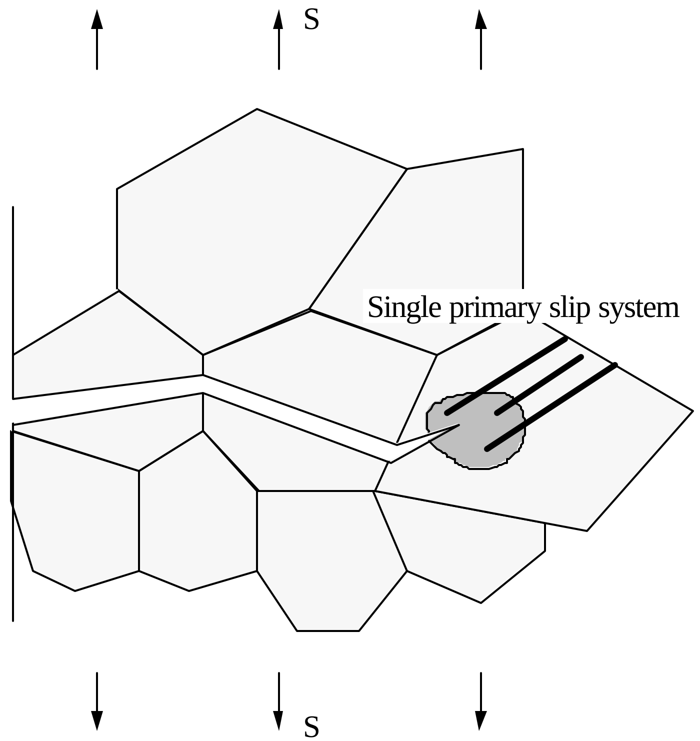
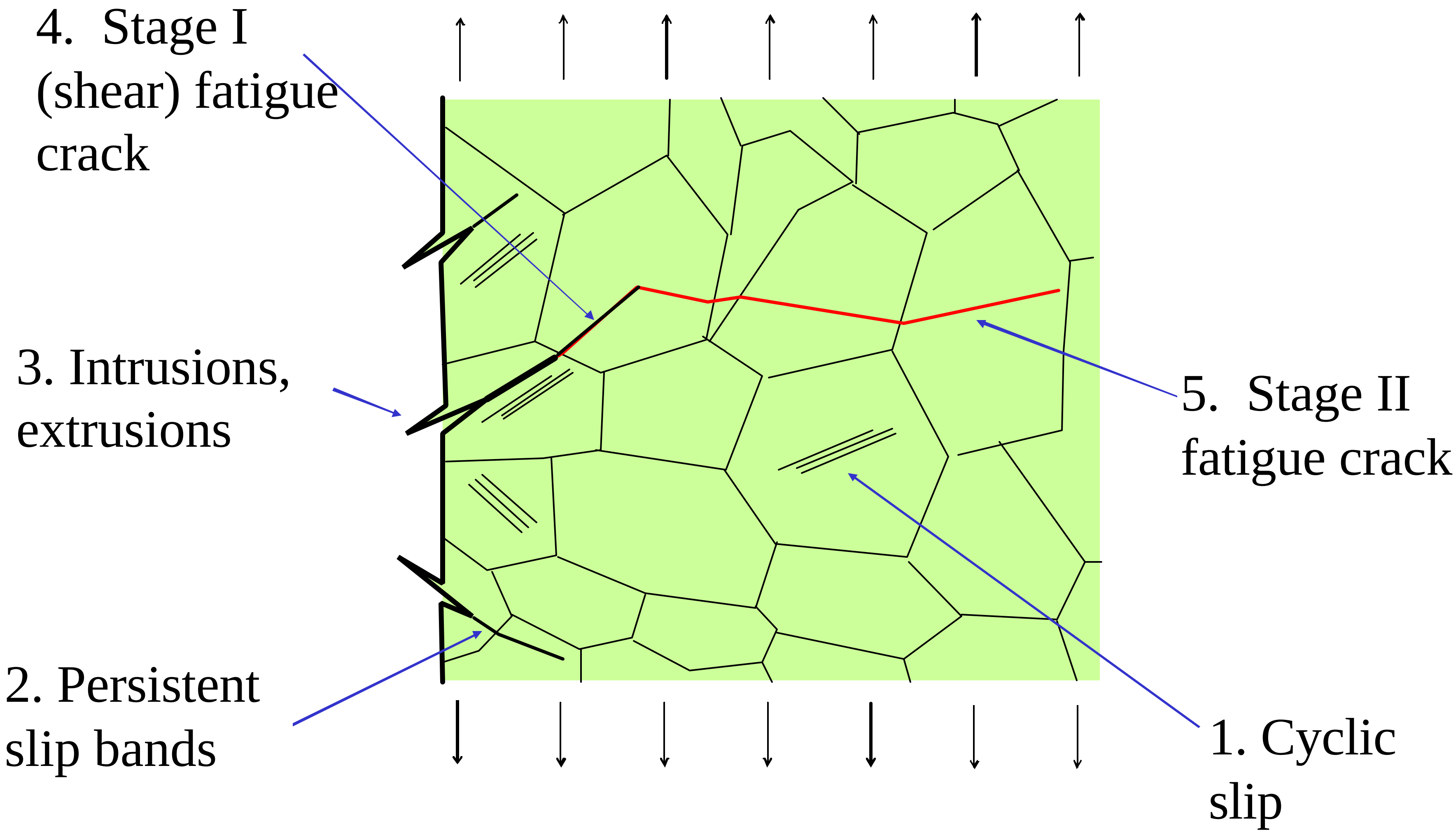
II Fatigue Mechanisms



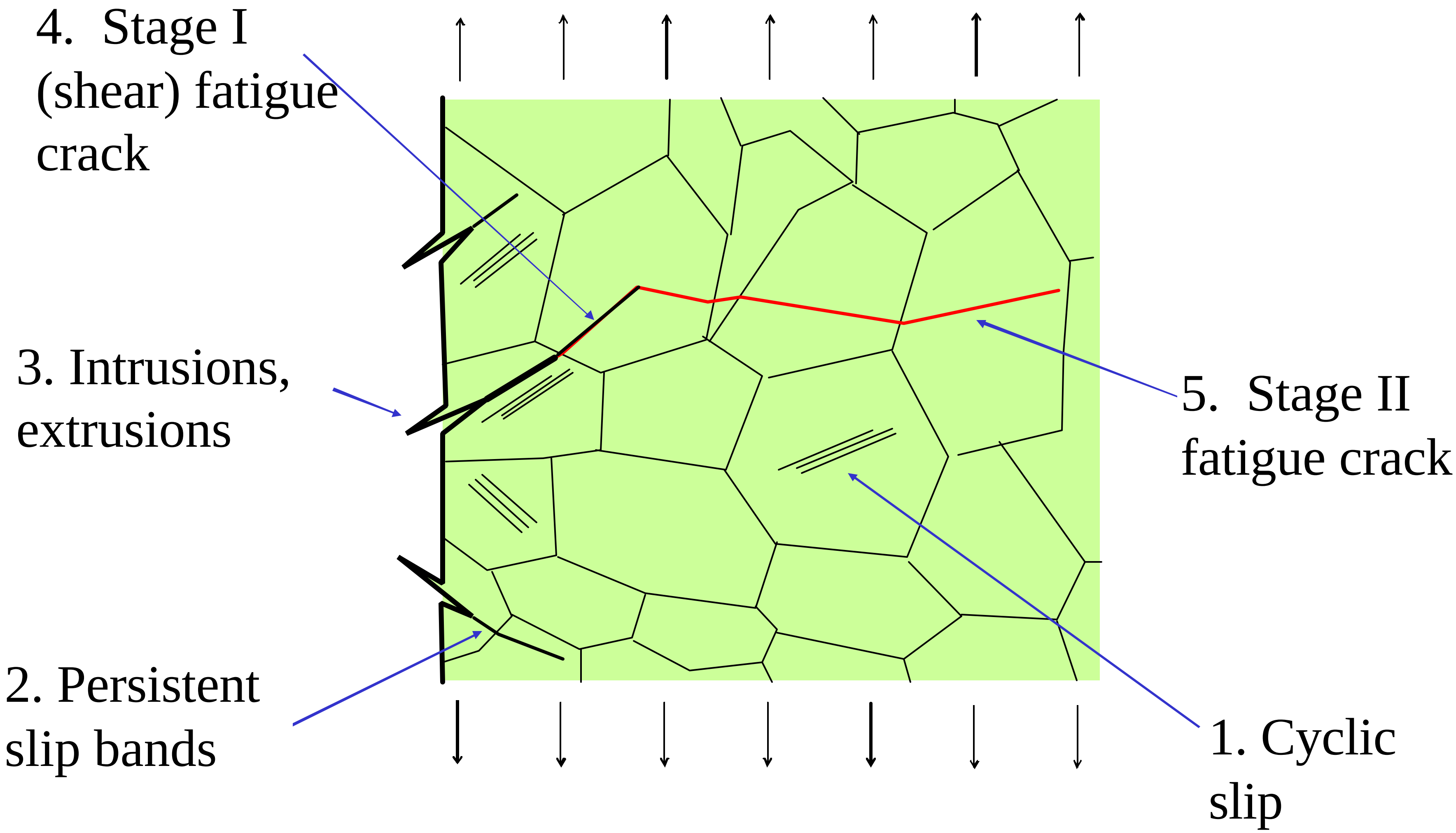
Current Theory of Fatigue



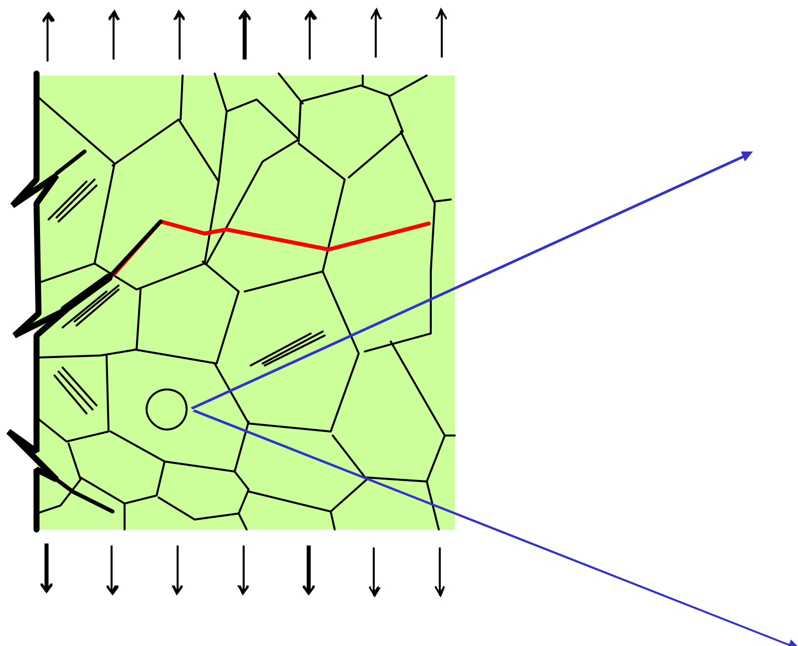
Outline

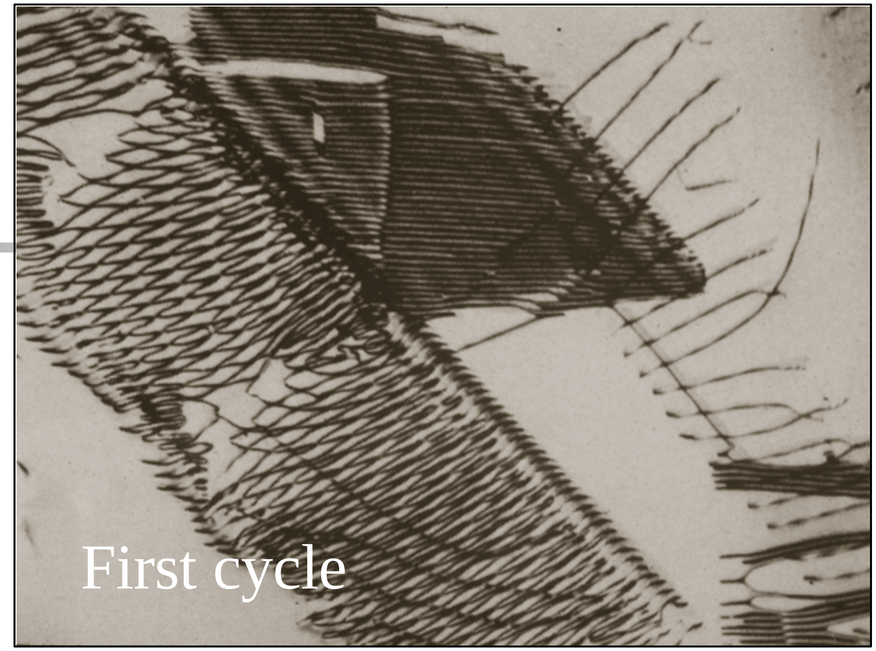
- 1. Cyclic slip
- 2. Persistent slip bands (PSB)
- 3. Intrusions and extrusions
- 4. Stage I crack growth
- 5. Stage II crack growth

