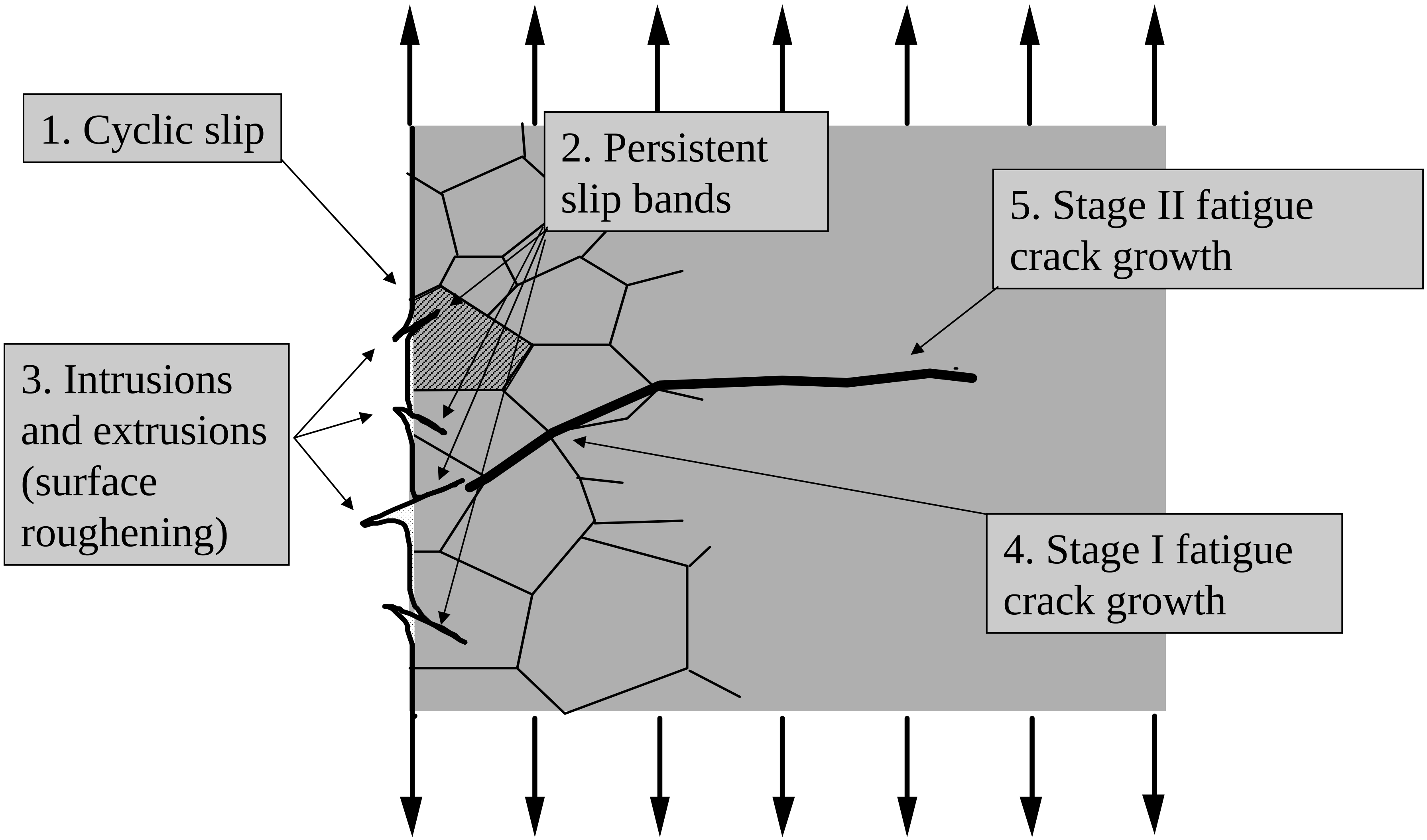
Modelling

Fred Lawrence
University of Illinois at Urbana
flawrenc@uiuc.edu & [217] 333-6928

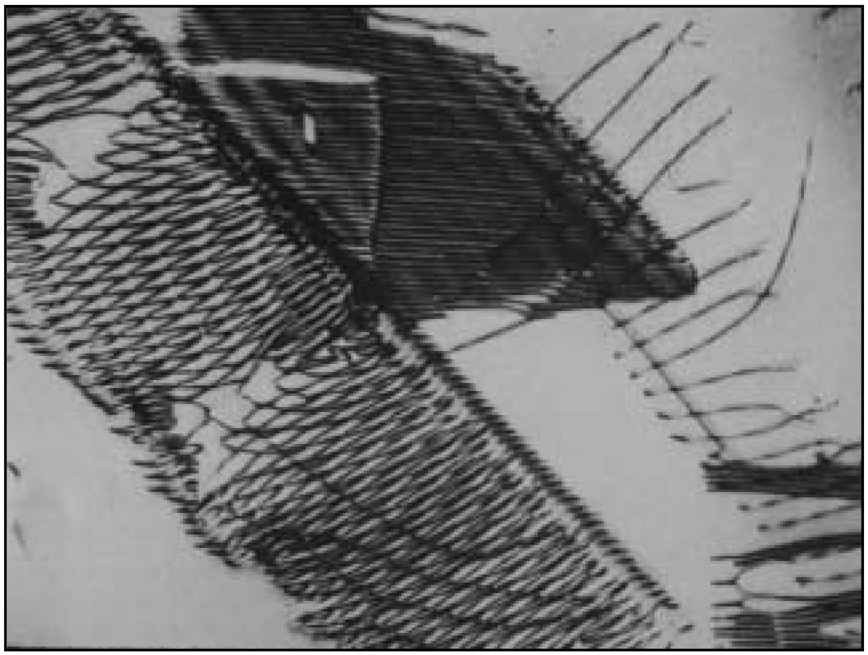
Outline

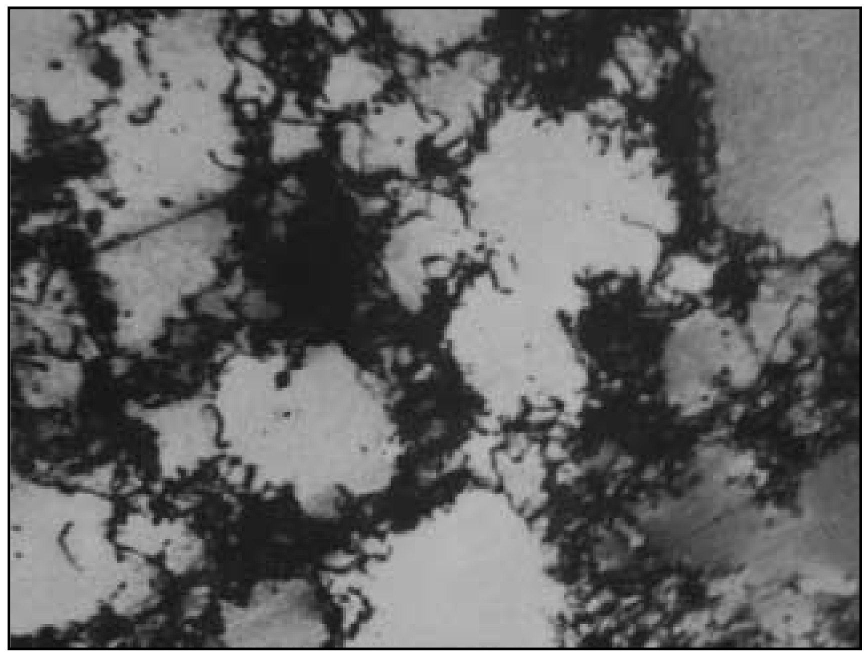
- Fatigue mechanisms
- Sources of knowledge
- Modelling
  - Crack nucleation
  - Non propagating cracks
  - Crack growth

Stages in the development of a fatigue crack



Cyclic slip





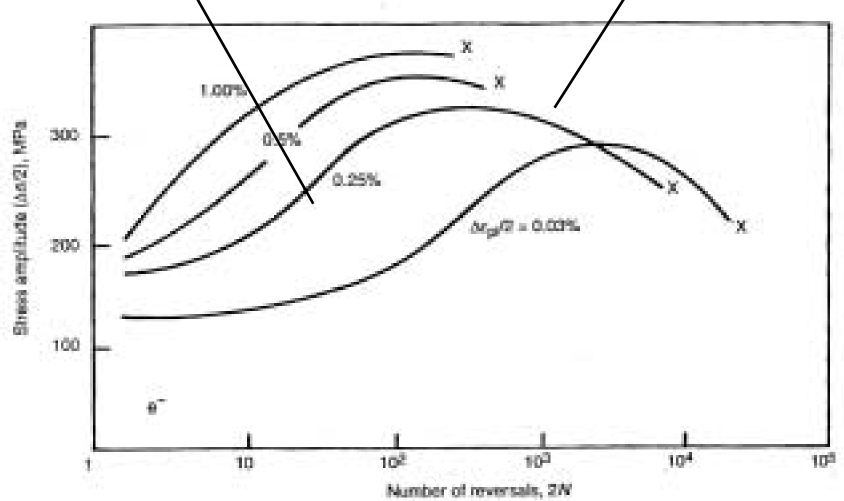
First cycle

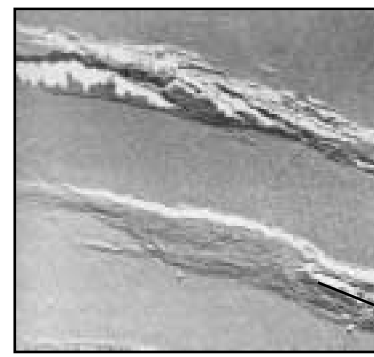
Many cycles later - cyclic hardening

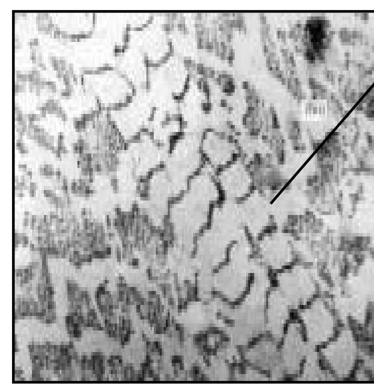
Cyclic stress-strain behavior

- Development of cell structures (hardening)
- Increase in stress amplitude (under strain control)
- Break down of cell structure to form PSBs
- Localization of slip in PSBs

cyclic hardening   cyclic softening







PSB

Slip Band Formation

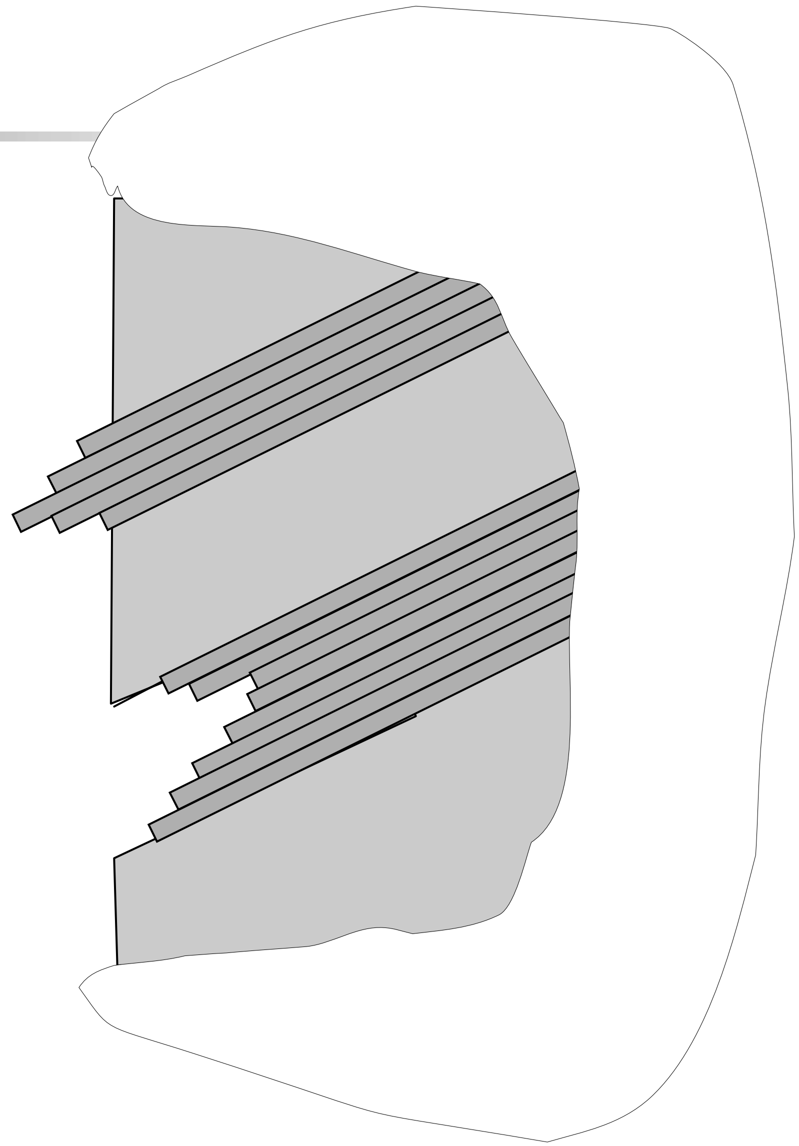
Cyclically hardened material

Extrusion

Cyclically hardened material

Intrusion

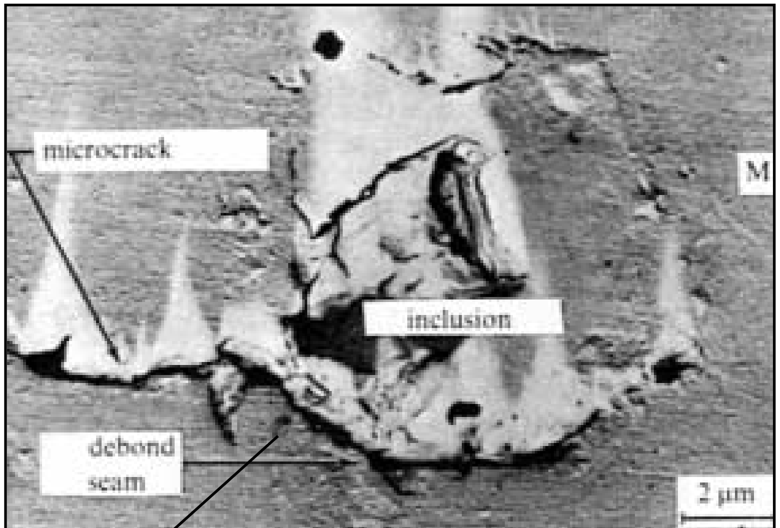
Cyclically hardened material

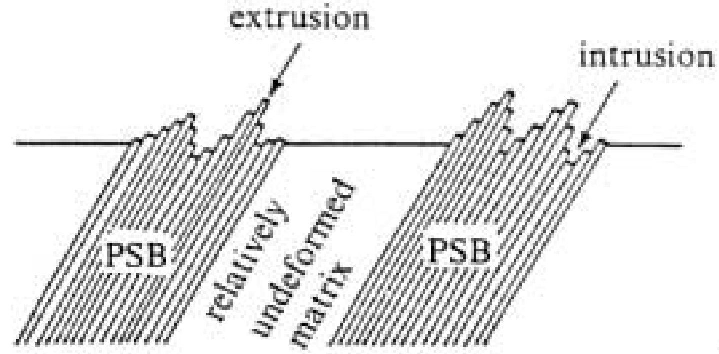


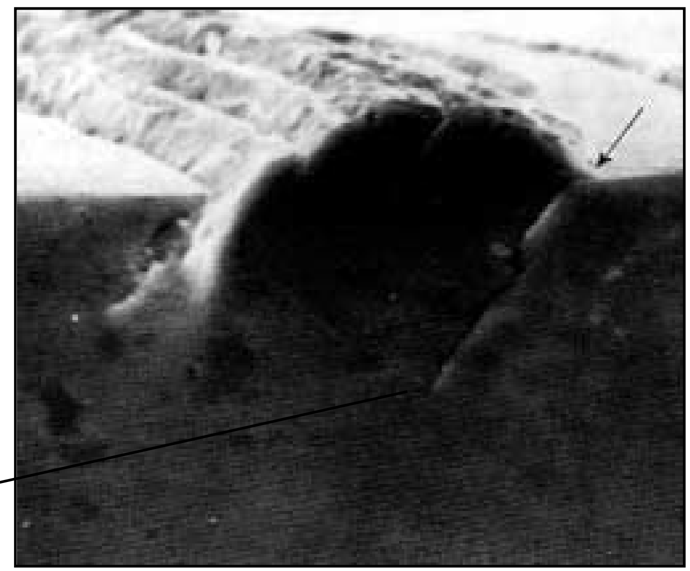
Intrusions and extrusions

Intrusions and extrusions on the surface of a Ni specimen

Crack initiation

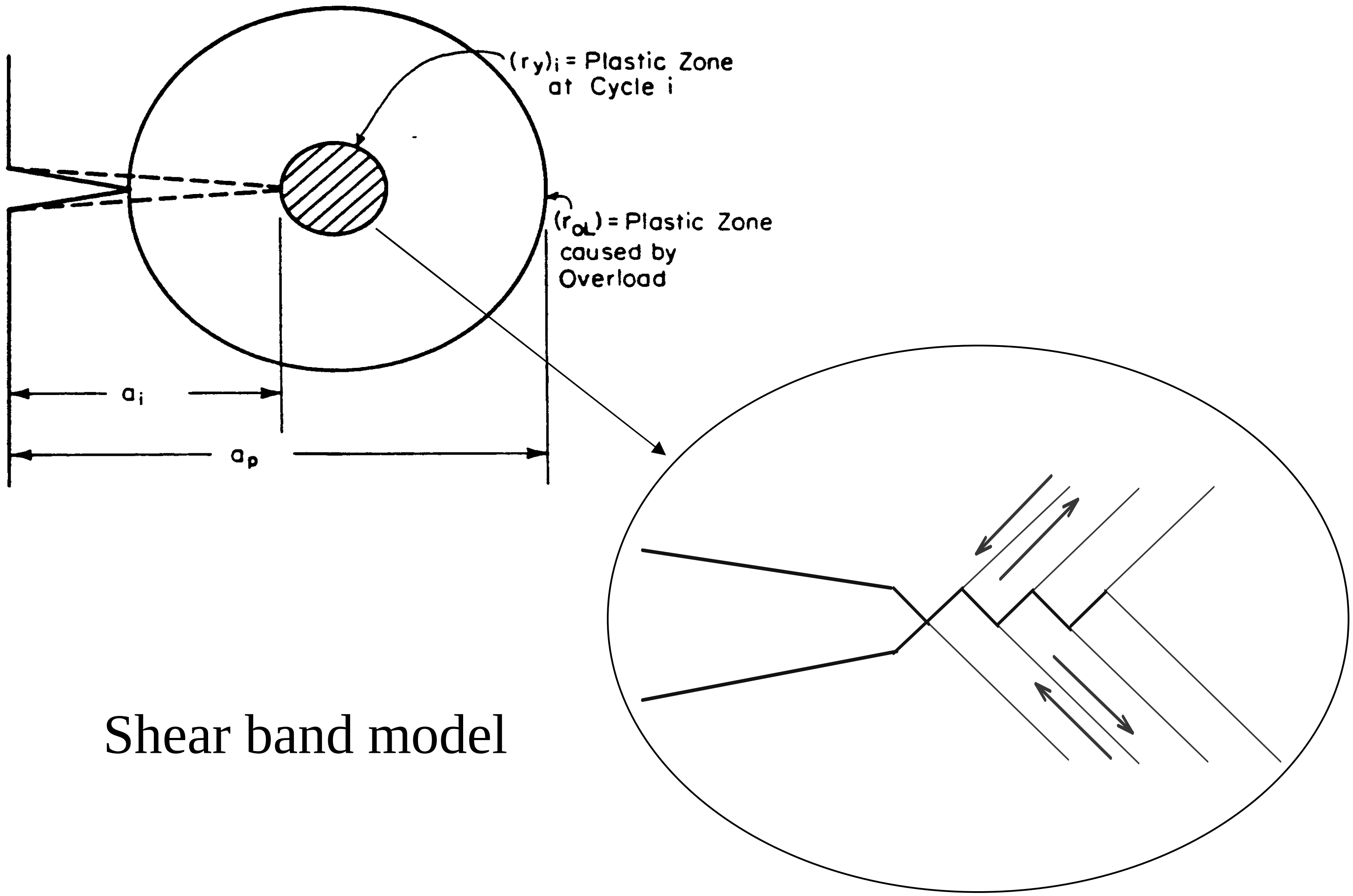






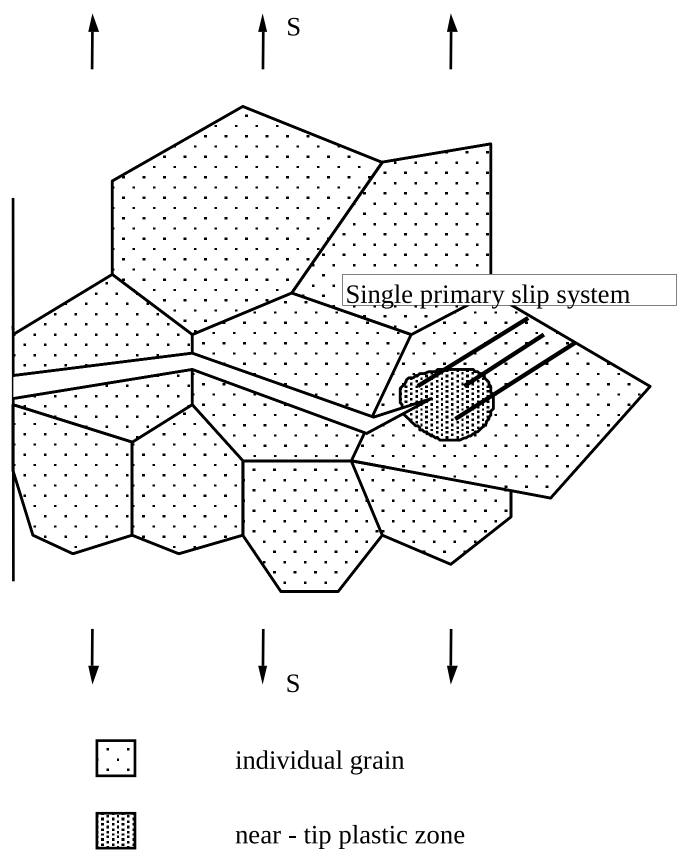
Fatigue crack initiation at an inclusion
Cyclic slip steps (PSB)
Fatigue crack initiation at a PSB

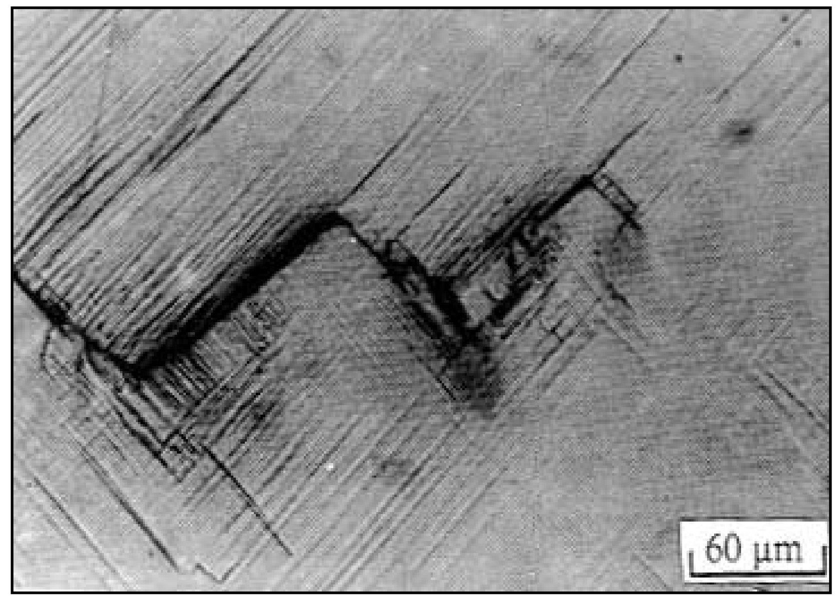
Cyclic Plastic Zone



Shear band model

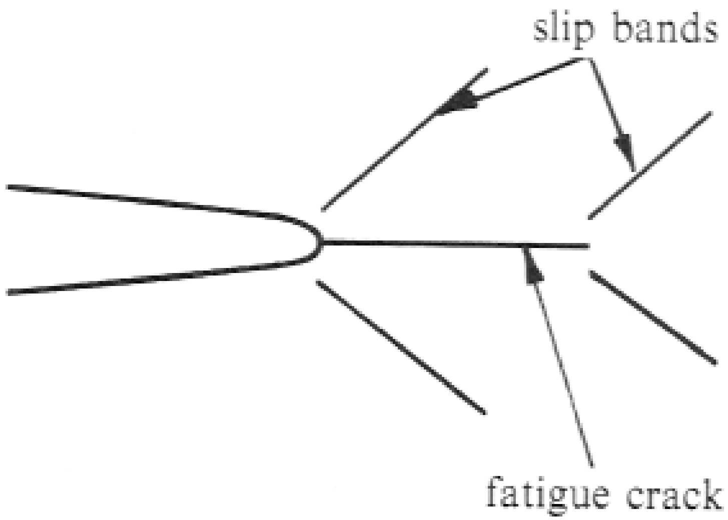
Stage I crack growth





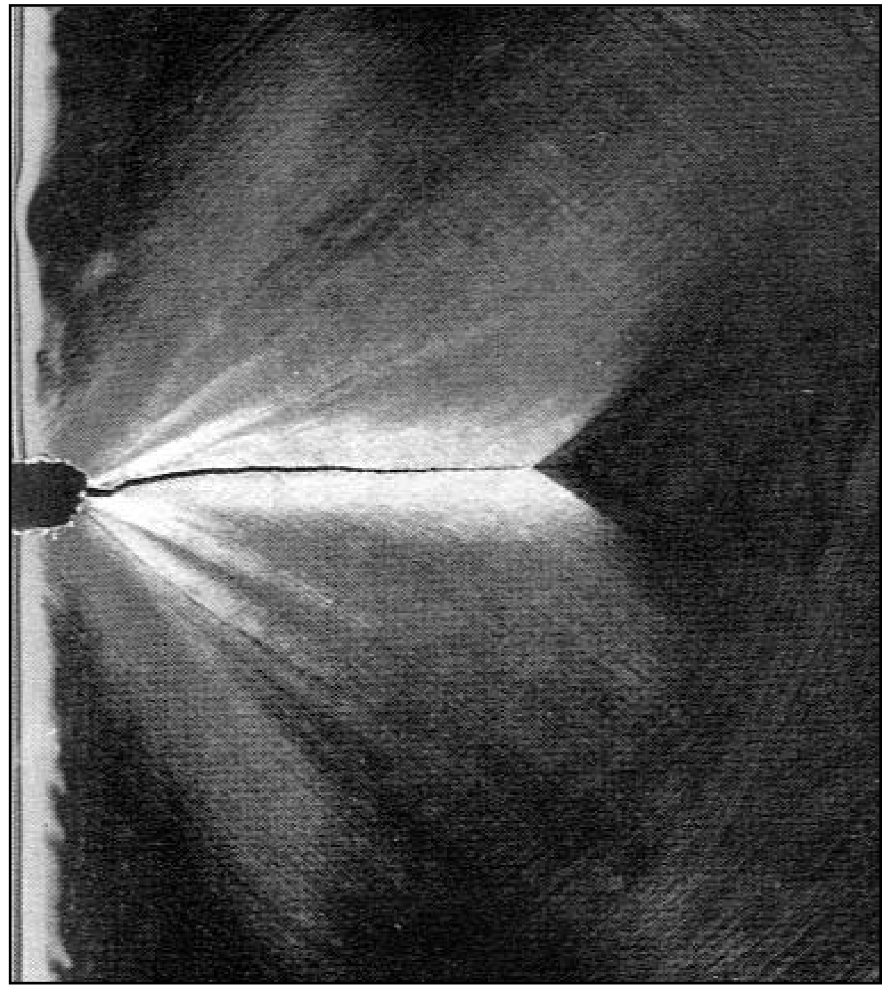
Stage I crack growth ($r_c \leq d$) is strongly affected by slip characteristics, microstructure dimensions, stress level, extent of near tip plasticity

