Physics of Fatigue

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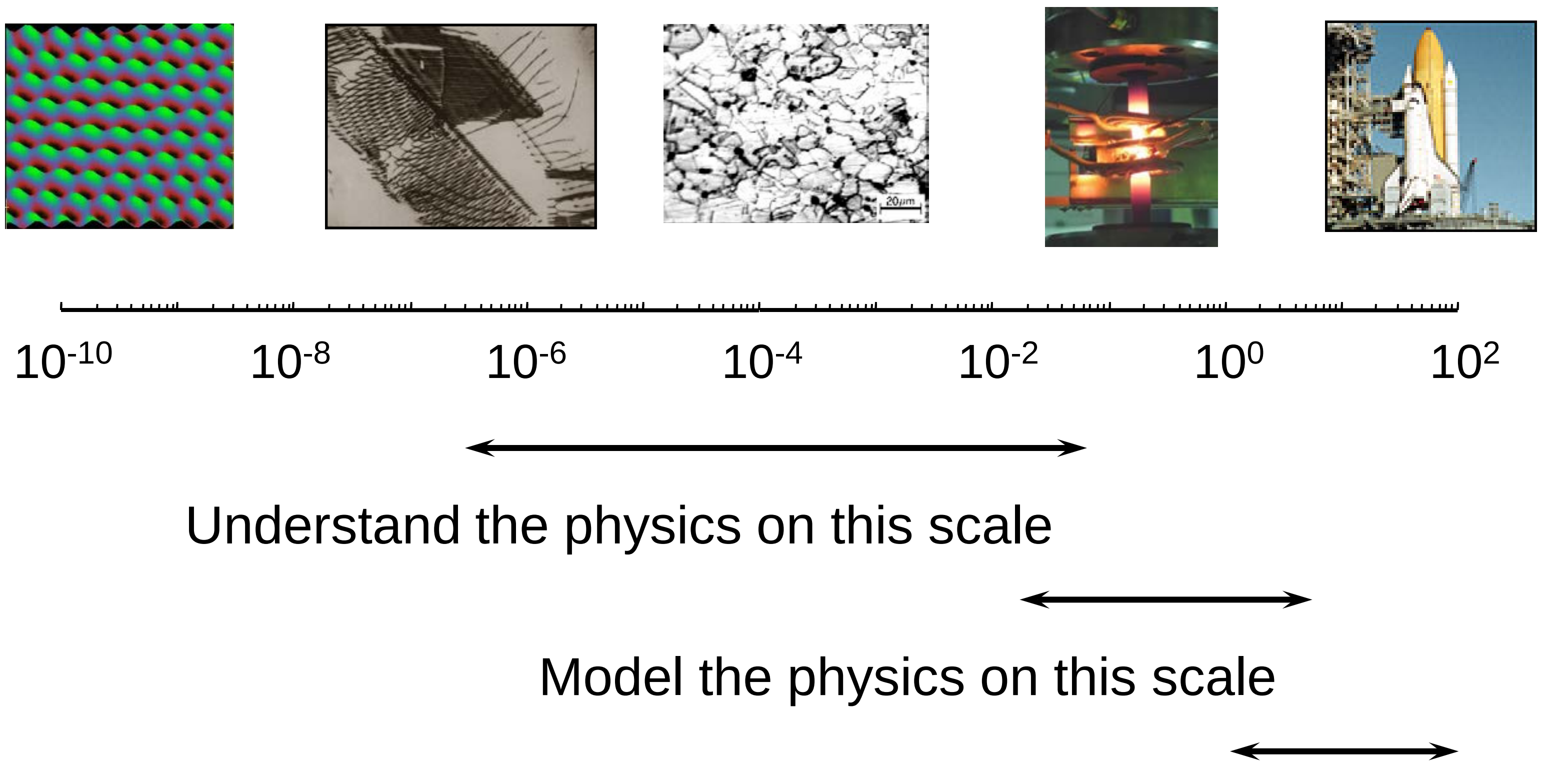
Fatigue, How and Why

- **Physics of Fatigue**
- Material Properties
- Introduction to eFatigue

Size Scale for Studying Fatigue



Atoms Dislocations Crystals Specimens Structures

10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 10^{0} 10^{2}

Understand the physics on this scale

Model the physics on this scale

Use the models on this scale

The Fatigue Process

- Crack nucleation
- Small crack growth in an elastic-plastic stress field
- Macroscopic crack growth in a nominally elastic stress field
- Final fracture

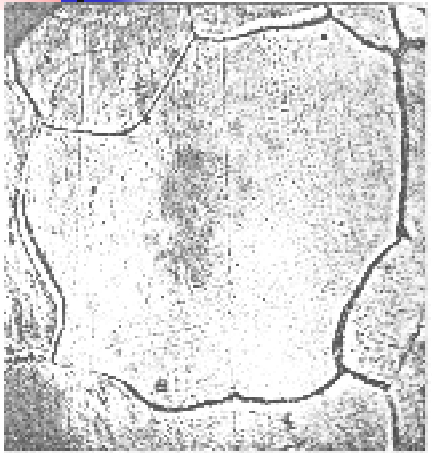
Mechanisms Crack Nucleation

Nucleation in Slip Bands inside Grain

Nucleation at Grain Boundaries

Nucleation at Inclusions

1903 - Ewing and Humfrey

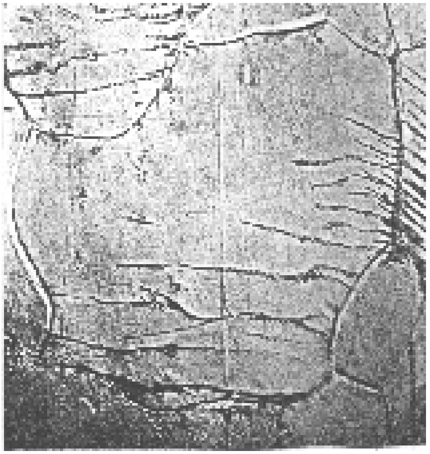


N = 1,000

N = 2,000

Cyclic deformation leads to the development of slip bands and fatigue cracks

N = 10,000

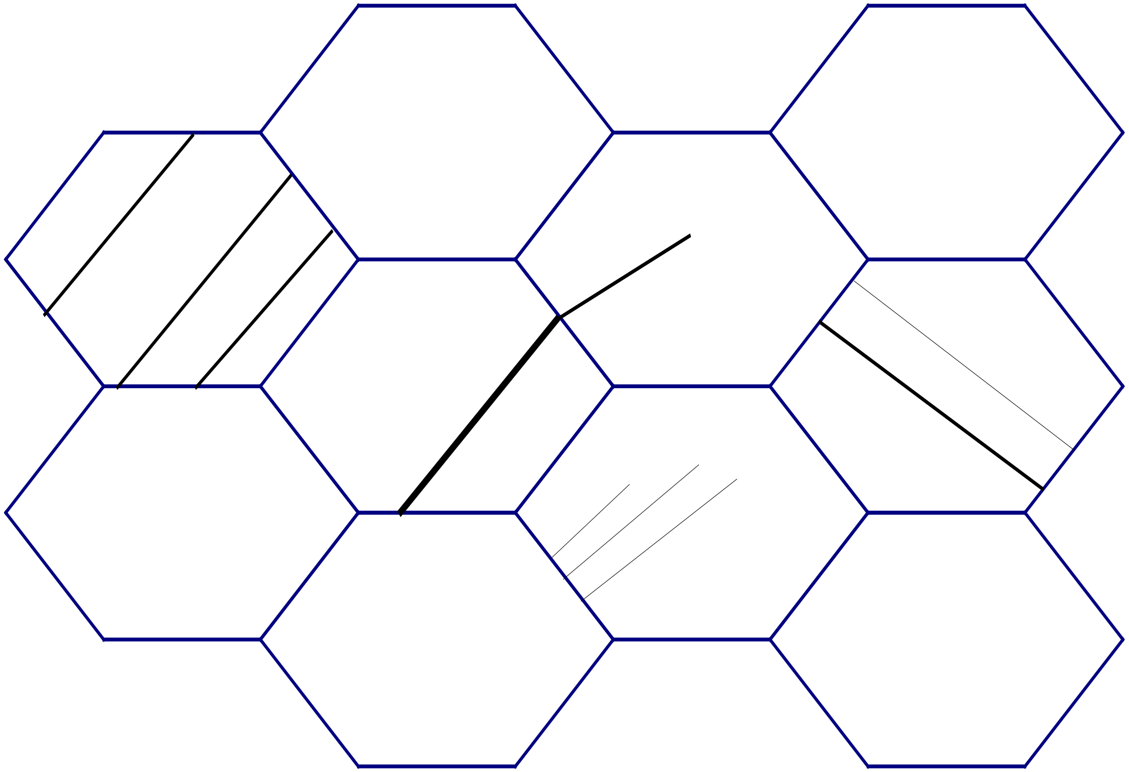


N = 40,000

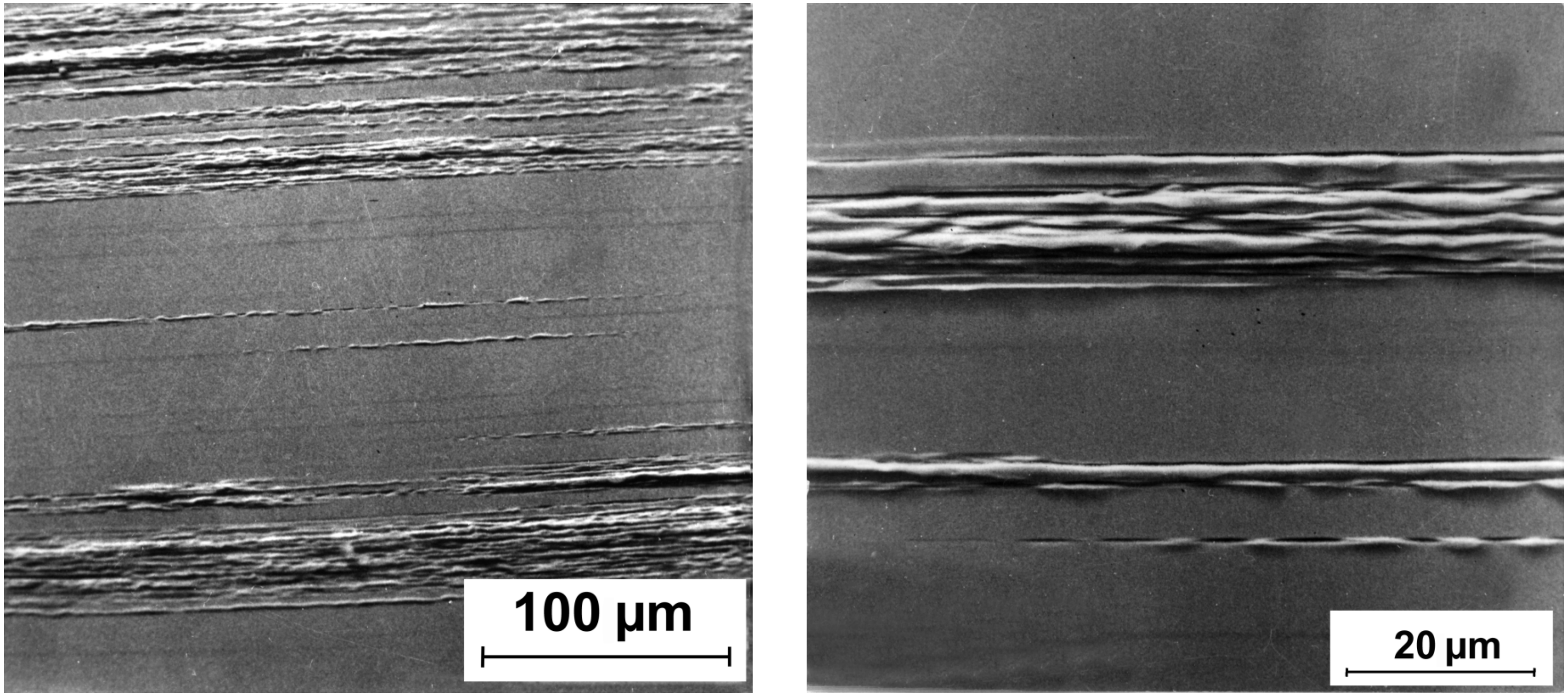
N_f = 170,000

Ewing, J.A. and Humfrey, J.C. "The fracture of metals under repeated alterations of stress", *Philosophical Transactions of the Royal Society*, Vol. A200, 1903, 241-250

Crack Nucleation

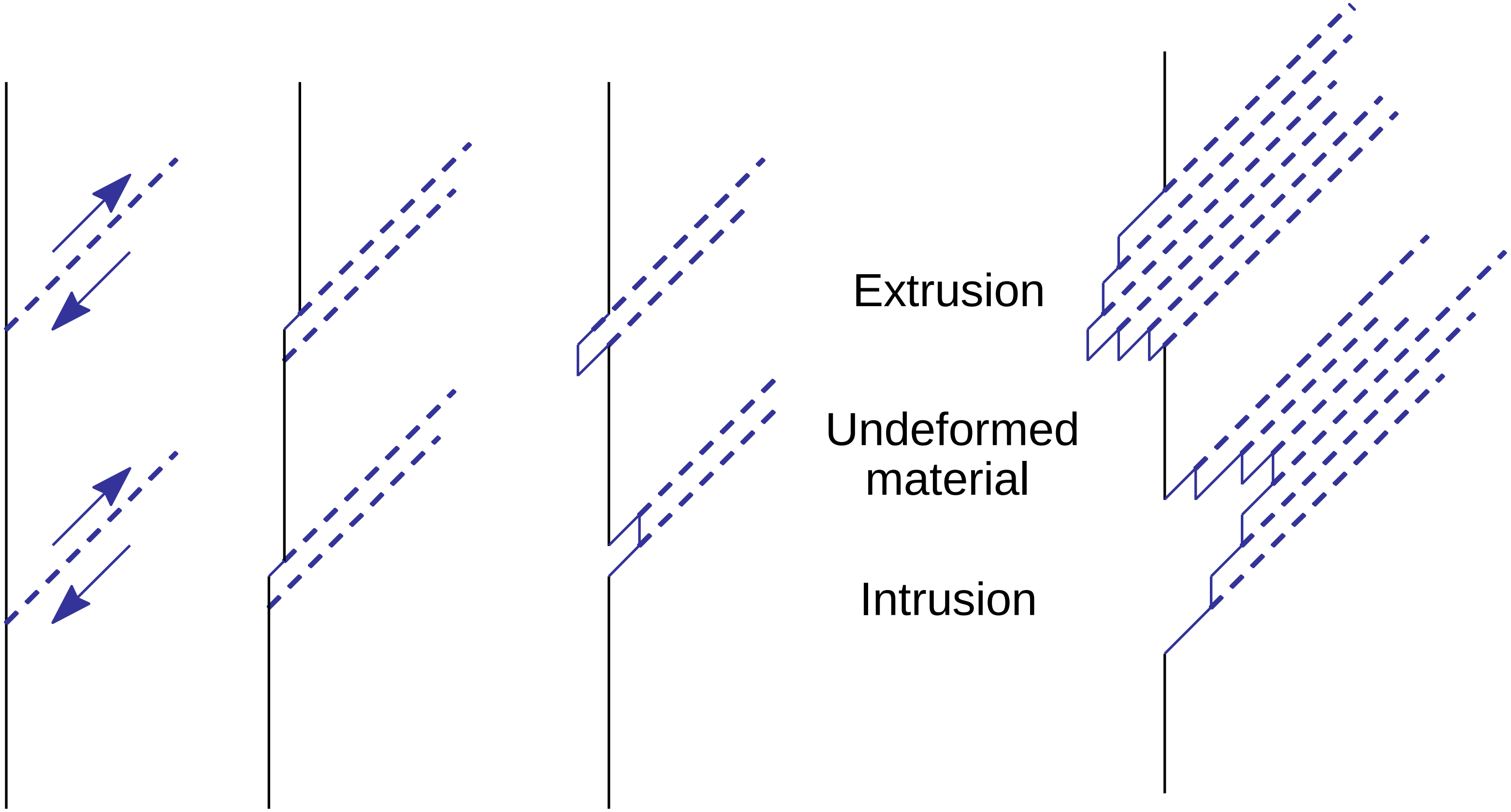


Slip Band in Copper



Polak, J. Cyclic Plasticity and Low Cycle Fatigue Life of Metals, Elsevier, 1991

Slip Band Formation



Extrusion

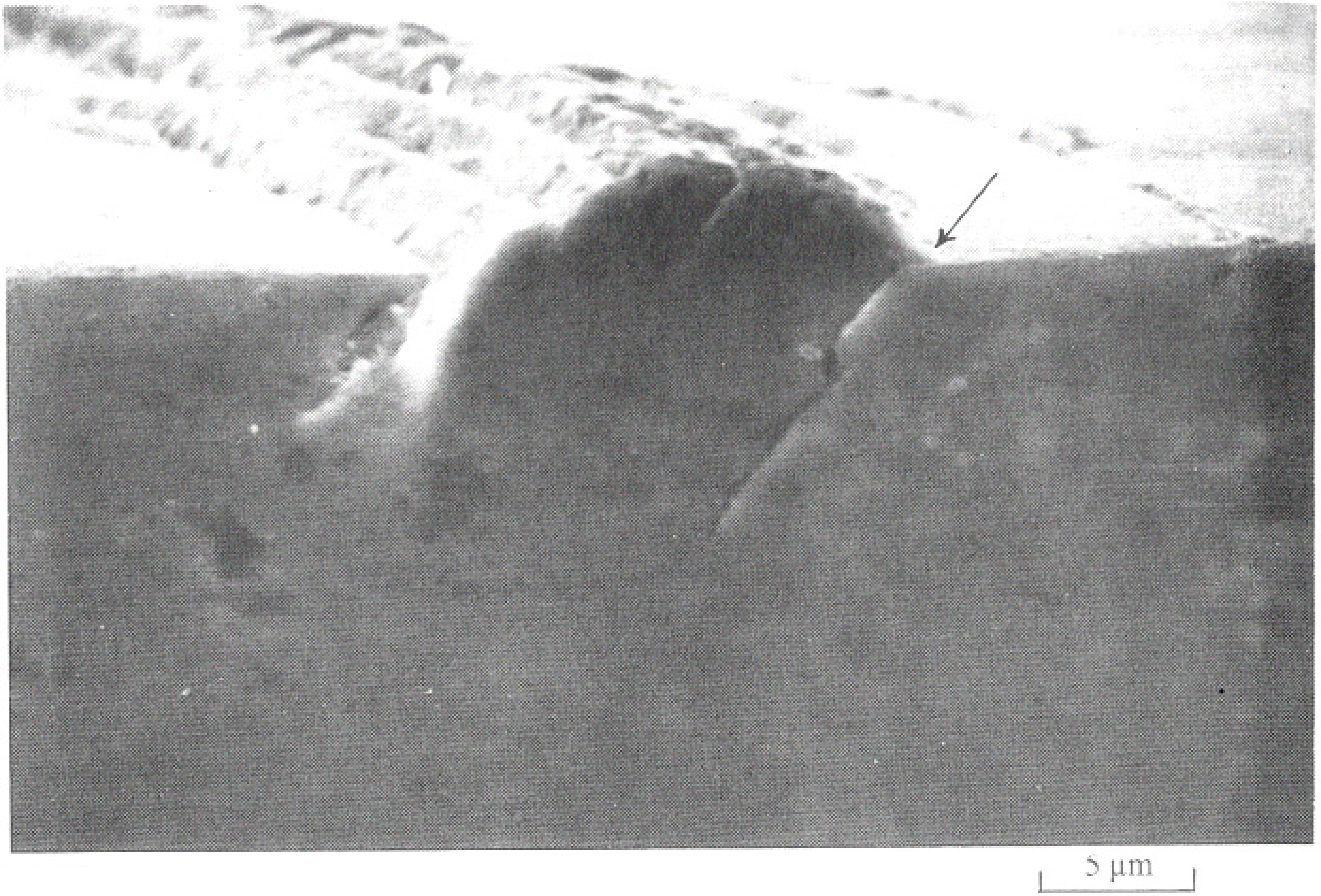
Undeformed material

Intrusion

Loading

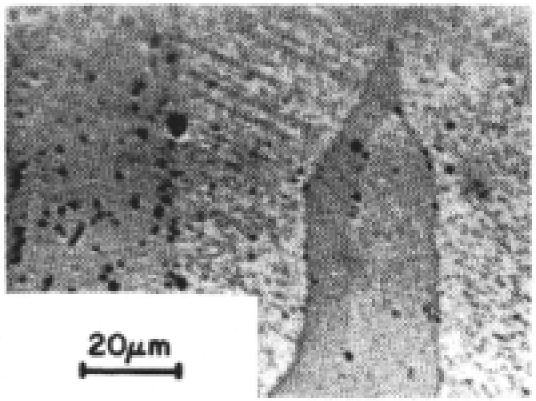
Unloading

Slip Bands

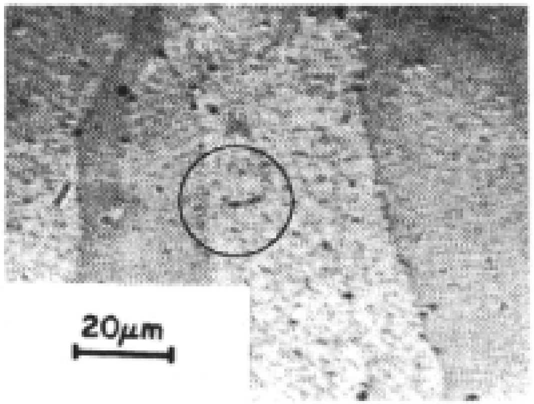


Ma, B-T and Laird C. “Overview of fatigue behavior in copper sinle crystals –II Population, size, distribution and growth Kinetics of stage I cracks for tests at constant strain amplitude”, Acta Metallurgica, Vol 37, 1989, 337-348

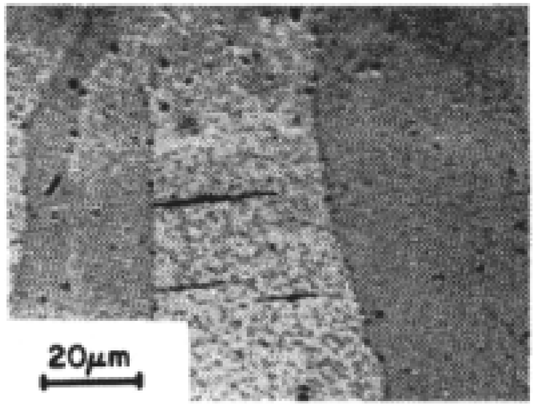
2124-T4 Cracking in Slip Bands



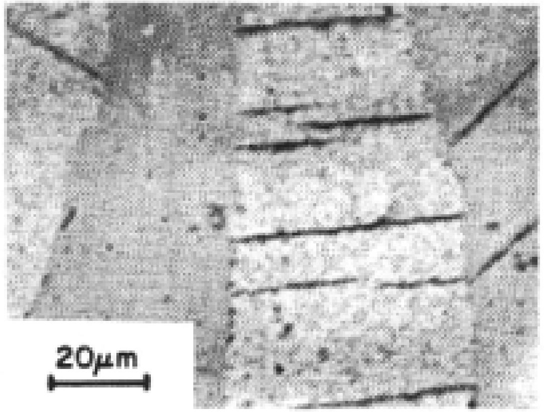
N = 60 (a)



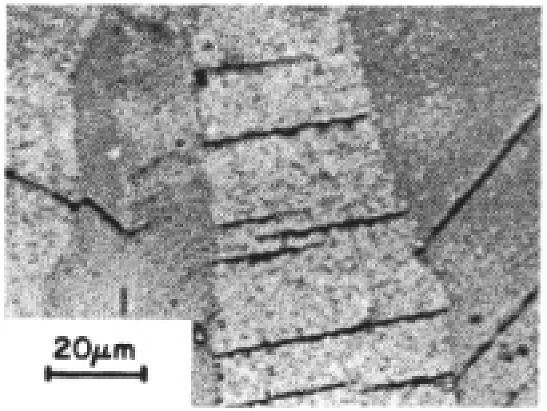
N = 240 (b)



N = 300 (c)



N = 1200 (d)

