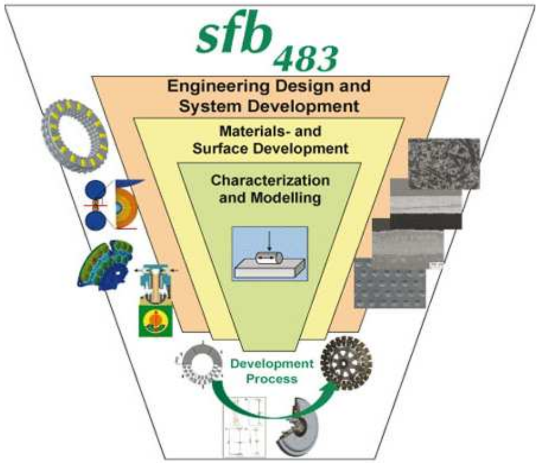
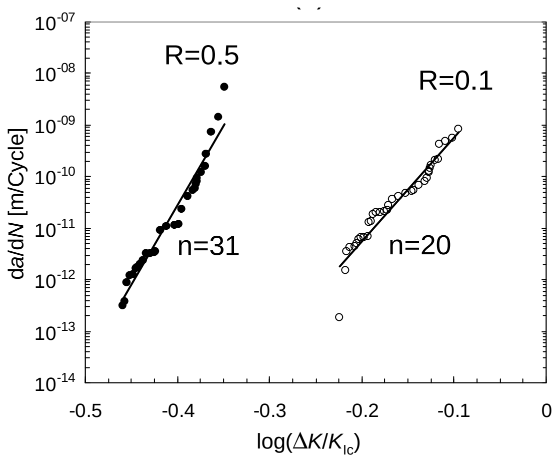
Karlsruhe Institute of Technology

Statistical analysis of fatigue crack propagation for natural flaws in silicon nitride

M. Härtelt*, H. Riesch-Oppermann*, J.J. Kruzic, O. Kraft***

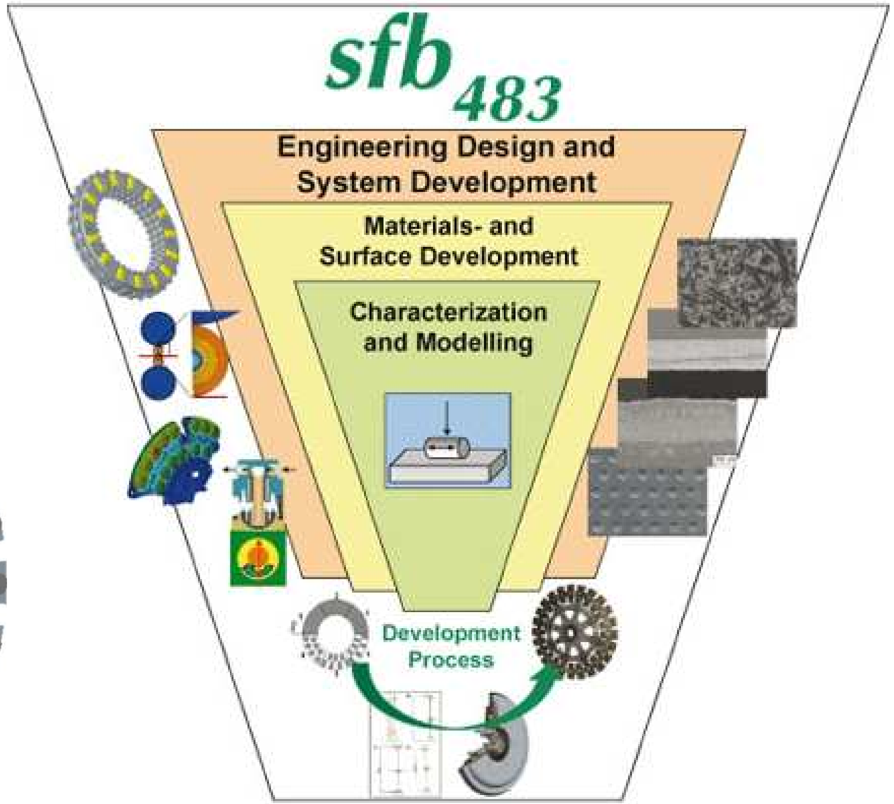
*** Karlsruhe Institute of Technology (KIT), Institute of Applied Materials (IAM)**
****Oregon State University, School of Mechanical, Industrial, and Manufacturing Engineering**



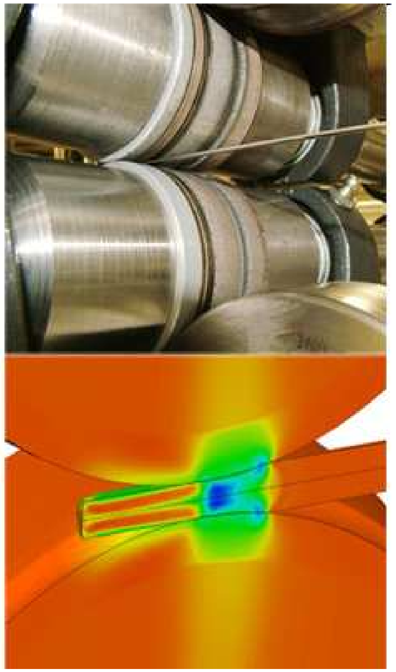


Motivation

Clutch



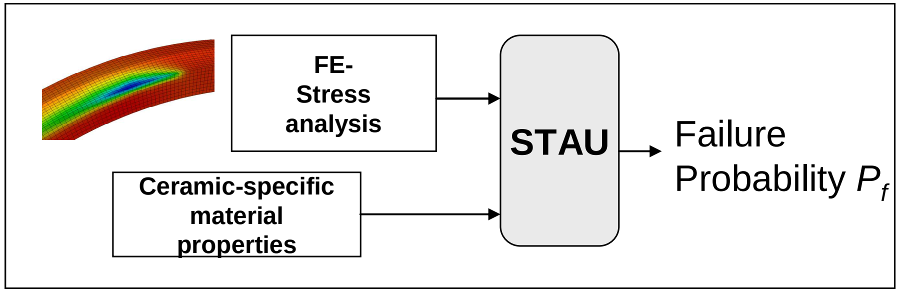
Wire rolling



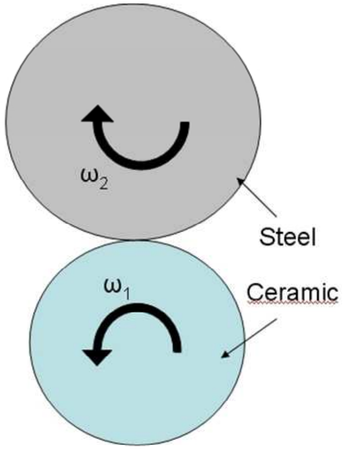
www.sfb483.kit.edu

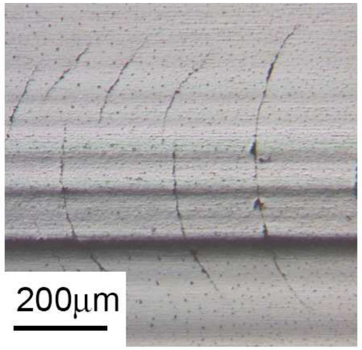
Motivation

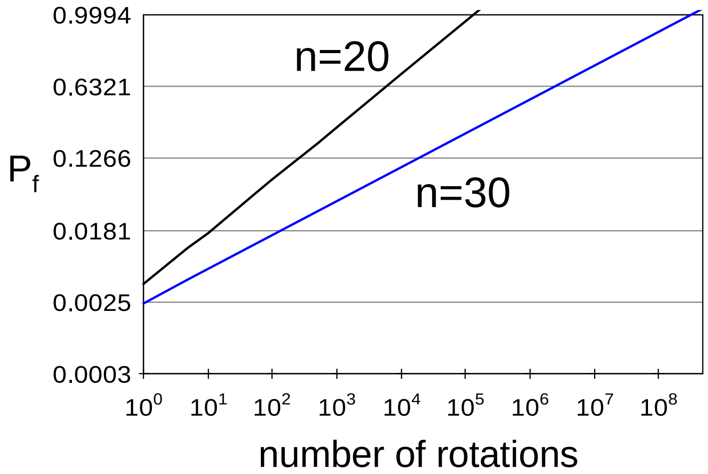
- Predicting component reliability based on natural flaws



