Task 6 - Safety Review and Licensing
On the Job Training on Stress Analysis

Static strength and High and Low-Cycle Fatigue at room temperature 2/2

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Pisa (Italy)
June 15 – July 14, 2015

Content

- Fatigue of metals
  - Definitions
  - Different approaches to fatigue, Stress/ Strain life
  - Low/ High Cycle Fatigue
  - Fatigue notch sensitivity

Books on Metal fatigue

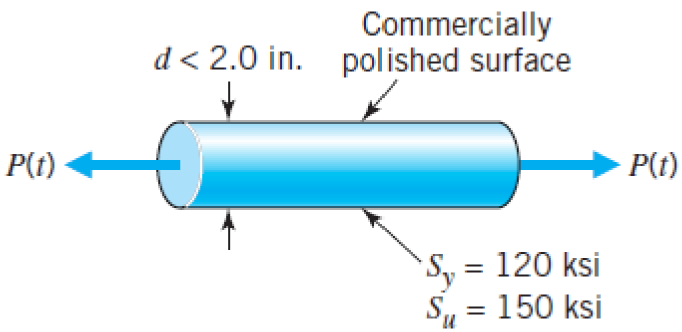
S. Suresh. Fatigue of Materials. Cambridge University Press 1998.

H. E. Boyer. Atlas of Fatigue Curves. ASM International 2003.

R. I. Stephens, A. Fatemi, R. R. Stephens, H. O. Fuchs . Metal Fatigue in Engineering. Wiley 2001.

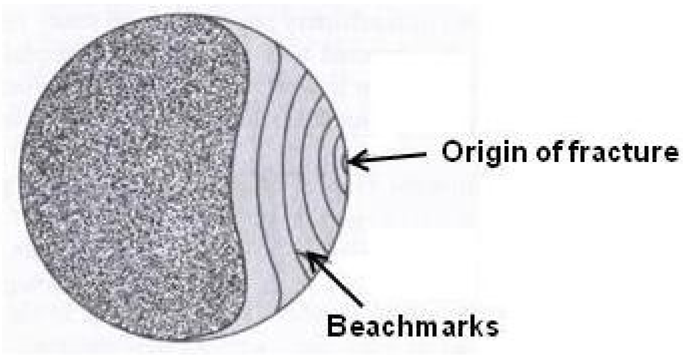
… and many many others

Cyclic load leading to fracture

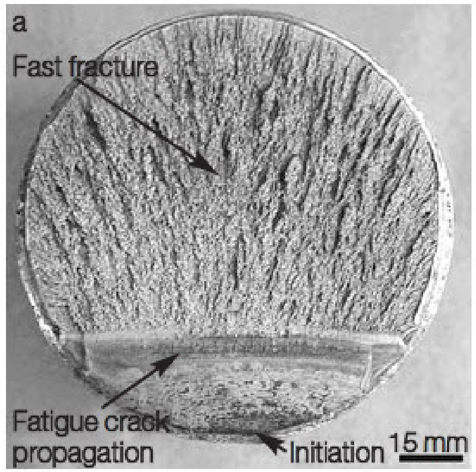


Cyclic loading, repeated thousands or even millions of times

Eventual
Fatigue Fracture

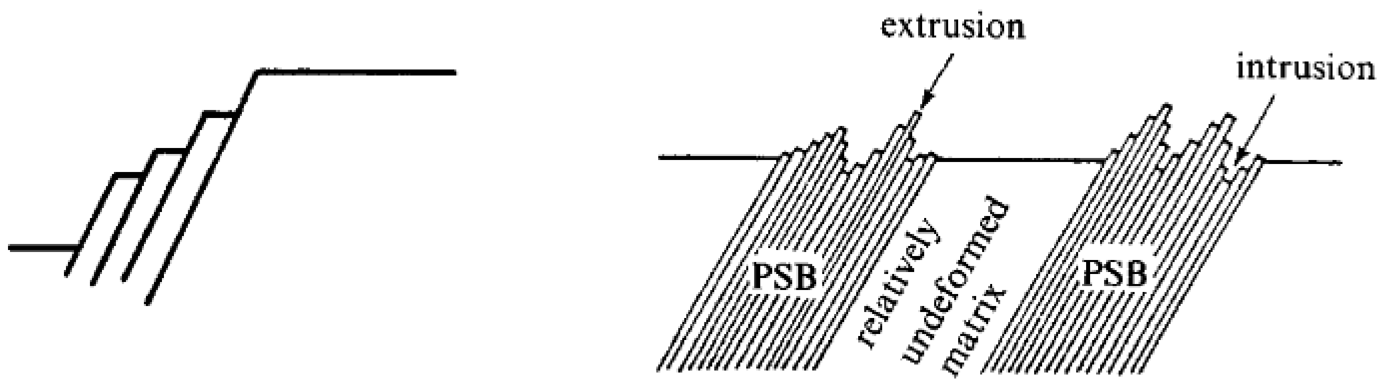


Fatigue Fracture with Beachmarks



Nucleation

Persistent Slip Bands, PSBs

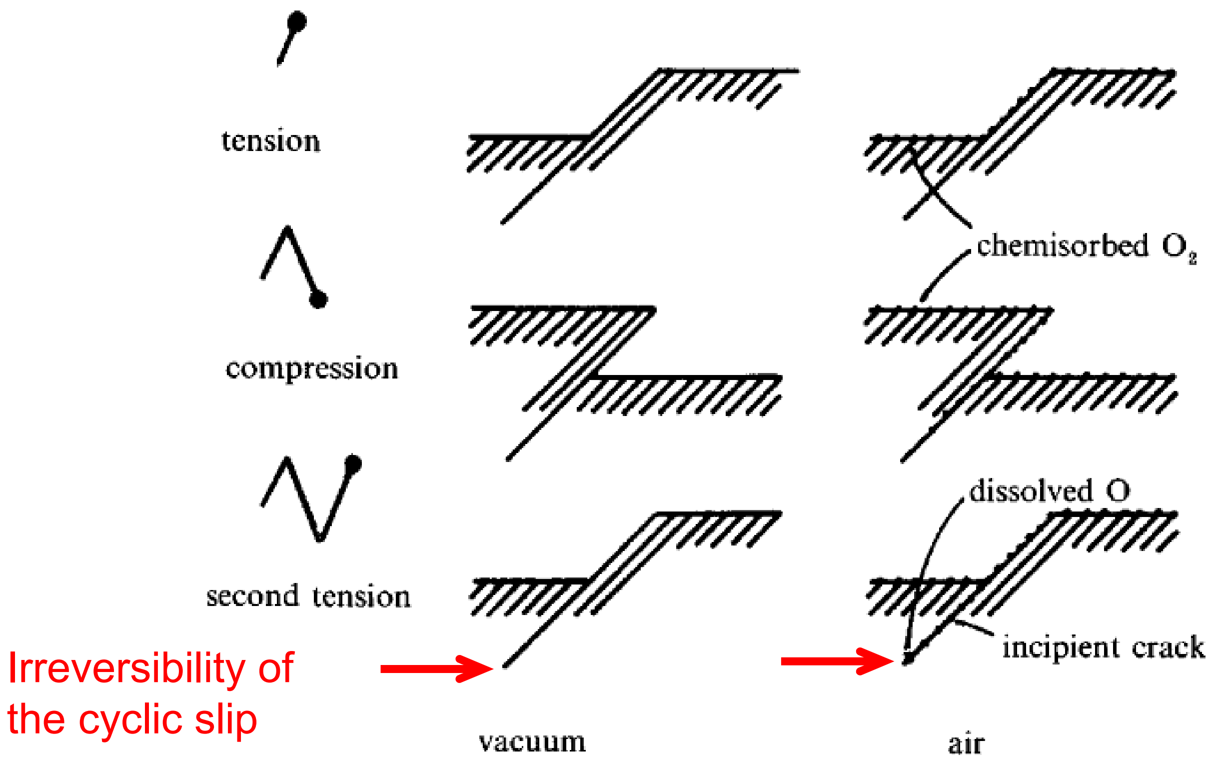


(*a*) (*b*)

These slip lines were termed 'persistent slip bands' (PSBs) by Thompson, Wadsworth & Louat (1956) who found that in Cu and Ni, the bands persistently reappeared at the same sites during continued cycling even after a thin layer of the surface containing these bands was removed by electropolishing.

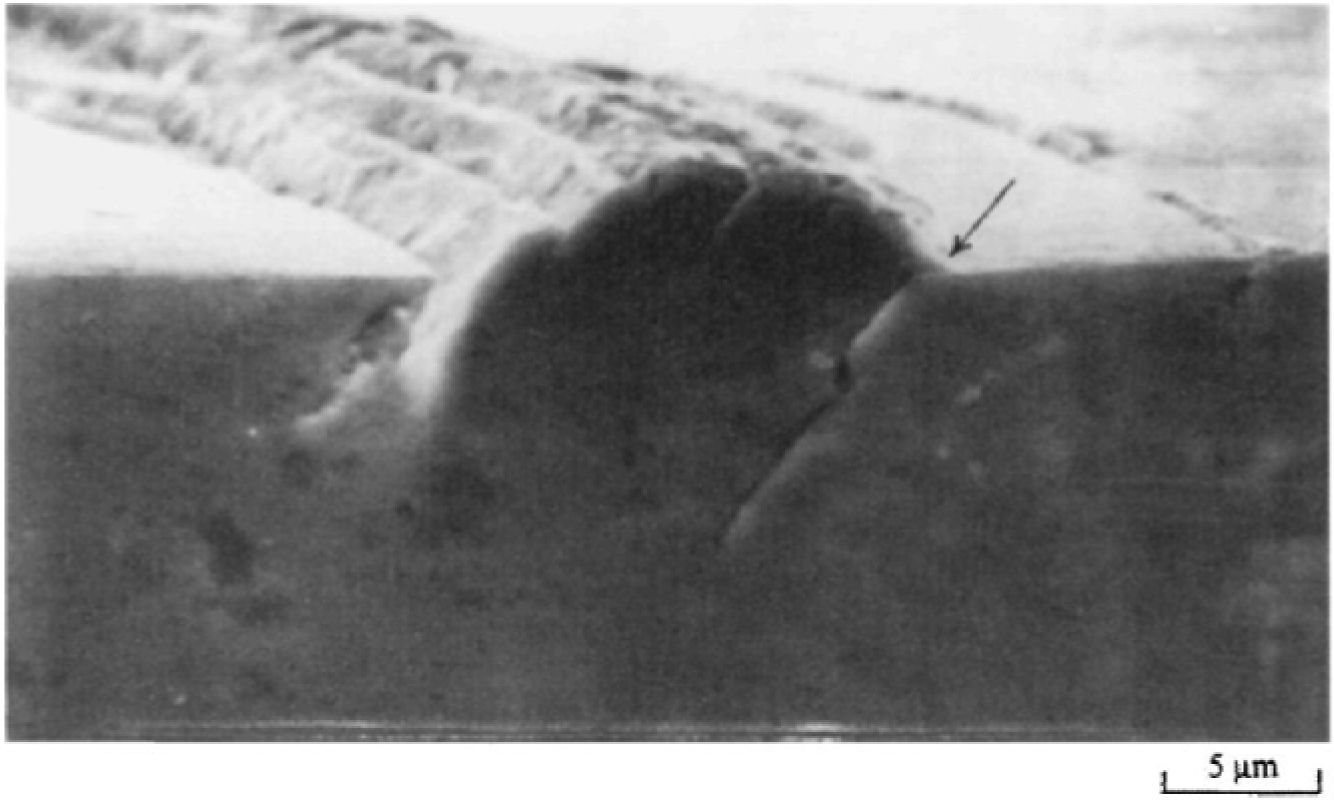
Nucleation

"Embryo" crack formation from PSBs



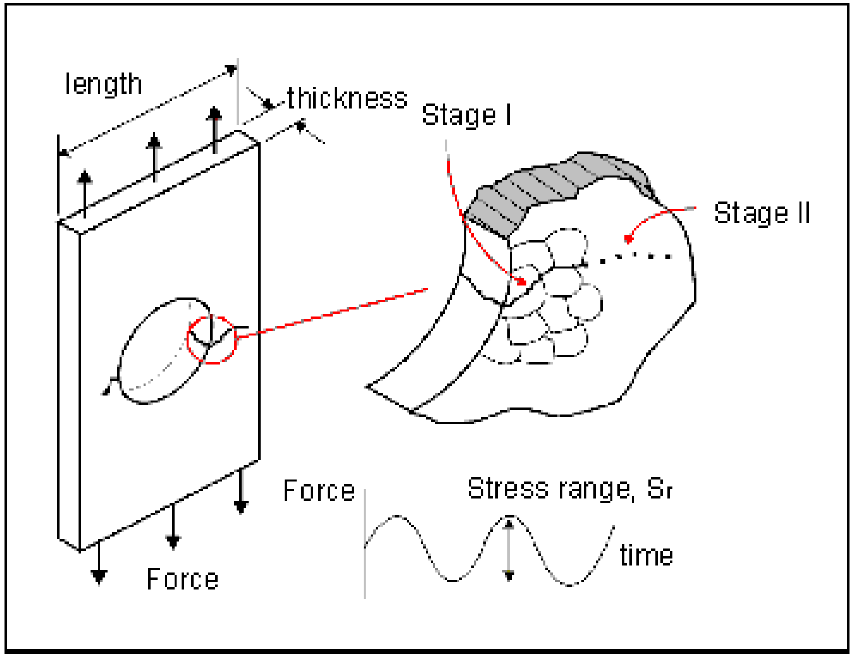
Nucleation

"Embryo" crack formation from PSBs

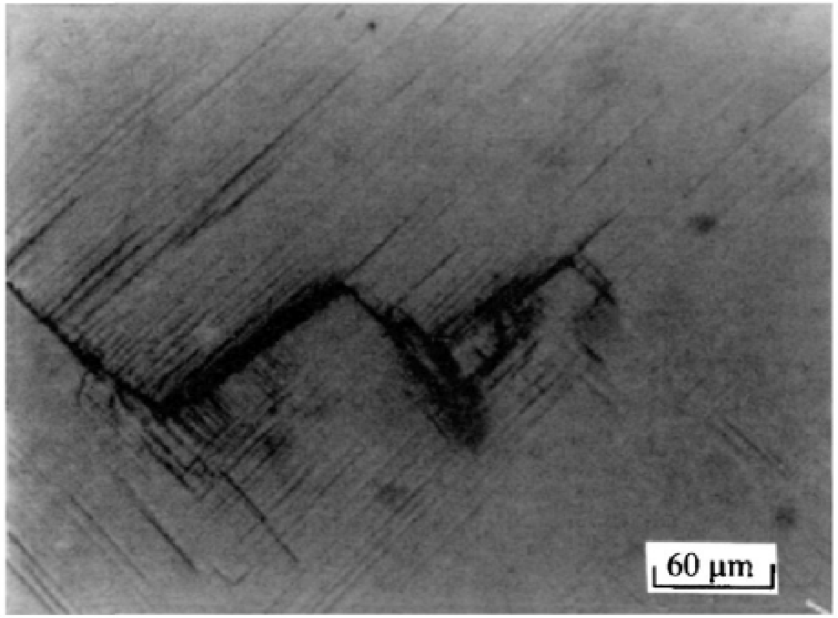


Stage I – Stage II

Forsyth ~1960



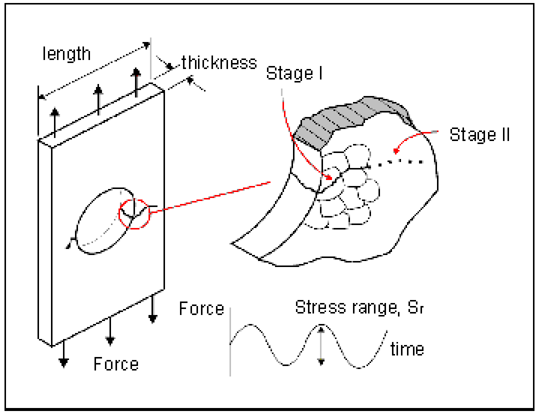
Stage I: propagation at 45°, single path or “zig-zag”, within a single grain (or very few grains)



