FATIGUE OF MATERIALS & STRUCTURES

G. Hénaff

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HIGH CYCLE FATIGUE

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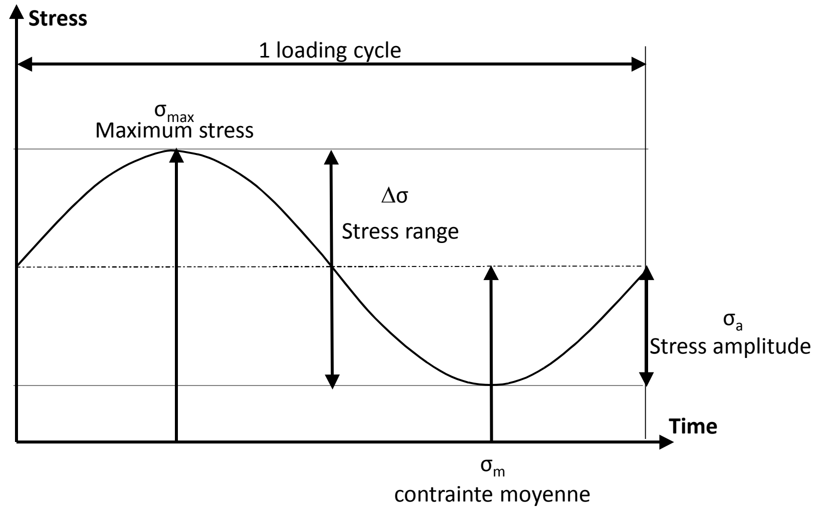

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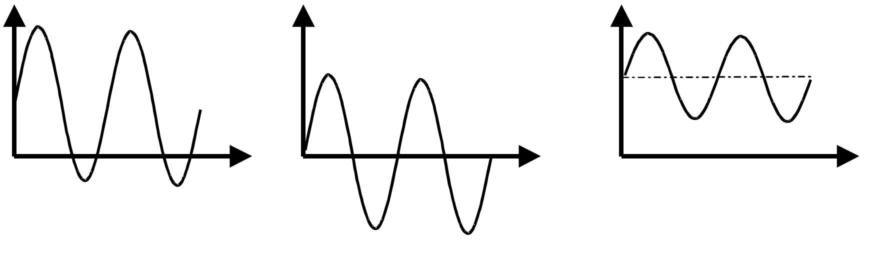


Alternate Stress

Symetric alternate stress (R=-1)

Tensile alternate stress (R>0)

Testing Machines

Electro-mechanical : low cycle fatigue (f < 1 Hz)

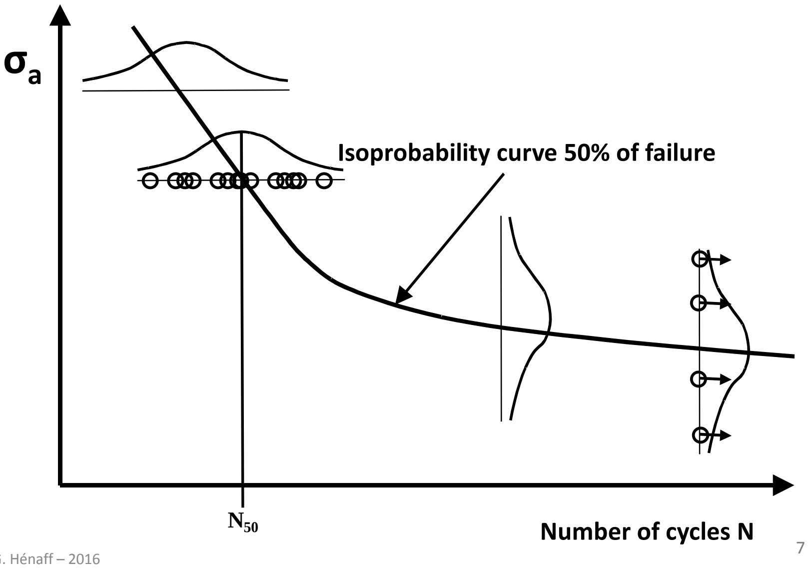
Servo-hydraulic : high cycle fatigue, propagation (f <50 Hz)

Resonant : high cycle fatigue, propagation (100 Hz <f <200 Hz)

