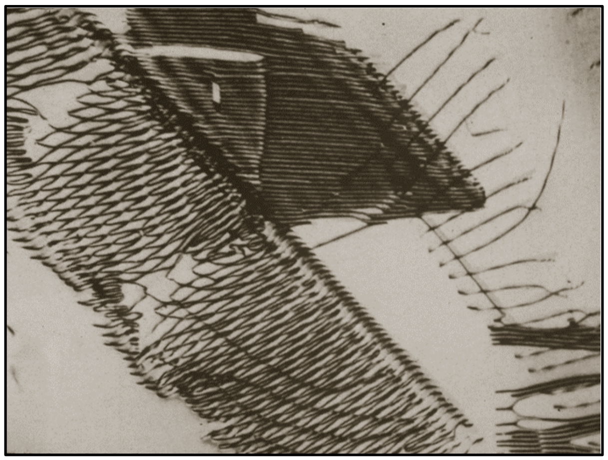
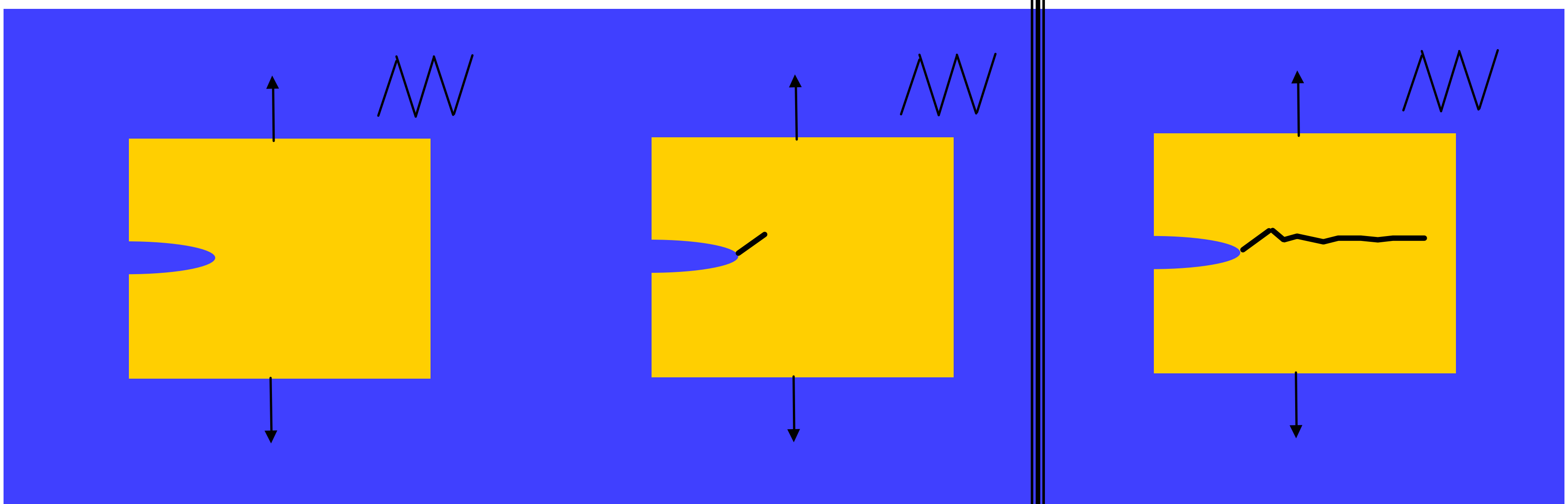
Materials Issues in Fatigue and Fracture



- 5.1 Fundamental Concepts
- 5.2 Ensuring Infinite Life
- **5.3 Finite Life**
- 5.4 Summary

A simple view of fatigue

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



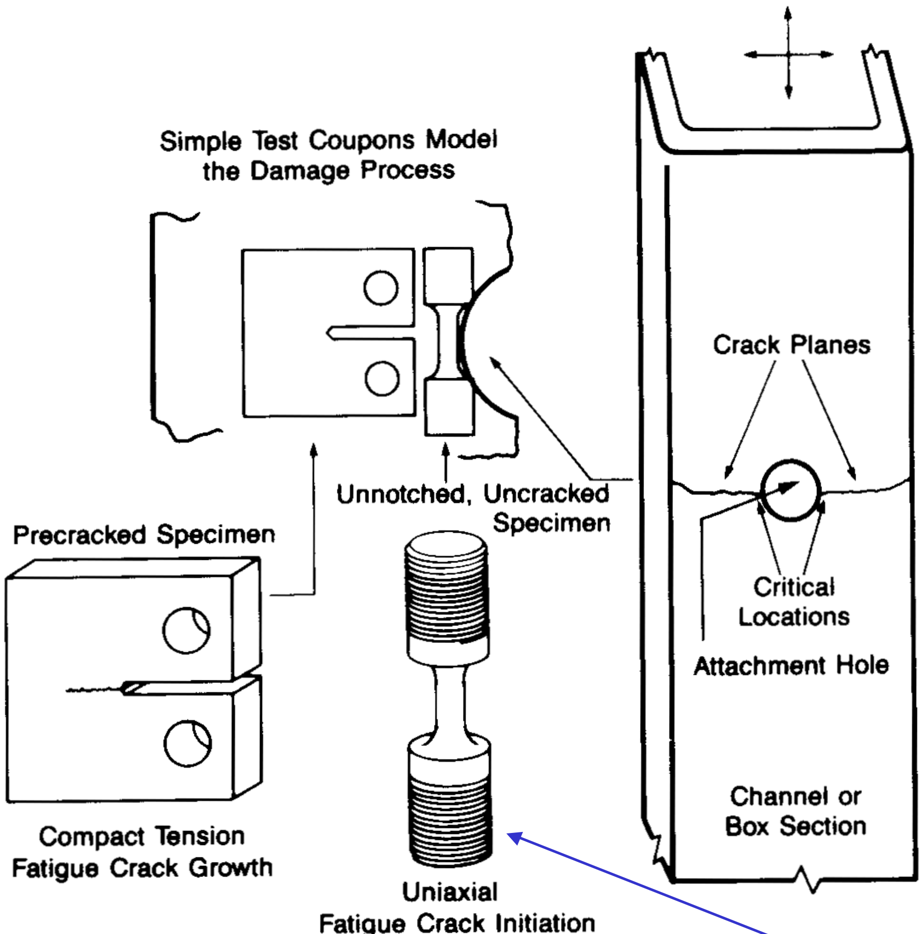
Cyclic nucleation and arrested growth

Infinite Life

Crack growth

Finite Life

Fatigue of a component



A smooth specimen

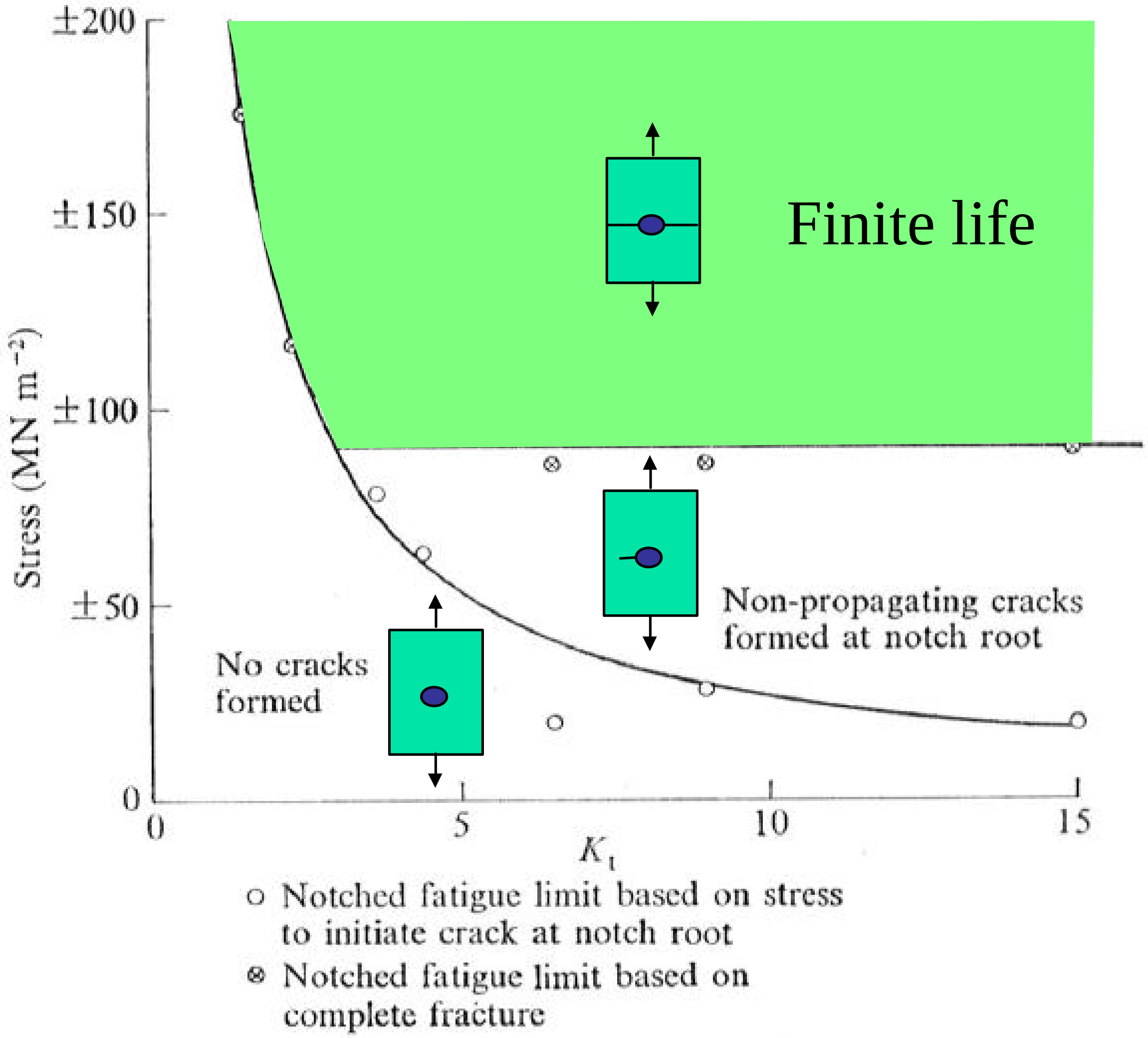
The fatigue life of an engineering component consists of two main life periods:

Initiation or nucleation of a fatigue crack (N_I)

And

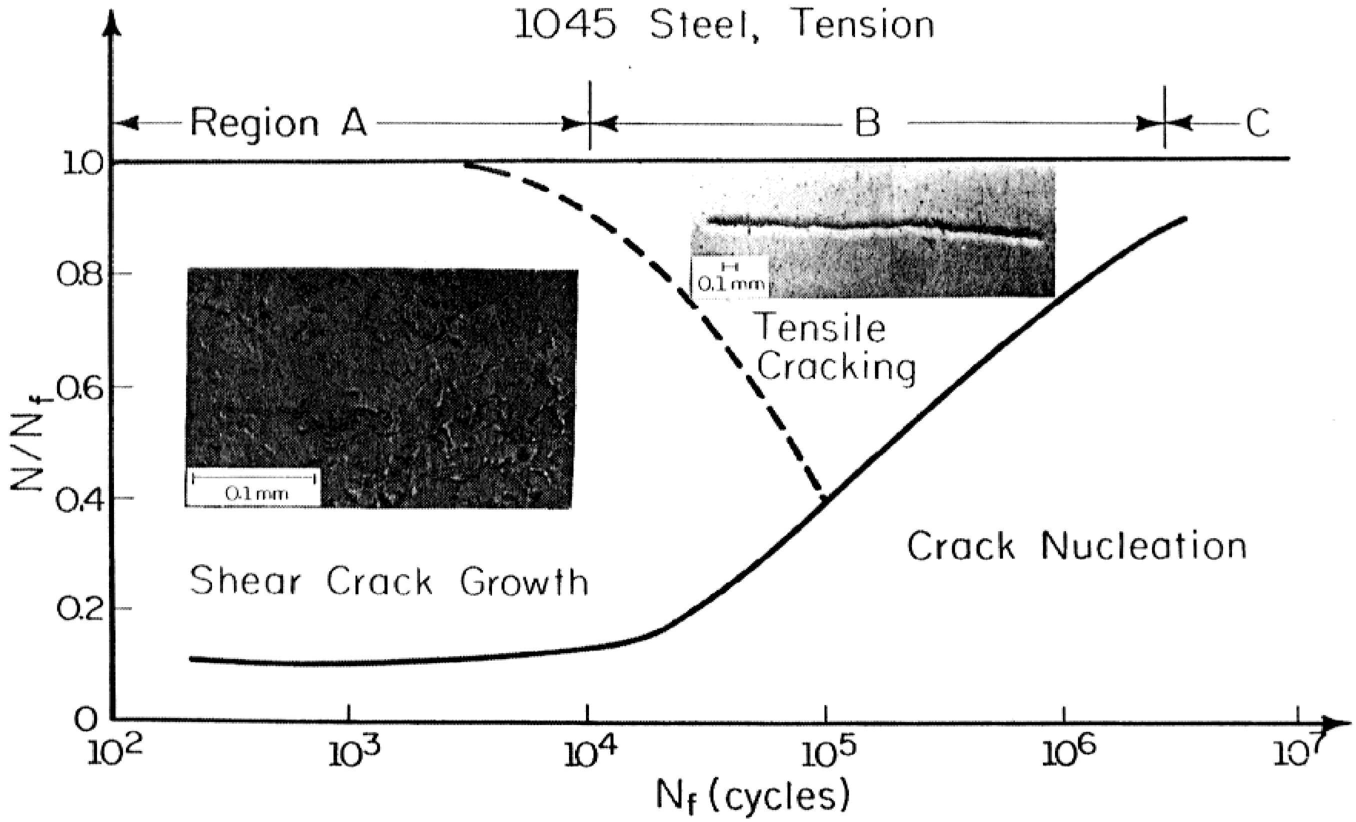
Its growth to failure (N_P)

Finite life - crack growth



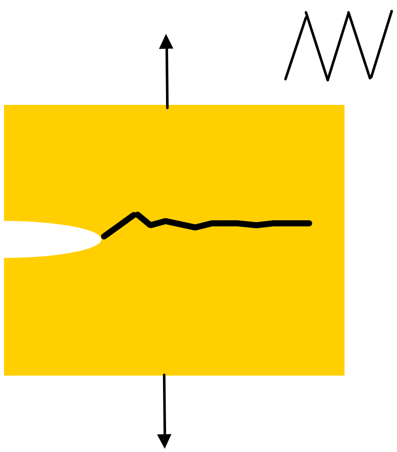
At sufficiently high alternating stresses a crack will nucleate and grow until the component breaks.