Stage II crack growth



Stage II crack growth ($r_c >> d$)

Fatigue crack growing in Plexiglas

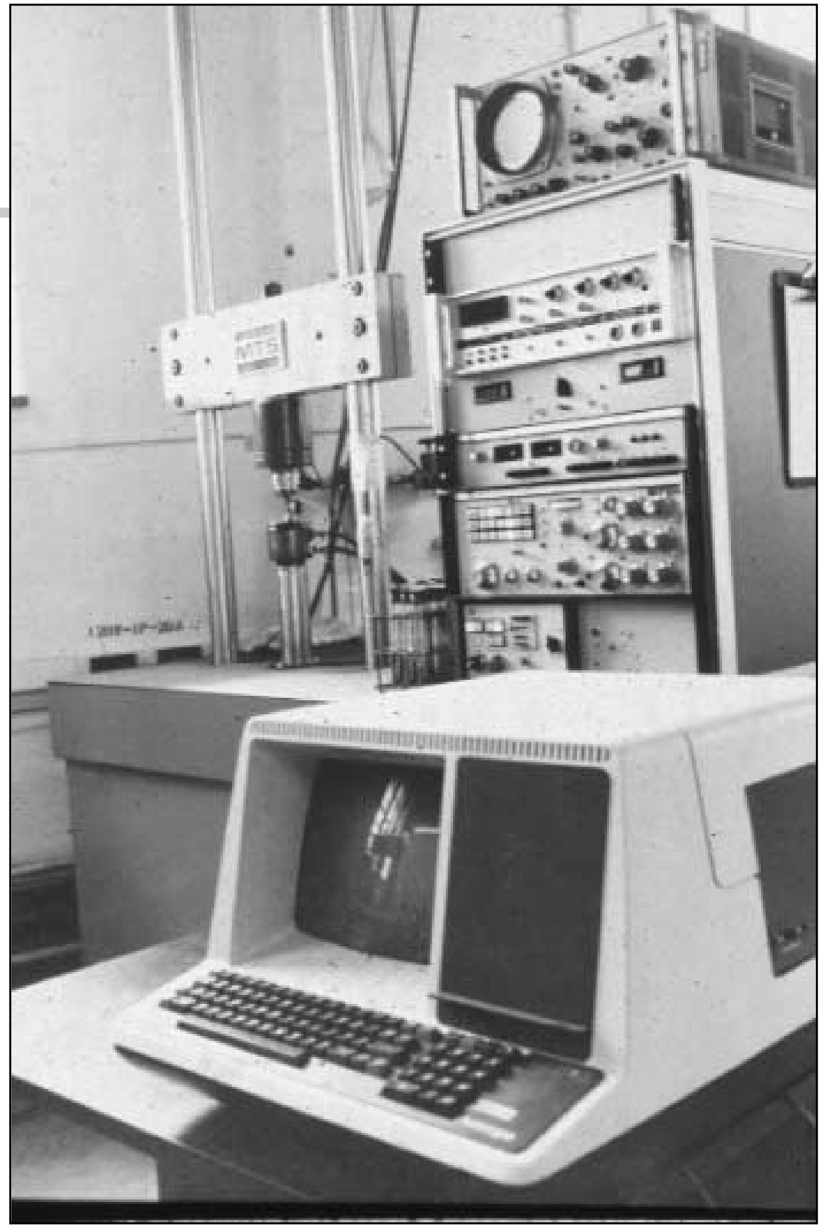


Outline

- Fatigue mechanisms
- Sources of knowledge
- Modelling
  - Crack nucleation
  - Non propagating cracks
  - Crack growth

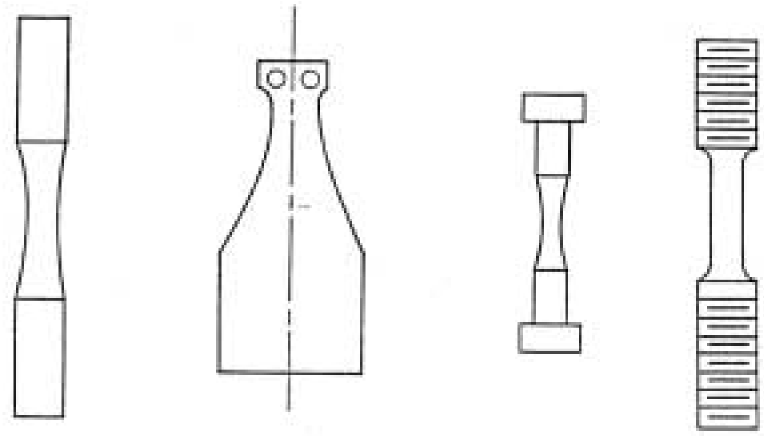
Source of knowldege

The intrinsic fatigue properties of the component's material are determined using small, smooth or cracked specimens.

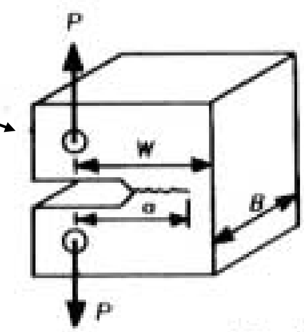


Laboratory fatigue test specimens

Smooth specimens



Crack growth specimen



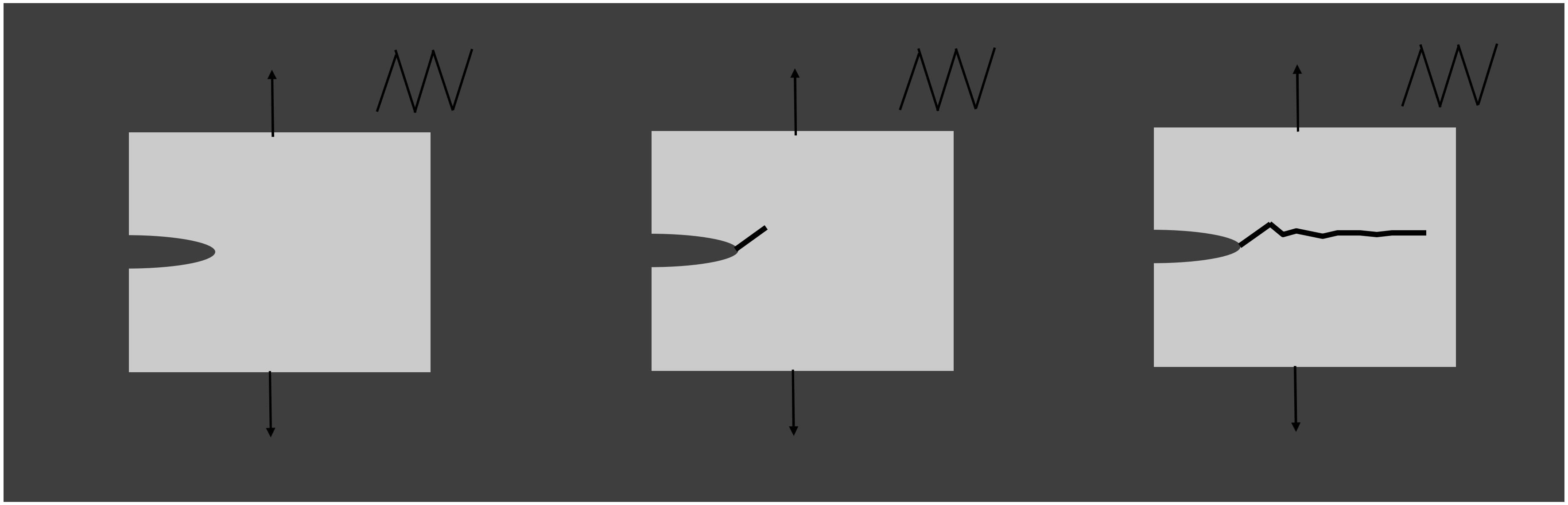
Compact tension specimen (CT):

$$K_I = \frac{P}{B\,W^{\frac{1}{2}}} \cdot f\left(\frac{a}{W}\right)$$

$$f\left(\frac{a}{W}\right) = \frac{\left(2+\frac{a}{W}\right)\left[0.886+4.64\left(\frac{a}{W}\right)-13.32\left(\frac{a}{W}\right)^2+14.72\left(\frac{a}{W}\right)^3-5.6\left(\frac{a}{W}\right)^4\right]}{\left(1-\frac{a}{W}\right)^{\frac{3}{2}}}$$

This information can be used to predict, to compute the answer to…….

The three BIG fatigue questions

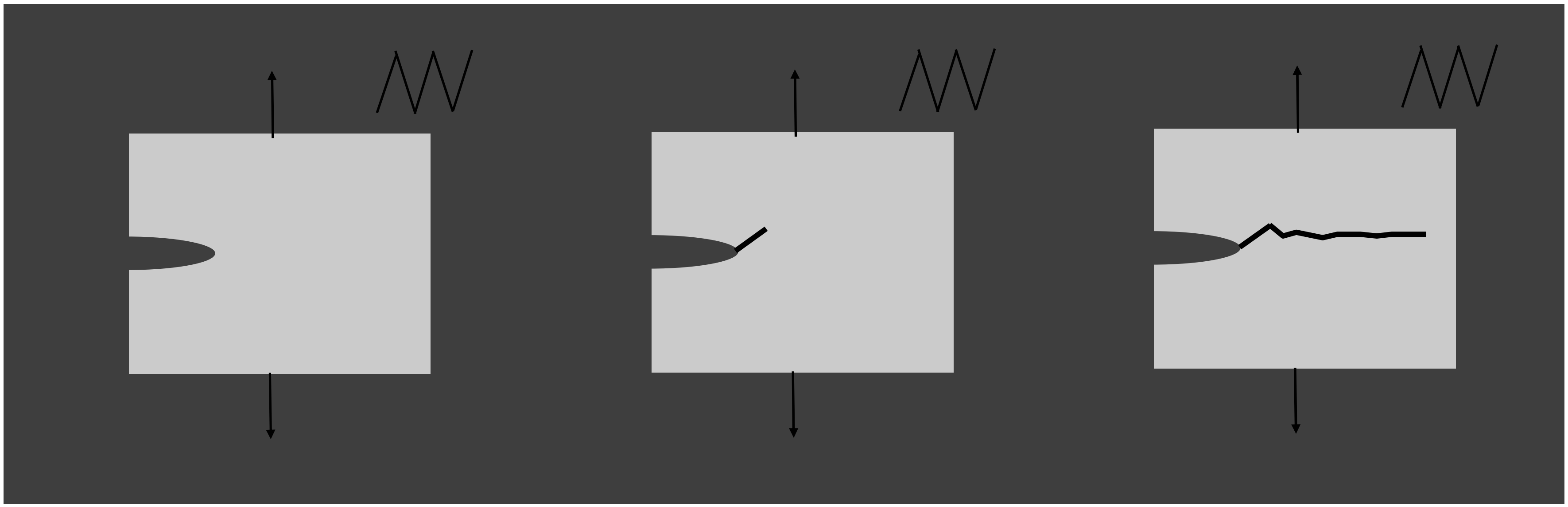


1. Will a crack nucleate?   2. Will it grow?   3. How fast will it grow?

Outline

- Fatigue mechanisms
- Sources of knowledge
- Modelling
  - Crack nucleation
  - Non propagating cracks
  - Crack growth

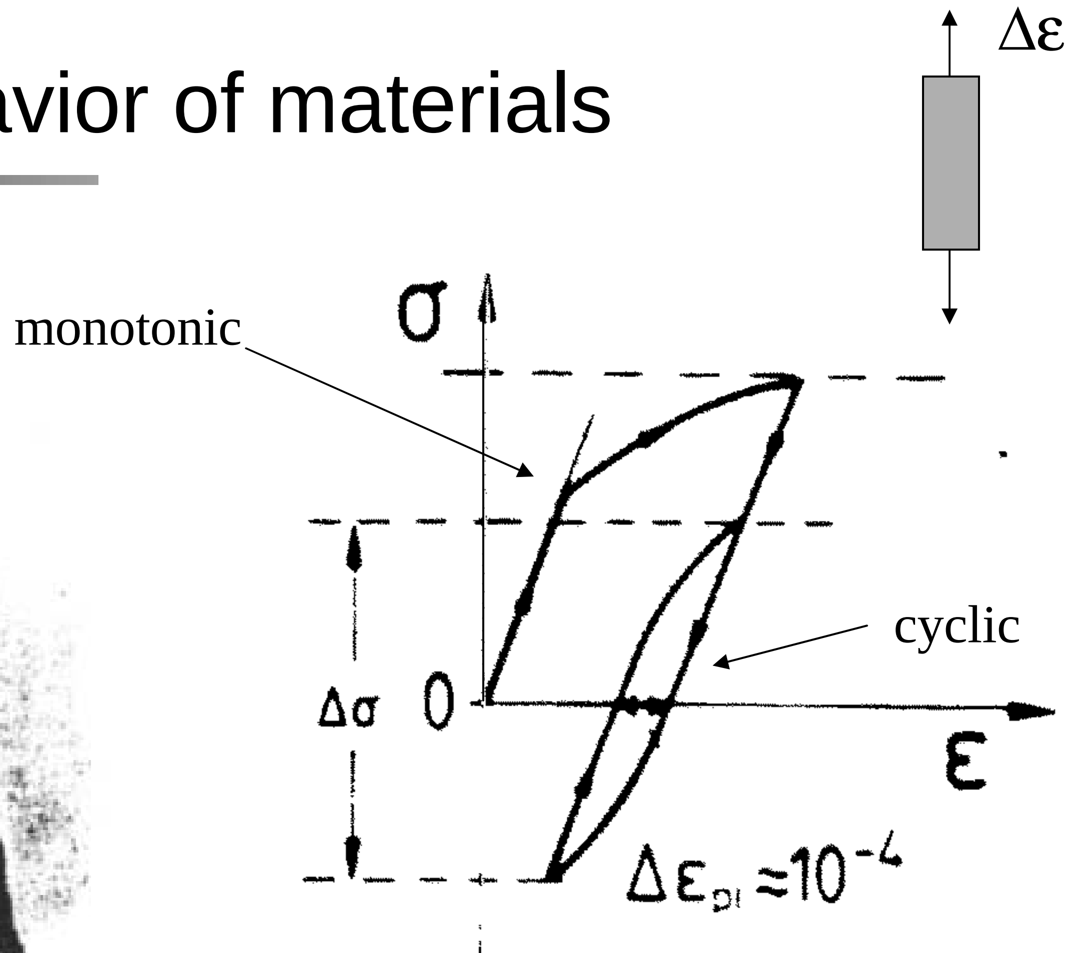
Crack nucleation



1. **Will a crack nucleate?**   2. Will it grow?   3. How fast will it grow?

Cyclic behavior of materials

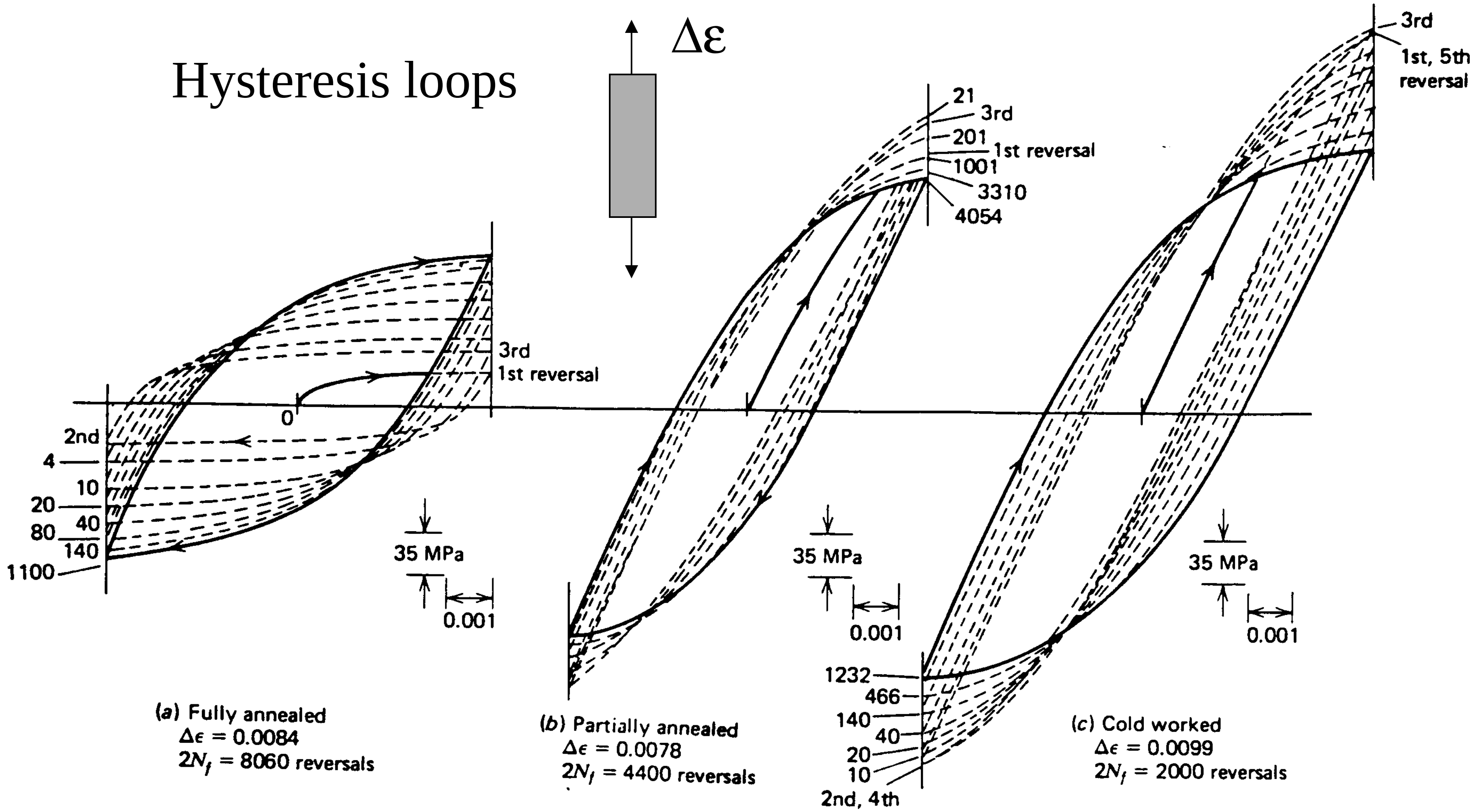
Fig. 1: Portrait of Johann Bauschinger, born on June 11, 1834, and died on November 25, 1893.



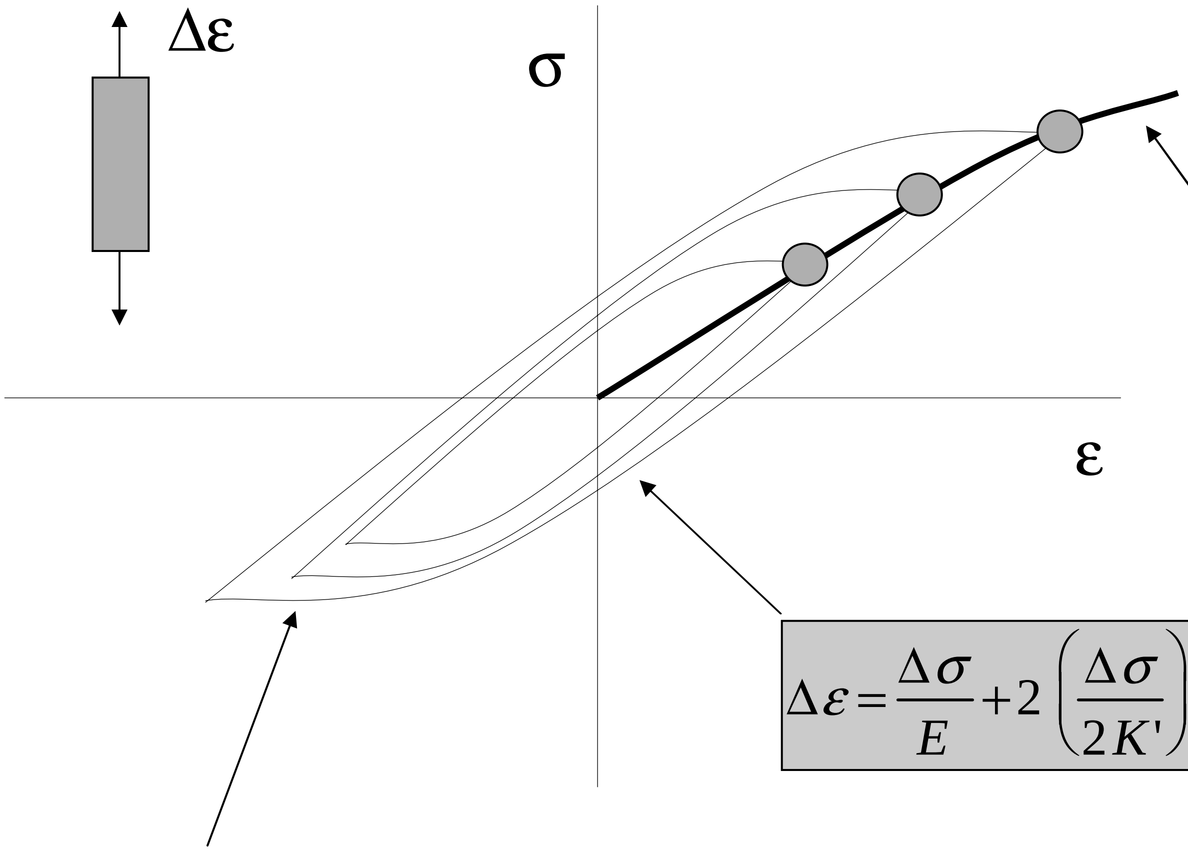
Bauschinger effect: monotonic and cyclic stress-strain different!

