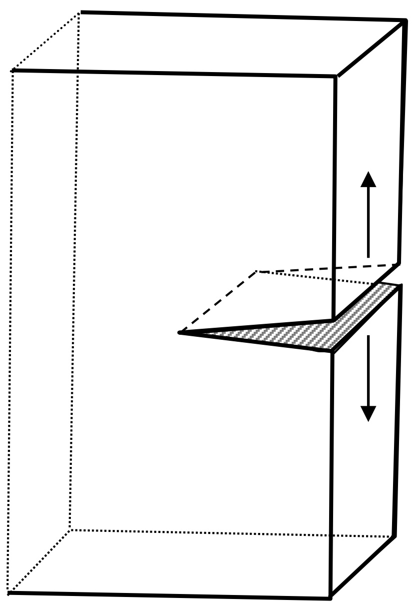
FATIGUE OF MATERIALS & STRUCTURES

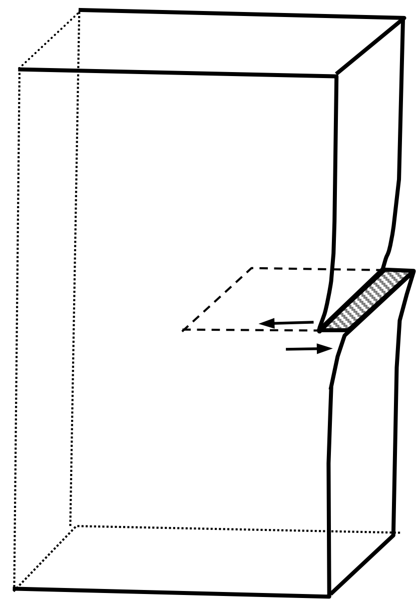
G. Hénaff

FATIGUE CRACK PROPAGATION

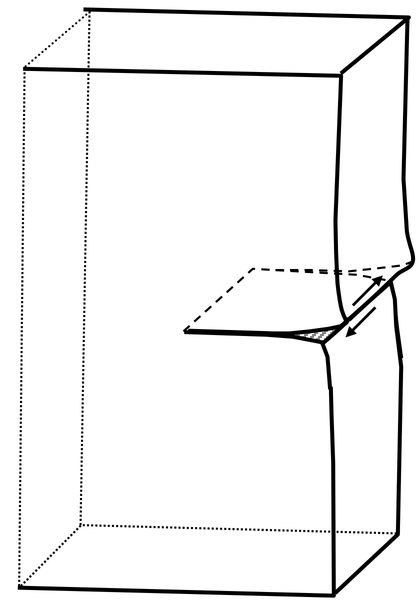
Opening modes



Opening

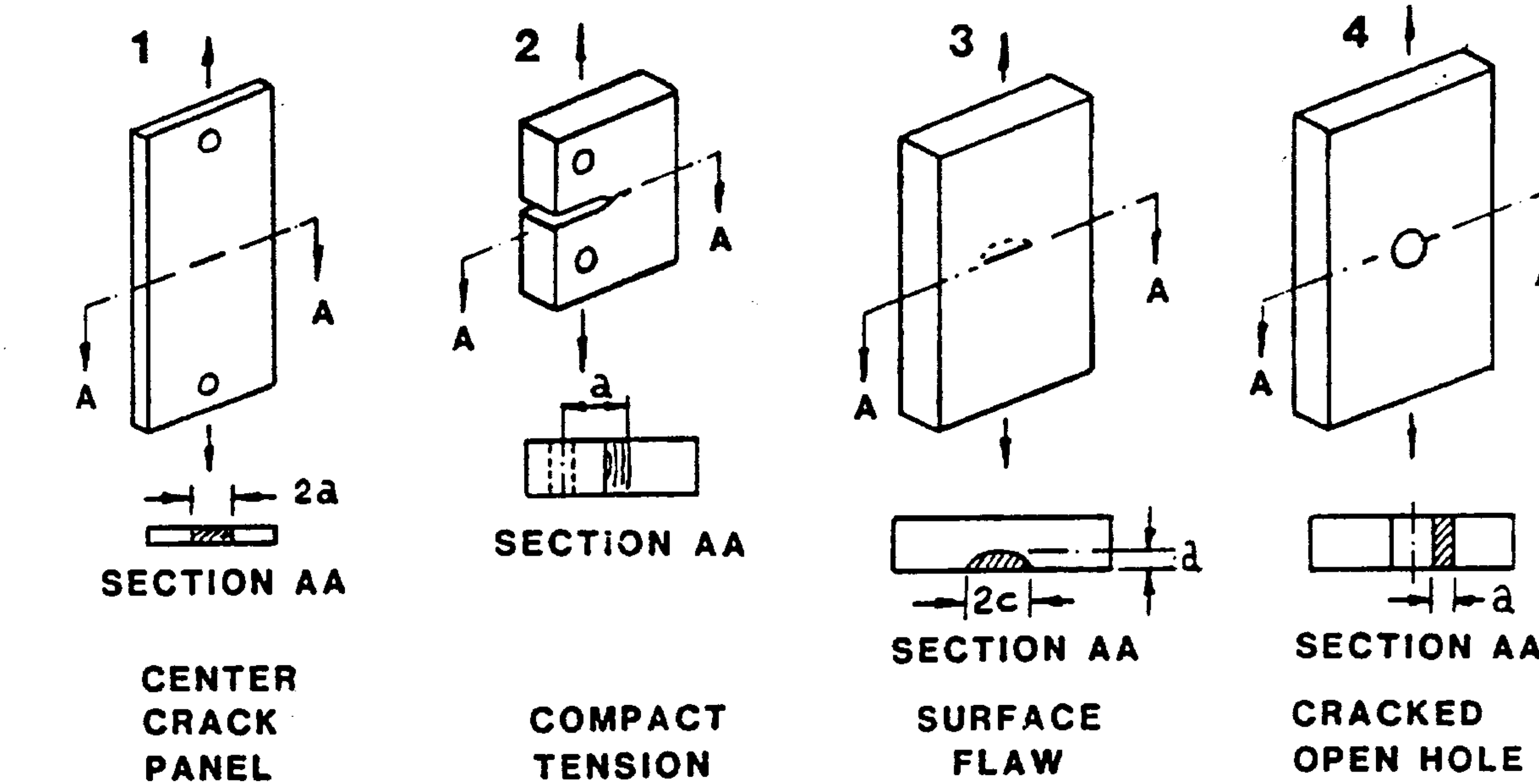


In-plane shearing

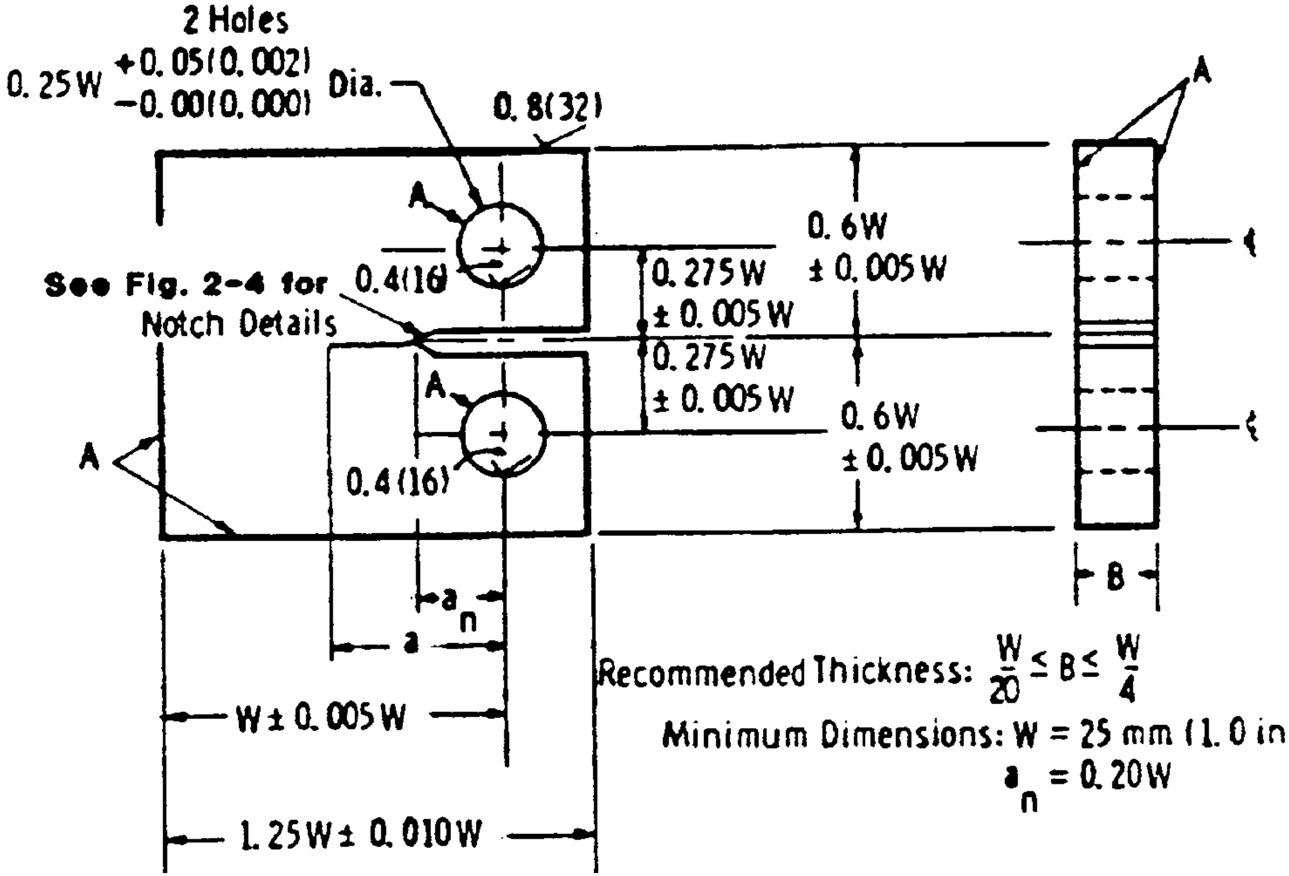


Out-of-plane shearing

Standard specimens

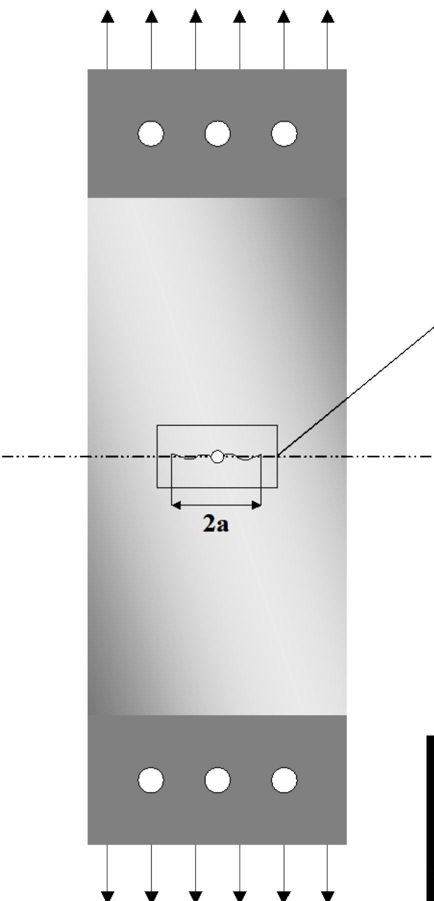


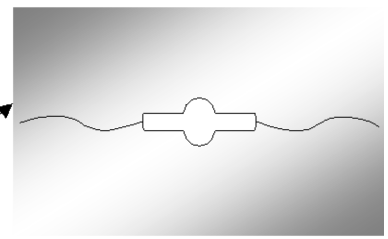
Compact tension specimen

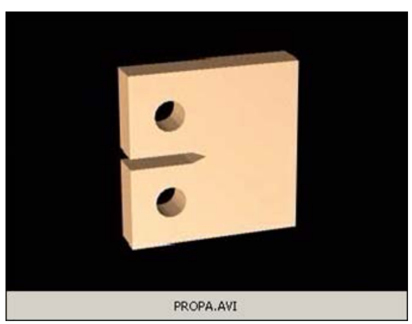


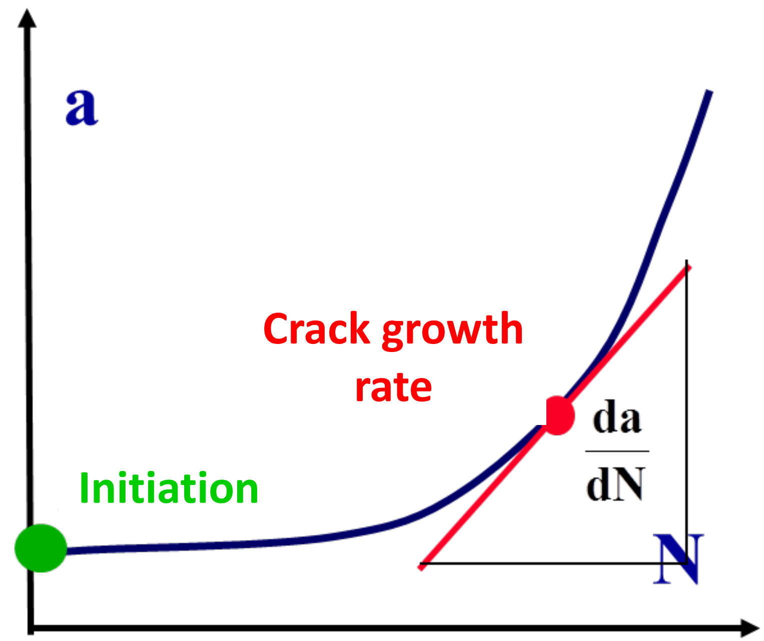
Fatigue crack propagation test

- Pre-cracked specimens
- Crack length monitoring of the crack length as a function of the number of aplled cycles (optical, compliance, potential drop)