Short and long life behavior



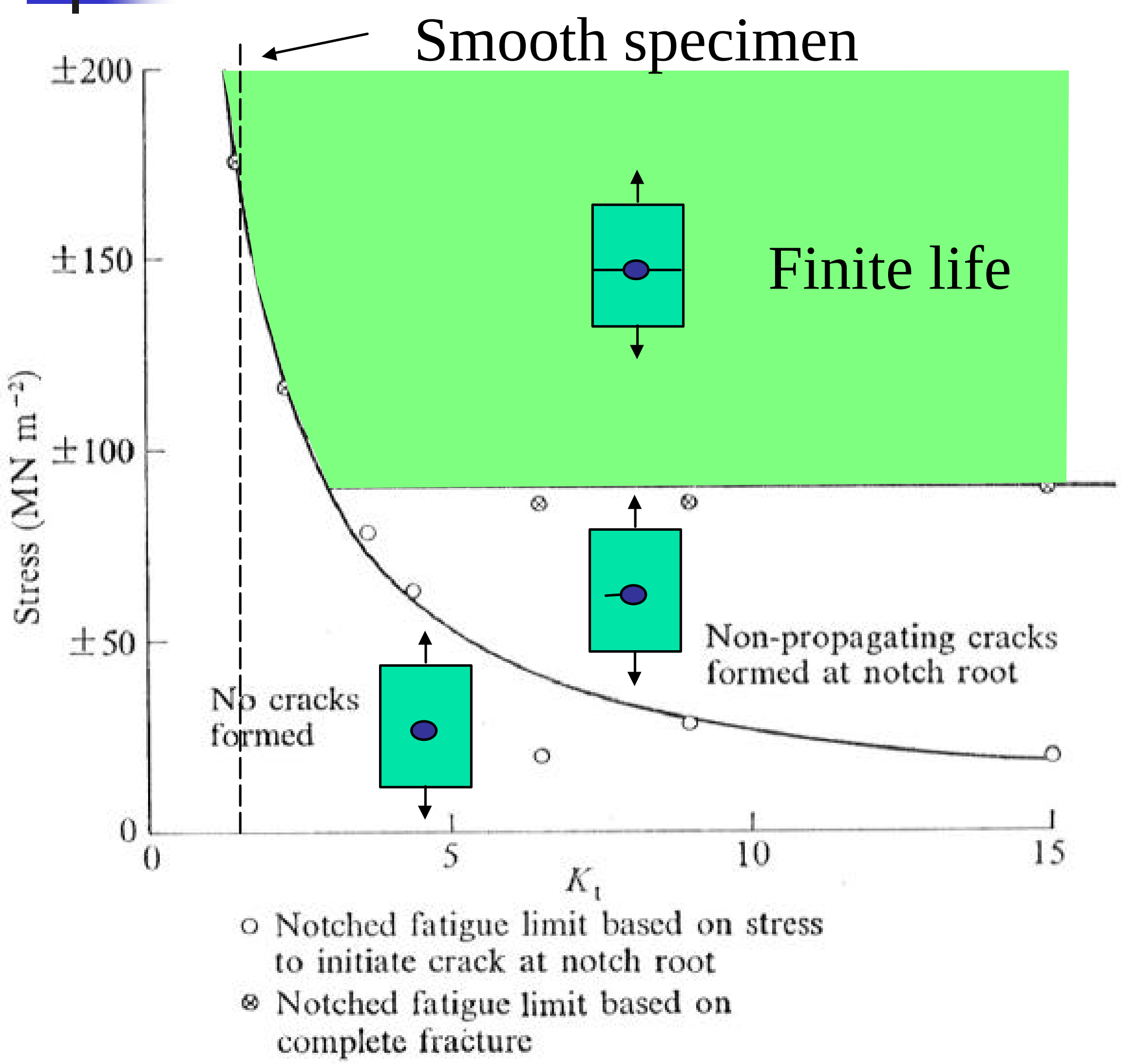
Crack nucleation dominates at long lives, crack growth dominates at short lives.

5.3 Finite Life



- **Smooth specimens**
- Short cracks
- Long cracks

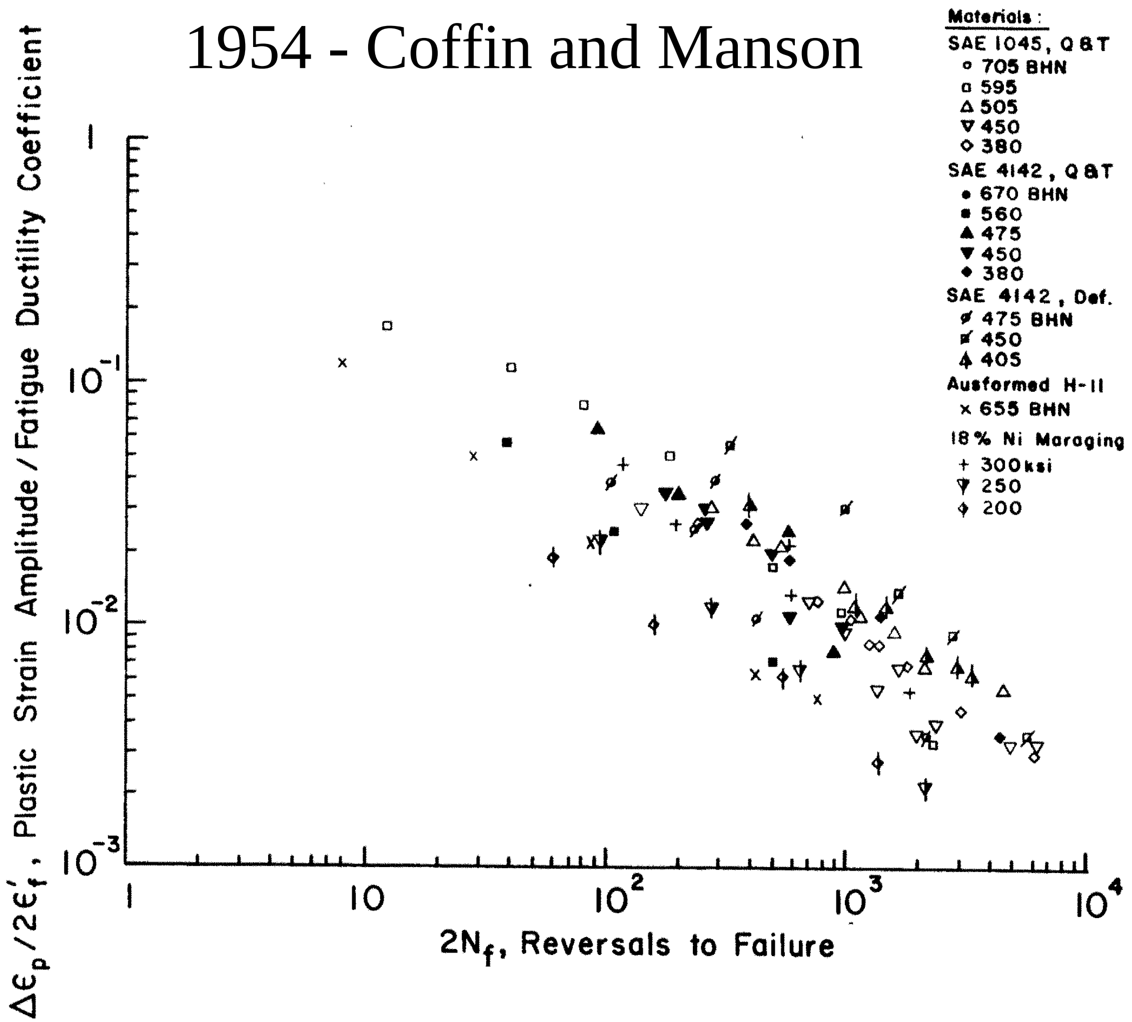
Finite life - crack growth



At sufficiently high alternating stresses even smooth specimens will nucleate a crack and ultimately fail in fatigue.

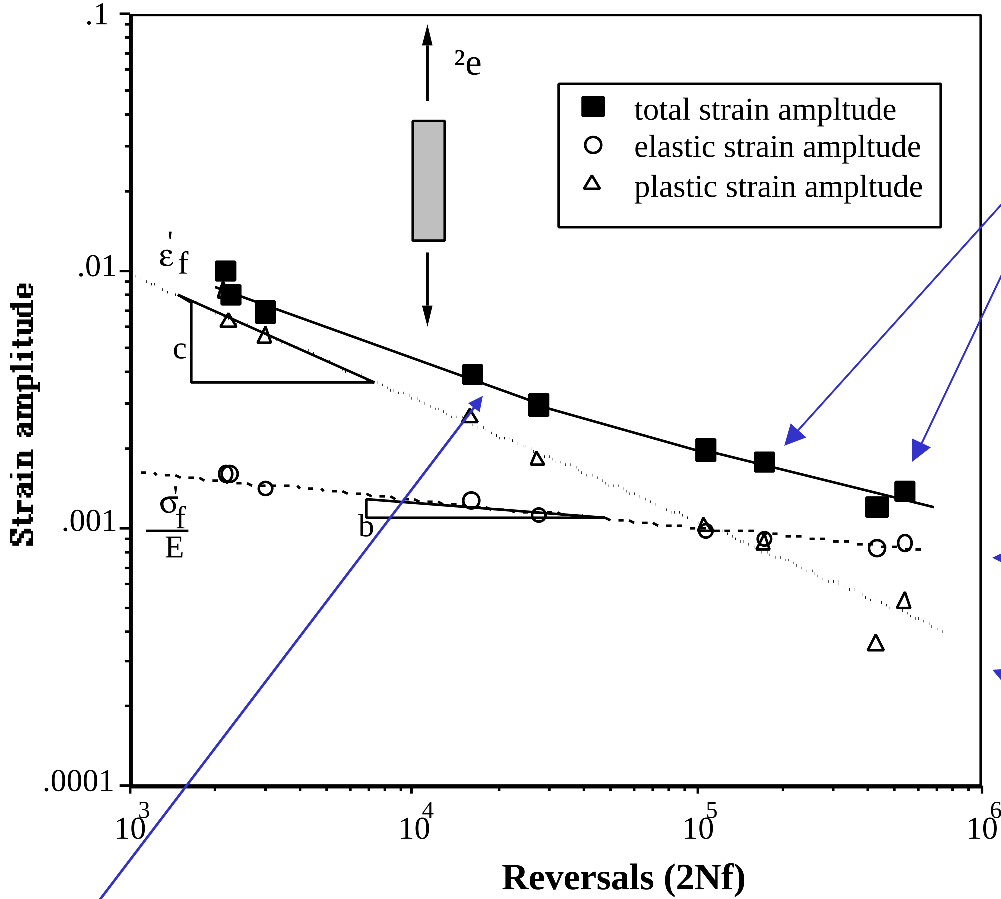
Plastic strains cause fatigue

1954 - Coffin and Manson



Plastic strains cause the nucleation of fatigue cracks. The life to fatigue failure of smooth specimens correlates with the plastic strain.

