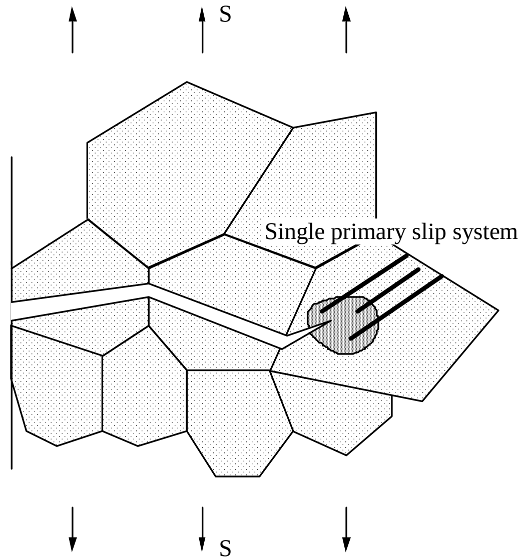
Mechanisms of Fatigue Crack Initiation and Growth

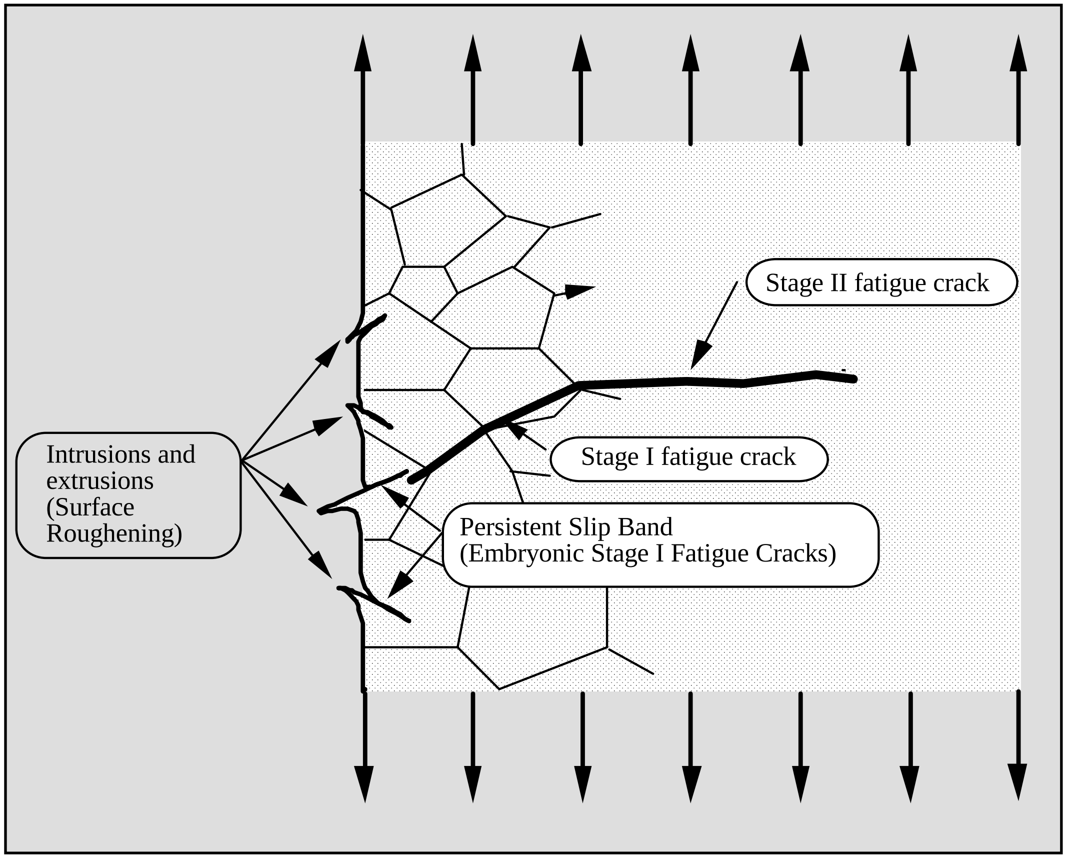


F. V. Lawrence

Fatigue Mechanisms

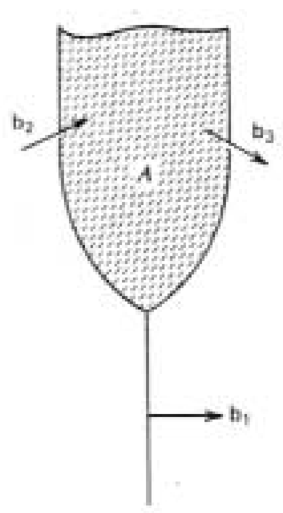
- Fatigue Crack Initiation Mechanisms
- Fatigue Crack Growth Mechanisms

Process of fatigue



Cyclic slip
Crack initiation
Stage I crack growth
Stage II crack growth
Failure

Planar or wavy slip?

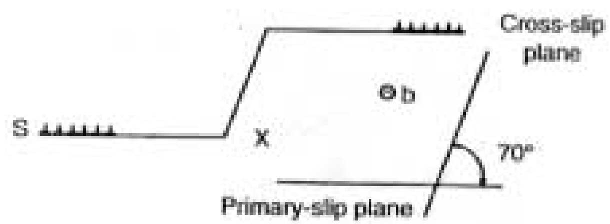


$$d = \frac{G\,(\mathbf{b}_2\ \mathbf{b}_3)}{2\pi\,\gamma}$$

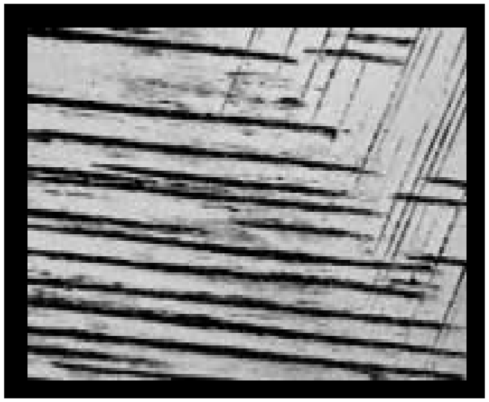
Material	γ Stacking Fault Energy ergs cm^{-2}
Aluminum	250
Iron	200
Nickel	200
Copper	90
Gold	75
Silver	25
Stainless Steel	<10
α Brass	<10