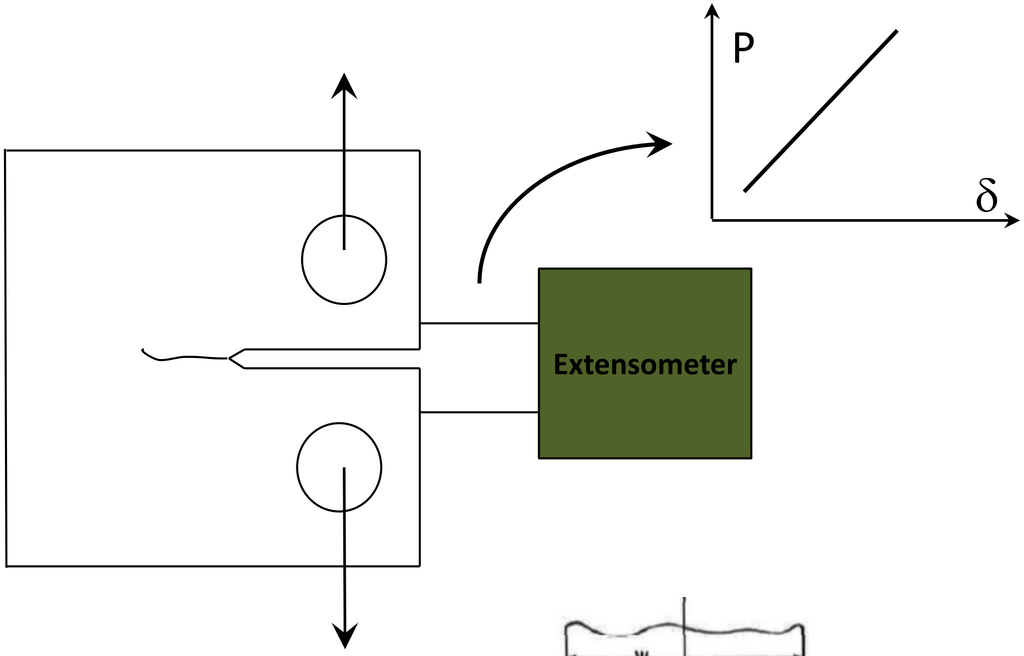




Crack length monitoring

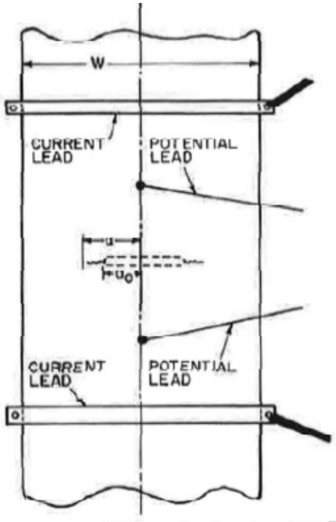
- Optical method (direct)

- Variation of Compliance

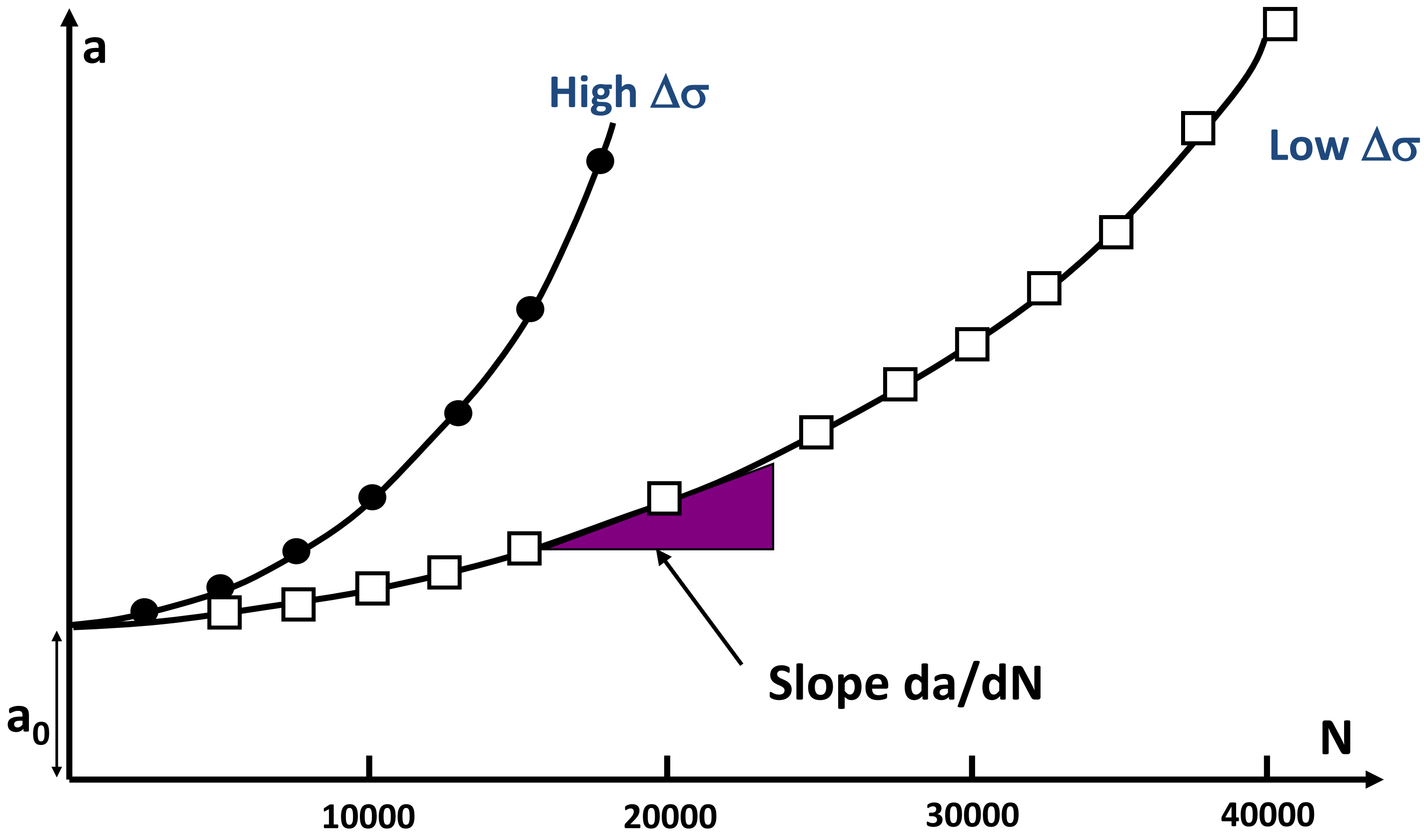


- Potential drop (requires a calibration)

$$\frac{V(a)}{V(a_0)} = \frac{\cosh^{-1}\left(\dfrac{\cosh \pi y / 2W}{\cosh \pi a / 2W}\right)}{\cosh^{-1}\left(\dfrac{\cosh \pi y / 2W}{\cosh \pi a_0 / 2W}\right)}$$

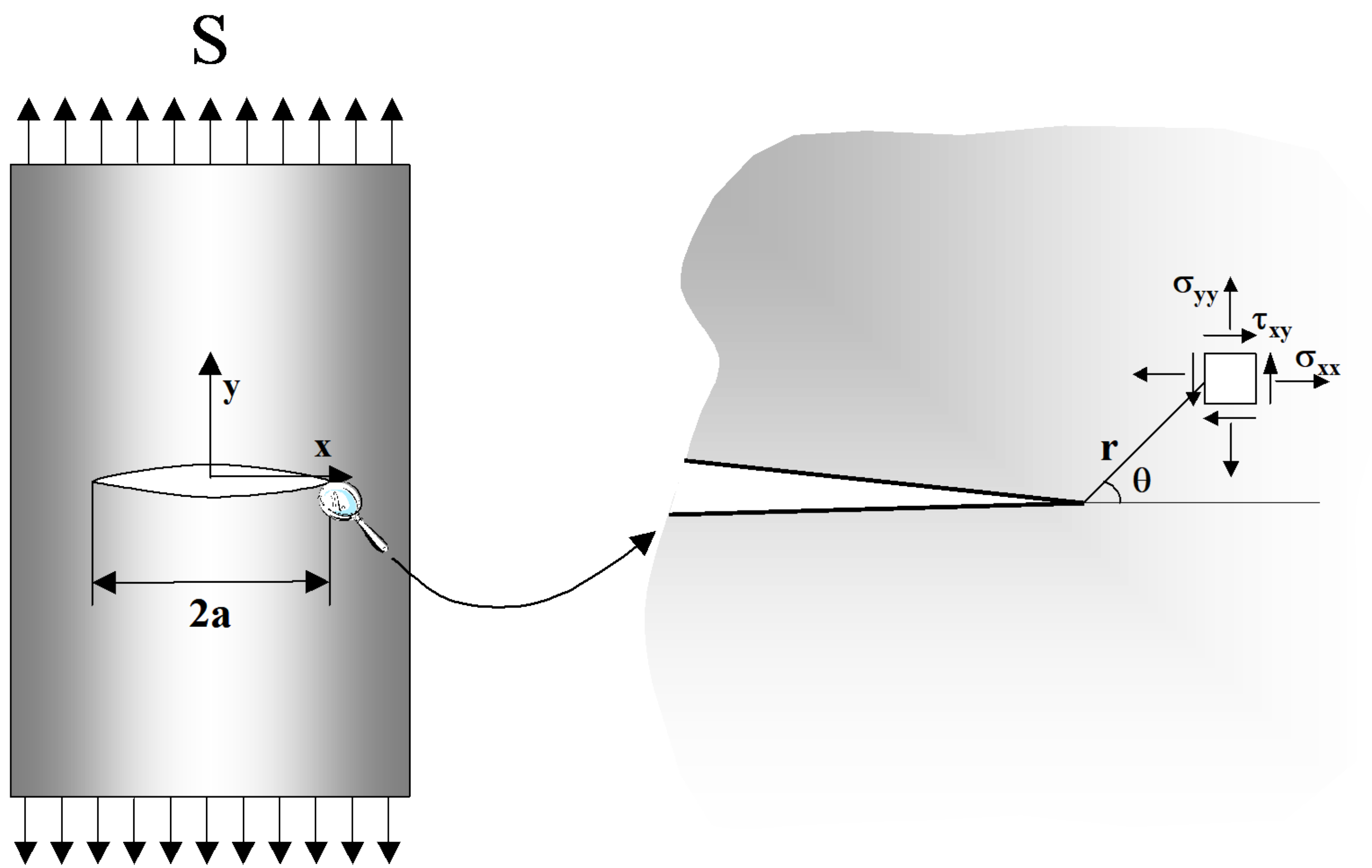


Propagation curves



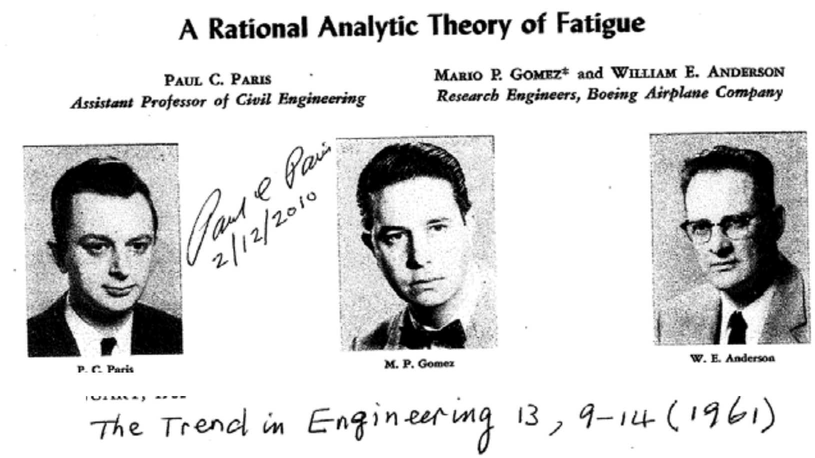
Use of LEFM

Static or monotonic loading: the stress intensity factor accounts for the stress/strain field at the crack tip



Use of LEFM

Idea: consider the *stress intensity factor range ΔK* as the *driving force* for crack growth under cylic loading


A Rational Analytic Theory of Fatigue

Paul C. Paris
Assistant Professor of Civil Engineering

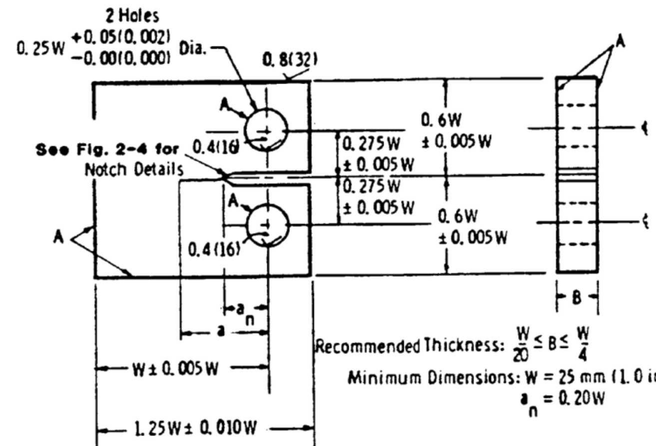
Mario P. Gomez* and William E. Anderson
Research Engineers, Boeing Airplane Company

The Trend in Engineering 13, 9–14 (1961)

$$\Delta K = \alpha \times \Delta\sigma \times \sqrt{\pi a}$$
$$= \alpha \times (\sigma_{max} - \sigma_{min}) \times \sqrt{\pi a}$$
$$= K_{max} - K_{min}$$

NB: even when $\Delta\sigma$ is kept constant, ΔK increases during crack growth

Stress intensity factor



COMPACT TENSION SPECIMEN

$$\Delta K = \frac{\Delta P}{B\sqrt{W}} \frac{(2+\alpha)}{(1-\alpha)^{3/2}} \left[0.886 + 4.64\alpha - 13.32\alpha^2 + 14.72\alpha^3 - 5.6\alpha^4 \right]$$

$\alpha = a/W$

WHERE $\Delta P = P_{max} - P_{min}$ FOR $R > 0$

$\Delta P = P_{max}$ FOR $R \leq 0$

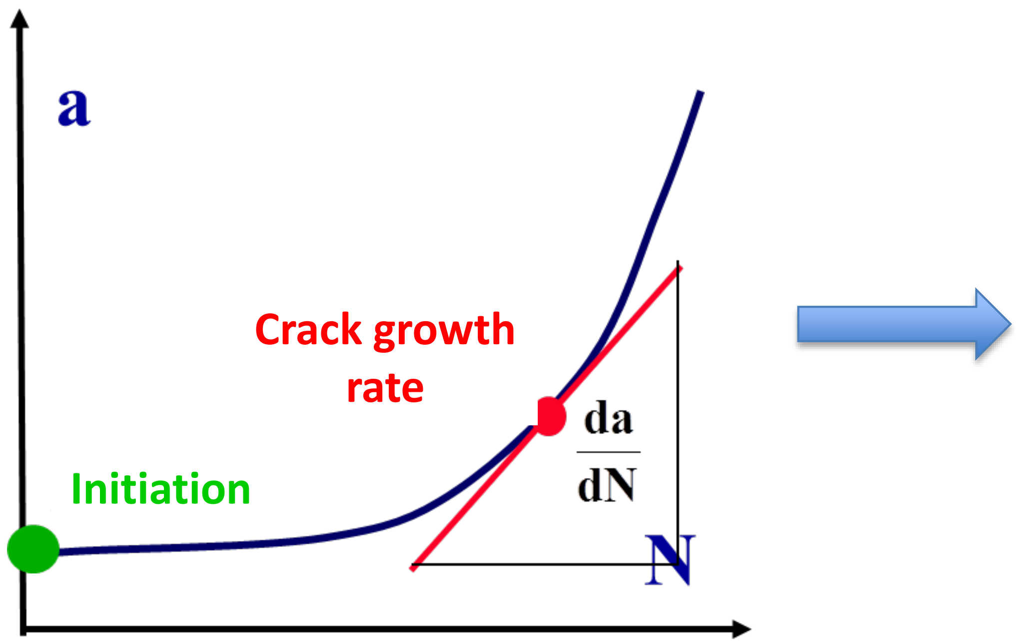
THIS EXPRESSION IS VALID FOR $a/W \geq 0.2$

