Matériaux Avancés
Advanced materials

Fatigue of Metals
Fatigue des matériaux

L. Barrallier[1]

[1] Laboratoire MSMP
ARTS ET MÉTIERS ParisTech – Aix en Provence

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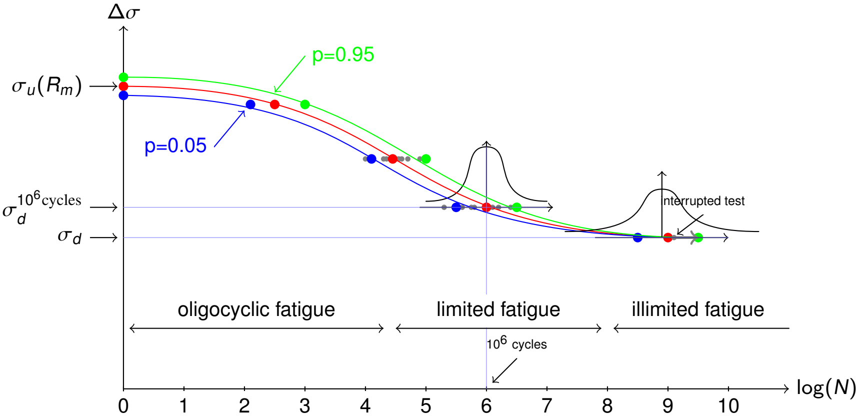
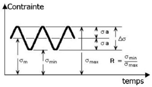
- 1837: Wilhelm Albert publishes the first article on fatigue. He devised a test machine for conveyor chains used in the Clausthal mines.
- 1839: Jean-Victor Poncelet describes metals as being tired in his lectures at the military school at Metz.
- 1842: William John Macquorn Rankine recognises the importance of stress concentrations in his investigation of railroad axle failures. The Versailles train crash was caused by axle fatigue.
- 1843: Joseph Glynn reports on fatigue of axle on locomotive tender. He identifies the keyway as the crack origin.
- 1848: Railway Inspectorate report one of the first tyre failures, probably from a rivet hole in tread of railway carriage wheel. It was likely a fatigue failure.
- 1849: Eaton Hodgkinson is granted a small sum of money to report to the UK Parliament on his work in ascertaining by direct experiment, the effects of continued changes of load upon iron structures and to what extent they could be loaded without danger to their ultimate security.
- 1854: Braithwaite reports on common service fatigue failures and coins the term fatigue.
- 1860: Systematic fatigue testing undertaken by Sir William Fairbairn and August Wöhler.

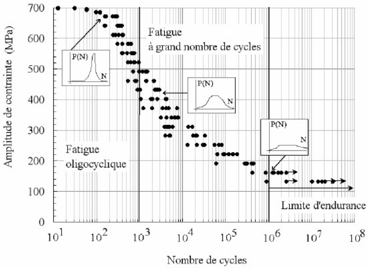
- 1870: Wöhler summarises his work on railroad axles. He concludes that cyclic stress range is more important than peak stress and introduces the concept of endurance limit.
- 1903: Sir James Alfred Ewing demonstrates the origin of fatigue failure in microscopic cracks.
- 1910: O. H. Basquin proposes a log-log relationship for SN curves, using Wöhler's test data.
- 1945: A. M. Miner popularises A. Palmgren's (1924) linear damage hypothesis as a practical design tool.
- 1954: L. F. Coffin and S. S. Manson explain fatigue crack-growth in terms of plastic strain in the tip of cracks.
- 1961: P. C. Paris proposes methods for predicting the rate of growth of individual fatigue cracks in the face of initial scepticism and popular defence of Miner's phenomenological approach.
- 1968: Tatsuo Endo and M. Matsuiski devise the rainflow-counting algorithm and enable the reliable application of Miner's rule to random loadings.
- 1970: W. Elber elucidates the mechanisms and importance of crack closure in slowing the growth of a fatigue crack due to the wedging effect of plastic deformation left behind the tip of the crack.