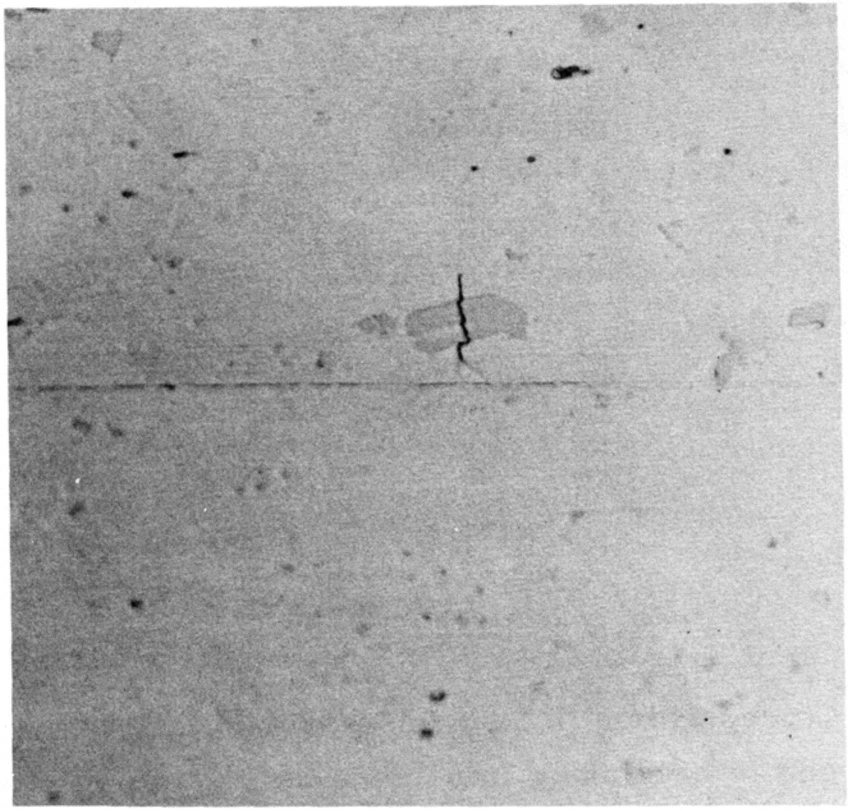


N = 2000 (e)

Crack at Particle

Material: BS L65 Aluminum

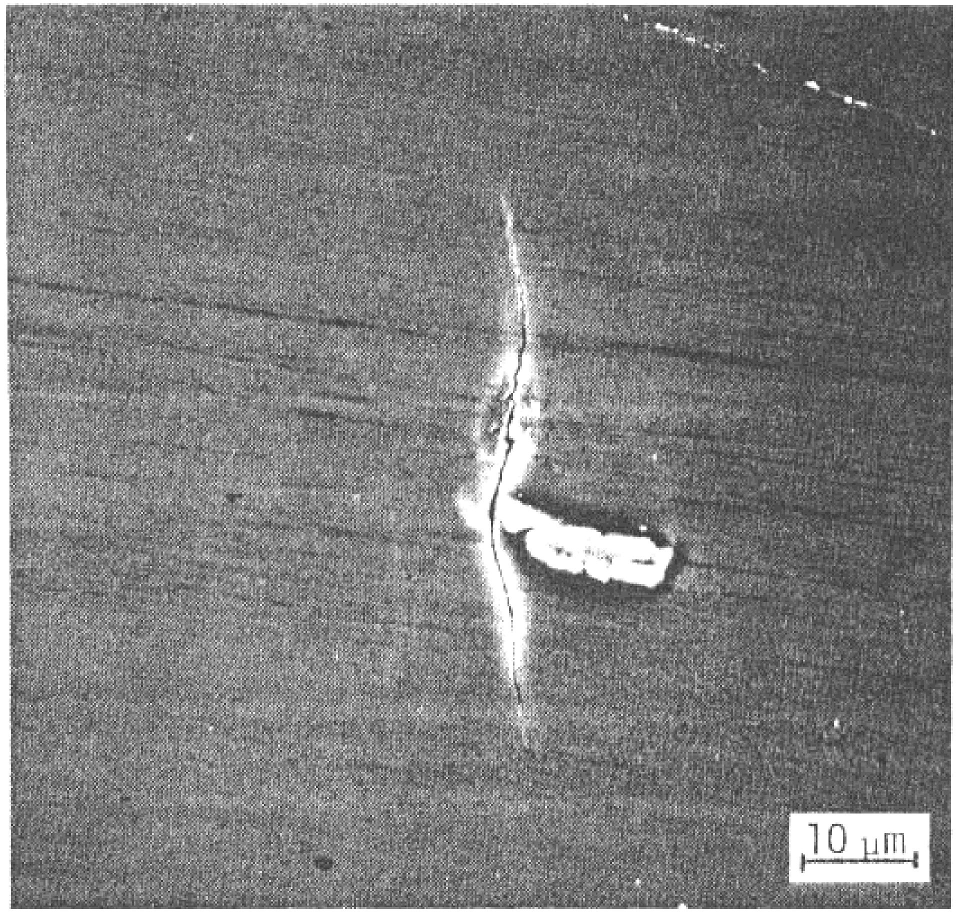
Loading: 63 ksi, R=0 for 500,000+ cycles, followed by 68 ksi, R=0 to failure. Cracks found during 68 ksi loading.



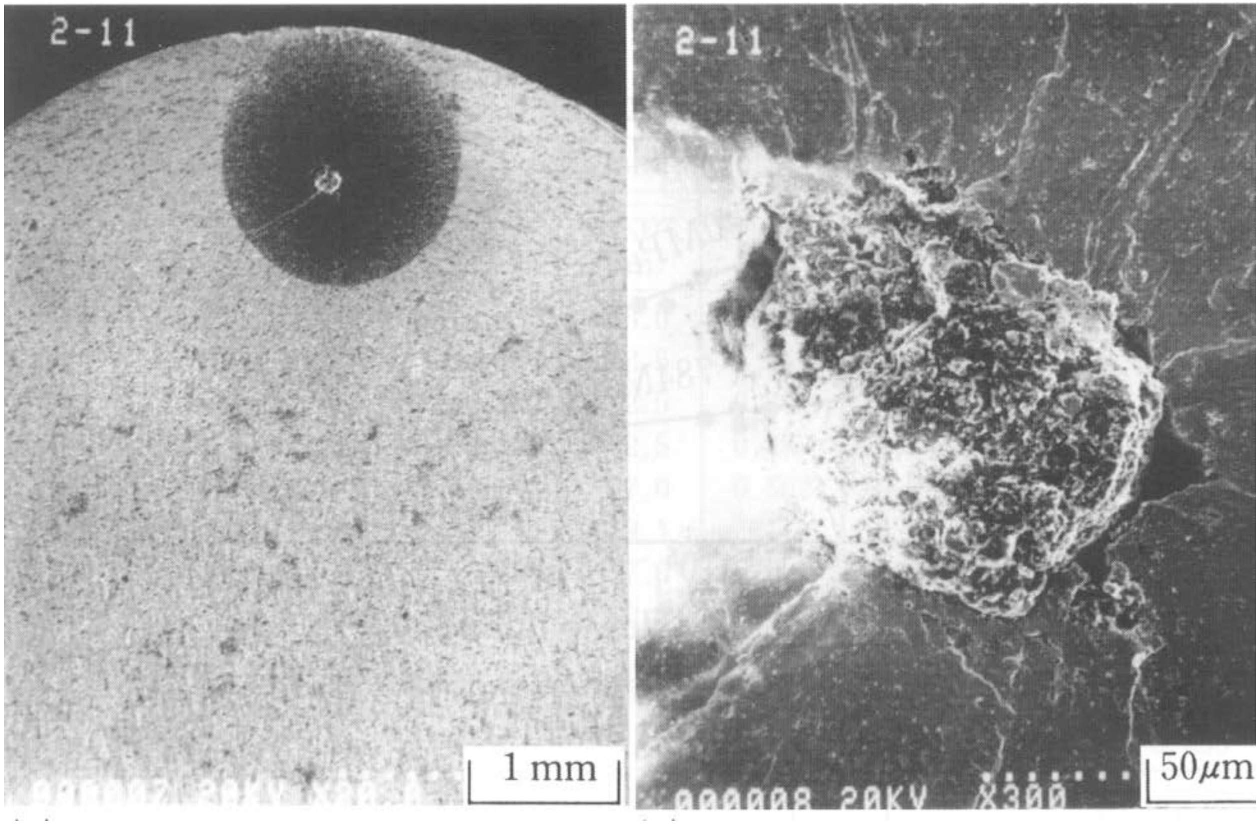
X 1000

S. Pearson, "Initiation of Fatigue Cracks in Commercial Aluminum Alloys and the Subsequent Propagation of Very Short Cracks," RAE TR 72236, Dec 1972.

7075-T6 Cracking at Inclusion

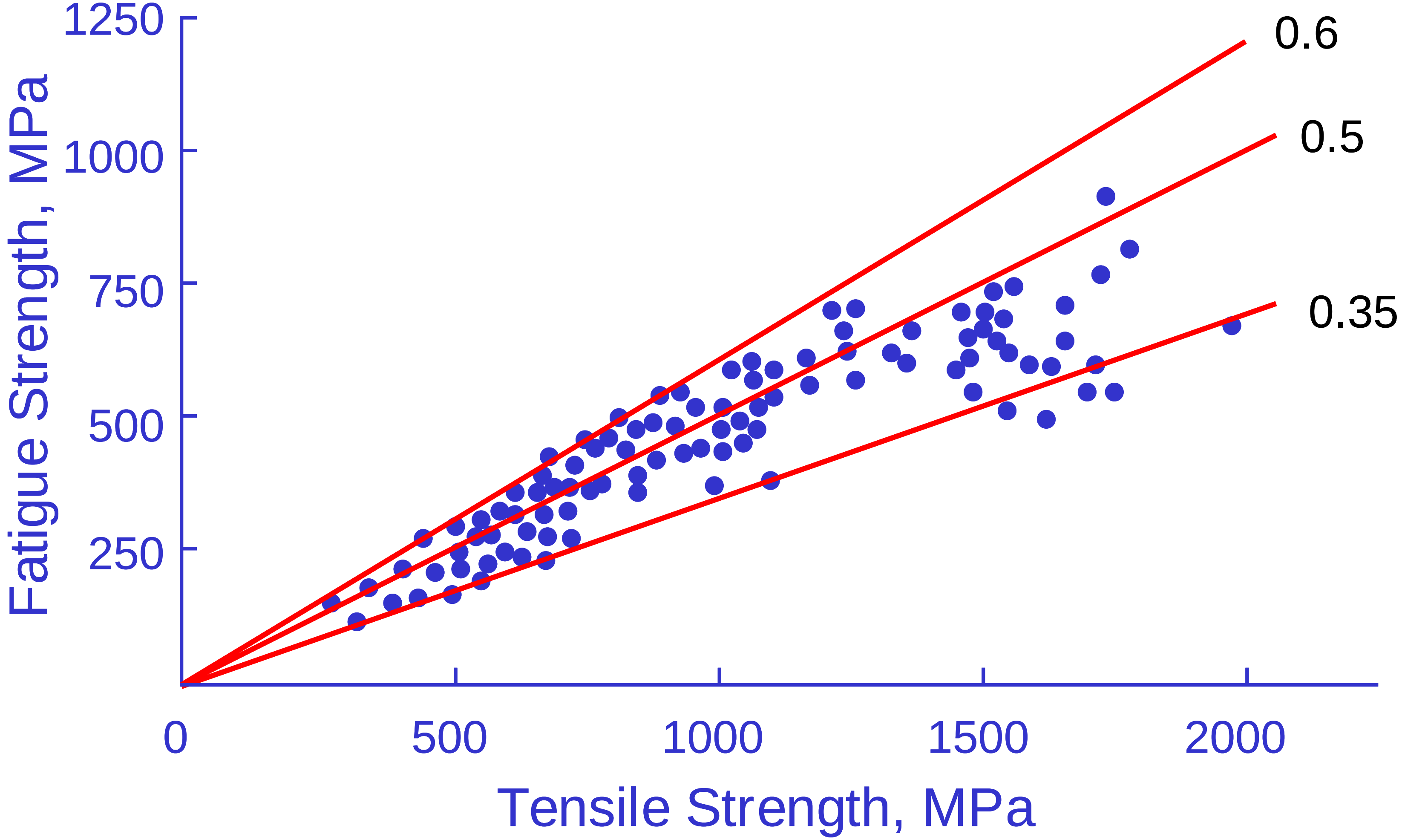


Subsurface Crack Initiation



Y. Murakami, Metal Fatigue: *Effects of Small Defects and Nonmetallic Inclusions*, 2002

Fatigue Limit and Strength Correlation

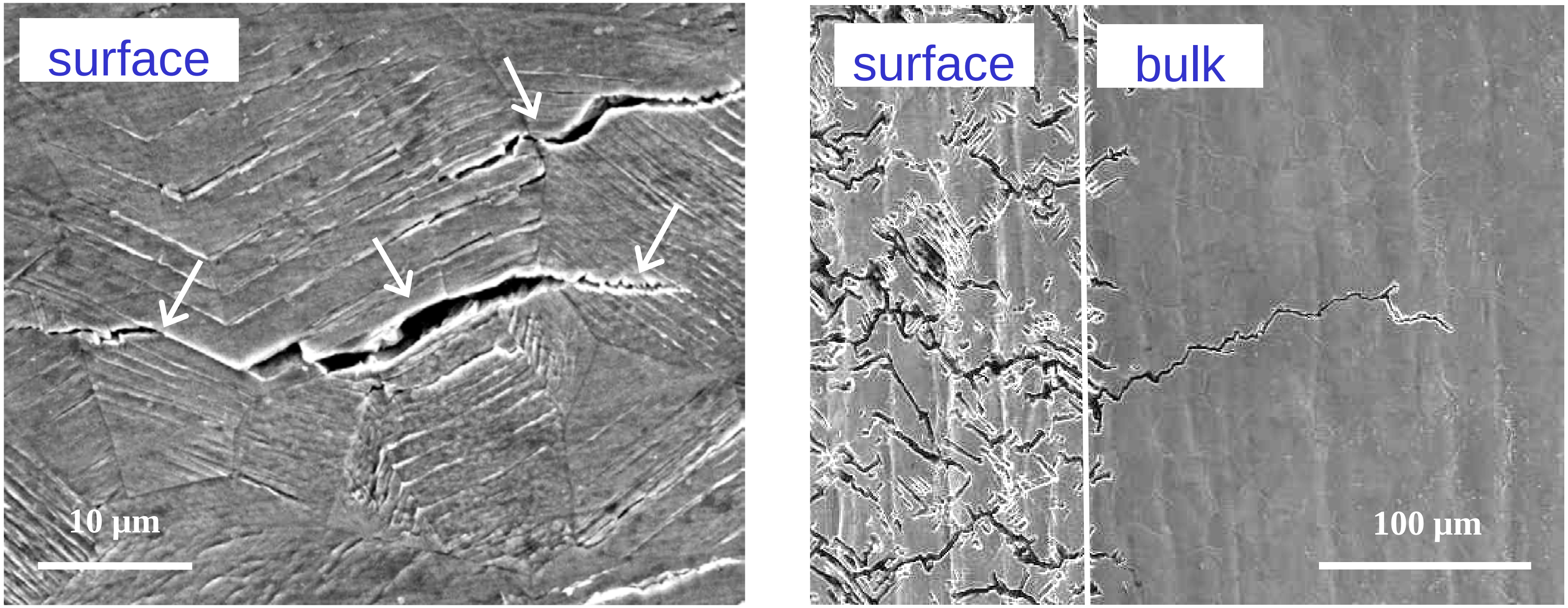


From Forrest, *Fatigue of Metals*, Pergamon Press, London, 1962

Crack Nucleation Summary

- Highly localized plastic deformation
- Surface phenomena
- Stochastic process

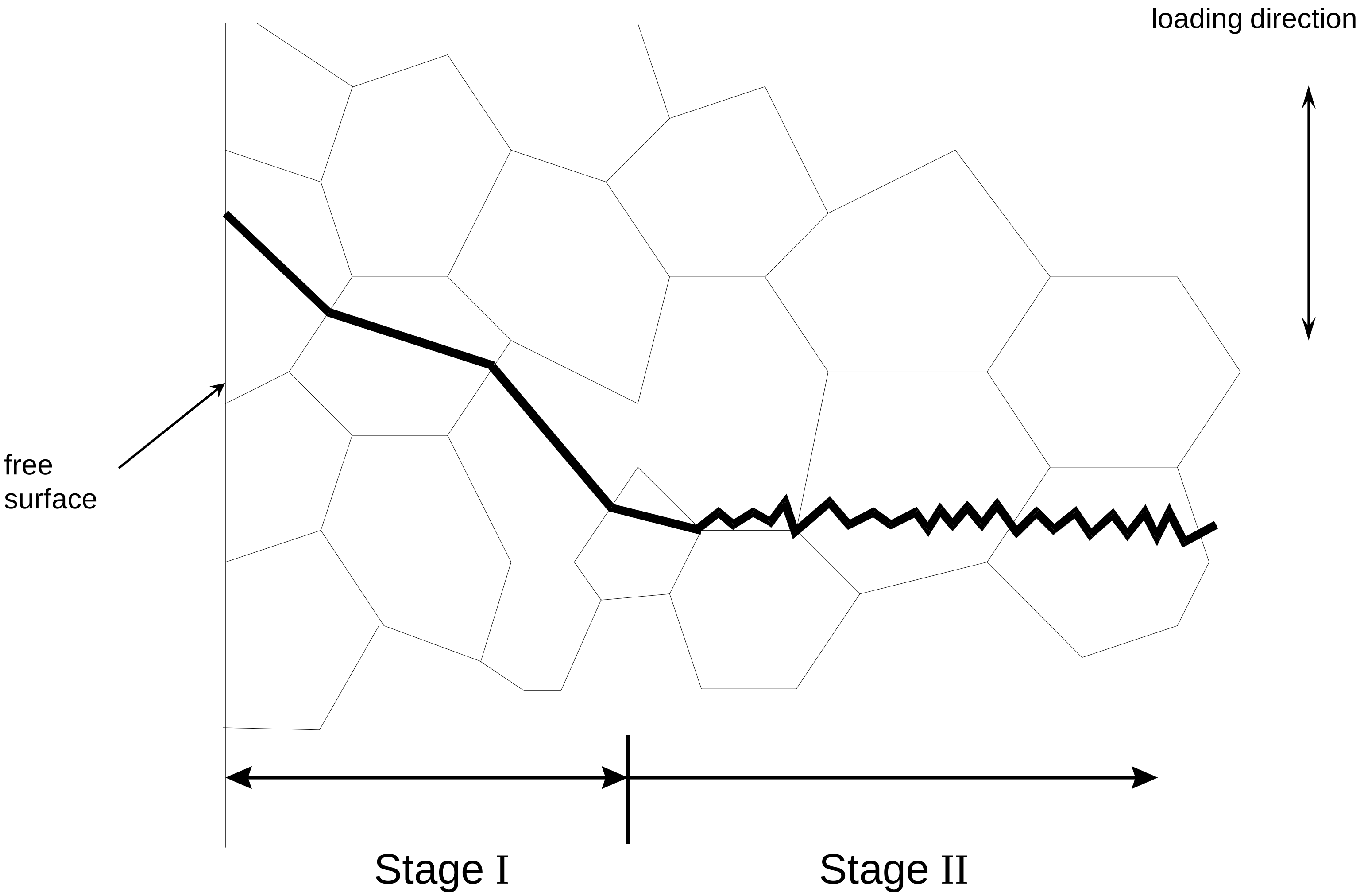
Surface Damage



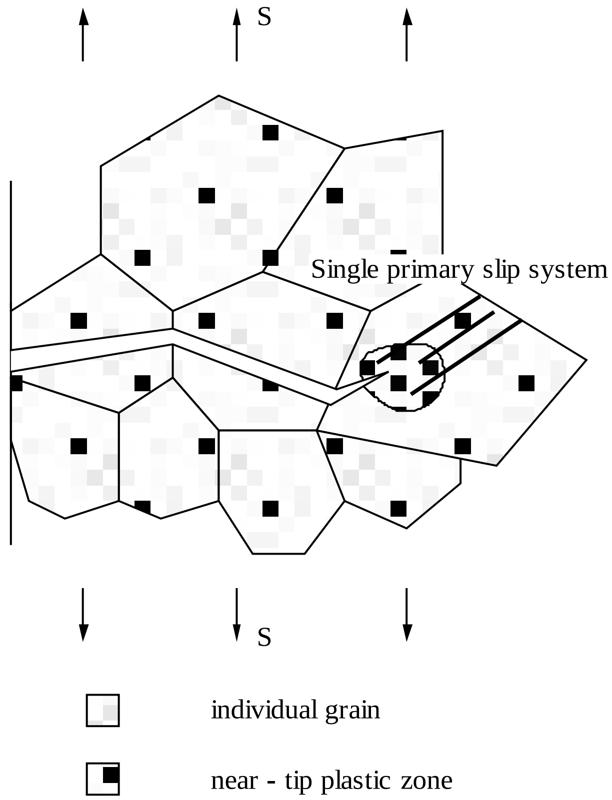
20-25 austenitic steel in symmetrical push-pull fatigue (20°C, $\Delta\varepsilon_p/2= \pm 0.4\%$) : short cracks on the surface and in the bulk

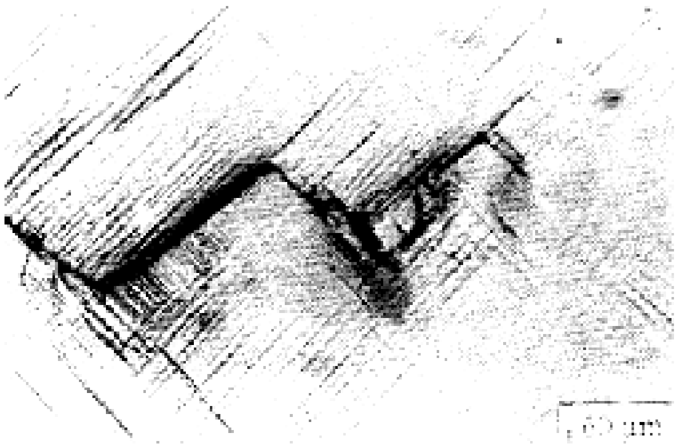
From Jacques Stolarz, Ecole Nationale Superieure des Mines
Presented at LCF 5 in Berlin, 2003