Cyclic Deformation

Hysteresis loops



MODEL: Cyclic stress-strain curve



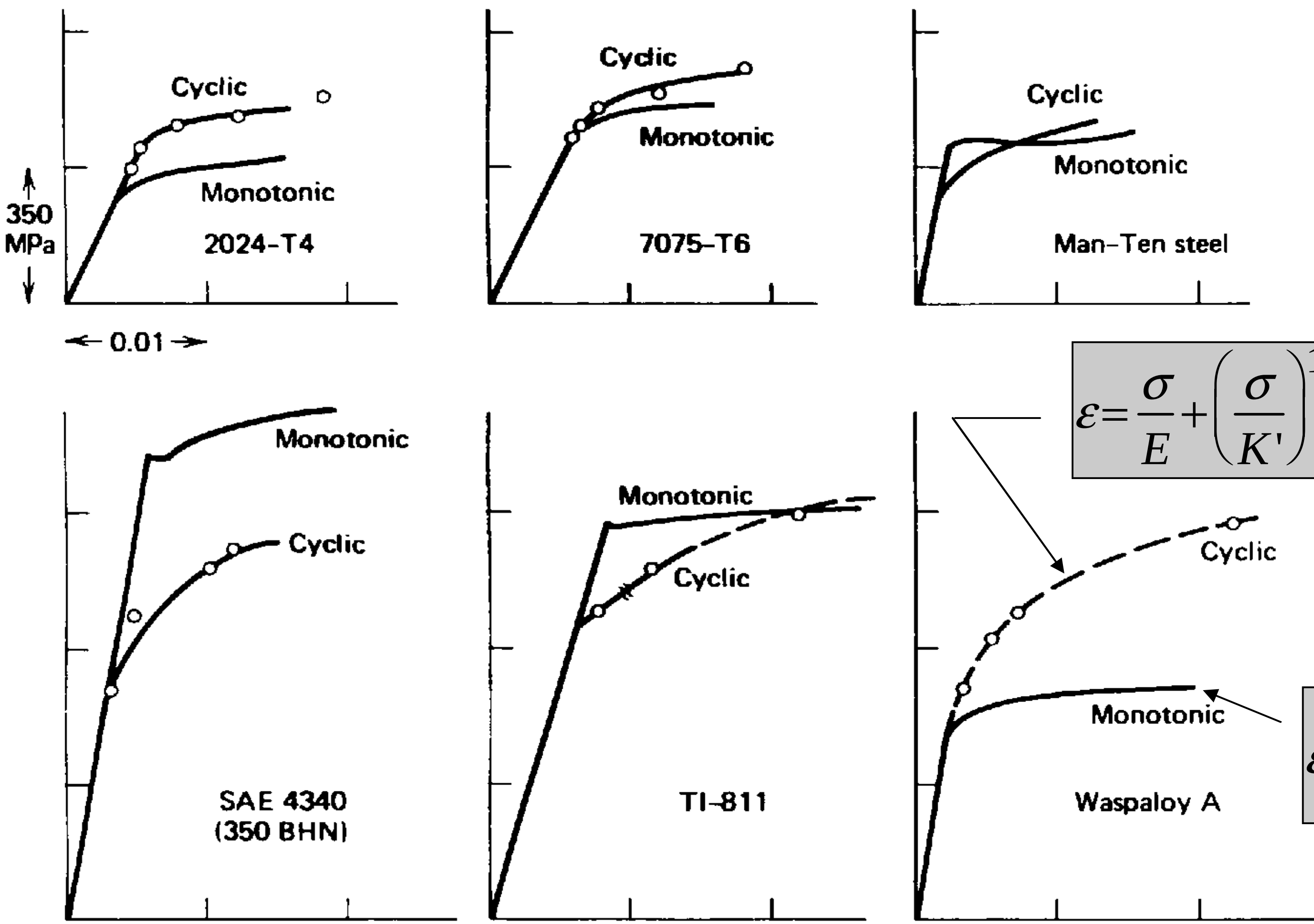
Cyclic stress-strain curve

$$\varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{K'}\right)^{1/n'}$$

$$\Delta\varepsilon = \frac{\Delta\sigma}{E} + 2\left(\frac{\Delta\sigma}{2K'}\right)^{1/n'}$$

Hysteresis loops for different levels of applied strain

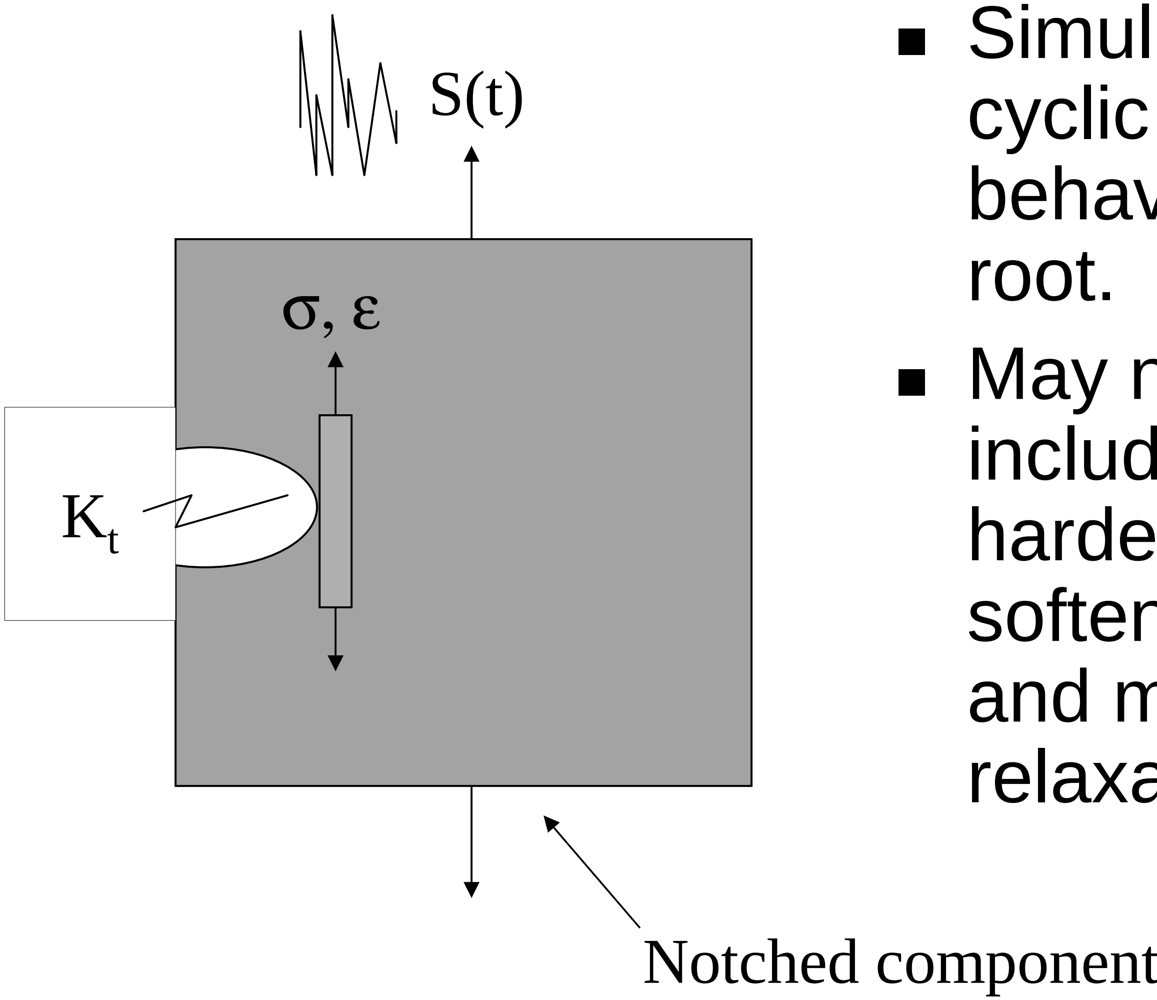
MODEL: Cyclic stress-strain curve



$$\varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{K'}\right)^{1/n'}$$

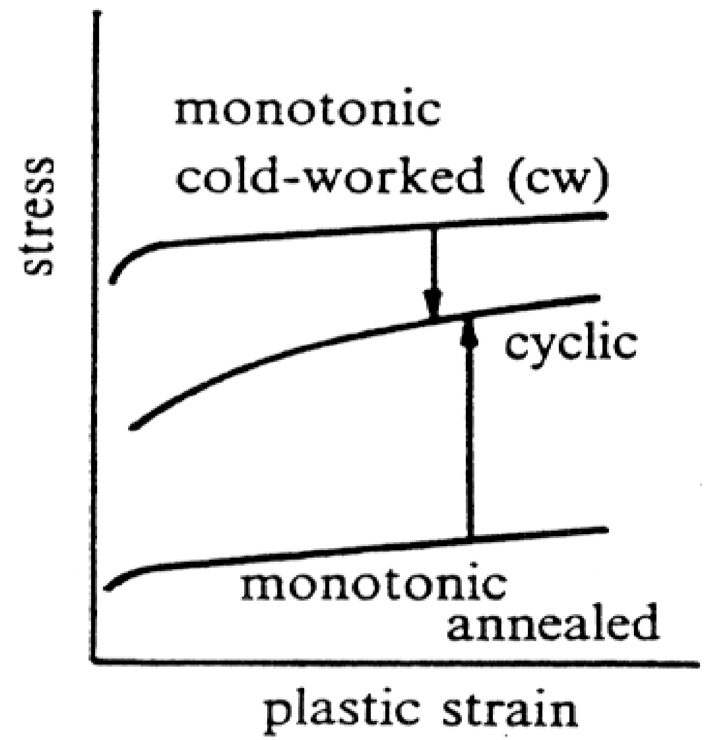
$$\varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{K}\right)^{1/n}$$

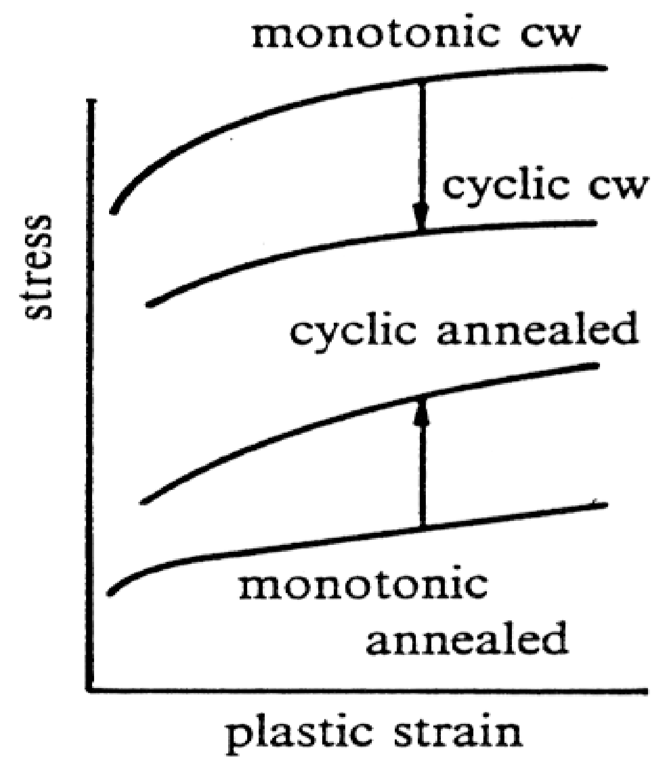
MODEL USES



- Simulate local cyclic stress-strain behavior at a notch root.
- May need to include cyclic hardening and softening behavior and mean stress relaxation effects.

Planar and wavy slip materials



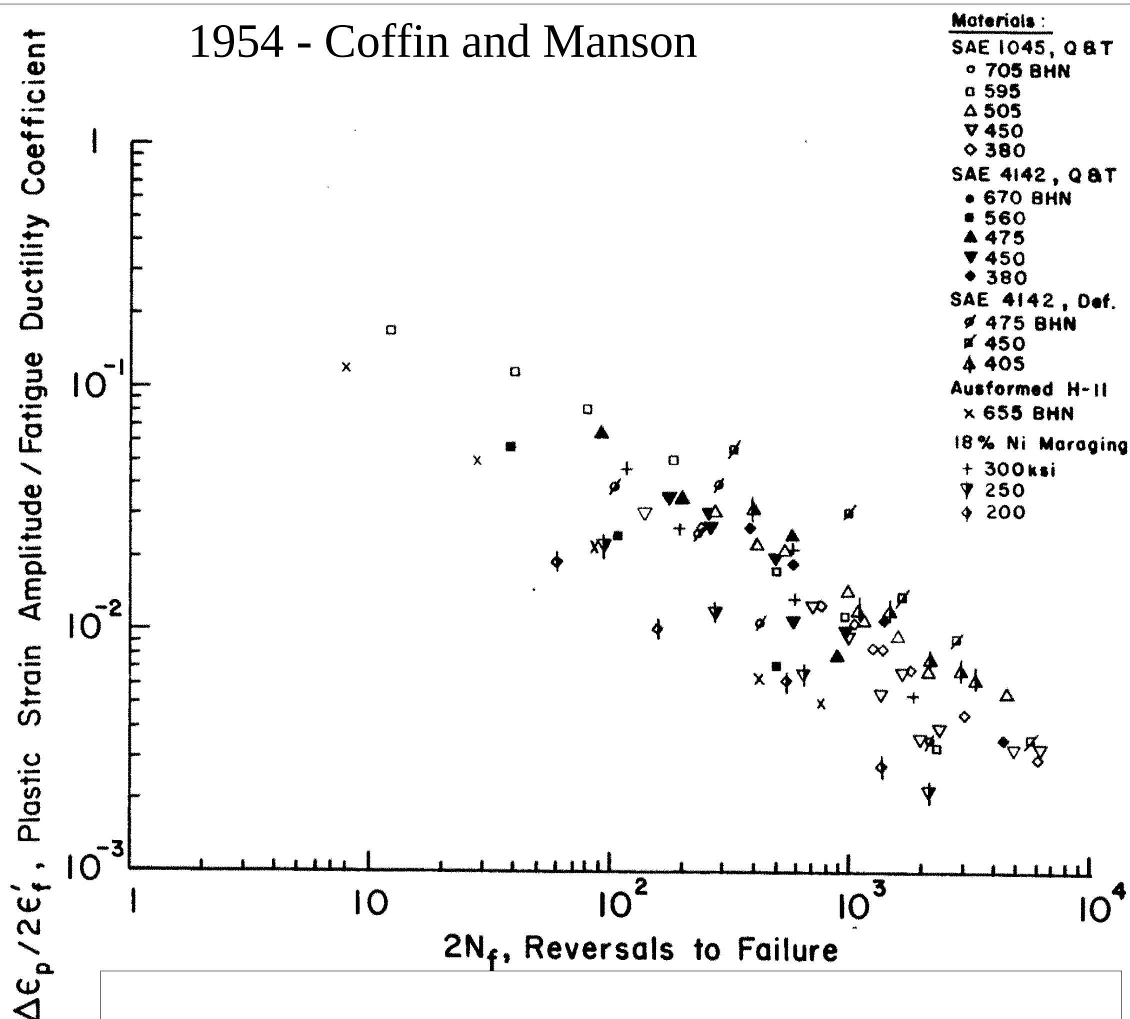


Wavy slip materials

Planar slip materials

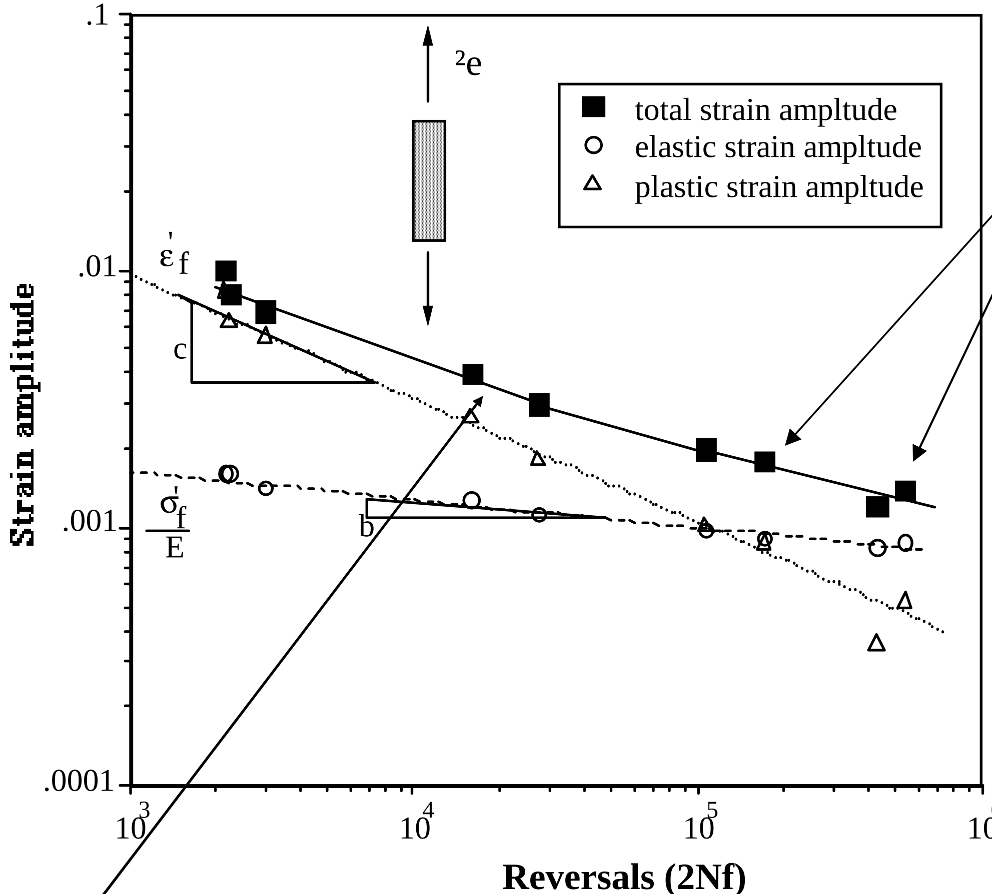
Concept of fatigue damage

1954 - Coffin and Manson



Plastic strains cause the accumulation of "fatigue damage."

MODEL: Strain-life curve



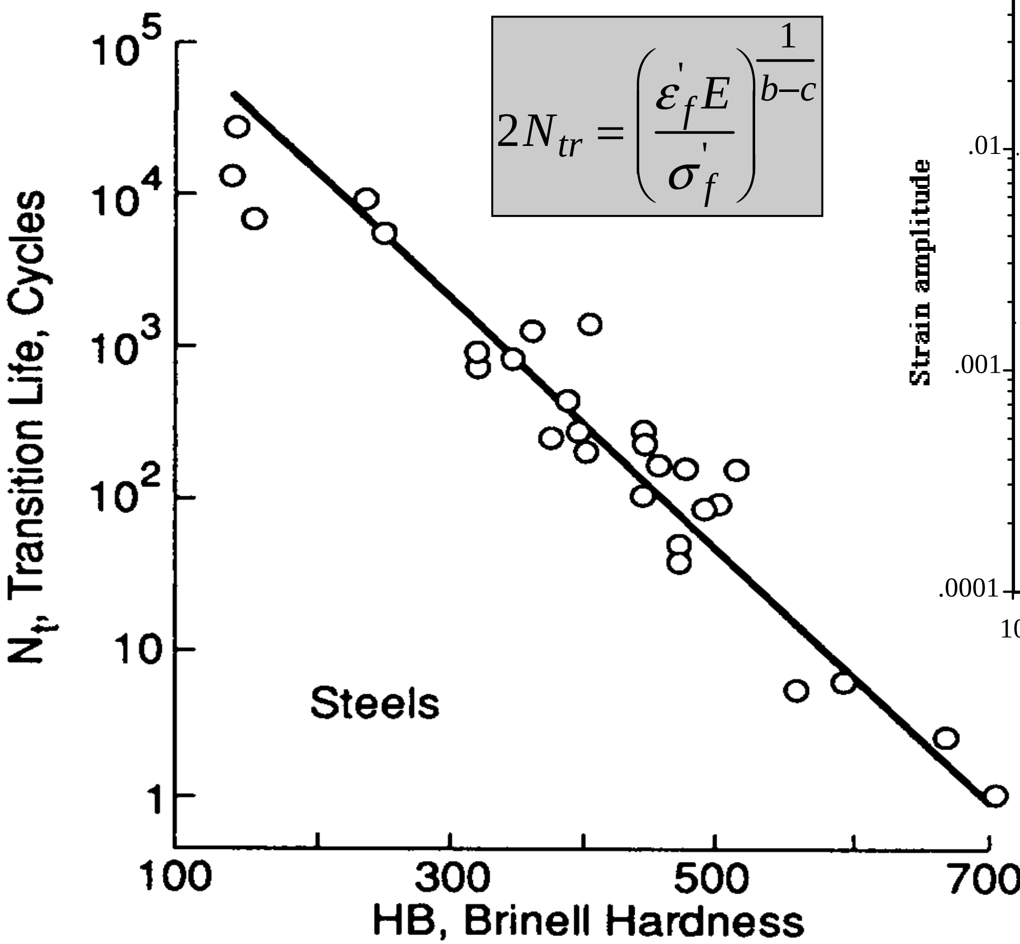
Fatigue test data from strain-controlled tests on smooth specimens.

Elastic component of strain, $\Delta\varepsilon_e$

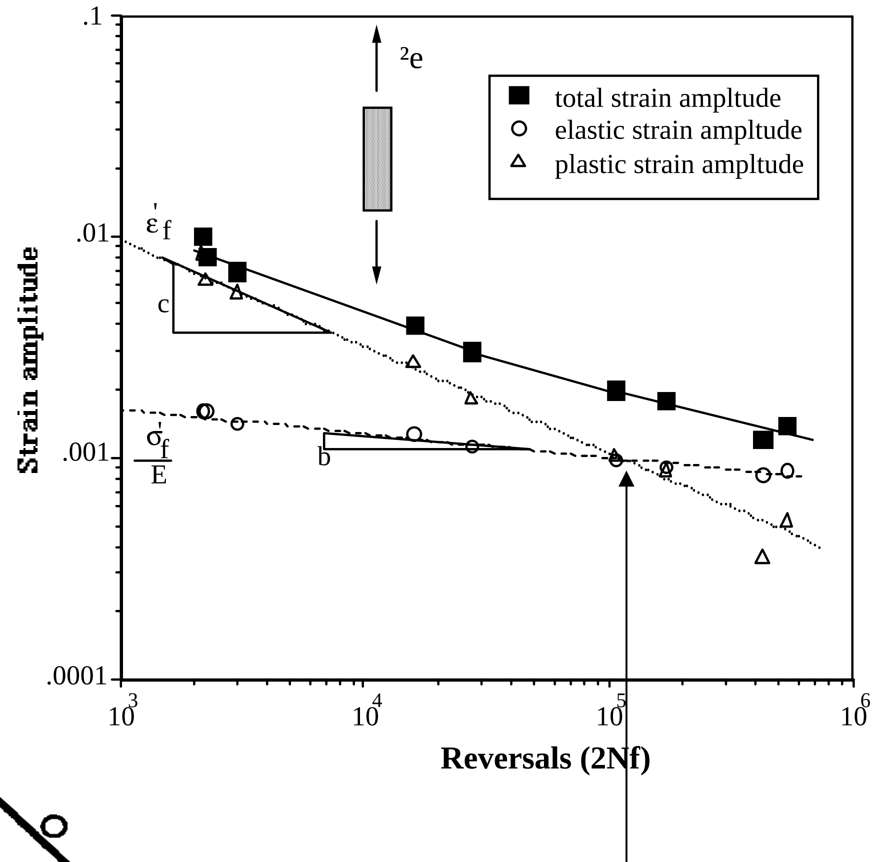
Plastic component of strain, $\Delta\varepsilon_p$

$$\Delta\varepsilon_t = \Delta\varepsilon_e + \Delta\varepsilon_p = \frac{\sigma'_f}{E}(2N_f)^b + \varepsilon'_f(2N_f)^c$$