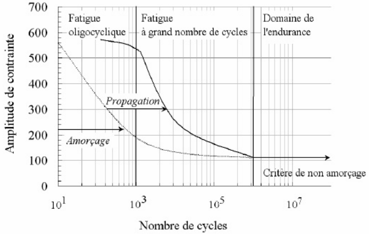
- Objective
  - Statistical approach of the failure of workpiece or representative sample
  - Cyclic loading, tensile-compression for exemple



- For a Wöhler curve
  - For a loading type ($R_\sigma = \frac{\sigma \text{min}}{\sigma \text{Max}}$)
  - For a given material (one microstructure)
  - 3 domains :
    - **oligocyclique** fatigue (low number of cycle to failure) for $\sigma_a = \frac{\Delta\sigma}{2} > \sigma_y \Rightarrow$ plastification at least for one cycle, fatigue life is linked to the plastic behavior of material
    - high number of cycle to failure or limited fatigue, in **macroscopical** elasticity domain ($N > 10^3 - 10^4$), a initiation crack is followed by a crack propagation
    - illimited fatigue (endurence), some time it exists a limit (case of steel), some times this tests are interrupted ($N > 10^7 - 10^9$) cycles (For tests at 10^8 cycles, time is approximative more than 23 days for a frequency of 50 Hz)
  - For a given temperature
  - In a given environment
- Remark
  - More the level of applied stress is low, more the initiation phase is important
  - Dispersions are more important when the level of applied stress is low

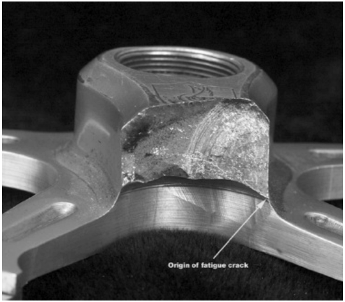


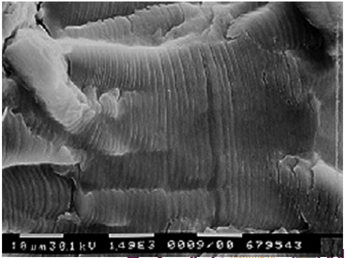




MP Surfaces Processing

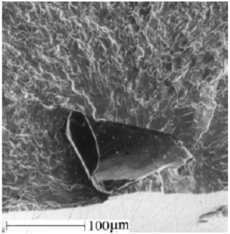
- Propagation of crack by fatigue ⇒ particular fracture surface
  - Lines at the fracture surface to show the stop position of the crack front
  - Observation at the macroscopique scale ⇒ stop lines
  - Observation at the microscopique scale ⇒ fatigue lines
- Possible initiation on
  - a pre-existent defect
  - a created defect during the the life of workpiece (pitting, stripes,...)
  - a very localized aera of material due to a local microplastification



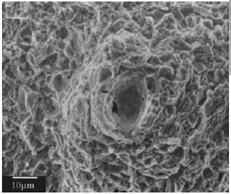


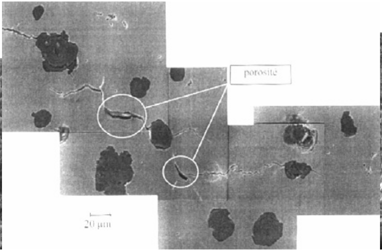
Fatigue lines in the case of aluminum alloy

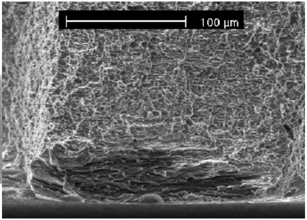
- Many possible defects
  - Segregations, inclusions, voids – foundry, plates
  - Porosities – sintered materials
  - Constituants of material : seconde phase, grain boundaries
  - Cracks linked to forming processes, surface treatments
  - Environment effects : pitting