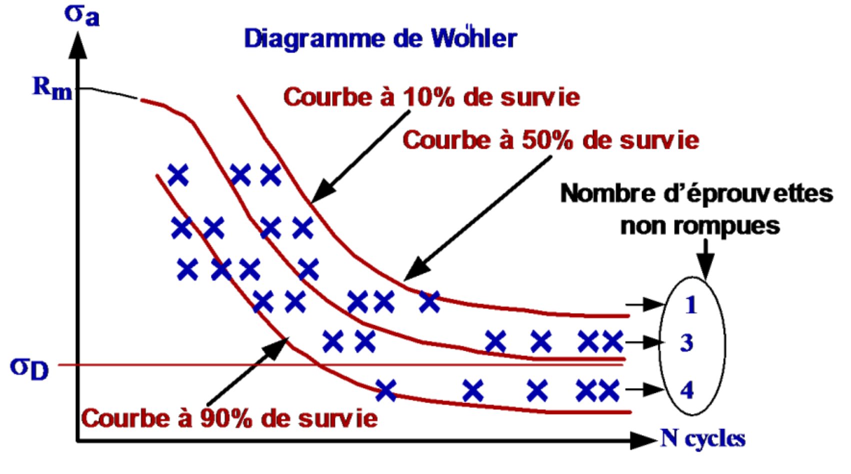
Methodology

- Fixed number of samples (geometry, surface);
- Stress amplitude levels fixed prior to testing ⇒ number of test pieces tested per stress level;
- For a given stress level, the distribution of lifetimes (number of cycles to failure) is determined.

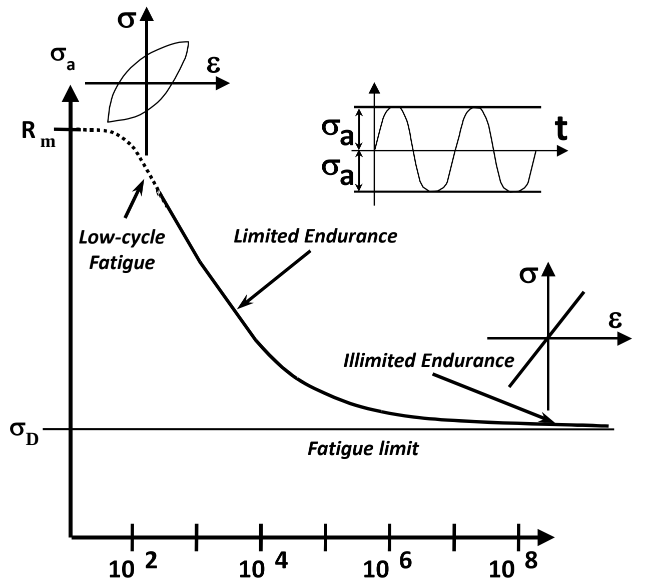
Isoprobability curves



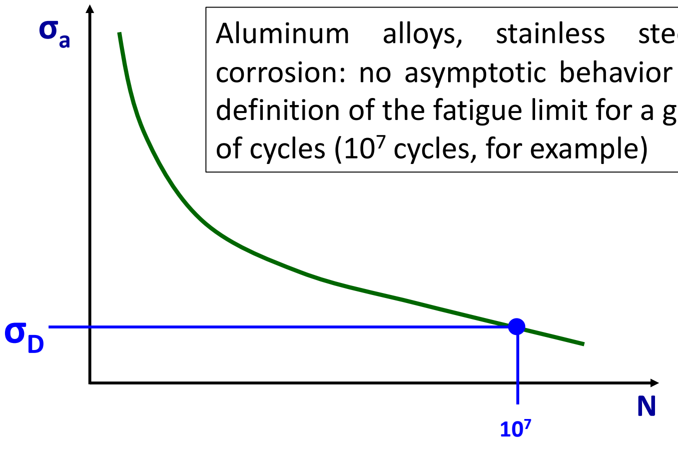
Wöhler Diagram



Endurance diagram



Arbitrary fatigue limit



Aluminum alloys, stainless steels, fatigue corrosion: no asymptotic behavior ⇒ arbitrary definition of the fatigue limit for a given number of cycles (10^7 cycles, for example)