Transition Fatigue Life

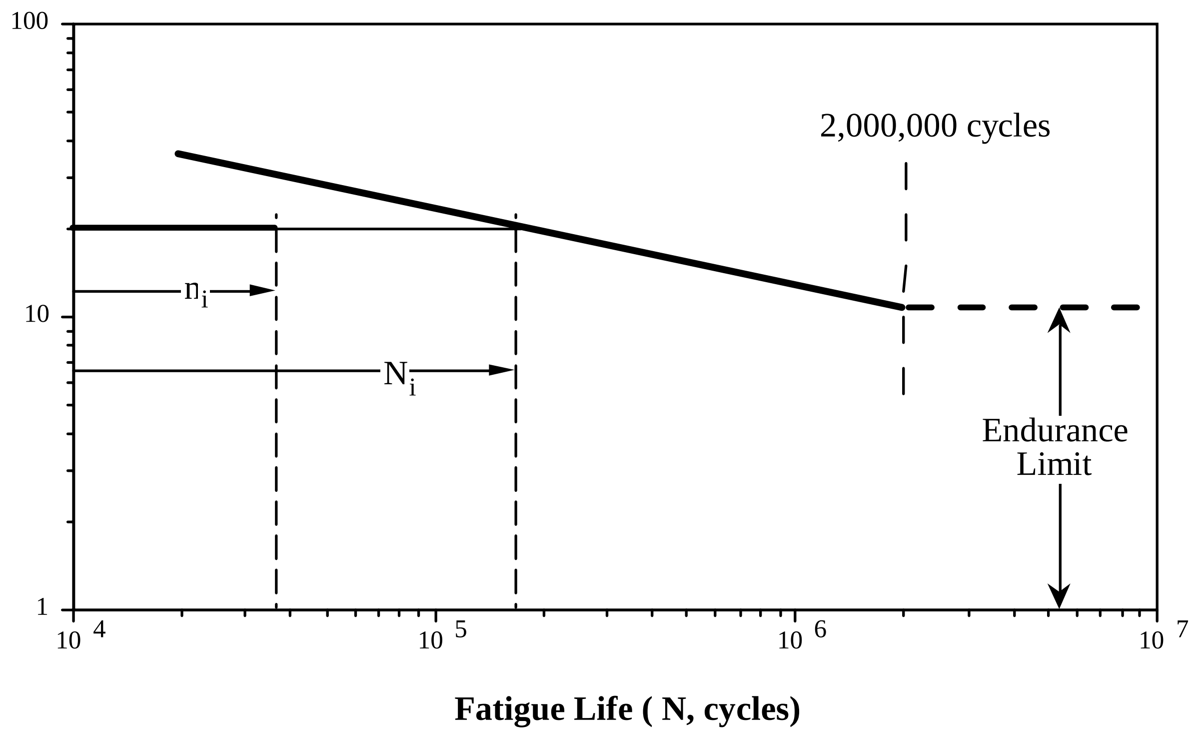


$$2N_{tr} = \left(\frac{\varepsilon_f' E}{\sigma_f'} \right)^{\frac{1}{b-c}}$$



Transition fatigue life, N_{tr}
Elastic strains = plastic strains

MODEL: Linear cumulative damage



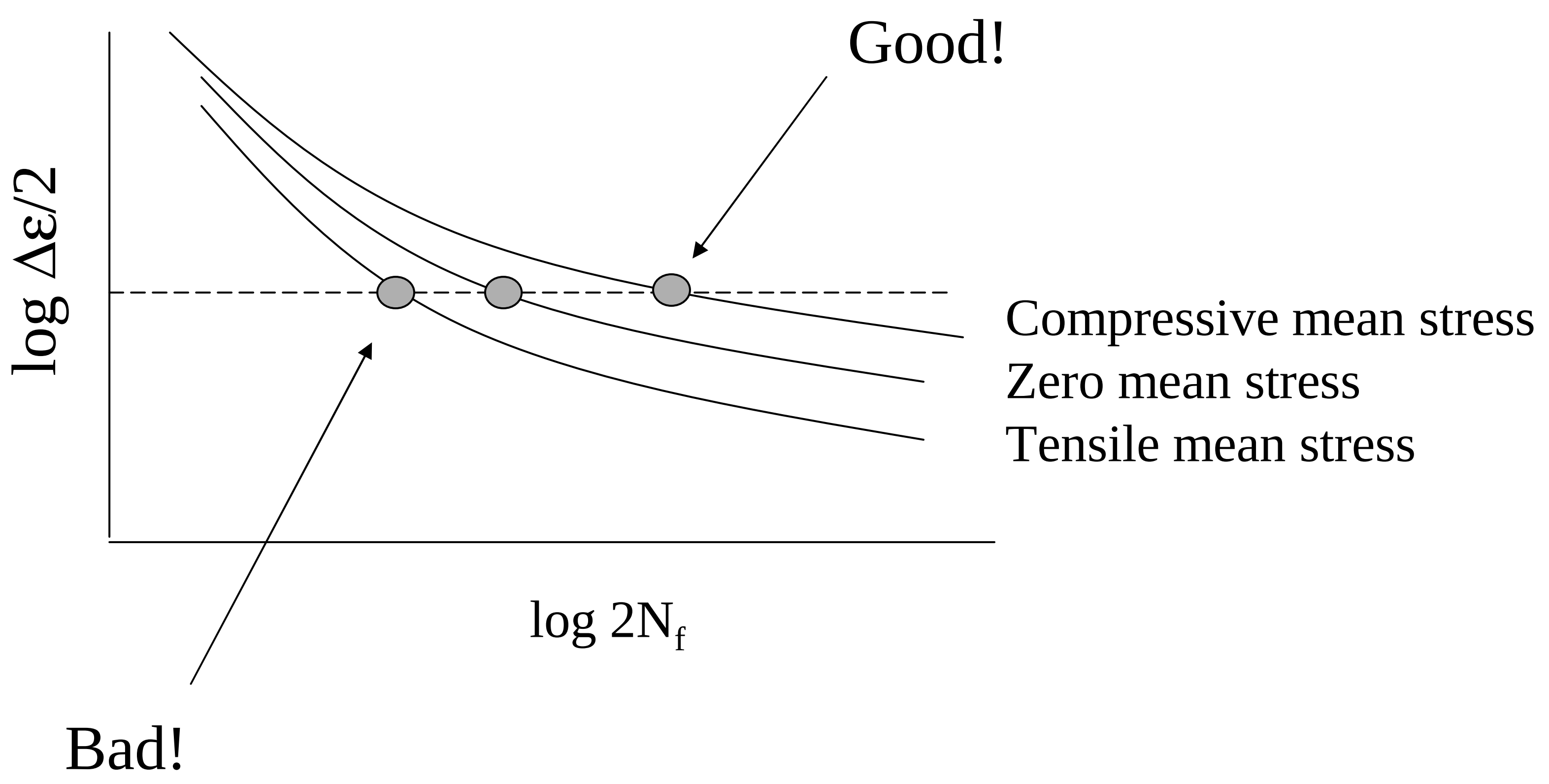
Miner's Rule of Cumulative Fatigue Damage is the best and simplest tool available to estimate the likelihood of fatigue failure under variable load histories. Miner's rule hypothesizes that fatigue failure will occur when the sum of the cycle ratios (n_i/N_i) is equal to or greater than 1

$$\sum_i \frac{n_i}{N_i} \geq 1.0$$

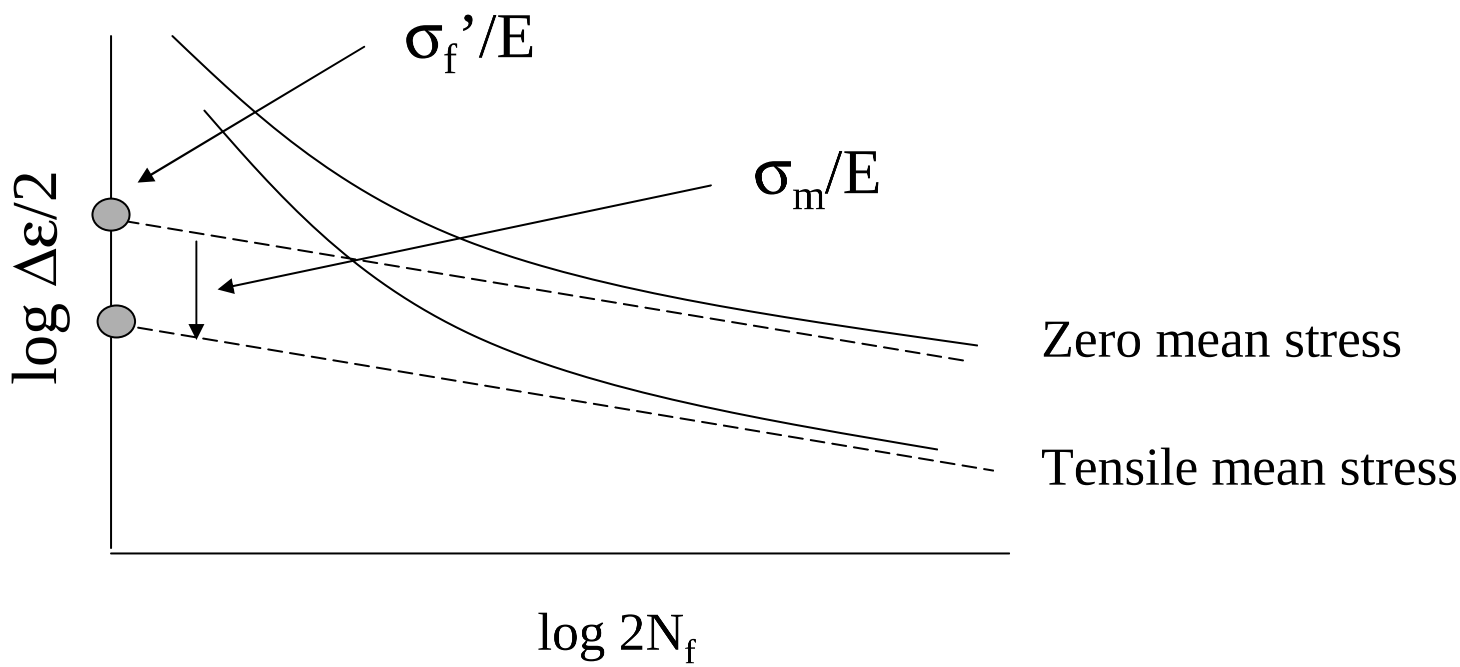
n_i = Number of cycles experienced at a given stress or load level.
N_i = Expected fatigue life at that stress or load level.

Mean stress effects

Effects the growth of (small) fatigue cracks.



MODEL: Morrow's mean stress correction

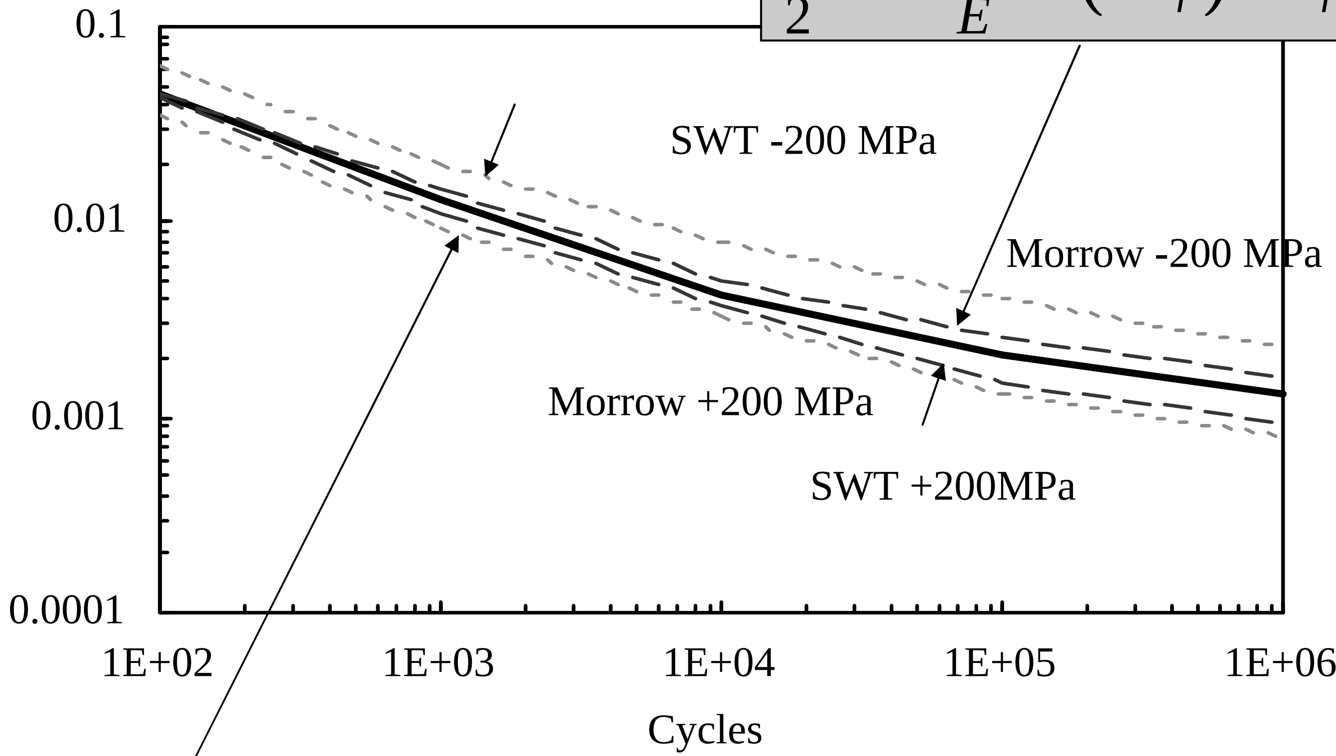


$$\frac{\Delta\varepsilon}{2} = \frac{\sigma_f^{'} - \sigma_m}{E}\left(2N_f\right)^b + \varepsilon_f^{'}\left(2N_f\right)^c$$

MODEL: Mean stress effects

Morrow

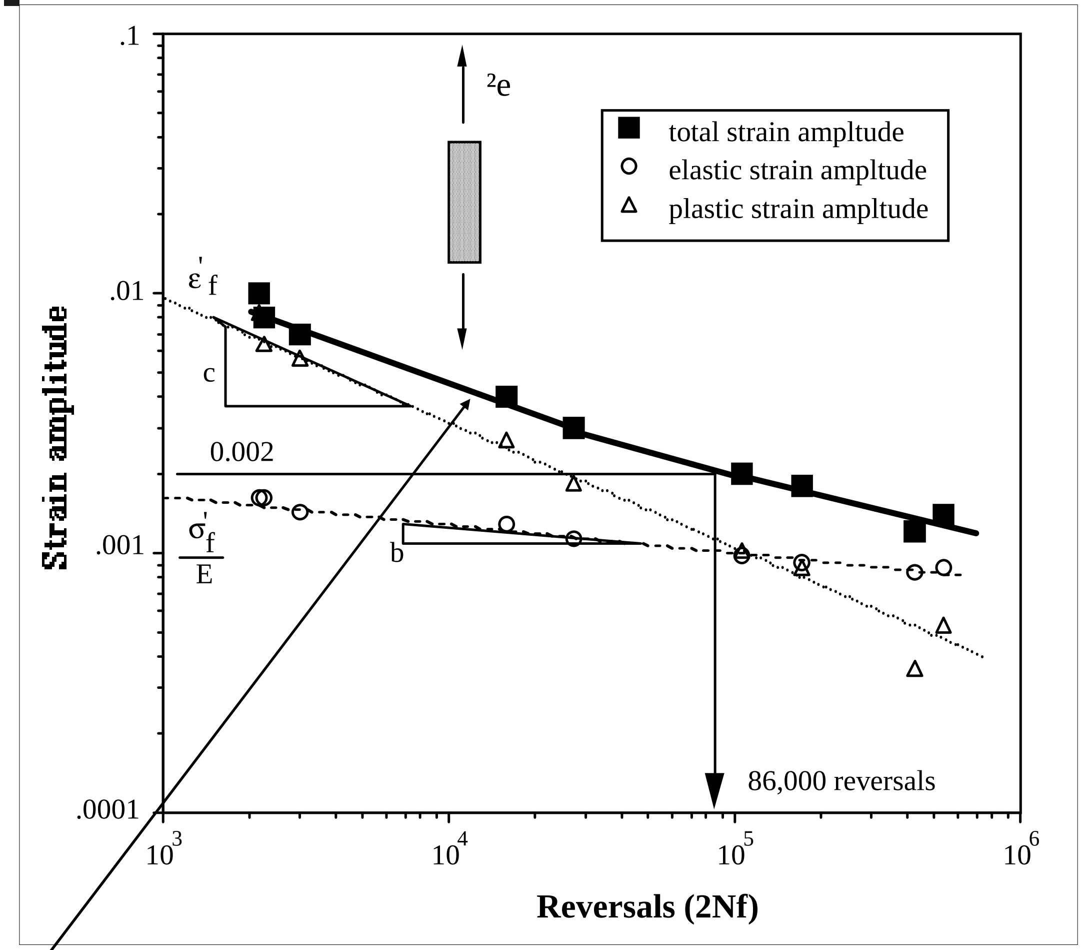
$$\frac{\Delta\varepsilon}{2}=\frac{\sigma_f^{'}-\sigma_m}{E}\left(2N_f\right)^b+\varepsilon_f^{'}\left(2N_f\right)^c$$



$$\frac{\sigma_{\max}\Delta\varepsilon}{2}=\frac{\sigma_f^{'\,2}}{E}\left(2N_f\right)^{2b}+\sigma_f^{'}\varepsilon_f^{'}\left(2N_f\right)^{b+c}$$

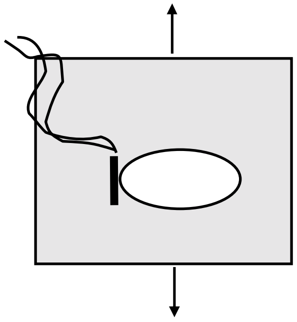
Smith-Watson-Topper

MODEL USES



$$\Delta\varepsilon_t = \Delta\varepsilon_e + \Delta\varepsilon_p = \frac{\sigma'_f}{E}(2N_f)^b + \varepsilon'_f\,(2N_f)^c$$

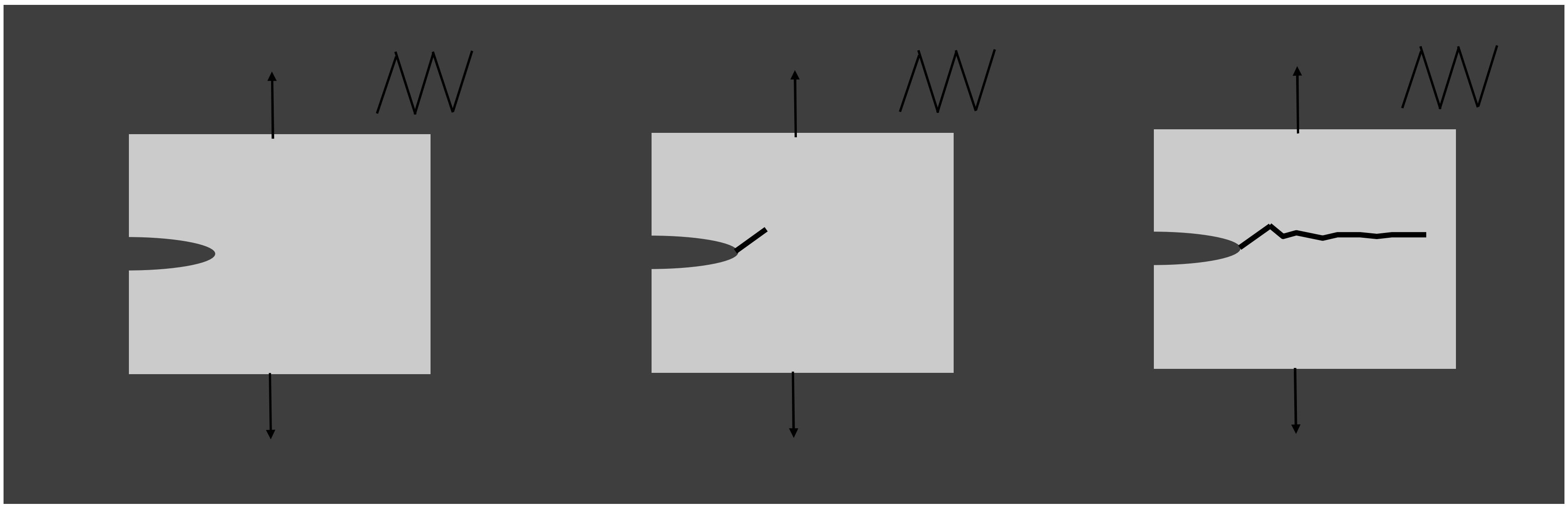
A strain gage mounted in a high stress region of a component indicates a cyclic strain of 0.002. The number of reversals to nucleate a crack ($2N_I$) is estimated to be 86,000 or 43,000 cycles.



Outline

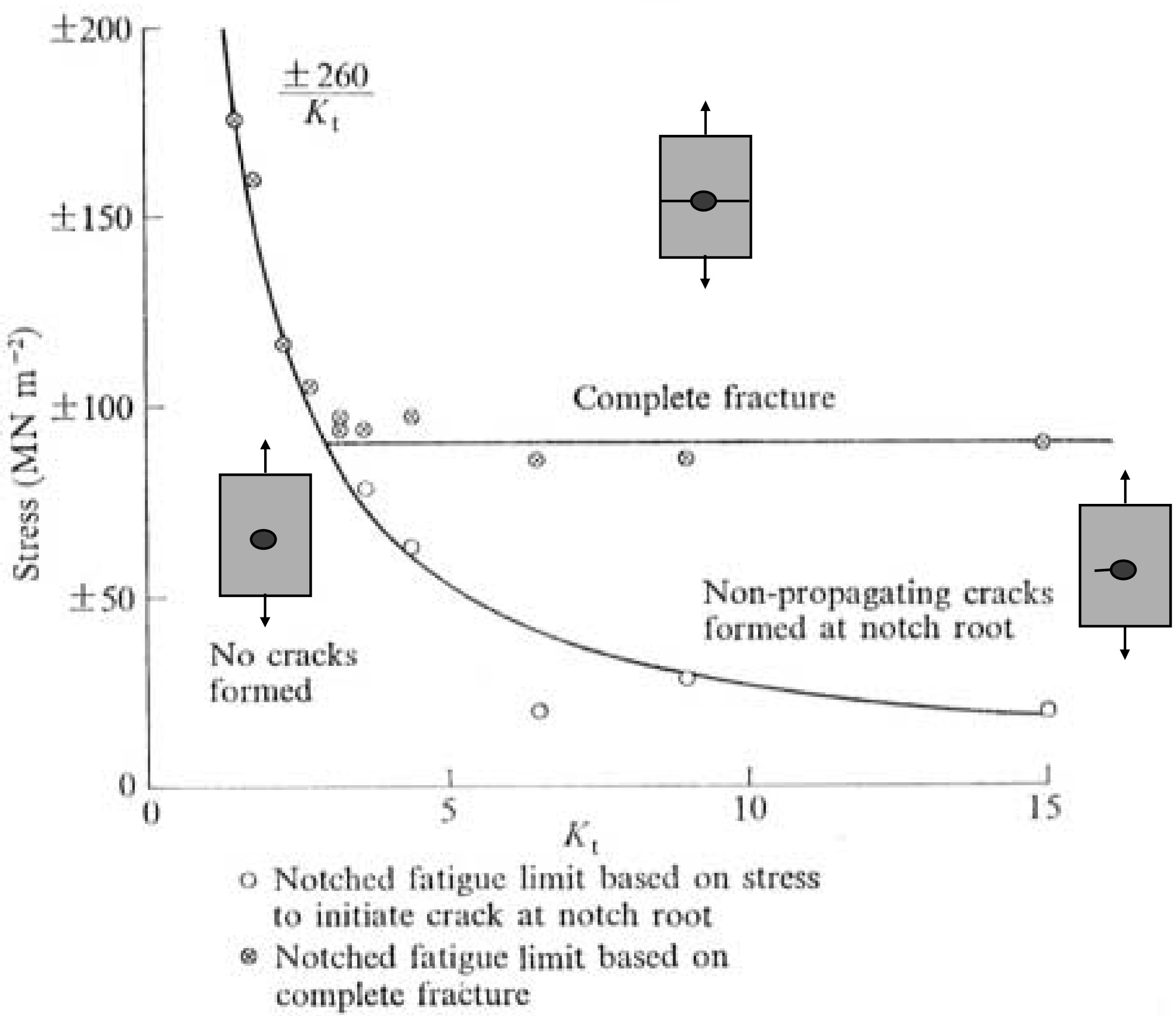
- Fatigue mechanisms
- Sources of knowledge
- Modelling
  - Crack nucleation
  - Non propagating cracks
  - Crack growth

The three BIG fatigue questions



1. Will a crack nucleate?
2. **Will it grow?**
3. How fast will it grow?

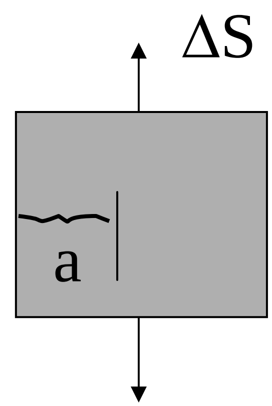
Non-propagating cracks



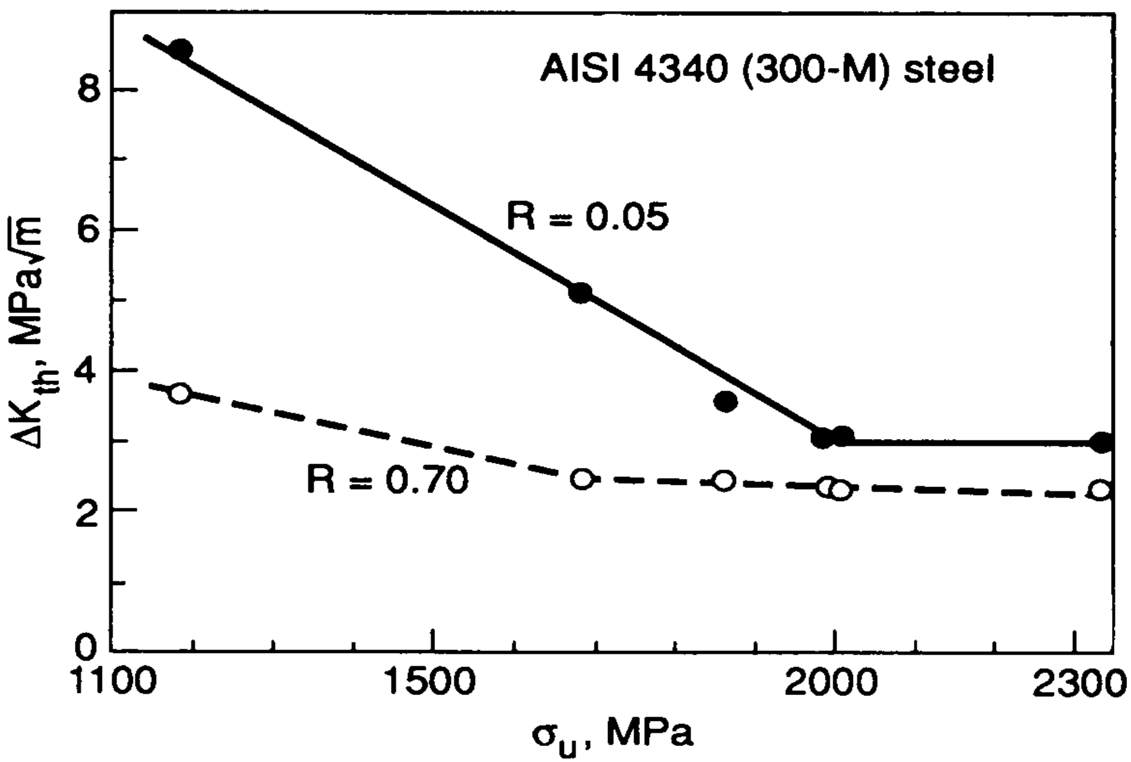
Sharp notches may nucleate cracks but the remote stress may not be large enough to allow the crack to leave the notch stress field.