Ceramic inclusion

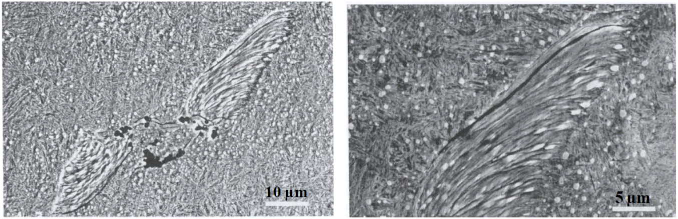




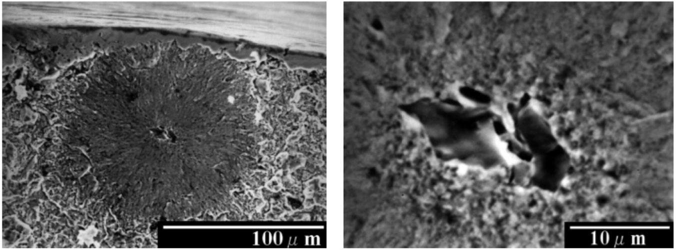


Porosity, N18 nickel alloy (powder metallurgy) – Porosities and graphite nodules in GS cast iron – Stress corrosion sous of Zircaloy 4

- Effets
  - Localized plastic deformation around deffect

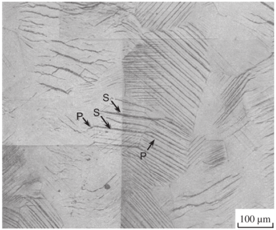


Fatigue butterfly near inclusion [Antaluca and *al.* (2005)]

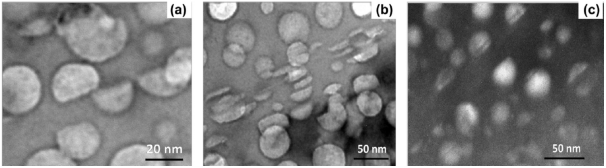


Fish-eyes around inclusion [Sakai and *al.* (2016)]

- Shear Bands
  - Localized in grain
  - Limitation of the propagation by the grains boundary
  - Shearing of coherent precipitates

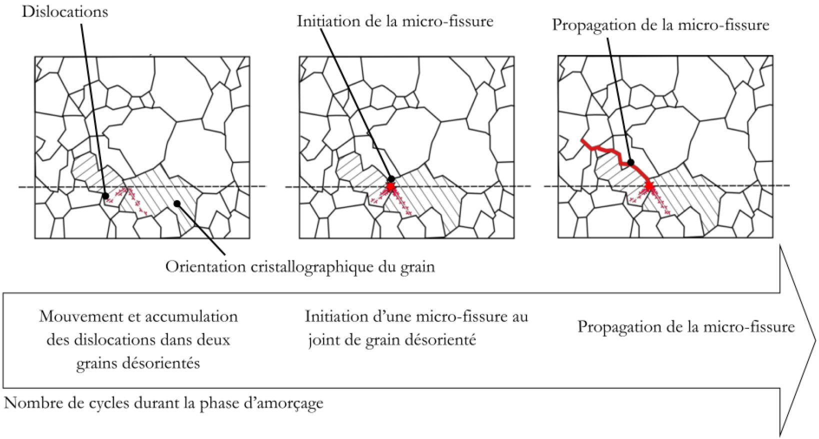


Shear bands in aluminum [Li and *al.* (2012)]



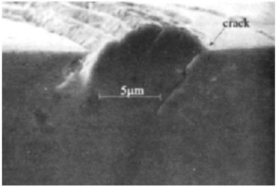
Shearing of cogent precipitates, nickel base alloys, a and b) undissolved shearing precipitates, c) partial dissolved shearing precipitates [Ho and *al.* (2015)]

- Crack initiation from shear bands and grain boundaries
- Crack propagation (inter or transgranular)



[Le and *al.* (2015)]

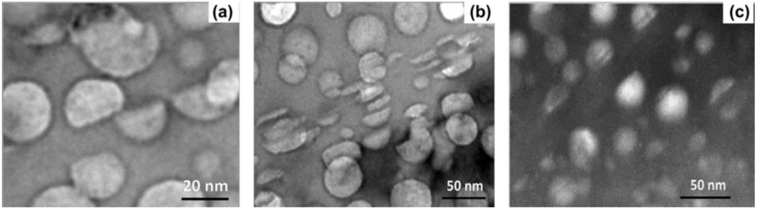
- Many possibilities
  - Superficial effects
  - Heterogeneities of deformations in the material between grains
- Origins
  - Local plastifications between the less favorable oriented grains (maximal Smidth factor)
  - Cyclic effet ⇒ formation of surface relief followed by a crack, in the grains formation of high dislocation density aeras ⇒ localized clivage, macroscopical crack
  - Coalescence of microcracks to generate macroscopical cracks



