Fatigue Made Easy

Historical Introduction

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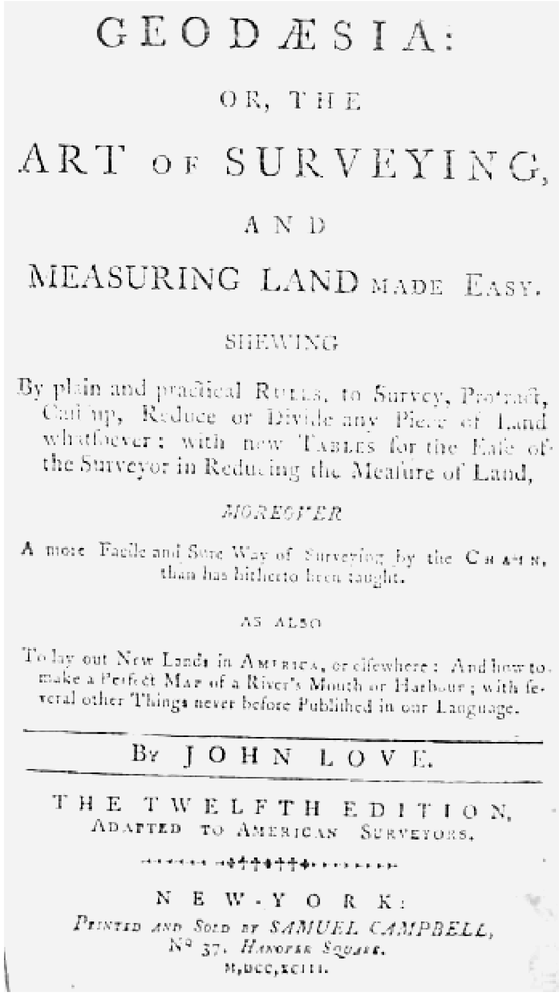
Surveying Made Easy



GEODÆSIA:

OR, THE

ART OF SURVEYING,

AND

MEASURING LAND MADE EASY.

SHEWING

By plain and practical RULES, to Survey, Protract, Cast up, Reduce or Divide any Piece of Land whatsoever: with new TABLES for the Ease of the Surveyor in Reducing the Measure of Land,

MOREOVER

A more Facile and Sure Way of Surveying by the CHAIN, than has hitherto been taught.

AS ALSO

To lay out New Lands in AMERICA, or elsewhere: And how to make a Perfect MAP of a River's Mouth or Harbour; with several other Things never before Published in our Language.

By JOHN LOVE.

THE TWELFTH EDITION, ADAPTED TO AMERICAN SURVEYORS.

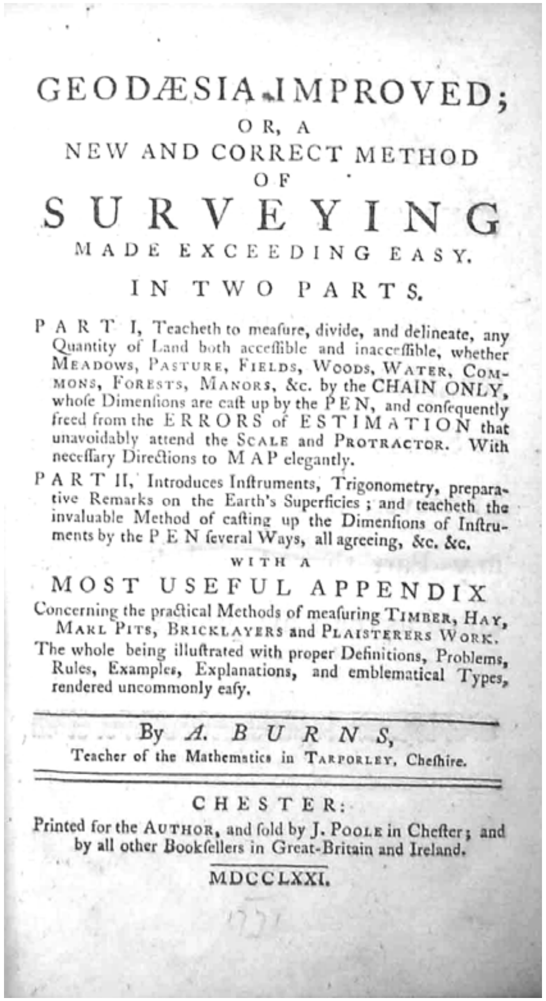
NEW-YORK:

PRINTED AND SOLD BY SAMUEL CAMPBELL, Nº 37, HANOVER SQUARE.

M,DCC,XCIII.

1688 1st

1793 12th



GEODÆSIA IMPROVED;

OR, A

NEW AND CORRECT METHOD

OF

SURVEYING

MADE EXCEEDING EASY.

IN TWO PARTS.

PART I, Teacheth to measure, divide, and delineate, any Quantity of Land both accessible and inaccessible, whether MEADOWS, PASTURE, FIELDS, WOODS, WATER, COMMONS, FORESTS, MANORS, &c. by the CHAIN ONLY, whose Dimensions are cast up by the PEN, and consequently freed from the ERRORS of ESTIMATION that unavoidably attend the SCALE and PROTRACTOR. With necessary Directions to MAP elegantly.

PART II, Introduces Instruments, Trigonometry, preparative Remarks on the Earth's Superficies; and teacheth the invaluable Method of casting up the Dimensions of Instruments by the PEN several Ways, all agreeing, &c. &c.

WITH A

MOST USEFUL APPENDIX

Concerning the practical Methods of measuring TIMBER, HAY, MARL PITS, BRICKLAYERS and PLAISTERERS WORK. The whole being illustrated with proper Definitions, Problems, Rules, Examples, Explanations, and emblematical Types, rendered uncommonly easy.

By A. BURNS,

Teacher of the Mathematics in TARPORLEY, Cheshire.

CHESTER:

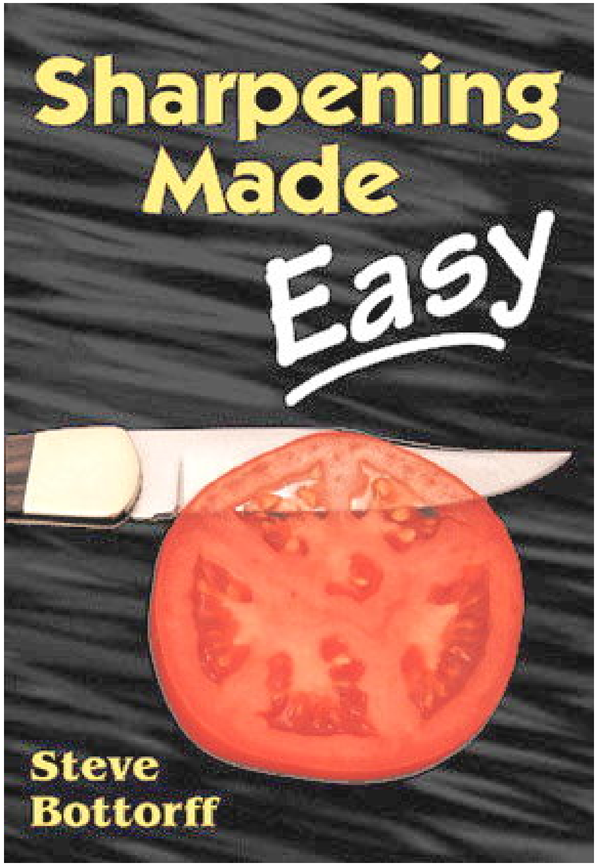
Printed for the AUTHOR, and sold by J. POOLE in Chester; and by all other Booksellers in Great-Britain and Ireland.

MDCCLXXI.

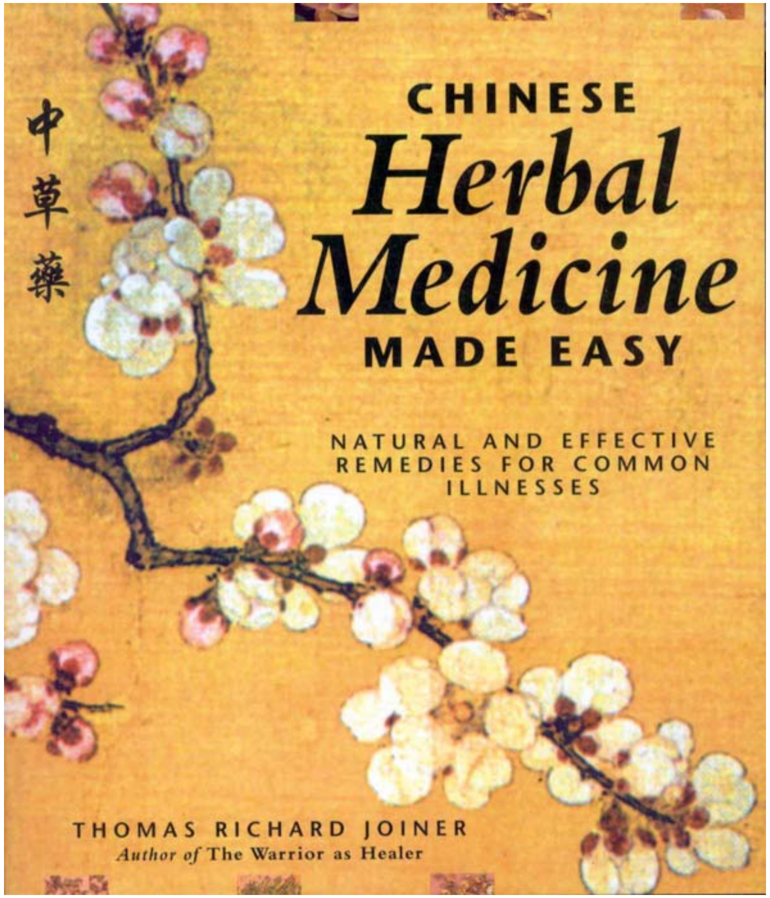
1771

<http://www.uzes.net/1600to1800books.htm>

… Made Easy

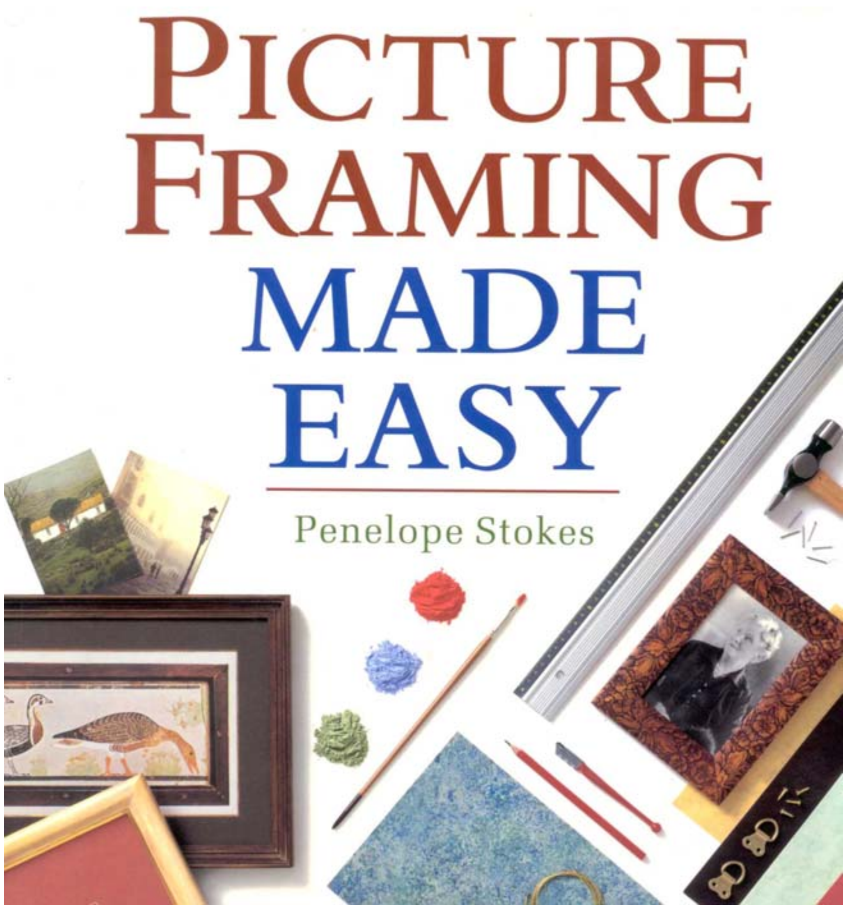


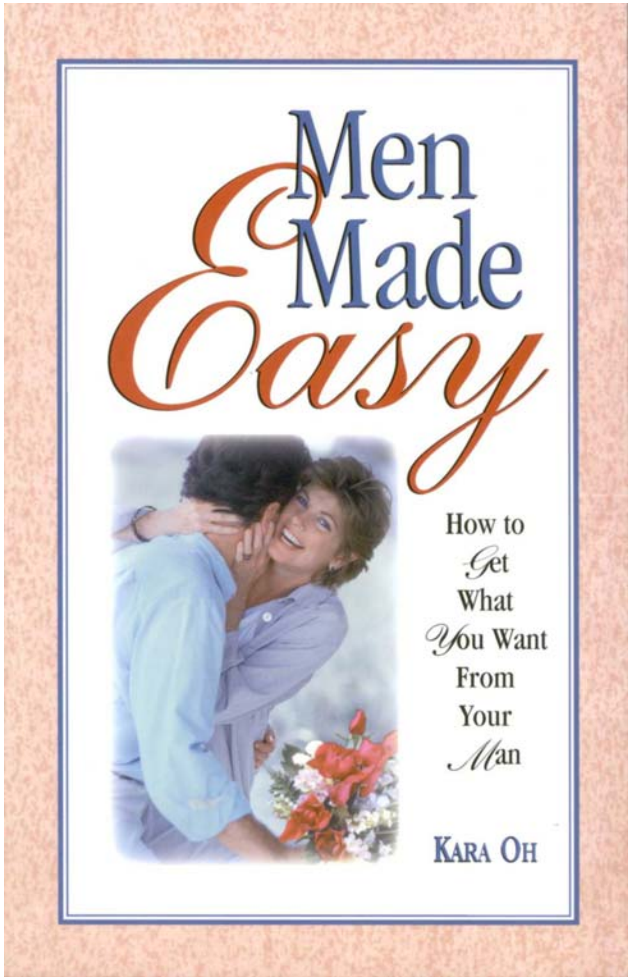
Sharpening
Made
Easy
Steve
Bottorff



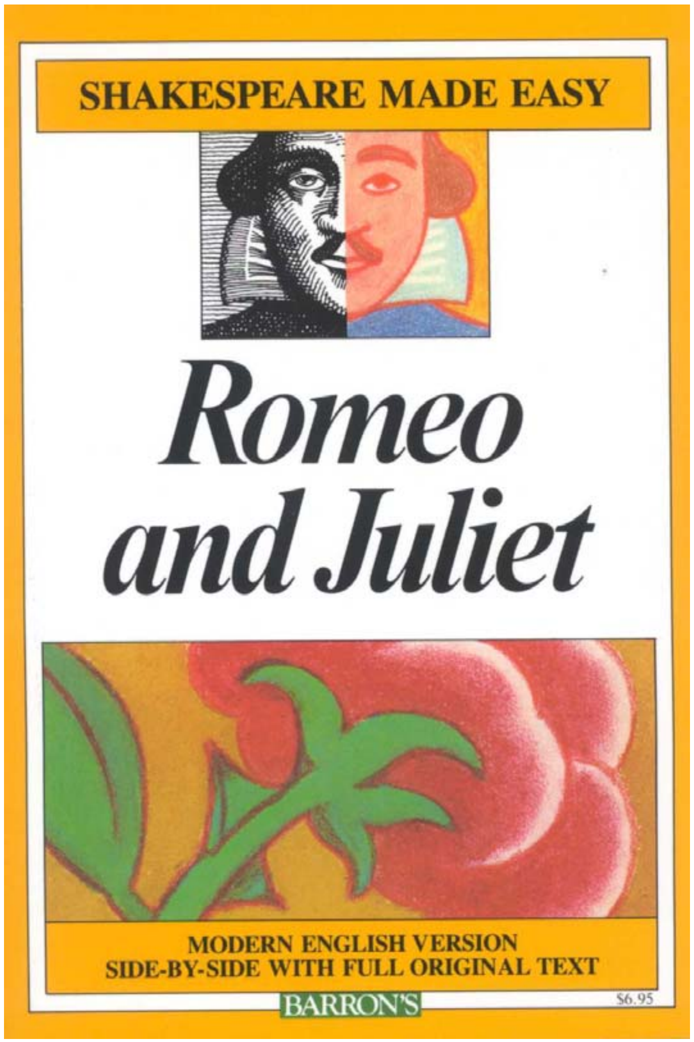
中
草
藥
CHINESE
Herbal
Medicine
MADE EASY
NATURAL AND EFFECTIVE
REMEDIES FOR COMMON
ILLNESSES
THOMAS RICHARD JOINER
Author of The Warrior as Healer

… Made Easy


PICTURE
FRAMING
MADE
EASY
Penelope Stokes


Men
Made
Easy
How to
Get
What
You Want
From
Your
Man
KARA OH

Shakespheare Made Easy



Original

Nurse Now God in heaven bless thee! Hark you sir.

Romeo What say'st thou, my dear nurse?

Nurse Is your man secret? Did you ne'er hear say
Two may keep counsel, putting one away?

Romeo I warrant thee my man's as true as steel.

Translation

Nurse May God in heaven bless you! But listen, sir – [*She beckons him to come nearer*]

Romeo Yes, dear Nurse?

Nurse Is your man trustworthy? Did you never hear it said, "Two can keep a secret if one doesn't know it"?

Romeo I guarantee my man's as true as steel.

Shakespheare Made Easy, Alan Durband, Hutchinson & Co Ltd, London, 1985

Seminar Outline

1. Historical background
2. Physics of fatigue
3. Characterization of materials
4. Similitude (why fatigue modeling works)
5. Variability
6. Mean stress
7. Stress concentrations
8. Surface effects
9. Variable amplitude loading
10. Welded structures

19th Century

1829	Albert	Repeated Loads
1839	Poncelet	“fatigue”
1843	Rankine	Stress Concentrations
1860	Wohler	Systematic Investigations
1886	Baushinger	Cyclic Deformation
1890	Goodman	Mean Stresses
1903	Ewing & Humfrey	Fatigue Mechanisms

At the dawn of the industrial revolution

The first major transportation disaster-Versailles accident of

May 11, 1842

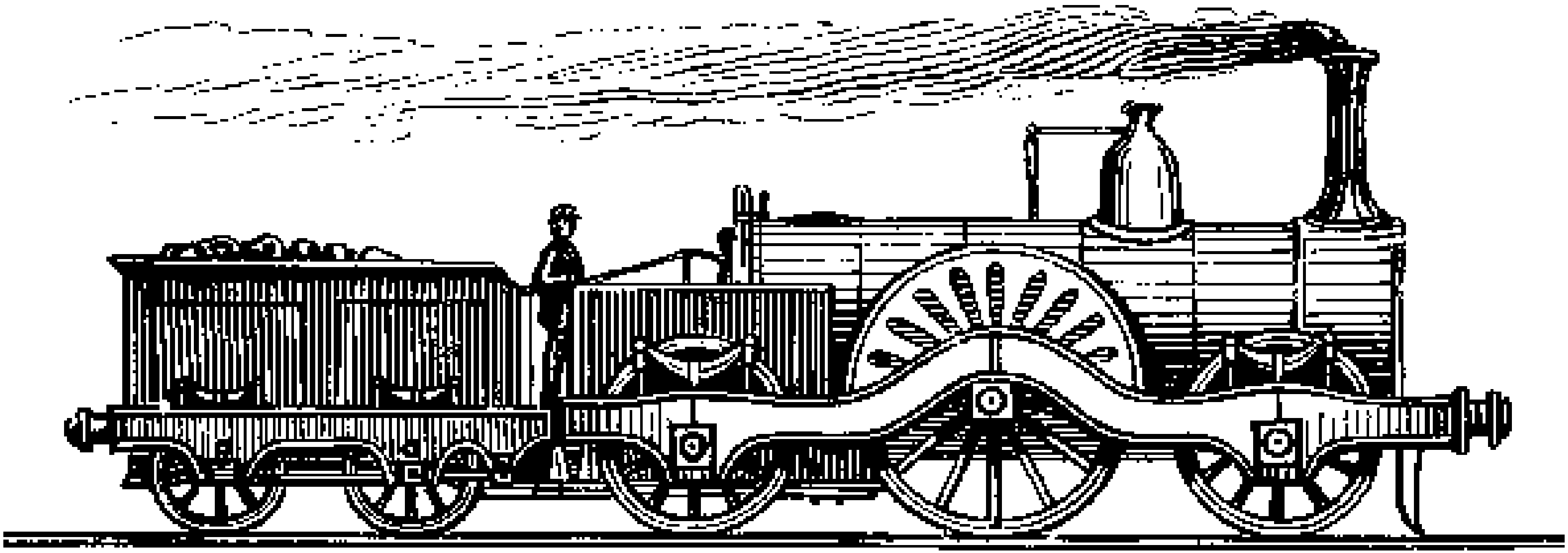
Versailles


Houilles
A86
Saint-Denis
Asnières-Sur-Seine
Drancy
Colombes
A14
Carrières-Sur-Seine
Clichy
Aubervilliers
Nanterre
Pantin
Chatou
Courbevoie
Lilas (Les)
Puteaux
Neuilly-Sur-Seine
Bagnolet
Paris
Suresnes
Montreuil
Celle-Saint-Cloud (La)
Saint-Cloud
A13
Garches
Boulogne-Billancourt
Ville-D'Avray
Sèvres
Issy-Les-Moulineaux
Gentilly
Meudon
Montrouge
Ivry-Sur-Seine
Versailles
Arcueil
Maisons-Alfort
Porte de Châtillon
Créteil
N286
Bagneux
Fontenay-Aux-Roses
Vitry-Sur-Seine
Buc
Châtenay-Malabry
Jouy-En-Josas
Chevilly-Larue
Antony

‘The Times’, May 11, 1842

“I have this day to announce to you one of the most frightful events that has occurred in modern times. … The train of the left bank was unusually long; … from 1500 to 1800 passengers. On arriving between Meudon and Bellevue the axle tree of the first engine broke. … The second engine … passed over it, and the boiler burst … The carriages arrived of course, and passed over the wreck, when six of them were … instantly ignited. Three were totally consumed, … without the possibility of escape to the unhappy inmates, who were locked up … The number of killed is variously estimated (between 40 and 80).”

Early steam engine



Typical broken axle of the 1840s

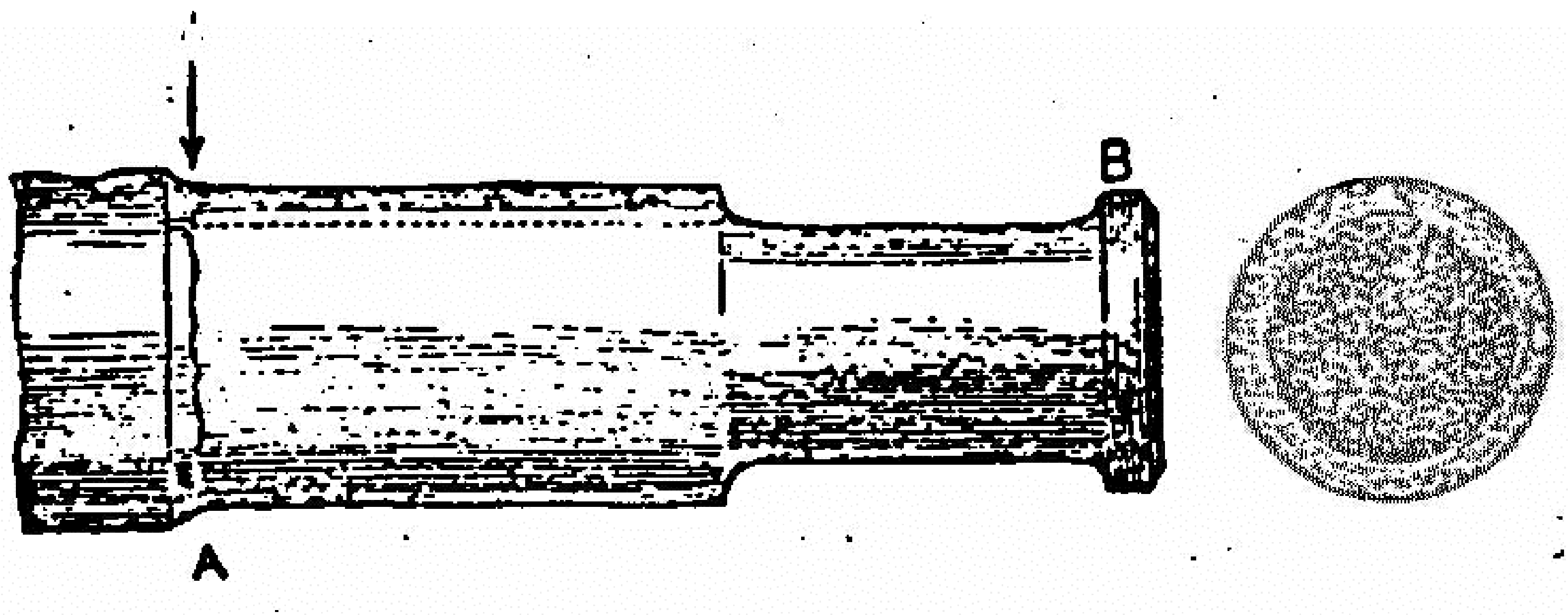


Fig 1. Classic appearance of a fatigue cracked railway axle from Glynn, 1844.

Expert opinions of the time

- "I never met one which did not present a crystallization fracture…"
- "the principal causes … are percussion, heat and magnetism"
- "the change … may take place instantaneously"
- "steam can speedily cause iron to become magnetic"

Rankine 1820 - 1872

Trained as a civil engineer

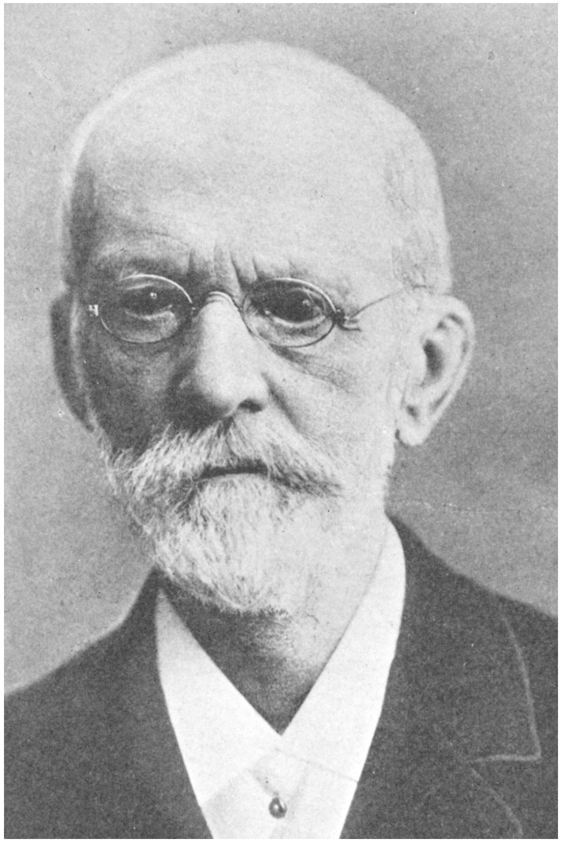
William Rankine’s second paper

- Stated that deterioration of axles is gradual
- “the fractures appear to have commenced with a smooth, regularly-formed, minute fissure, extending all round the neck of the journal, and penetrating on an average to a depth of half an inch. … until the thickness of sound iron in the center became insufficient to support the shocks to which it was exposed.”

Rankine ...

- “In all the specimens the iron remained fibrous; proving that no material change had taken place in the structure”
- He noted that fractures occurred at sharp corners
- He recommended that the journals be formed with a large curve in the shoulder (which is exactly right!)

Wöhler 1819 - 1914

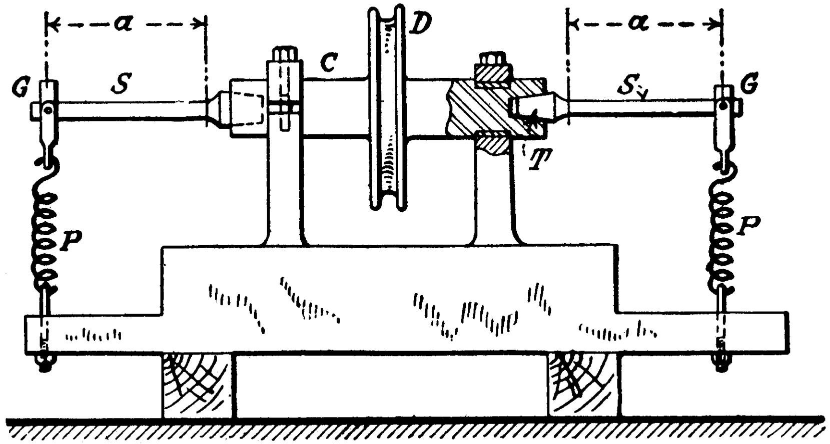


Prussian Railway Service

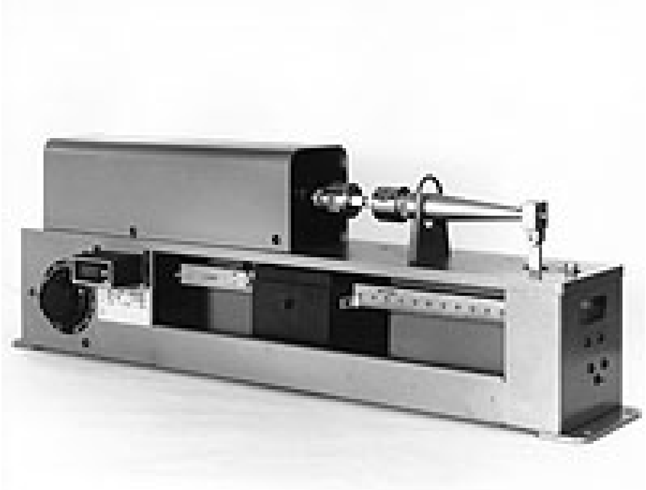
Work done before the development of the metallurgical microscope

Critical value of stress below which failure will not occur

Wöhler Tests



Wöhler circa 1850

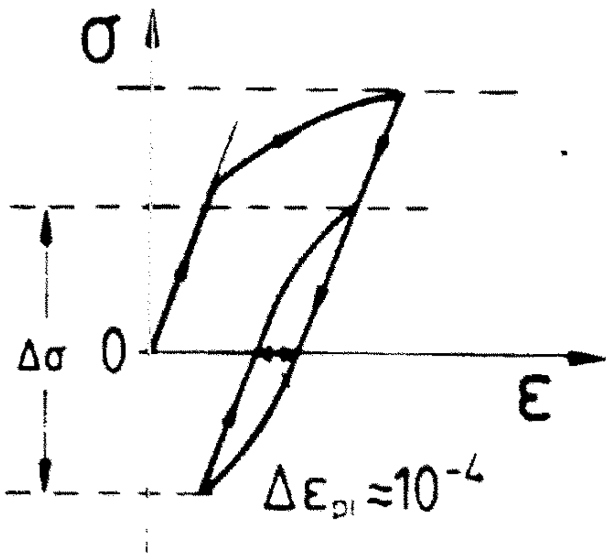


Fatigue Dynamics circa 2000

Wöhler Observations

- Steel will rupture at stress less than the elastic limit if the stress is repeated a sufficient number of times
- Stress range rather than maximum stress determines the number of cycles
- There appears to be a limiting stress range which may be applied indefinitely without failure
- As the maximum stress increases, the limiting stress range decreases

Bauschinger 1834 - 1893



Cyclic Behavior of Materials
Bauschinger Effect
Natural Elastic Limit

Goodman

Mechanics Applied to Engineering
John Goodman, 1890

".. whether the assumptions of the theory are justifiable or not …. We adopt it simply because it is the easiest to use, and for all practical purposes, represents Wöhlers data.

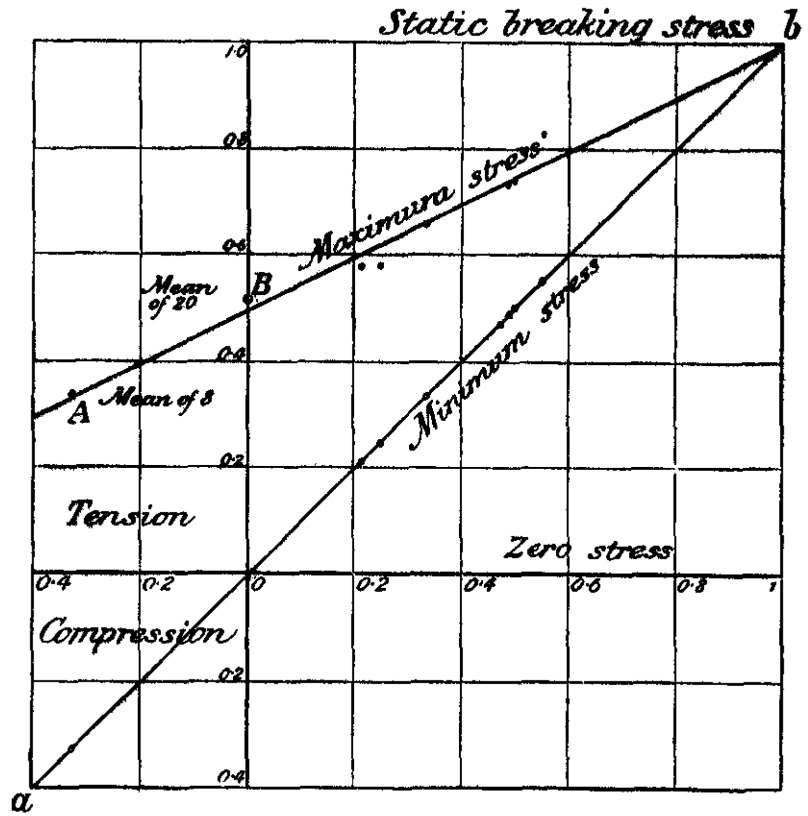
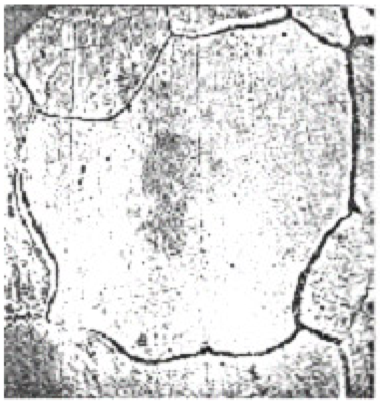


FIG. 517.

1903 - Ewing and Humfrey



N = 1,000

N = 2,000

N = 10,000

N = 40,000 N_f = 170,000

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

Ewing and Humfrey (1903) The Fracture of Metals Under Repeated Alterations of Stress, *Philosophical Transactions of the Royal Society*, A, Vol 221, 241-253

Their Description of Fatigue

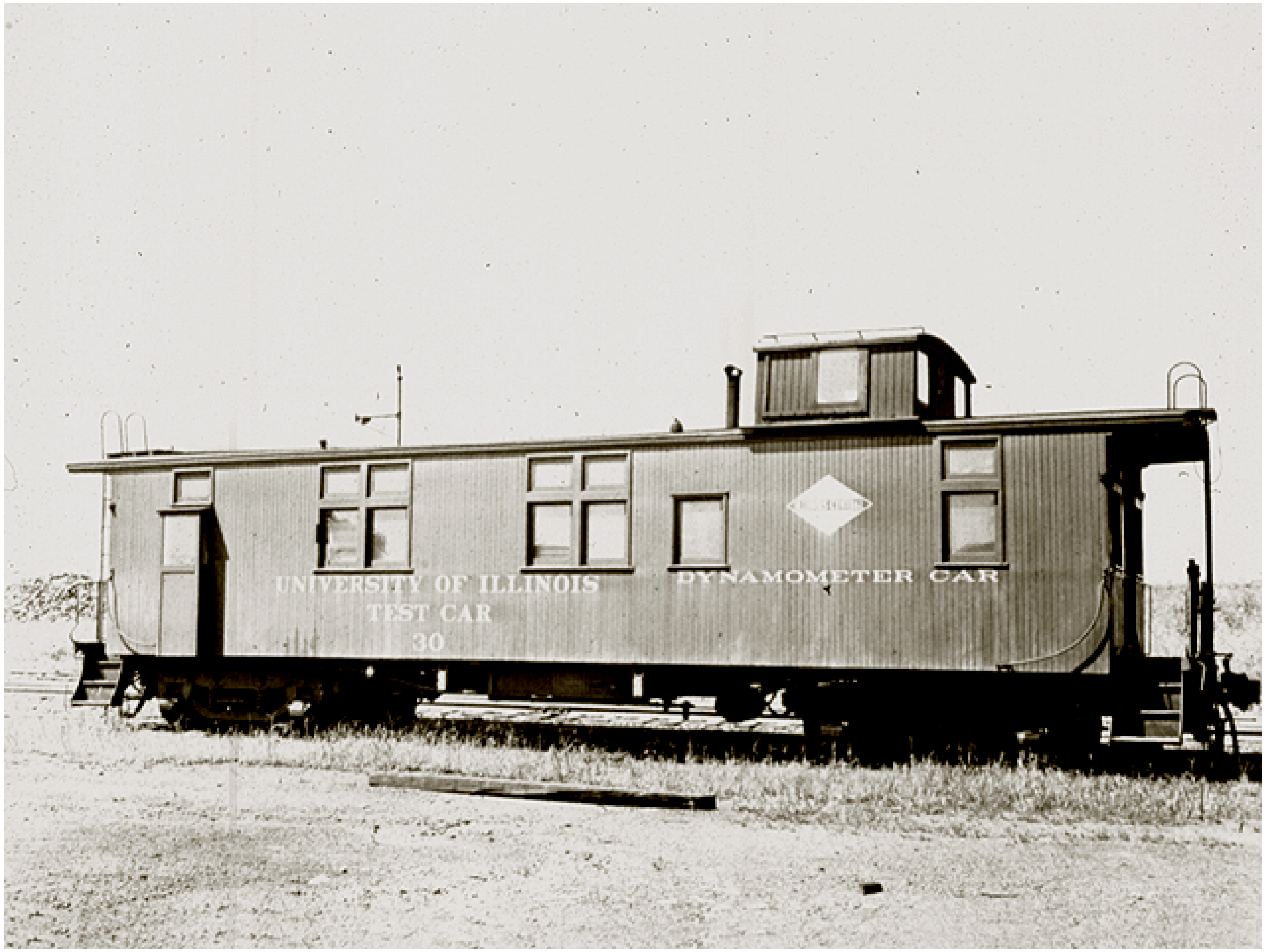
The course of the breakdown was as follows: The first examination, made after a few reversals of the stress, showed slip lines on some of the crystals … after more reversals of stress additional slip lines appeared …. After many reversals they changed into comparatively wide bands with rather hazily defined edges … some parts of the crystals became almost covered with dark markings …. at this stage some of the crystals had cracked.

Once an incipient crack forms across a set of crystals, the effect of further reversals is mainly confined to the neighborhood of the crack tip.

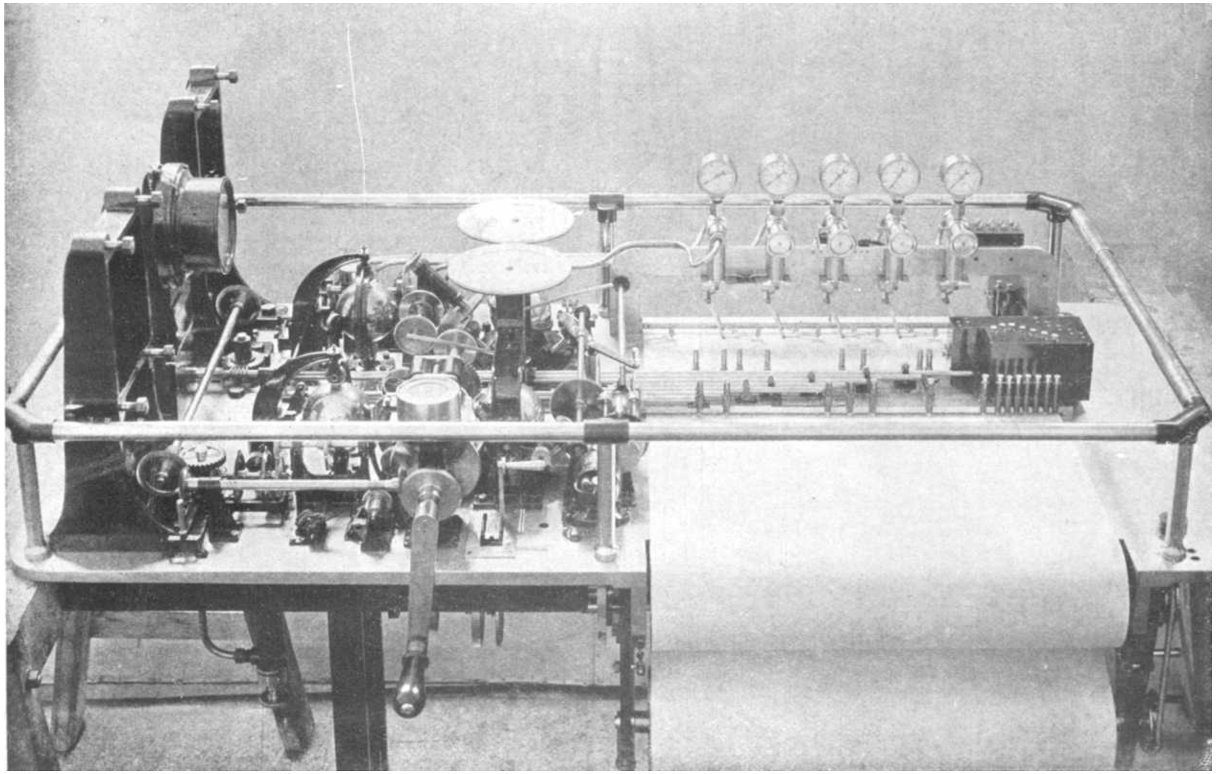
20th Century

1920	Griffith	Fracture Mechanics
1945	Miner	Cumulative Damage
1954	Coffin & Manson	Plastic Strains
1961	Paris	Crack Growth
1963	Peterson	Strain-Life Method
1967	Endo	Cycle Counting

Circa 1910 Data Acquisition



Early Strip Chart



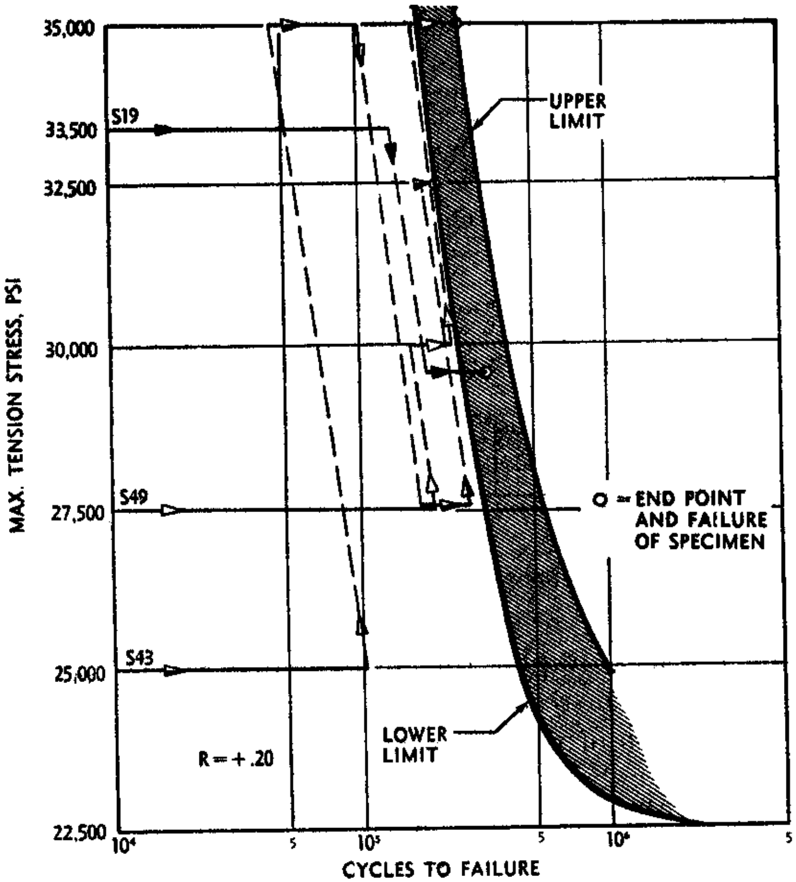
Griffith 1893-1963

Circa1920 studied scratches and the effect of surface finish on fatigue for the Royal Aircraft Establishment

$$\sigma\sqrt{\pi a} = \sqrt{2\gamma E}$$

Griffith (1920) The Phenomena of Rupture and Flow in Solids, *Philosophical Transactions of the Royal Society*, A, 221, 163-198

Miner

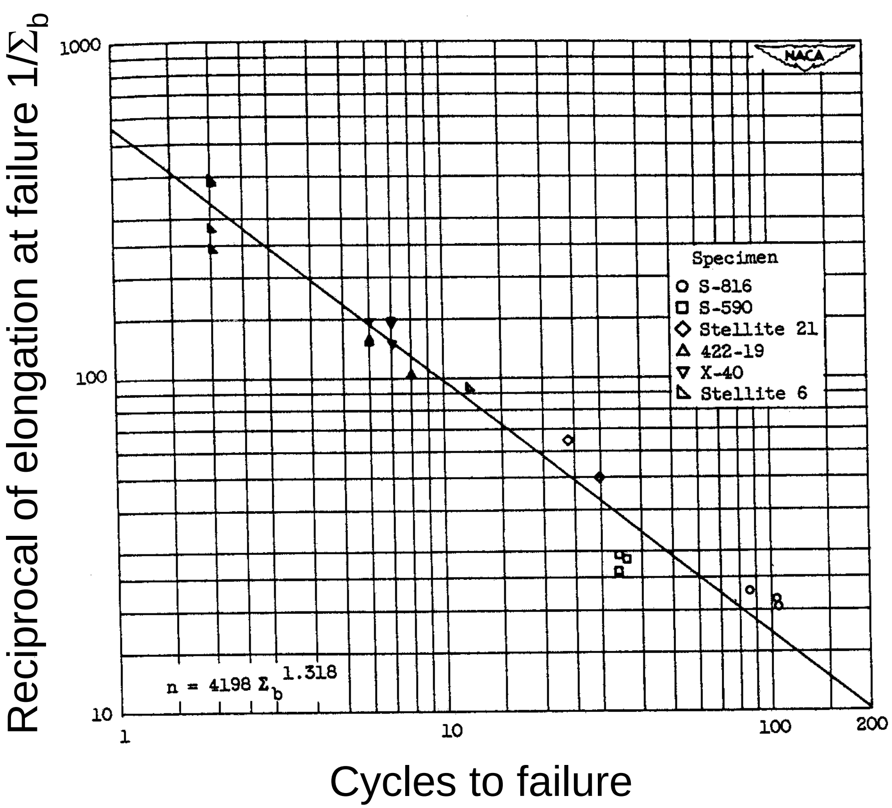


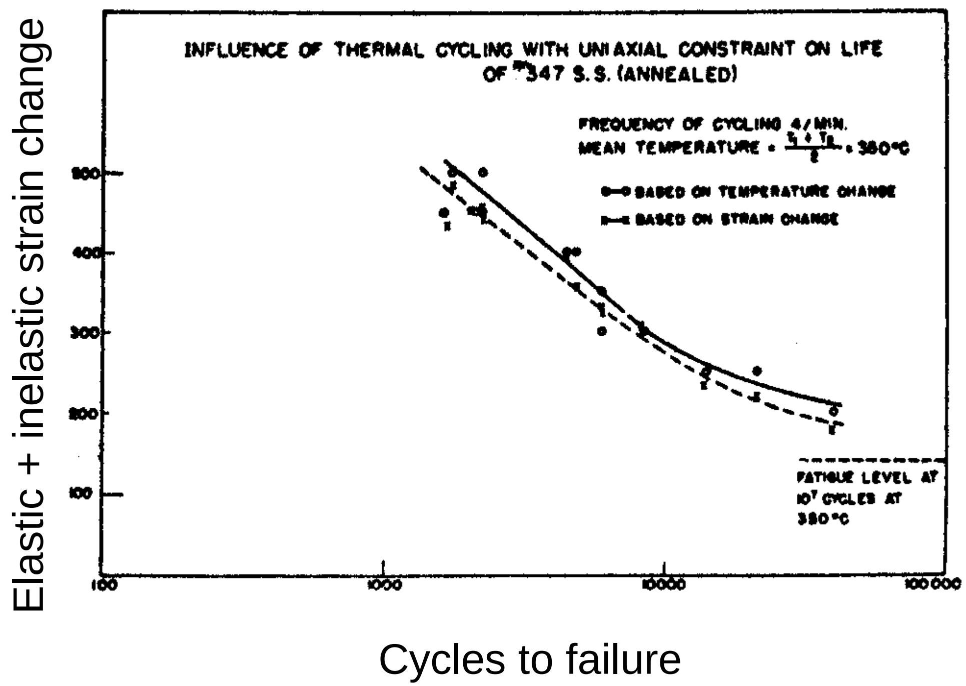
The phenomenon of cumulative damage under repeated loads was assumed to be related to the net work absorbed by a specimen

"proved" linear damage rule

Miner (1945) Cumulative Damage in Fatigue, *Journal of Applied Mechanics*, Vol. 12, 1945, A159-A164

1954 - Coffin and Manson

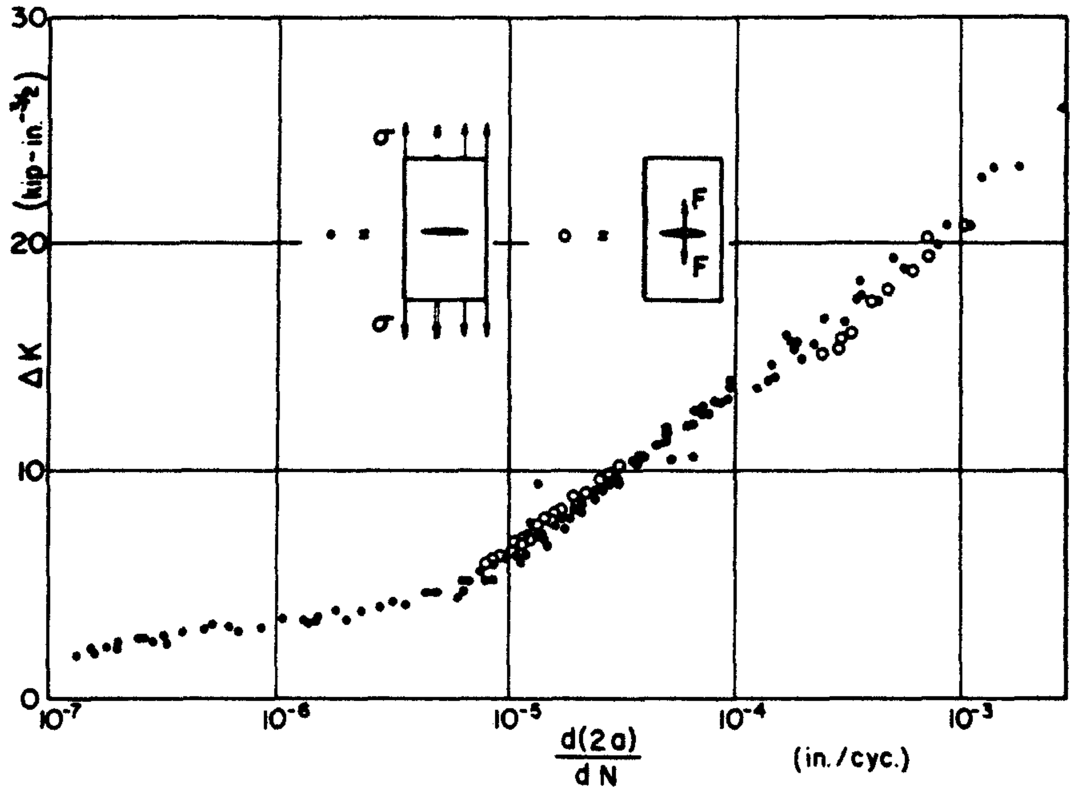




Manson (1953) Behavior of Materials Under Conditions of Thermal Stress, NACA Technical Note 2933

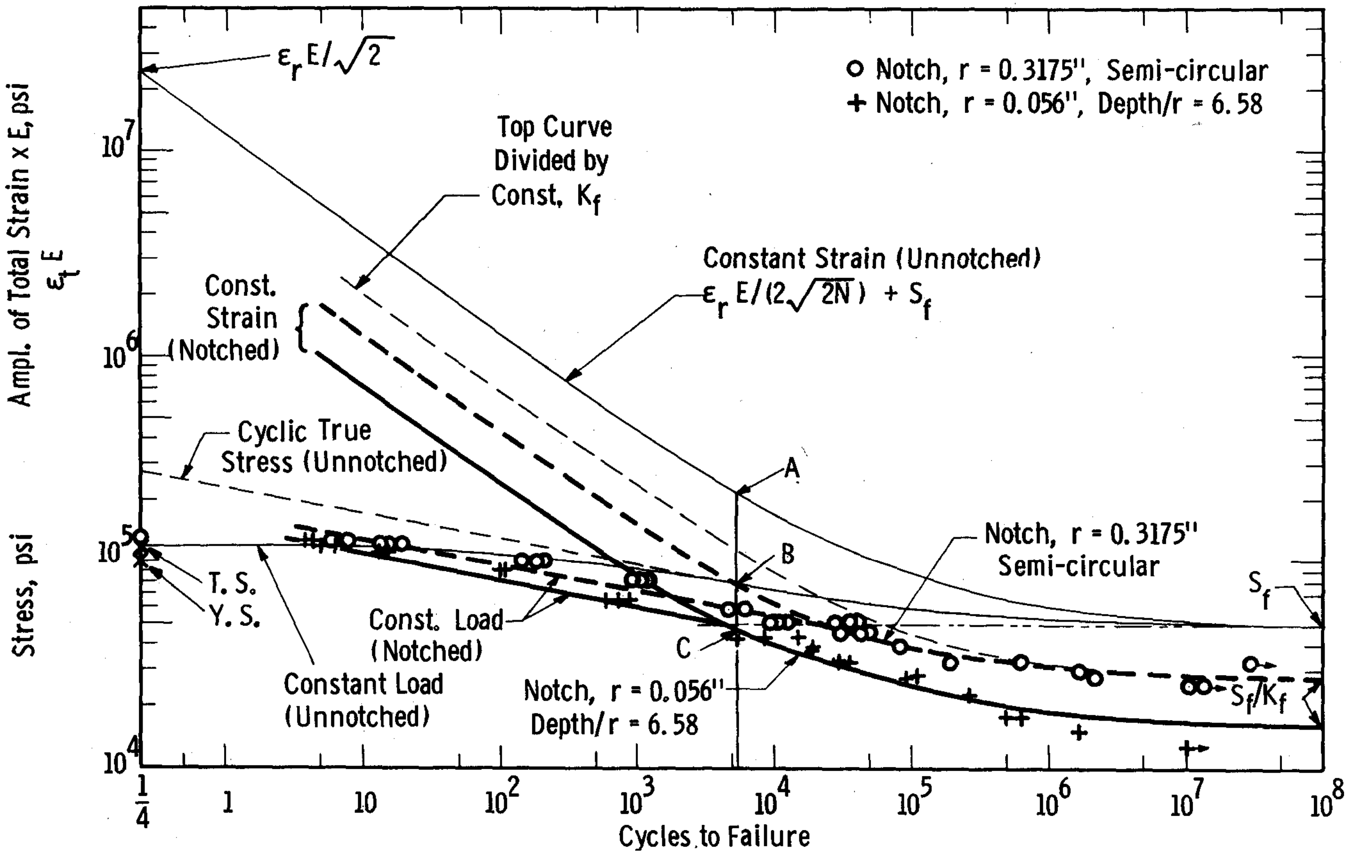
Coffin (1954) A Study of the Effects of Cyclic Thermal Stress on a Ductile Metal, *Transactions ASME*, Vol. 76, 931-950

1961 - Paris



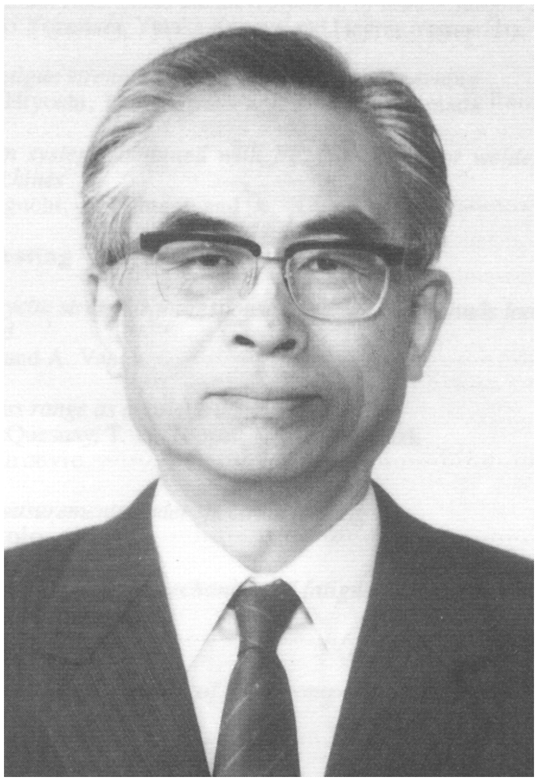
Paris (1963) The Fracture Mechanics Approach to Fatigue, Proceedings of the Tenth Sagamore Army Materials Conference, 107-132

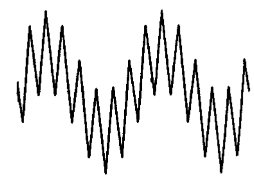
1963 Peterson

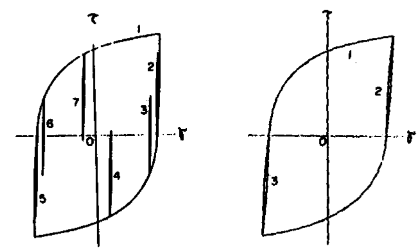


Peterson (1963) Fatigue of Metals: Part 3 Engineering and Design Aspects, *Materials Research and Standards*, 122-139

Endo 1925 - 1989



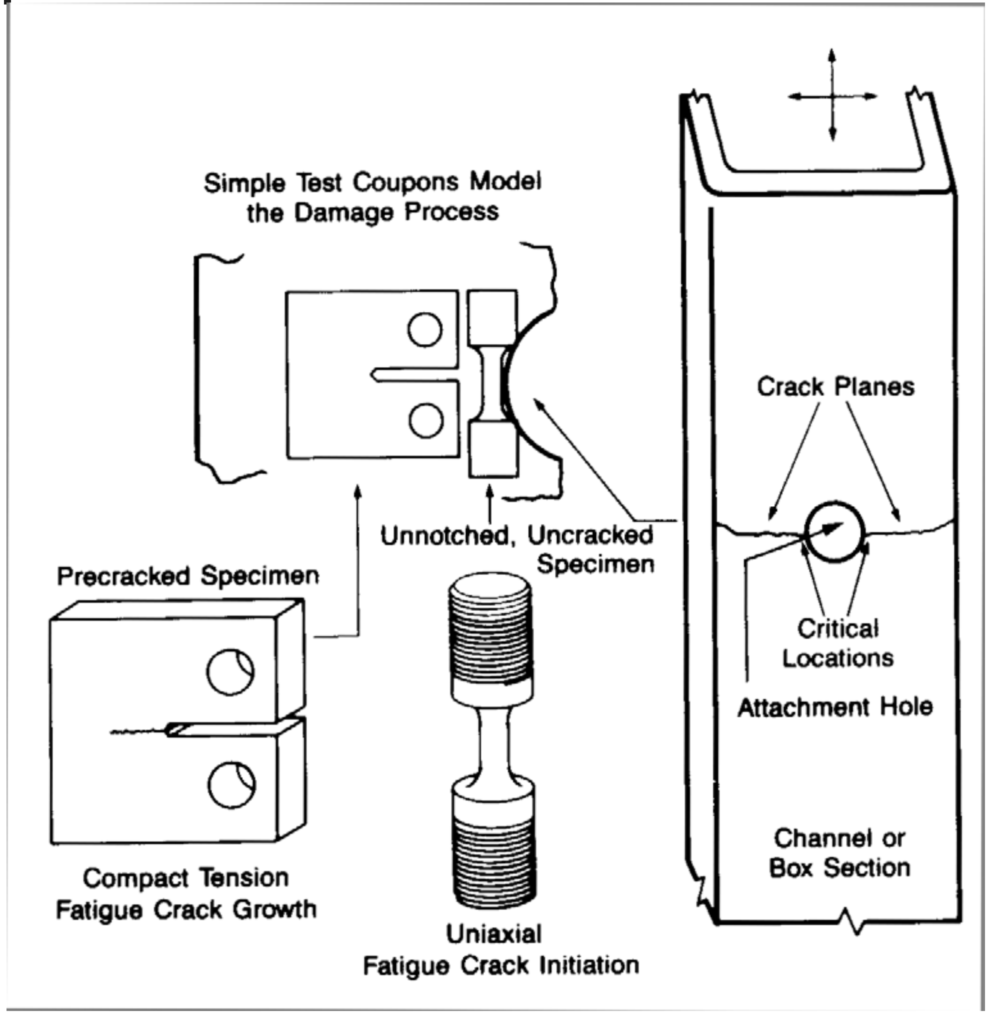




What could be more basic than learning to count correctly?

Matsuishi and Endo (1968) Fatigue of Metals Subjected to Varying Stress – Fatigue Lives Under Random Loading, Proceedings of the Kyushu District Meeting, JSME, 37-40

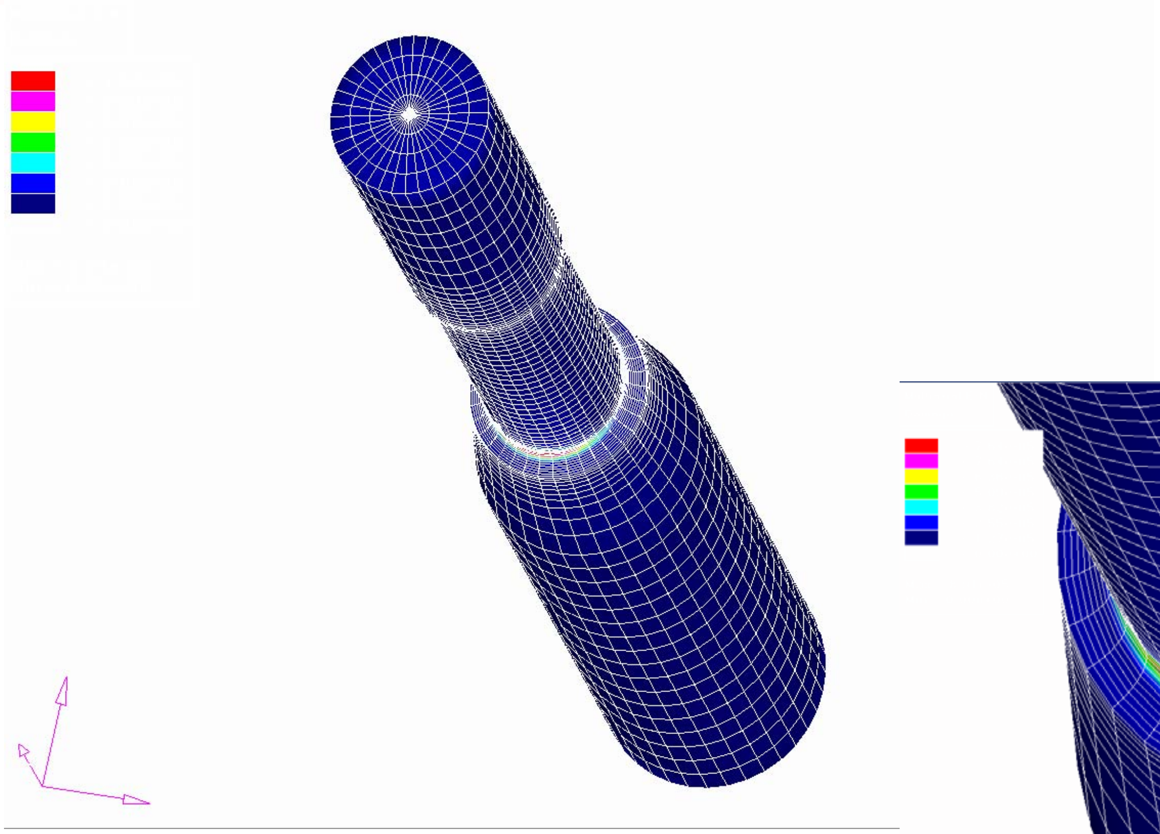
1980's – Software Development

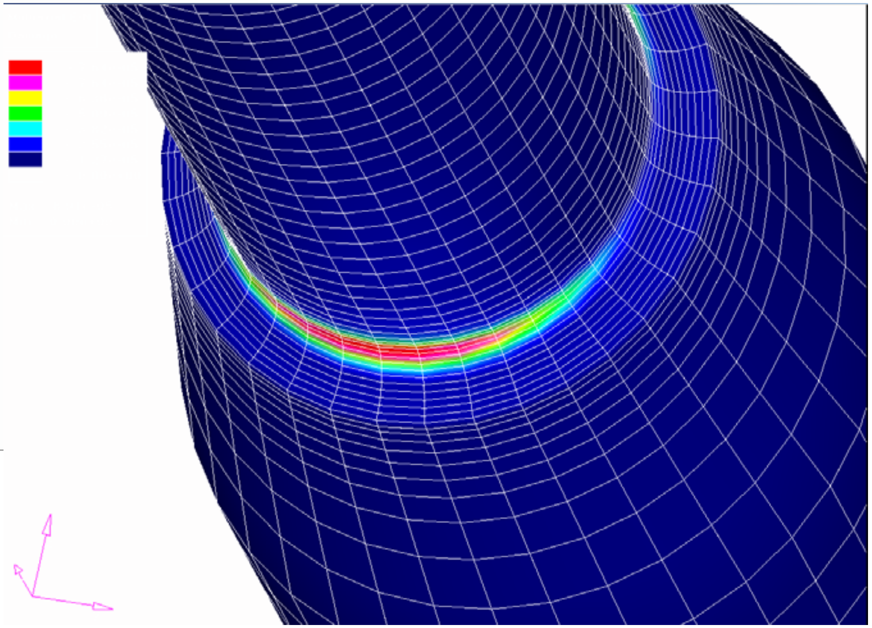


Development of the local strain approach.

Fatigue crack growth modeling established

1990's Finite Element

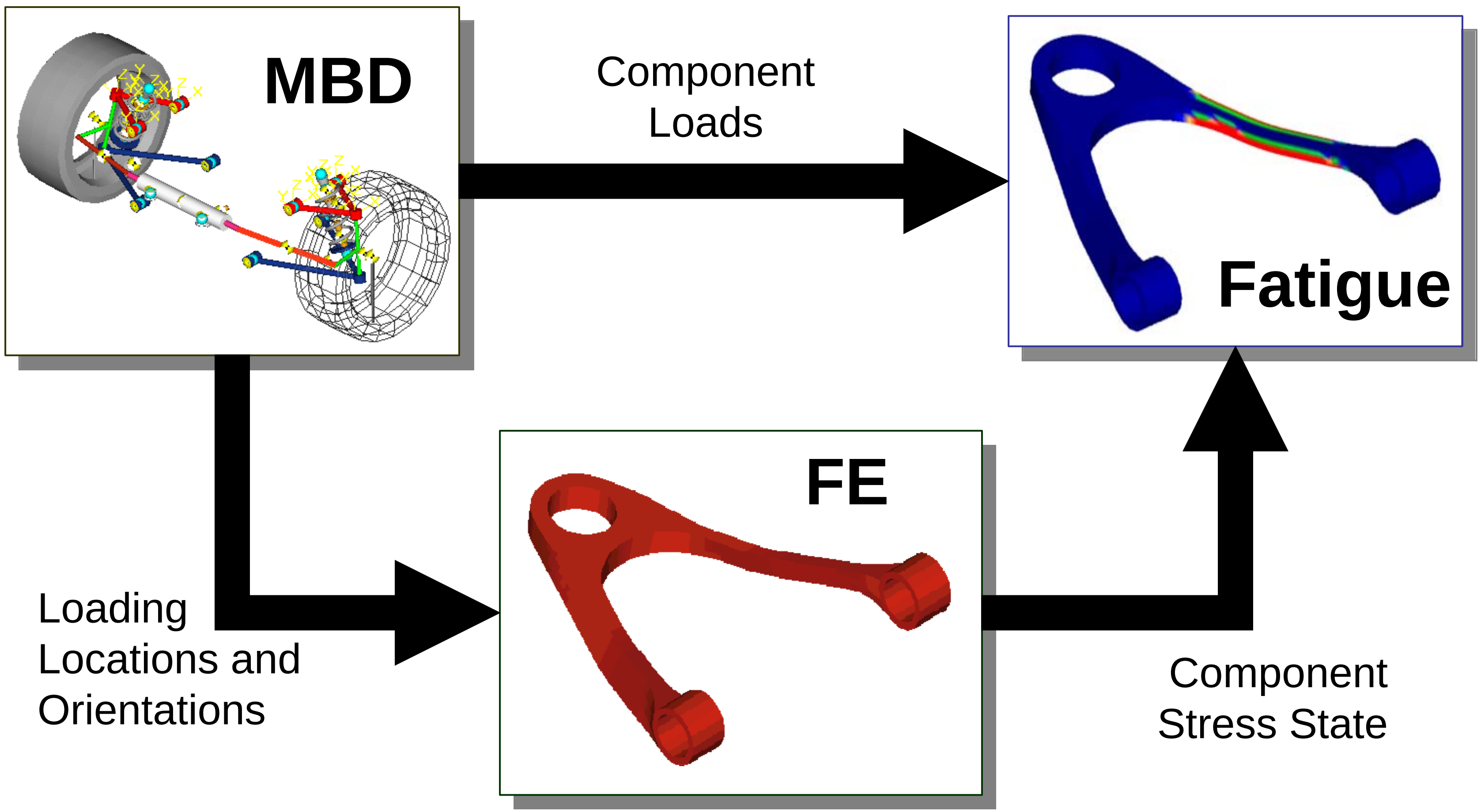




2000's

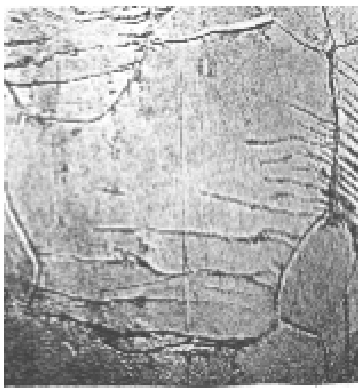
- Integrated Systems
- Gigacycle Fatigue
- Micro/nano Fatigue

Integrated Systems



Gigacycle Fatigue

surface microcracks ← | microcrack arrest | → internal nucleation



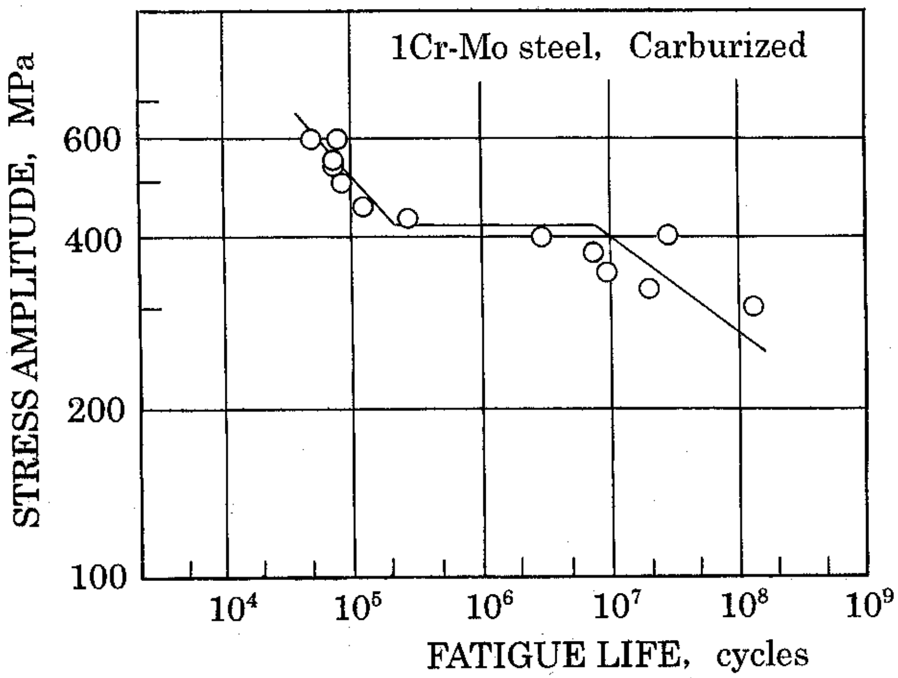
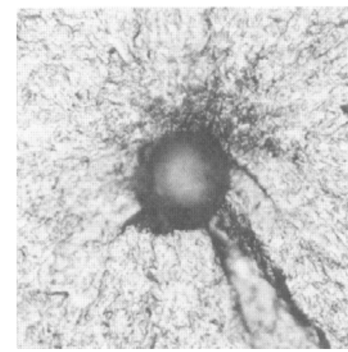
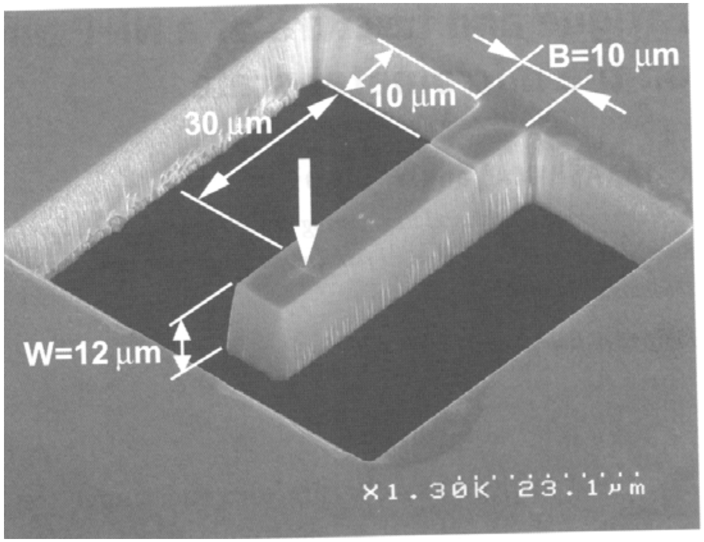


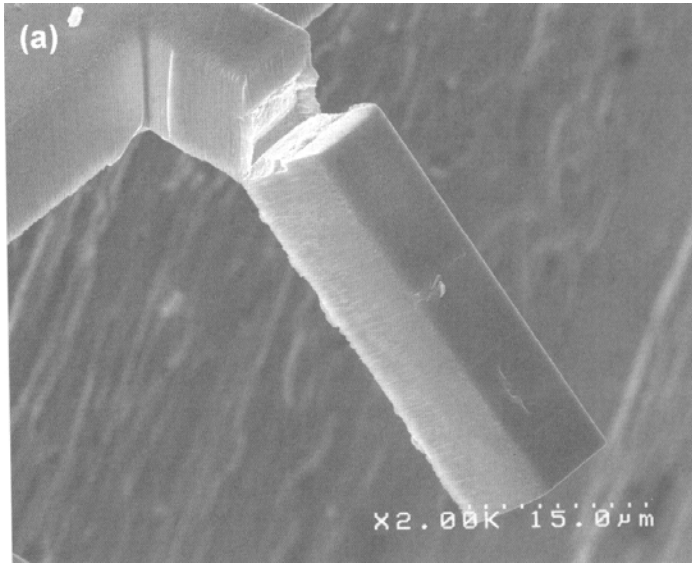
Fig. 2 A typical stepwise *S–N* curve for a carburized steel.[3]



Murakami, Nomoto, and Ueda, "Fracture Mechanisms and Fracture Mechanics at Ultrasonic Frequencies" *Fatigue and Fracture of Engineering Materials and Structures*, Vol. 22, No. 7, 1999, 581-590

Micro/ Nano Fatigue





Takashima and Higo, “Fatigue and Fracture of a Ni-P Amorphous Alloy Thin Film on the Micrometer Scale”, *Fatigue and Fracture of Engineering Materials and Structures*, Vol. 28, No. 8, 2005, 703-710

Things Worth Remembering

- The physics of fatigue has been well known for over 100 years
- Application of this knowledge still poses challenges

Fatigue Seminar

Fatigue Made Easy

Physics of Fatigue Damage

Professor Darrell F. Socie

Mechanical Science and Engineering

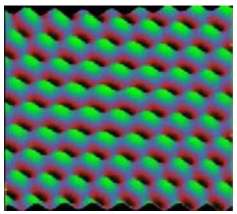
University of Illinois

Seminar Outline

1. Historical background
2. Physics of fatigue
3. Characterization of materials
4. Similitude (why fatigue modeling works)
5. Variability
6. Mean stress
7. Stress concentrations
8. Surface effects
9. Variable amplitude loading
10. Welded structures

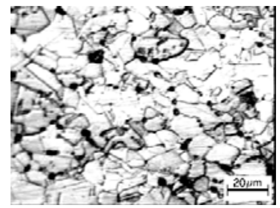
Size Scale for Studying Fatigue

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 (10^{-6} – 10^{-2})

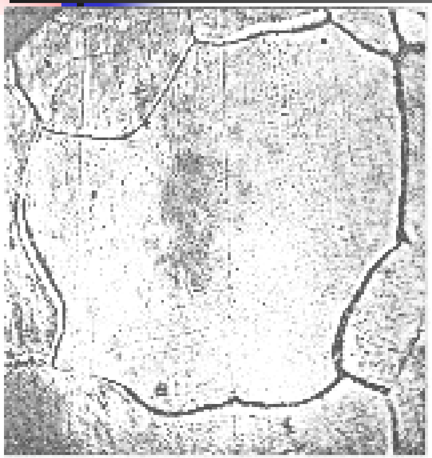
Model the physics on this scale (10^{-2} – 10^{0})

Use the models on this scale (10^{0} – 10^{2})

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

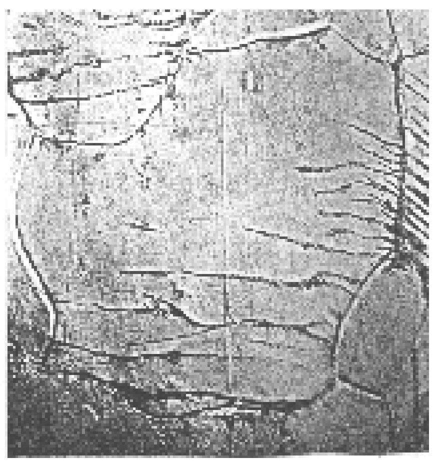
1903 - Ewing and Humfrey



N = 1,000

N = 2,000

N = 10,000

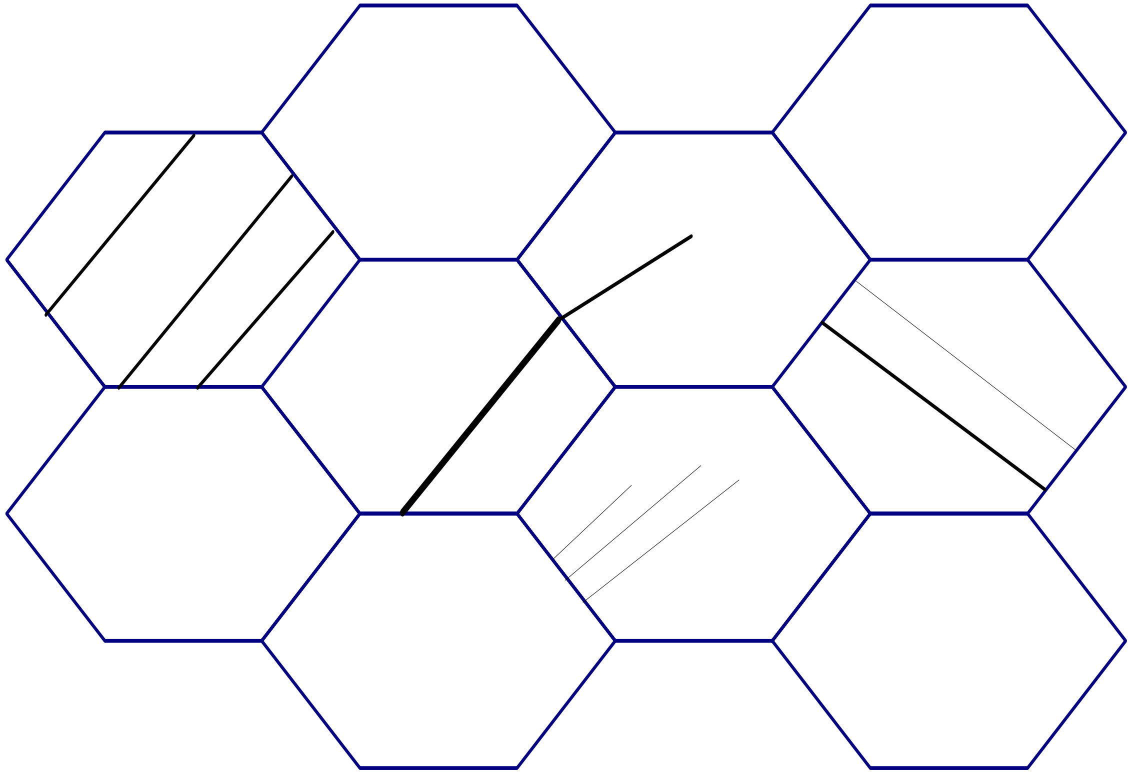


N = 40,000 N_f = 170,000

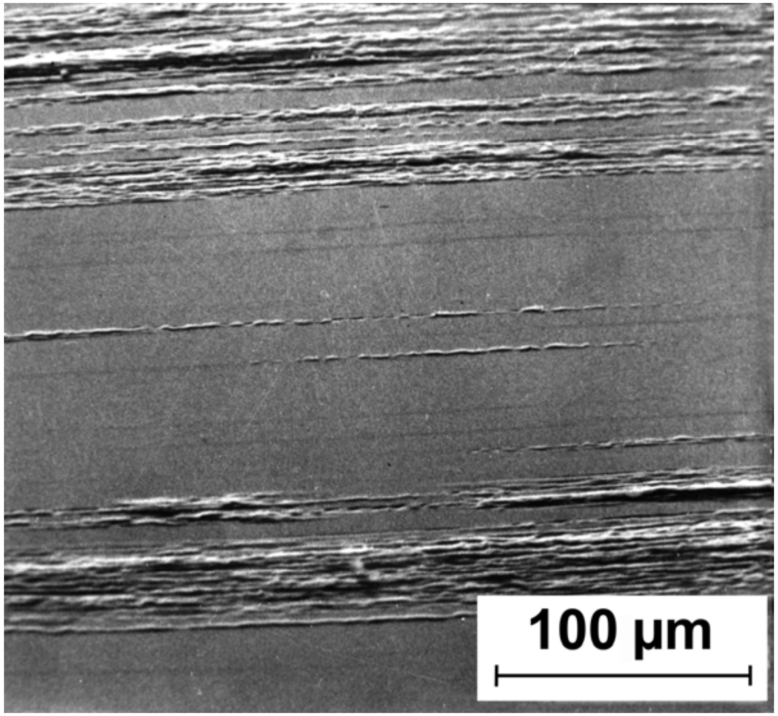
Cyclic deformation leads to the development of slip bands and fatigue cracks

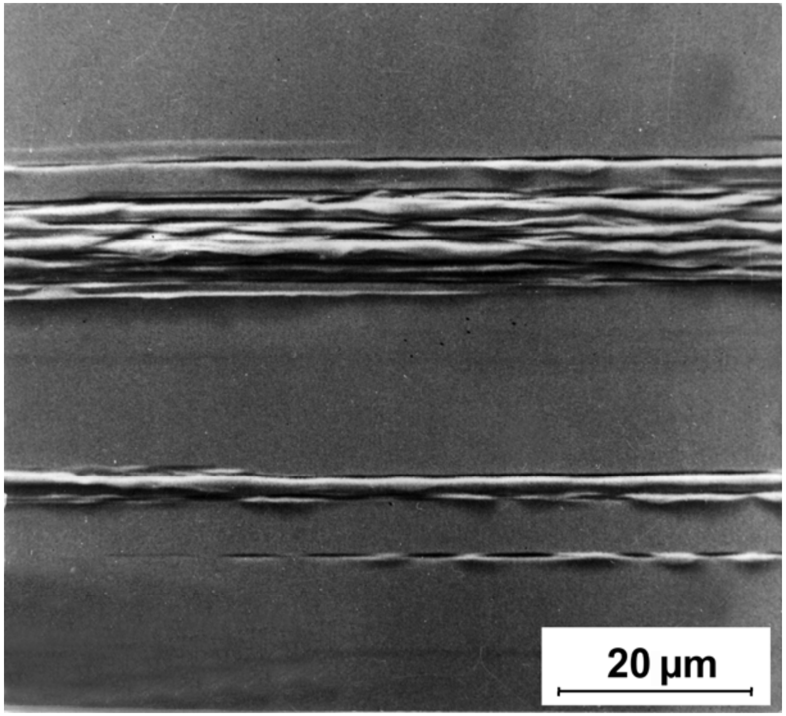
Ewing, J.A. and Humfrey, J.C. “The fracture of metals under repeated alterations of stress”, *Philosophical Transactions of the Royal Society*, Vol. A200, 1903, 241-250