Threshold Stress Intensity

$$\Delta K = Y\,\Delta S\sqrt{\pi a}$$

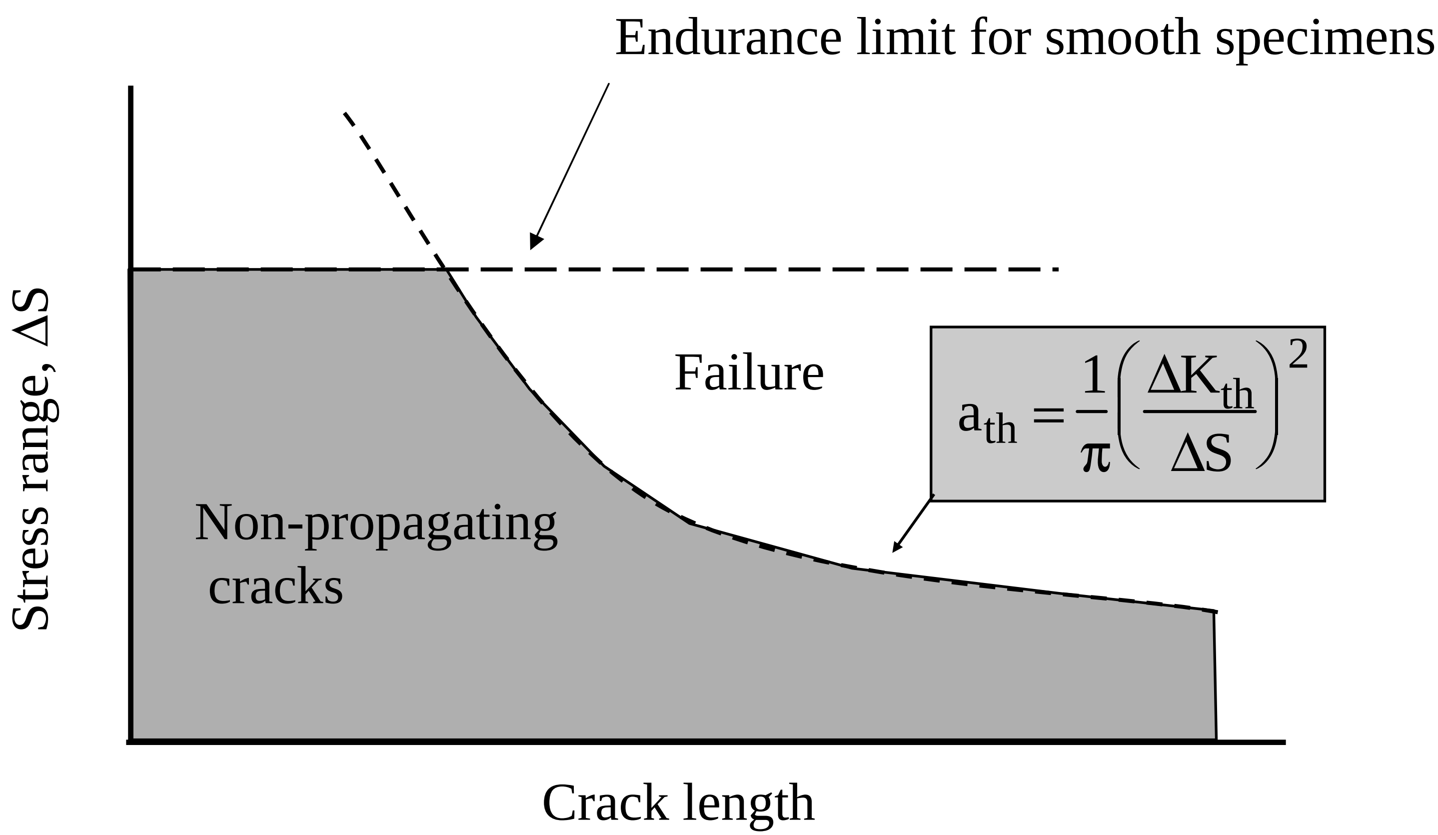


The forces driving a crack forward are related to the stress intensity factor



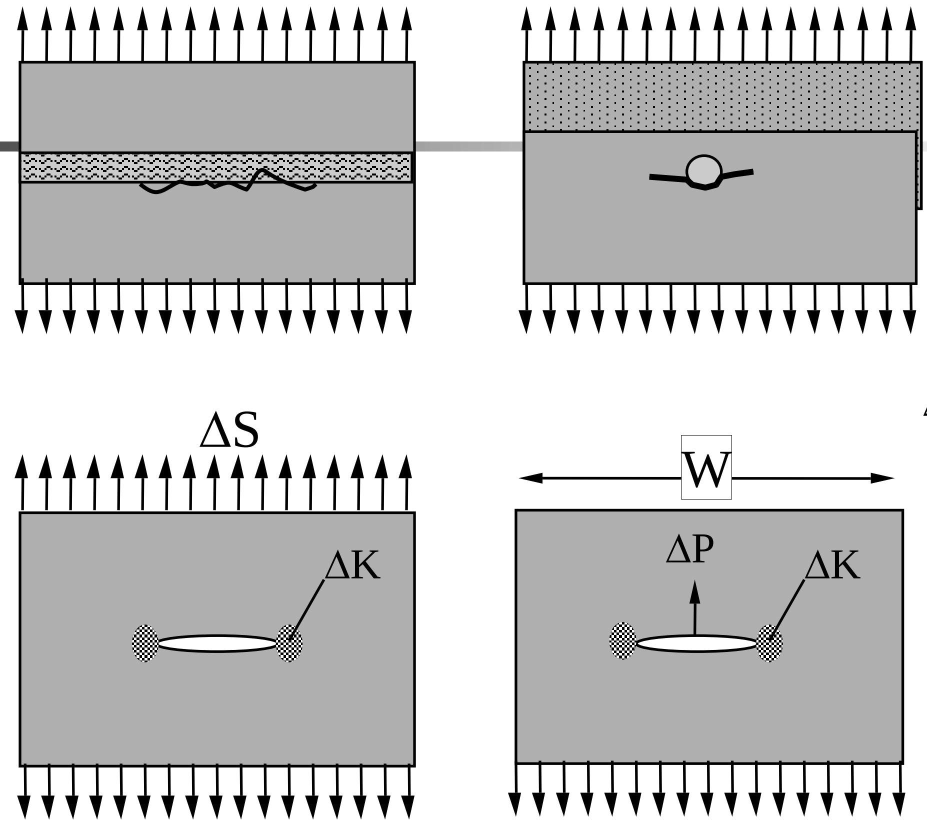
At or below the threshold value of ΔK, the crack doesn't grow.

MODEL: Non-propagating cracks



Groove Welded Butt Joint

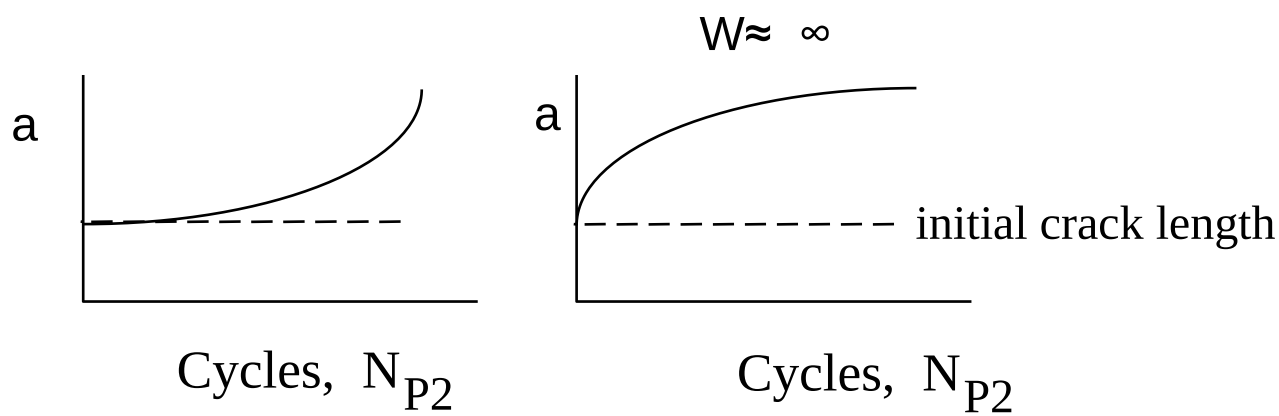
Tensile-Shear Spot Weld



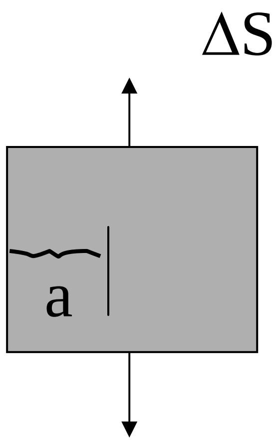
$$\Delta K = \Delta S\sqrt{\pi a}$$

$$\Delta K = \frac{Y}{2}\left(\frac{\Delta P / B}{\sqrt{\pi a}} + \Delta S\sqrt{\pi a}\right)$$

$$\Delta P = \Delta S\ W$$



MODEL USES



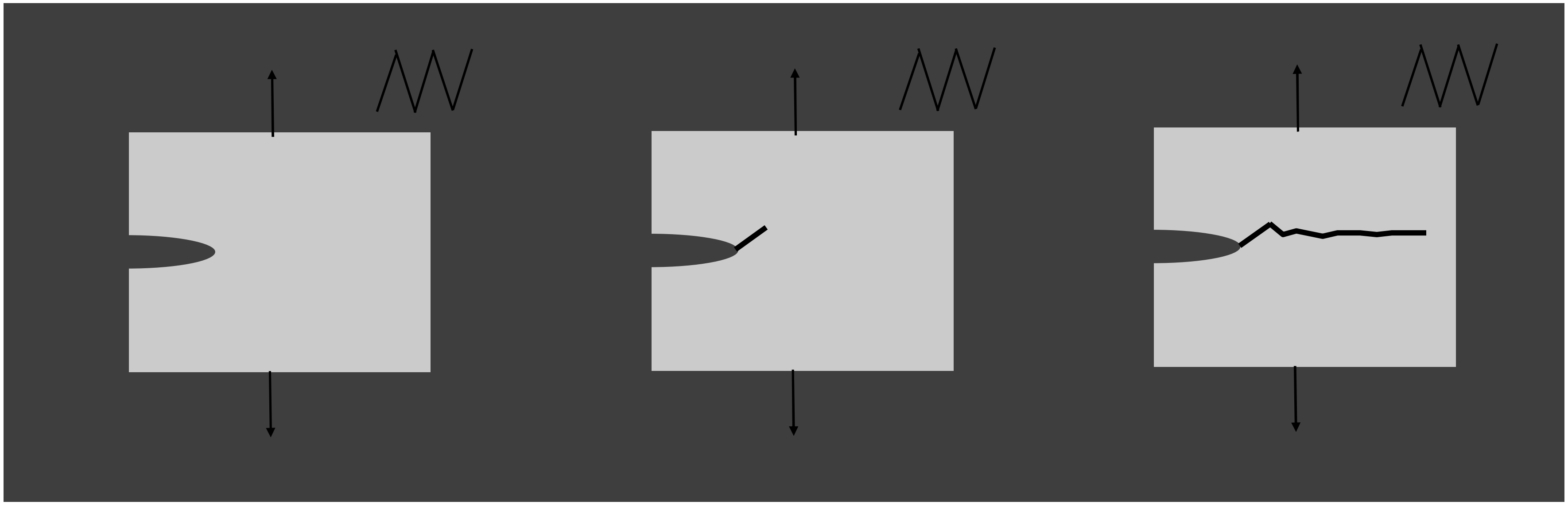
$$a_{th} = \frac{1}{\pi}\left(\frac{\Delta K_{th}}{\Delta S}\right)^2$$

- Will the defect of length a grow under the applied stress range ΔS?
- How sensitive should our NDT techniques be to ensure safety?

Outline

- Fatigue mechanisms
- Sources of knowledge
- Modelling
  - Crack nucleation
  - Non propagating cracks
  - Crack growth

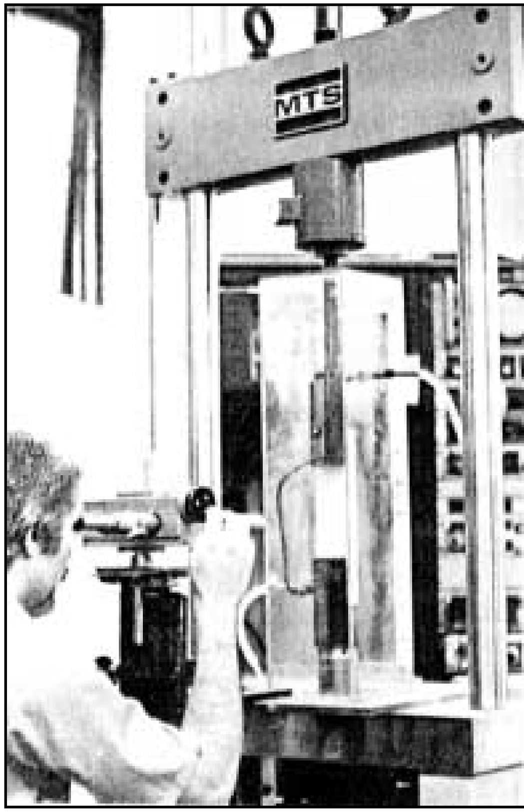
The three BIG fatigue questions

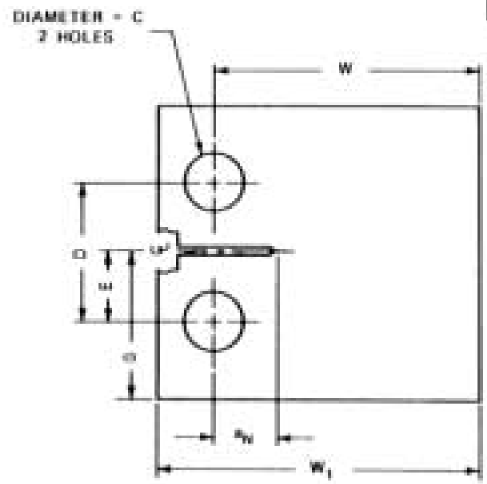


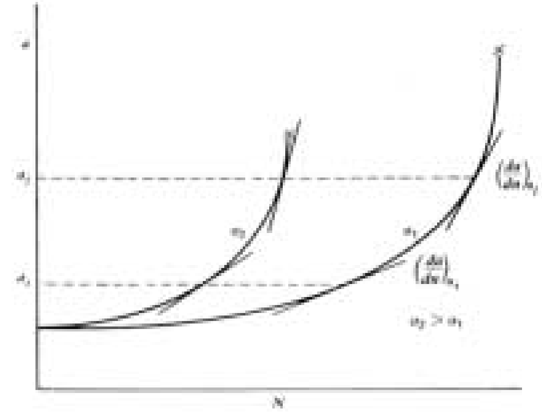
1. Will a crack nucleate? 2. Will it grow? **3. How fast will it grow?**

How fast will it grow???

Measuring Crack Growth - Everything we know about crack growth begins here!

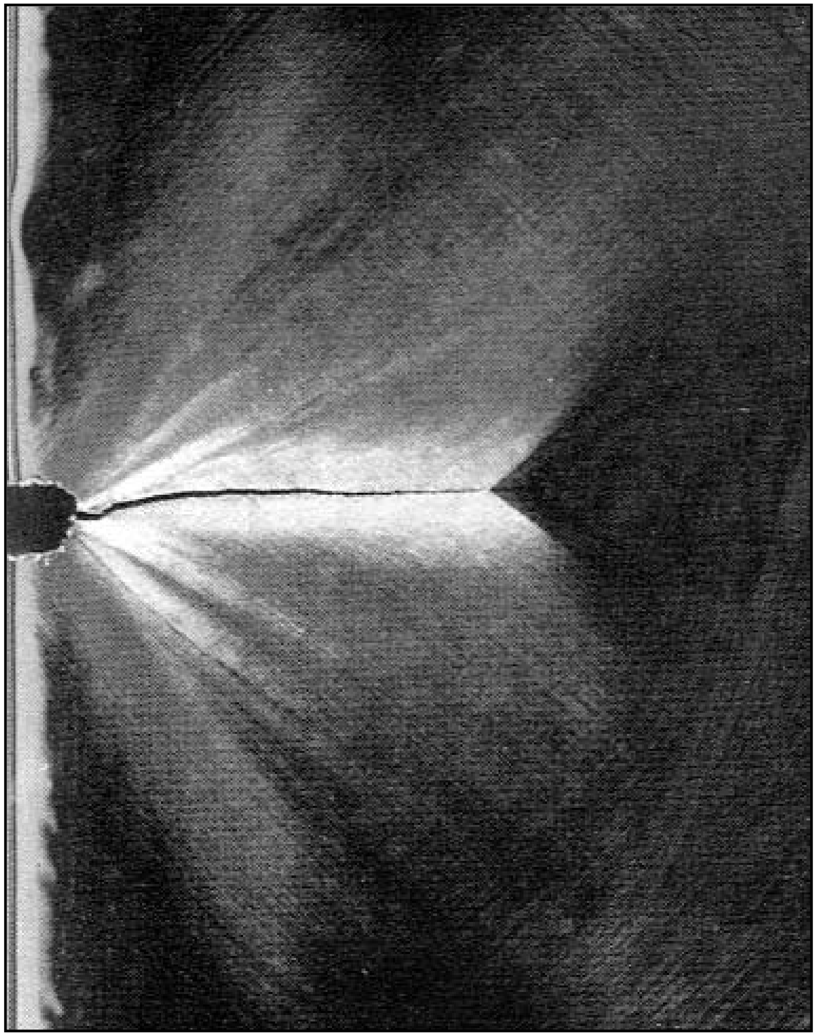






Cracks grow faster as their length increases.

MODEL: Paris Power Law



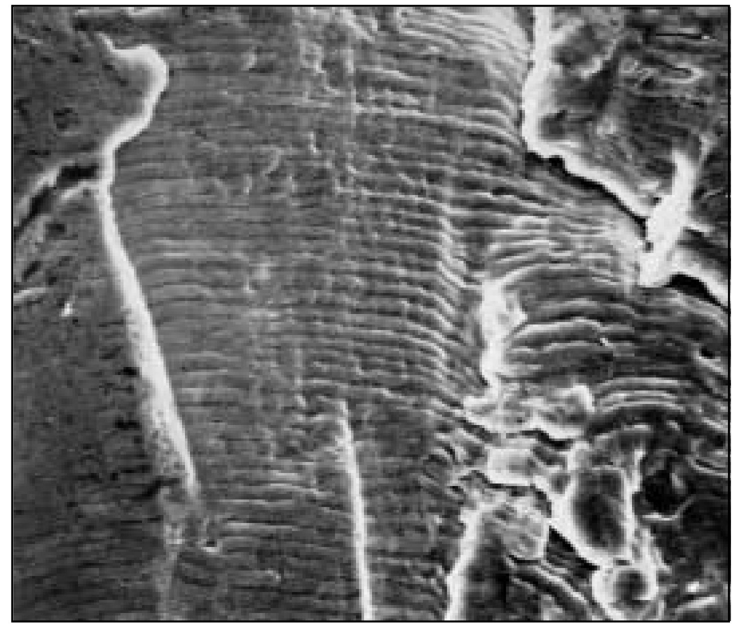
Growth of fatigue cracks is correlated with the range in stress intensity factor: ΔK.

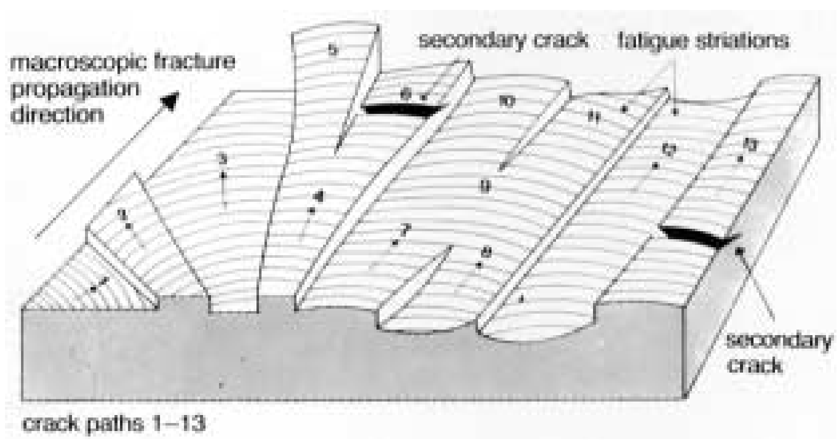
$$\Delta K = Y\ \Delta S \sqrt{\pi a}$$

$$\frac{da}{dN} = C(\Delta K)^n$$

Fatigue fracture surface

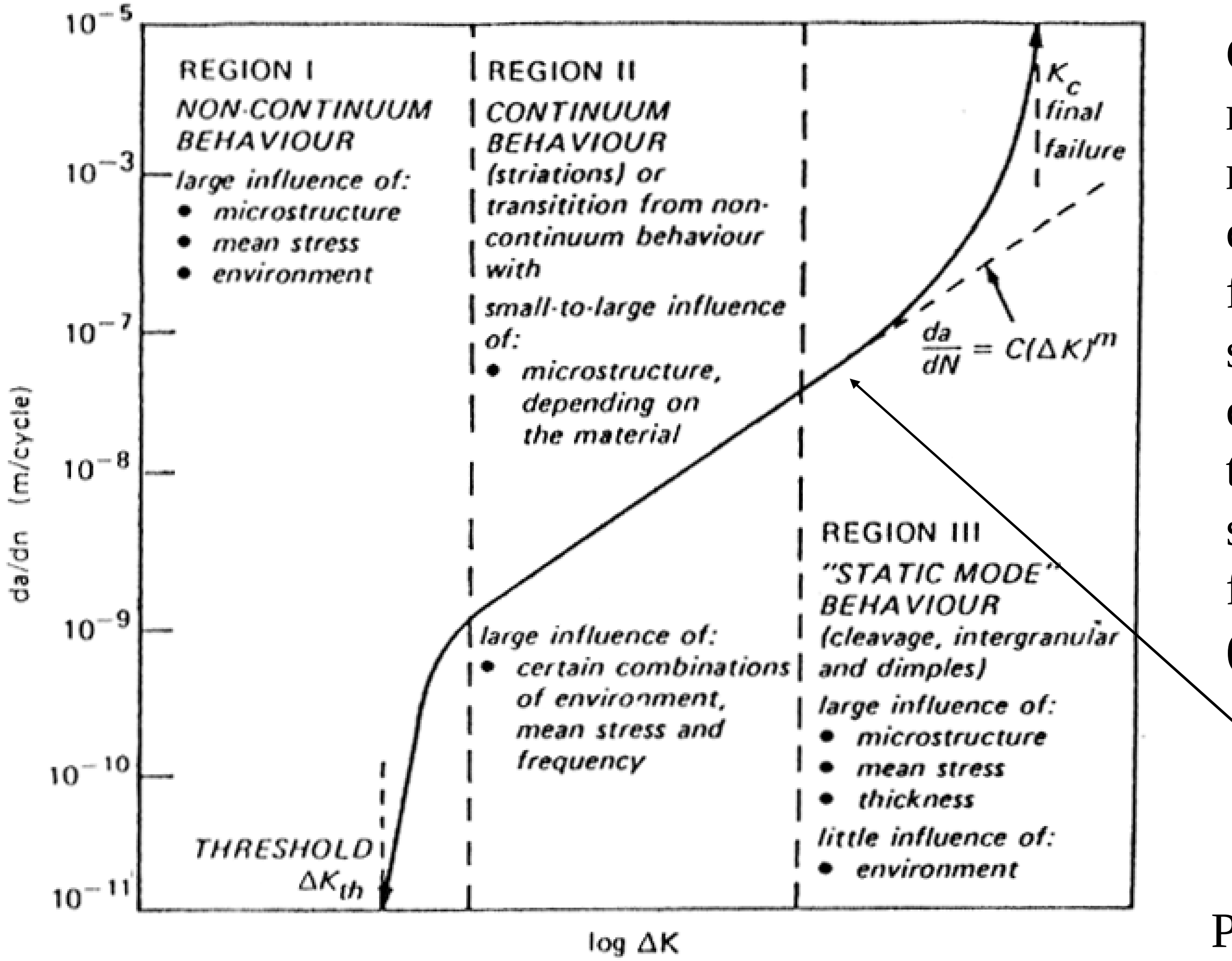
Scanning electron microscope image - striations clearly visible





Schematic drawing of a fatigue fracture surface

MODEL: Crack growth rate versus ΔK

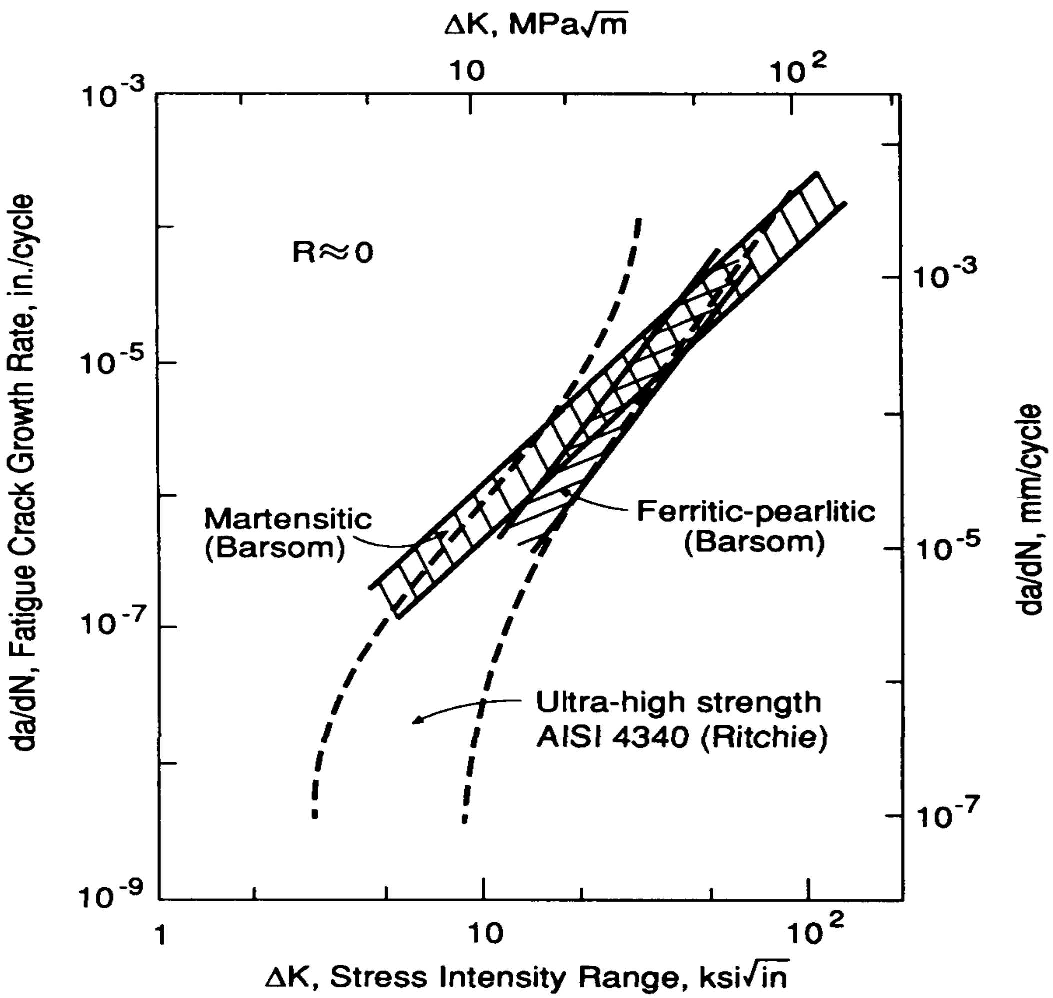


Crack growth rate (da/dN) is related to the crack tip stress field and is thus strongly correlated with the range of stress intensity factor: ($\Delta K = Y \Delta S \sqrt{\pi a}$).