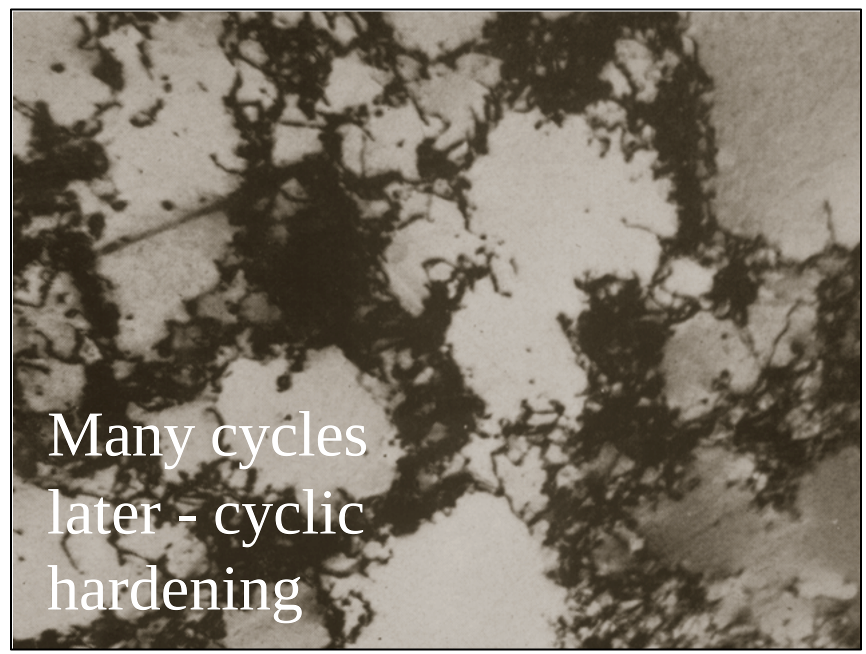
Process of fatigue



1. Cyclic slip

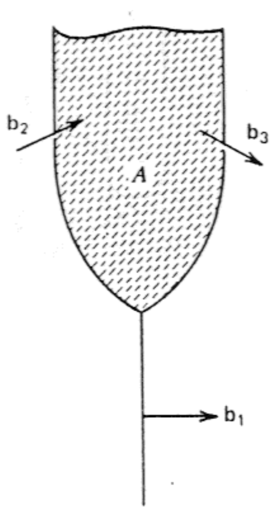






Cyclic slip occurs within a grain and therefore operates on an atomic scale and are thus is controlled by features seen at that scale.

1. Cyclic slip



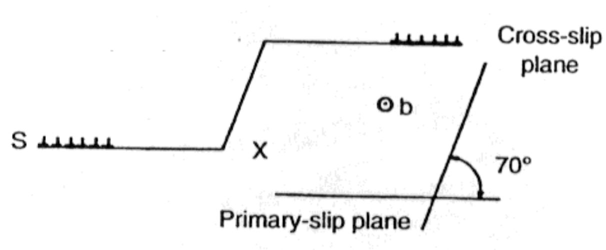
Material	γ Stacking Fault Energy ergs cm^{-2}
Aluminum	250
Iron	200
Nickel	200
Copper	90
Gold	75
Silver	25
Stainless Steel	<10
α Brass	<10

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

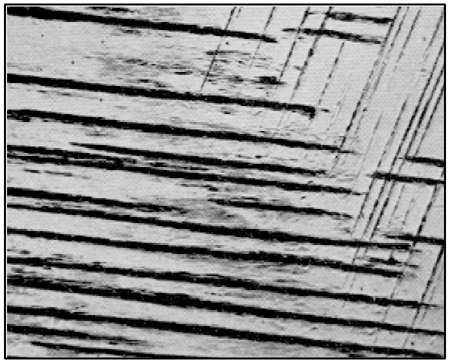
- Planar or wavy slip?