CENTER CRACKED PANEL SPECIMEN

$$\Delta K = \frac{\Delta P}{B} \sqrt{\frac{\pi\alpha}{2W} \sec\frac{\pi\alpha}{2}}$$ WHERE $\alpha = 2a/W$

THIS EXPRESSION IS VALID FOR $2a/W < 0.95$

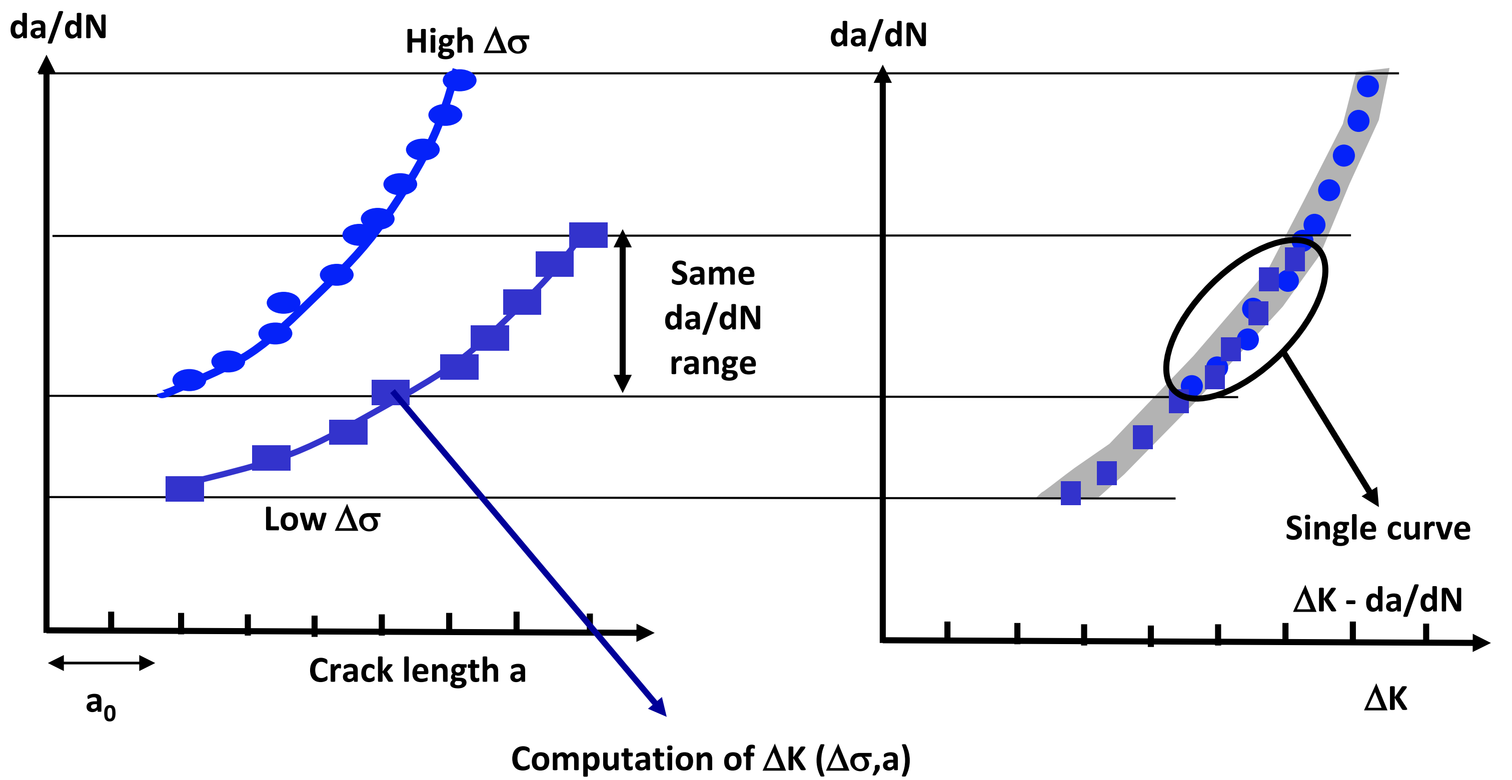
LEFM concepts



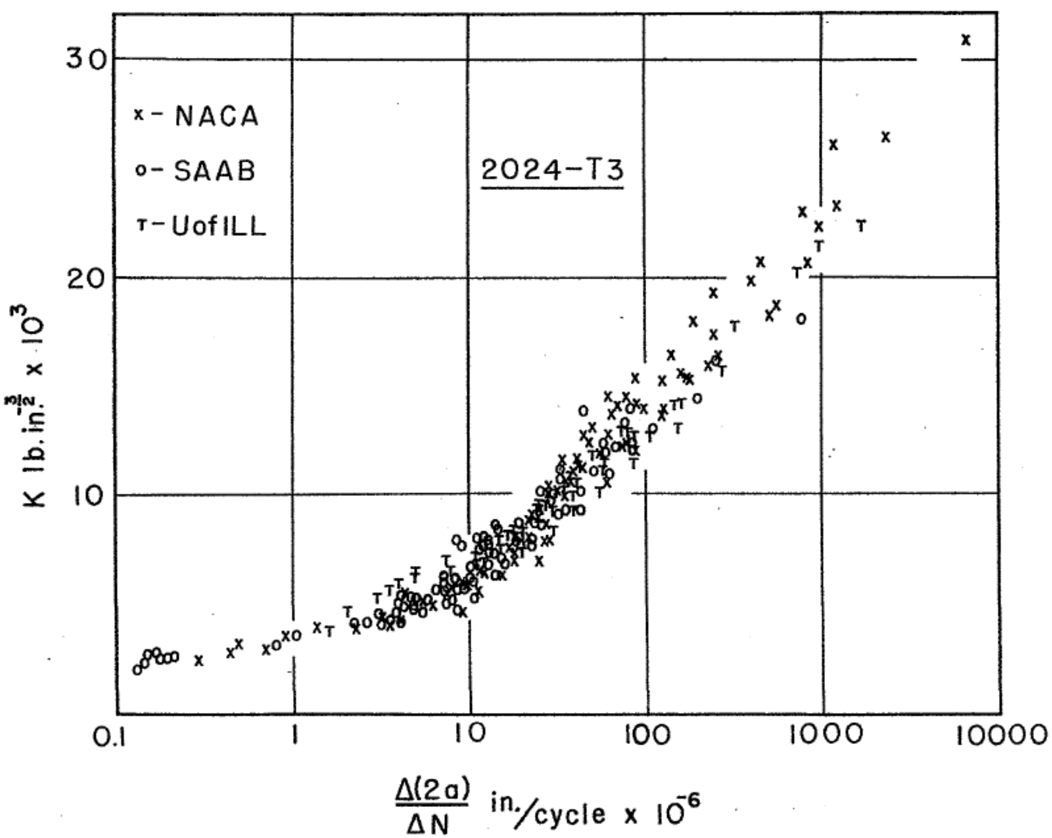
Depends on specimen geometry, initial crack size, applied stress range, …

Principle of similarity: a given value of ΔK (for a wide variety of σ and a values) induces the same cyclic stress/strain field at the crack tip, therefore the same damage and as a consequence the same crack growth rate

Principle of similarity



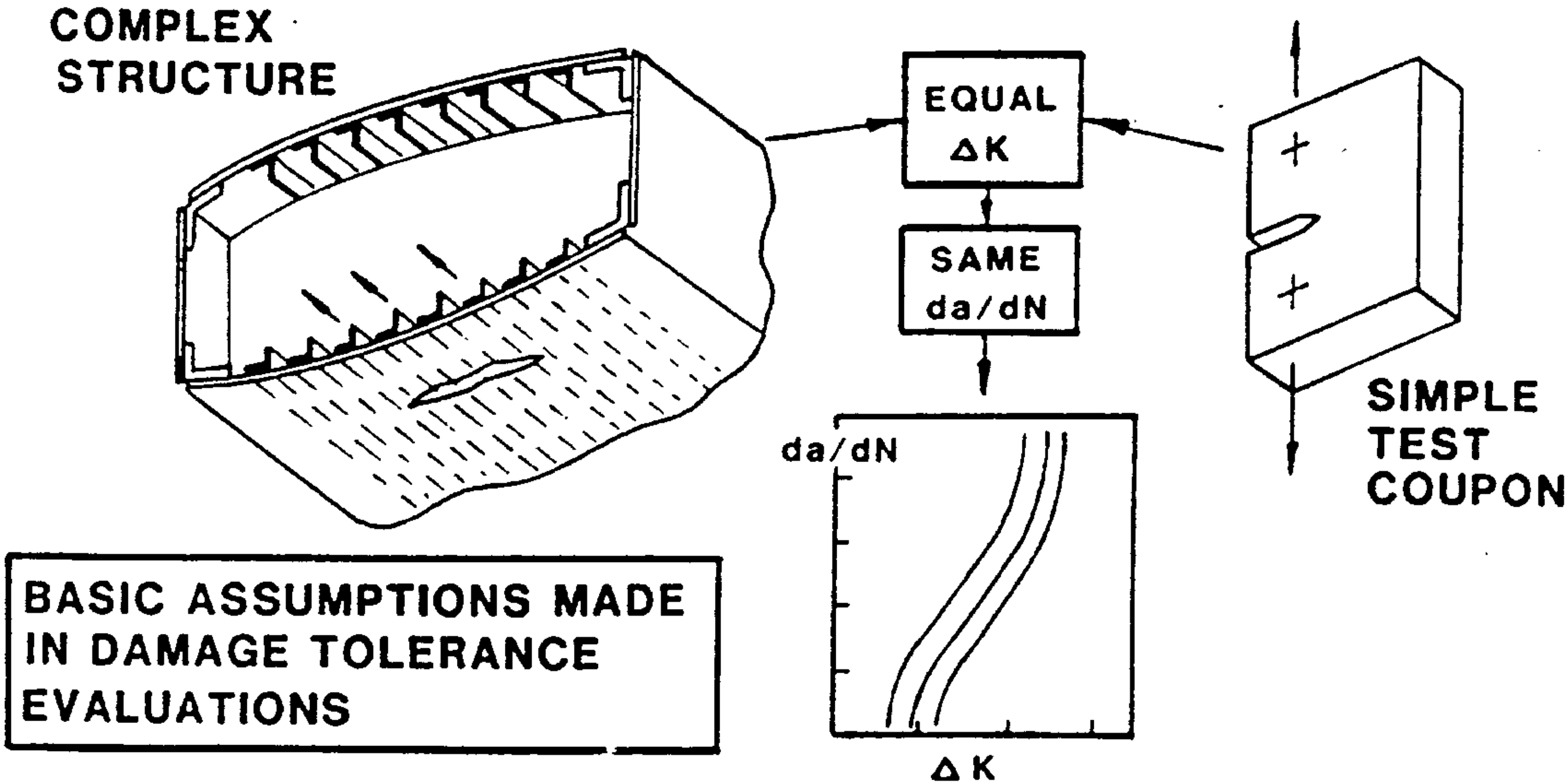
Paris correlation



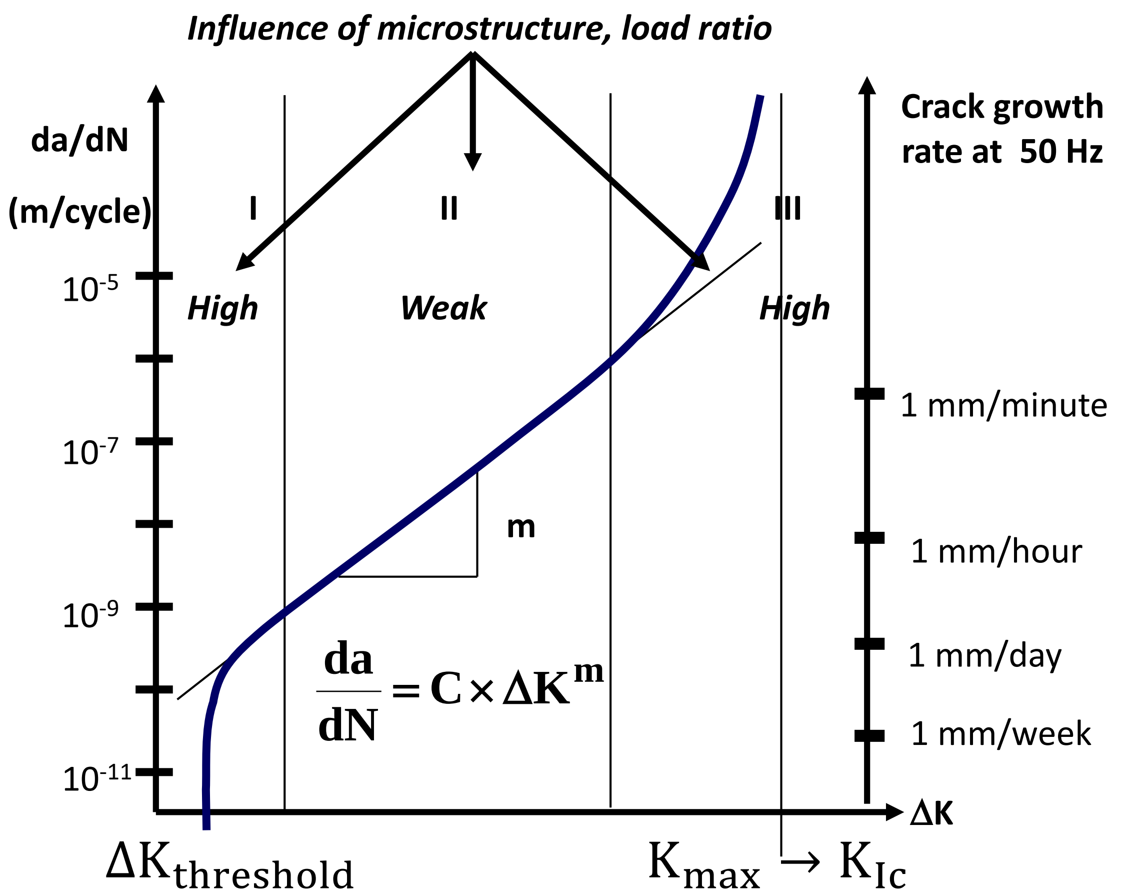
Conclusion

On the basis of the experimental data given, it is evident that rates of crack growth—for example, those in 2024-T3 and 7075-T6 skins of aircraft structure—may be computed by the theory presented over a wide range of nominal stress levels and crack sizes. The ramifications of such broad correlation imply an analytic theory of fatigue based on a concept of growth from initial imperfections through which structural life may be predicted.

