intergranular
      - Fatigue: “beach marks”, “striations”
  - Final failure at critical size
    - Crack length $a = a_c$
    - Crack mechanism = expected unstable mode
      - Usually ductile fracture
Example: Failure of a High-Strength Steel Spring in Seawater

- Initiation at a corrosion pit
- Significant 2\textsuperscript{nd} stage growth
  - Intergranular mode
- Final fracture at expected $a_c$
  - Ductile mode
Fatigue

- Phenomenology
  - Cyclic load causes failure at stresses well below ultimate strength
  - Failure is often sudden after a long period of use
  - Material grows “tired” from accumulated wear and tear
    - (Like students and professors, at the tail end of a long semester)

- Two distinct situations:
  - Growth of a pre-existing crack
  - Nucleation and growth of a fresh crack
Fatigue Crack Growth

- **Driving force**
  - Cyclic applied stress ($\Delta \sigma_a$)
  - Cycles crack tip stress ($\Delta \sigma_T$)

- **Growth mechanism**
  - Plastic deformation irreversible
    - Due to hardening
  - Deformation cycle grows crack
    - LeChatelie’s Principle

- **Implications**
  - Crack growth rate $\propto \Delta \sigma_T$
    - Or $\Delta K = \Delta \sigma_T \sqrt{\rho}$
  - Crack grows in steps
    - Leaves marks on fracture surface
    - “fatigue striations”
    - “beach marks”
Fatigue: Microscopic Appearance

- Fatigue striations in SEM
  - Not always visible - best in low-strength materials
  - Sometimes only one per cycle
    - Can compute crack growth rate and back out stress
Fatigue Crack Growth Rate

- Crack growth driven by $\Delta K$
  \[ \Delta K = Q(\Delta \sigma_a)\sqrt{a} \]
  - No growth below threshold ($\Delta K_{th}$)
  - Power law at intermediate $\Delta K$
    \[ \frac{da}{dn} = A(\Delta K)^m \] - “Paris Law”
    - $m \sim 2$ for steels
- Crack tip acceleration
  - As $a$ increases, $\Delta K$ increases
  - Crack growth rate accelerates
  - Often have very rapid growth near $a_c$
  - Crack is not safe because it is small
Fatigue: Macroscopic Appearance

- Crankshaft fatigue in an aircraft engine
  - Pre-existing cracks
  - Visible beach marks
  - Instability and failure
Fatigue via Crack Nucleation and Growth

- Assume no meaningful pre-existing crack
- Cyclic deformation to failure
  - Life (cycles) decreases exponentially with cyclic stress amplitude
  - For about 90% of life, damage accumulates without cracking
  - At about 90% of life, cracks nucleate and grow to failure
- Fatigue limit
  - No growth in $10^8$ cycles when $\Delta \sigma < \Delta \sigma_f$
Fatigue Damage

• Prior to crack nucleation
  – Increase in dislocation density
  – Reconfiguration of dislocations (well-defined dislocation “cells”)
  – Damage is internal, very difficult to detect

• Eventual crack nucleation at well-developed cell walls

P. Lukas et al. Z. Metallkd. 56 (1965) 109
Low-Cycle Fatigue

- Crack nucleation, growth and failure in a Ti rod
  - Loaded a few hundred cycles in tension and torsion
Defeating Fatigue: Design for Infinite Life

- Cyclic stress below fatigue limit
  - Asymptote on s-n curve
  - Cyclic s like that in service
  - Note $s_1$ is a median value
  - $s \ll s_1$ for confidence

- Cyclic stress intensity below threshold
  - Combination of stress and crack size
  - Requires inspection

\[
\Delta K = Q\Delta \sigma \sqrt{a}
\]

\[
a_t = Q^{-2} \left[ \frac{\Delta K_t}{\Delta \sigma} \right]^2
\]
Defeating Fatigue: Design for Safe Life

- From s-n curve
  - Restrict allowed cycles to safe value
  - Problems:
    - counting meaningful cycles
    - no good NDE before cracking

- From crack growth curve
  - Use NDE
    - Assume worst possible flaw ($a_0$)
  - Choose “safe” inspection interval ($n'$)
  - Use NDE
    - Restart clock if no flaw detected
    - Retire or repair if flaw detected