- Example: Rolling contact fatigue test







- Predictions are strongly affected by the crack growth exponent

Motivation

Scope of this talk

- Obtain more information on crack propagation behaviour of natural flaws in ceramics
- Reduce uncertainties in the parameters

Overview

- Calculation of crack growth curves
- Example: Si_3N_4
- Pooling procedure
- Fracture mechanics model

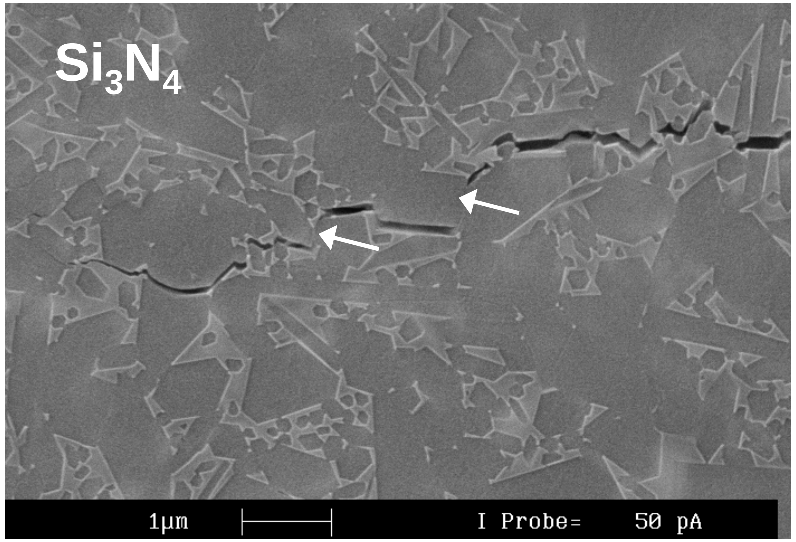
Slow crack propagation in ceramics

Subcritical crack propagation

- Quasi-static effect

$$\frac{da}{dt} = A_S \cdot \left(\frac{K_I}{K_{Ic}} \right)^{n_S}$$

A_S ,n_S: material properties



Cyclic crack propagation

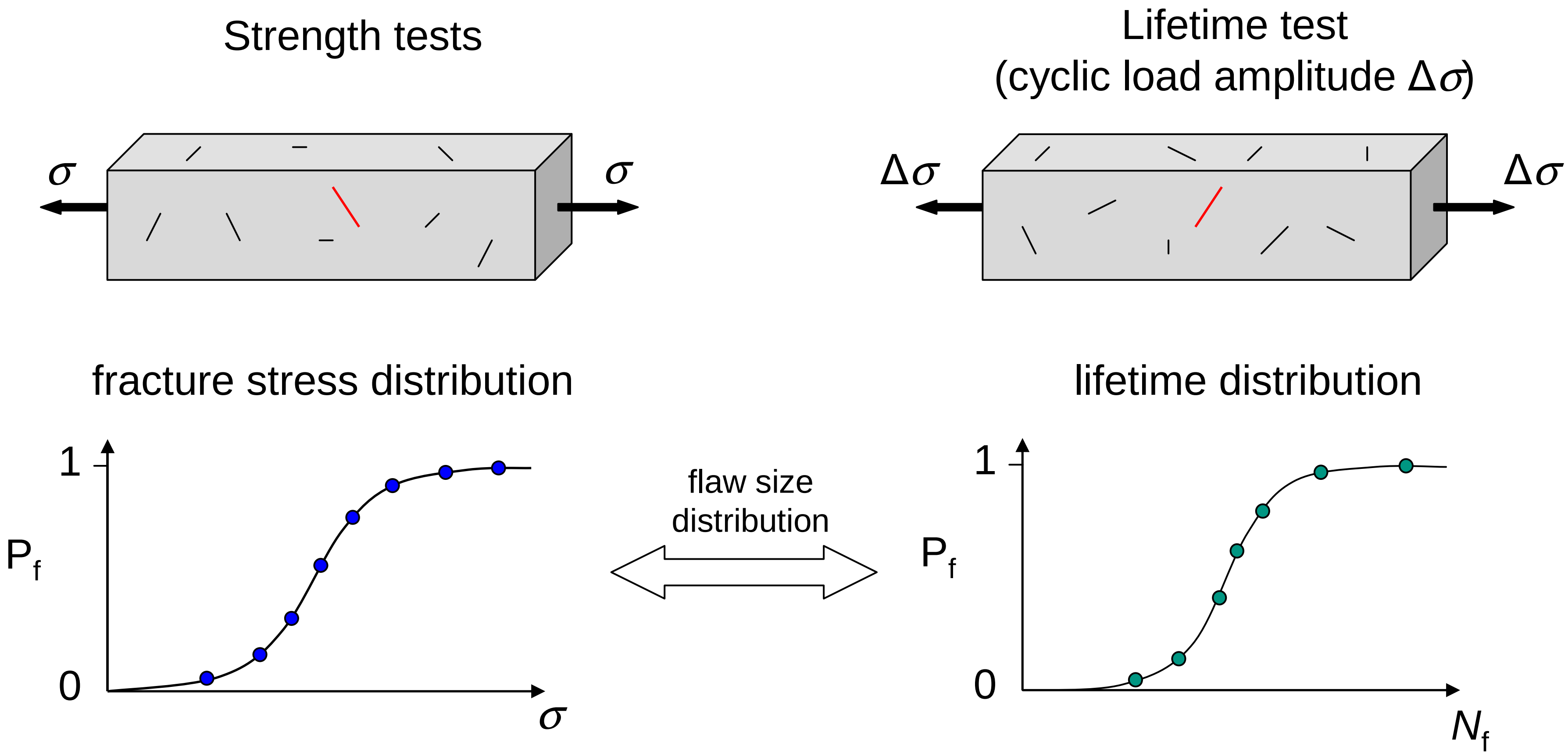
- Degradation of strengthening effects (grain bridging)

$$\frac{da}{dN} = A \cdot \left(\frac{\Delta K_I}{K_{Ic}} \right)^{n}$$

A ,n: material properties, may depend on the load ratio R

Image: S. Fünfschilling (KIT)