1. Cyclic slip

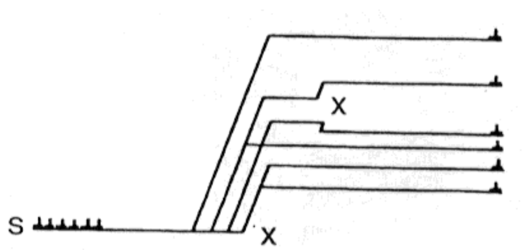
Cu-Al alloys, Cu-Zn, Aust. SS



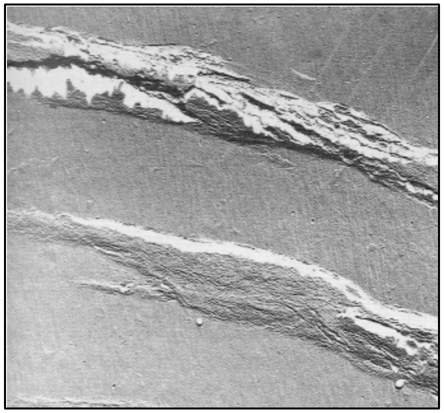
Planar slip in Cu-Al



Ni, Cu, Al Fe



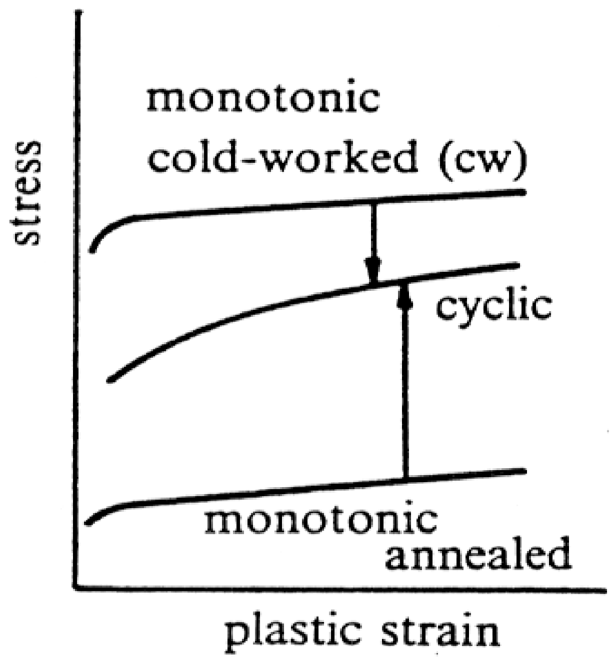
Wavy slip in steel



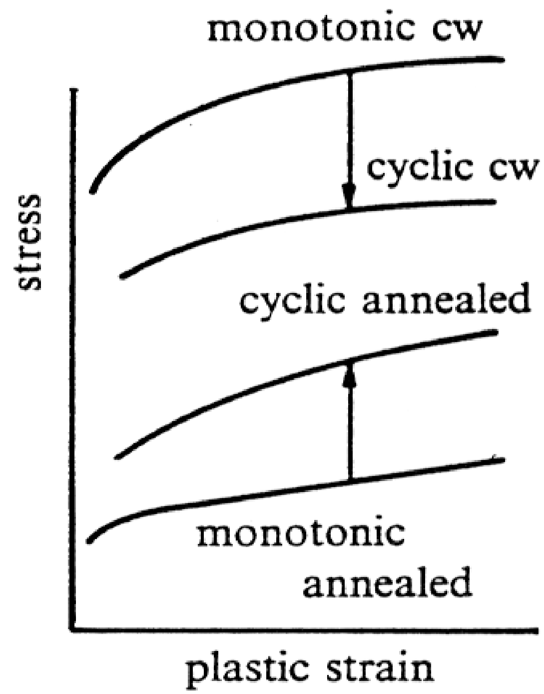
- Stacking-fault energy effects

1. Cyclic slip

Wavy slip materials



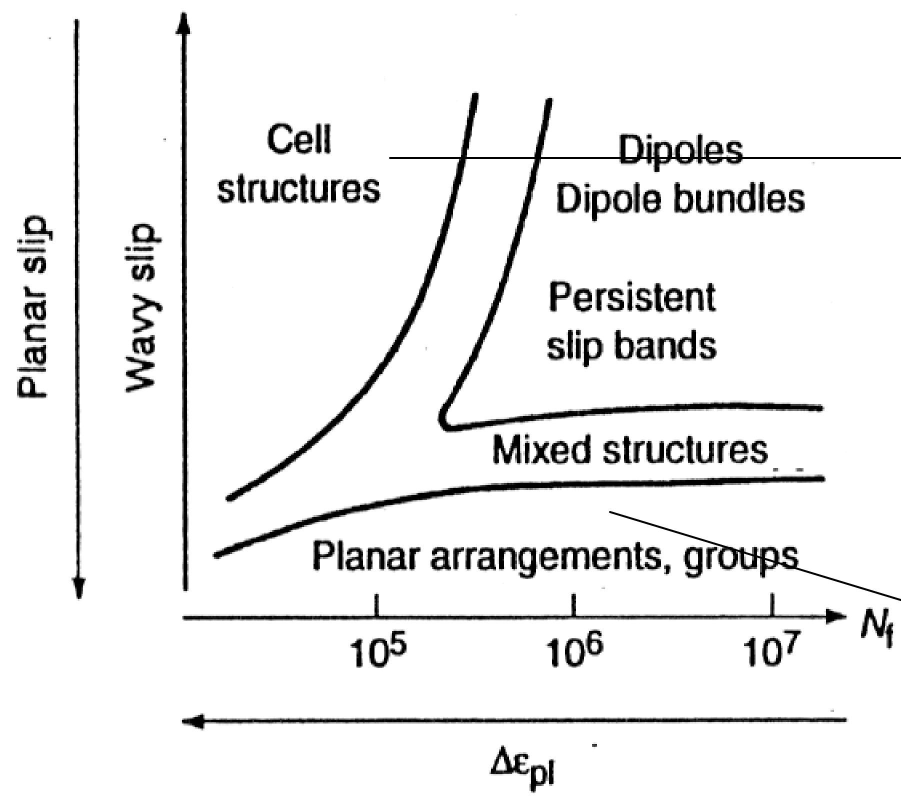
Planar slip materials

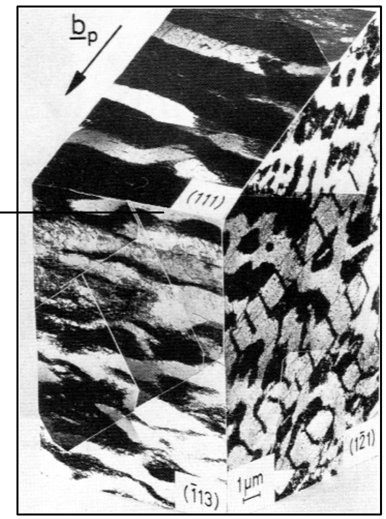


- Planar and wavy slip materials

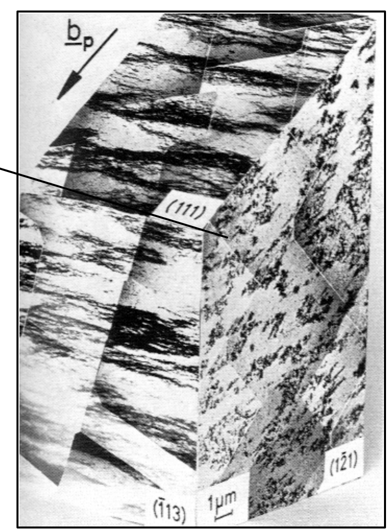
1. Cyclic slip

Dislocation cell structures in copper





$\gamma = 10^{-3}$

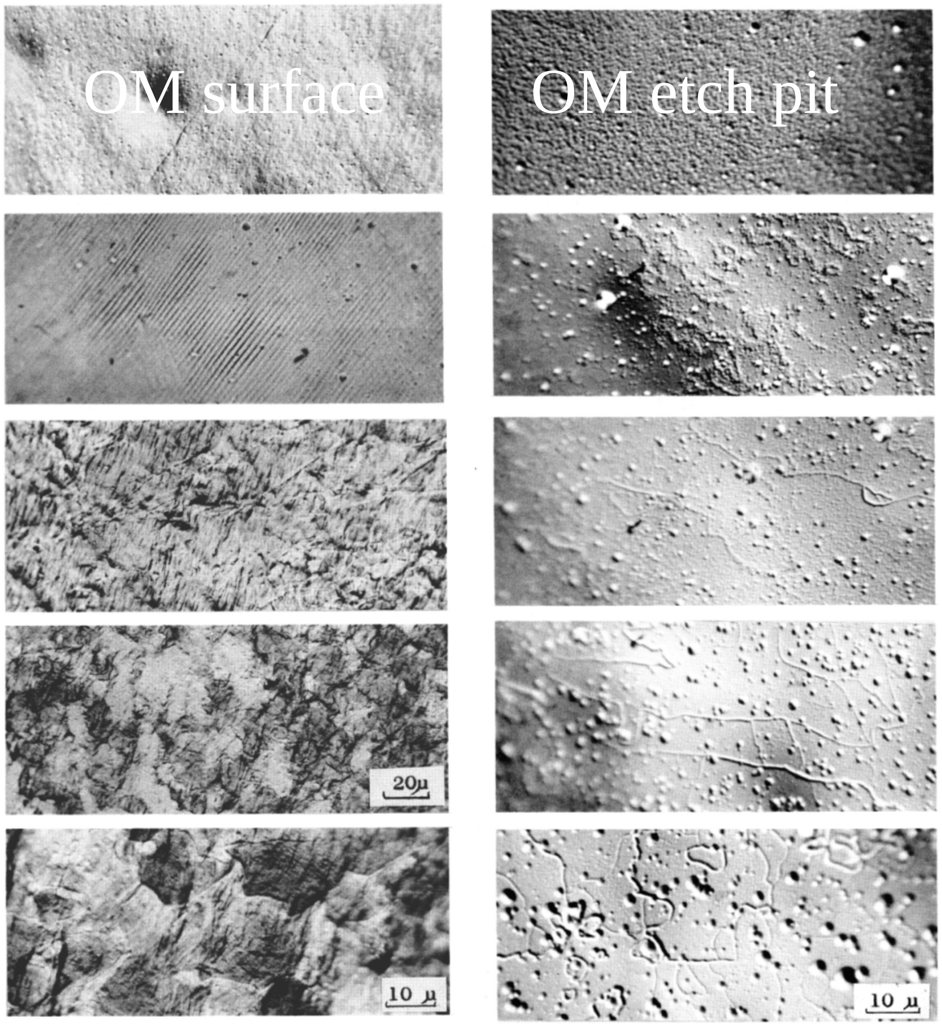


$\gamma = 10^{-5}$

- Development of cell structures

Example

Stress range = ±25 ksi.



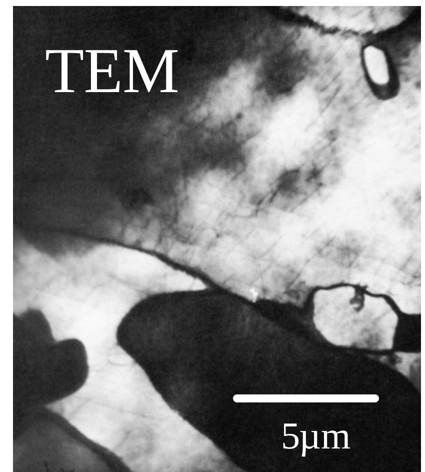
60 cycles

1,000 cycles

5,000 cycles

20,000 cycles

80,000 cycles
(failure)



- Fatigue of an Fe single crystal

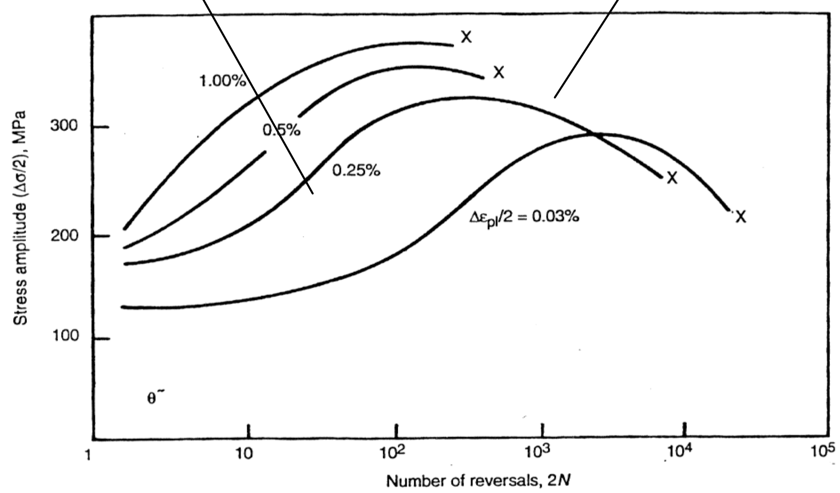
Outline

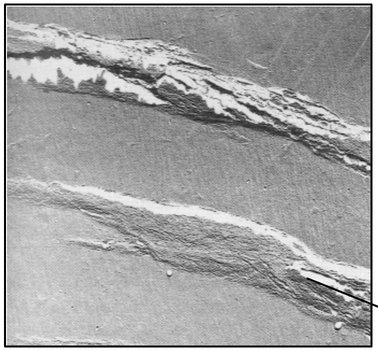
- 1. Cyclic slip
- 2. Persistent slip bands (PSB)
- 3. Intrusions and extrusions
- 4. Stage I crack growth
- 5. Stage II crack growth

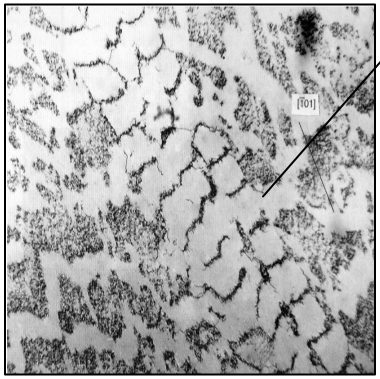
2. Persistent slip bands (PSB)