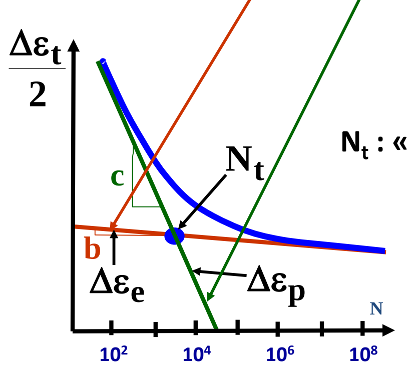
Limited Endurance

- **About 10^5 to 10^7 cycles**

- **Empirical relations:**
  - Weibull : $\mathbf{N \times (\sigma - \sigma_D) = Cste}$
  - Basquin : $\mathbf{N_f \times \sigma^a = Cste}$
  - Bastenaire : $\mathbf{N_f + B = \dfrac{A \times e^{-C(\sigma - \sigma_D)}}{\sigma - \sigma_D}}$

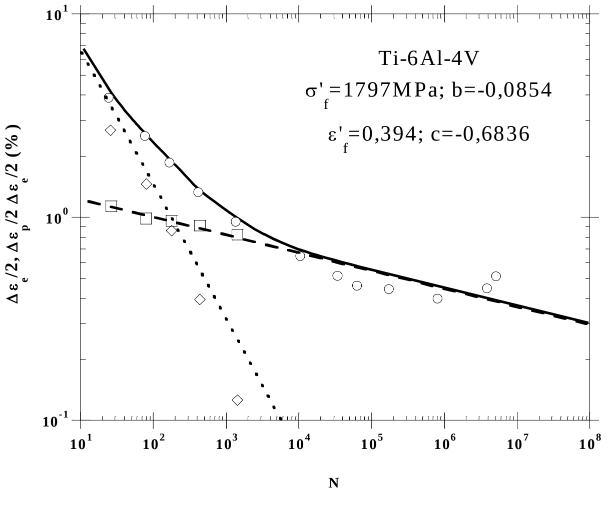
ε-N curve

$$\frac{\Delta\varepsilon_t}{2} = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} = \underbrace{\frac{\sigma'_f}{E} \times N_f^b}_{\text{Basquin}} + \underbrace{\varepsilon'_f \times N_f^c}_{\text{Manson-Coffin}}$$

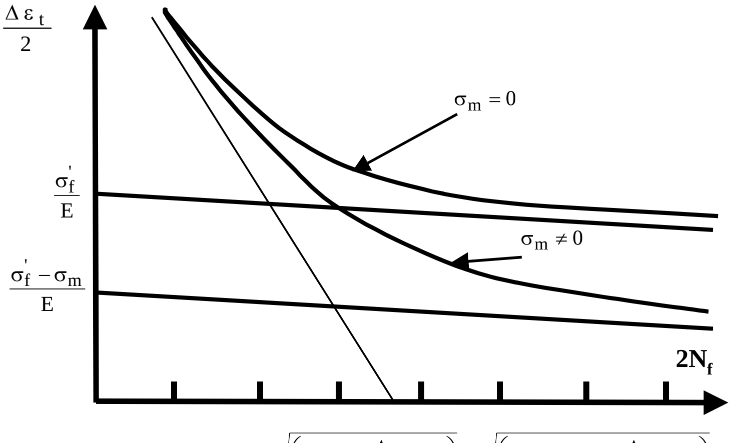


N_t : « Elastic-Plastic » transition

ε-N curve

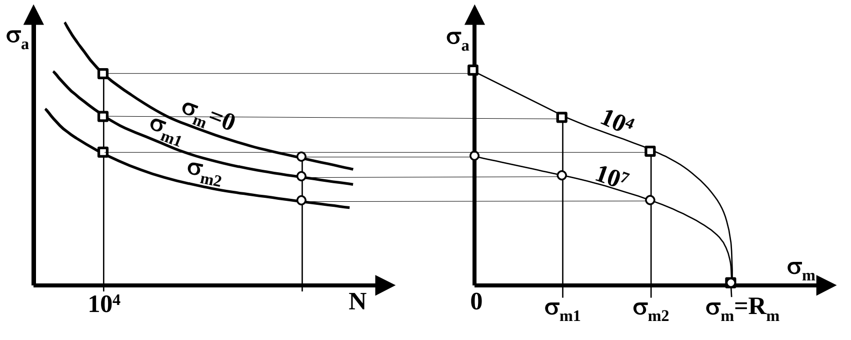


Influence of Mean Stress



Smith-Watson-Topper: $P_{SWT} = \sqrt{\left(\sigma_{\max} \times \frac{\Delta\varepsilon_t}{2} \times E\right)} = \sqrt{\left((\sigma_a + \sigma_m) \times \frac{\Delta\varepsilon_t}{2} \times E\right)}$