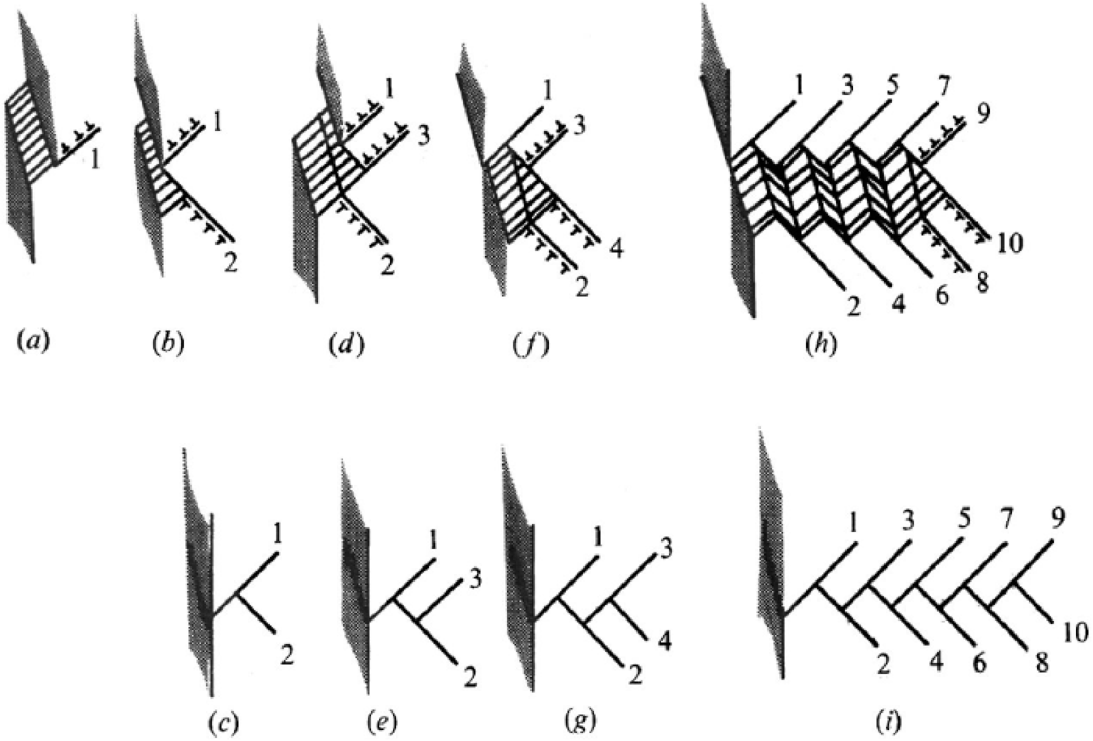
Single slip system

Stage I – Stage II

Forsyth ~1960

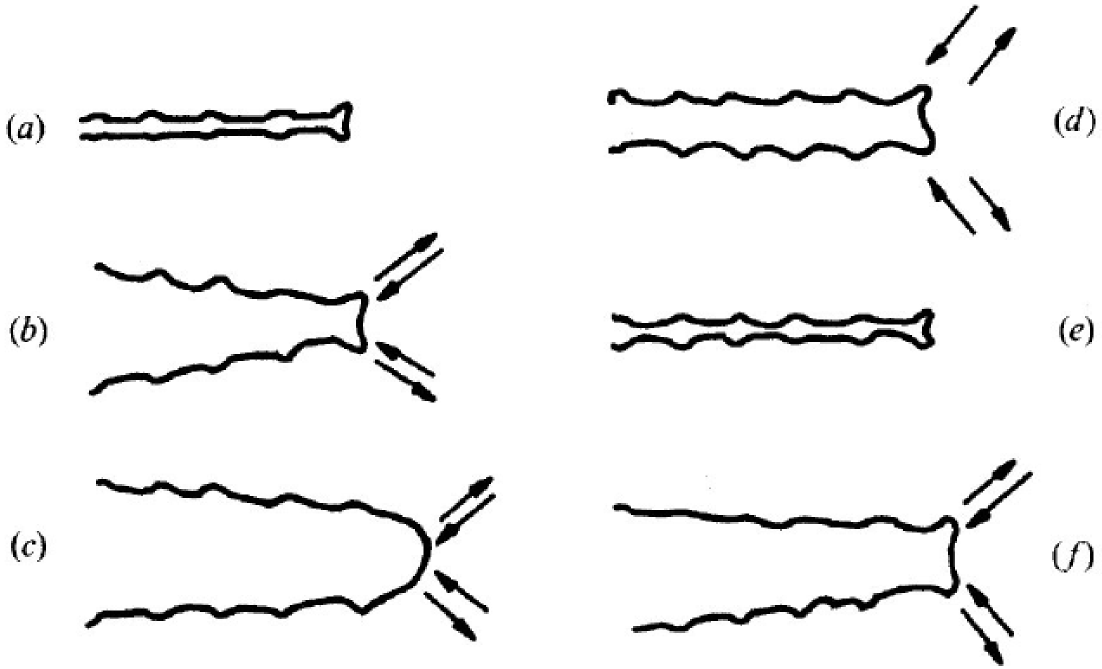


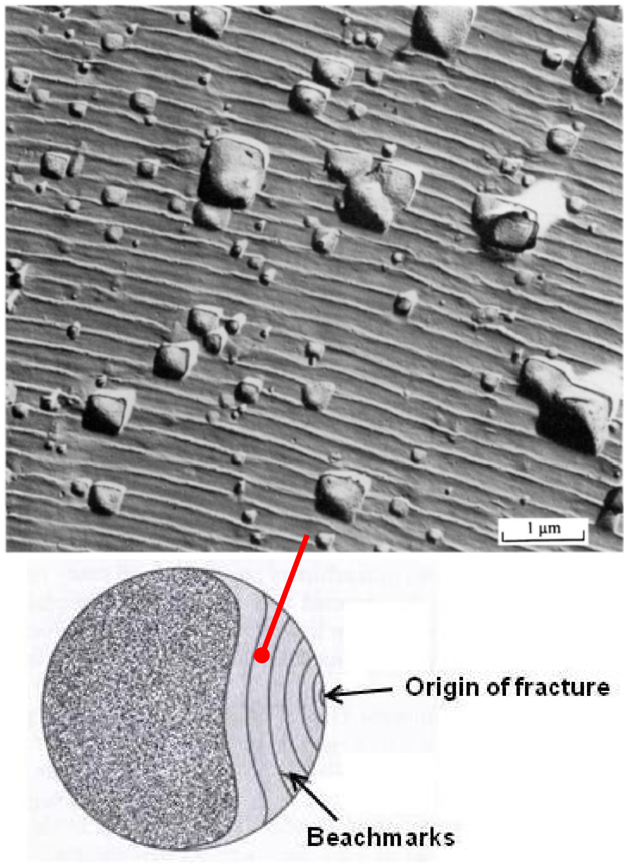
Stage II: perpendicular propagation on many grains



Two slip systems

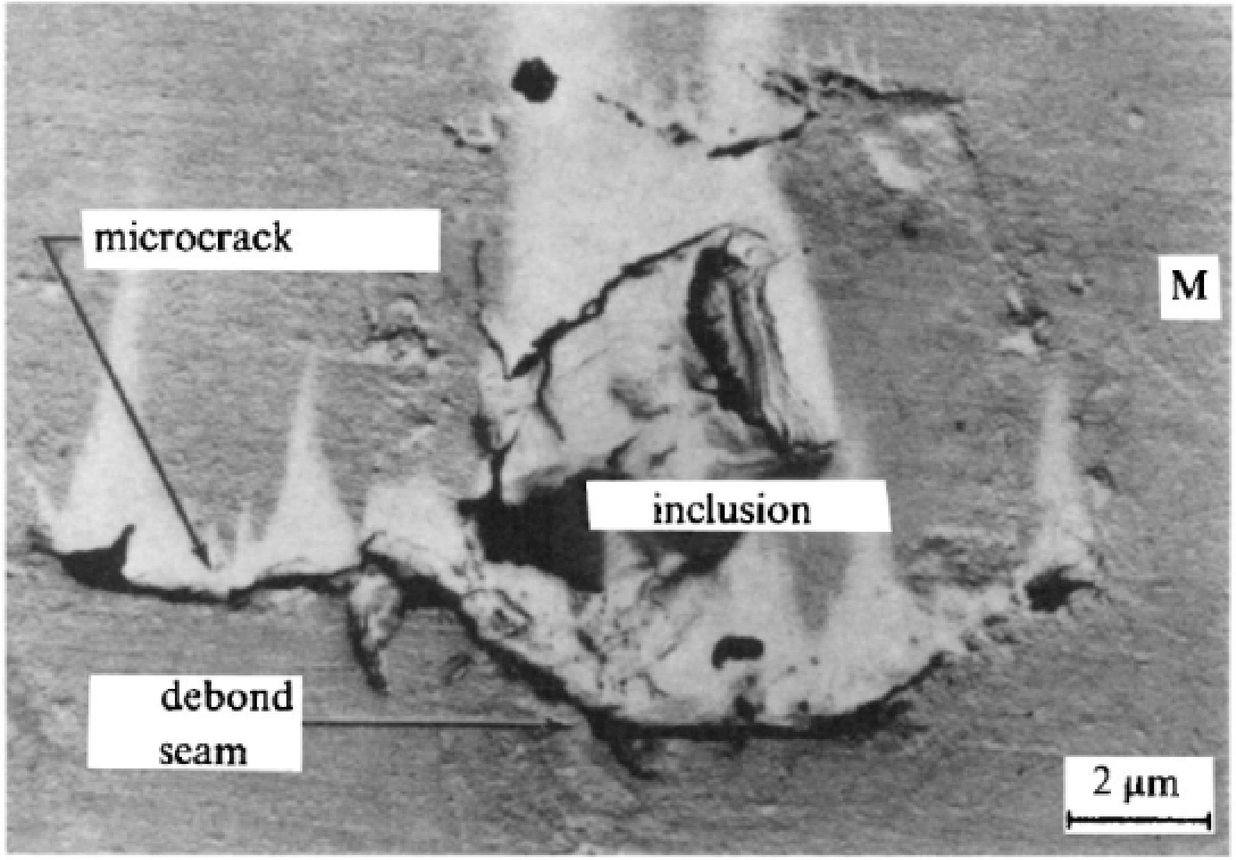
Stage II propagation and striations (beachmarks)