- 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

Outline

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- 5. Stage II crack growth

3. Intrusions and extrusions

Intrusions and extrusions on the surface of a Ni specimen

3. Intrusions and extrusions

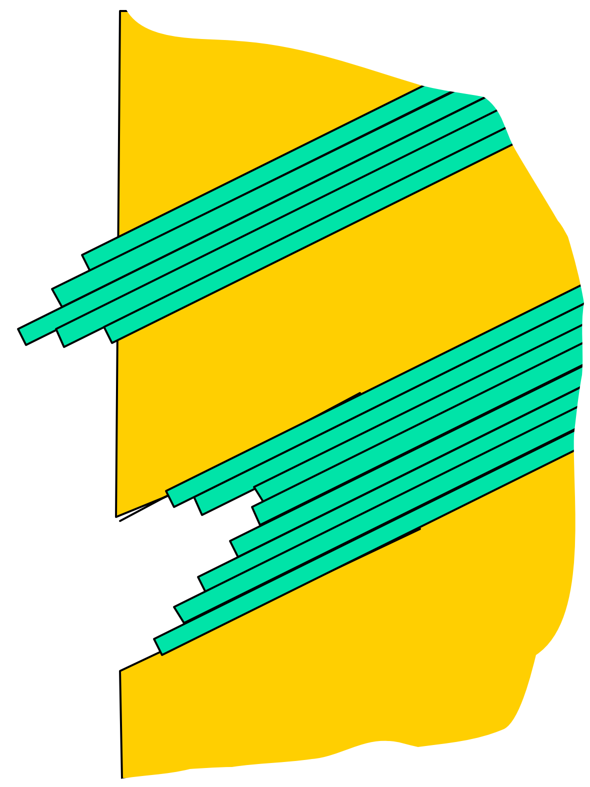
Cyclically hardened material

Extrusion

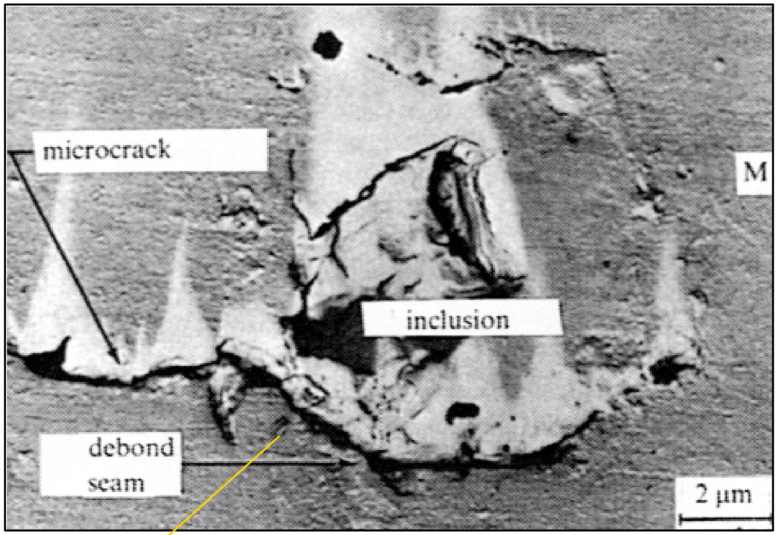
Cyclically hardened material

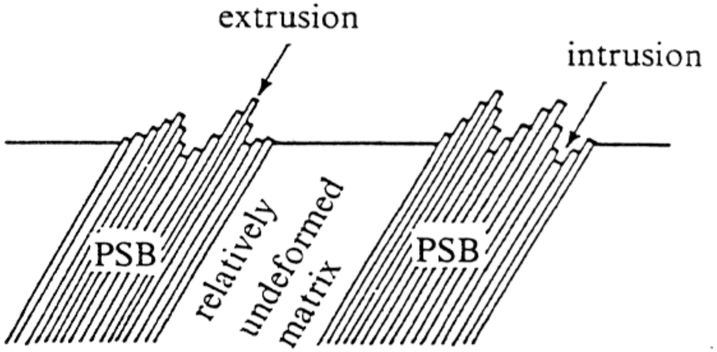
Intrusion

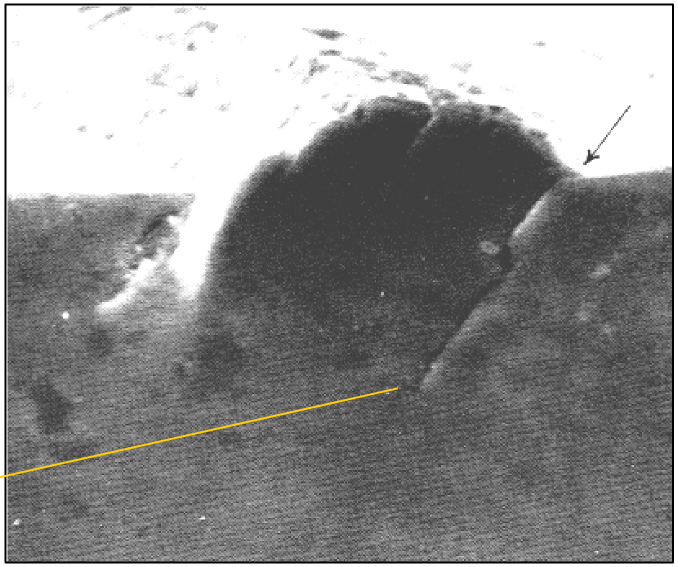
Cyclically hardened material



3. Intrusions and extrusions





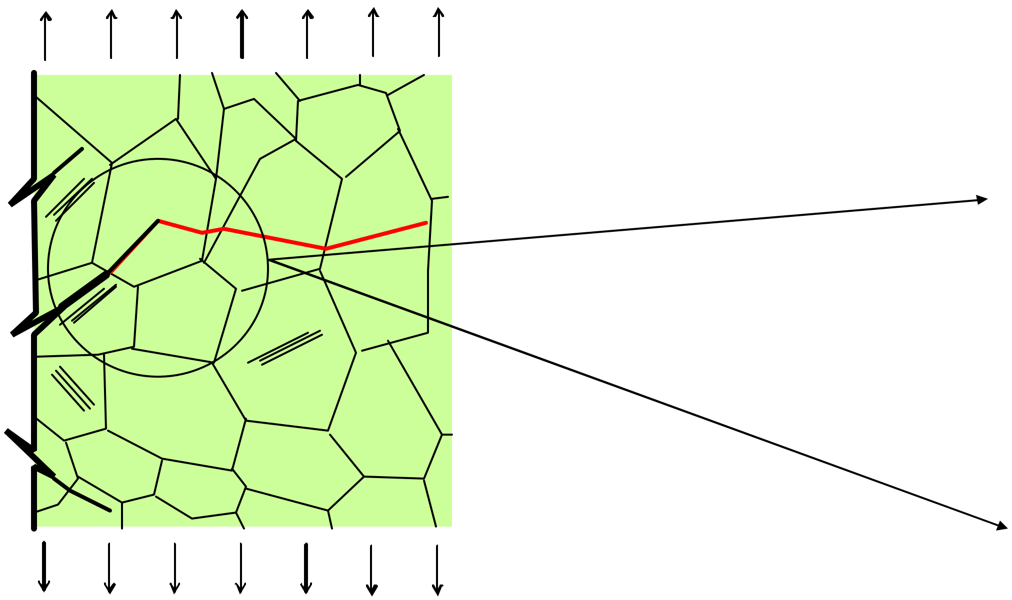


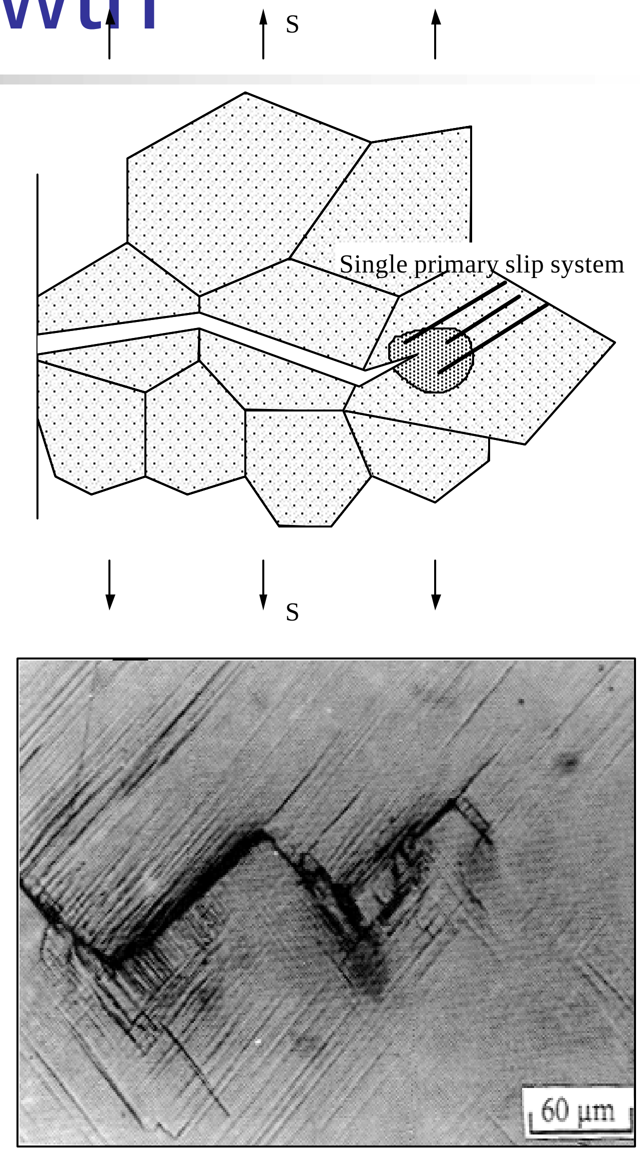
Fatigue crack initiation at an inclusion
Cyclic slip steps (PSB)
Fatigue crack initiation at a PSB

Outline

- 1. Cyclic slip
- 2. Persistent slip bands (PSB)
- 3. Intrusions and extrusions
- 4. Stage I crack growth
- 5. Stage II crack growth

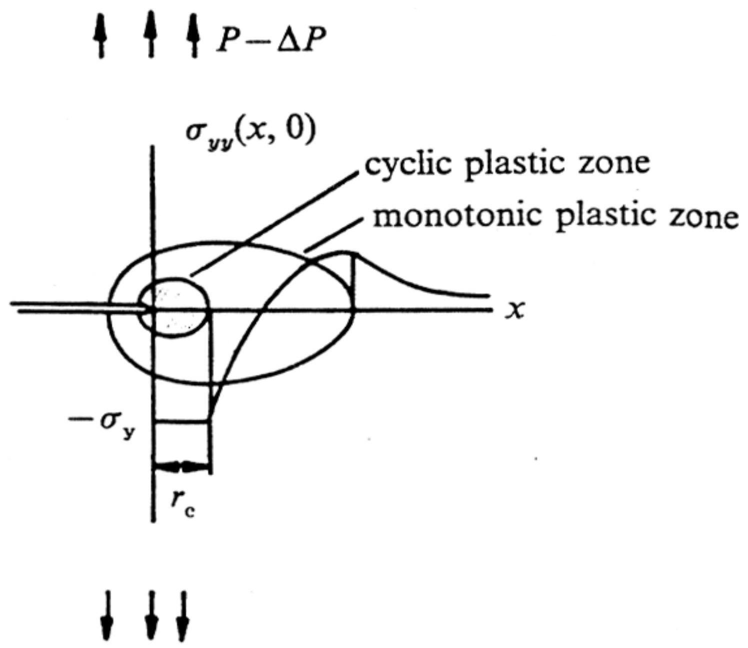
4. Stage I crack growth





Stage I fatigue cracks are the size of the grains and are thus controlled by features seen at that scale: grain boundaries, mean stresses, environment.

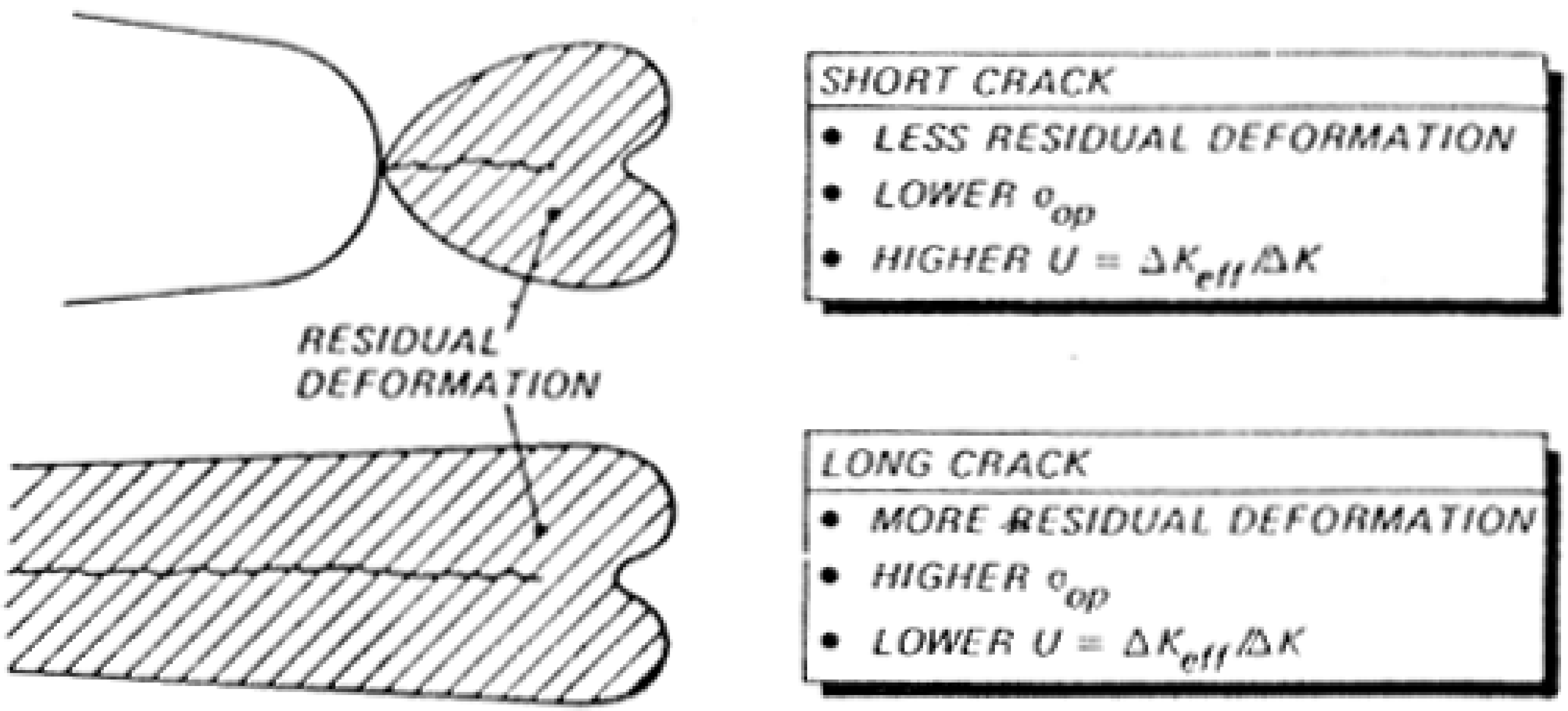
4. Stage I crack growth



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

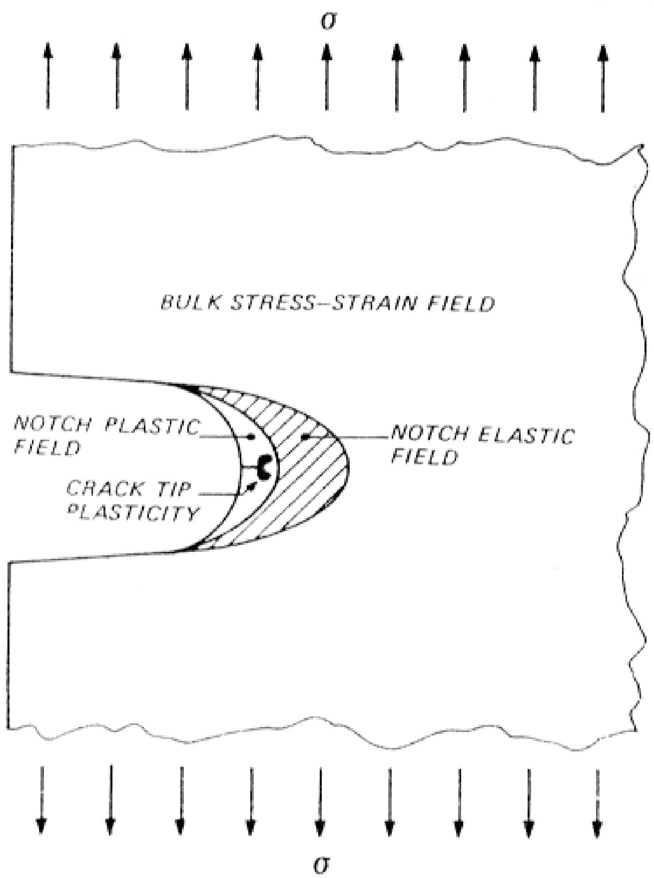
Cyclic plastic zone is the region ahead of a growing fatigue crack in which slip takes place. Its size relative to the microstructure determines the behavior of the fatigue crack, i.e.. Stage I and Stage II behavior.