Transposability of laboratory data to structures

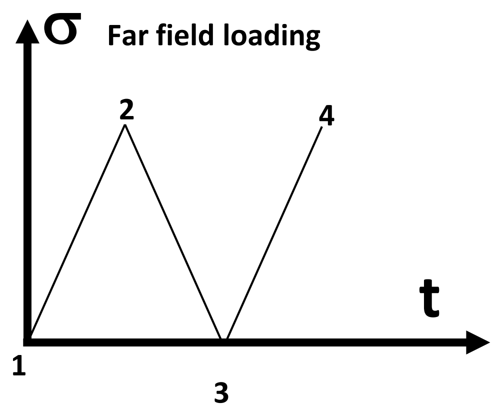


da/dN-ΔK curve

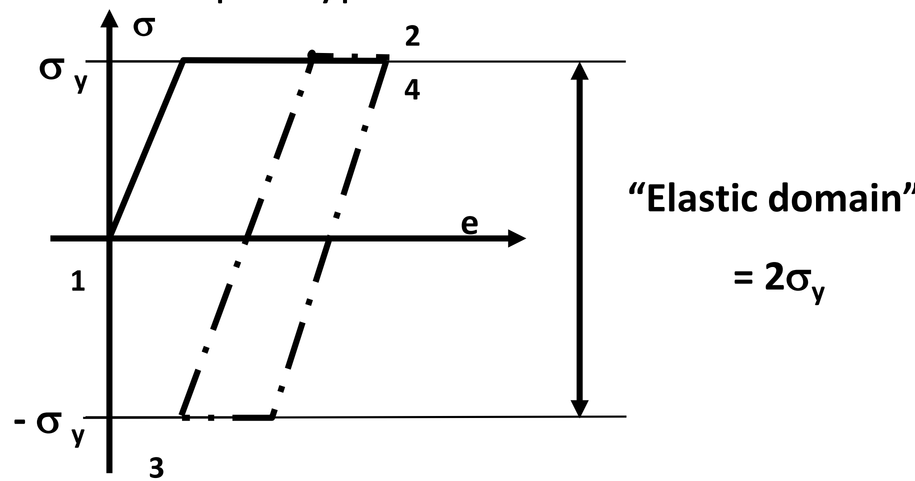


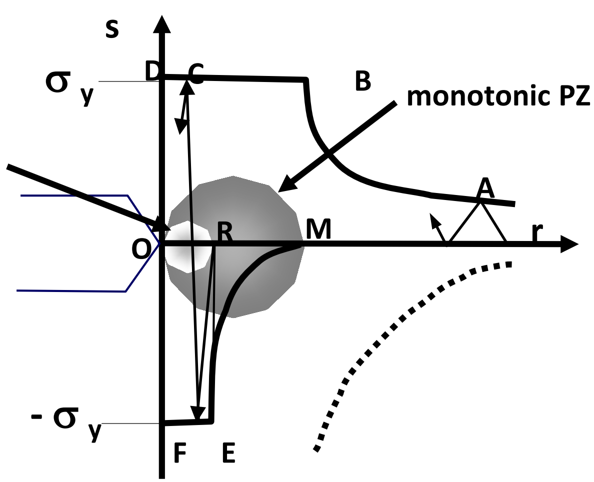
Mechanisms

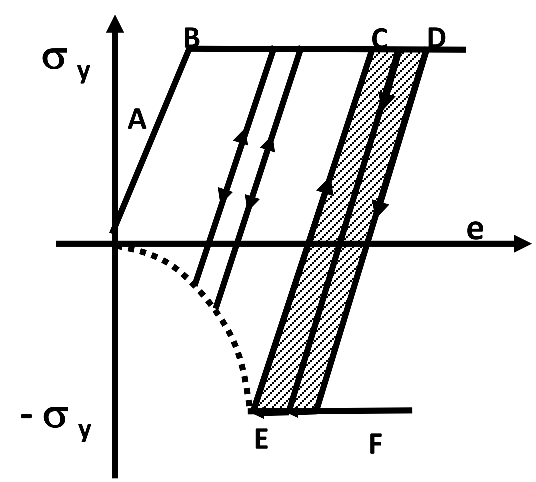
Cyclic deformation at the crack tip



elasto-perfectly plastic behaviour

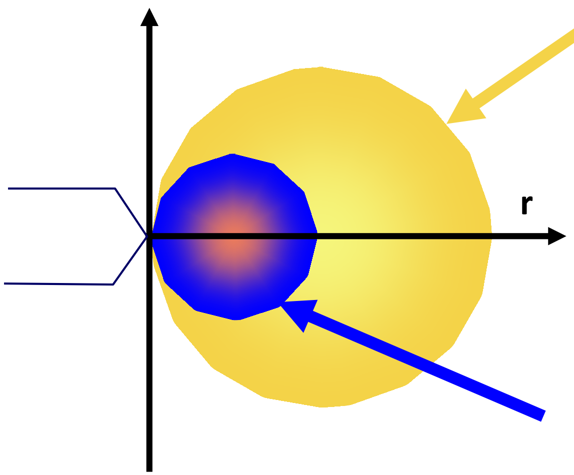






Cyclic plastic zone size

monotonic PZ : $r_p \propto \dfrac{K_I^2}{\sigma_y^2}$



cyclic PZ:

$$K \to \Delta K$$

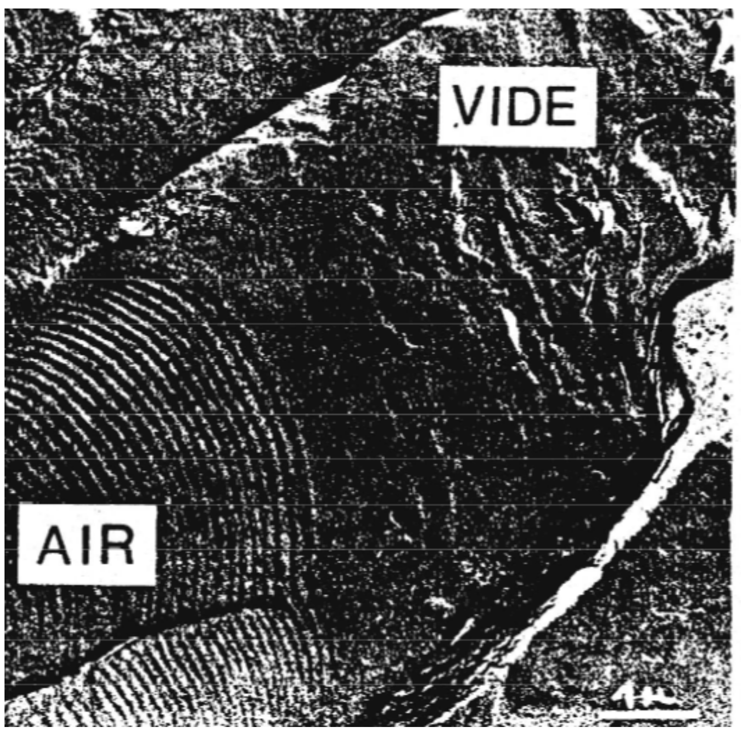
$$\sigma_y \to 2\sigma_y$$

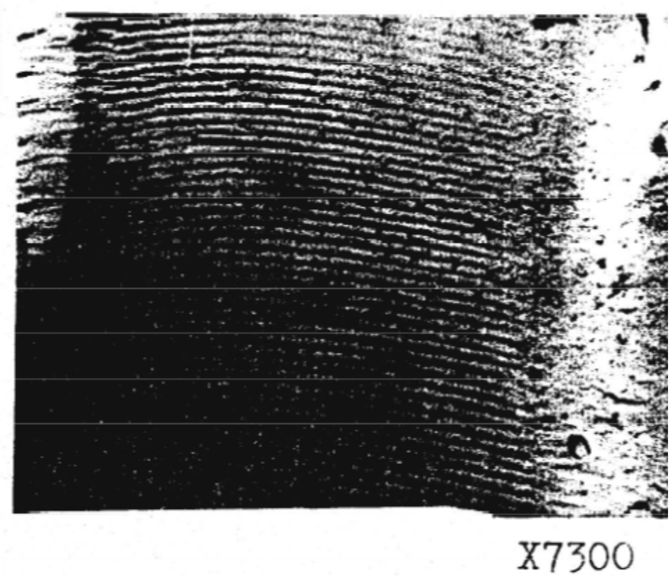
$$r_{p_{cyclic}} \propto \frac{\Delta K^2}{(2\sigma_y)^2}$$

Example: at R=0, the cyclic PZ size is 4 times smaller than the monotonic PZ size.

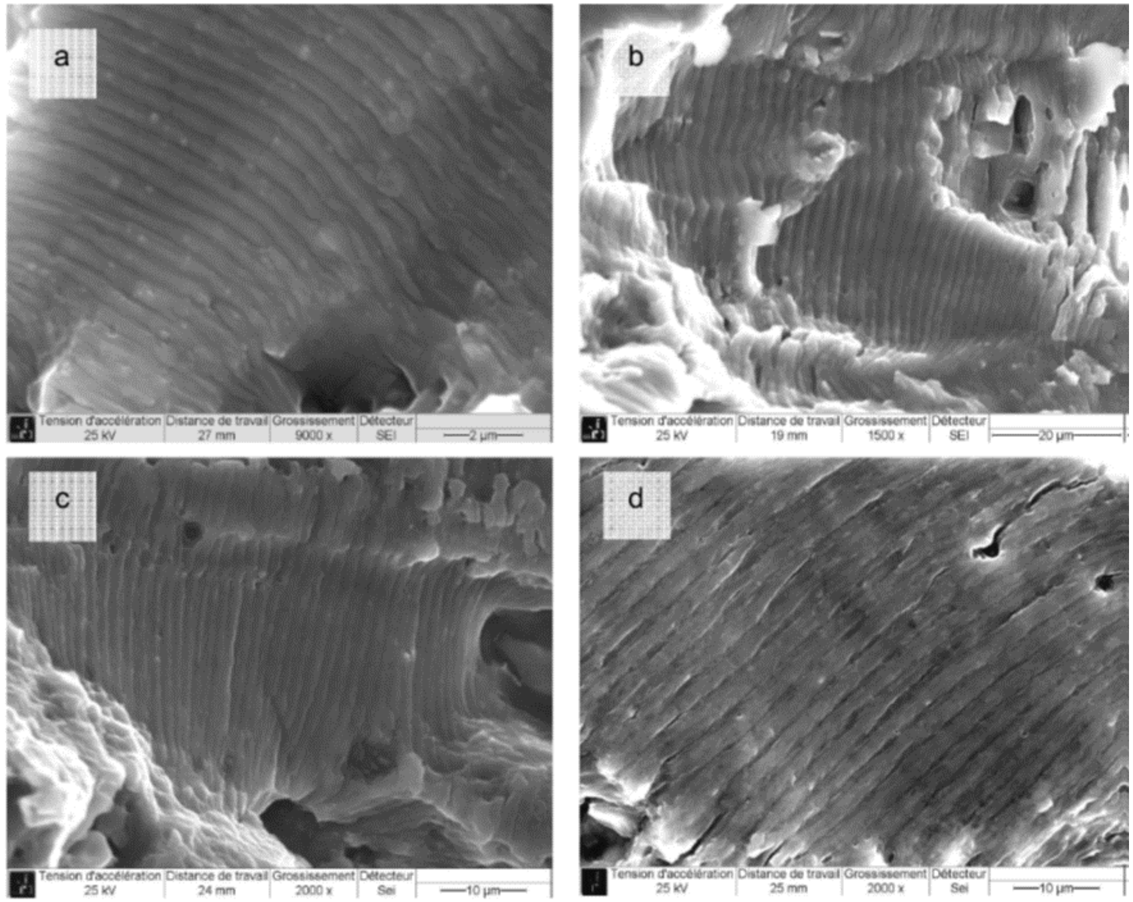
Propagation mechanisms: fatigue striations

- Periodic markings on fracture surfaces;
- Intermediate crack growth rate range ($5x10^{-8}$ - 10^{-5} m/cycle);
- Clearly defined in Aluminum alloys, much less in high strength alloys;
- No striation in inert environment.