Cross-section of superficial microcrack (extrusion effect)

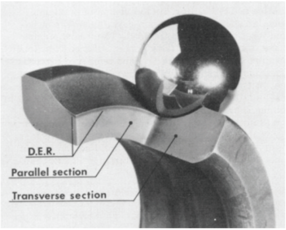
Microcracks network at the surface of TiAl6V4 smooth specimen

- Shear Bands
  - Shearing of coherent precipitates

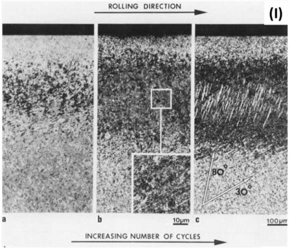


Shearing of cogent precipitates, nickel base alloys, a and b) undissolved shearing precipitates, c) partial dissolved shearing precipitates [Ho and *al.* (2015)]

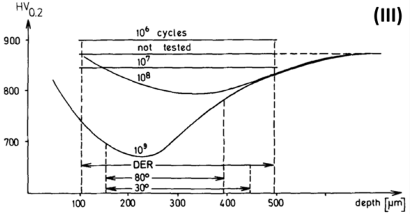
- Martensite / tempered martensite microstructure
- Metallurgical transformations at the maximum of shear hertz stress
  - dissolved tempered carbures
  - carbon diffusion



Ball bearing and Dark Etching Region (DER) [Swahn and *al.* (1976)]

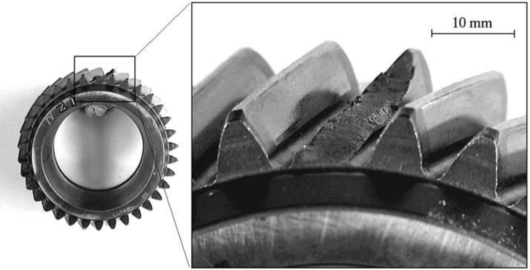


Optical micrography of DER (nital 2%) [Swahn and *al.* (1976)]

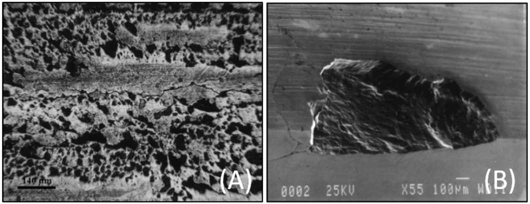


Hardness softening effect [Swahn and *al.* (1976)]

- Surface fatigue: near surface cracks (pitting)
- Volume fatigue: stress concentration at the tooth roots

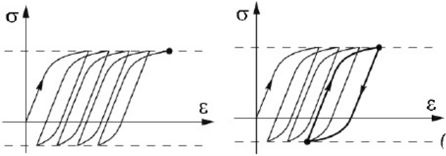


Gears failure (volume and surface fatigue)

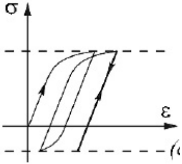


Pitting or contact/surface fatigue [Noyel and *al.* (2015)]

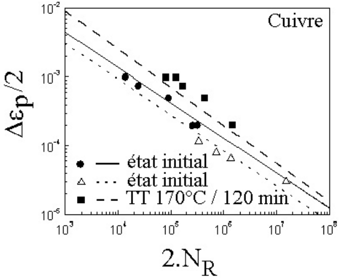
- Multiple behavior
  - Plastique instability / progressive growth at every cycle : *Rochet* phenomena $\Rightarrow$ failure criterion : Rocher deformation > maximal plastic deformation of material
  - Stabilisation of mechanic cycle : accommodation (plastification at every cycle) $\Rightarrow N_r = f(\Delta\epsilon_p/2)$ (Manson-Coffin line – $N_r = A(\Delta\epsilon_p^n)$)
  - Plasticity $\rightarrow$ elasticity : adaptation $\Rightarrow$ high cycle of failure fatigue