Stage I and Stage II



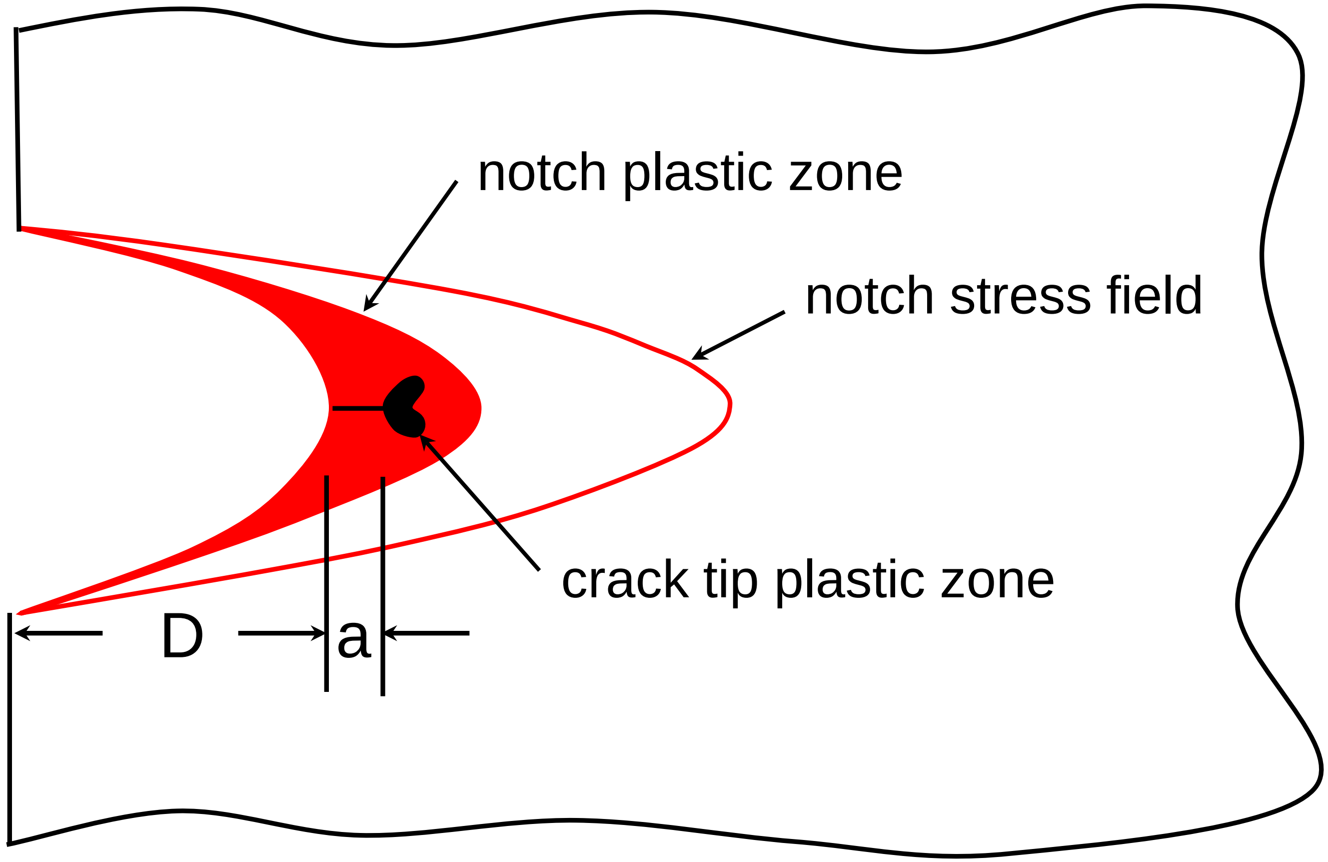
Stage I Crack Growth





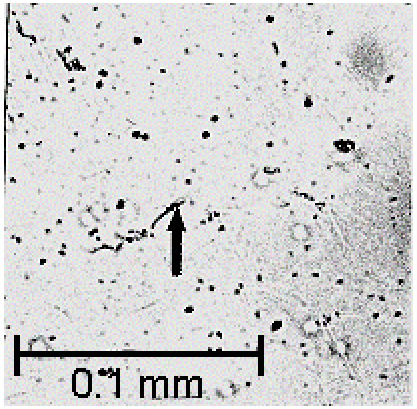
Stage I crack is strongly affected by slip characteristics, microstructure dimensions, stress level, extent of near tip plasticity

Small Cracks at Notches

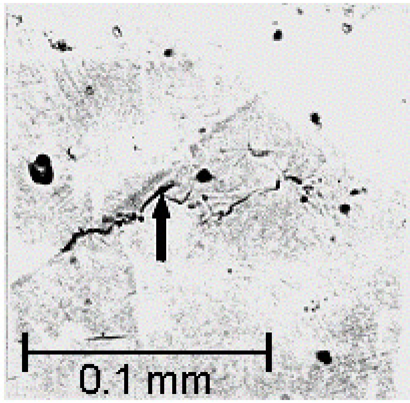


Crack growth controlled by the notch plastic strains

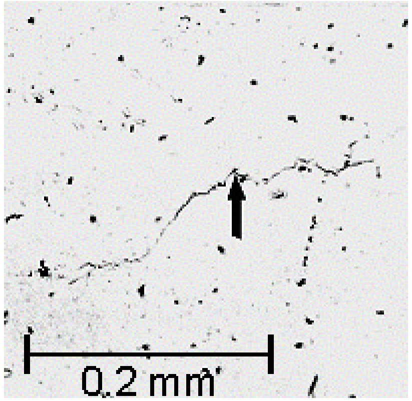
Small Crack Growth



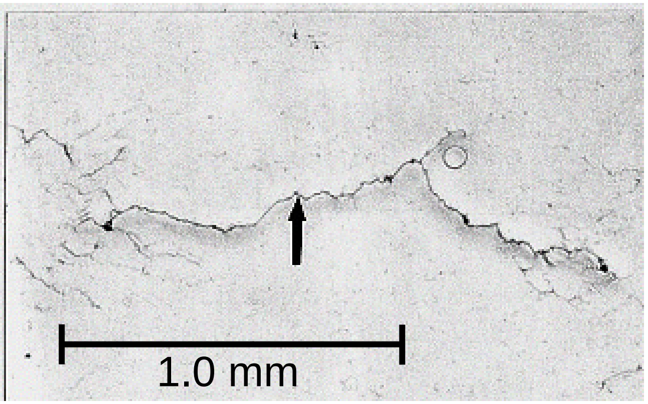
N = 160



N = 240



N = 520



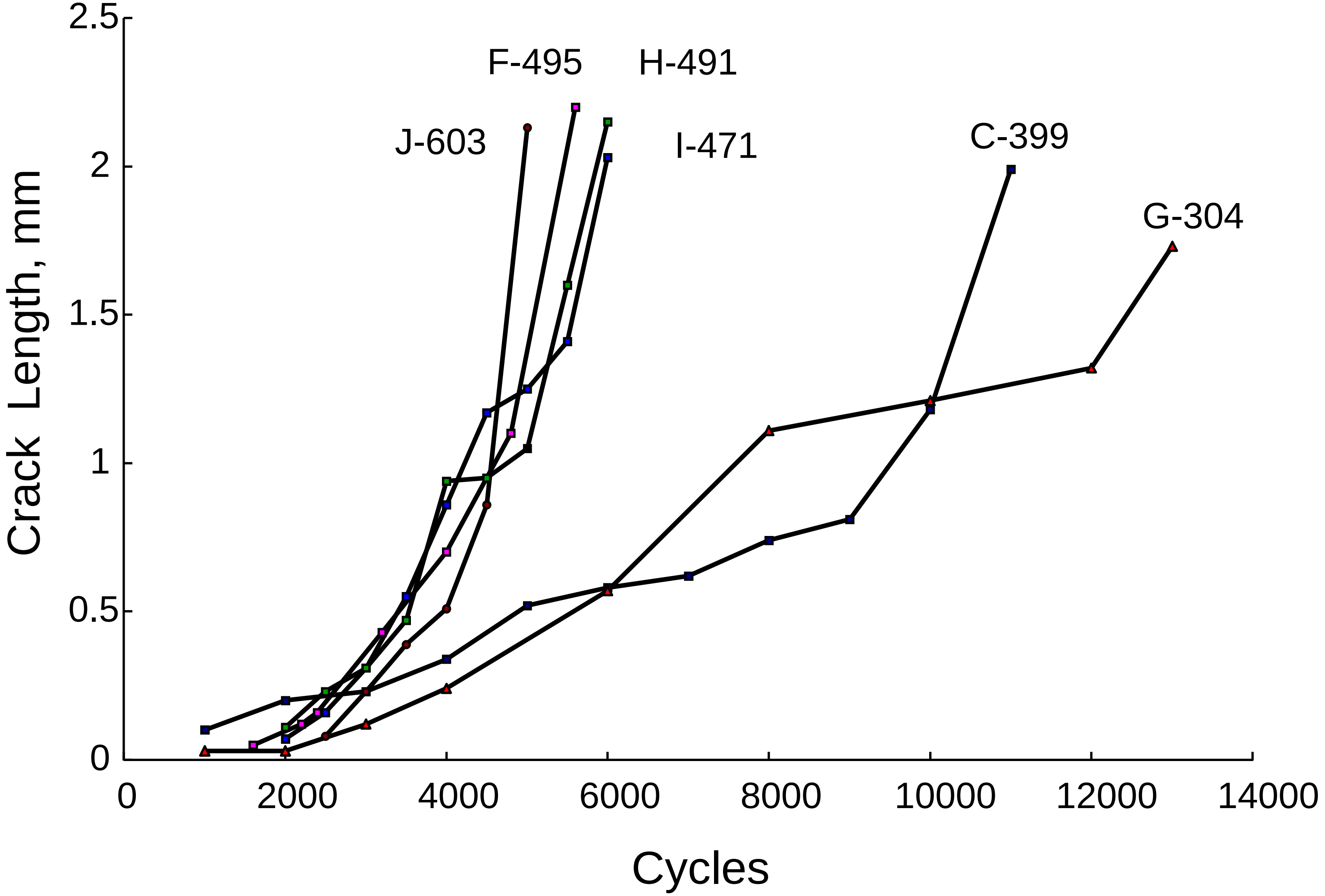
N = 900

Inconel 718

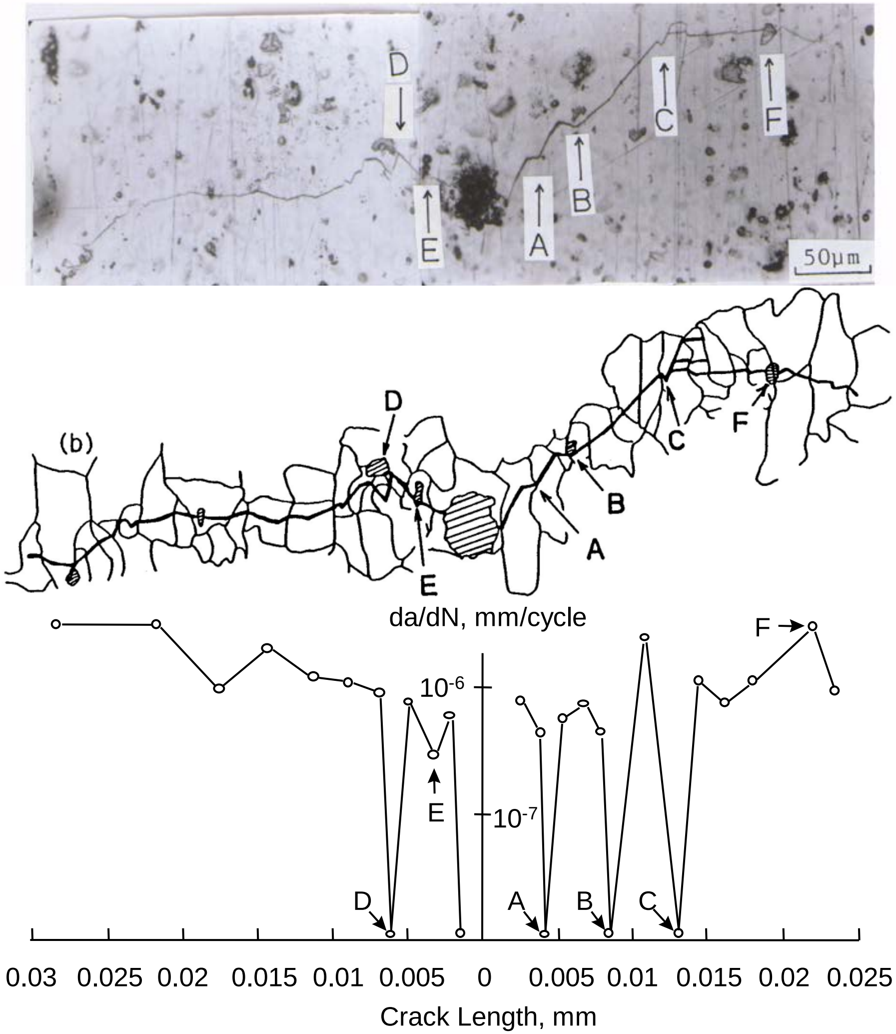
$\Delta\varepsilon = 0.02$

$N_f = 936$

Crack Length Observations

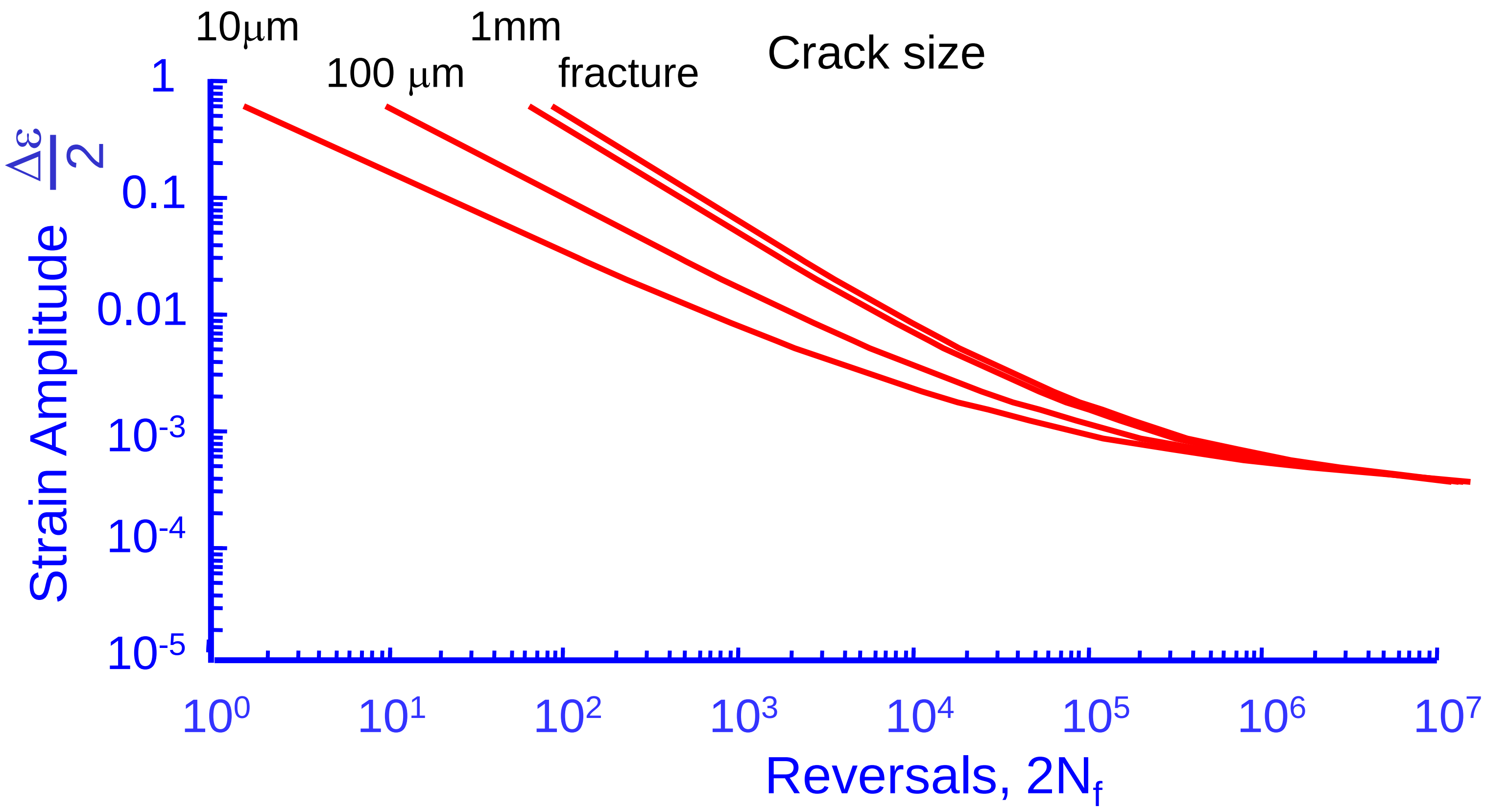


Crack - Microstructure Interactions



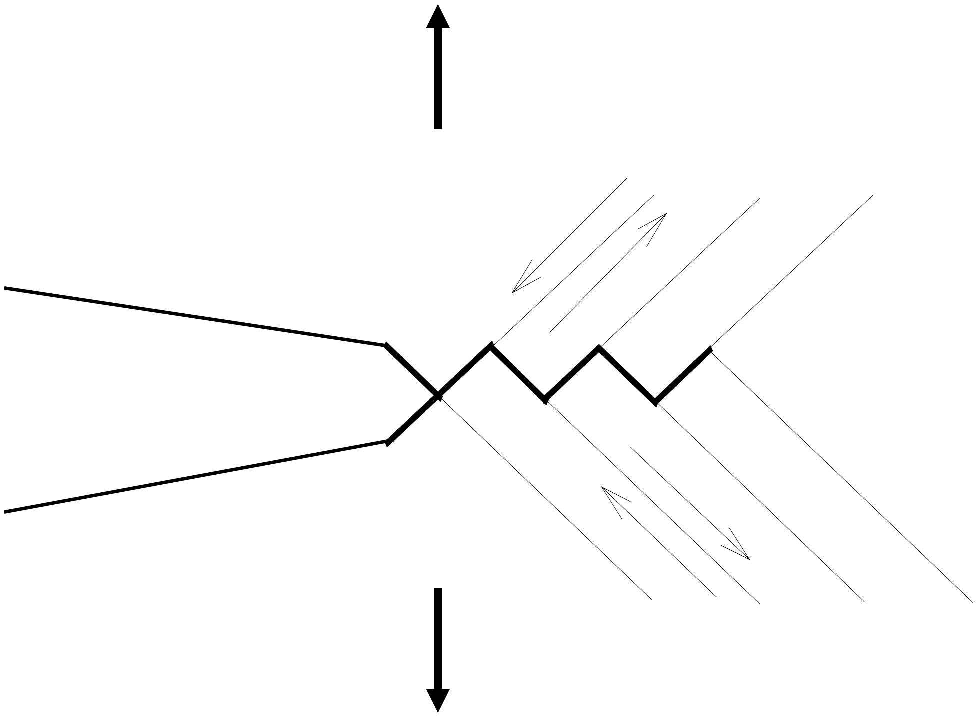
Akiniwa, Y., Tanaka, K., and Matsui, E.,"Statistical Characteristics of Propagation of Small Fatigue Cracks in Smooth Specimens of Aluminum Alloy 2024-T3, *Materials Science and Engineering*, Vol. A104, 1988, 105-115

Strain-Life Data



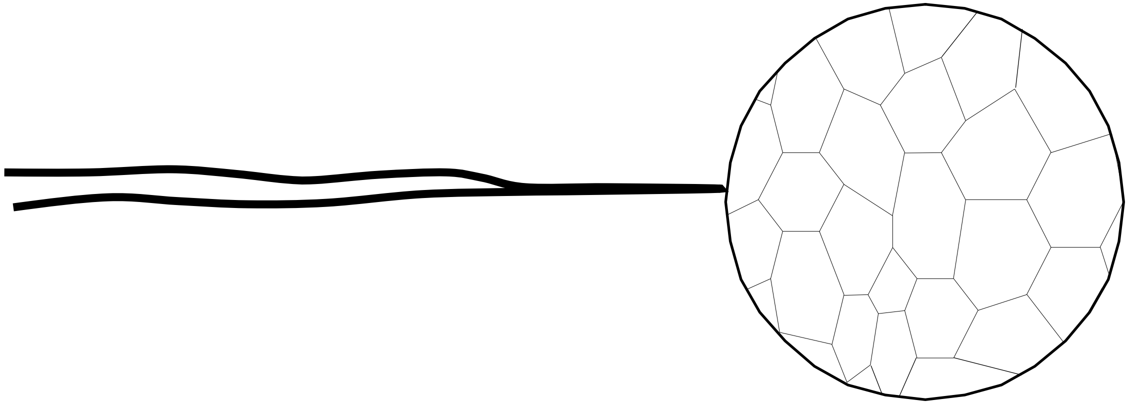
Most of the life is spent in microcrack growth in the plastic strain dominated region

Stage II Crack Growth



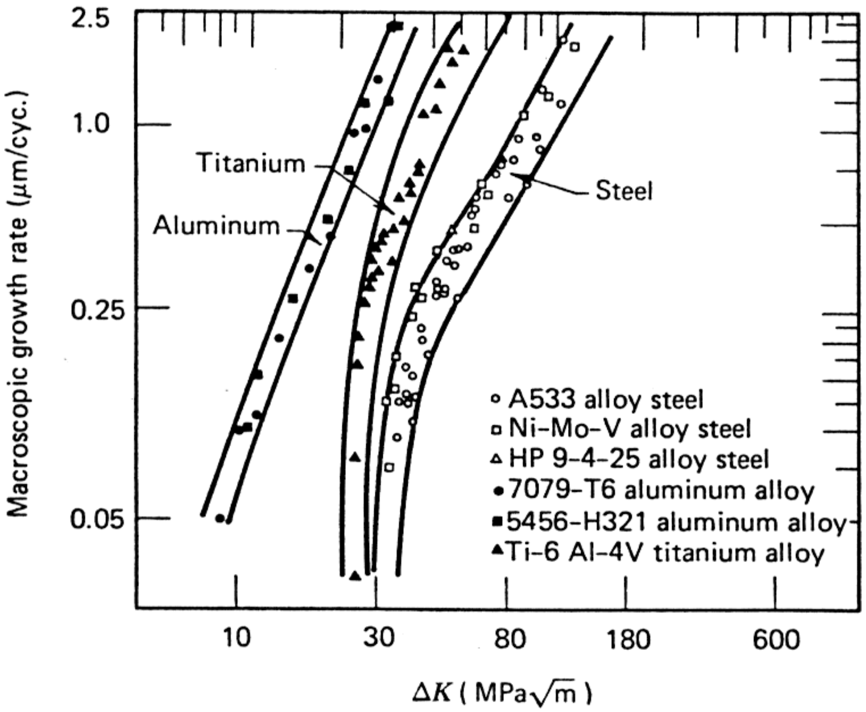
Locally, the crack grows in shear
Macroscopically it grows in tension

Long Crack Growth



Plastic zone size is much larger than the material microstructure so that the microstructure does not play such an important role.