$$\frac{da}{dN} = C(\Delta K)^n$$

Paris power law

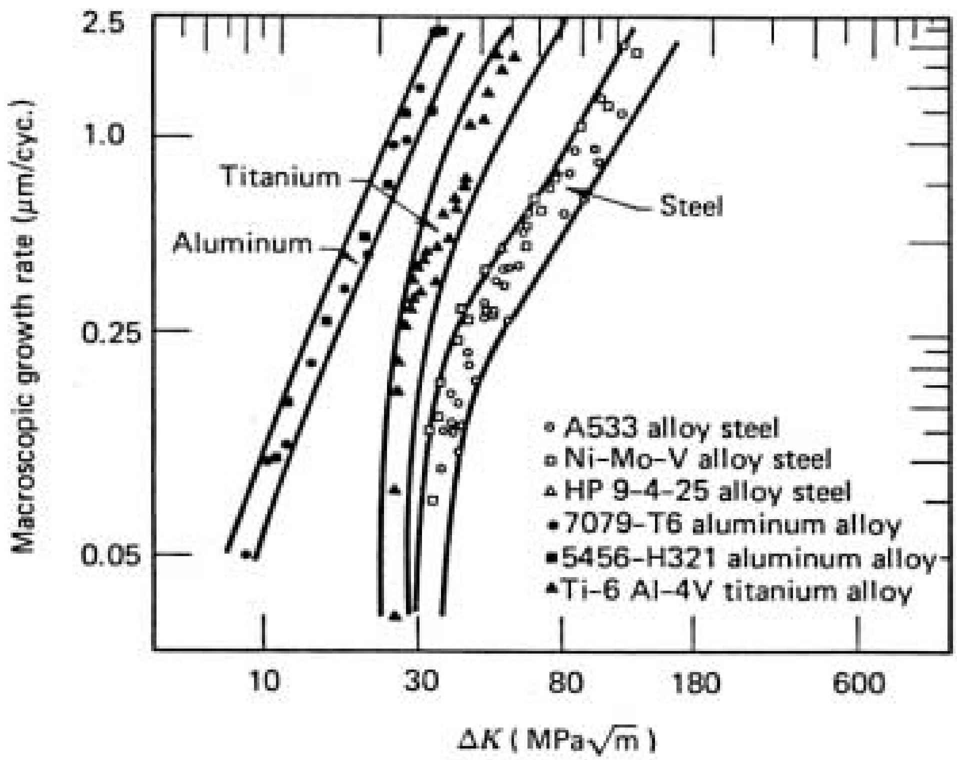
Crack Growth Data

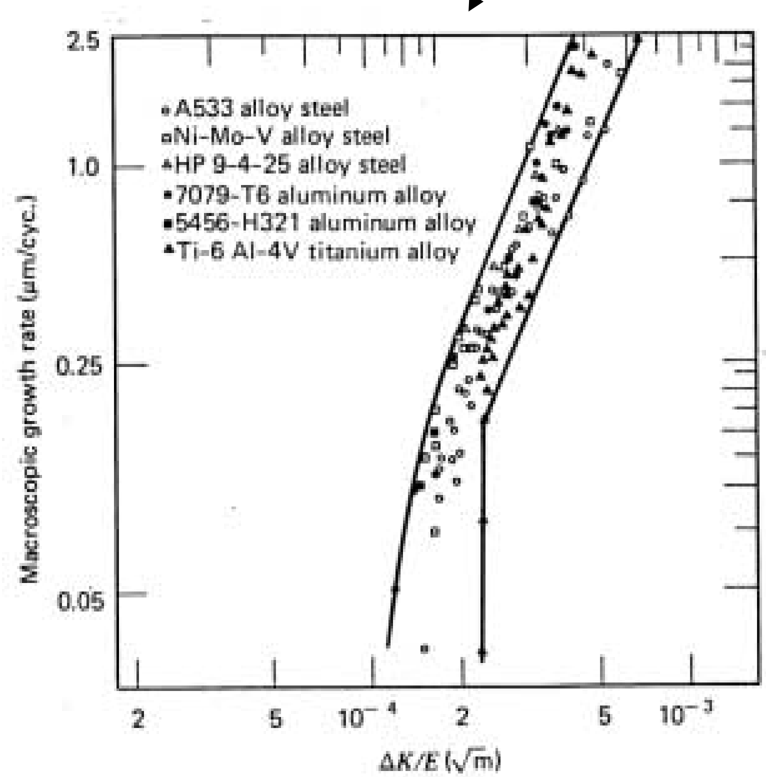


All ferritic-pearlitic, that is, plain carbon steels behave about the same irrespective of strength or grain size!

Crack growth rates of metals

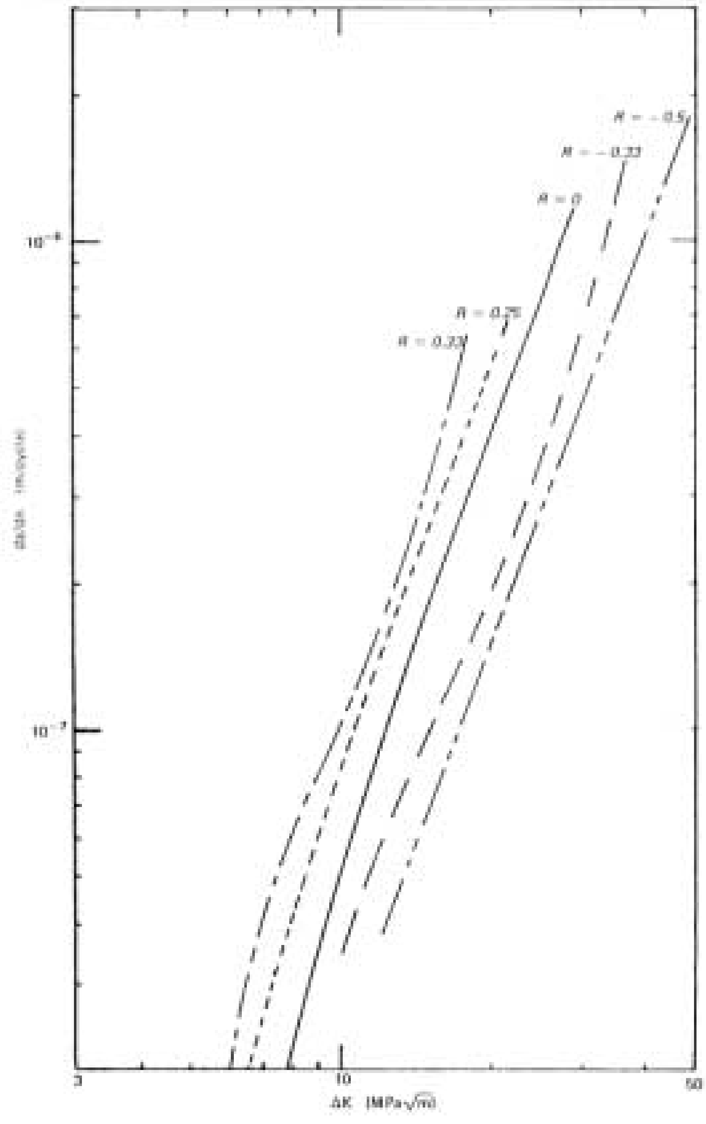
$$\frac{\Delta K}{E}$$





The fatigue crack growth rates for Al and Ti are much more rapid than steel for a given ΔK. However, when normalized by Young's Modulus all metals exhibit about the same behavior.

MODEL: Mean stresses (R ratio)



$$\frac{da}{dN} = \frac{C\,\Delta K^{m}}{(1-R)\,K_c - \Delta K}$$

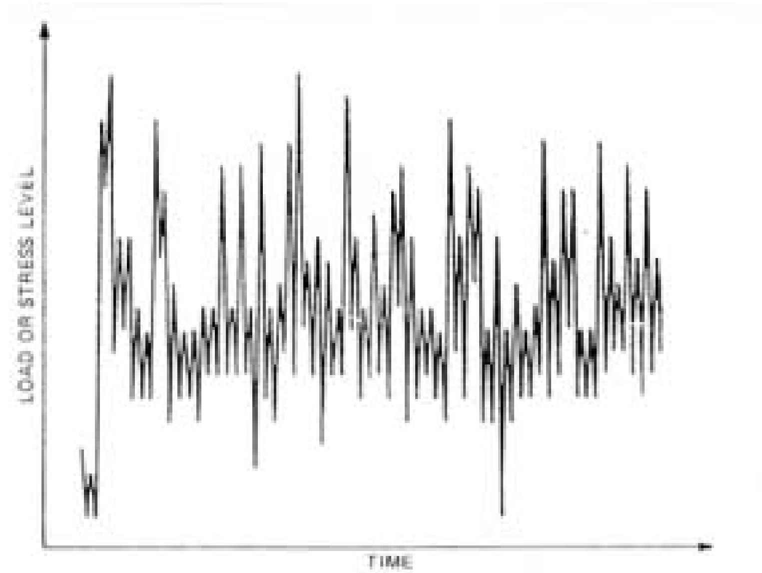
Forman’s equation which includes the effects of mean stress.

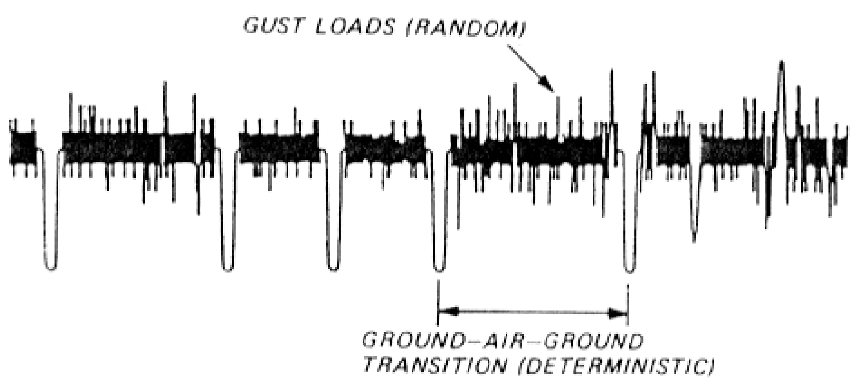
$$\frac{da}{dN} = \frac{C\,\Delta K^{m}}{(1-R)^{\gamma}}$$

Walker’s equation which includes the effect of mean stress.

PROBLEM: Variable load histories?

While some applications are actually constant amplitude, many or most applications involve variable amplitude loads (VAL) or variable load histories (VLH).

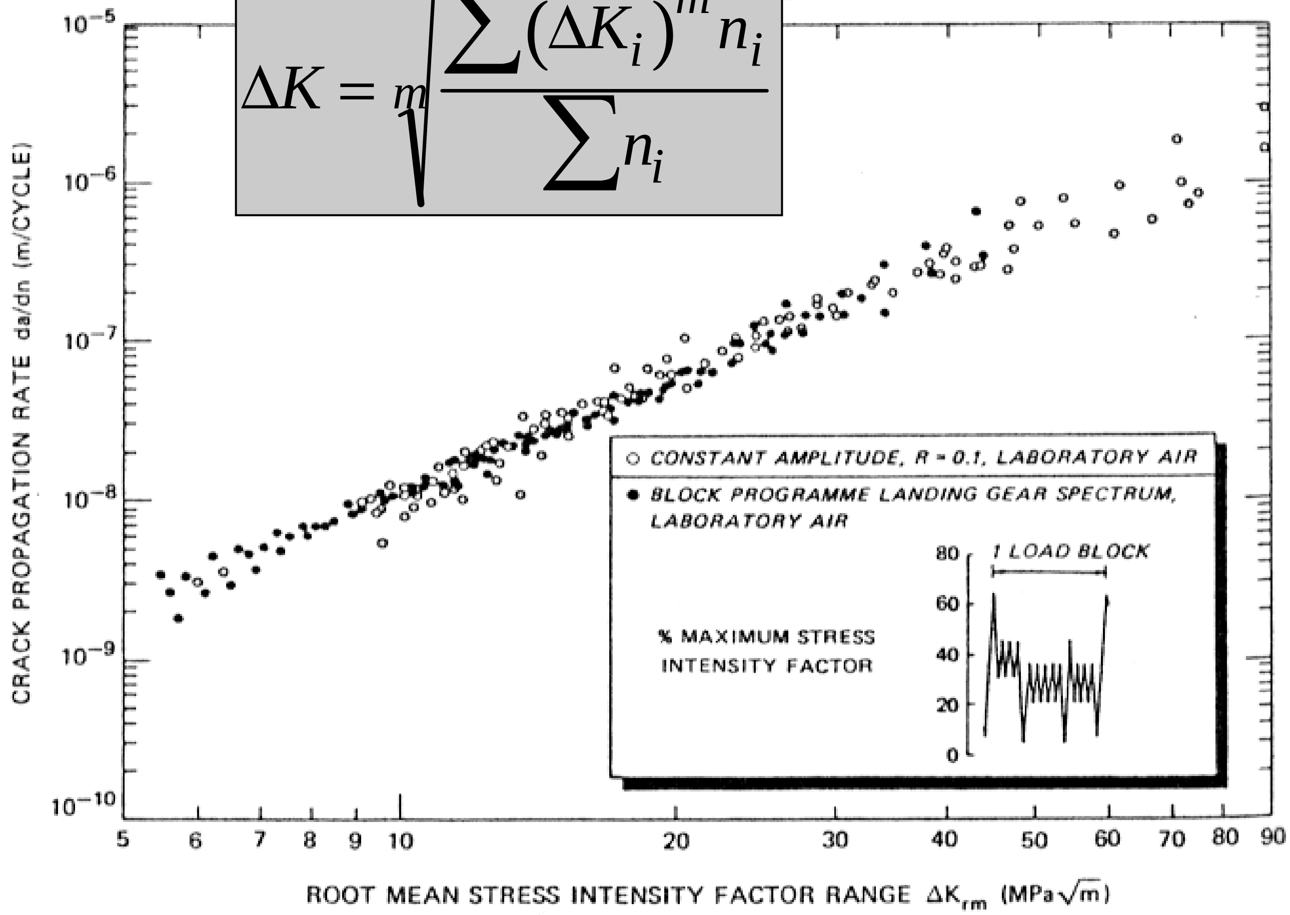




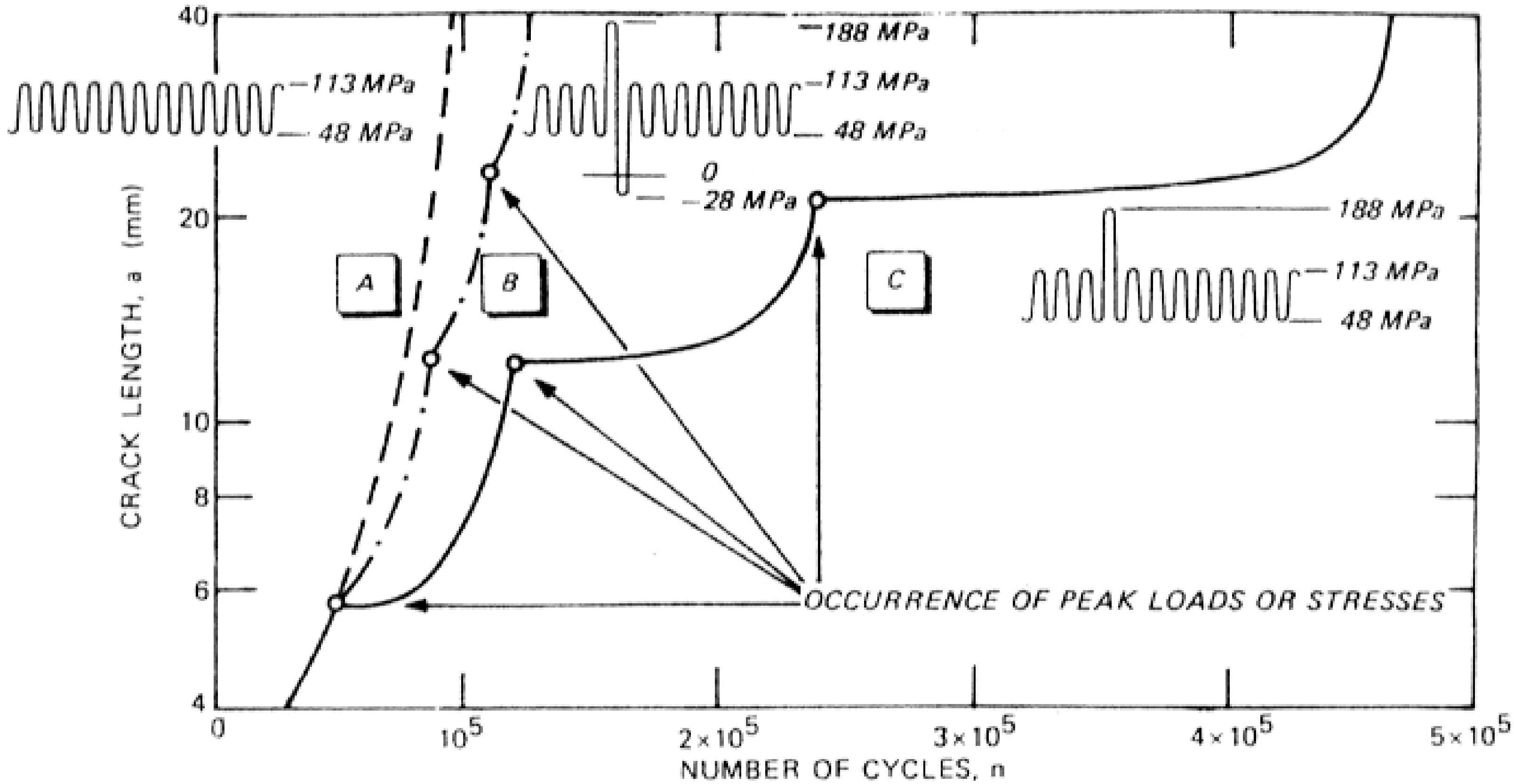
Aircraft load histories

FIX: Root mean cube method

$$\Delta K = \sqrt[m]{\frac{\sum (\Delta K_i)^m n_i}{\sum n_i}}$$

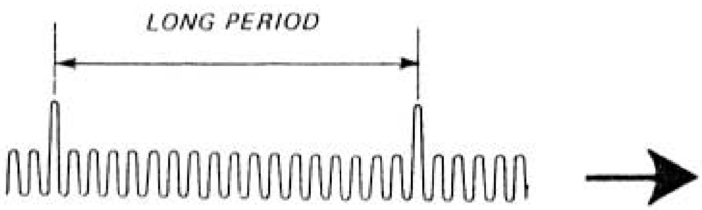


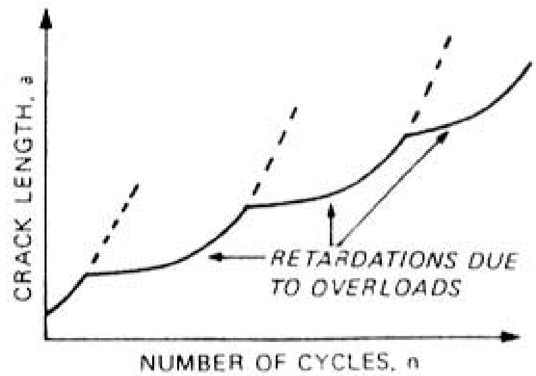
PROBLEM: Overloads, under-loads?



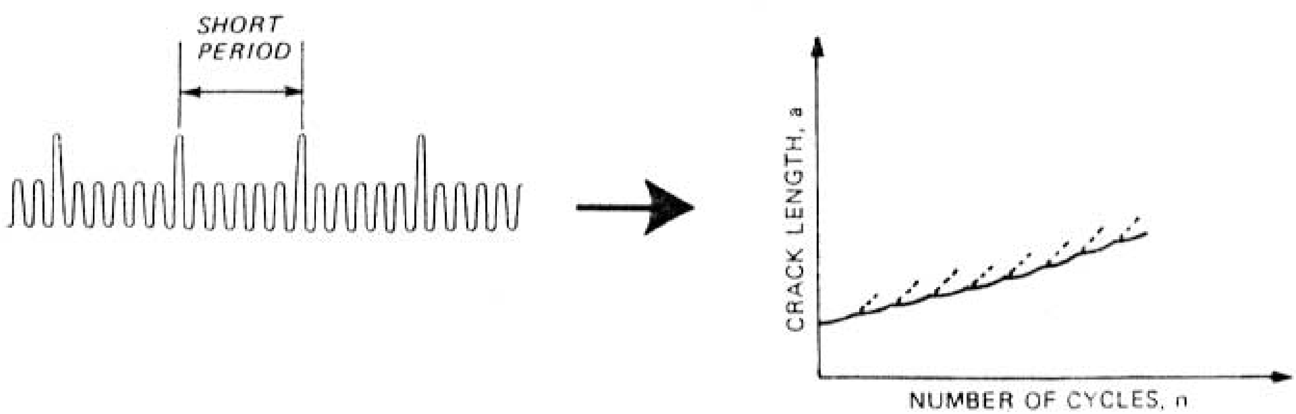
Overloads retard crack growth, under-loads accelerate crack growth.

PROBLEM: Periodic overloads?





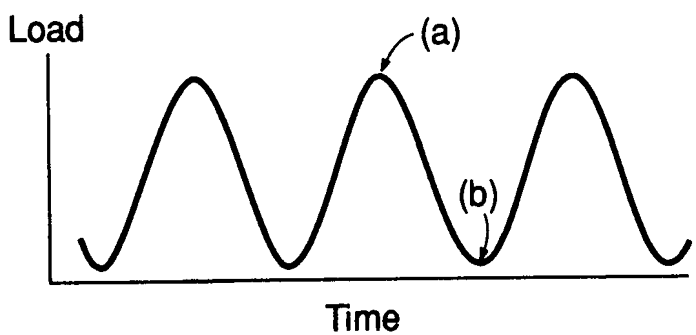
Effects of Periodic Overloads

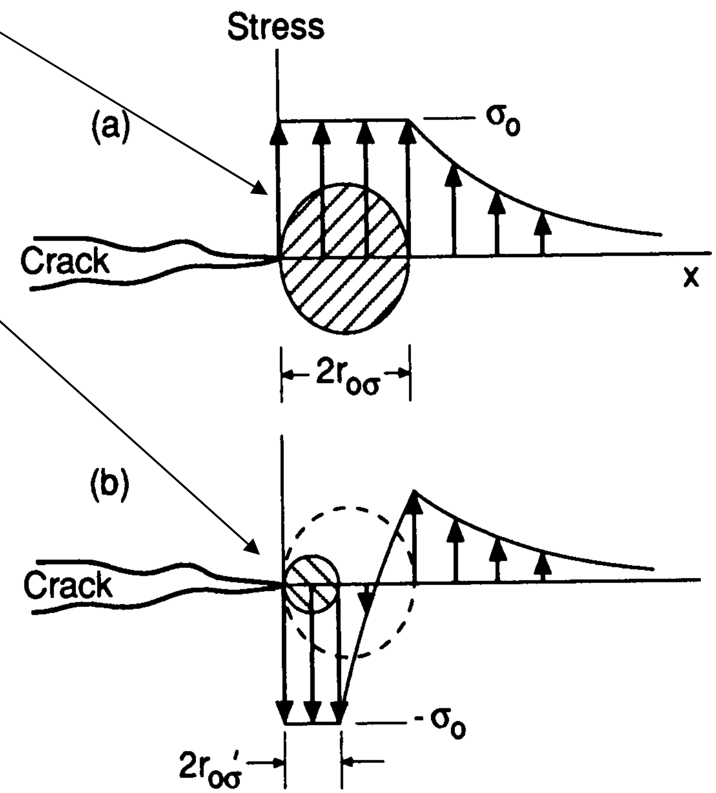


Infrequent overloads help, but more frequent may be even better. Too frequent overloads very damaging.