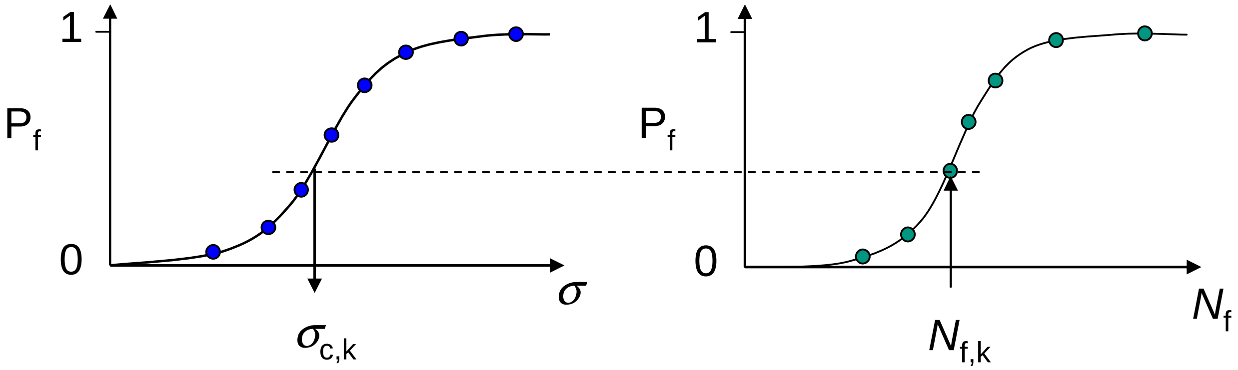
Crack propagation curves



- Fracture governed by critical flaw
- Strength and lifetime distribution related by flaw size distribution
  → Statistical procedure

Crack propagation curves

- Indirect method for calculating crack growth curves (Fett et al.[1])



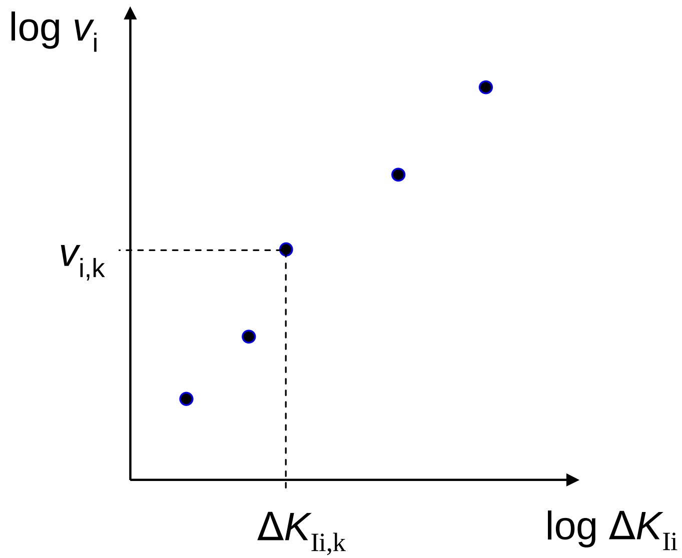
- Each lifetime $N_{f,k}$ is assigned to a strength $\sigma_{c,k}$

→ initial crack propagation rate $v_{i,k}$:

$$v_i = \frac{2\Delta K_i^2}{N_f \Delta\sigma^2 Y^2} \cdot - \frac{d\log\left(\Delta K_i\right)}{d\log\left(\Delta\sigma^2 N_f Y^2\right)}$$

$$\Delta K_{Ii} = \Delta\sigma\, Y_I \sqrt{a_i}$$

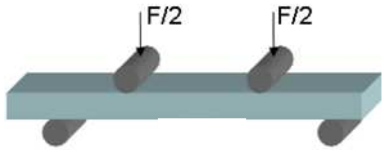
ΔK_{Ii} – initial stress intensity range



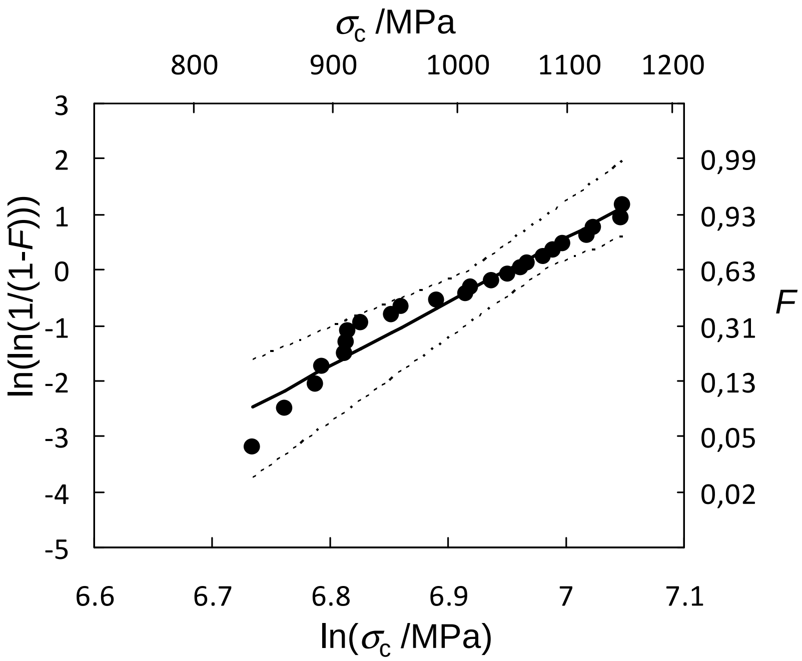
1 T. Fett et al., *J. Mater. Sci.*, 26 (12) 3320–3328 (1991).

Si_3N_4 – SL200

- Commercial powder: 3% Y_2O_3 and 3% Al_2O_3
- 4-point-bending setup (static and cyclic test)