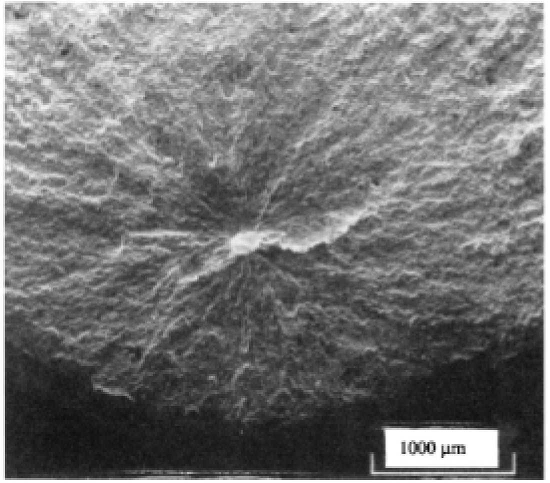


Fatigue Fracture with Beachmarks

Stage I usually at Inclusions (or other defects) in commercial metals

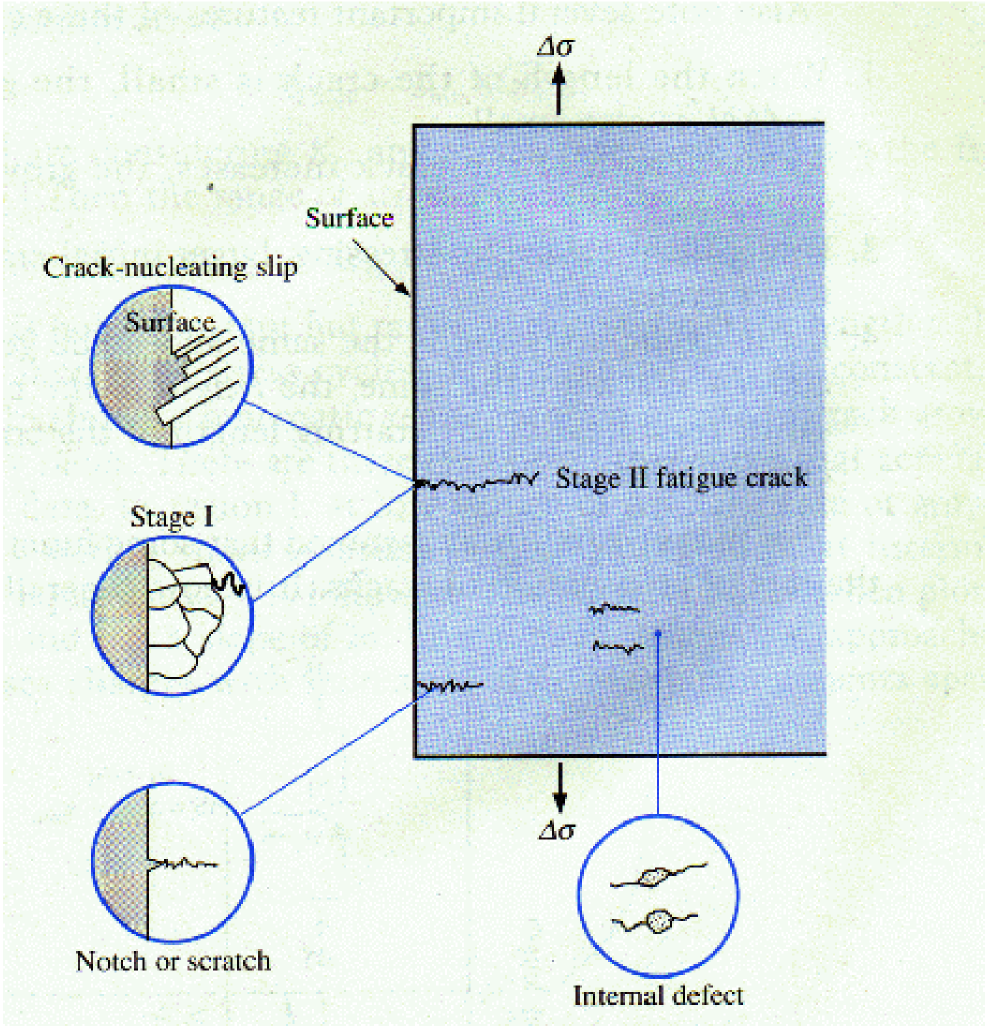


Even subsurface nucleation

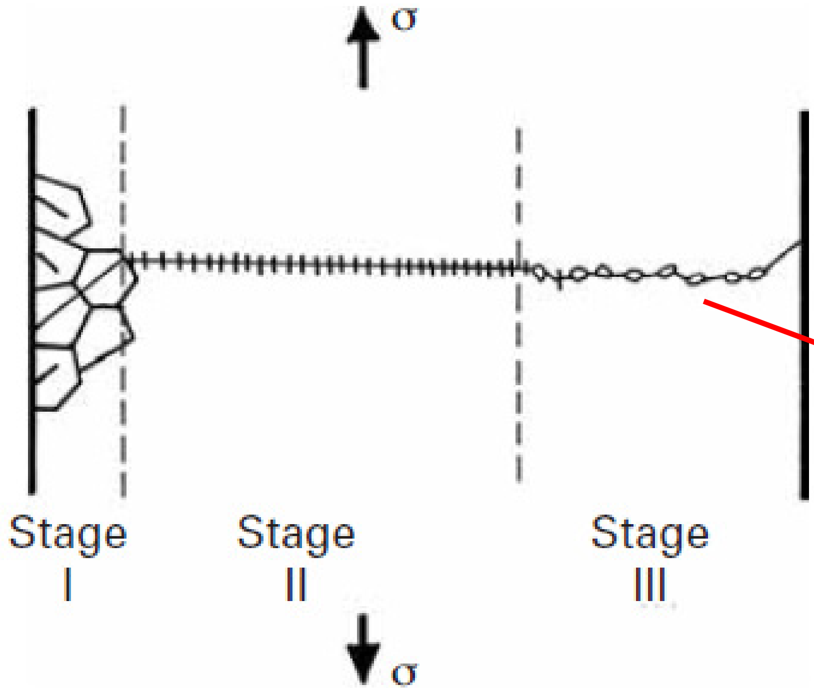


Different possible

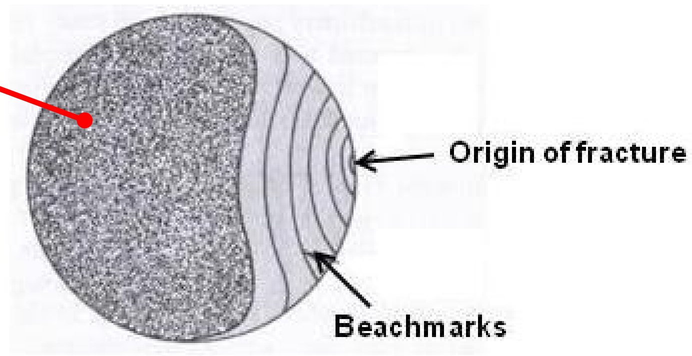
nucleation scenarios



Stage III is the final fracture, so called "Sudden" or "Unstable"



This can be considered a <u>static</u> fracture…



Fatigue Fracture with Beachmarks

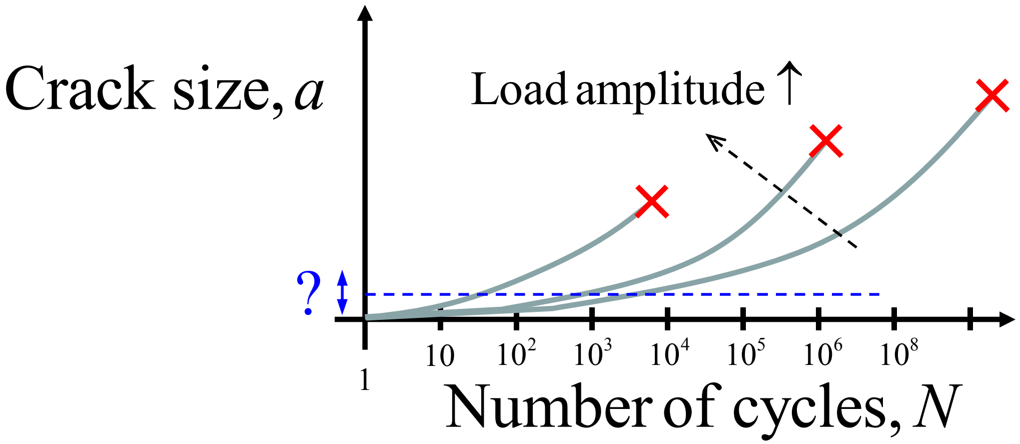
What is the transition point from Nucleation to Propagation?

Stage I to Stage II

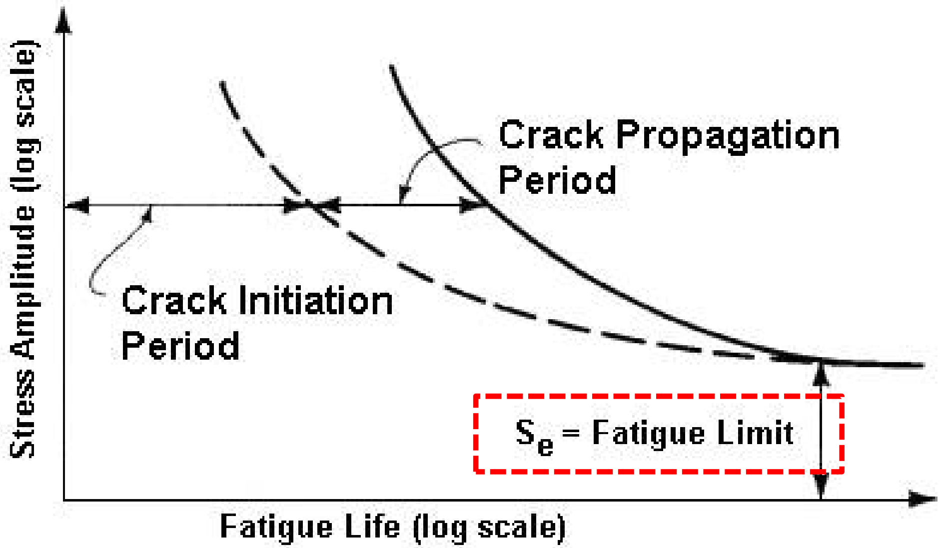
1 mm

It does not matter

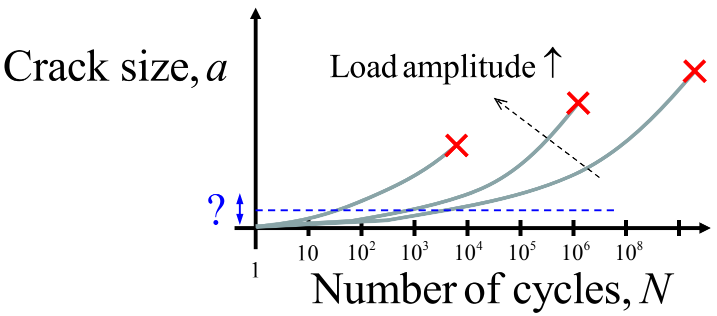
It depends on the <u>inspection</u> method



Nucleation to Propagation percentage of the entire fatigue life



No crack evolution below the Fatigue Limit
Design value



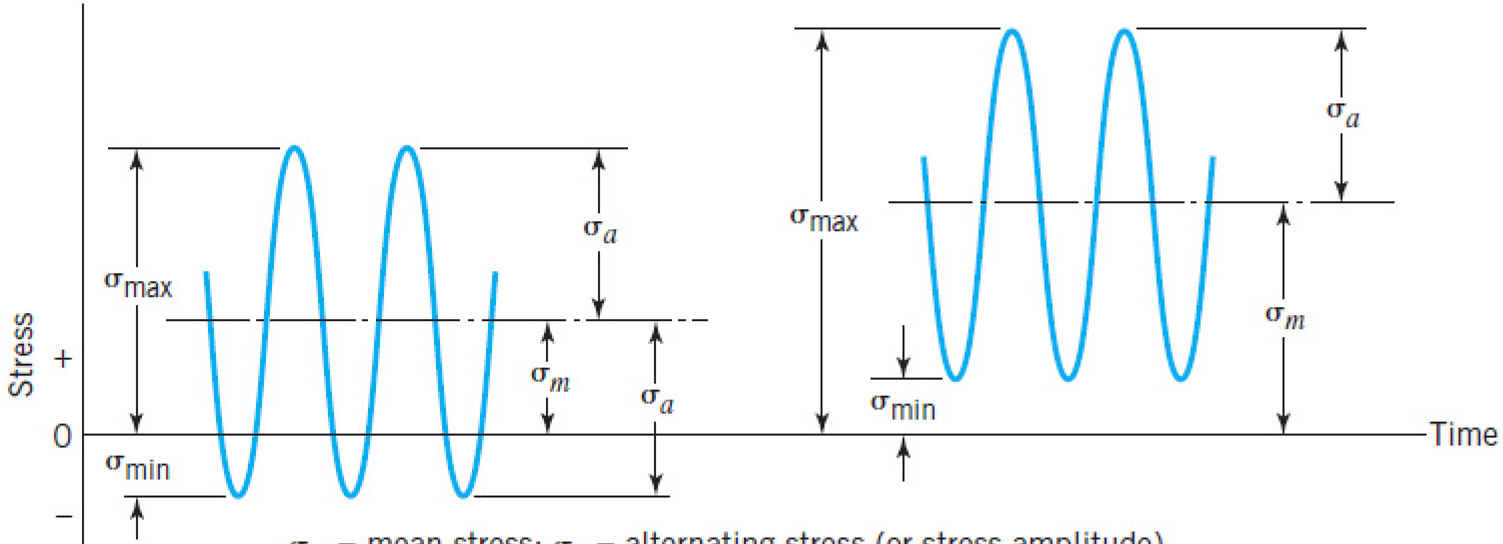
Engineering approaches

Stress life (High Cycle Fatigue – HCF)

Strain life (Low Cycle Fatigue – LCF)

Fracture Mechanics (Damage Tolerant Design)

Definitions



σ_m = mean stress; σ_a = alternating stress (or stress amplitude)

σ_{max} = maximum stress; σ_{min} = minimum stress

$\sigma_m = (\sigma_{max} + \sigma_{min})/2$

$\sigma_a = (\sigma_{max} - \sigma_{min})/2$

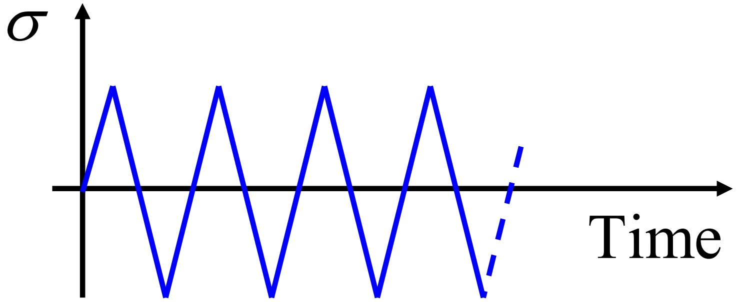
Amplitude and mean stresses

Definitions

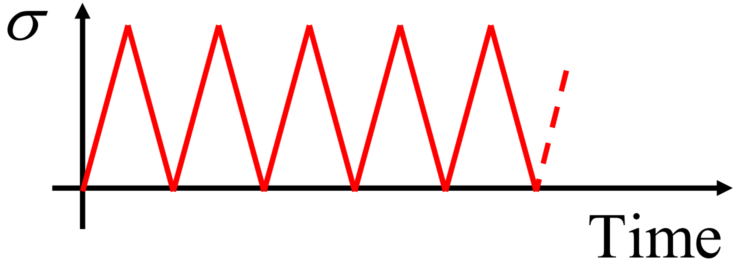
$$\text{Load ratio: } R = \frac{\sigma_{\min}}{\sigma_{\max}}$$

$$\text{Ex.: Alternate load: } R = -1$$

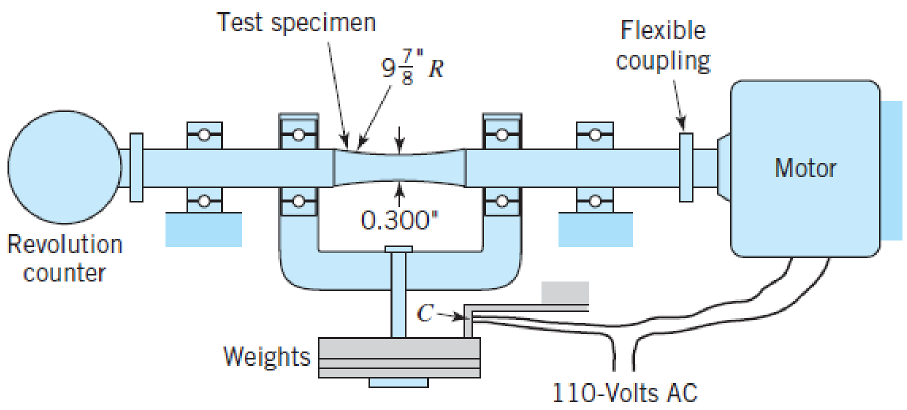
(default for testing)



$$\text{Repeated load: } R = 0$$



S-N curves – Testing machines (historical)



Moore rotating bending machine
4-pont bending load scheme

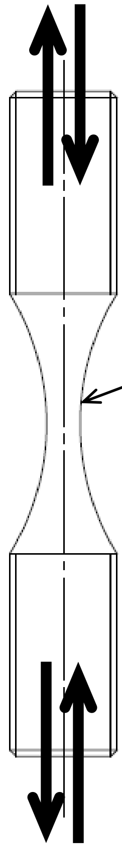
Homework:

Find the load cycle experienced at the mid section of the specimen, depending on the weight and sizes of the specimen