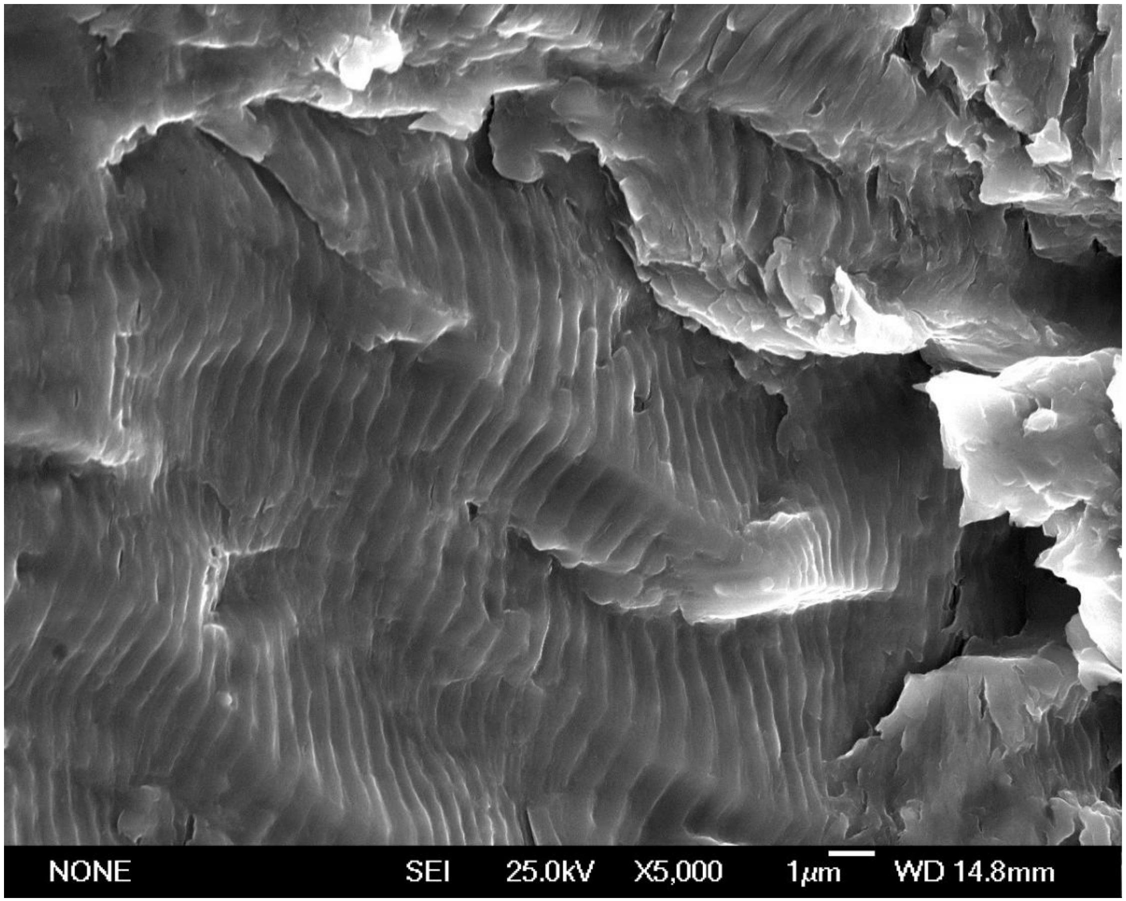


Propagation mechanisms: fatigue striations



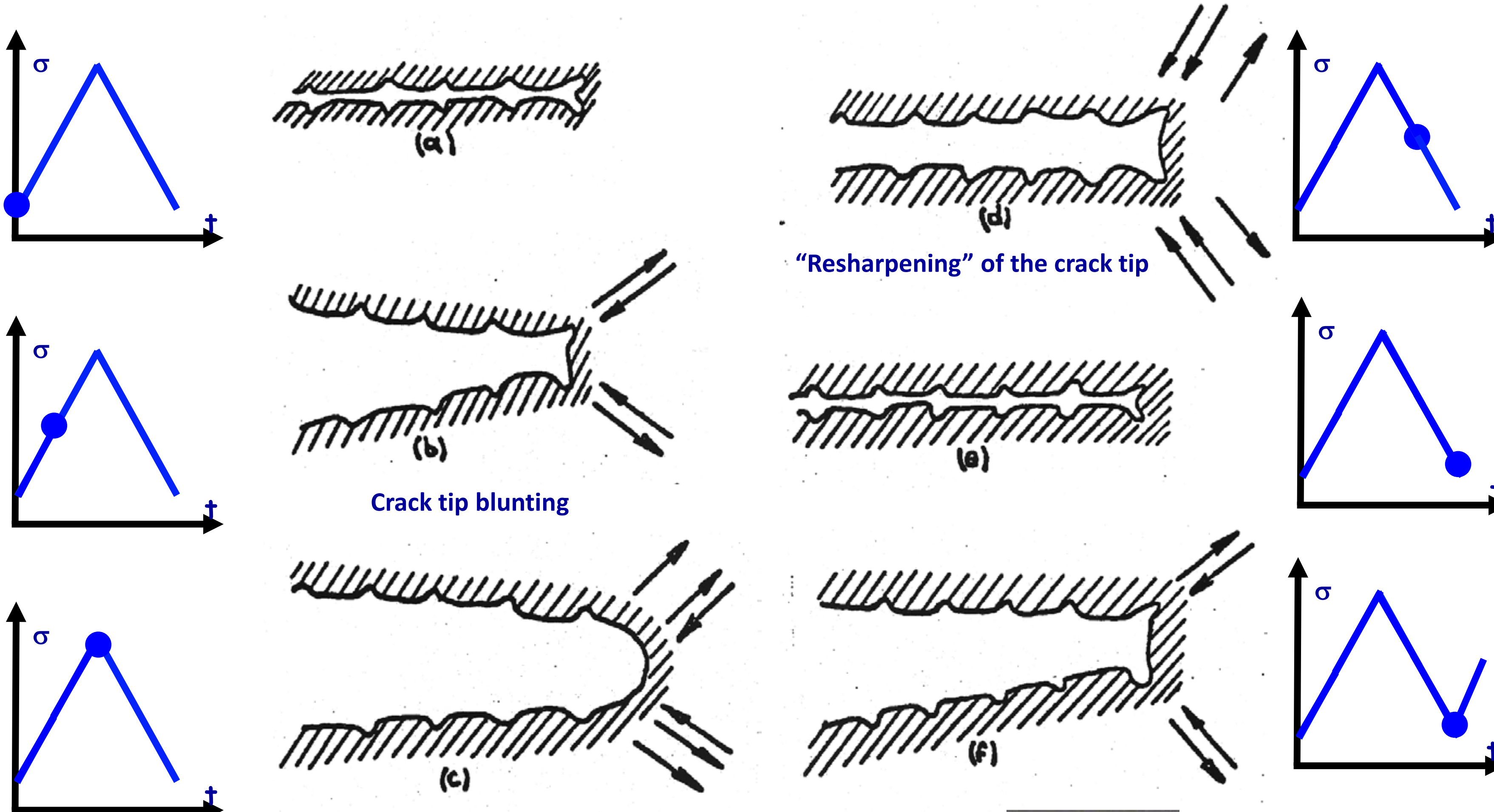
Striations afte fatigue at R=0.1 in a 2024 T351 alloy from the teardown of a A320 MSN004 wing: tip, maximum stress 400 MPa (a) and 300 MPa (b); engine area maximum stress 275 MPa (c) et 300 MPa (d) (Thèse F. Billy, ENSMA)

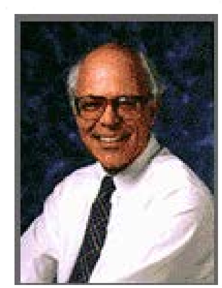
Mécanismes de Propagation : Stries de Fatigue



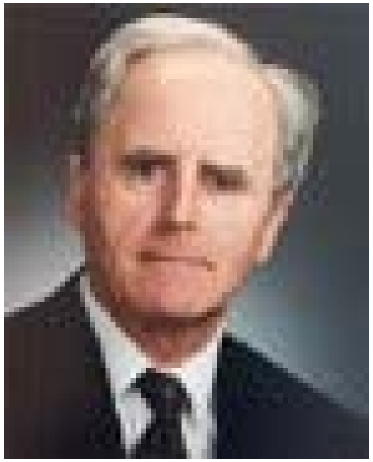
Striations in a precipition-hardened martensitic stainless steel used in aerostructures (thèse L. Dimithe-Aboumou, ENSMA)

Striation formation: Laird mechanism

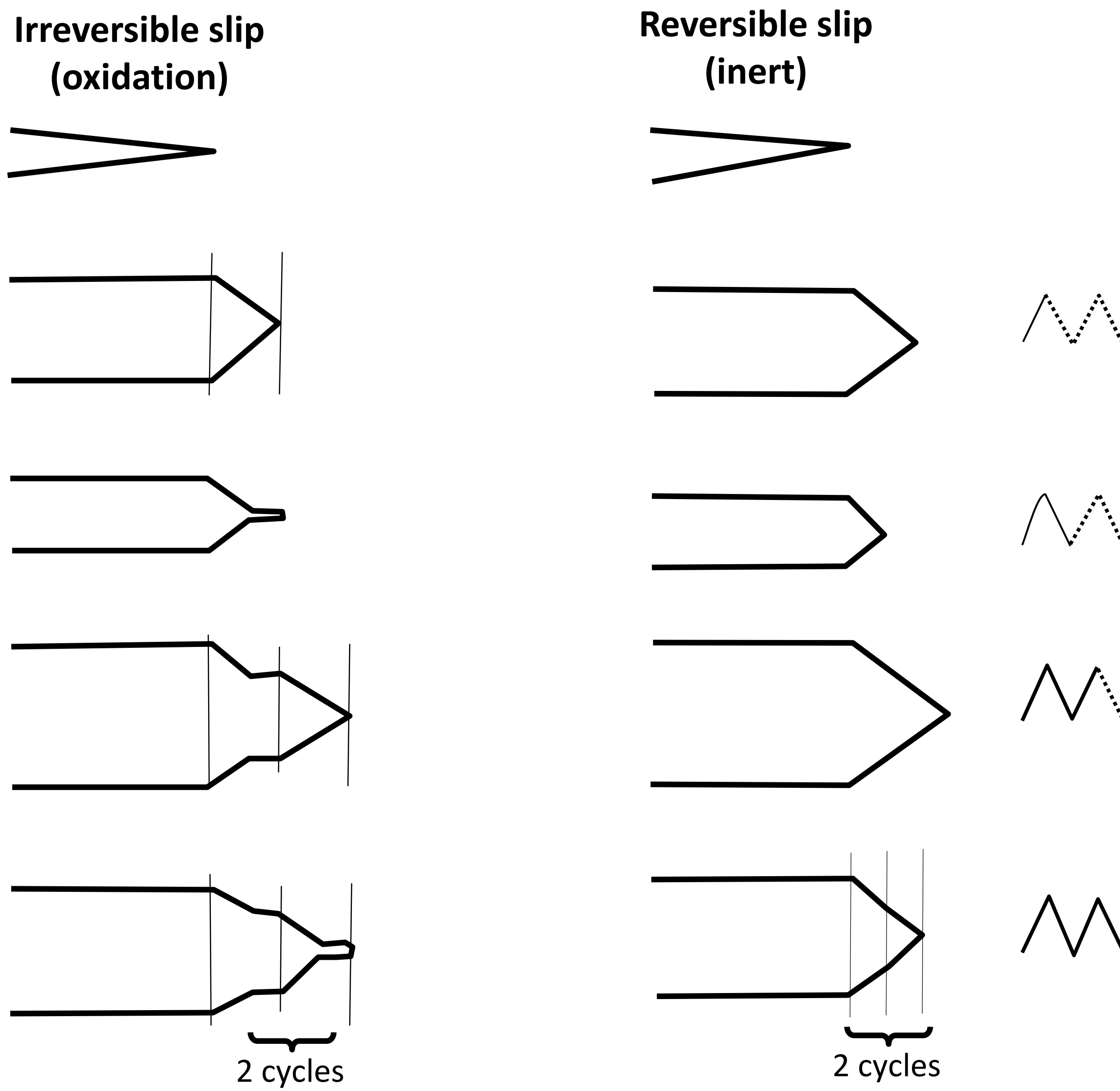




Striation formation: Pelloux mechanism

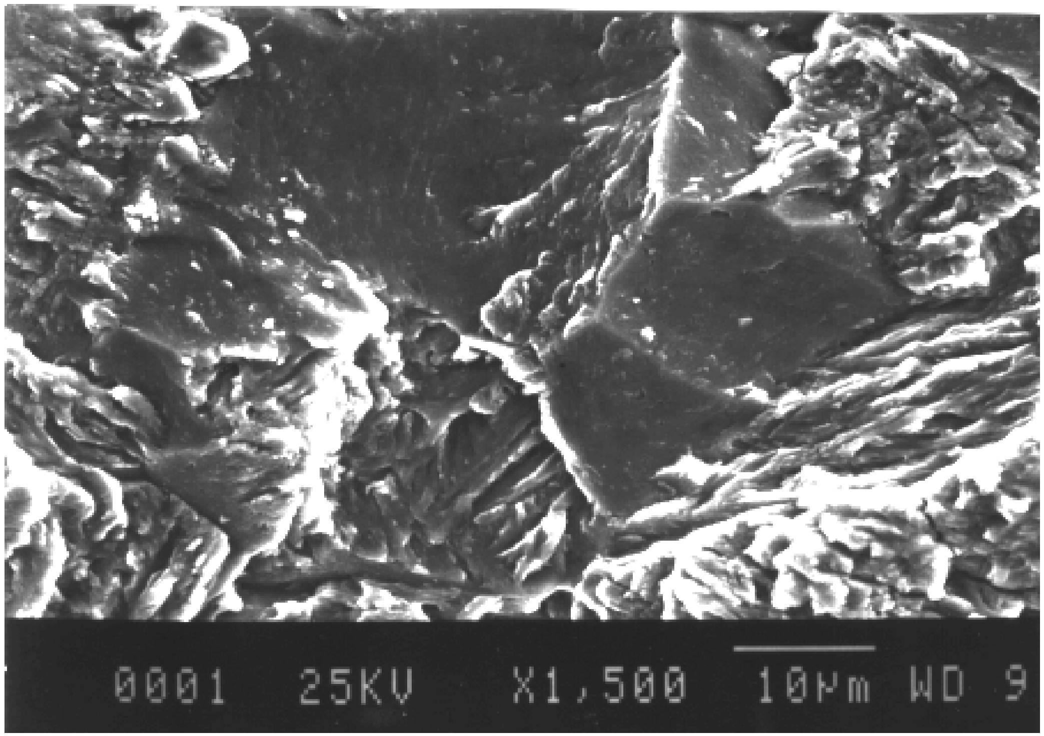


Dr. Regis Pelloux
1931 - 2015



→ Accounts for the absence of striation in vacuum

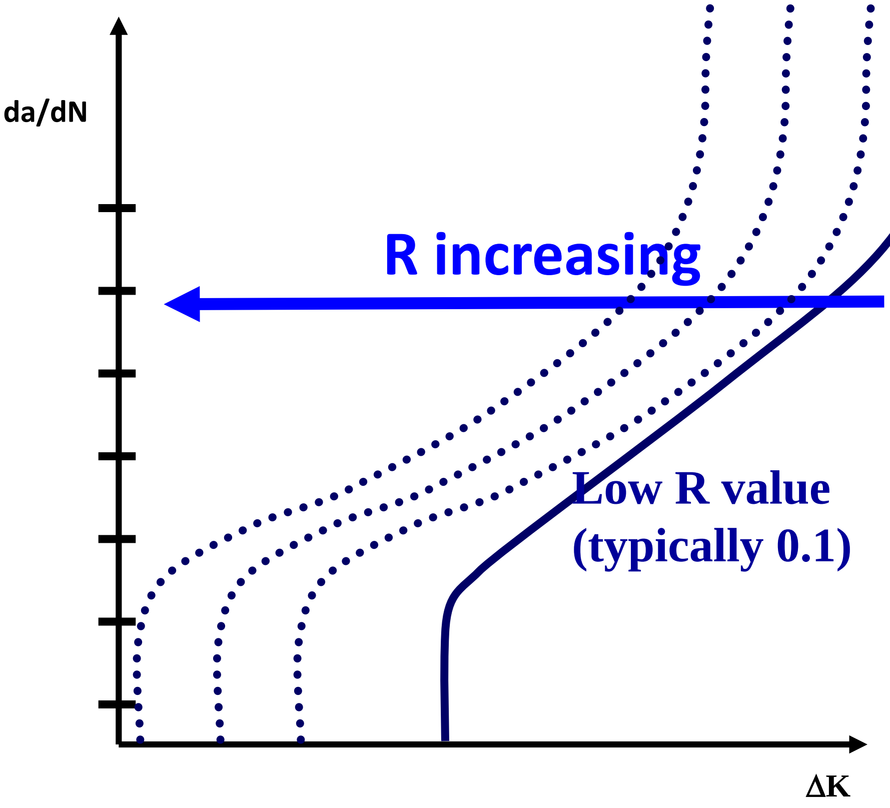
Propagation mechanisms in the near-threshold region



More brittle aspect of the fracture surfaces(cleavage-like fracture, intergranular decohesions,….)