Influence of Mean Stress

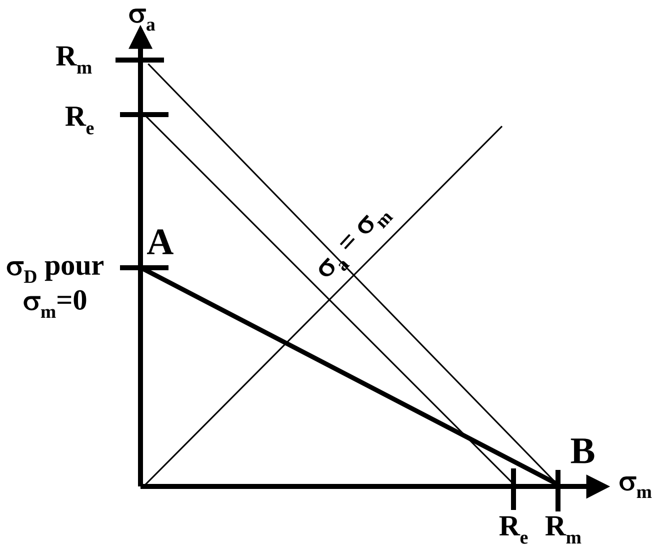


Influence of Mean Stress

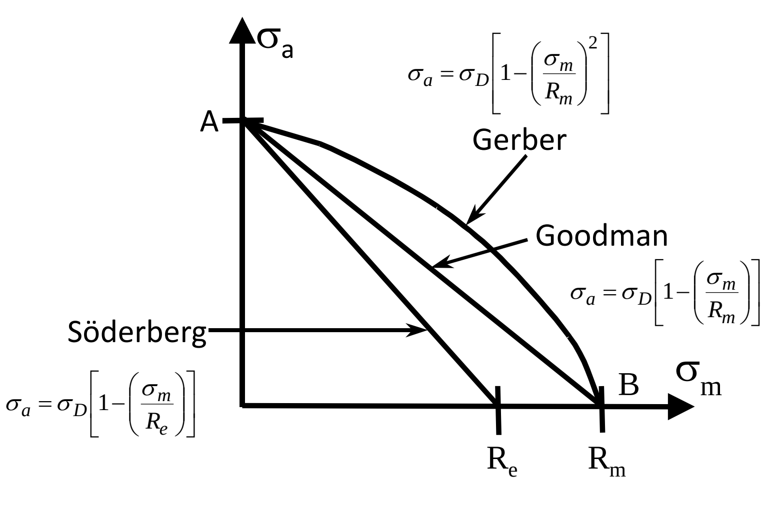
- Experimental observation: The permissible stress amplitude decreases when the mean stress increases

- Taken into account by the use of abacuses (*admissible stress as a function of the mean stress*)→ Different representations.