Strain-life curve



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

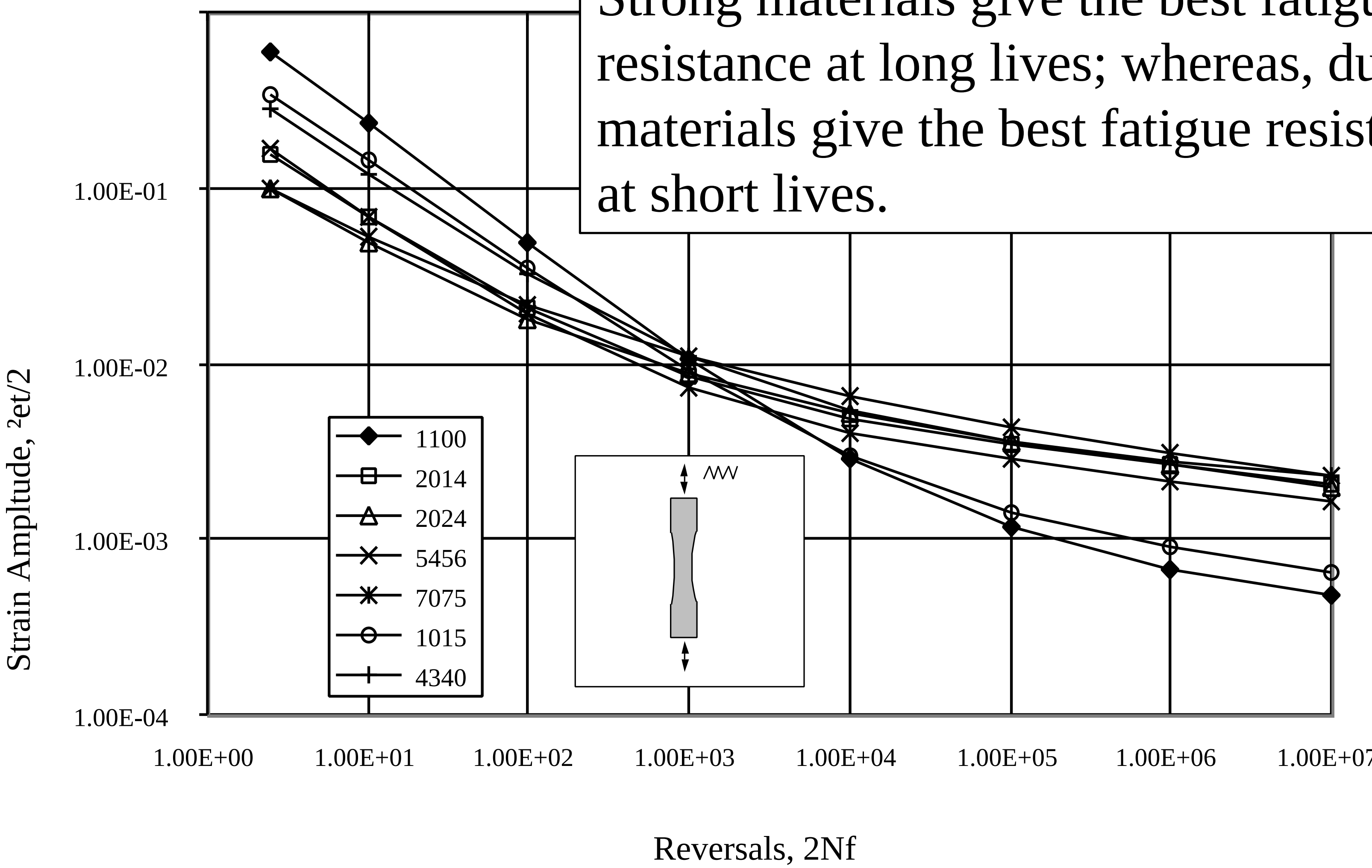
Elastic component of strain, ? ε_e

Plastic component of strain, ? ε_p

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

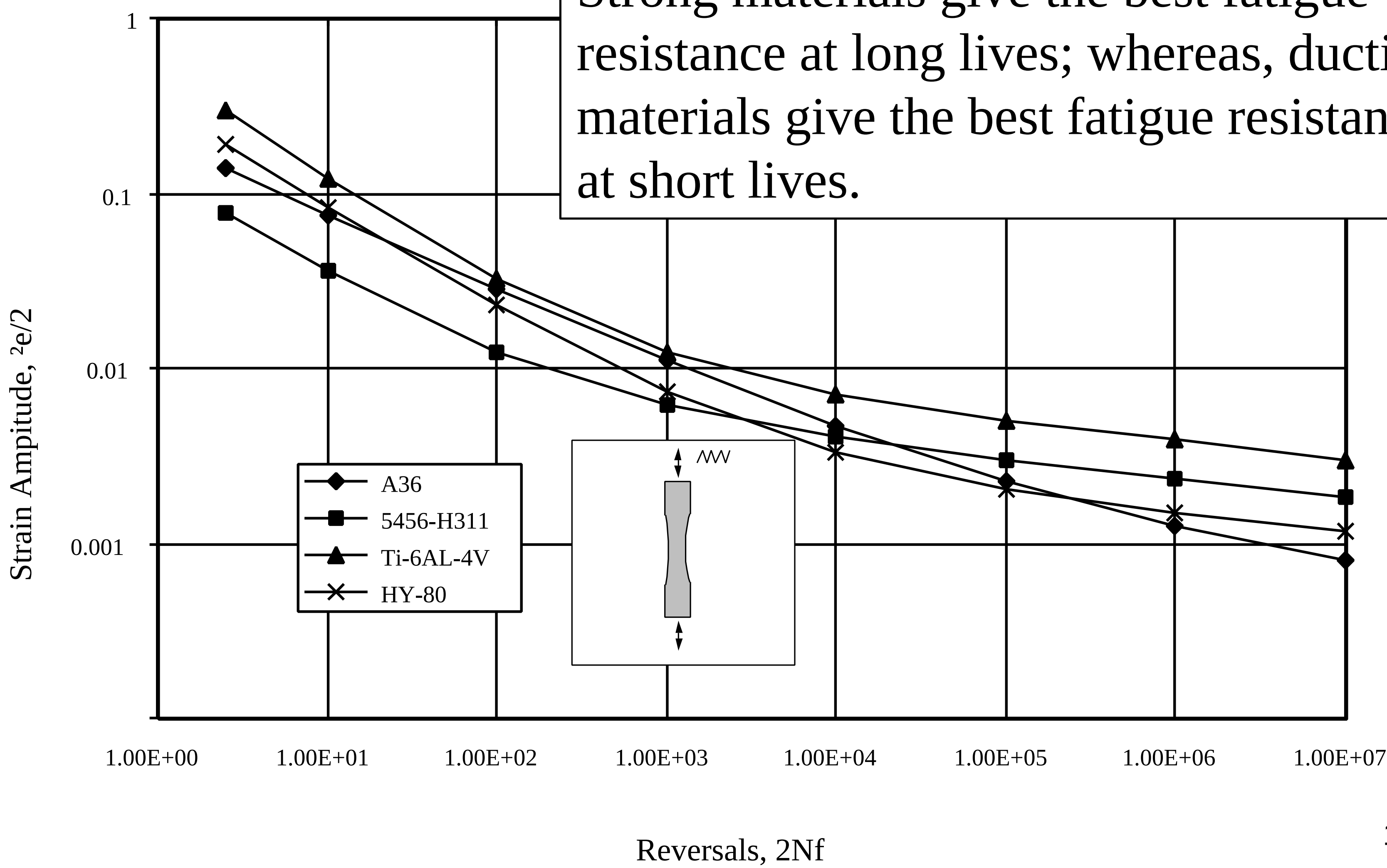
Behavior of Aluminum Alloys

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

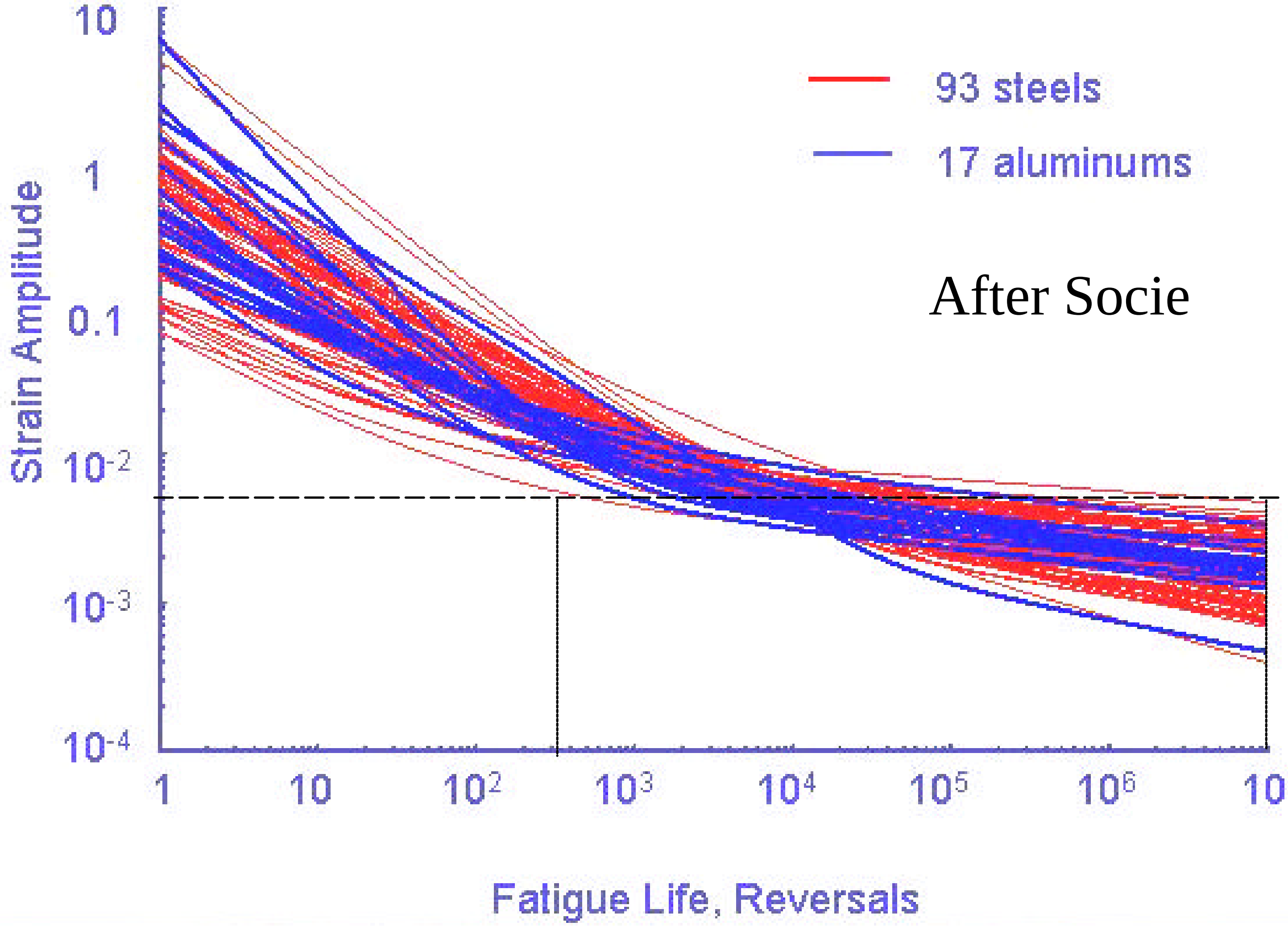


Comparison of various metals

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

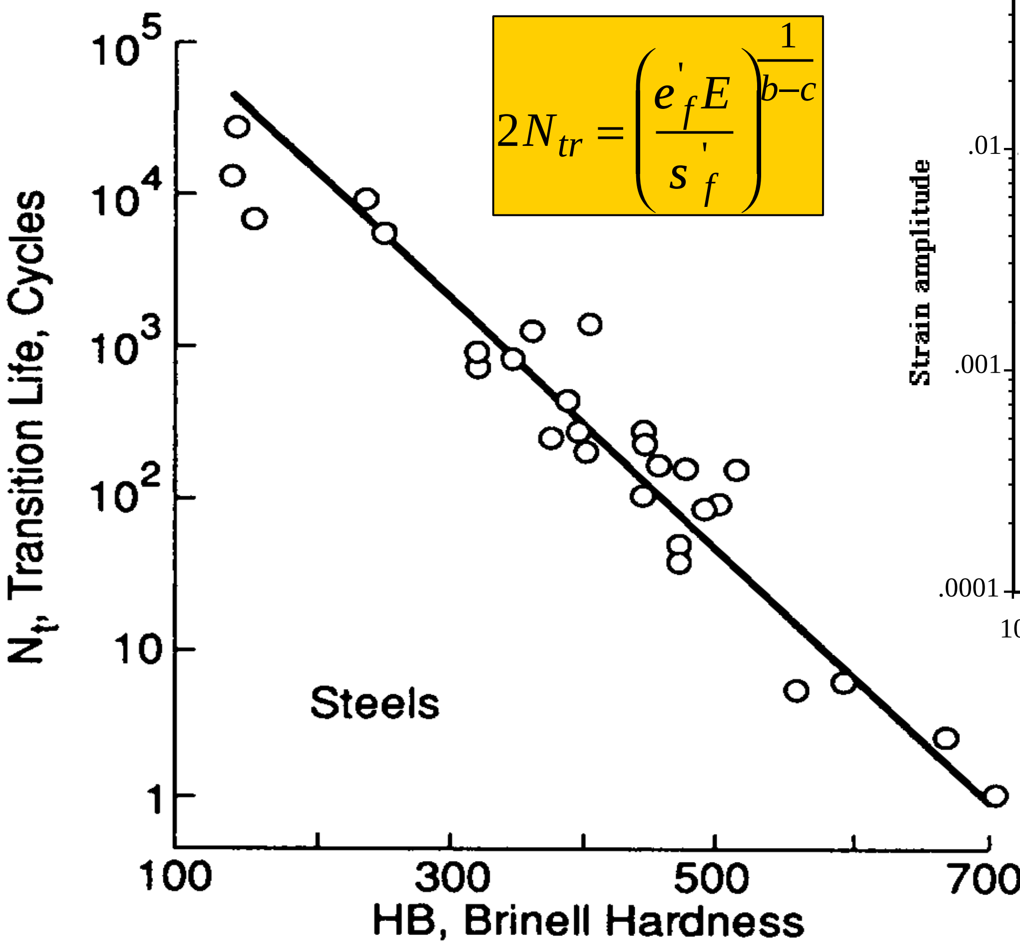


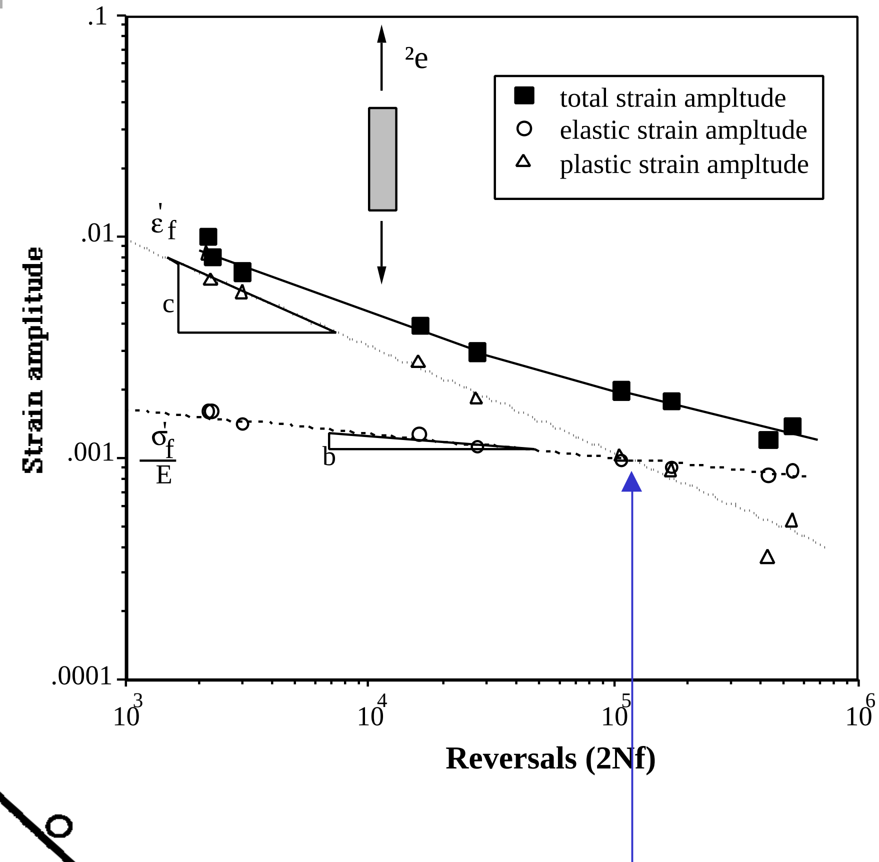
Smooth specimen behavior



Transition Fatigue Life

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

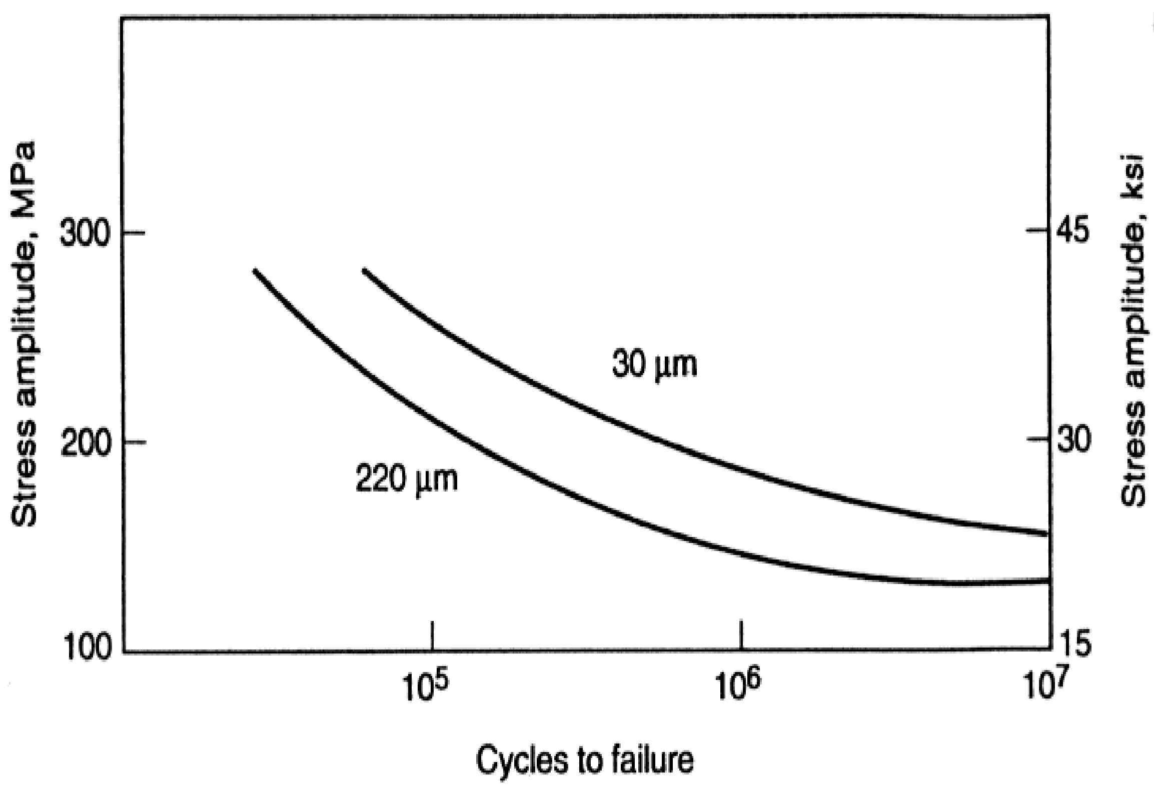




Transition fatigue life, N_{tr}

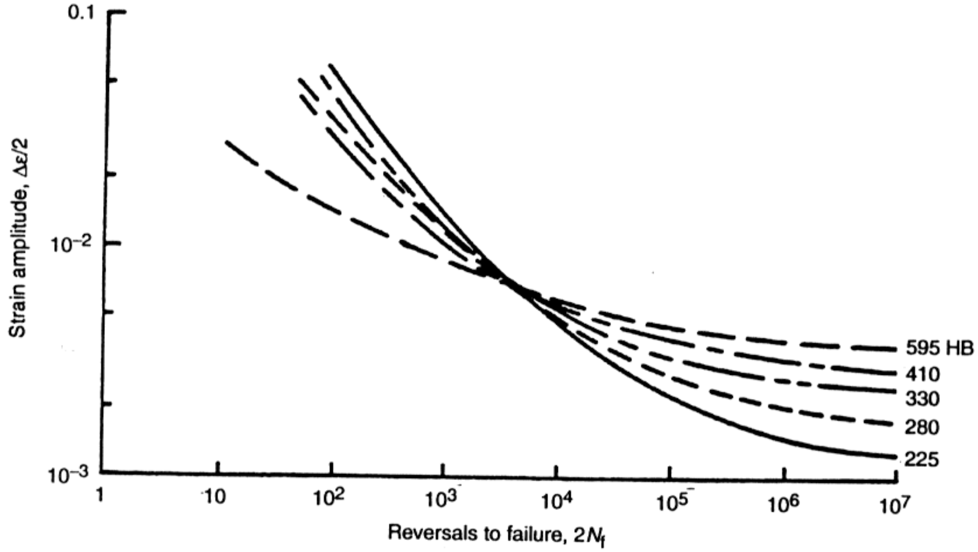
Elastic strains = plastic strains

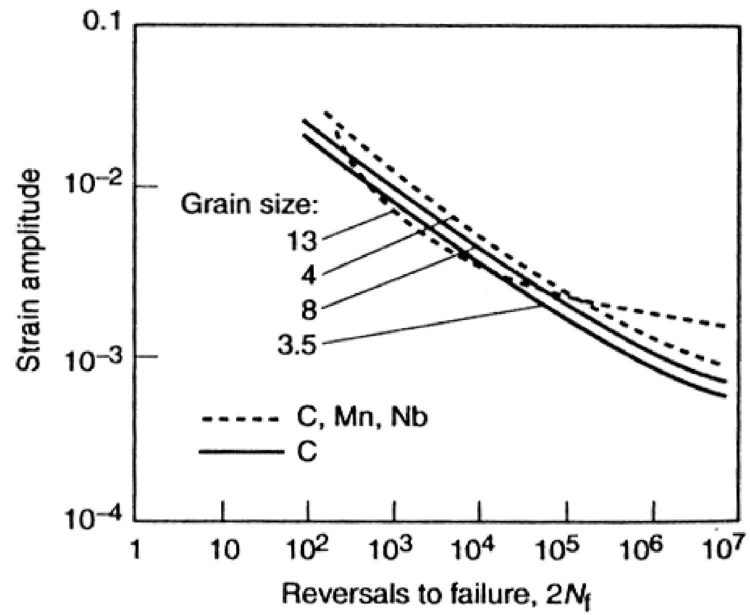
Aluminum - smooth specimens



Initiation and small crack growth dominate so fatigue strength correlates with UTS and small grain size.

Steel - smooth specimens