Factors of influence

Influence of load ratio



When R increases:

- da/dN increases for a fixed value of ΔK;
- $\Delta K_{Threshold}$ decreases.

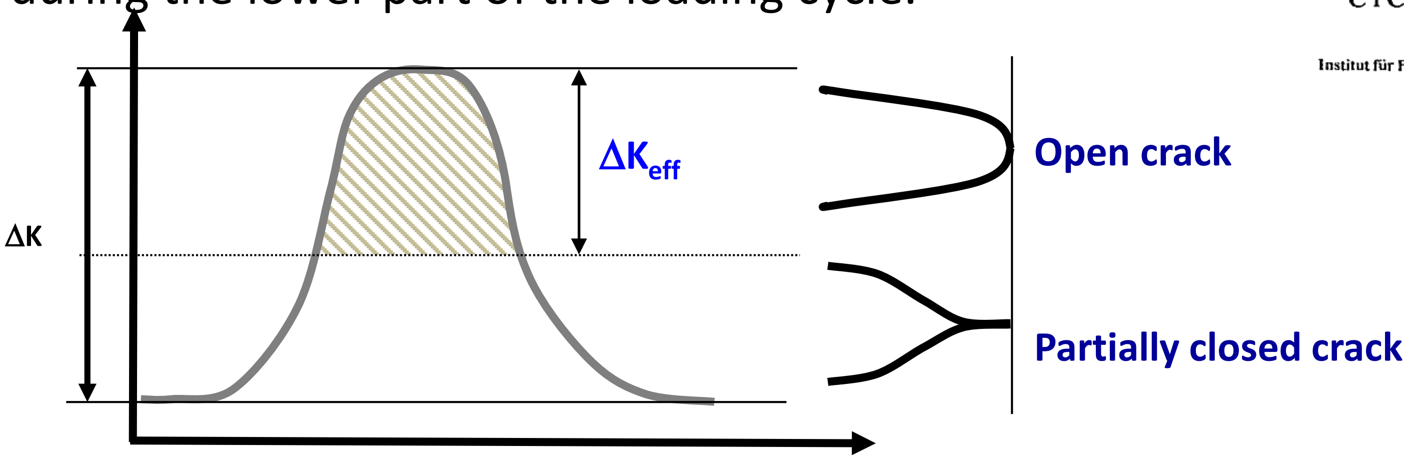
Crack closure

Experimental evidence that a fatigue crack , even when loaded in tension (R>0) can be partially closed during the lower part of the loading cycle.

Engineering Fracture Mechanics, 1970, Vol. 2, pp. 37–45. Pergamon Press. Printed in Great Britain

FATIGUE CRACK CLOSURE UNDER CYCLIC TENSION

WOLF ELBER
Institut für Festigkeit, Mülheim, Germany



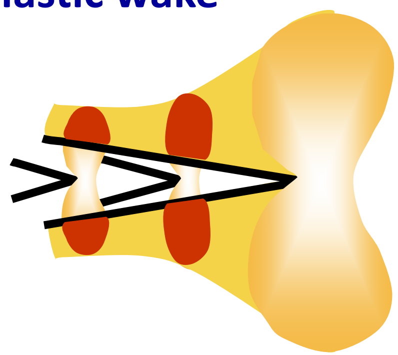
Hyp : a crack can propagate only when it is fully open $\Rightarrow$ da/dN fonction of ΔK_{eff}

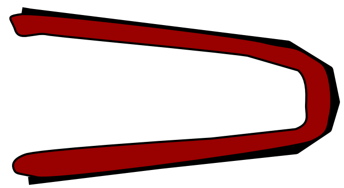
Elber (1970): $\Delta K_{eff} = U \times \Delta K$

For the 2024 T351 alloy in Paris regime: $U = a + b \times R$

Crack closure sources

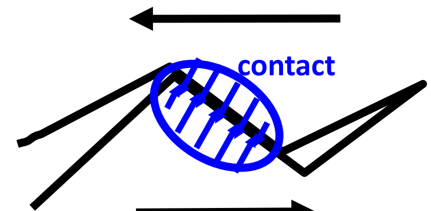
Plastic wake





Formation of a thick oxide layer ⇒ "wedge" effect"

Residual mode II displacement



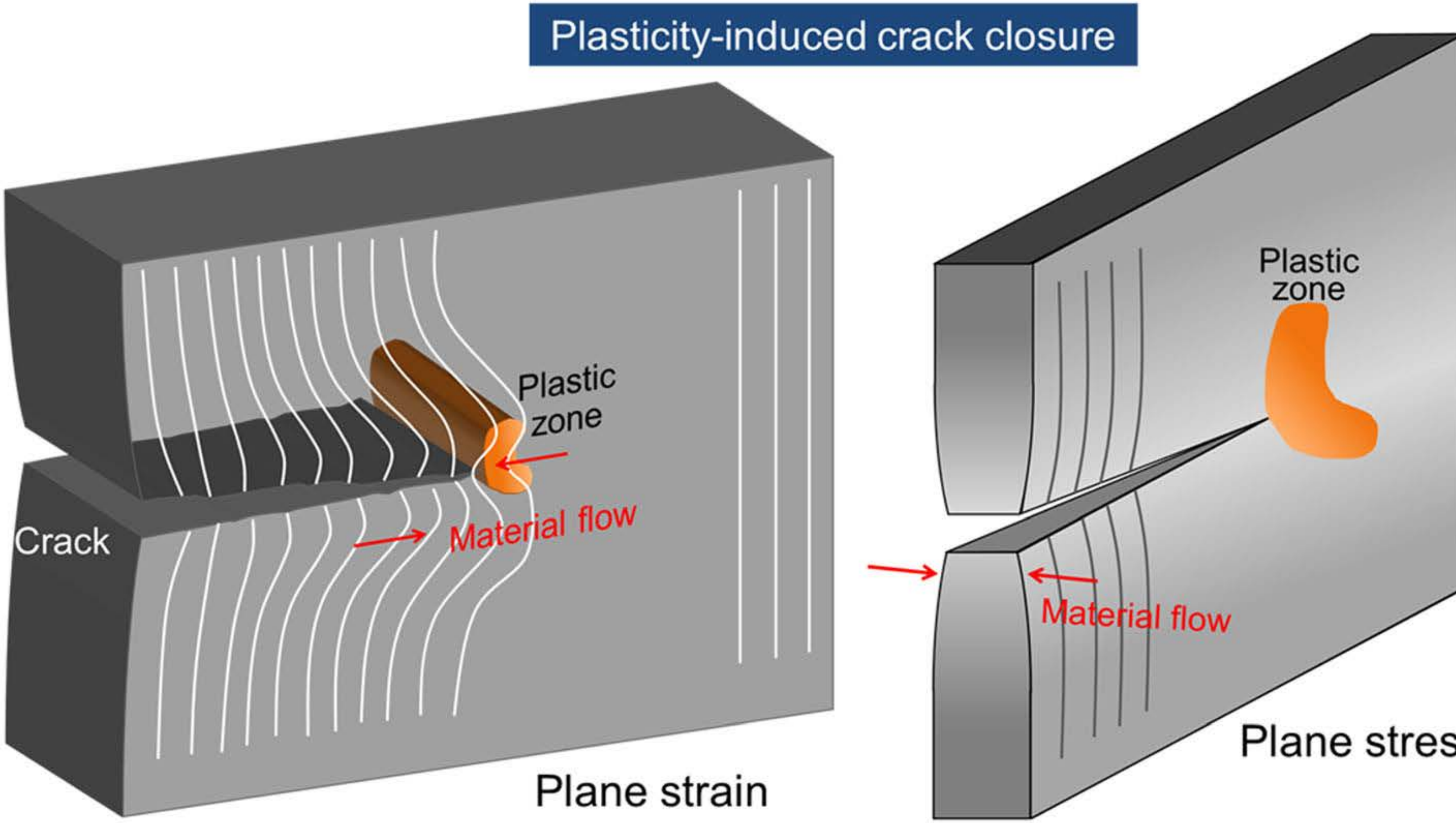
Plasticity induced closure

Oxide induced closure

Roughness induced closure

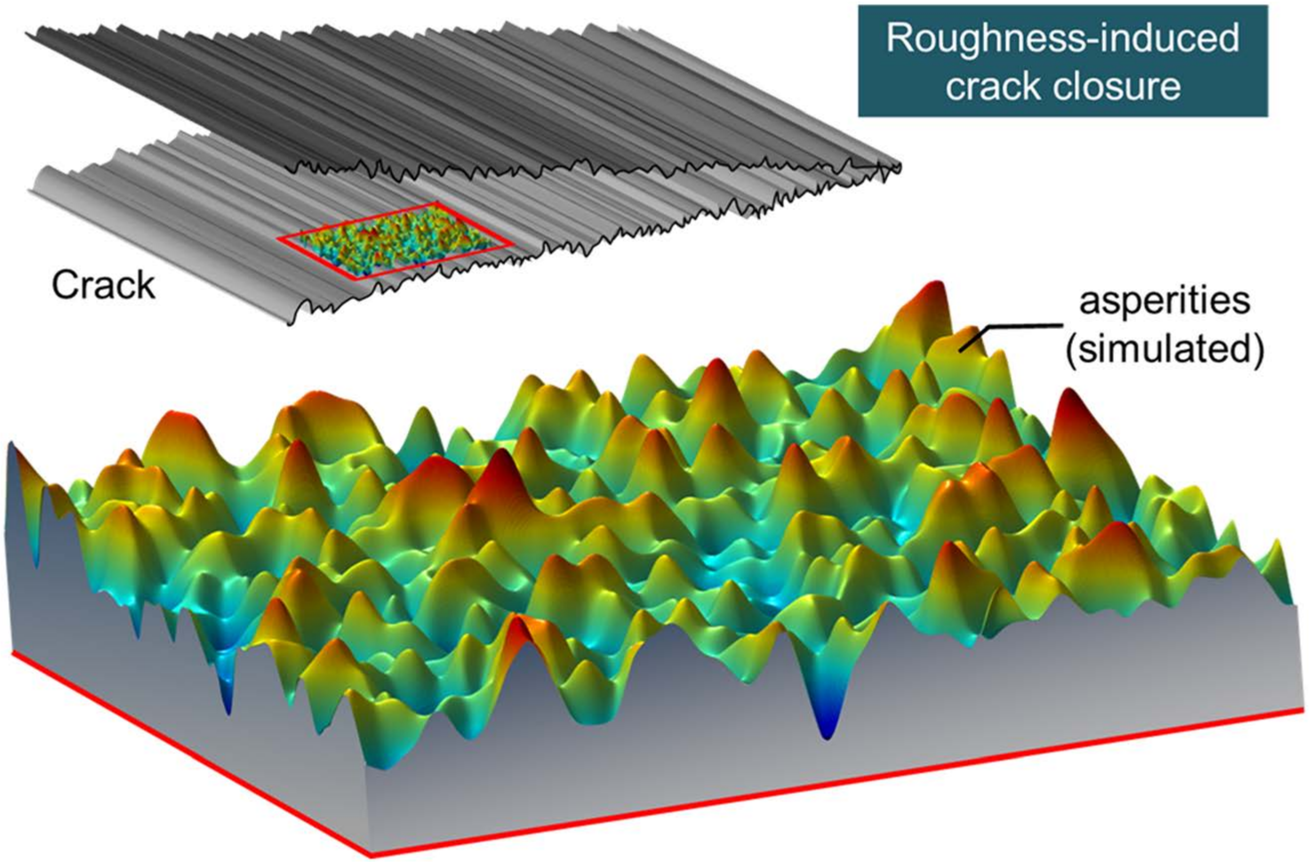
G. Hénaff – 2016

Plasticity-Induced Closure



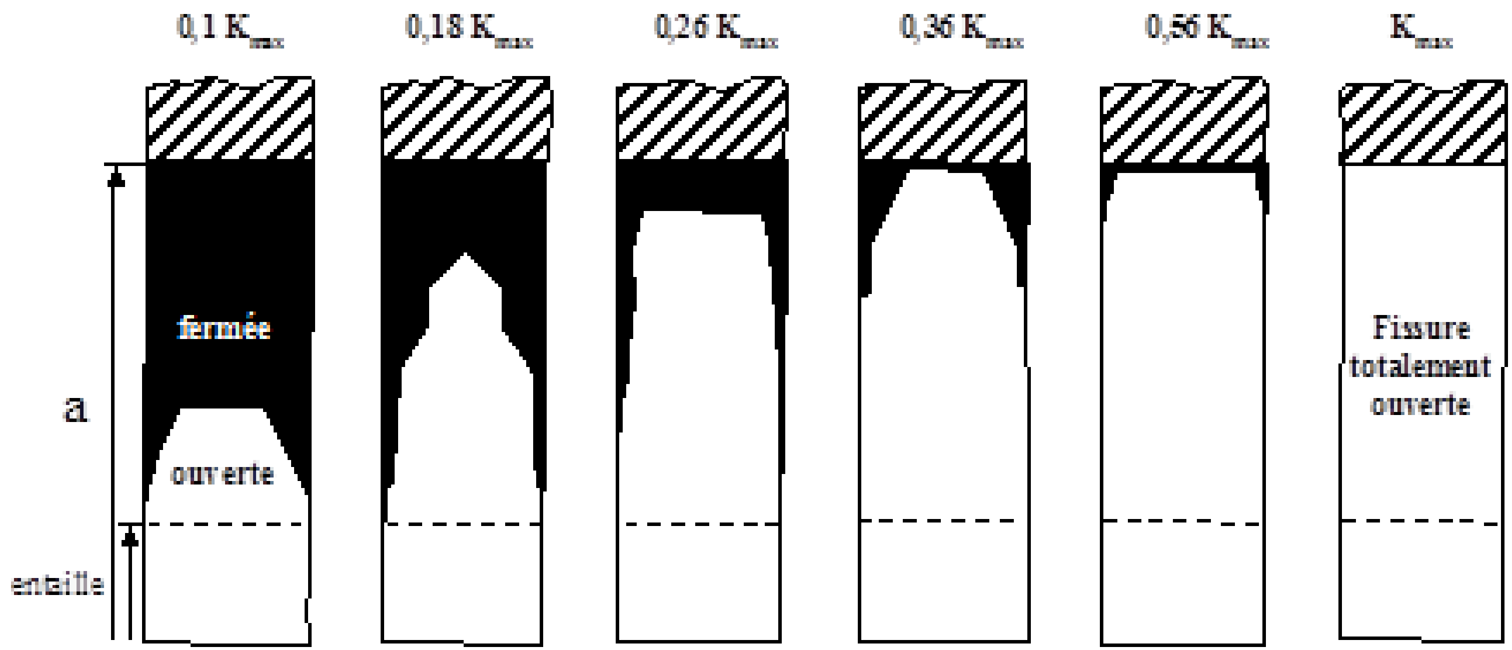
The material flow from the bulk that accumulates on the crack flanks, thereby giving rise to the premature contact as noted by Sun and Sehitoglu