4. Stage I crack growth



- Short Cracks, Long Cracks

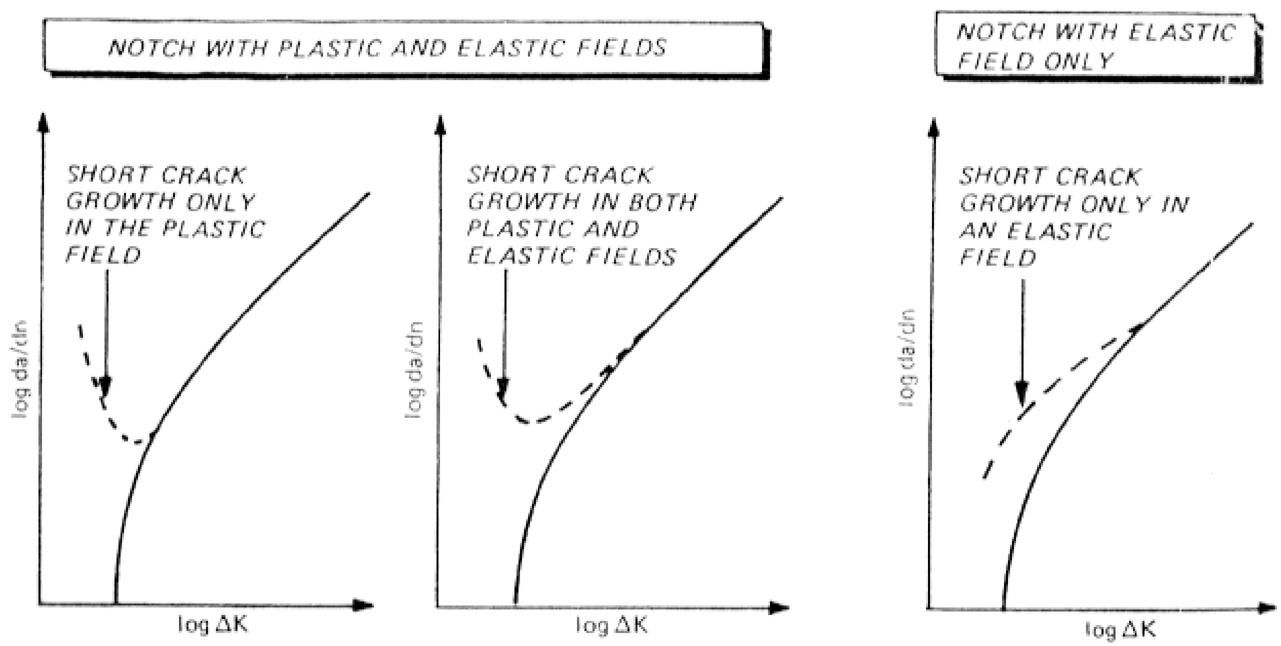
4. Stage I crack growth



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

- Crack Growth at a Notch

4. Stage I crack growth



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

- Growth of Small Cracks

Outline

- 1. Cyclic slip
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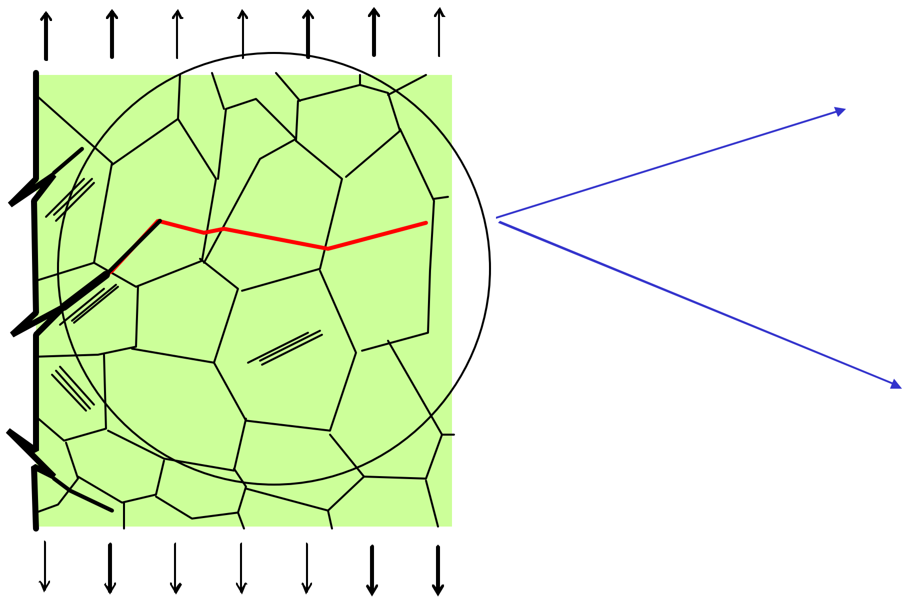
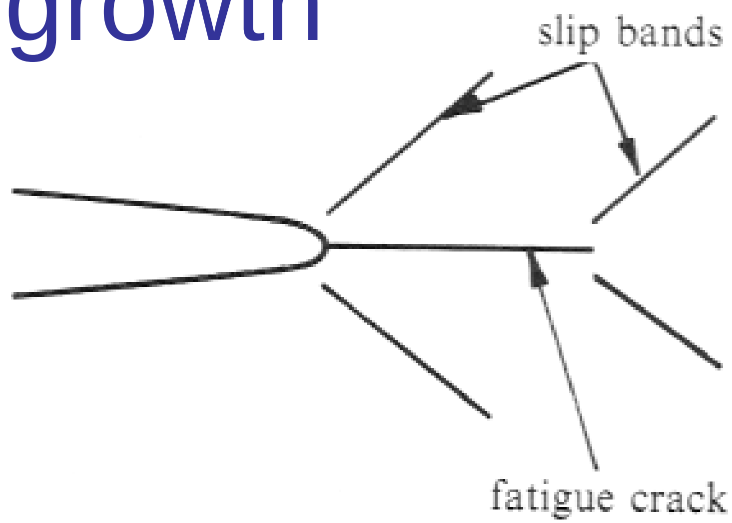
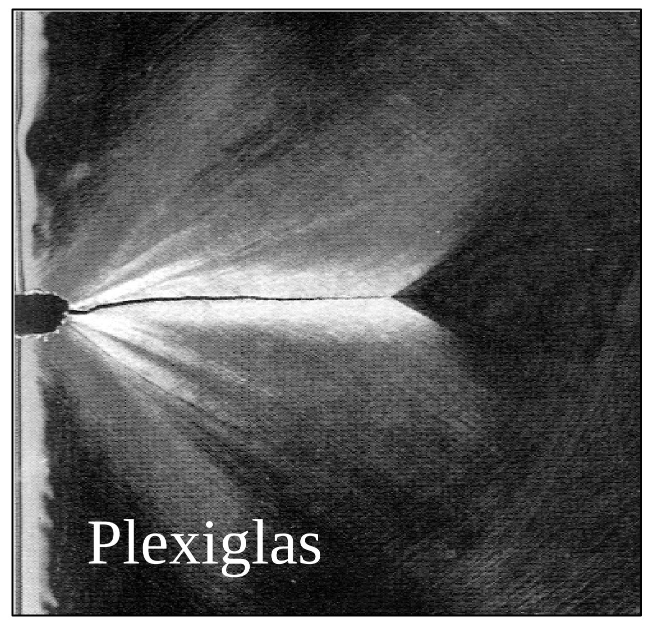
- 4. Stage I crack growth
- 5. Stage II crack growth

5. Stage II crack growth

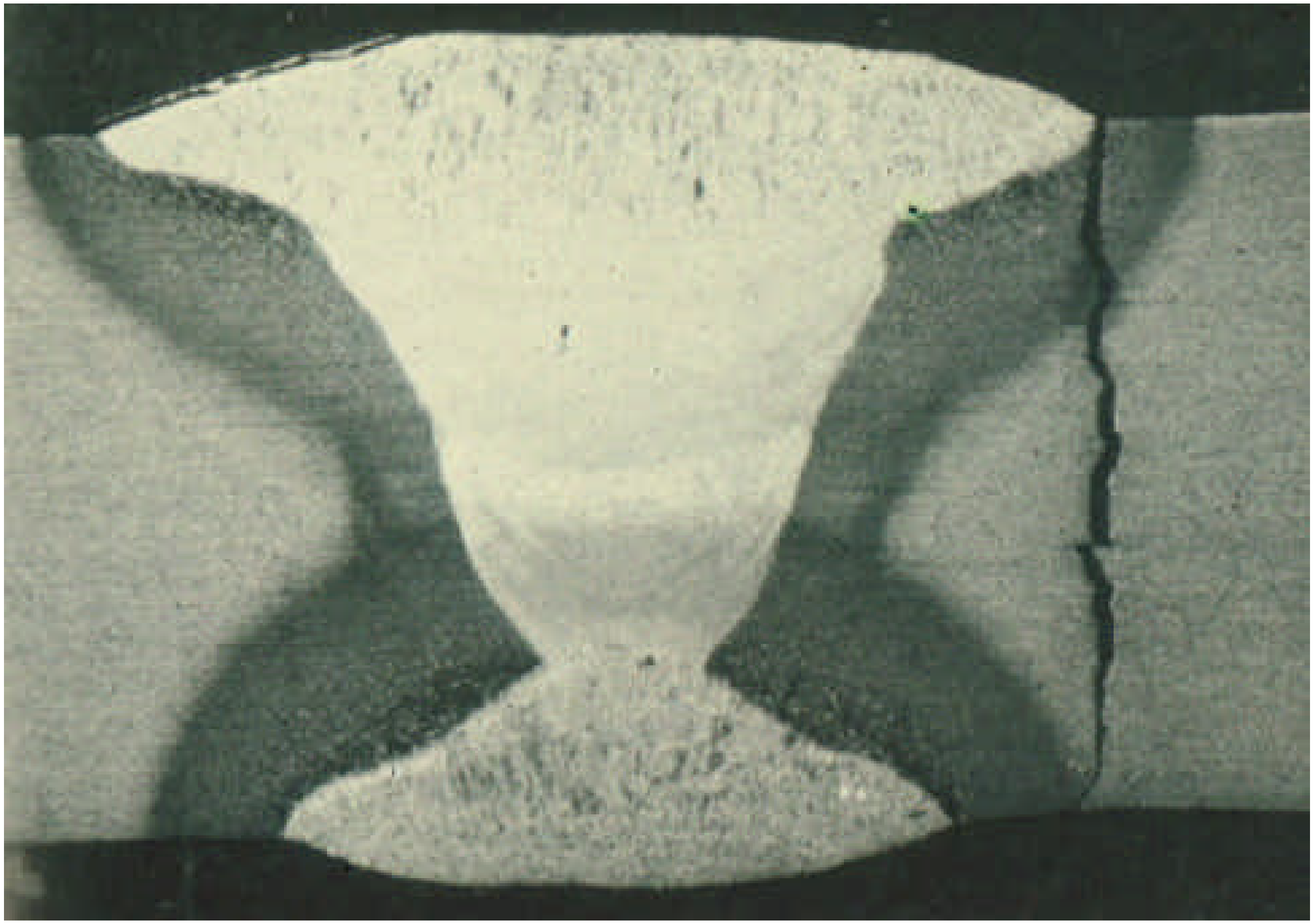






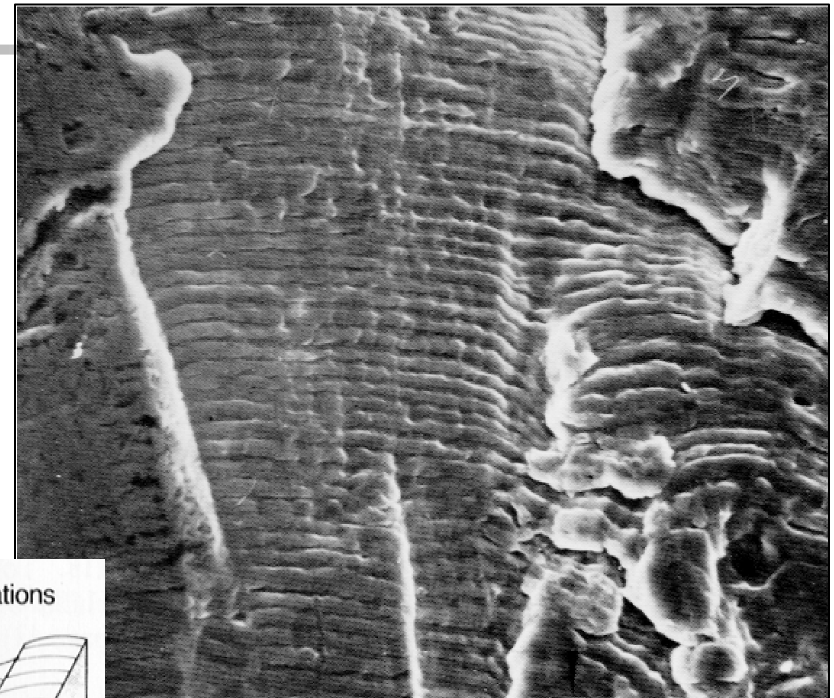
Stage II fatigue cracks much larger than the grain size and are thus sensitive only to large scale microstructural features - texture, global residual stresses, etc.