S-N **curves – Testing machines**

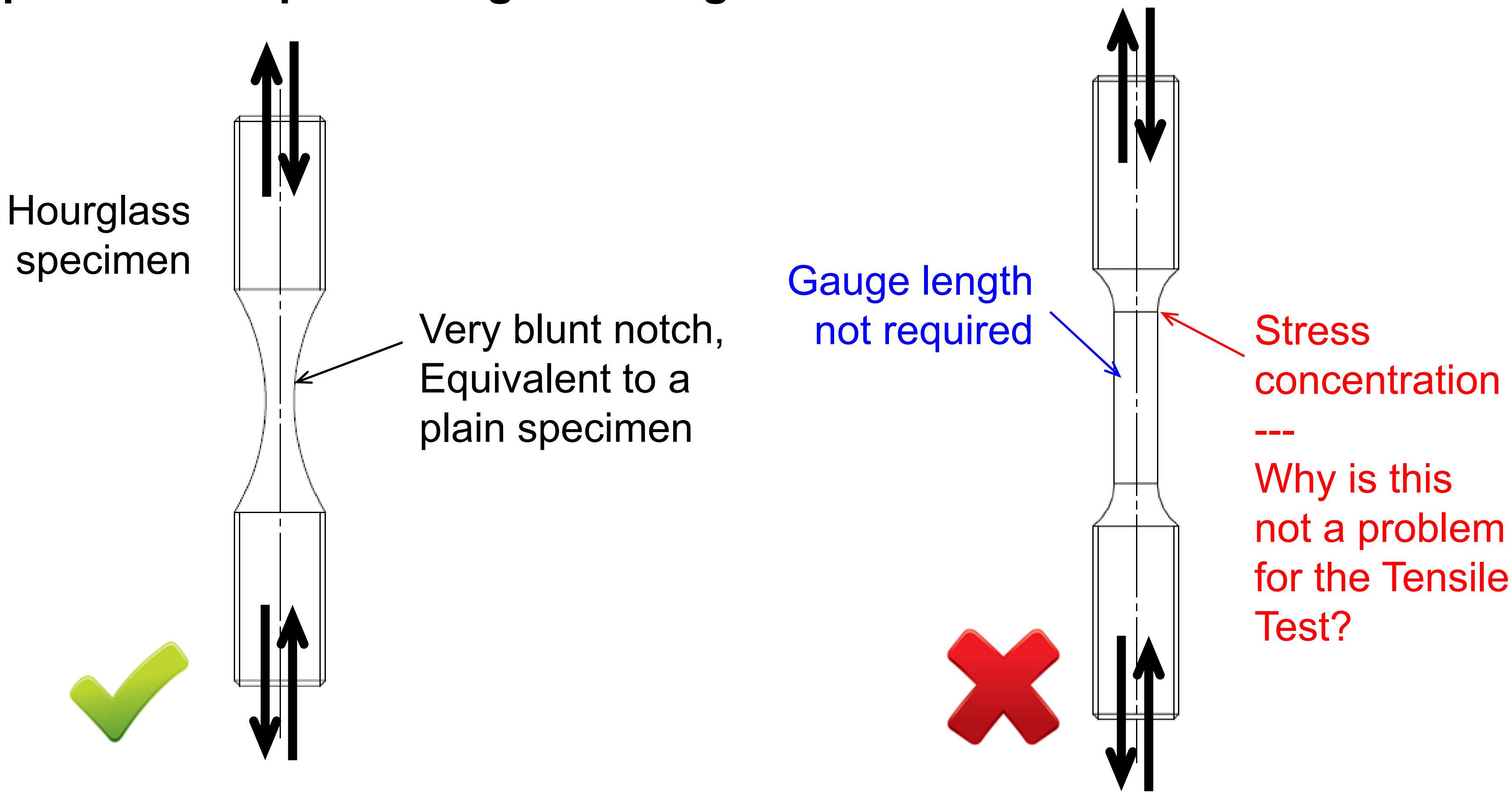
Resonance based
Push-pull fatigue
testing machine
100-150 Hz
Ex.: RUMUL

Hourglass
specimen



Very blunt notch,
Equivalent to a
plain specimen

Specimen shape for fatigue testing



S-N **curves, or Wöhler curve**

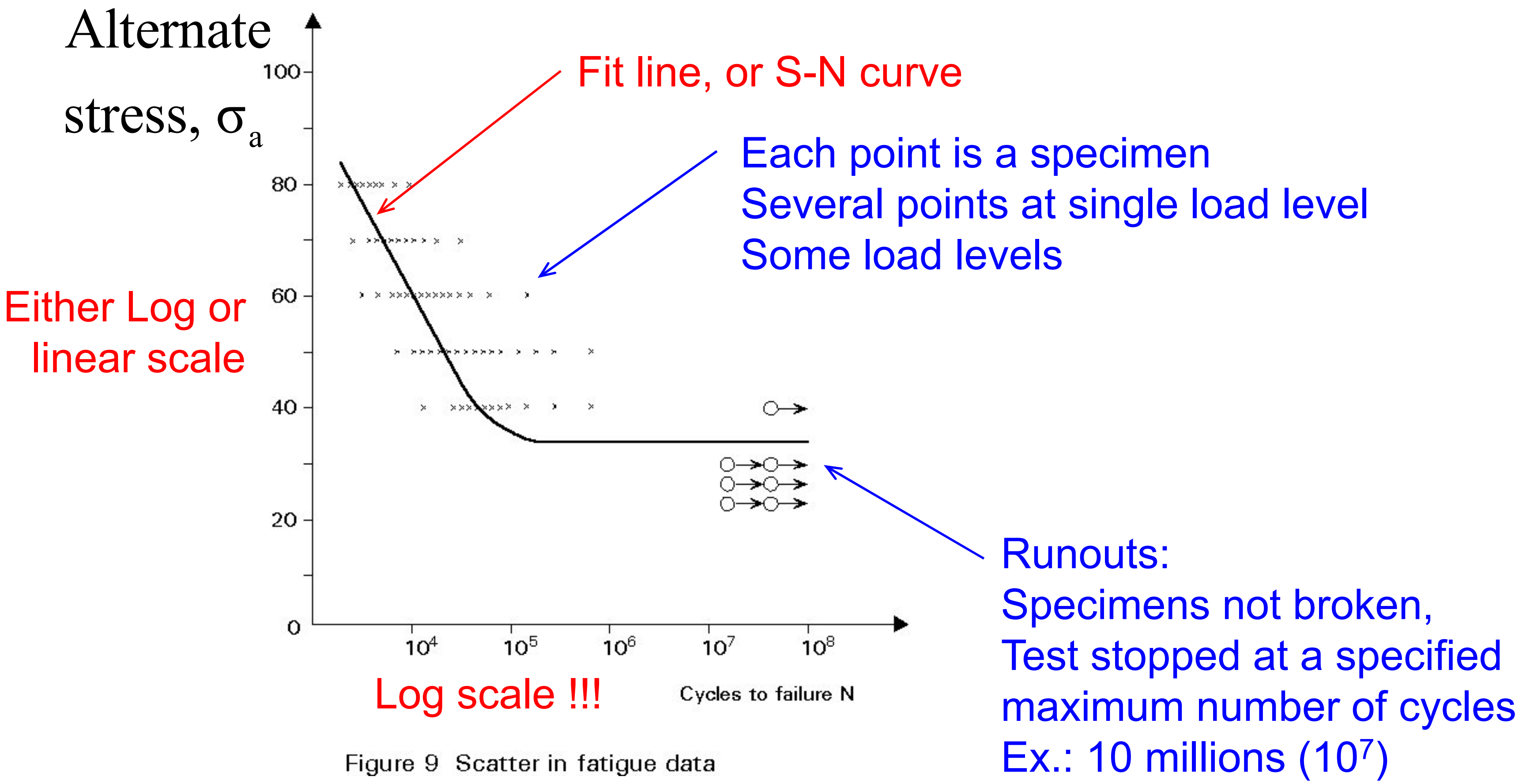
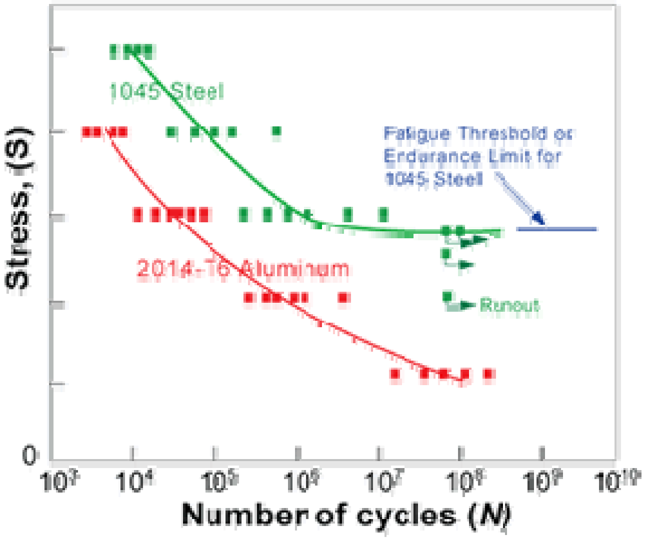
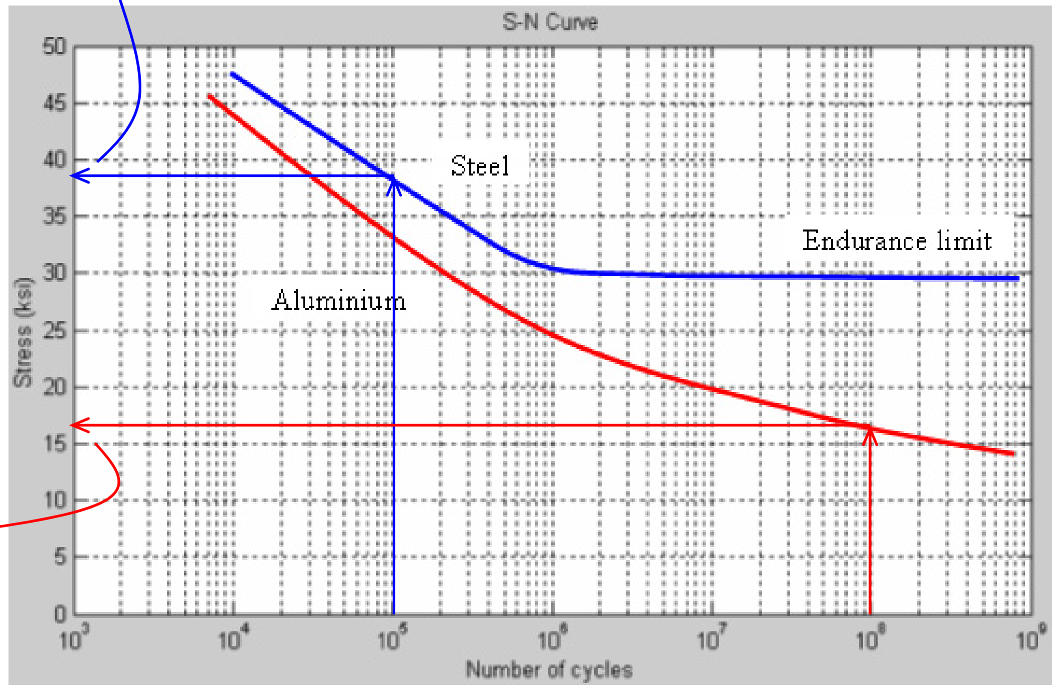


Figure 9 Scatter in fatigue data

Endurance limit, only for steels



Fatigue strength at 10^5



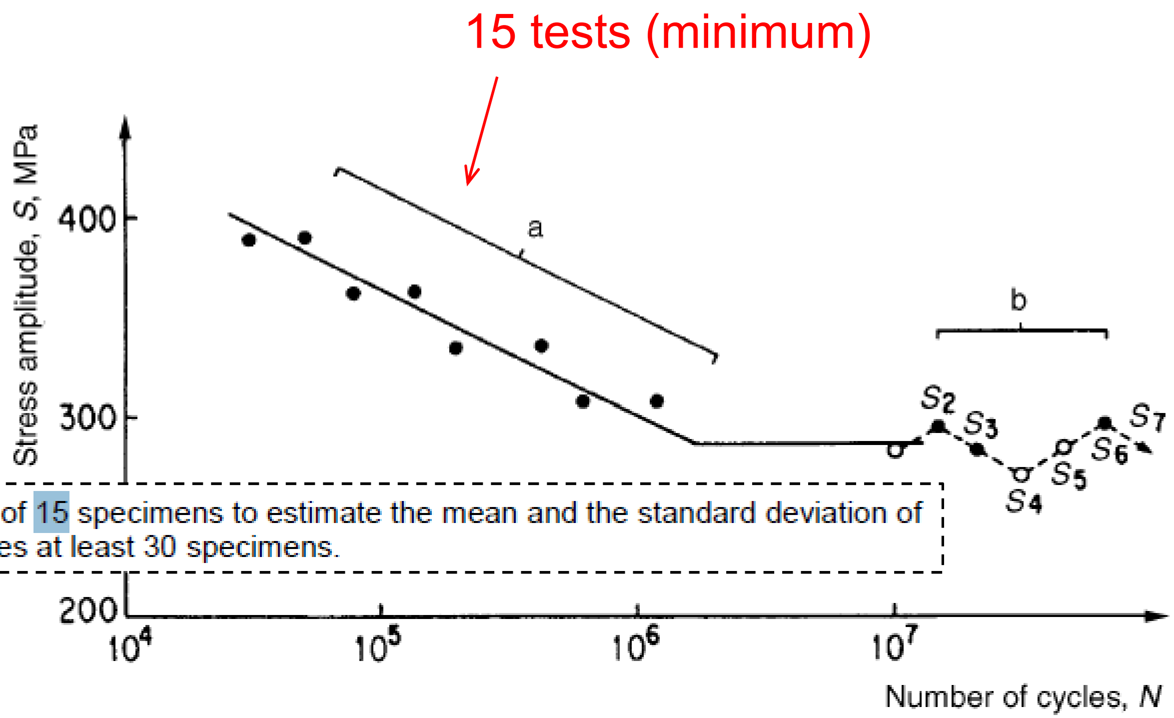
Fatigue strength at 10^8

Standard ISO 12107

BRITISH STANDARD

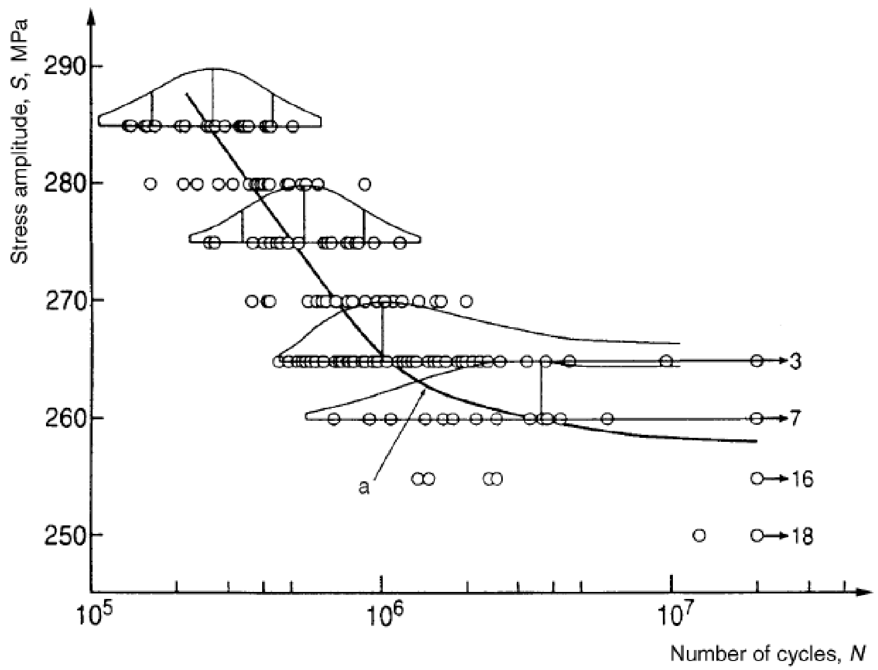
BS ISO 12107:2003

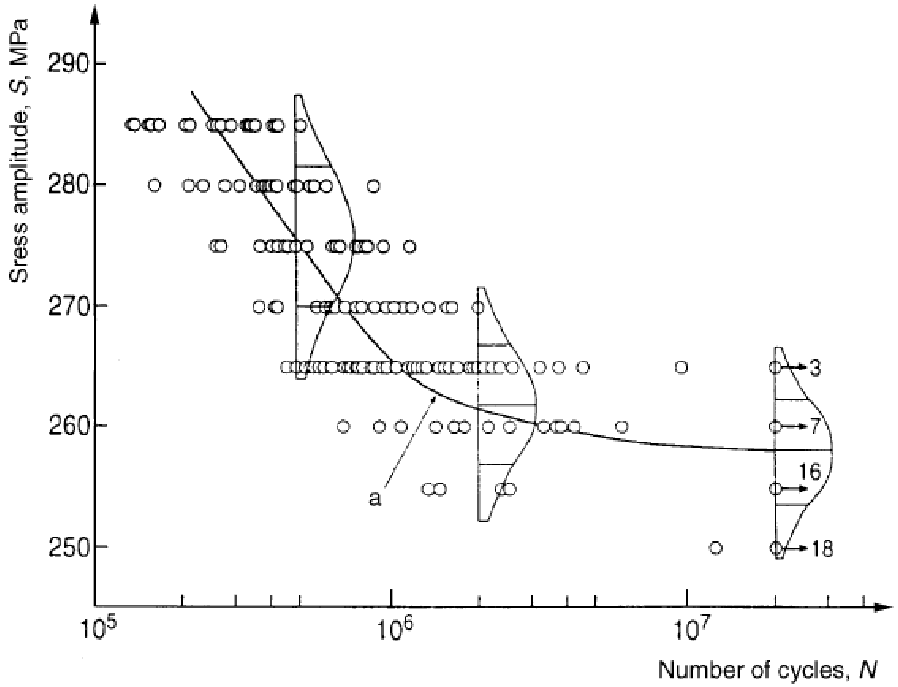
Metallic materials — Fatigue testing — Statistical planning and analysis of data



Exploratory research requires a minimum of 15 specimens to estimate the mean and the standard deviation of the fatigue strength. Reliability data requires at least 30 specimens.