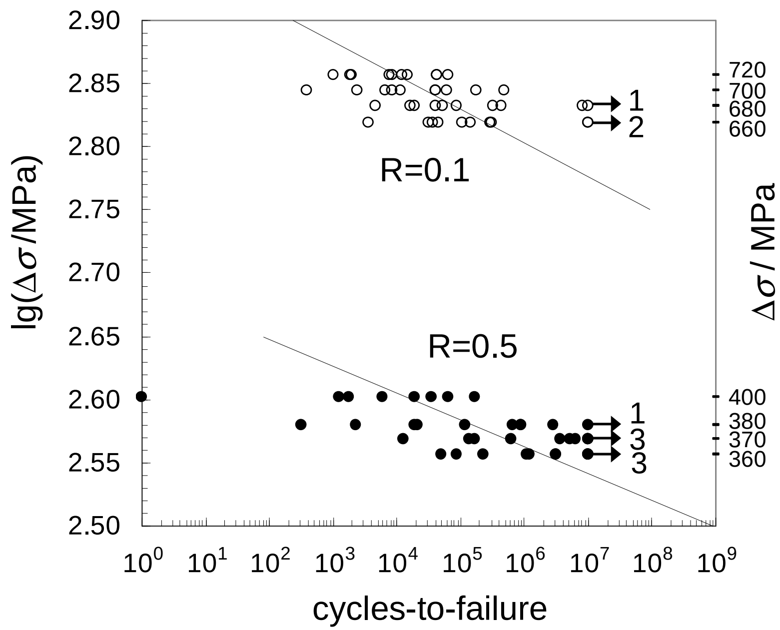


Strength distribution



m=12; σ_0=1044 MPa

S-N-curve in ambient air

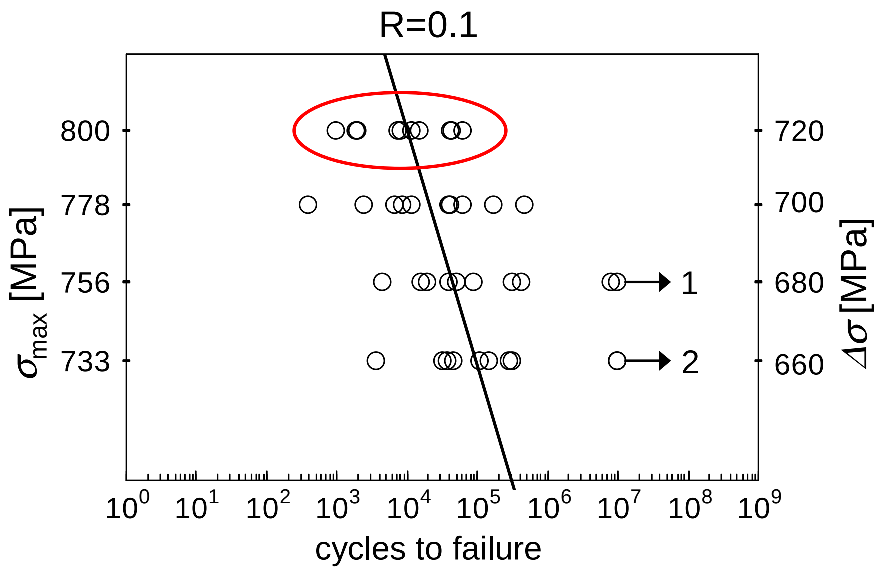


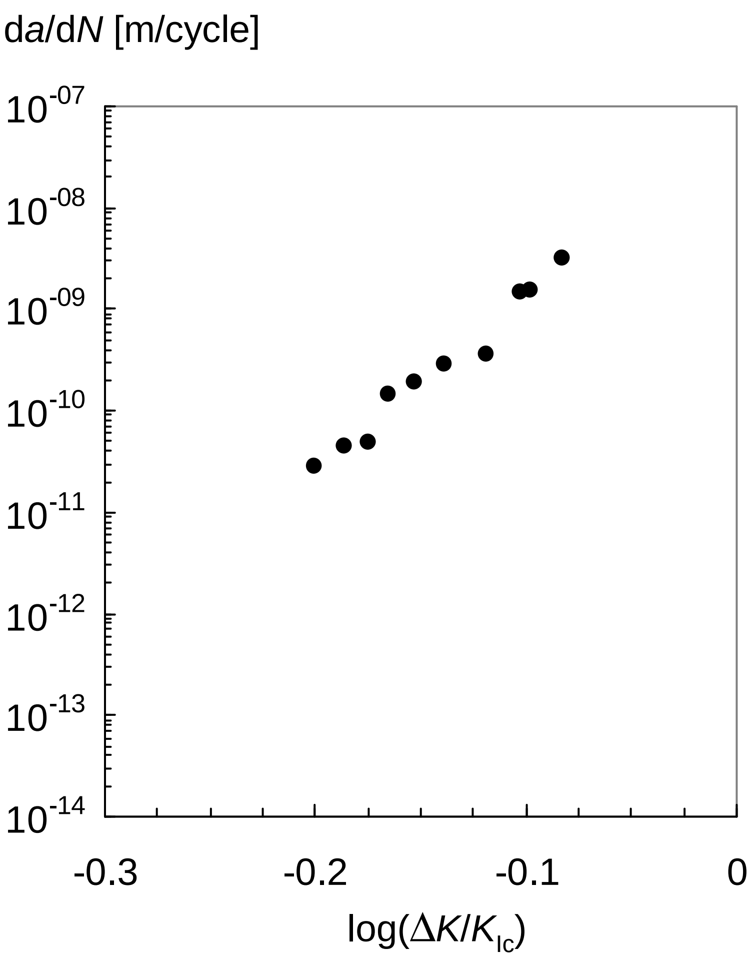
Experiments: T. Schwind et al., *Int. J. Mat. Res.*, 99, 1090–1097, 2008