Roughness-Induced Closure



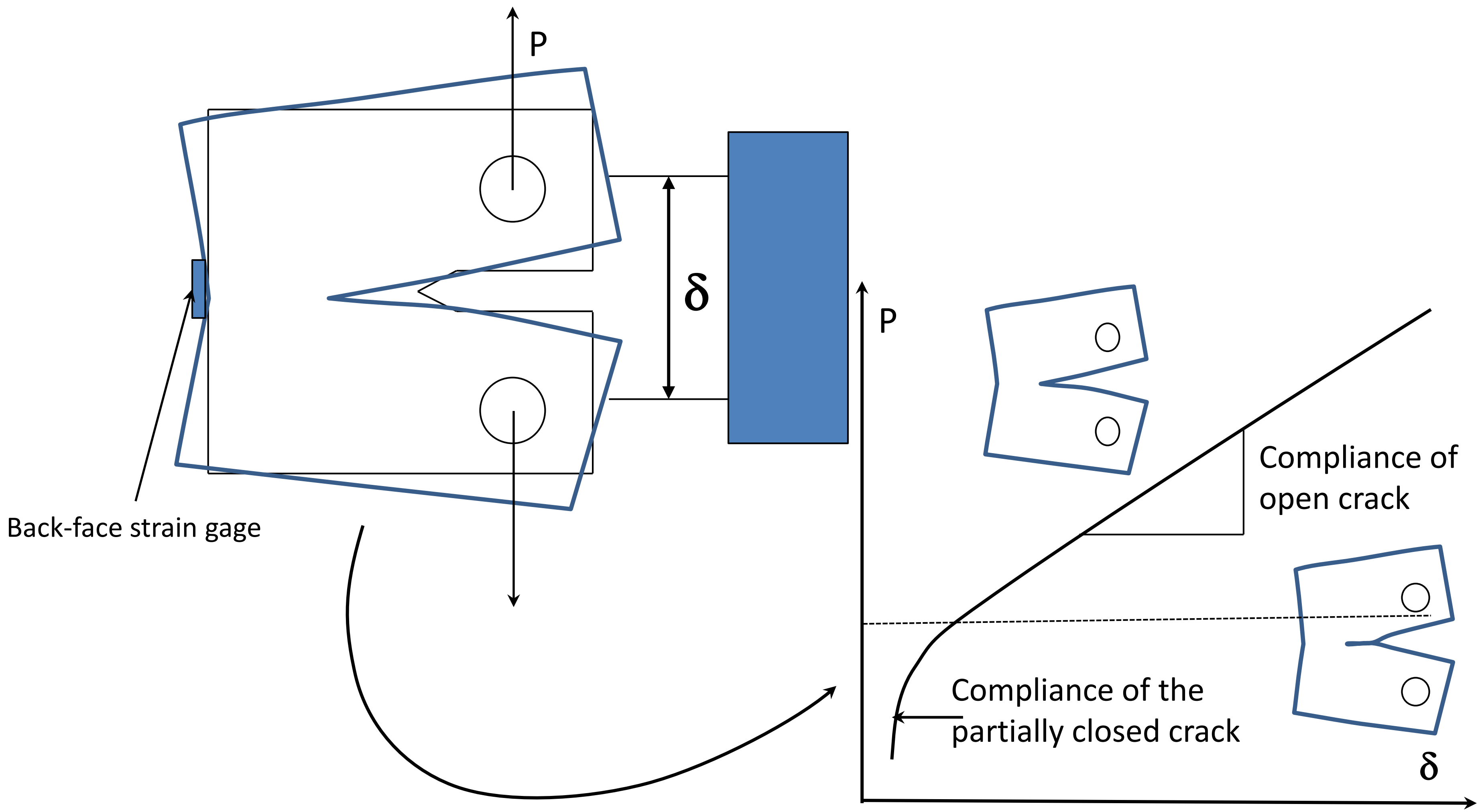
Garcia and Sehitoglu modelled roughness-induced crack closure as a contact problem with random distribution of surface asperities.

Opening kinematics



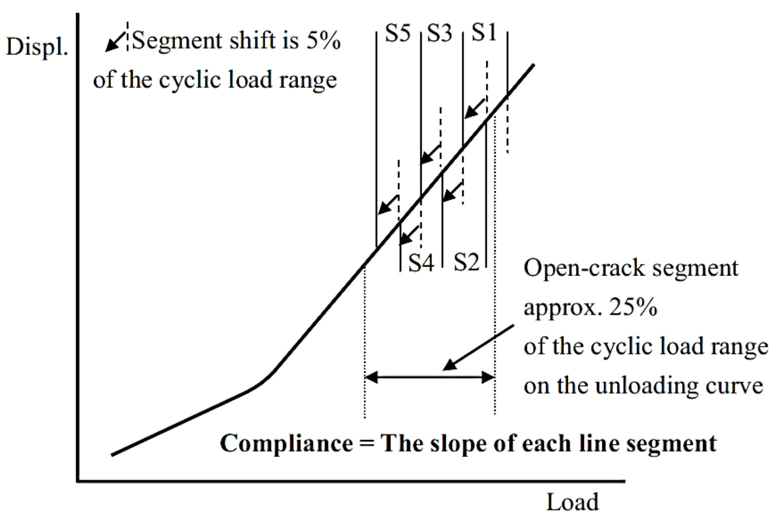
FEM Simulation of the crack opening in a CCT specimen (after Chermahini et al. 1988).

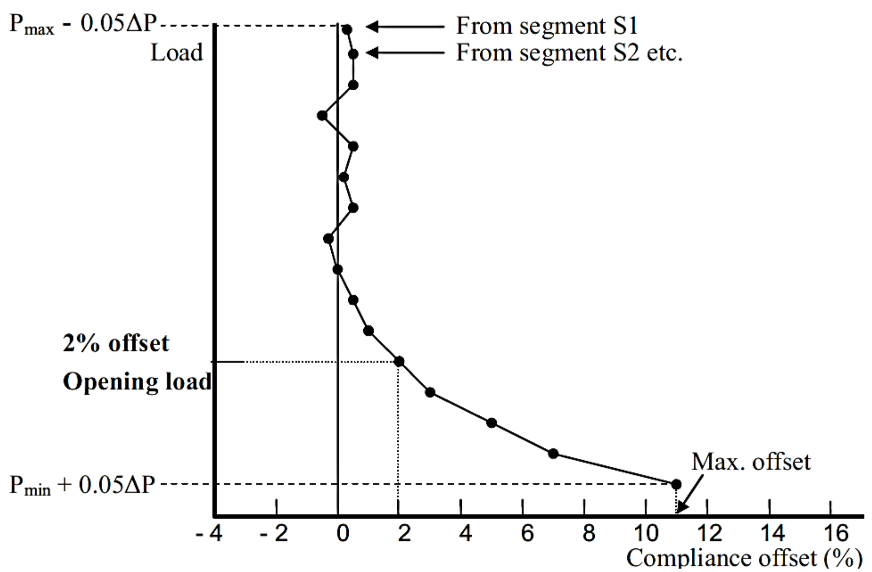
Experimental measurement of the crack opening load



Experimental measurement of the crack opening load

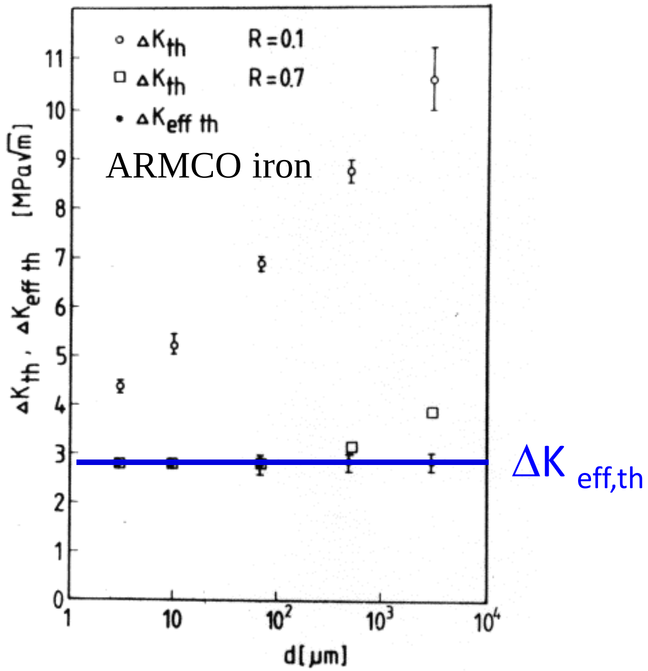
$$\text{Compliance offset}(\%) = \frac{[(\text{open-crack compliance})-(\text{compliance})]}{(\text{open-crack compliance})} \times 100$$





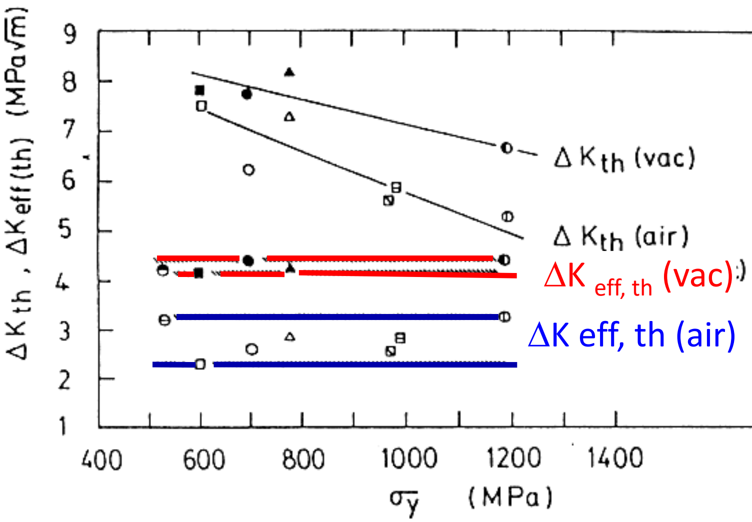
Influence of metallurgical parameters

Grain size



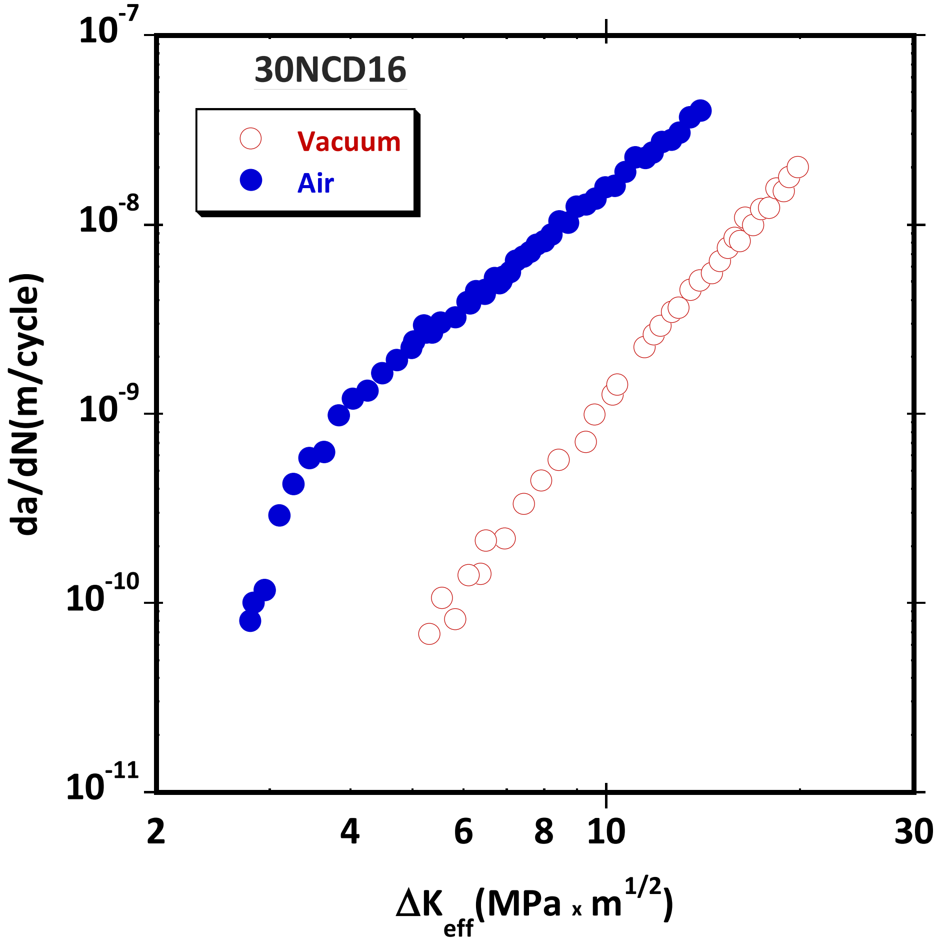
The coarser the grain, the higher the threshold ↔ *crack closure effect*