Example

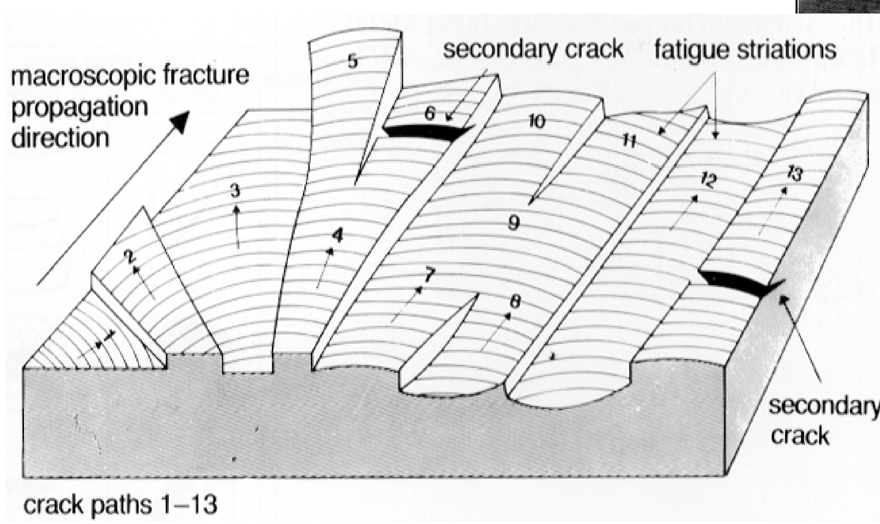


- Stage II fatigue crack in a weldment

5. Stage II crack growth

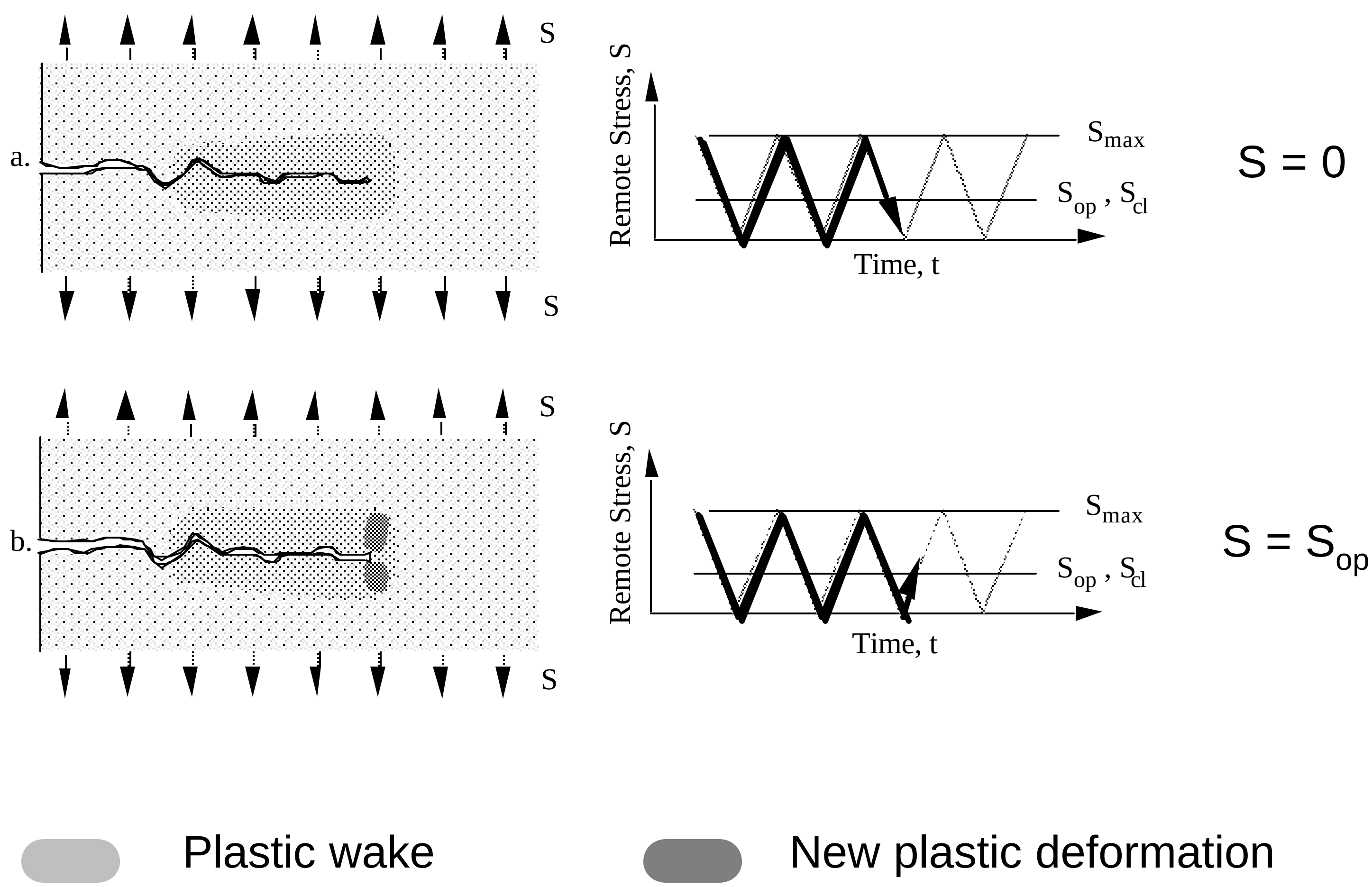


Scanning electron microscope image - striations clearly visible

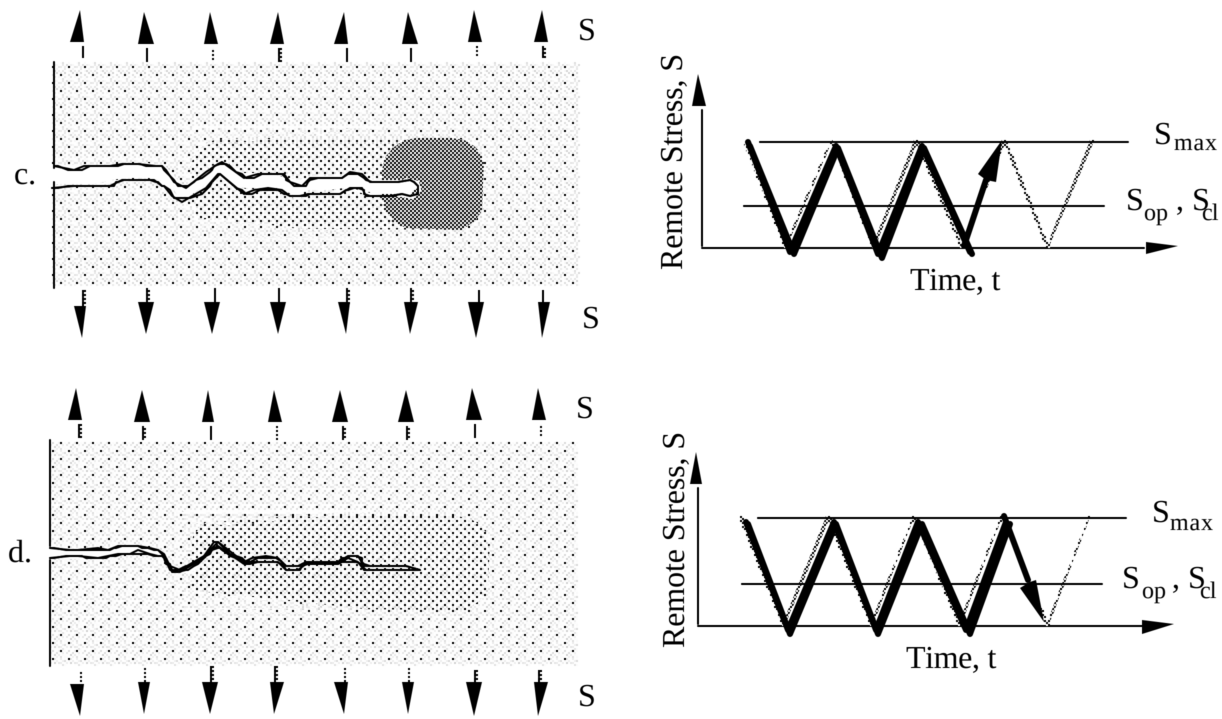


Schematic drawing of a fatigue fracture surface

5. Stage II crack growth



5. Stage II crack growth



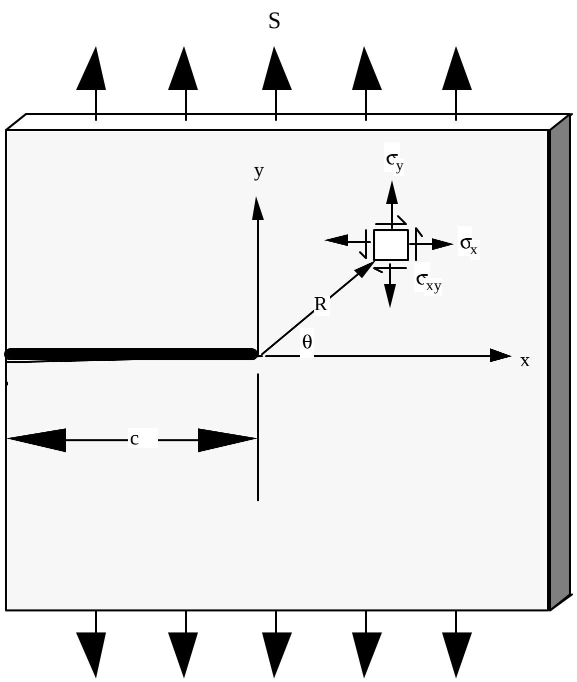
$S = S_{max}$

$S = 0$

Plastic wake

New plastic deformation

Elastic stresses near a crack tip



$$\sigma_x = \frac{S\sqrt{\pi c}}{\sqrt{2\pi R}}\cos\frac{\theta}{2}\left(1-\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right) = \frac{K_I}{\sqrt{2\pi R}} f_1(\theta)$$