Crack growth curve R=0.1

- Separate evaluation for each load level $\Delta\sigma$

$\Delta\sigma$ = 720 MPa

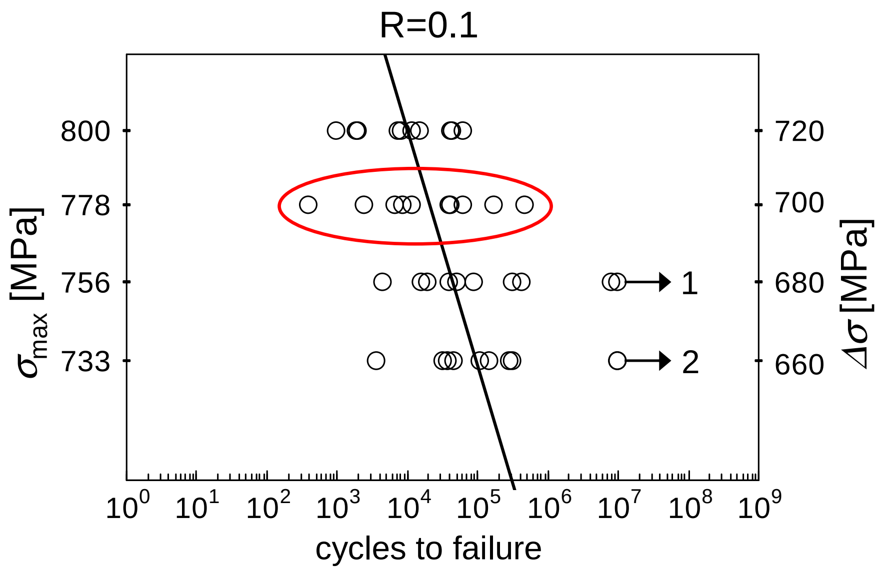


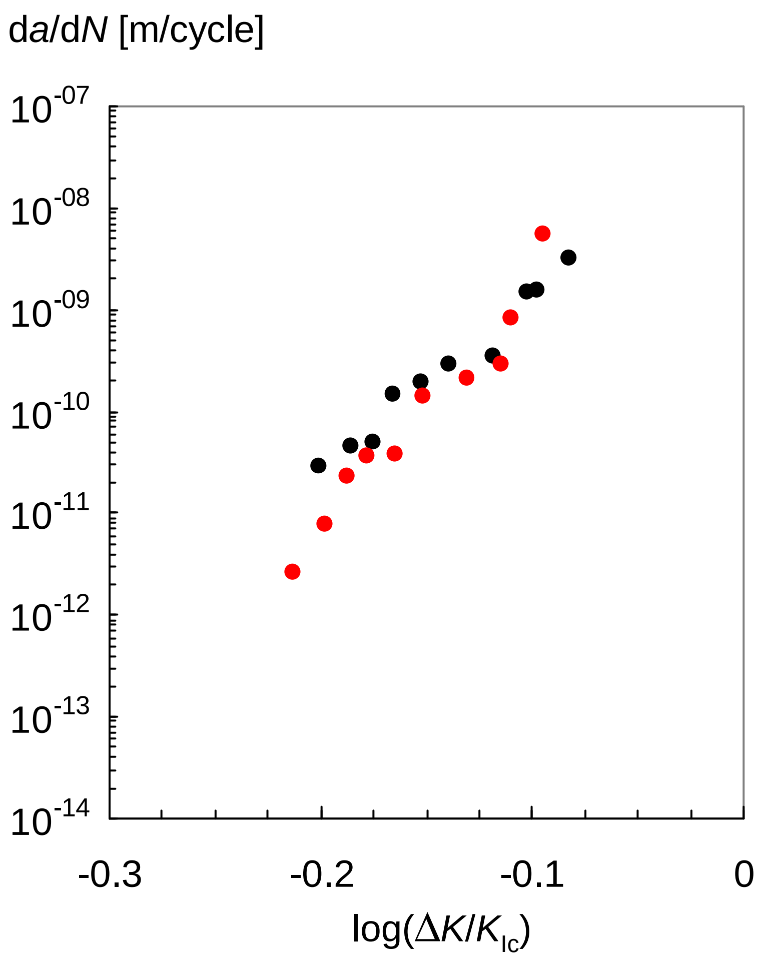


Crack growth curve R=0.1

- Separate evaluation for each load level $\Delta\sigma$

$\Delta\sigma$ = 700 MPa

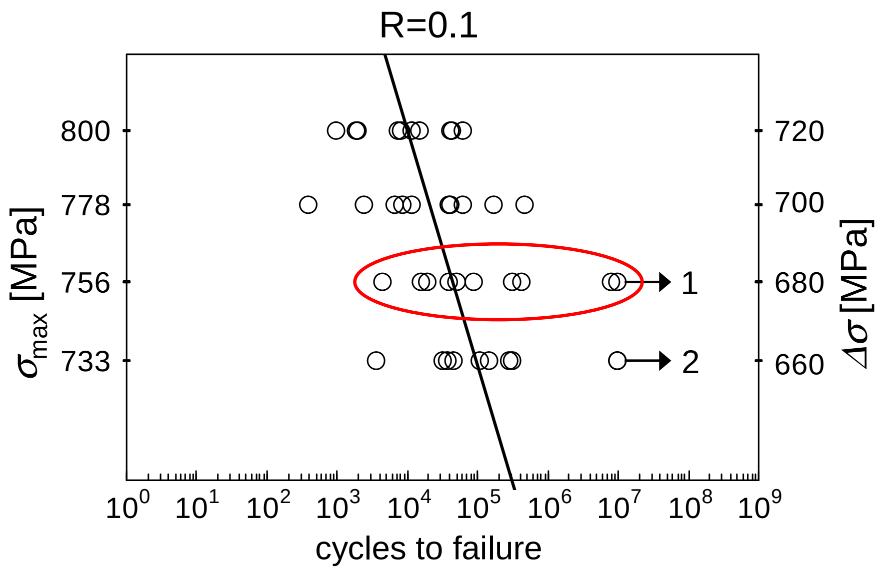


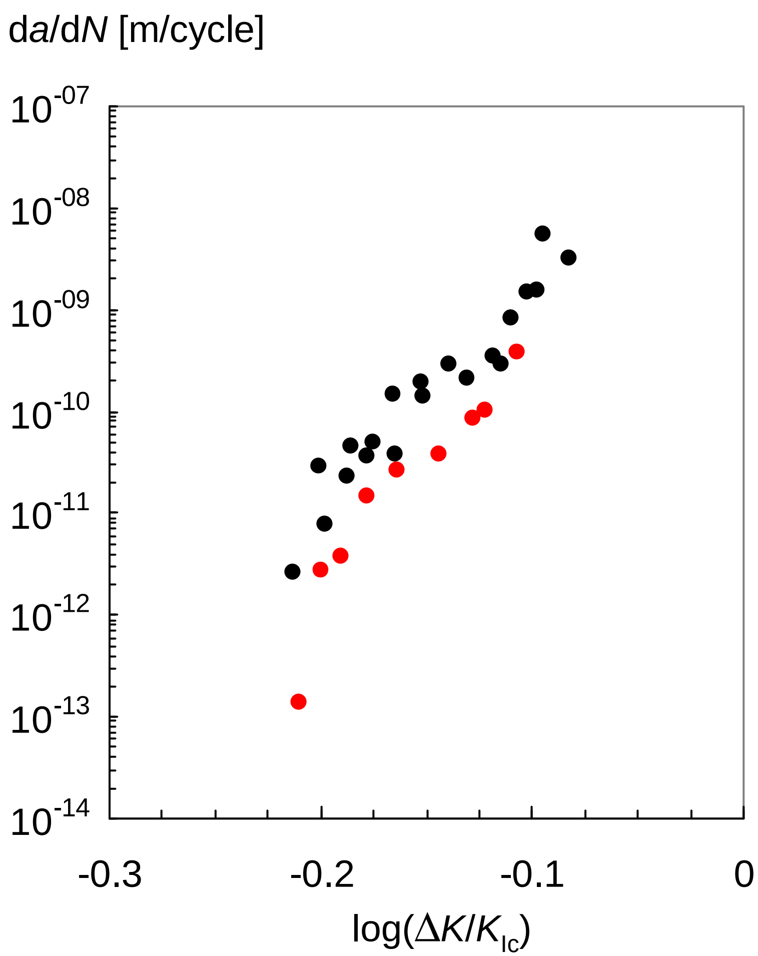


Crack growth curve R=0.1

- Separate evaluation for each load level $\Delta\sigma$

$\Delta\sigma$ = 680 MPa

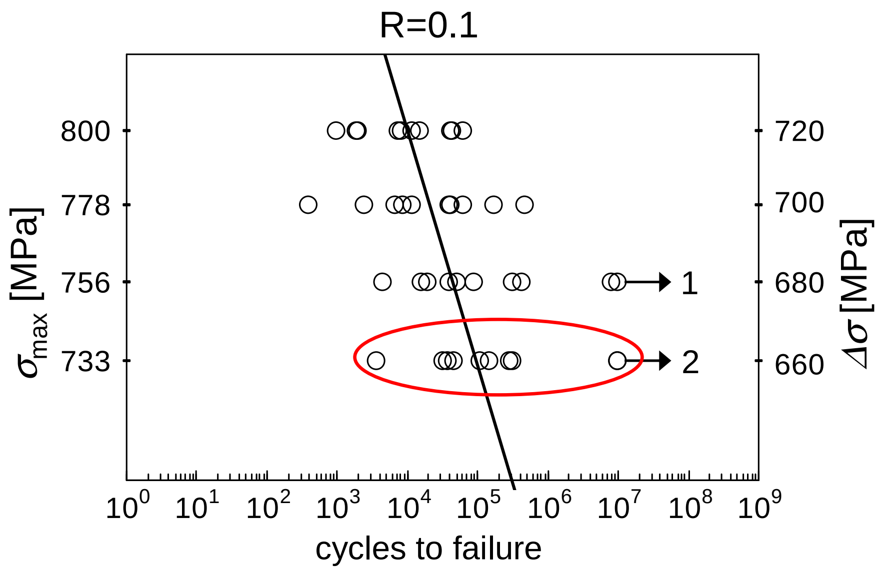