Crack Nucleation



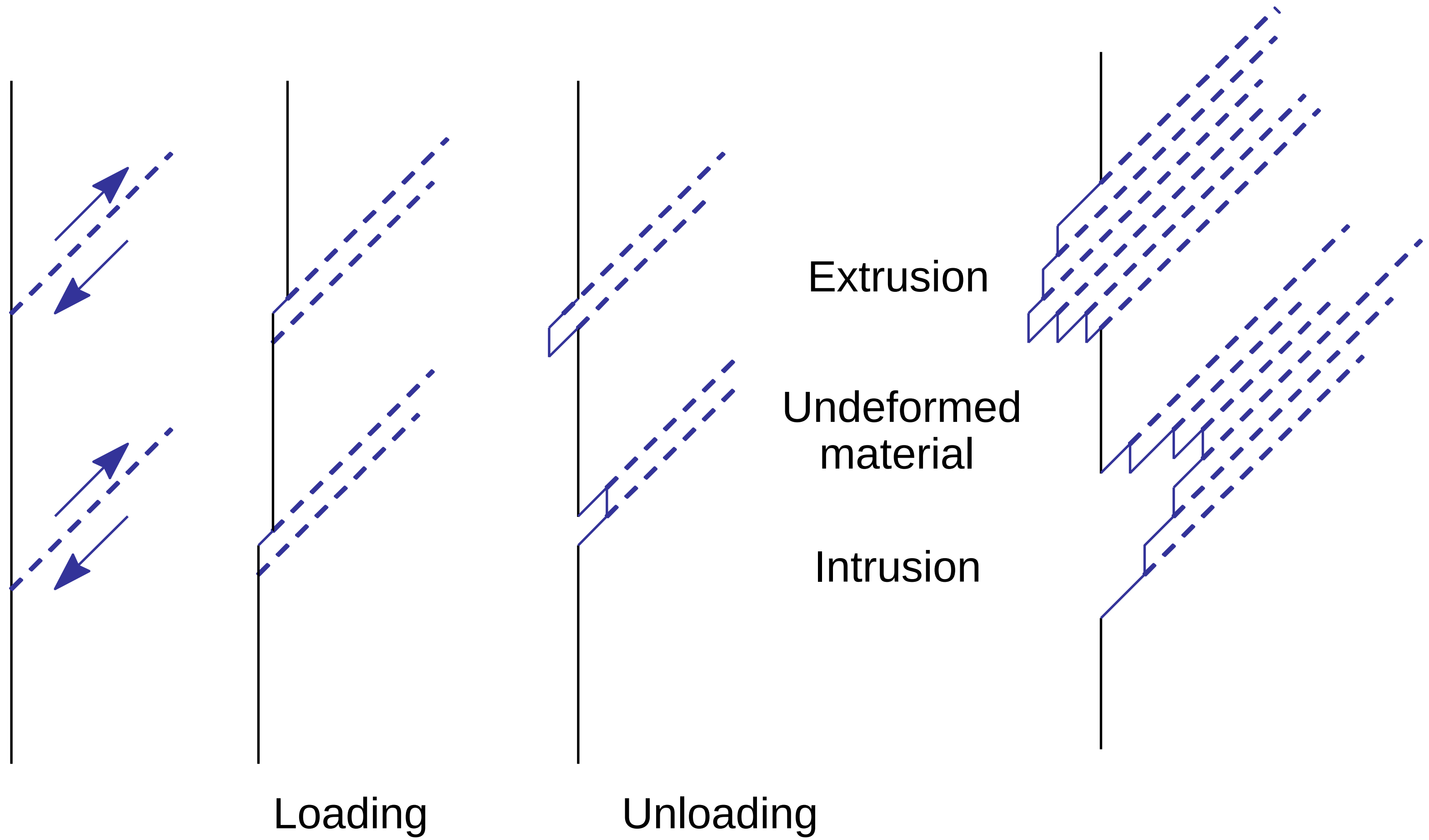
Slip Band in Copper



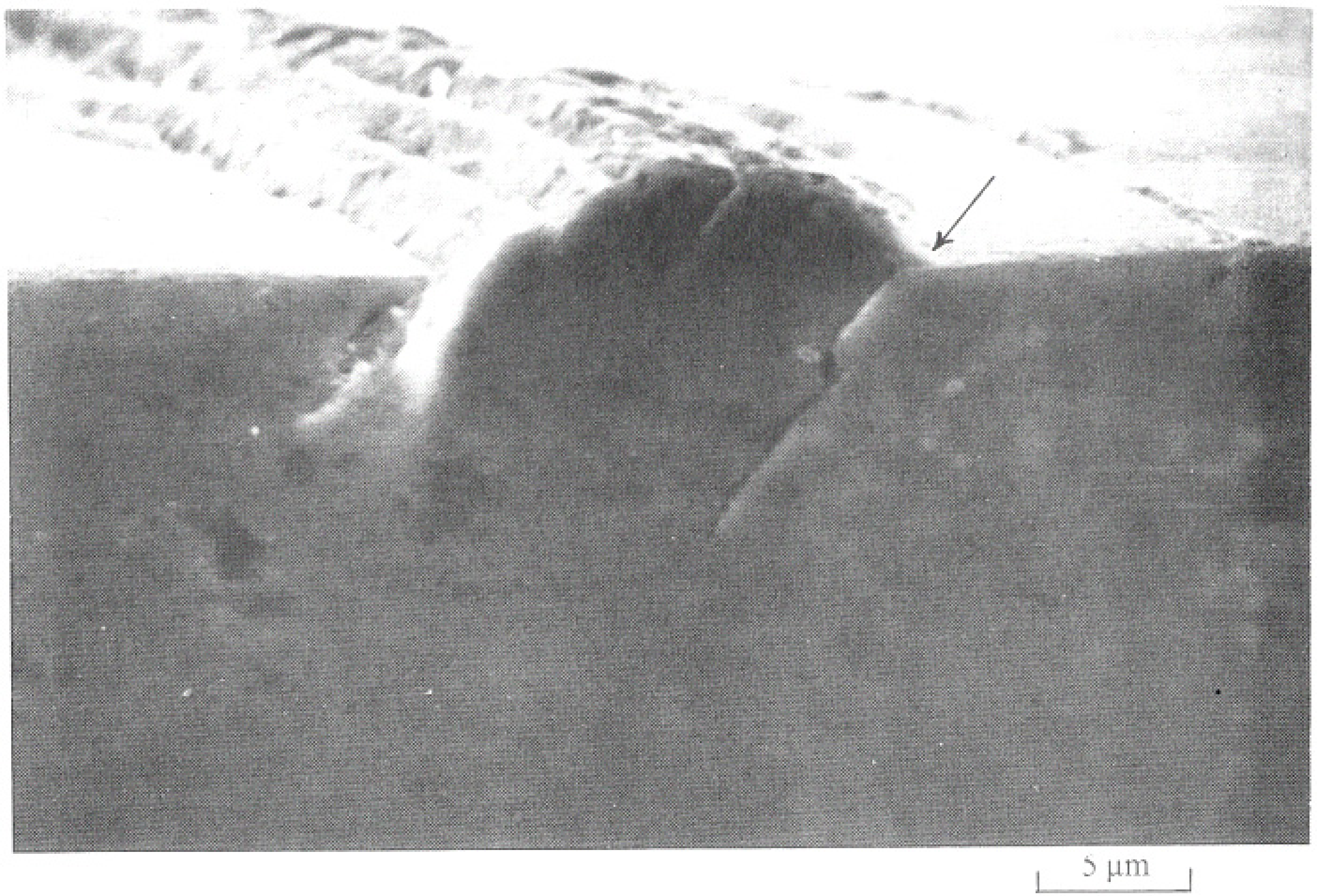


Polak, J. Cyclic Plasticity and Low Cycle Fatigue Life of Metals, Elsevier, 1991

Slip Band Formation

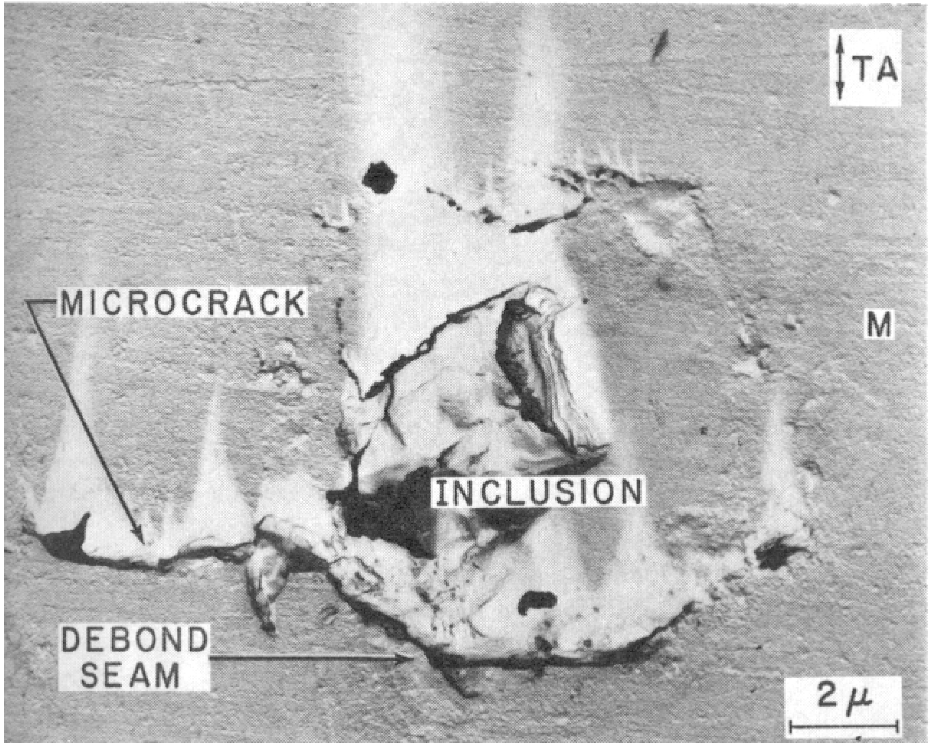


Slip Bands



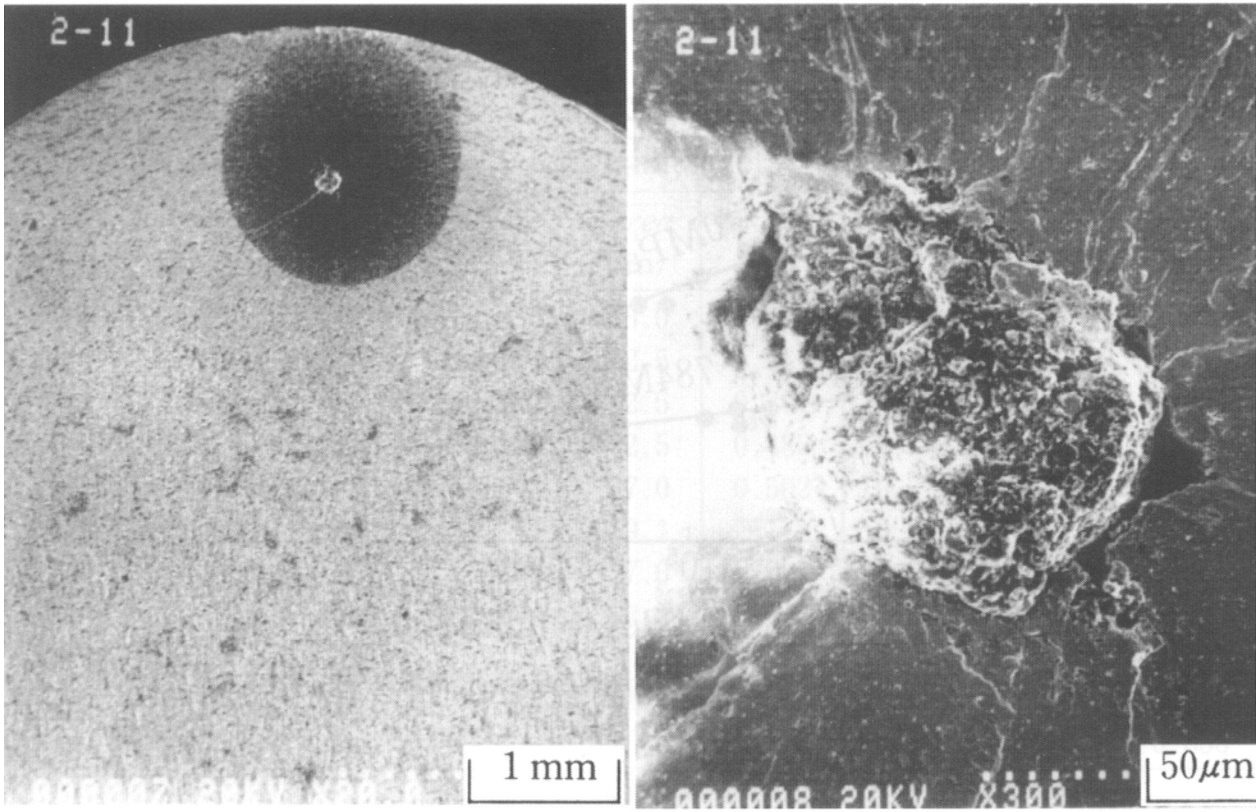
Ma, B-T and Laird C. "Overview of fatigue behavior in copper sinle crystals –II Population, size, distribution and growth Kinetics of stage I cracks for tests at constant strain amplitude", Acta Metallurgica, Vol 37, 1989, 337-348

Crack Initiation at Inclusions



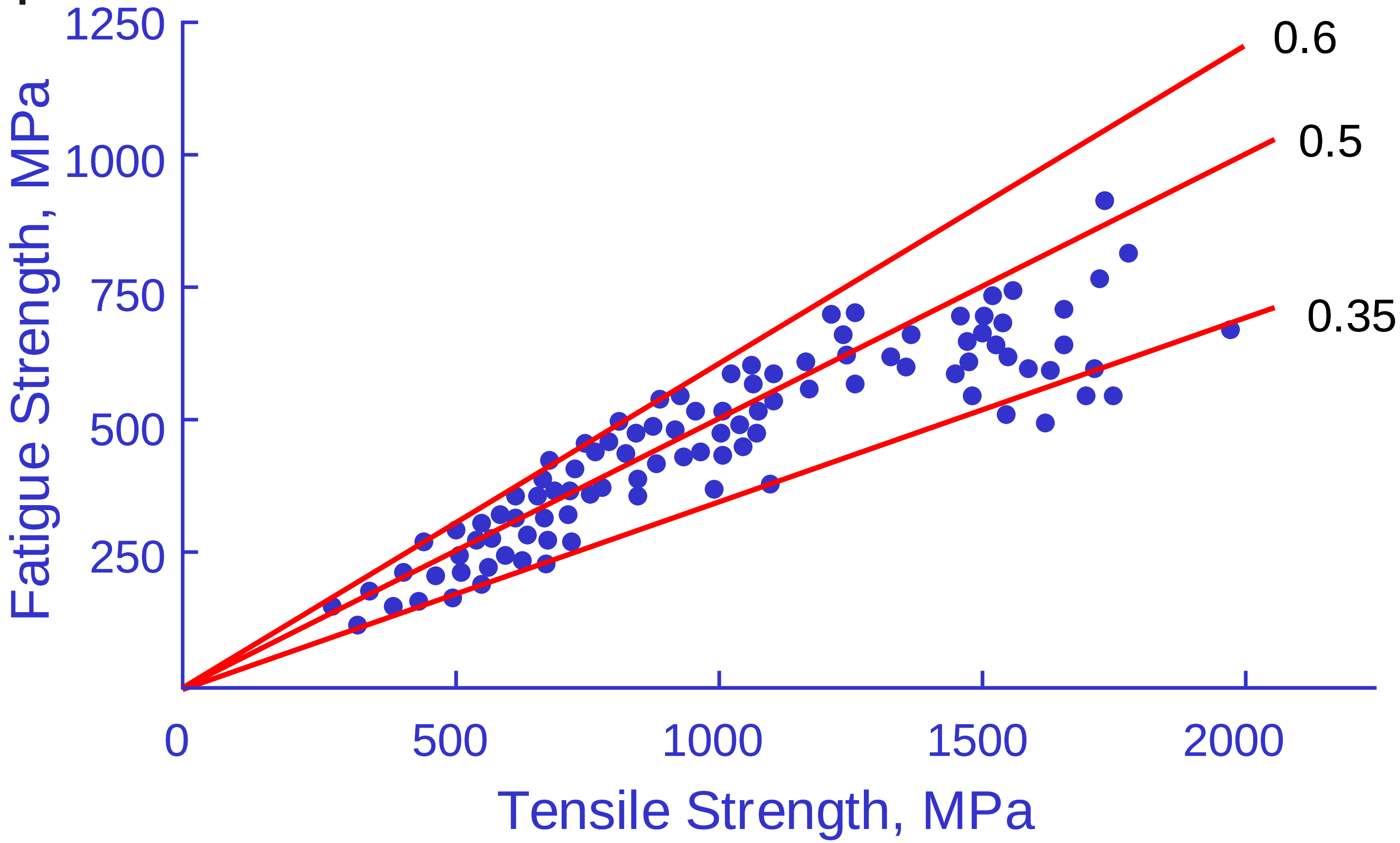
Langford and Kusenberger, "Initiation of Fatigue Cracks in 4340 Steel", *Metallurgical Transactions*, Vol 4, 1977, 553-559

Subsurface Crack Initiation



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

Fatigue Limit and Strength Correlation

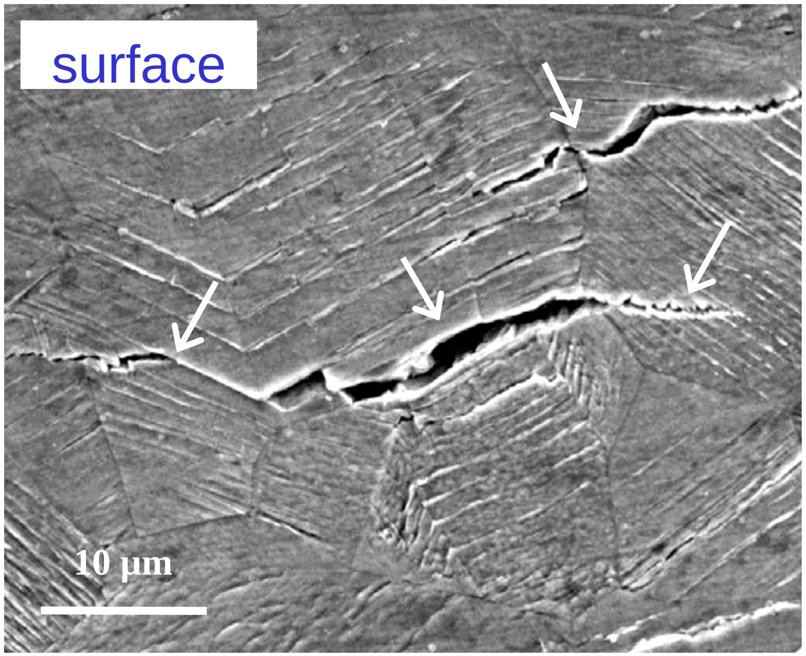


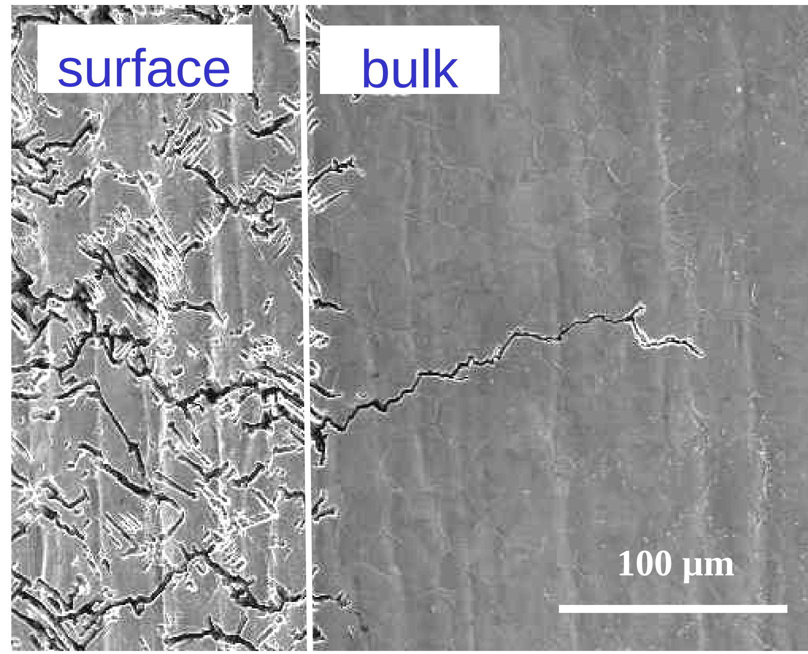
From Forrest, *Fatigue of Metals*, Pergamon Press, London, 1962

Crack Nucleation Summary

- Highly localized plastic deformation
- Surface phenomena
- Stochastic process

Surface Damage

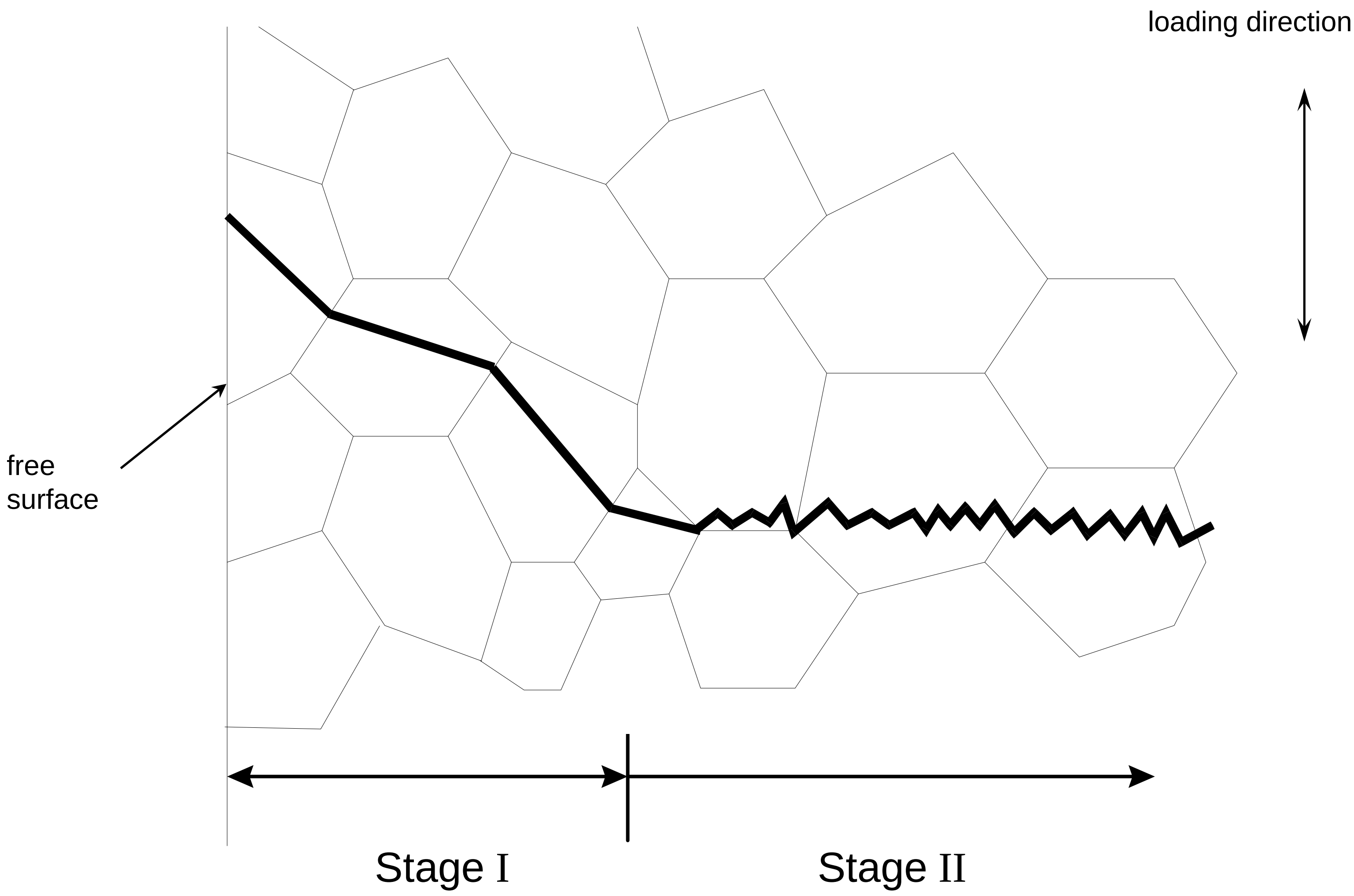




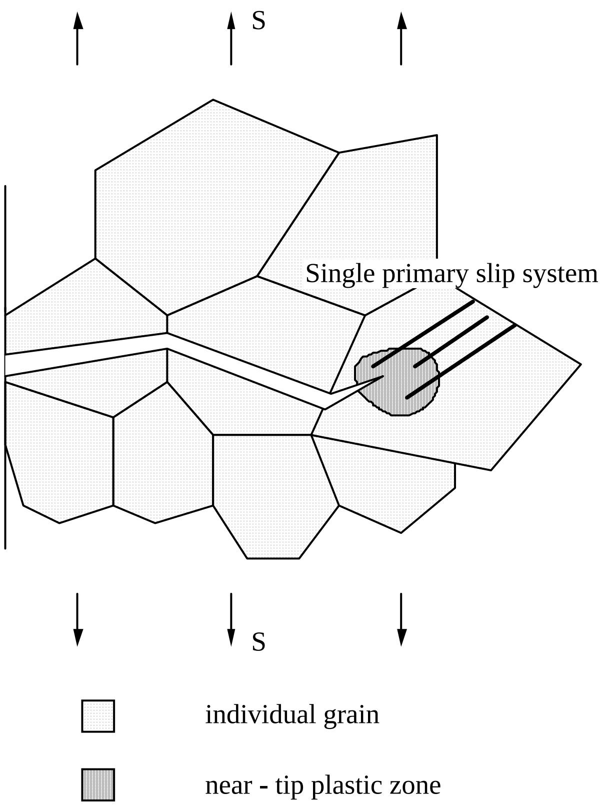
20-25 austenitic steel in symmetrical push-pull fatigue (20°C, $\Delta\varepsilon_p/2 = \pm 0.4\%$) : short cracks on the surface and in the bulk

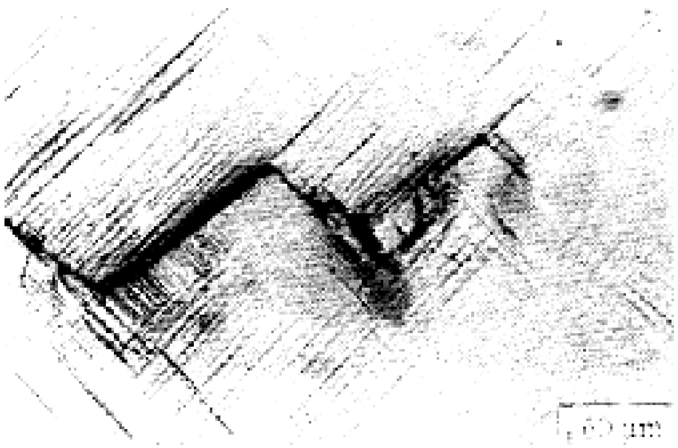
From Jacques Stolarz, Ecole Nationale Superieure des Mines
Presented at LCF 5 in Berlin, 2003

Stage I and Stage II



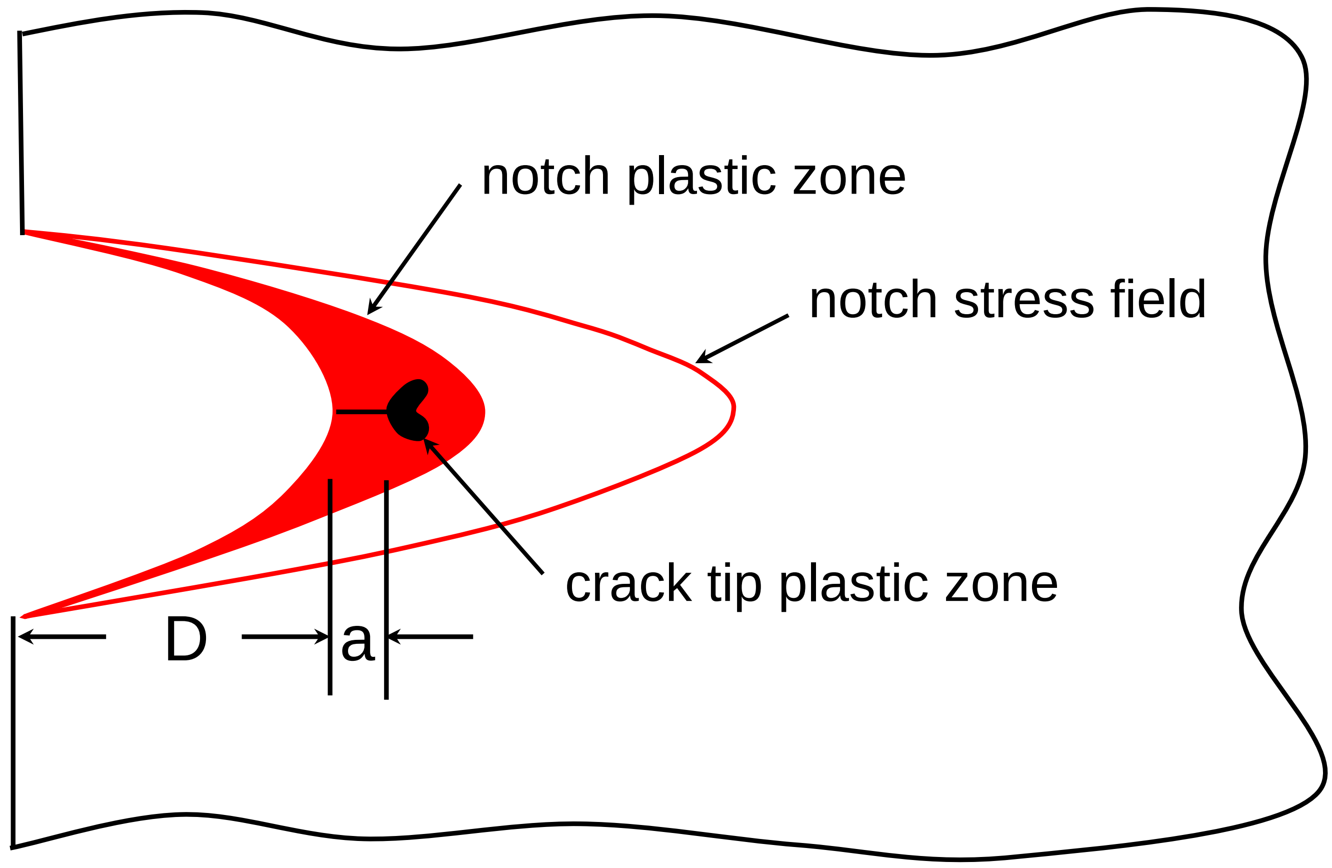
Stage I Crack Growth





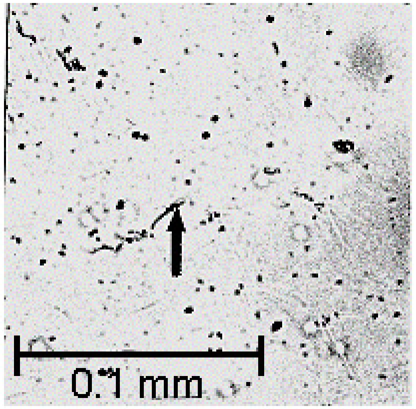
Stage I crack is strongly affected by slip characteristics, microstructure dimensions, stress level, extent of near tip plasticity

Small Cracks at Notches

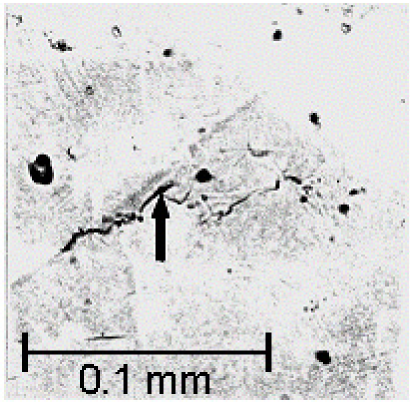


Crack growth controlled by the notch plastic strains

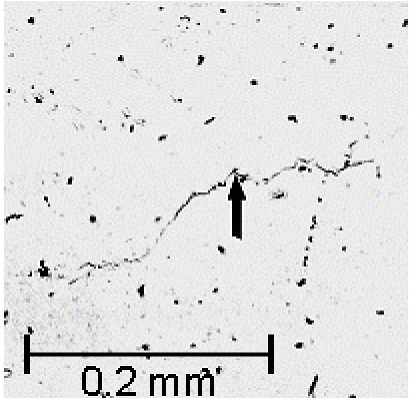
Small Crack Growth



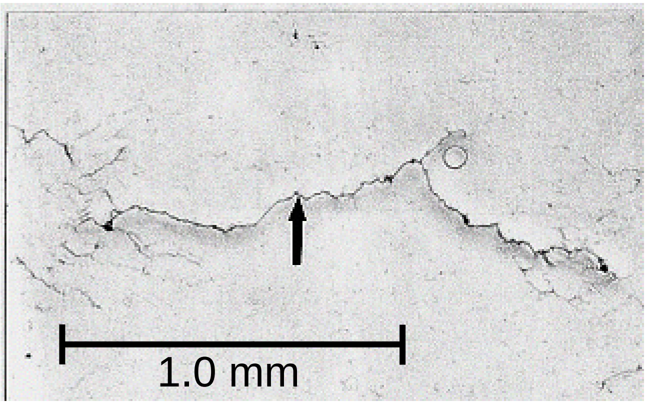
N = 160



N = 240



N = 520



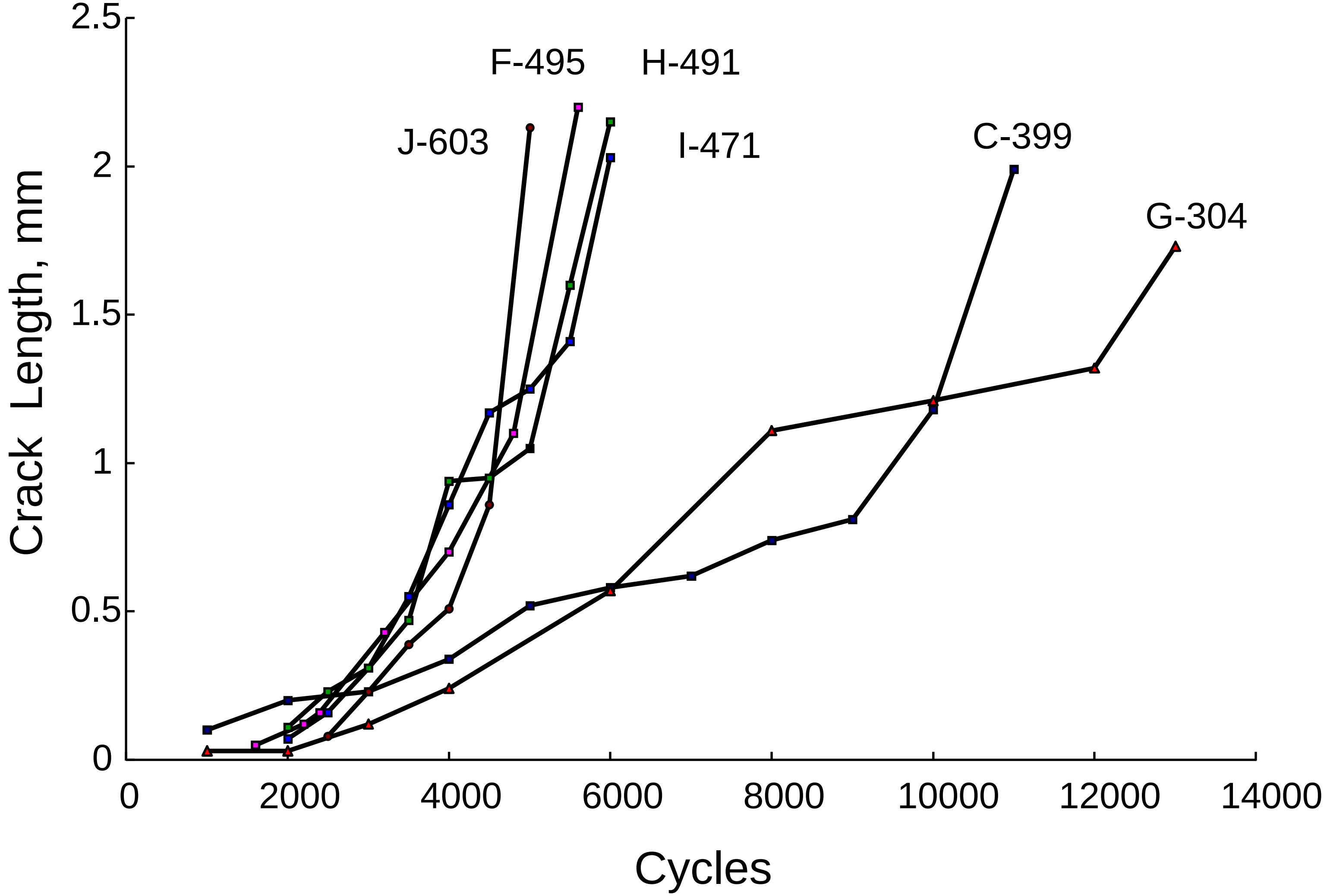
N = 900

Inconel 718

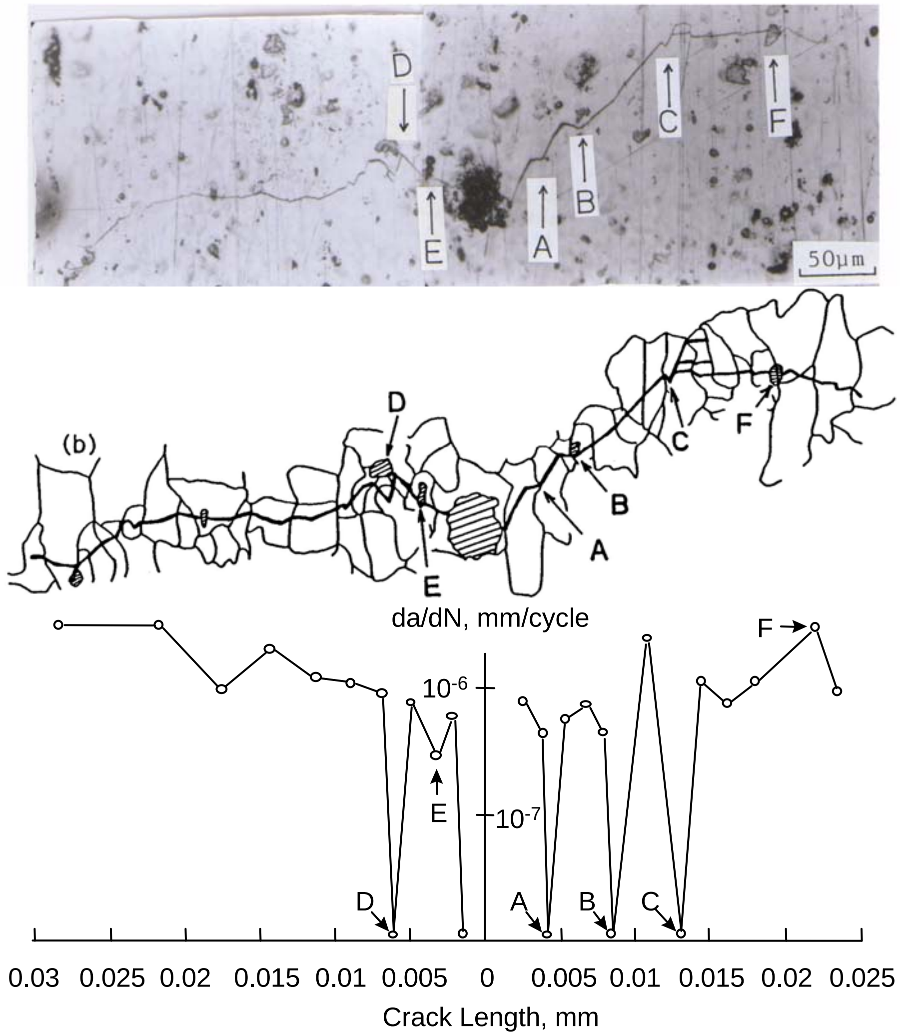
$\Delta\varepsilon = 0.02$

$N_f = 936$

Crack Length Observations

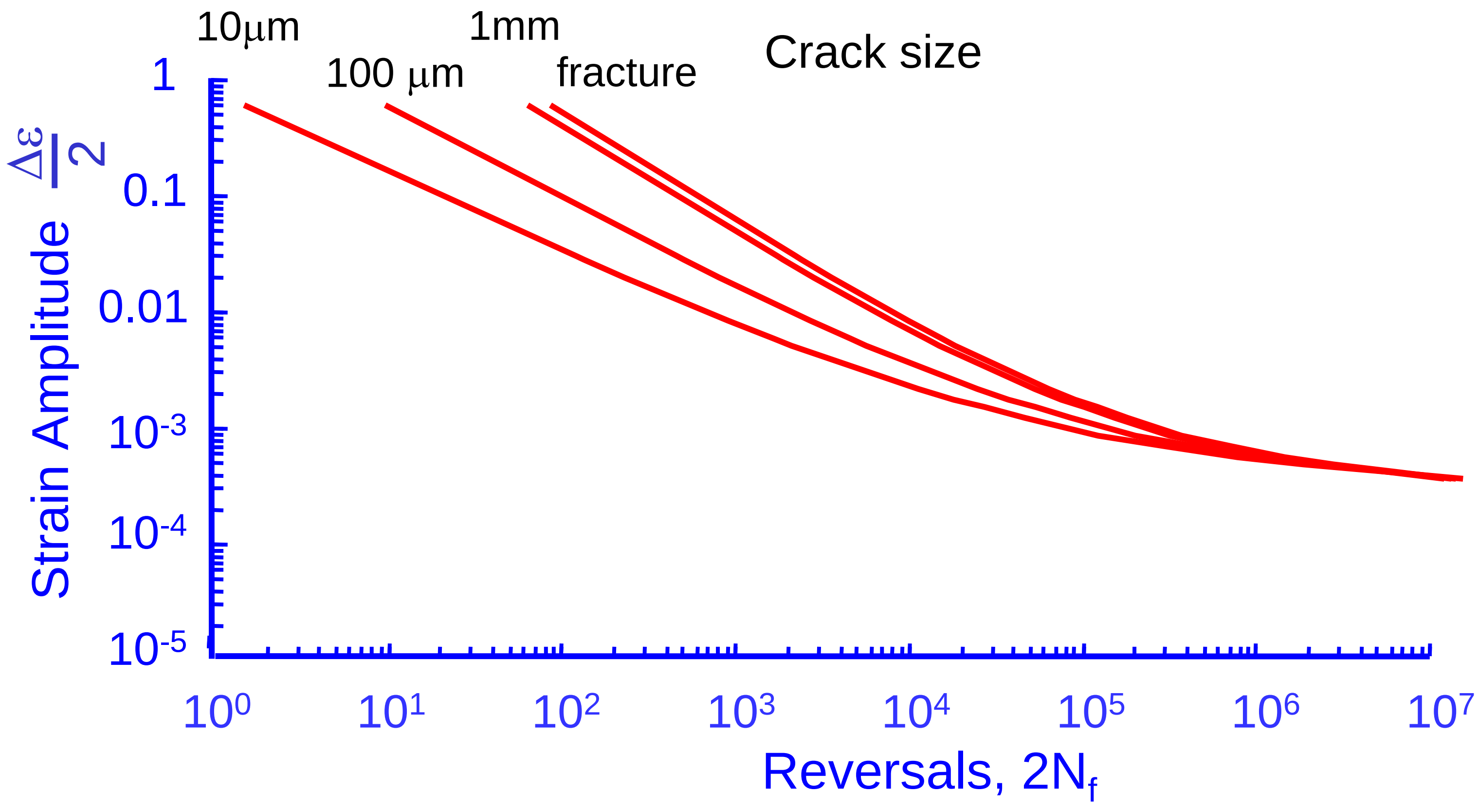


Crack - Microstructure Interactions



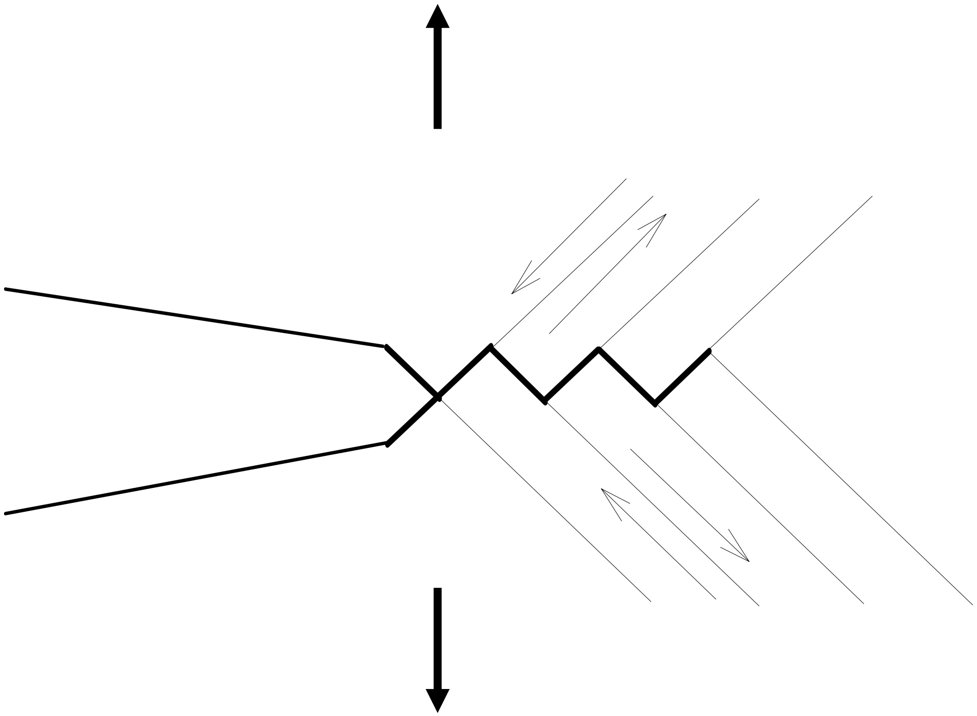
Akiniwa, Y., Tanaka, K., and Matsui, E.,"Statistical Characteristics of Propagation of Small Fatigue Cracks in Smooth Specimens of Aluminum Alloy 2024-T3, *Materials Science and Engineering*, Vol. A104, 1988, 105-115

Strain-Life Data



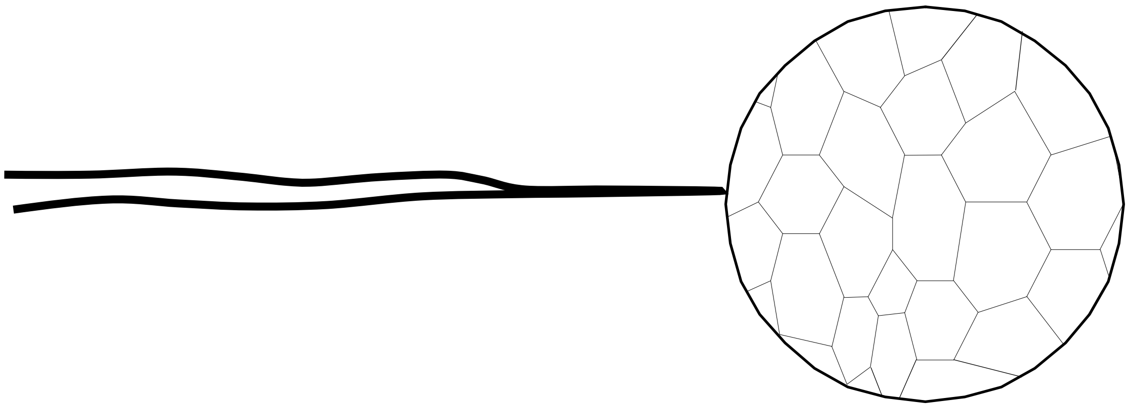
Most of the life is spent in microcrack growth in the plastic strain dominated region

Stage II Crack Growth



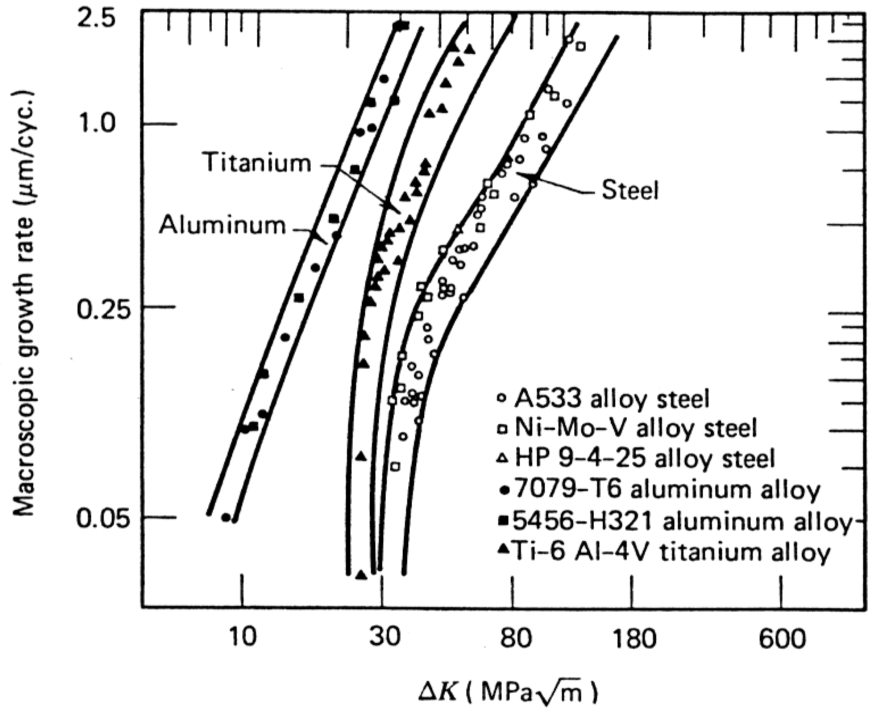
Locally, the crack grows in shear
Macroscopically it grows in tension

Long Crack Growth



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

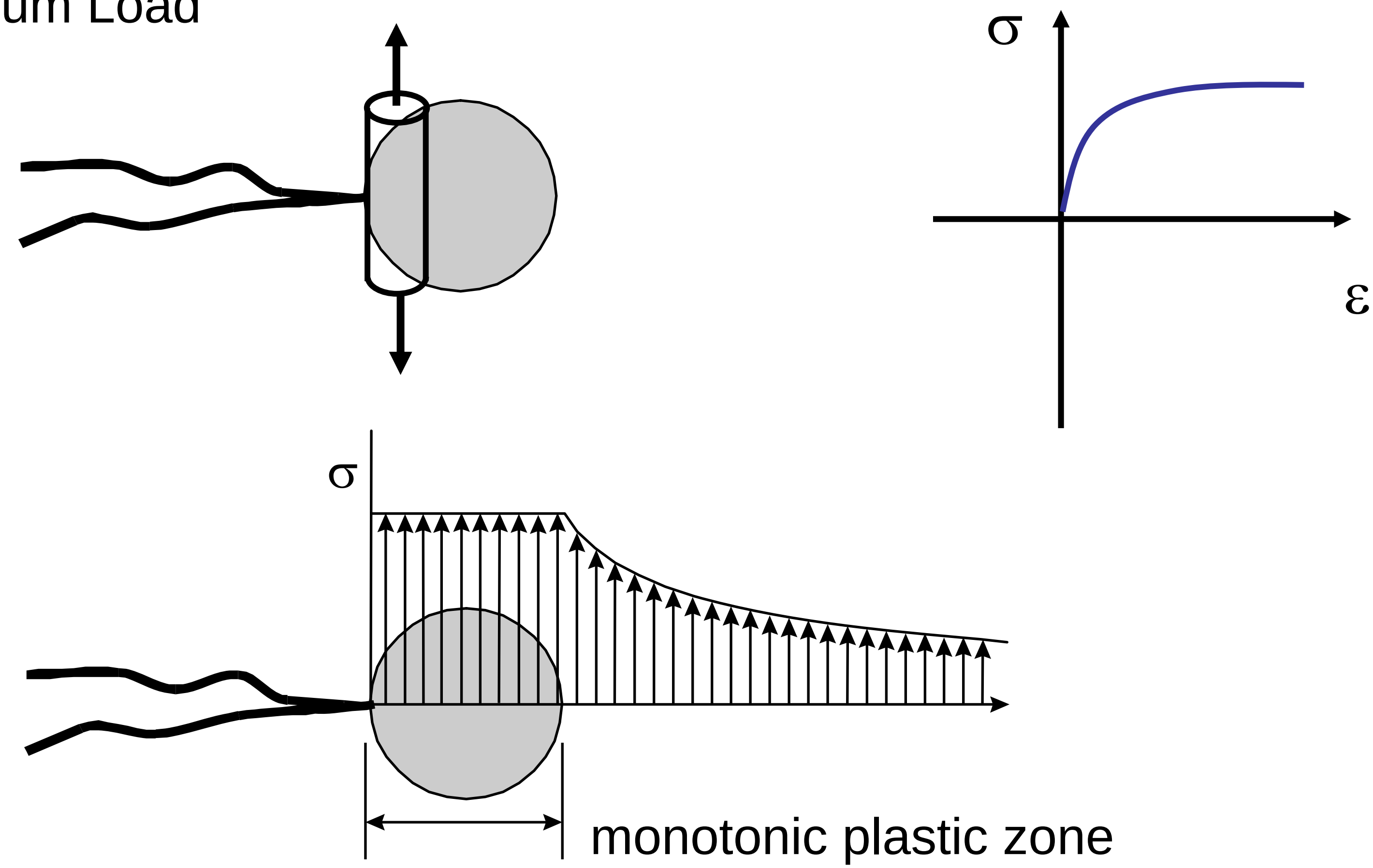
Crack Growth Rates of Metals



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

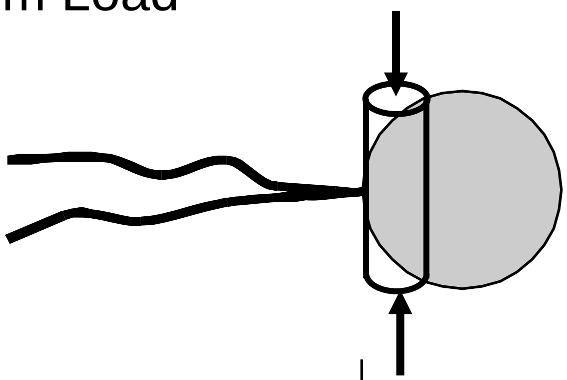
Stresses Around a Crack

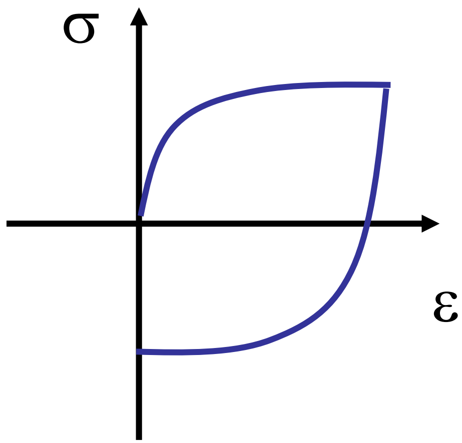
Maximum Load

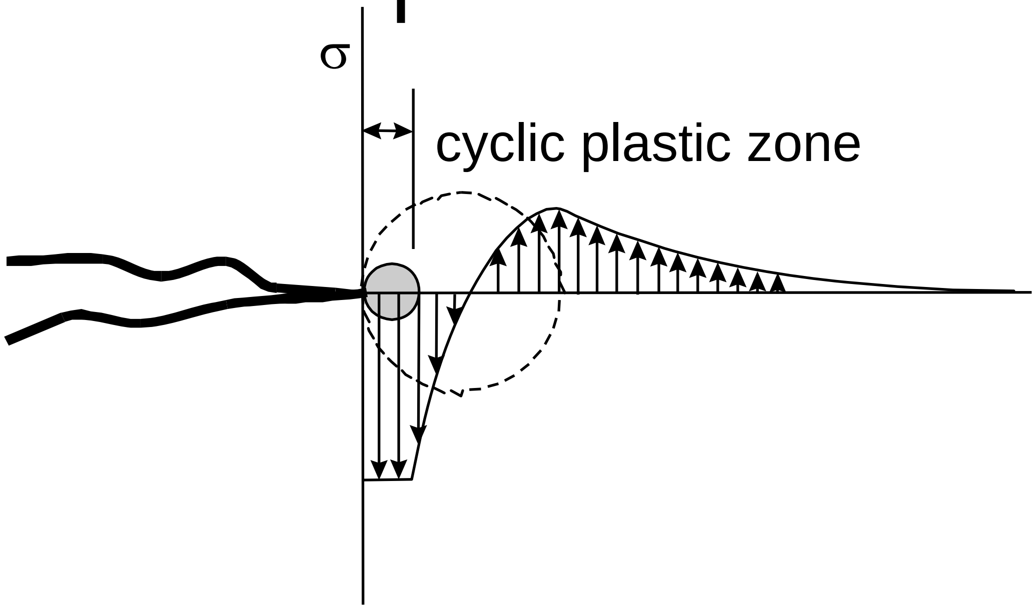


Stresses Around a Crack (continued)

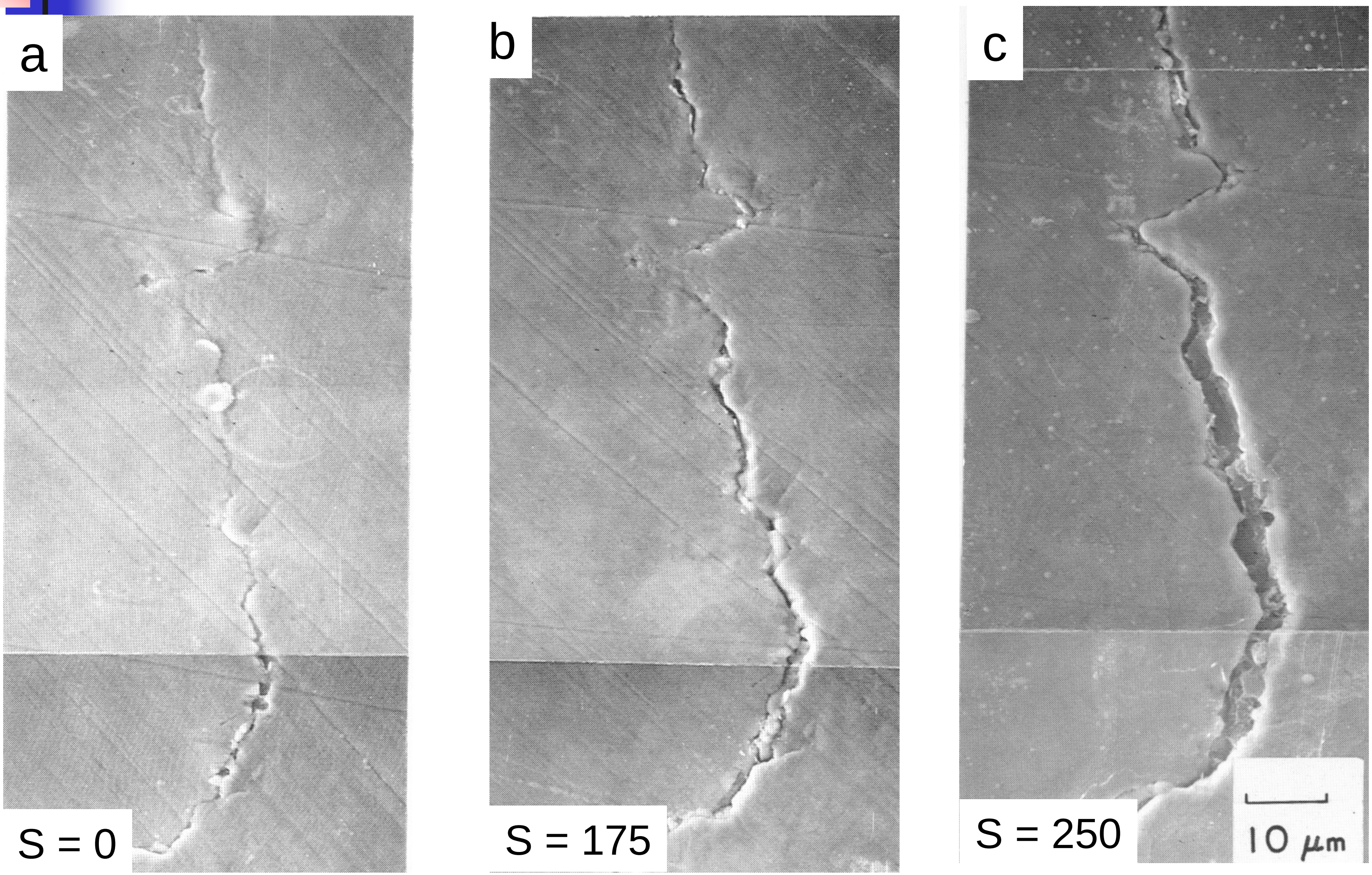
Minimum Load



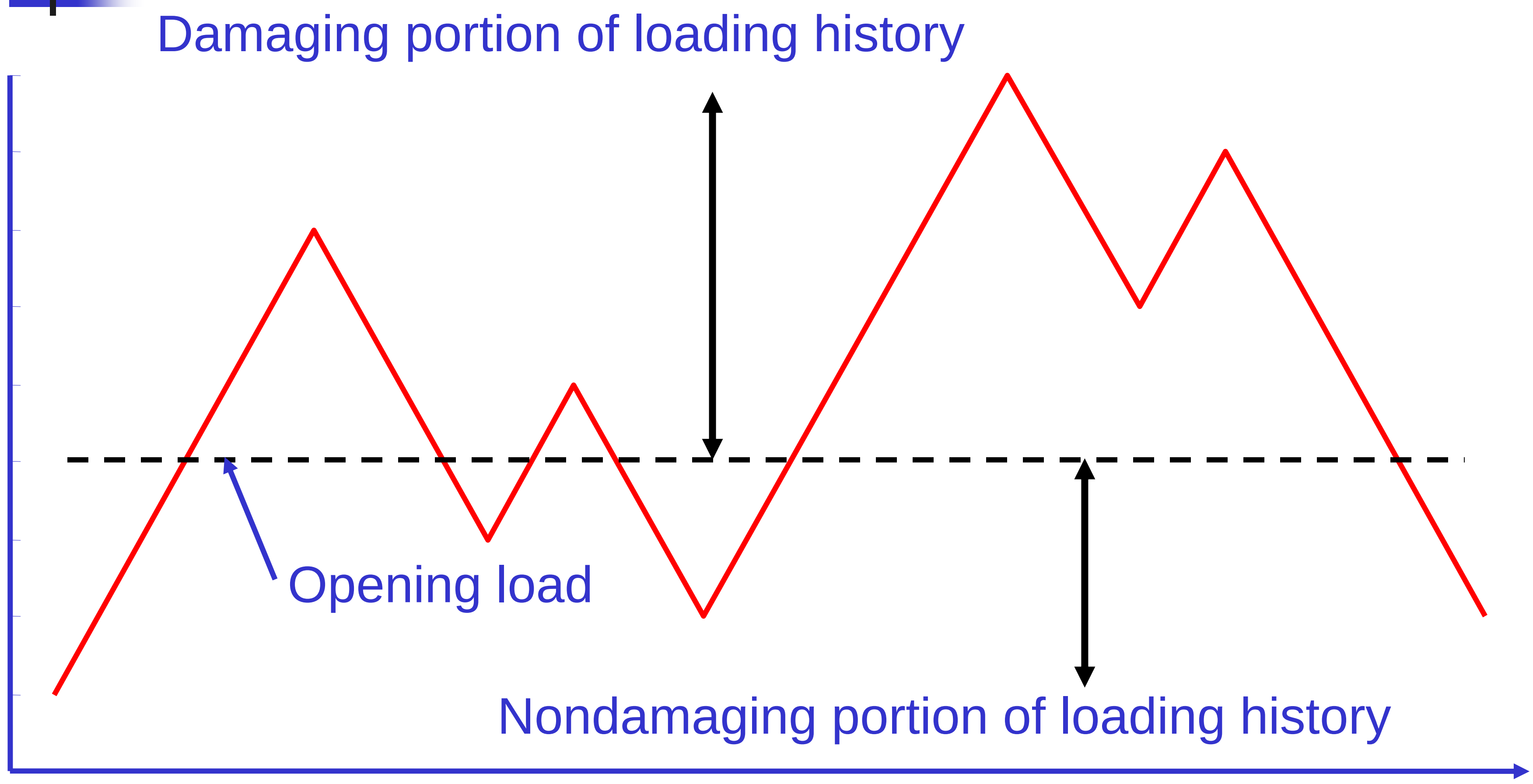




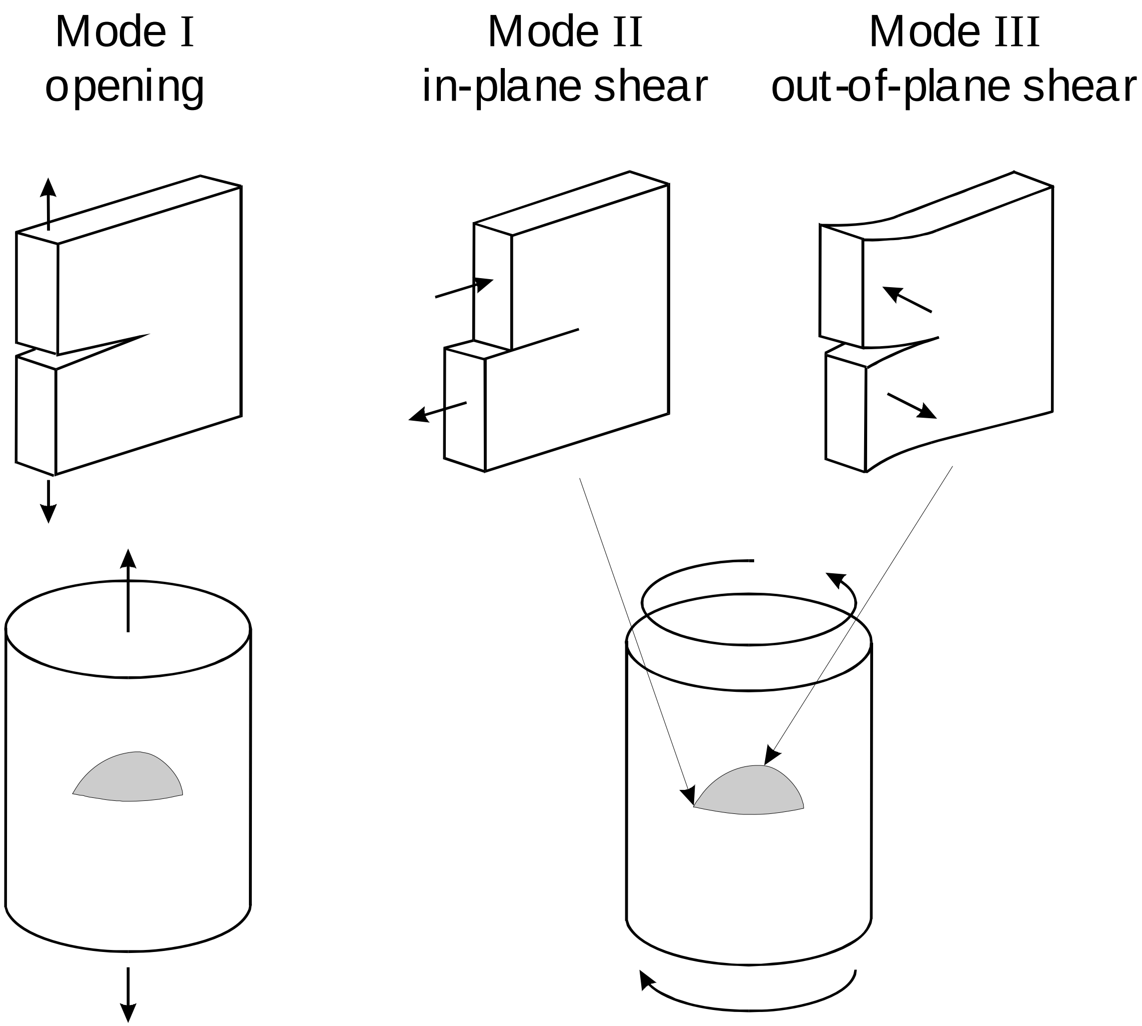
Crack Closure



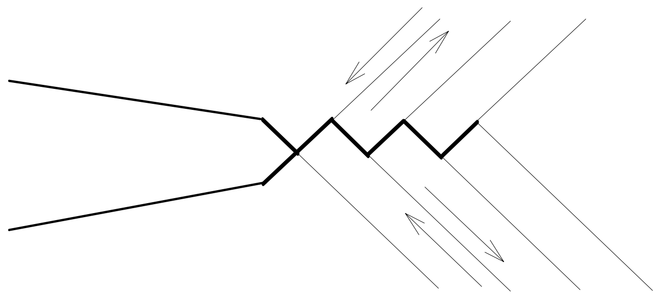
Crack Opening Load

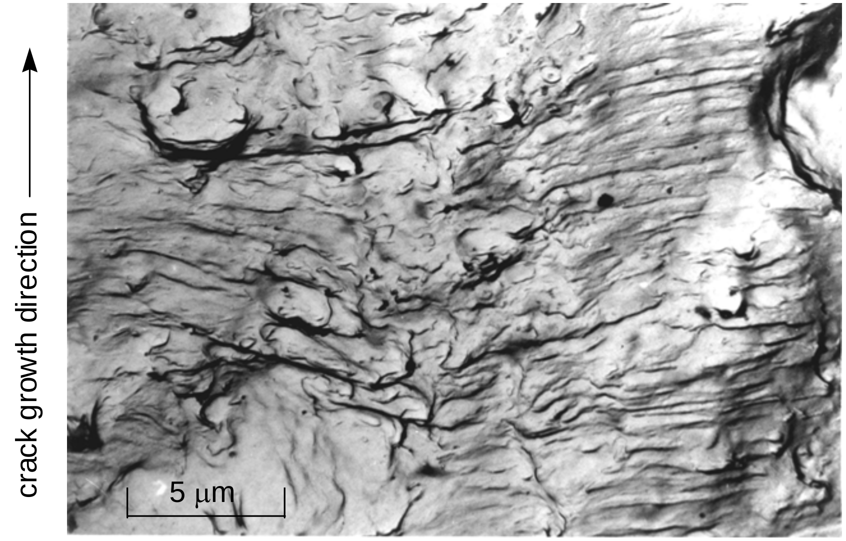


Mode I, Mode II, and Mode III

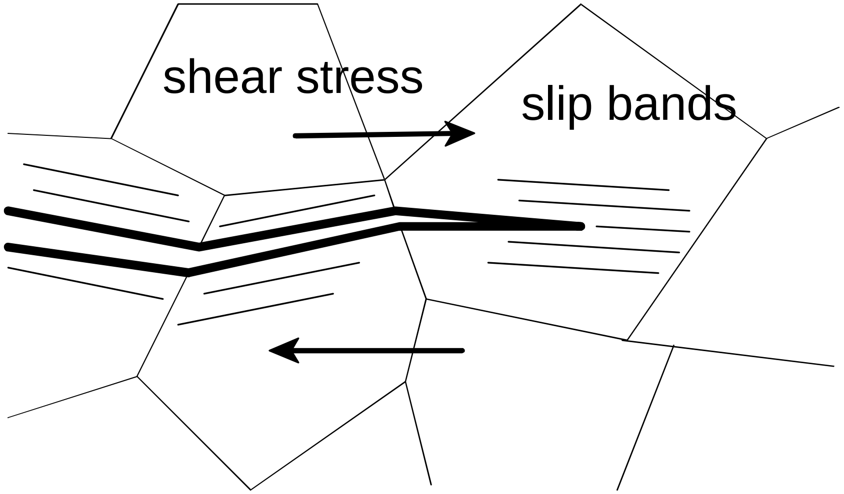


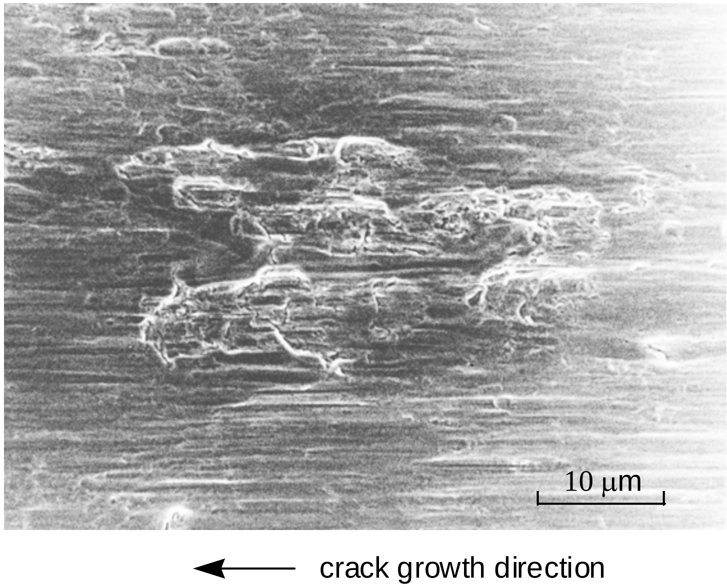
Mode I Growth



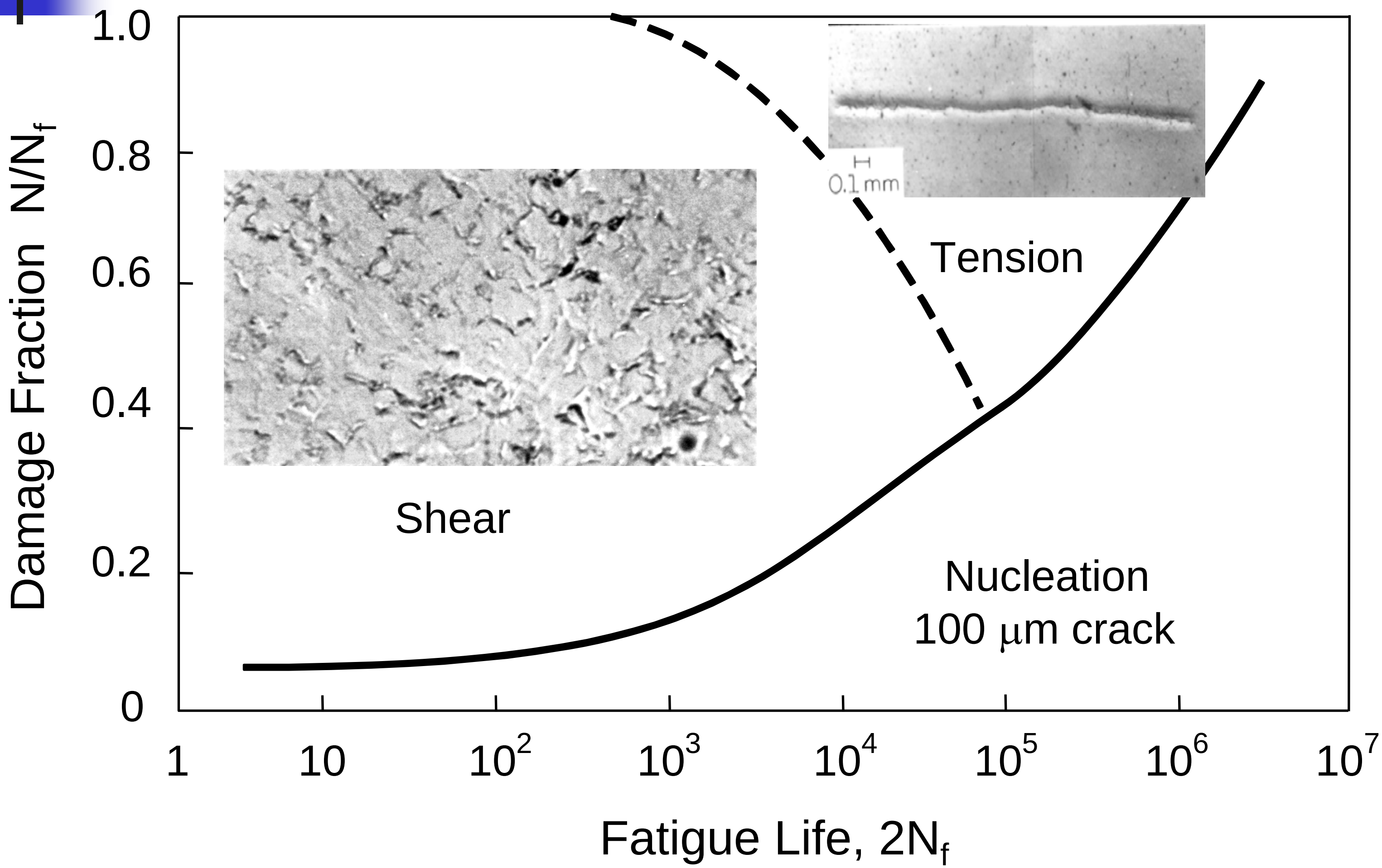


Mode II Growth

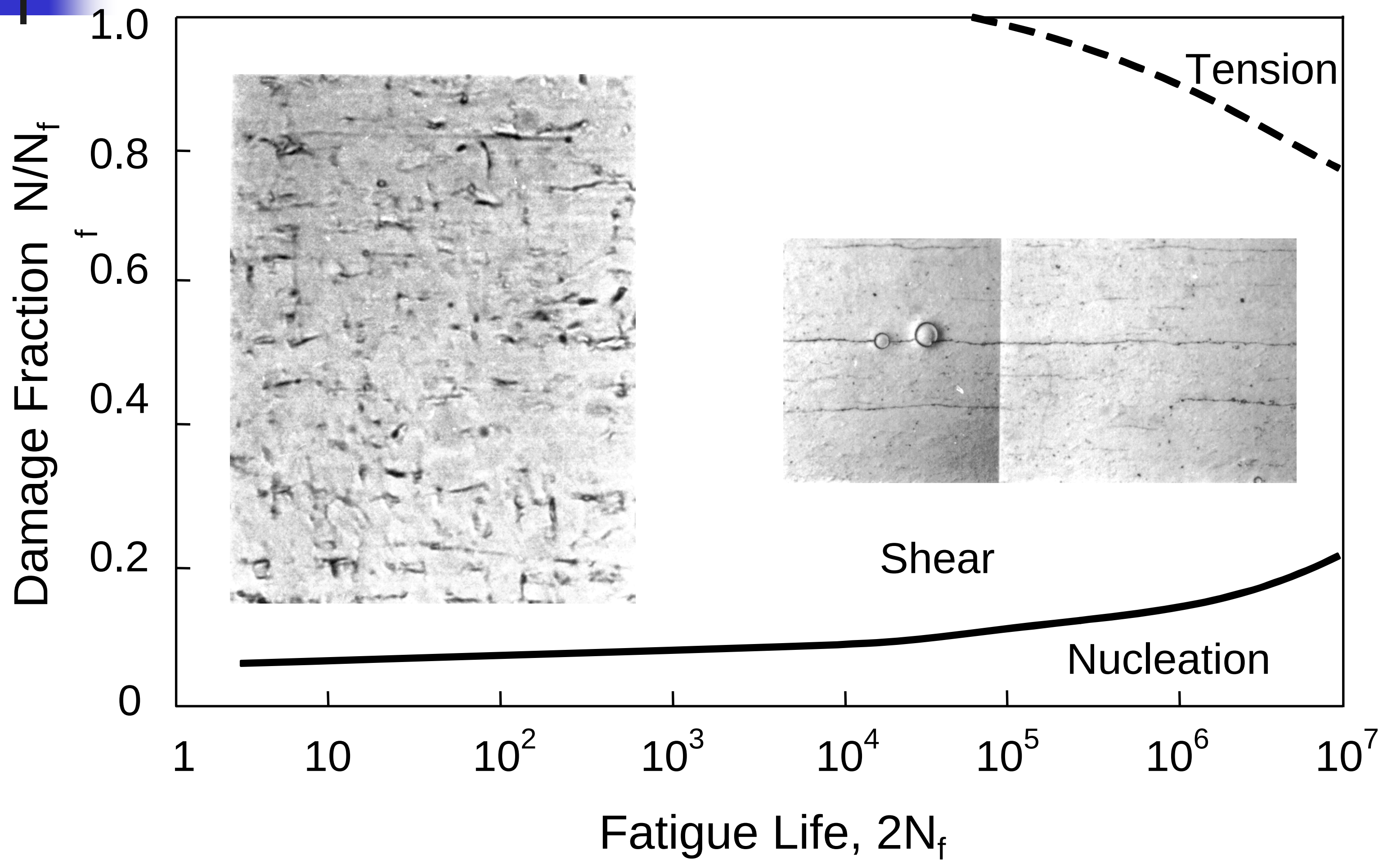




1045 Steel - Tension



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 Seminar

Fatigue Made Easy

Characterization of Materials

Professor Darrell F. Socie
Mechanical Science and Engineering
University of Illinois

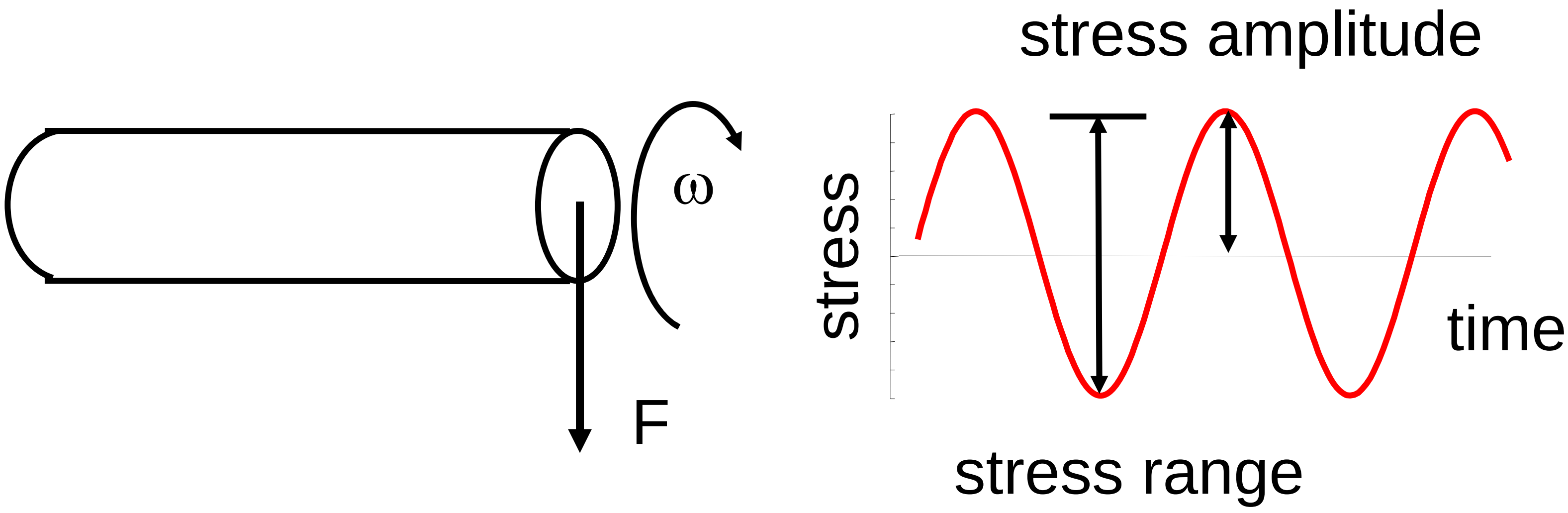
Seminar Outline

1. Historical background
2. Physics of fatigue
3. Characterization of materials
4. Similitude (why fatigue modeling works)
5. Variability
6. Mean stress
7. Stress concentrations
8. Surface effects
9. Variable amplitude loading
10. Welded structures

Characterization

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

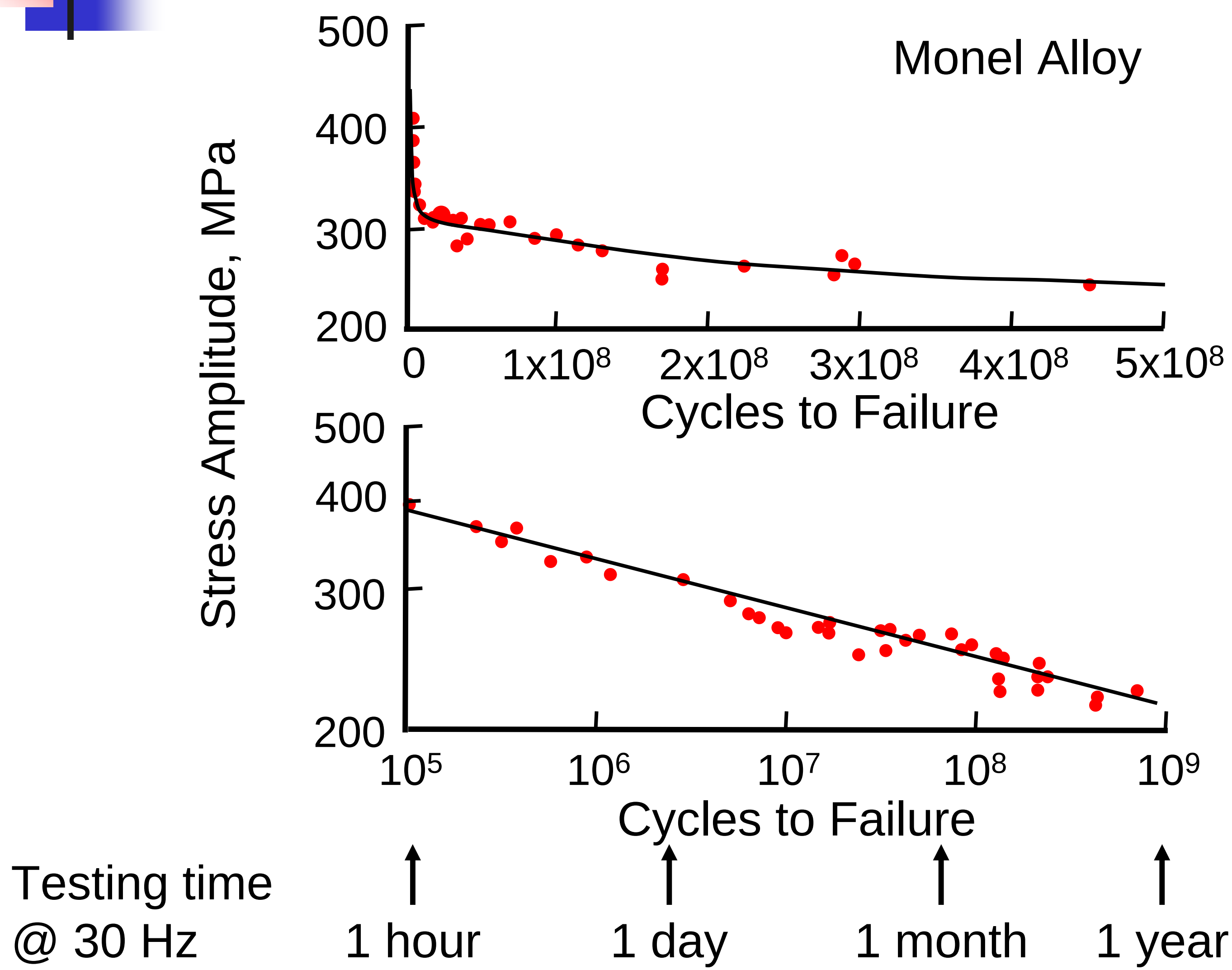
Bending Fatigue



Bending stress:

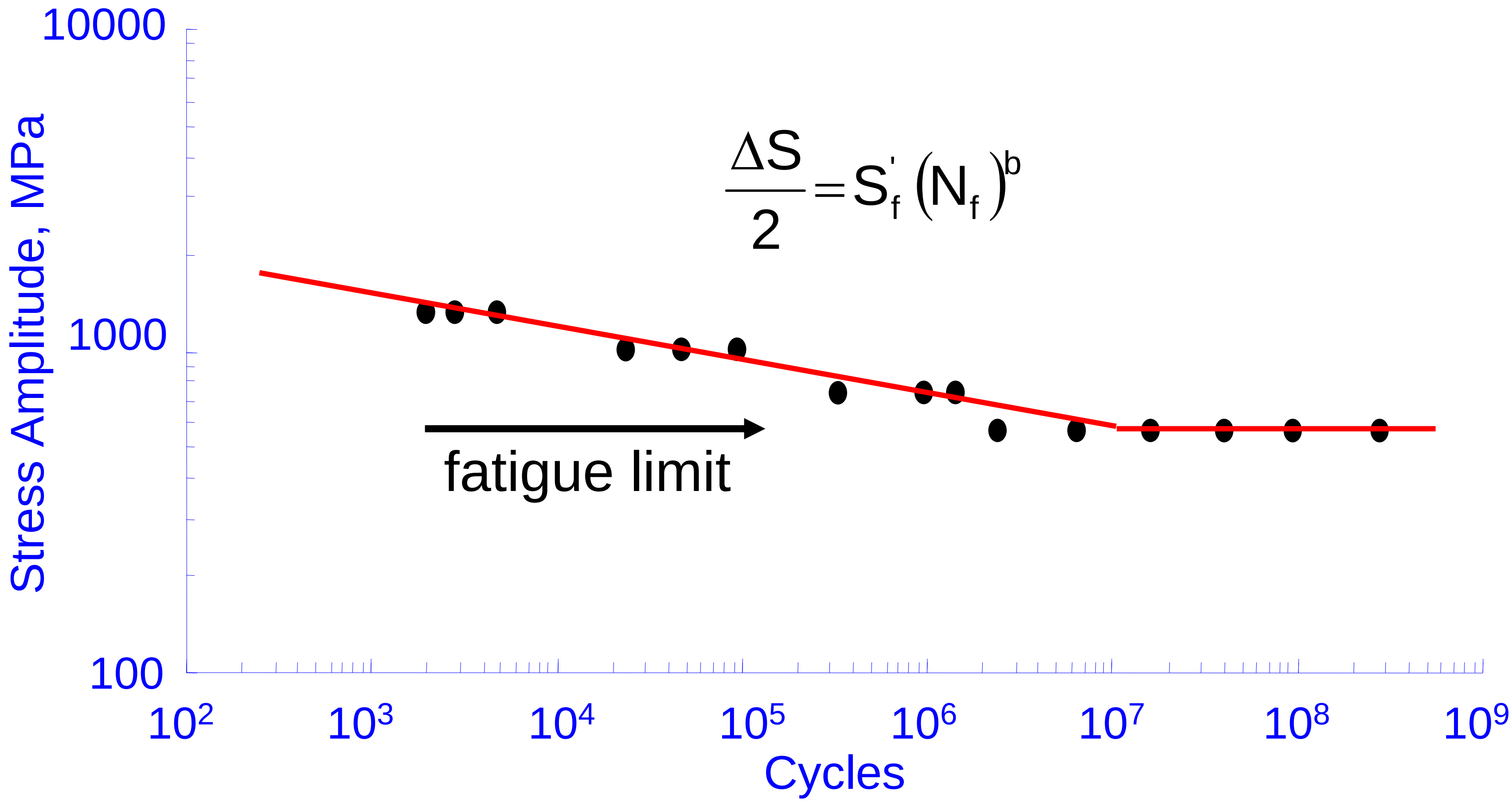
$$\sigma = \frac{Mc}{I}$$

SN Curve



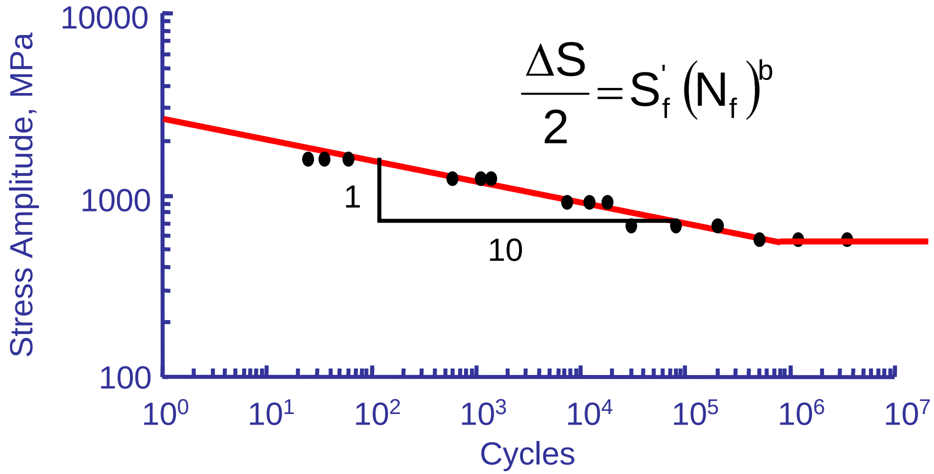
Monel Alloy
Stress Amplitude, MPa
500
400
300
200
0
1x10^8
2x10^8
3x10^8
4x10^8
5x10^8
Cycles to Failure
500
400
300
200
10^5
10^6
10^7
10^8
10^9
Cycles to Failure
Testing time
@ 30 Hz
1 hour
1 day
1 month
1 year

SN Curve



The fatigue limit is usually only found in steel laboratory specimens

Fatigue Damage

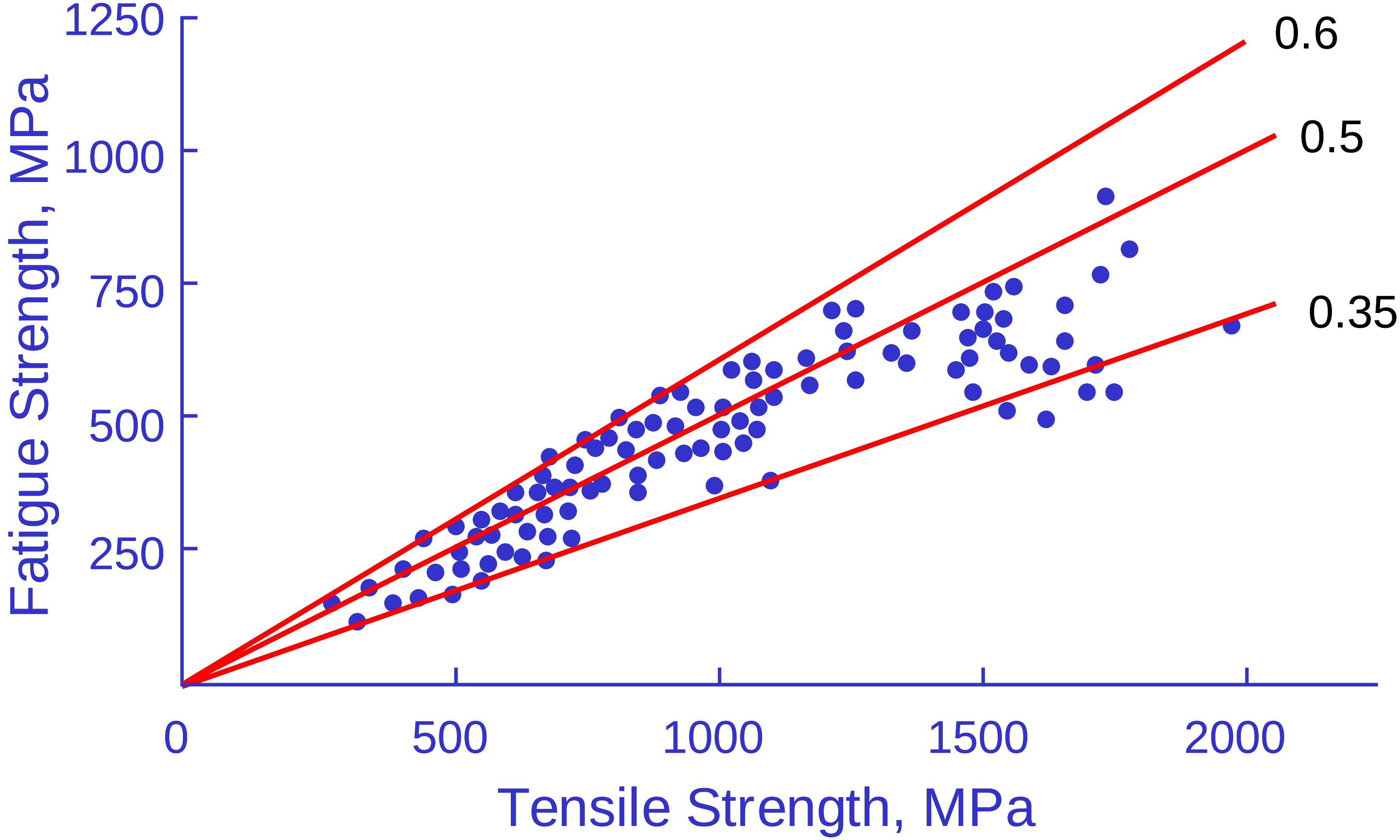


$$\frac{\Delta S}{2} = S_f' \left(N_f\right)^b$$

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

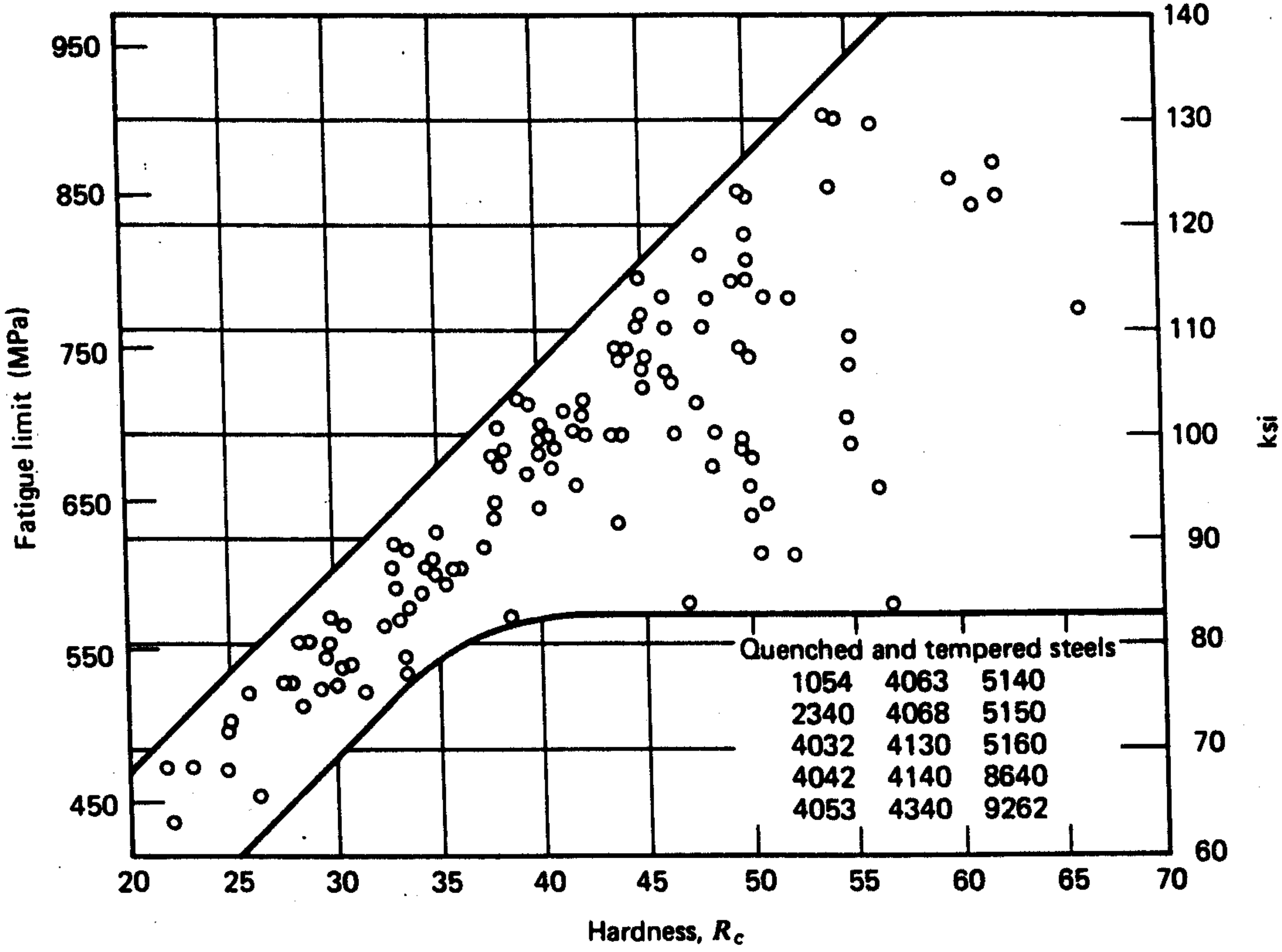
$$\text{Damage} \propto \Delta S^{10}$$

Fatigue Limit Strength Correlation

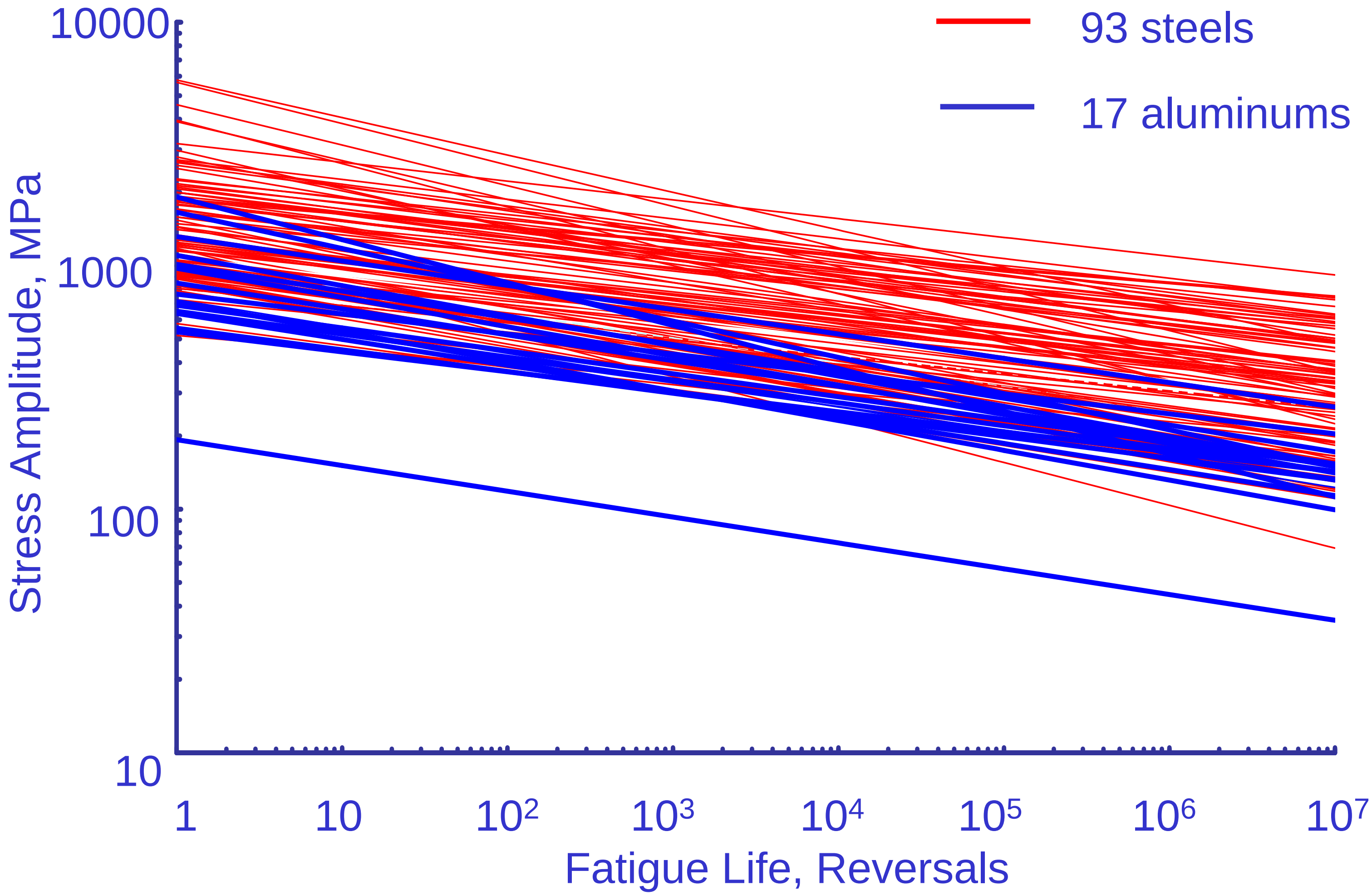


From Forrest, *Fatigue of Metals*, Pergamon Press, London, 1962

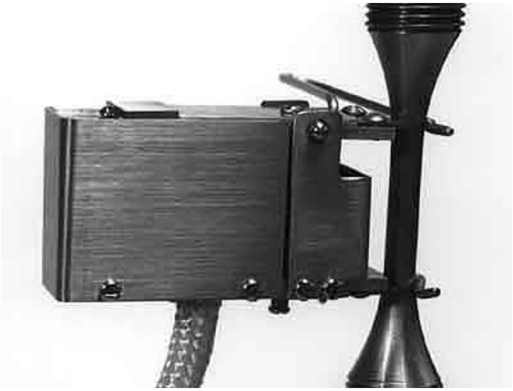
Fatigue Limit Strength Correlation

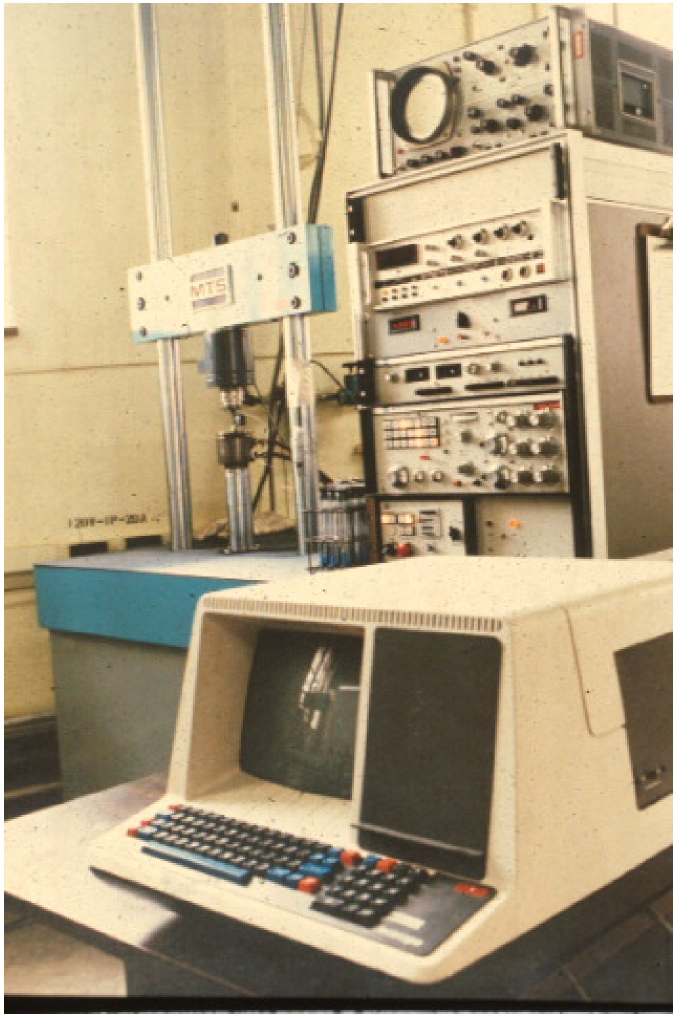


SN Materials Data

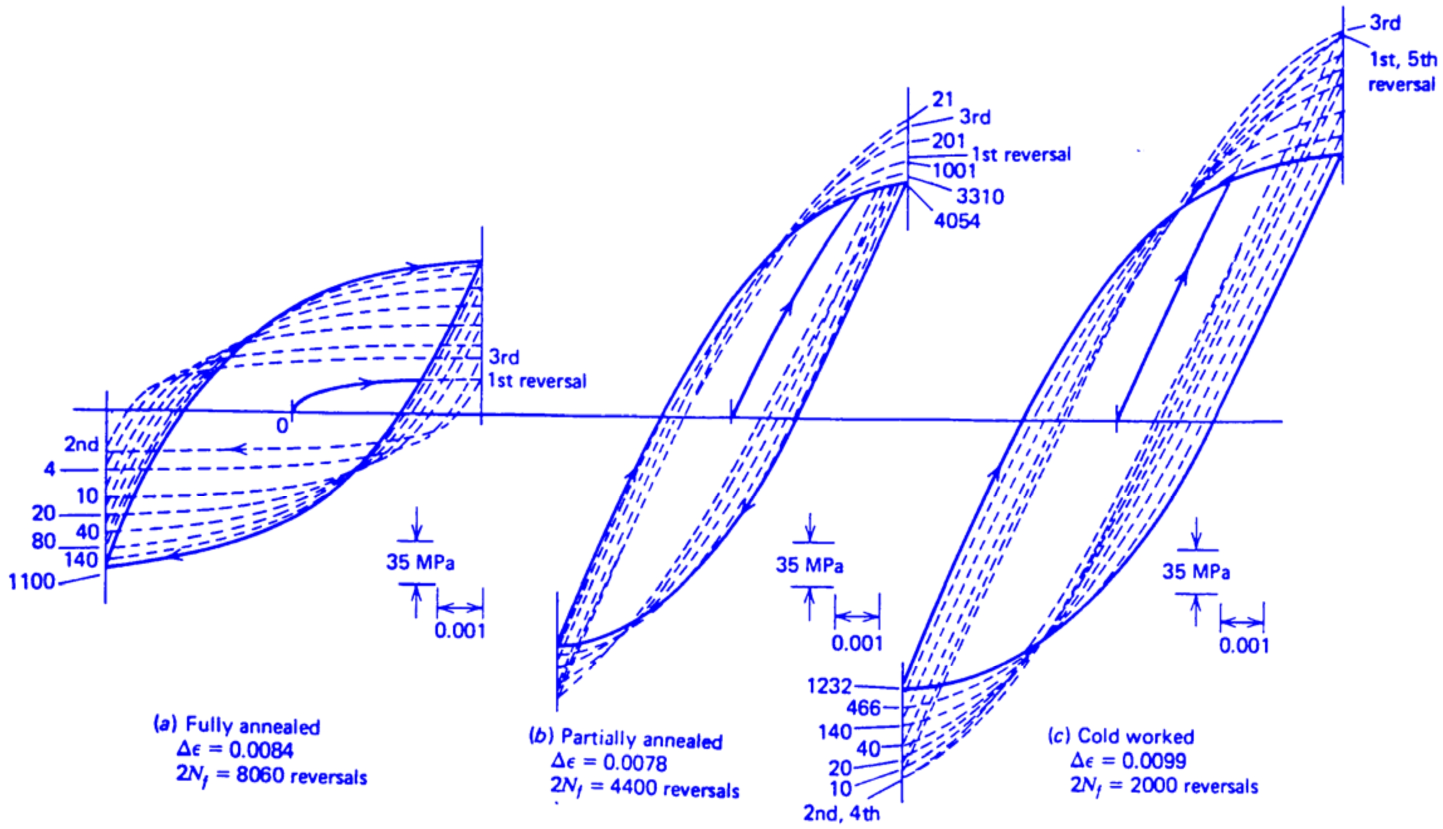


Strain Controlled Testing



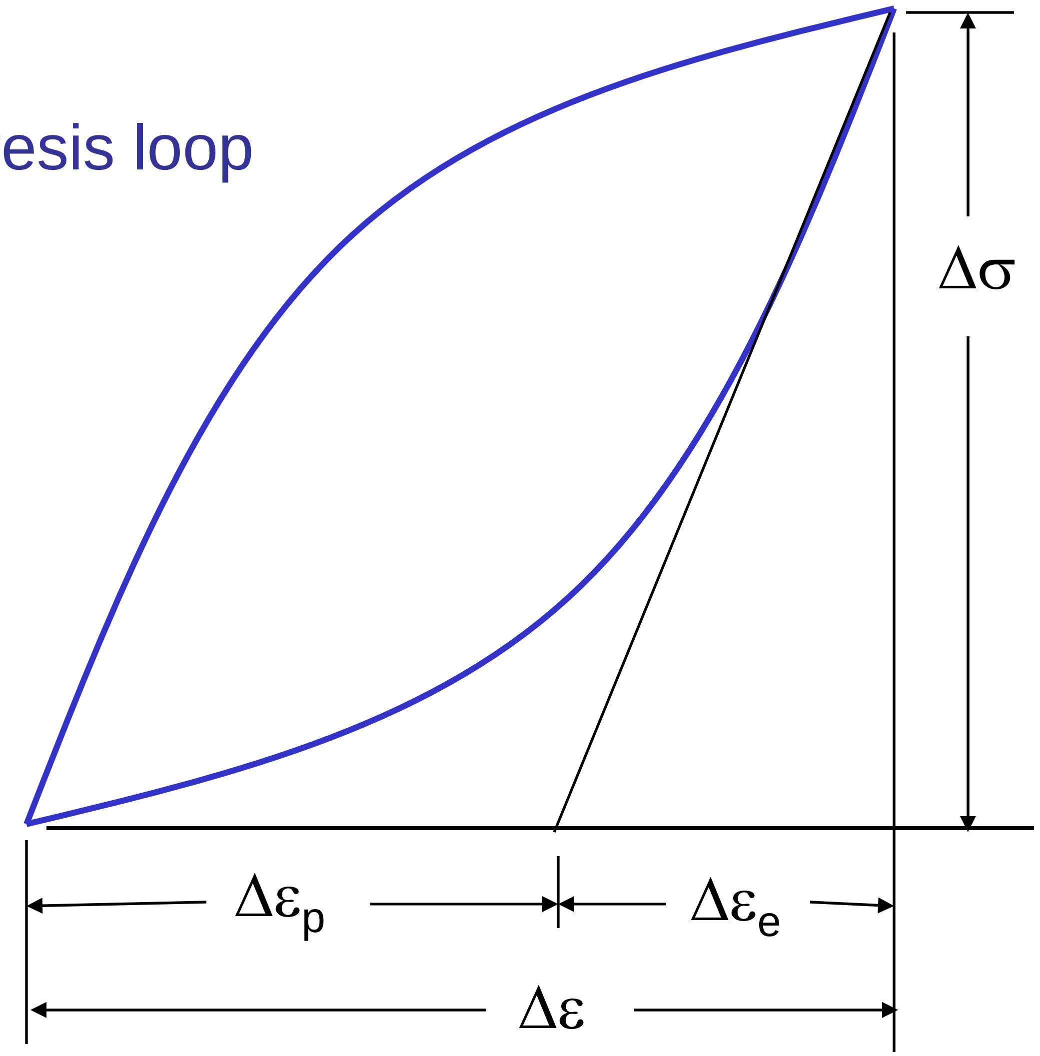


Cyclic Hardening / Softening

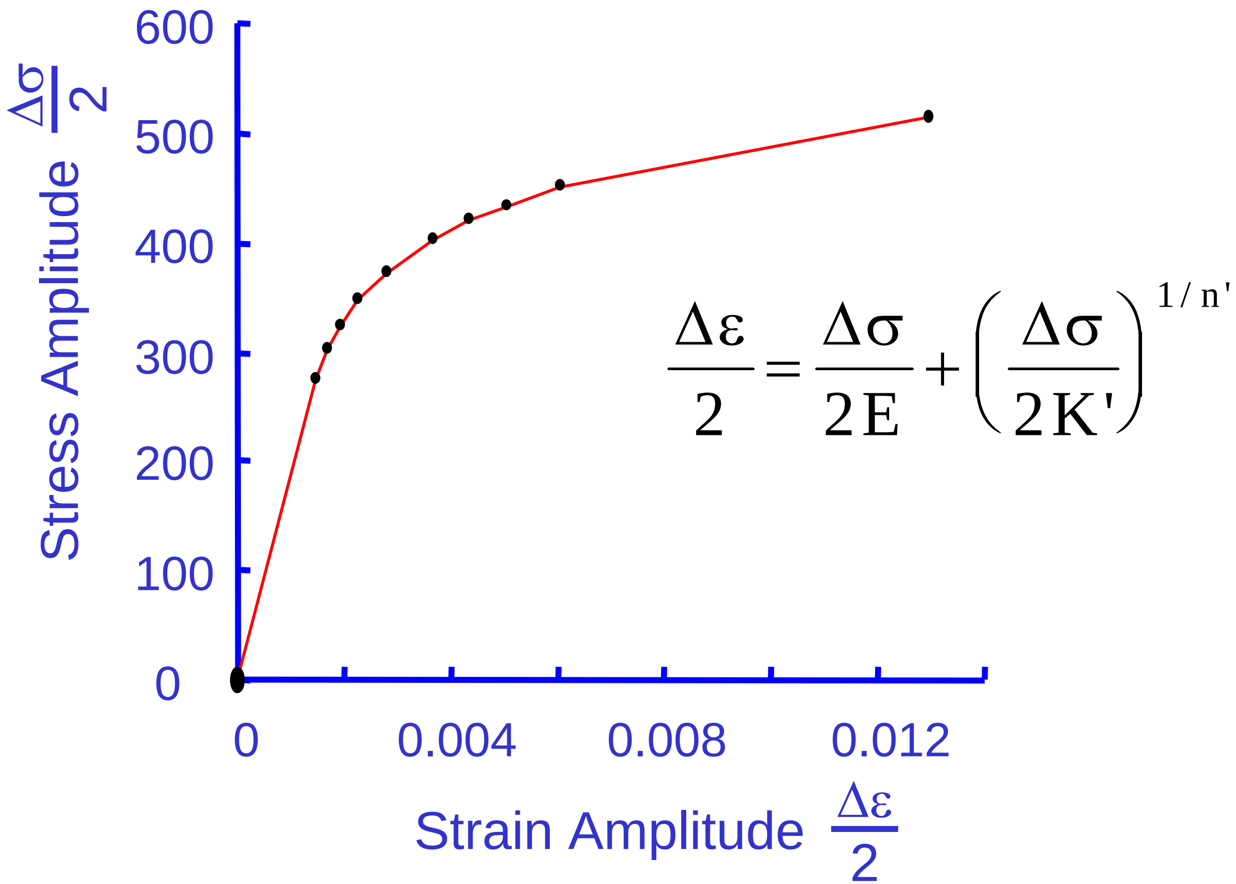


Stable Hysteresis Loop

Hysteresis loop

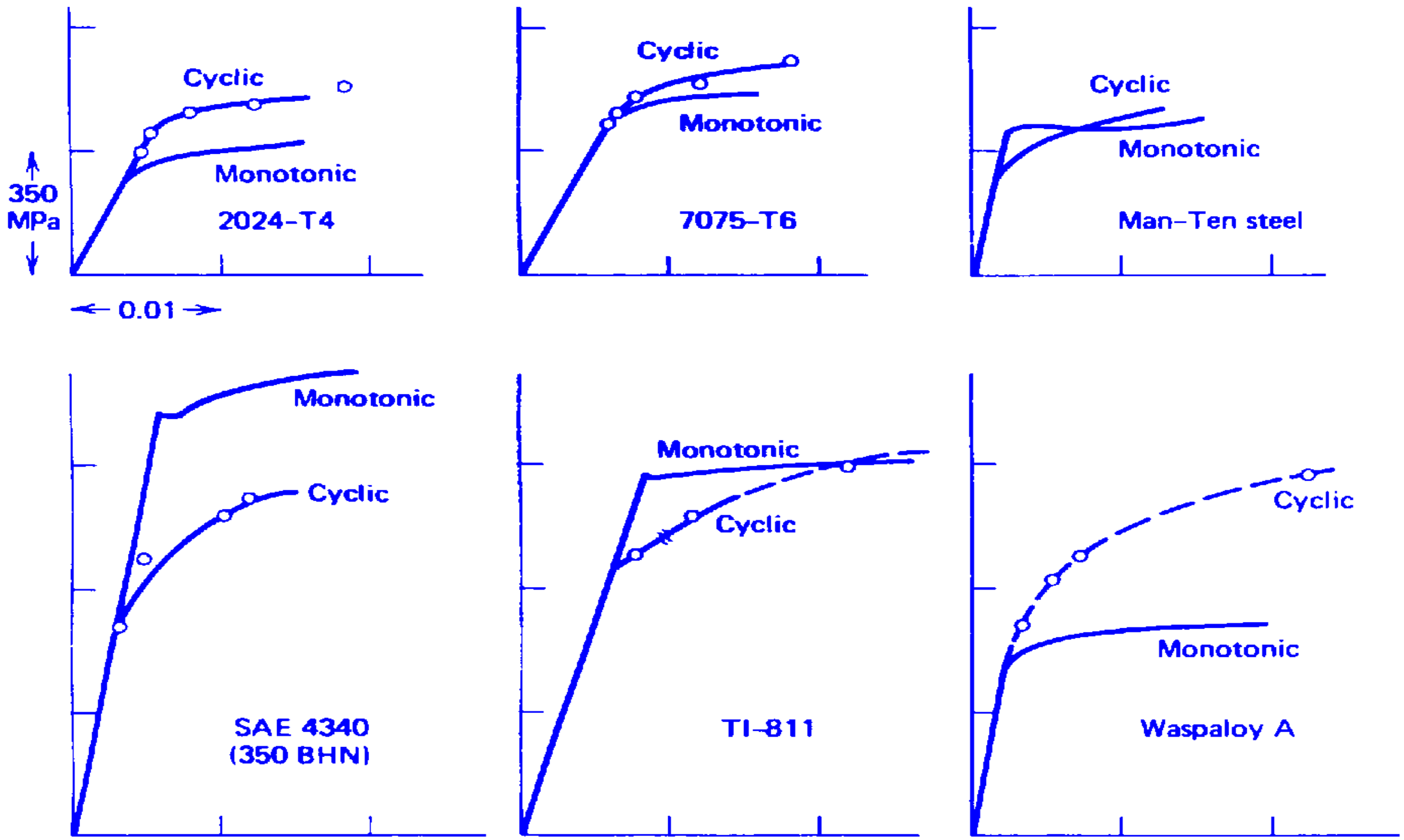


Strain-Life Data $\sigma - \varepsilon$

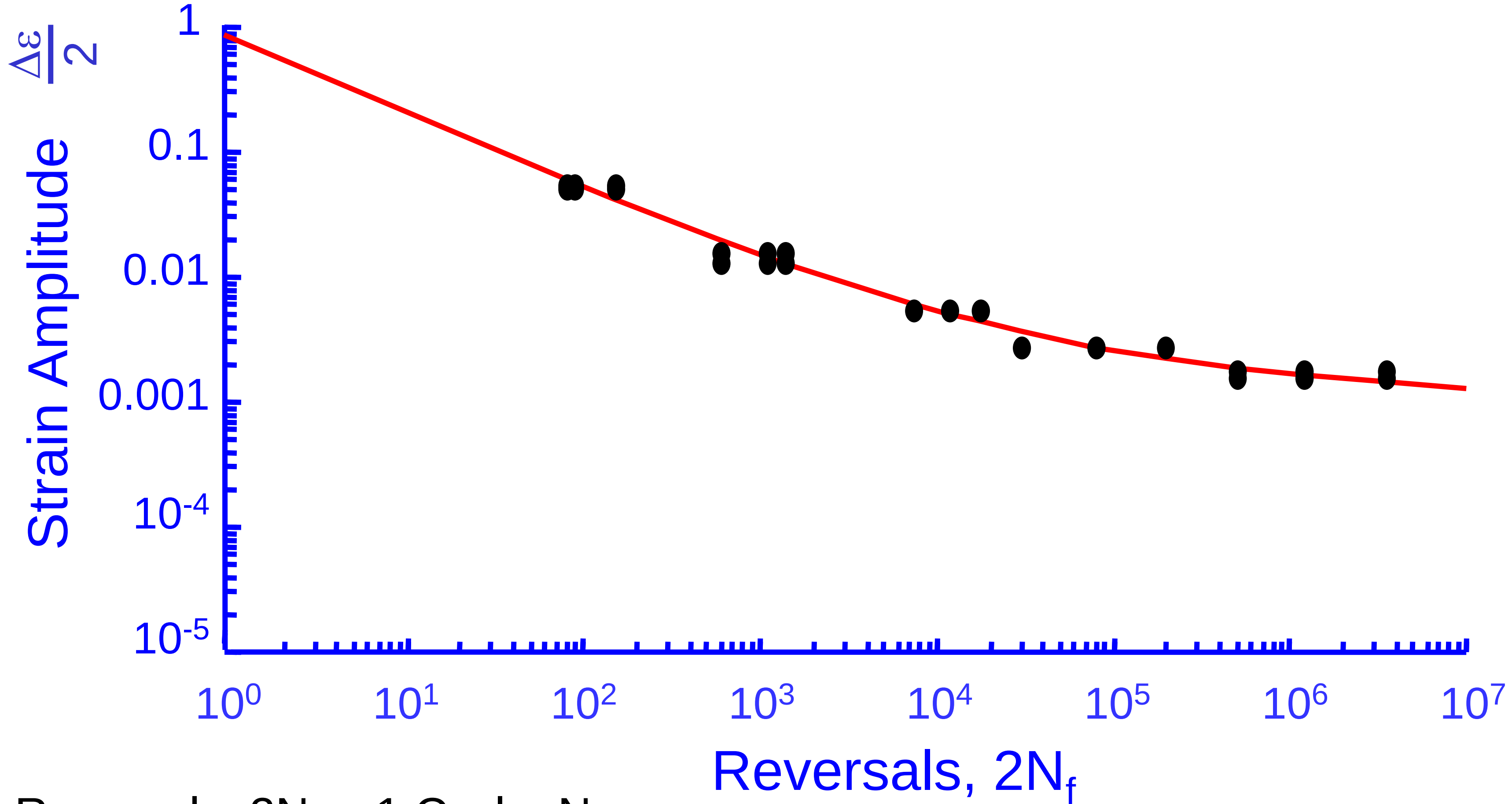


During cyclic deformation, the material deforms on a path described by the cyclic stress strain curve

Cyclic Stress Strain Curve

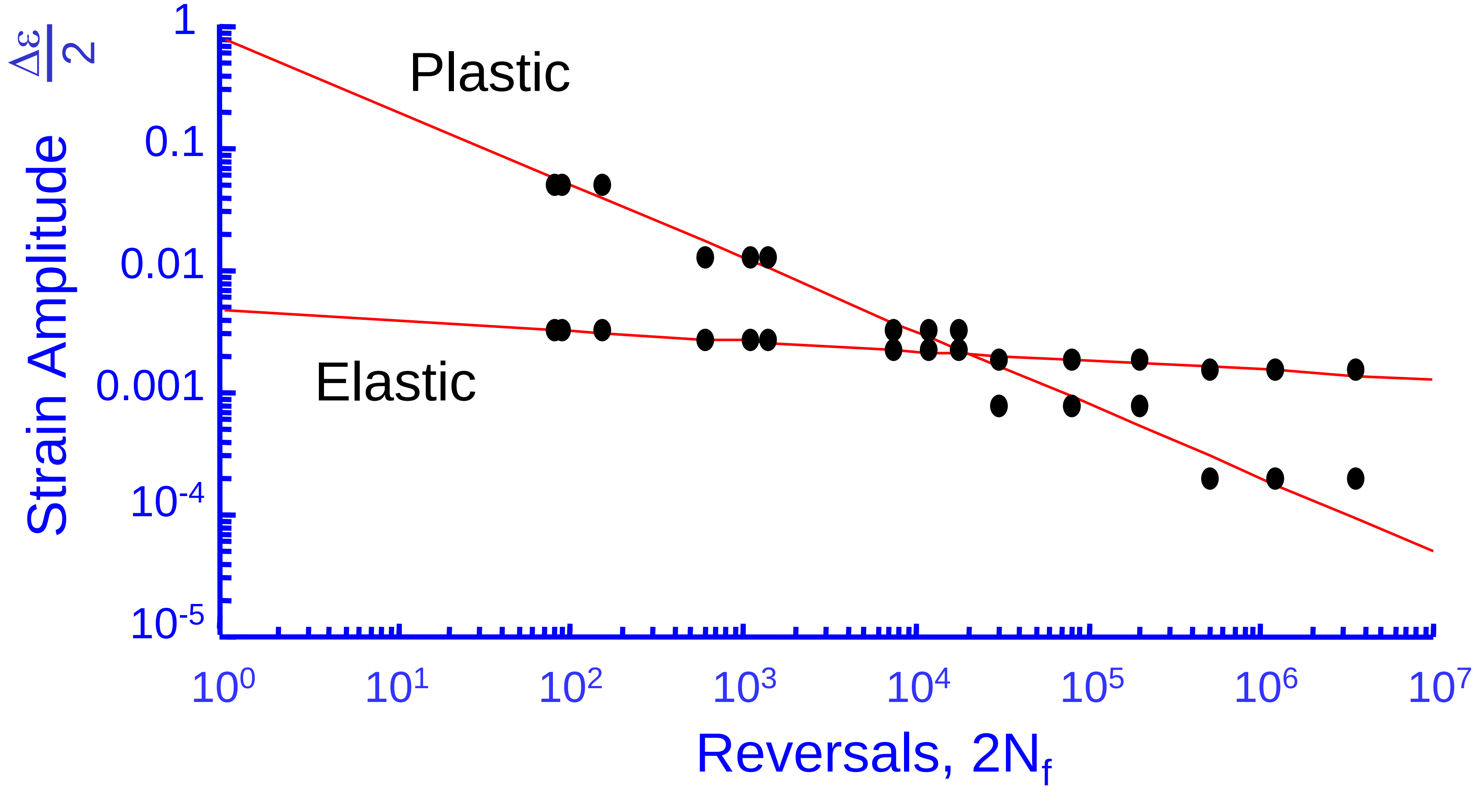


Strain-Life Data $\Delta\varepsilon$ - $2N_f$

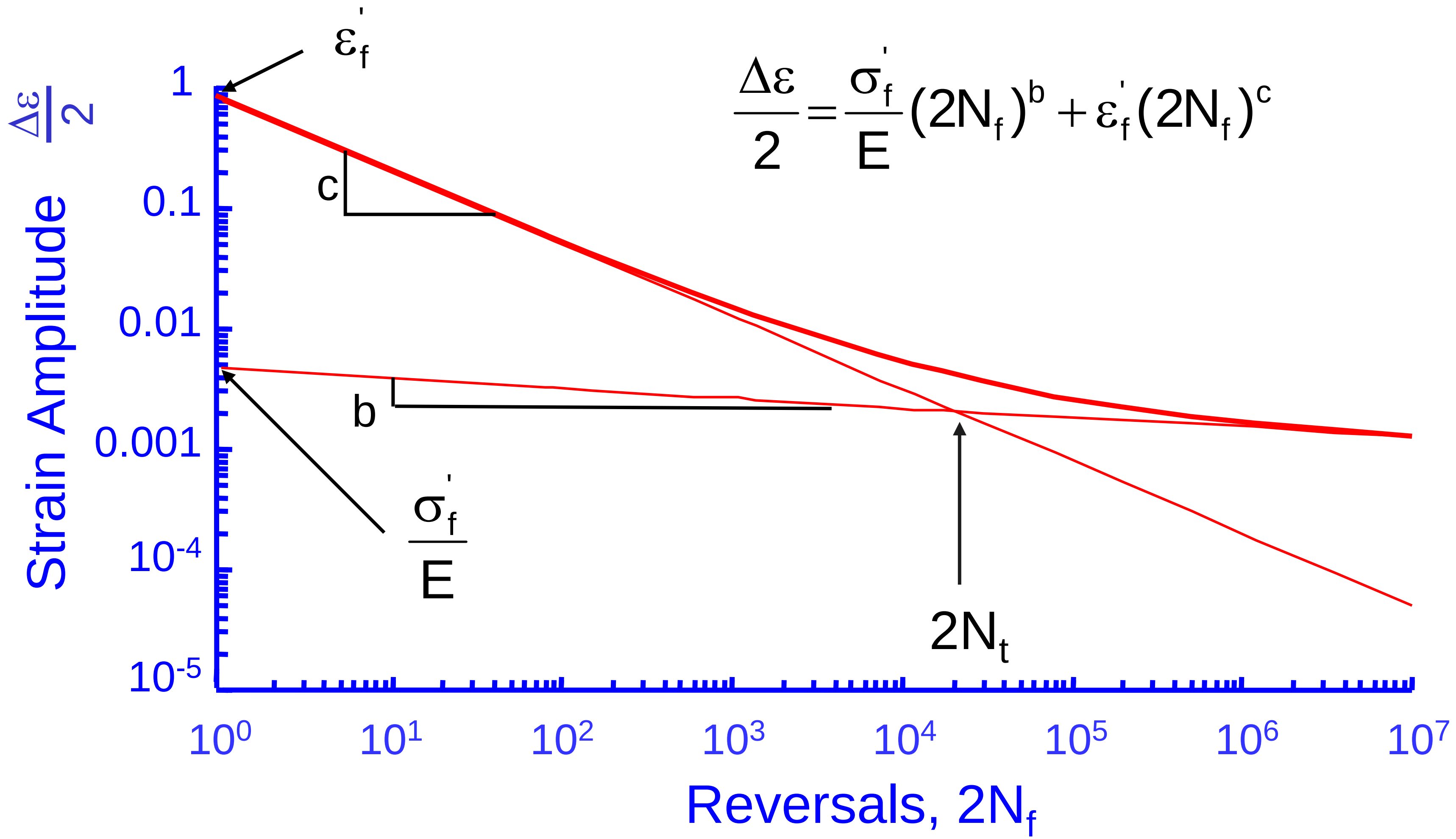


2 Reversals, $2N_f$ = 1 Cycle, N_f

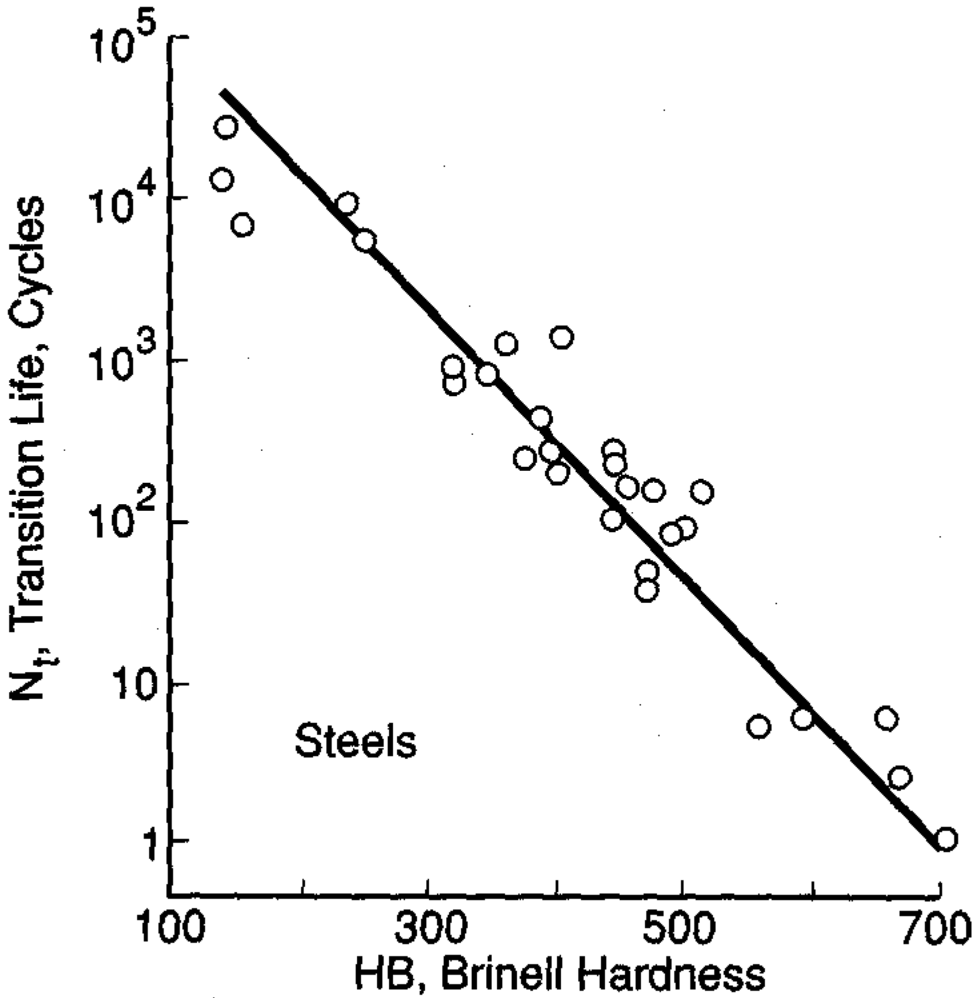
Elastic and Plastic Strain-Life Data



Strain-Life Curve

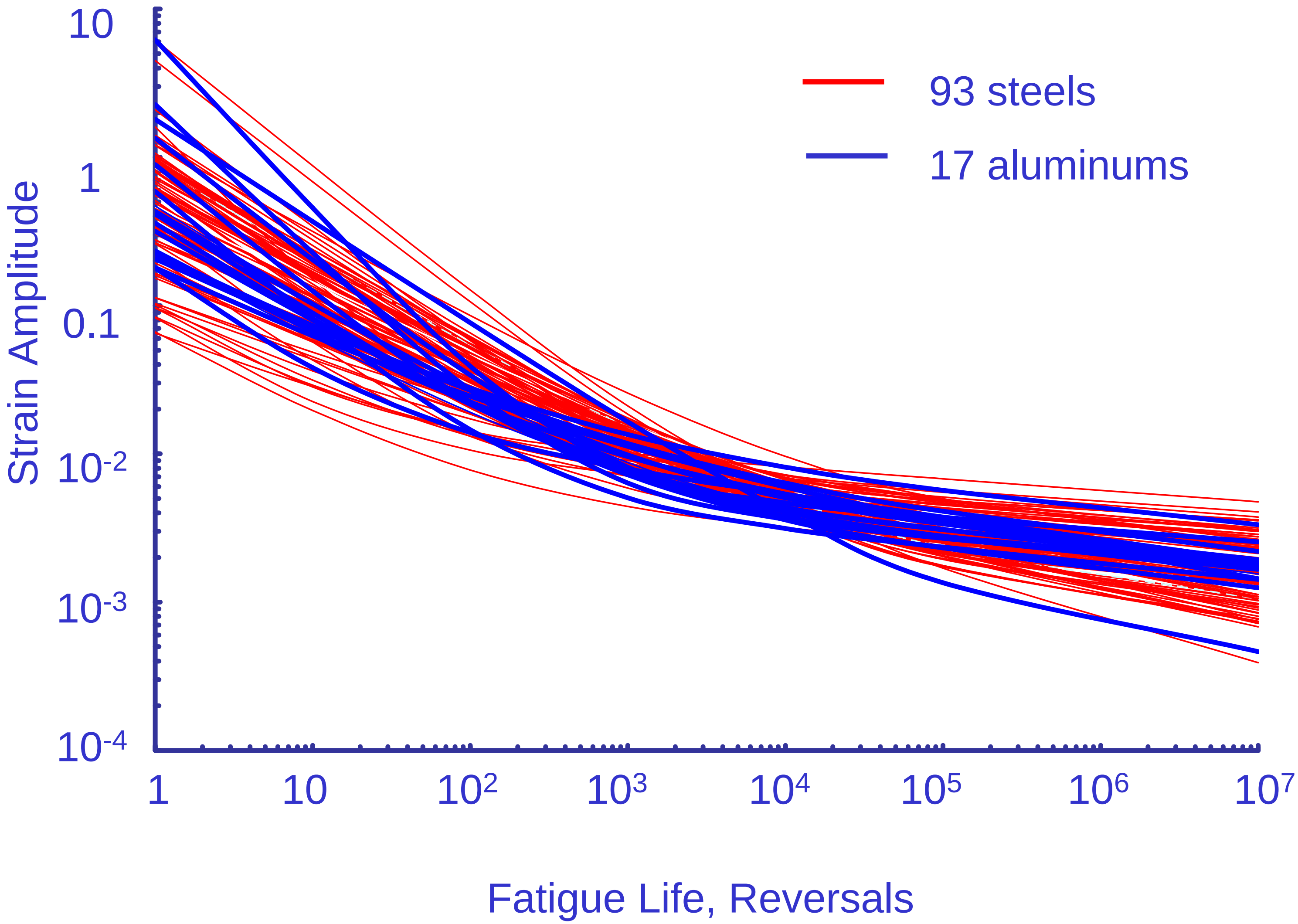


Transition Fatigue Life



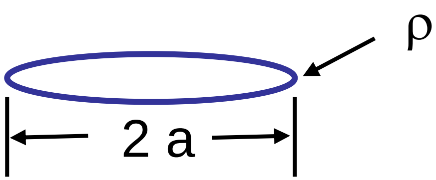
From Dowling, Mechanical Behavior of Materials, 1999

εN Materials Data



Crack Growth Testing

Stress Concentration of a Crack



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

$$K_T \sim 2000$$

for a crack

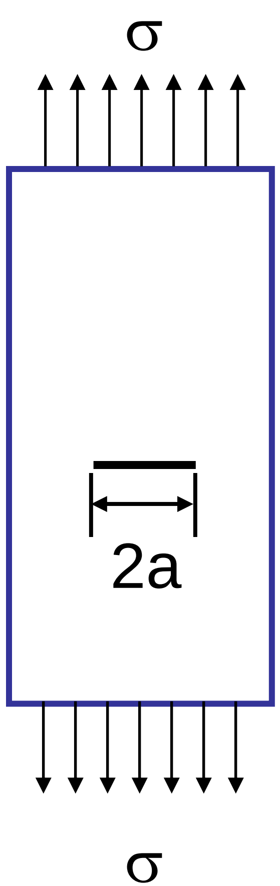
$a \sim 10^{-3}$

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

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

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

Stress Intensity Factor

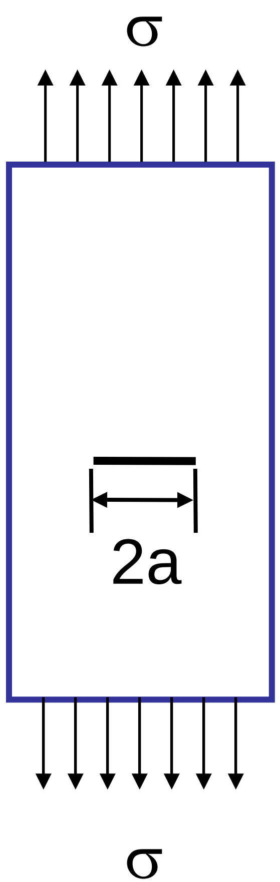


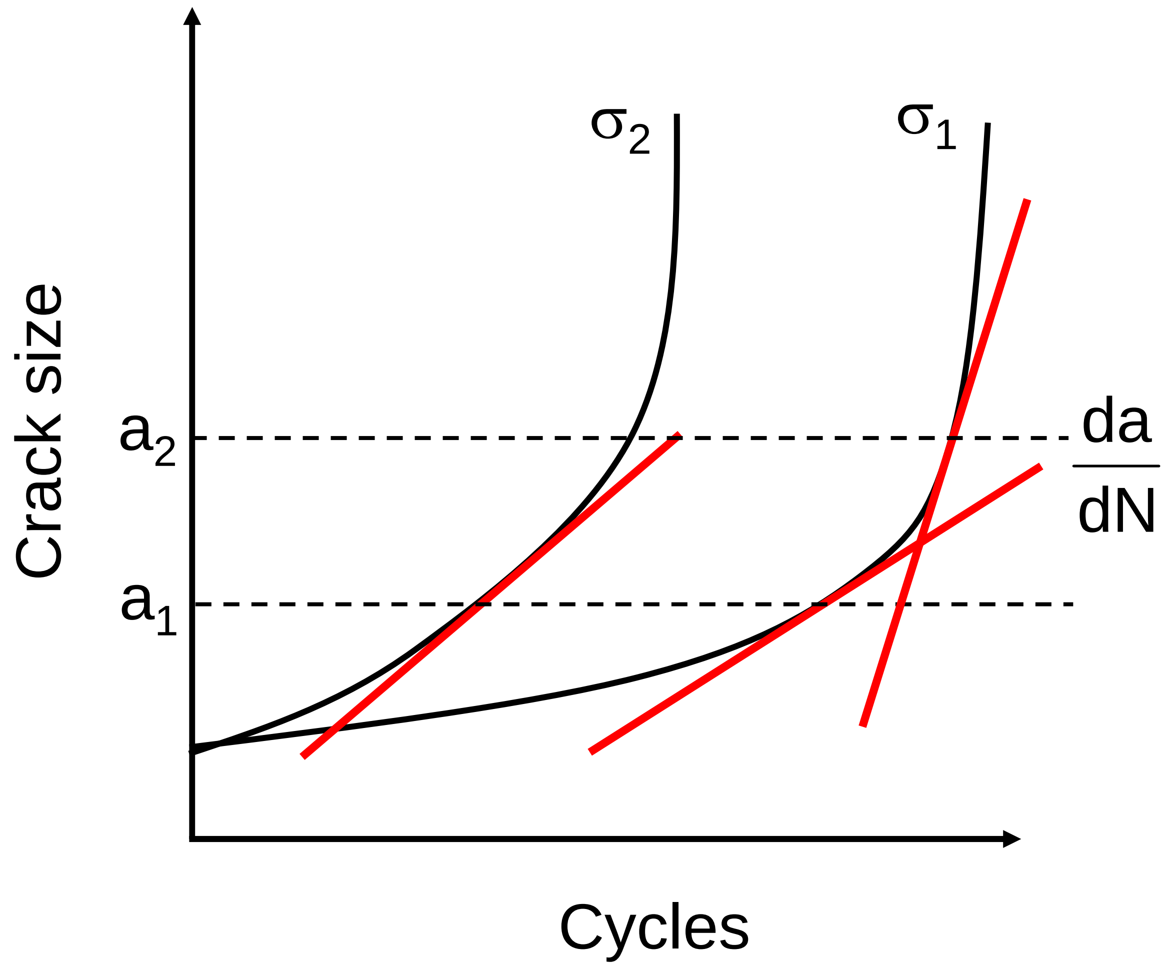
$$K = \sigma \sqrt{\pi a}$$

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

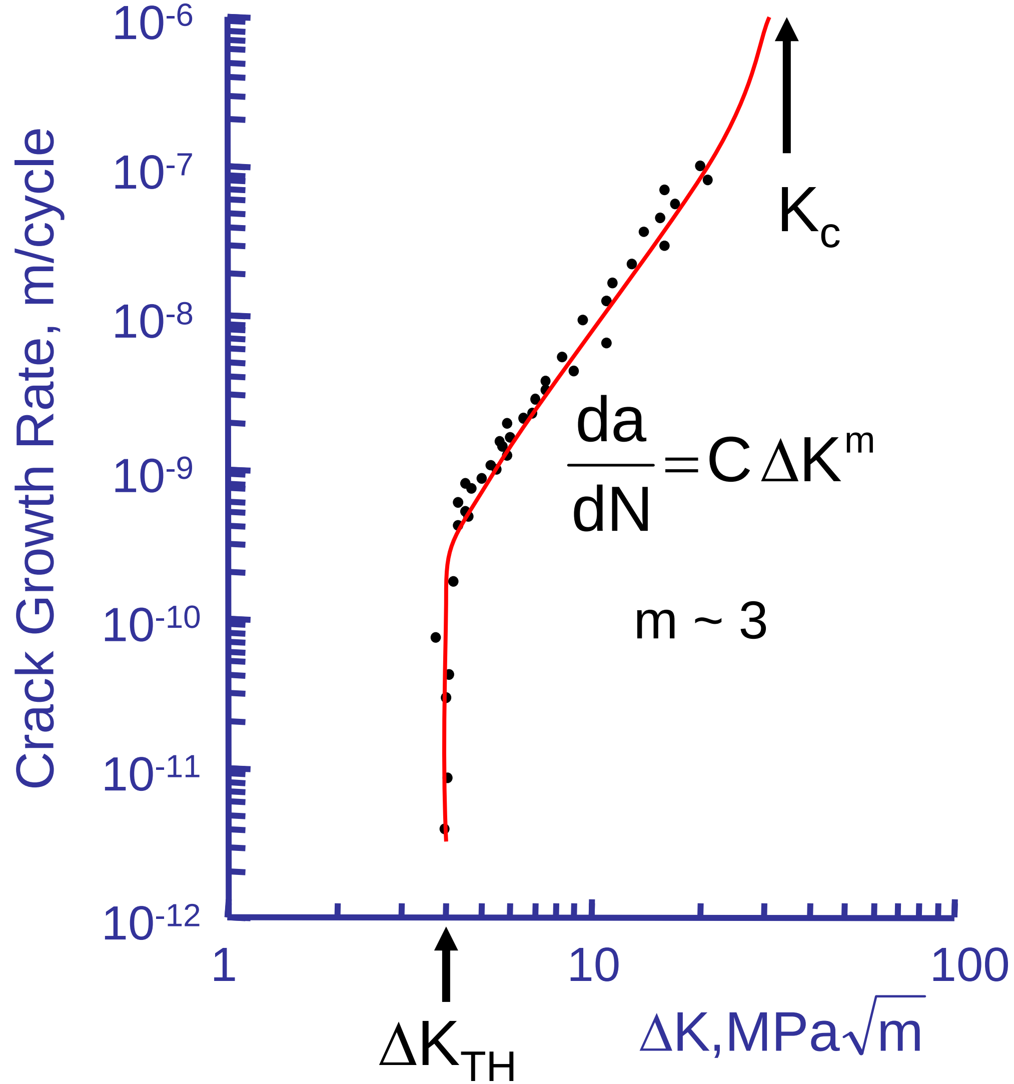
Two cracks with the same K will have the same behavior

Crack Growth Measurements





Crack Growth Data



Threshold Region

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

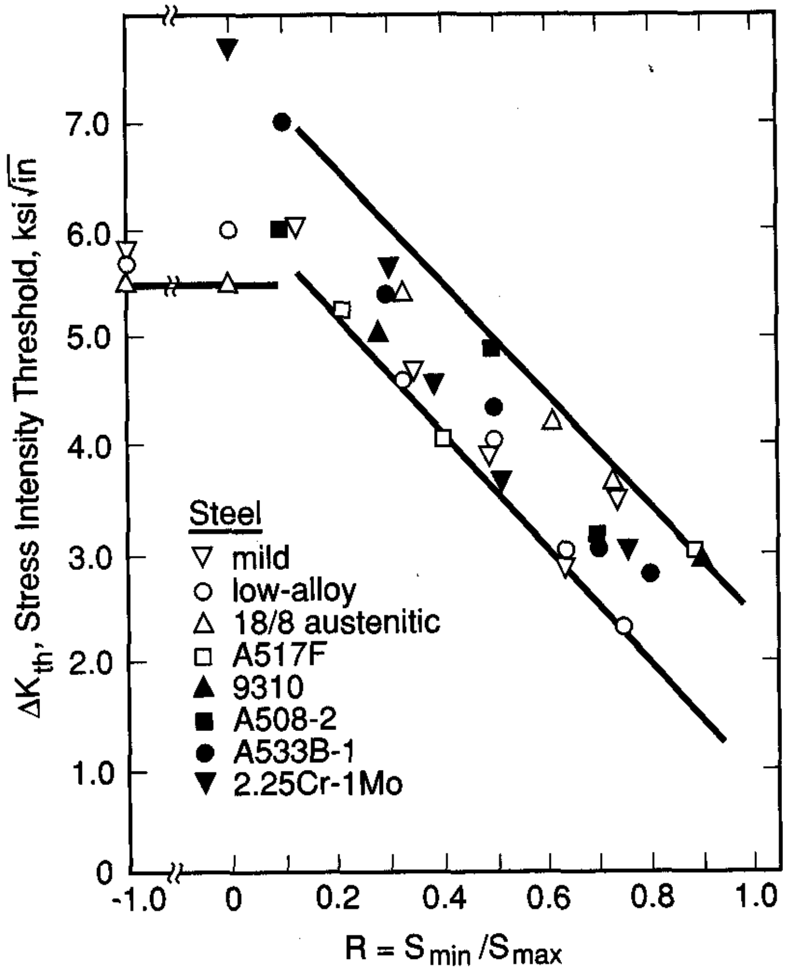
threshold stress intensity

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

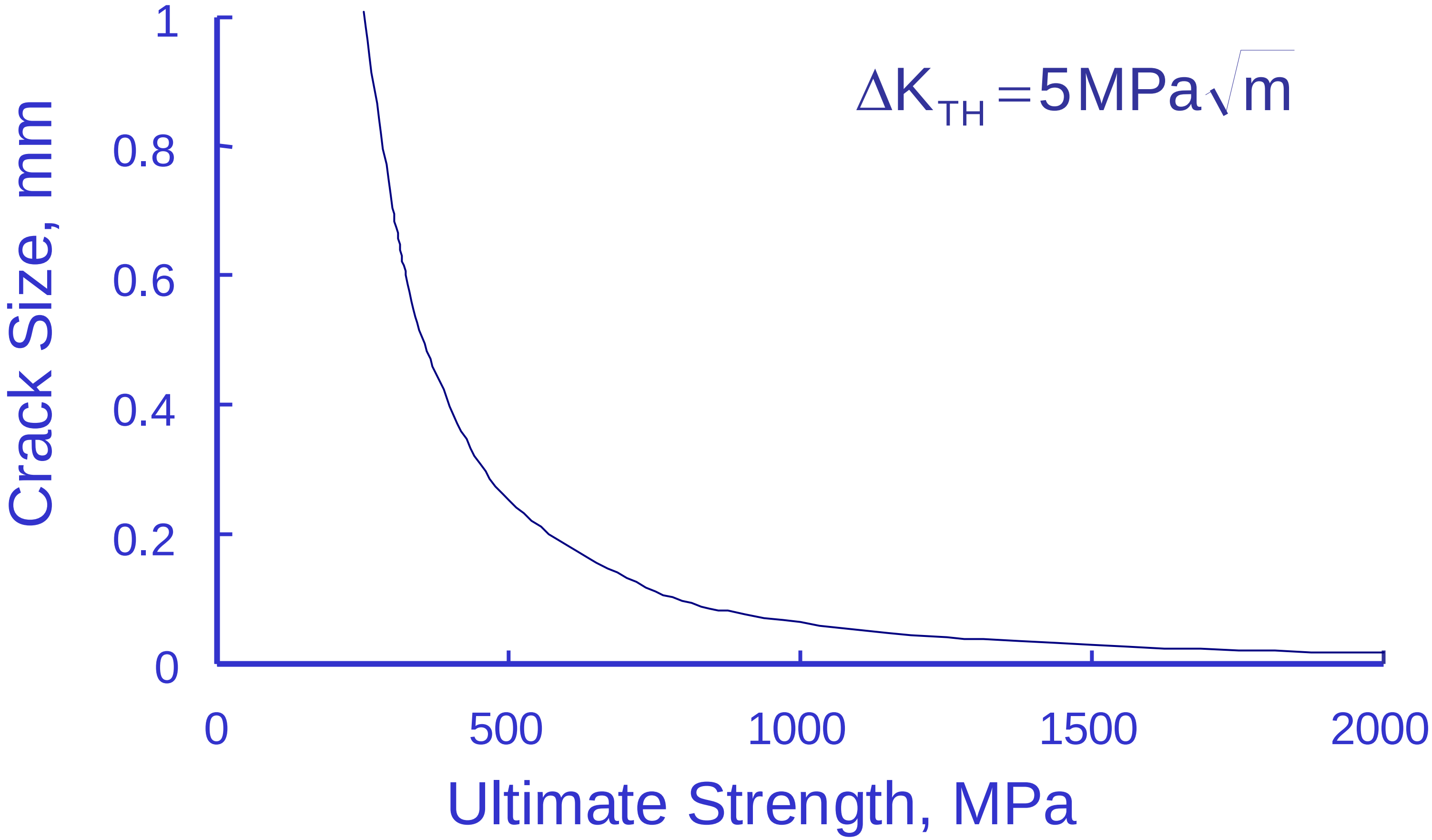
$$\Delta K_{TH} > \Delta\sigma 1.12 \frac{2}{\pi}\sqrt{\pi a}$$

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

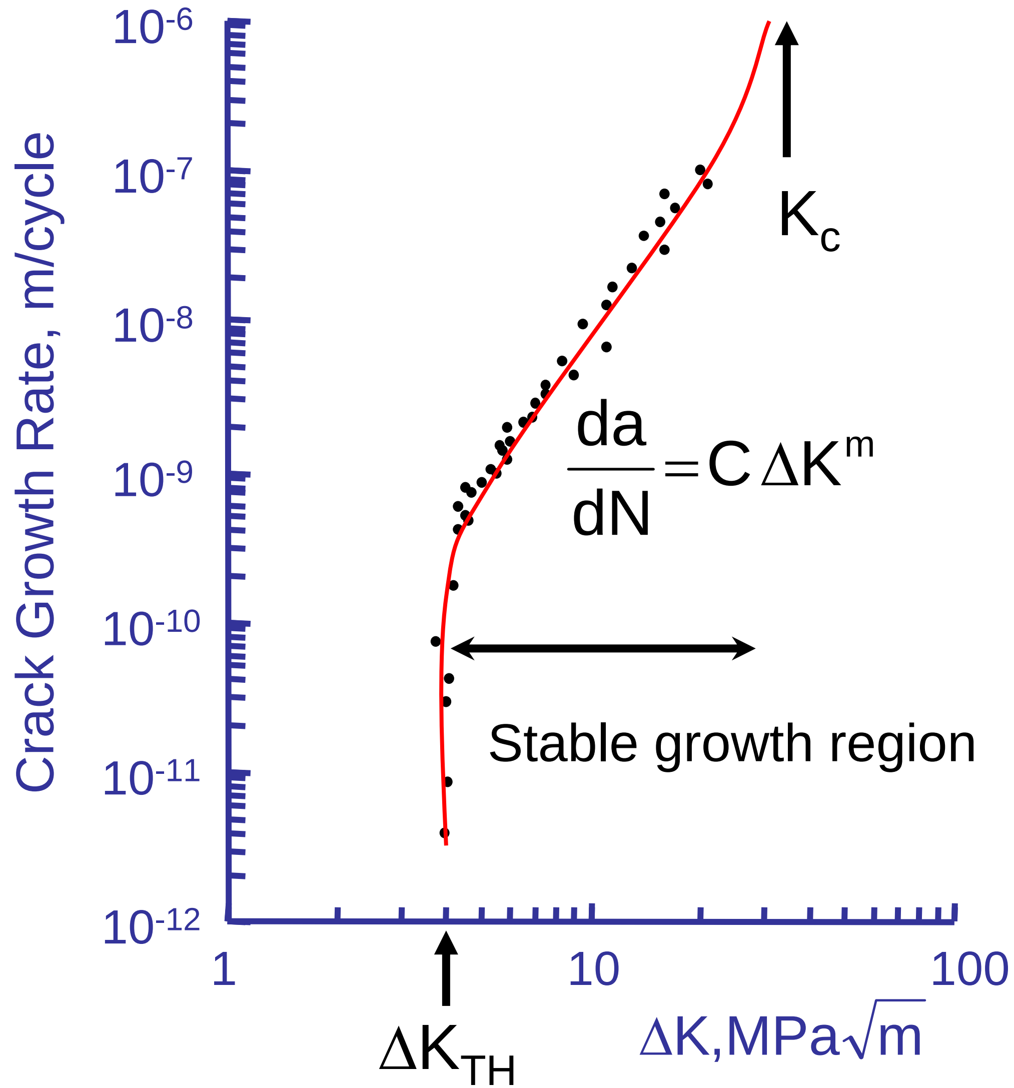
Smooth specimen fatigue limit $\approx \dfrac{\sigma_u}{2}$

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

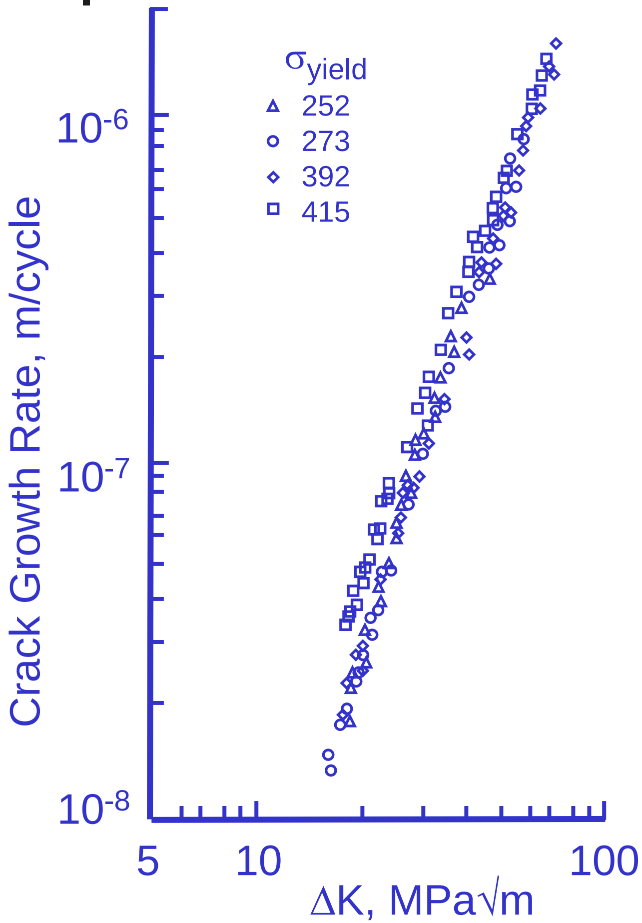
Non-propagating Crack Sizes



Stable Crack Growth



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

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 Seminar

Fatigue Made Easy

Similitude

Professor Darrell F. Socie
Mechanical Science and Engineering
University of Illinois

Seminar Outline

1. Historical background
2. Physics of fatigue
3. Characterization of materials
4. Similitude (why fatigue modeling works)
5. Variability
6. Mean stress
7. Stress concentrations
8. Surface effects
9. Variable amplitude loading
10. Welded structures

Fatigue Analysis

Material Data

Component Geometry

Service Loading

Analysis

?

Fatigue Life Estimate

The Similitude Concept

Why Fatigue Modeling Works !

What is the Similitude Concept

The “Similitude Concept” allows engineers to relate the behavior of small-scale cyclic material test specimens, defined under carefully controlled conditions, to the likely performance of real structures subjected to variable amplitude fatigue loads under either simulated or actual service conditions.

Fatigue Analysis Techniques

Stress - Life

BS 7608, Eurocode 3

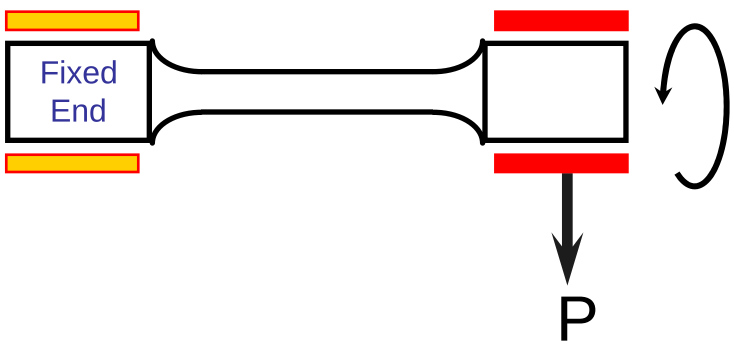
Strain - Life

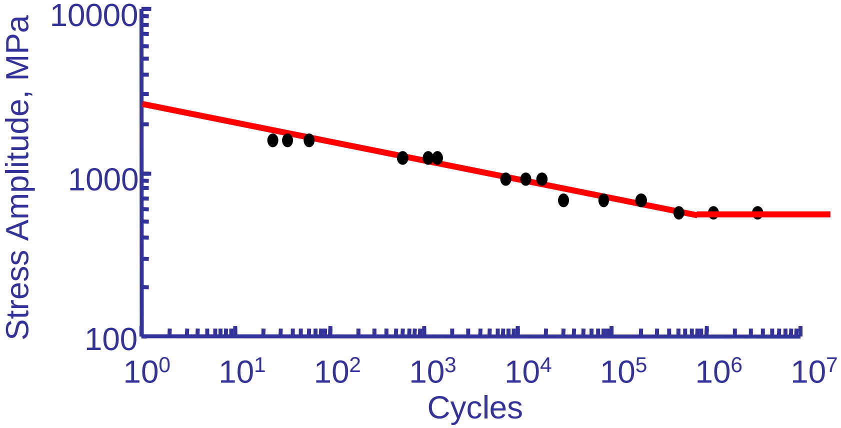
Crack Growth

Life Estimation

Method	Physics	Size
Stress-Life	Crack Nucleation	0.01 mm
BS 7608	Crack Growth	1 - 10 mm
Strain-Life	Microcrack Growth	0.1 - 1 mm
Crack Growth	Macrocrack Growth	> 1mm

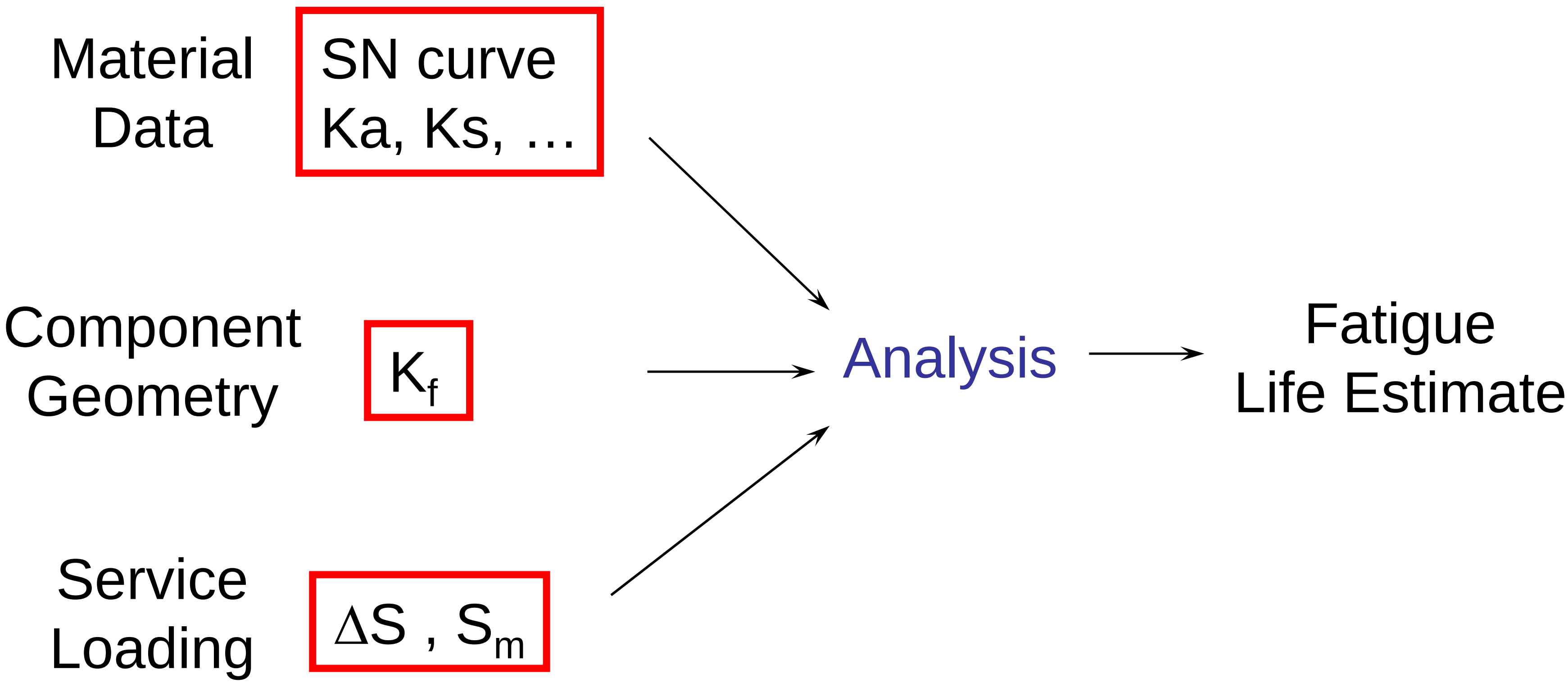
Stress-Life Fatigue Modeling





The Similitude Concept states that if the instantaneous loads applied to the 'test' structure (wing spar, say) and the test specimen are the same, then the response in each case will also be the same and can be described by the material's S-N curve. Due account can also be made for stress concentrations, variable amplitude loading etc.

Fatigue Analysis: Stress-Life



Stress-Life

- Major Assumptions:
  - Most of the life is consumed nucleating cracks
  - Elastic deformation
  - Nominal stresses and material strength control fatigue life
  - Accurate determination of K_f for each geometry and material

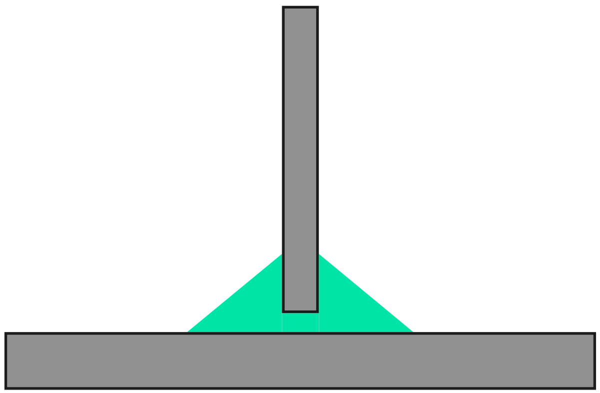
Stress-Life

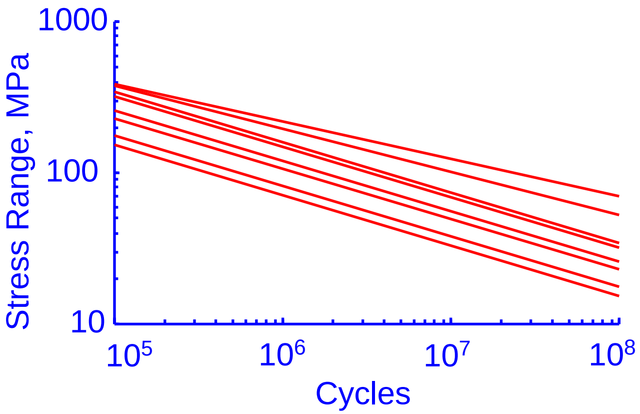
- Advantages:
  - Changes in material and geometry can easily be evaluated
  - Large empirical database for steel with standard notch shapes

Stress-Life

- Limitations:
  - Does not account for notch root plasticity
  - Mean stress effects are often in error
  - Requires empirical K_f for good results

BS 7608 Fatigue Modeling

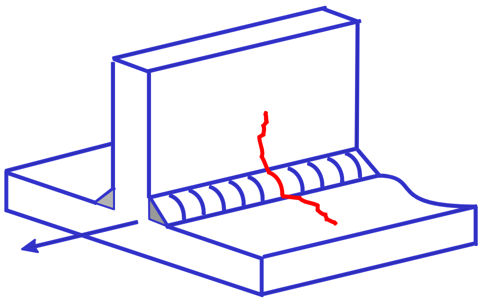




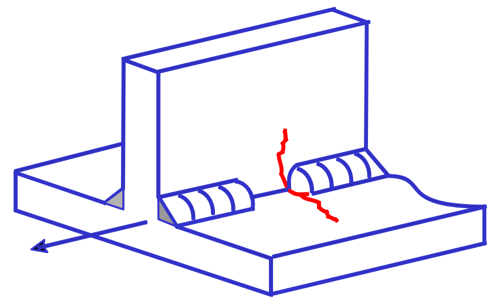
The Similitude Concept states that if the instantaneous loads applied to the ‘test’ structure (welded beam on a bulldozer, say) and the test specimen (standard fillet weld) are the same, then the response in each case will also be the same and can be described by one of the standard BS 7608 Weld Classification S-N curves.

Weld Classifications

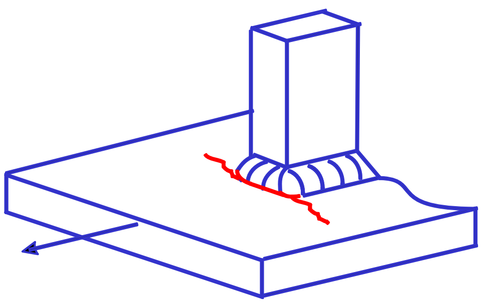
D



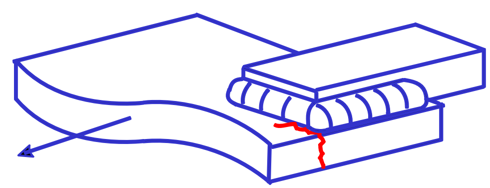
E



F2



G



Fatigue Analysis: BS 7608

Material Data — Weld SN curve

Component Geometry — Class

Service Loading — ΔS

→ Analysis → Fatigue Life Estimate

BS 7608

- Major Assumptions:
  - Crack growth dominates fatigue life
  - Complex weld geometries can be described by a standard classification
  - Results independent of material and mean stress for structural steels

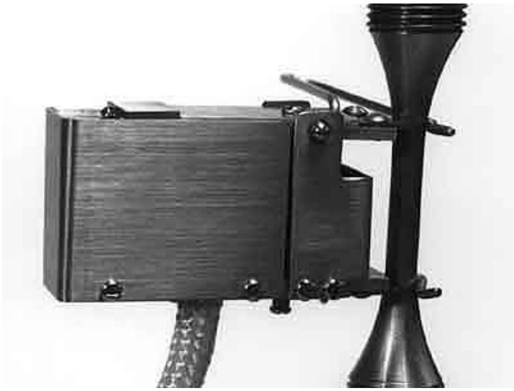
BS 7608

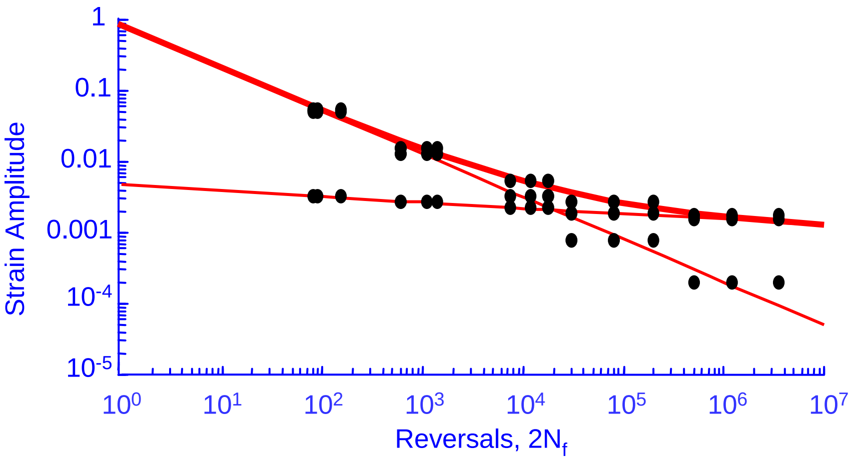
- Advantages:
  - Manufacturing effects are directly included
  - Large empirical database exists

BS 7608

- Limitations:
  - Difficult to determine nominal stress and weld class for complex shapes
  - No benefit for improving manufacturing process

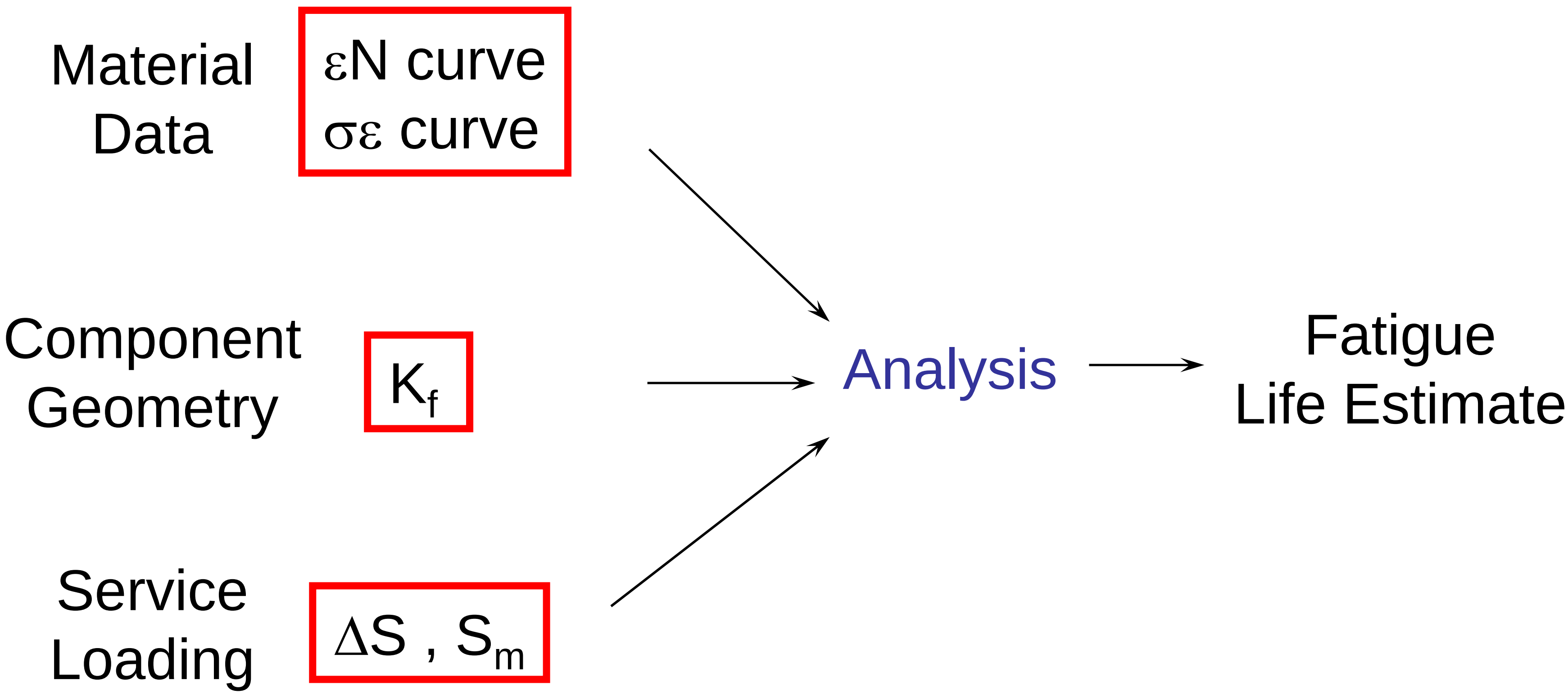
Strain-Life Fatigue Modeling





The Similitude Concept states that if the instantaneous strains applied to the ‘test’ structure (vehicle suspension, say) and the test specimen are the same, then the response in each case will also be the same and can be described by the material’s e-N curve. Due account can also be made for stress concentrations, variable amplitude loading etc.