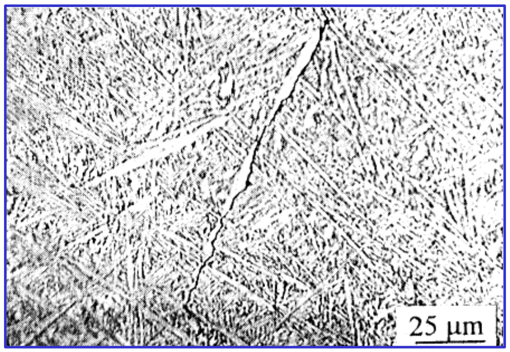




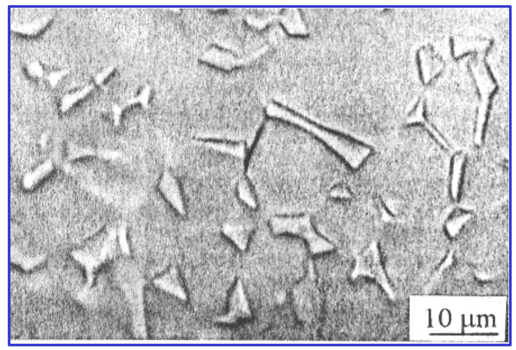
As with aluminum, both tensile strength (hardness) and grain size influence the long-life fatigue resistance. Ductility is more important at short lives. At lives of ˜ 5x103, all have the same fatigue resistance.

Titanium - smooth specimens

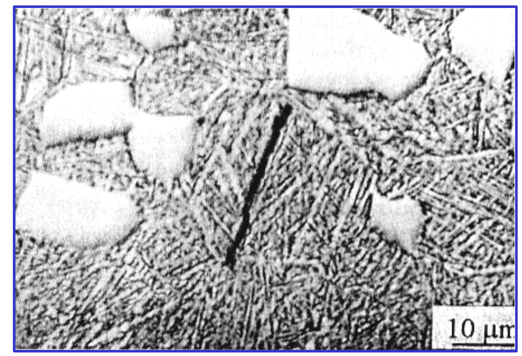
SN curves for Ti (R = -1)..grain size effects



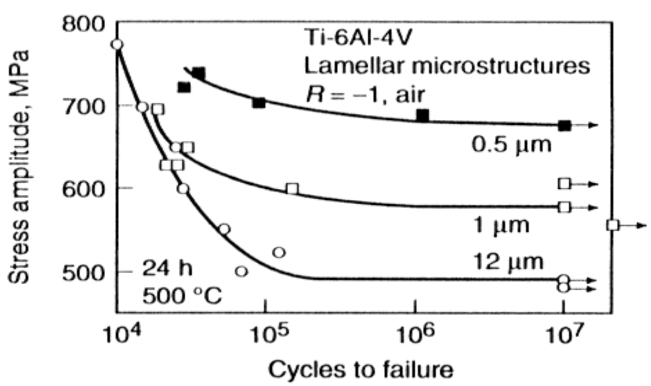
Lamellar α



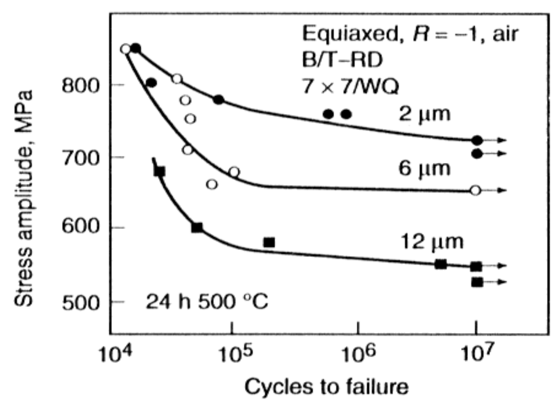
Equiaxed α



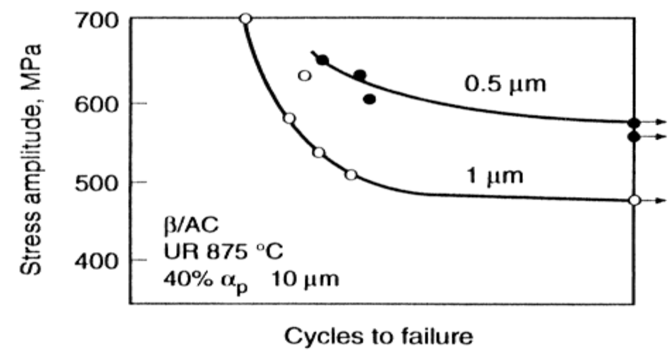
Duplex



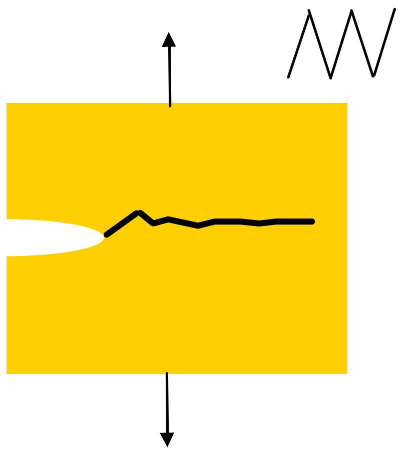
(a)



(b)

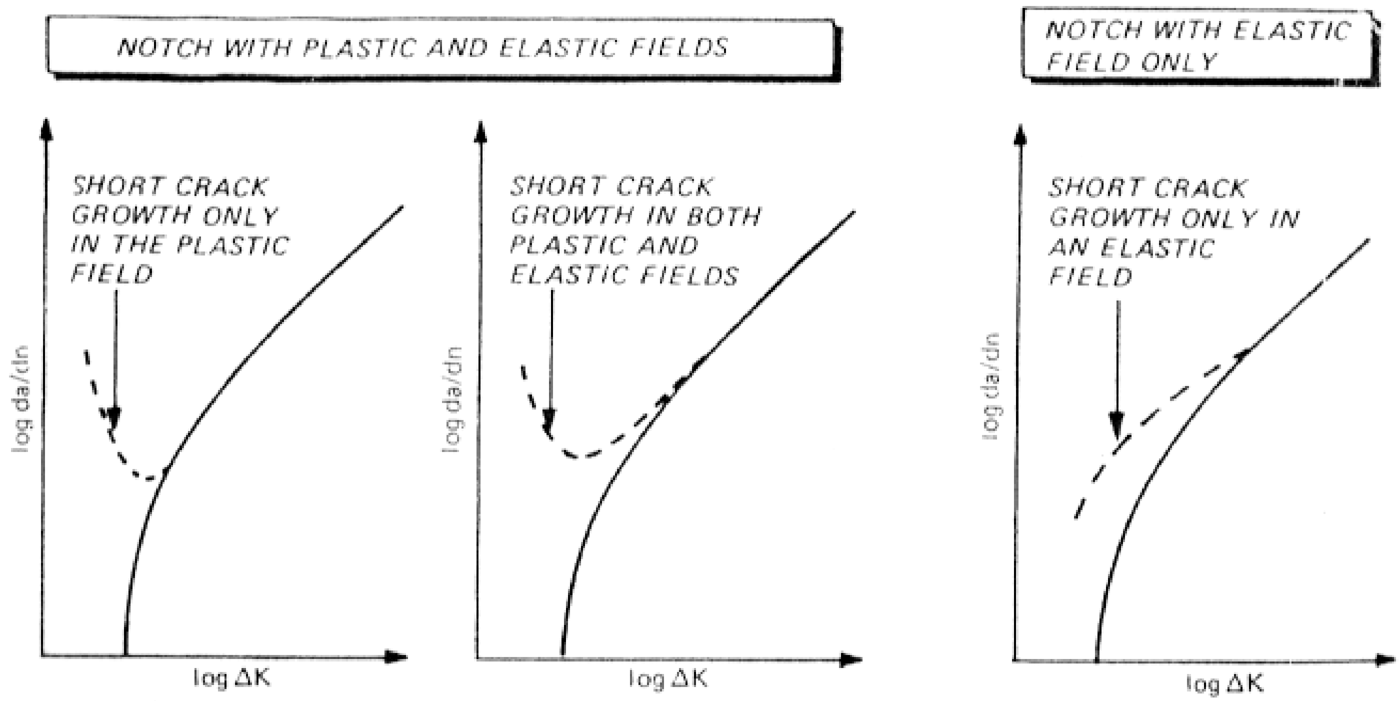


5.3 Finite Life



- Smooth specimens
- **Short cracks**
- Long cracks

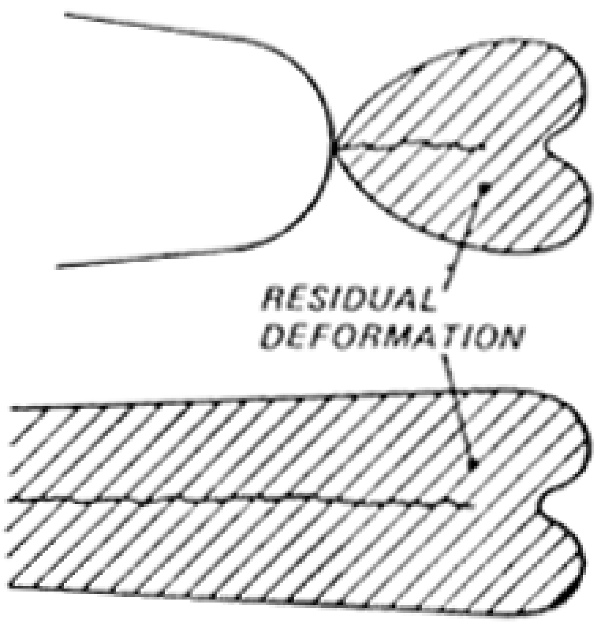
Growth of Small Cracks



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

Short Cracks, Long Cracks

$$? K_{eff} = U \; ? K$$



SHORT CRACK

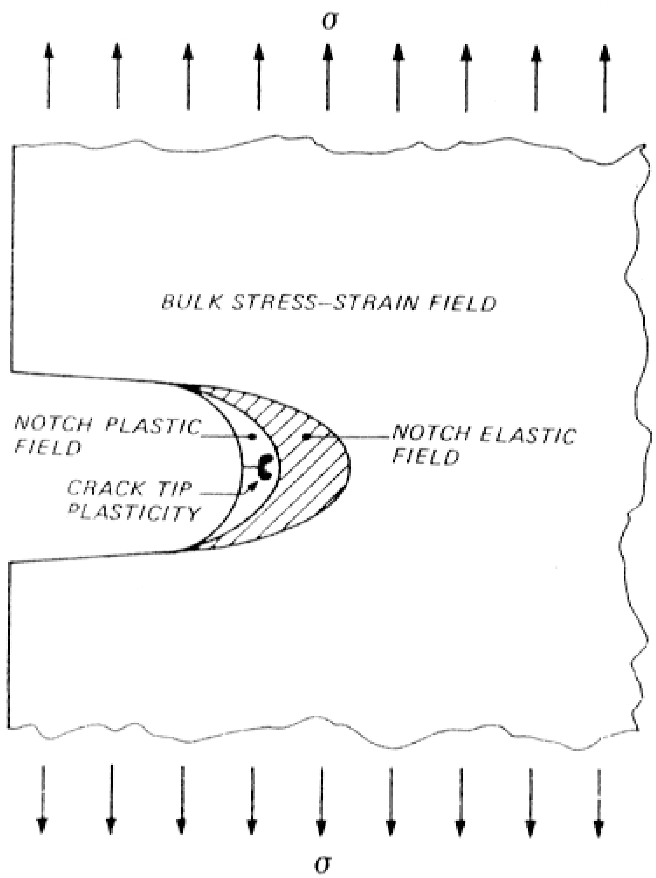
- LESS RESIDUAL DEFORMATION
- LOWER σ_{op}
- HIGHER $U = \Delta K_{eff} / \Delta K$