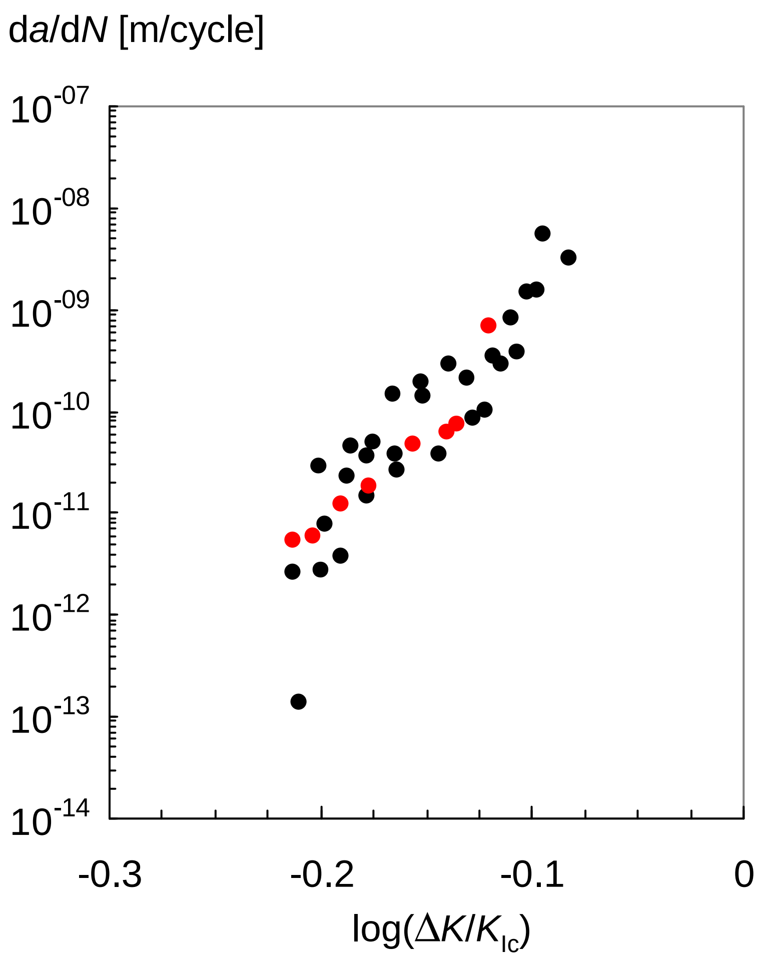


Crack growth curve R=0.1

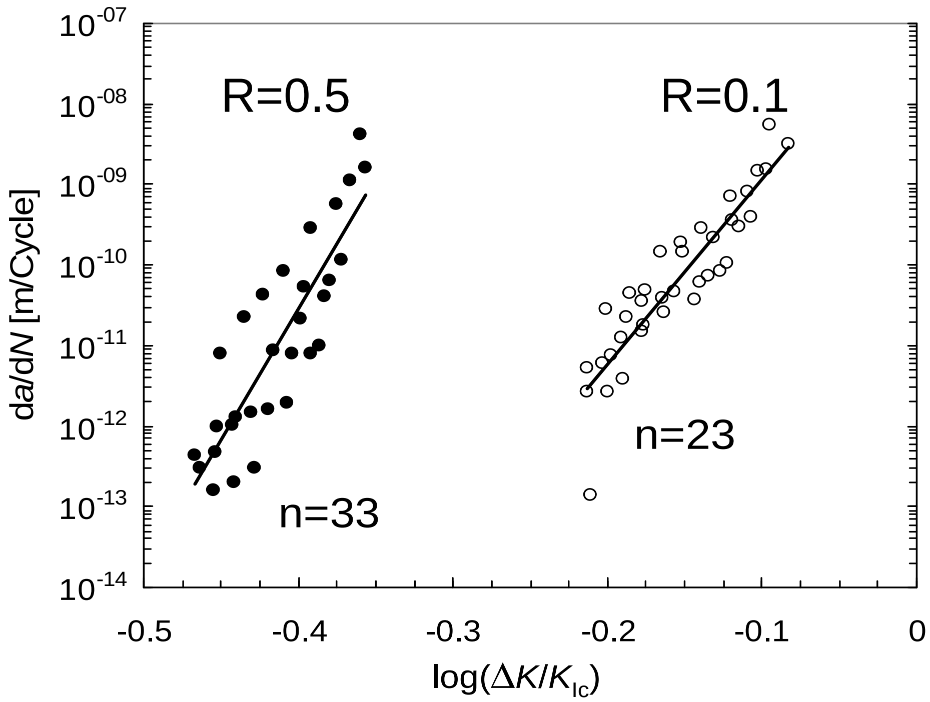
- Separate evaluation for each load level $\Delta\sigma$

$\Delta\sigma$ = 660 MPa





Crack growth curves



- power-law fit:

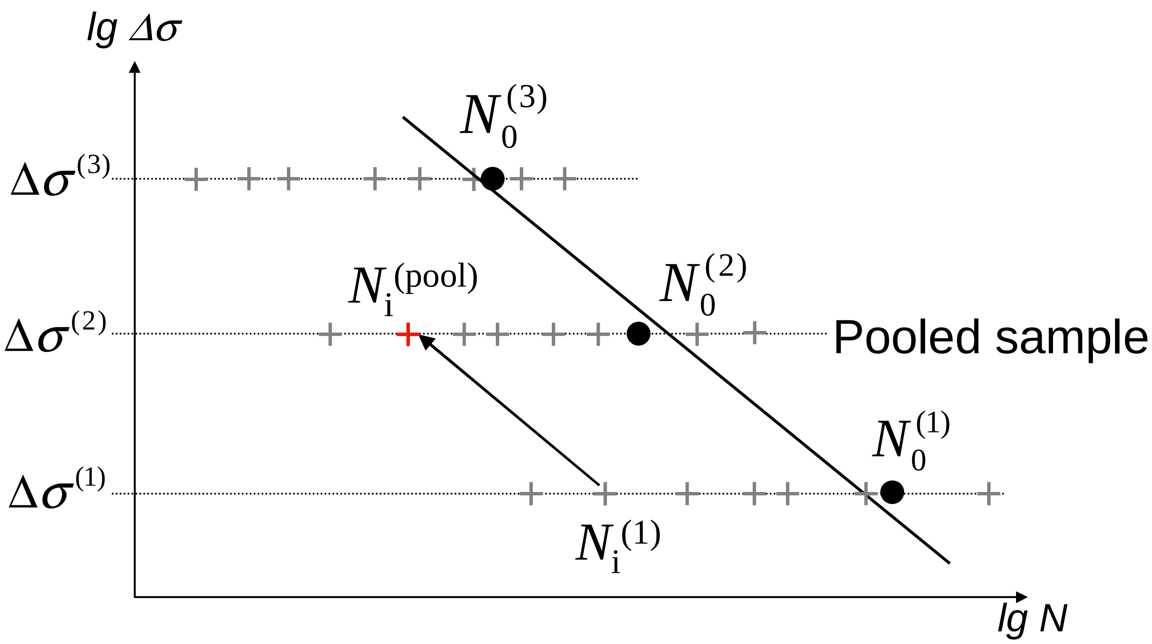
$$\frac{\mathrm{d}a}{\mathrm{d}N} = A \cdot \left(\frac{\Delta K_\mathrm{I}}{K_\mathrm{Ic}} \right)^n$$

- Crack growth exponent *n* depends on the load ratio *R*
- Scatter in data caused by sparse database available for each $\Delta\sigma$
  → Uncertainty in the parameters