Fatigue Analysis: Strain-Life



Strain-Life

- Major Assumptions:
  - Local stresses and strains control fatigue behavior
  - Plasticity around stress concentrations
  - Accurate determination of K_f

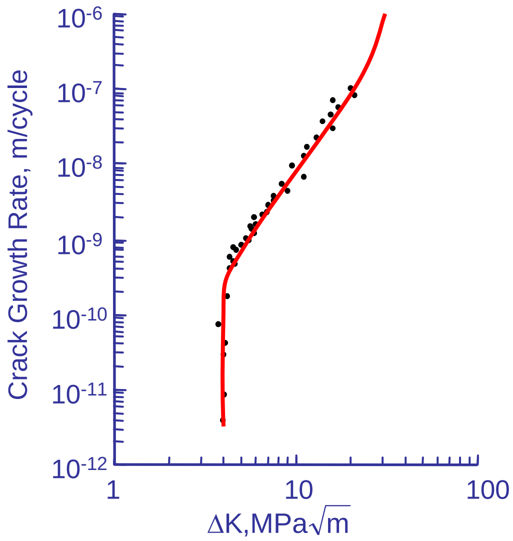
Strain-Life

- Advantages:
  - Plasticity effects
  - Mean stress effects

Strain-Life

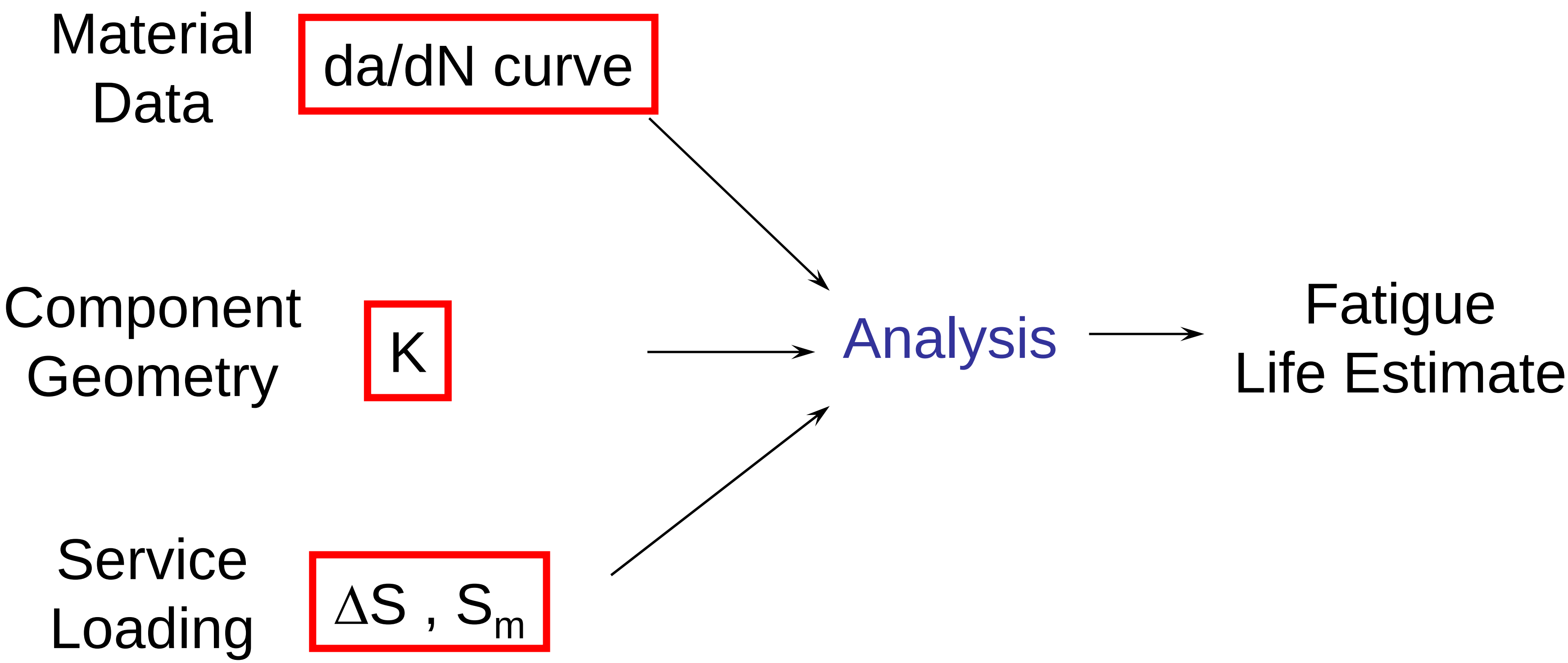
- Limitations:
  - Requires empirical K_f
  - Long life situations where surface finish and processing variables are important

Crack Growth Fatigue Modeling



The Similitude Concept states that if the stress intensity (K) at the tip of a crack in the ‘test’ structure (welded connection on an oil platform leg, say) and the test specimen are the same, then the crack growth response in each case will also be the same and can be described by the Paris relationship. Account can also be made for local chemical environment, if necessary.

Fatigue Analysis: Crack Growth



Crack Growth

- Major Assumptions:
  - Nominal stress and crack size control fatigue life
  - Accurate determination of initial crack size

Crack Growth

- Advantage:
  - Only method to directly deal with cracks

Crack Growth

- Limitations:
  - Complex sequence effects
  - Accurate determination of initial crack size

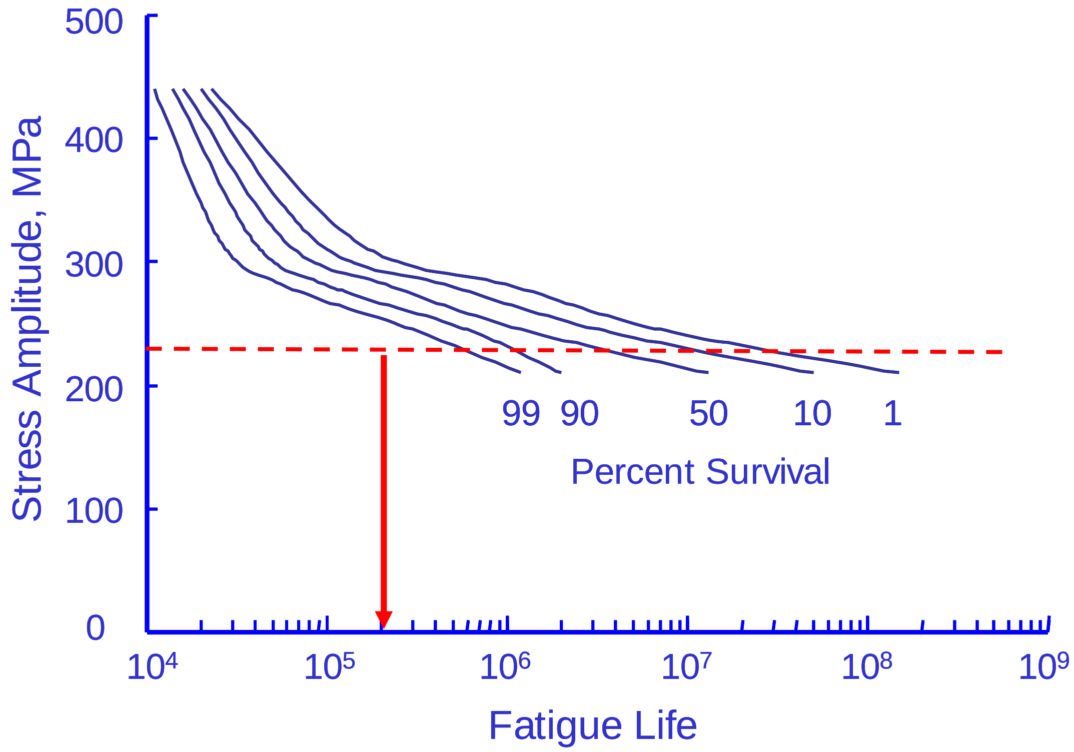
Choose the Right Model

- Similitude
  - Failure mechanism
  - Size scale

Design Philosophy

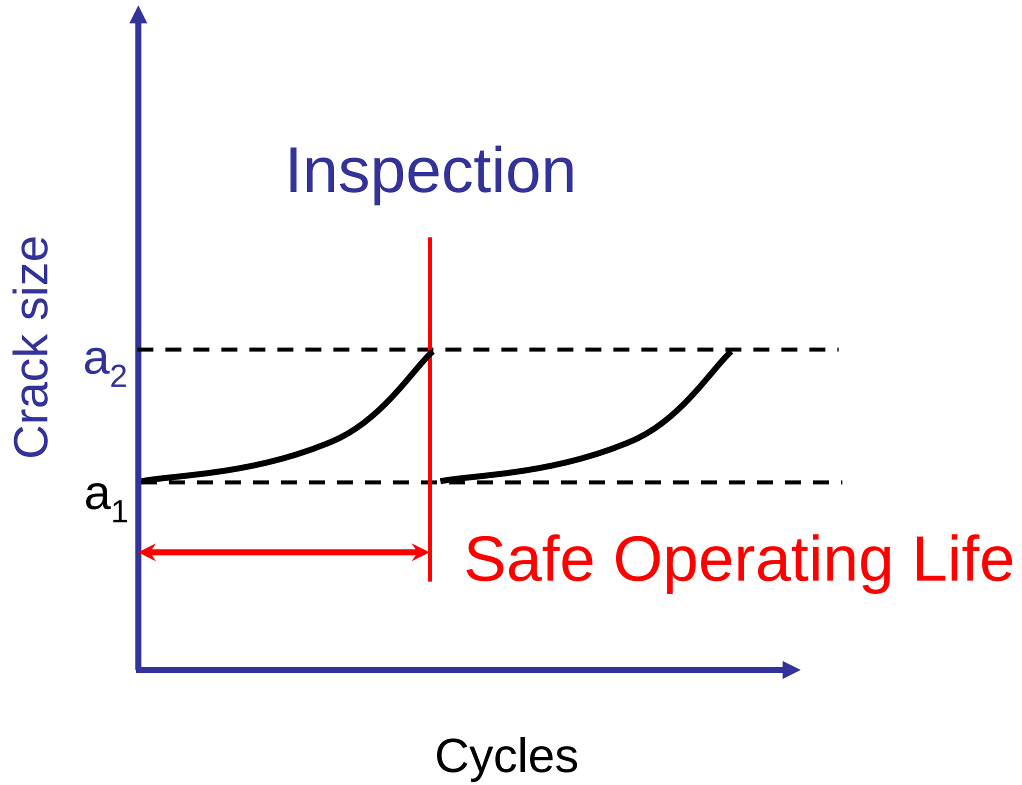
- Safe Life
- Damage Tolerant

Safe Life



Choose an appropriate risk and replace critical parts after some specified interval

Damage Tolerant



Inspect for cracks larger than a_1 and repair

Inspection

A Boeing 777 costs $250,000,000

A new car costs $25,000

For every $1 spent inspecting and maintaining a B 777 you can spend only 0.01¢ on a car

Things Worth Remembering

- Questions to ask
  - Will a crack nucleate ?
  - Will a crack grow ?
  - How fast will it grow ?
- Similitude
  - Failure mechanism
  - Size Scale

Fatigue Seminar

Fatigue Made Easy

Variability

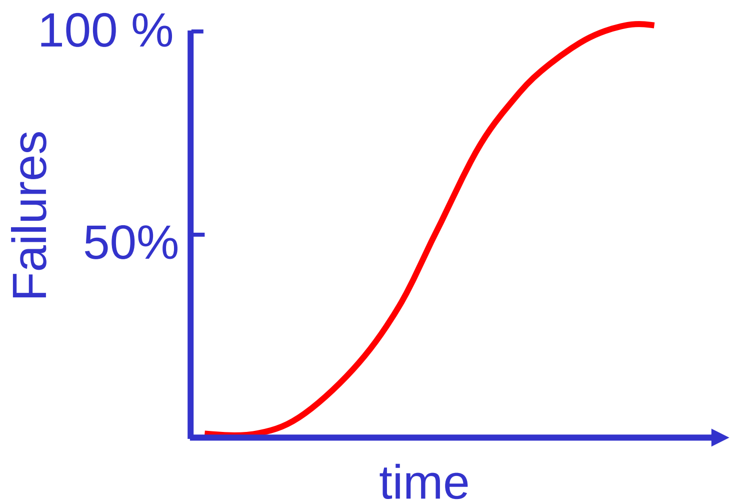
Professor Darrell F. Socie
Mechanical Science and Engineering
University of Illinois

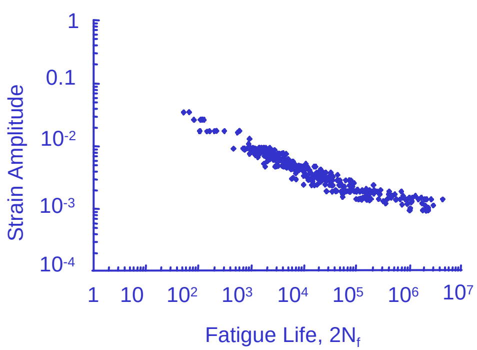
Seminar Outline

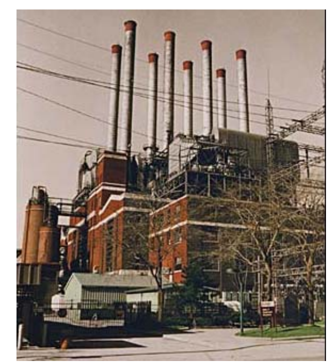
1. Historical background
2. Physics of fatigue
3. Characterization of materials
4. Similitude
5. Variability
6. Mean stress
7. Stress concentrations
8. Surface effects
9. Variable amplitude loading
10. Welded structures

Sources of Variability

customers ← Stress → usage

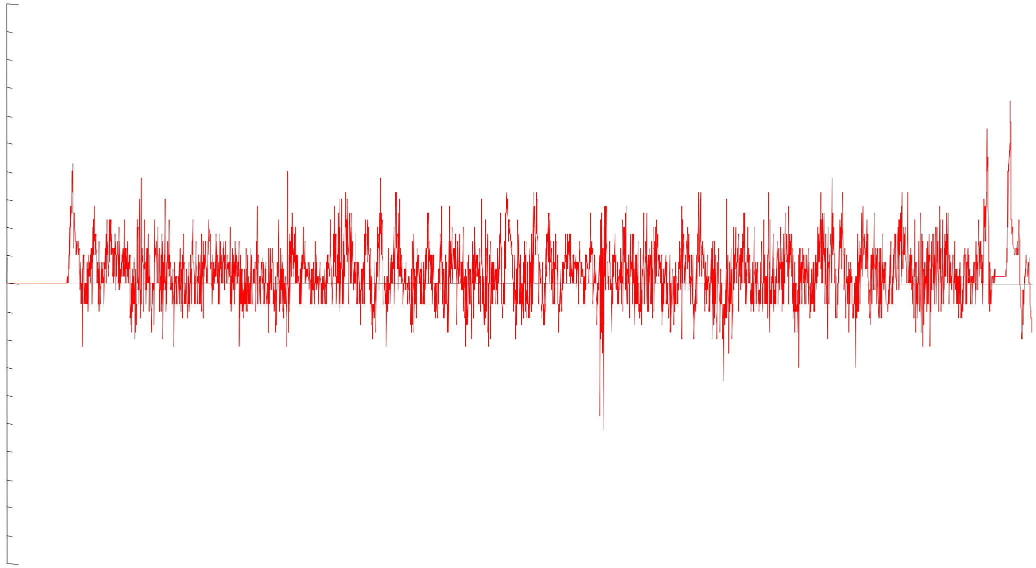






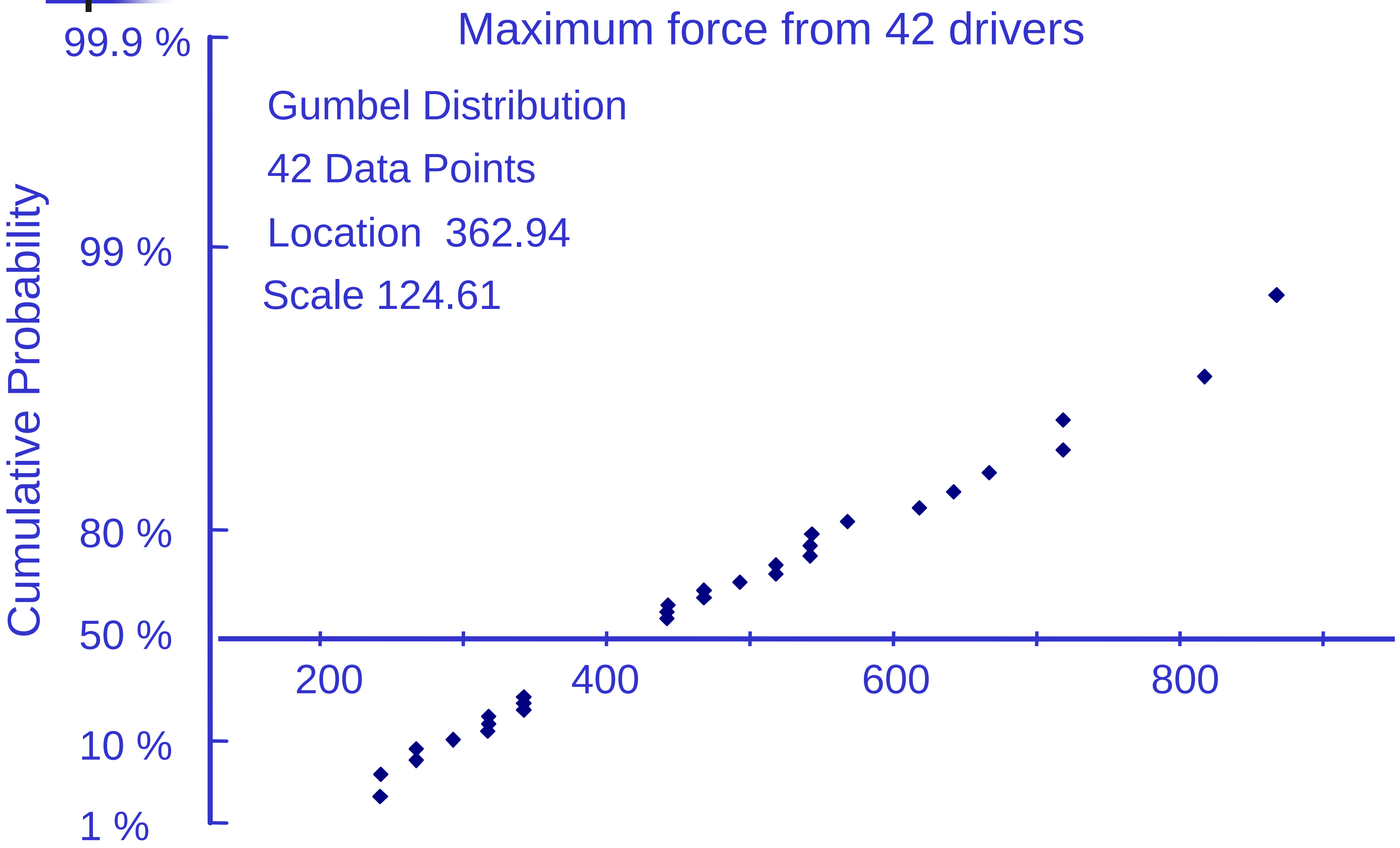
materials ← Strength → manufacturing

"Average" Load History

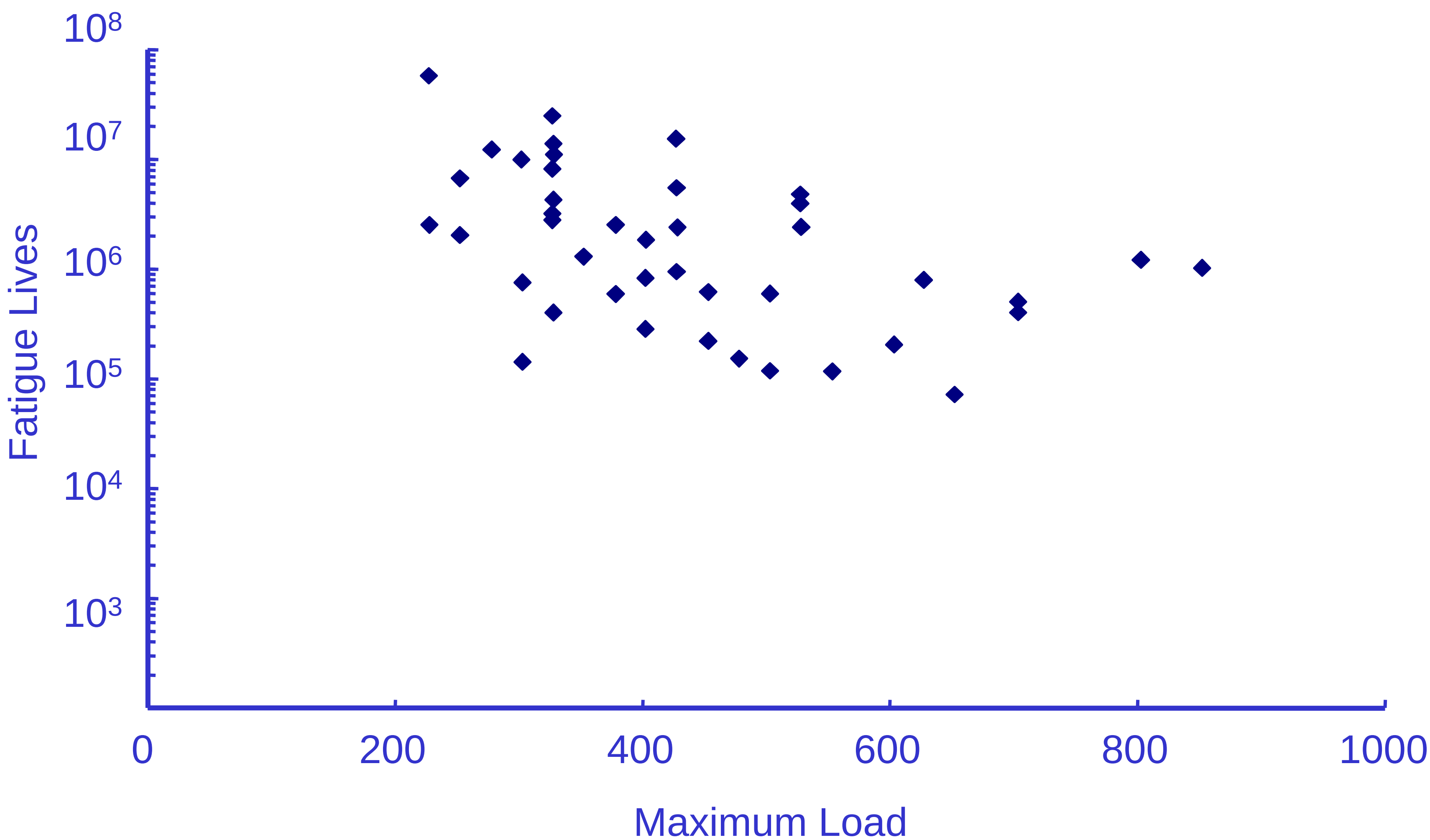


Take a loading history that produces "average" fatigue damage and multiply it by a scale factor to obtain the distribution of loads.

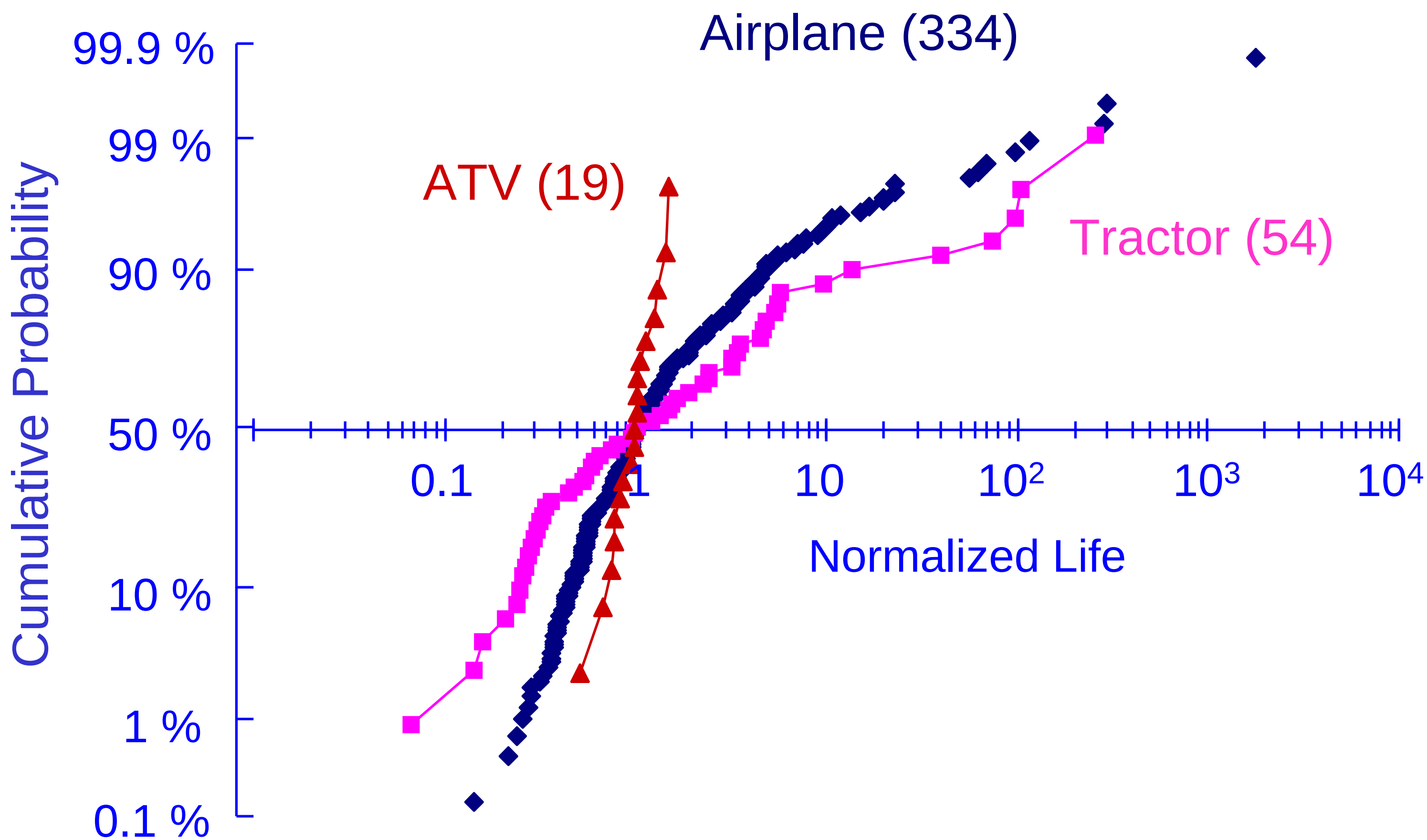
Gumble Probability Plot



Maximum Load Correlation

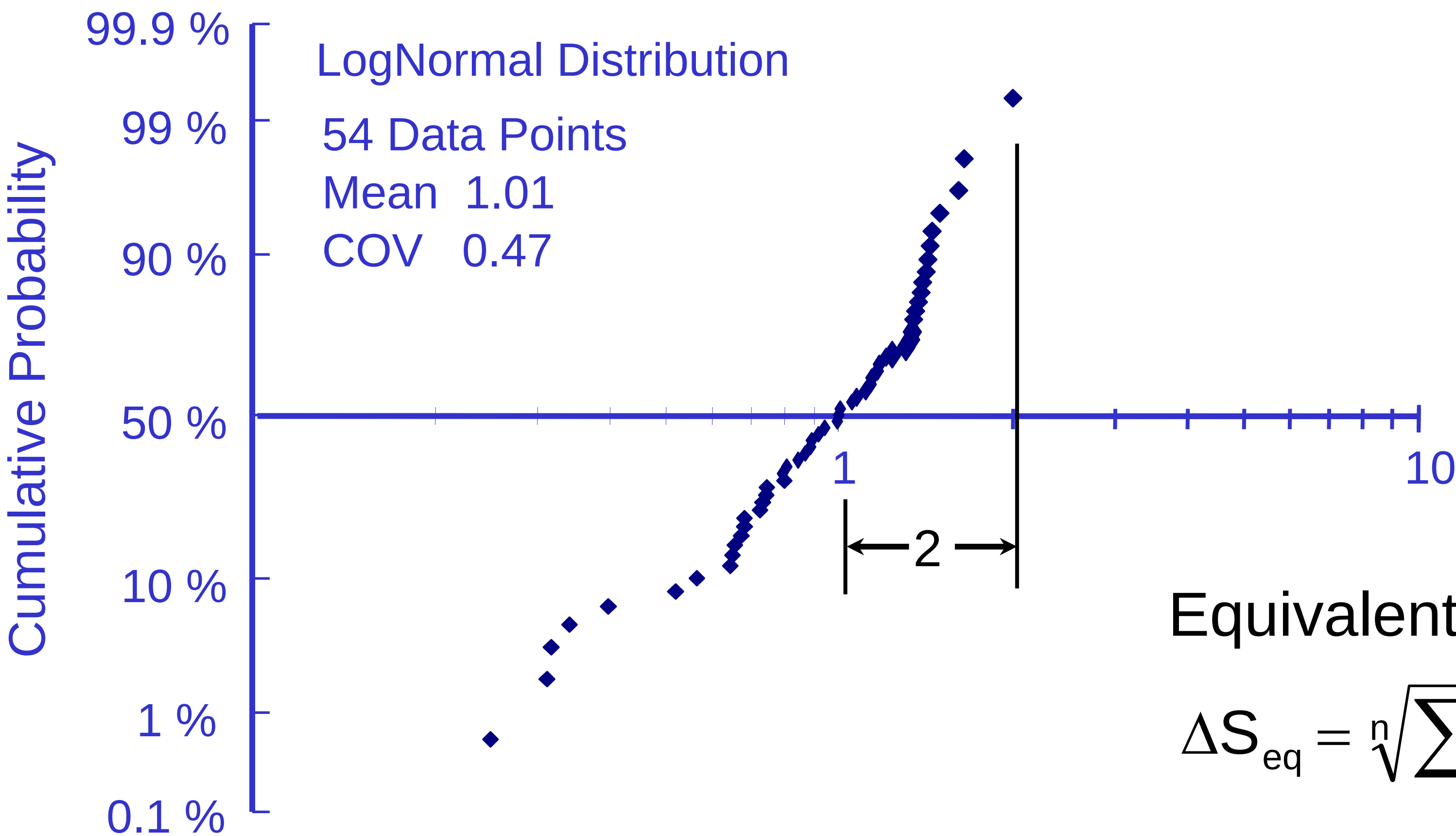


Variability in Fatigue Lives



Calculated fatigue lives for actual service usage data

Variability in Loading

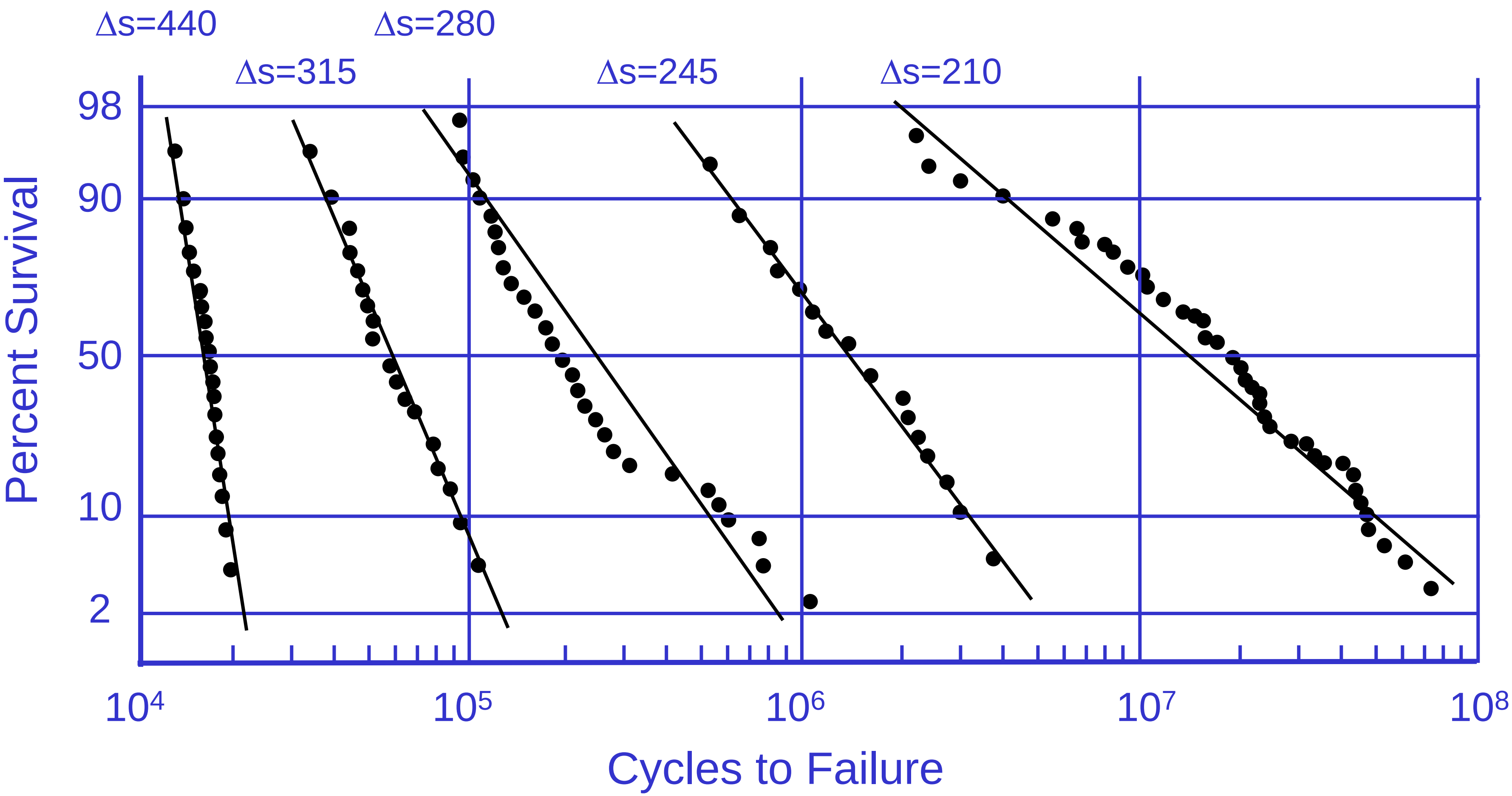


Equivalent Load

$$\Delta S_{eq} = \sqrt[n]{\sum \Delta S^n}$$

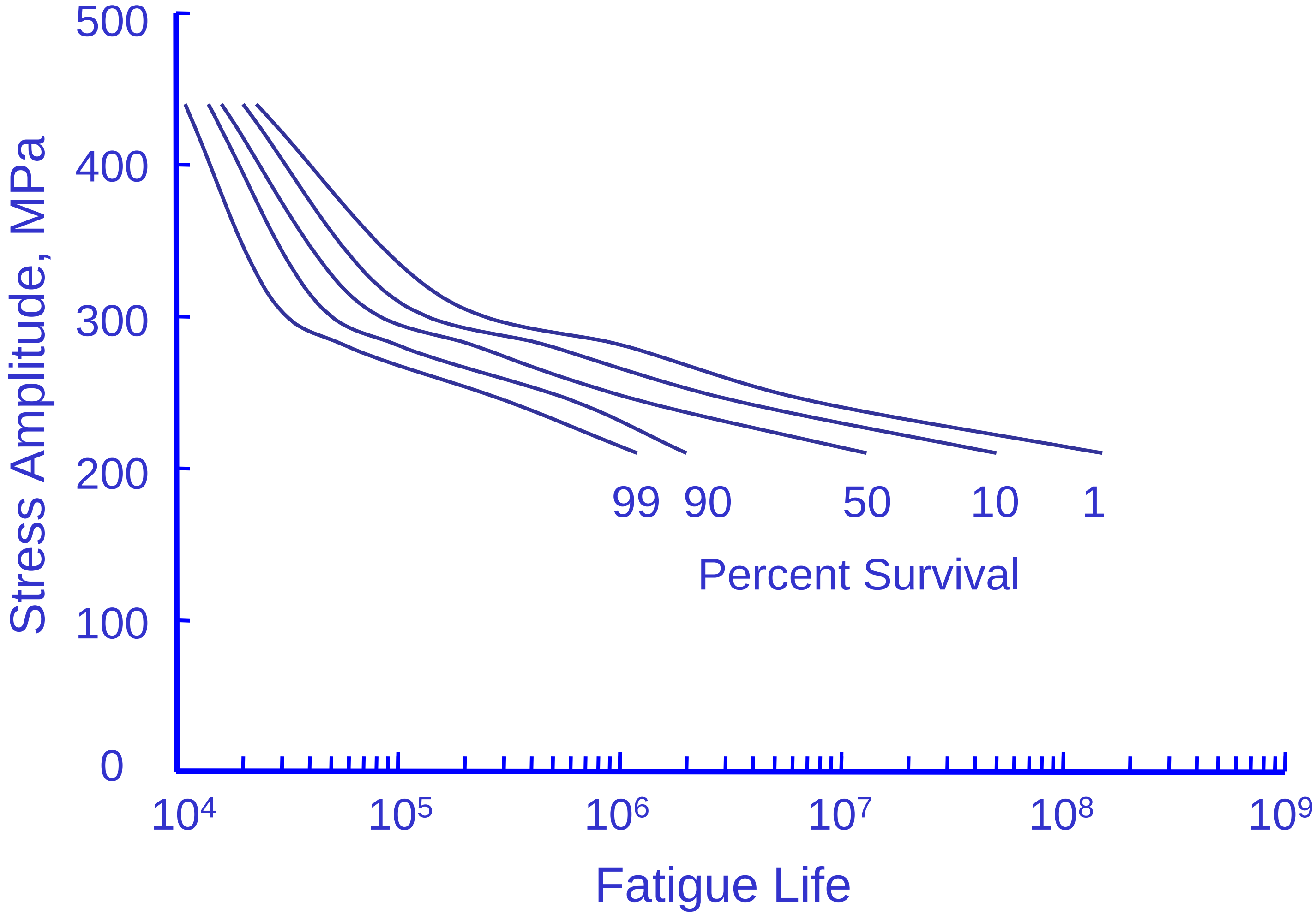
n ~ 4 - 6

Statistical Variability of Fatigue Life



Sinclair and Dolan, "Effect of Stress Amplitude on the Variability in Fatigue Life of 7075T6 Aluminum Alloy" Transactions ASME, 1953

P-S-N Curve



500
400
300
200
100
0
Stress Amplitude, MPa
99
90
50
10
1
Percent Survival
10^4
10^5
10^6
10^7
10^8
10^9
Fatigue Life

Variability in Strength and Life

$$\frac{\Delta S}{2} = S_f^{'}(N_f)^b \quad b \approx 1/10$$

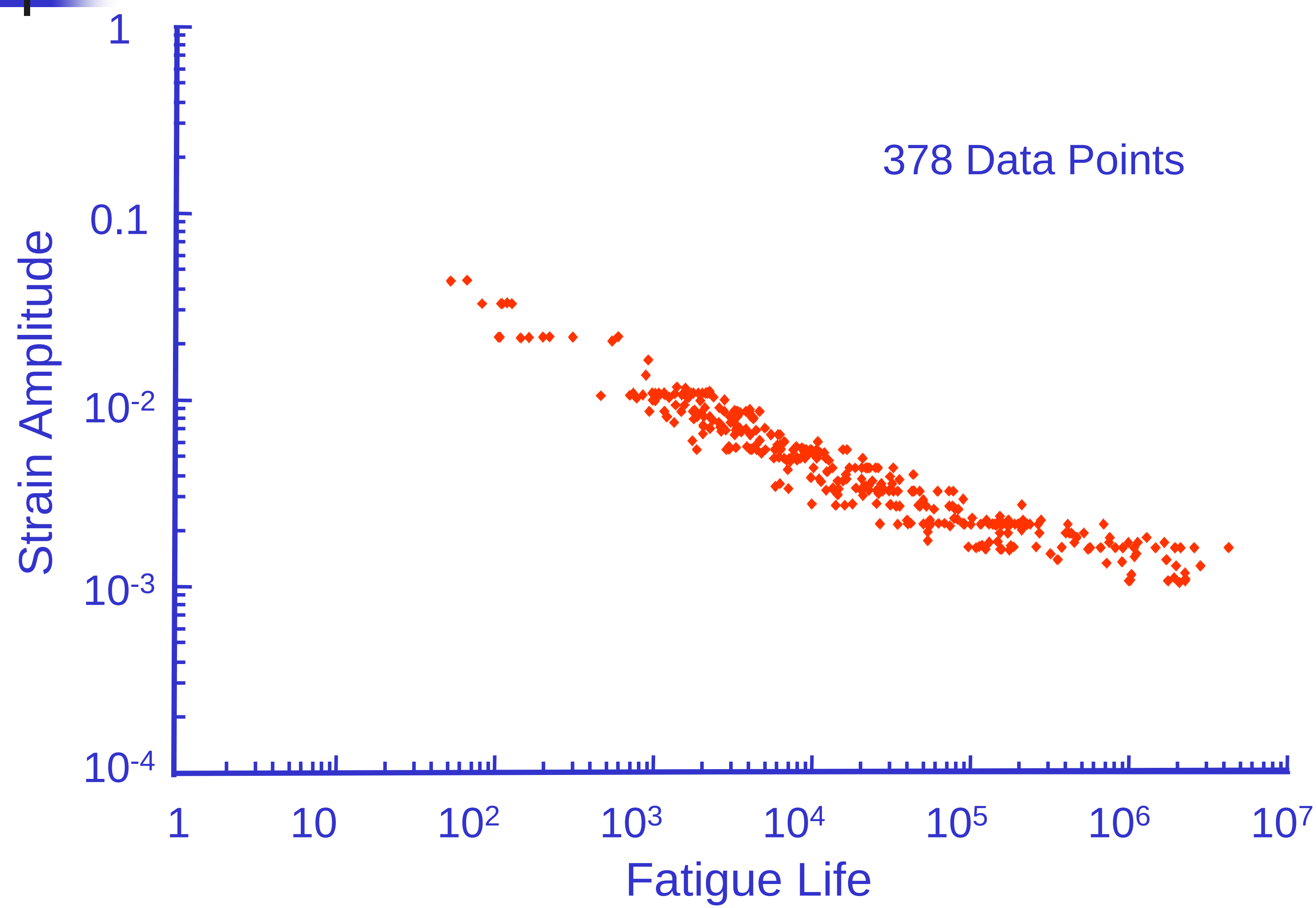
Suppose $S_f^{'}$ has a COV = 0.1

The variability in N_f will be:

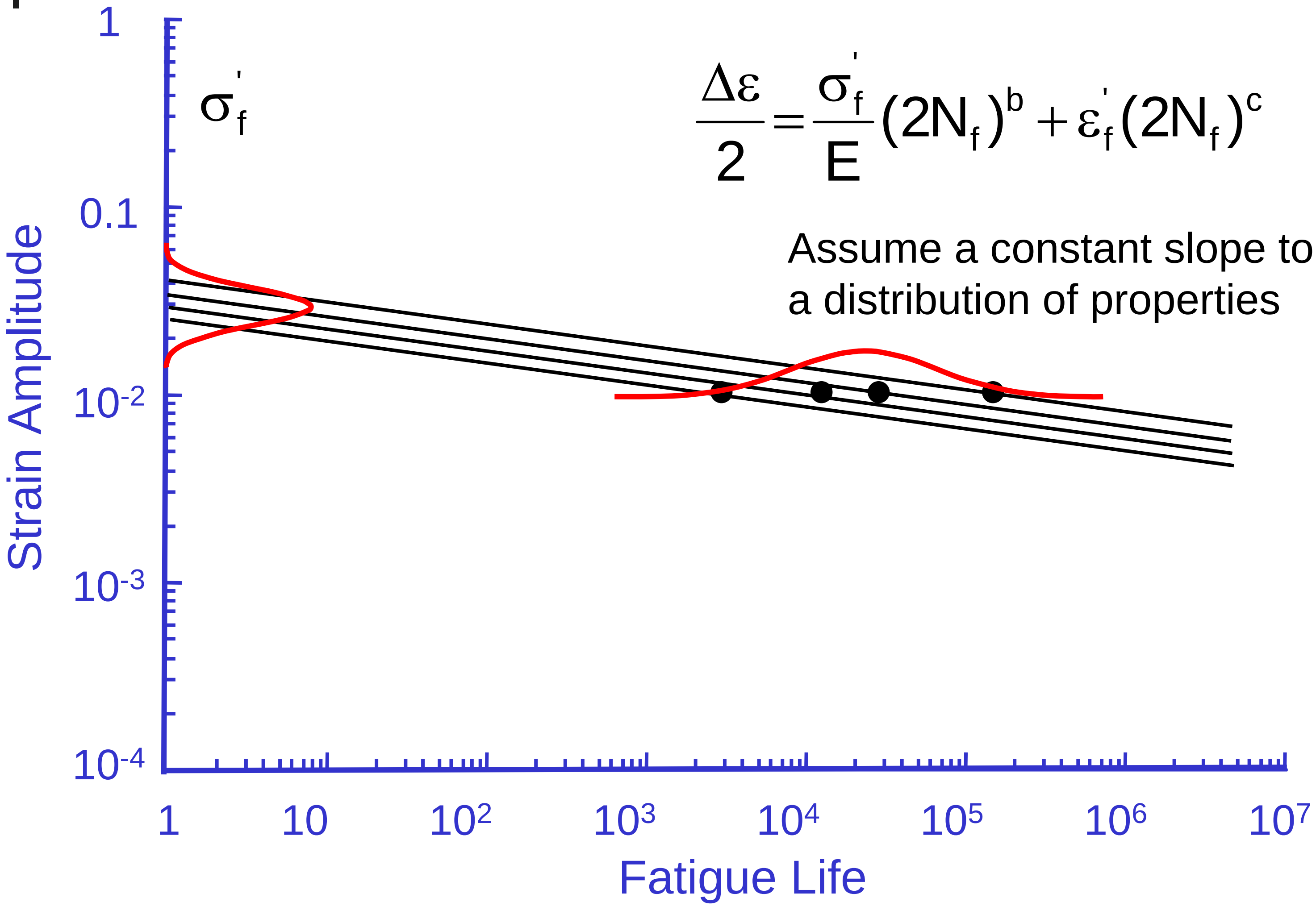
$$COV_{N_f} = \sqrt{\left(1 + COV_{S_f^{'}}{}^2\right)^{b^2} - 1} = \sqrt{\left(1 + (0.1)^2\right)^{10^2} - 1} = 1.3$$

A 10% variation in strength results in a factor of 20 in fatigue life

Strain Life Data for 980X Steel



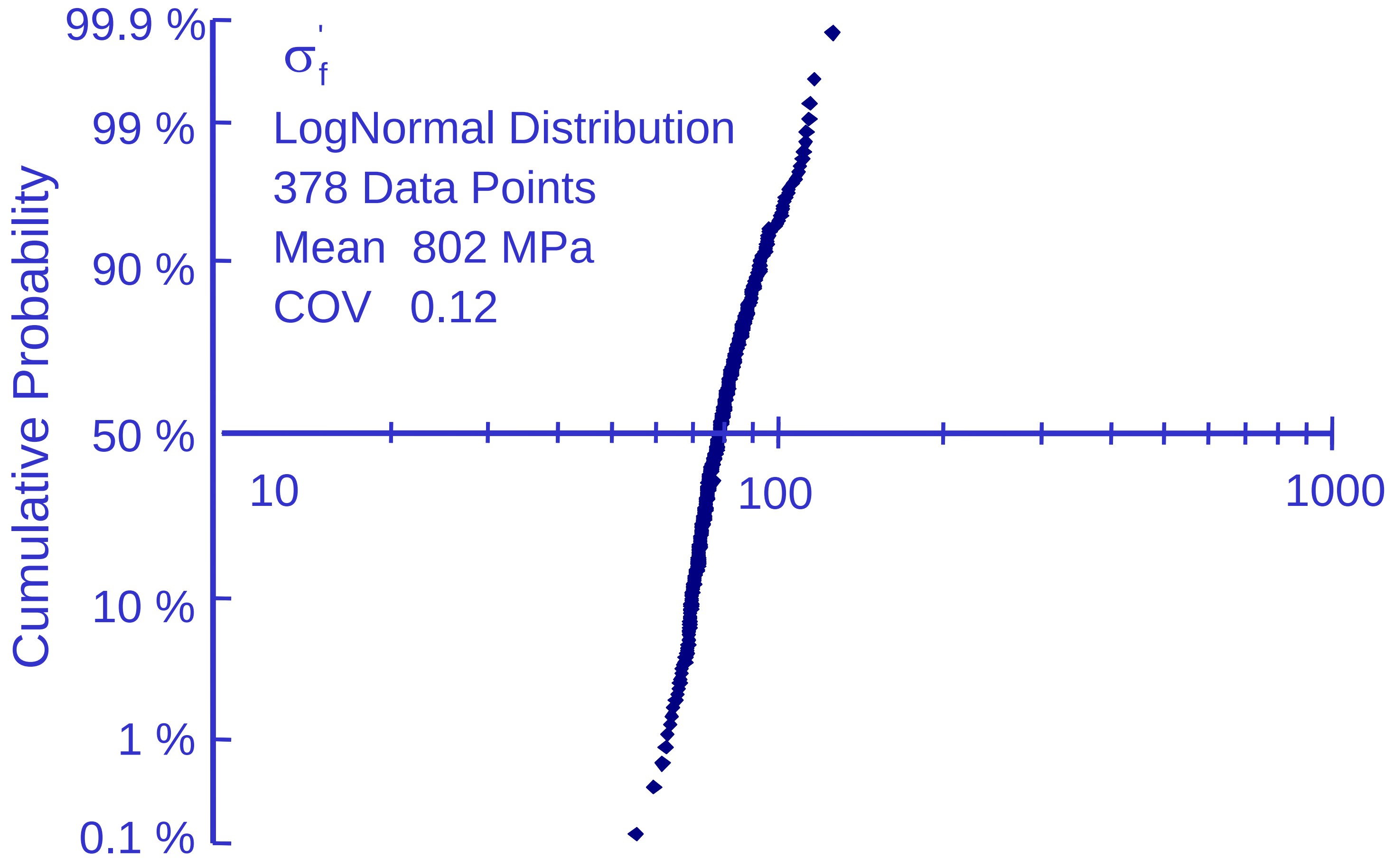
Curve Fitting



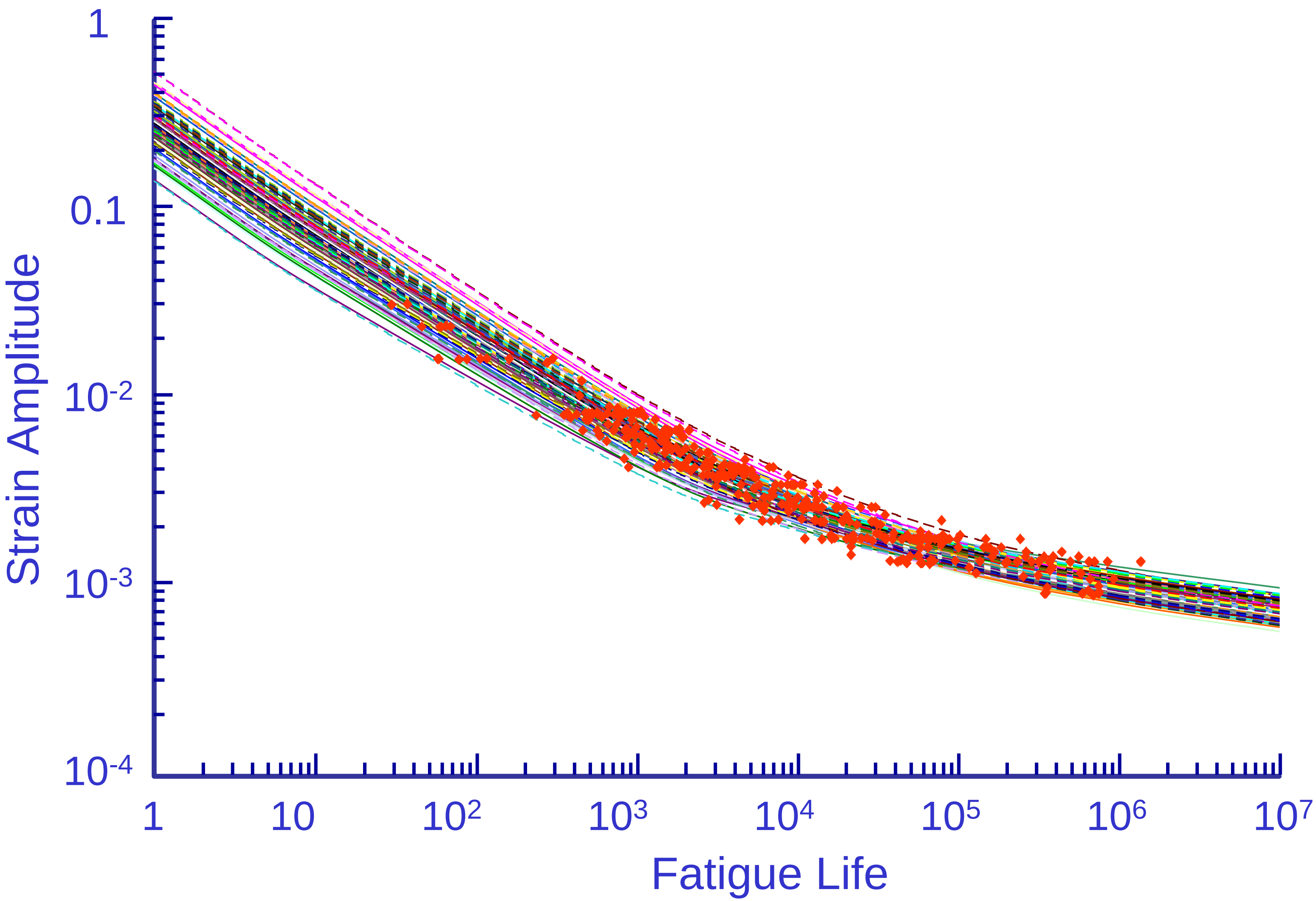
$$\frac{\Delta\varepsilon}{2} = \frac{\sigma_f'}{E}(2N_f)^b + \varepsilon_f'(2N_f)^c$$

Assume a constant slope to get a distribution of properties

σ_f' Distribution



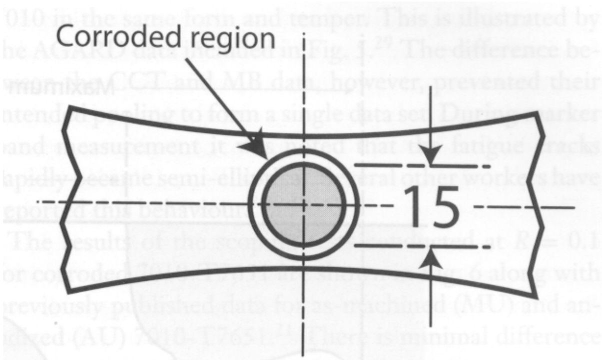
Material Property Simulation

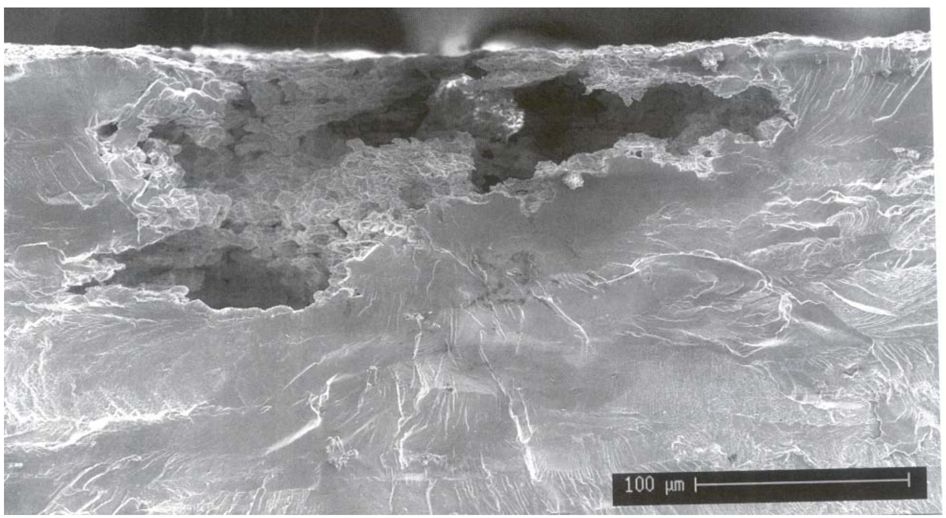


Typical Variability

- Pit Size
- Bolt Preload Force
- Surface Roughness

Pits That Initiated Cracks





7010-T7651

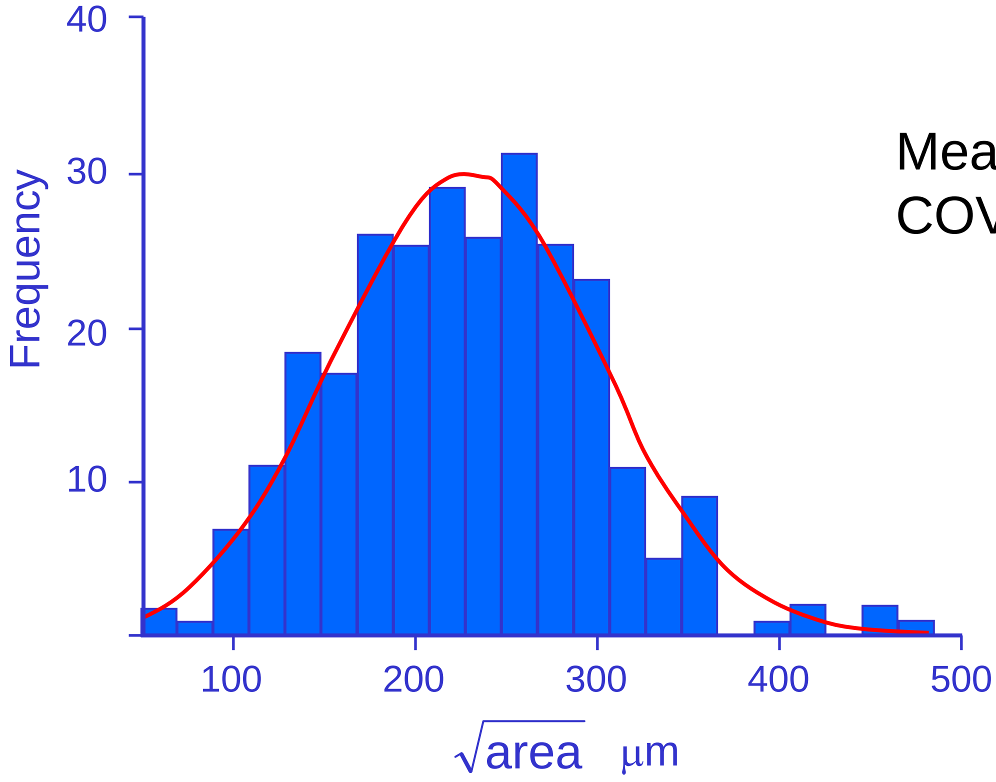
Pre-corroded specimens

300 specimens

246 failed from pits

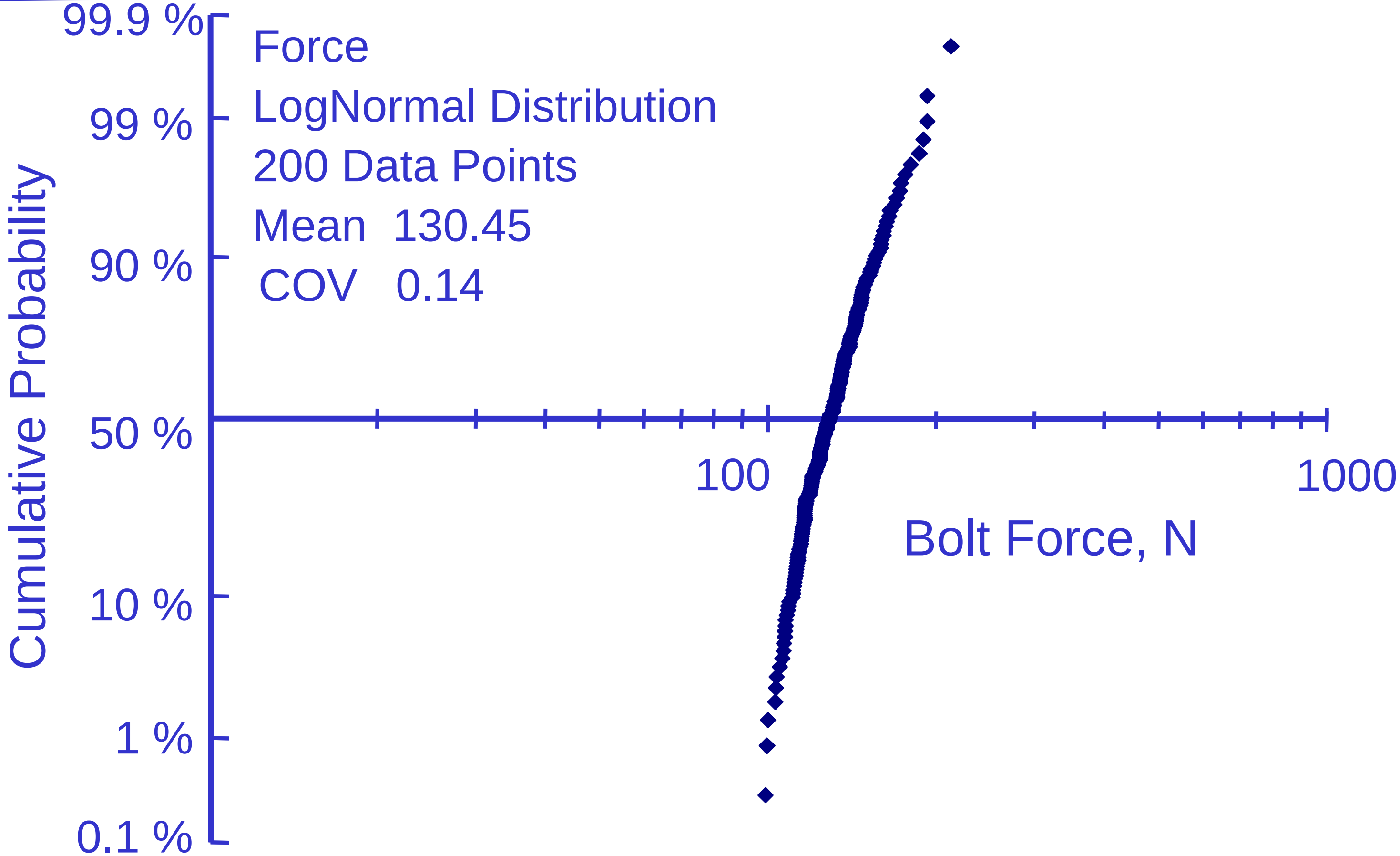
Crawford et.al."The EIFS Distribution for Anodized and Pre-corroded 7010-T7651 under Constant Amplitude Loading" *Fatigue and Fracture of Engineering Materials and Structures*, Vol. 28, No. 9 2005, 795-808

Pit Size Distribution



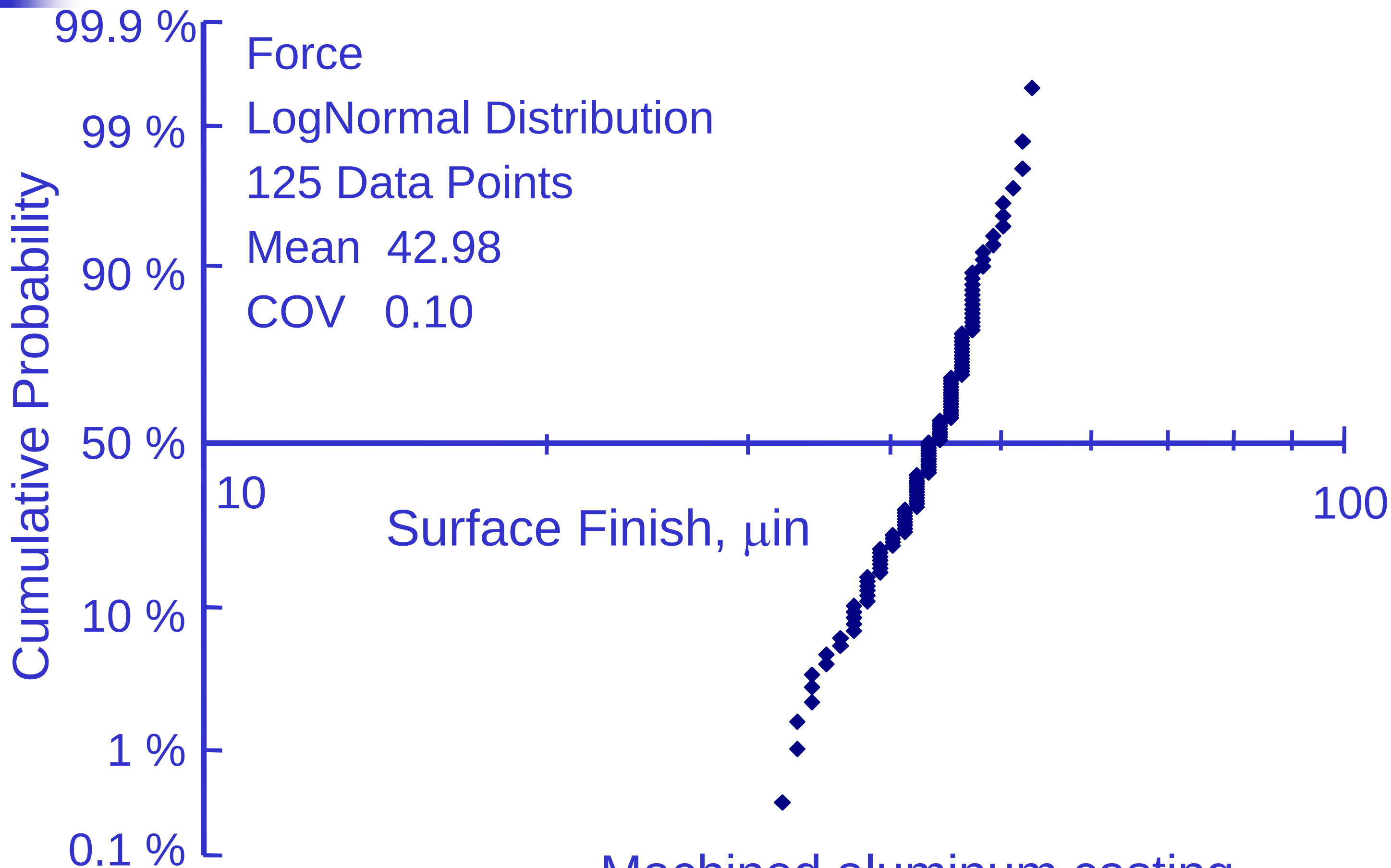
Mean = 230
COV = 0.32

Variability in Bolt Force



Preload force in bolts tightened to 350 Nm

Surface Roughness Variability



Machined aluminum casting

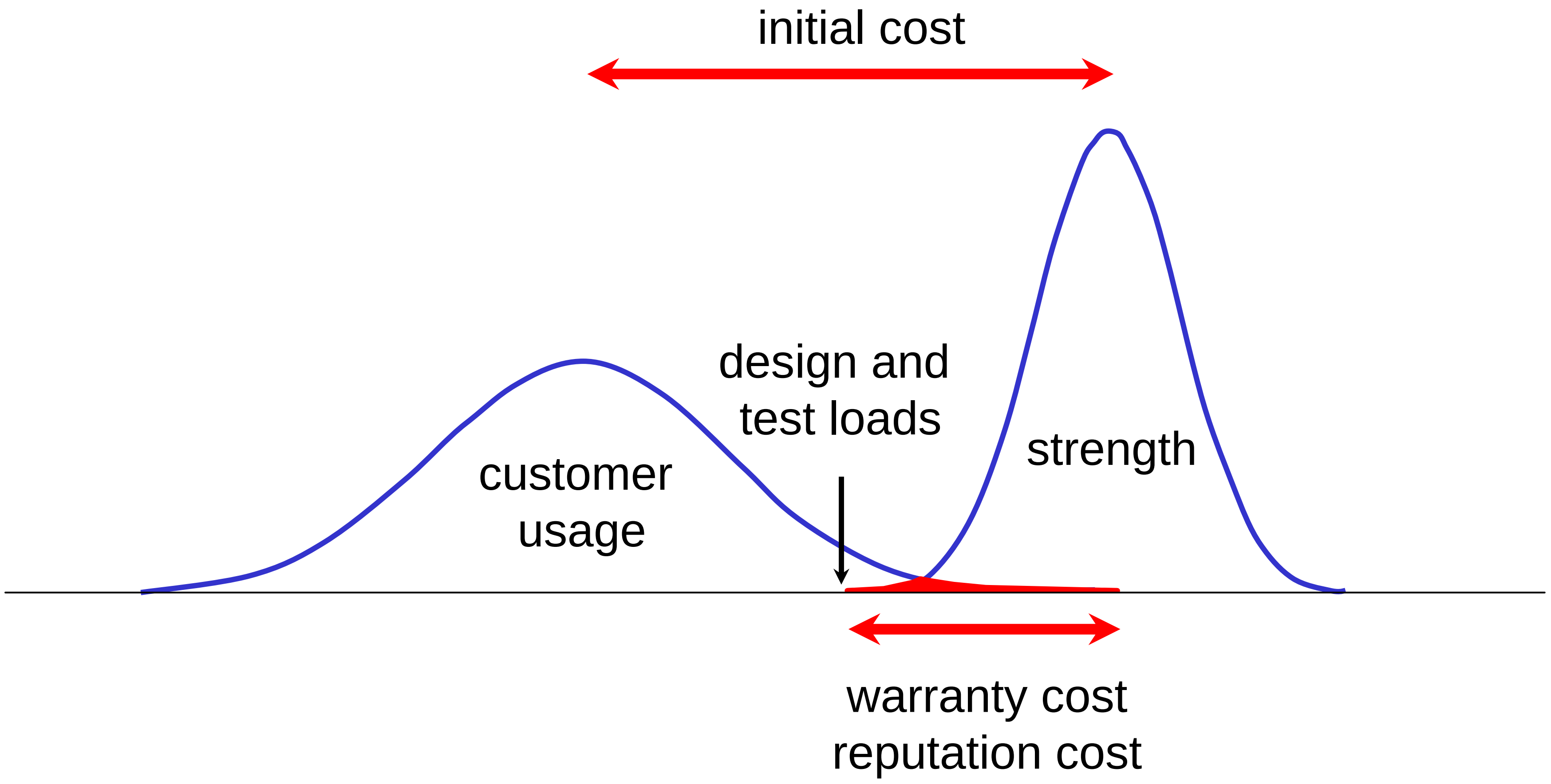
Variability Summary

	Source	COV
Stress	Service Loading	0.47
	Environment	0.33
Strength	Materials	0.12
	Manufacturing	0.14
	Surface Finish	0.10

$$\text{COV} \quad C = \sqrt{\prod_{i=1}^{n} \left(1 + C_{X_i}^{\;2}\right)^{a_i^2} - 1}$$

Largest variability dominates

Stress - Strength



Things Worth Remembering

- Fatigue data inherently contains a lot of variability
- The variability is predictable and quantifiable

Fatigue Seminar

Fatigue Made Easy

Mean Stress

Professor Darrell F. Socie

Mechanical Science and Engineering

University of Illinois

Seminar Outline

1. Historical background
2. Physics of fatigue
3. Characterization of materials
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6. Mean stress
7. Stress concentrations
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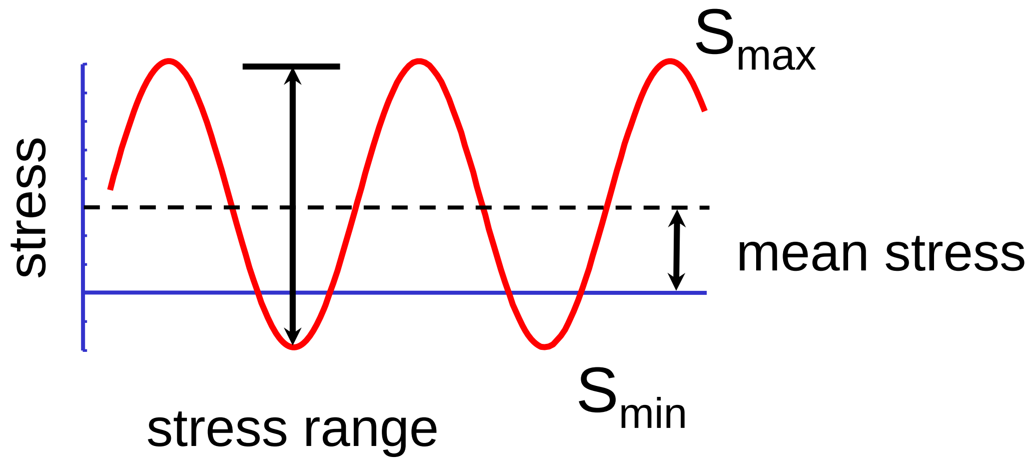
9. Variable amplitude loading
10. Welded structures

Mean Stresses



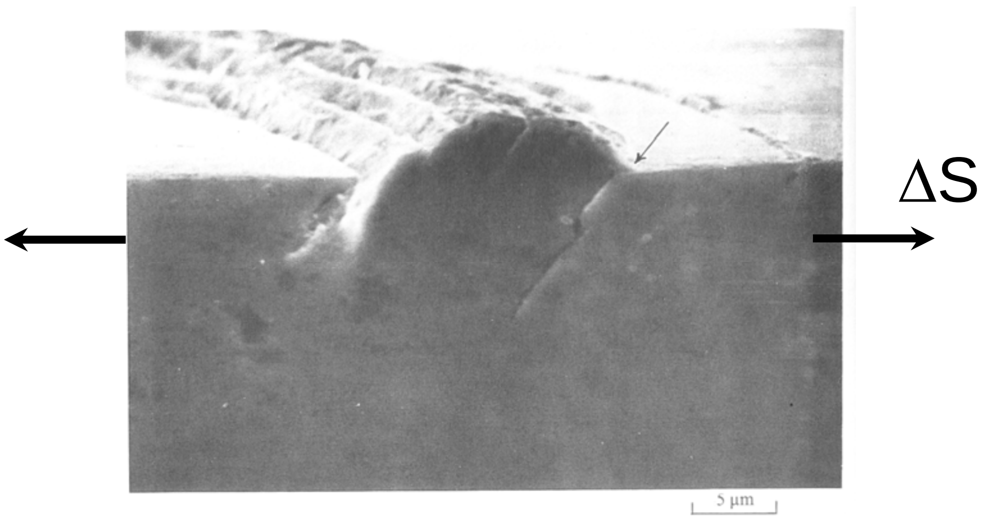
$$S_{mean} = \frac{S_{max} + S_{min}}{2}$$

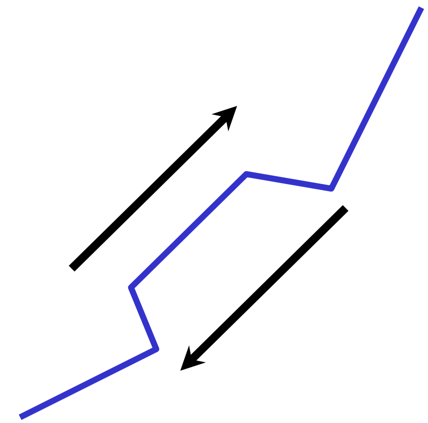
$$R = \frac{S_{min}}{S_{max}}$$

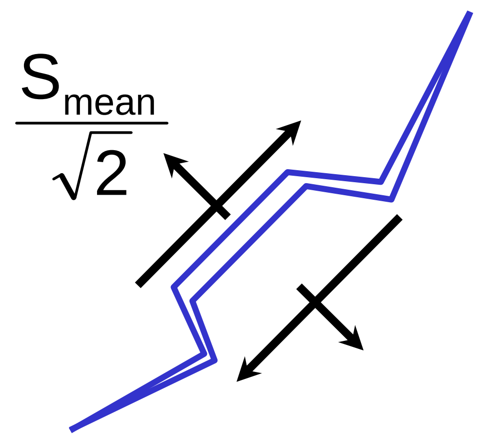
General Observations

- Tensile mean stresses reduce the fatigue life or decrease the allowable stress range
- Compressive mean stresses increase the fatigue life or increase the allowable stress range

Mechanism







Fatigue damage is a shear process

Tensile mean stresses open microcracks and make sliding easier

Goodman 1890

Mechanics Applied to Engineering
John Goodman, 1890

"‥ whether the assumptions of the theory are justifiable or not …. We adopt it simply because it is the easiest to use, and for all practical purposes, represents Wöhlers data.

$$S_{ultimate} = S_{min} + 2\ \Delta S$$

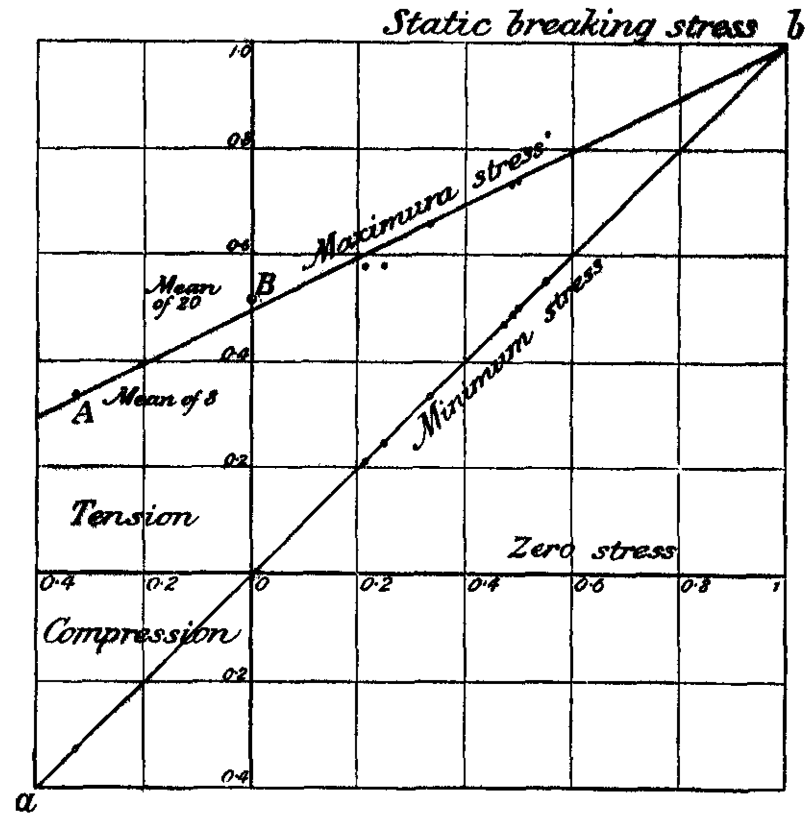
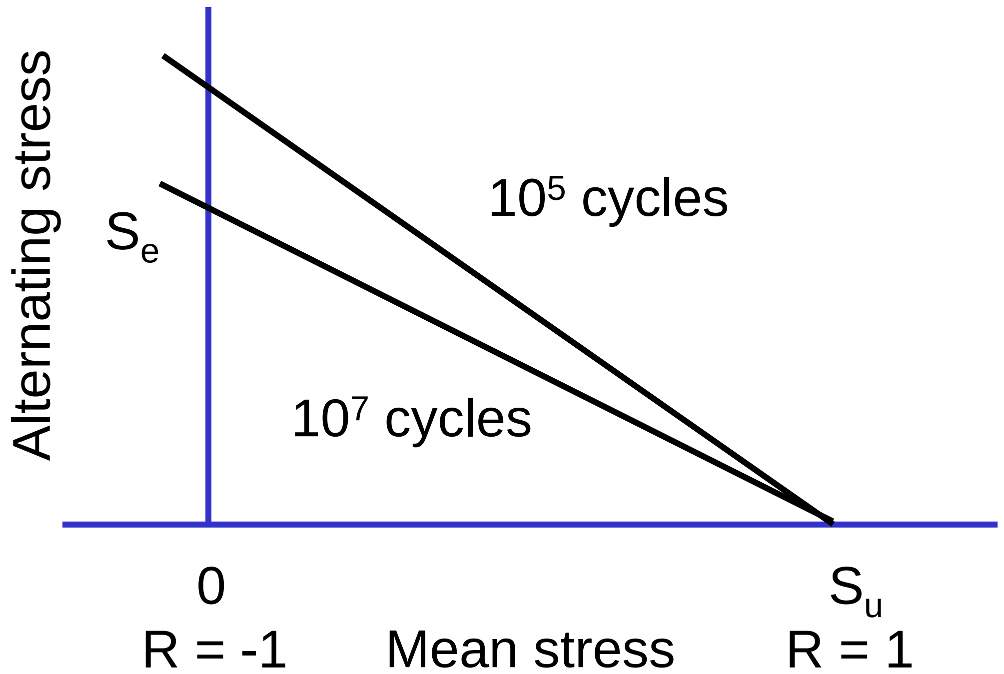


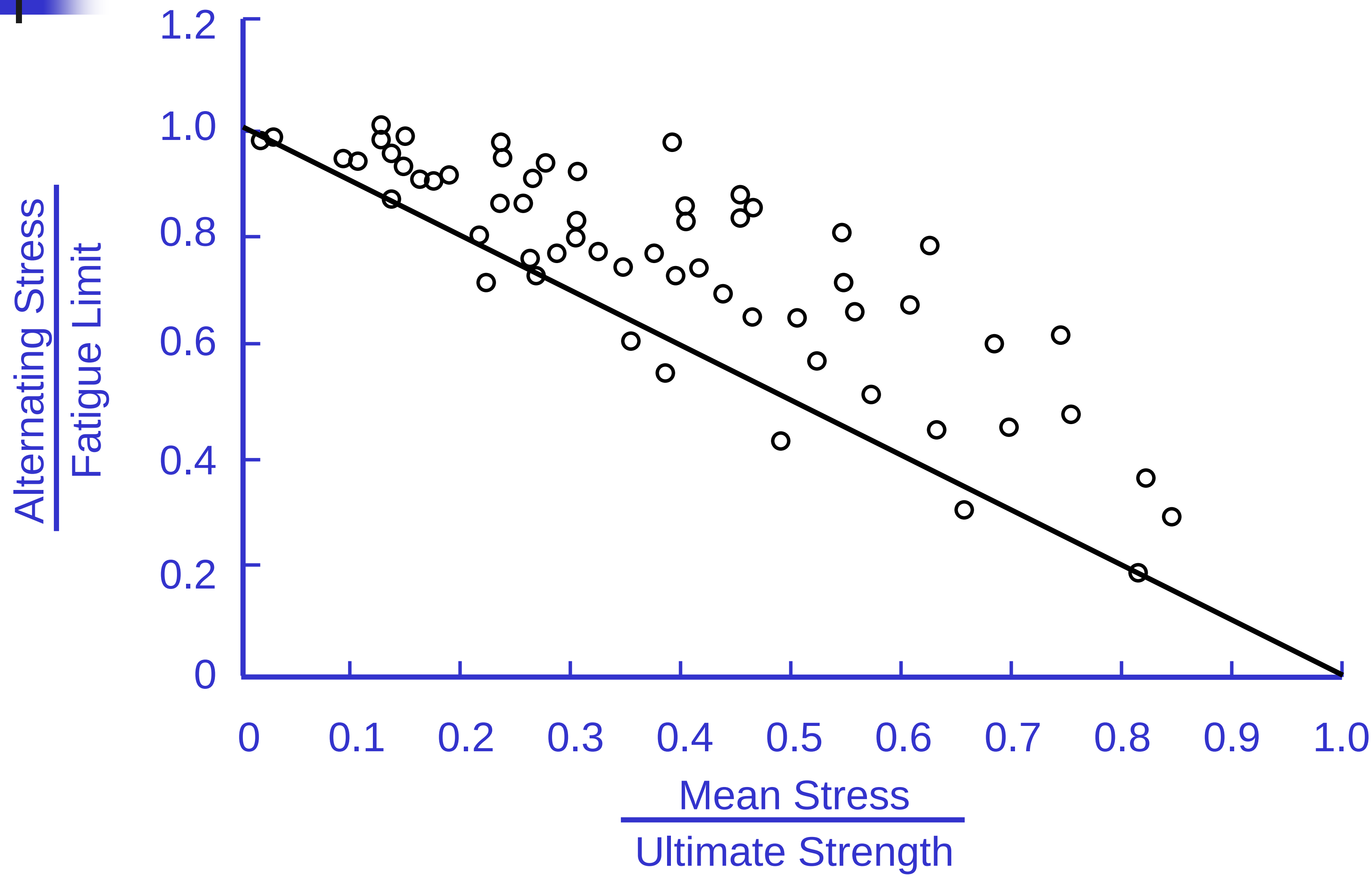
Fig. 517.