FIX: MODEL for crack tip stress fields

Monotonic plastic zone size
Cyclic plastic zone size

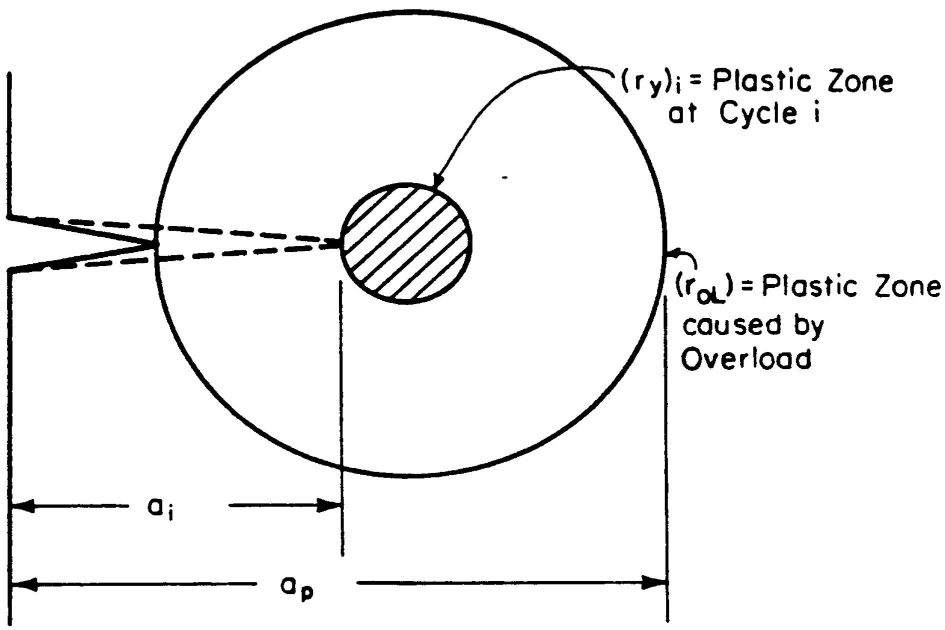




$$r_y = \frac{1}{\beta\pi}\left(\frac{K}{\sigma_y}\right)$$

ß is 2 for (a) plane stress and 6 for (b)

MODEL: Overload plastic zone size



$$r_y = \frac{1}{\beta\pi}\left(\frac{K}{\sigma_y}\right)$$

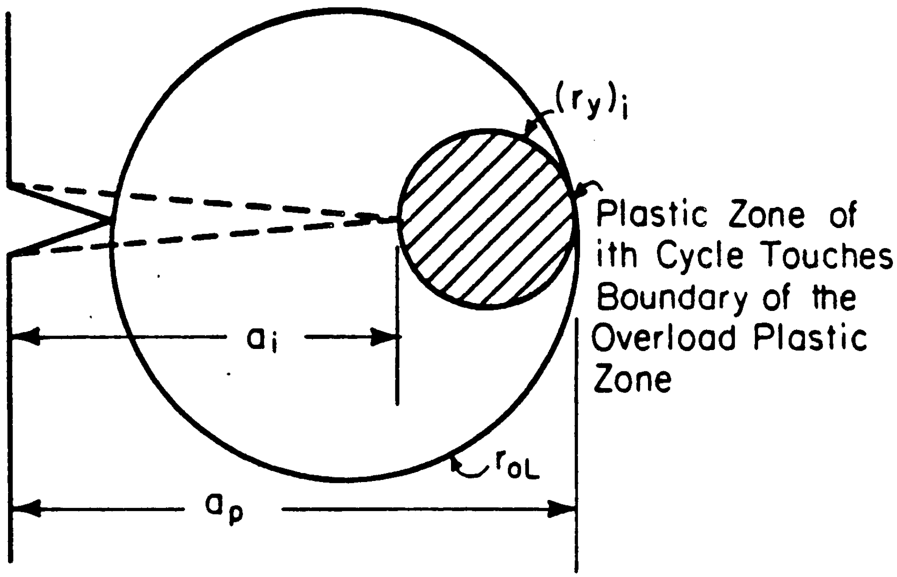
Crack growth retardation ceases when the plastic zone of ith cycle reaches the boundary of the prior overload plastic zone.

ß is 2 for plane stress and 6 for plain strain.

MODEL: Retarded crack growth

Wheeler model

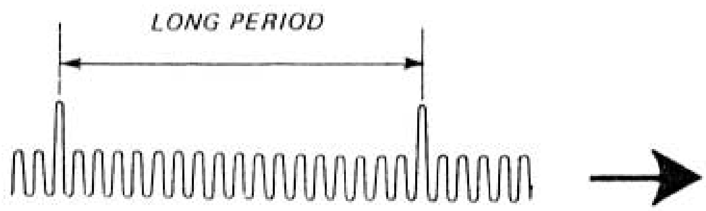
$$\left(\frac{da}{dN}\right)_{VA} = \beta\left(\frac{da}{dN}\right)_{CA}$$

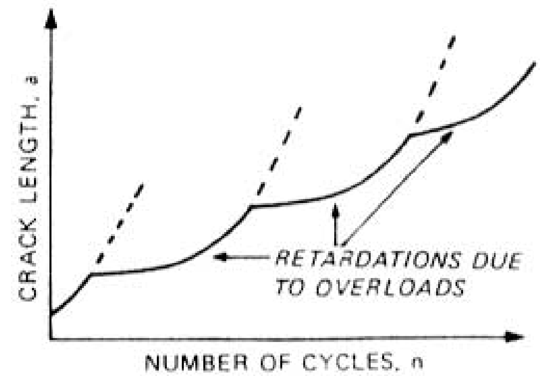


$$\beta = \left(\frac{2\,r_y}{a_p - a_i}\right)^k$$

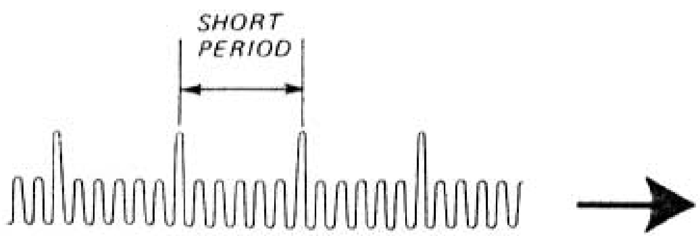
$$r_y = \frac{1}{2\pi}\left(\frac{K}{\sigma_{ys}}\right)^2$$

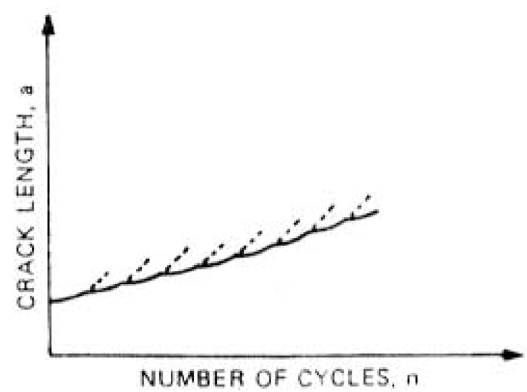
Retarded crack growth





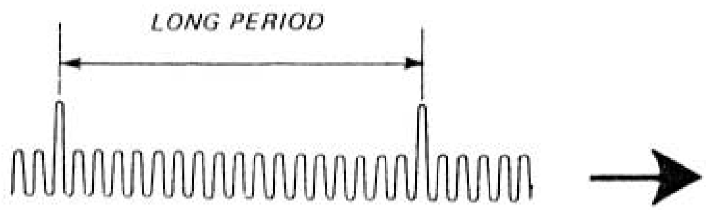
Effects of Periodic Overloads

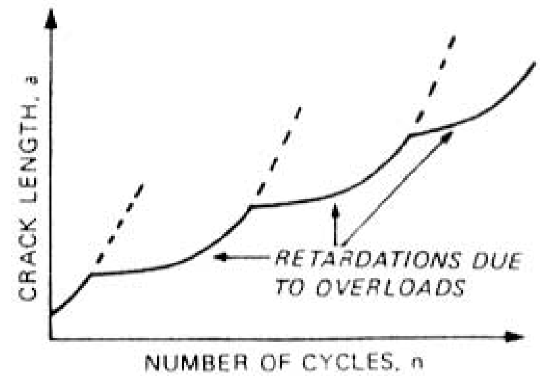




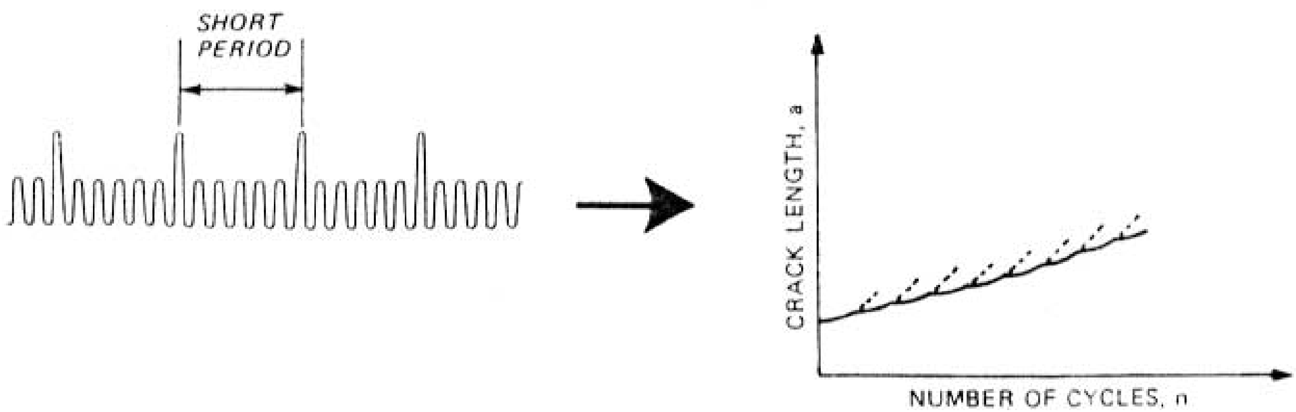
Infrequent overloads help, but more frequent may be even better. Too frequent overloads very damaging.

PROBLEM: Periodic overloads?



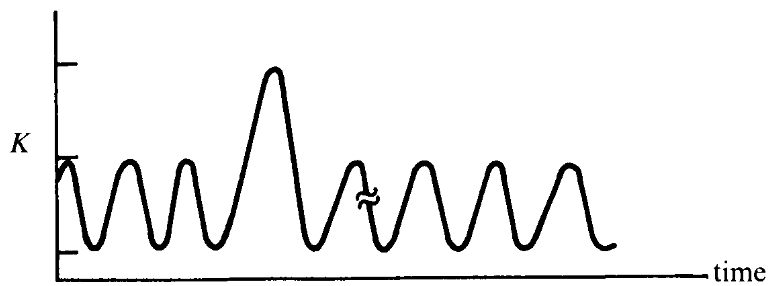


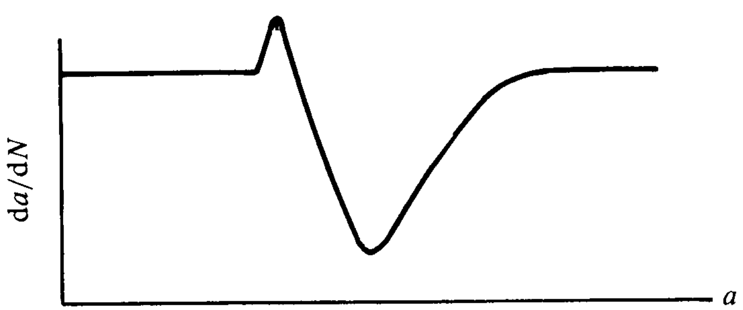
Effects of Periodic Overloads



Infrequent overloads help, but more frequent may be even better. Too frequent overloads very damaging.

Sequence Effects





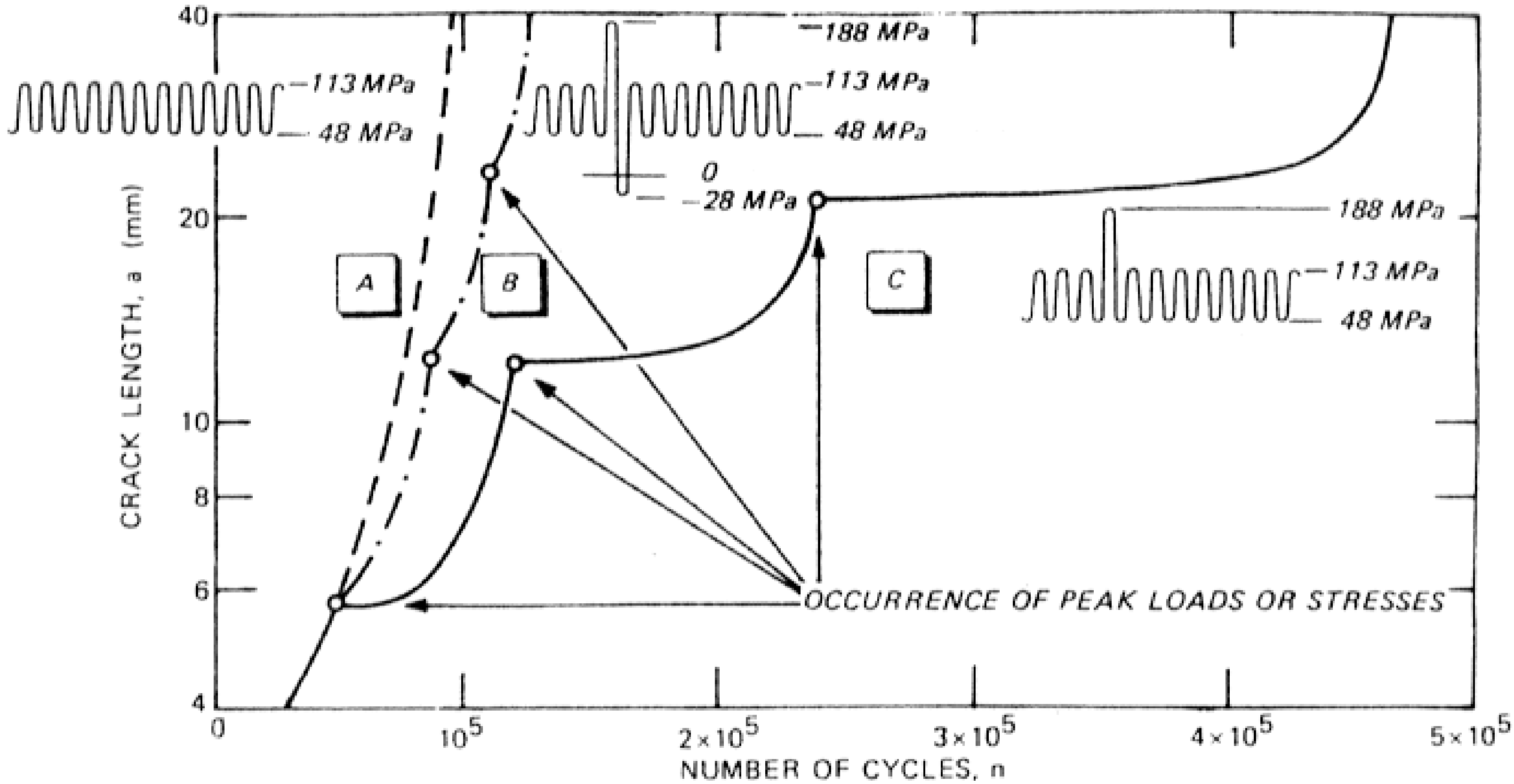
Last one controls!

Compressive overloads accelerate cdrack growth by reducing roughness of fracture surfaces.

Compressive followed by tensile overloads…retardation!

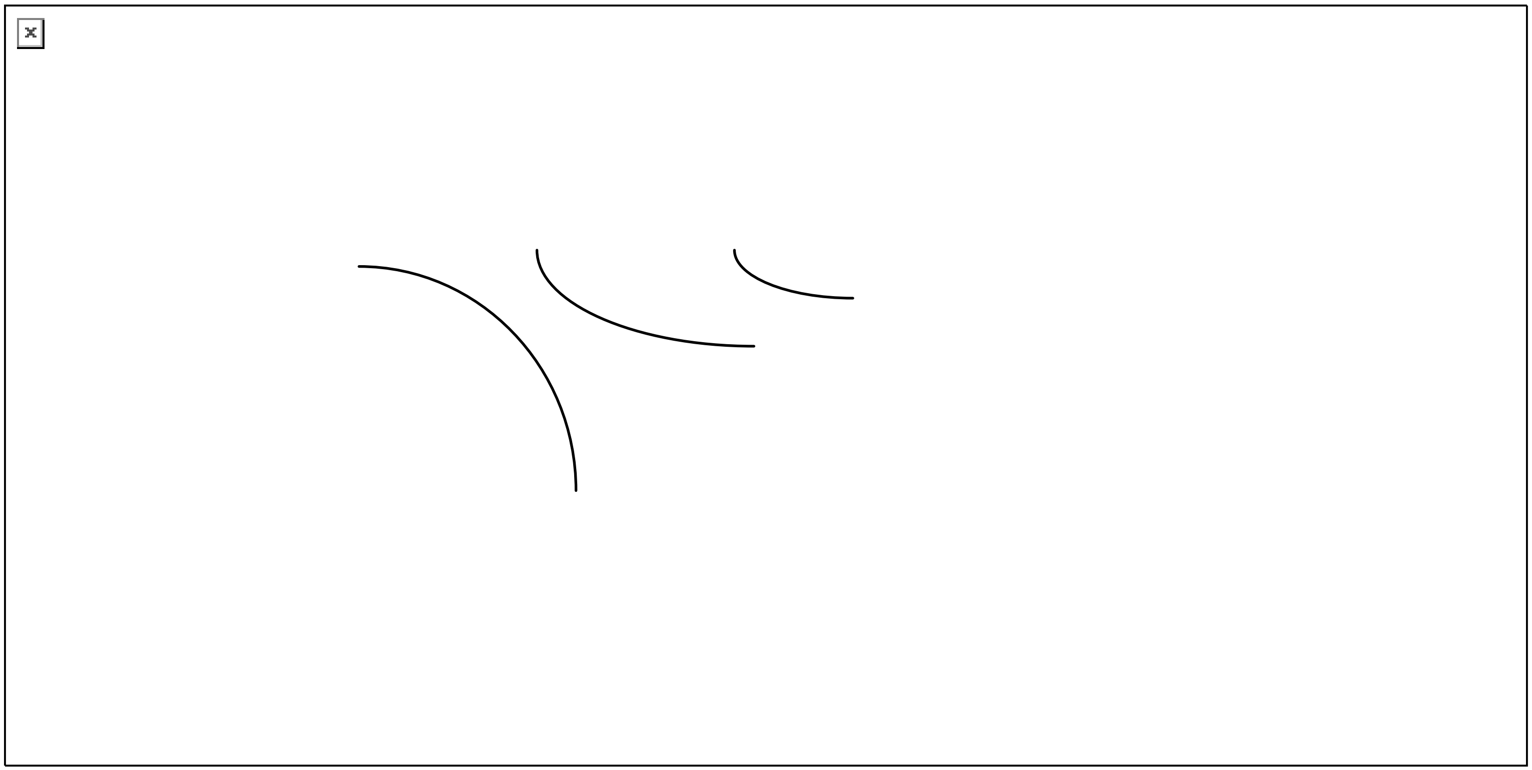
Tensile followed by compressive, little retardation

Sequence effects



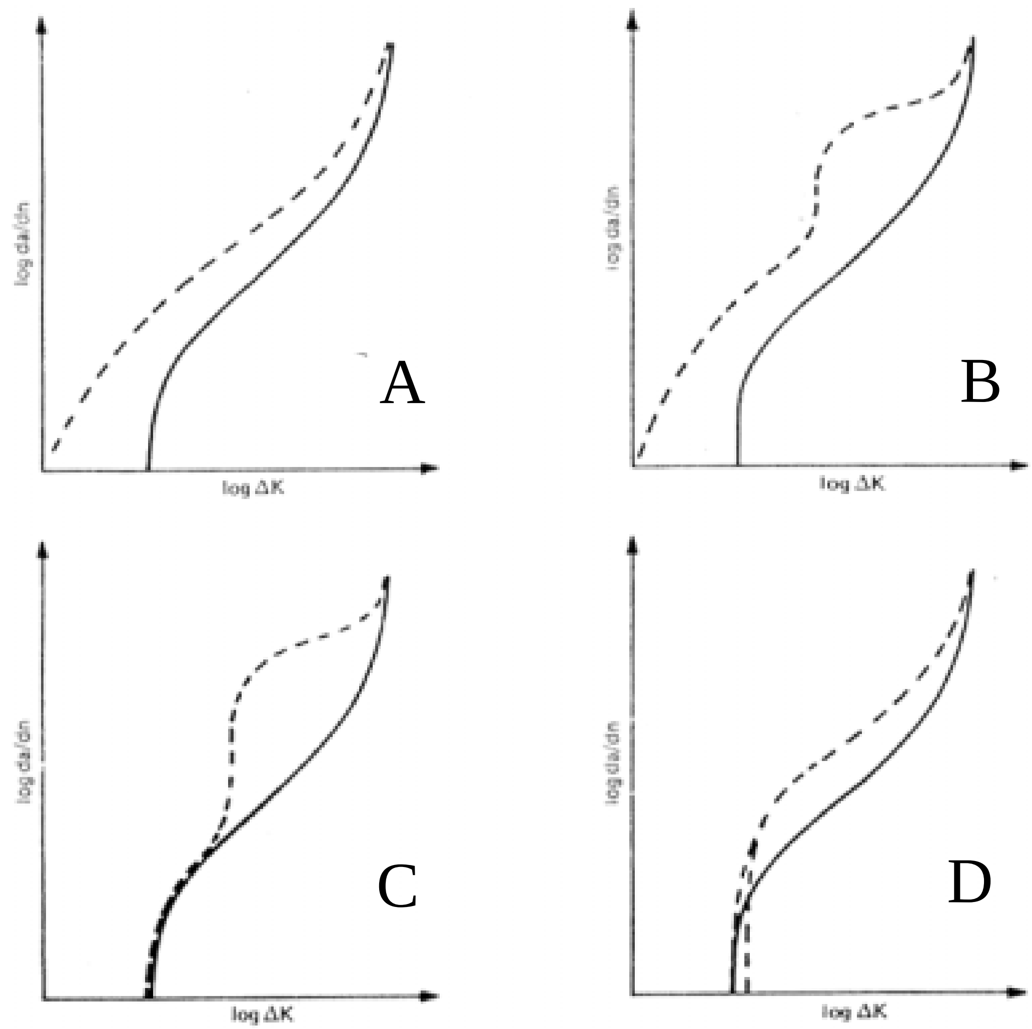
Overloads retard crack growth, under-loads accelerate crack growth.

PROBLEMS: Small Crack Growth?



Small cracks don't behave like long cracks! Why?

PROBLEMS: Environment?



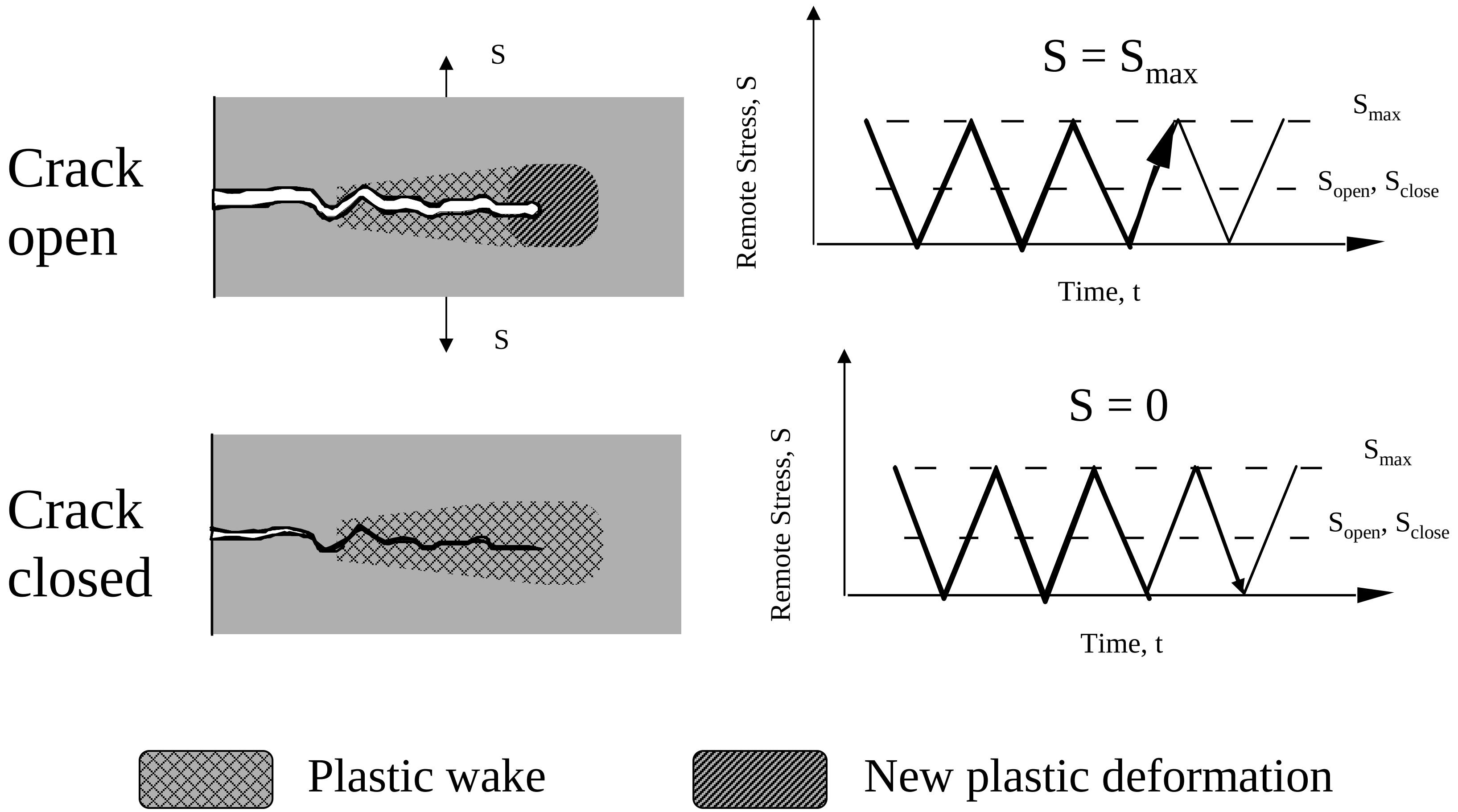
A. Dissolution of crack tip.