LONG CRACK

- MORE RESIDUAL DEFORMATION
- HIGHER σ_{op}
- LOWER $U = \Delta K_{eff} / \Delta K$

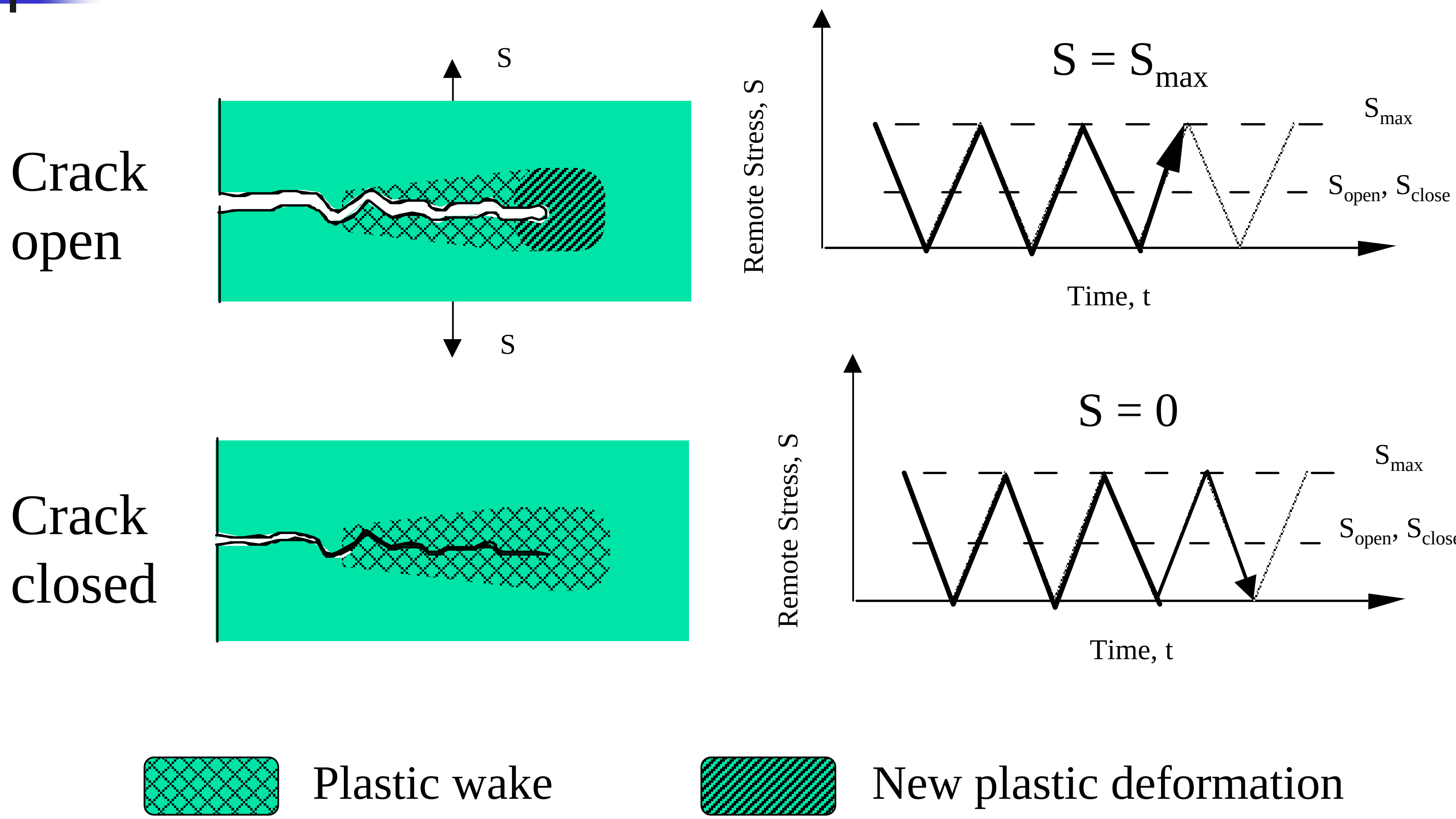
$$U = \frac{\Delta K_{eff}}{\Delta K} = \frac{S_{max} - S_{open}}{S_{max} - S_{min}} = \frac{1}{1-R}\left(1 - \frac{S_{open}}{S_{max}}\right)$$

Crack Growth at a Notch

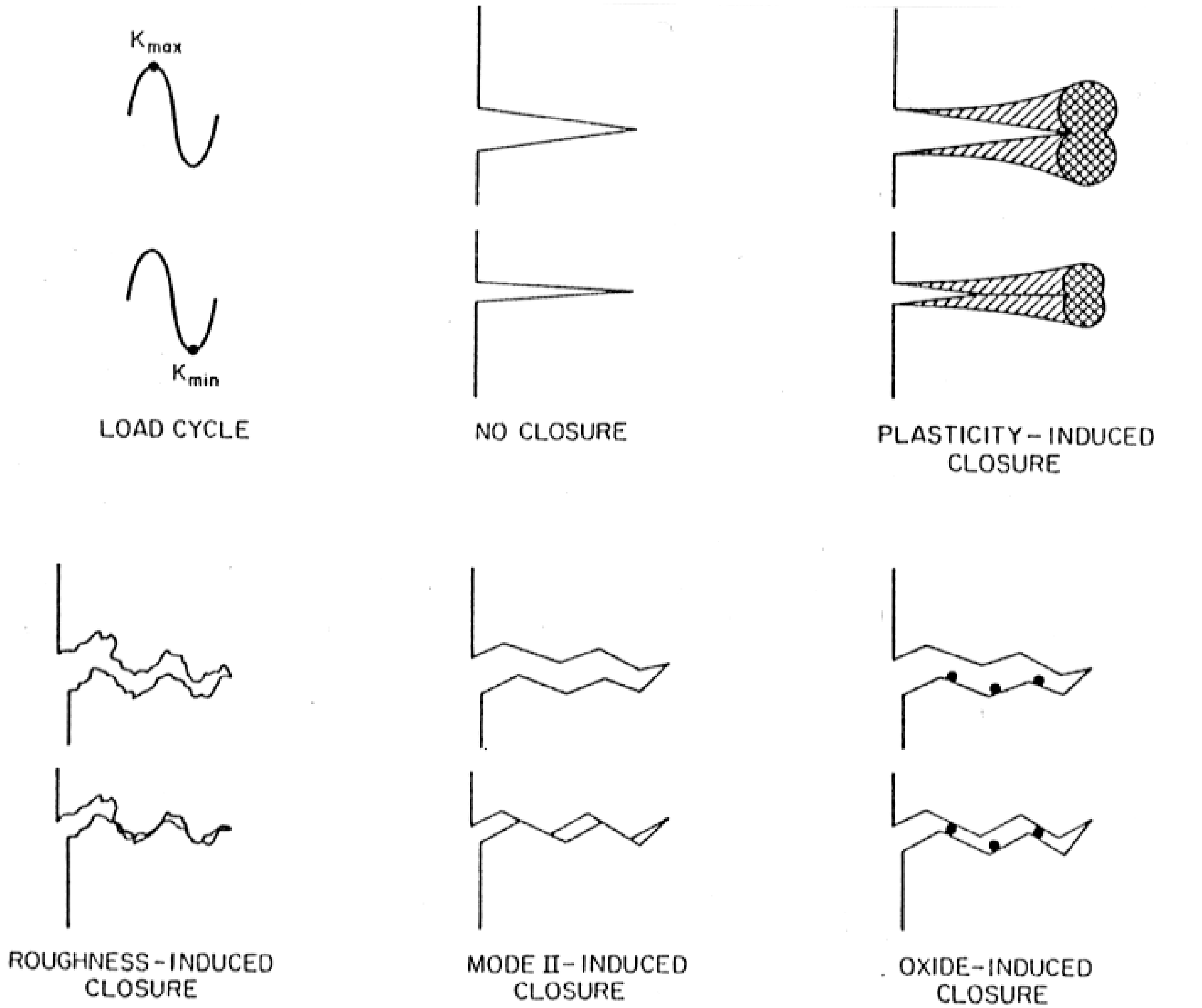


Cracks growing from notches don't know that that stress field they are experiencing is confined to the notch root.