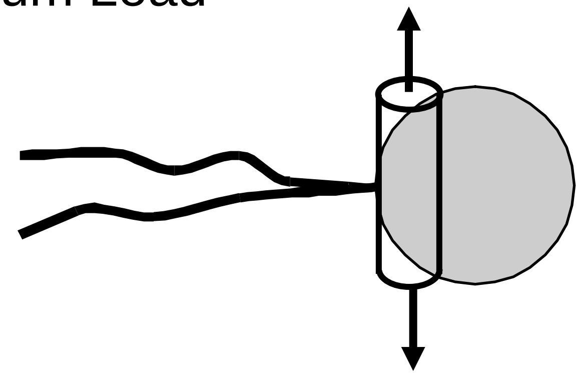
Crack Growth Rates of Metals

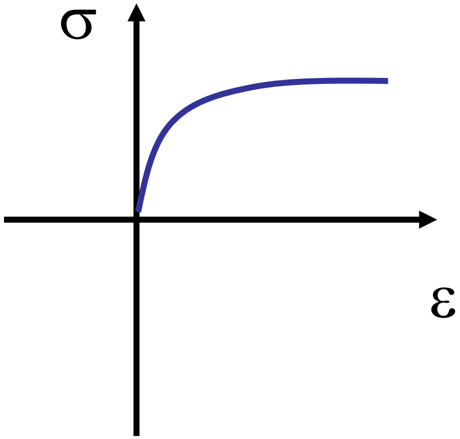


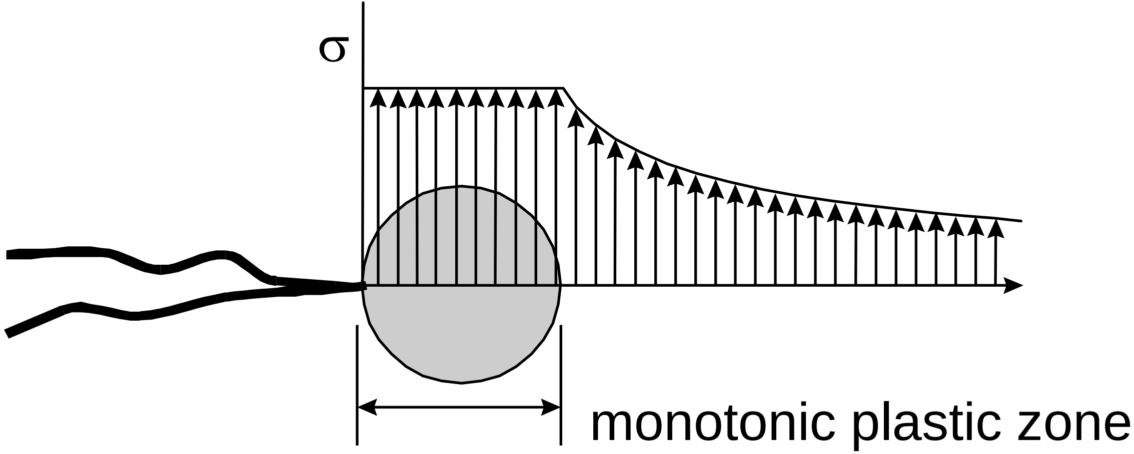
Material strength does not play a major role in fatigue crack growth

Stresses Around a Crack

Maximum Load

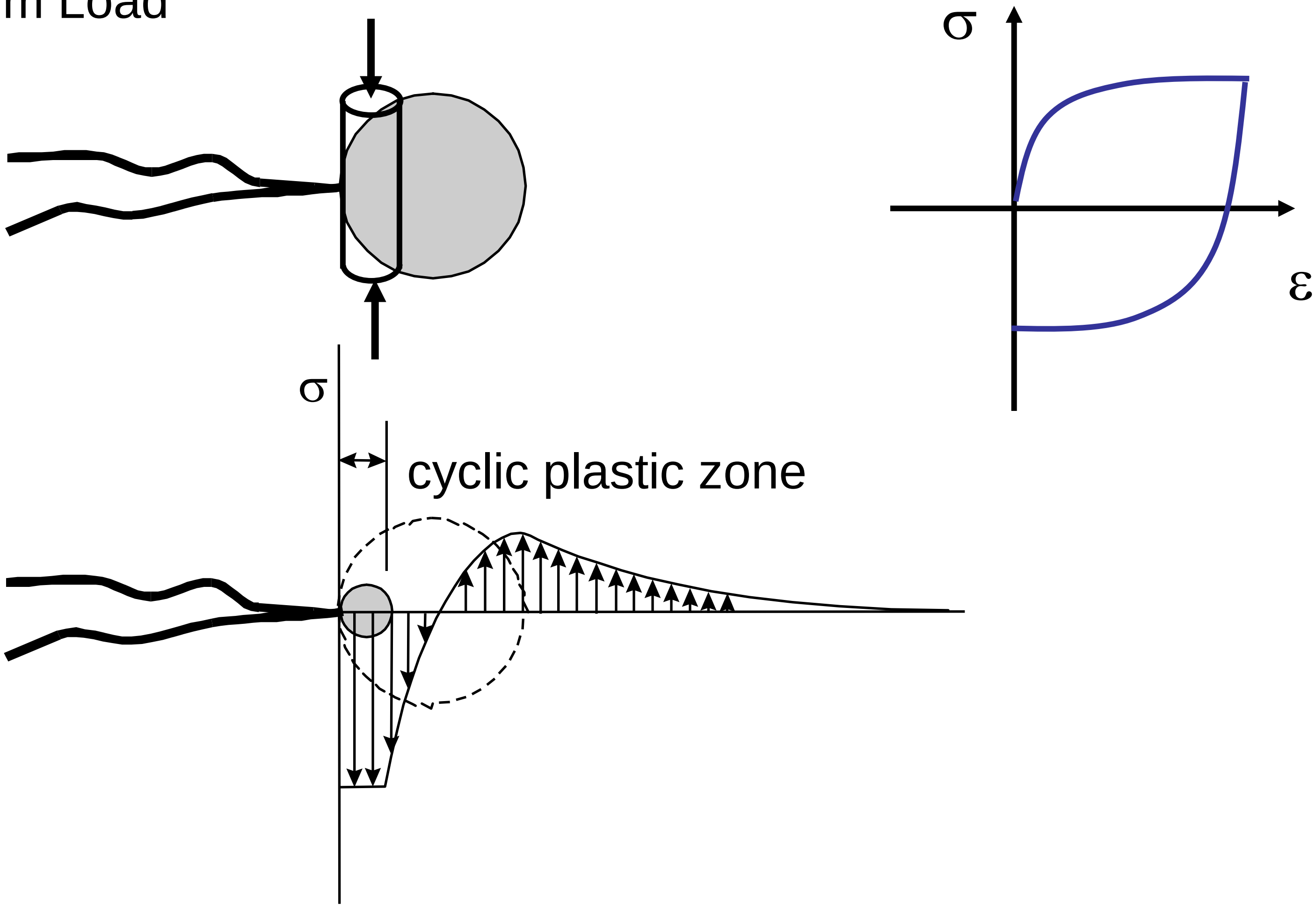




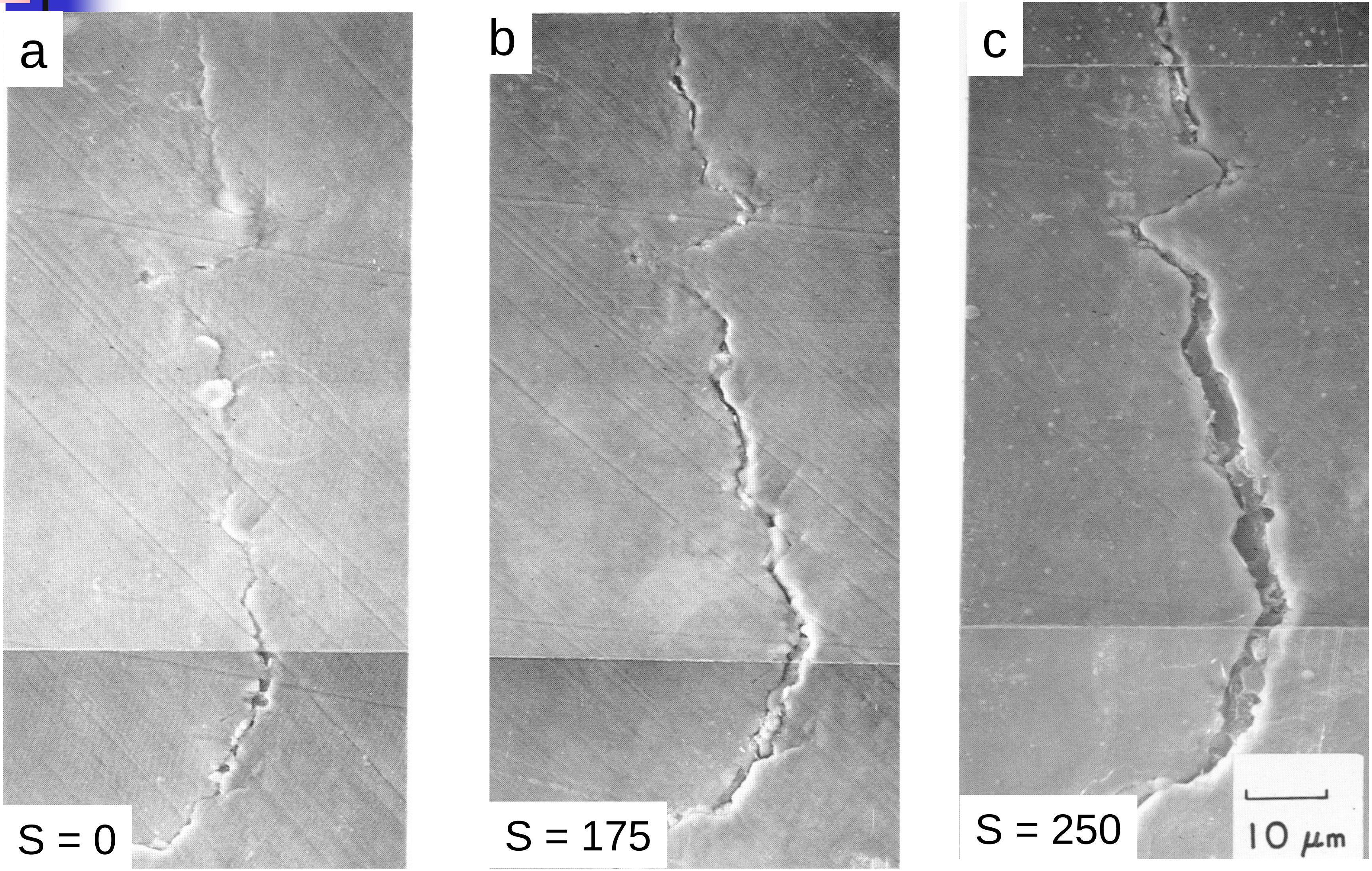


Stresses Around a Crack (continued)

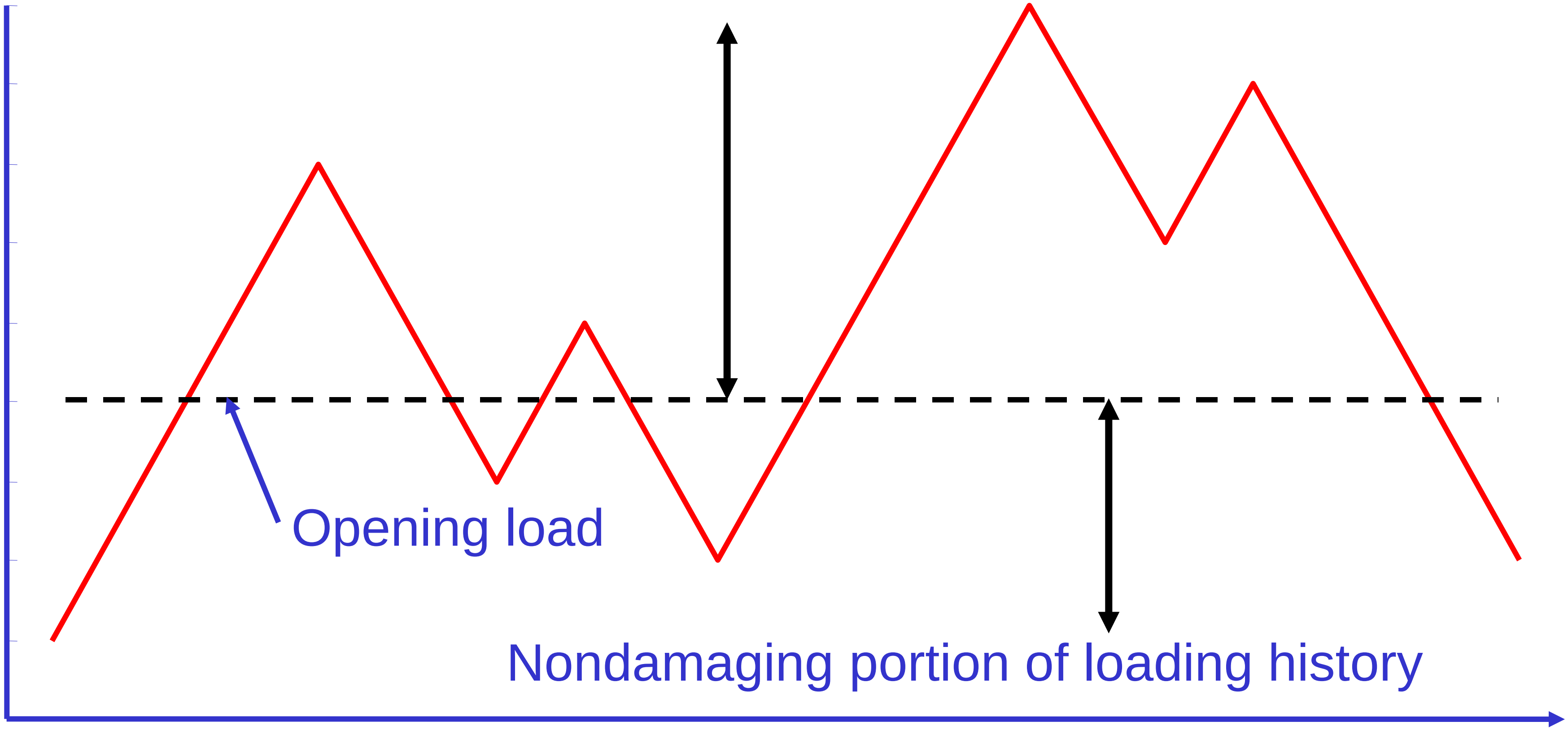
Minimum Load



Crack Closure



Crack Opening Load

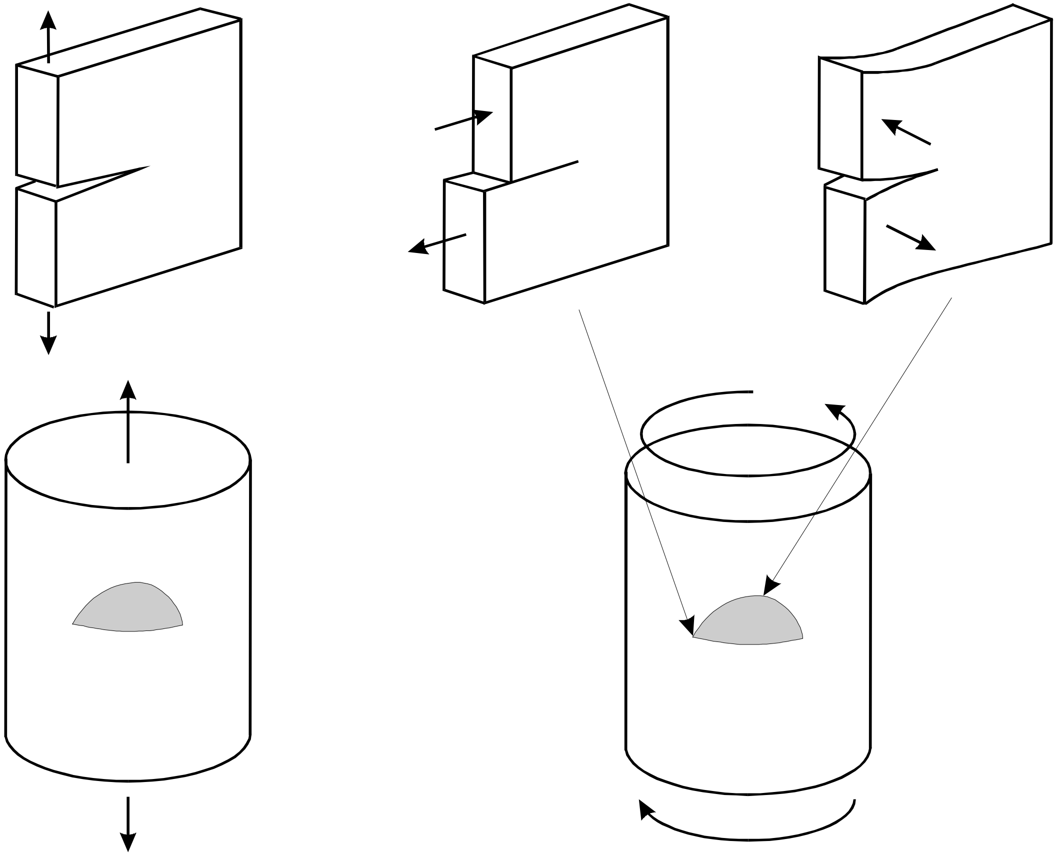


Damaging portion of loading history

Opening load

Nondamaging portion of loading history

Mode I, Mode II, and Mode III

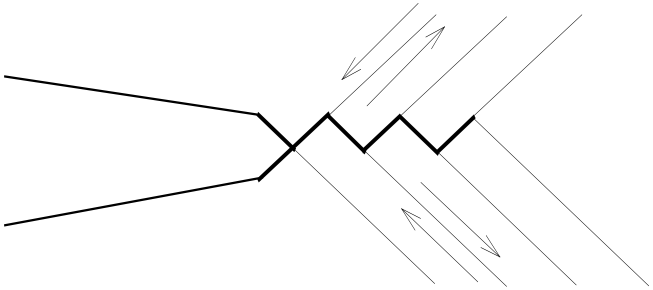


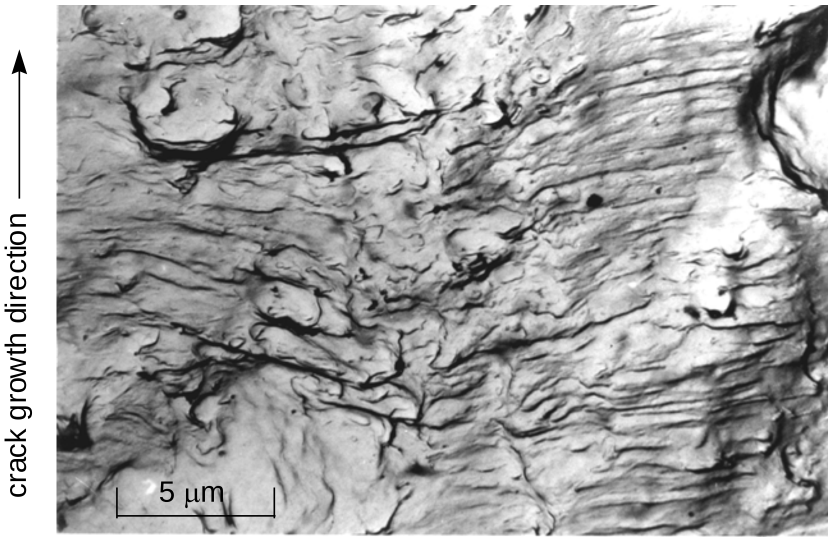
Mode I
opening

Mode II
in-plane shear

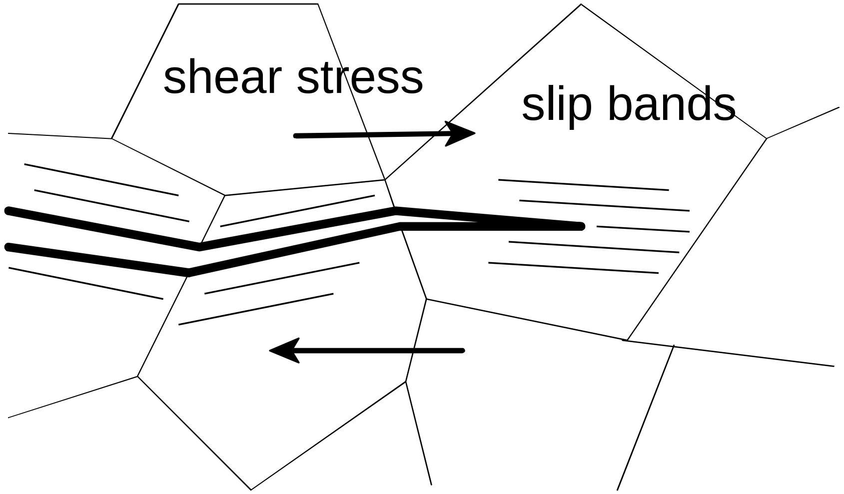
Mode III
out-of-plane shear

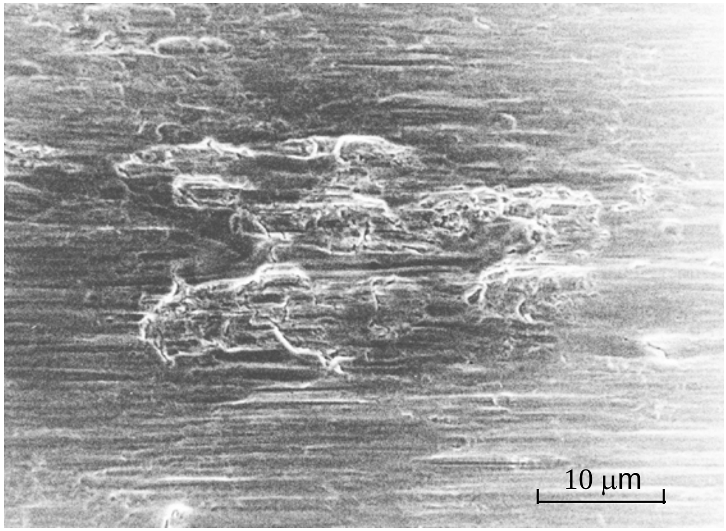
Mode I Growth





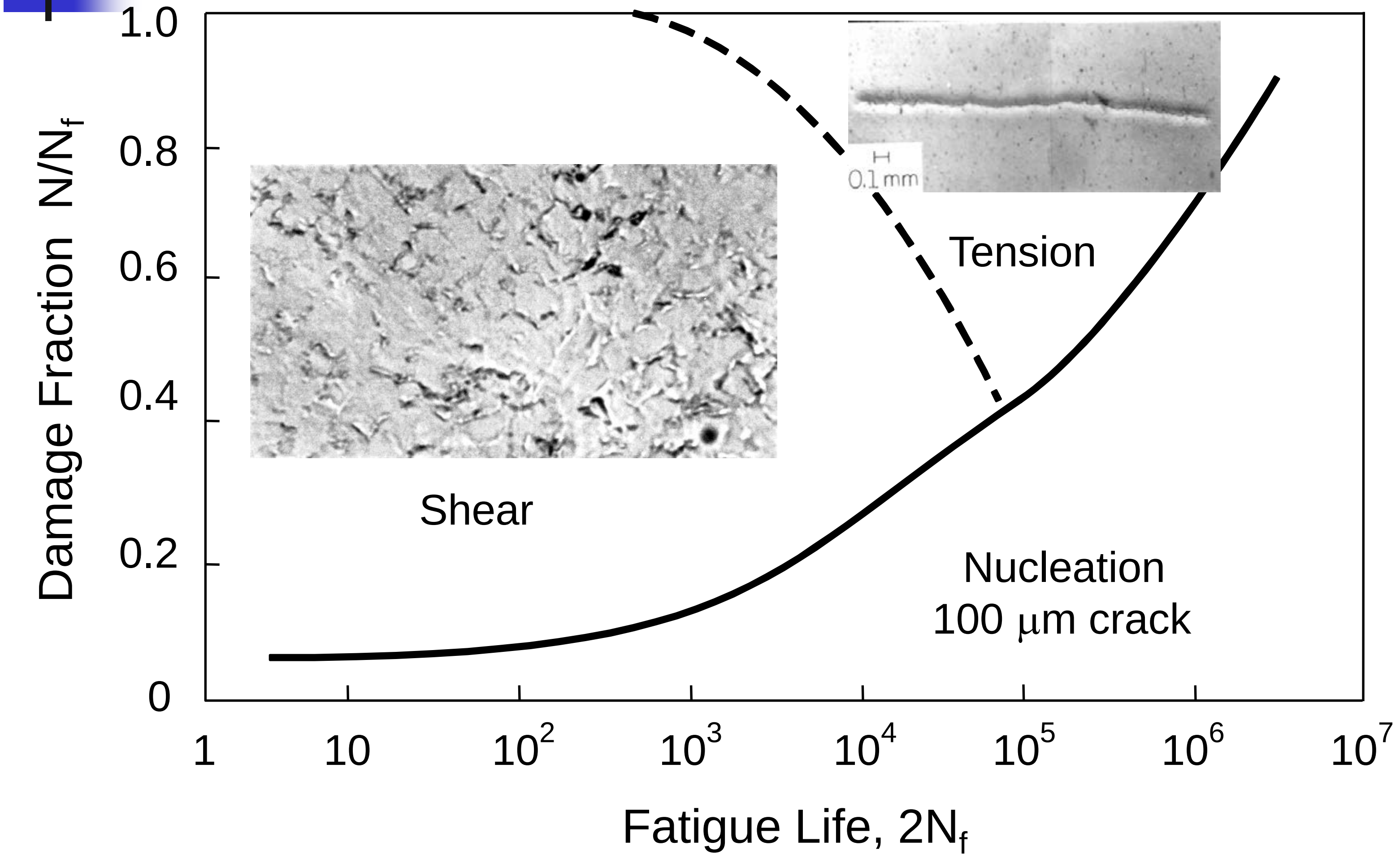
Mode II Growth



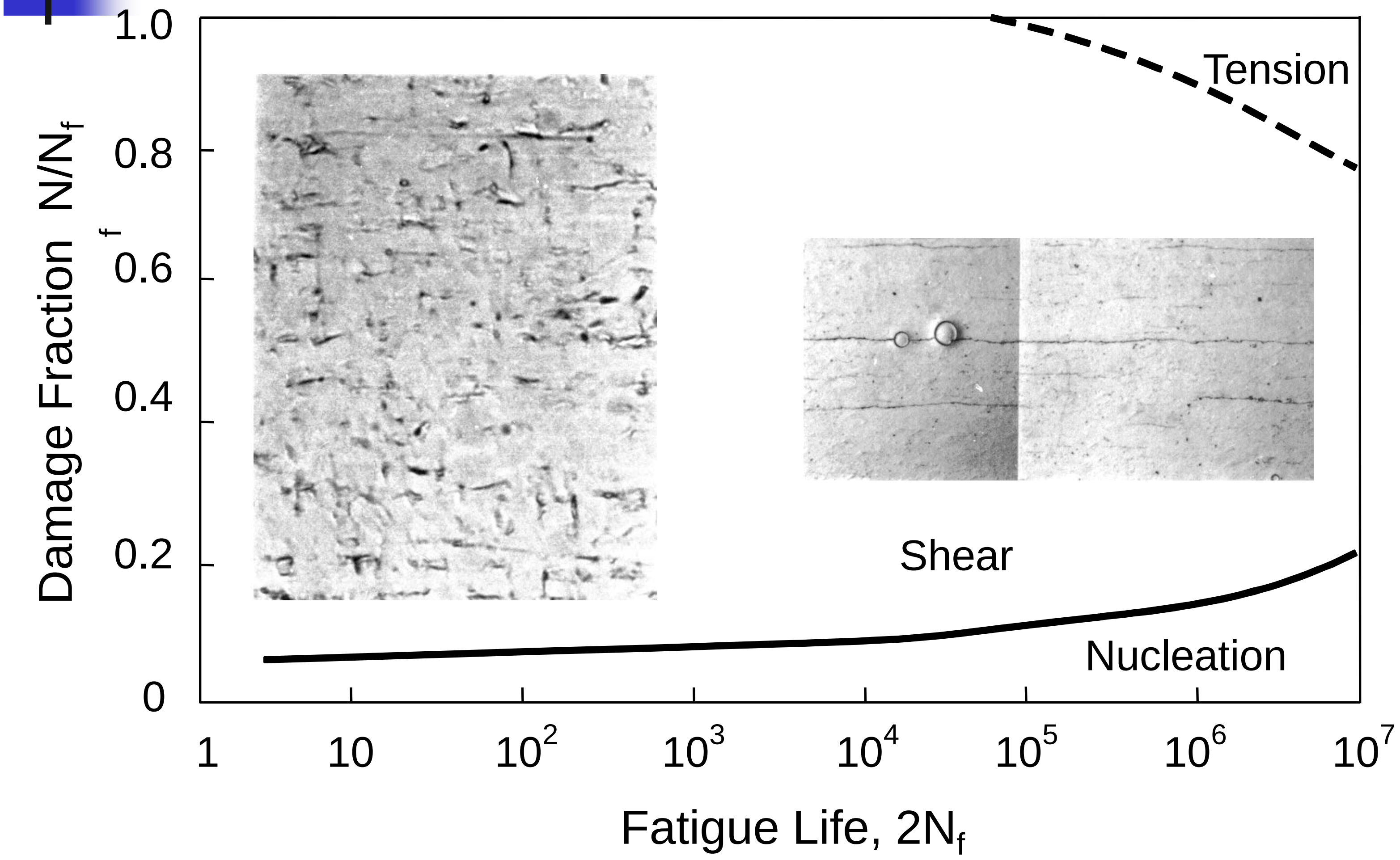


← crack growth direction

1045 Steel - Tension



1045 Steel - Torsion



Things Worth Remembering

- Fatigue is a localized process involving the nucleation and growth of cracks to failure.
- Fatigue is caused by localized plastic deformation.
- Most of the fatigue life is consumed growing microcracks in the finite life region
- Crack nucleation is dominate at long lives.