Stacking-fault energy effects

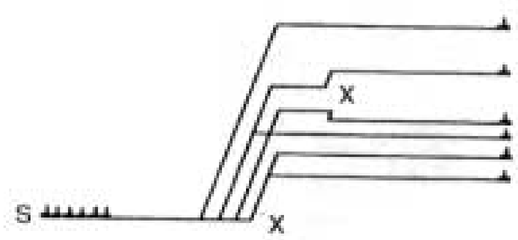
Cu-Al alloys, Cu-Zn, Aust. SS



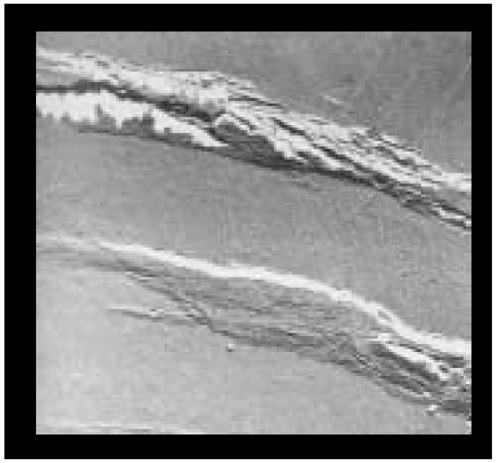
Planar slip in Cu-Al



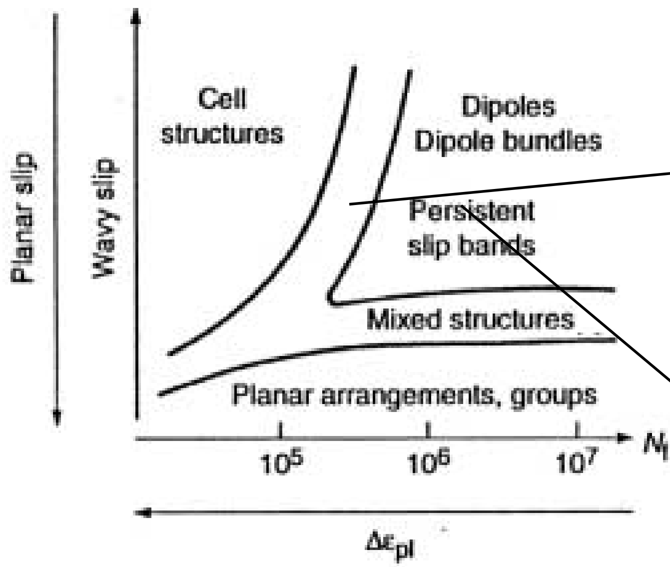
Ni, Cu, Al Fe

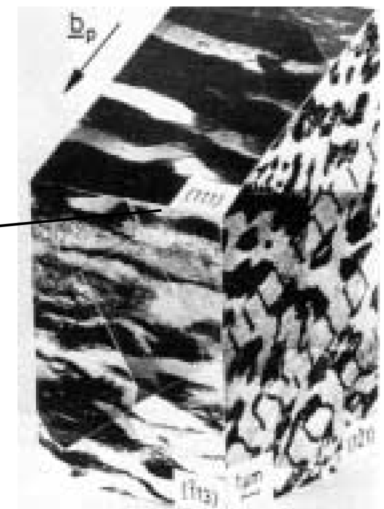


Wavy slip in steel

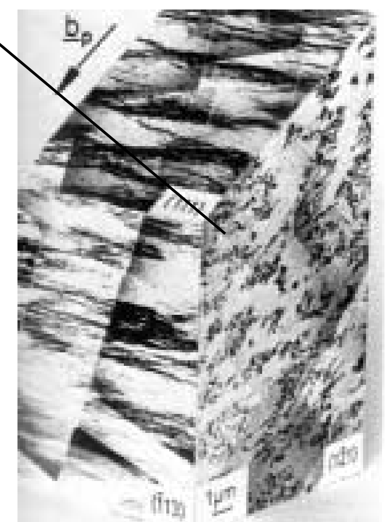


Development of cell structures





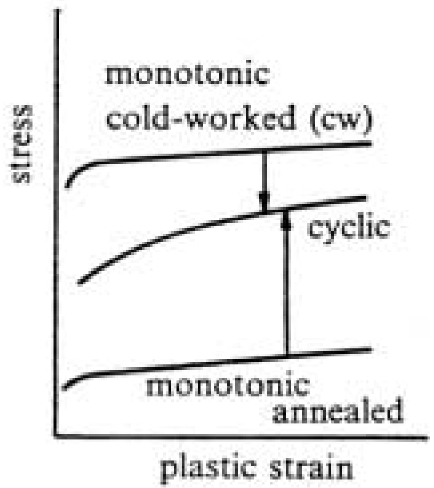
$\gamma = 10^{-3}$

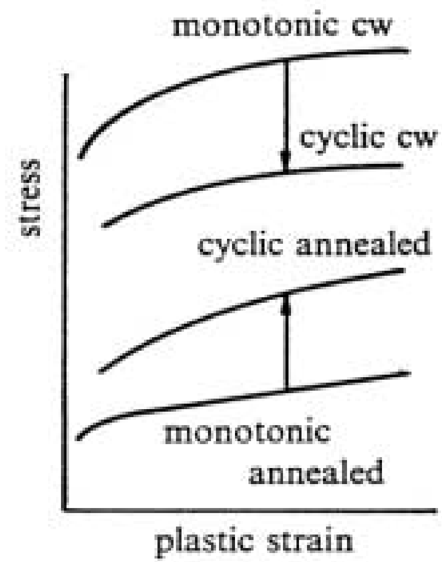


$\gamma = 10^{-5}$

Dislocation cell structures in copper

Planar and wavy slip materials

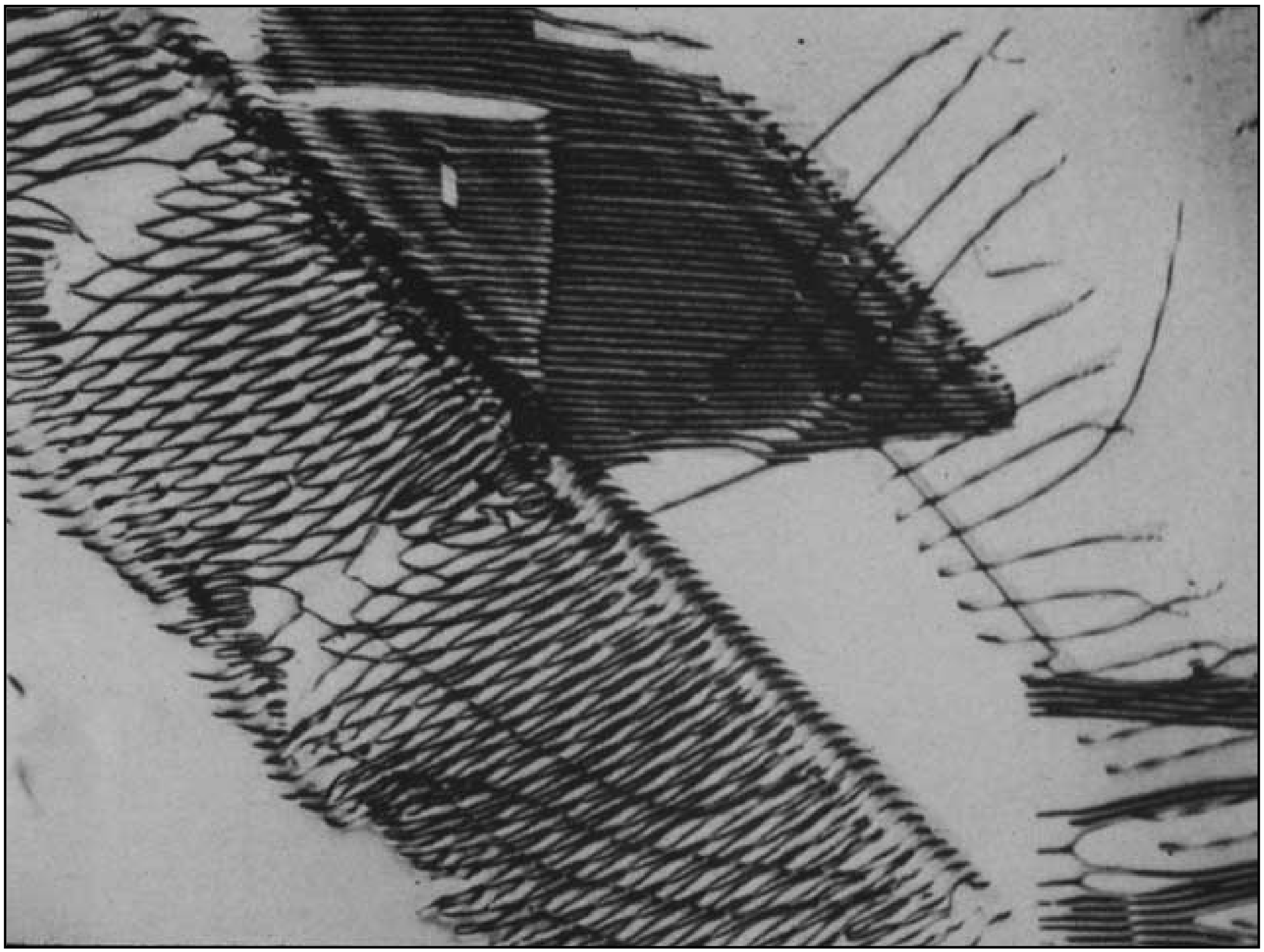




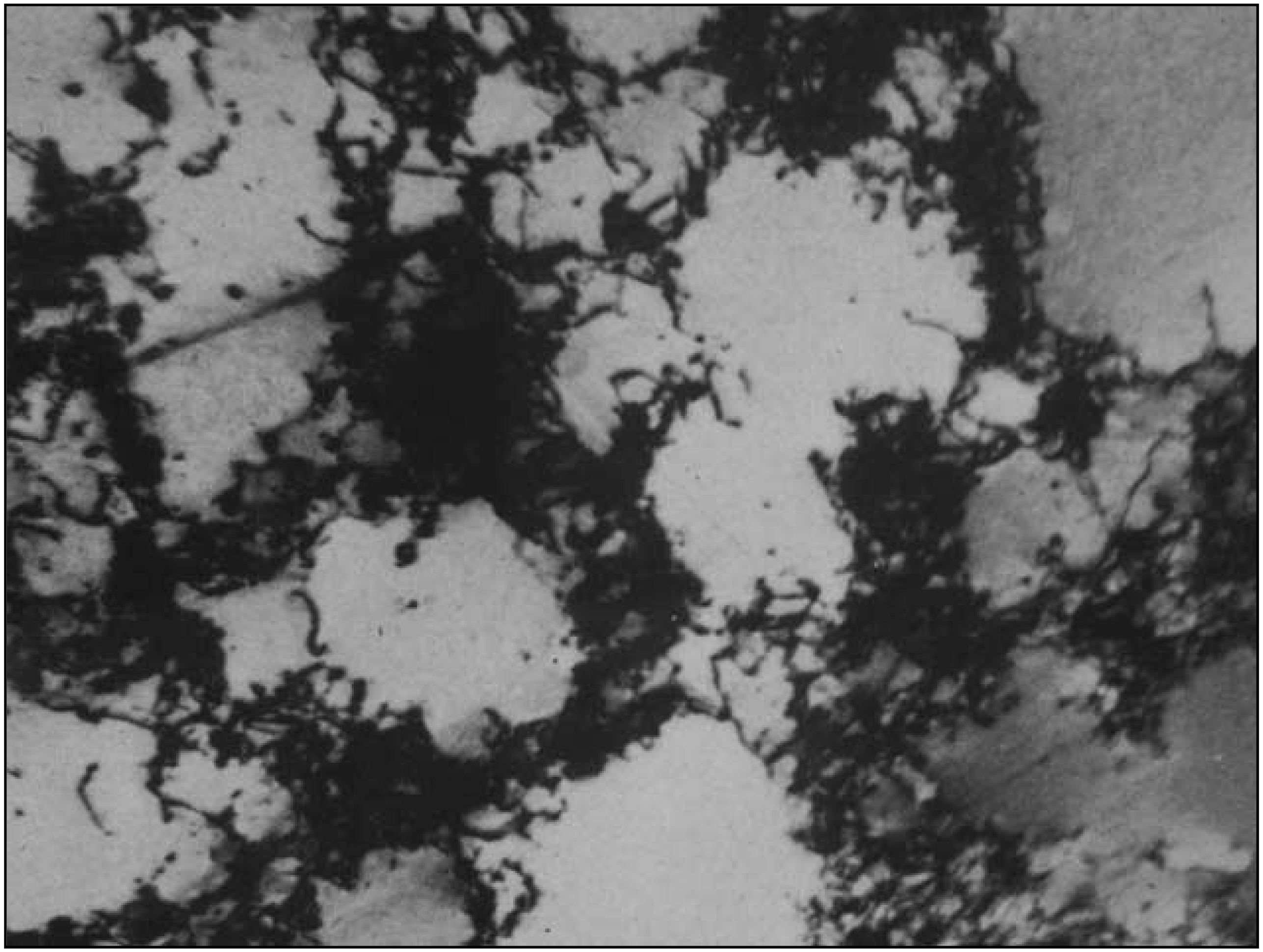
Wavy slip materials