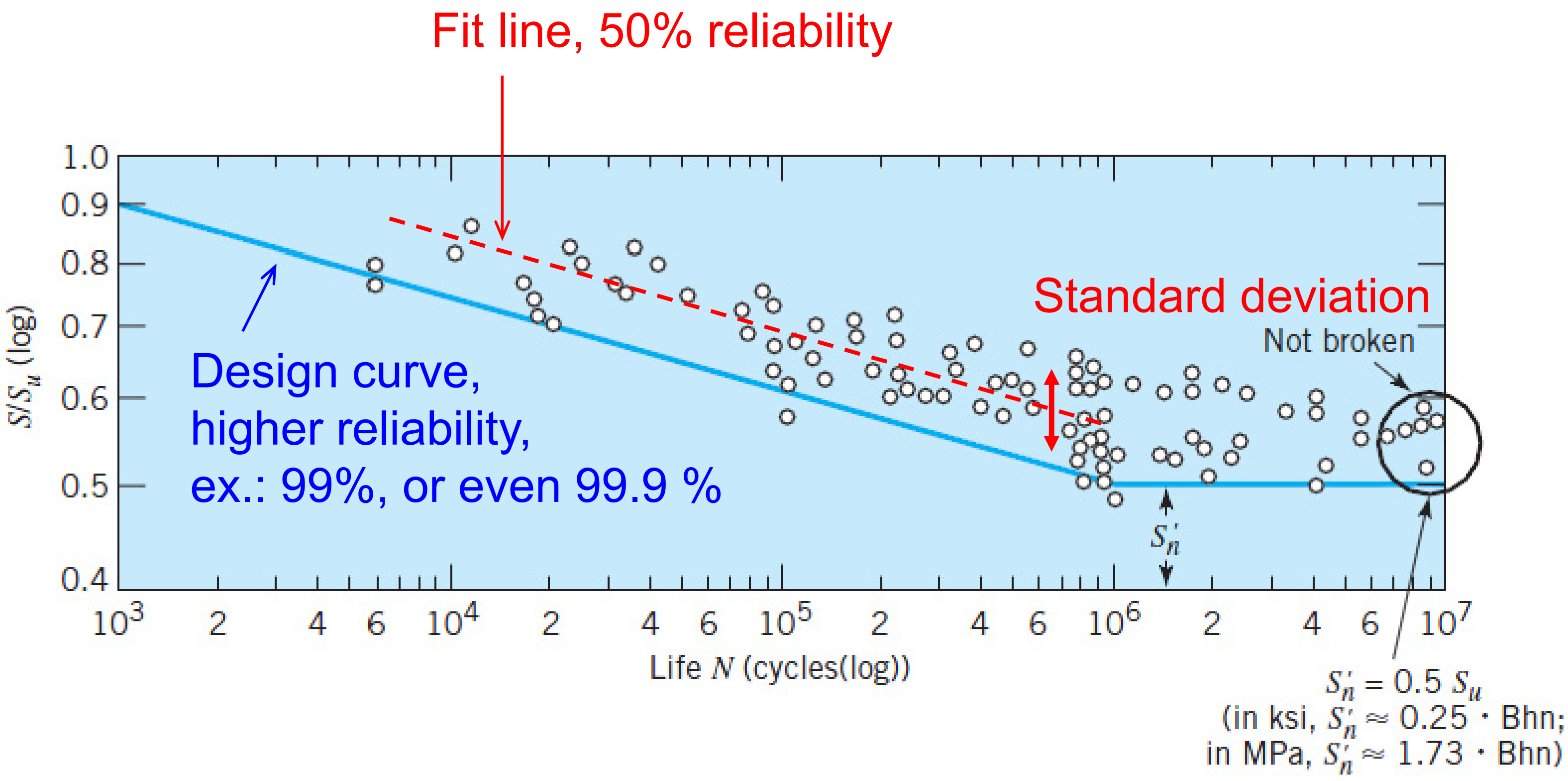
Number of cycle/ Stress scatter



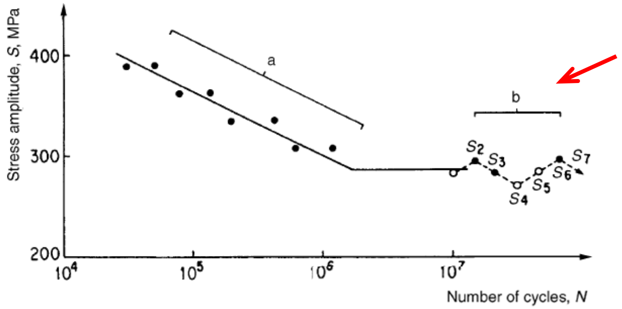


Very uncertain design values, especially in terms of Finite life Number of cycles to failure

Design curve



Testing procedure for Fatigue Endurance



Numerical procedure to calculate Mean and Standard Deviation

Table A.2 — Example of staircase test data

Stress S_i MPa	**Sequence number of specimen**																
			1				**5**					**10**					**15**
540									X								X
520				X				O		X		X				O	
500			O		X		O				O		X		O		
480		O*				O								O			
460	O*																

X for failure

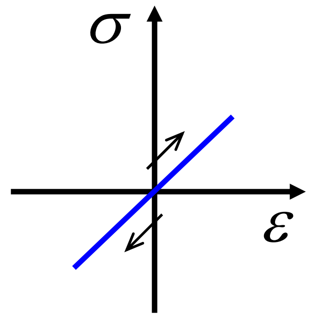
O for non-failure

* not counted

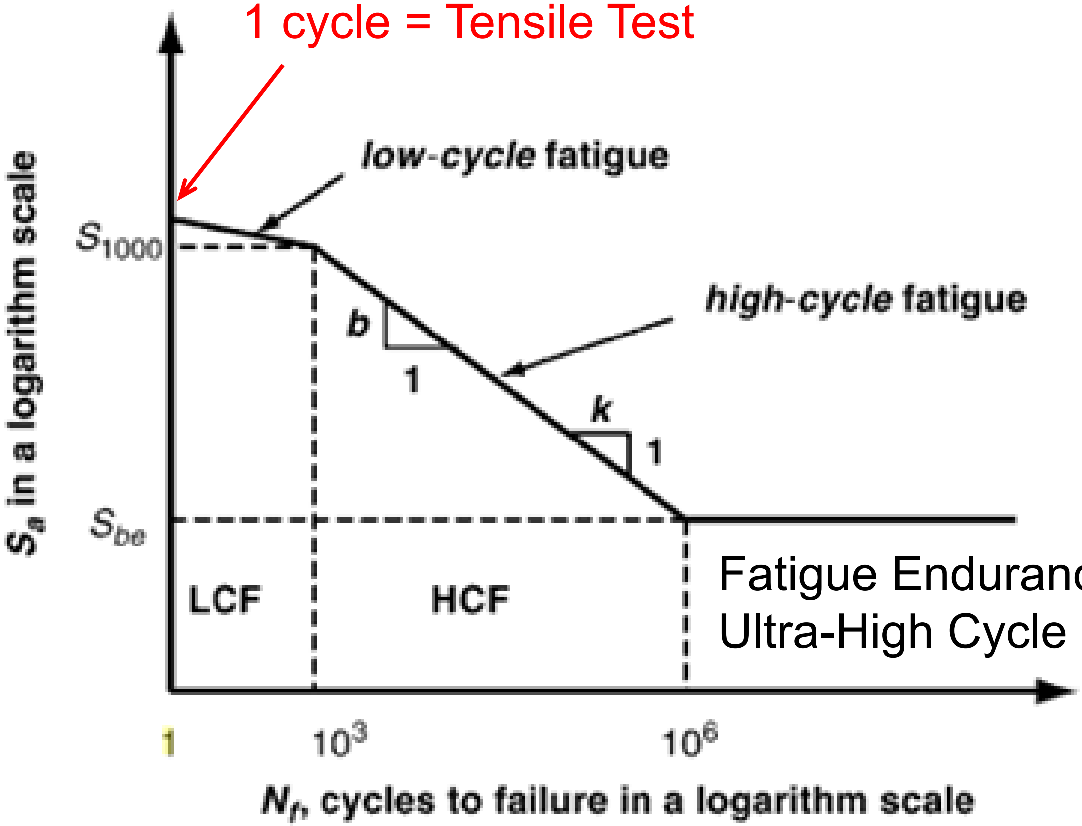
Number of required specimens: 15-20

Different regions of the *S-N* curve

HCF
Elastic
cyclic loading

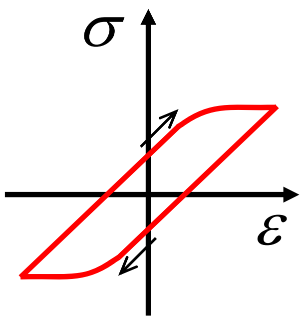


1 cycle = Tensile Test



Fatigue Endurance/
Ultra-High Cycle Fatigue (UHCF)

LCF
Elastic-plastic
cyclic loading



S-N **curve values for Steels**

$$R = -1$$

$$N_f = 1, \sigma_a = S_U$$

$$N_f = 10^3, \sigma_a \approx 0.9\, S_U$$

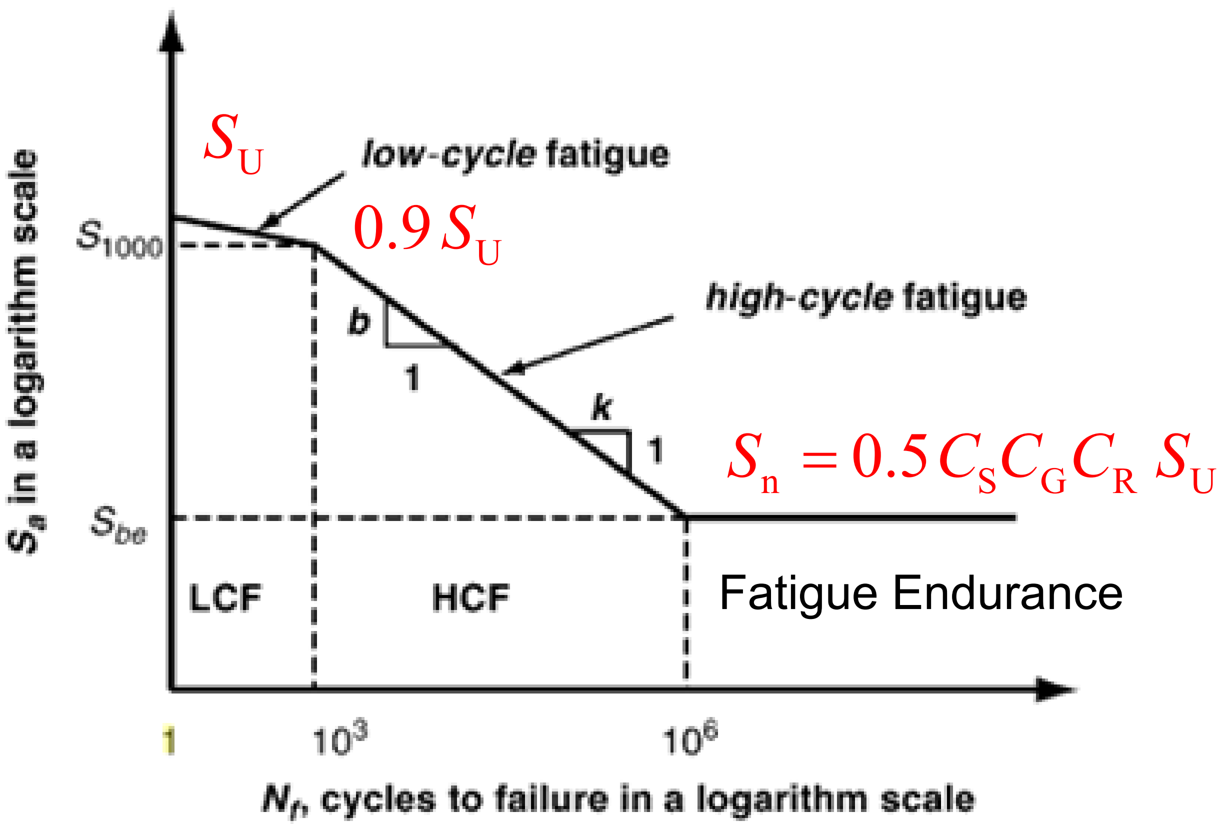
$$N_f = 10^6,$$

$$\sigma_a = 0.5\, C_S C_G C_R\, S_U$$

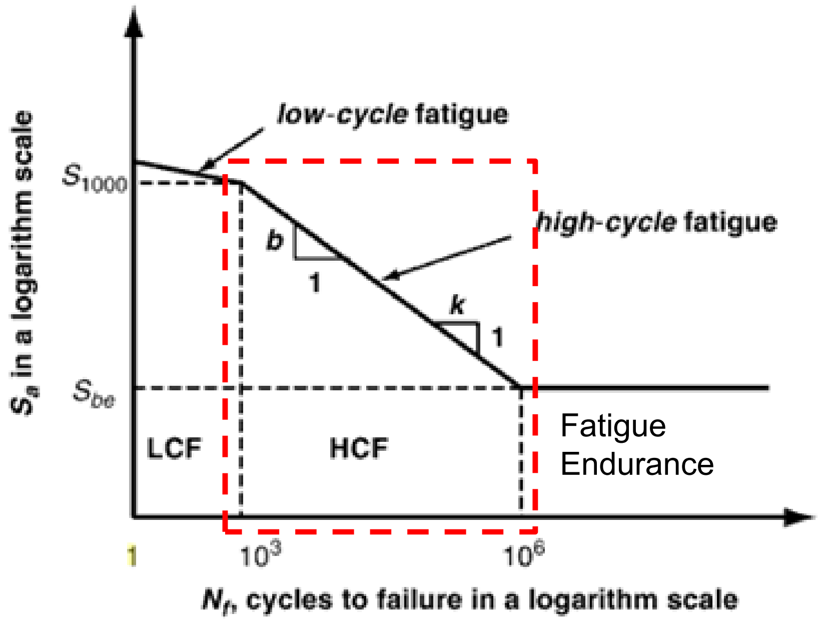
C_S: Surface factor

C_G: Gradient factor

C_R: Reliability factor



Basquin's law (HCF)