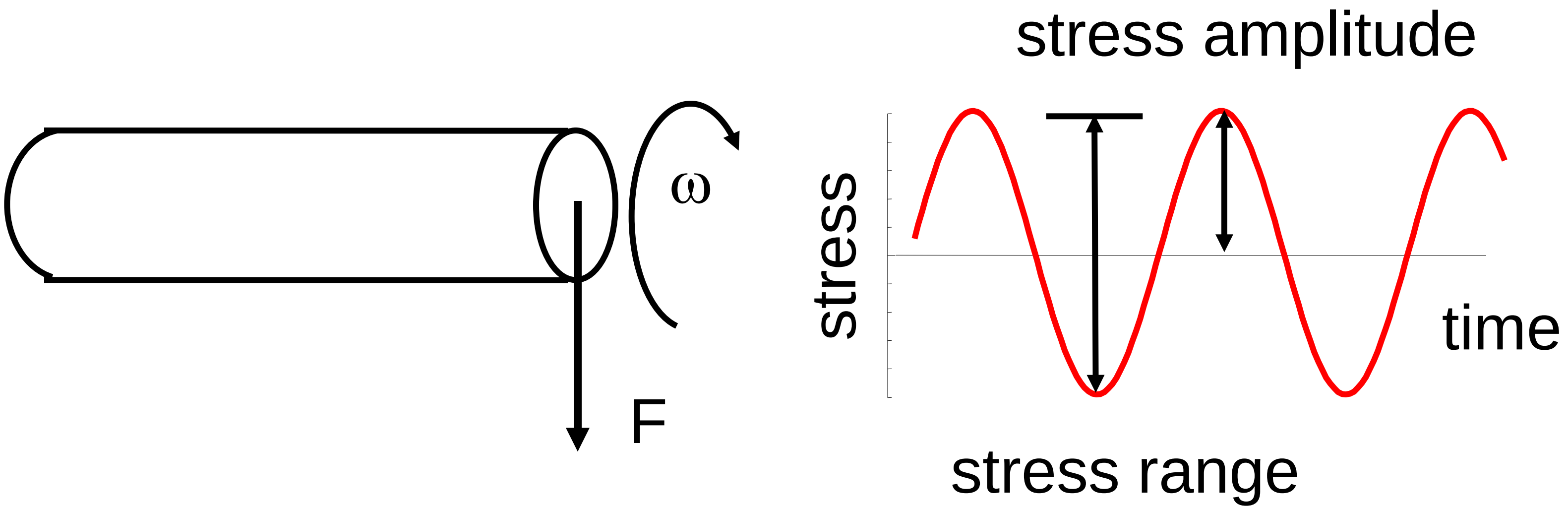
Fatigue, How and Why

- Physics of Fatigue
- **Material Properties**
- Introduction to eFatigue

Characterization

- Stress Life Curve
  - Fatigue Limit
- Strain Life Curve
  - Cyclic Stress Strain Curve
- Crack Growth Curve
  - Threshold Stress Intensity

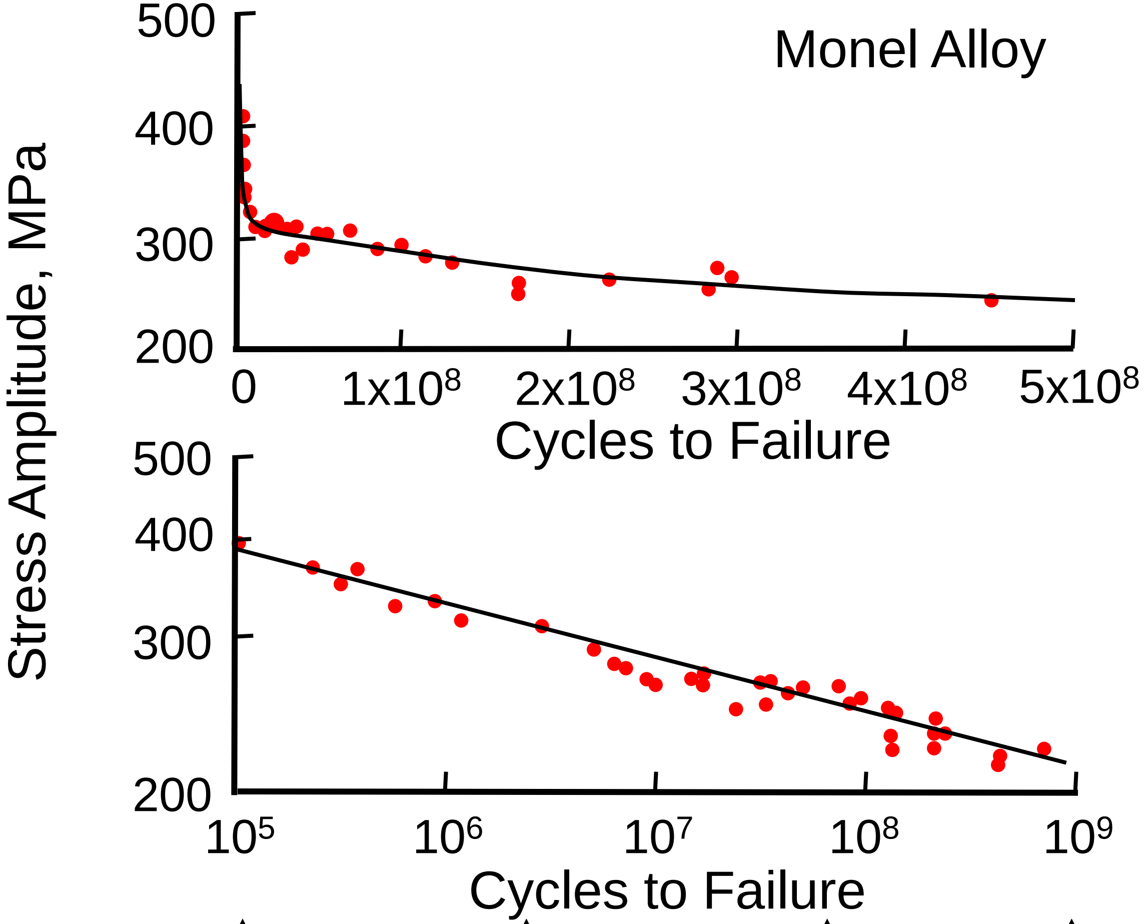
Bending Fatigue



Bending stress:

$$\sigma = \frac{Mc}{I}$$

SN Curve



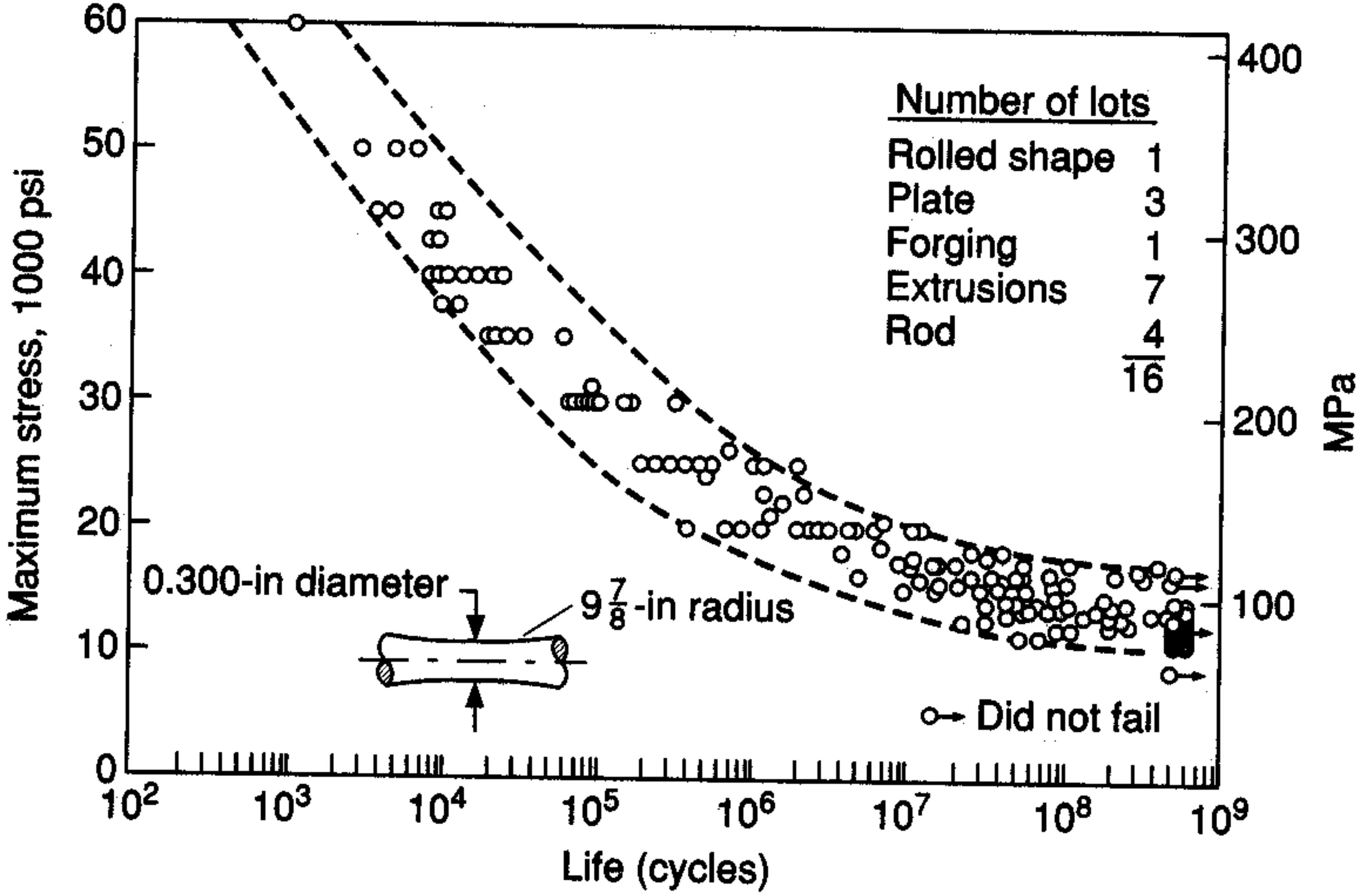
Testing time
@ 30 Hz

1 hour ↑ 1 day ↑ 1 month ↑ 1 year ↑

Fatigue Strength

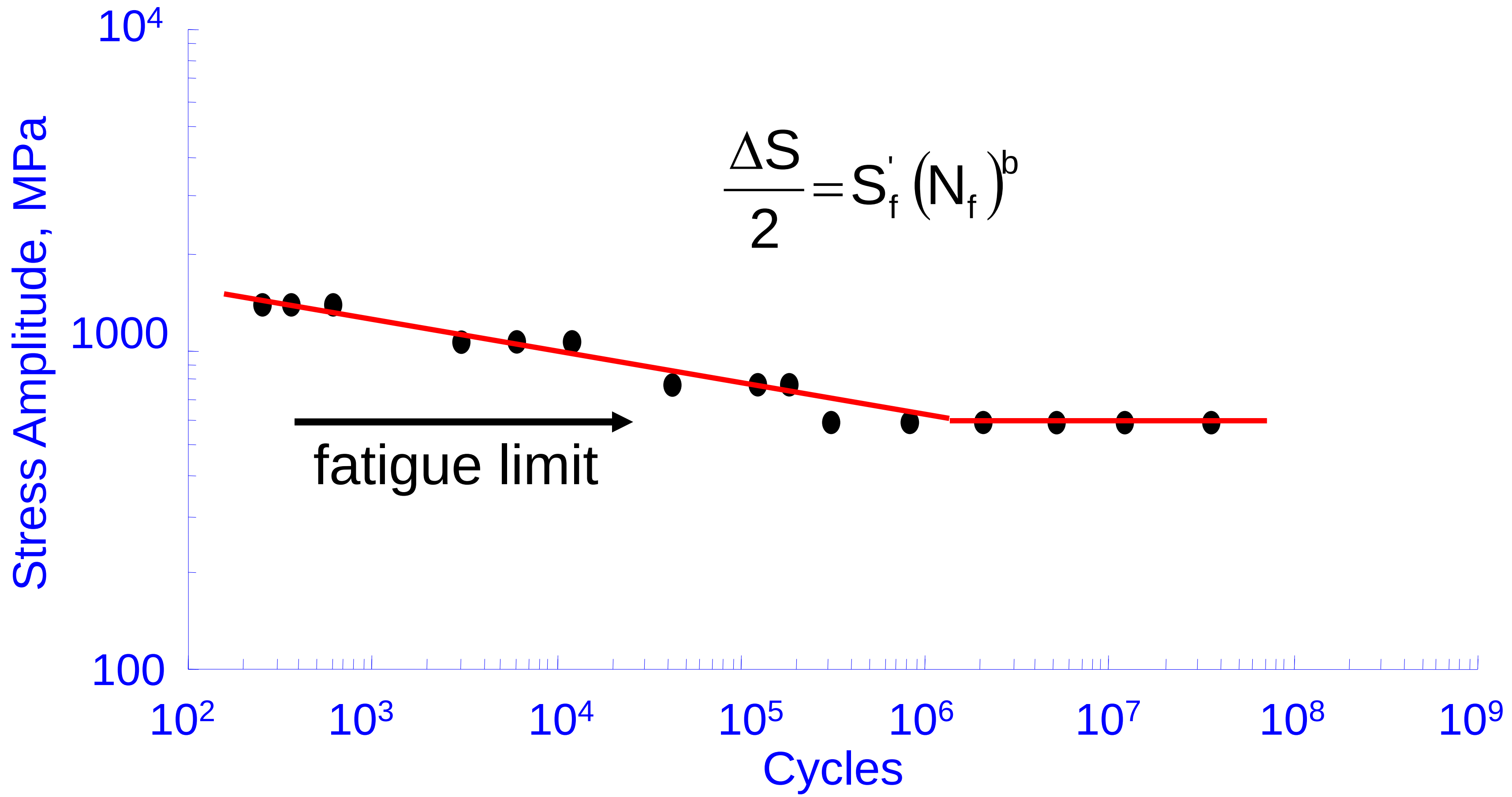
Alloy	Fatigue Life 10^5	10^6	10^7	10^8	10^9
2014-T4	290	235	186	152	138
2024-T4	297	214	166	145	138
6061-T6	186	152	117	104	90
7075-T6	276	200	166	152	145

6061-T6 Aluminum Test Data



Sharpe et. al. Fatigue Design of Aluminum Components and Structures , 1996

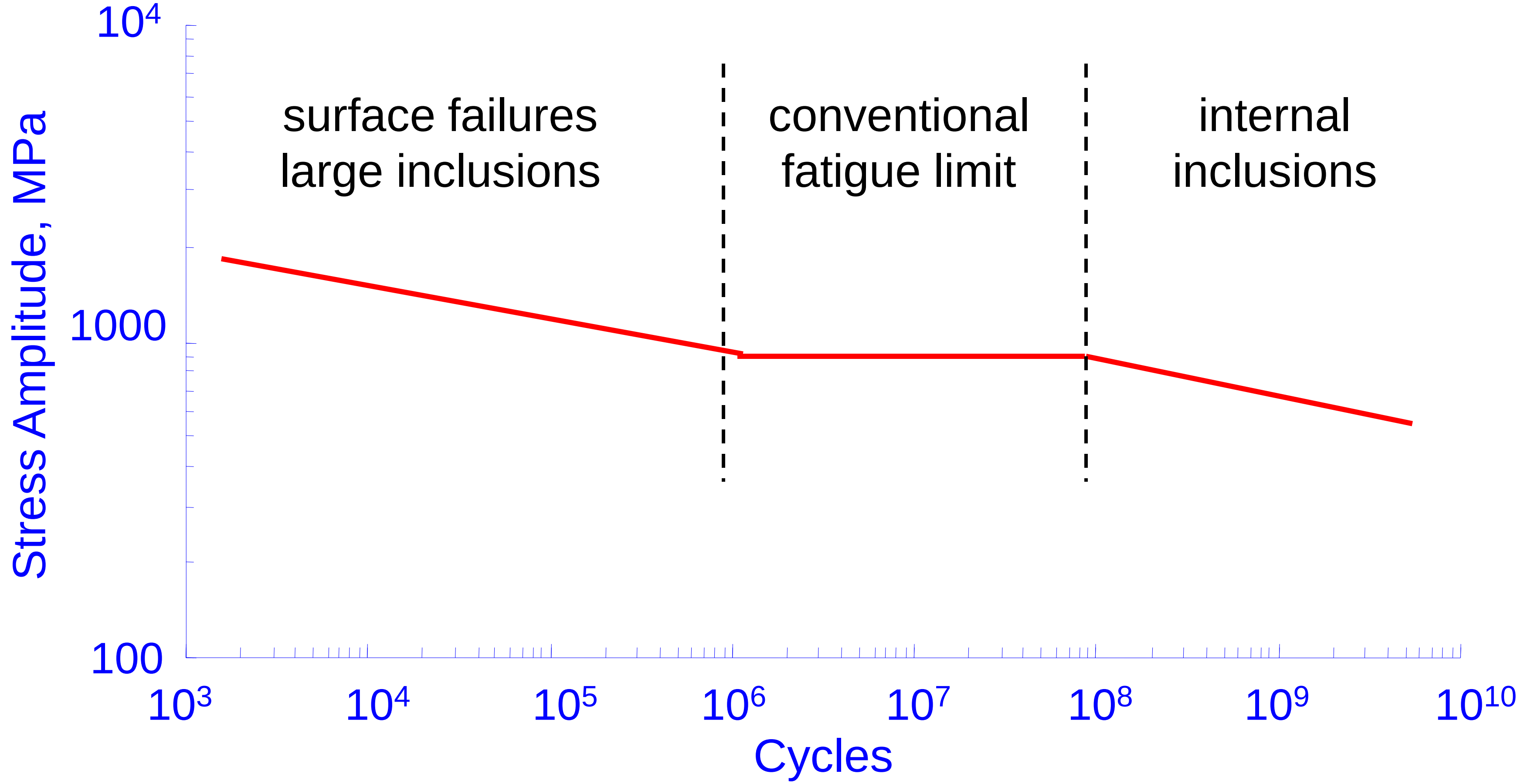
SN Curve for Steel



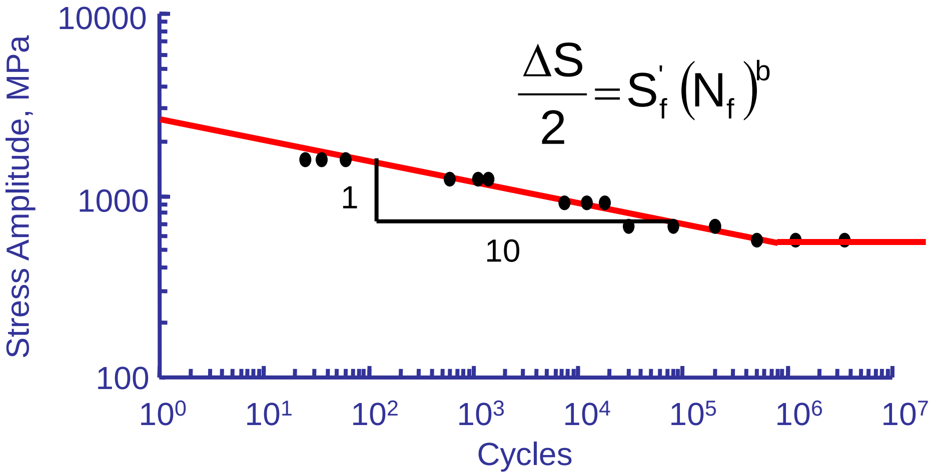
$$\frac{\Delta S}{2} = S_f^{'} \left(N_f\right)^b$$