Planar slip materials

Cyclic Slip - initial arrangements



Cyclic Hardening

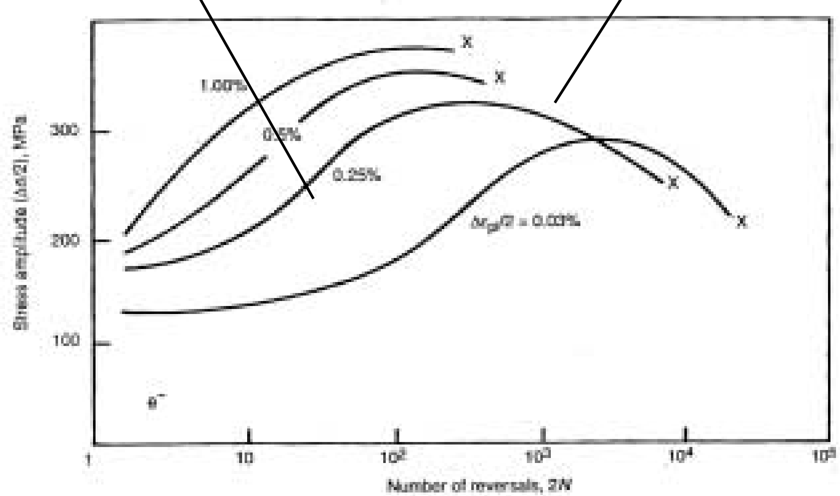


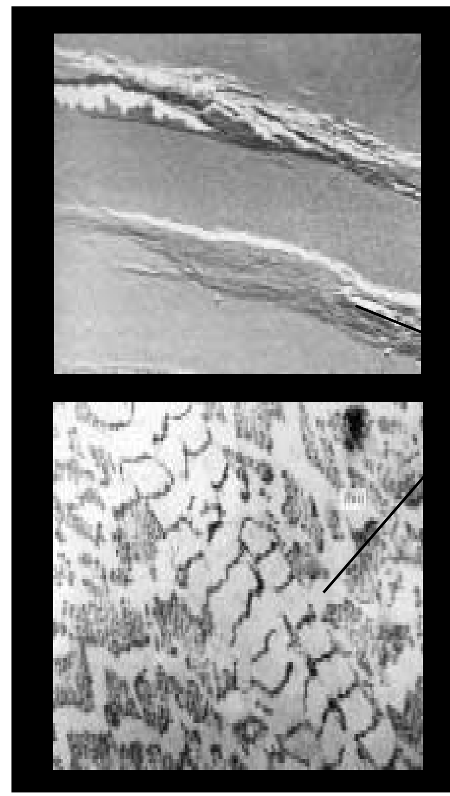
Events leading to crack initiation

- 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

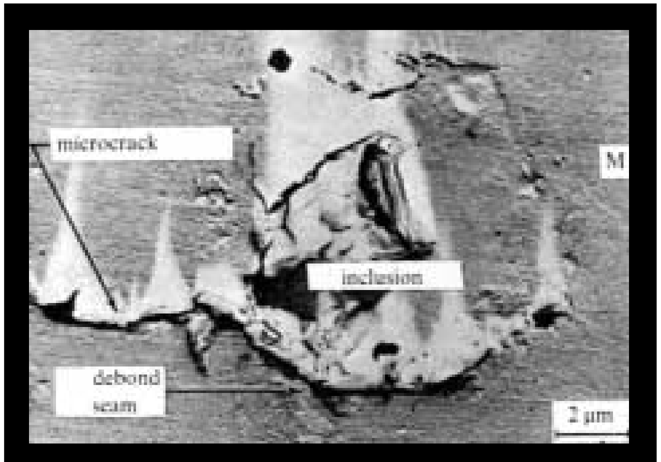
cyclic softening

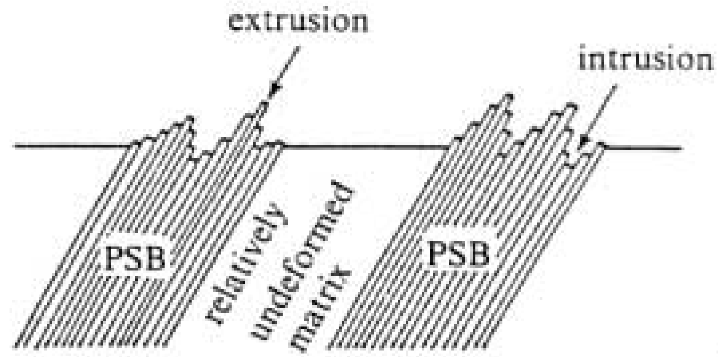


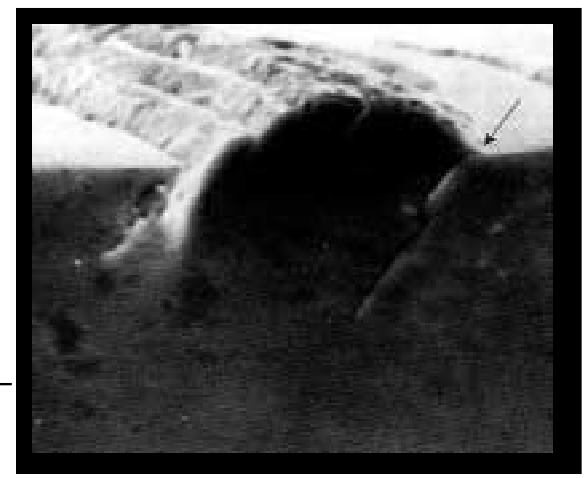


PSB

Crack initiation

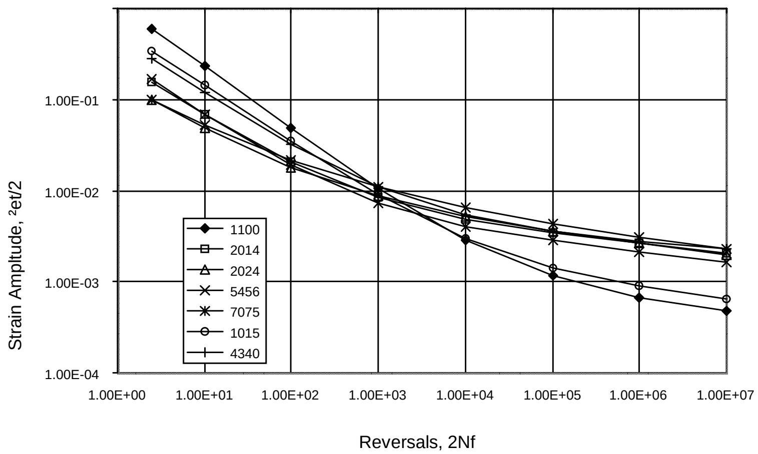


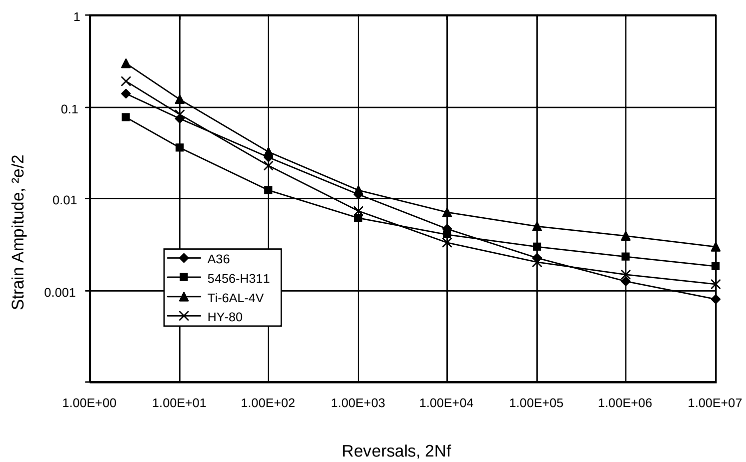


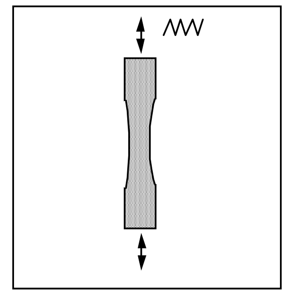


Fatigue crack initiation at an inclusion
Cyclic slip steps (PSB)
Fatigue crack initiation at a PSB