Rochet phenomena – Accommodation



Adaptation



Manson-Coffin diagram in the case of copper

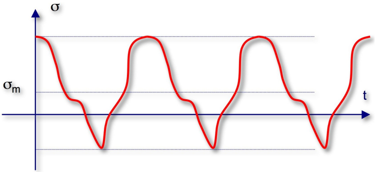
- What to do ?
  - Conservative hypthesis: we assume that there is a defect in the material whose size is equal to the resolution of the means of control used ⇒ Fracture mechanics
  - Use of failure criteria based on the use of Wöhler curves ⇒ fatigue criterion
- What show the observation ?
  - Crack propagation is sensitive to the amplitude of applied stress $\Delta\sigma_a$ and to the average stress σ_m
  - Stress states are generally triaxial, we must consider in developing a fatigue criterion
  - Compressive stress is more favorable than tensile stress

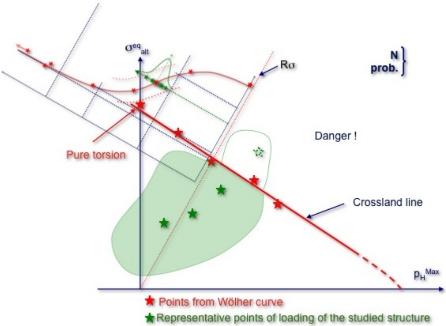
More than 89 680 cycles...and a part of the fuselage goes ...(B737-200 april 88)

vicinity of S-11R, a small area of structure pulled forward and up. Below S-11R, the skin torn but the departure direction was unclear.

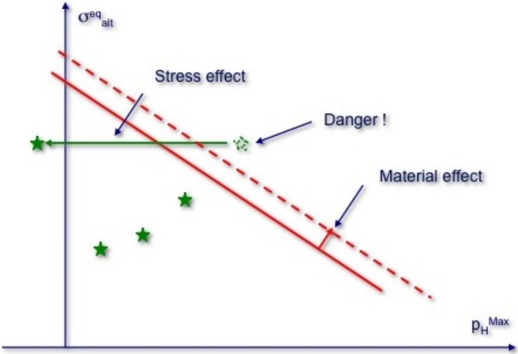
Indications of preexisting cracks were found in the
of BS 540, on each side of a rivet hole in the BS 360
and in lap joint rivet holes in a piece recovered from

- Crossland $\Rightarrow$ graph $\sigma^{eq}_{alt} - pH_{Max}$
- Hypothesis
  - $\underline{\underline{\sigma}}_a = \underline{\underline{\sigma}}_{moy} + \underline{\underline{\sigma}}_{alt} f(t)$ with $f(t)$ periodical fonction with one minima and one maxima
  - σ^{eq}_{alt} in von Mises sense ($\sigma^{eq}_{alt} = \frac{1}{\sqrt{2}} \sqrt{(\sigma_{I alt} - \sigma_{II alt})^2 + (\sigma_{II alt} - \sigma_{III alt})^2 + (\sigma_{I alt} - \sigma_{III alt})^2})$)
  - $pH_{Max} = \frac{1}{3} \text{Max}(\sigma_{Ia} + \sigma_{IIa} + \sigma_{IIIa})$
  - $R_\sigma = \frac{\sigma_{min}}{\sigma_{Max}}$
  - $\sigma_{moy} = \frac{\sigma_{Max}+\sigma_{min}}{2}$ $\sigma_{alt} = \frac{\sigma_{Max}-\sigma_{min}}{2}$ (for unixial case)
- Triaxial fatigue criterion is valid for
  - One material and one given microstructure
  - One given temperature
  - One given environment
  - One given number of cycle to failure
  - One given failure (or not) probability