The fatigue limit is usually only found in steel laboratory specimens

Very High Cycle Fatigue of Steel



Fatigue Damage

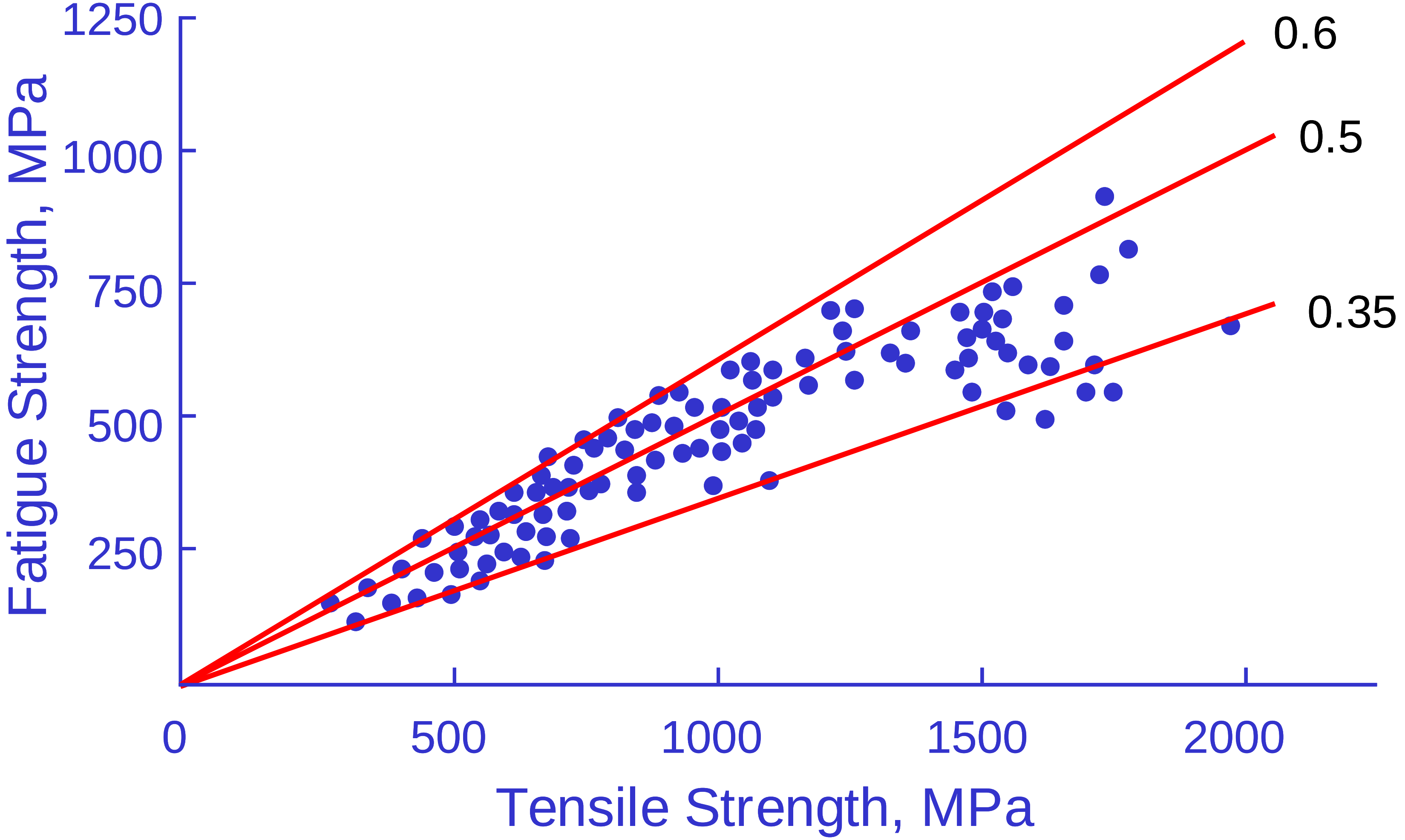


$$\frac{\Delta S}{2} = S_f^{'} \left(N_f \right)^b$$

$$N_f = \left(\frac{\Delta S}{2 S_f^{'}} \right)^{\frac{1}{b}}$$

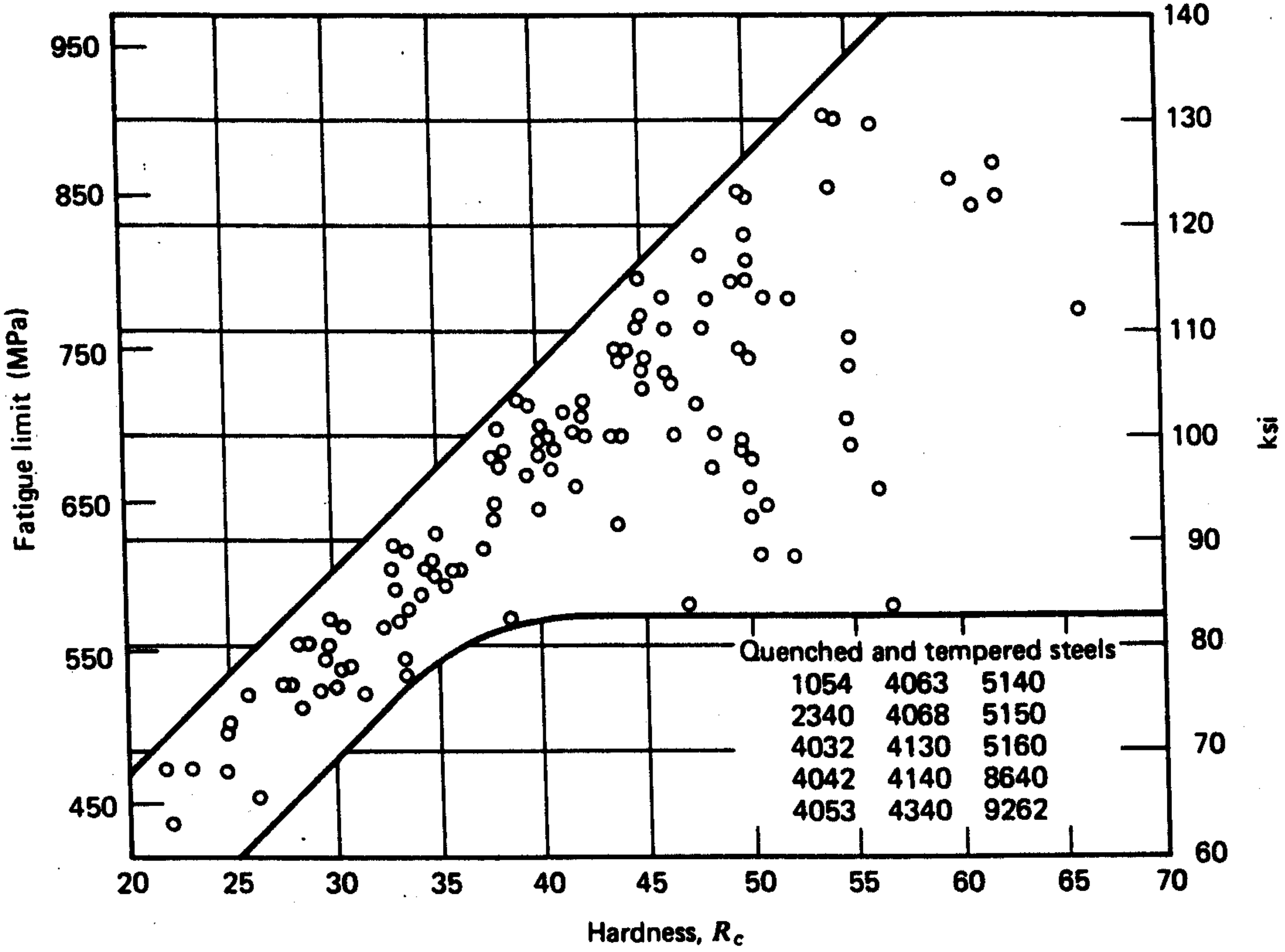
$$\text{Damage} \propto \Delta S^{10}$$

Fatigue Limit Strength Correlation

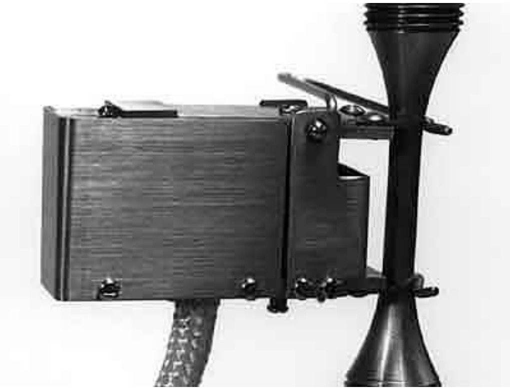


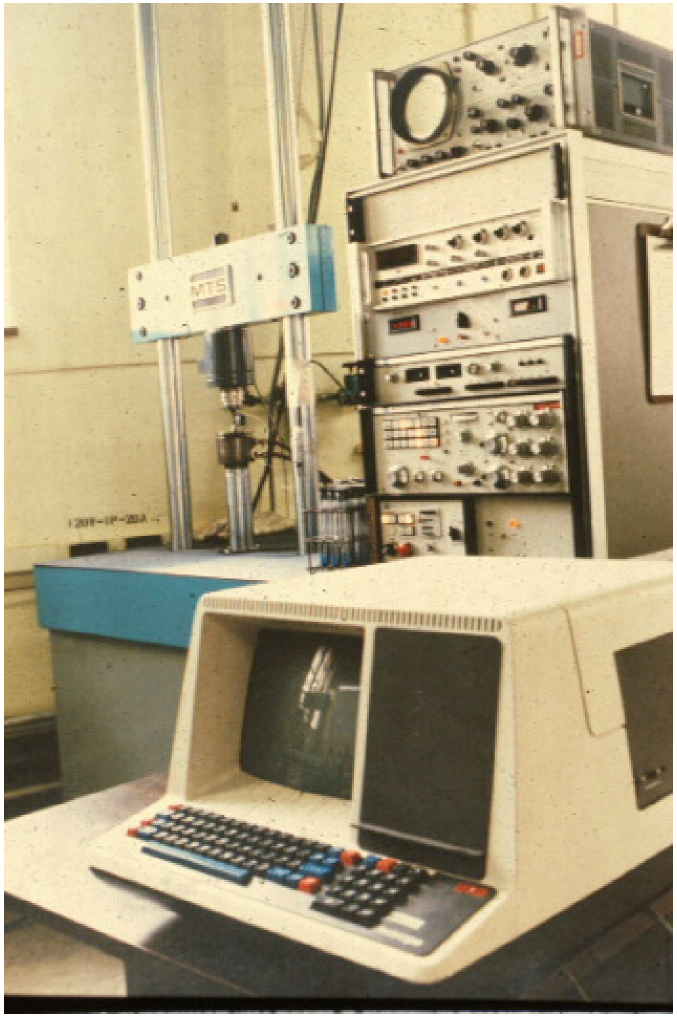
From Forrest, *Fatigue of Metals*, Pergamon Press, London, 1962

Fatigue Limit Strength Correlation

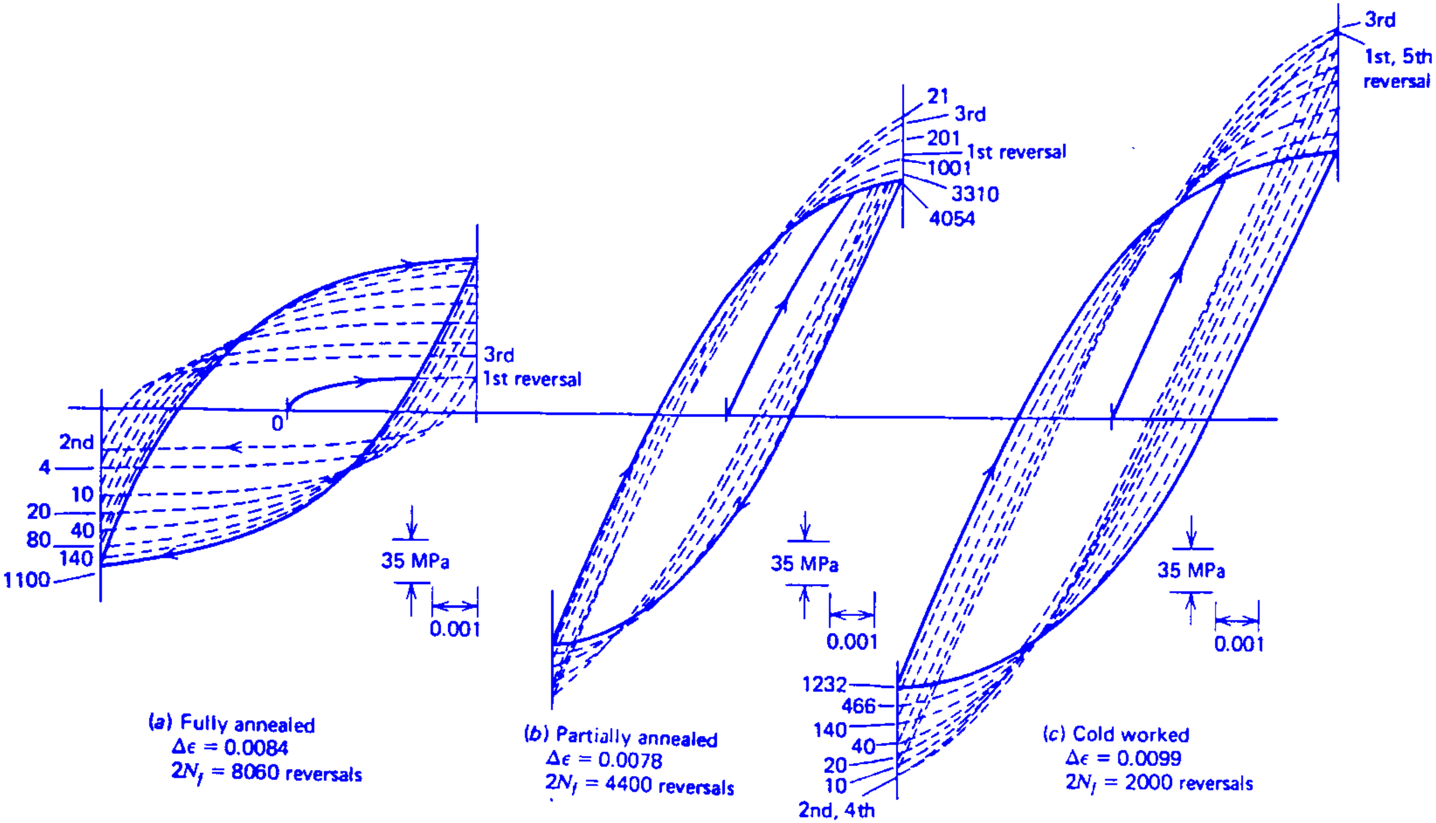


Strain Controlled Testing





Cyclic Hardening / Softening



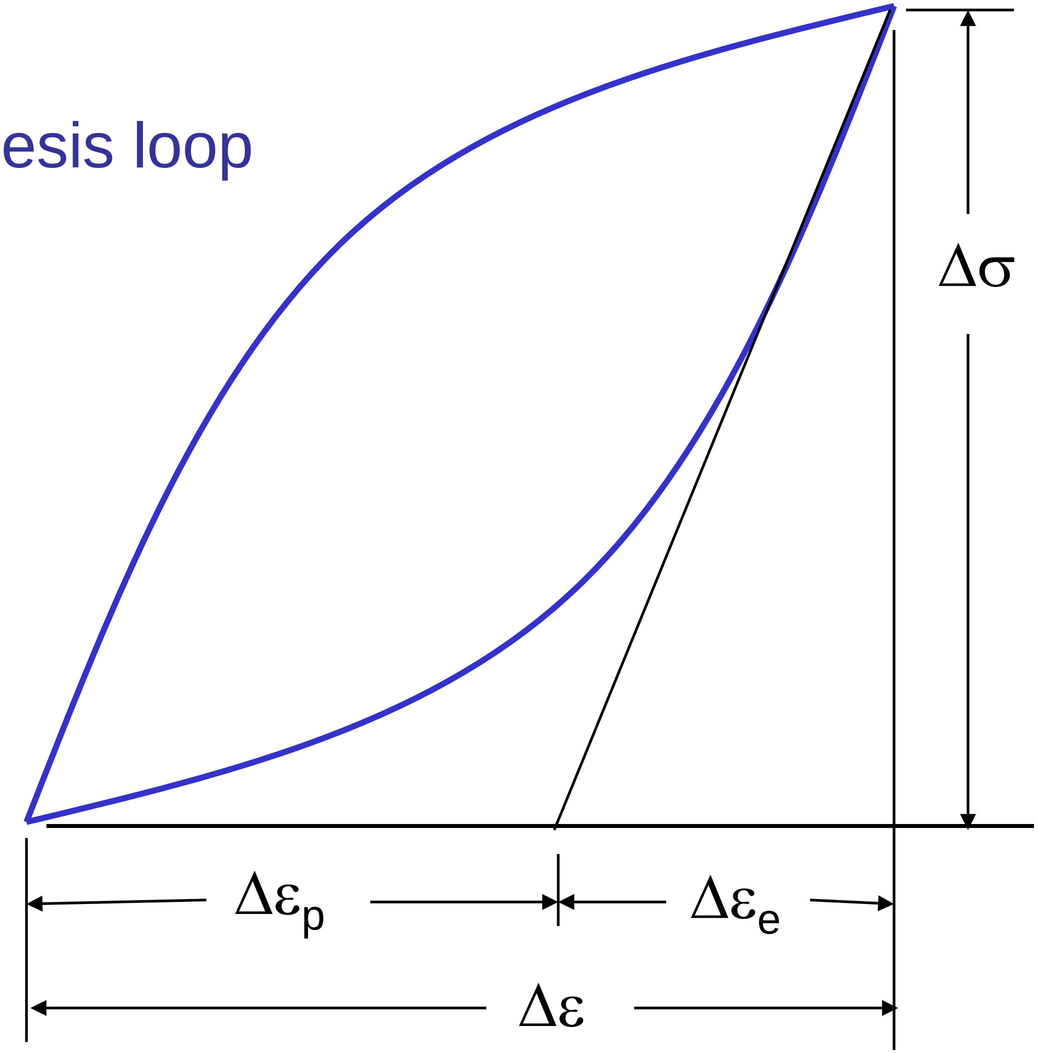
(a) Fully annealed
$\Delta\epsilon = 0.0084$
$2N_f = 8060$ reversals

(b) Partially annealed
$\Delta\epsilon = 0.0078$
$2N_f = 4400$ reversals

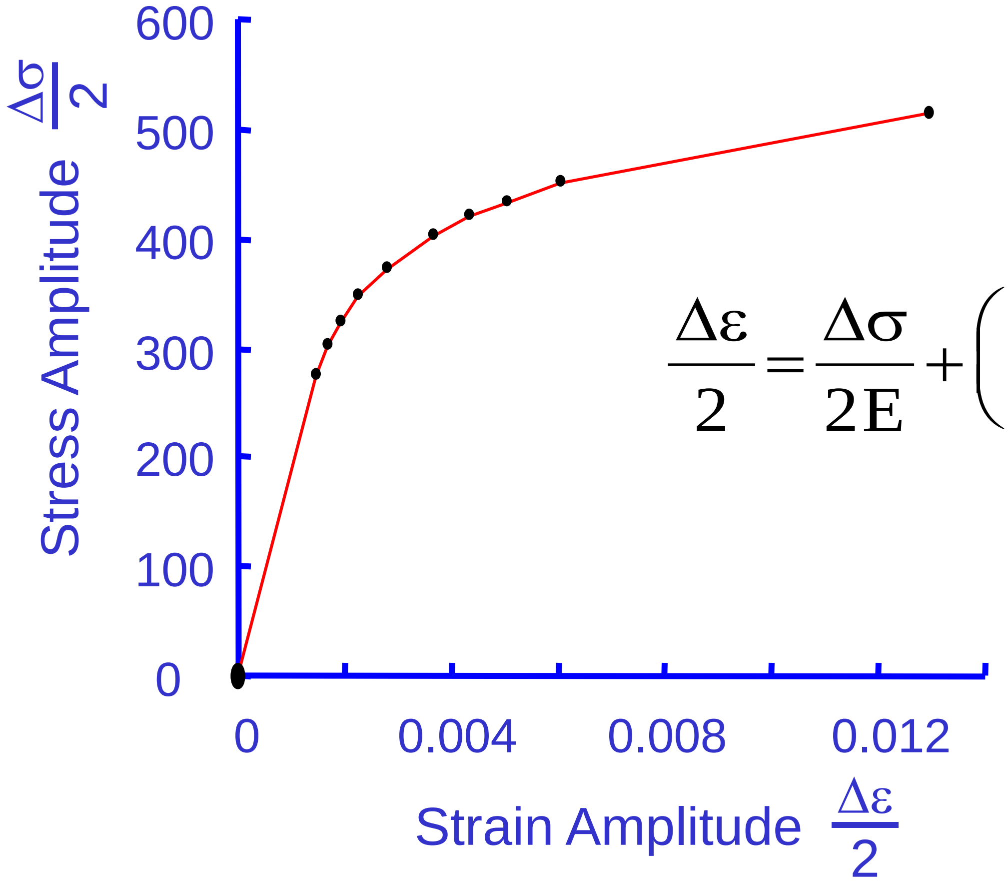
(c) Cold worked
$\Delta\epsilon = 0.0099$
$2N_f = 2000$ reversals

Stable Hysteresis Loop

Hysteresis loop



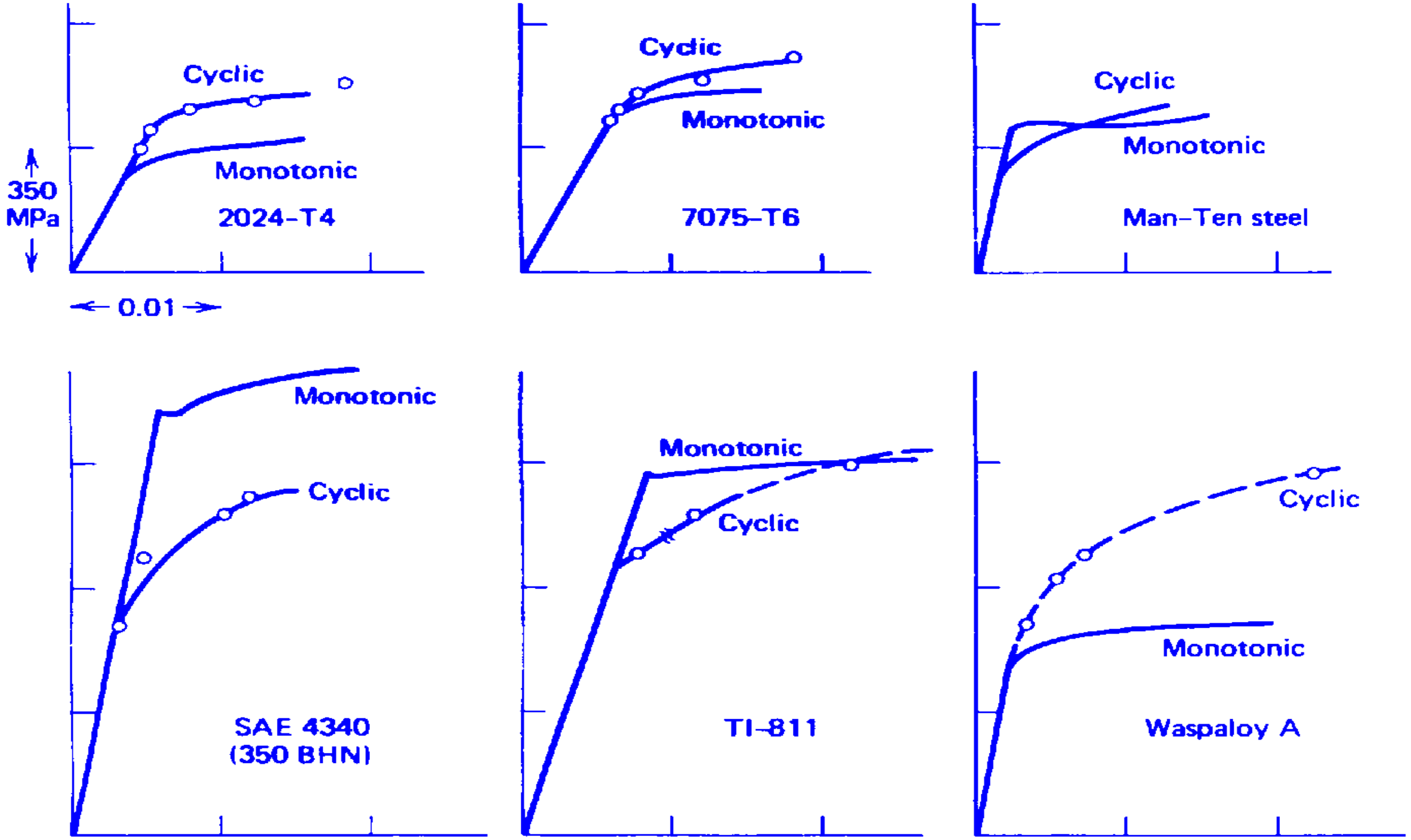
Strain-Life Data $\sigma - \varepsilon$



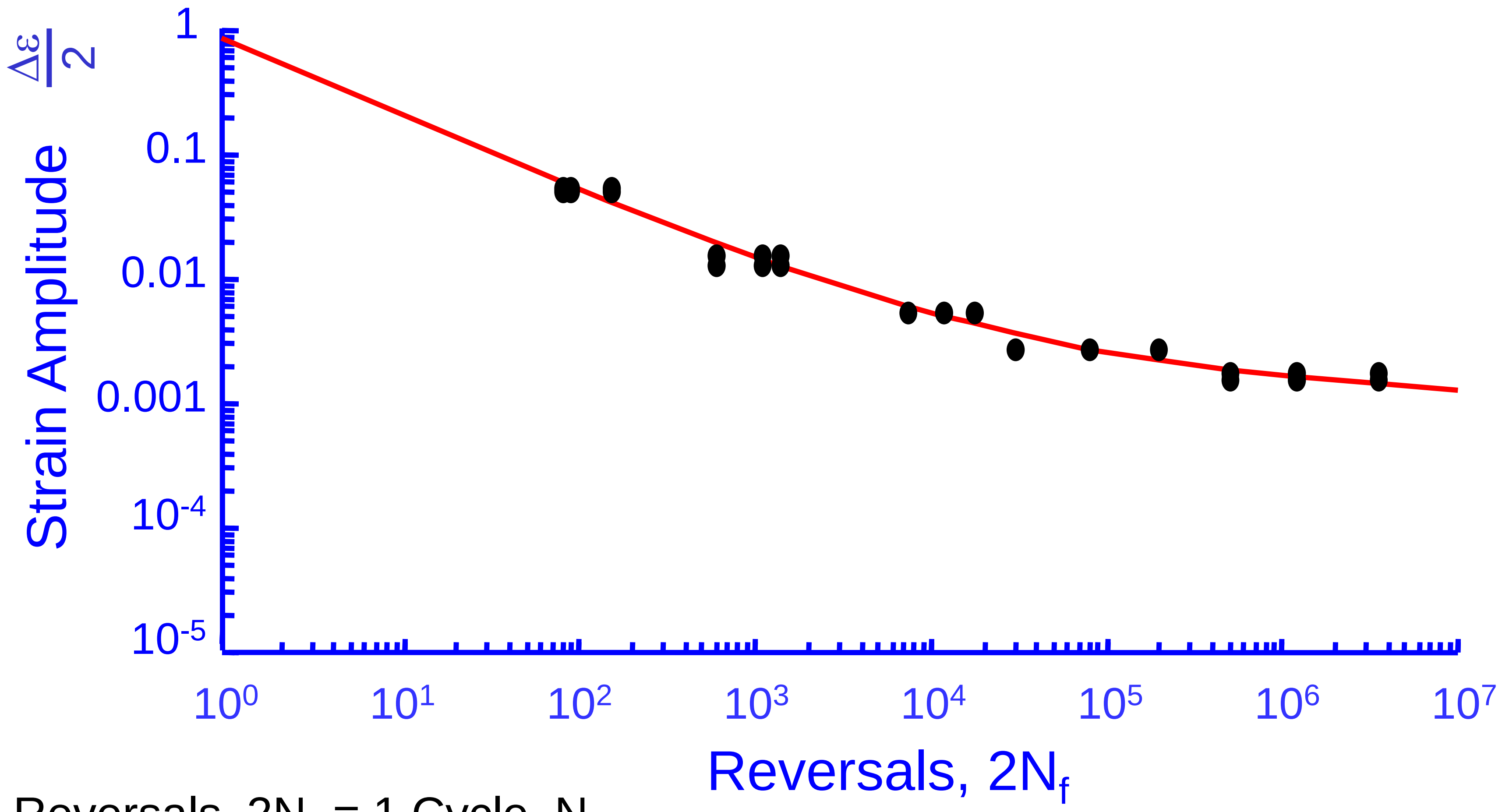
$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\sigma}{2E} + \left(\frac{\Delta\sigma}{2K'}\right)^{1/n'}$$