B. Dissolution plus H+ acceleration.

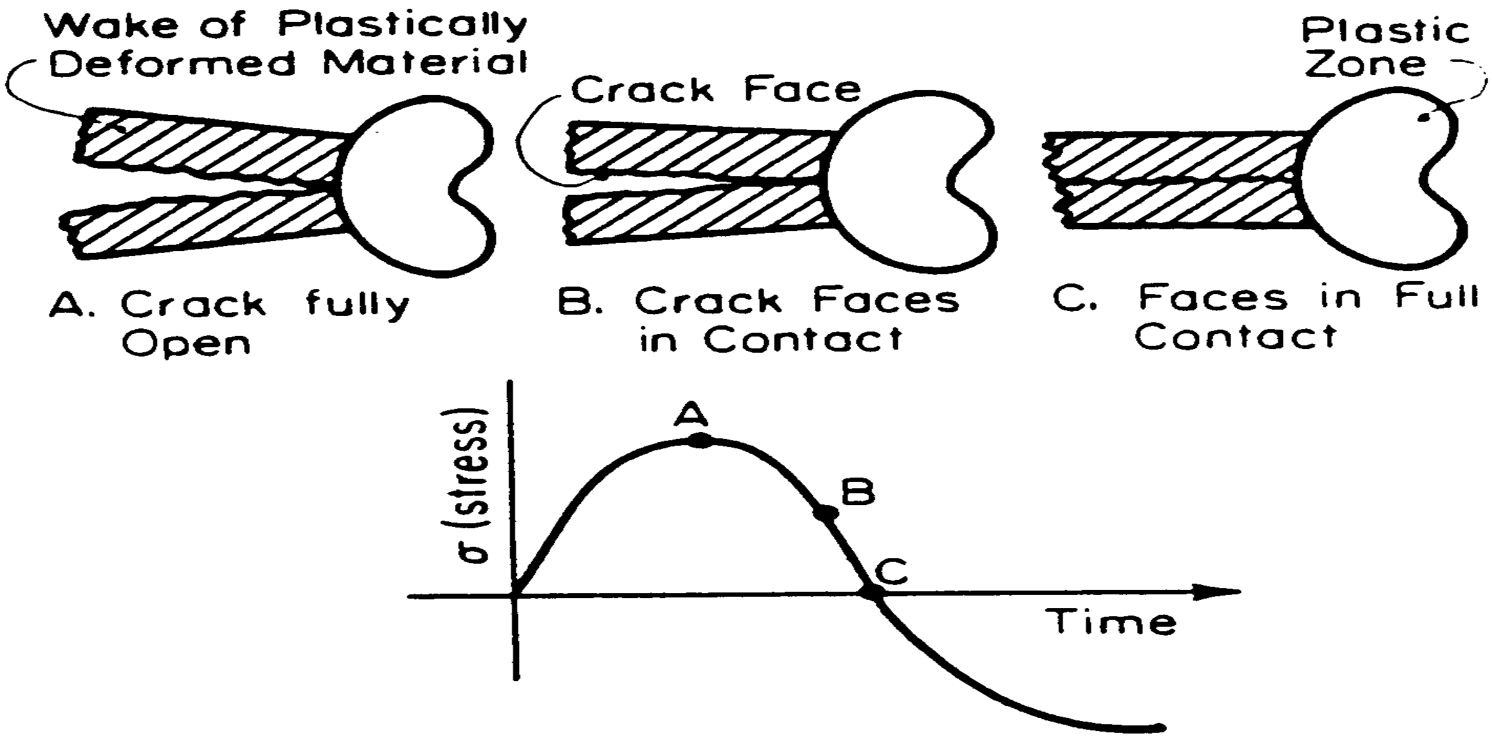
C. H+ acceleration

D. Corrosion products may retard crack growth at low ΔK.

FIX: Crack closure

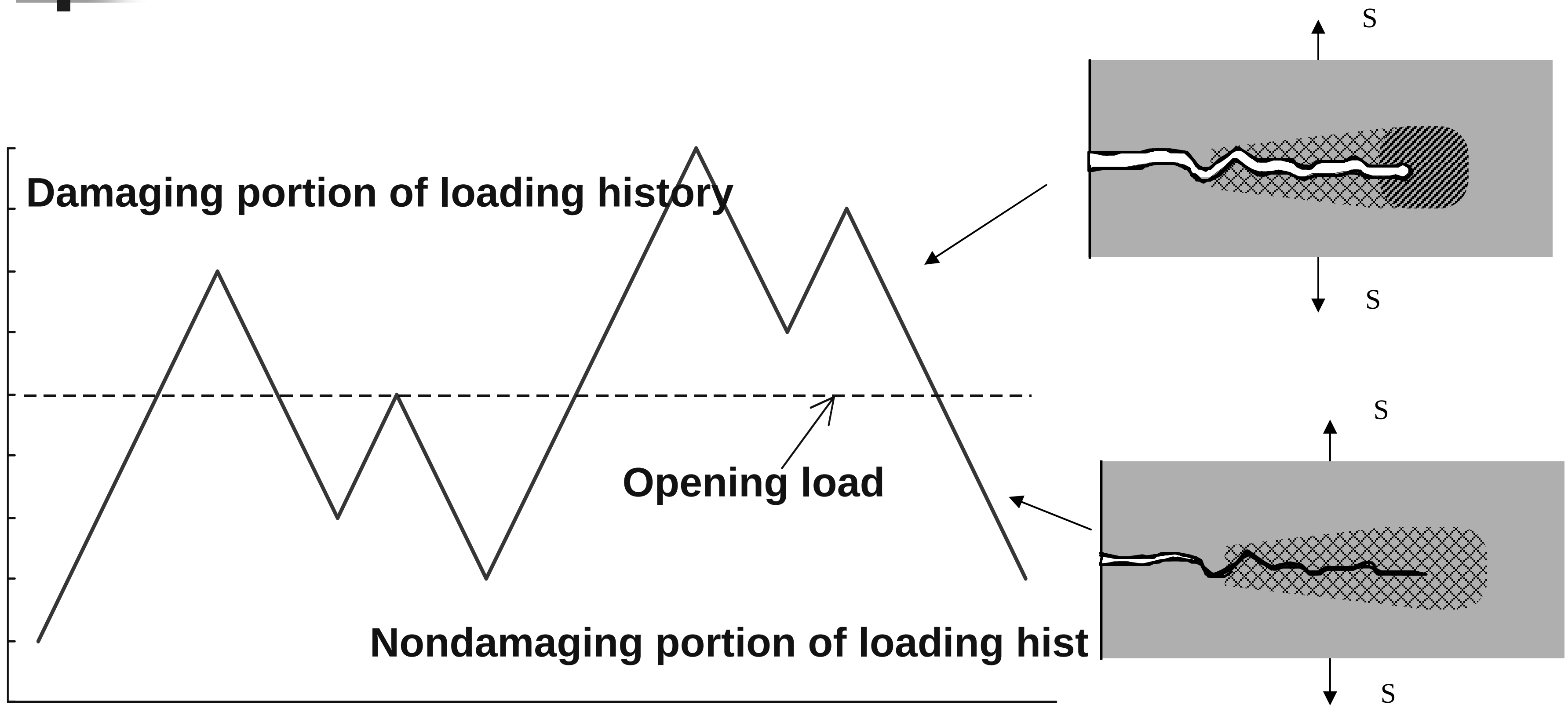


CAUSE: Plastic Wake

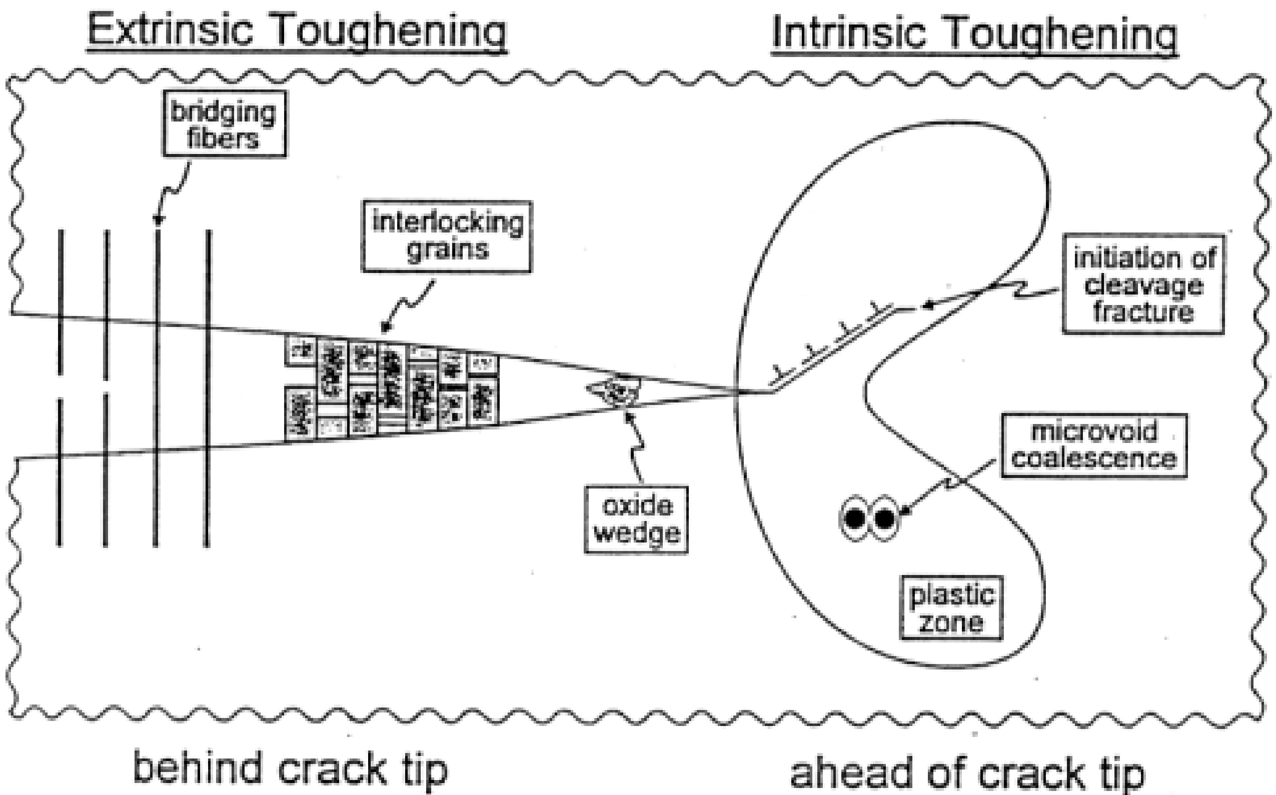


Short cracks can’t do this so they behave differently!

“Effective” part of load history



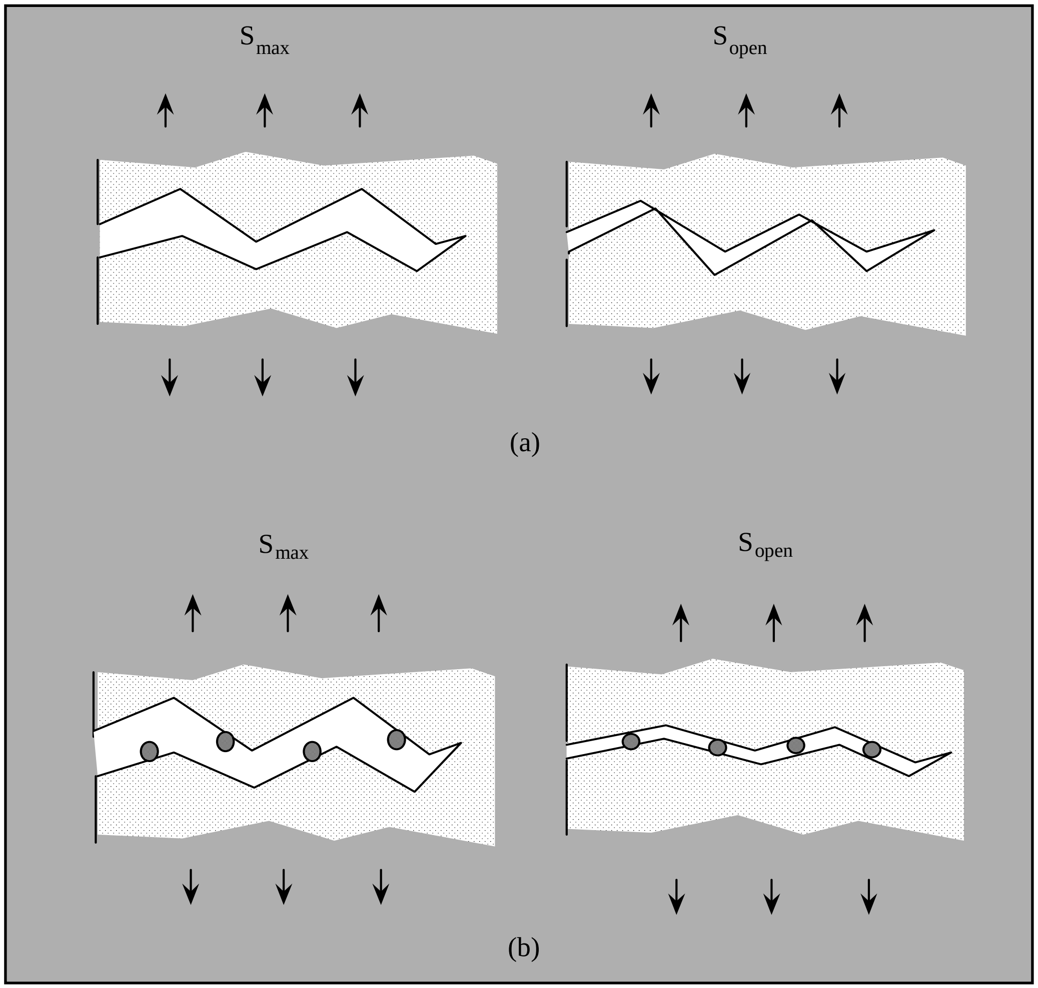
MODEL: Crack closure



$$\frac{da}{dn} = C\ (\Delta K)^m (K_{max})^p$$

Extrinsic
Intrinsic

Other sources of crack closure



Roughness induced crack closure (RICC)

Oxide induced crack closure (OICC)

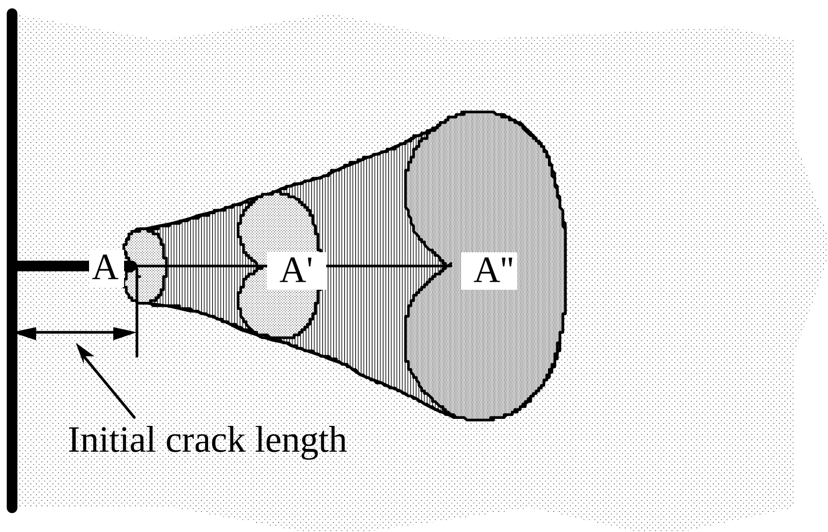
MODEL: Crack closure

$$\Delta K_{eff} = U \, \Delta K$$

$$U = \frac{\Delta K_{eff}}{\Delta K} = \frac{S_{max} - S_{open}}{S_{max} - S_{min}} = \frac{1}{1-R}\left(1 - \frac{S_{open}}{S_{max}}\right)$$

$$U \approx 0.5 + 0.4R$$ (sometimes)

Plasticity induced crack closure (PICC)



A, A', A" Crack tip positions

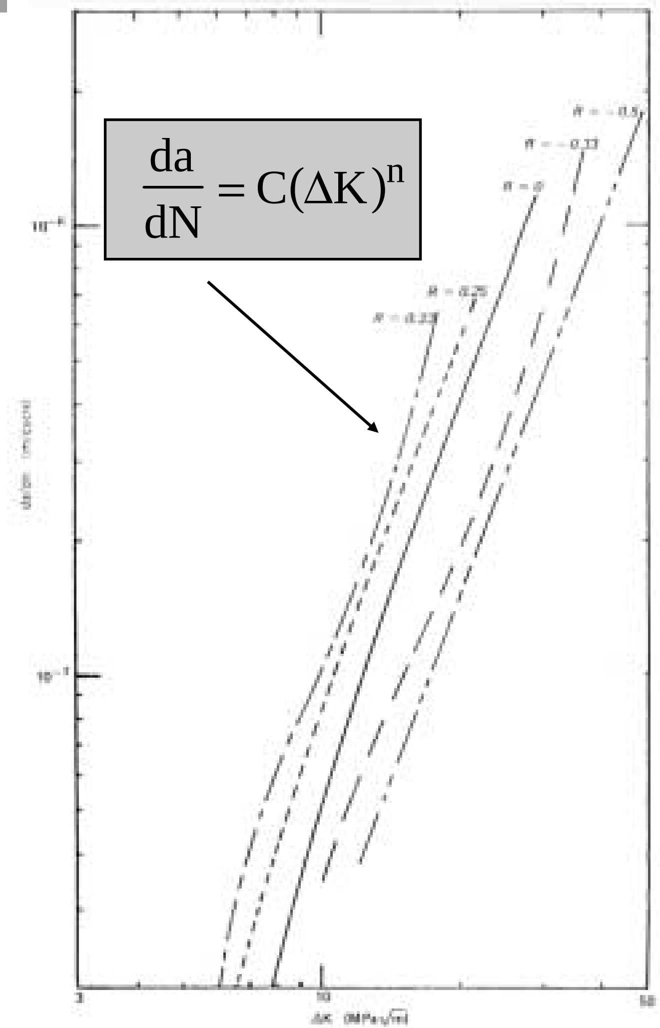
Plastic zones for crack positions A...A"

Plastic wake

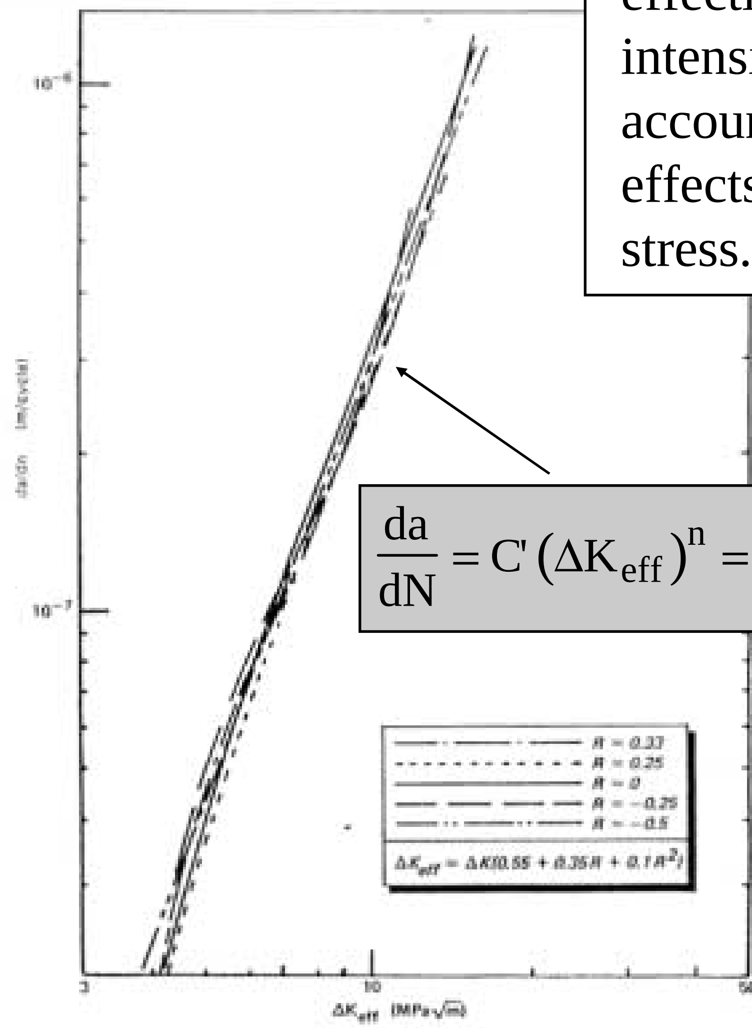
MODEL USE: $\Delta K_{effective}$

The use of the effective stress intensity factor accounts for the effects of mean stress.

$$\frac{da}{dN} = C(\Delta K)^n$$



$$\frac{da}{dN} = C'\left(\Delta K_{eff}\right)^n = C'\left(U\Delta K\right)^n$$

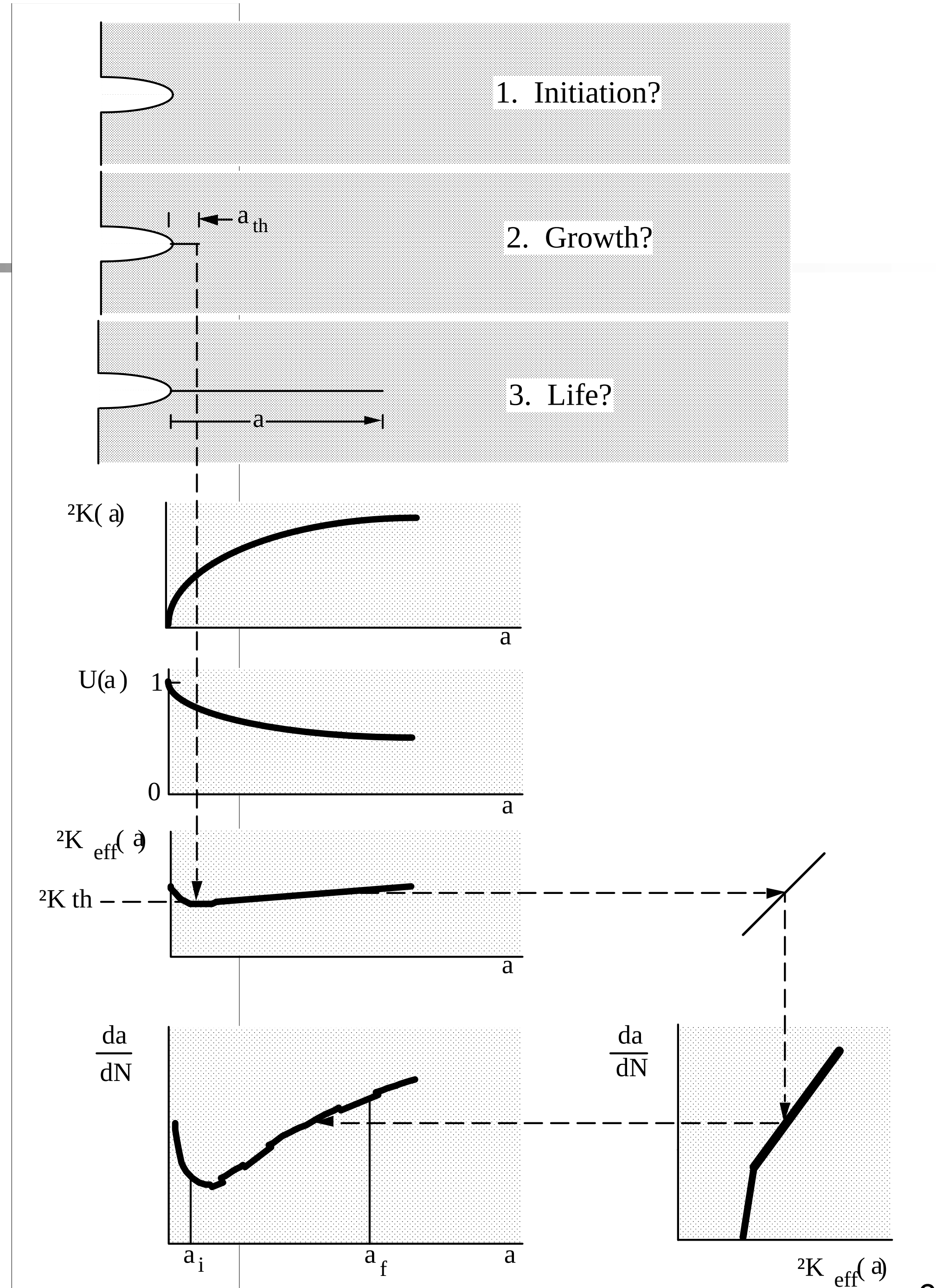


MODEL USE

Use of ΔK_{eff}

Crack closure at a notch model. Information about U(a) becomes the “sticking point.”

$$N_F = \int_{a_i}^{a_f} \left(\frac{da}{dN}\right)^{-1} da$$



Bilinear Paris Law

PROBLEM: Fully plastic conditions?

Correlate crack growth rate with strain intensity?

$$\Delta K = E \, \Delta\varepsilon \, Y(a)\sqrt{a}$$

Correlate crack growth rate with values of the J integral?

$$\Delta K^2 = \Delta J \, E = 1.6 \, \Delta\sigma^2 \, a + \frac{5.0 \, \Delta\sigma^2 \Delta\varepsilon_p \, a \, E}{1 + n'}$$

PROBLEM: Fully plastic conditions?

Correlate crack growth rate with values of the crack tip opening displacement (COD)?