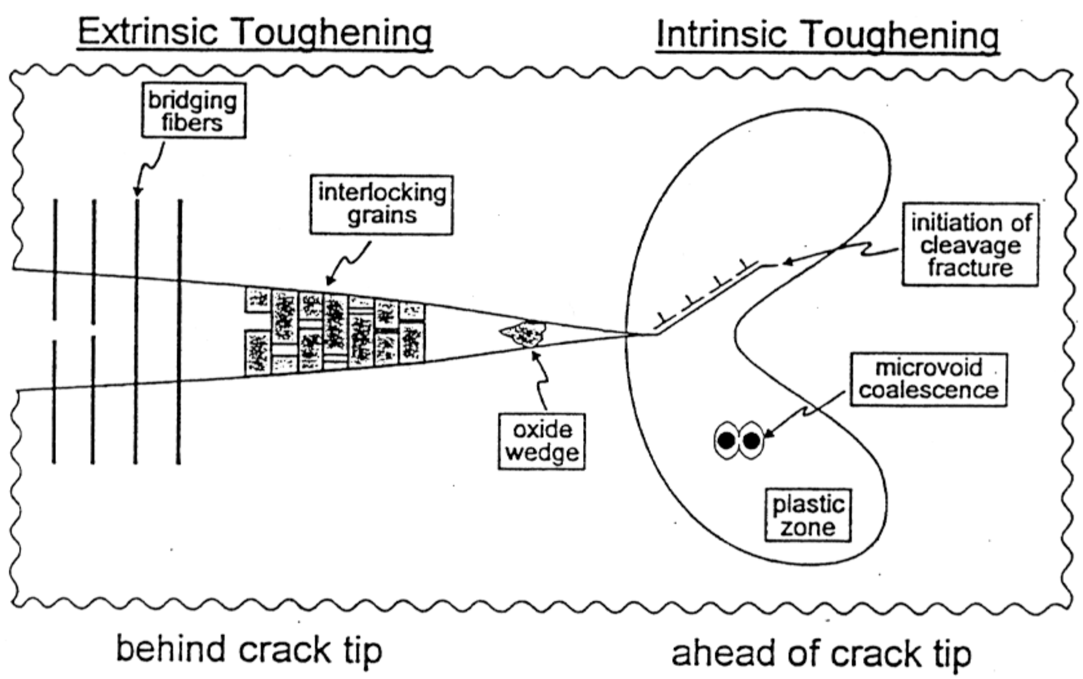
Crack closure



Crack Closure Mechanisms



Intrinsic, extrinsic crack closure

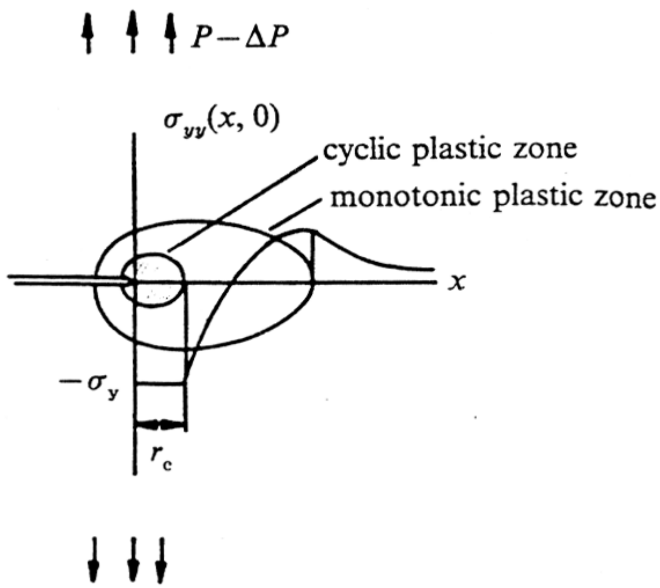


$$\frac{da}{dn} = C\ (\Delta K)^m (K_{max})^p$$

Extrinsic

Intrinsic

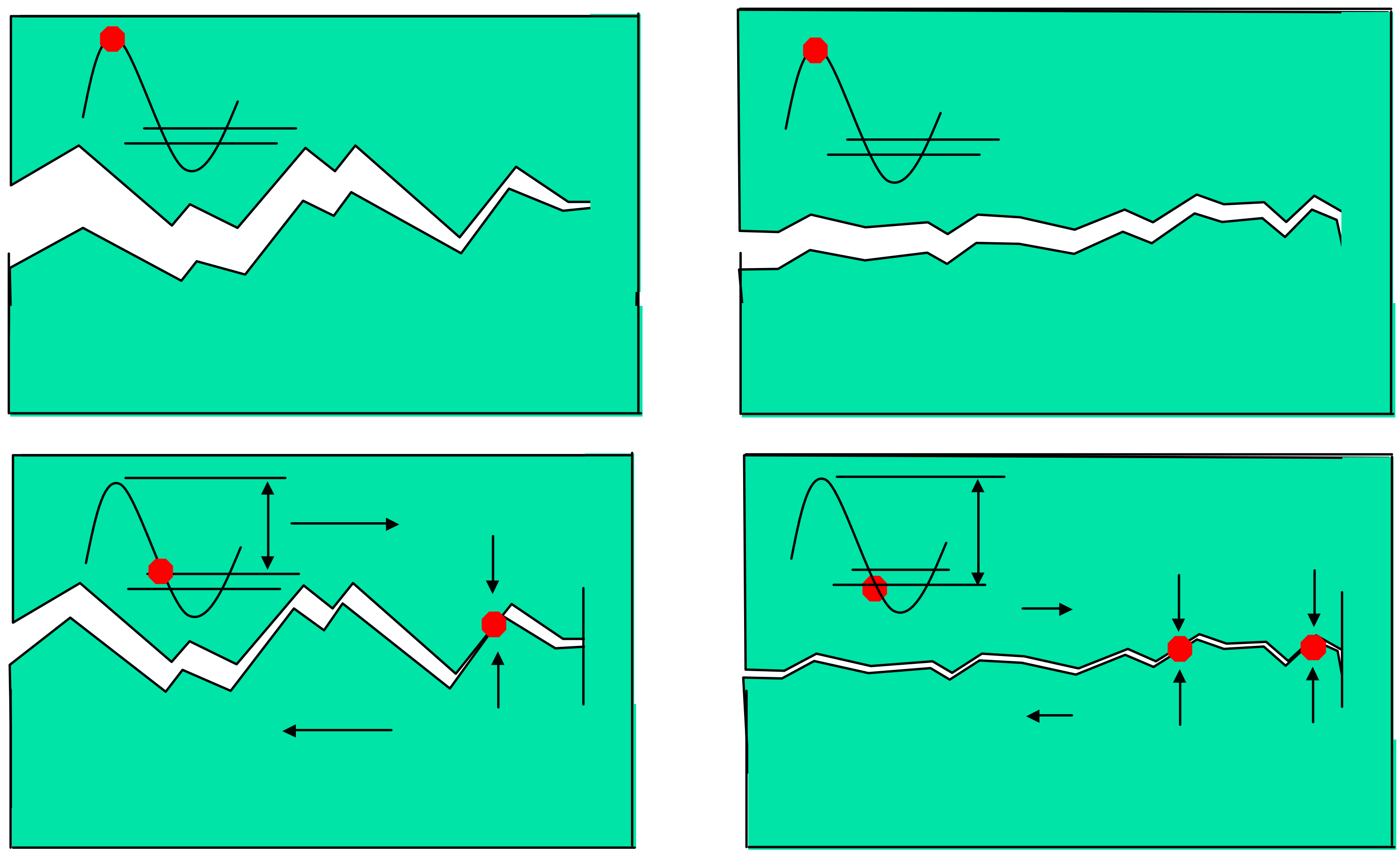
Cyclic plastic zone size



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

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.

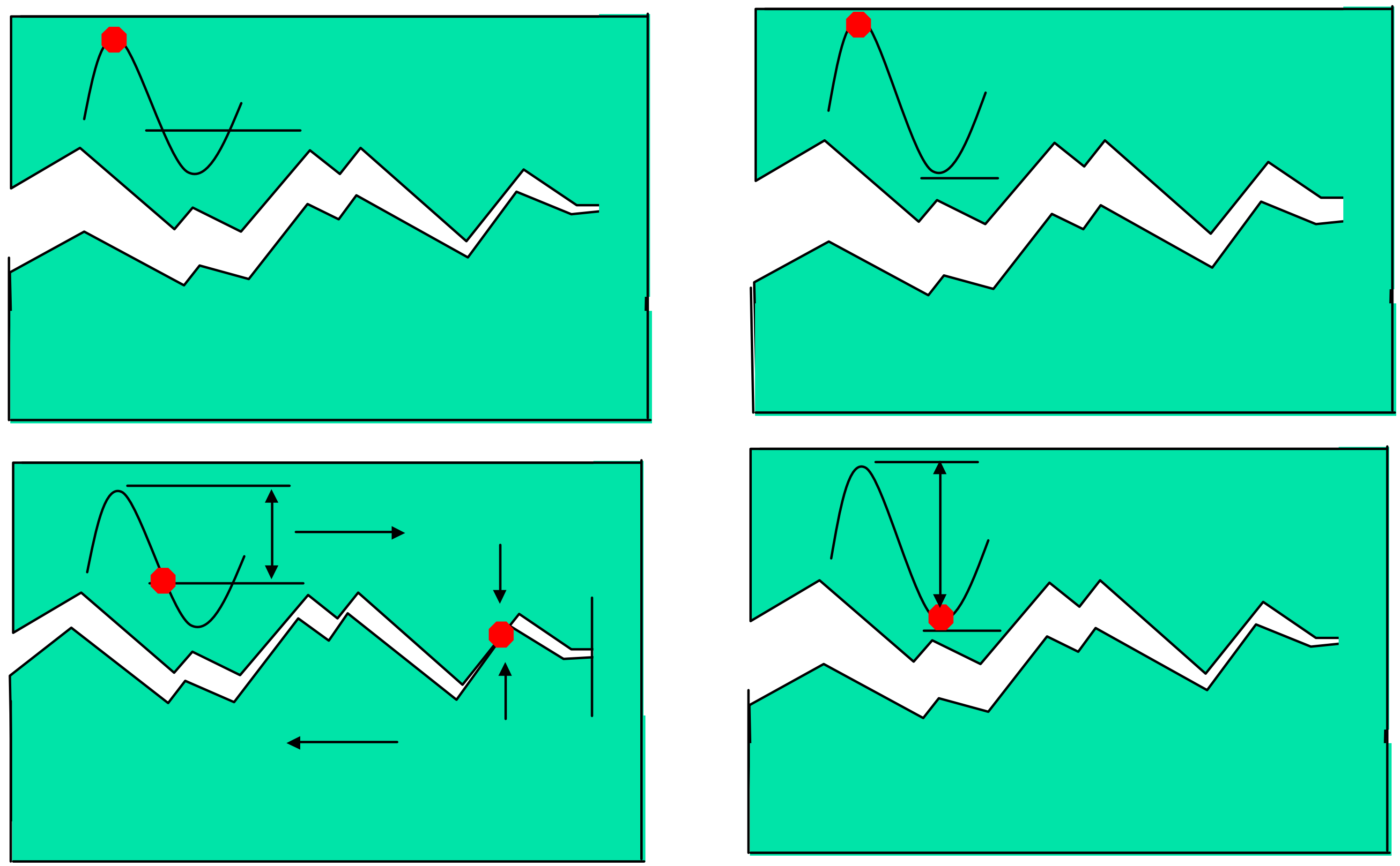
Effect of grain size



Greater Mode II displacement (slower)

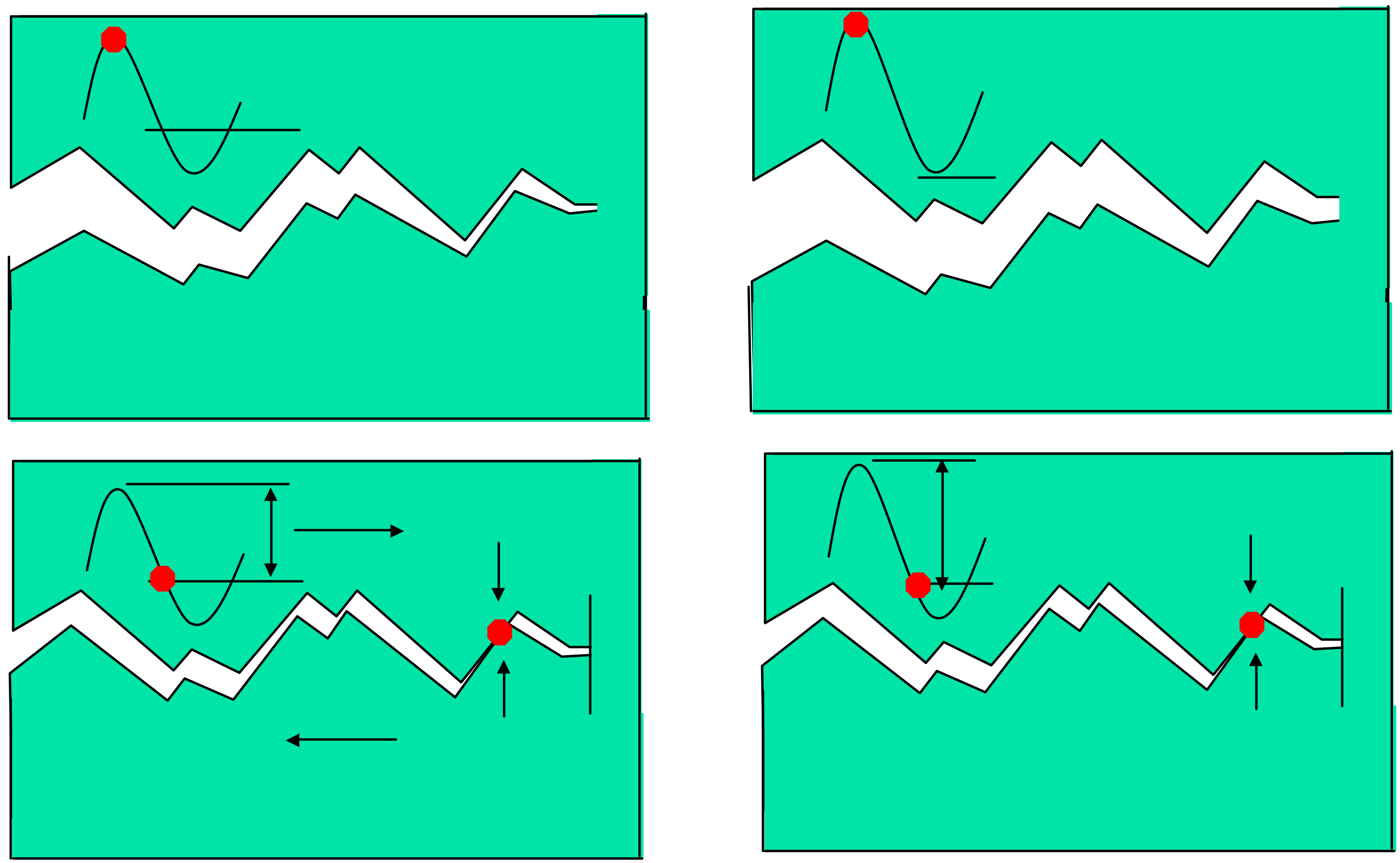
Lesser Mode II displacement (faster)

Effect mean stress



R ~ 0 (slower) R ~ 0.5 (faster)