Effects of strength and ductility



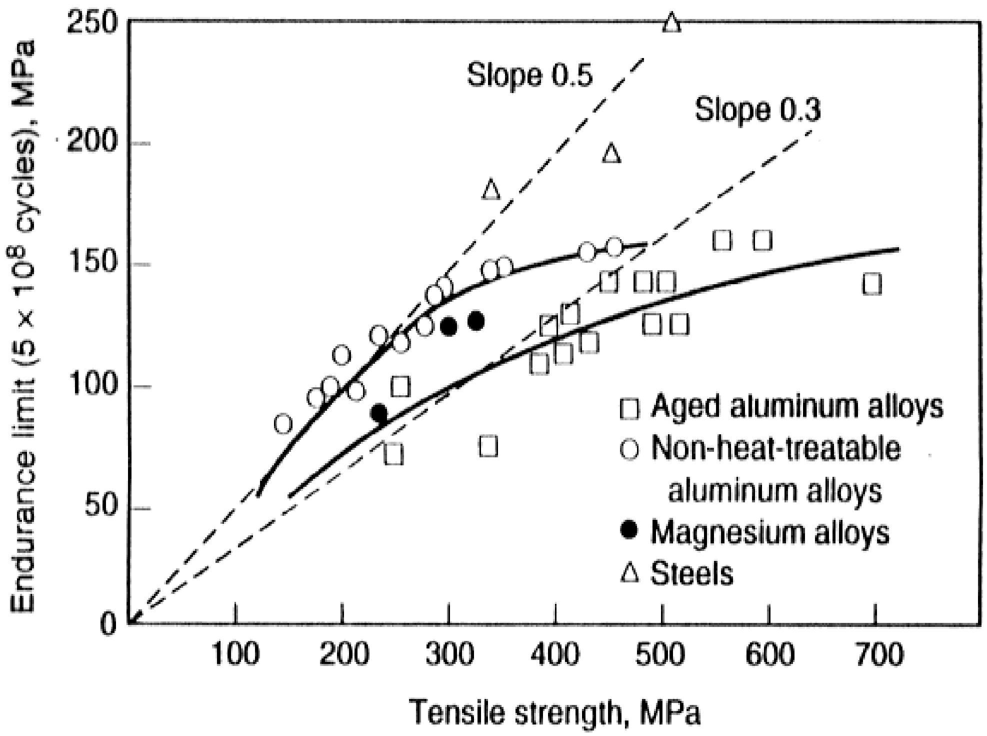




Strain controlled test on smooth specimen

- Strong materials give the best fatigue resistance at long lives; whereas, ductile materials give the best fatigue resistance at short lives

High-cycle fatigue Strength

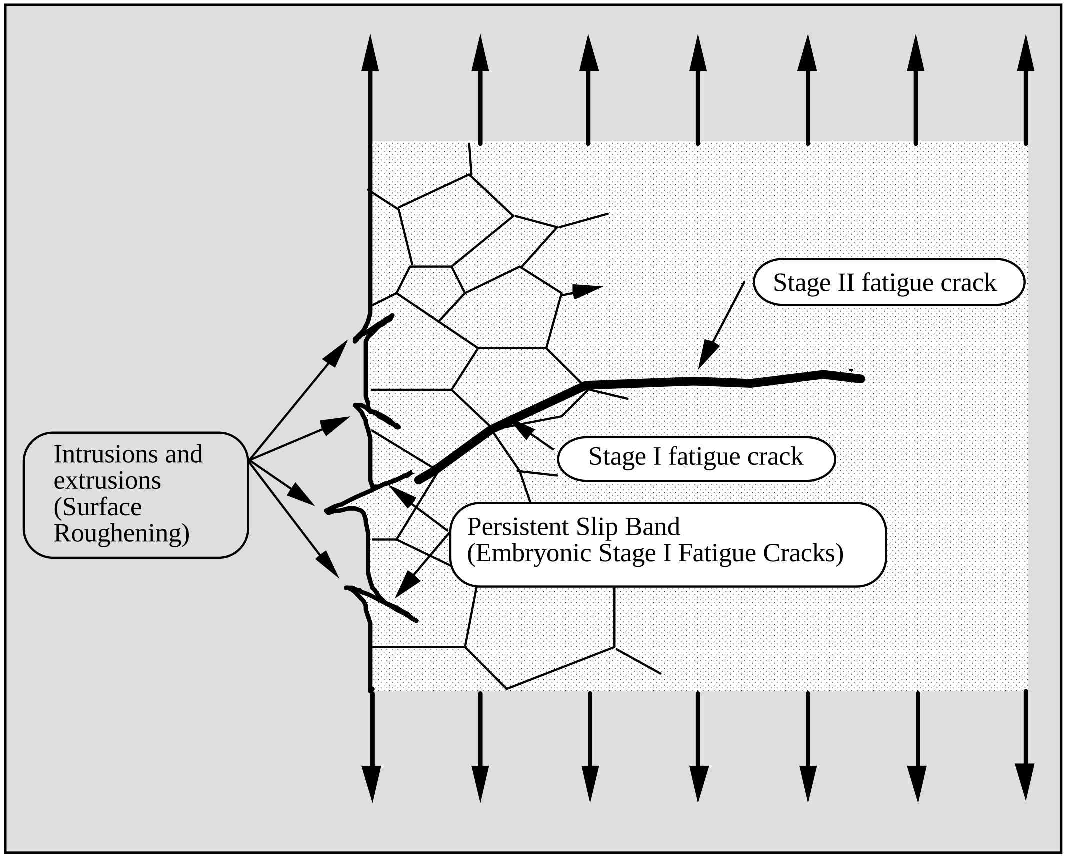


Stronger materials resist crack initiation better.

Fatigue Mechanisms

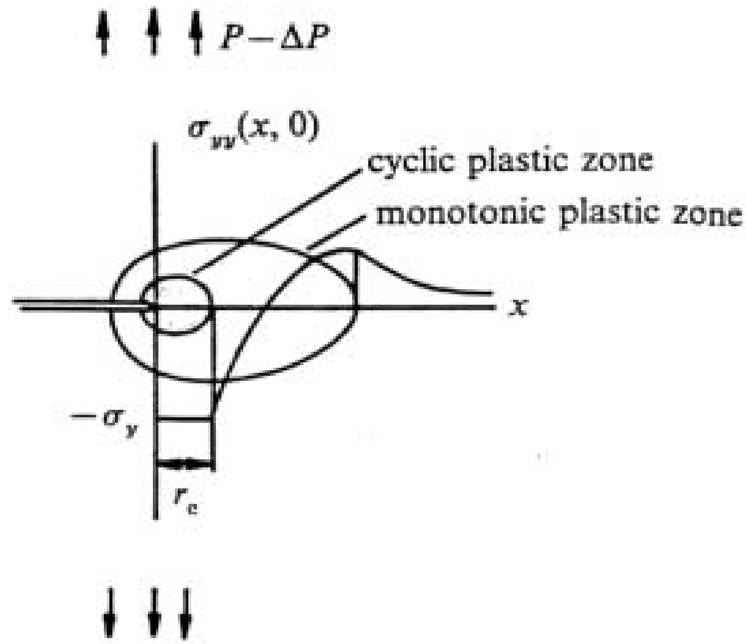
- Fatigue Crack Initiation Mechanisms
- Fatigue Crack Growth Mechanisms

Process of fatigue



Cyclic slip
Crack initiation
Stage I crack growth
Stage II crack growth
Failure

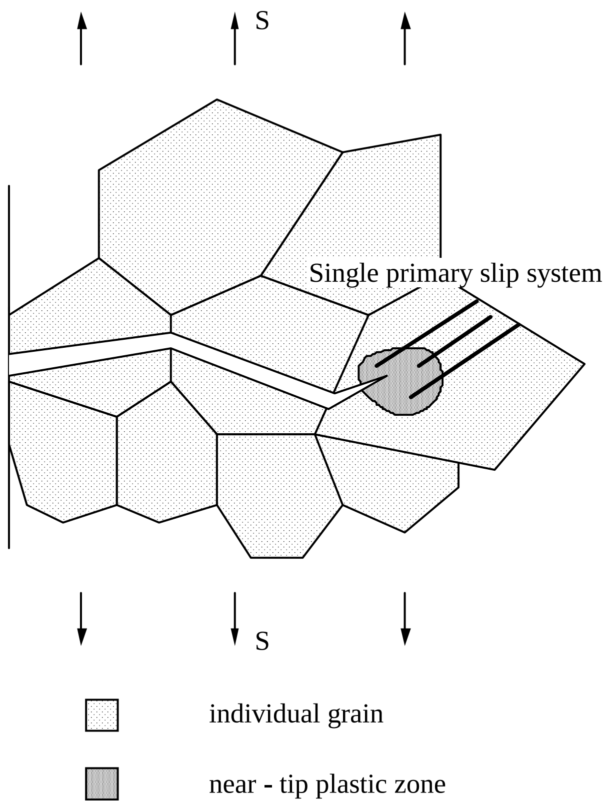
Cyclic plastic zone size

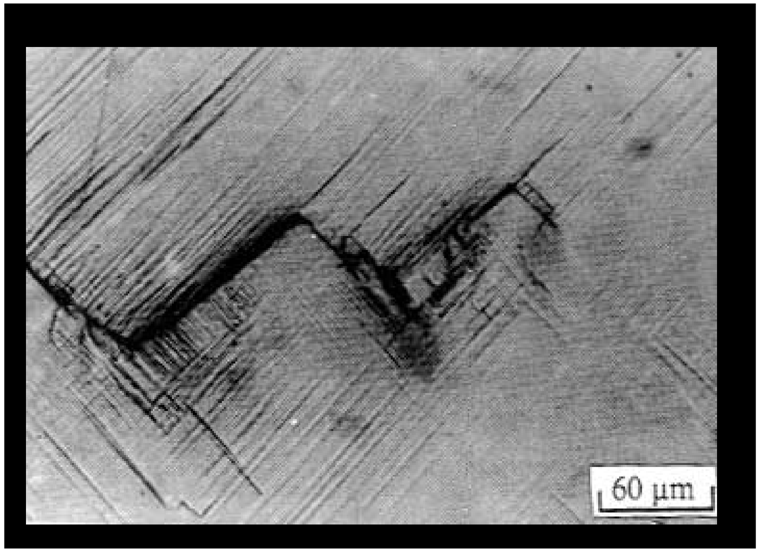


$$r_c = \frac{1}{\pi}\left(\frac{\Delta K_I}{2\sigma_y'}\right)^2$$

Cyclic plastic zone is the region ahead of a growing fatigue crack in which slip takes place. Its size relative to the microstructure determines the behavior of the fatigue crack, i.e.. Stage I and Stage II behavior.