Different forms, same law:

$$\sigma_a = \sigma_f'(2N_f)^b$$

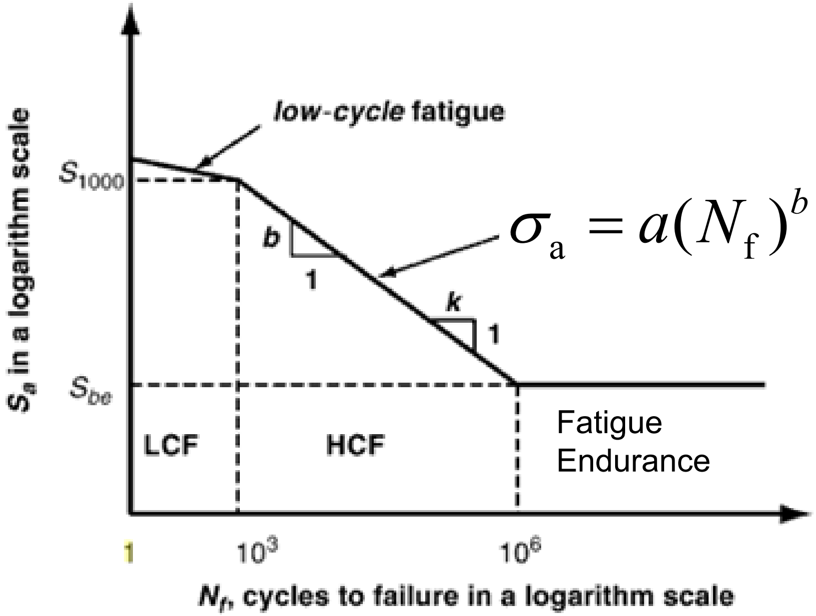
$$\sigma_a = a(N_f)^b$$

$$\sigma_a = a(N_f)^{-\frac{1}{k}}$$

$$k = -1/b$$

a, b are material properties

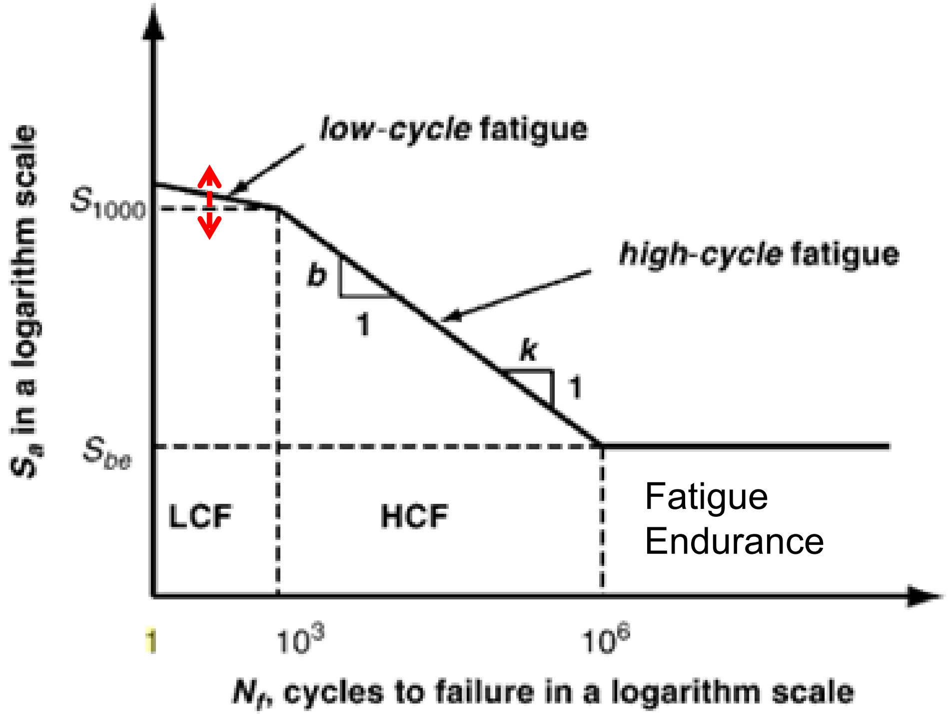
Basquin's law (HCF)



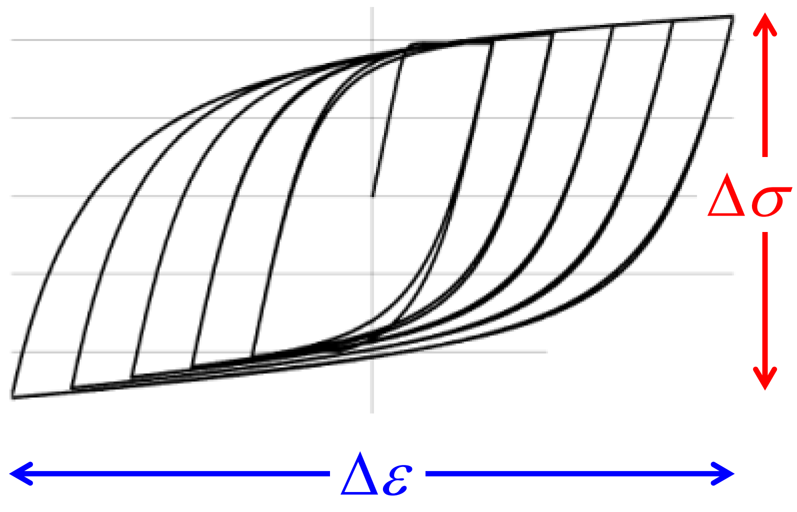
Exercise:

Find the *a, b* parameters for the Steel HCF line as function of the Ultimate Tensile Strength and the correcting factors C_X

LCF requires the Strain life approach



LCF, Elastic-plastic cyclic loading:
Limited Stress sensitivity
Remarkable Strain variation



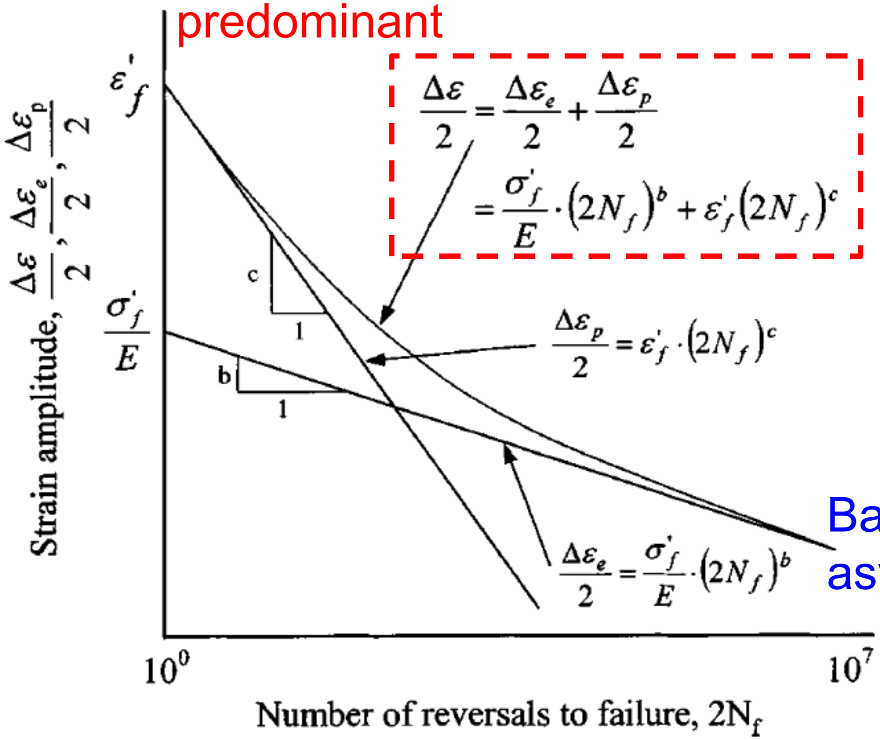
$$\Delta\sigma = 2\sigma_a$$

$$\Delta\varepsilon = 2\varepsilon_a$$

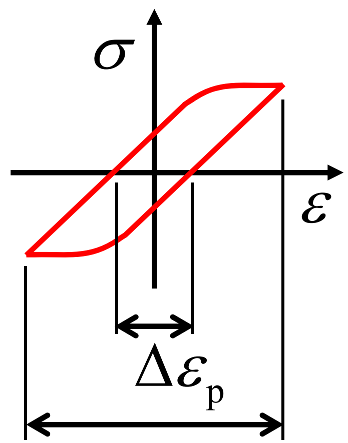
Manson-Coffin law

Composition of two asymptotes:
Elastic (Basquin)
Plastic predominant

Plastic predominant



Basquin's asymptote



$$\Delta\varepsilon = \Delta\varepsilon_e + \Delta\varepsilon_p$$

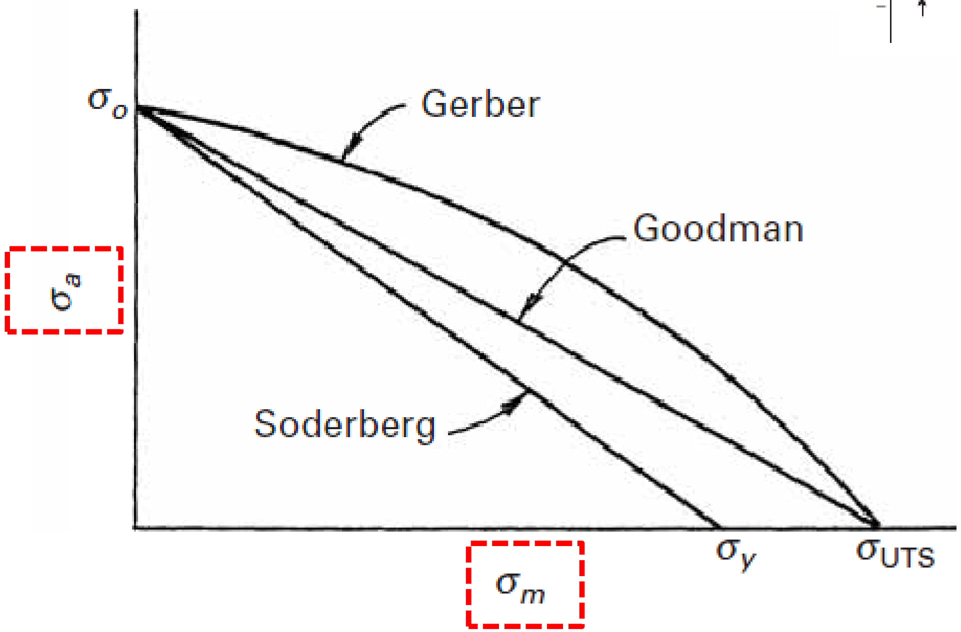
In notched component, Δε may be found through the Neuber's rule...

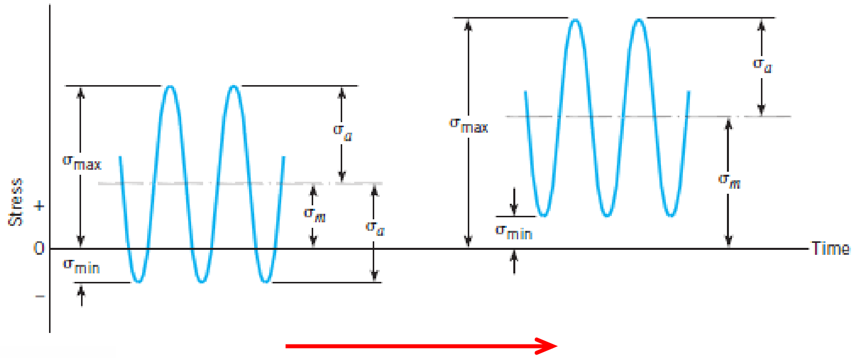
Material parameters:

$\sigma'_f, b, \varepsilon'_f, c$

Mean stress effect, different models

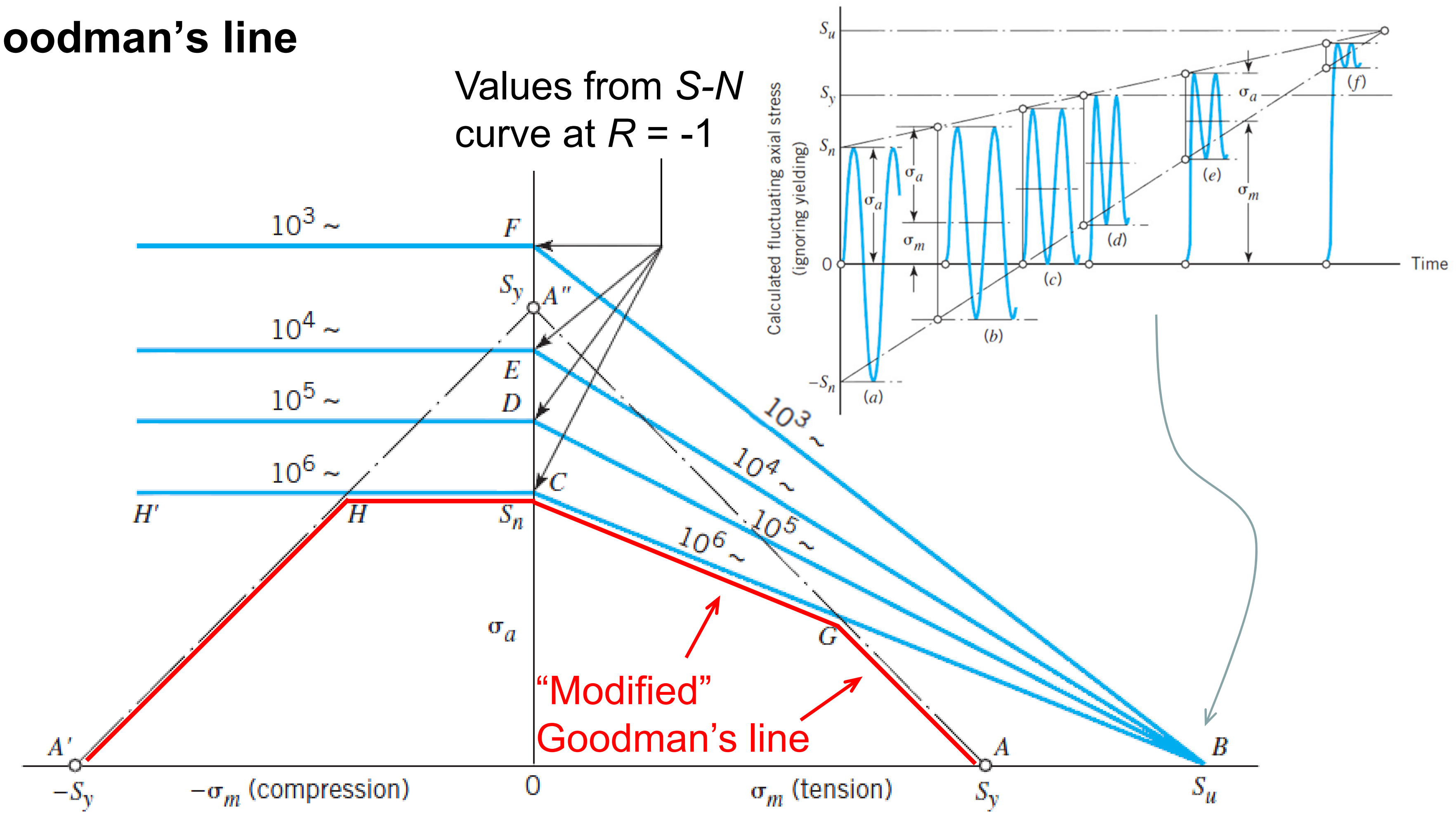
Haigh's diagram



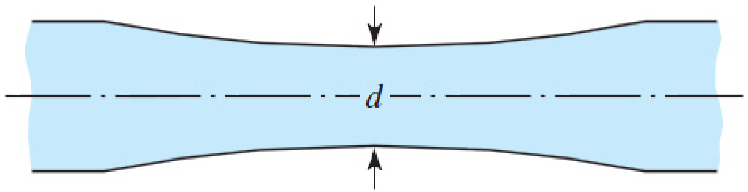


Higher mean stress,
same alternate

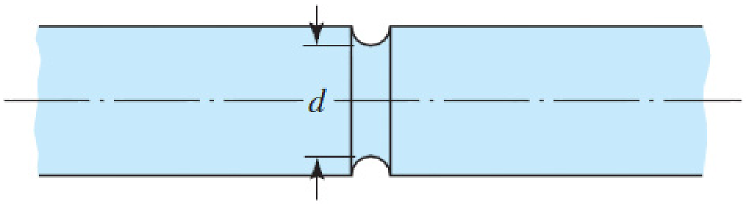
Goodman's line



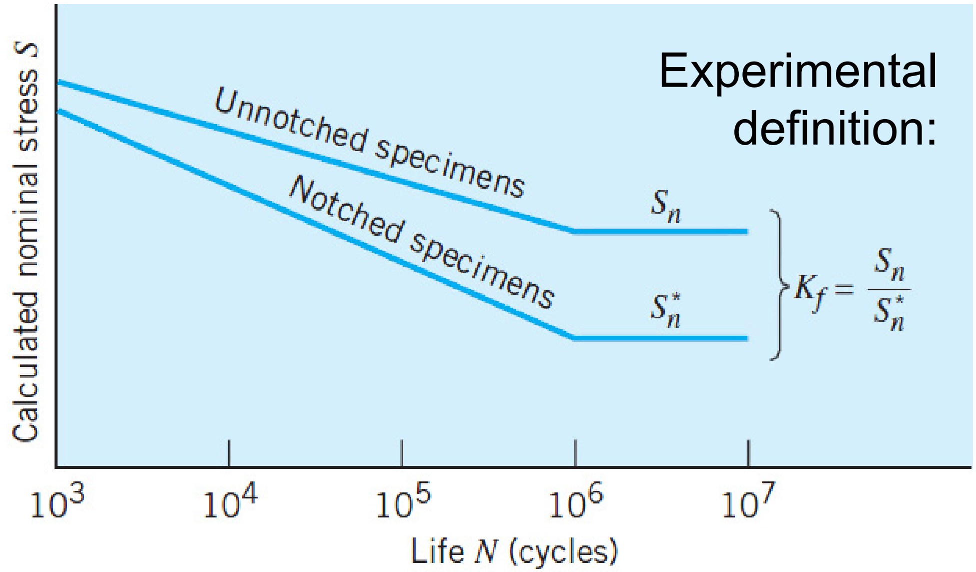
Fatigue Stress Concentration Factor - K_f



(a) Unnotched specimen

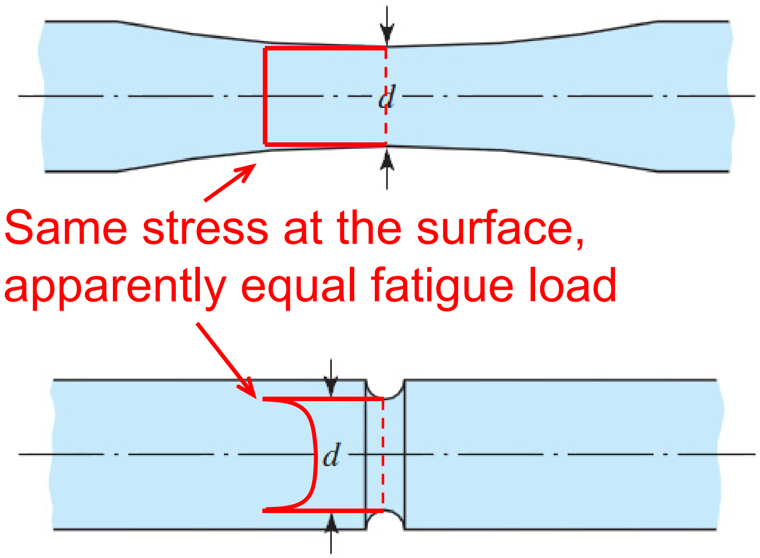


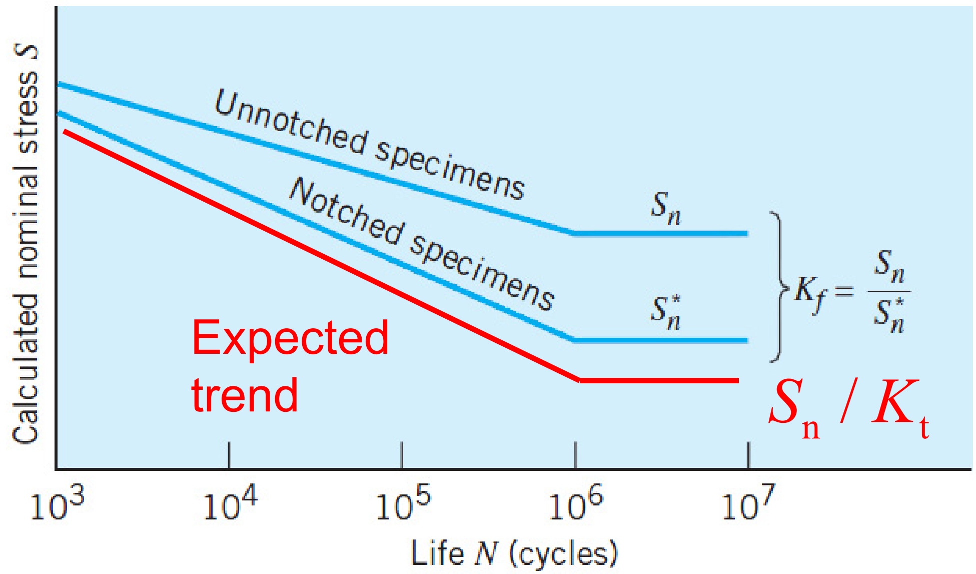
(b) Notched specimen (*)



(c) Illustration of fatigue stress concentration factor, K_f

$K_f < K_t$





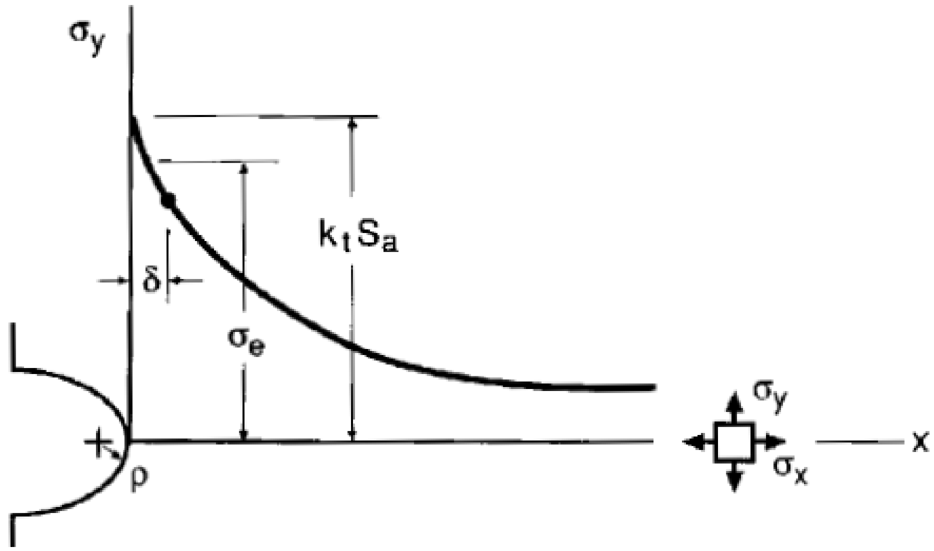
(c) Illustration of fatigue stress concentration factor, K_f

In fact, fortunately:

$$S_n / K_t < S_n^*$$

Why $K_f < K_t$?

Process zone concept



In other words, some finite volume of material must be involved for the fatigue damage process to proceed. The size of the active region can be characterized by a dimension δ, called the *process zone size*, as illustrated in Fig. 10.3. Thus, the stress that controls the initiation of fatigue damage is not the highest stress at $x = 0$, but rather the somewhat lower value that is the average out to a distance $x = \delta$. This average stress is then expected to be the same as the smooth specimen fatigue limit σ_e, so that k_f is estimated by

$$k_f = \frac{(\text{average } \sigma_y \text{ out to } x = \delta)}{S_a} = \frac{\sigma_e}{S_a} \qquad (10.2)$$

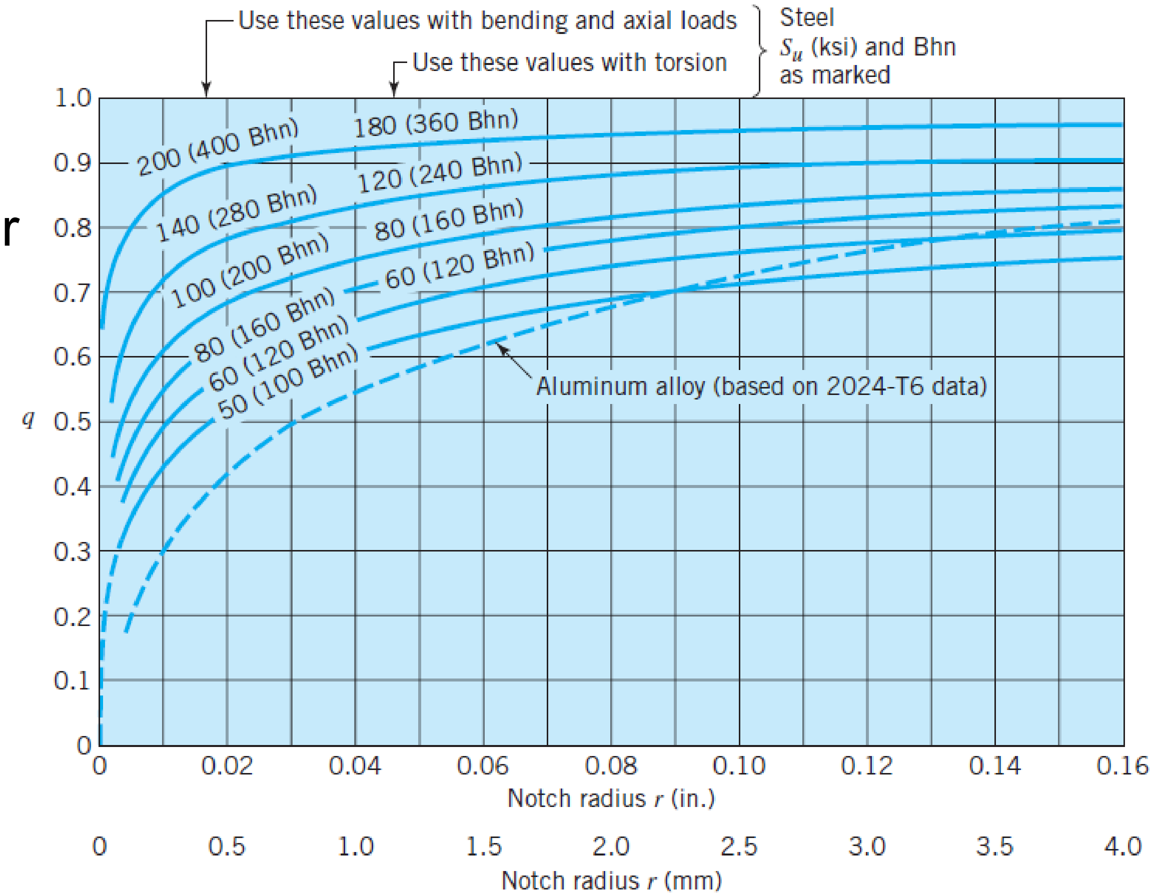
How to calculate K_f

The notch sensitivity factor

$$q = \frac{K_f - 1}{K_t - 1}$$

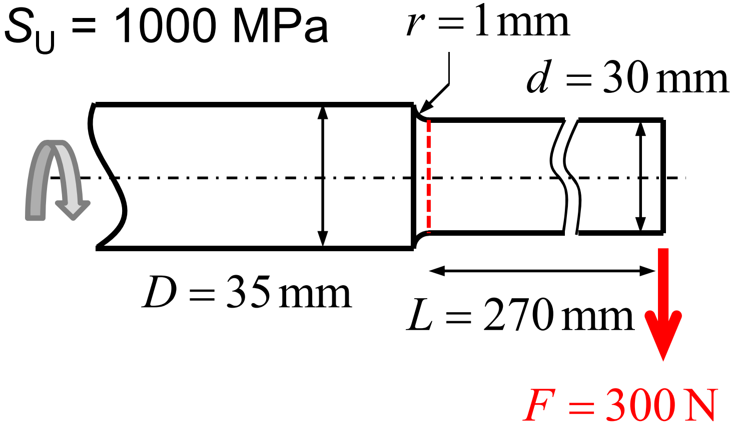
$\rightarrow$

$$K_f = 1 + q(K_t - 1)$$



q ranges from 0 to 1 and it depends on the Notch radius and on the material strength (Ultimate Tensile Strength)