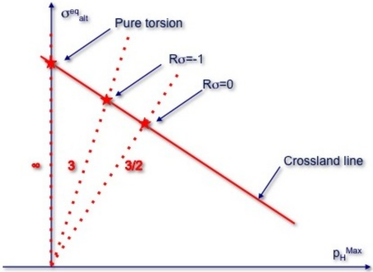


- Material modification (surface treatment)
  - Generally, the slope of Crossland line does not vary
  - if HV $\nearrow \rightarrow \sigma_d \nearrow \rightarrow$ upward shift of the line
- Residual stress effect
  - $\underline{\underline{\sigma}}_{\text{true}} = \underline{\underline{\sigma}}_{\text{a}} + \underline{\underline{\sigma}}_{\text{res}}$
  - Generally $\underline{\underline{\sigma}}_{\text{res}} = \begin{pmatrix} \sigma_{I\text{res}} & 0 & 0 \\ 0 & \sigma_{II\text{res}} & 0 \\ 0 & 0 & 0 \end{pmatrix}$ close to the surface
  - $pH_{\text{Max}} = pH_{\text{Max}\,a} + \frac{2}{3}(\sigma_{I\text{res}} + \sigma_{II\text{res}})$
  - if $(\sigma_{I\text{res}} + \sigma_{II\text{res}}) < 0$ it won otherwise be careful



- **Compressive residual stress is good**...
  - ...insofar as they do not change during operation ⇒ stress relaxation
  - and they are correctly proportioned

- Pure torsion loading
  - $\underline{\underline{\sigma}}_{moy} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} = \underline{\underline{0}}$
  - $\underline{\underline{\sigma}}_{alt} = \begin{pmatrix} 0 & \sigma_{alt} & 0 \\ \sigma_{alt} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} f(t)$ with $f(t)$ periodic function in [-1..1] range
  - $pH_{Max} = 0$ for pure shear stress
  - $\sigma^{eq\,2}_{alt} = \frac{1}{2}((\sigma_{11\,alt} - \sigma_{22\,alt})^2 + (\sigma_{22\,alt} - \sigma_{33\,alt})^2 + (\sigma_{11\,alt} - \sigma_{33\,alt})^2 + 6(\sigma_{12}{}^2_{alt} + \sigma_{13}{}^2_{alt} + \sigma_{23}{}^2_{alt})) = 3\sigma^2_{alt}$
    $\sigma^{eq}_{alt} = \sqrt{3}\sigma_{alt}$
  - slope is ∞
- Traction-compression loading $R_\sigma = -1$
  - $\underline{\underline{\sigma}}_{moy} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} = \underline{\underline{0}}$
  - $\underline{\underline{\sigma}}_{alt} = \begin{pmatrix} \sigma & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} f(t)$ with $f(t)$ periodic function in [-1..1] range
  - $pH_{Max} = \frac{1}{3}\sigma$
  - $\sigma^{eq\,2}_{alt} = \frac{1}{2}(\sigma_{11\,alt} - \sigma_{22\,alt})^2 + (\sigma_{22\,alt} - \sigma_{33\,alt})^2 + (\sigma_{11\,alt} - \sigma_{33\,alt})^2 + 6(\sigma_{12}{}^2_{alt} + \sigma_{13}{}^2_{alt} + \sigma_{23}{}^2_{alt}) = \sigma^2$
    $\sigma^{eq}_{alt} = \sigma$
  - slope is 3



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- Traction-traction loading $R_\sigma = 0$
  - $\underline{\underline{\sigma}}_{moy} = \begin{pmatrix} 0.5\sigma & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$
  - $\underline{\underline{\sigma}}_{alt} = \begin{pmatrix} 0.5\sigma & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} f(t)$ with $f(t)$ periodic function in [-1..1] range
  - $pH_{Max} = \frac{1}{3}\sigma$
  - ${\sigma^{eq}_{alt}}^2 = \frac{1}{2}(\sigma_{11\,alt} - \sigma_{22\,alt})^2 + (\sigma_{22\,alt} - \sigma_{33\,alt})^2 + (\sigma_{11\,alt} - \sigma_{33\,alt})^2 + 6(\sigma_{12\,alt}^2 + \sigma_{13\,alt}^2 + \sigma_{23\,alt}^2) = 0.5^2\sigma^2$
    $\sigma^{eq}_{alt} = 0.5\sigma$
  - slope is $\frac{3}{2}$