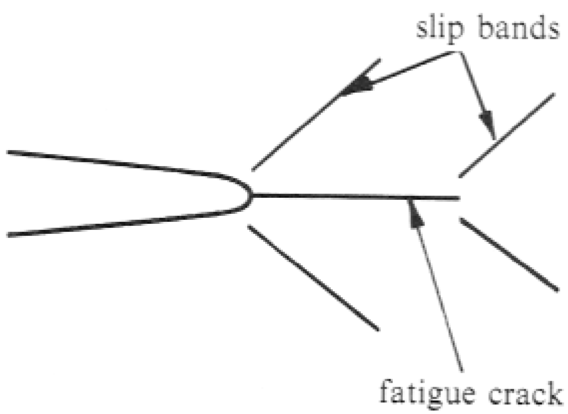
Stage I crack growth



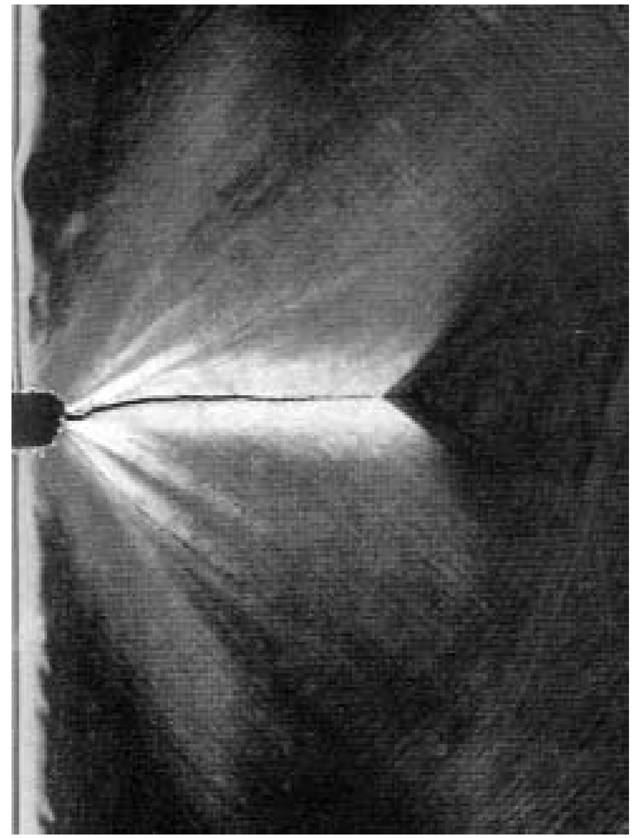


Stage I crack growth ($r_c \leq d$) is strongly affected by slip characteristics, microstructure dimensions, stress level, extent of near tip plasticity

Stage II crack growth



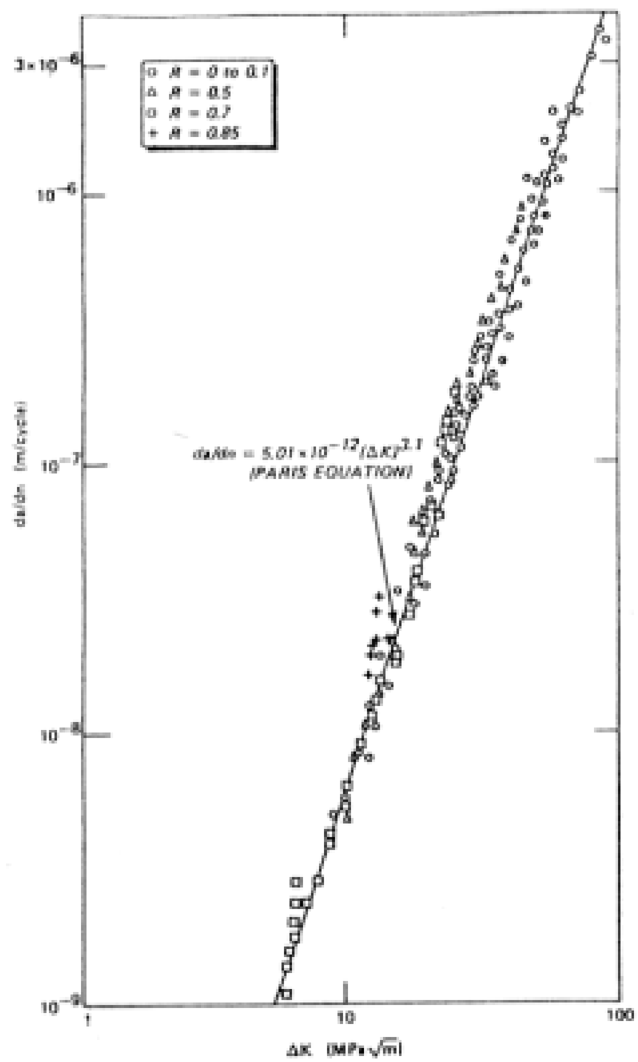
Stage II crack growth (rc >> d)

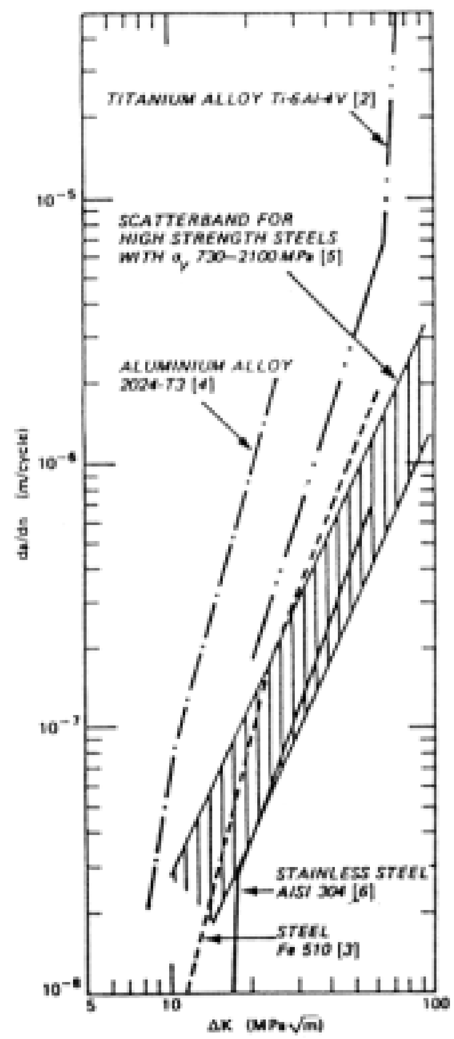


Fatigue crack growing in Plexiglas

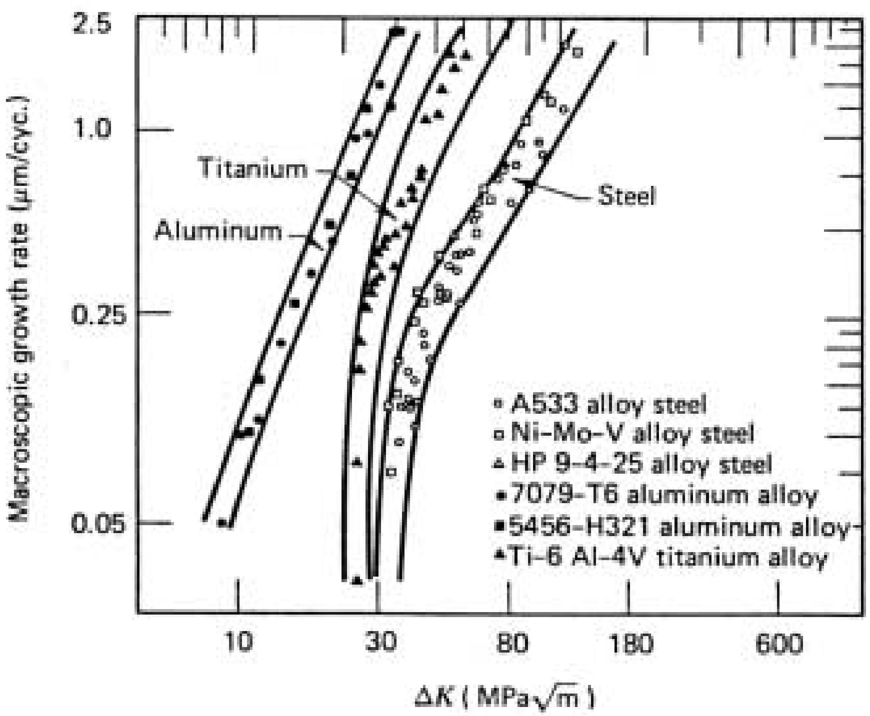
Behavior of Structural Materials

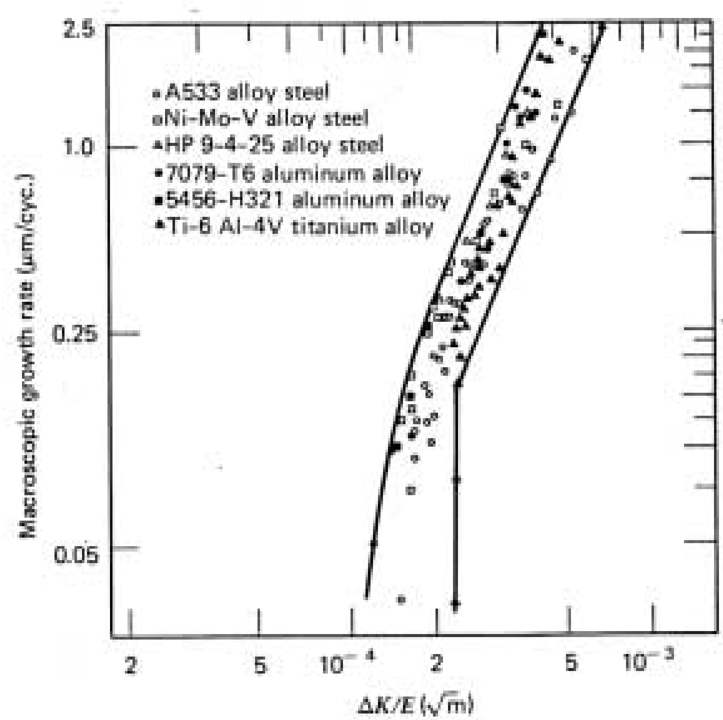
Ferritic-Pearlitic steels all have about the same crack growth rates