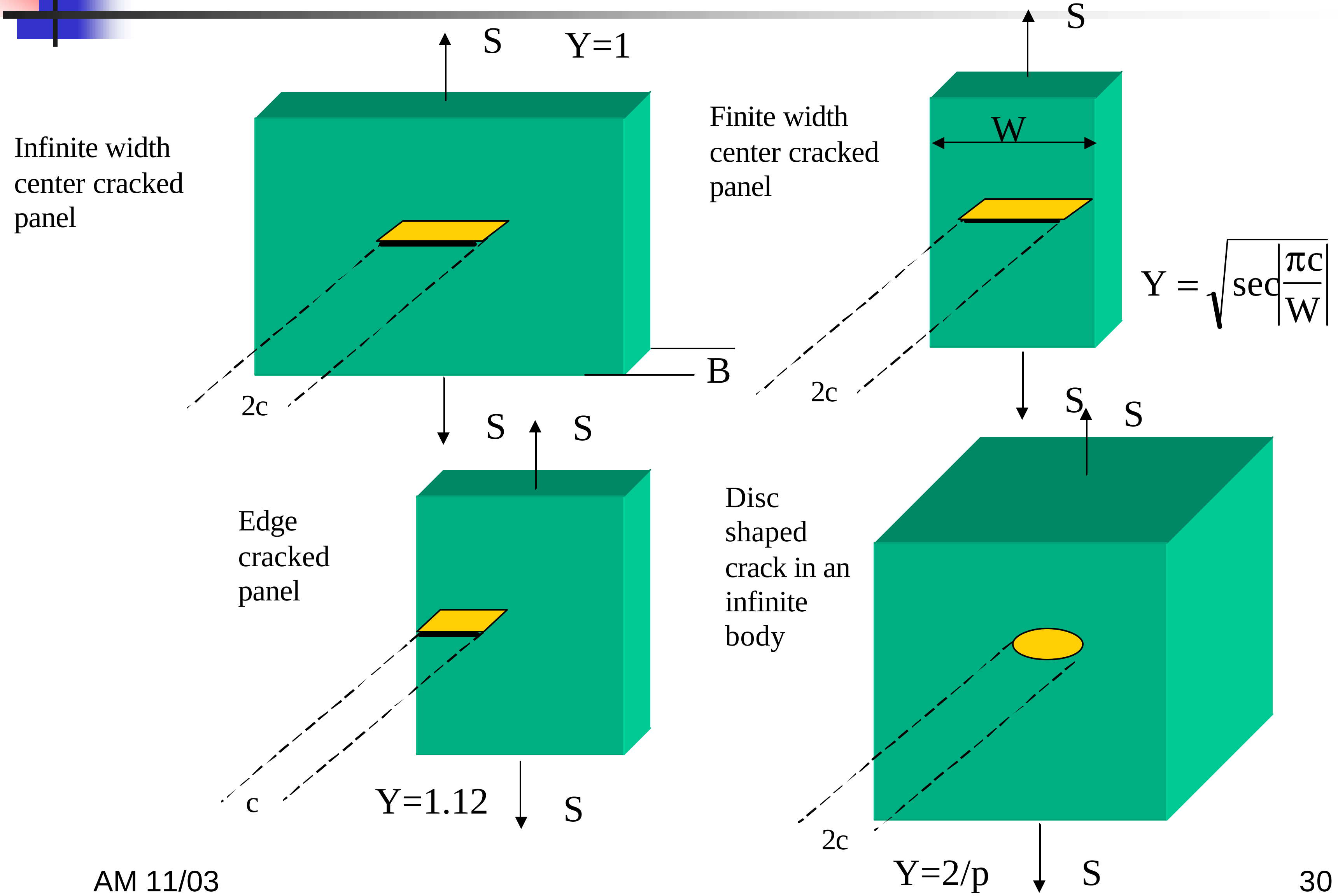
$$\sigma_y = \frac{S\sqrt{\pi c}}{\sqrt{2\pi R}}\cos\frac{\theta}{2}\left(1+\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right) = \frac{K_I}{\sqrt{2\pi R}} f_2(\theta)$$

$$\tau_{xy} = \frac{S\sqrt{\pi c}}{\sqrt{2\pi R}}\cos\frac{\theta}{2}\left(\sin\frac{\theta}{2}\cos\frac{\theta}{2}\sin\frac{3\theta}{2}\right) = \frac{K_I}{\sqrt{2\pi R}} f_3(\theta)$$

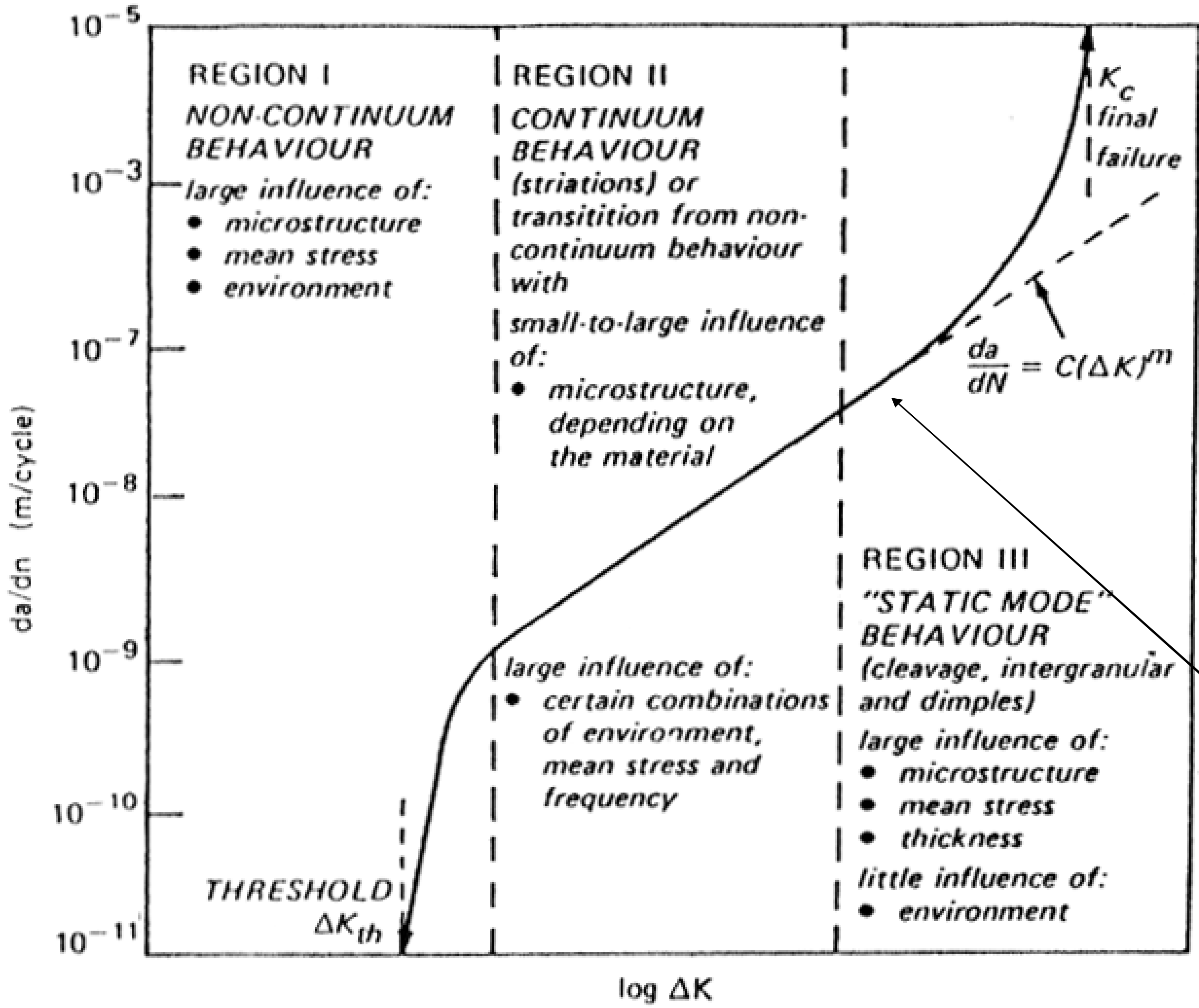
The magnitude stress field near a crack tip depends upon the stress intensity factor (K_I). Wouldn't it be nice if this quantity correlates with the speed with which fatigue cracks grow? Let's see if it works! Rather, let's see if we can MAKE it work!

Range of stress intensity factor $\Delta K \equiv Y\Delta S\sqrt{pa}$

Geometry correction factor (Y)



5. Stage II crack growth

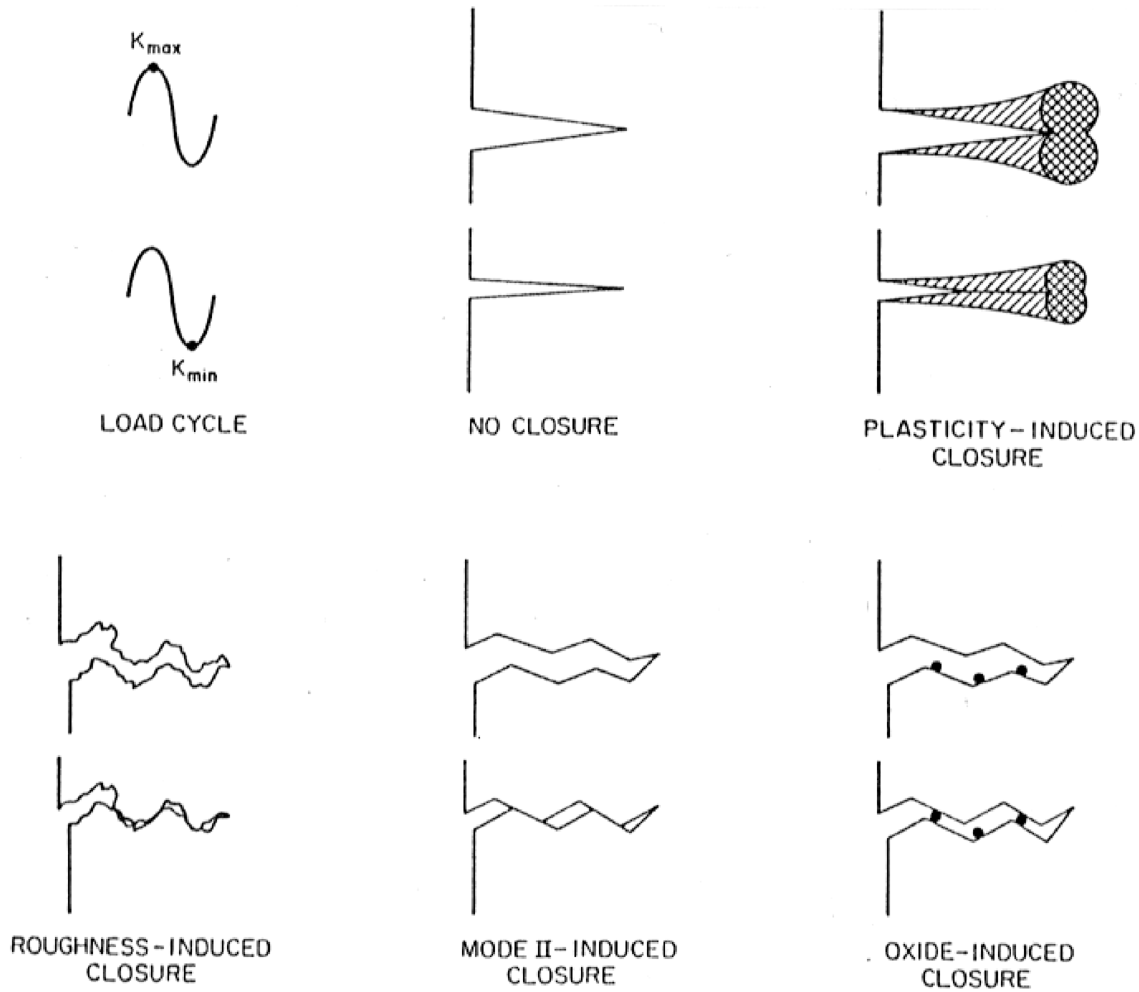


Crack growth rate (da/dN) is related to the crack tip stress field and is thus strongly correlated with the range of stress intensity factor:
(? K=Y? Svpa).