Rotating shaft
AISI 4340,
S_U = 1000 MPa



Calculate the margin with respect to the fatigue endurance

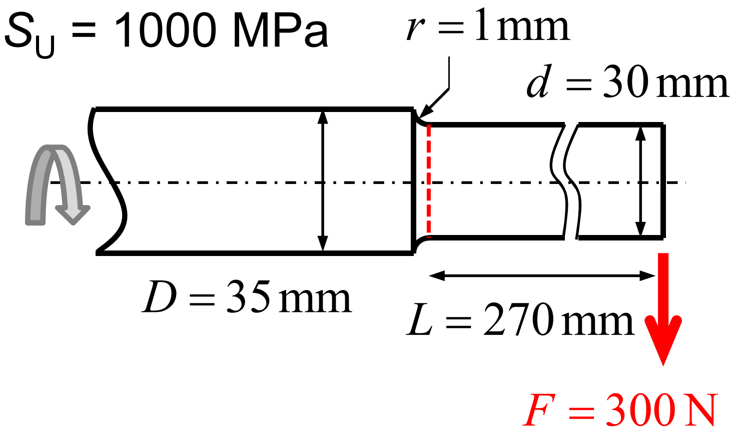
Step 1:

Calculate the material fatigue limit

$$C_S = 0.7$$
$$C_G = 0.8$$
$$C_R = 0.814$$
$$\rightarrow$$
$$S_n = C_S C_G C_R \frac{S_U}{2} = 228\,\text{MPa}$$

R.C. Juvinall, K.M. Marshek, Fundamentals of Machine Component Design - Wiley 2011

Rotating shaft
AISI 4340,
S_U = 1000 MPa



Calculate the margin with respect to the fatigue endurance

Step 2:

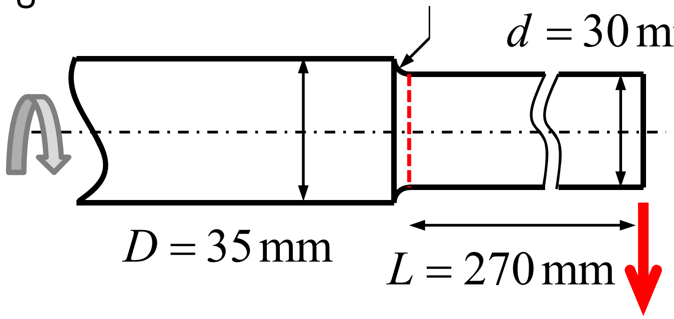
Calculate the bending nominal stress

$$M = FL = 81 \times 10^3\ \text{N mm} = 81.0\ \text{N m}$$

$$W = \frac{\pi}{32} d^3 = 2.65 \times 10^3\ \text{mm}$$

$$\sigma_n = \frac{M}{W} = 31\,\text{MPa}$$

Rotating shaft
AISI 4340,
S_U = 1000 MPa



Calculate the margin with respect to the fatigue endurance

Step 3:

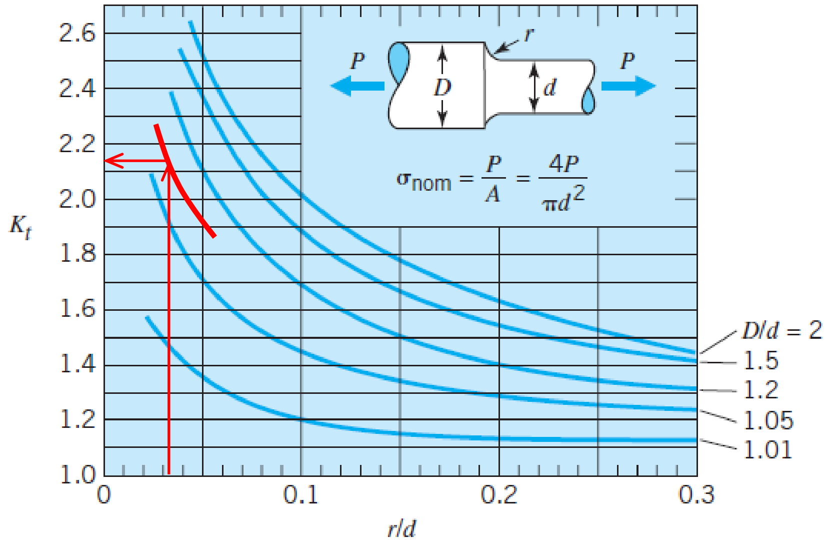
Calculate the Stress Concentration Factor

$$\frac{r}{d} = 0.033$$

$$\frac{D}{d} = 1.167$$

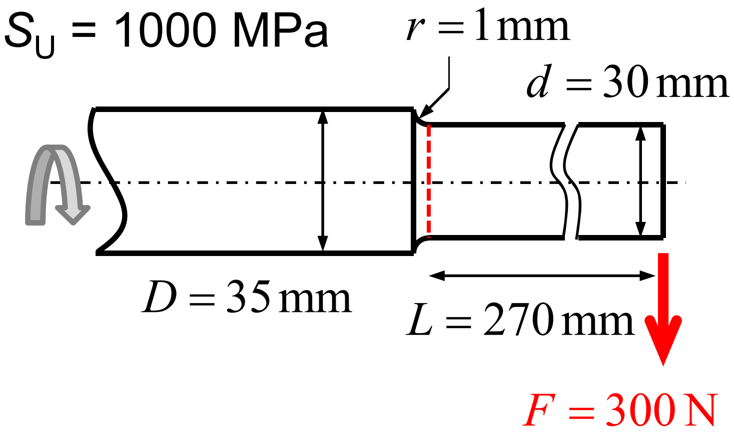
$$\rightarrow$$

$$K_t = 2.15$$



R.C. Juvinall, K.M. Marshek, Fundamentals of Machine Component Design - Wiley 2011

Rotating shaft
AISI 4340,
S_U = 1000 MPa



Calculate the margin with respect to the fatigue endurance

Step 4:
Calculate the Fatigue St. Conc. Factor

$$\text{Bhn} = \frac{S_U}{3.45} = 290\ \text{(Brinell)}$$

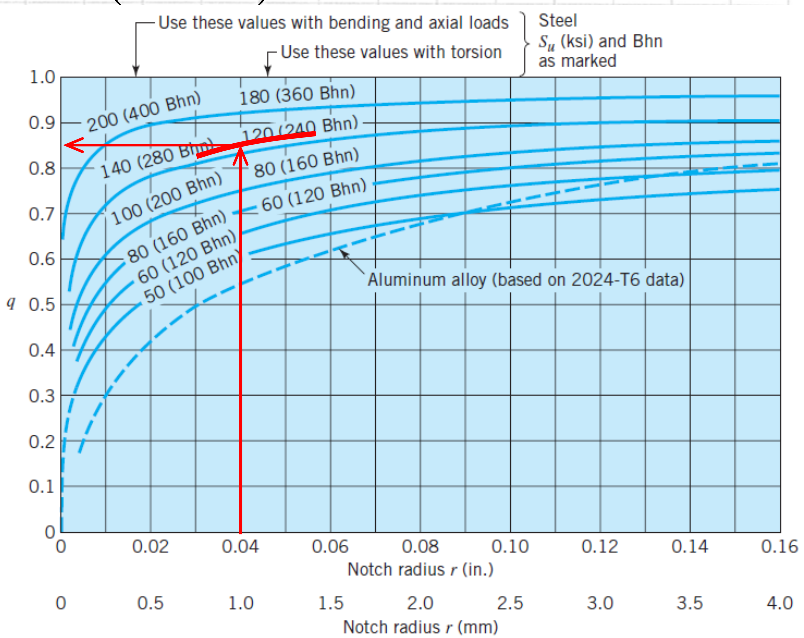
$q = 0.85$

$\rightarrow$

$K_f =$

$1 + q(K_t - 1)$

$= 1.98$



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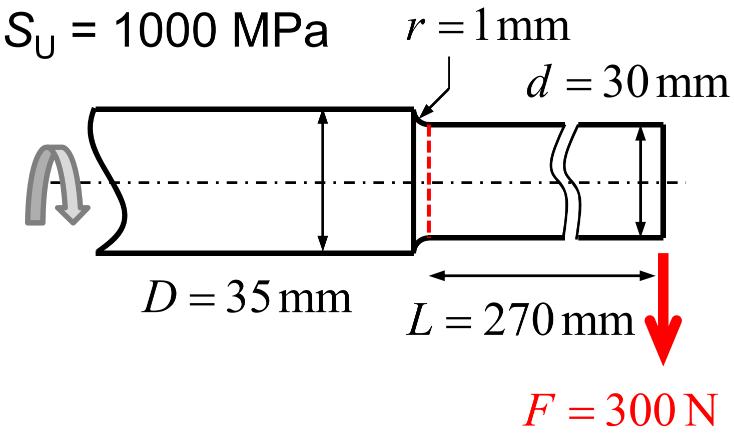
Rotating shaft
AISI 4340,
S_U = 1000 MPa



Calculate the margin with respect to the fatigue endurance

Step 5:

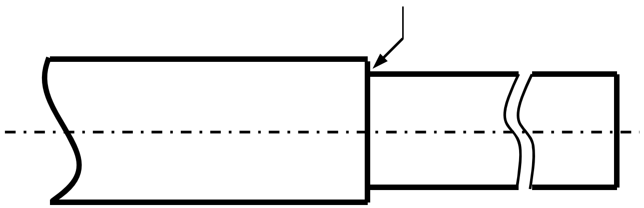
Calculate the Safety Factor

$$SF = \frac{S_n}{\sigma_n K_f} = 3.8$$

$$SF > 1, \ \text{Ok!}$$

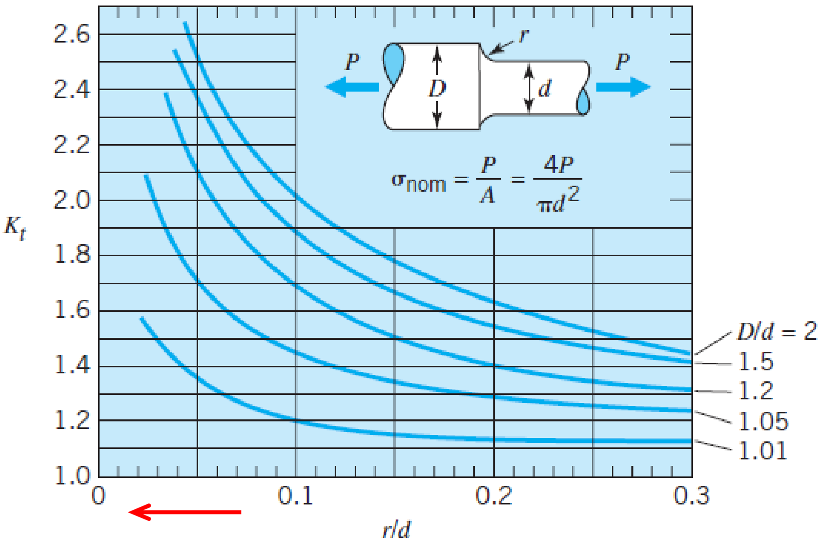
Singularity for vanishingly small radius

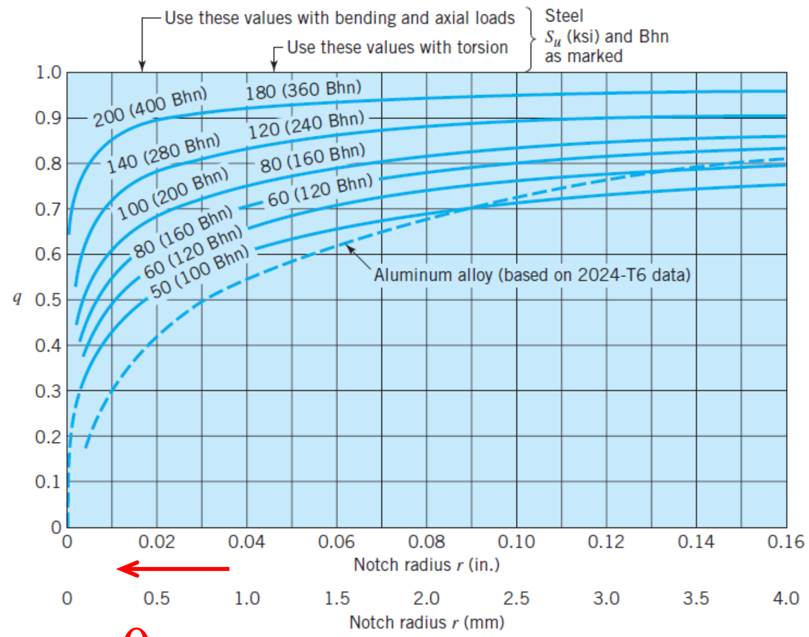
$r \to 0$



$$K_f \approx q(\to 0) \times K_t(\to \infty) = ?$$

$K_t \to \infty$

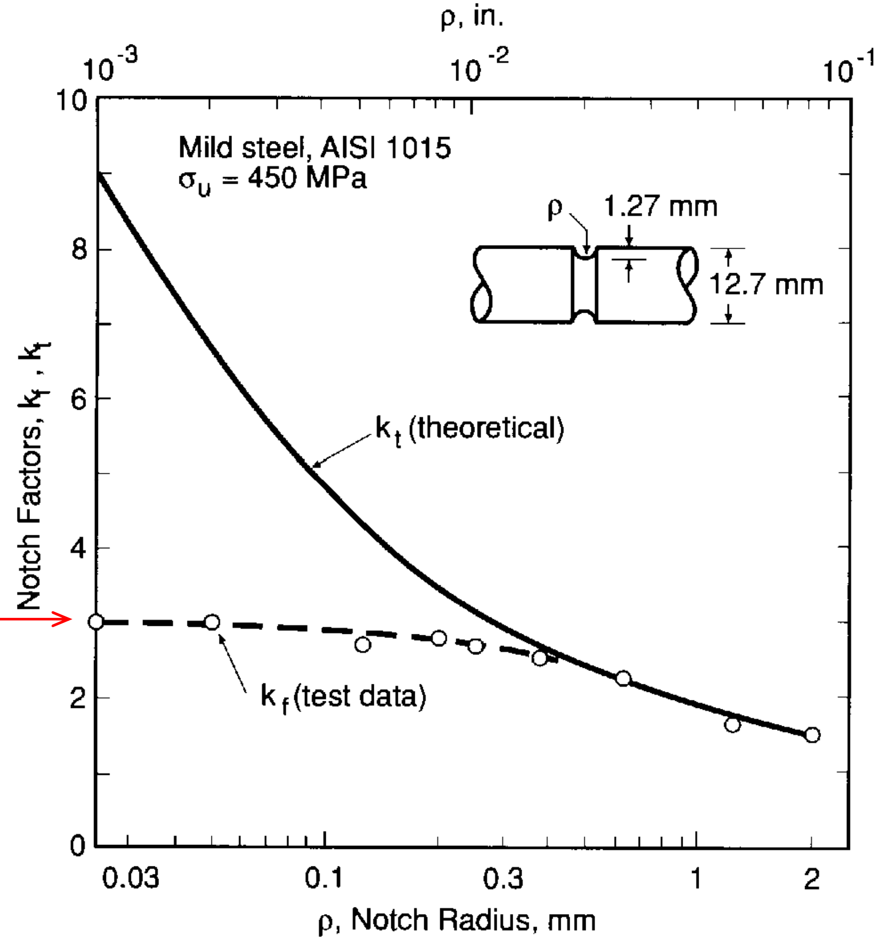




$q \to 0$

Singularity for vanishingly small radius

The limiting ($r \to 0$) value for K_f, is finite, but how to calculate?



Fracture Mechanics !