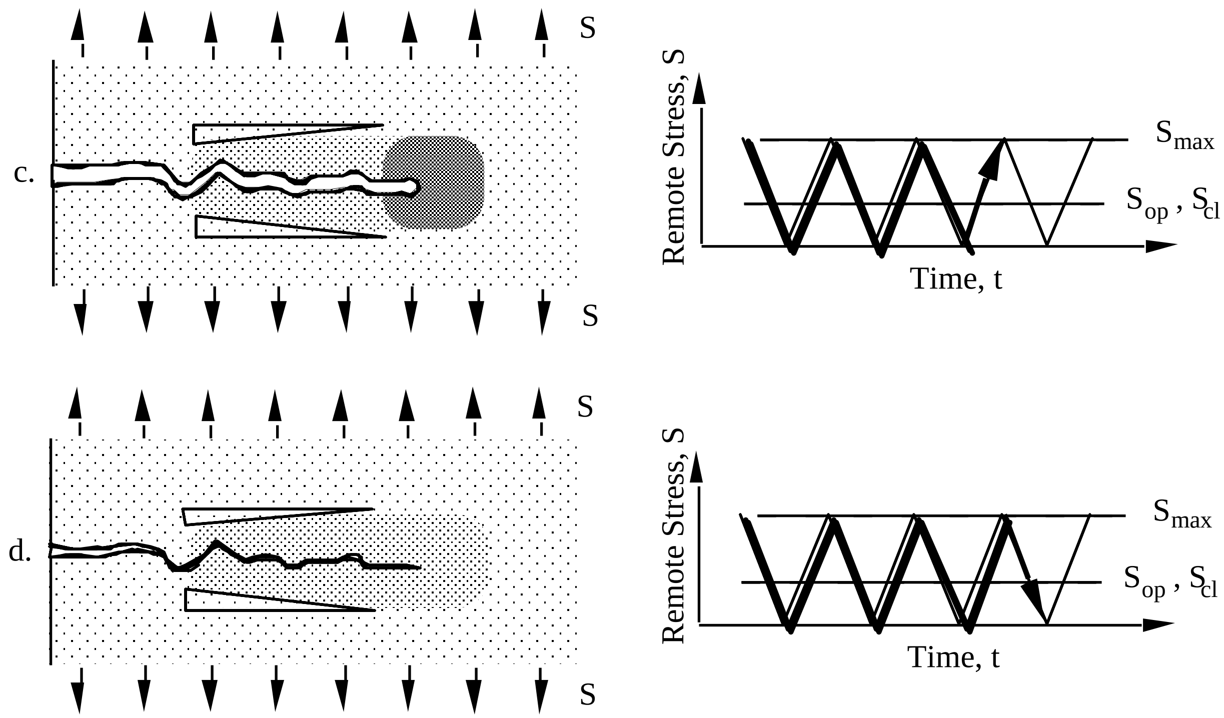
Crack Growth Rates of Metals





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.

Crack closure



$S = S_{max}$

$S = 0$

Plastic wake

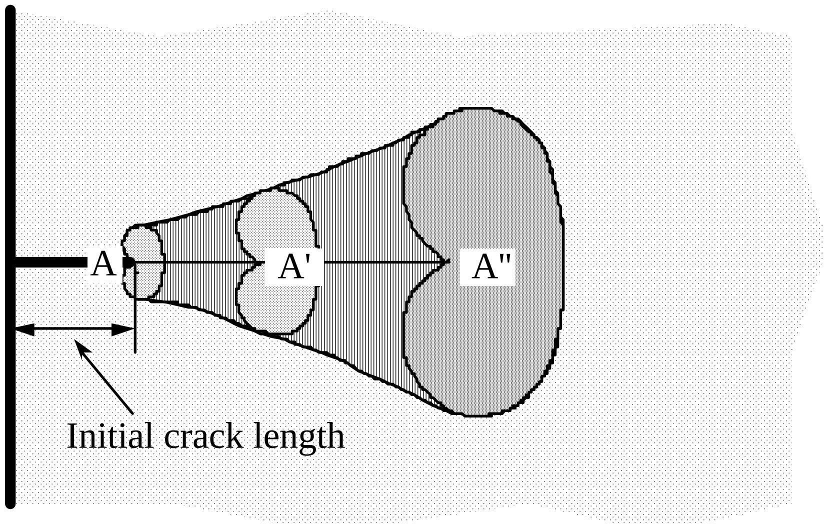
New plastic deformation

Crack closure

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

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

Plasticity induced crack closure (PICC)