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

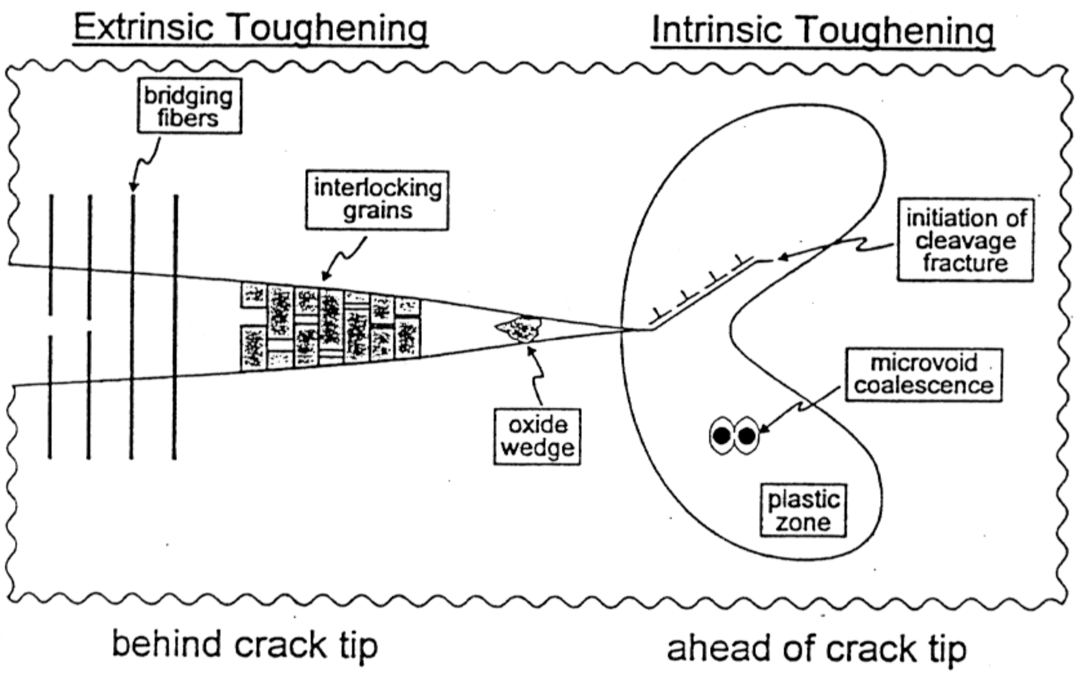
Paris power law

5. Stage II crack growth



- Crack Closure Mechanisms

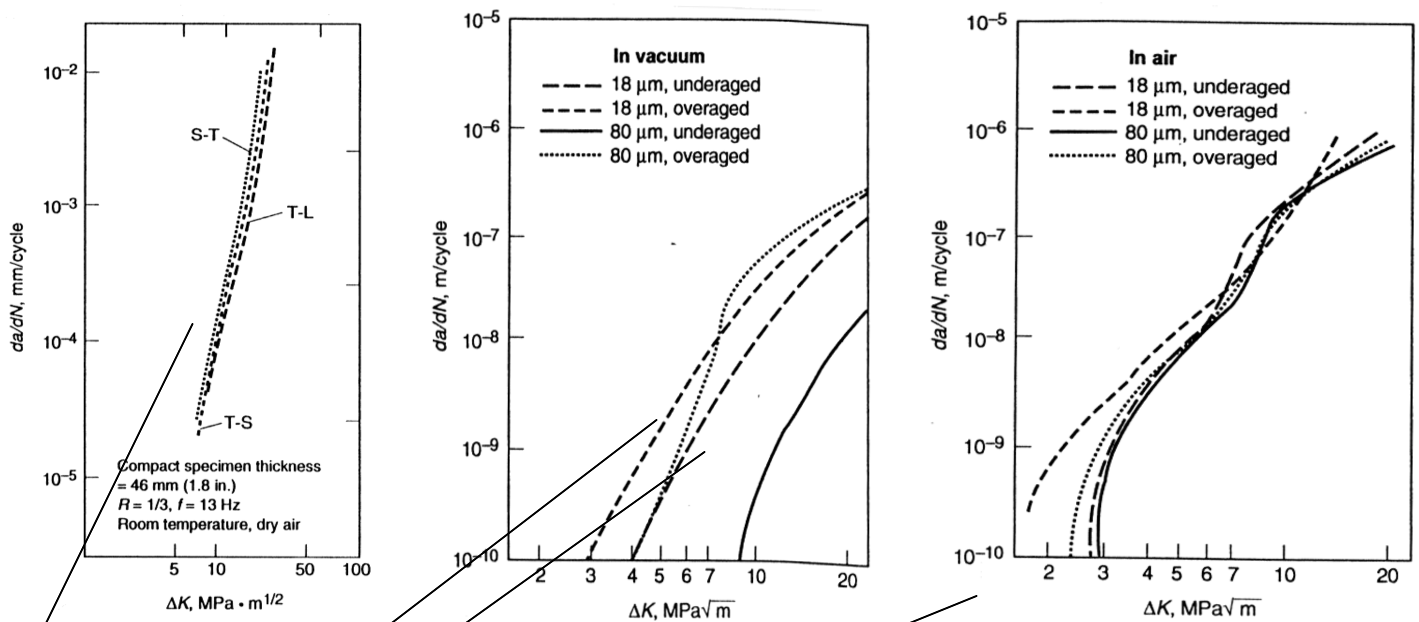
5. Stage II crack growth



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

Extrinsic
Intrinsic

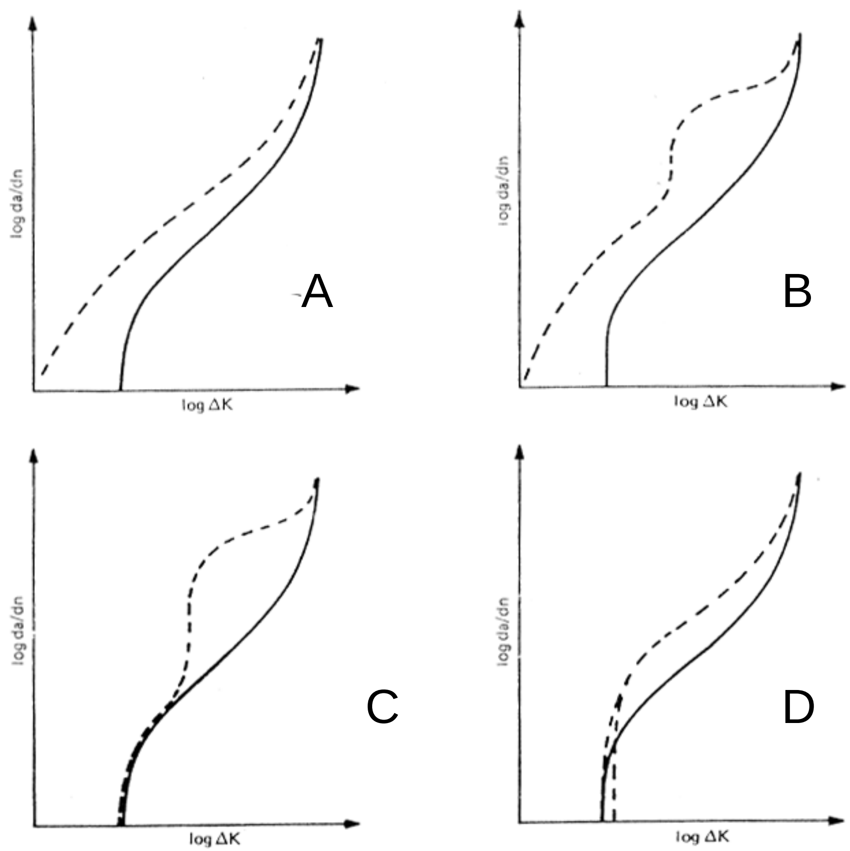
Example



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

- Aluminum - crack growth

5. Stage II crack growth



A. Dissolution of crack tip.

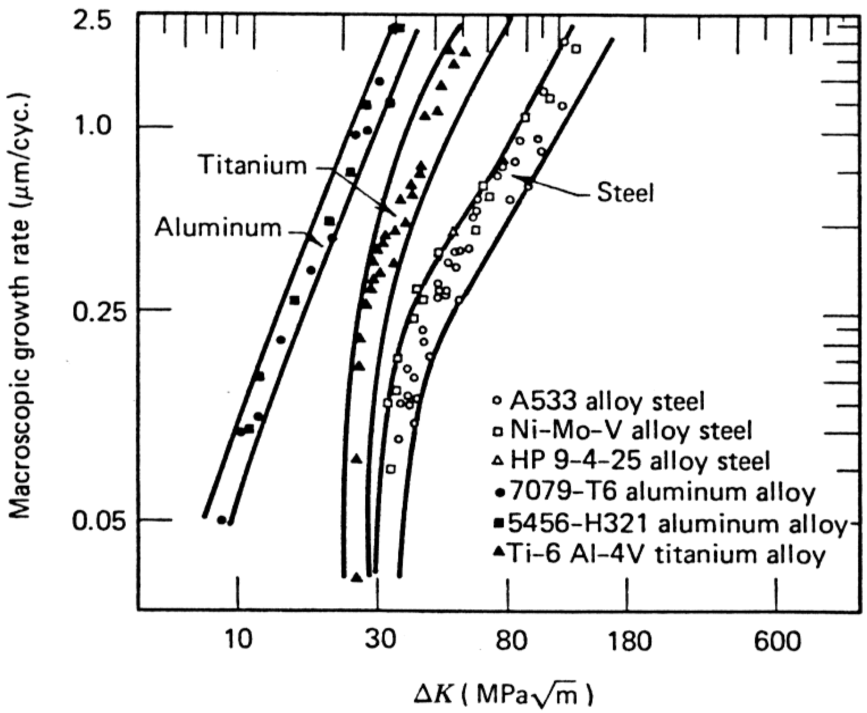
B. Dissolution plus H+ acceleration.

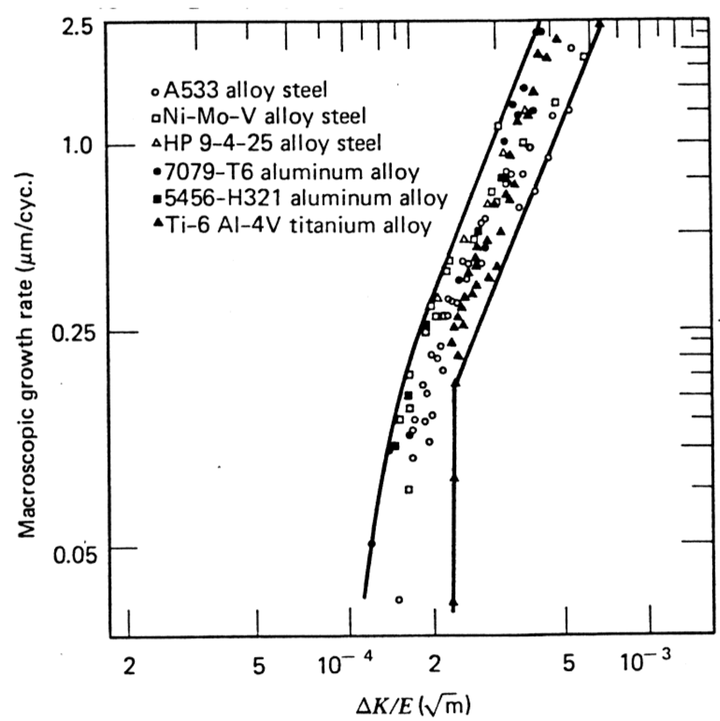
C. H+ acceleration

D. Corrosion products may retard crack growth at low ?K.

- Effects of Environment

Example





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

- Crack Growth Rates of Metals

Summary

- Fatigue is a complex process involving many steps but it may be broken down into the initiation and growth of fatigue cracks.
- The growth of fatigue cracks is often considered to be the most important feature of fatigue from an engineering perspective.