Goodman Diagram



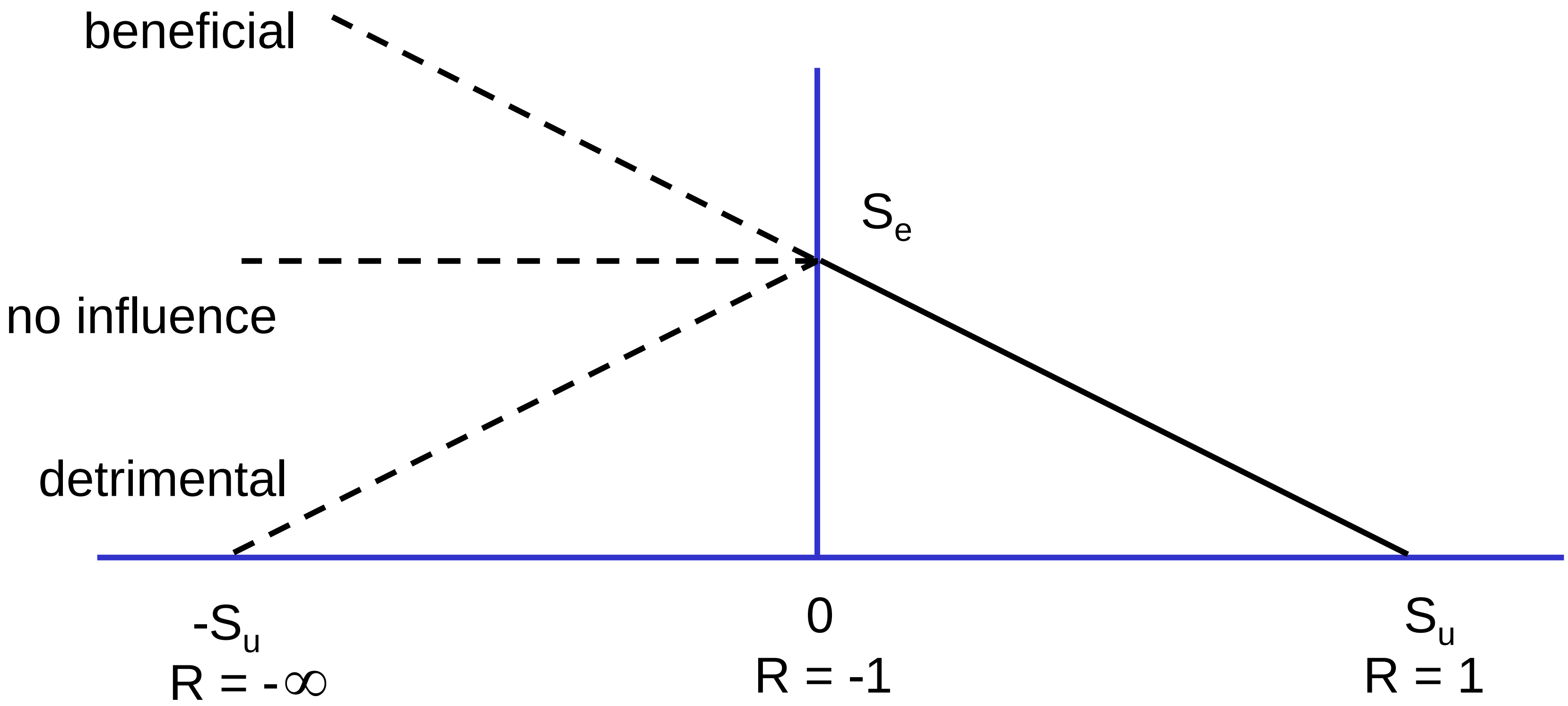
$$\frac{\Delta S}{2} = \left(\frac{\Delta S}{2}\right)_{R=-1}\left(1 - \frac{S_{mean}}{S_{ultimate}}\right)$$

Test Data (1941)

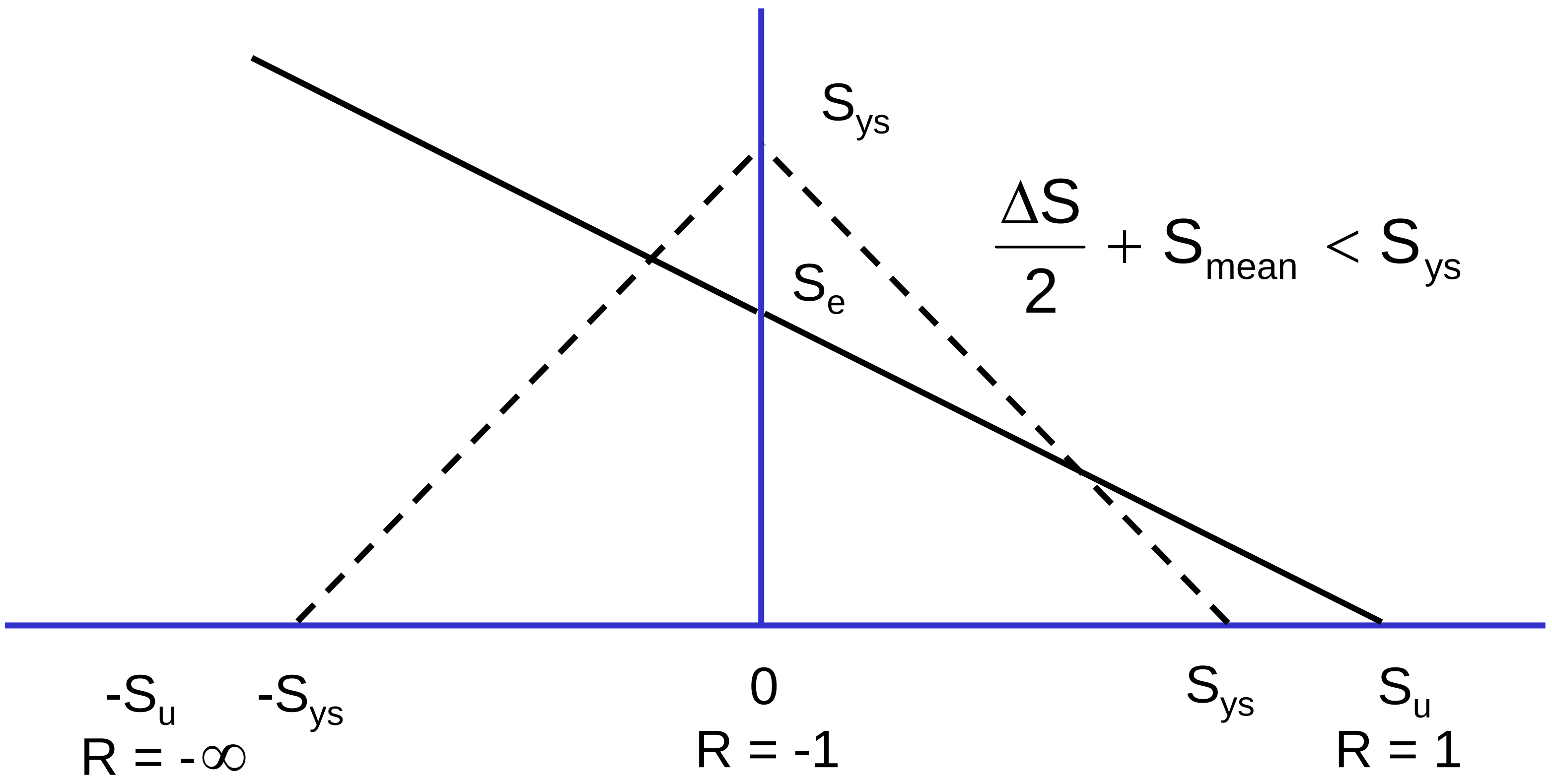


J.O. Smith, The Effect of Range of Stress on the Fatigue Strength of Metals, Engineering Experiment Station Bulletin 334, University of Illinois, 1941

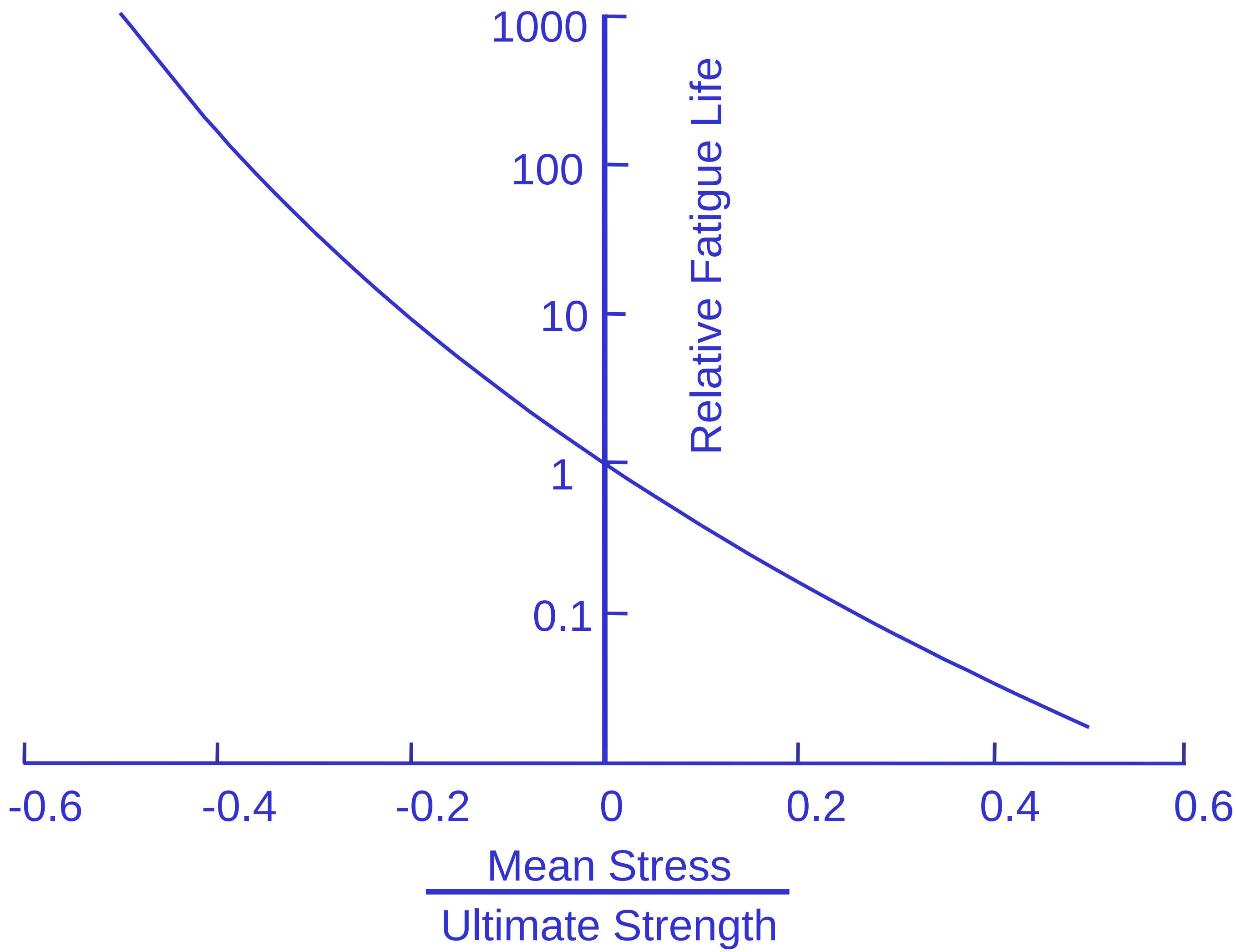
Compression



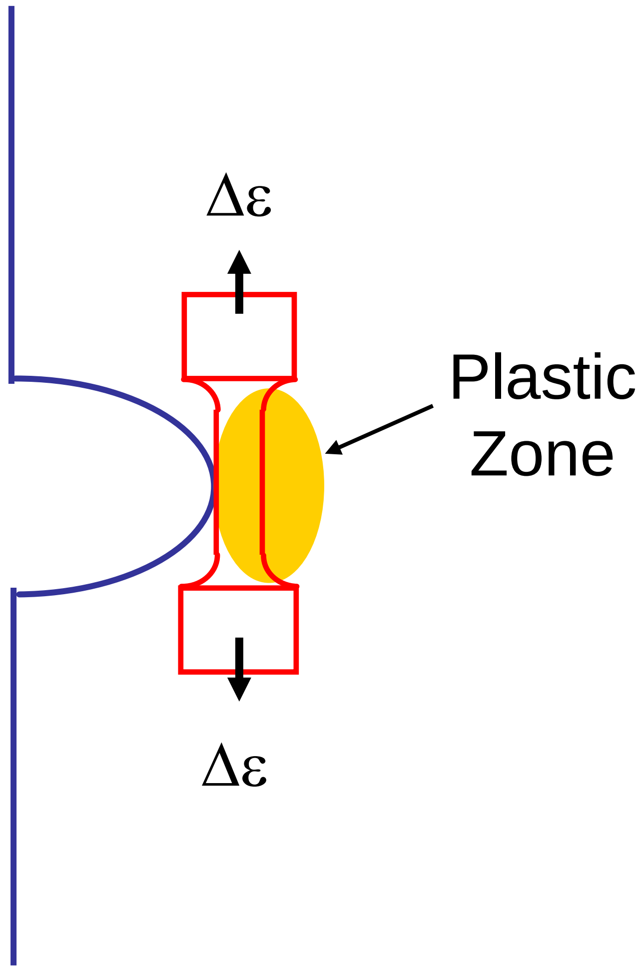
Modified Goodman (no yielding)



Mean Stress Influence on Life

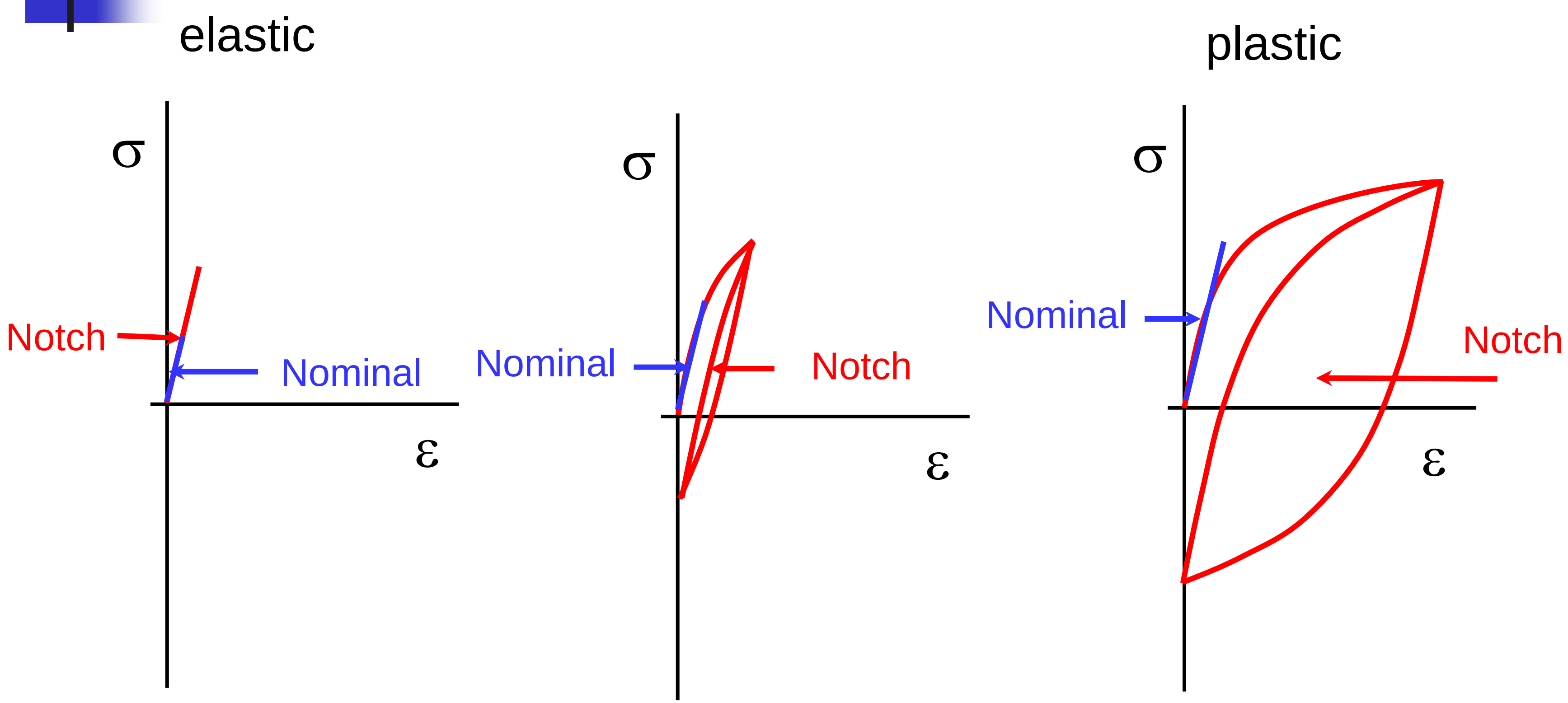


Stress Concentrations



The elastic material surrounding the plastic zone around a stress concentration forces the material to deform in strain control

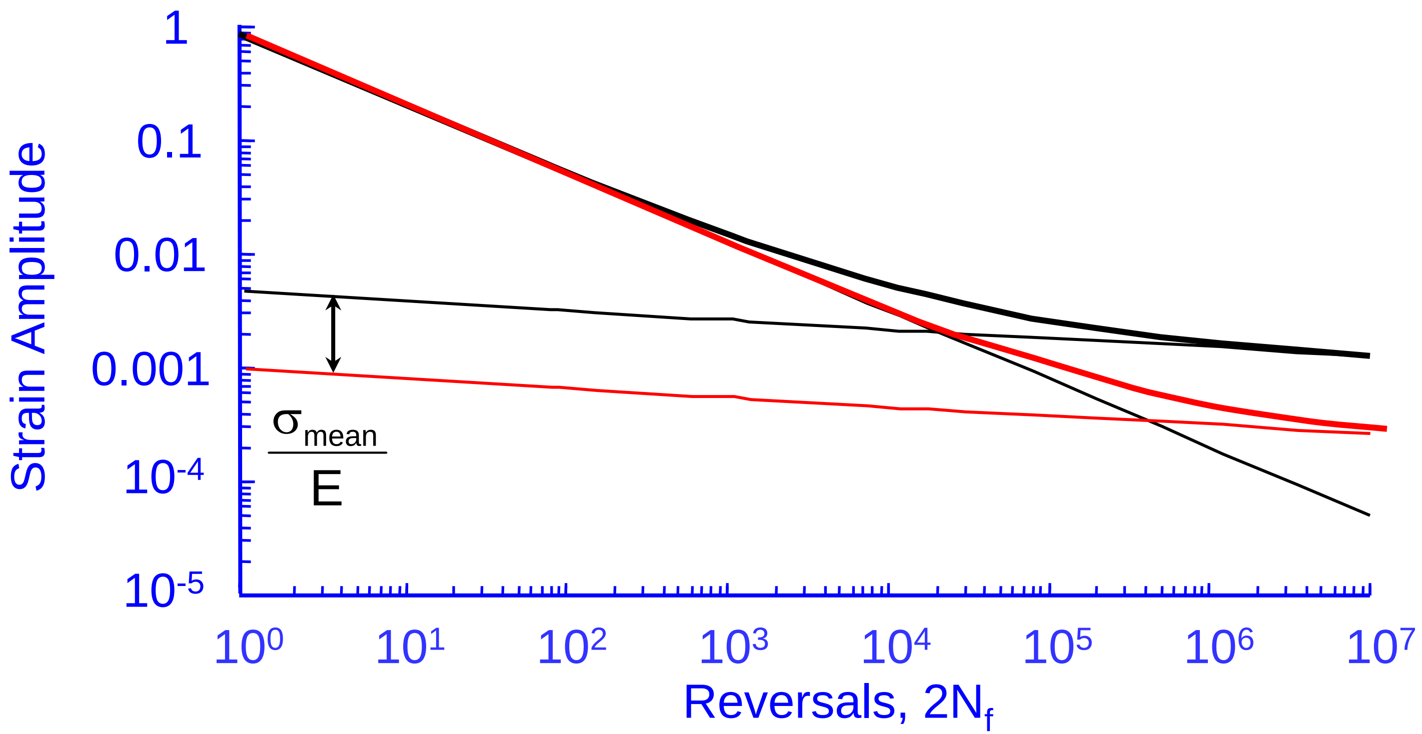
Mean Stresses at Notches



Nominal mean stress is less than notch mean stress

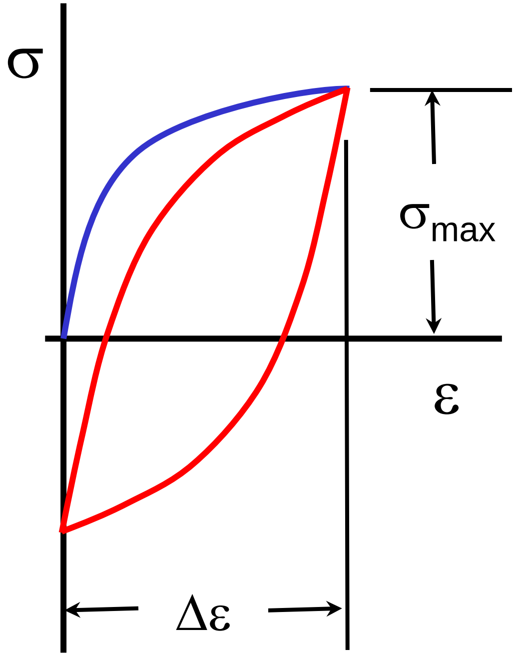
Nominal mean stress is greater than notch mean stress

Morrow Mean Stress Correction



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

Smith Watson Topper



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

Mean Stress Relaxation

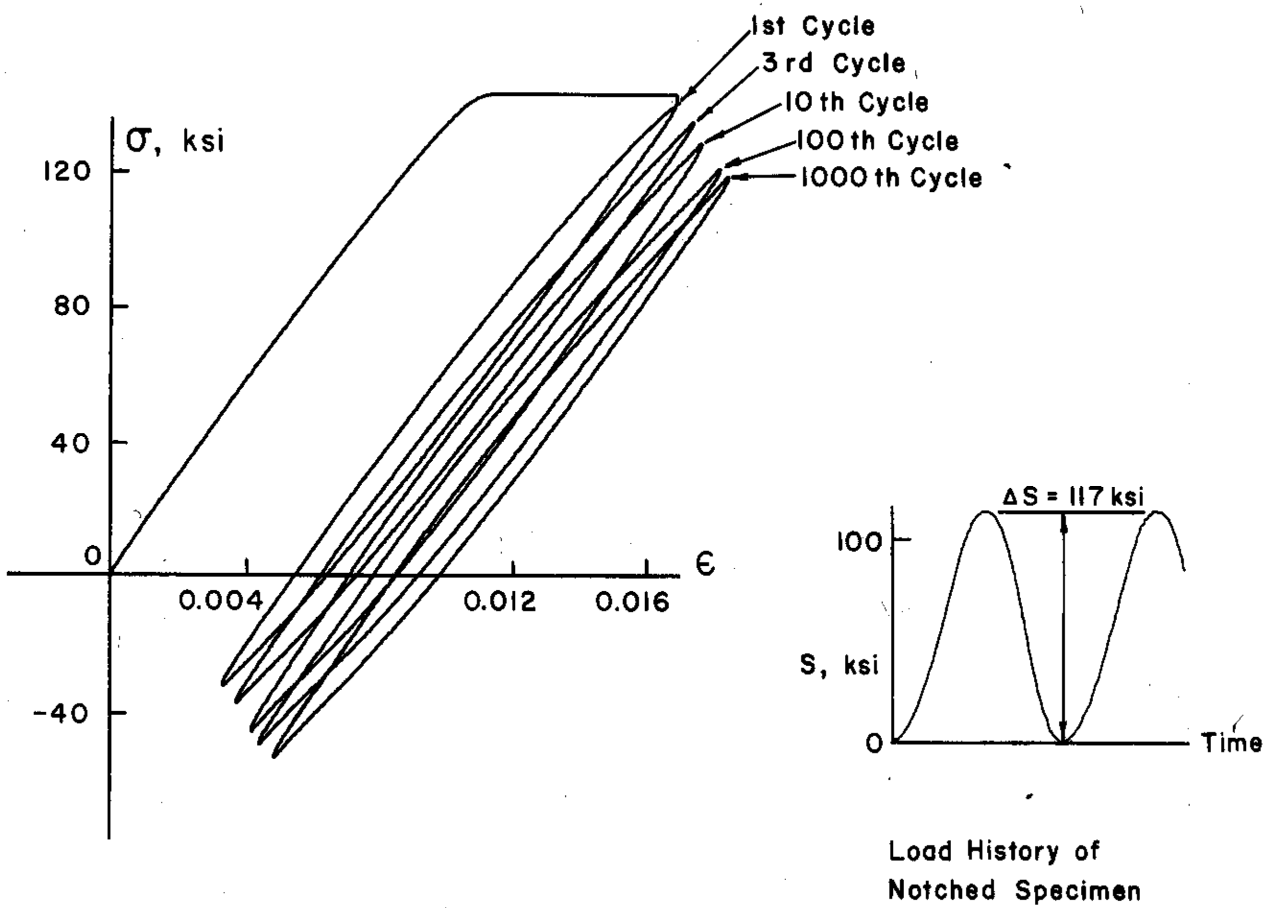
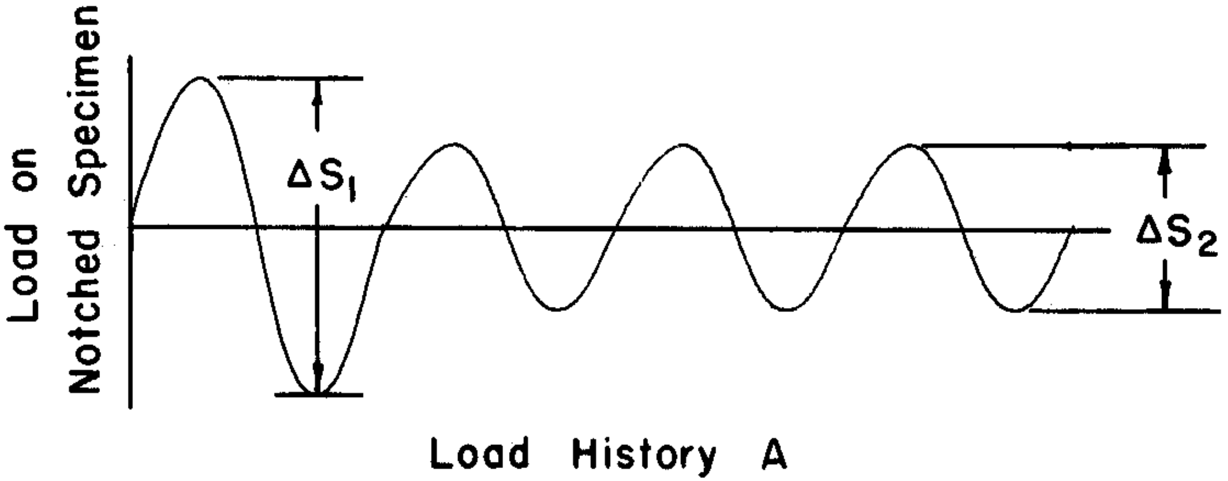
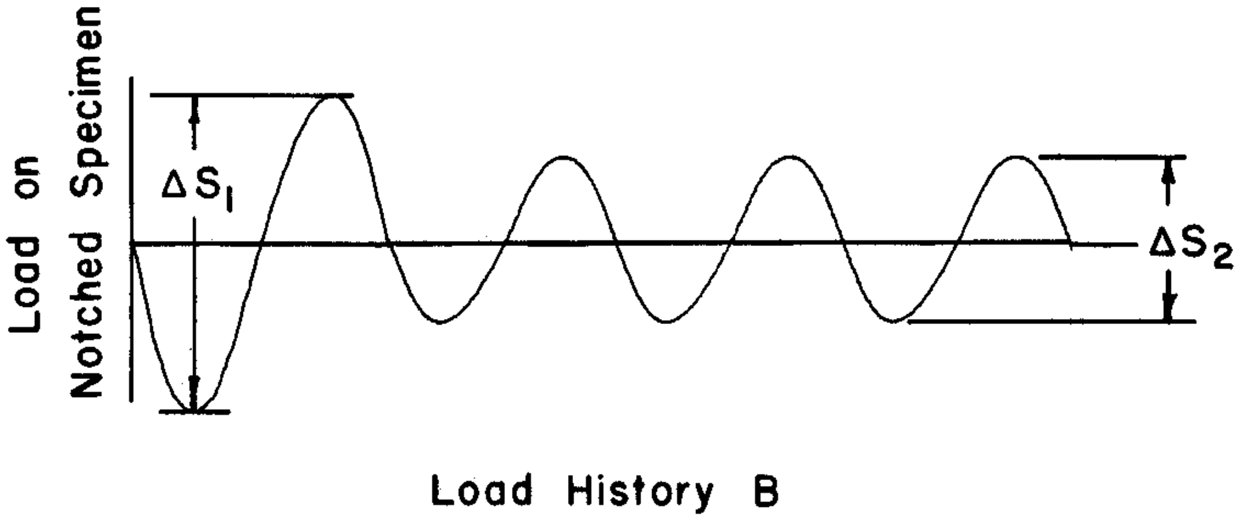


FIG. 7—*Cyclic softening and relaxation of mean stress under Neuber control (Ti-8Al-1Mo-1V, $K_t = 1.75$).*

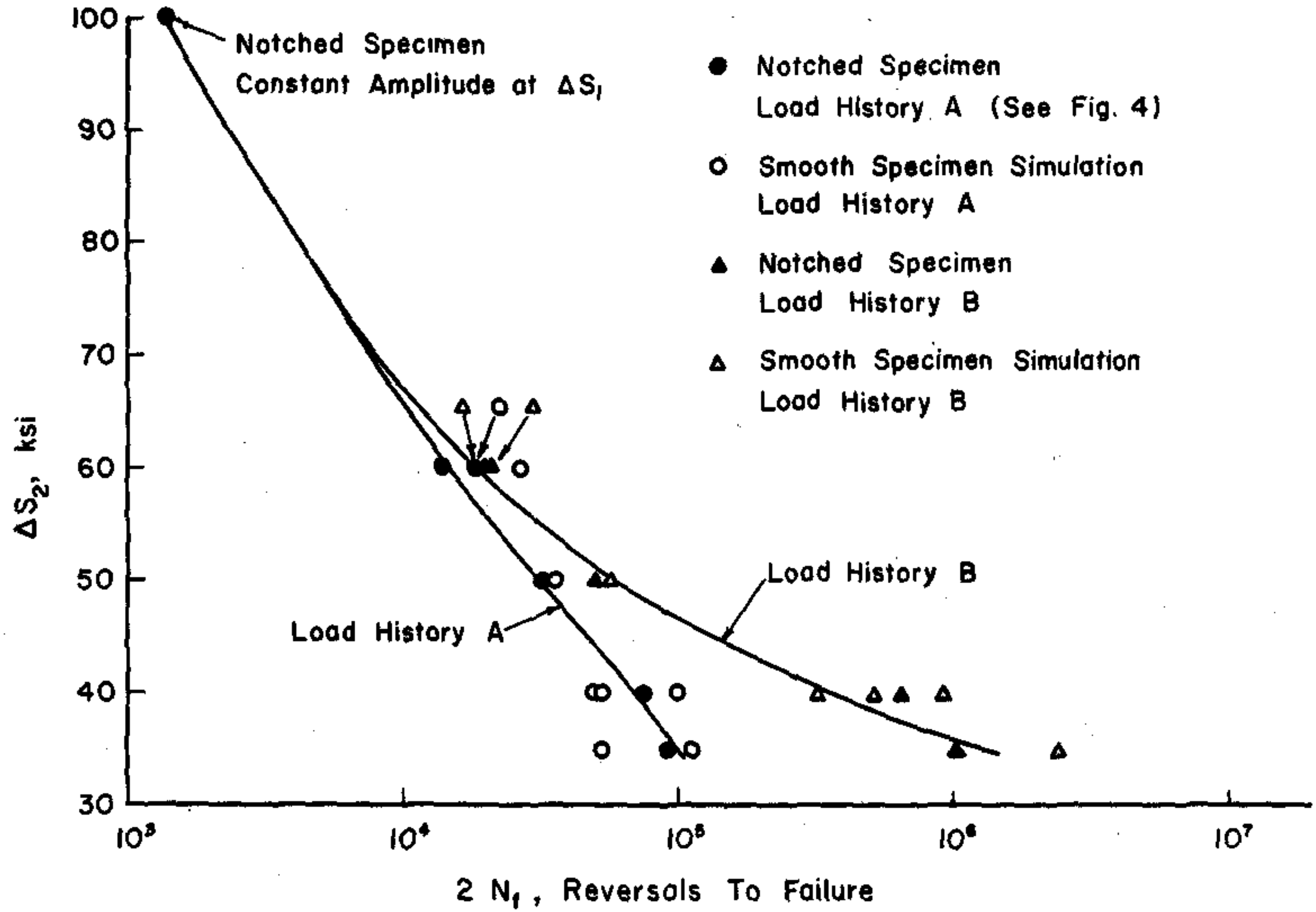
Stadnick and Morrow, "Techniques for Smooth Specimen Simulation of Fatigue Behavior of Notched Members" ASTM STP 515, 1972, 229-252

Loading Histories





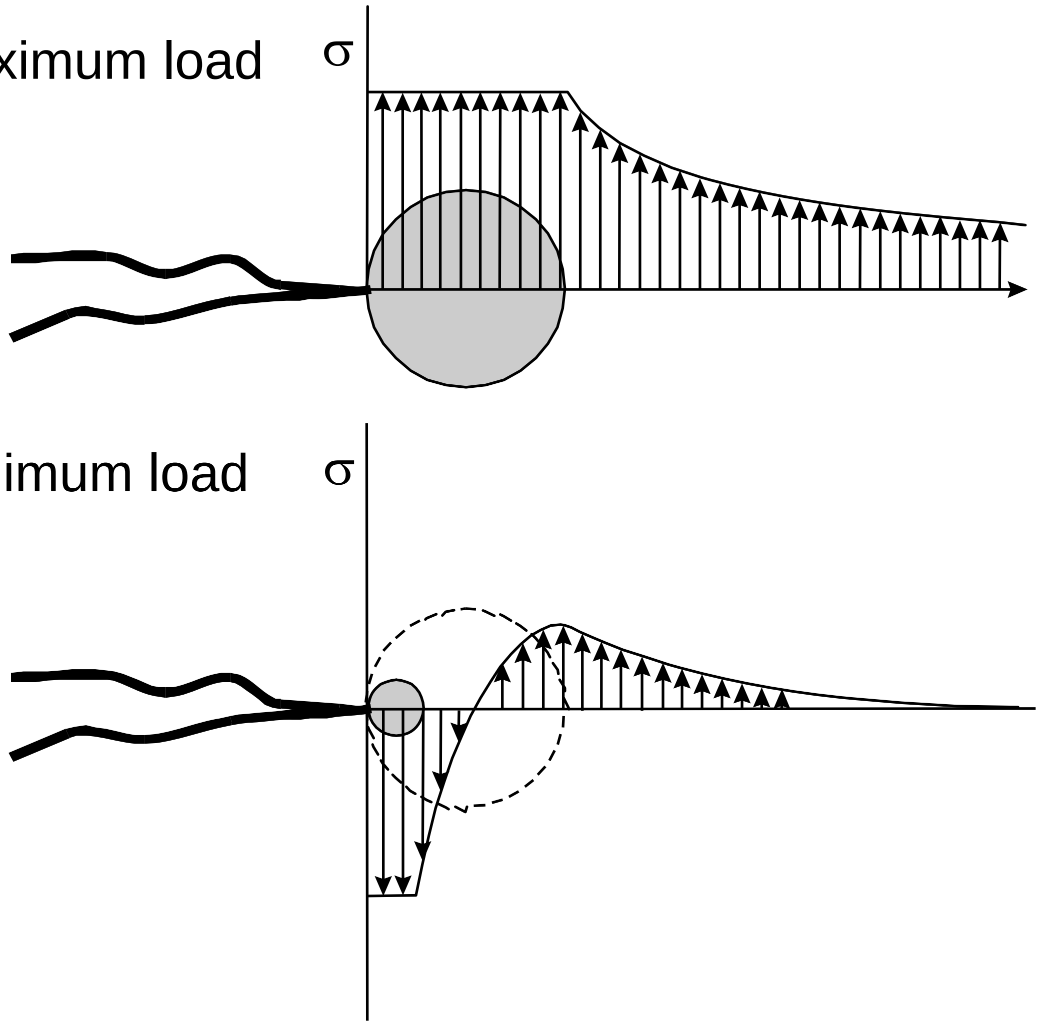
Test Results

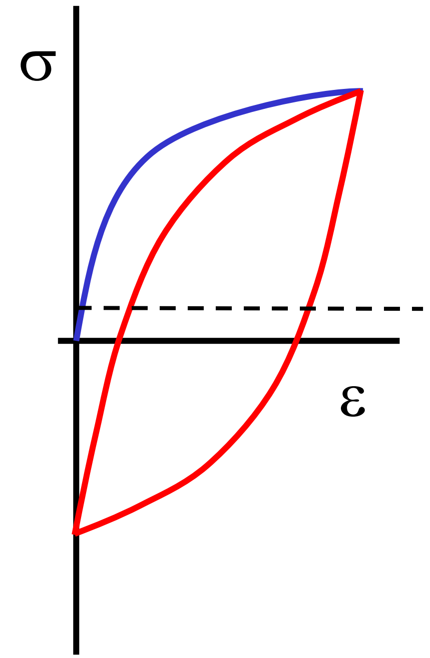


Crack Growth Physics

Maximum load

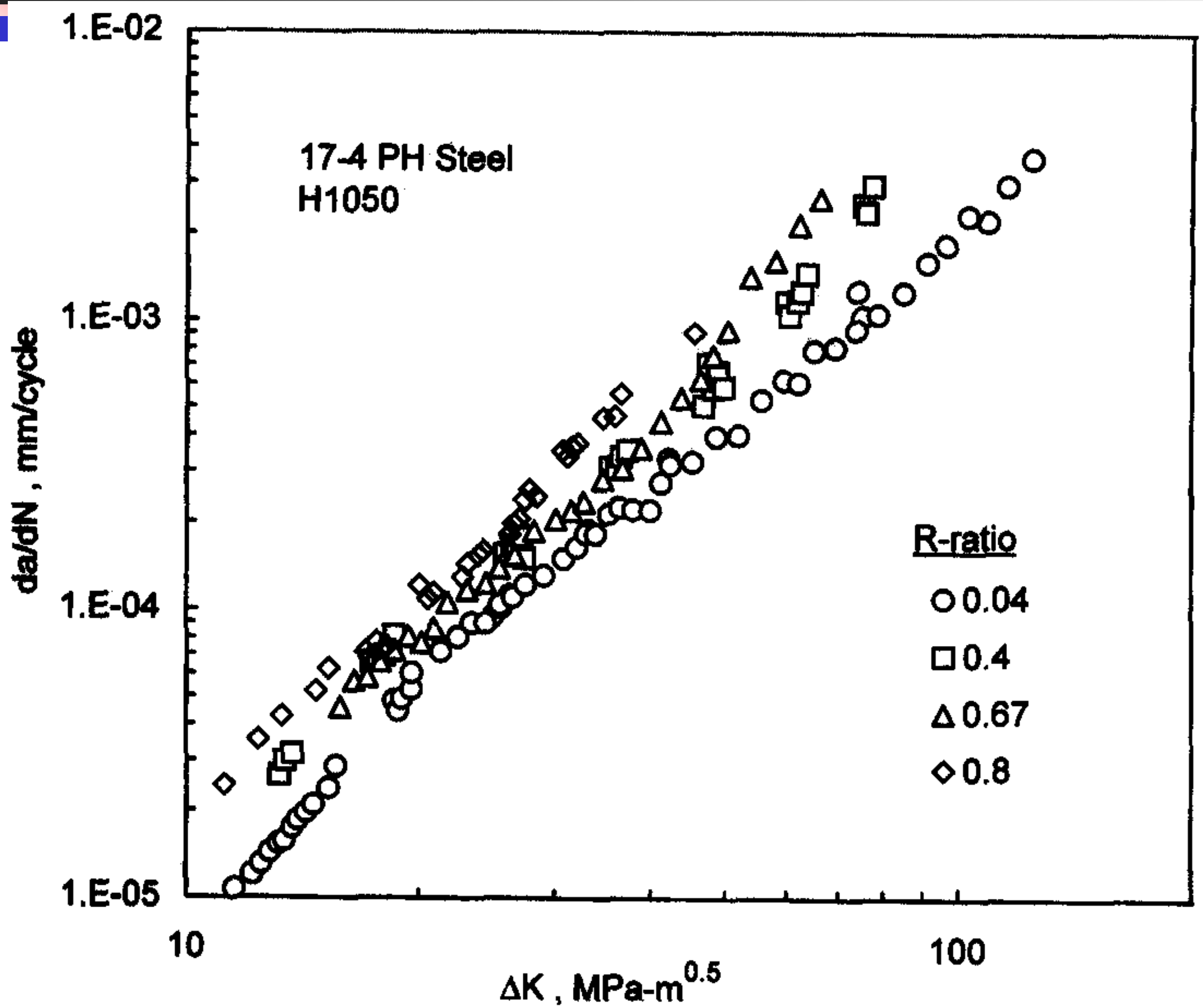
Minimum load





Mean stresses in plastic zone are small

Mean Stress Effects

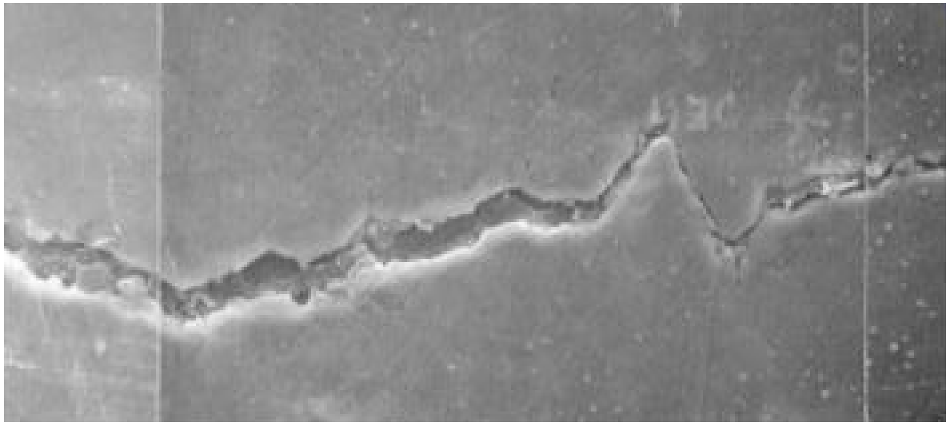


$$\frac{da}{dN} = \frac{C\,\Delta K^m}{(1-R)^\gamma}$$

$$0 < \gamma < 0.5$$

From: Dowling and Thangjitham, An Overview and Discussion of Basic Methodology for Fatigue, ASTM STP 1389,2000, 3-38

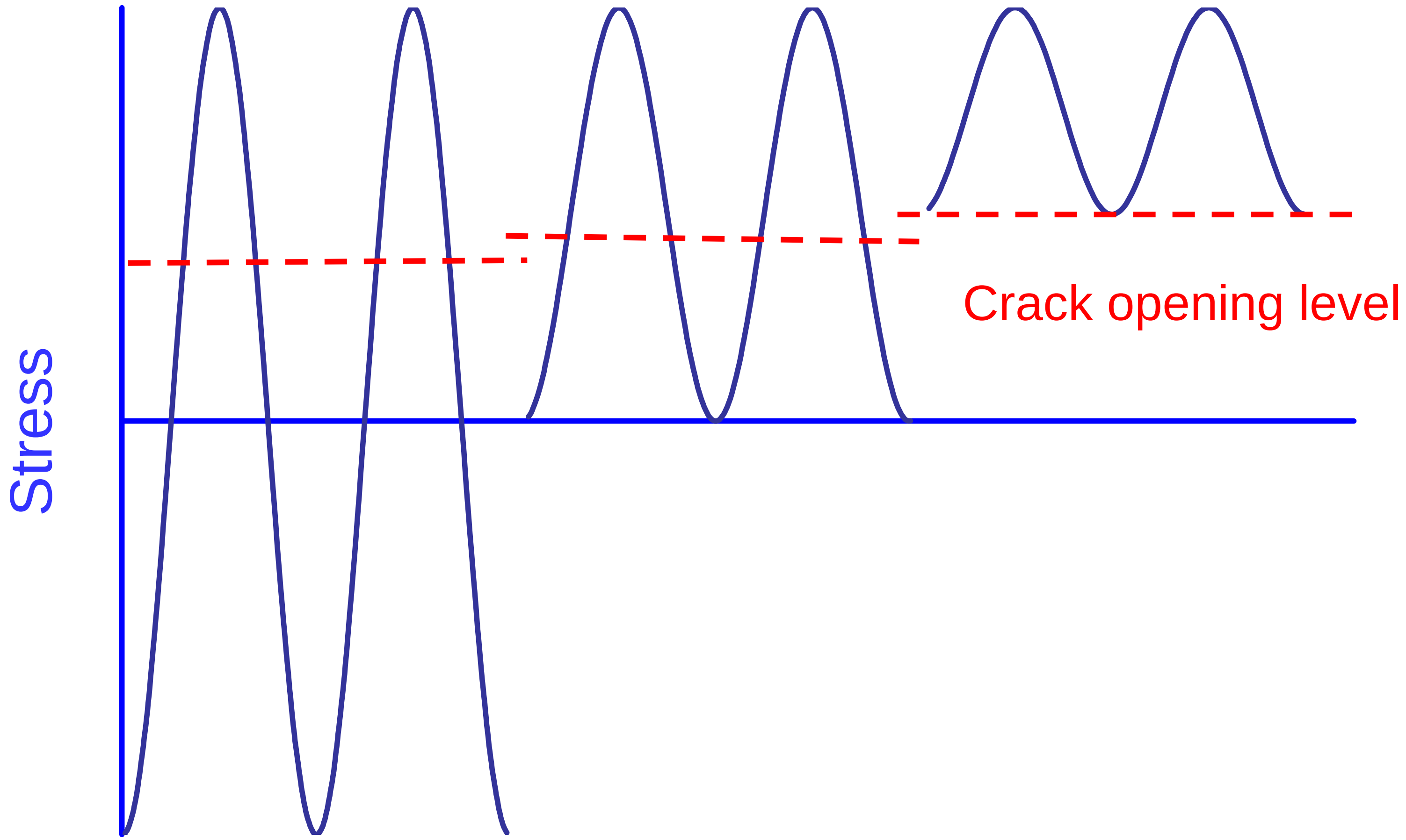
Compression



Crack open

Crack closed

Compressive Stresses



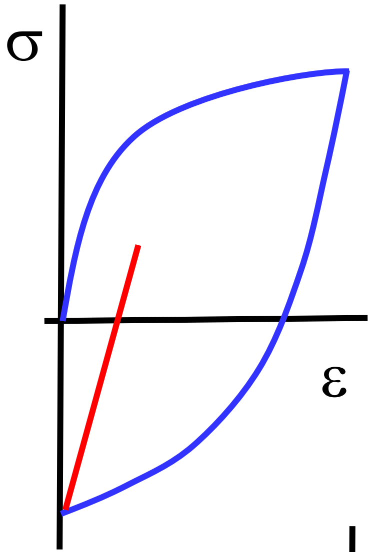
Compressive stresses are not very damaging in crack growth

Sources of Mean/Residual Stress

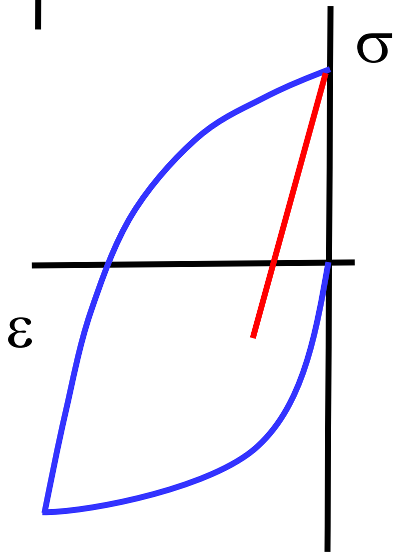
- Loading History
- Fabrication
- Shot Peening
- Heat Treating

Loading History

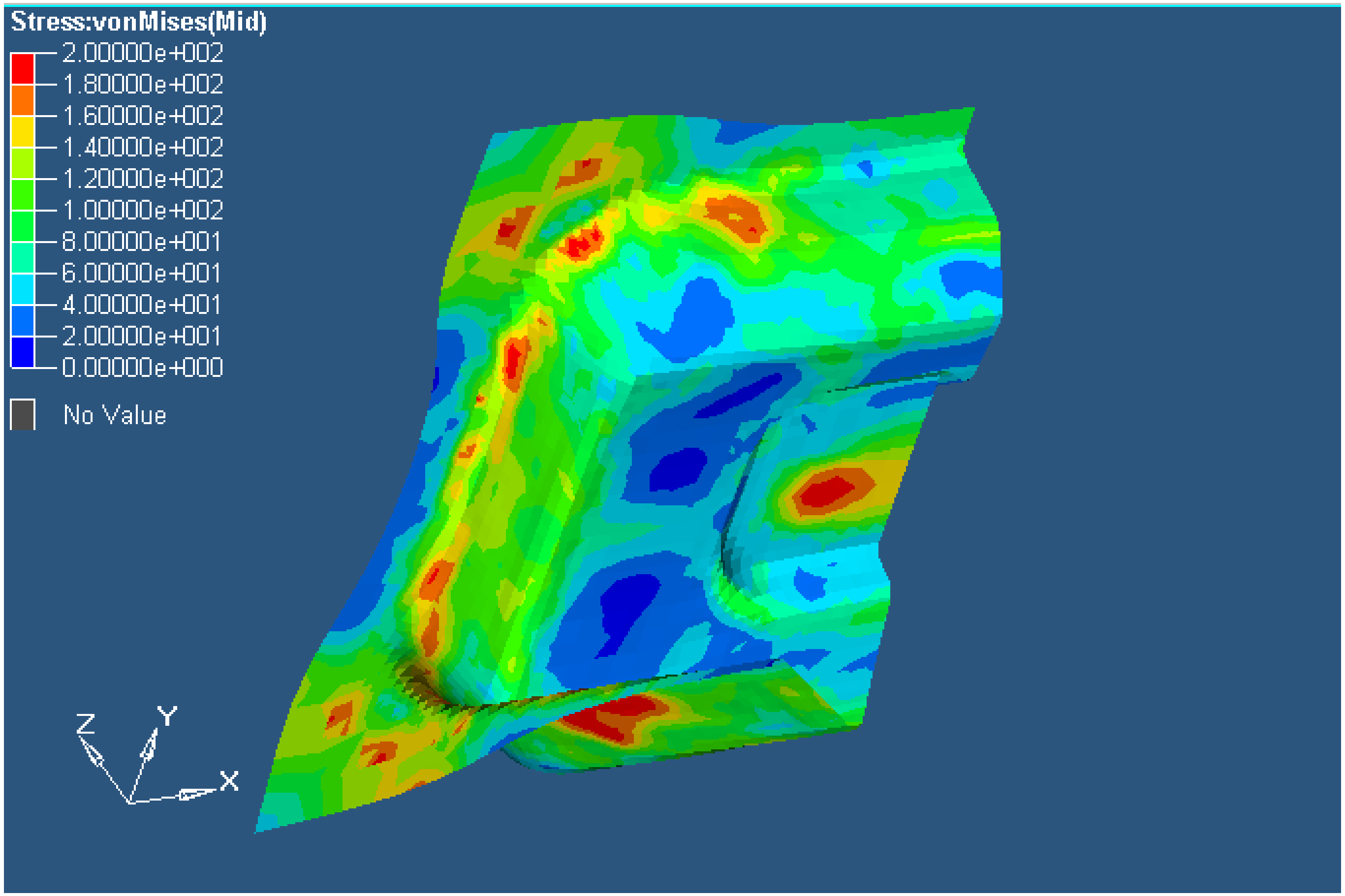
Tension overloads produce favorable compressive residual stress



Compressive overloads produce unfavorable tensile residual stress



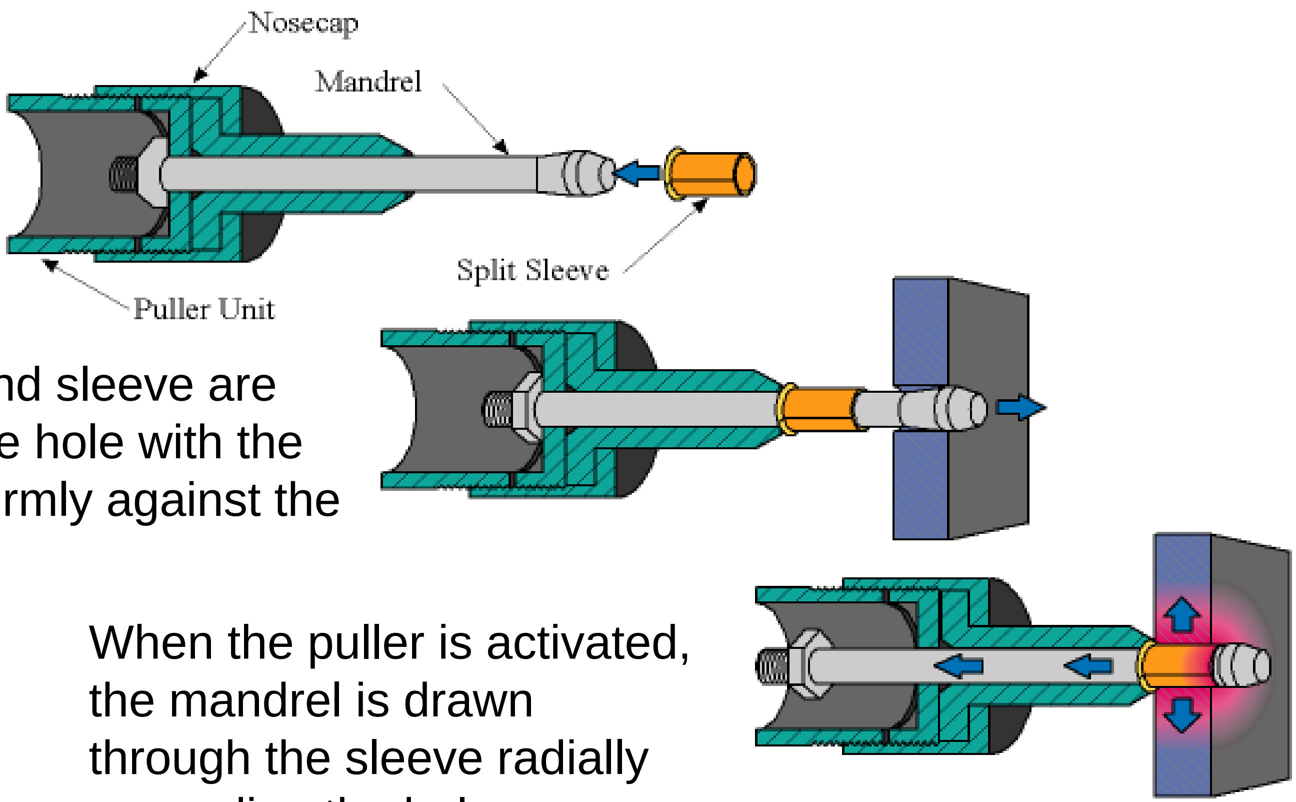
Fabrication



Cold Expansion

1965 Basic Cx process conceptualized (Boeing)

The split sleeve is slipped onto the mandrel, which is attached to the hydraulic puller unit.

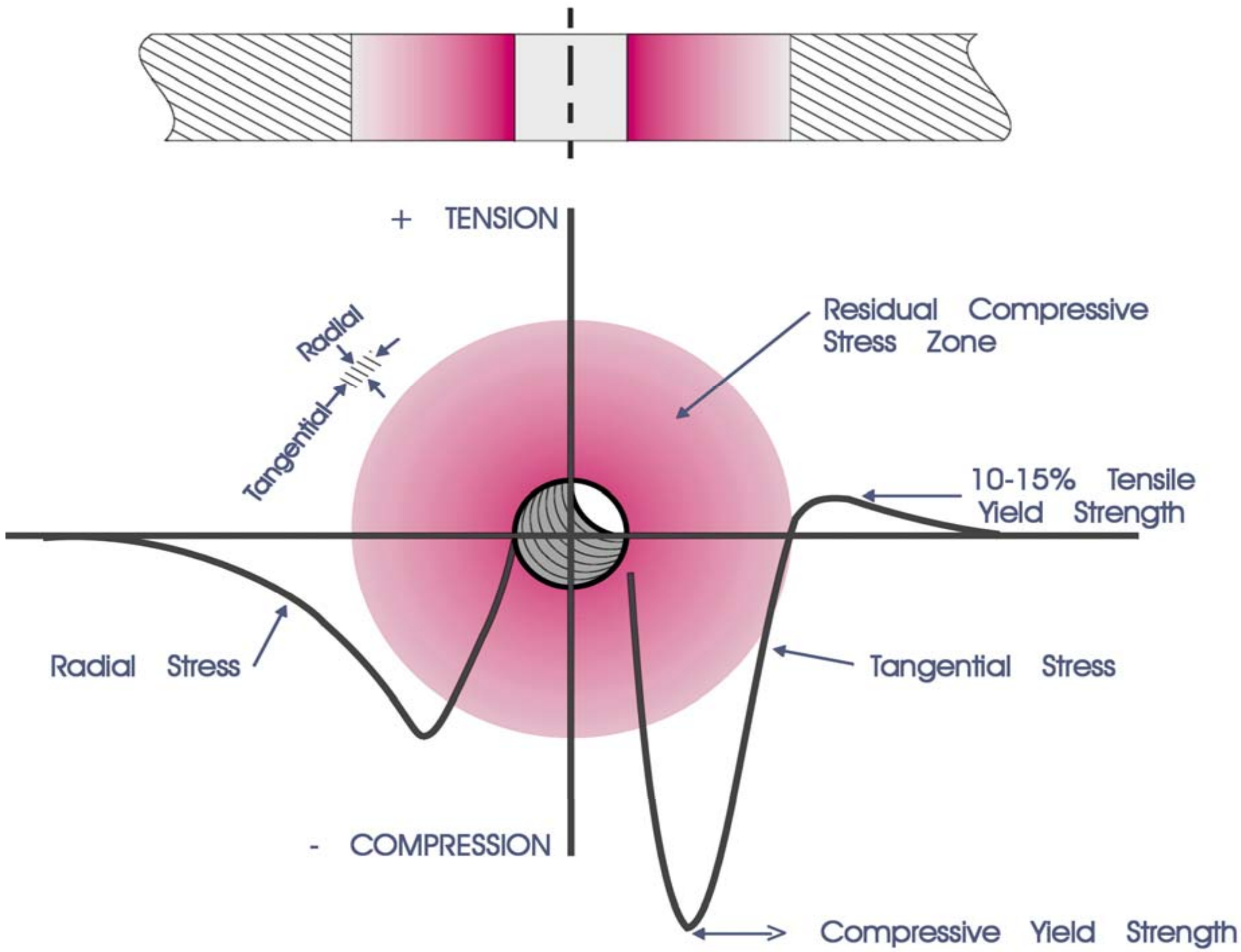


The mandrel and sleeve are inserted into the hole with the nosecap held firmly against the workpiece.

When the puller is activated, the mandrel is drawn through the sleeve radially expanding the hole.

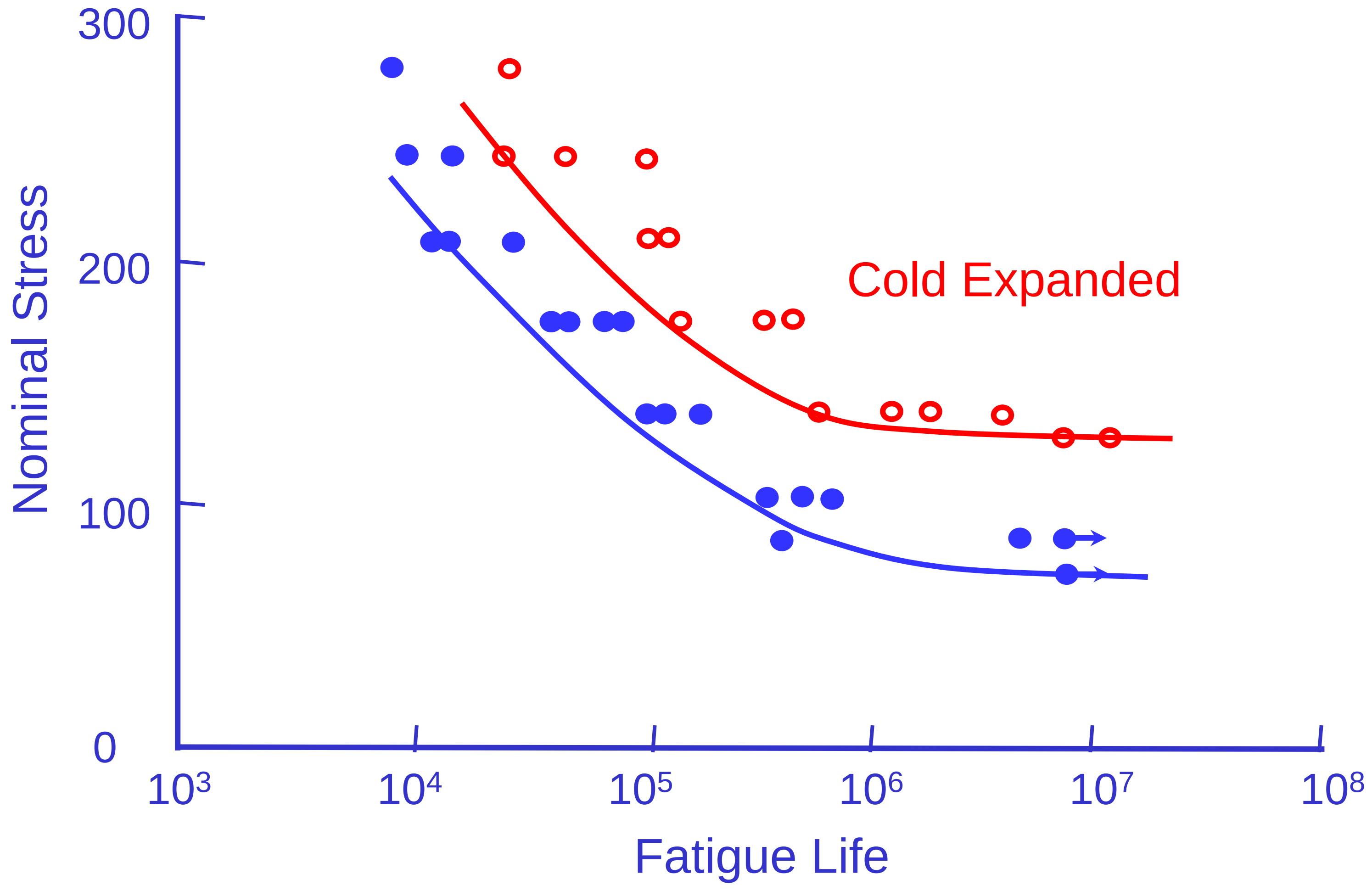
Courtesy of Fatigue Technology Inc.

Theory of Cold Expansion



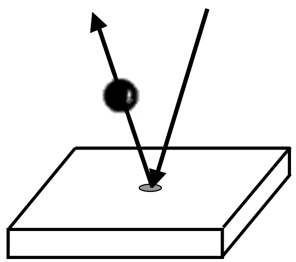
Courtesy of Fatigue Technology Inc.

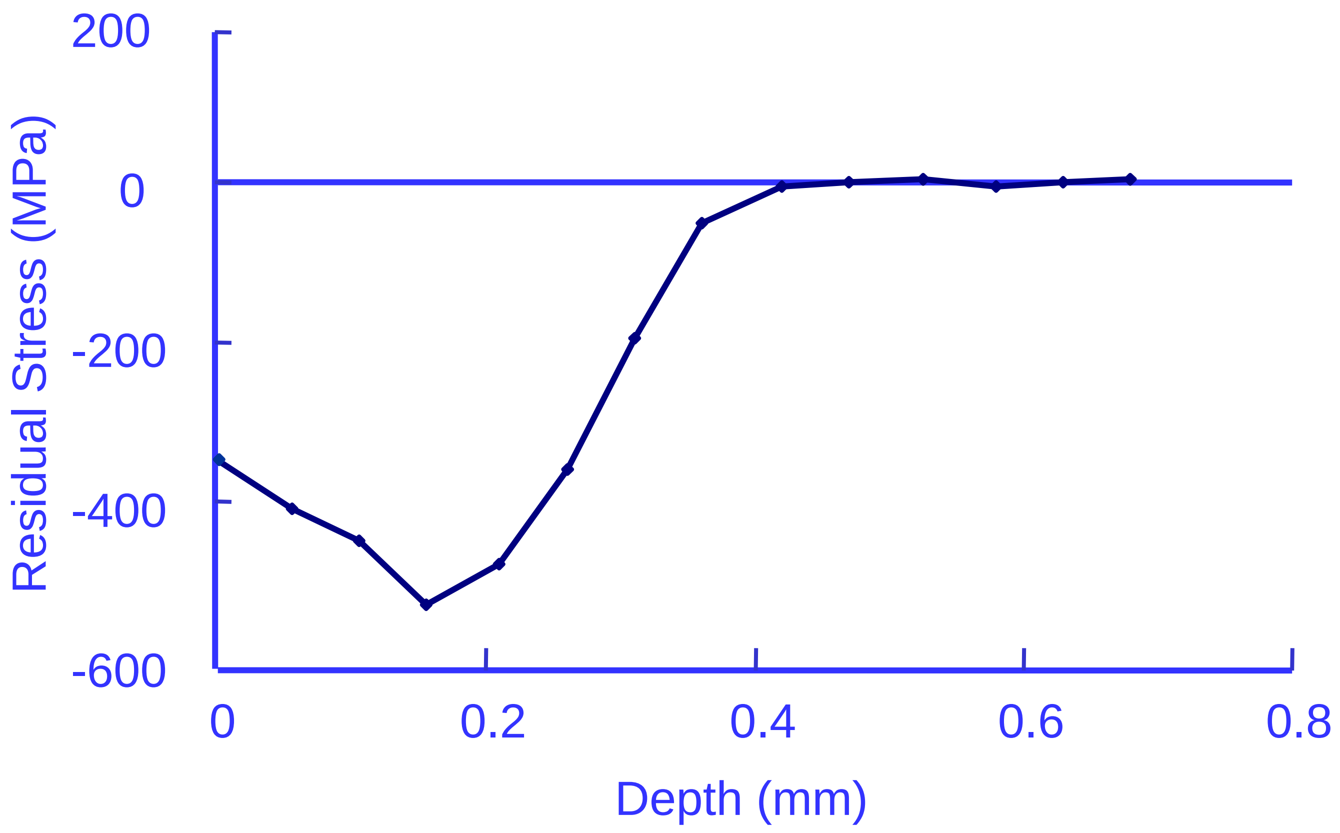
Fatigue Life Improvement



Courtesy of Fatigue Technology Inc.

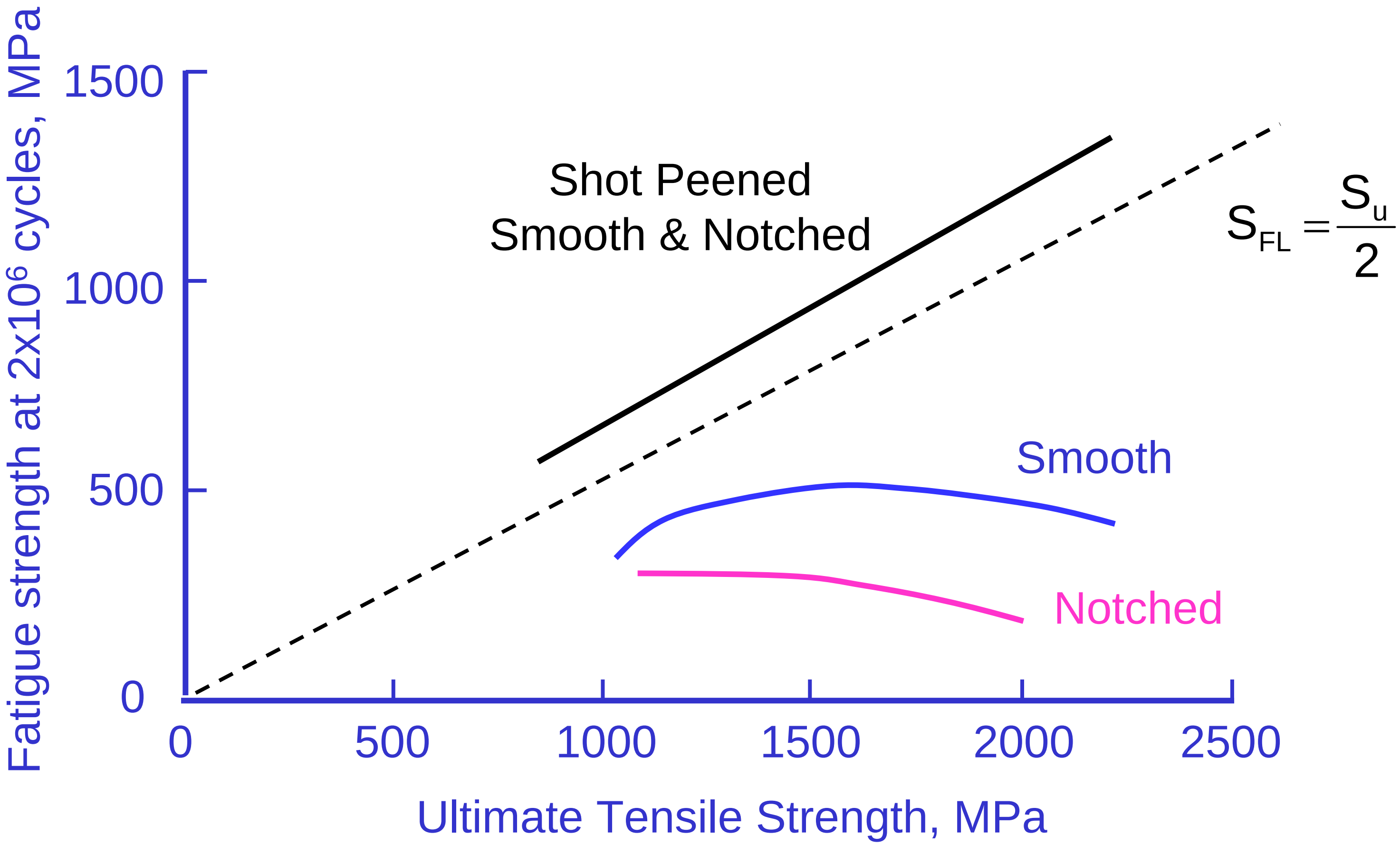
Shot Peening





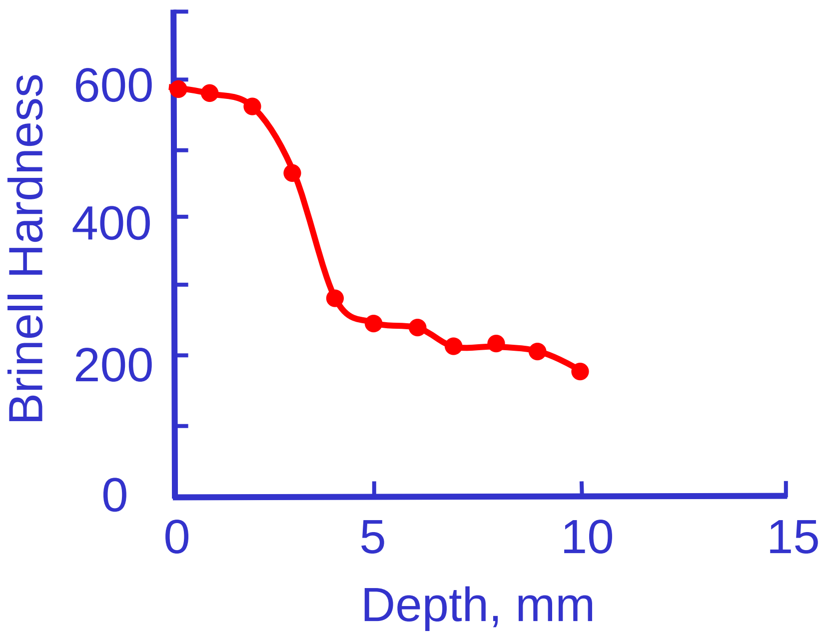
Residual stress in a shot peened leaf spring

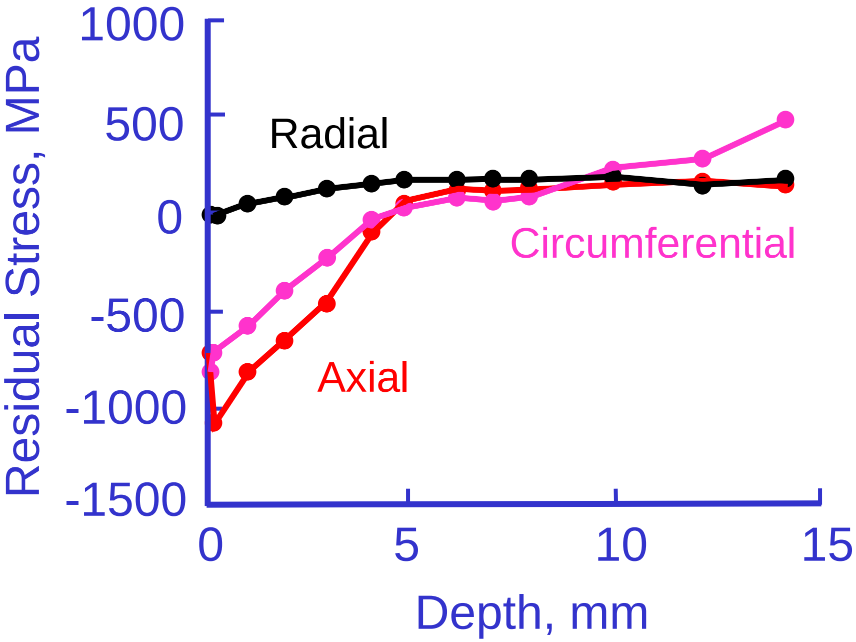
Shot Peening Results



www.metalimprovement.com

Heat Treating





50 mm diameter induction hardened 1045 steel shaft

Things Worth Remembering

- Local mean stress rather than the nominal mean stress governs the fatigue life
- Mean stress has the greatest effect on crack nucleation

Fatigue Seminar

Fatigue Made Easy

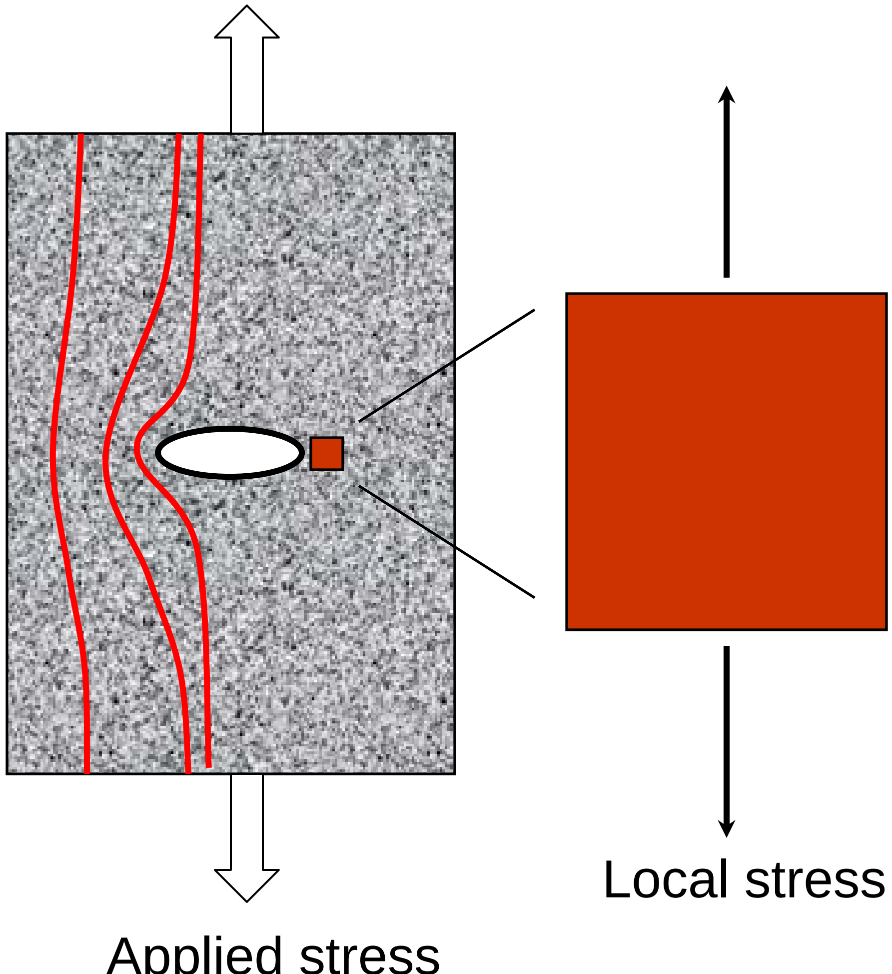
Stress Concentrations

Professor Darrell F. Socie
Mechanical Science and Engineering
University of Illinois

Seminar Outline

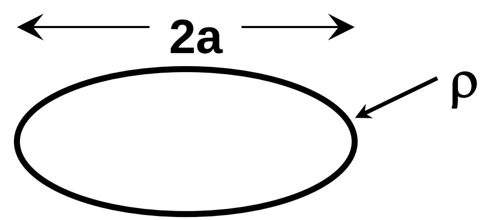
1. Historical background
2. Physics of fatigue
3. Characterization of materials
4. Similitude
5. Variability
6. Mean stress
7. Stress concentrations
8. Surface effects
9. Variable amplitude loading
10. Welded structures

Stress Concentration Factor

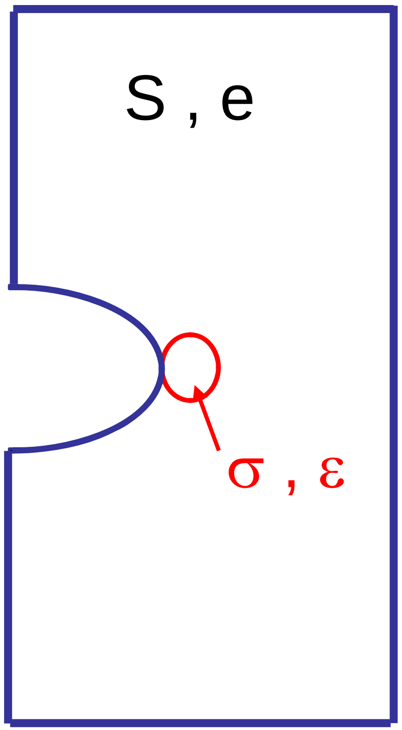


$$\sigma_{local} = \sigma_{applied}\left(1 + 2\sqrt{\frac{a}{\rho}}\right)$$

Inglis Solution 1910



Define K_σ and K_ε after Yielding



Define: nominal stress, S

nominal strain, e

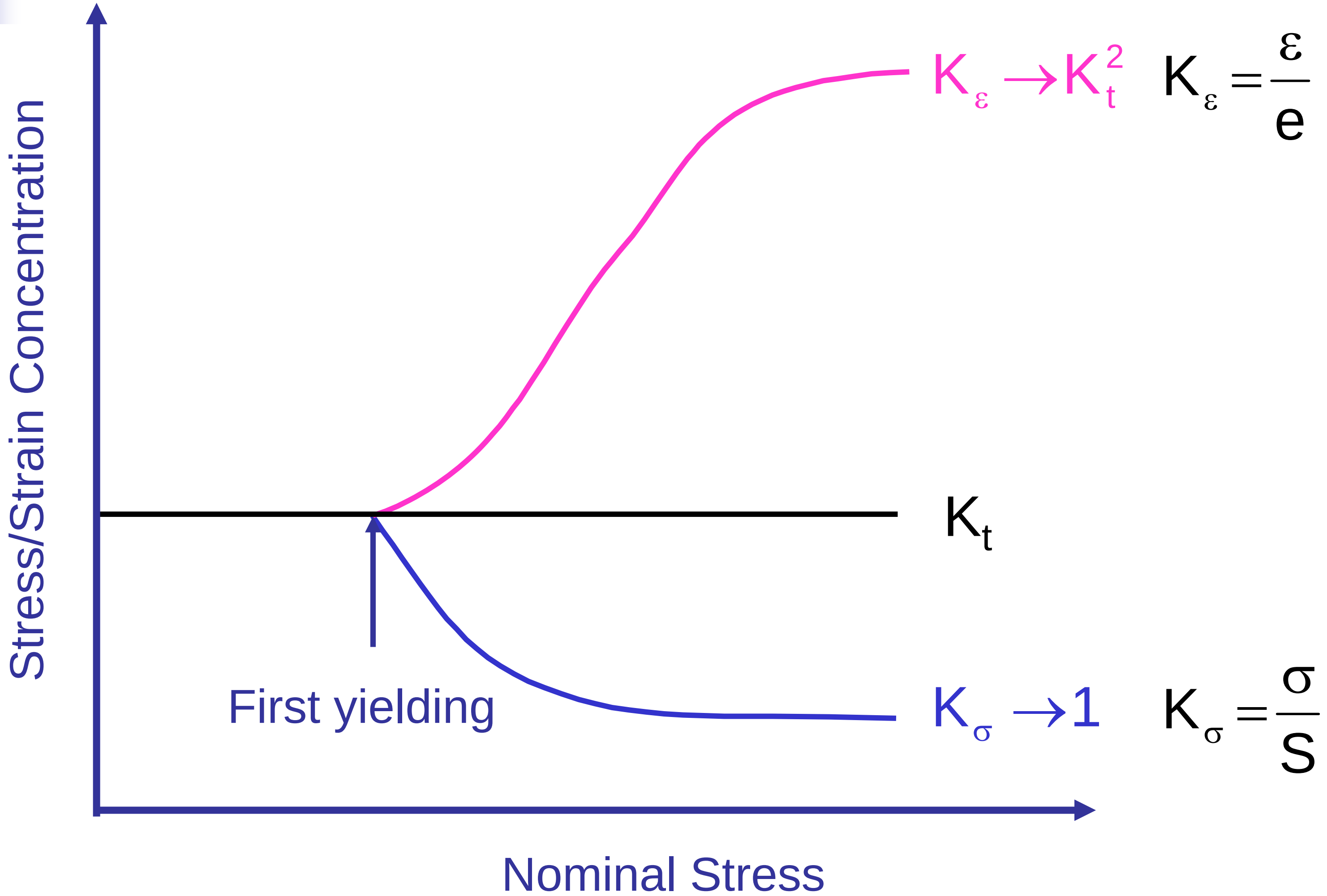
notch stress, σ

notch strain, ε

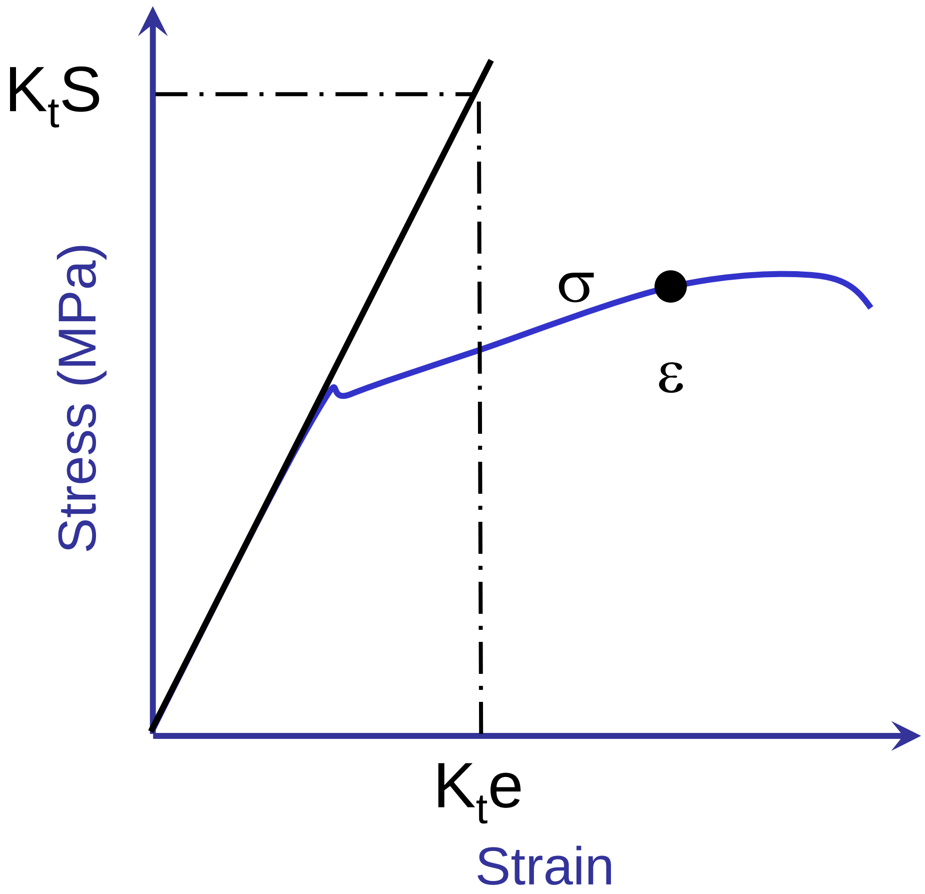
Stress concentration $K_\sigma = \frac{\sigma}{S}$

Strain concentration $K_\varepsilon = \frac{\varepsilon}{e}$

Stress and Strain Concentration



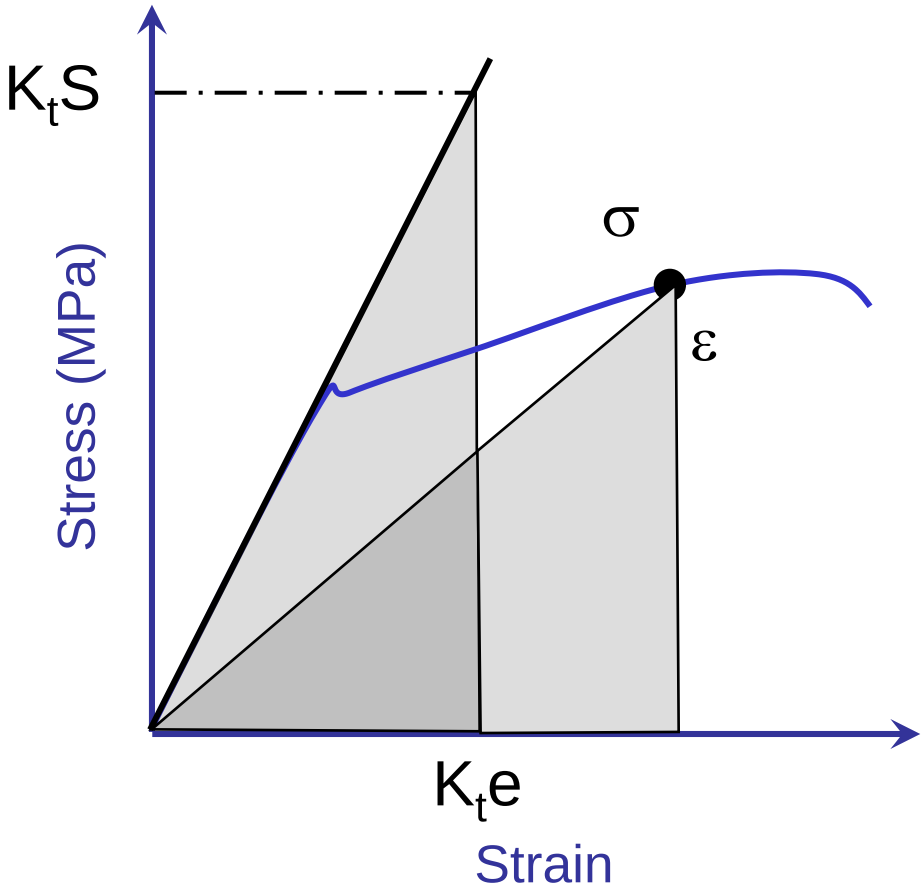
K_σ and K_ε



$$K_\sigma = \frac{\sigma}{S}$$

$$K_\varepsilon = \frac{\varepsilon}{e}$$

Neuber's Rule



Actual stress

$$\underbrace{K_t S}\, K_t e = \sigma \varepsilon$$

Stress calculated with elastic assumptions

Neuber's Rule for Fatigue

Stress and strain amplitudes

$$\frac{K_t\,\Delta S}{2}\,\frac{K_t\,\Delta e}{2} = \frac{\Delta\sigma}{2}\,\frac{\Delta\varepsilon}{2}$$

Elastic nominal stress

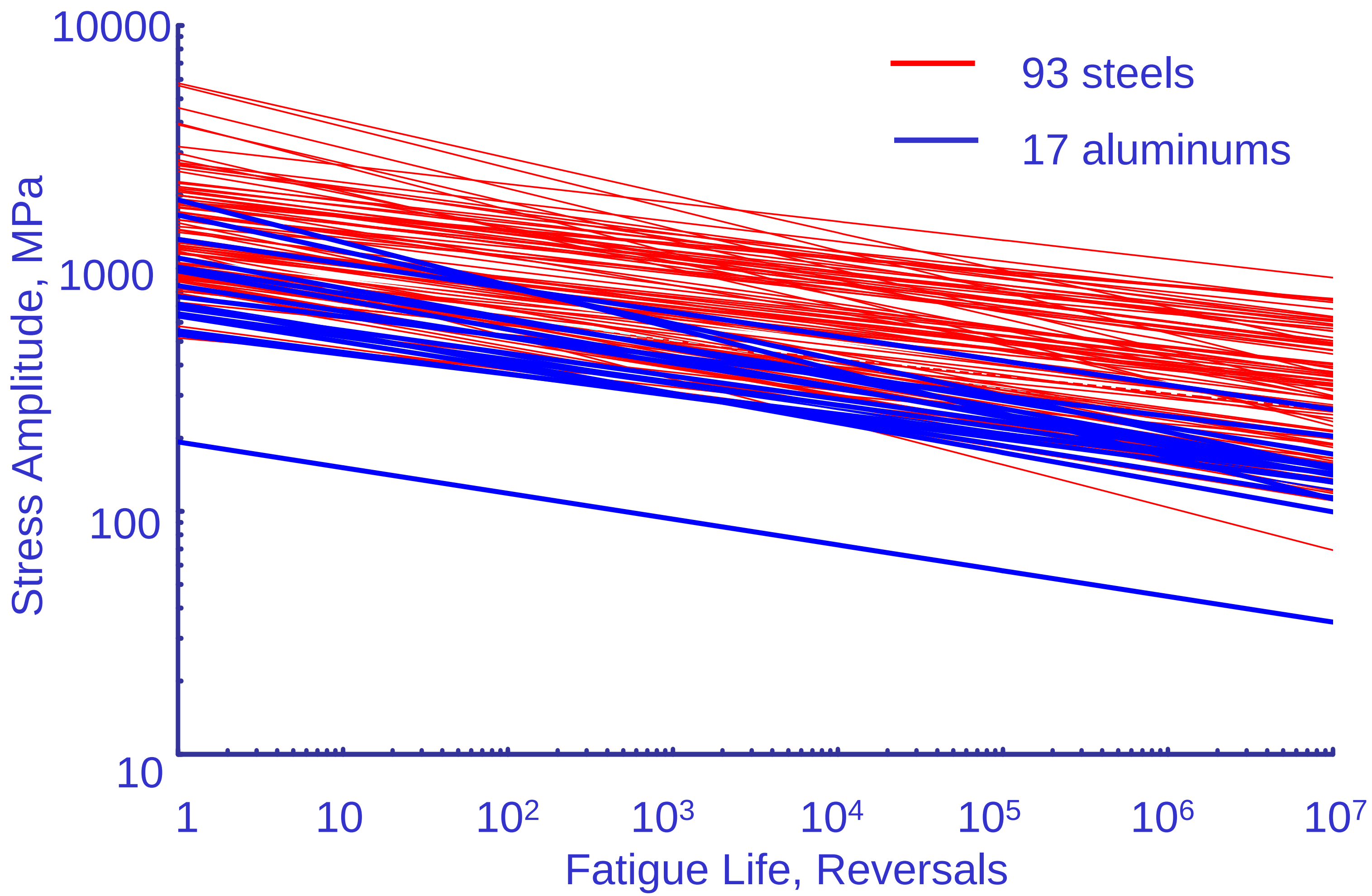
$$\frac{\Delta e}{2} = \frac{\Delta S}{2E}$$