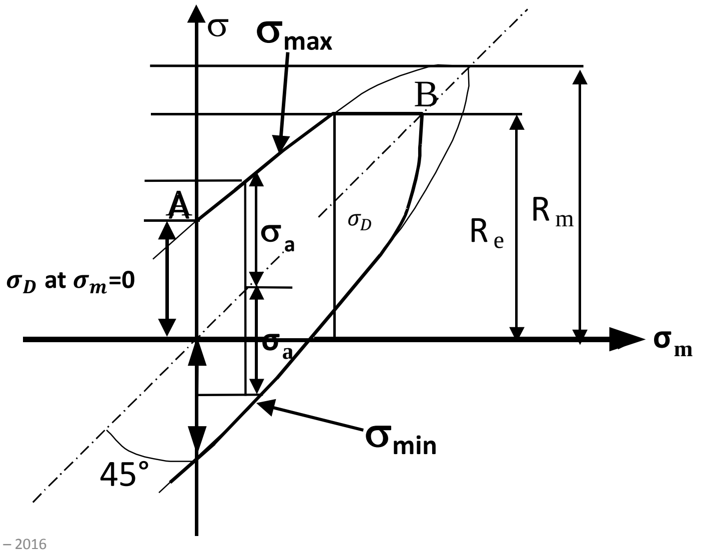
Haigh Diagram



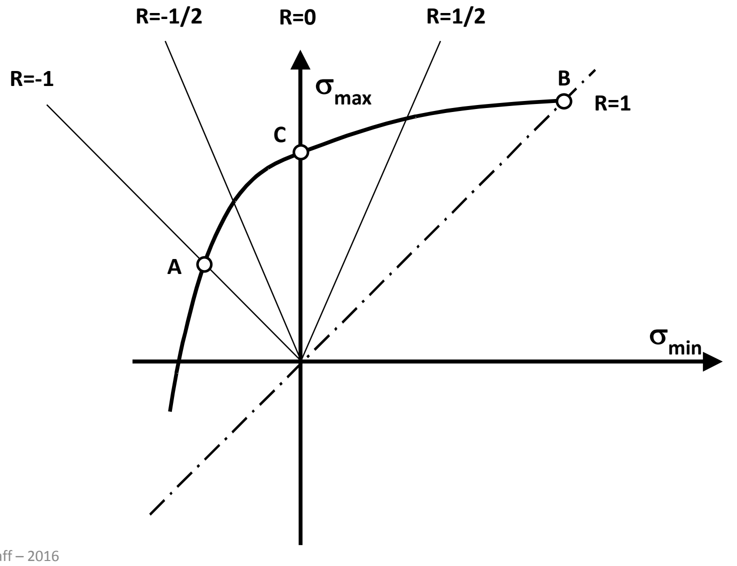
Influence of mean stress



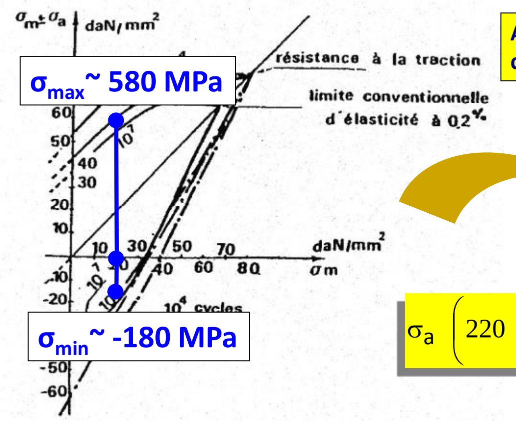
Goodman-Smith Diagram



Ros diagram



Example: Goodman-Smith

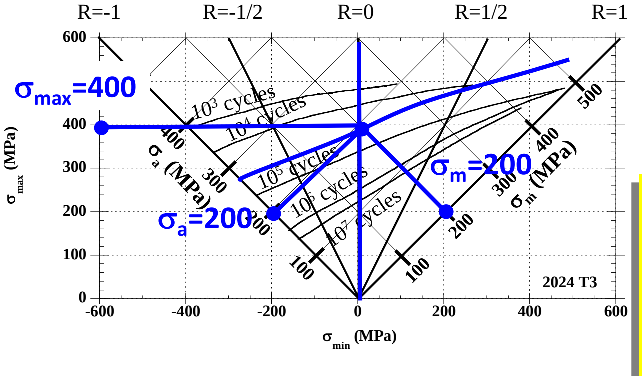


Admissible stress amplitude $N_f = 10^5$ cycles and σ_m=200MPa ?

$$\sigma_a\left(220\ \text{MPa} - 10^5\right) = 580 - 200 = 380\ \text{MPa}$$

Example: Haigh diagram

Admissible stress amplitude at R=0 with $N_f=10^5$ cycles?