Yield strength



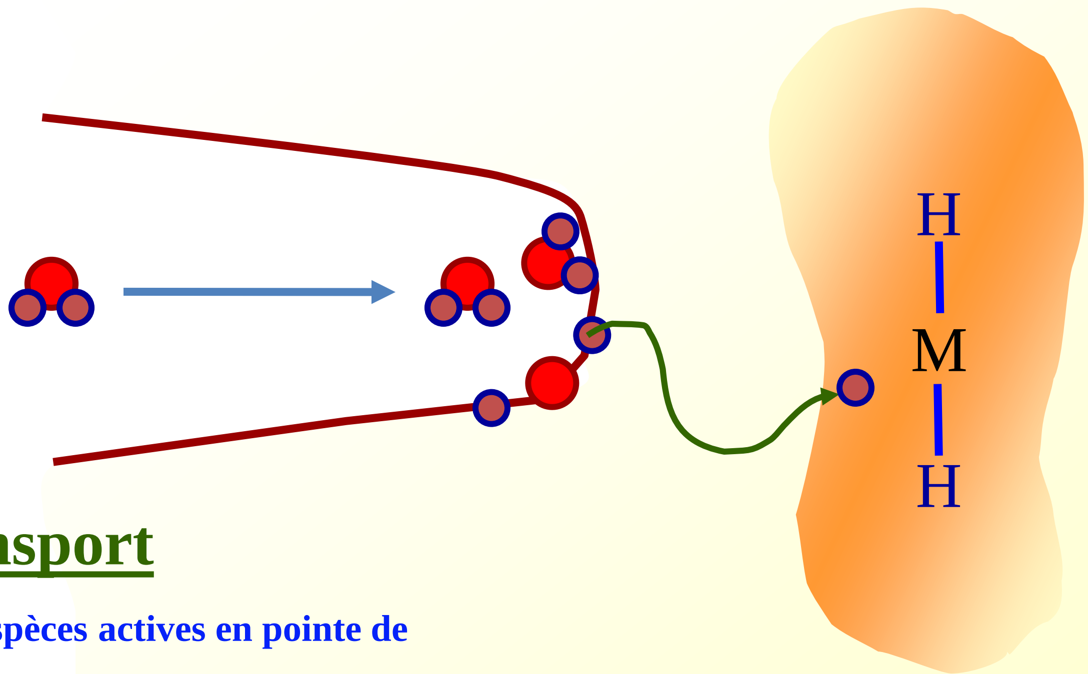
The higher the yield strength, the lower the threshold ↔ *crack closure effect*

Influence of environment



A moist environment induces a loss of resistance

Propagation assistée par l'hydrogène



Transport

accès des espèces actives en pointe de fissure

adsorption physique

adsorption chimique et dissociation

pénétration et diffusion de l'hydrogène en pointe de fissure

Réaction de fragilisation

Fatigue Crack Propagation Laws

Empirical Laws:

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

Paris

$$\frac{da}{dN} = \frac{C \times \Delta K^{m}}{\left((1-R)K_c - \Delta K\right)}$$

Forman

Theoretical approaches:

$$\frac{da}{dN} = A \times \frac{\Delta K^{4}}{\mu \sigma_0^2 U}$$

Cumulative damage at the crack tip

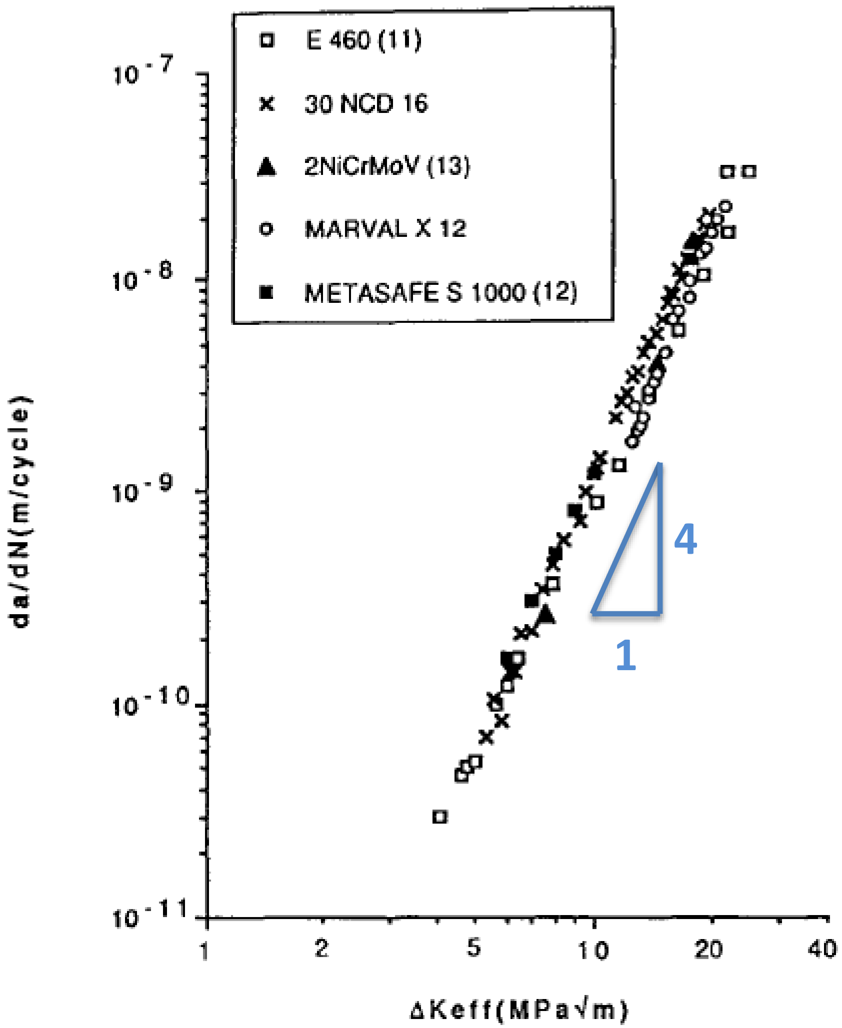
$$\frac{da}{dN} = A \times \frac{\Delta K^{4}}{\varepsilon_f E^2 \sigma_y^2 \rho}$$

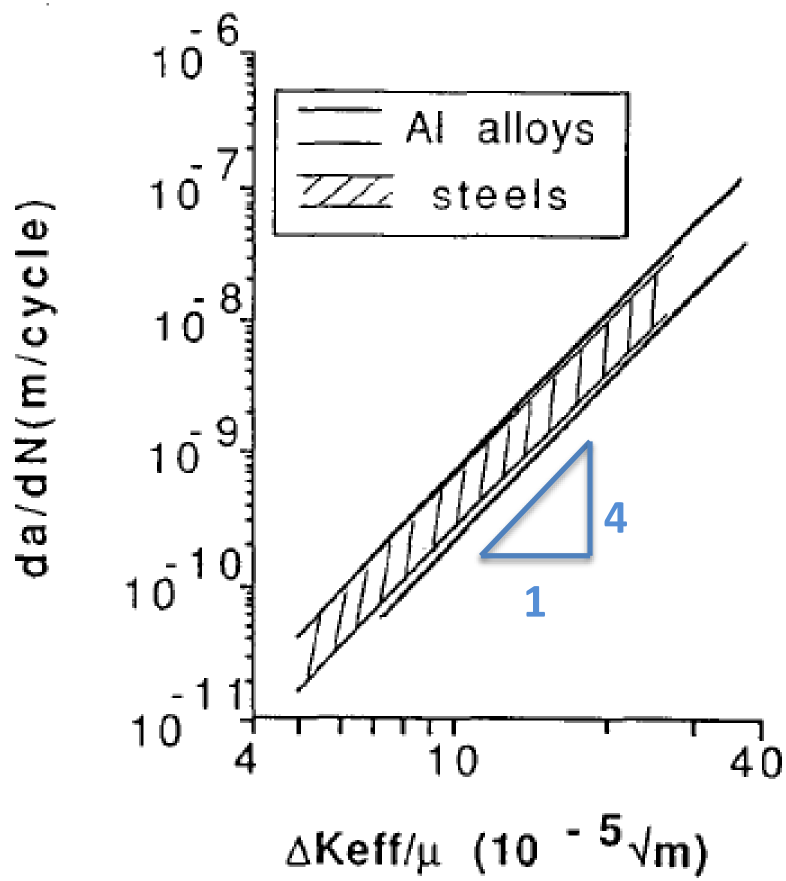
Manson-Coffin at the crack tip (McClintock, Antolovitch,…)

$$\frac{da}{dN} = \frac{1}{2} CTOD = \frac{\Delta K^{2}}{2E\sigma_y}$$

CTOD (Pelloux)

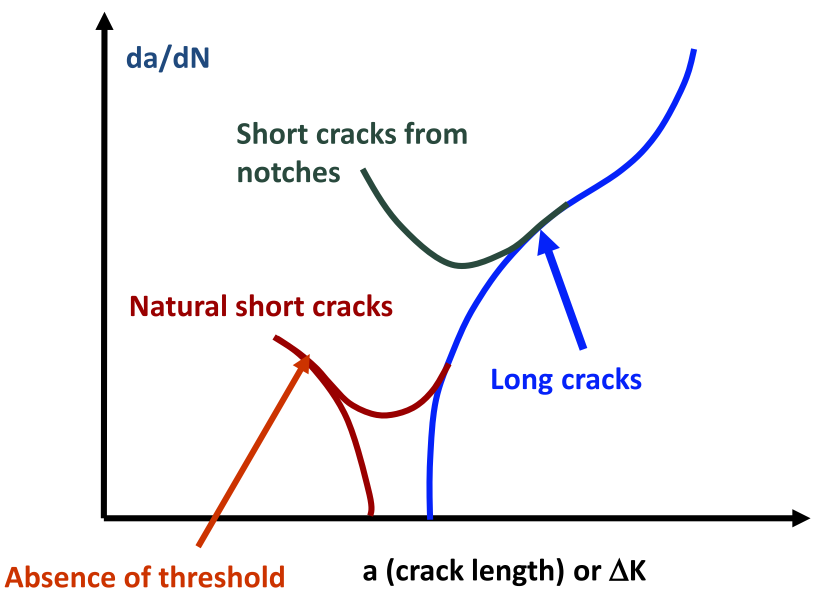
Intrinsic fatigue crack growth (inert, ΔK_{eff})

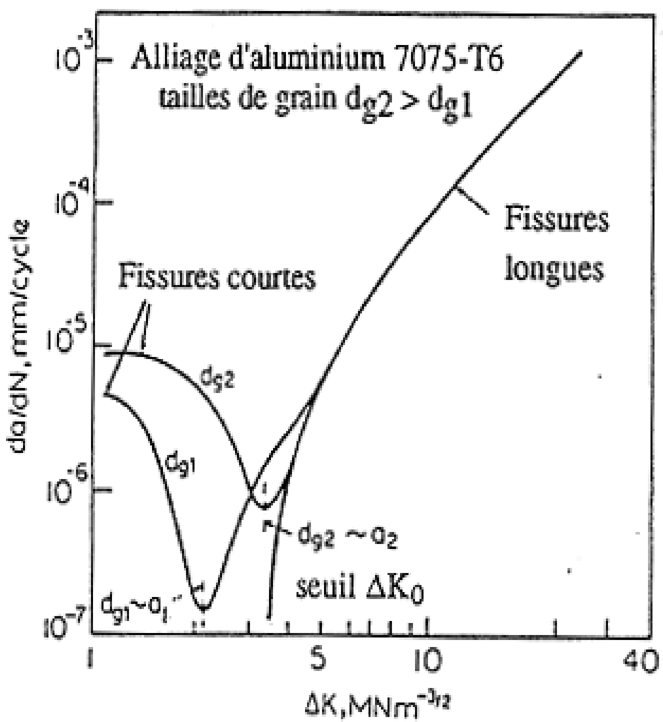




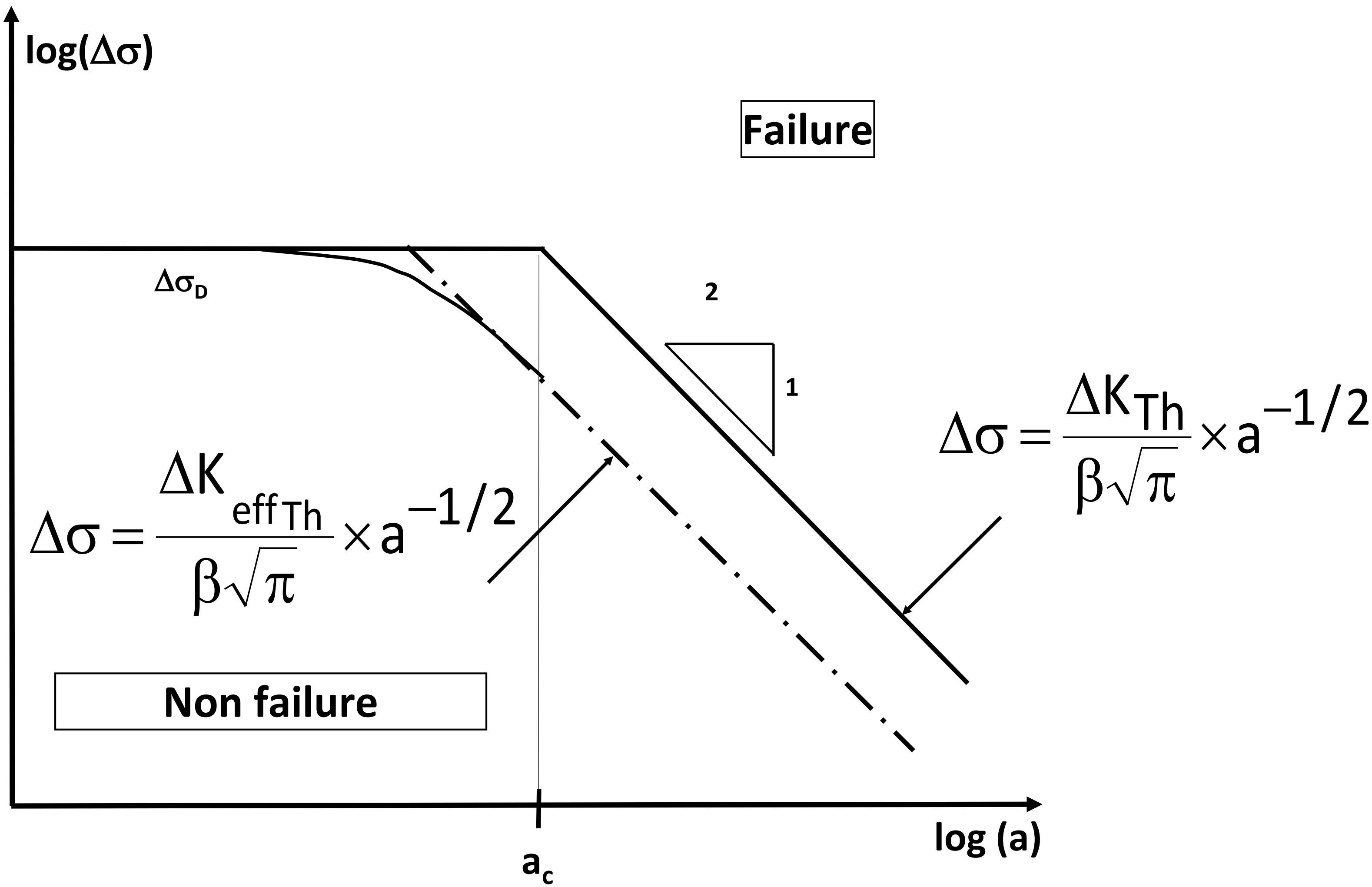
Short cracks

Def : cracks for which at least one dimension is small with respect to other dimensions (geometry, grain size,…)





Kitagawa diagram



Kitagawa Diagram