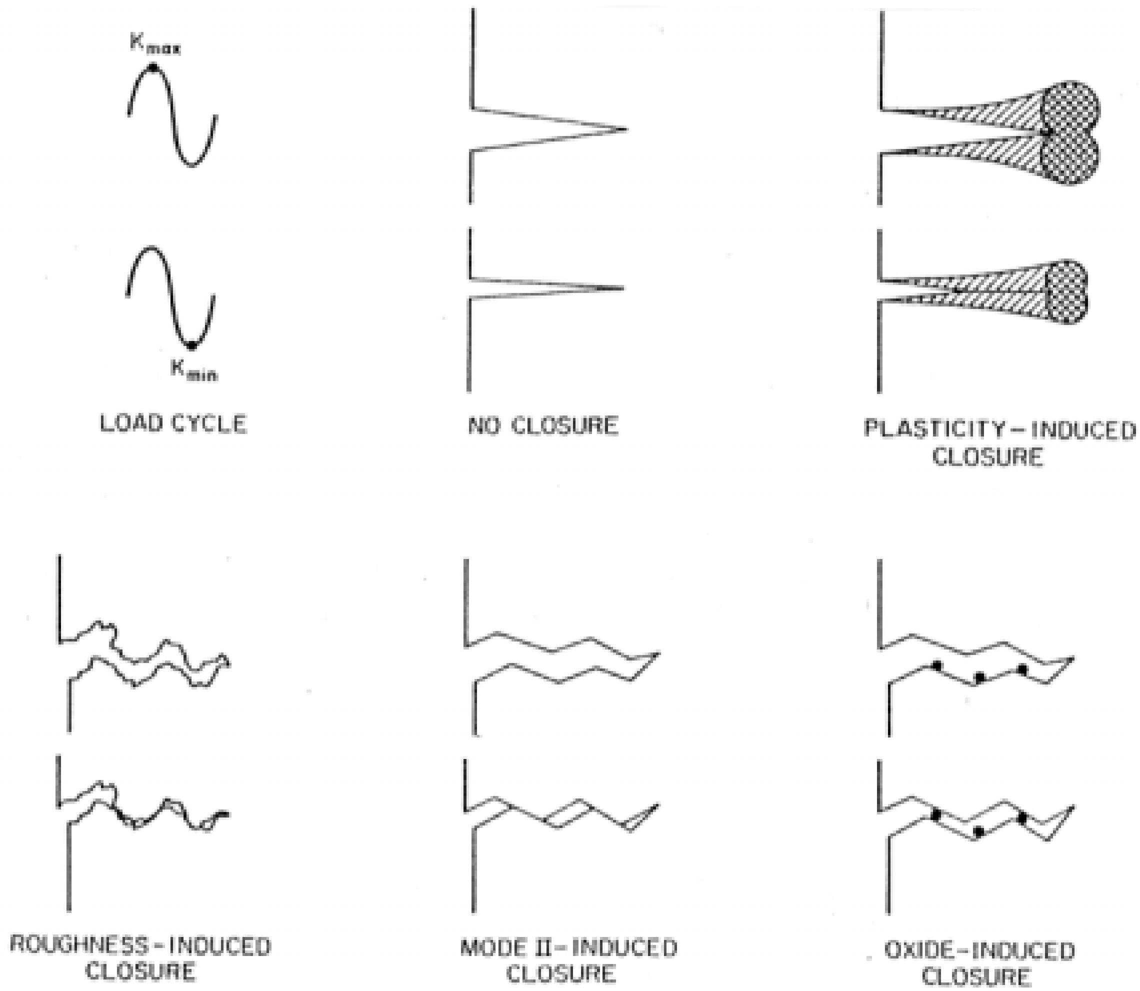


A, A', A" Crack tip positions

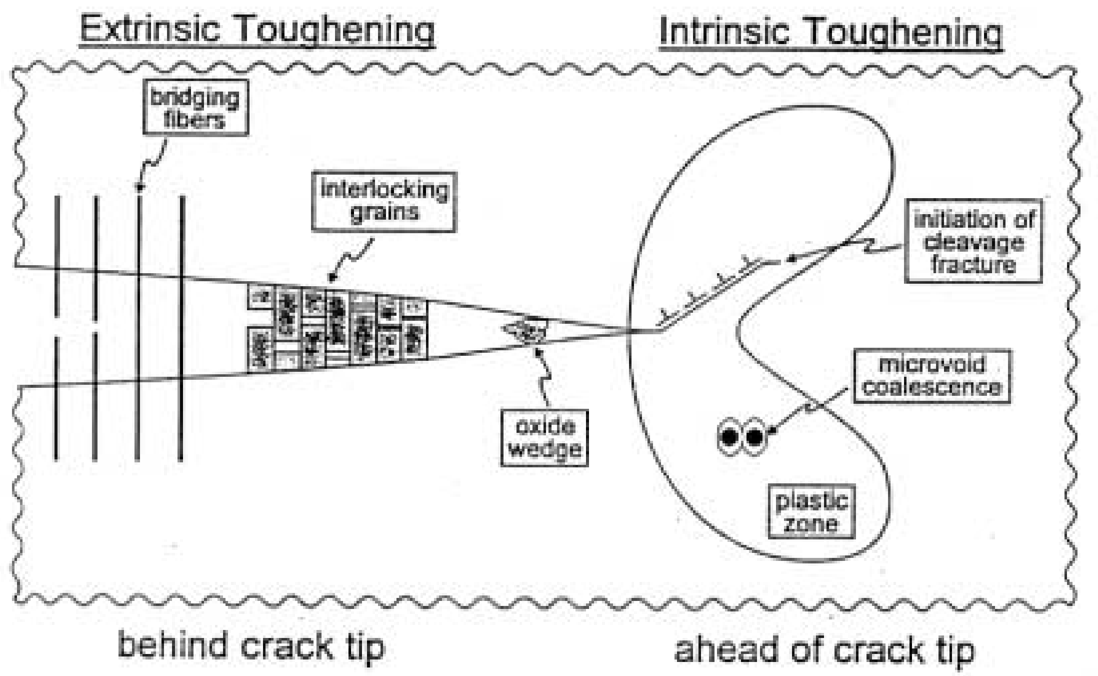
Plastic zones for crack positions A...A”

Plastic wake

Crack Closure Mechanisms



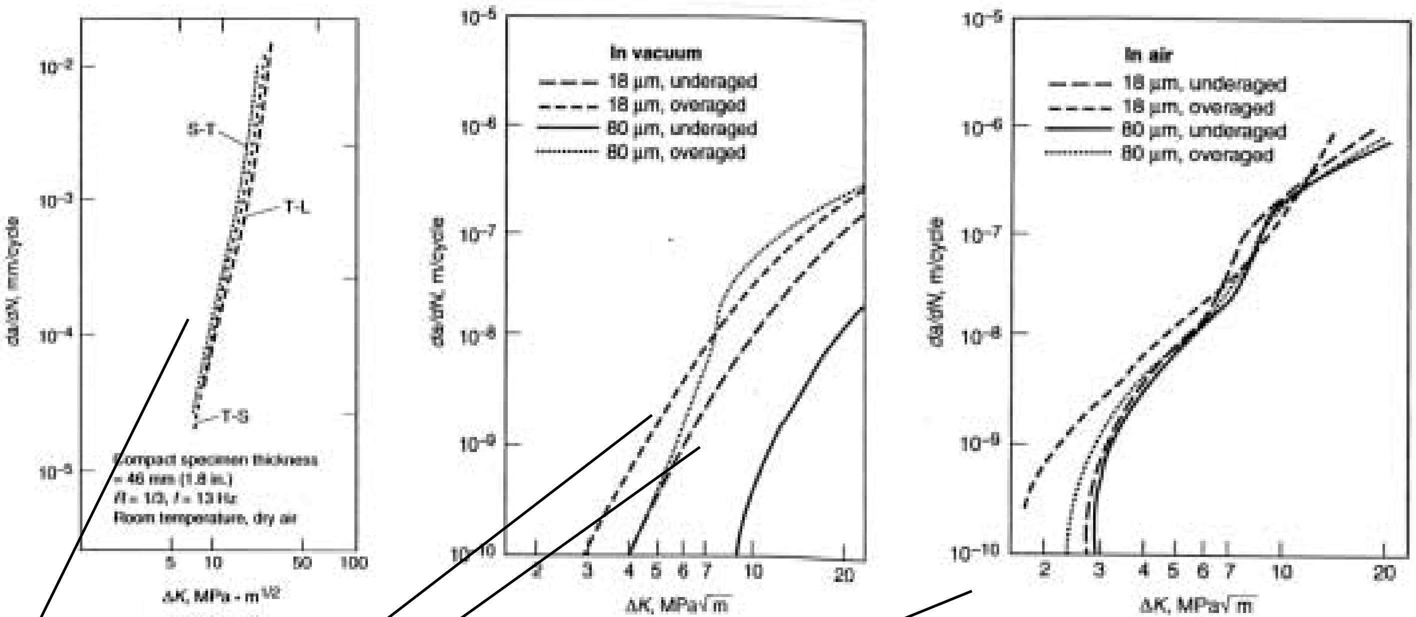
Intrinsic, extrinsic crack closure



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

Extrinsic
Intrinsic

Aluminum - crack growth

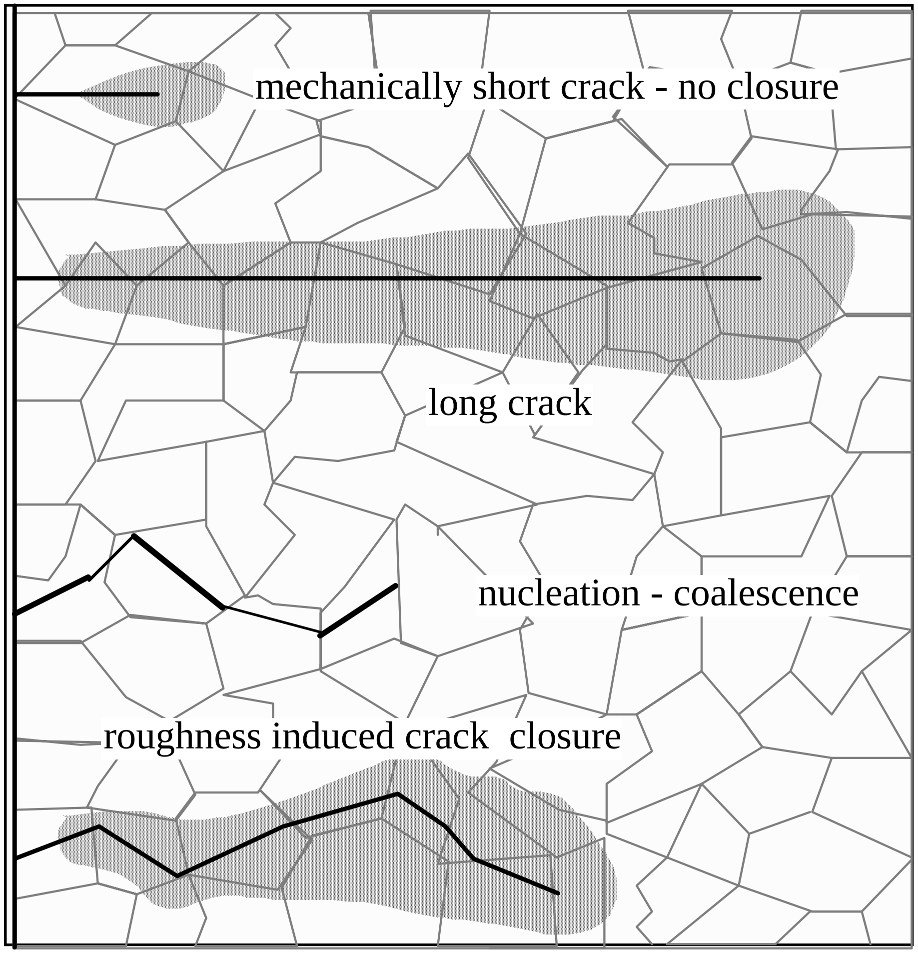


- Orientation of microstructural texture
- Grain size
- Strength
- Environment

Subcritical Crack Growth

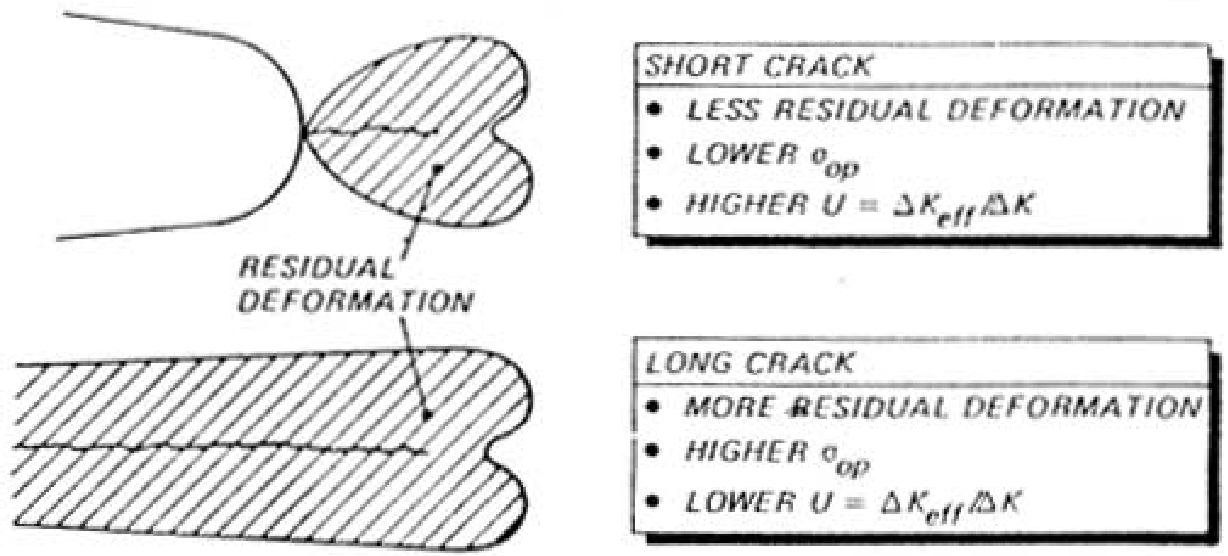
- Subcritical Crack Growth
- Measuring Crack Growth
- Use of Paris Power Law
- Variable Amplitude Loads
- Crack Closure
- Small Cracks
- Environmental Effects