Effect stress range

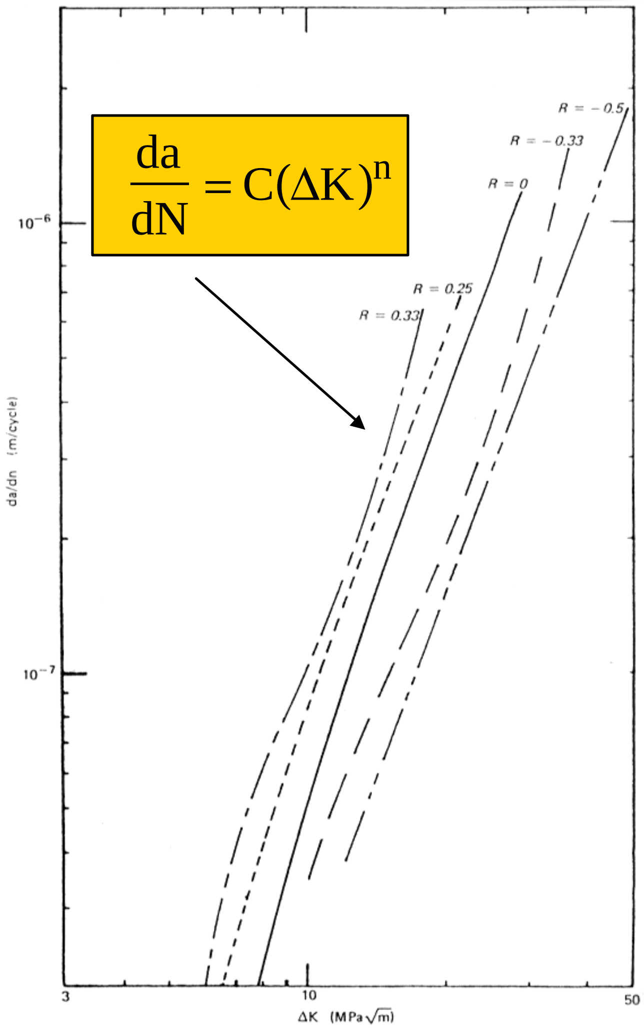


Near threshhold: closure important   High stress range: closure less important

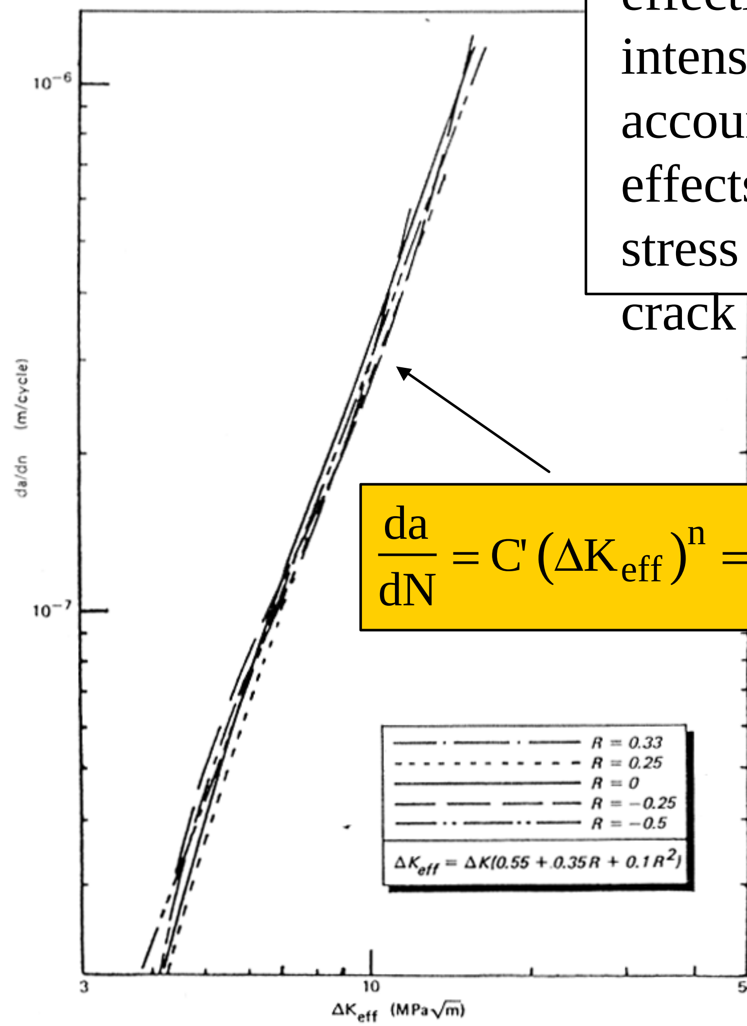
?$K_{effective}$

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

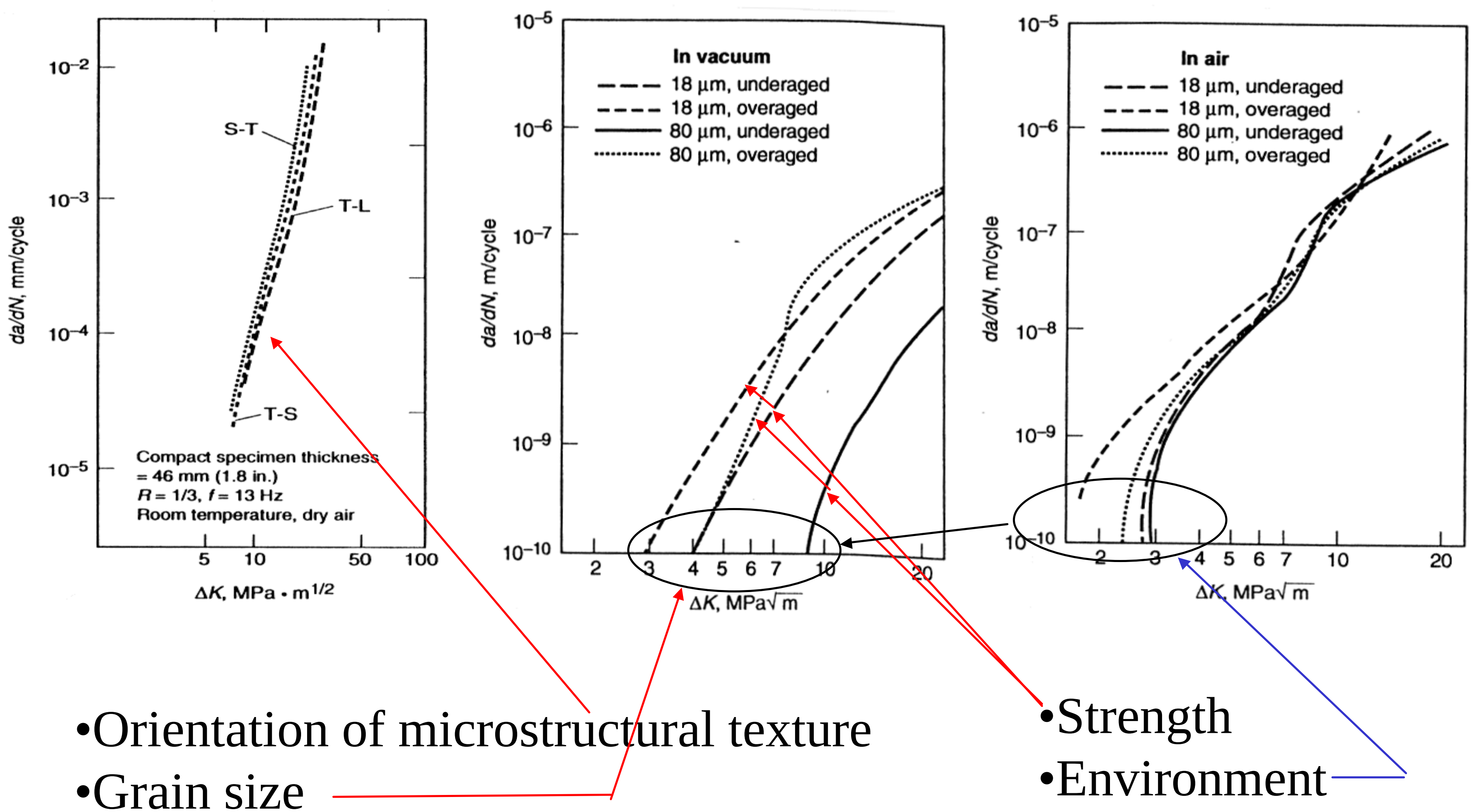
$$\frac{da}{dN} = C(\Delta K)^n$$



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

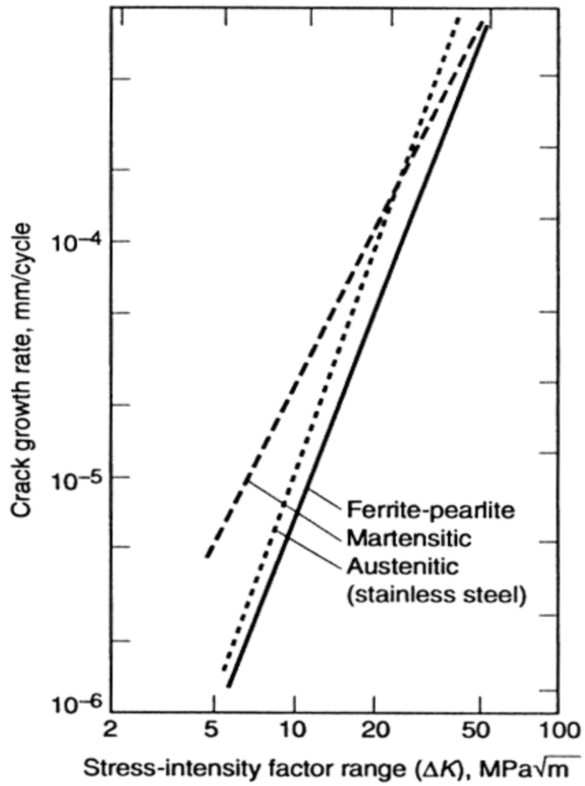


Aluminum - crack growth

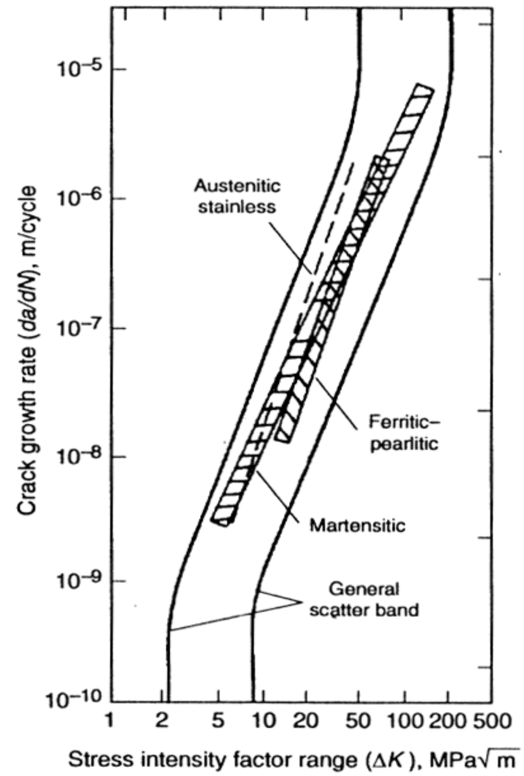


- Orientation of microstructural texture
- Grain size
- Strength
- Environment

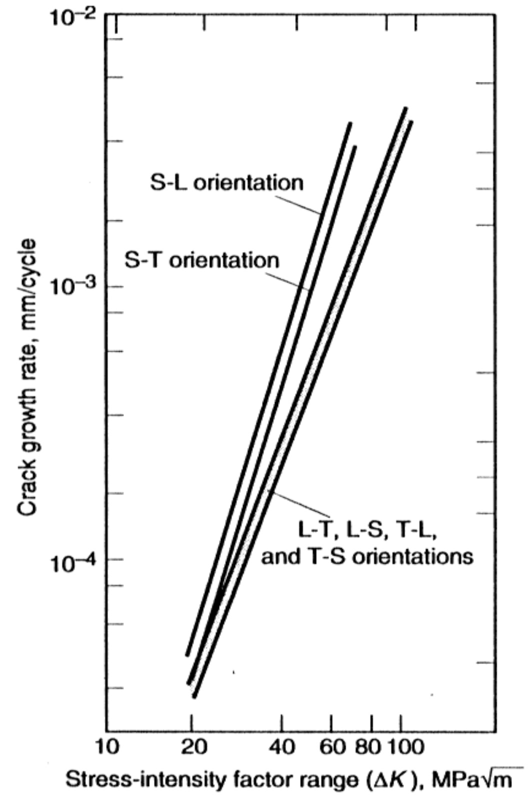
Steel - crack growth



upper bound



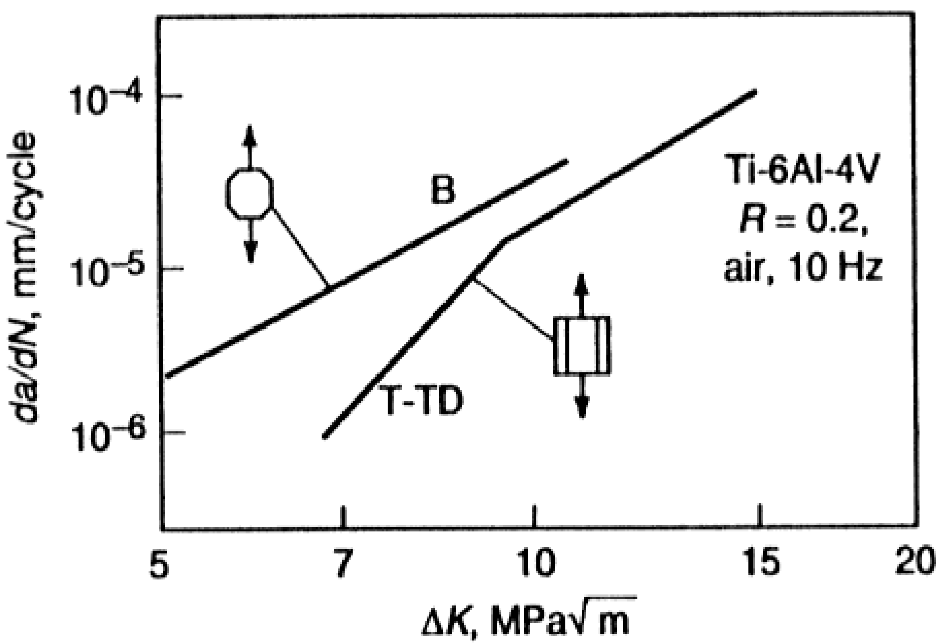
scatter bands

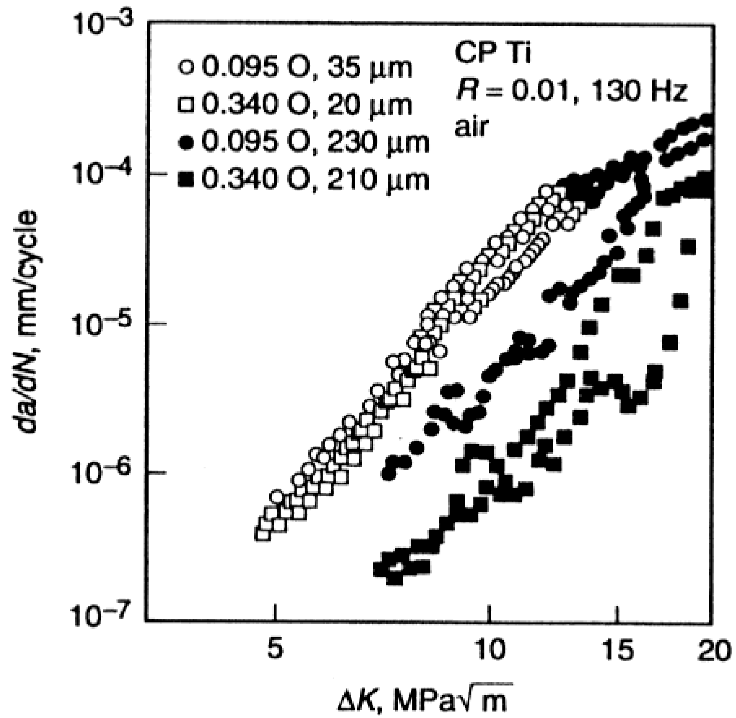


orientation

Crack growth behavior of FP-steels does not vary much

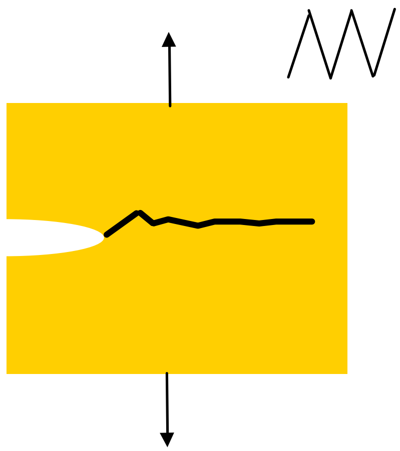
Titanium - crack growth