During cyclic deformation, the material deforms on a path described by the cyclic stress strain curve

Cyclic Stress Strain Curve

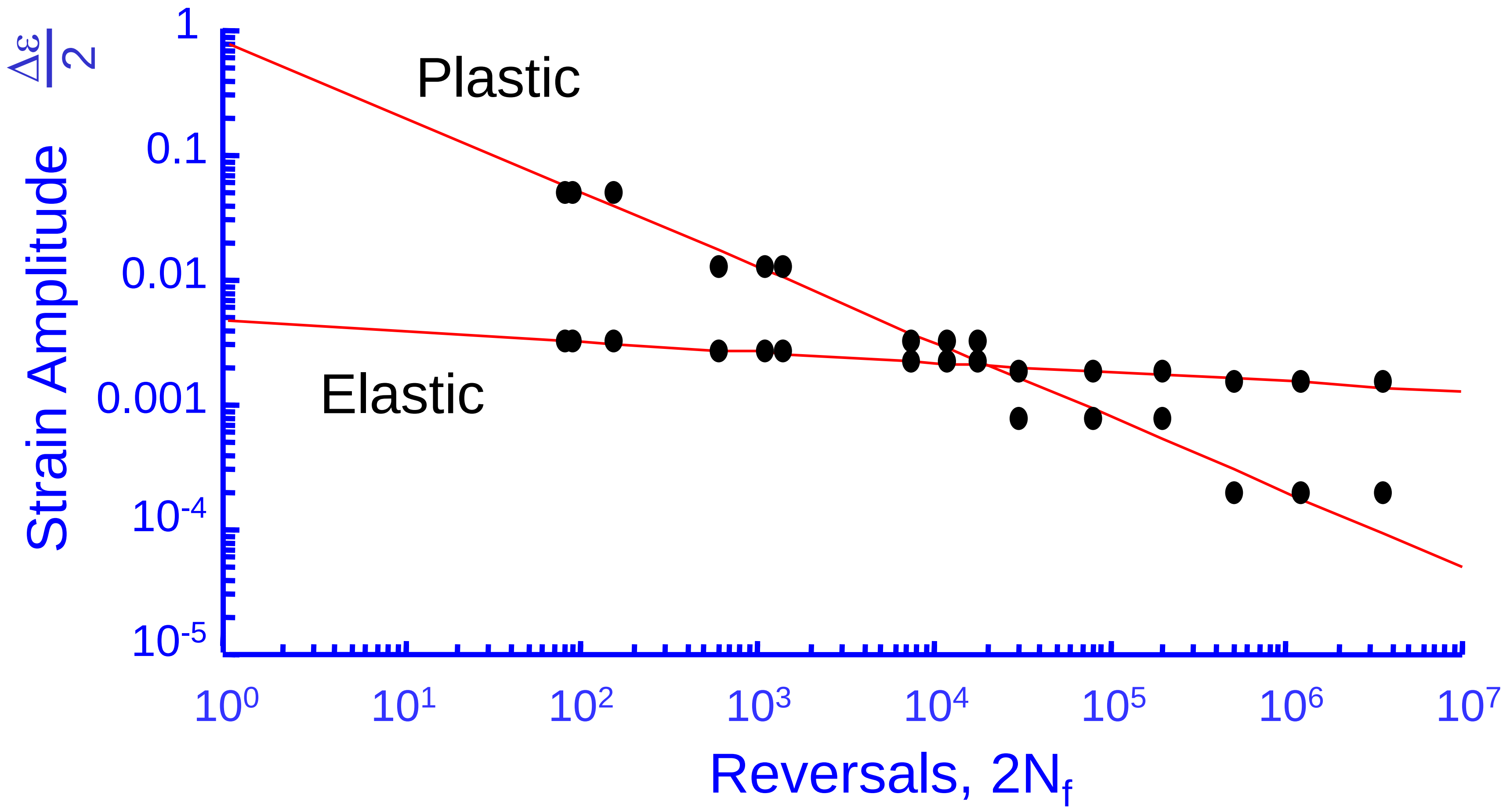


Strain-Life Data $\Delta\varepsilon$ - $2N_f$

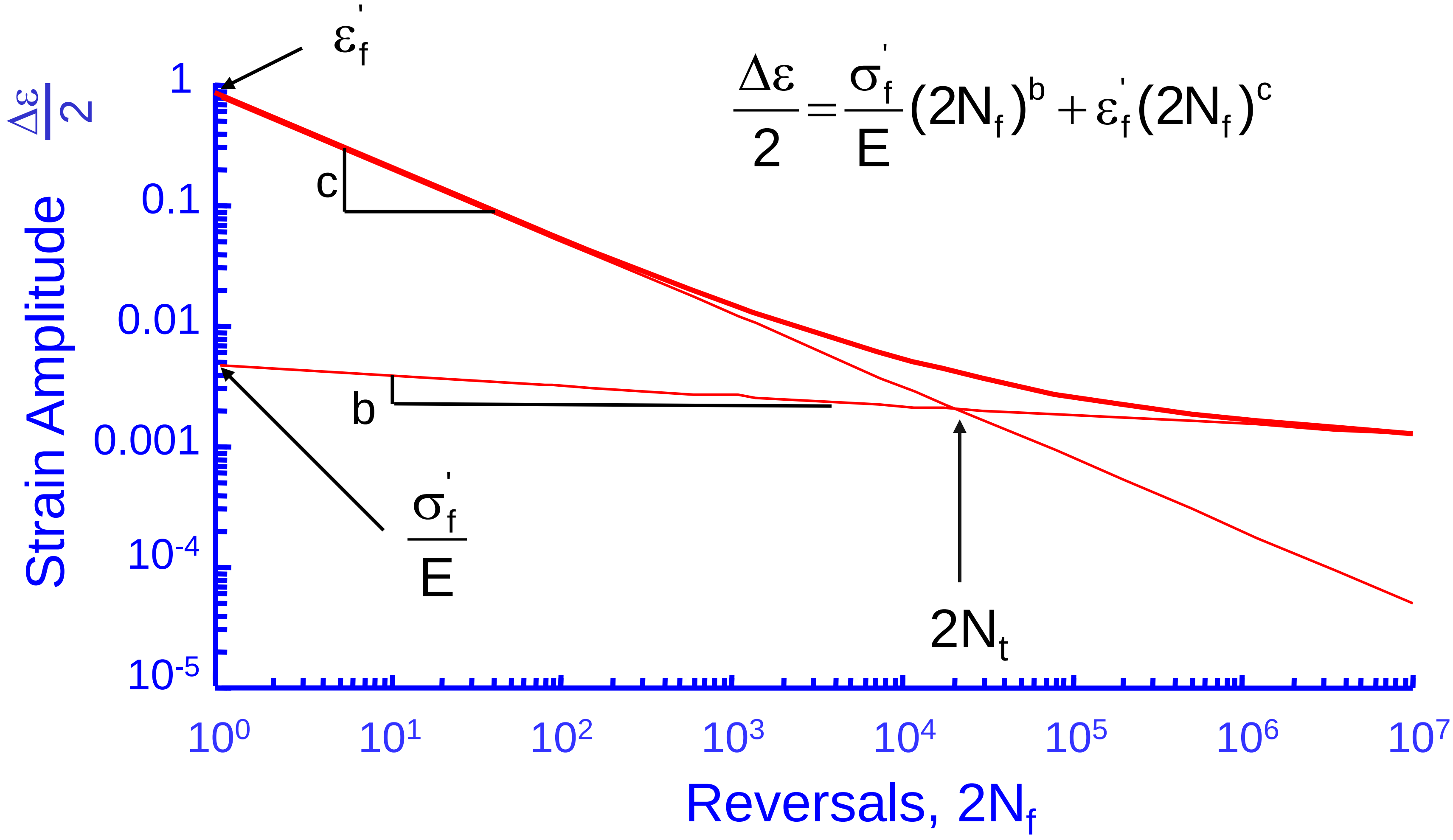


2 Reversals, $2N_f$ = 1 Cycle, N_f

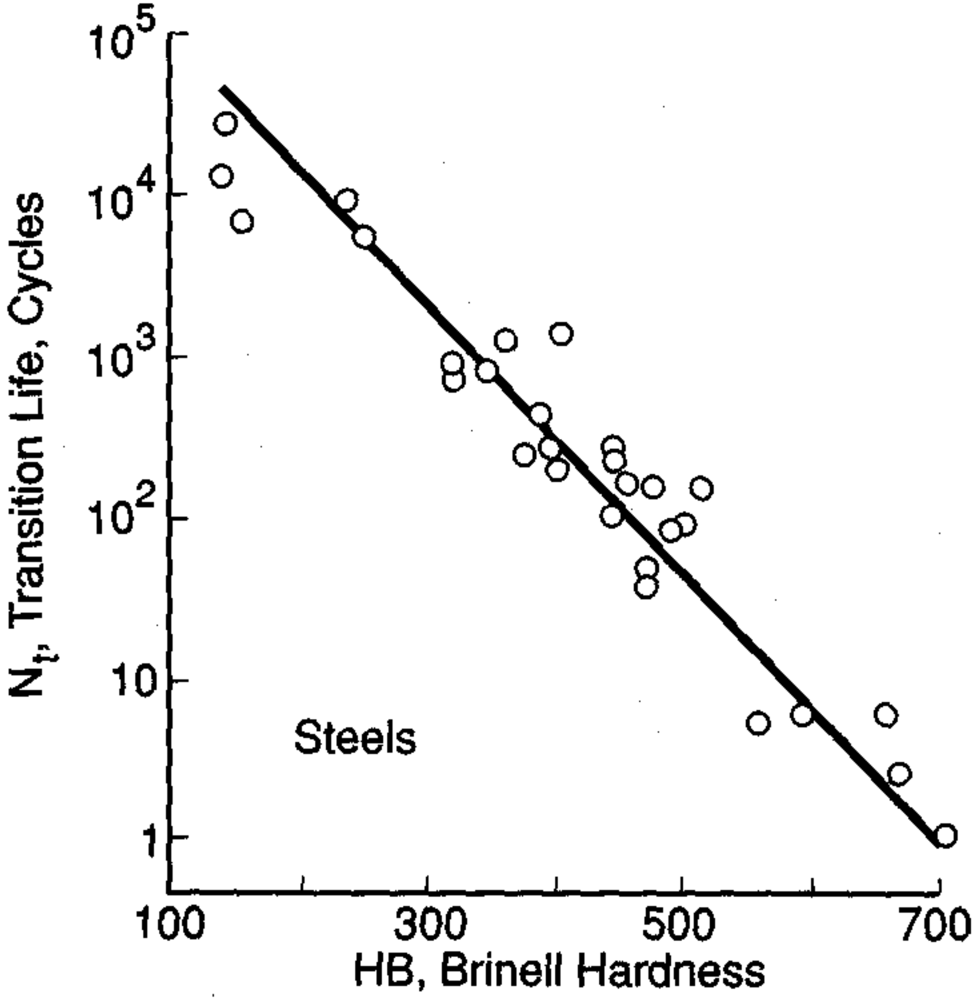
Elastic and Plastic Strain-Life Data



Strain-Life Curve



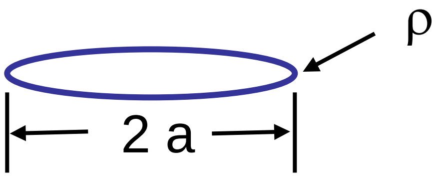
Transition Fatigue Life



From Dowling, Mechanical Behavior of Materials, 1999

Crack Growth Testing

Stress Concentration of a Crack



$$K_T = 1 + 2\sqrt{\frac{a}{\rho}}$$

$$K_T \sim 2000$$

for a crack

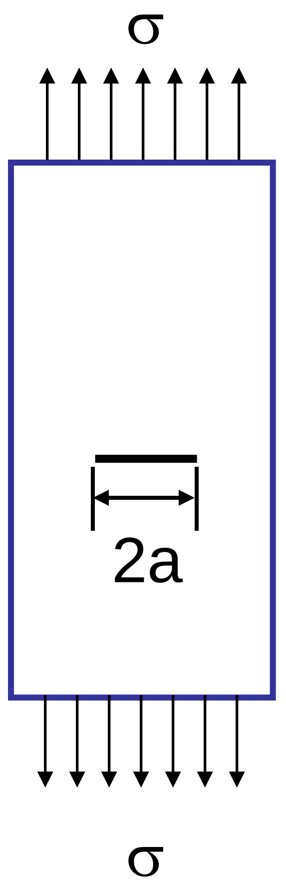
$a \sim 10^{-3}$

$\rho \sim 10^{-9}$

$$\sigma_{local} = 2000\,\sigma_{applied}$$

Traditional material properties like tensile strength are not very useful for cracked structures

Stress Intensity Factor

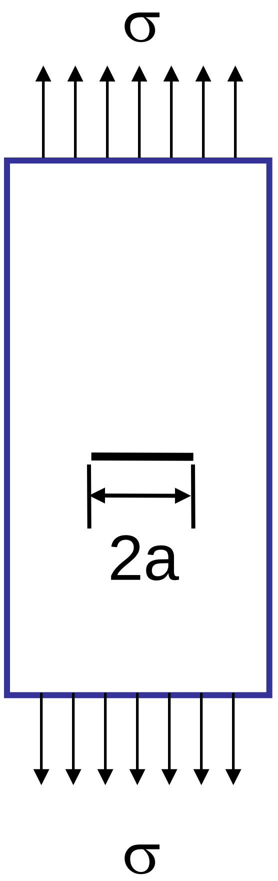


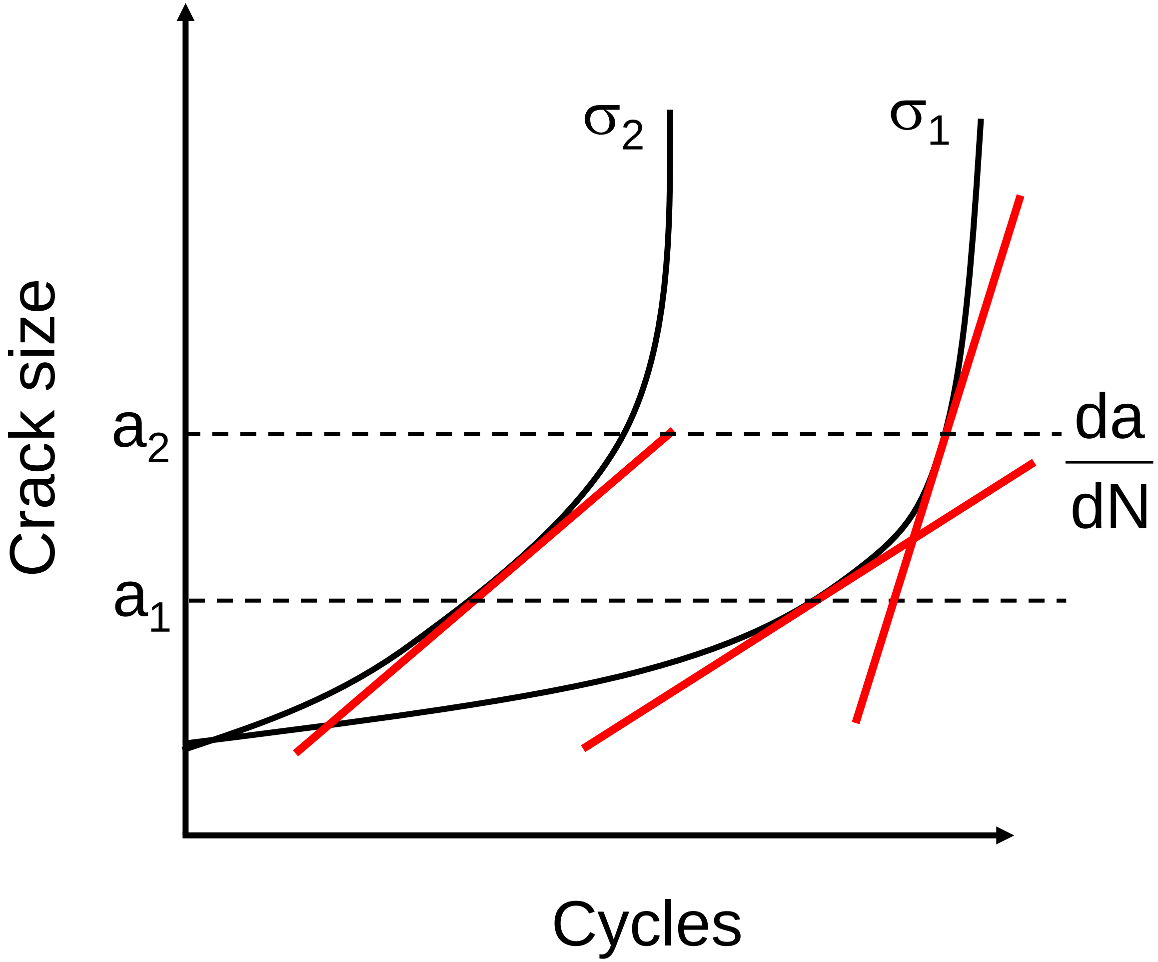
$$K = \sigma \sqrt{\pi a}$$

K characterizes the magnitude of the stresses, strains, and displacements in the neighborhood of a crack tip

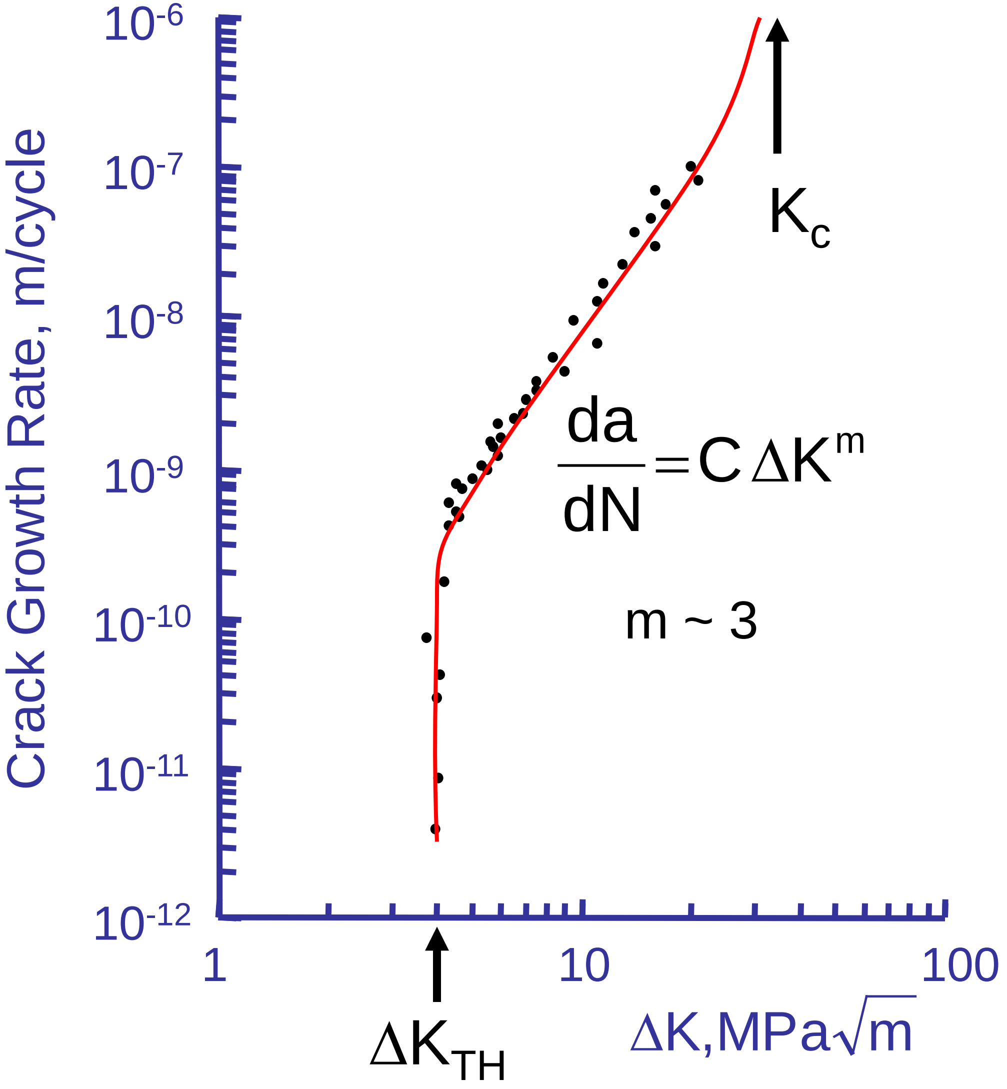
Two cracks with the same K will have the same behavior