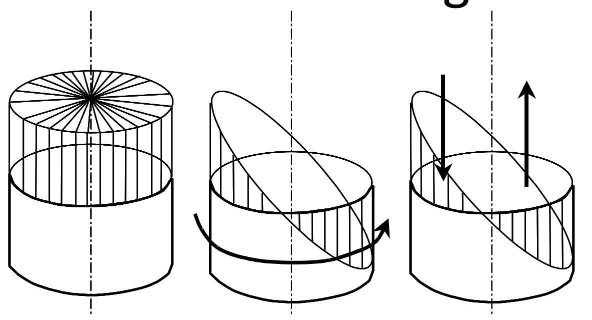


$$\sigma_a\left(R = 0 - 10^5\right) = 200\ \text{MPa}$$

$$\sigma_{max} = 400\ \text{MPa}$$

$$\sigma_m = 200\ \text{MPa} = \sigma_{max} - \sigma_a$$

Influence of loading mode



Tension | Rotative bending | Plane bending

	Plane bending	Tension / Compression	Torsion
x σ_D rotative bending	1.05	0.9	0.6

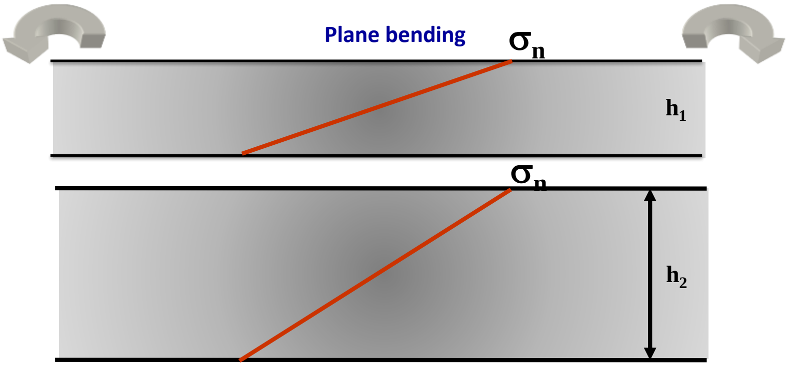
Scale effect

- Observation : for a given stress amplitude value, the higher the dimensions of the testpiece, the lower the fatigue strength.
- Causes :
  - mechanical;
  - probabilistic.
- Scale effect coefficient :

$$K_e = \frac{\sigma_D}{\sigma_{D_0}}$$

Determined on a reference sample with small dimensions

Scale effect: stress gradient

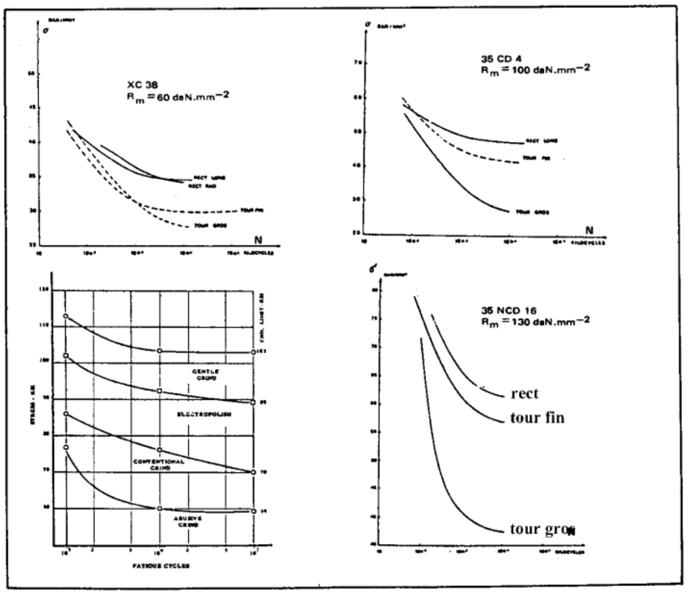


- Difference in stress gradients:
  - small thickness ⇒ high gradient. The less loaded layers support the highly loaded surface layers;
  - high thickness ⇒ small gradient. All the surface layer are nearly loaded in a similar way ⇒ loss in fatigue resistance

Scale effect: probabilistic aspect

- The larger the dimensions of a component (volume, area), the more likely it is to have defects that behave as privileged initiation sites

Influence of surface finishing



Influence of surface finishing

Surface finishing factor: $K_S = \frac{\sigma_{D_S}}{\sigma_D}$

with :

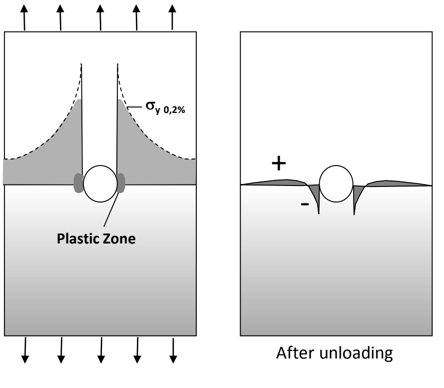
σ_{D_S} fatigue limit with the surface finishing under consideration ;

σ_D fatigue imit with a reference surface finishing.