Substitute and rearrange

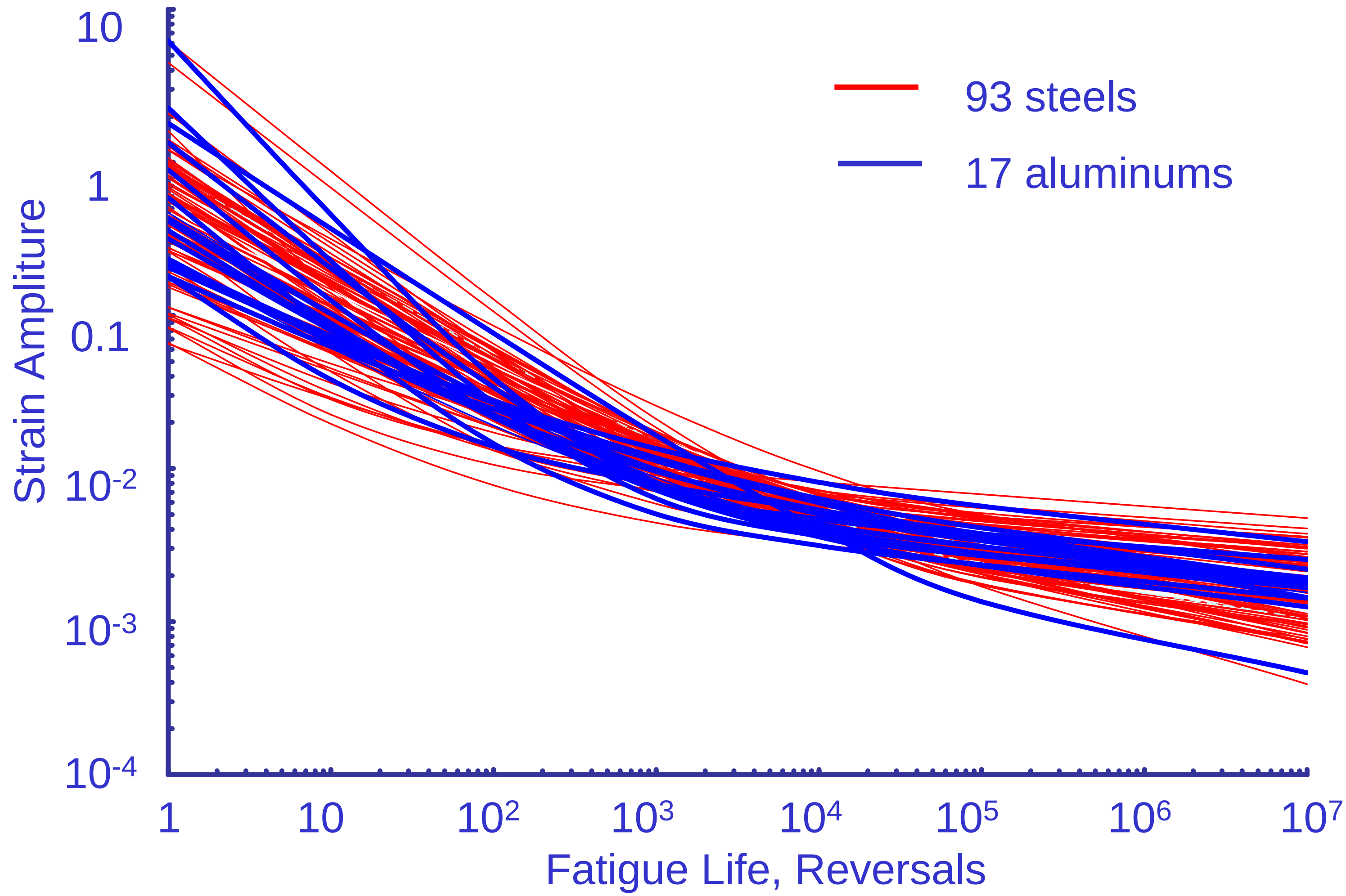
$$K_t\,\frac{\Delta S}{2} = \sqrt{E\,\frac{\Delta\sigma}{2}\,\frac{\Delta\varepsilon}{2}}$$

The product of stress times strain controls fatigue life

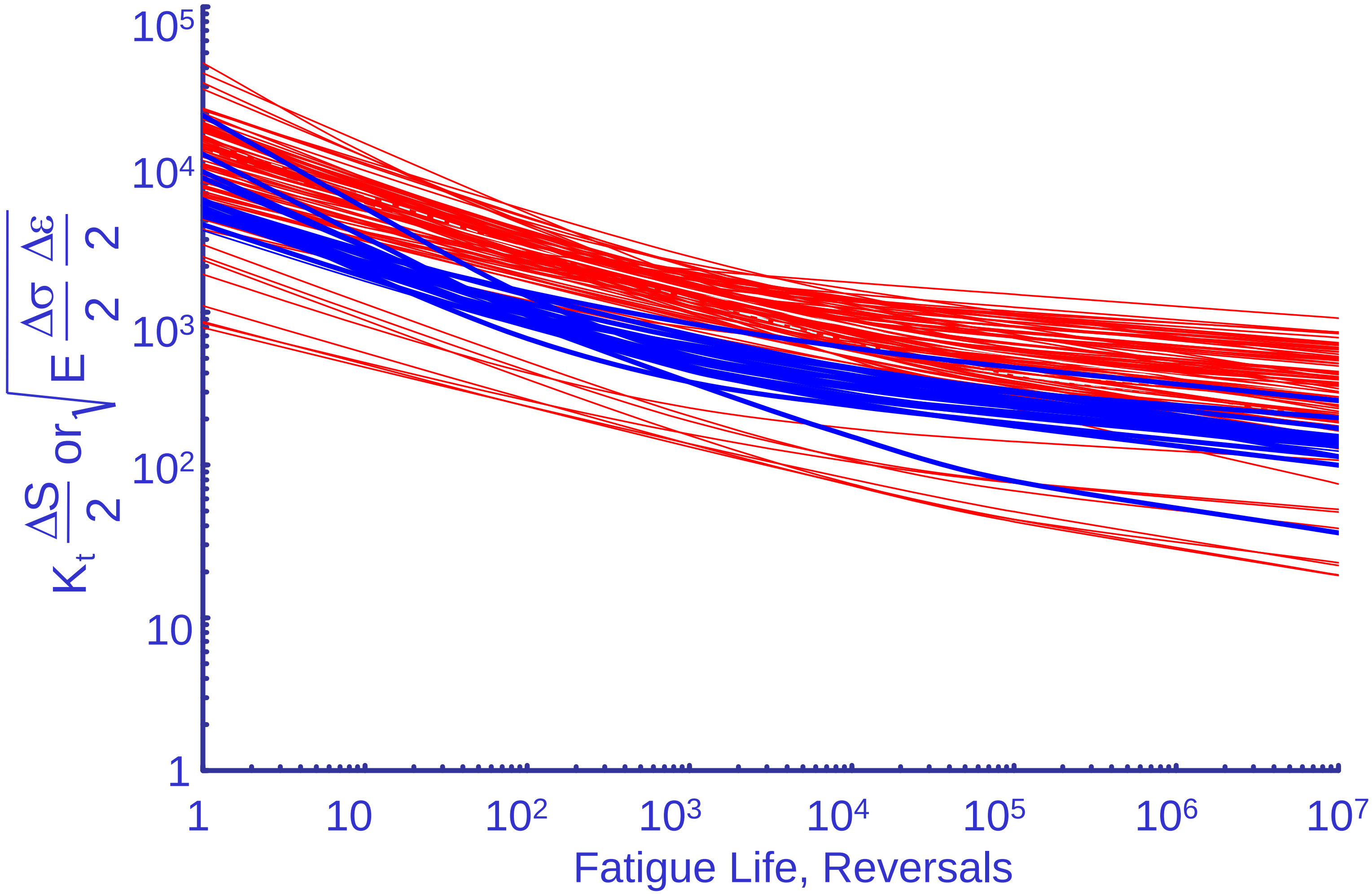
SN Materials Data



εN Materials Data



$$\sqrt{E \frac{\Delta\sigma}{2} \frac{\Delta\varepsilon}{2}}$$



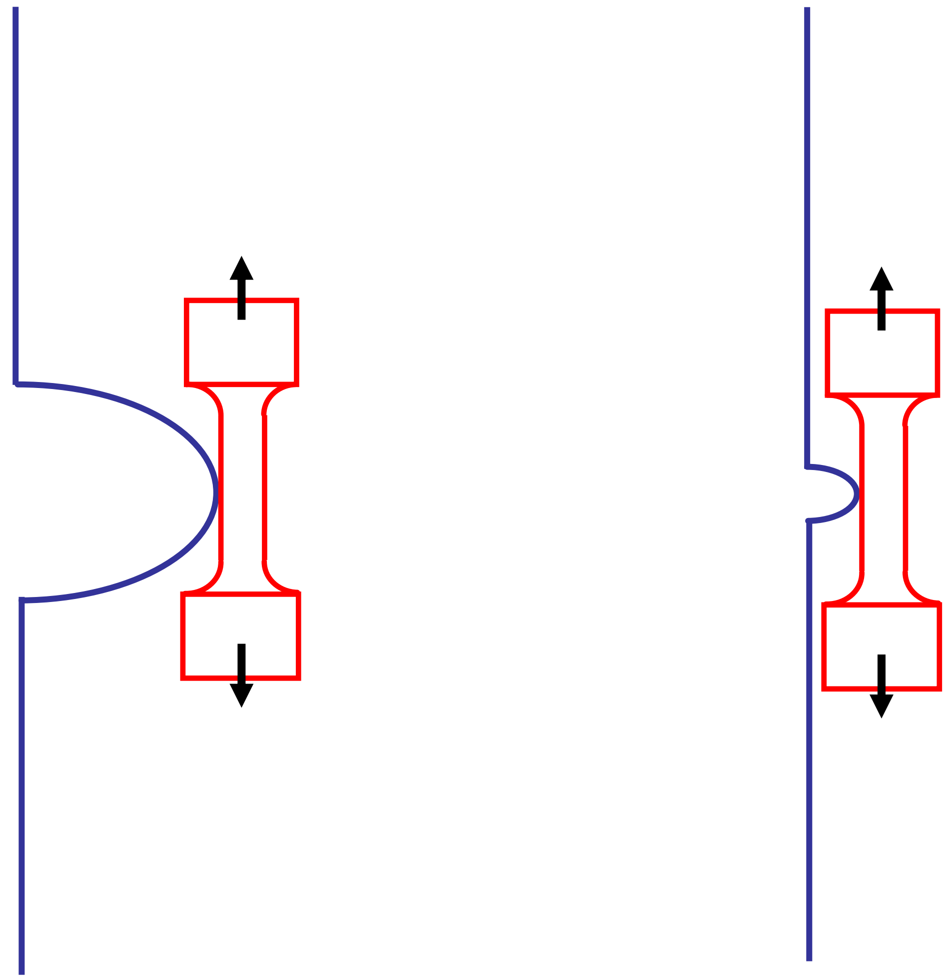
A Dilemma

Stress analysis and stress concentration factors are independent of size and are related only to the ratio of the geometric dimensions to the loads

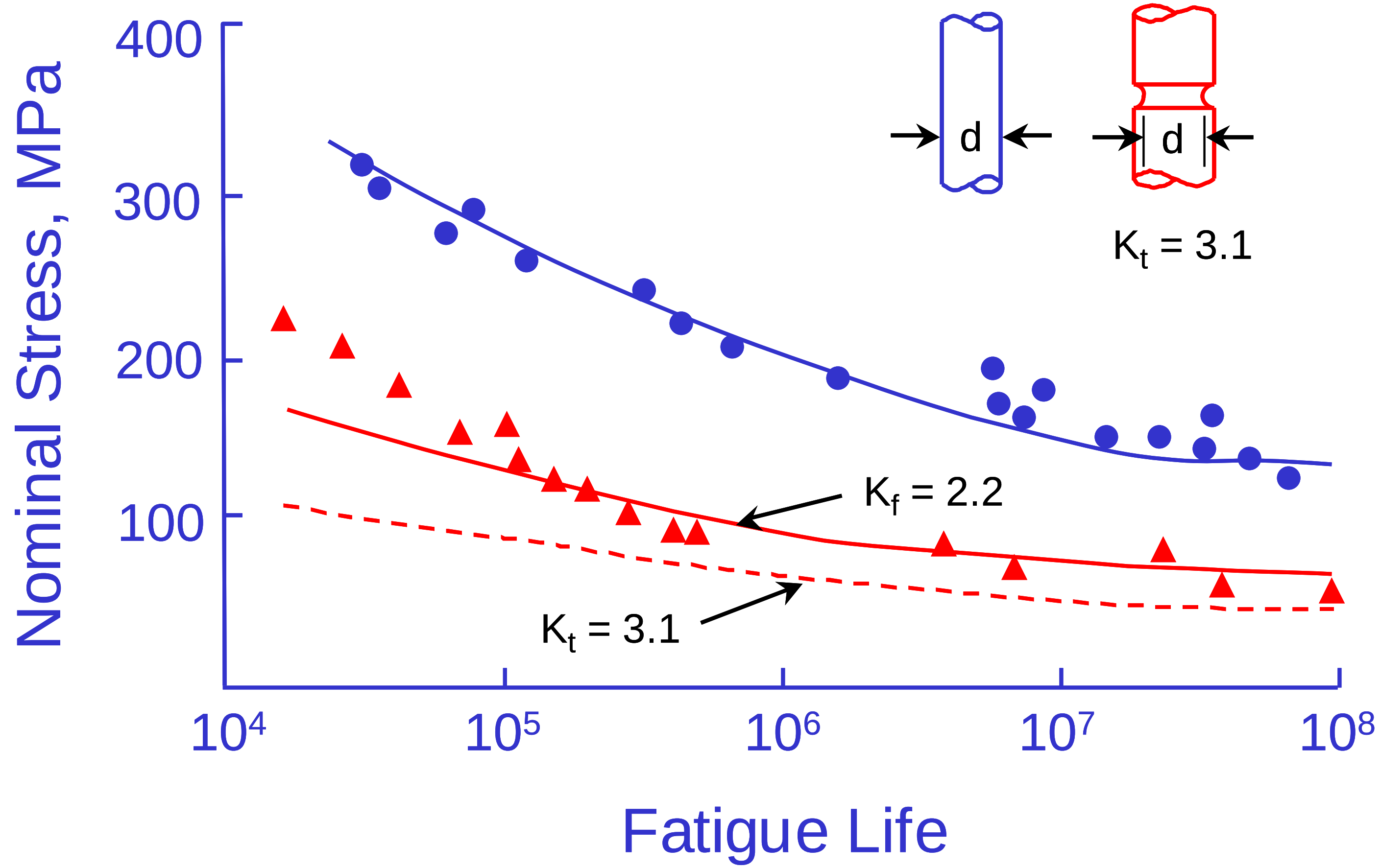
Fatigue is a size dependent phenomenon

How do you put the two together ?

Similitude

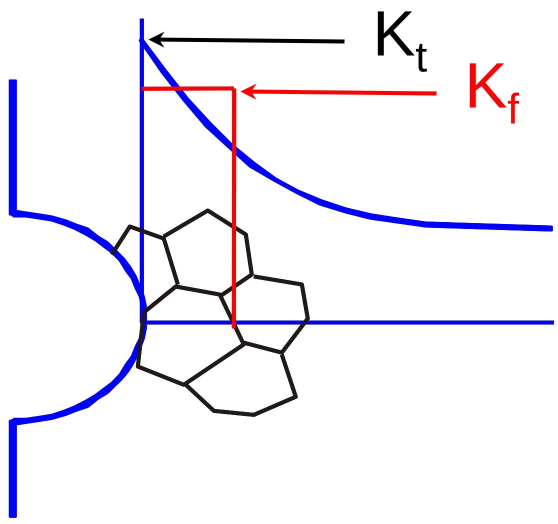


Fatigue of Notches

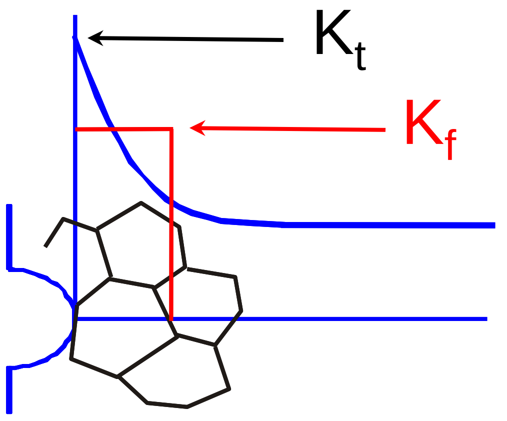


From Dowling, Mechanical Behavior of Materials, 1999

Notch Size

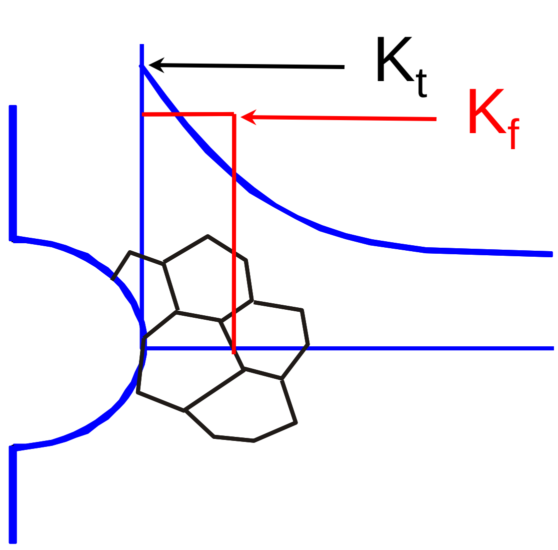


Large Notch

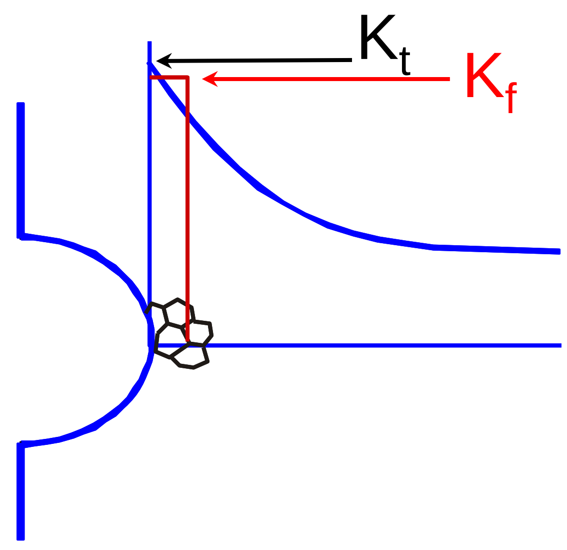


Small Notch

Microstructure Size

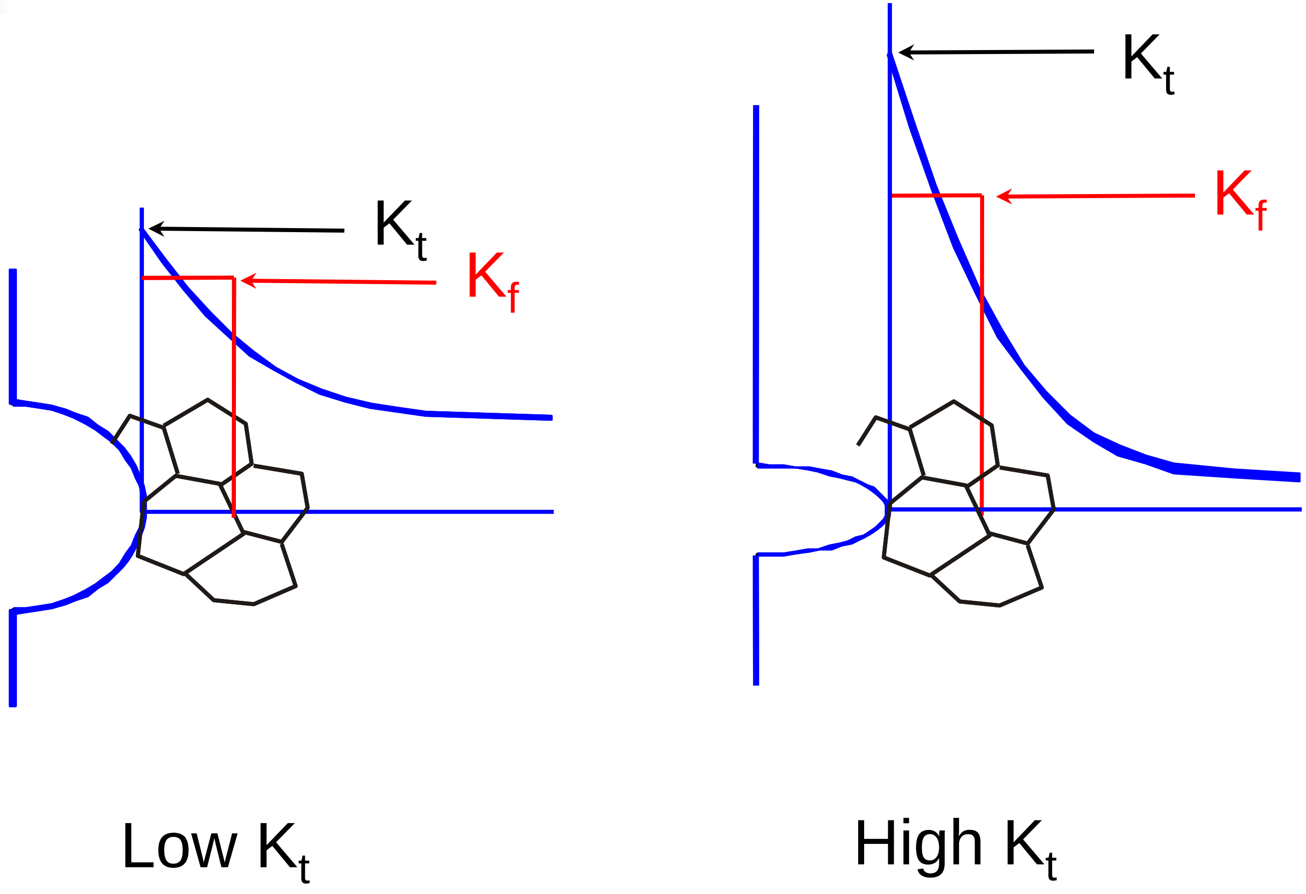


Low Strength

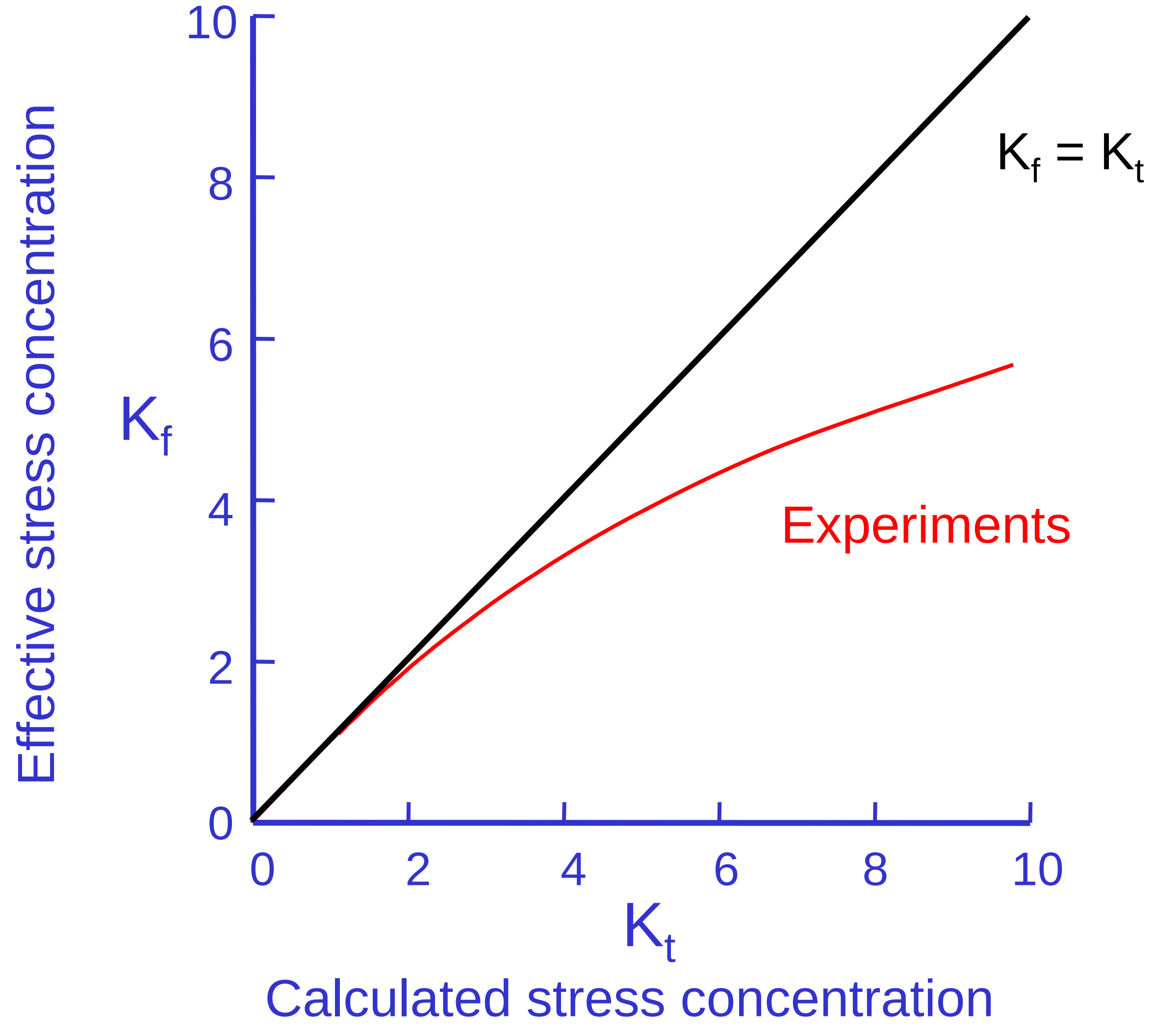


High Strength

Stress Gradient



K_t vs K_f

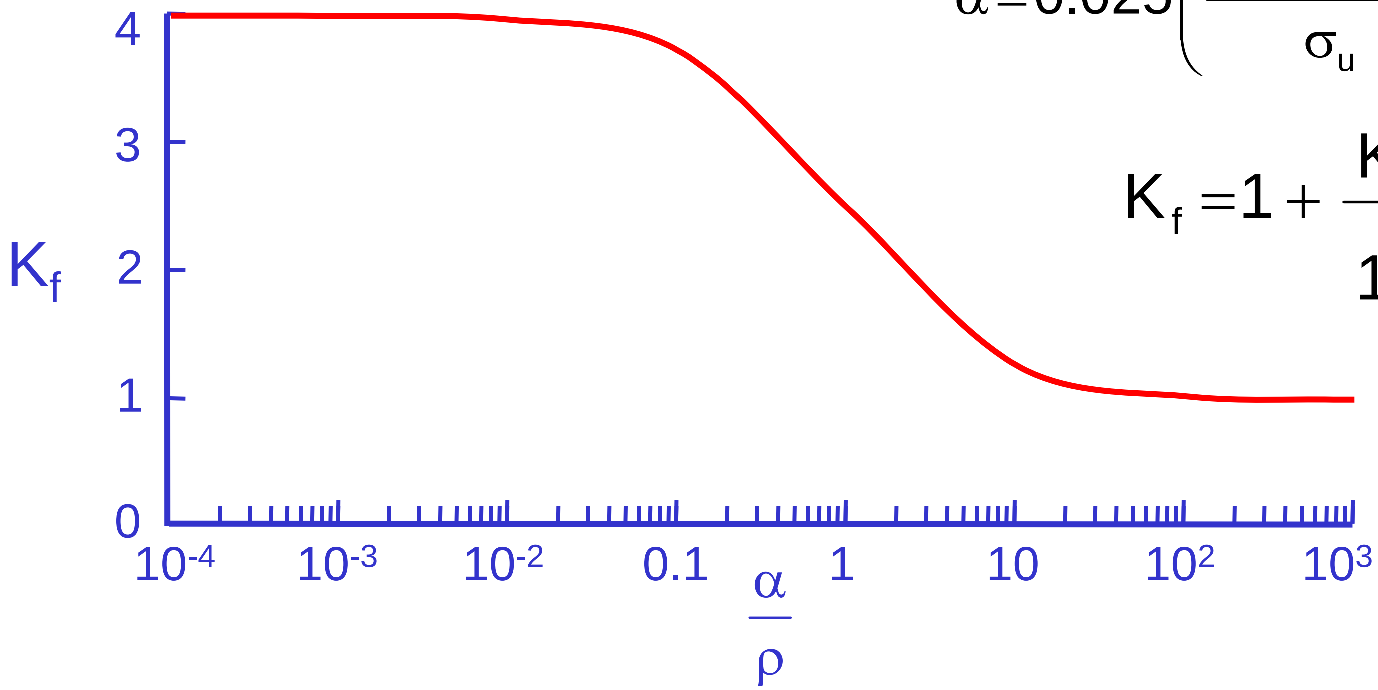


10
8
6
4
2
0
Effective stress concentration
K_f
$K_f = K_t$
Experiments
0
2
4
6
8
10
K_t
Calculated stress concentration

Peterson's Equation

$$\alpha = 0.025\left(\frac{2070\text{MPa}}{\sigma_u}\right)^{1.8}\ \text{mm}$$

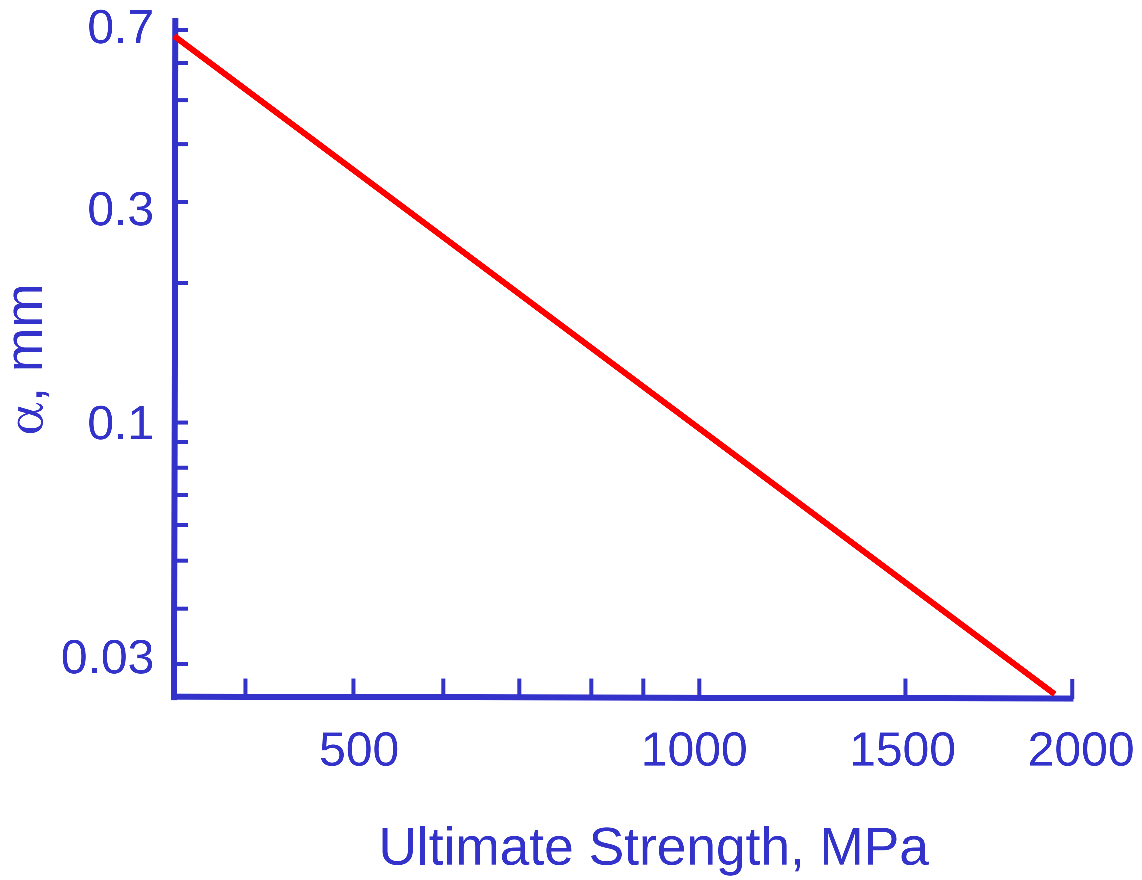
$$K_f = 1 + \frac{K_t - 1}{1 + \frac{\alpha}{\rho}}$$



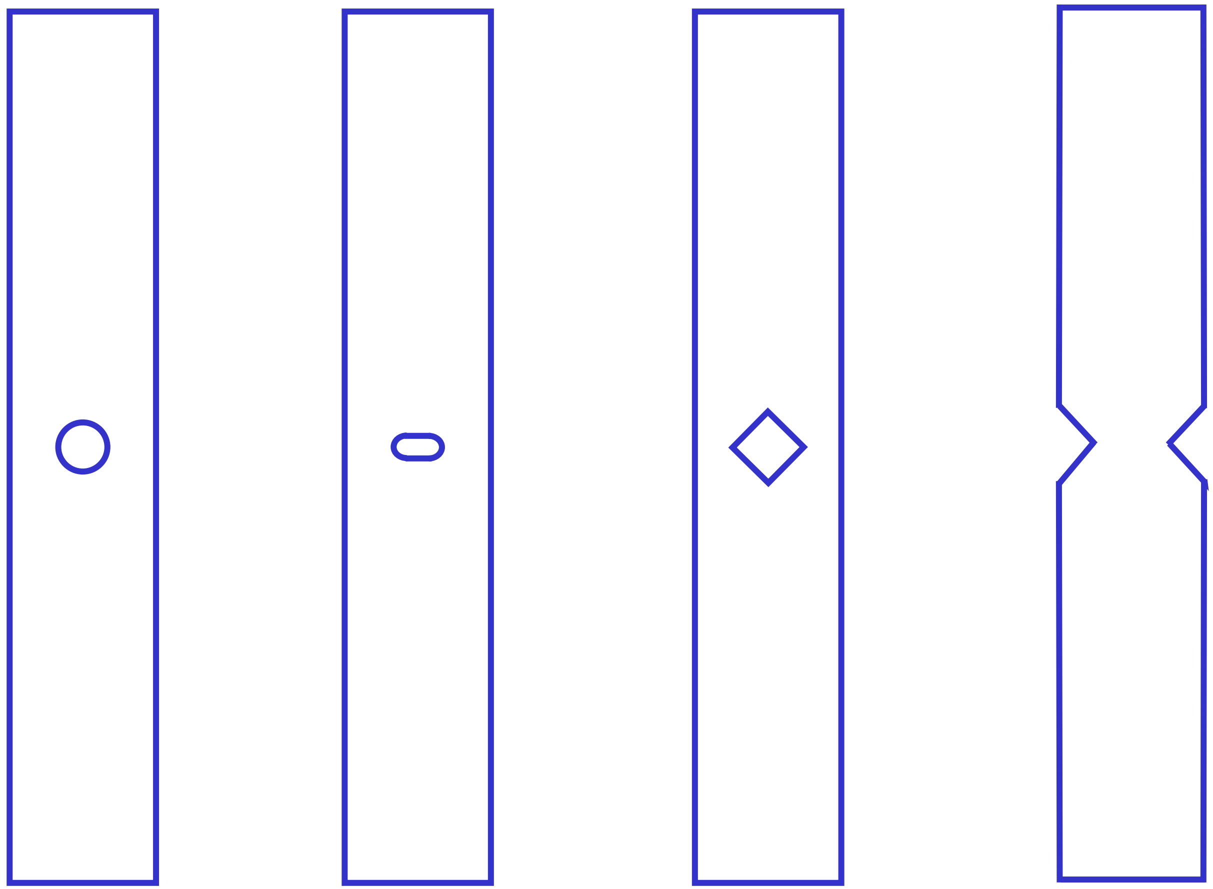
No effect when $\rho << \alpha$

Full effect when $\rho >> \alpha$

Peterson's Constant

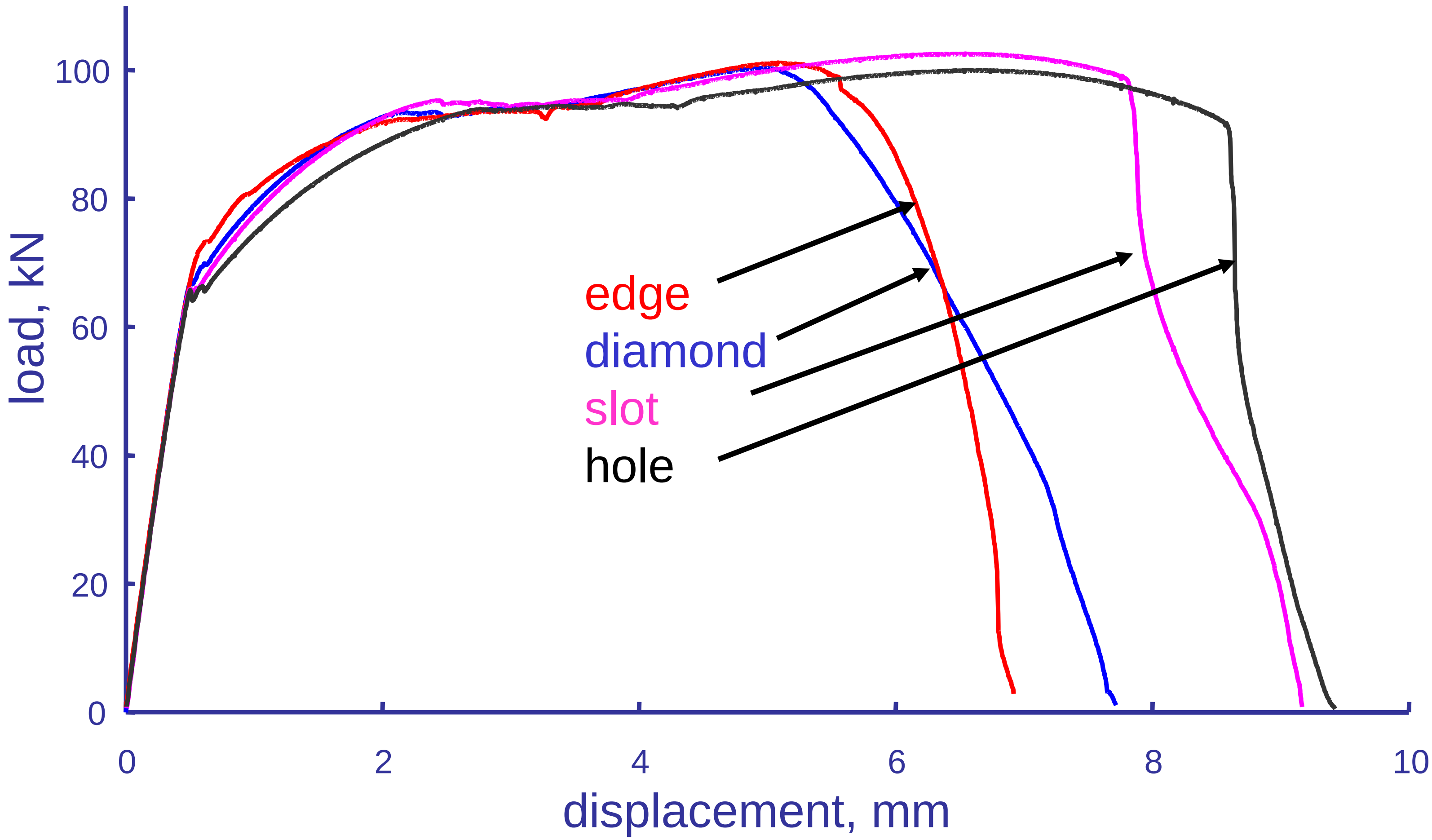


Static Strength

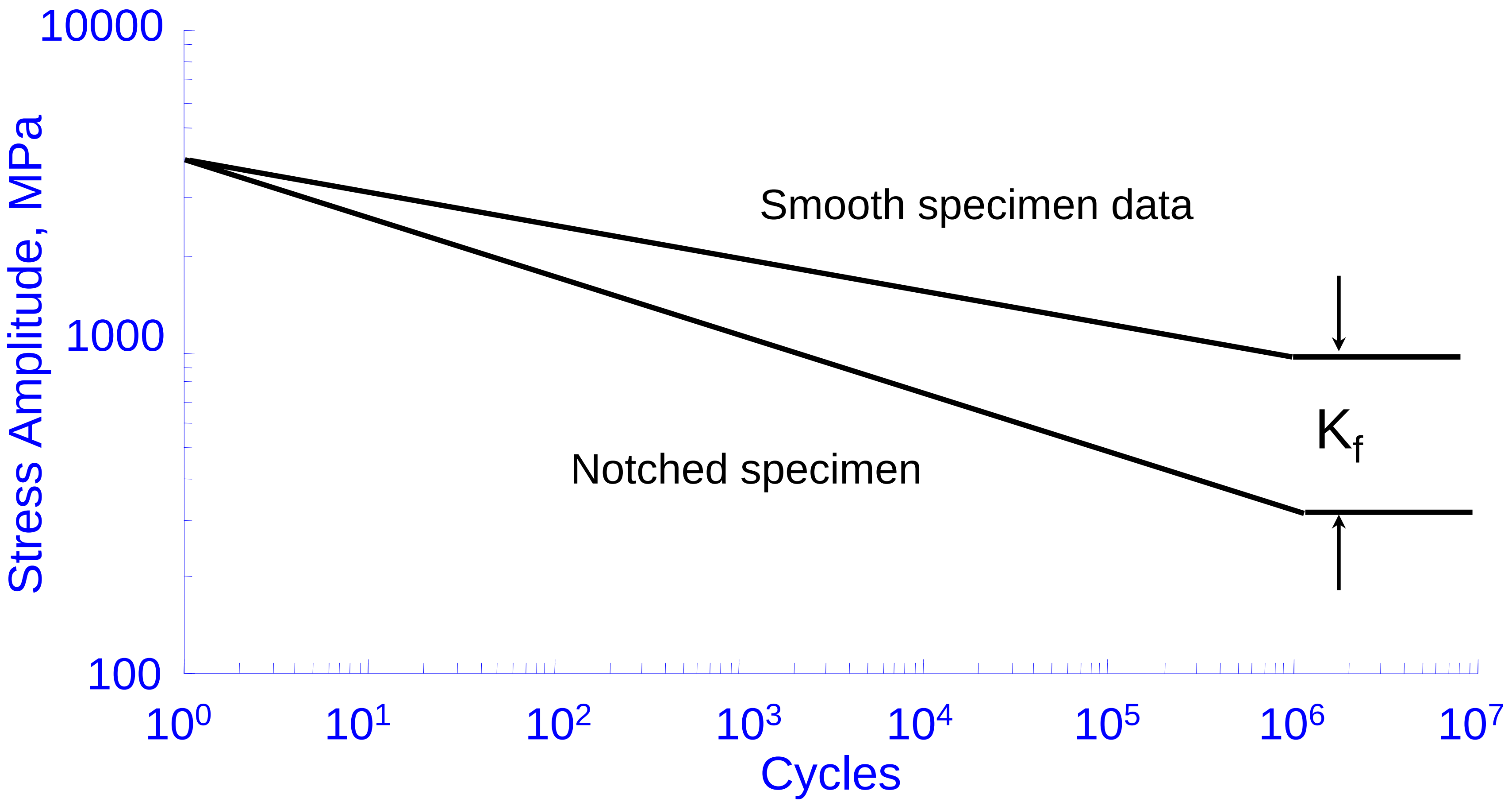


hole	slot	diamond	edge
K_t = 2.5	K_t = 5	K_t = 20	K_t = 20

1018 Steel Test Data

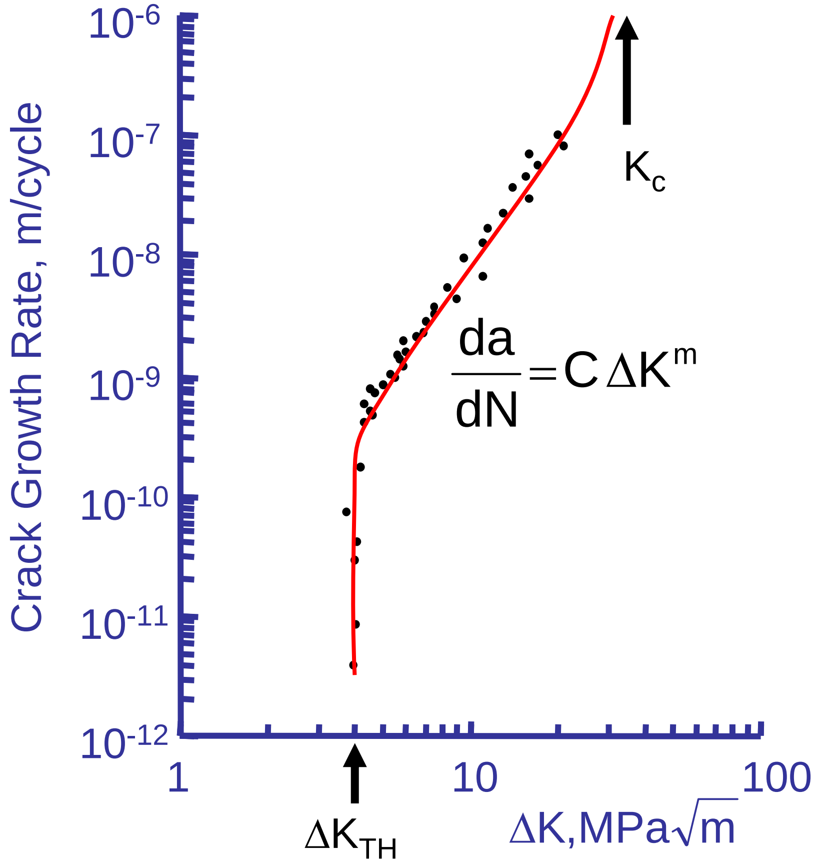


Notched SN Curve



Stress concentrations are not very important at short lives

Crack Growth Data

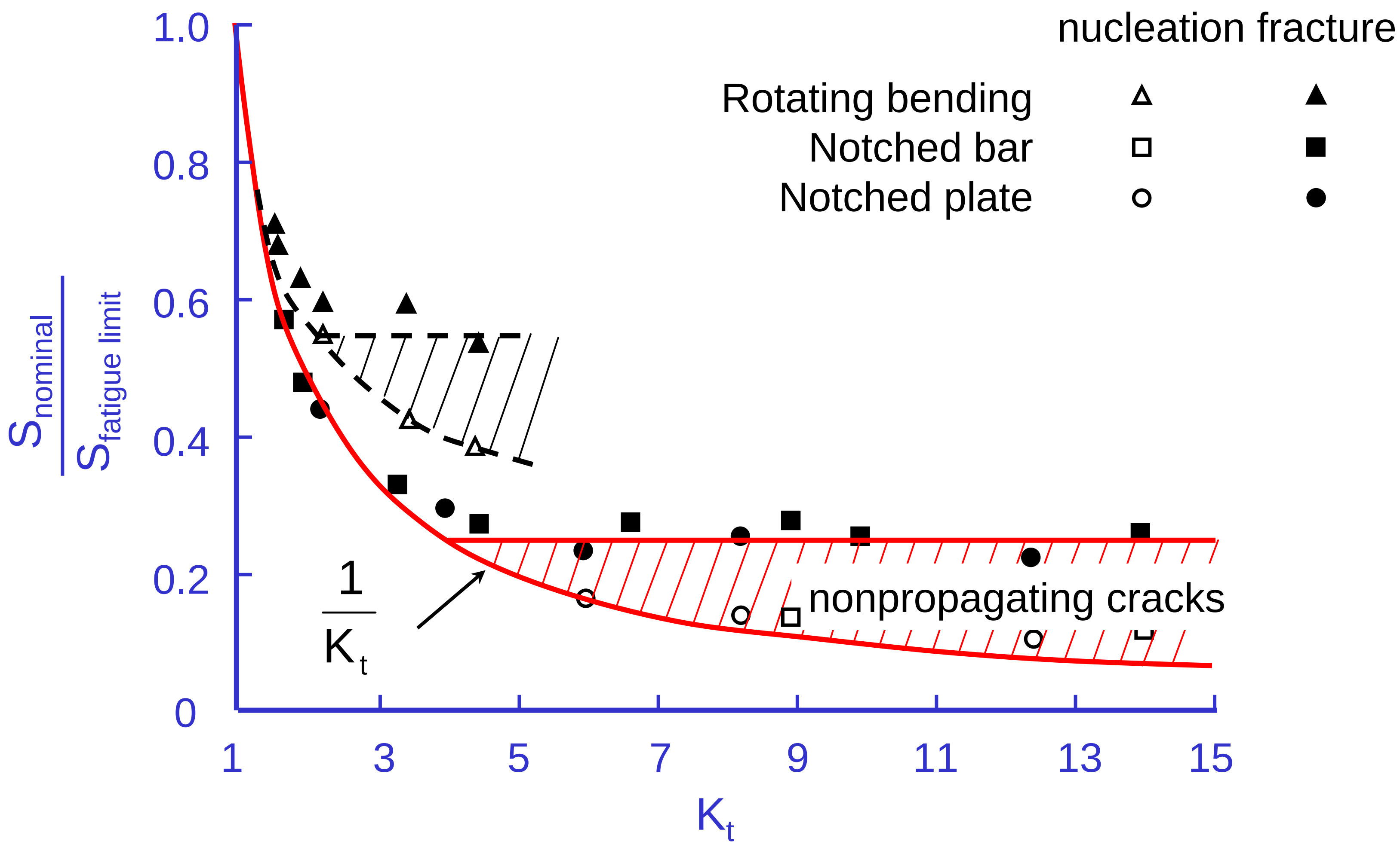


$$\frac{da}{dN} = C\,\Delta K^m$$

Nonpropagating cracks

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

Frost Data



Frost, "A Relation Between the Critical Alternating Propagation Stress and Crack Length for Mild Steel" Proceedings of the Institute for Mechanical Engineers, Vol. 173, No. 35, 1959, 811-836

Significance

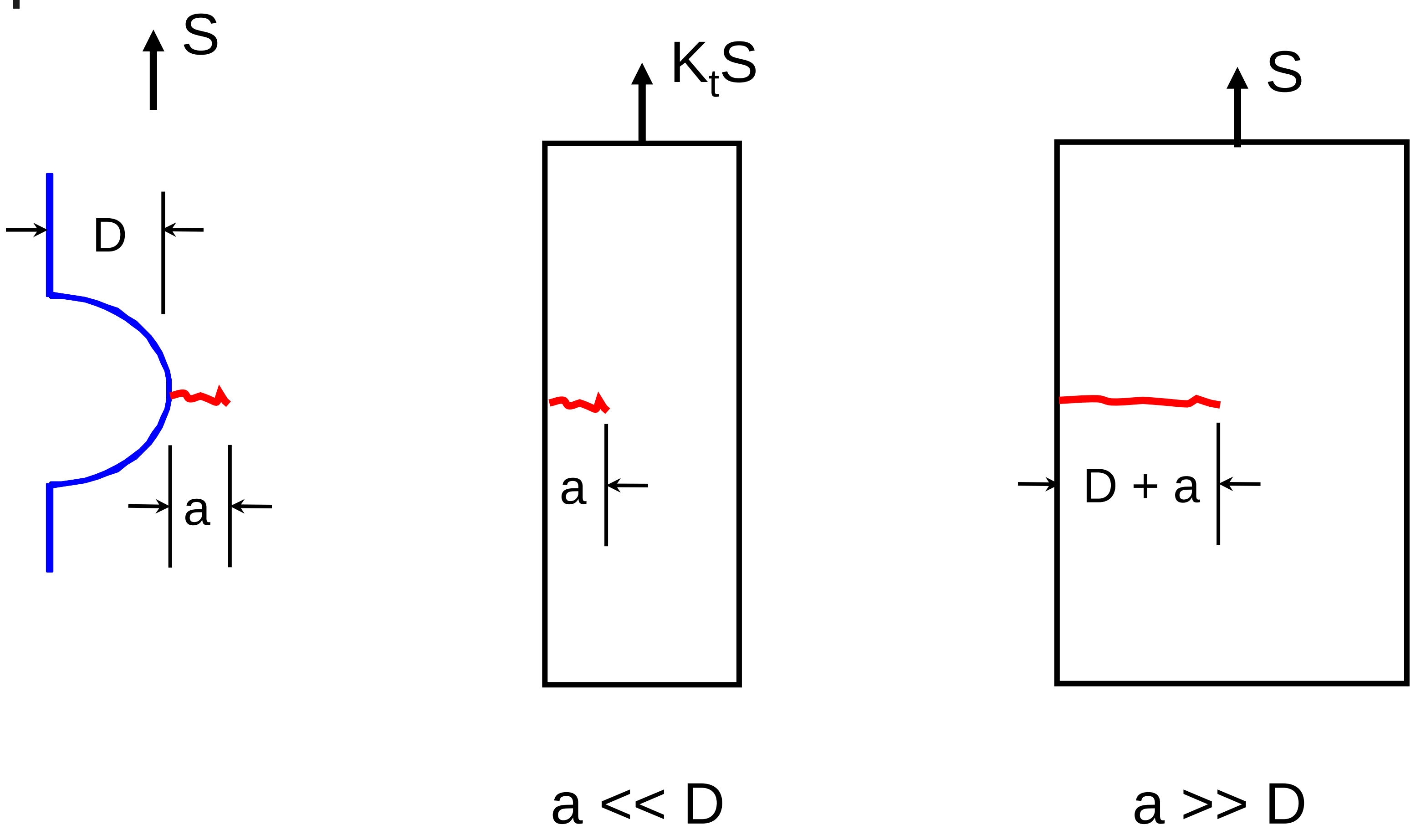
For K_t > 4, the notch acts like a crack with a depth D

$$S_{fl} = \frac{\Delta K_{th}}{\sqrt{\pi D}}$$

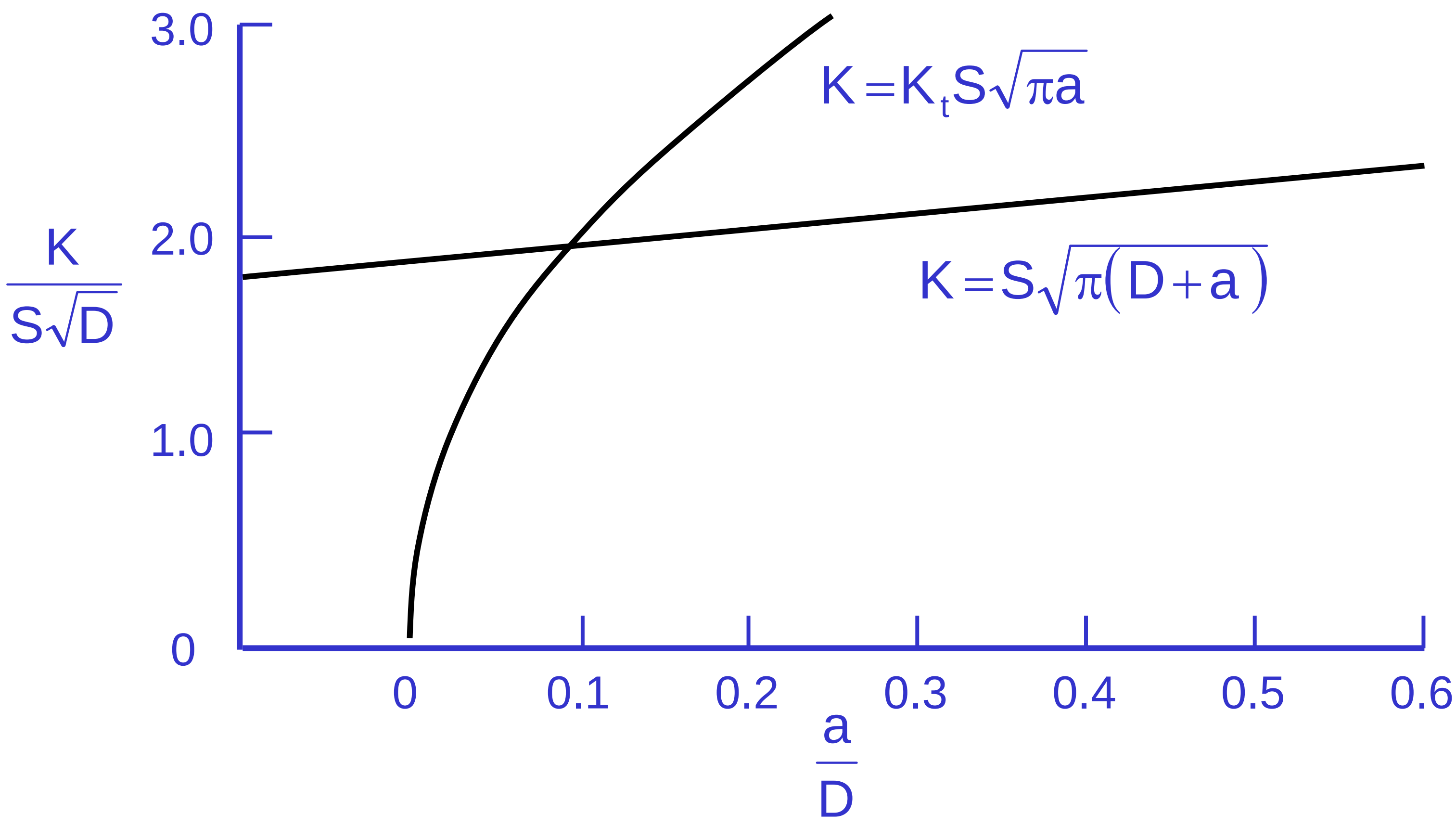
K_t does not play a role for sharp notches !

A stress concentration behaves like a crack
once a stress concentration becomes large (Kt > 4)

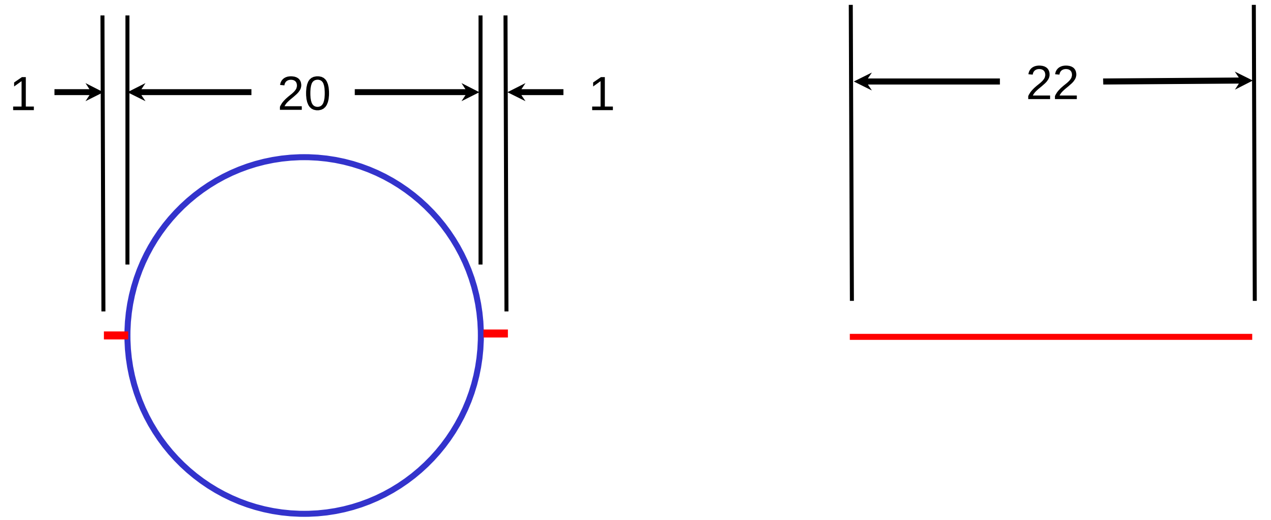
Cracks at Notches



Stress Intensity Factors

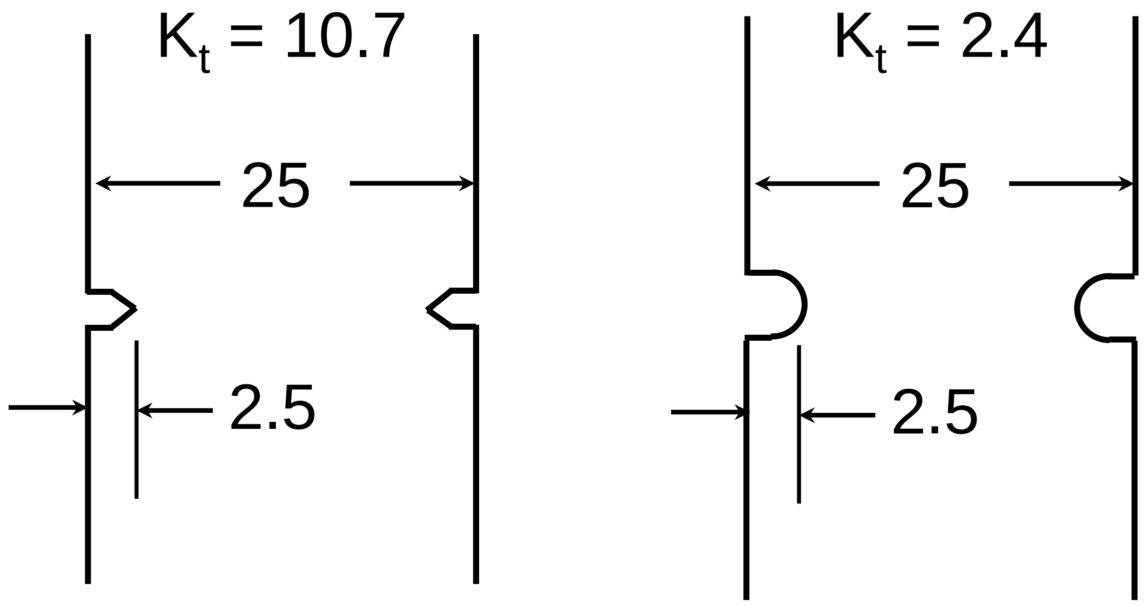


Cracks at Holes



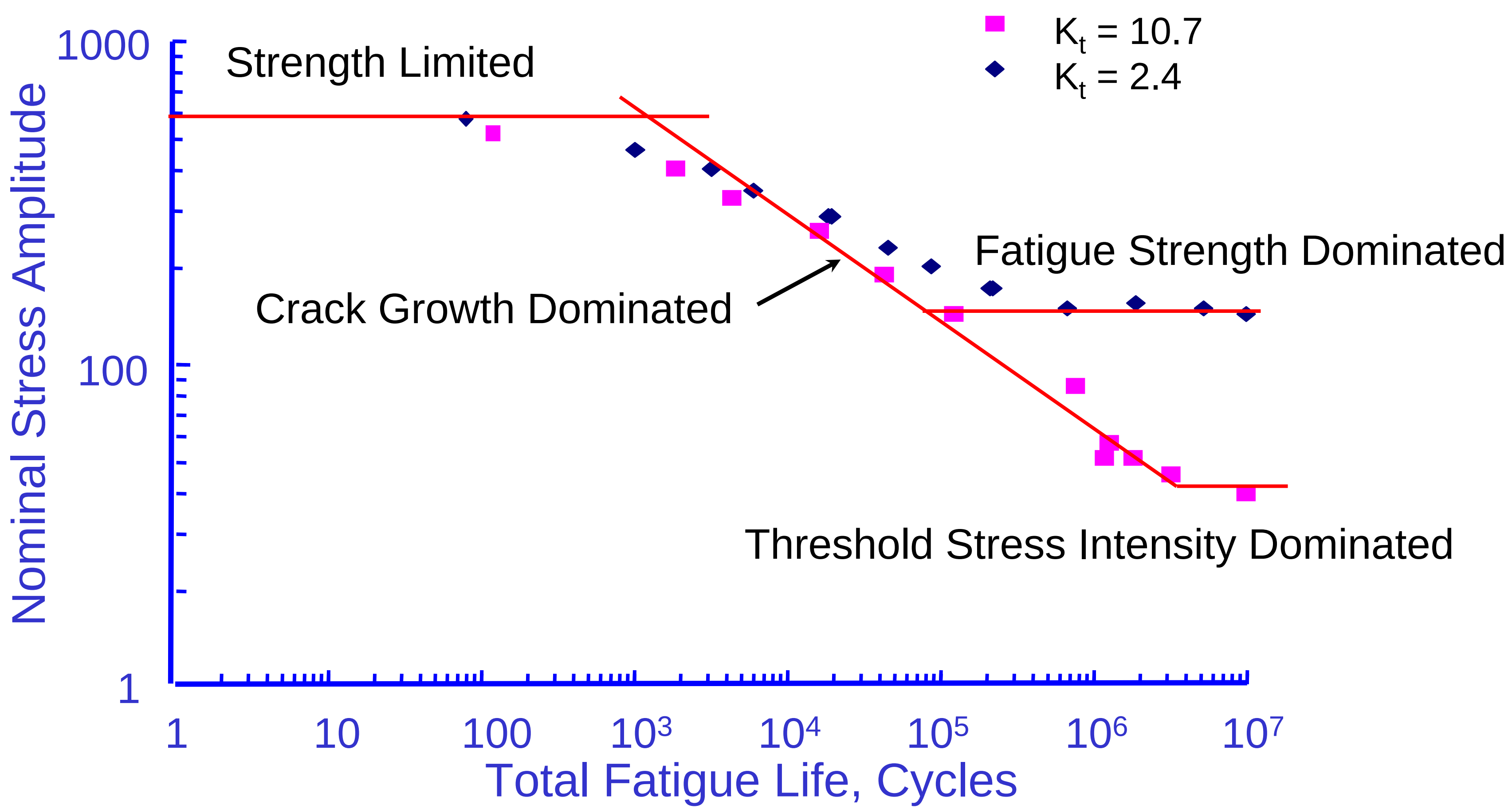
Once a crack reaches 10% of the hole radius, it behaves as if the hole was part of the crack

Specimens with Similar Geometry



Ultimate Strength 780 MPa
Yield Strength 660 MPa

Test Results



Things Worth Remembering

- Fatigue may be thought of as a failure of the average stress concept, consequently, fatigue usually begins at stress concentrators which are most frequently located on the surface
- The severity of a stress concentrator in fatigue is size dependent
- Small stress concentrators are more effective in high strength materials

Fatigue Seminar

Fatigue Made Easy

Surface Effects

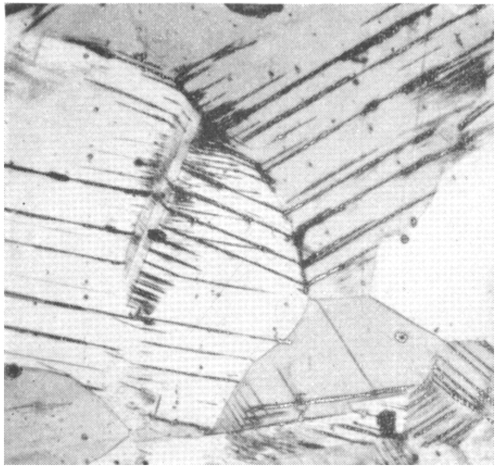
Professor Darrell F. Socie
Mechanical Science and Engineering
University of Illinois

Seminar Outline

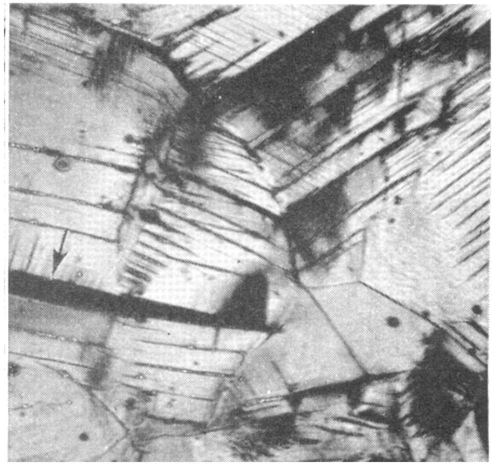
1. Historical background
2. Physics of fatigue
3. Characterization of materials
4. Similitude (why fatigue modeling works)
5. Variability
6. Mean stress
7. Stress concentrations
8. Surface effects
9. Variable amplitude loading
10. Welded structures

Modern View of the Fatigue Limit

The fatigue limit is the stress where a crack may nucleate but will not grow through the first microstructural barrier such as the grain size, pearlite colony size, prior austenite grain size, eutectic cell size or precipitate spacing.

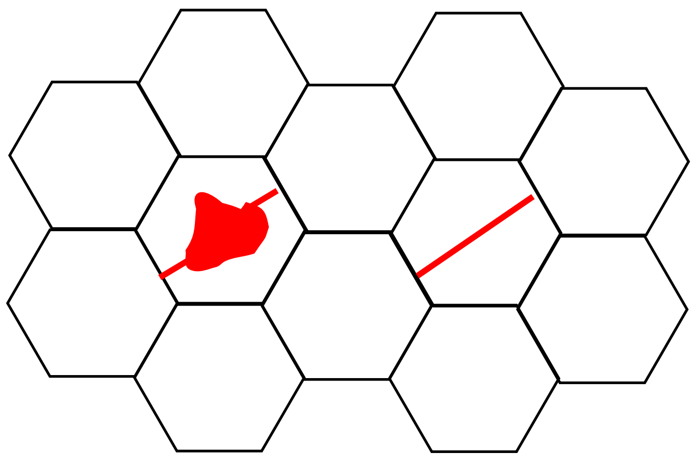


Slip Bands

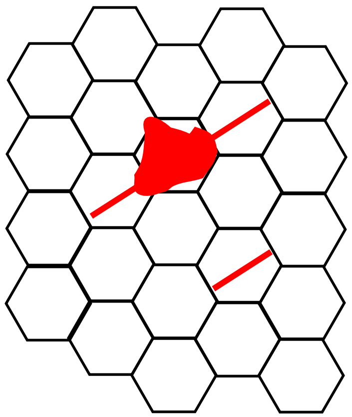


Crack

Intrinsic Flaws



Little effect of surface pit because it is smaller than the grain size



Large effect of defect because it is larger than the grain size

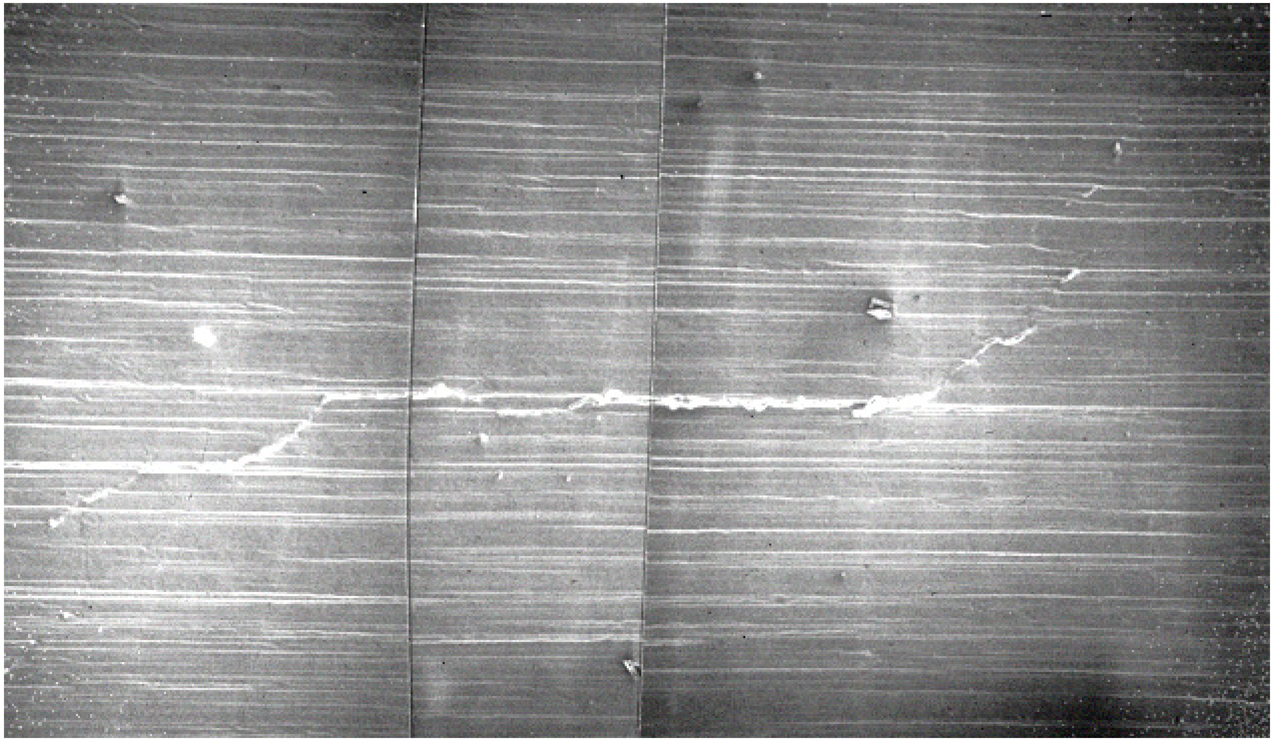
Surface Finish Influence

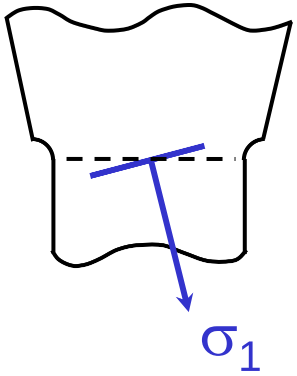
Method	Physics	Size	Influence of Surface Finish
Stress-Life	Crack Nucleation	0.01 mm	Strong
Strain-Life	Microcrack Growth	0.1 - 1 mm	Moderate
Crack Growth	Macrocrack Growth	> 1mm	None

Sources of Surface Effects

- Machining
  - Cutting
  - Grinding
- Corrosion
  - General
  - Pitting
- Processing
  - Cutting/Shearing
  - Casting
  - Forging
  - Plating
- Foreign Object Damage
  - Nicks
  - Scratches

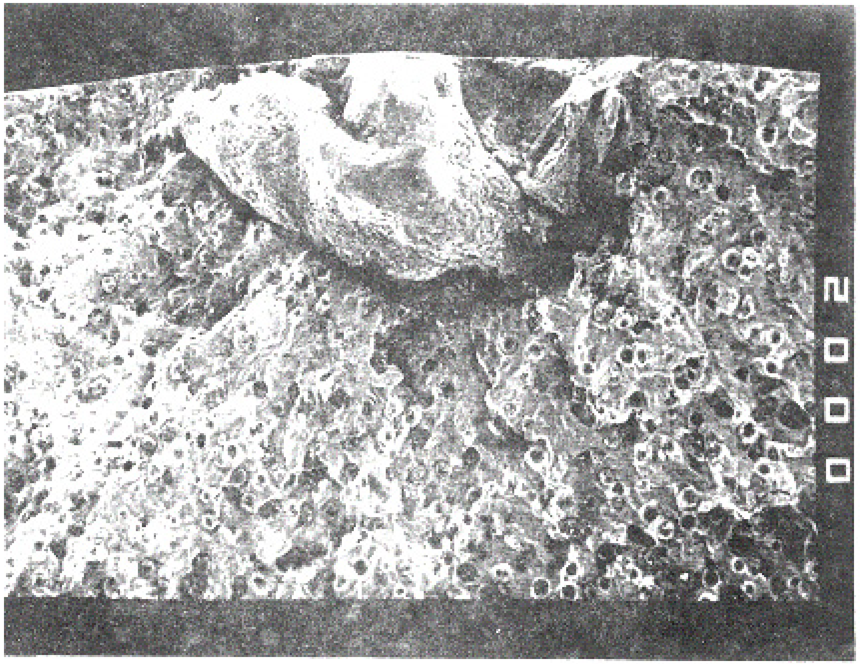
Machining





Cracks start in machining marks not in the direction of the maximum principal stress

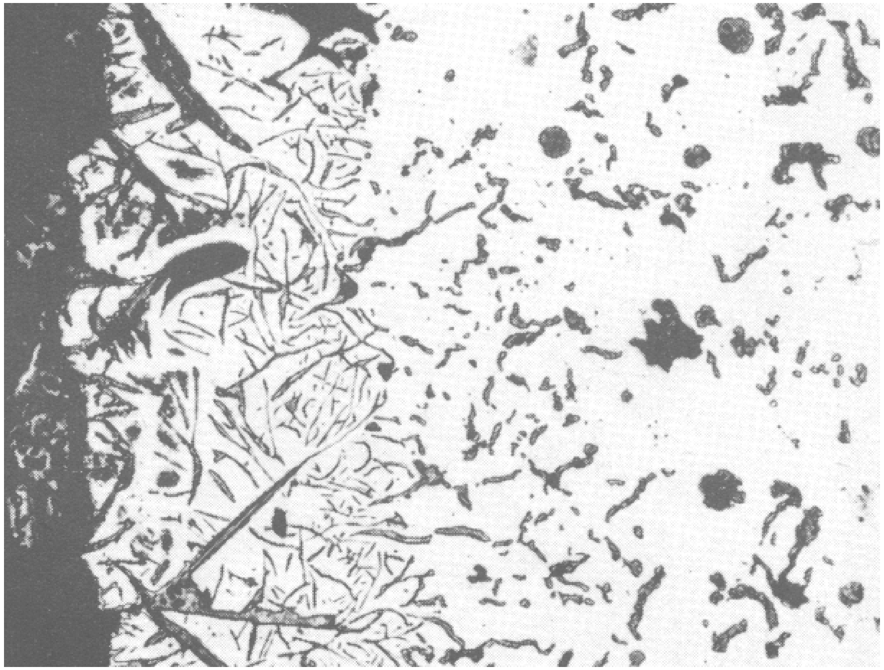
Casting



100 μm

Surface flaw in gray cast iron

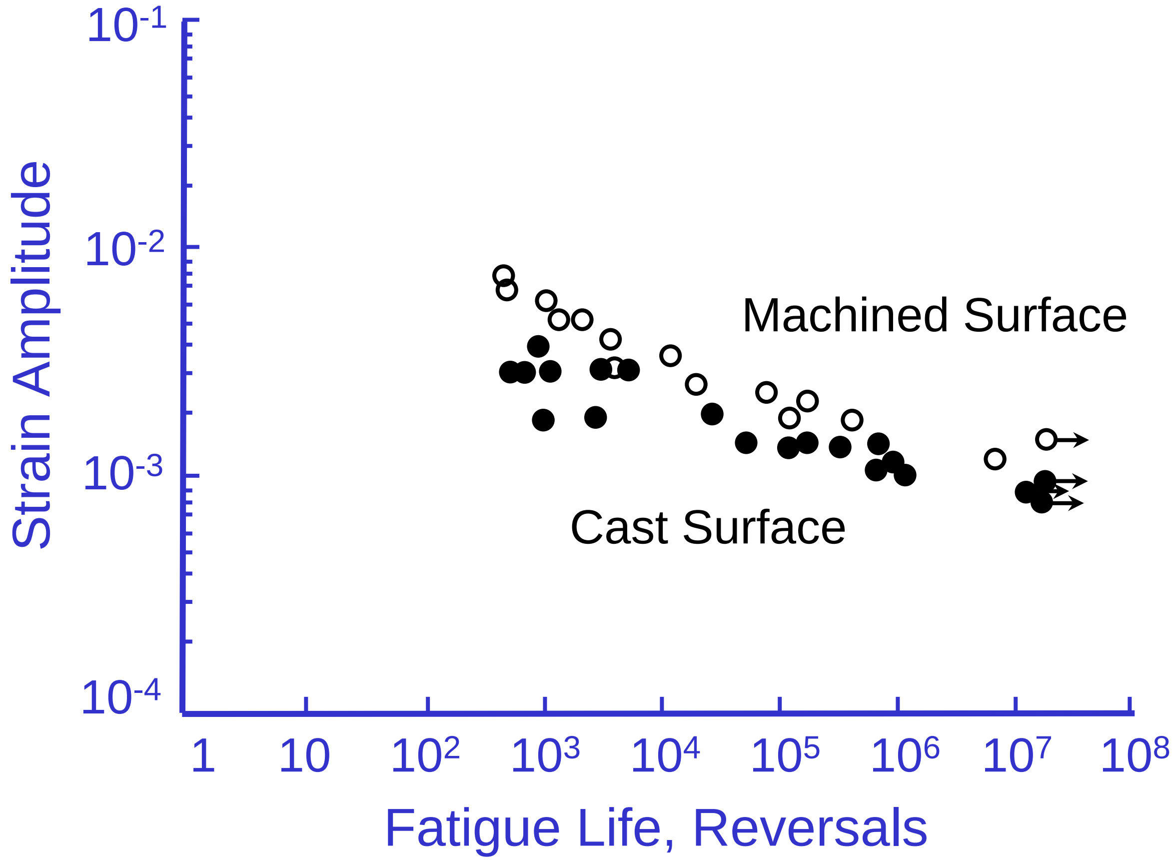
Nodular Iron Surface



Flake graphite formed on the surface of a nodular iron casting

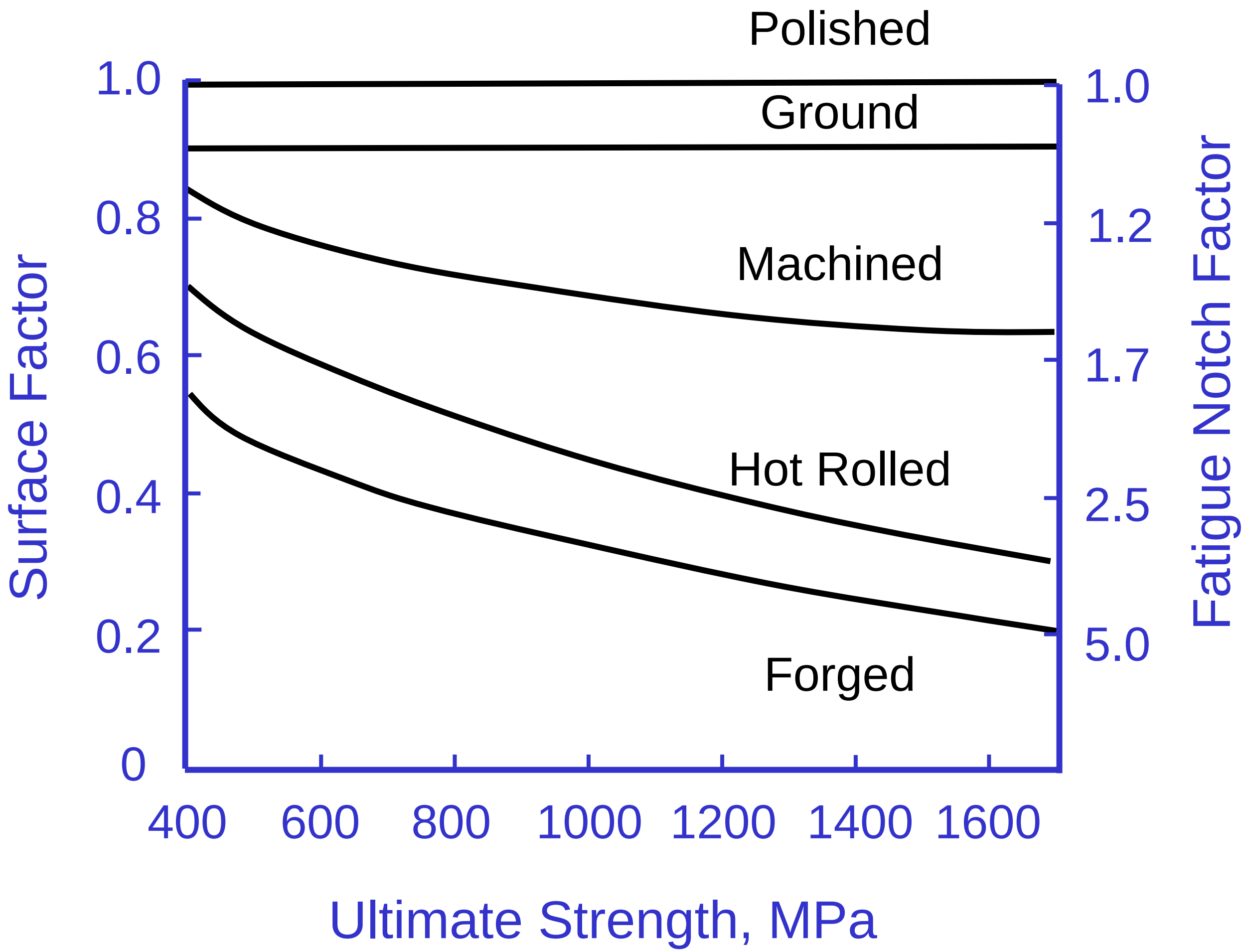
Starkey and Irving, “A Comparison of the Fatigue Strength of Machined and As-cast Surfaces of SG Iron” International Journal of Fatigue, July, 1982, 129-136