Long cracks, short cracks

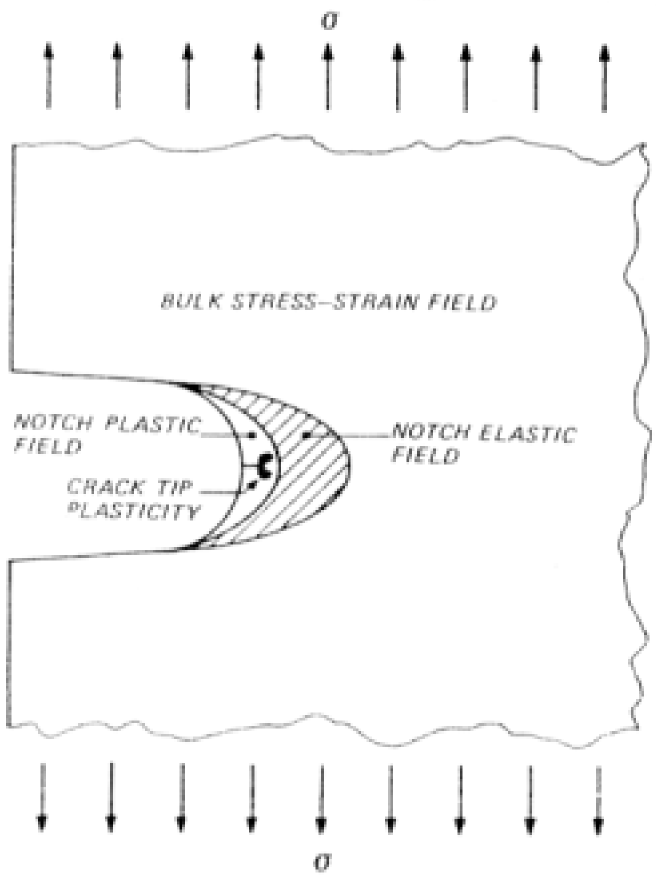


How fatigue cracks grow and particularly the 3-D aspects of fatigue crack growth is not fully understood.

Short Cracks, Long Cracks

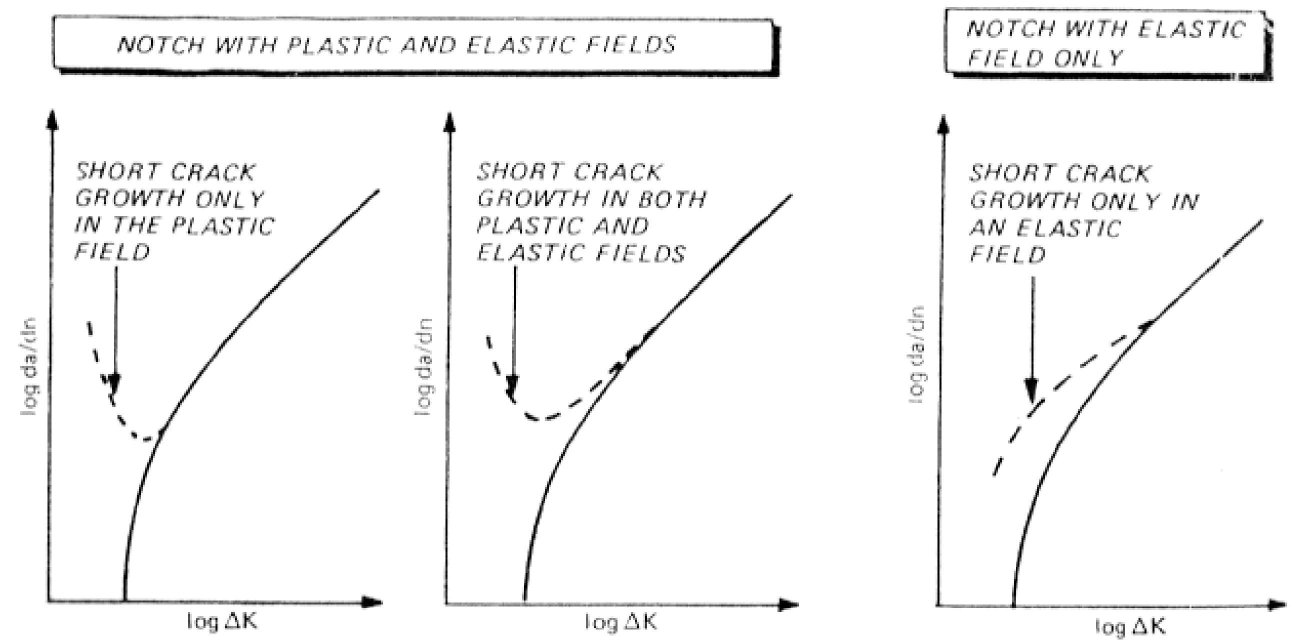


Crack Growth at a Notch



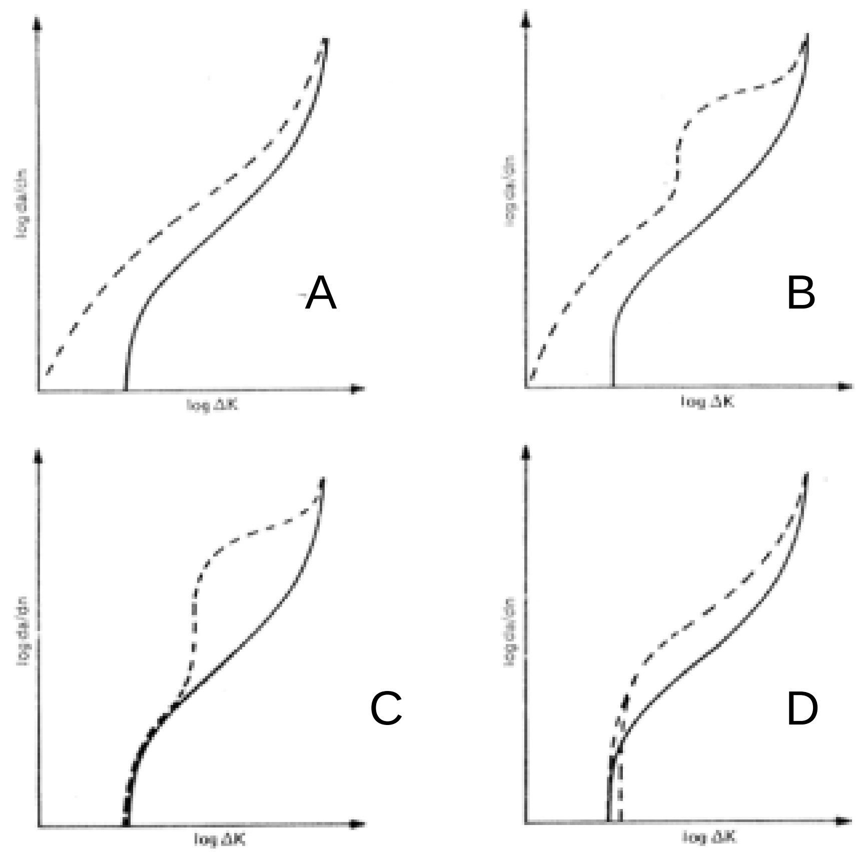
Cracks growing from notches don't know that that stress field they are experiencing is confined to the notch root.

Growth of Small Cracks



Here the ΔK is the remote stress intensity factor based on remote stresses….

Effects of Environment



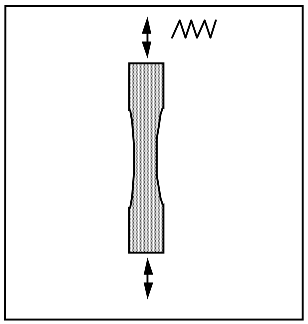
A. Dissolution of crack tip.

B. Dissolution plus H+ acceleration.

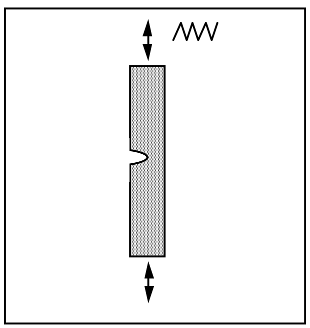
C. H+ acceleration

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

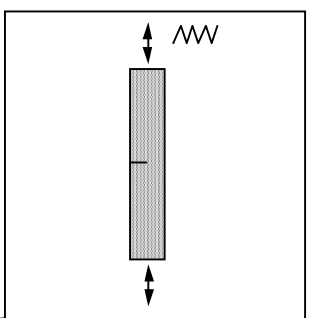
Optimum microstructure?



Smooth specimen (Kt ≈ 1) - at long lives life dominated by initiation so pick small, high-strength microstructures



Notched Specimen (Kt ≈ 2) - at long lives initiation and crack growth equally important. Avoid high tensile residuals therefore use lower strength materials



Cracked specimen (Kt > 5) - in the absence of tensile residuals and for near conditions, large grain size preferred

Summary

- Fatigue may be thought of as a failure of the average stress concept; consequently, fatigue usually begins at stress concentrators which are most frequently at the surface of a component.
- Fatigue is a localized process involving the nucleation and growth of cracks to failure.
- Fatigue is caused by plastic deformation.
- The cyclic deformation of metals is fundamentally different from the monotonic deformation.

Summary

- The greatest portion of the fatigue life is spent nucleating and growing a fatigue crack to a length at which it can be detected.
- The range of effective stress intensity factor, that is, the idea of crack closure allows the growth of fatigue cracks to be rationalized.
- The behavior of small cracks is in many respects quite different from long cracks.