Residual stresses

- Induced (on purpose or not) by:
  - Inhomogeneous plastic deformations (especially in the vicinity of stress concentrators)
  - Process
  - Surface treatment (shot blasting, shot peening, coating,…)
  - Expanded holes
  - Joining

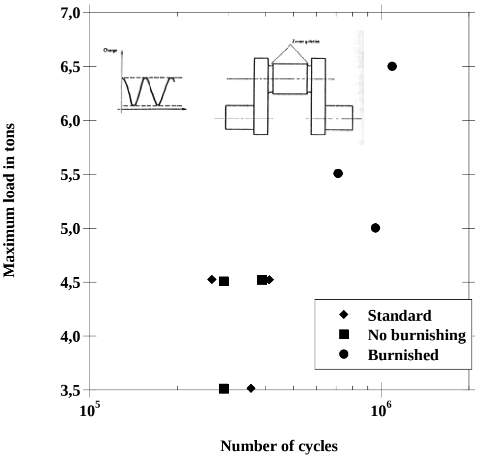
Residual stresses near a stress concentrator



Residual stresses induced by machining

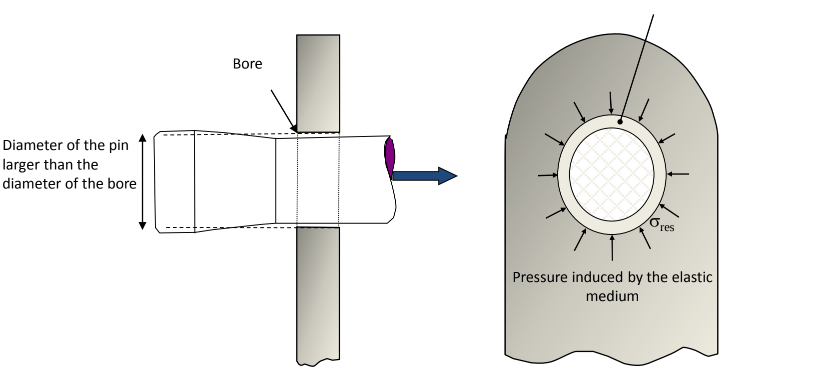
Surface finishing	Machining parameters			Maximum surface reisudal stresses. (MPa)	Surface roughness (µm)	Fatigue limit (MPa)	
	Depth of pass (mm)	Advance (mm/tr)	Cutting speed (m/s)			Without annealing	After annealing at 650°C
Polished	0.1			-200	0.6	270	250
Turned	0.5	0.16	120	+100	17	215	240
Turned	0.5	0.32	120	+200	27	190	220
Turned	0.5	0.50	120	+600	46	175	205

Burnishing



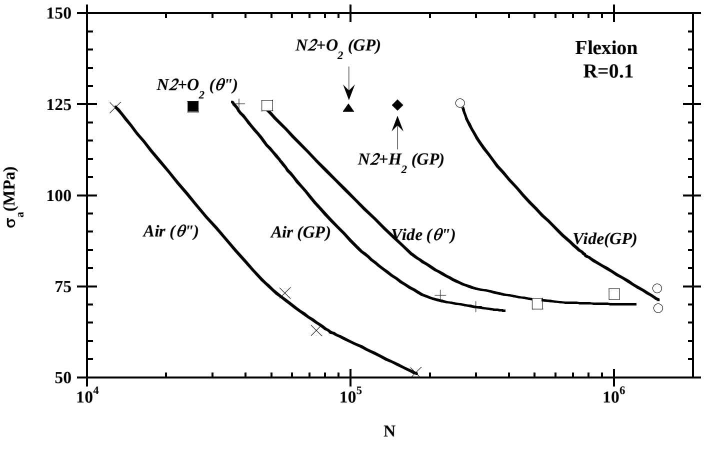
The residual stresses introduced by burnishing induce a higher fatigue resistance

Expanded holes



Before tension After tension

Influence of environment



- The fatigue life is lower in an active environment (air) than in an inert environment (vacuum)
- Related effect: influence of frequency