Test Data

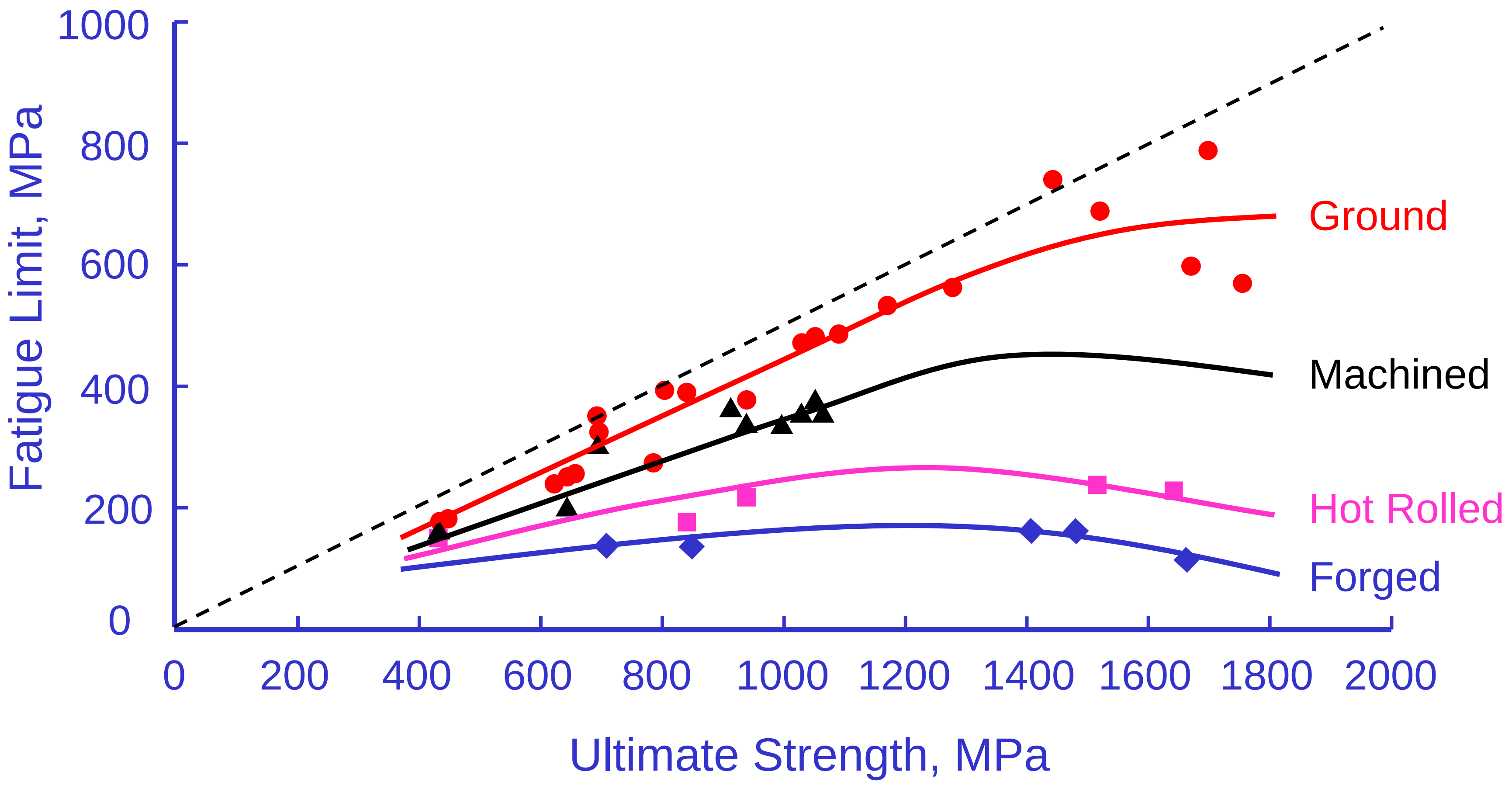


Strain Amplitude
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Machined Surface
Cast Surface
1
10
10^2
10^3
10^4
10^5
10^6
10^7
10^8
Fatigue Life, Reversals

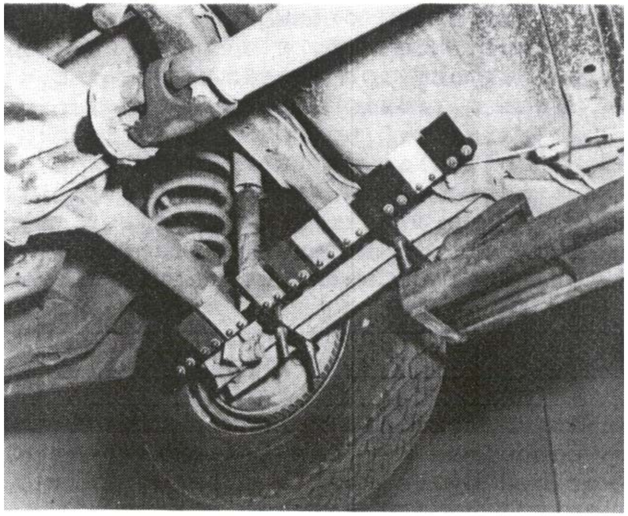
Surface Reduction Factors



Noll and Lipson 1945



Hiam and Pietrowski 1978



Driven for 1 or 2 years
in Southern Ontario
before making specimens
to evaluate corrosion effects

Strain controlled fatigue testing

Hiam and Pietrowski, “The Influence of Forming and Corrosion on the Fatigue Behavior of Automotive Steels”, SAE Paper 780040, 1978

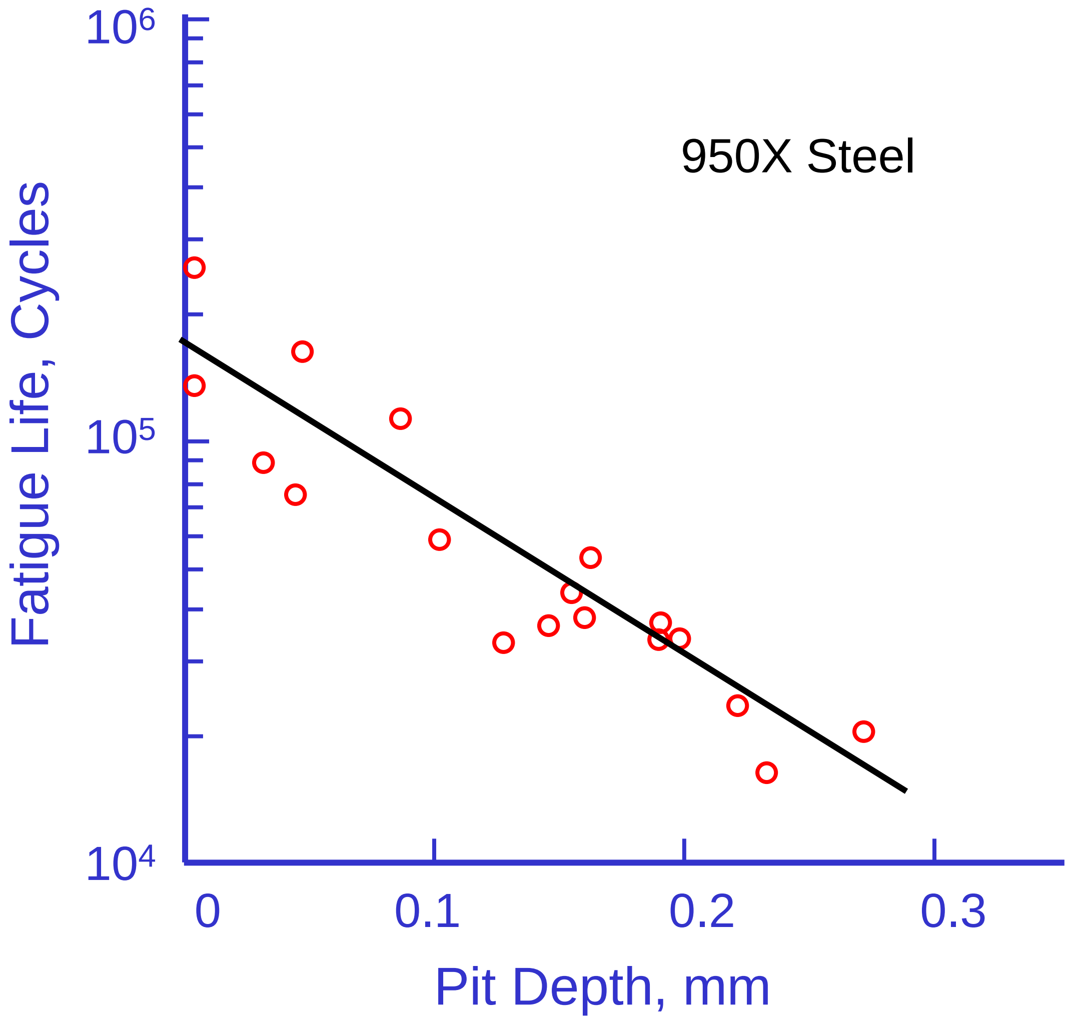
K_f for pitting

	Hot Rolled Surface	Corroded Surface
950X	1.12	1.49
0.06% C HSLA	1.18	1.65
0.18% C HSLA		1.90

Surface finish factor predicts K_f = 1.6 for a Hot Rolled Surface

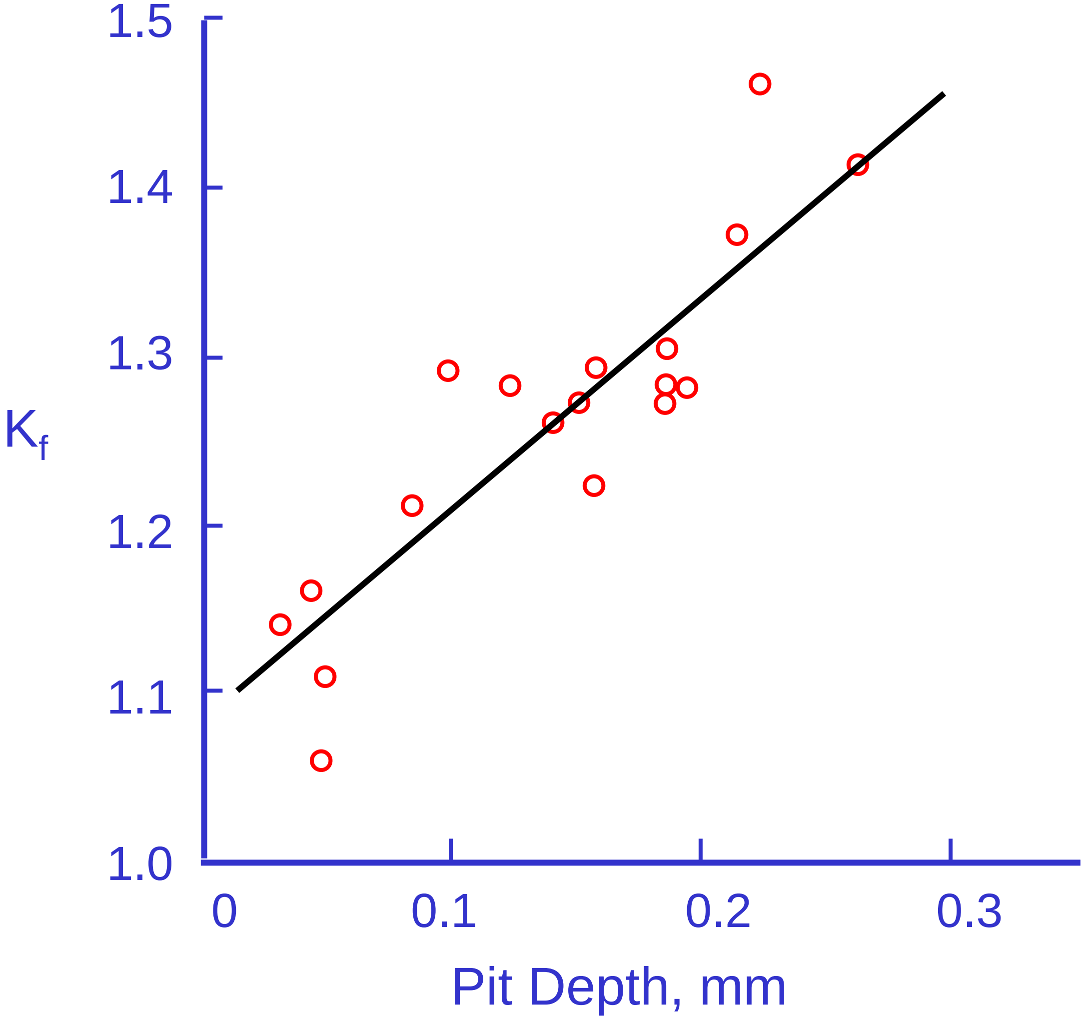
from Hiam and Pietrowski

Pit Depth Effects on Life

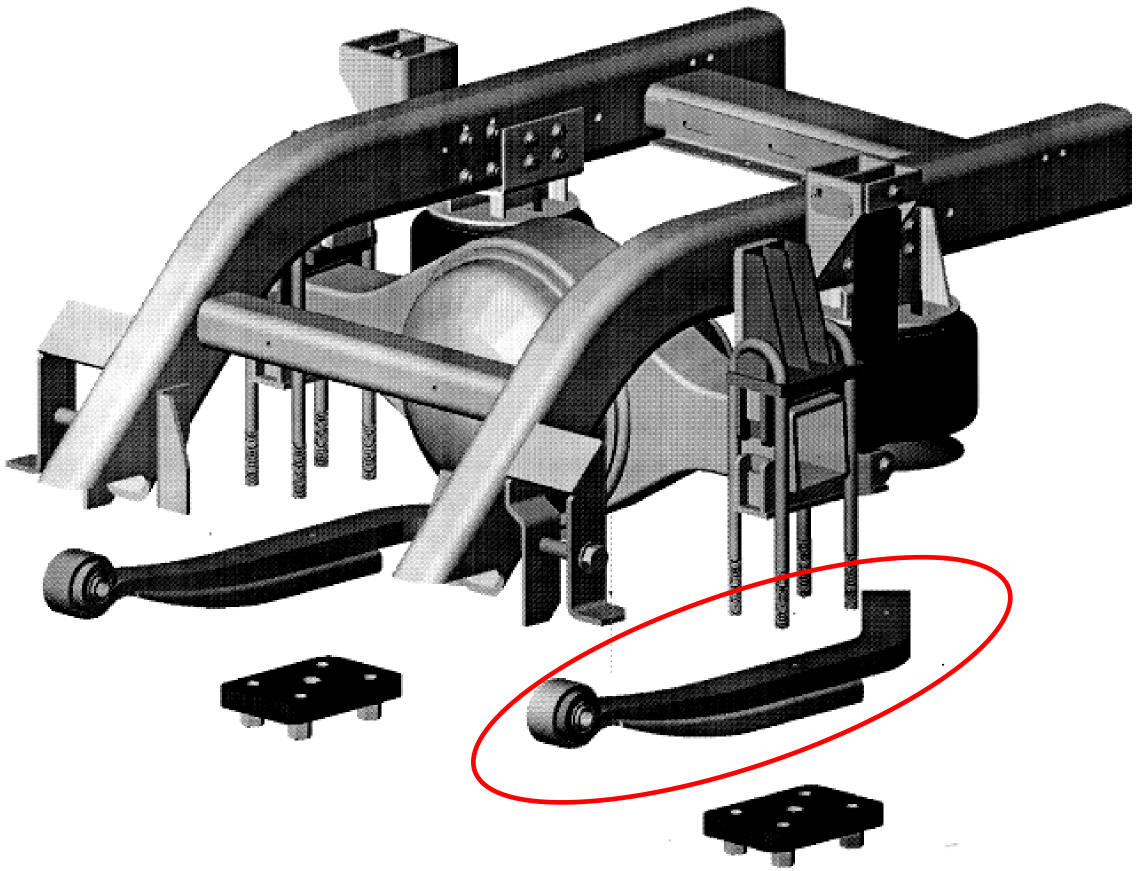


from Hiam and Pietrowski

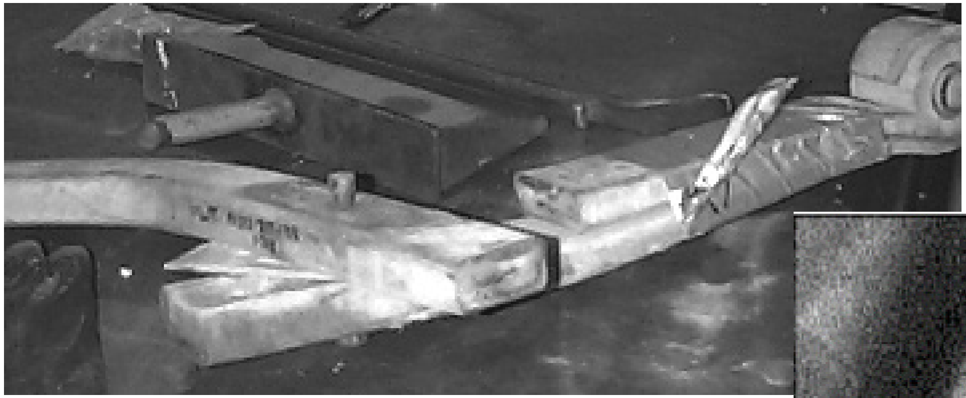
Fatigue Notch Factor for Pits



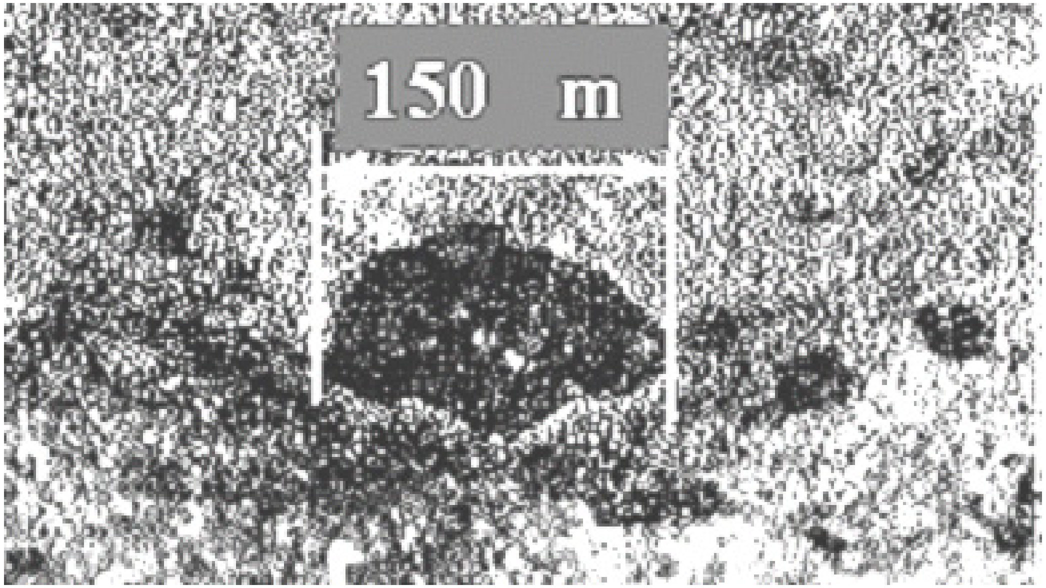
Suspension



Spring Failures

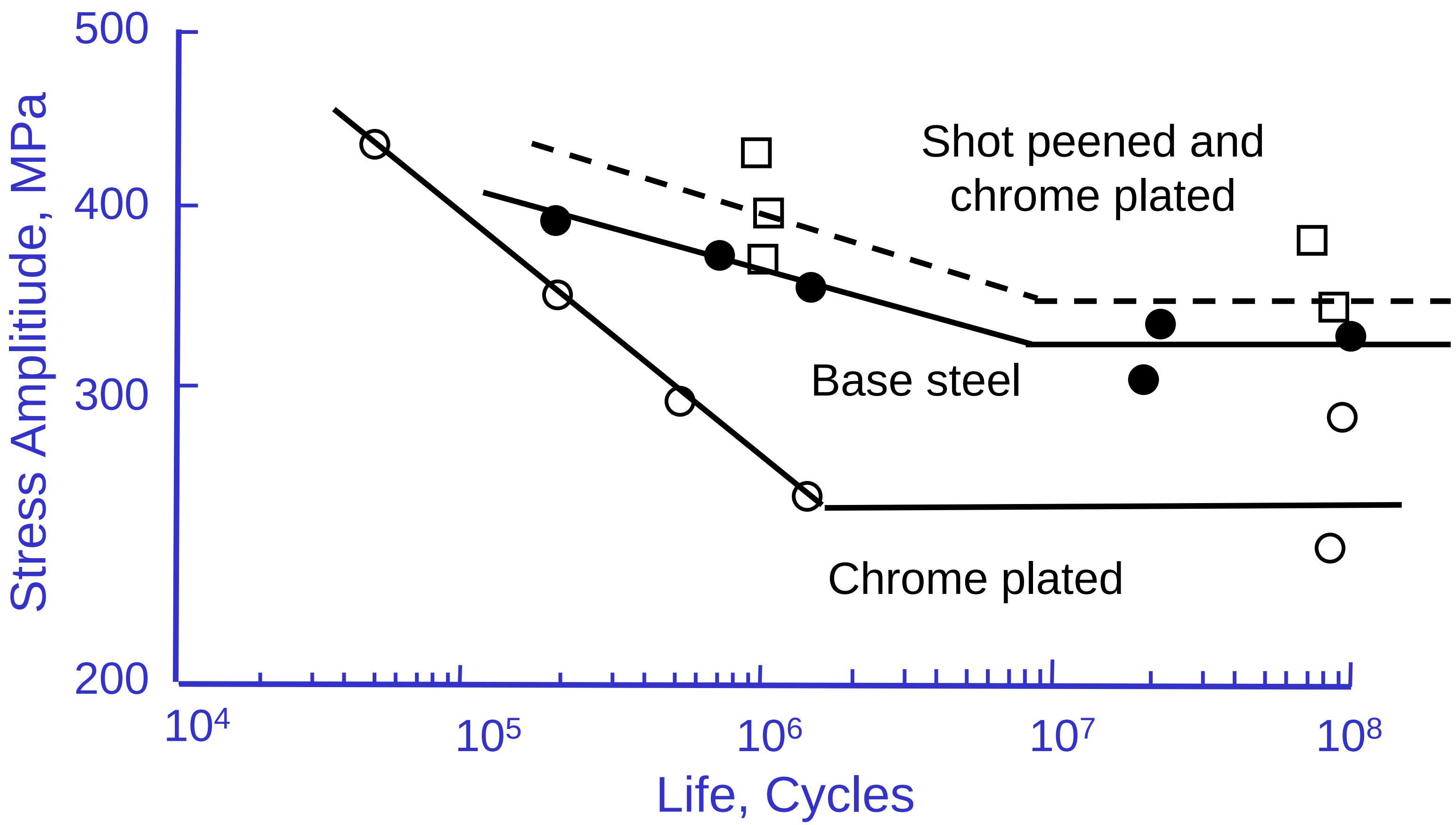


Microscopic Examination



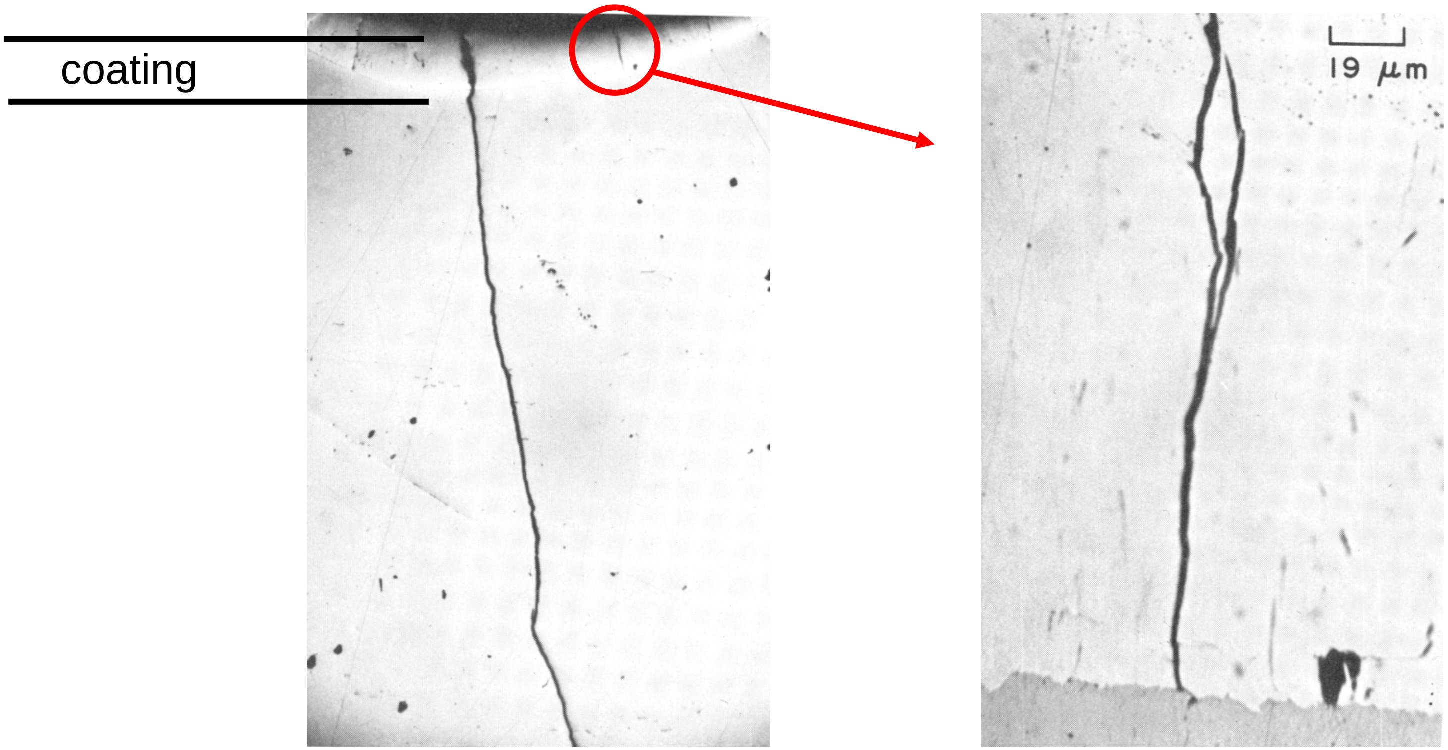
Corrosion Pits

Chrome Plating



Almen, “Fatigue Loss and Gain by Electroplating” , Product Engineering, Vol. 22, No. 5, 1951, 109-116

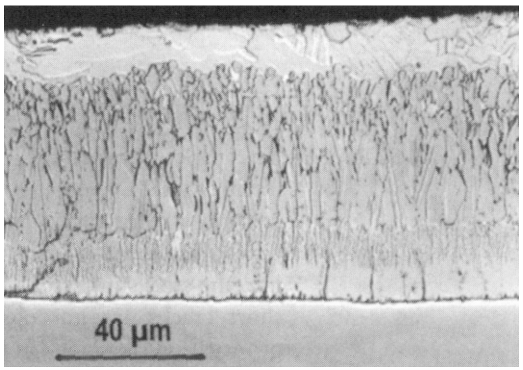
Hard Chrome Plating

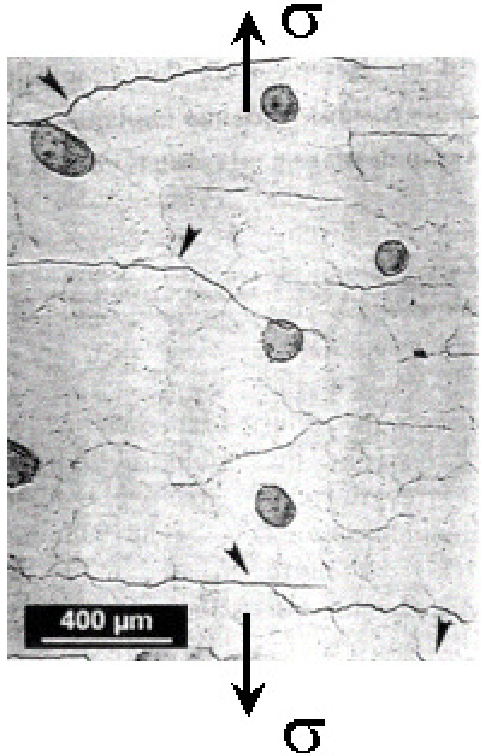


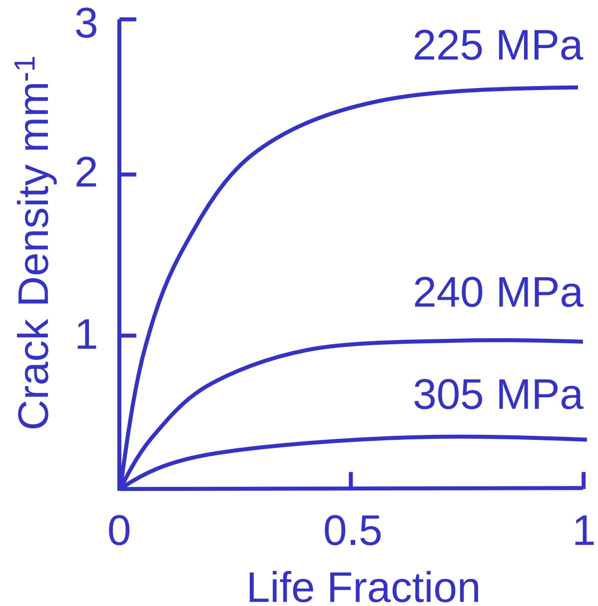
In addition to cracks, coatings frequently have high tensile residual stresses

Metals Handbook, Volume 9, Fractography and Atlas of Fractographs

Galvanized Steel

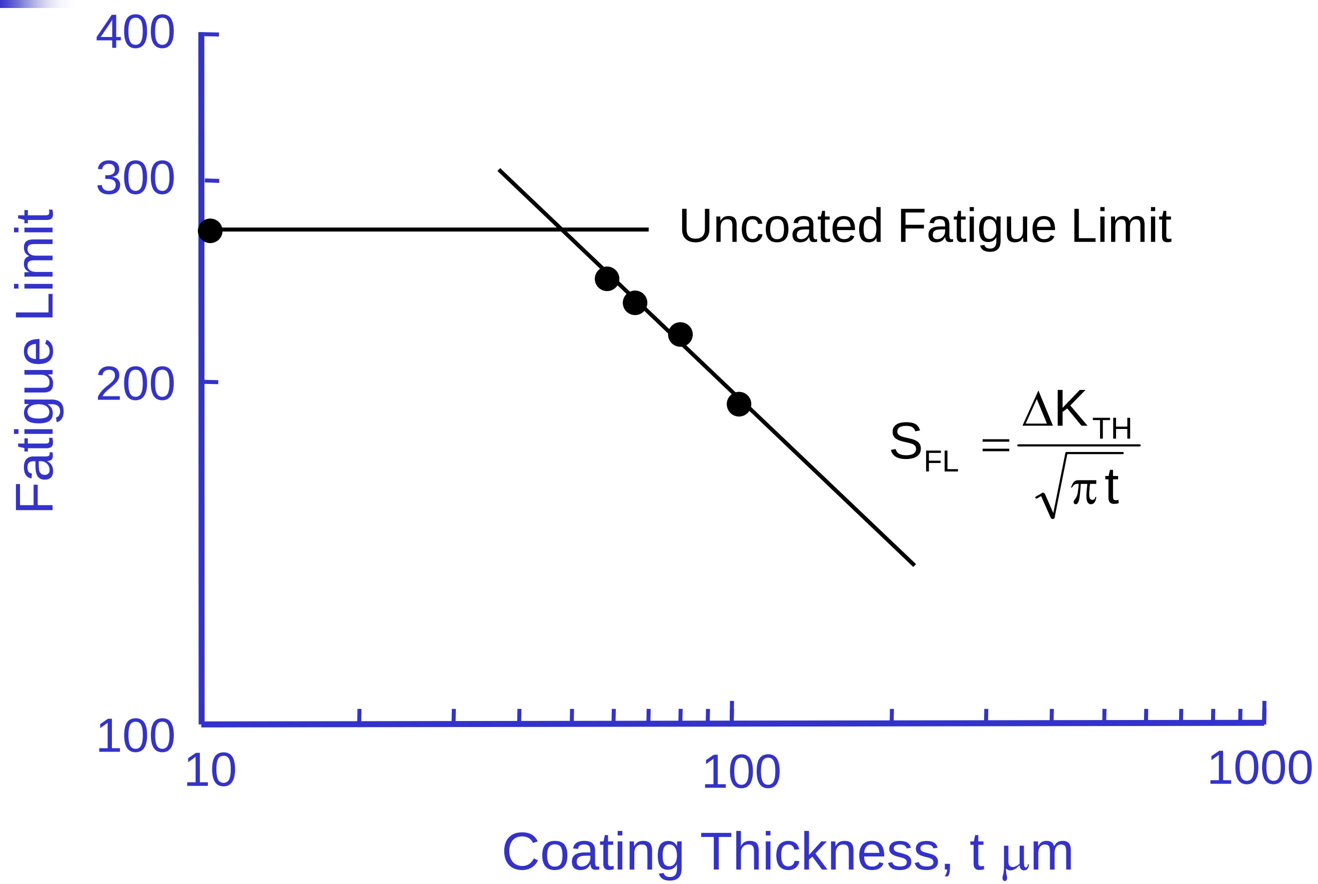






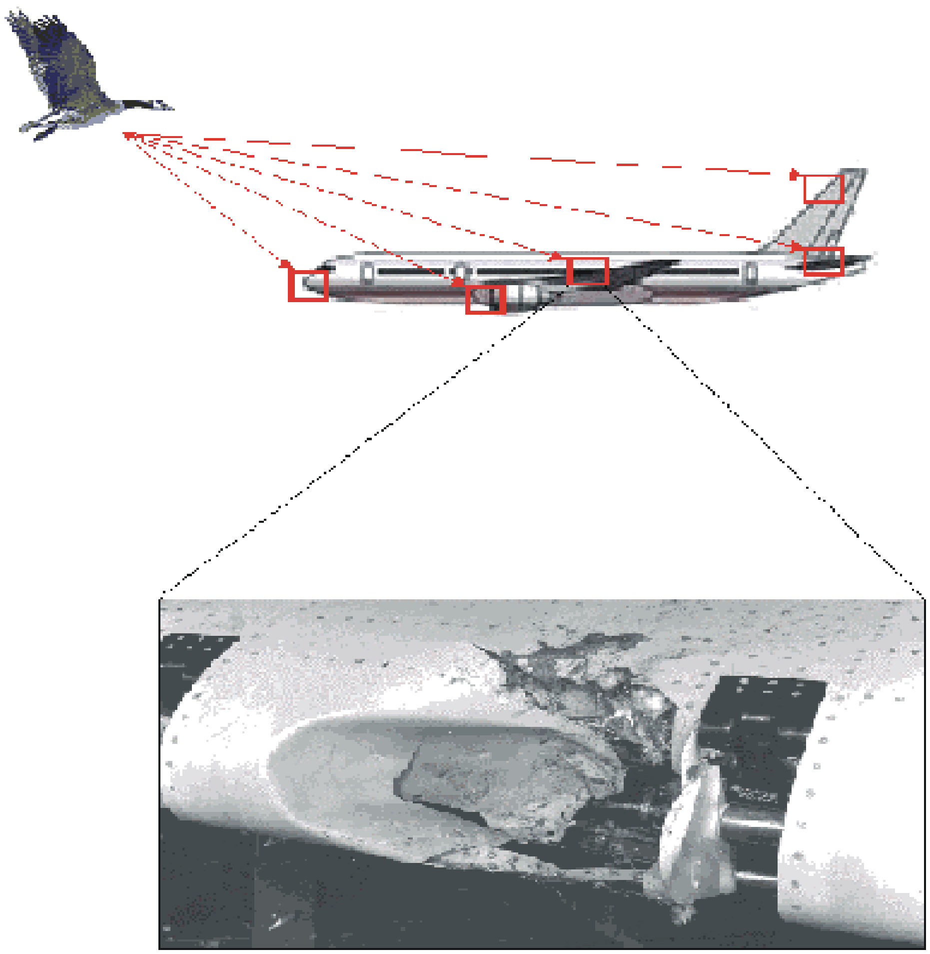
Vogt, Boussac, Foct, "Prediction of Fatigue Resistance of a Hot-dip Galvanized Steel"
Fatigue and Fracture of Engineering Materials and Structures, Vol. 23, No. 1, 2001,33-40

Fatigue Limit for Galvanized Steel



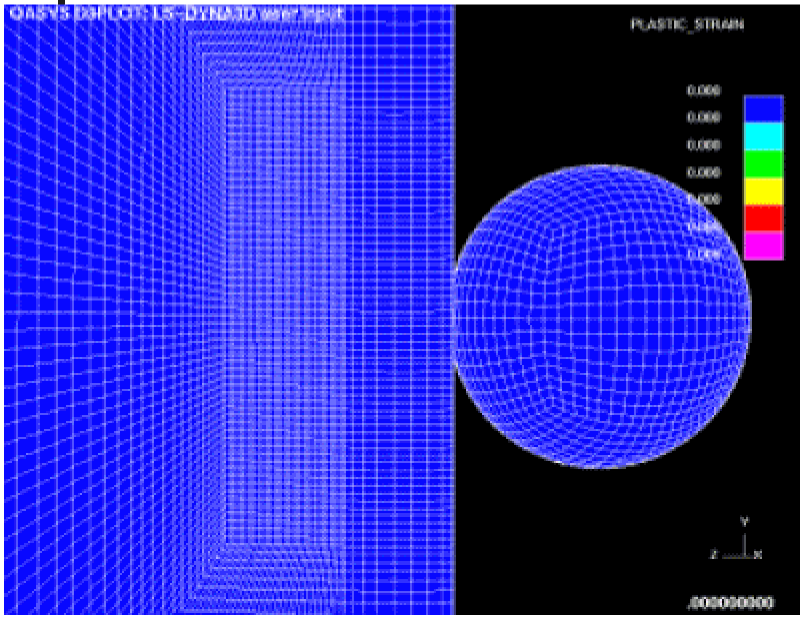
Coatings can be modeled with a crack equal to the coating thickness

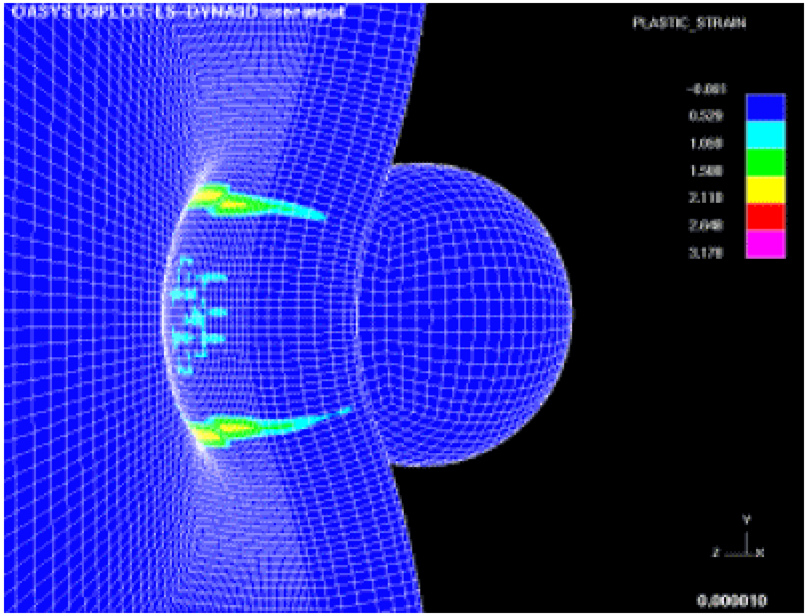
Foreign Object Damage



http://www.eng.ox.ac.uk/~ftgwww/frontpage/fod2.html

Foreign Object Damage





http://www.eng.ox.ac.uk/~ftgwww/frontpage/fod2.html

Upper Control Arm

Serial Number

Things Worth Remembering

- Fatigue crack nucleation is a surface phenomena and everything about the surface affects the fatigue life
- Most of the design rules are conservative having been developed for materials of the 1950's

Fatigue Seminar

Fatigue Made Easy

Variable Amplitude Loading

Professor Darrell F. Socie
Mechanical Science and Engineering
University of Illinois

Seminar Outline

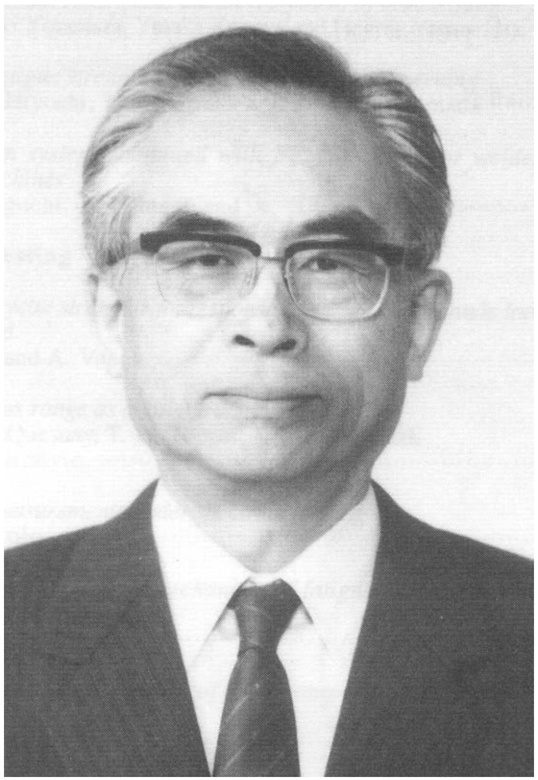
1. Historical background
2. Physics of fatigue
3. Characterization of materials
4. Similitude (why fatigue modeling works)
5. Variability
6. Mean stress
7. Stress concentrations
8. Surface effects
9. Variable amplitude loading
10. Welded structures

Variable Amplitude Loading

How to you identify cycles ?

How do you assess fatigue damage for a cycle ?

Rainflow Cycle Counting



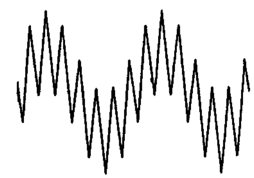


図6. 重畳波尖頭値の系列値

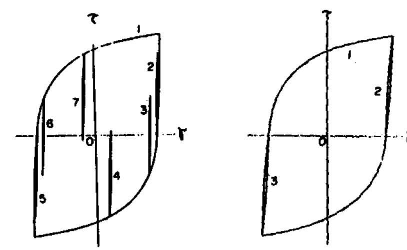


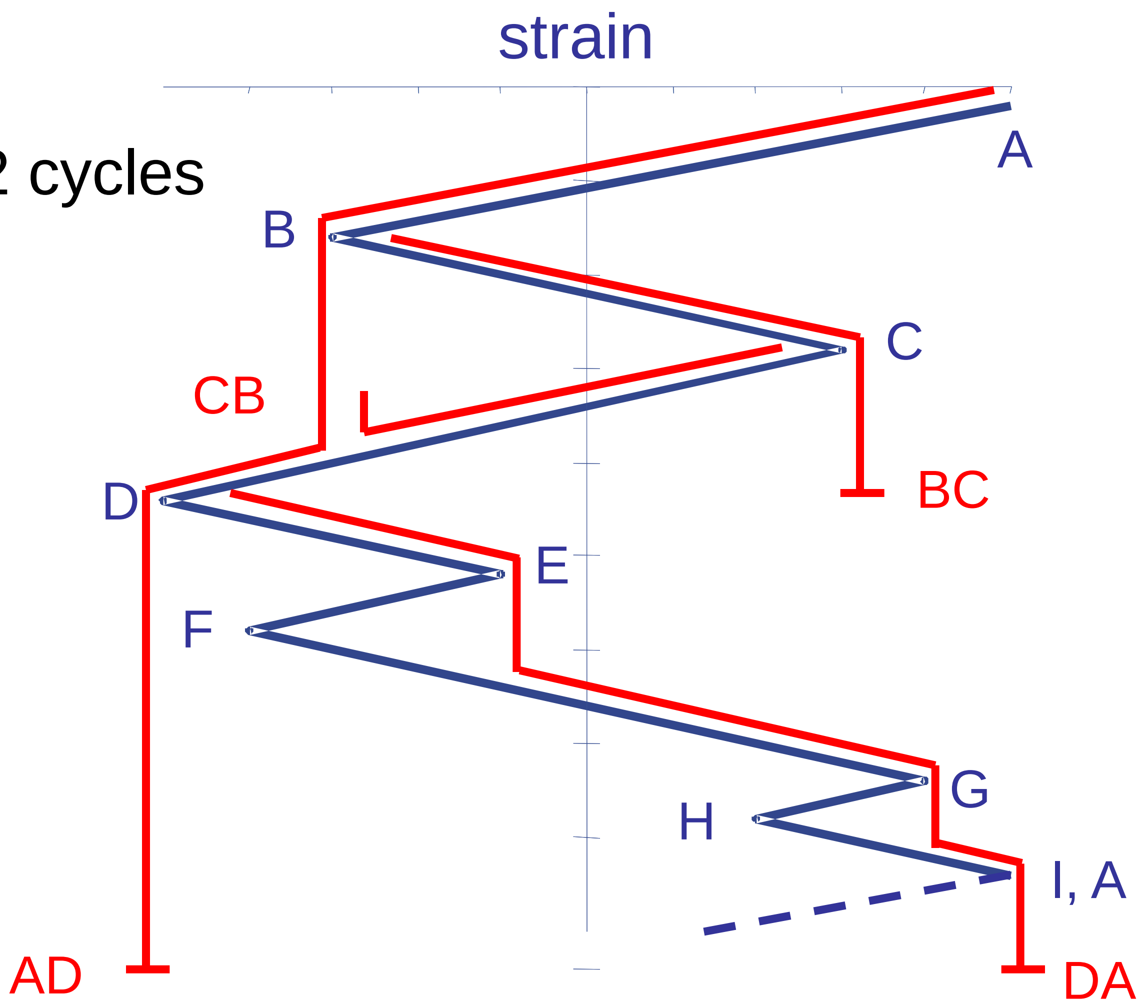
図7(a) 重畳波履歴曲線　図7(b) 双子波履歴曲線

What could be more basic than learning to count correctly?

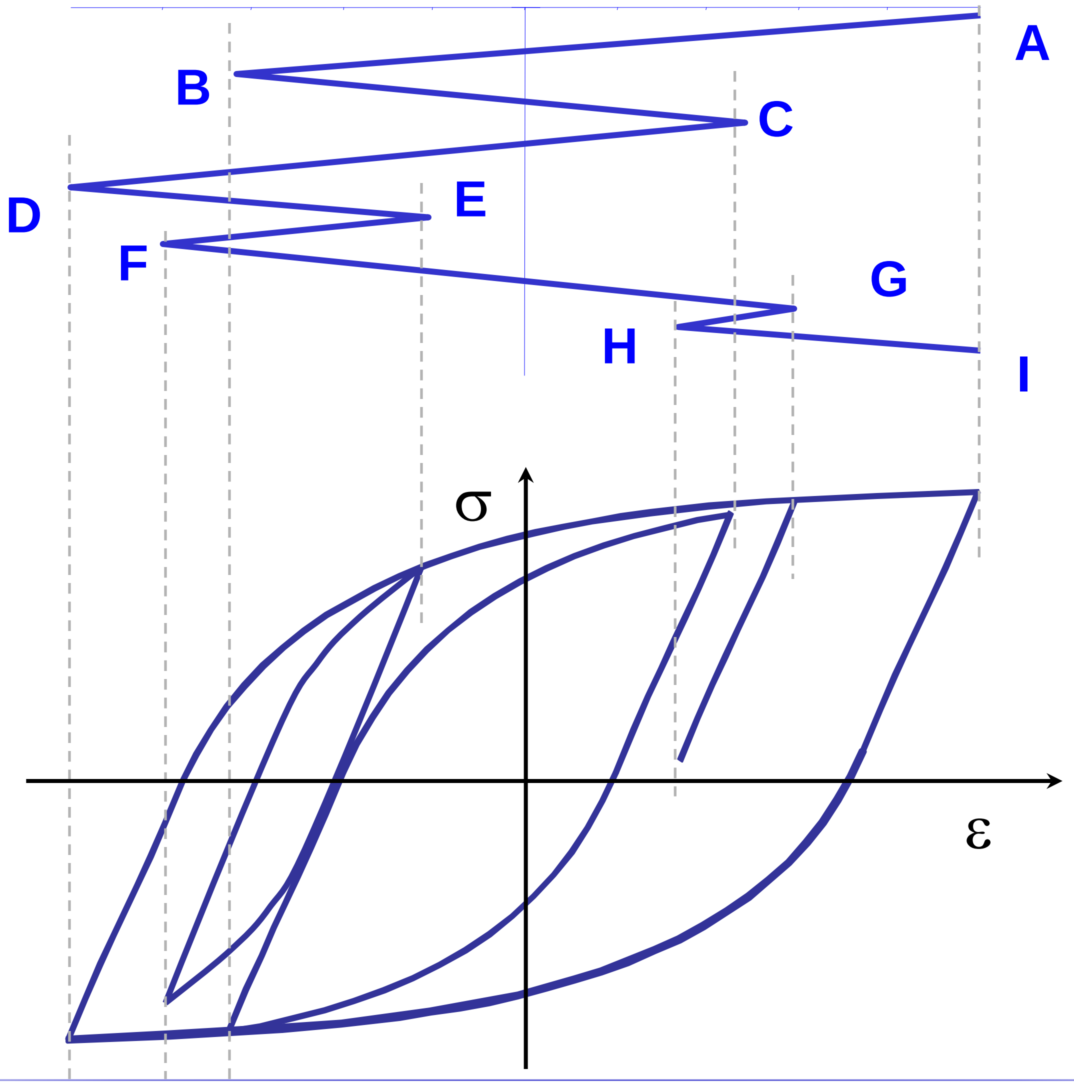
Matsuishi and Endo (1968) Fatigue of Metals Subjected to Varying Stress – Fatigue Lives Under Random Loading, Proceedings of the Kyushu District Meeting, JSME, 37-40

Rainflow

Counts 1/2 cycles

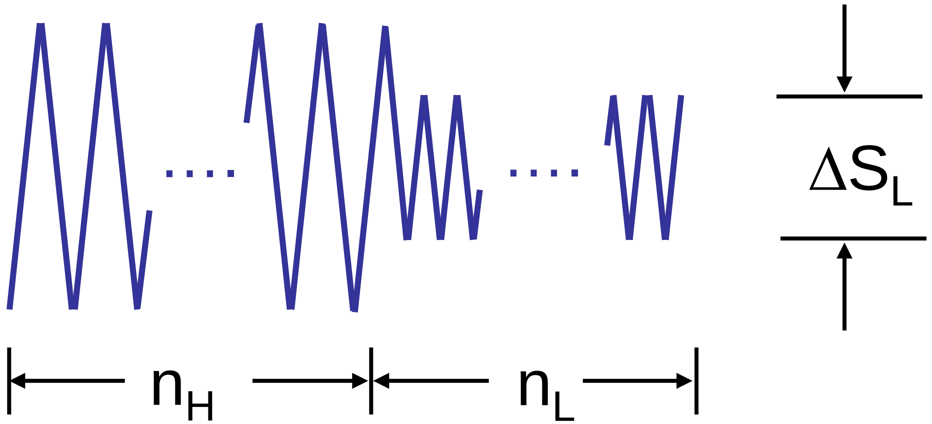


Rainflow and Hysteresis

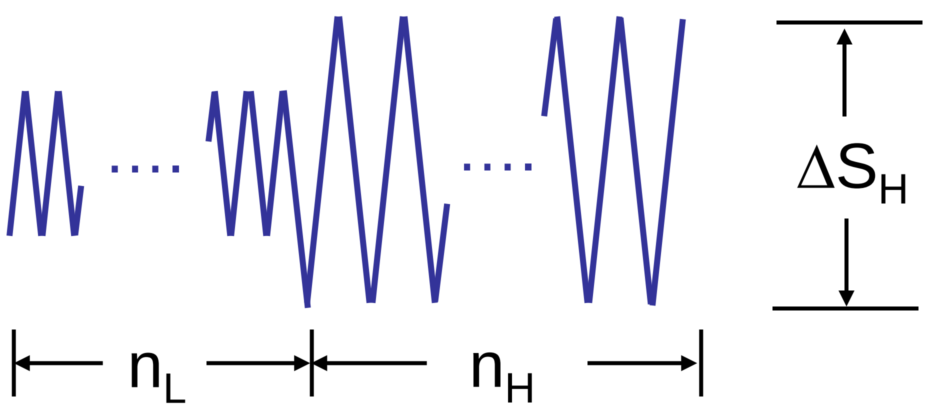


Cumulative Damage

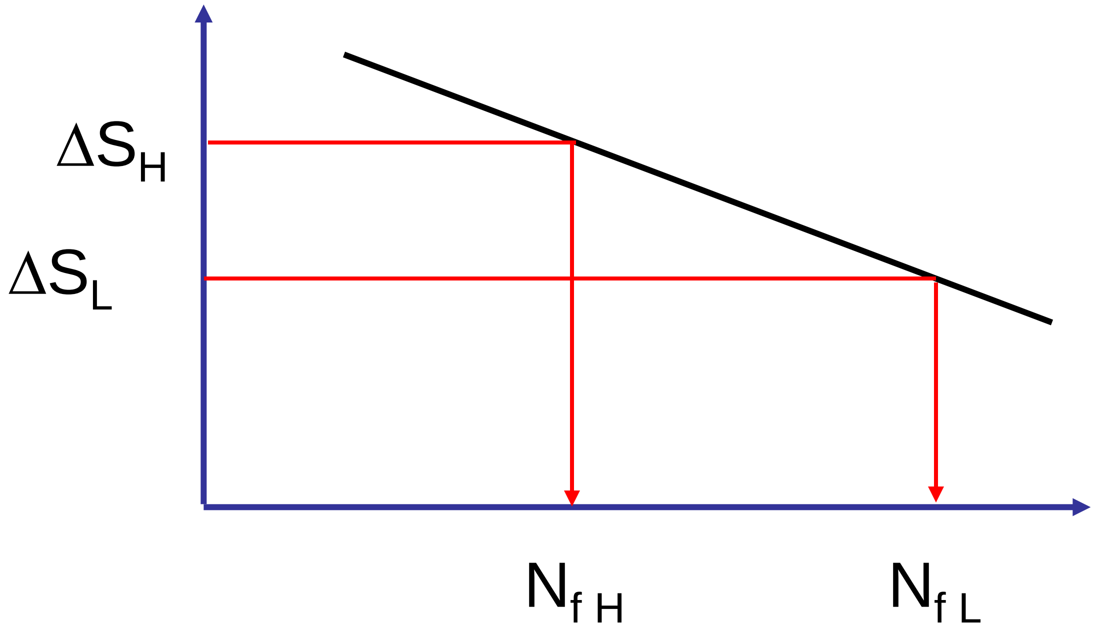
High - Low



Low - High



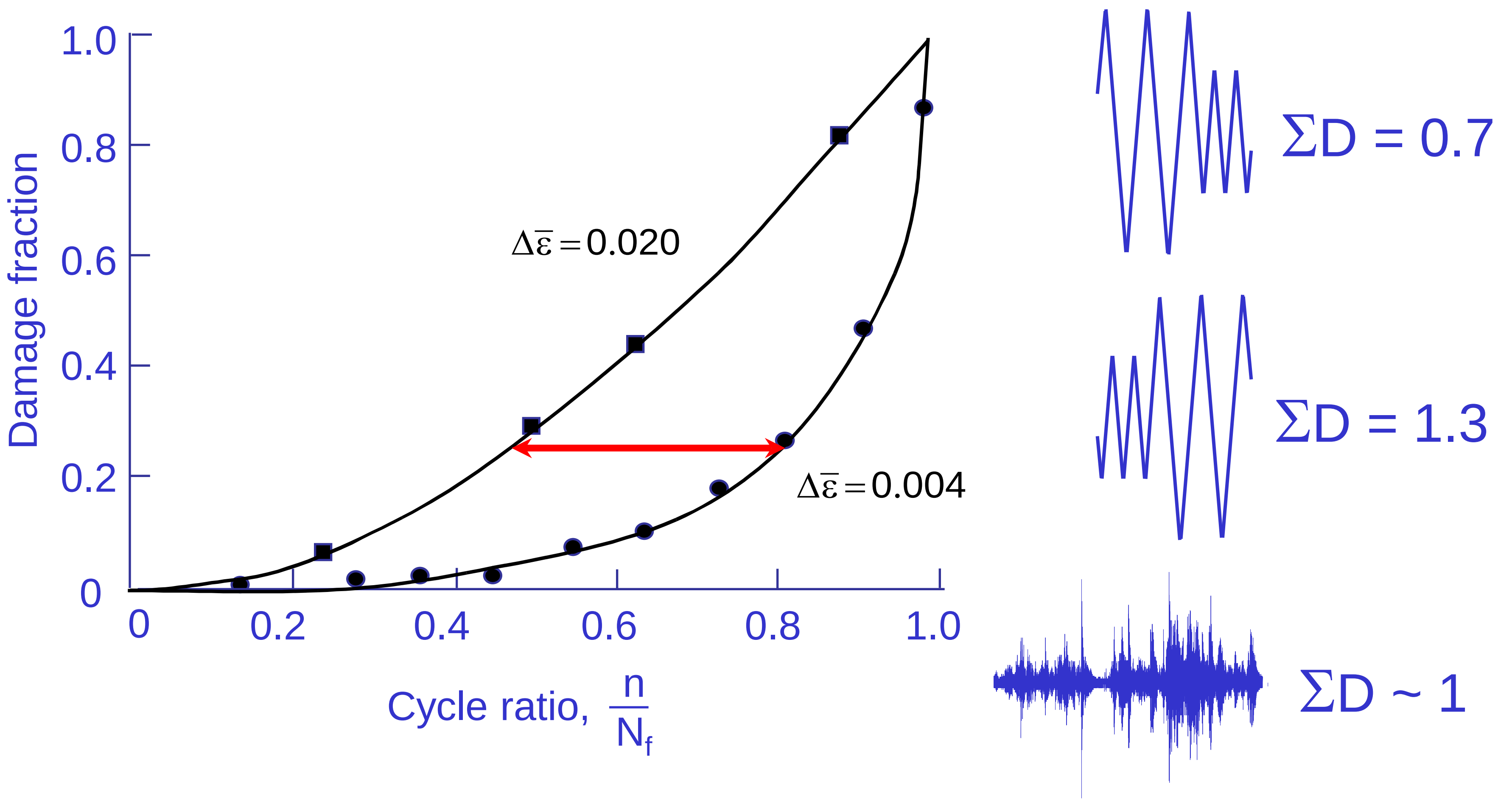
Linear Damage



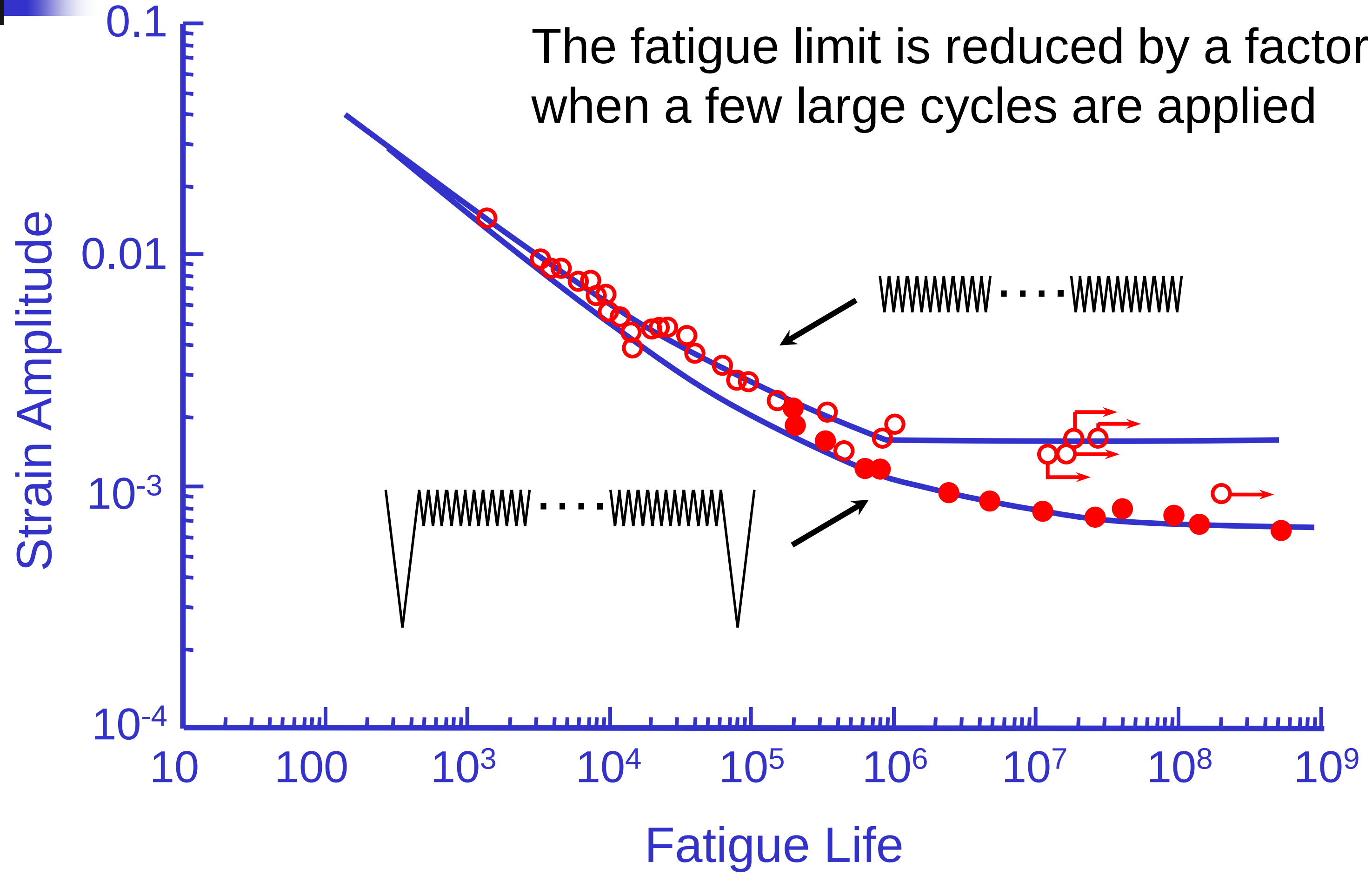
Miner's Rule:

$$\text{Damage} = \sum \frac{n}{N_F} = \frac{n_H}{N_{f\,H}} + \frac{n_L}{N_{f\,L}}$$

Nonlinear Damage

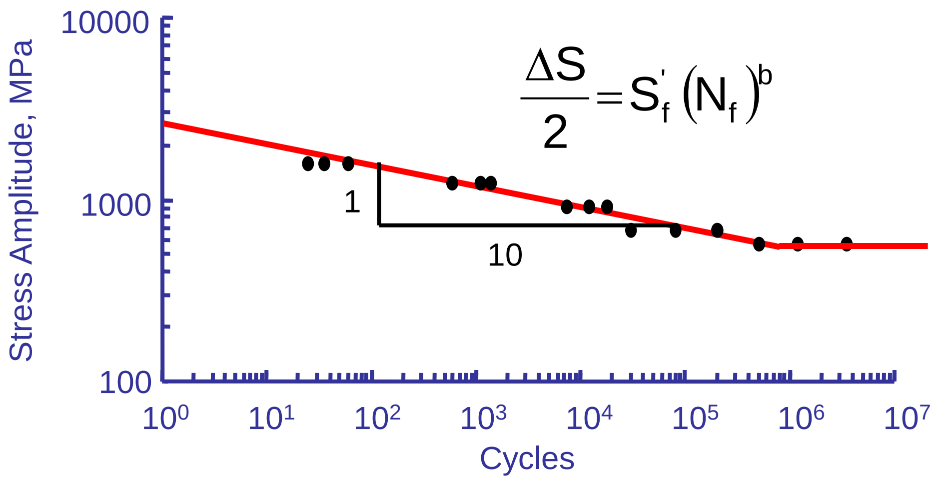


Periodic Overload Results



Bonnen and Topper, "The Effects of Periodic Overloads on Biaxial Fatigue of Normalized SAE 1045 Steel" ASTM STP 1387, 2000, 213-231

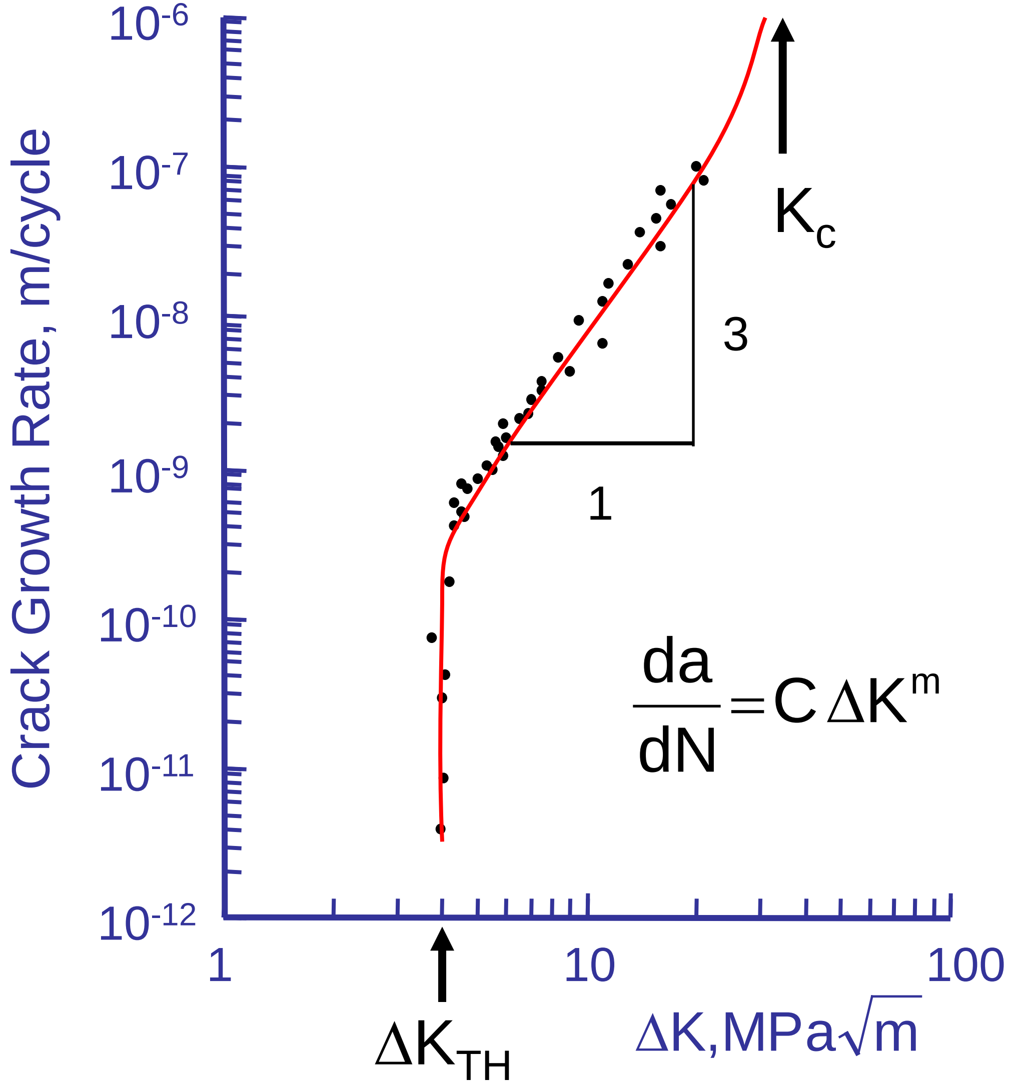
Fatigue Damage Calculations



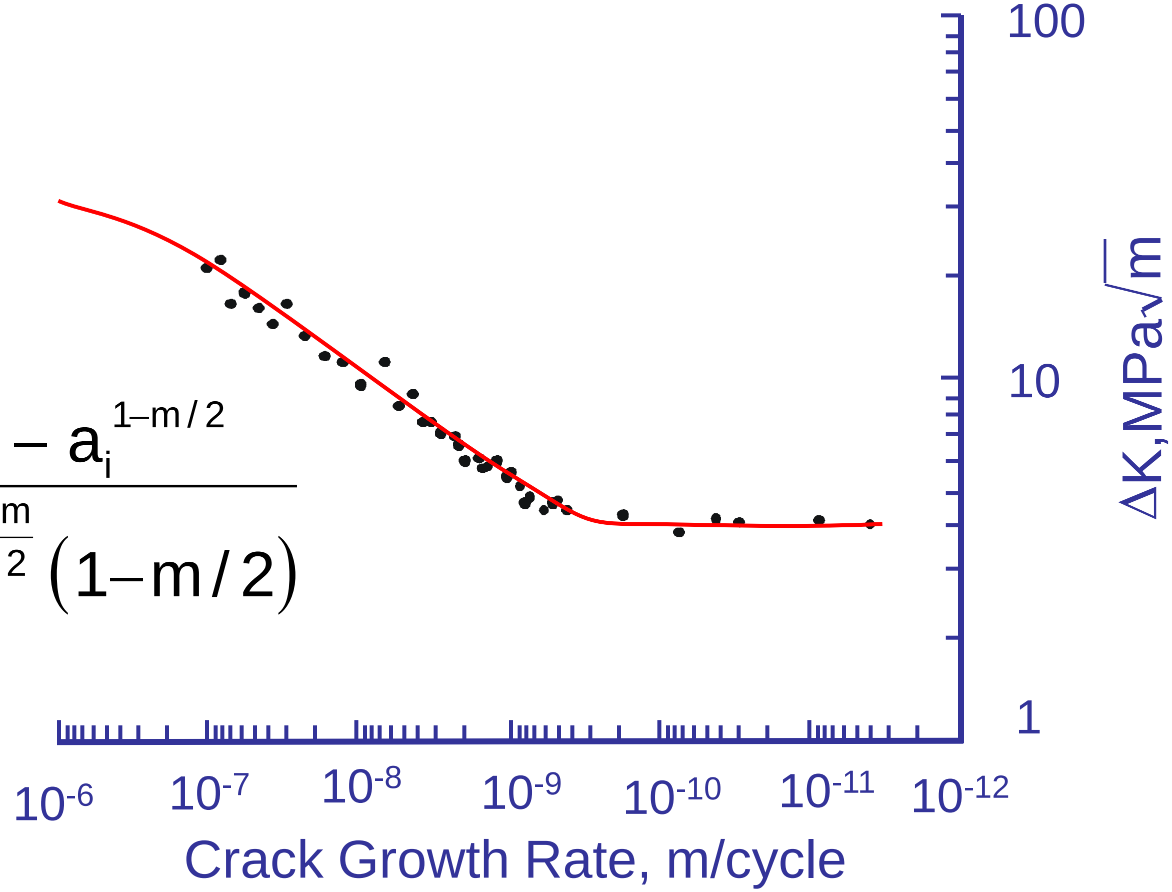
$$N_f = \left(\frac{\Delta S}{2 S_f^{'}} \right)^{\frac{1}{b}}$$

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

Crack Growth Data



Crack Growth Data



$$N_f = \frac{a_f^{1-m/2} - a_i^{1-m/2}}{C\,\Delta S^m \pi^{\frac{m}{2}} (1-m/2)}$$

$$\text{Damage} \propto \Delta S^3$$

Multiple Choice

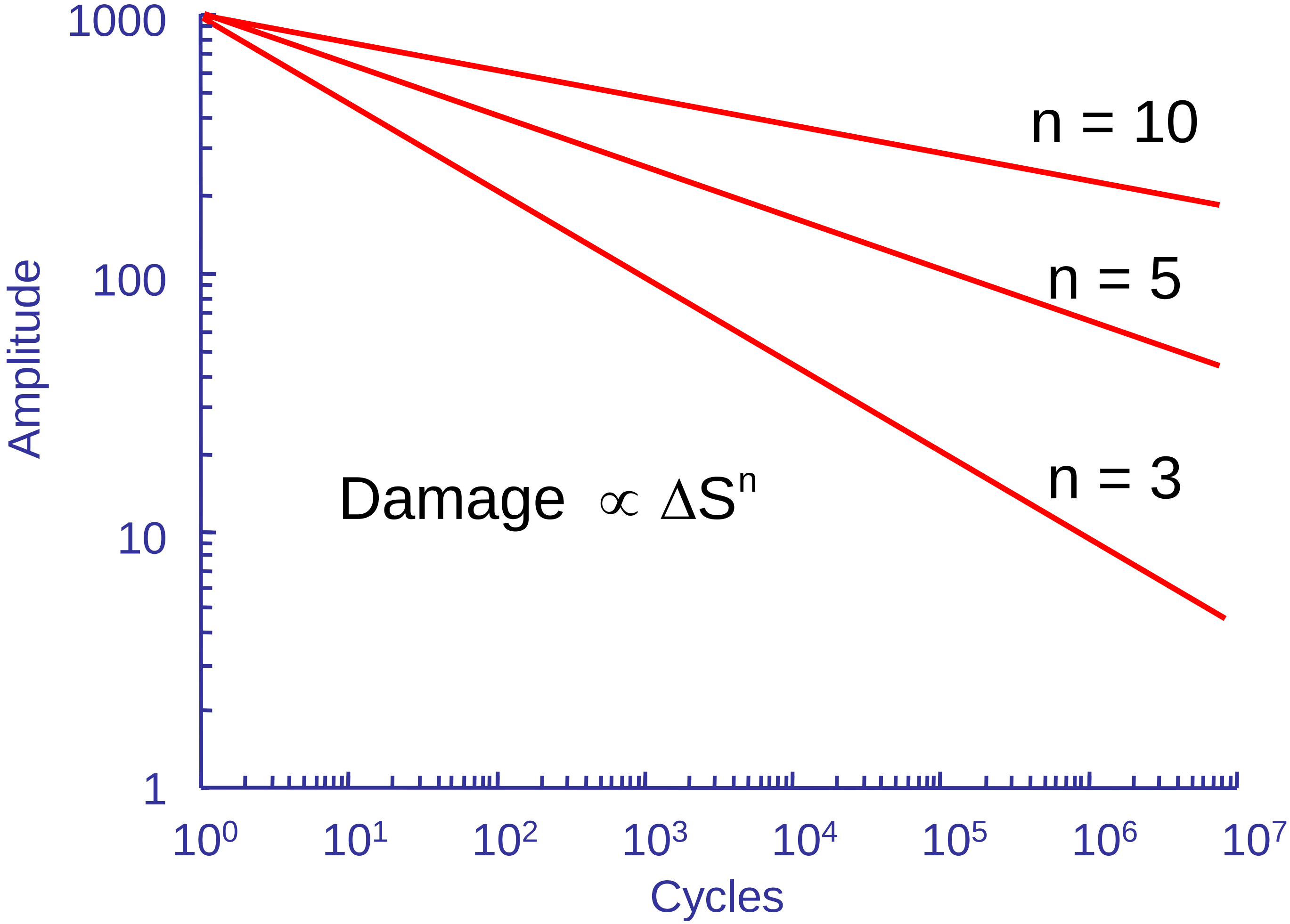
Which cycles do the most fatigue damage ?

(a) a few large cycles

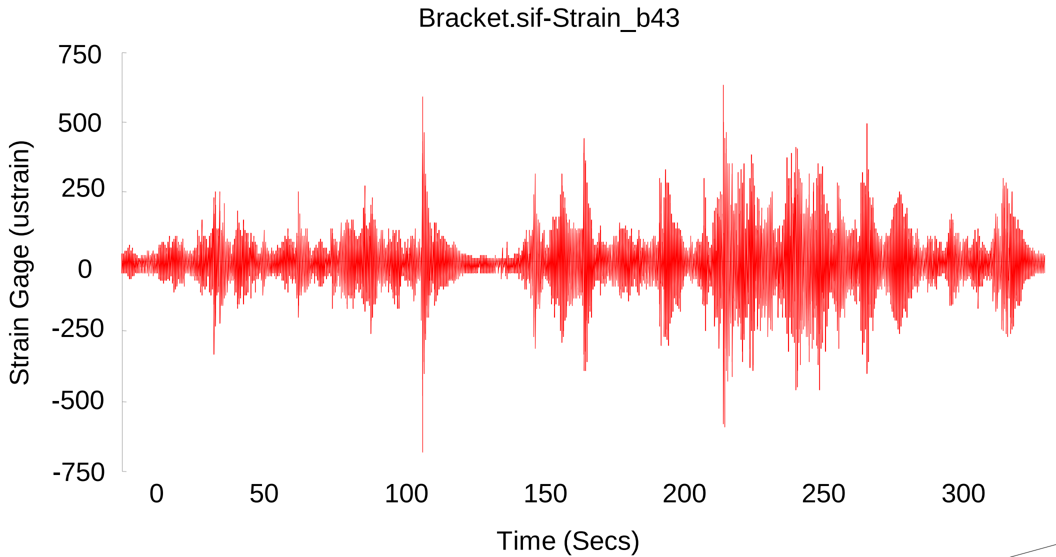
(b) a moderate number of intermediate cycles

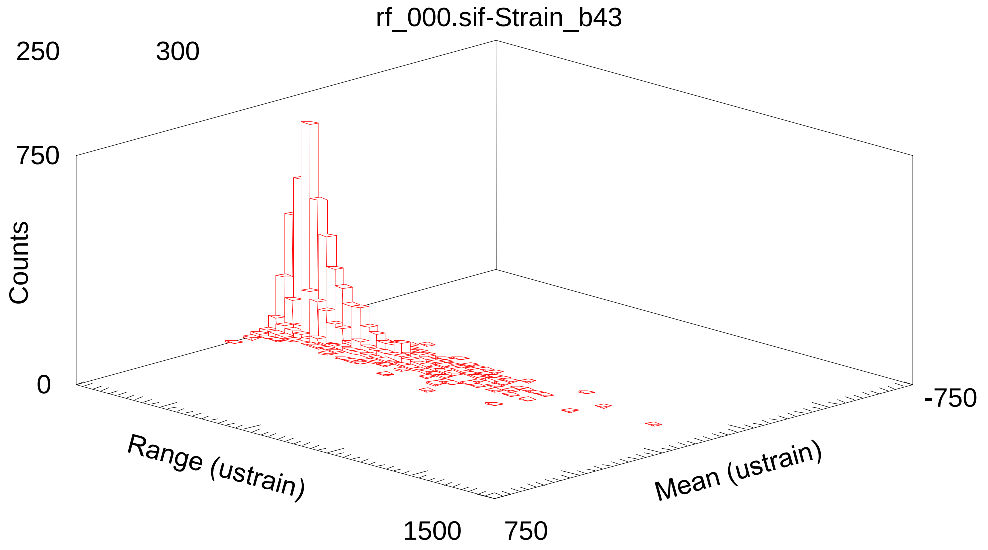
(c) a large number of small cycles

Fatigue Data

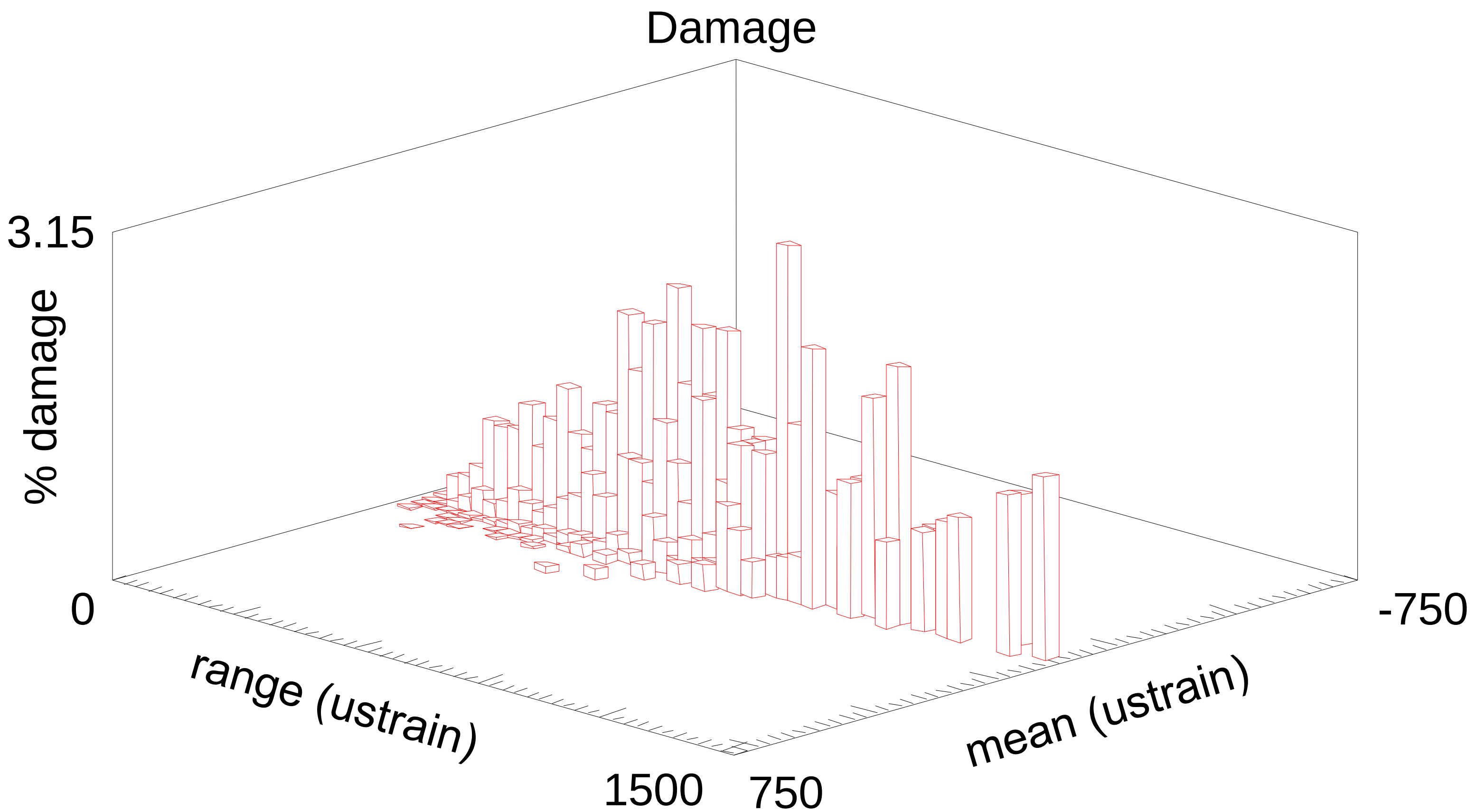


Loading History

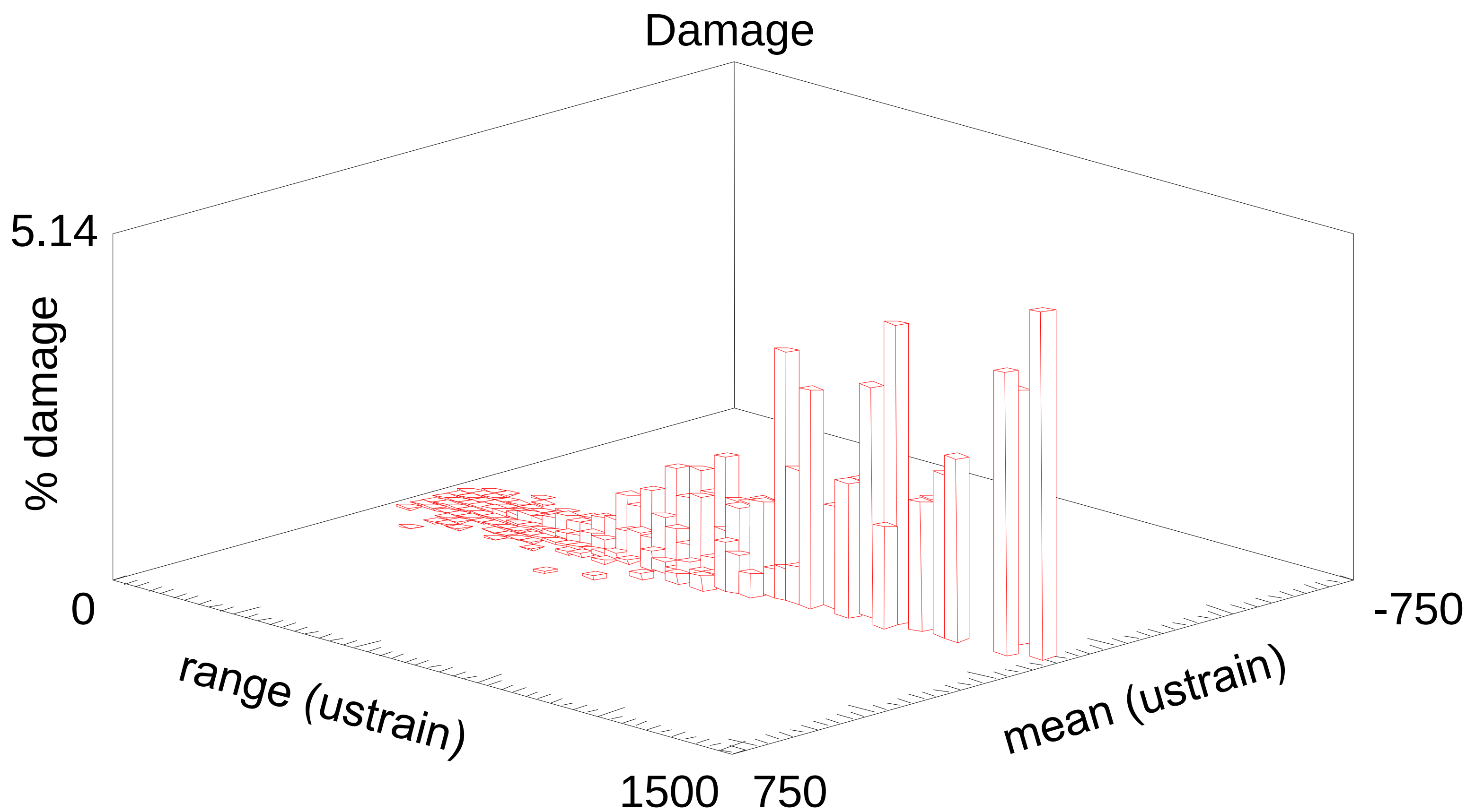




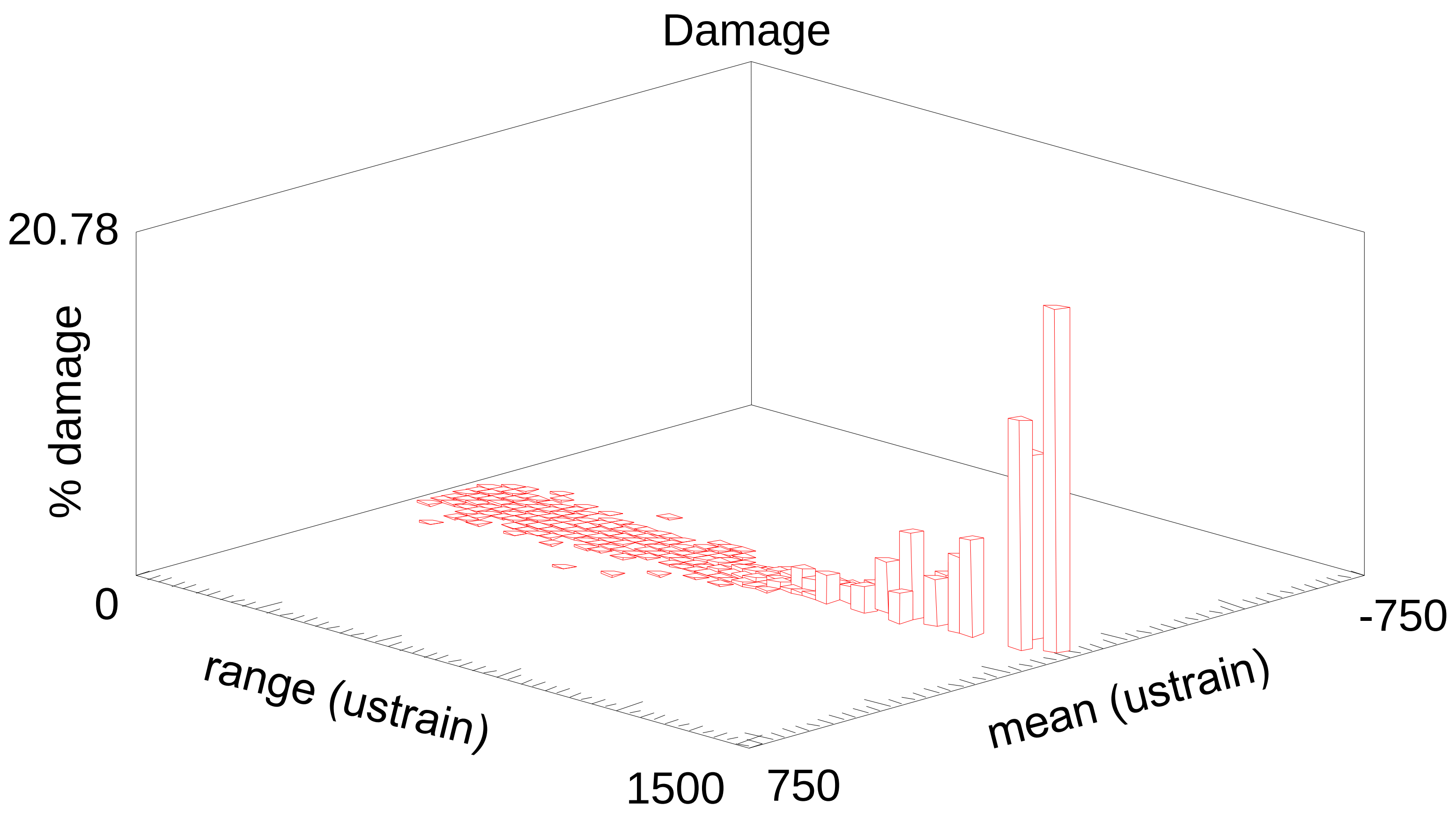
Slope = 3



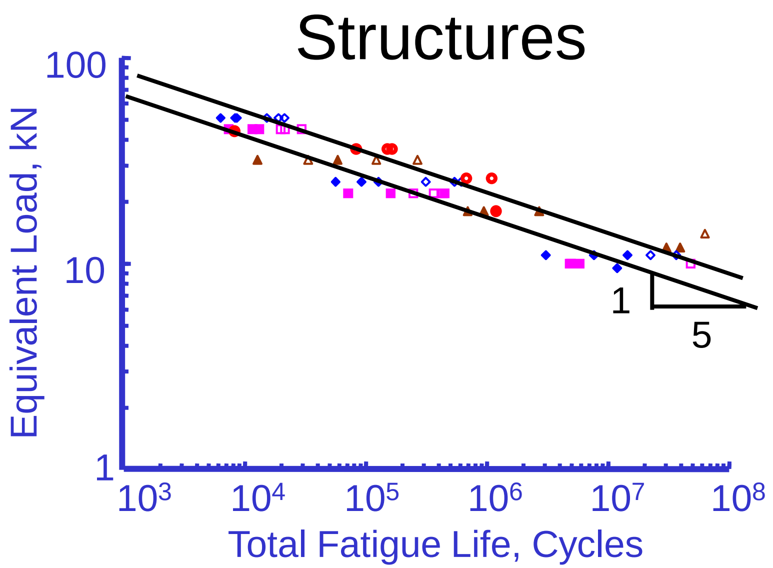
Slope = 5

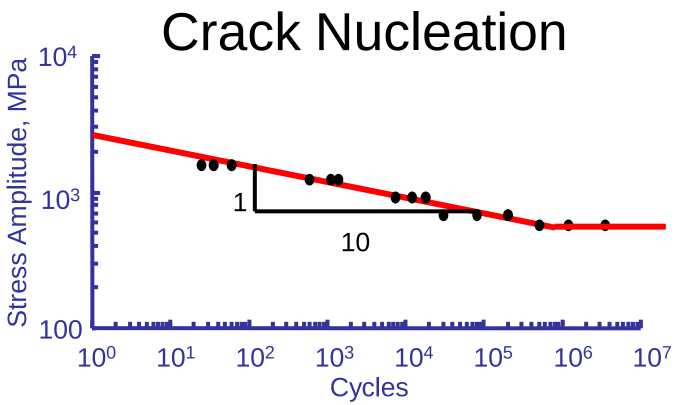


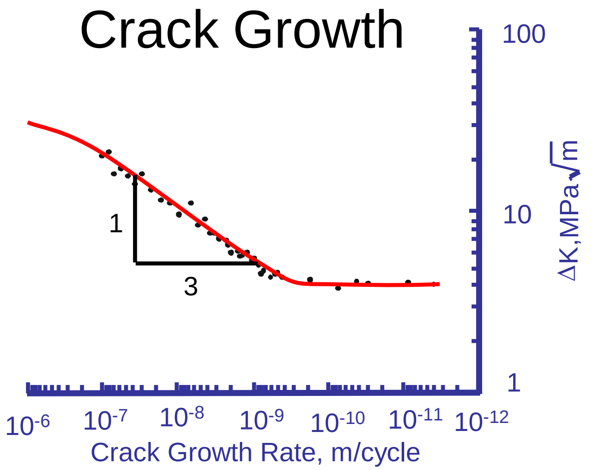
Slope = 10


Damage
20.78
% damage
0
range (ustrain)
1500
750
mean (ustrain)
-750

Mechanisms and Slopes







A combination of nucleation and growth

Equivalent Load

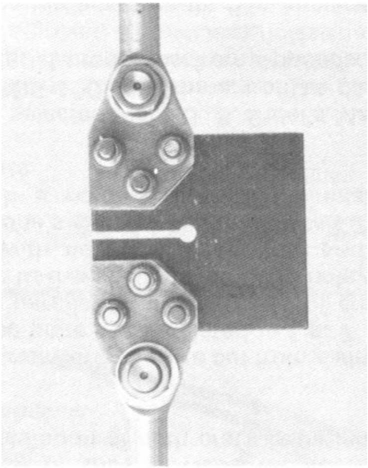
Equivalent constant amplitude loading

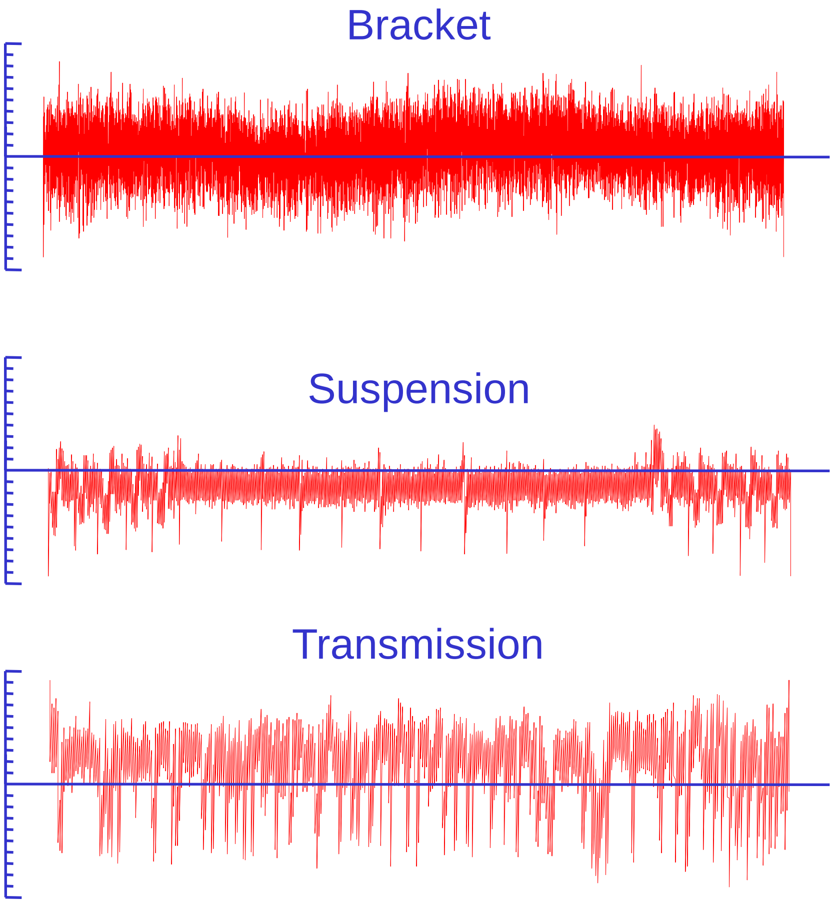
$$\Delta\overline{S} = \sqrt[n]{\frac{\sum_{i=1}^{N} \Delta S_i^{\,n}}{N}}$$

Typically n ranges from 4 to 6 for structures

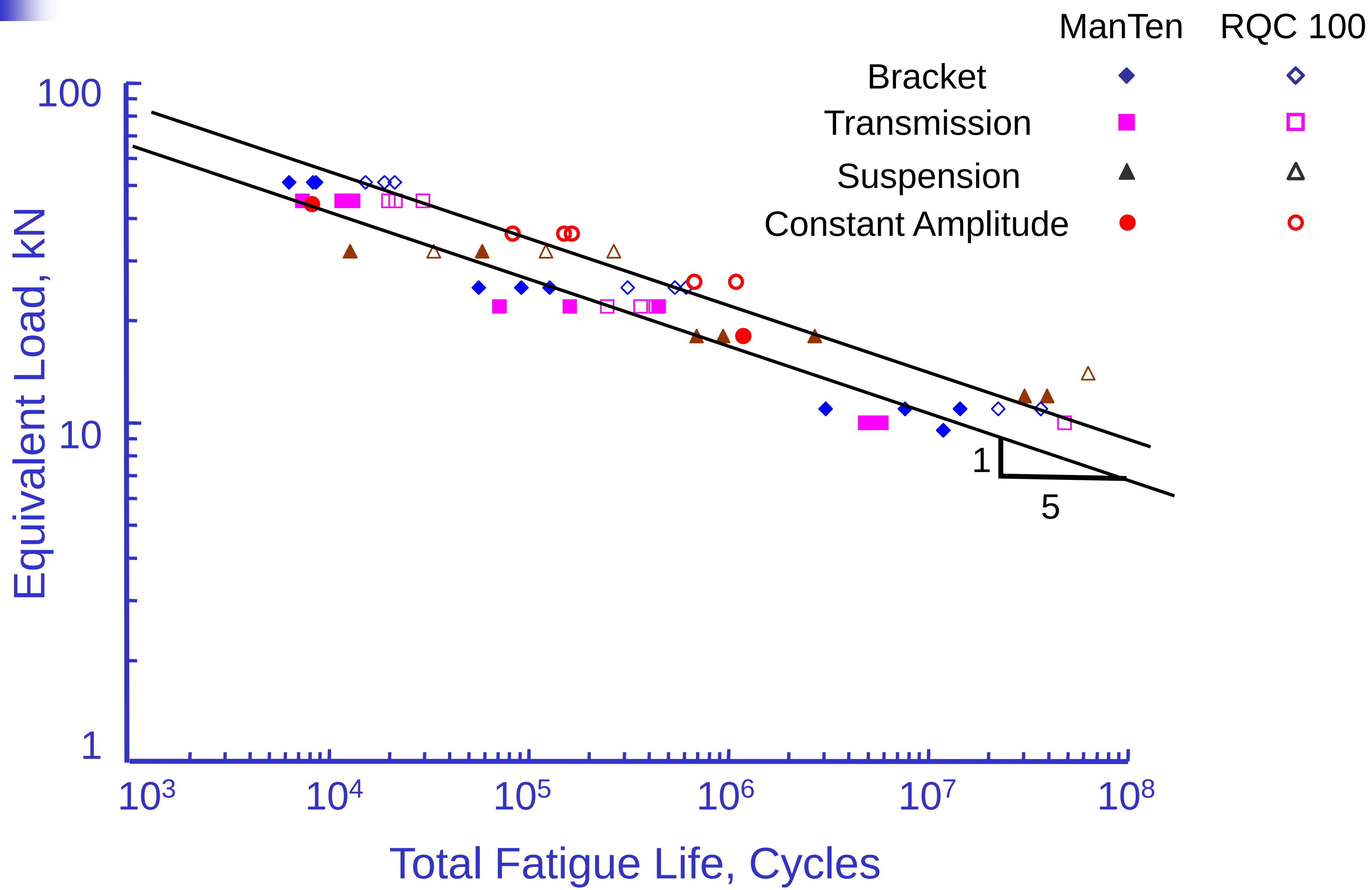
N cycles at an amplitude of $\Delta\overline{S}$ does as much damage as the entire loading history

SAE Keyhole Specimen





SAE Keyhole Test Data



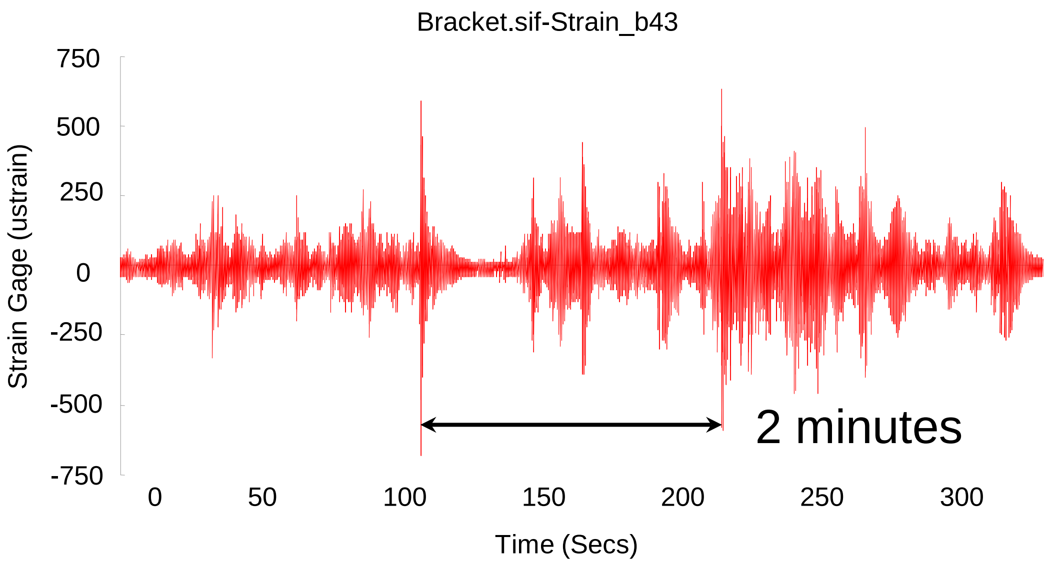
How Many Cycles ?