Crack Growth Measurements





Crack Growth Data



$$\frac{da}{dN} = C\,\Delta K^m$$

Threshold Region

$$\Delta K_{TH} > \Delta\sigma\sqrt{\pi a}\, f\left(\frac{a}{w}\right)$$

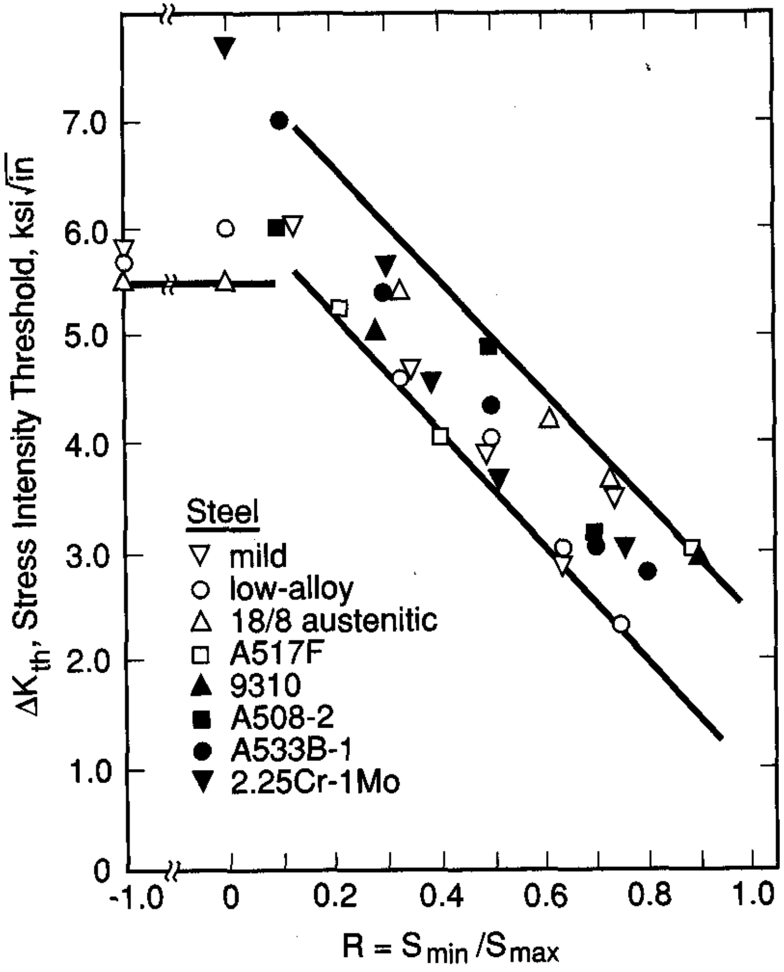
threshold stress intensity

flaw shape

flaw size

operating stresses

Threshold Stress Intensity



From Dowling, Mechanical Behavior of Materials, 1999

Non-propagating Crack Sizes

Small cracks are frequently semielliptical surface cracks

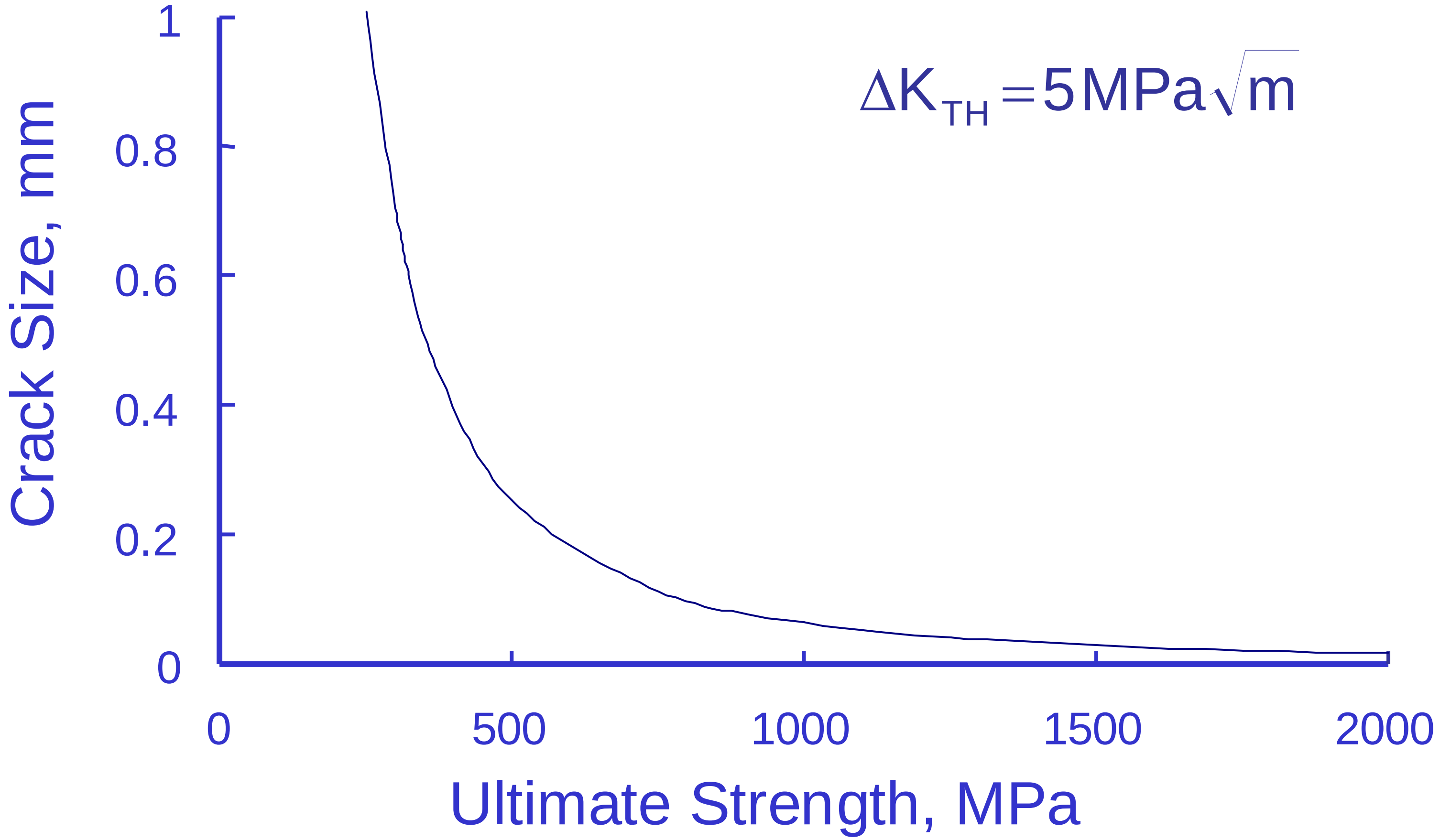
$$\Delta K_{TH} > \Delta\sigma 1.12 \frac{2}{\pi}\sqrt{\pi a}$$

$$a_c = 0.63\left(\frac{\Delta K_{TH}}{\Delta\sigma}\right)^2$$

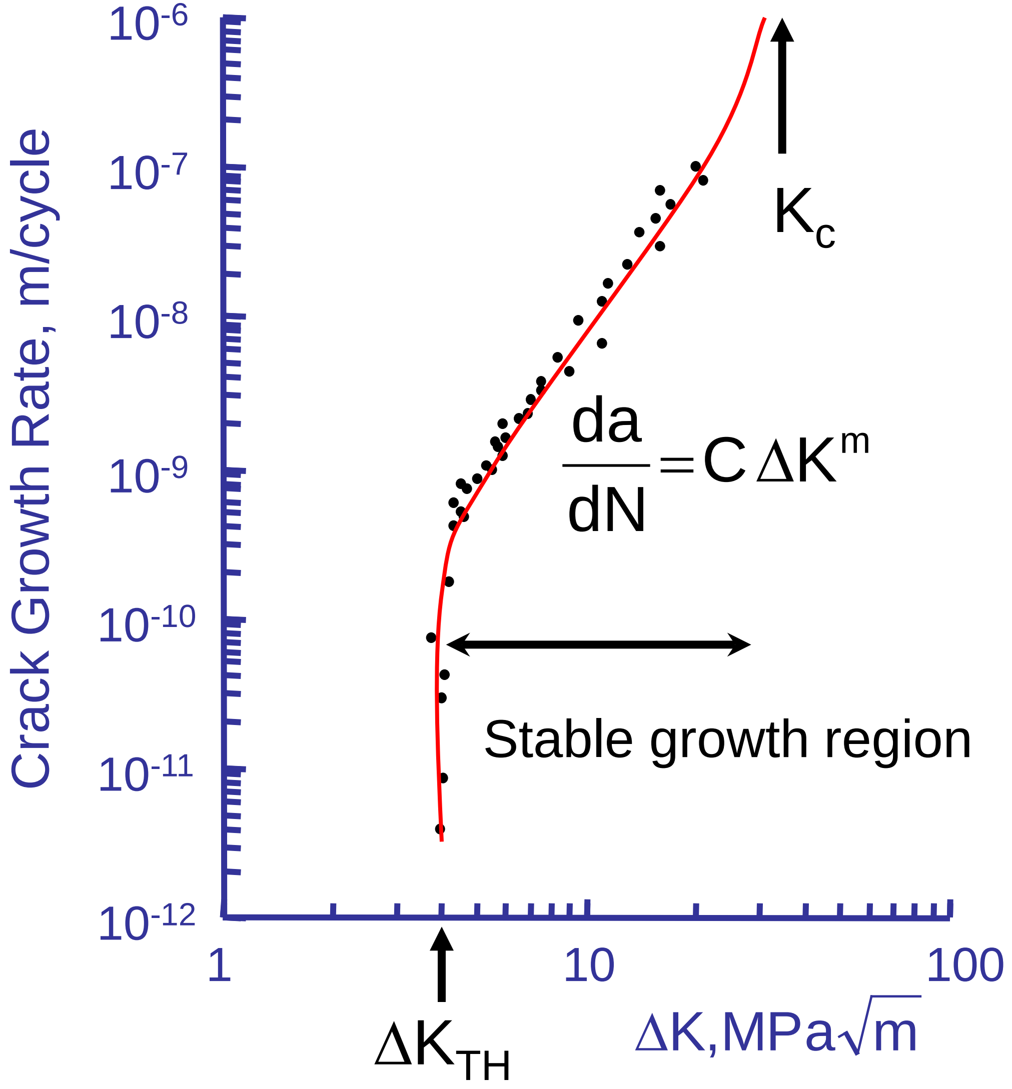
Smooth specimen fatigue limit $\approx \dfrac{\sigma_u}{2}$

$$a_c = 2.52\left(\frac{\Delta K_{TH}}{\sigma_u}\right)^2$$

Non-propagating Crack Sizes

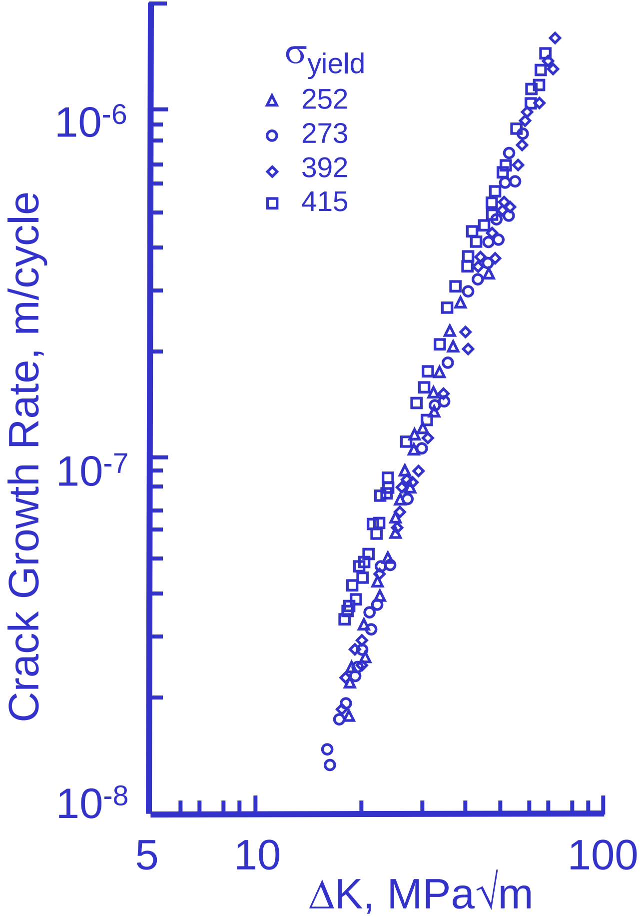


Stable Crack Growth



$$\frac{da}{dN} = C\,\Delta K^m$$

Crack Growth Data



Ferritic-Pearlitic Steel:

$$\frac{da}{dN} = 6.9 \times 10^{-12} \left(\Delta K \, MPa\sqrt{m} \right)^{3.0}$$

Martensitic Steel:

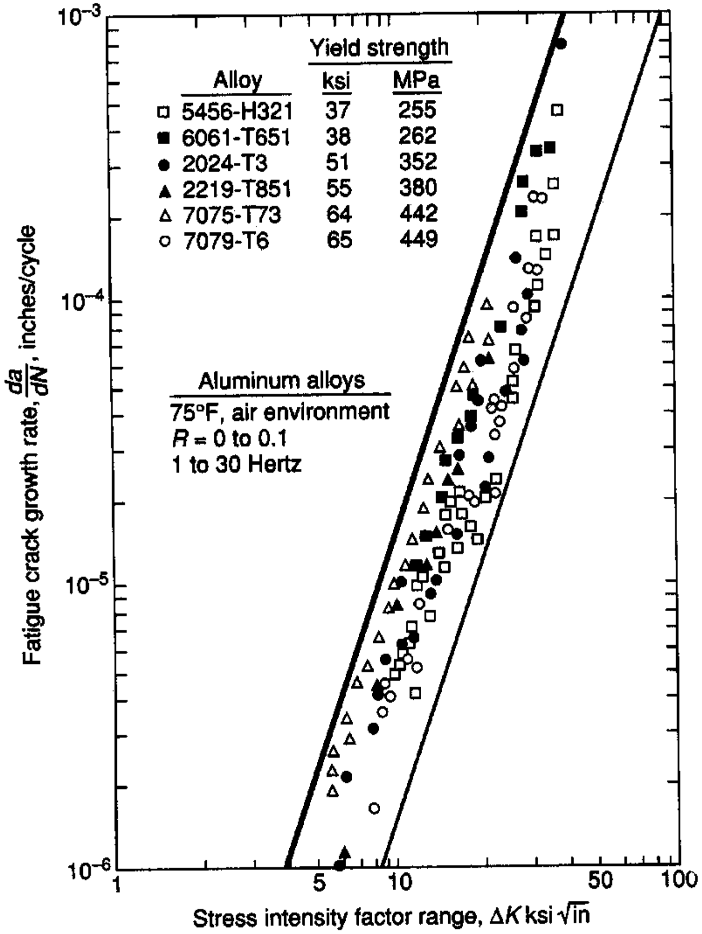
$$\frac{da}{dN} = 1.4 \times 10^{-10} \left(\Delta K \, MPa\sqrt{m} \right)^{2.25}$$

Austenitic Stainless Steel:

$$\frac{da}{dN} = 5.6 \times 10^{-12} \left(\Delta K \, MPa\sqrt{m} \right)^{3.25}$$

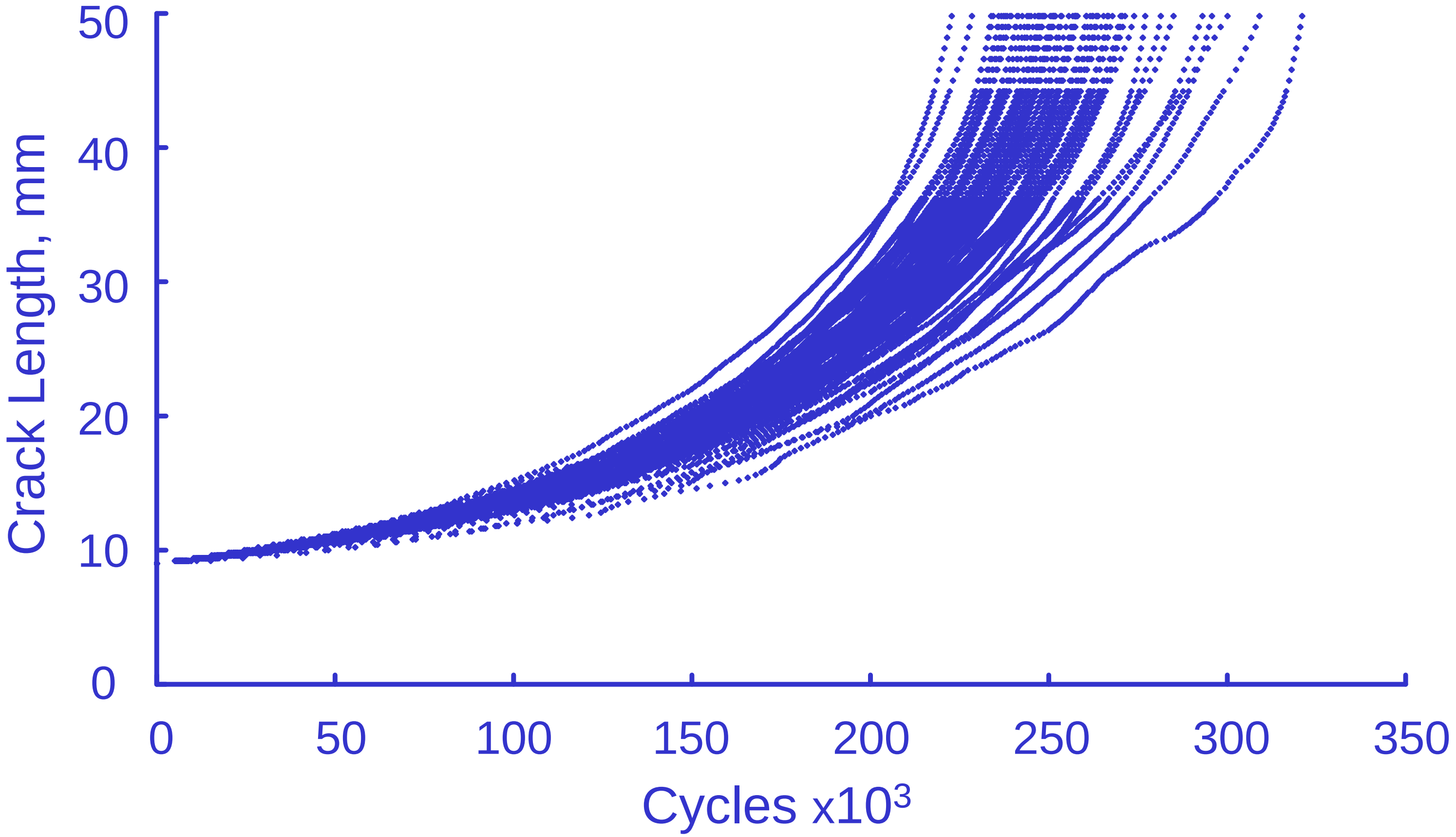
Barsom, “Fatigue Crack Propagation in Steels of Various Yield Strengths”
Journal of Engineering for Industry, Trans. ASME, Series B, Vol. 93, No. 4, 1971, 1190-1196

Aluminum Crack Growth Rate Data



Sharp, Nordmark and Menzemer, *Fatigue Design of Aluminum Components and Structures*, 1996

Crack Growth Data



Virkler, Hillberry and Goel, “The Statistical Nature of Fatigue Crack Propagation”, Journal of Engineering Materials and Technology, Vol. 101, 1979, 148-153

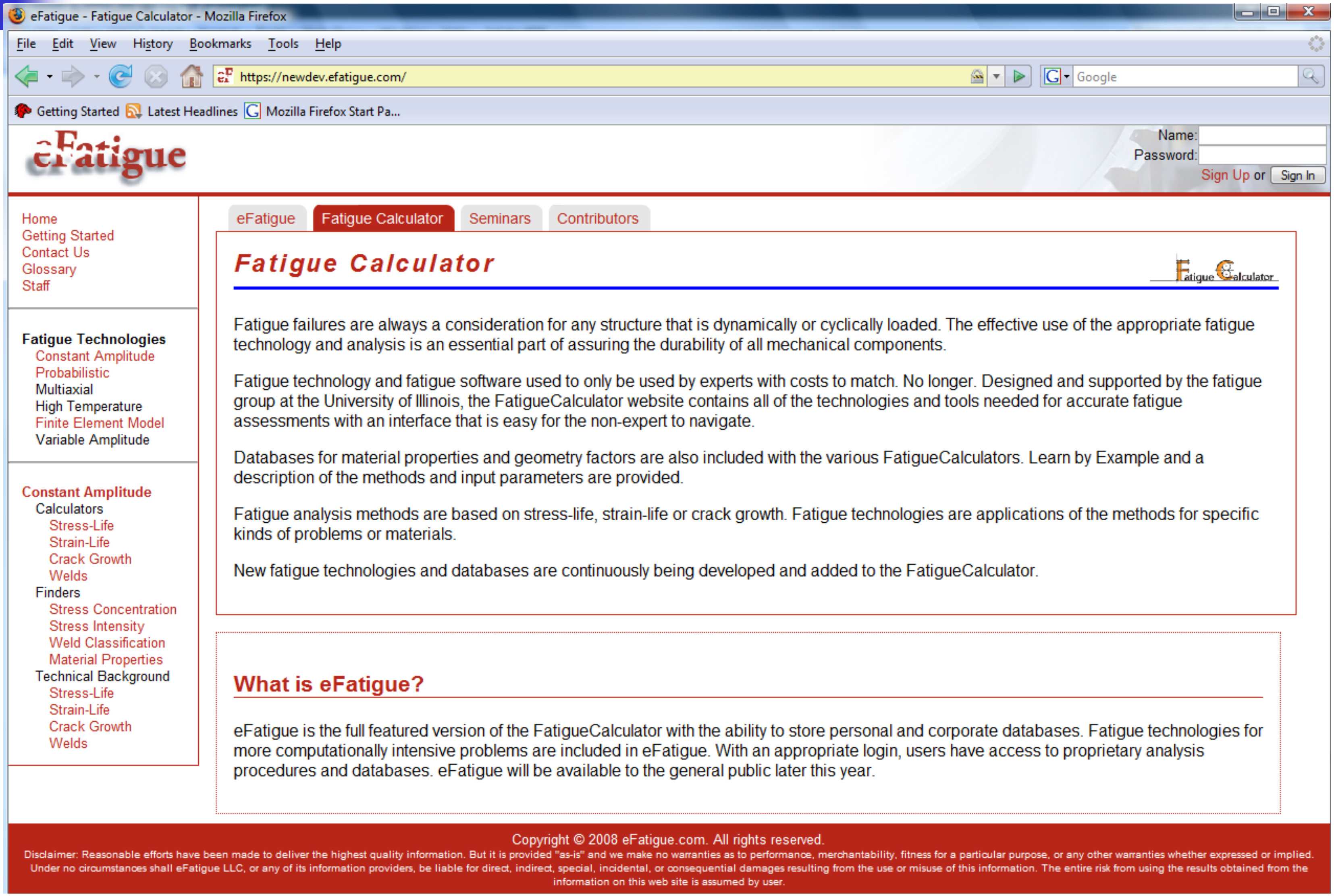
Things Worth Remembering

Method	Physics	Size
Stress-Life	Crack Nucleation	0.01 mm
Strain-Life	Microcrack Growth	0.1 - 1 mm
Crack Growth	Macrocrack Growth	> 1mm

Fatigue, How and Why

- Physics of Fatigue
- Material Properties
- **Introduction to eFatigue**

eFatigue.com



Fatigue Calculator

Fatigue failures are always a consideration for any structure that is dynamically or cyclically loaded. The effective use of the appropriate fatigue technology and analysis is an essential part of assuring the durability of all mechanical components.

Fatigue technology and fatigue software used to only be used by experts with costs to match. No longer. Designed and supported by the fatigue group at the University of Illinois, the FatigueCalculator website contains all of the technologies and tools needed for accurate fatigue assessments with an interface that is easy for the non-expert to navigate.

Databases for material properties and geometry factors are also included with the various FatigueCalculators. Learn by Example and a description of the methods and input parameters are provided.

Fatigue analysis methods are based on stress-life, strain-life or crack growth. Fatigue technologies are applications of the methods for specific kinds of problems or materials.

New fatigue technologies and databases are continuously being developed and added to the FatigueCalculator.

What is eFatigue?

eFatigue is the full featured version of the FatigueCalculator with the ability to store personal and corporate databases. Fatigue technologies for more computationally intensive problems are included in eFatigue. With an appropriate login, users have access to proprietary analysis procedures and databases. eFatigue will be available to the general public later this year.

Physics of Fatigue