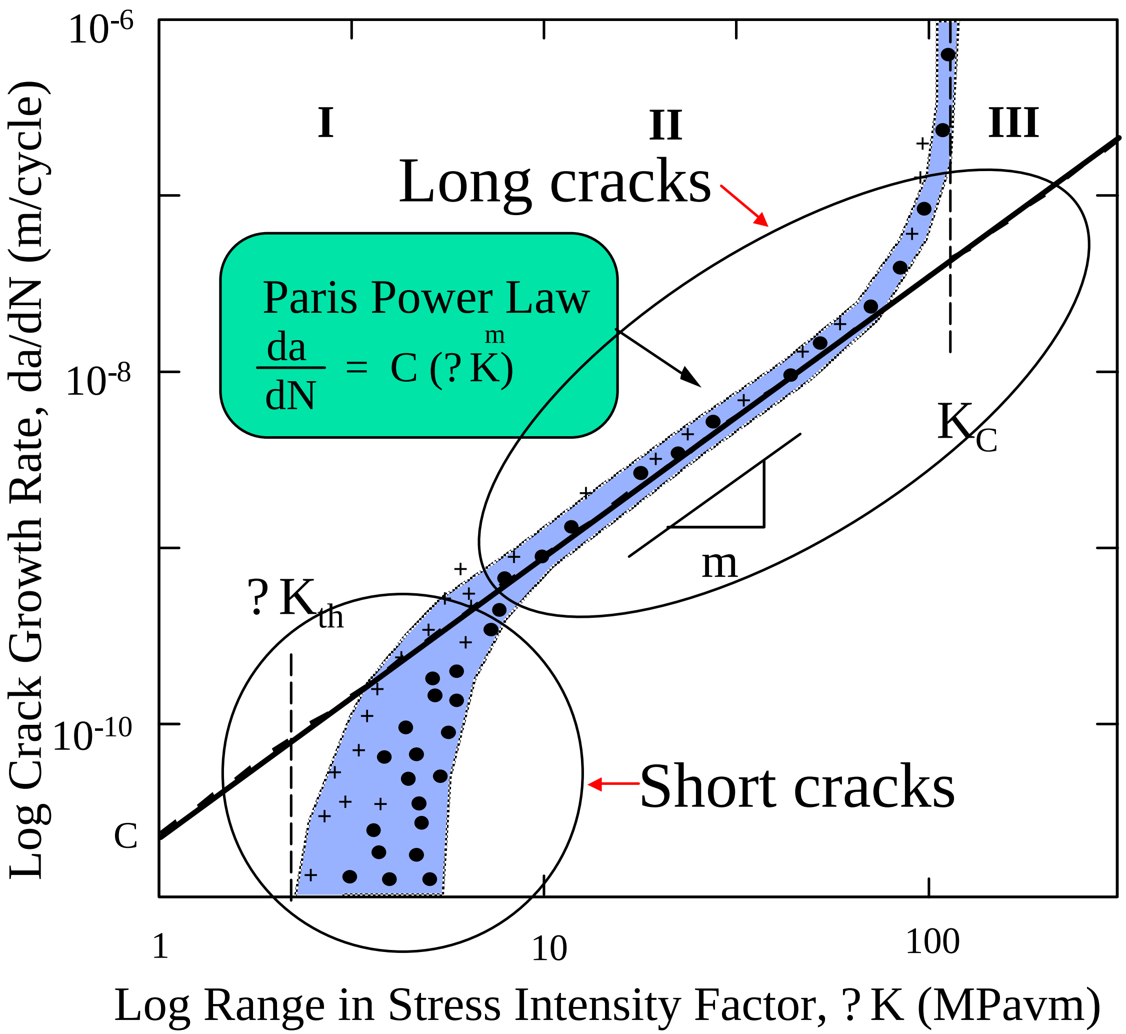
Orientation can make a large difference with Ti. As with steel and Al, grain size (also O_2 content) make a large difference. Large GS = good!

5.3 Finite Life



- Smooth specimens
- Short cracks
- **Long cracks**

Behavior of long cracks

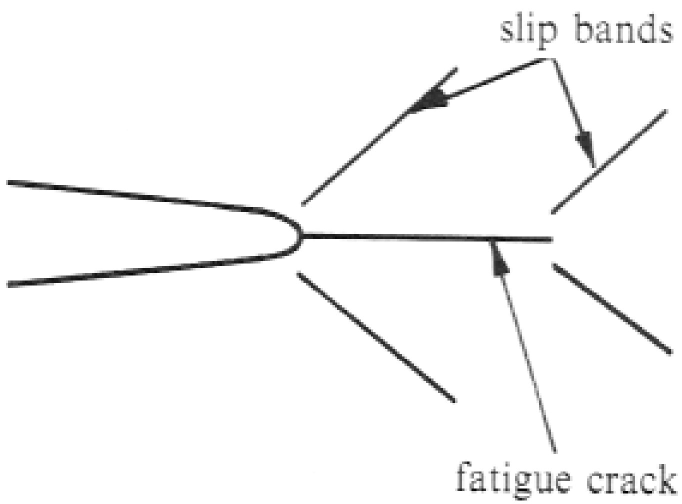


I Sensitive to microstructure and environment

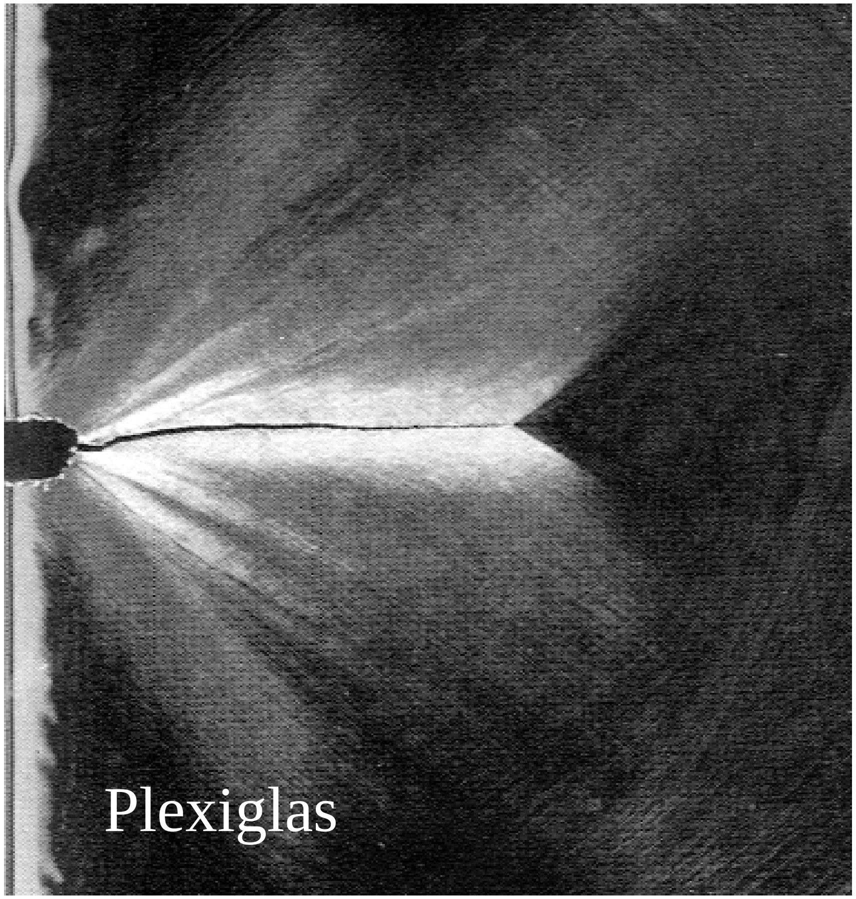
II Paris power Law

III Approaching fracture when K_{max} ~ K_{IC}.

Stage II crack growth

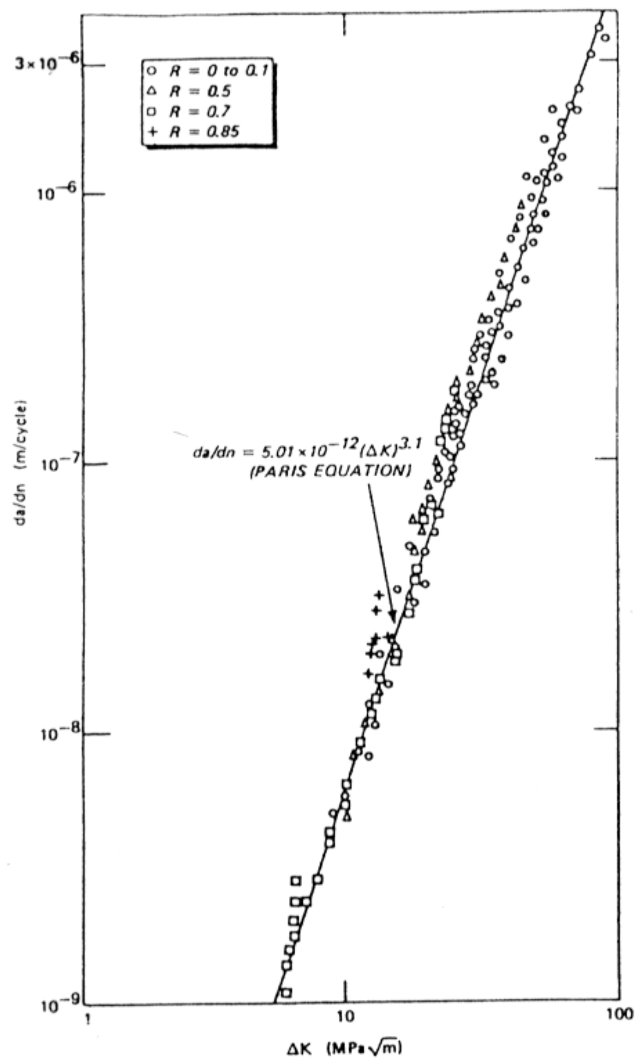


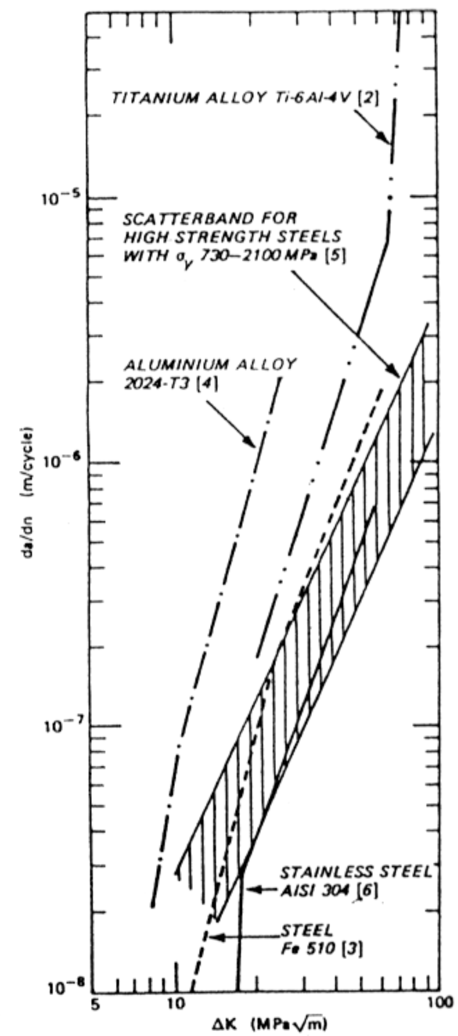
Stage II
crack growth
($r_c >> d$)



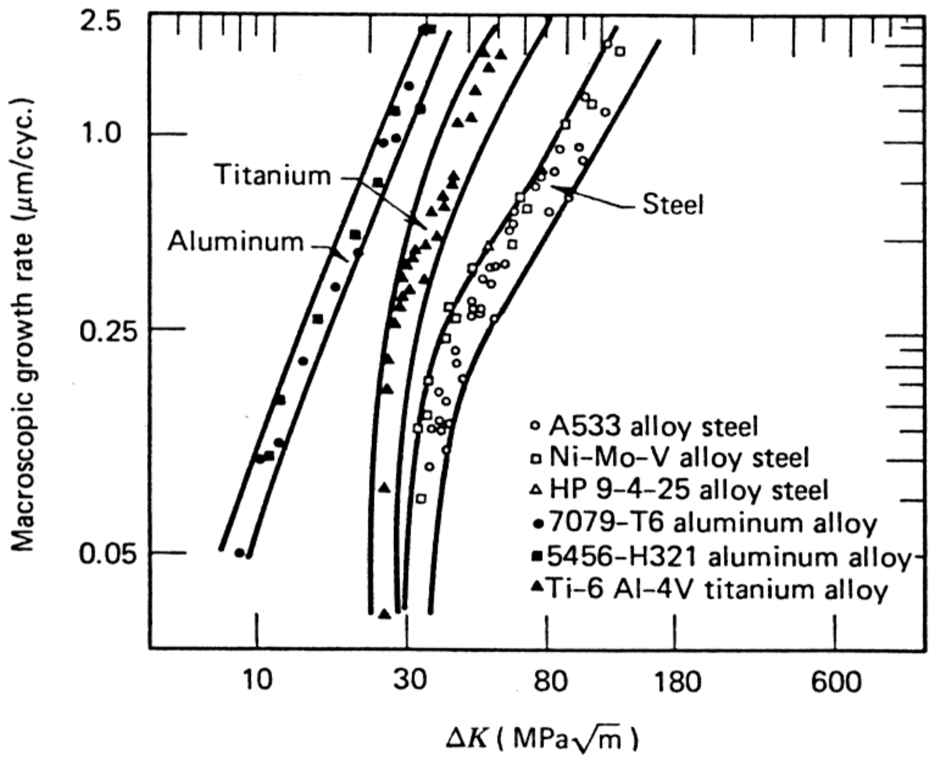
Behavior of structural metals

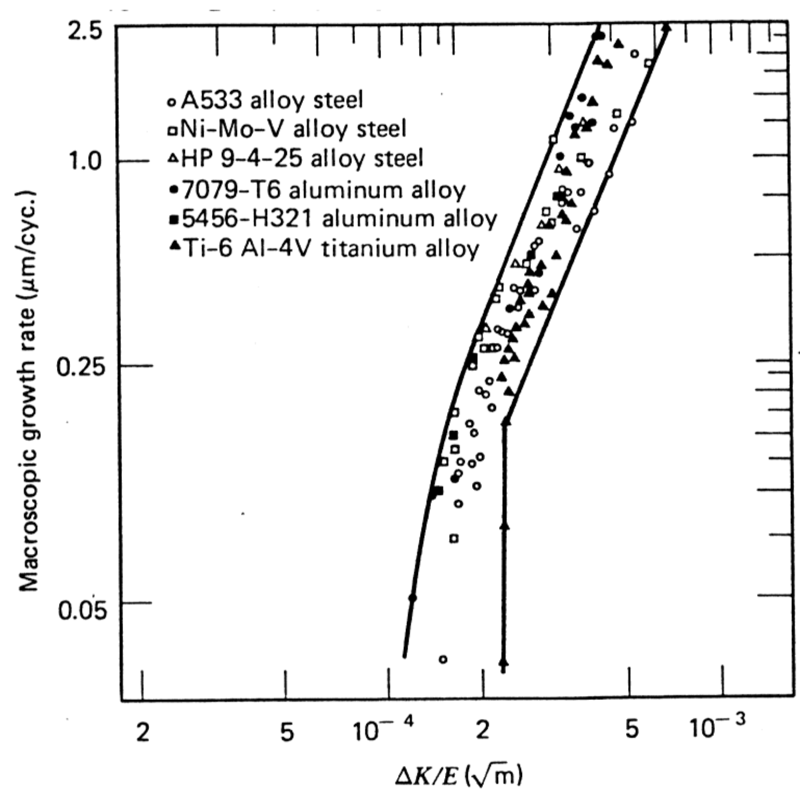
Ferritic-Pearlitic steels all have about the same crack growth rates





Crack Growth Rates of Metals





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