Engine:

2 starts/day for 10 years = 7000 cycles

3000 rpm for 100,000 miles (2000 hrs) = 3.6×10^8 cycles

How Many Cycles ? (continued)



Bracket Vibration:

0.5 per minute for 100,000 miles (2000 hrs) = 60,000 cycles

12 hz continuous vibration for 2000 hrs = 8.6 x 10^7 cycles

Things Worth Remembering

- Rainflow counting is employed to identify cycles
- The slope of the fatigue curve (damage mechanism) has a large influence on how much damage is caused by smaller cycles

Fatigue Seminar

Fatigue Made Easy

Welded Structures

Professor Darrell F. Socie
Mechanical Science and Engineering
University of Illinois

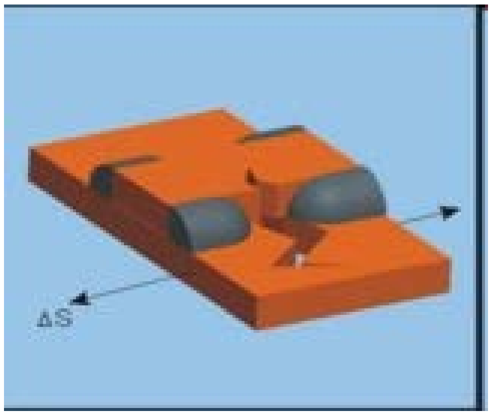
Seminar Outline

1. Historical background
2. Physics of fatigue
3. Characterization of materials
4. Similitude (why fatigue modeling works)
5. Variability
6. Mean stress
7. Stress concentrations
8. Surface effects
9. Variable amplitude loading
10. Welded structures

Analyzing Welds

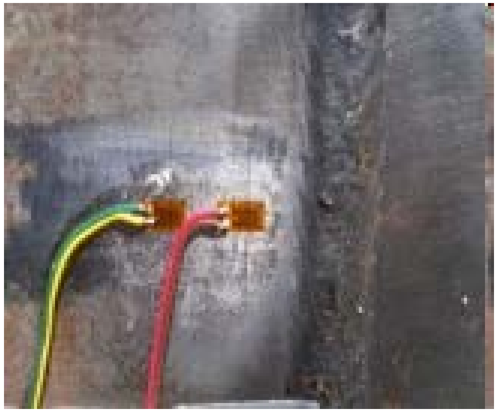
- Nominal Stress
- Structural or Hot Spot Stress
- Local Stress Strain
- Crack Growth

Nominal Stress



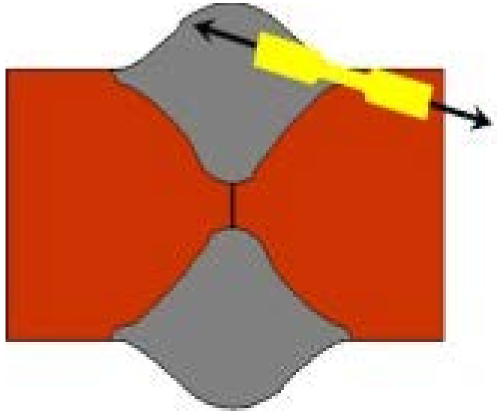
Nominal stress approaches are based on extensive tests of welded joints and connections. Weld joints are classified by type , loading and shape. For example, a transversely loaded butt weld. It is assumed and confirmed by experiments that welds of a similar shape have the same general fatigue behavior so that a single design SN curve can be employed for any weld class. The designer need only determine the nominal stress and select a weld class. There is no need to directly consider the stress concentration effects of the weld.

Structural Stress



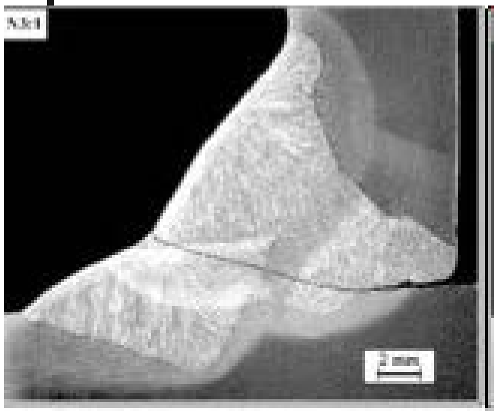
Structural stress approaches are often referred to as "hot-spot methods". The structural stress includes the macroscopic stress concentrating effects of the weld detail but not the local peak stress caused by the notch at the weld toe. There are various methods used to determine the structural stress. They involve extrapolating the computed or measured stresses from two points near the weld to a structural stress at the weld toe. This method works in situations where there is no clear definition of the nominal stress.

Local Stress Strain



Local stress or strain approaches include both the macroscopic stress concentration due to the weld shape and the local stress concentration at the weld toe. To apply traditional methods of fatigue analysis to welds, an appropriate value of the stress concentration factor and residual stress must be selected. Although the smallest radius produces the largest stress concentration factor, its effect in fatigue is smaller because of the gradient effect. As a result there is a critical radius for fatigue that can be used to compute the fatigue notch factor.

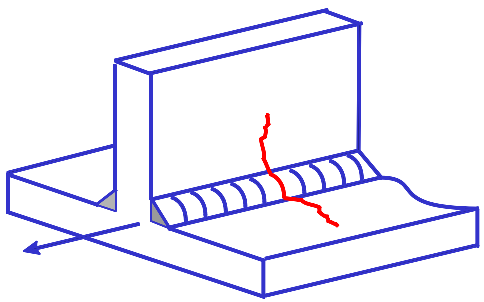
Crack Growth



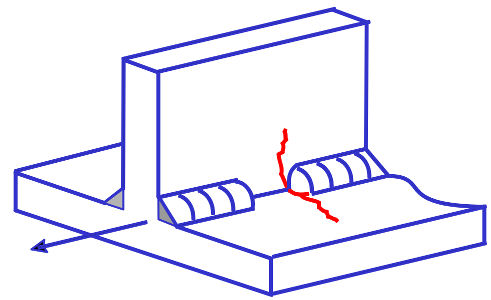
Many weld details have planar lack of fusion defects. This is particularly true of fillet welds. In this case fracture mechanics models for crack growth are the most appropriate fatigue technology.

Nominal Stress Weld Classifications

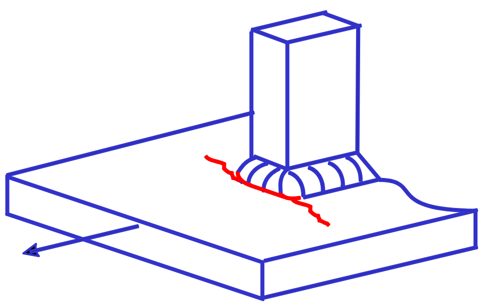
D



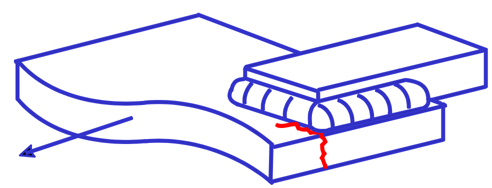
E



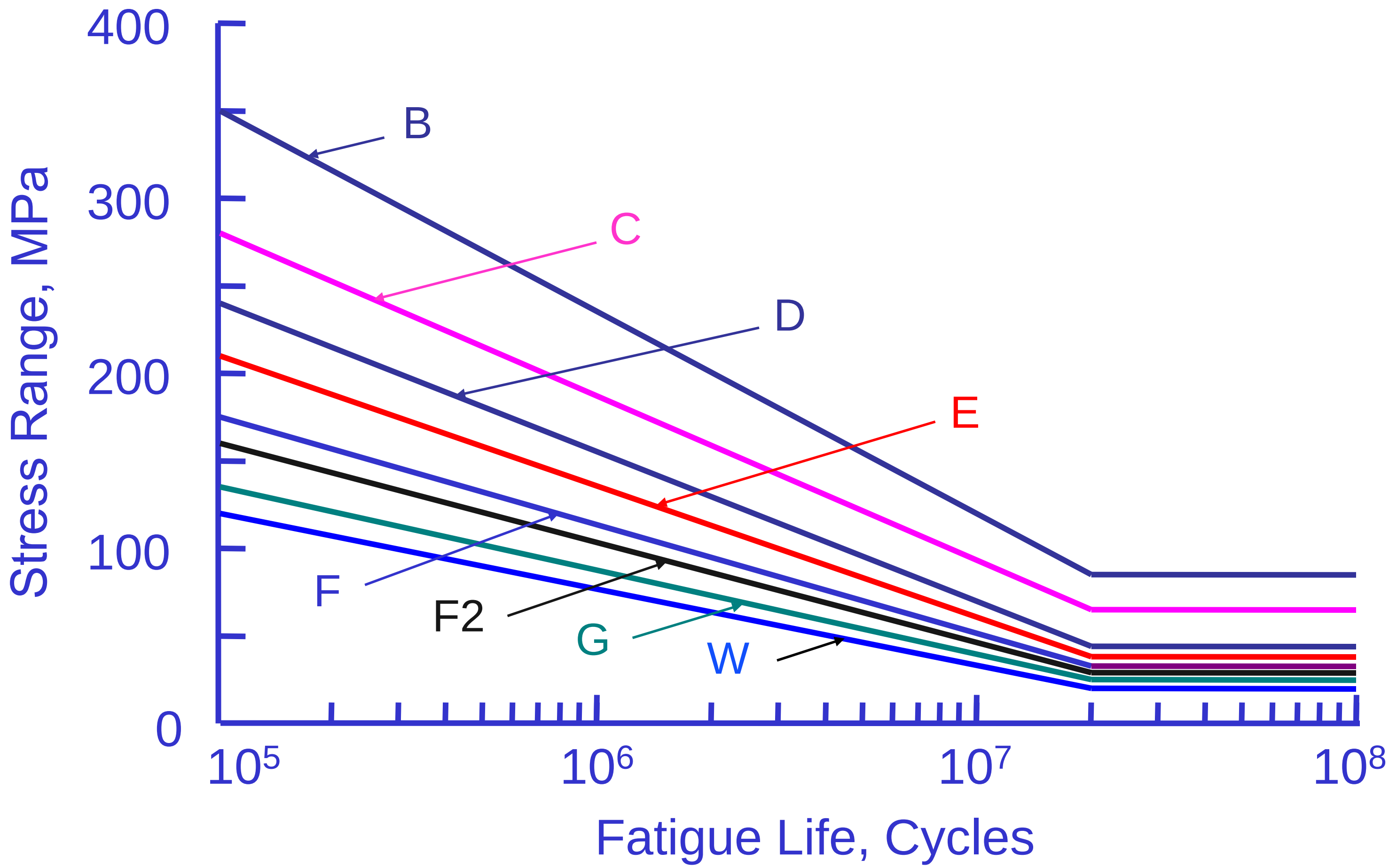
F2



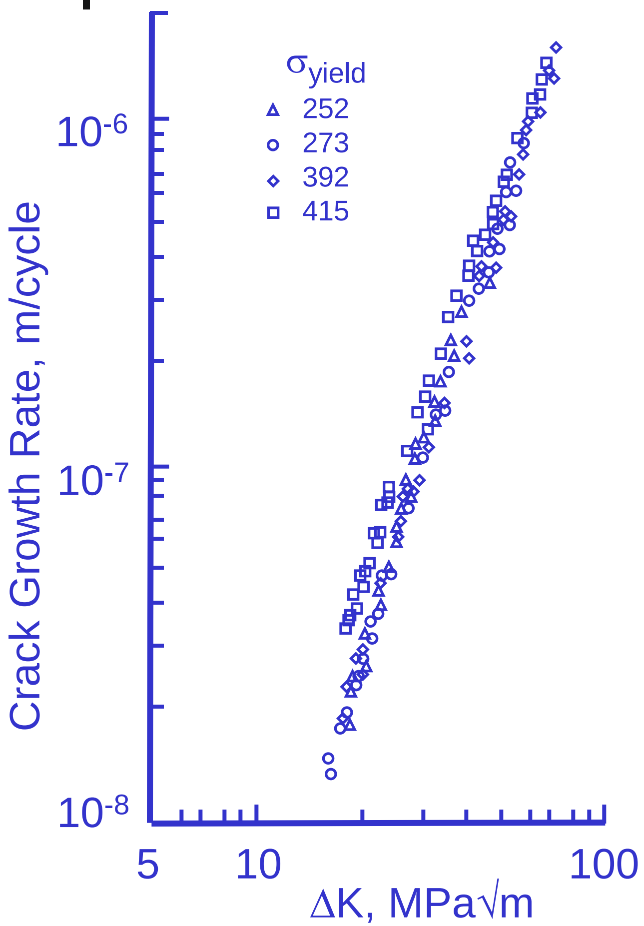
G



BS 7608 - Steel



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:

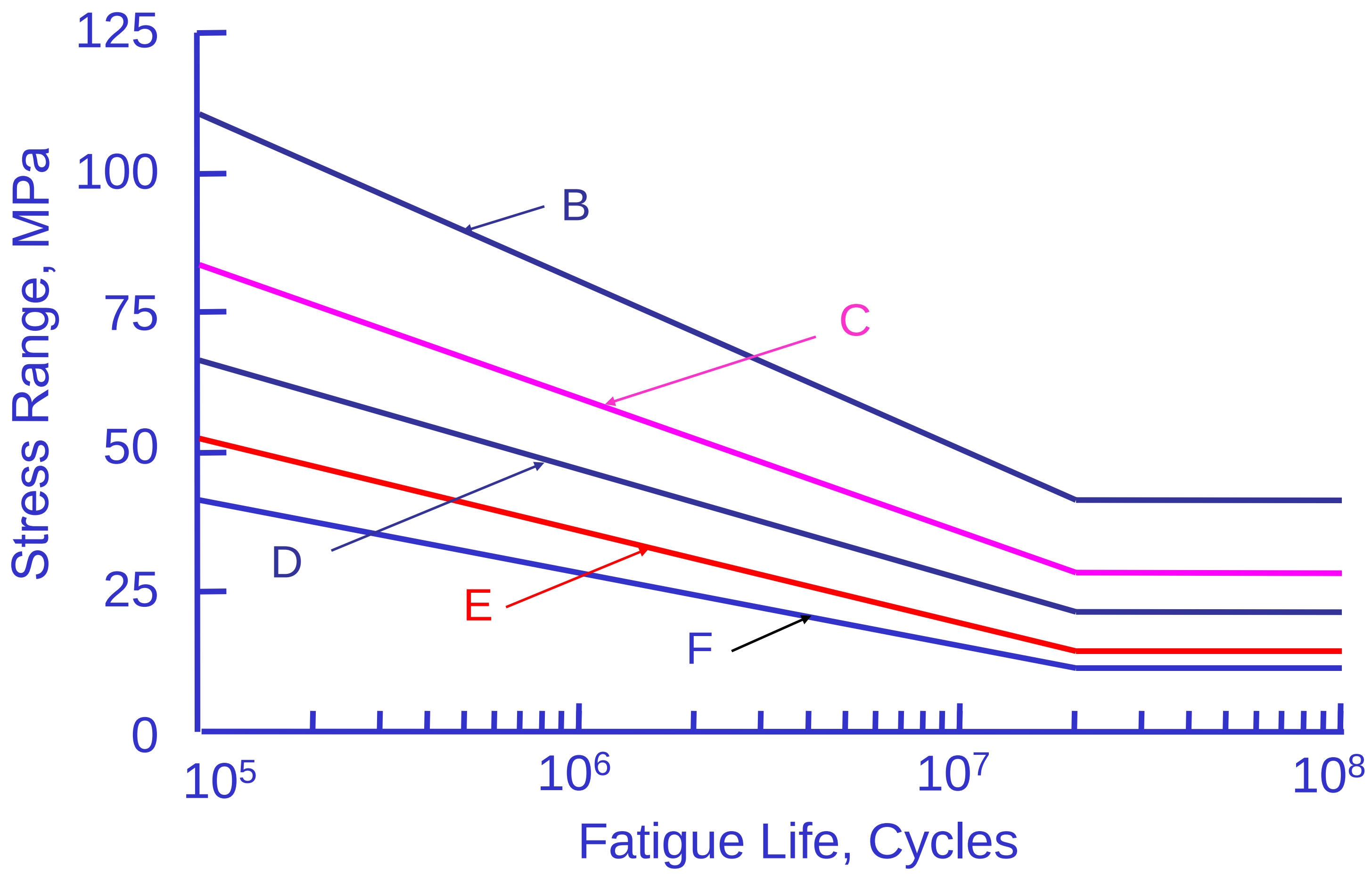
$$\frac{da}{dN} = 1.4 \times 10^{-10} \left(\Delta K \, MPa\sqrt{m}\right)^{2.25}$$

Austenitic Stainless Steel:

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

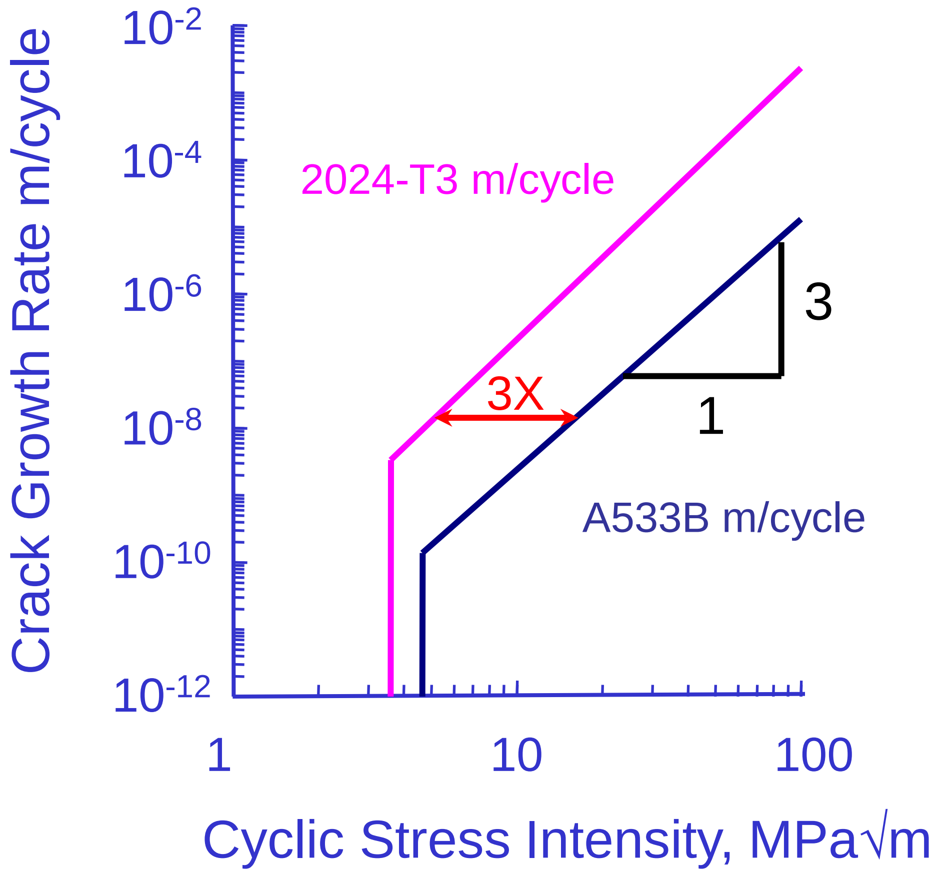
Barsom, "Fatigue Crack Propagation in Steels of Various Yield Strengths"
Journal of Engineering for Industry, Trans. ASME, Series B, Vol. 93, No. 4, 1971, 1190-1196

Nominal Stress - Aluminum



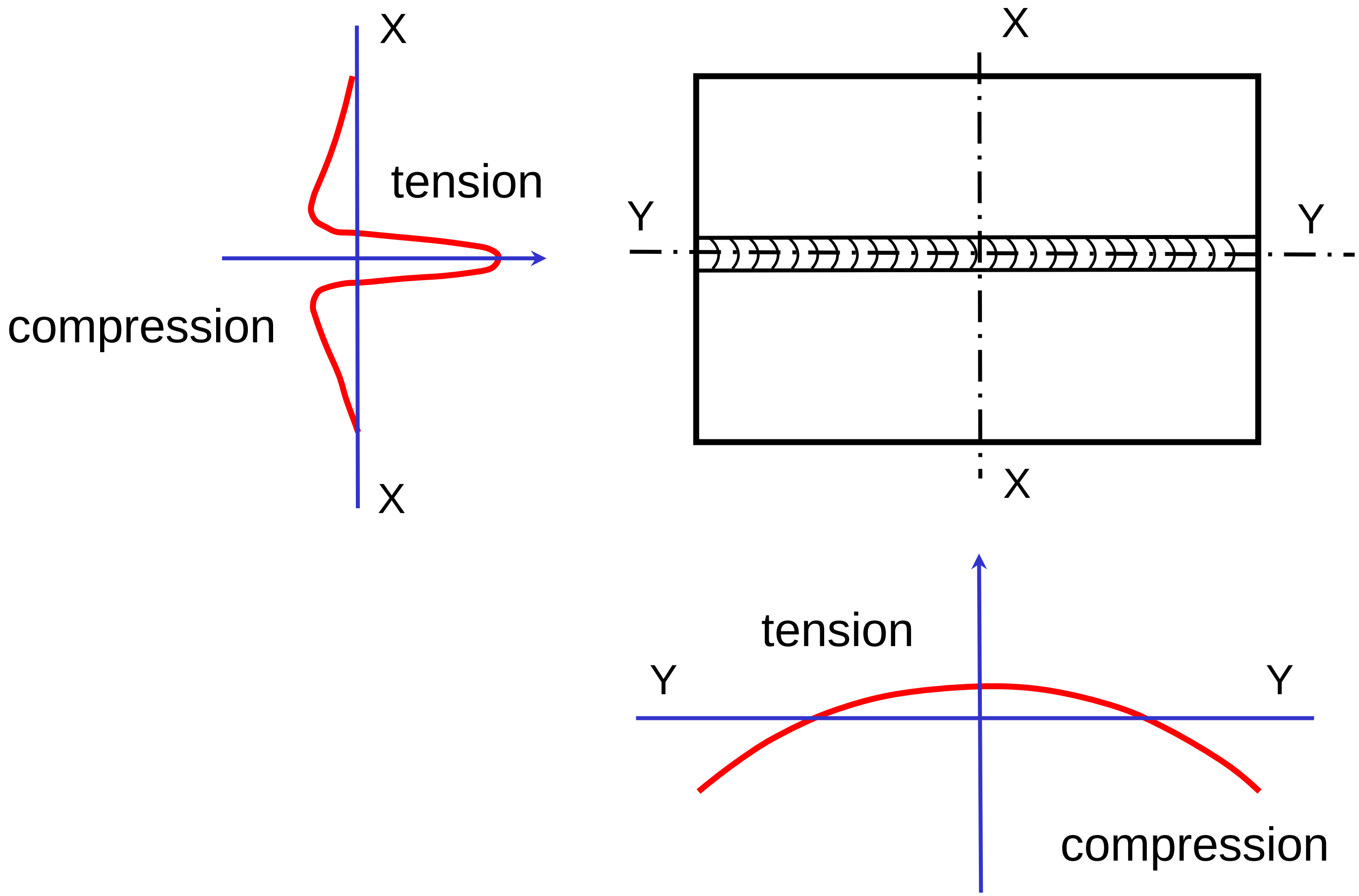
Sharp, "Behavior and Design of Aluminum Structures",McGraw-Hill, 1992

Crack Growth Data

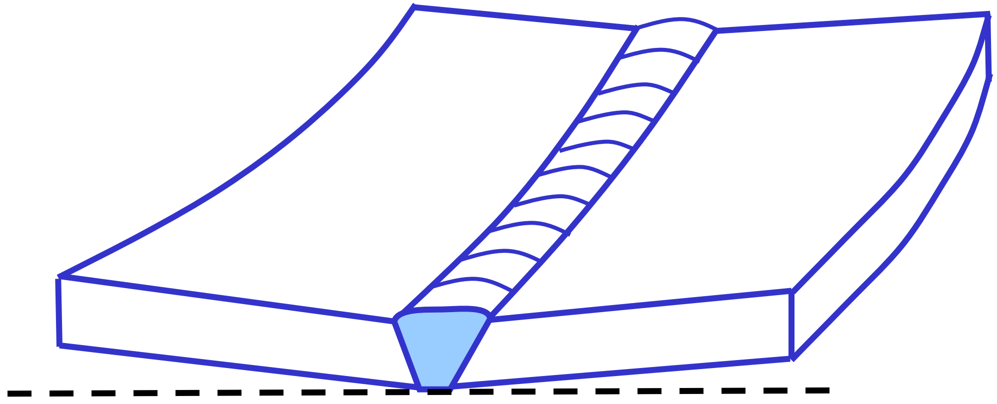


Steel welds are 3 times stronger than aluminum

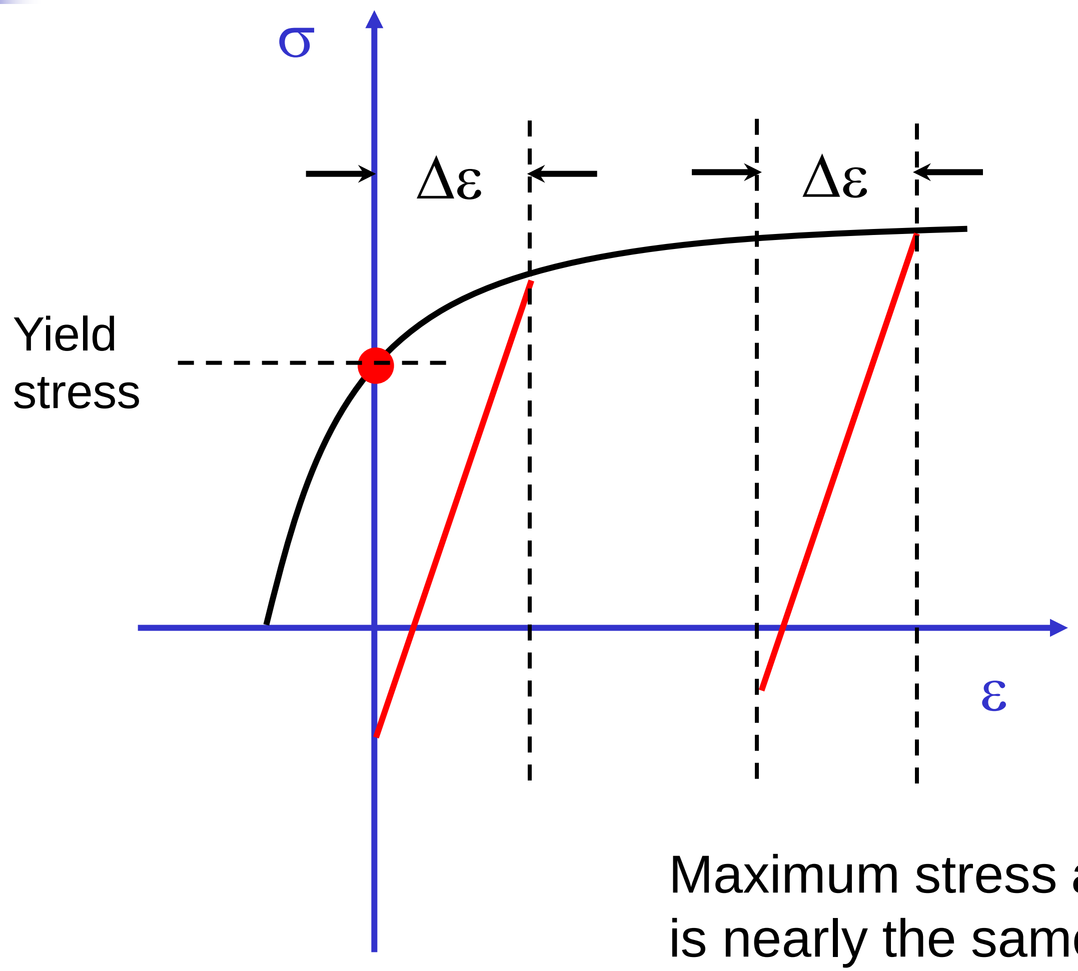
Residual Stress from Welding



Weld Distortion



Weld Toe Residual Stress

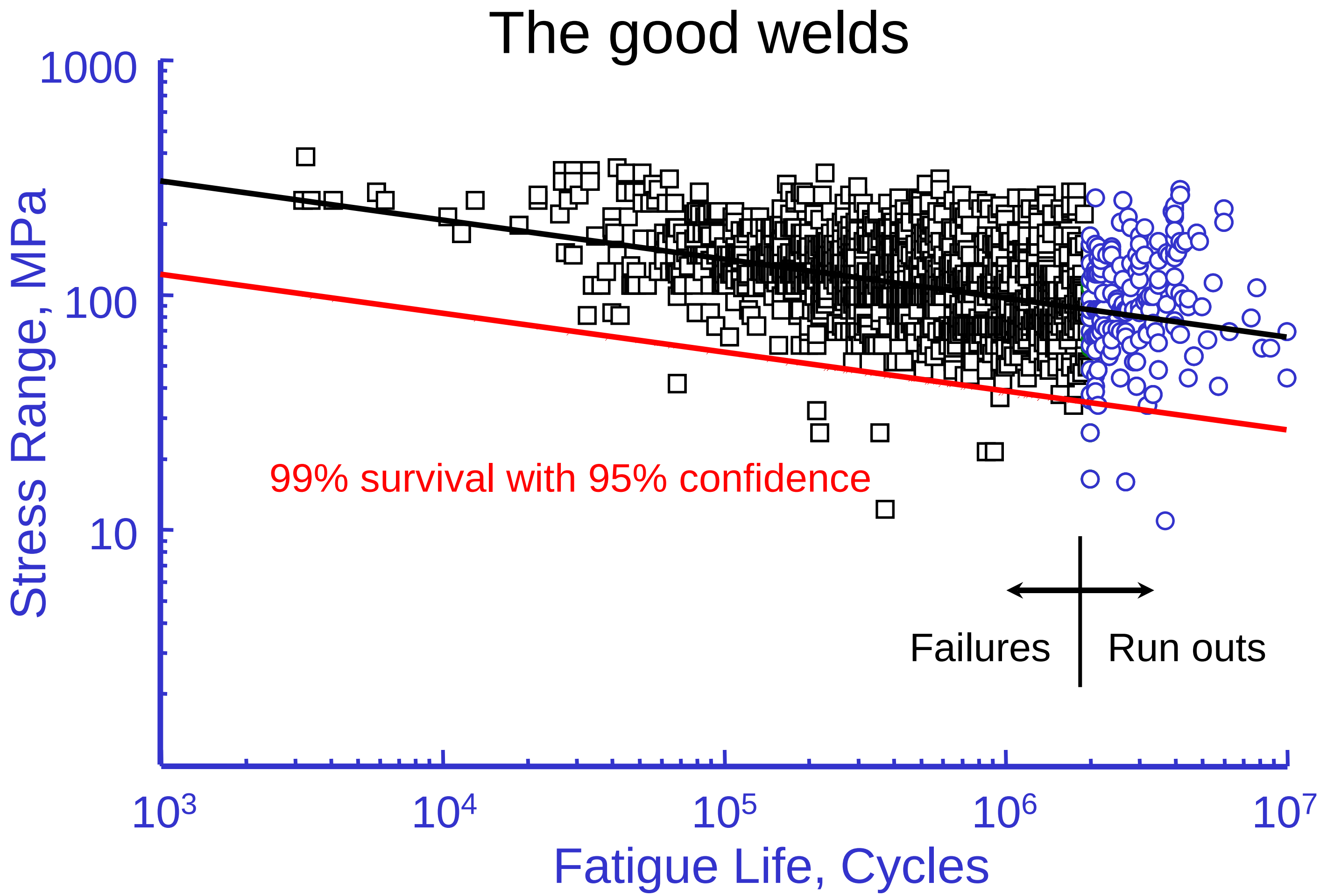


Maximum stress at the weld toe is nearly the same for any cycle

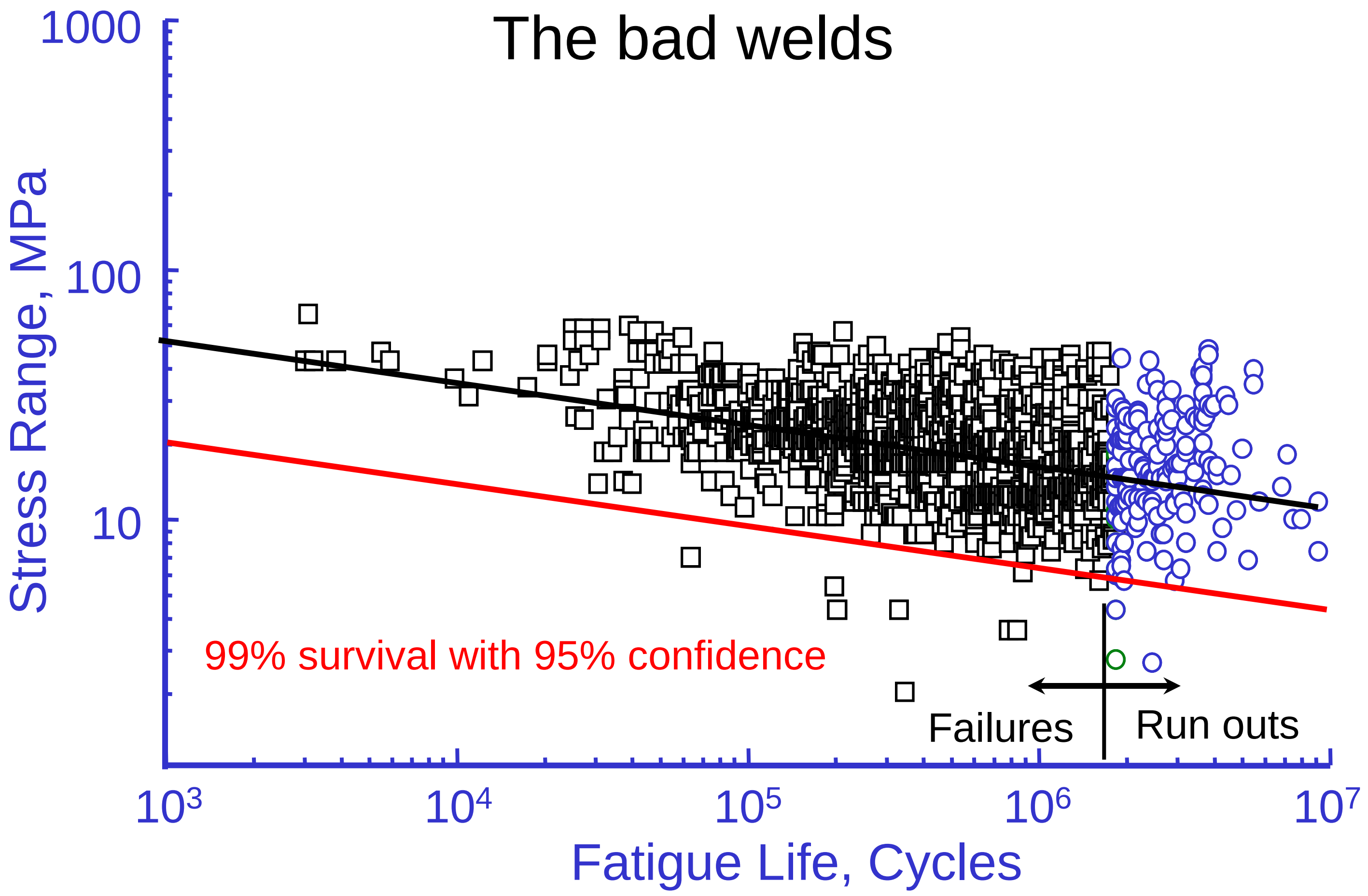
Mean Stress Effects

- As welded structures usually have the maximum possible mean stress
- Stress relief, peening, etc. will have a substantial effect on the fatigue life

Butt and Fillet Weld Test Data



Weld Terminations



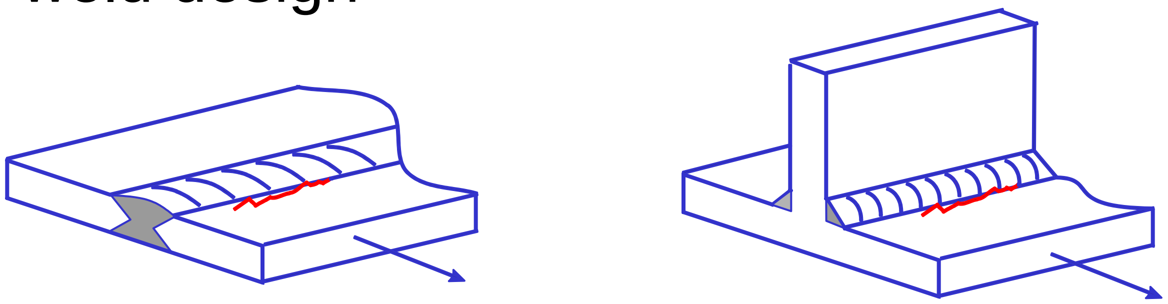
Sources of Inherent Scatter

- Weld quality
- Mean, fabrication and residual stresses
- Stress concentrations (geometry)
- Weldment size
- Material properties

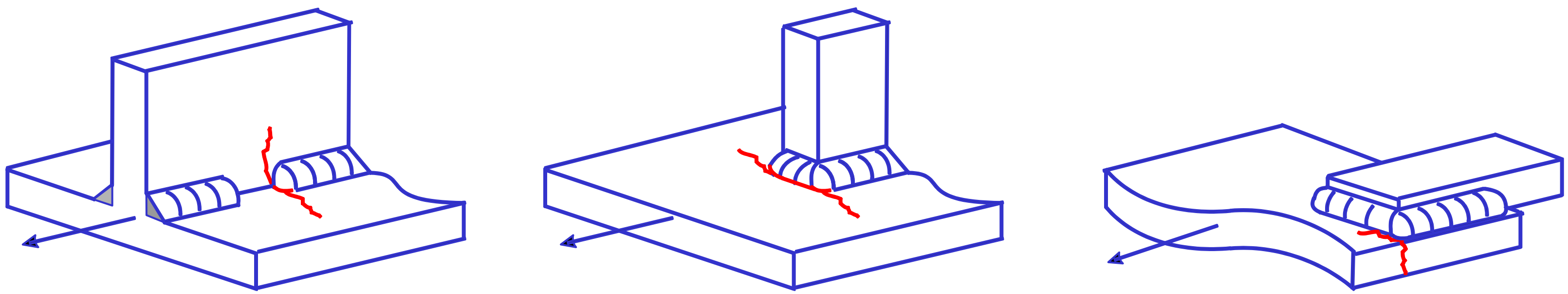
Opportunities for Improvement !

The Good and Bad

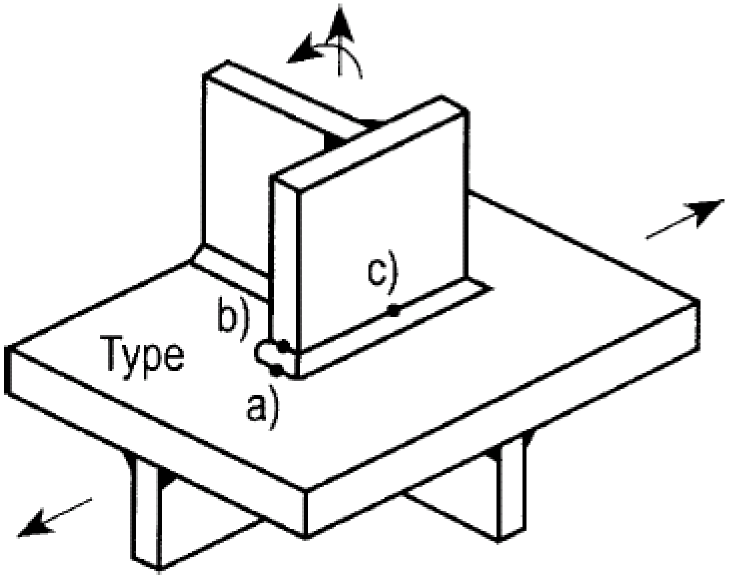
Good weld design



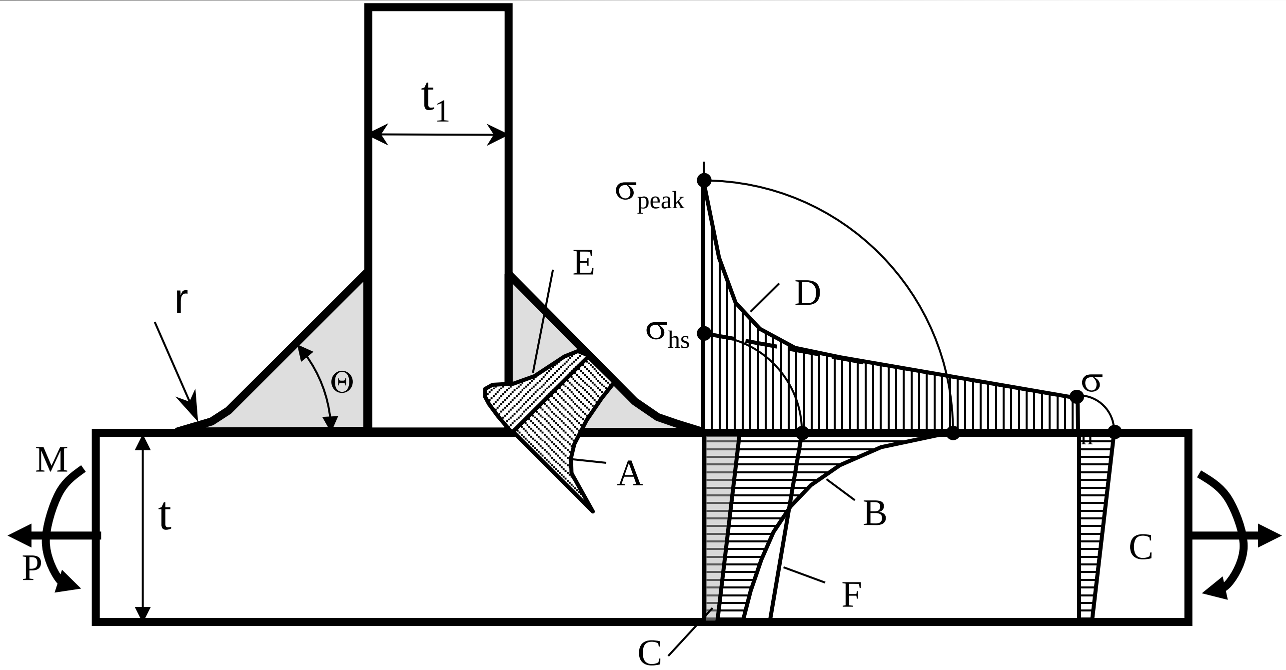
Bad weld design



Nominal Stress ?



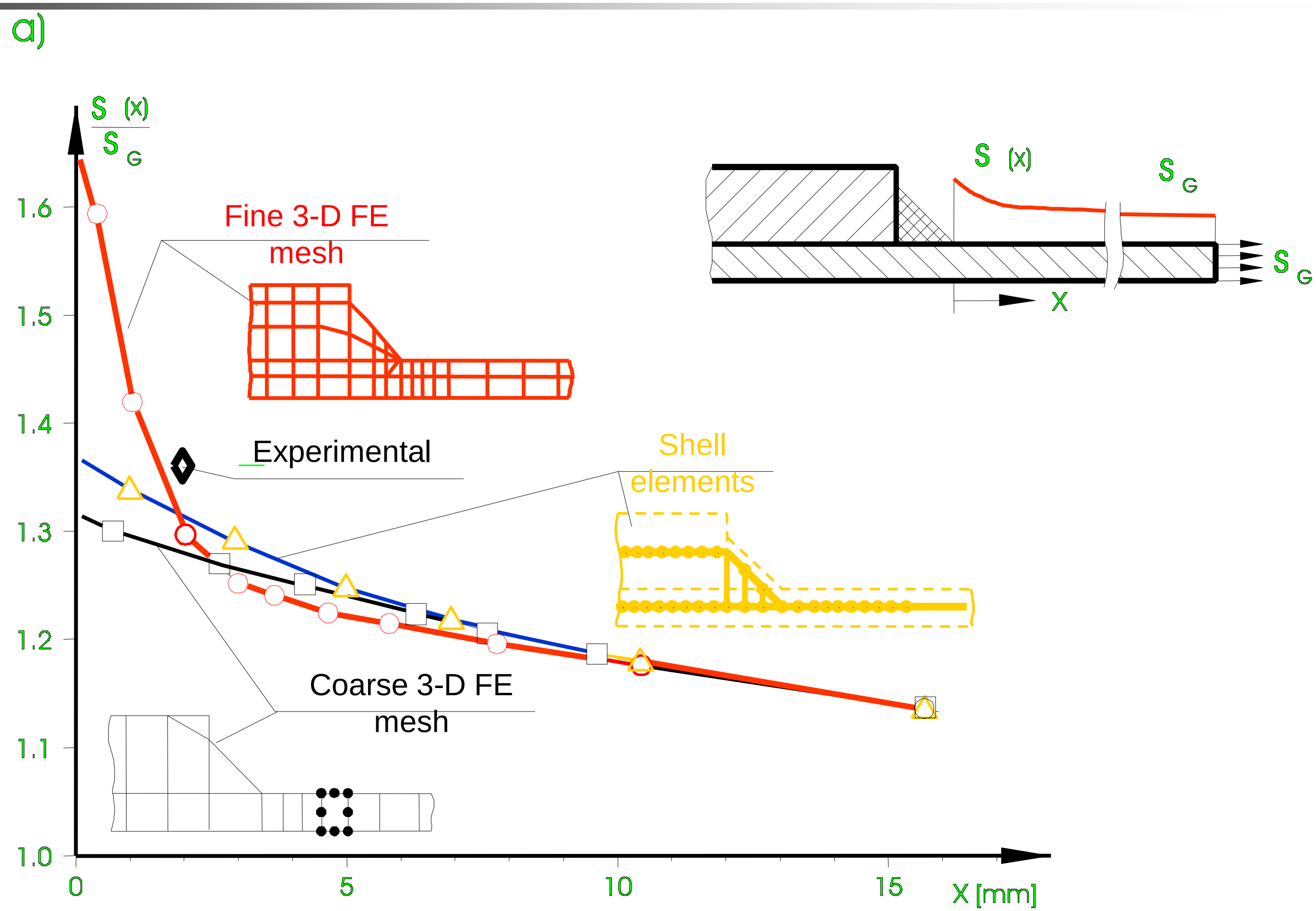
Stress Distributions in Weldments



Various stress distributions in a T-butt weldment with transverse fillet welds;

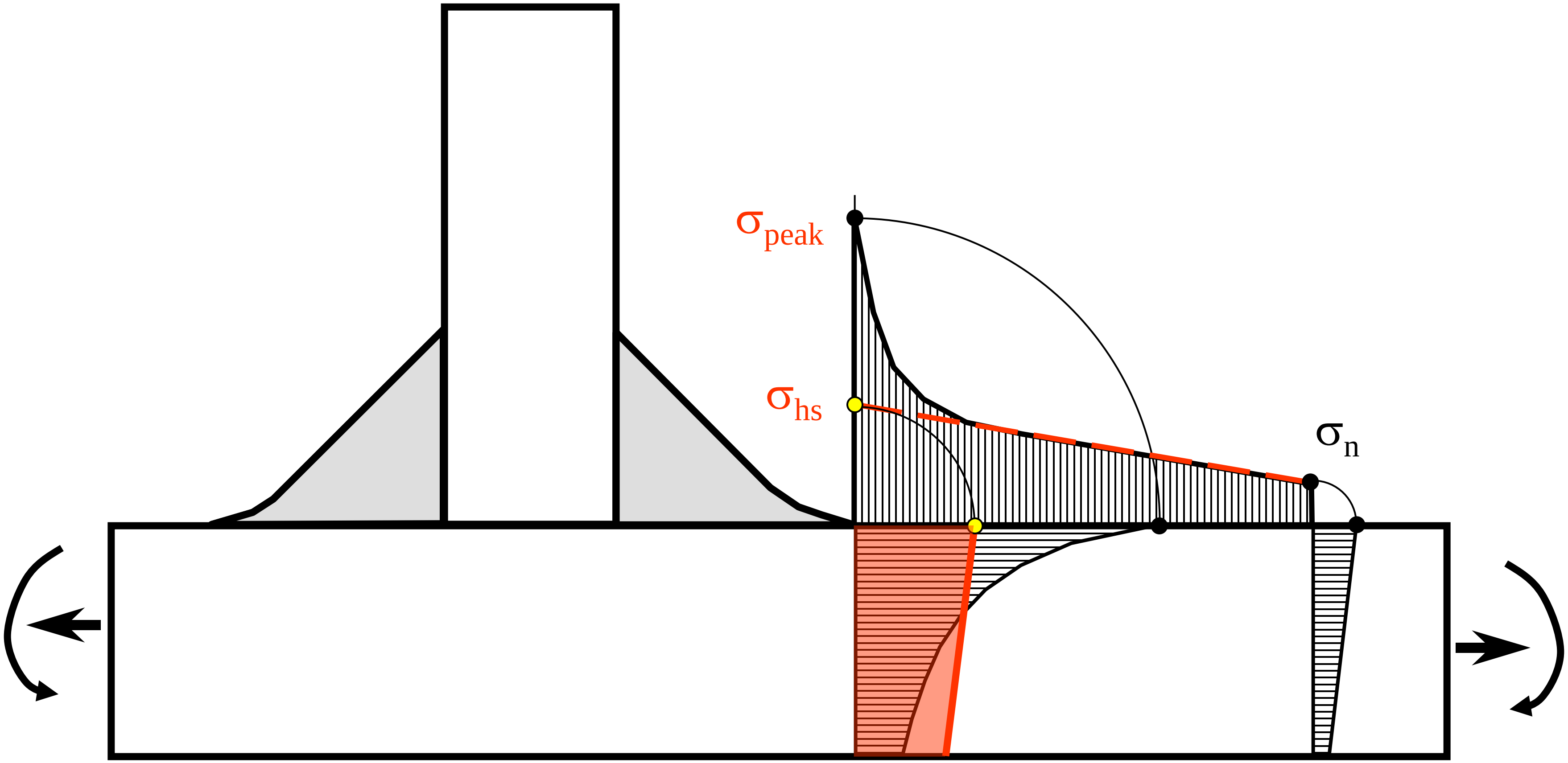
- Normal stress distribution in the weld throat plane (A),
- Through the thickness normal stress distribution in the weld toe plane (B),
- Through the thickness normal stress distribution away from the weld (C),
- Normal stress distribution along the surface of the plate (D),
- Normal stress distribution along the surface of the weld (E),
- Linearized normal stress distribution in the weld toe plane (F).

Finite Element Models

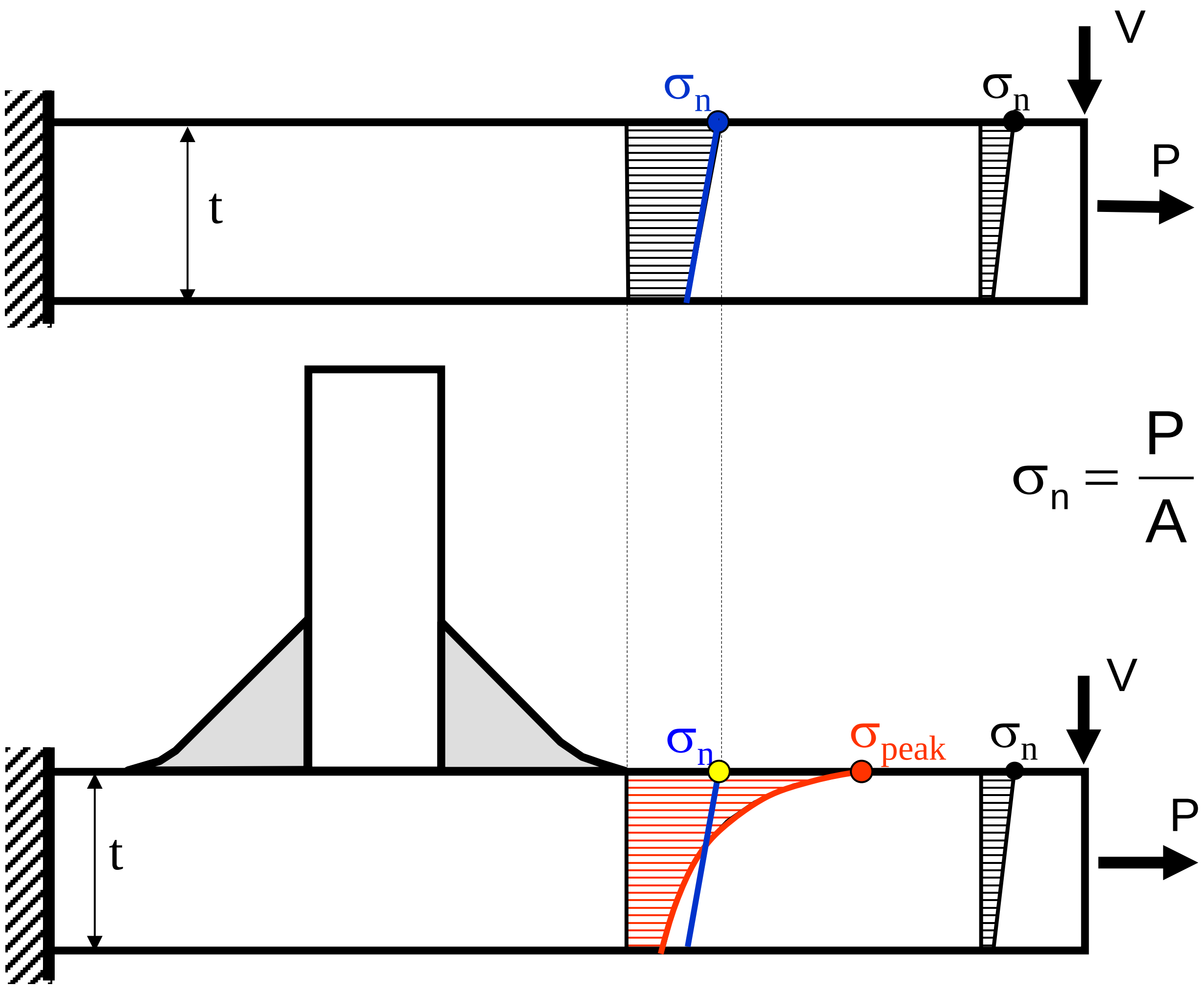


Stress magnitudes and distributions obtained from various FE models

Peak and Hot Spot Stress



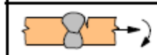
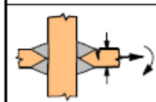
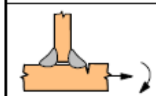
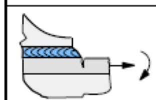
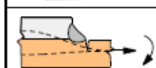
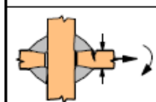
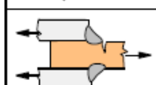
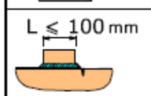
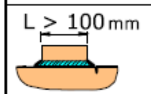
Physical Meaning of Hot Spot Stress



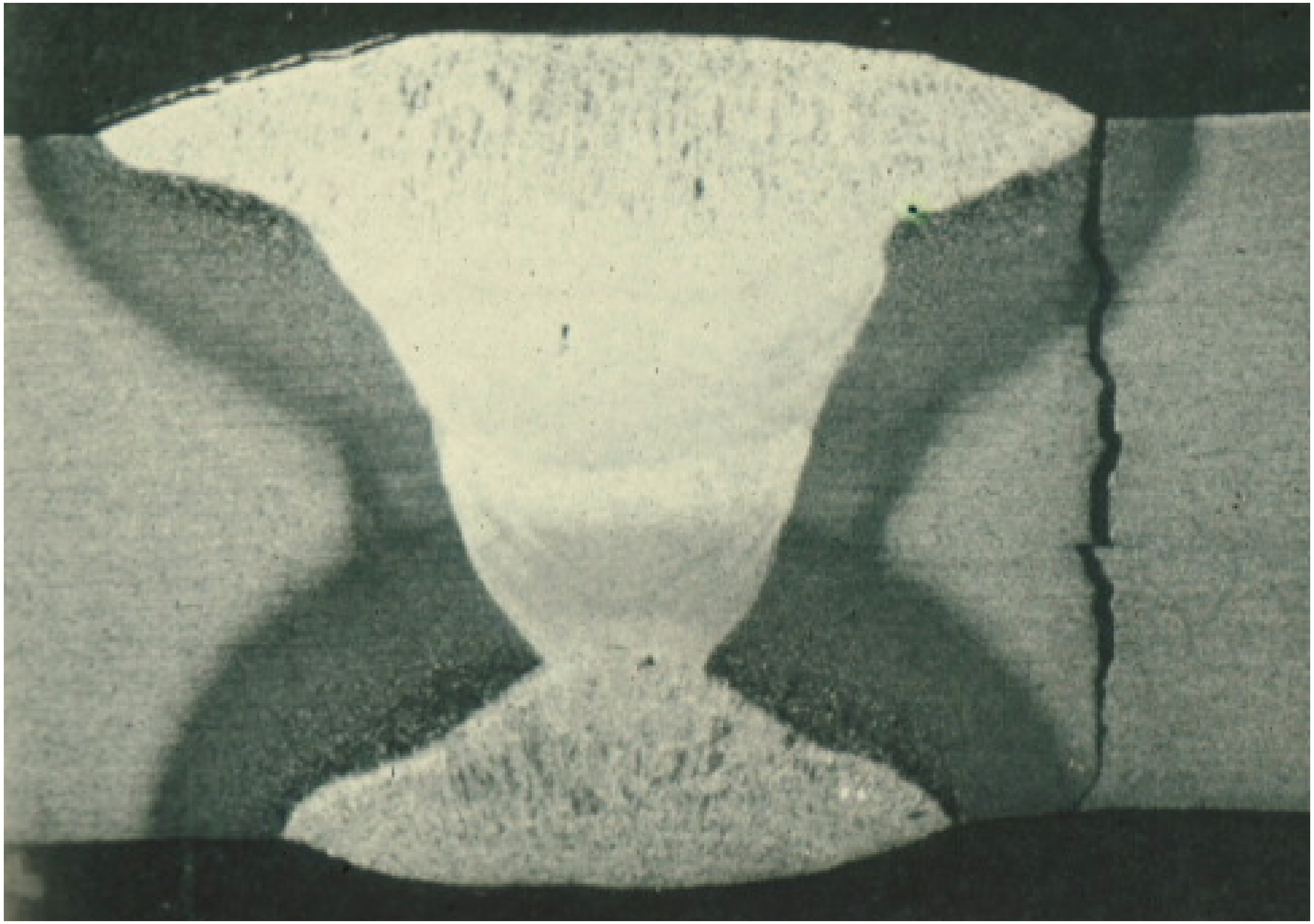
$$\sigma_n = \frac{P}{A} + \frac{Mc}{I}$$

Hot Spot SN Curves

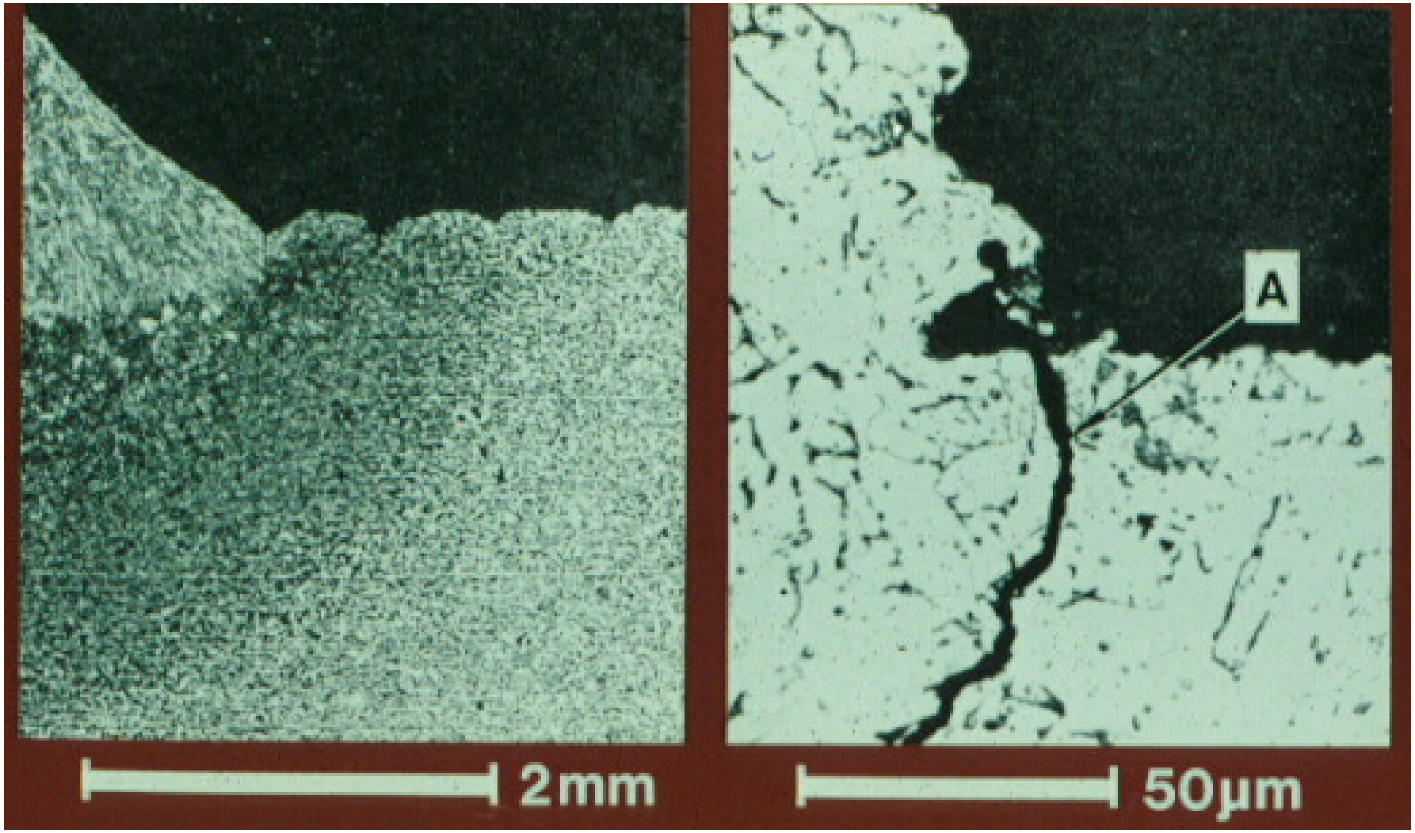
Table 3. *Hot spot S-N curves for steel plates up to 25 mm thick.*

Joint	Description	Quality	FAT	$\Delta\sigma_{R,L}$	n
	Butt joint	As-welded, NDT.	100	74	0.2
	Cruciform or T-joint with full penetration welds	K-butt welds, no lamellar tearing.	100	74	0.3
	Non-load carrying fillet welds	Transverse non-load carrying attachment, not thicker than the main plate, as-welded.			
	Bracket end, welds either welded around or not	Fillet weld(s) as-welded			
	Cover plate ends and similar joints				
	Cruciform joint with load-carrying fillet welds	Fillet weld(s) as-welded	90	66	0.3
	Lap joint with load-carrying fillet welds				
	Type "b" joint with short attachment	Fillet or full penetration weld, as-welded.	100	74	0.1
	Type "b" joint with long attachment	Fillet or full penetration weld, as-welded.	90	66	0.1

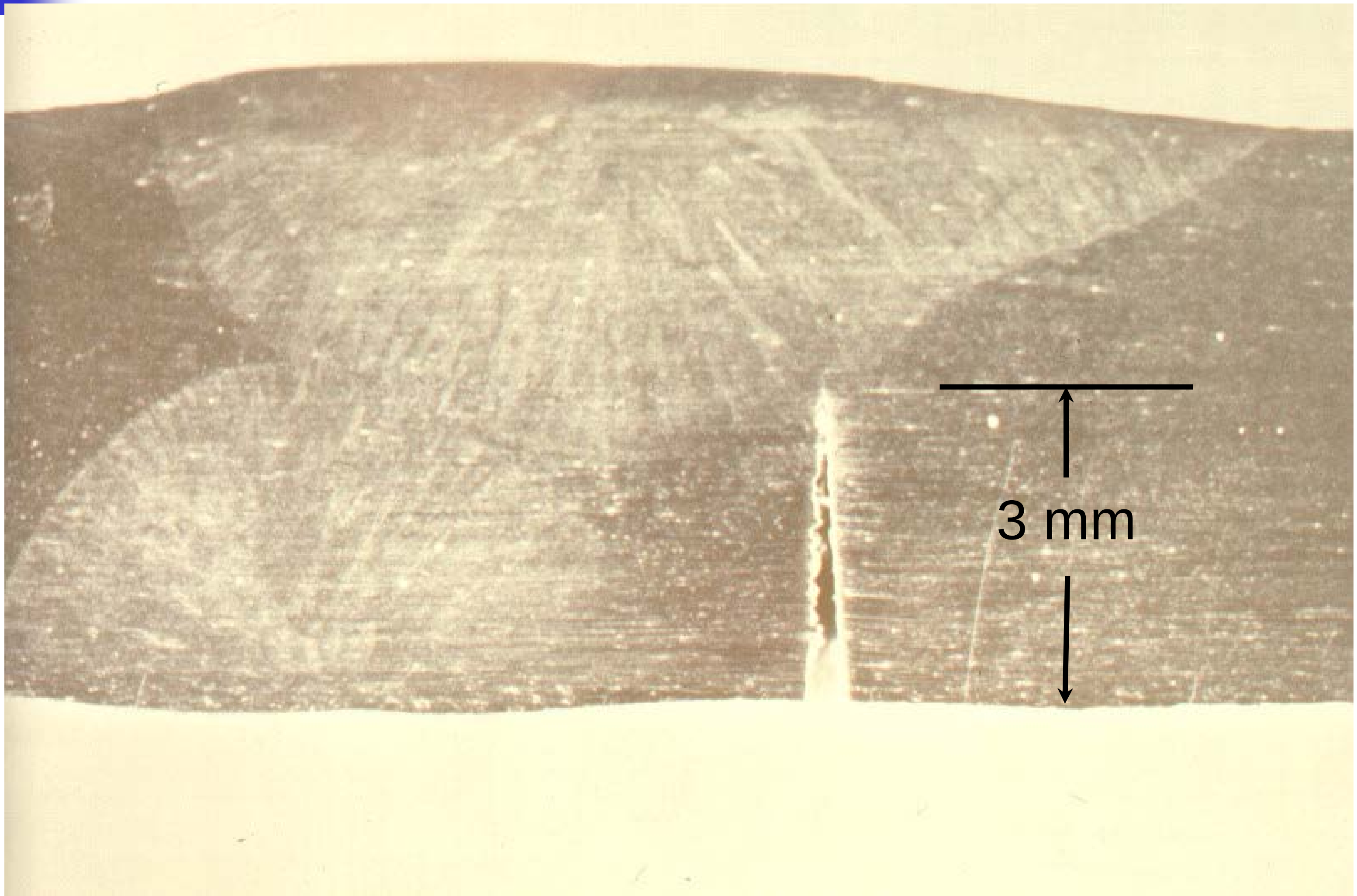
Typical Butt Weld



Weld Toe



Macroscopic LOF



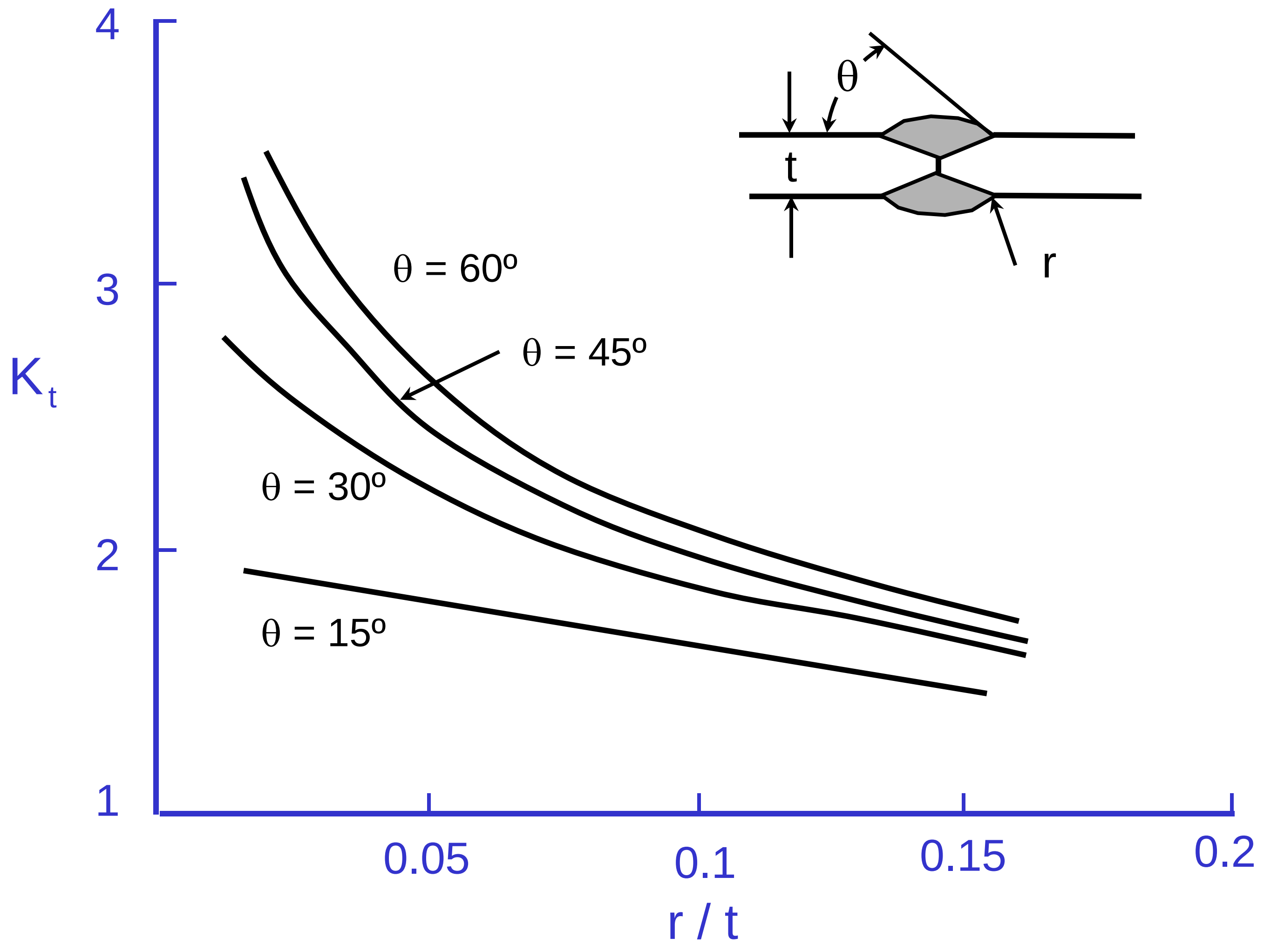
Weld Flaws

Even good welds contain initial crack like flaws 0.1 to 1 mm long. Reducing the size or eliminating these flaws will substantially improve fatigue lives.

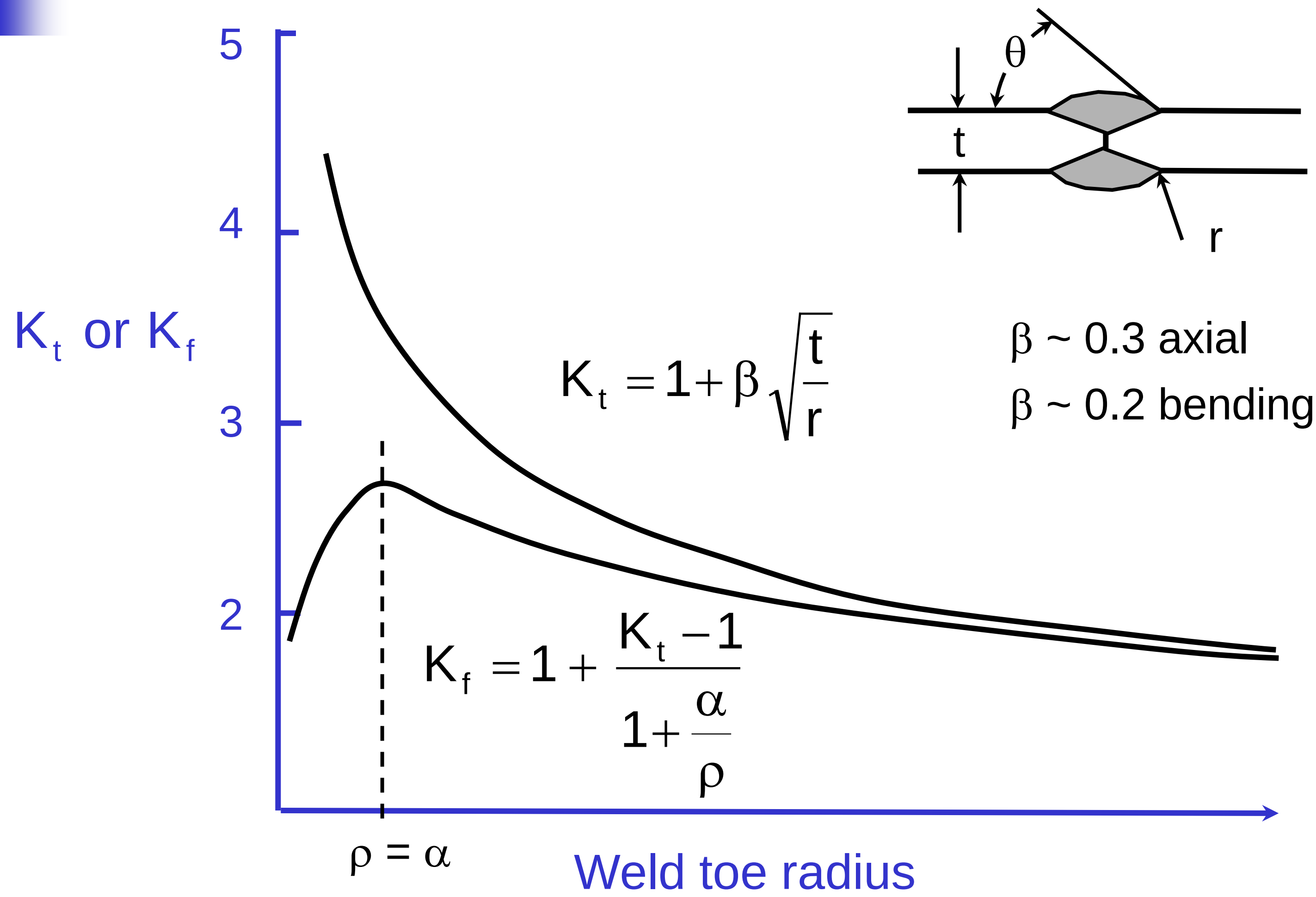
Weld Improvement

- Reduce weld toe stresses
- Stress relieve
- Improve local geometry

Macroscopic Shape



K_{fmax}



$$K_{f\,max} = 1 + 0.15\,\beta\,S_u\sqrt{t} \quad MPa\sqrt{m}$$

Things Worth Remembering

- Local weld toe stresses, geometry and flaws control the life of weldments

Fatigue Seminar