M. Härtelt et al., J.Am.Ceram.Soc., (2011), in press

Pooling procedure

- Increase number of data available for one load level

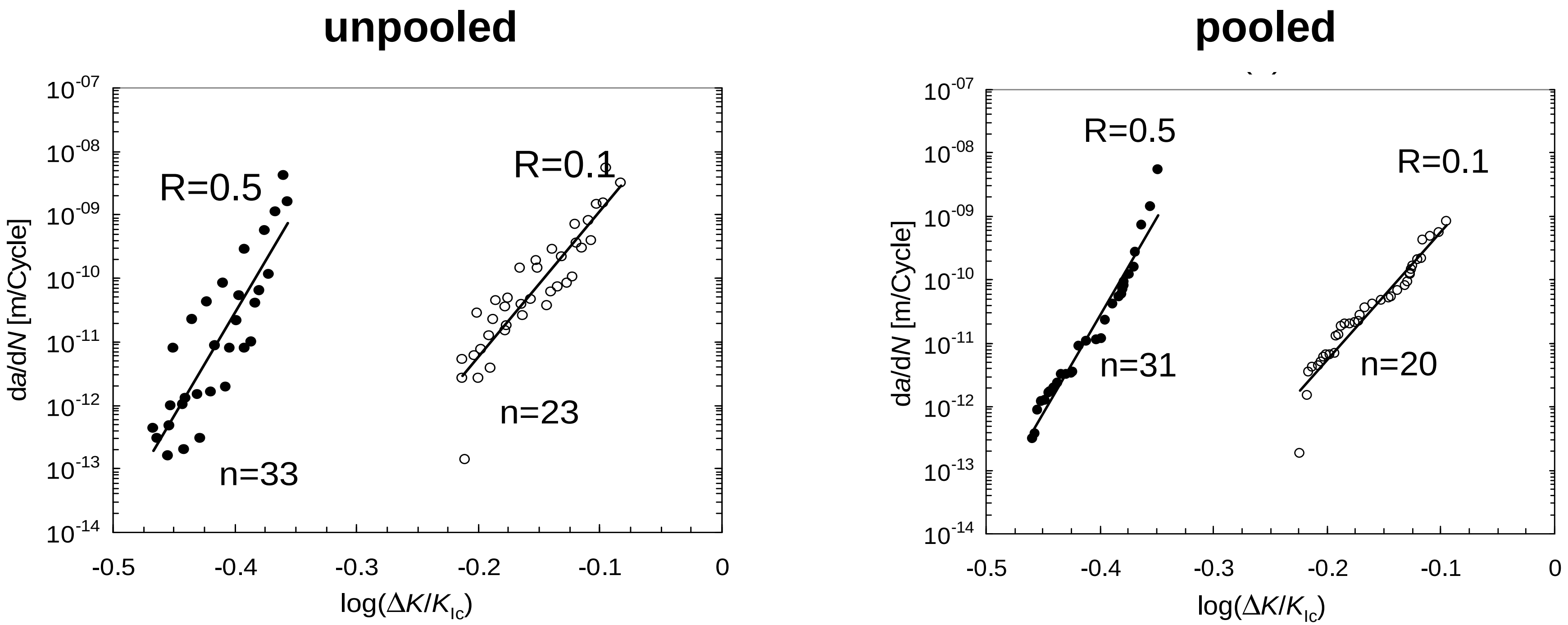


- Conversion using Weibull-distribution:

$$N_i^{(pool)} = N_i^{(1)} \left(\frac{N_0^{(pool)}}{N_0^{(1)}} \right)$$

- Relation between $\Delta\sigma$ and N_0 follows from S-N-curve fit

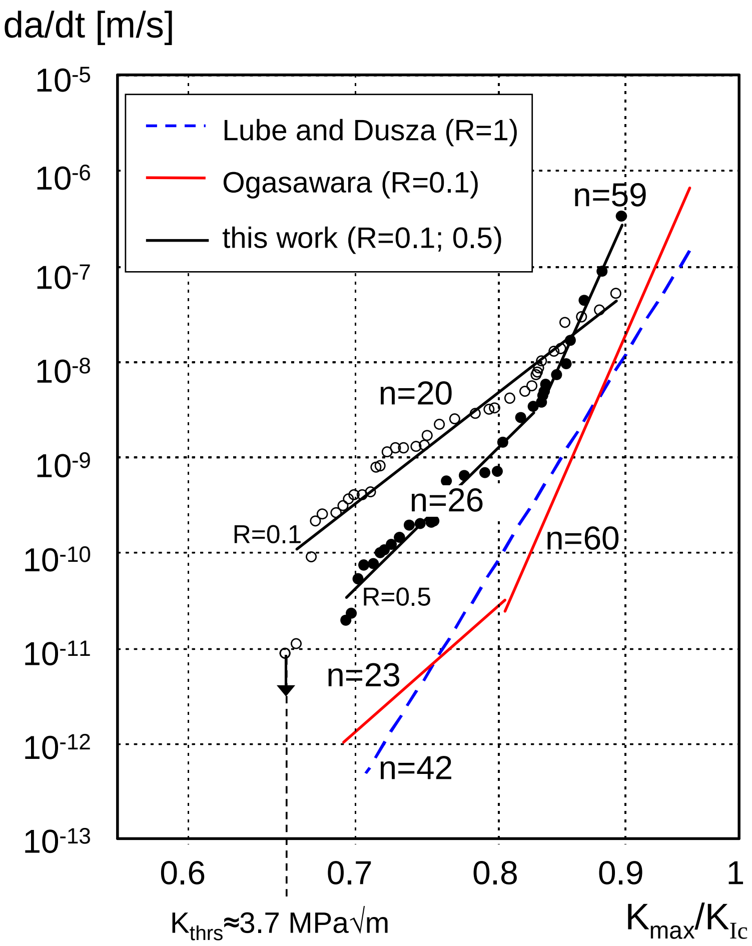
Pooled crack growth curves



- Scatter (uncertainty in *n*) is decreased by pooling
- variation of *n* with *R* remains

M. Härtelt et al., J.Am.Ceram.Soc., (2011), in press

Pooled crack growth curves



- Pooling allows for better comparison with other data from natural flaws
- Bi-modal shape for R=0.5

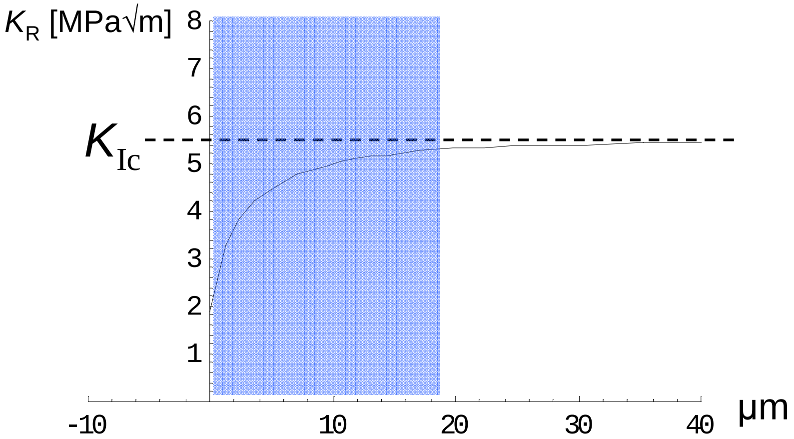
M. Härtelt et al., J.Am.Ceram.Soc., (2011), in press

Ogasawara et al., J.Am.Ceram.Soc. 77[2] 514 (1994)

Lube and Dusza, J.Eur.Ceram.Soc. 27[2-3] 1203 (2007)

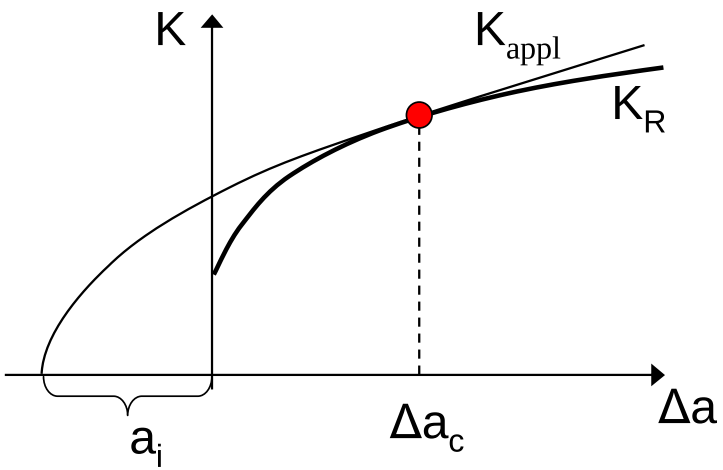
Fracture mechanics model: R-curve

- $\Delta K_{Ii}=\Delta\sigma Y_I\sqrt{a_i} \rightarrow a_i$ from strength measurement



- Steeply rising R-curve[1] affects failure criterion used for natural flaws

- Calculation of ΔK_{Ii}: R-curve behaviour

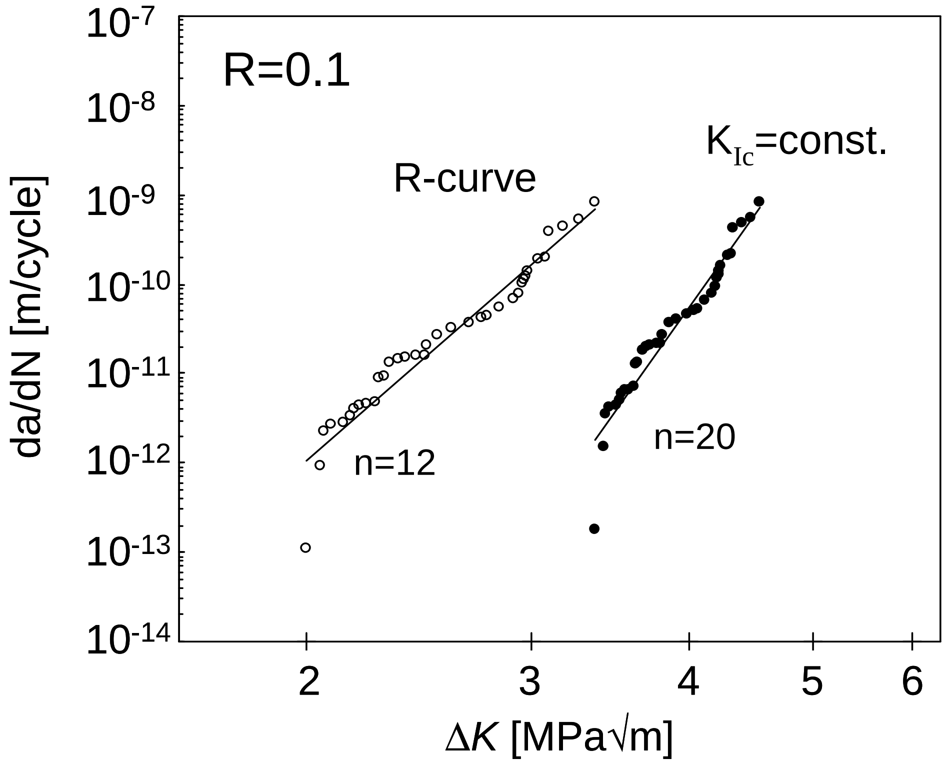


$\Delta K_{Ii}=\Delta\sigma Y_I\sqrt{a_i}$

a_i: initial flaw size from tangent criterion

[1] T. Fett et al., J.Am.Ceram.Soc. 91[11]:3638 (2008)

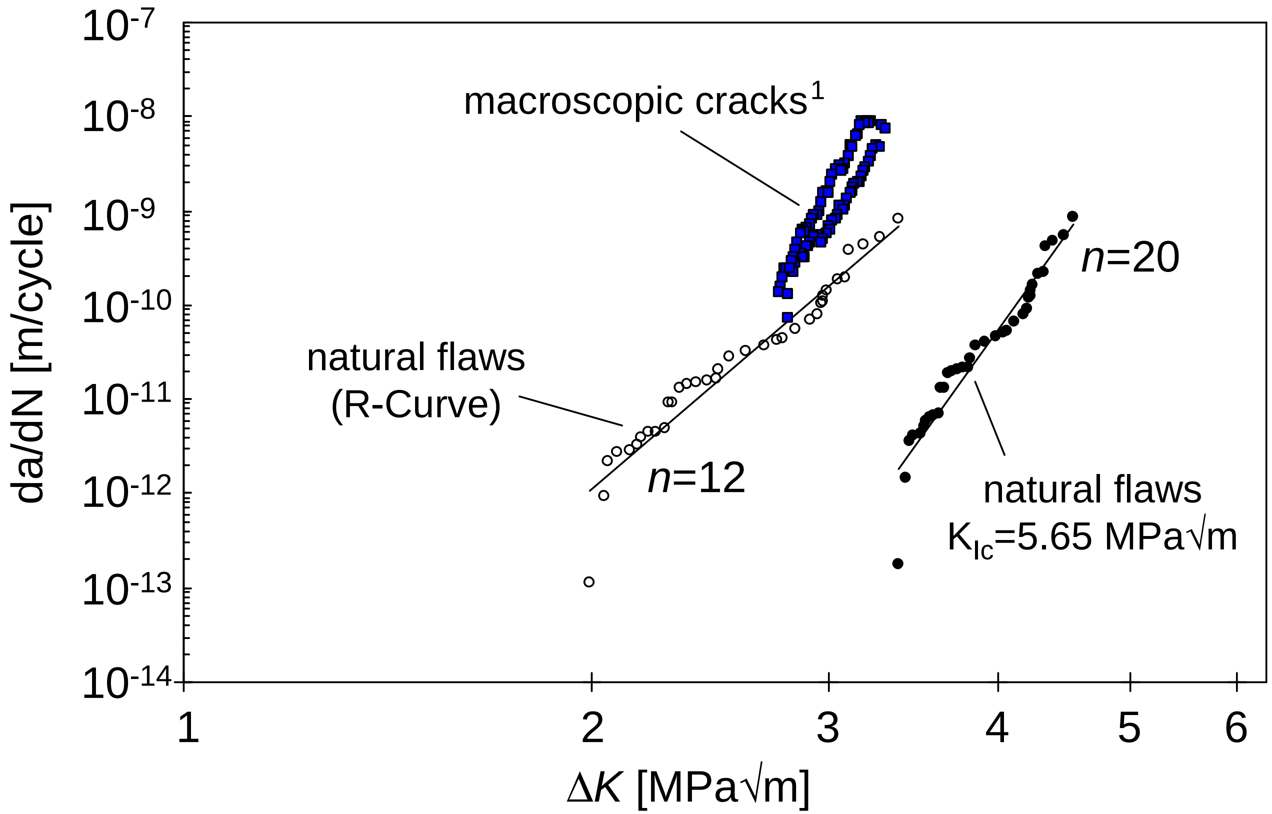
R-curve influence



K_{Ic}=5.65 MPa√m

- R-curve: ΔK_{Ii}-values decrease → shift of crack growth curve
- Crack growth exponent decreases → shape of R-curve

R-curve influence



[1] experiments: J. Kruzic

- Better agreement with crack growth curves from macroscopic cracks obtained for the same material

Summary

- Statistical evaluation of crack growth curves for natural flaws
- Indirect method combining strength and lifetime tests

Si_3N_4-SL200:

- Sparse lifetime database → Uncertainty in the estimated parameters
- Pooling:

  - reduce scatter in the crack growth curves by combining measurements from different load levels $\Delta\sigma$.

  - gives better insight in the fatigue mechanism

- Consideration of R-curve

  - allows for comparison with data from macroscopic cracks

  - gives more realistic crack growth data

Acknowledgements

Dr. Theo Fett

Dr. Stefan Fünfschilling

Dr. Thomas Schwind

Financial support by the “Deutsche Forschungsgemeinschaft” (DFG) is gratefully acknowledged. The work was performed within the framework of the Collaborative Research Centre 483 “High performance sliding and friction systems based on advanced ceramics” at the University of Karlsruhe.