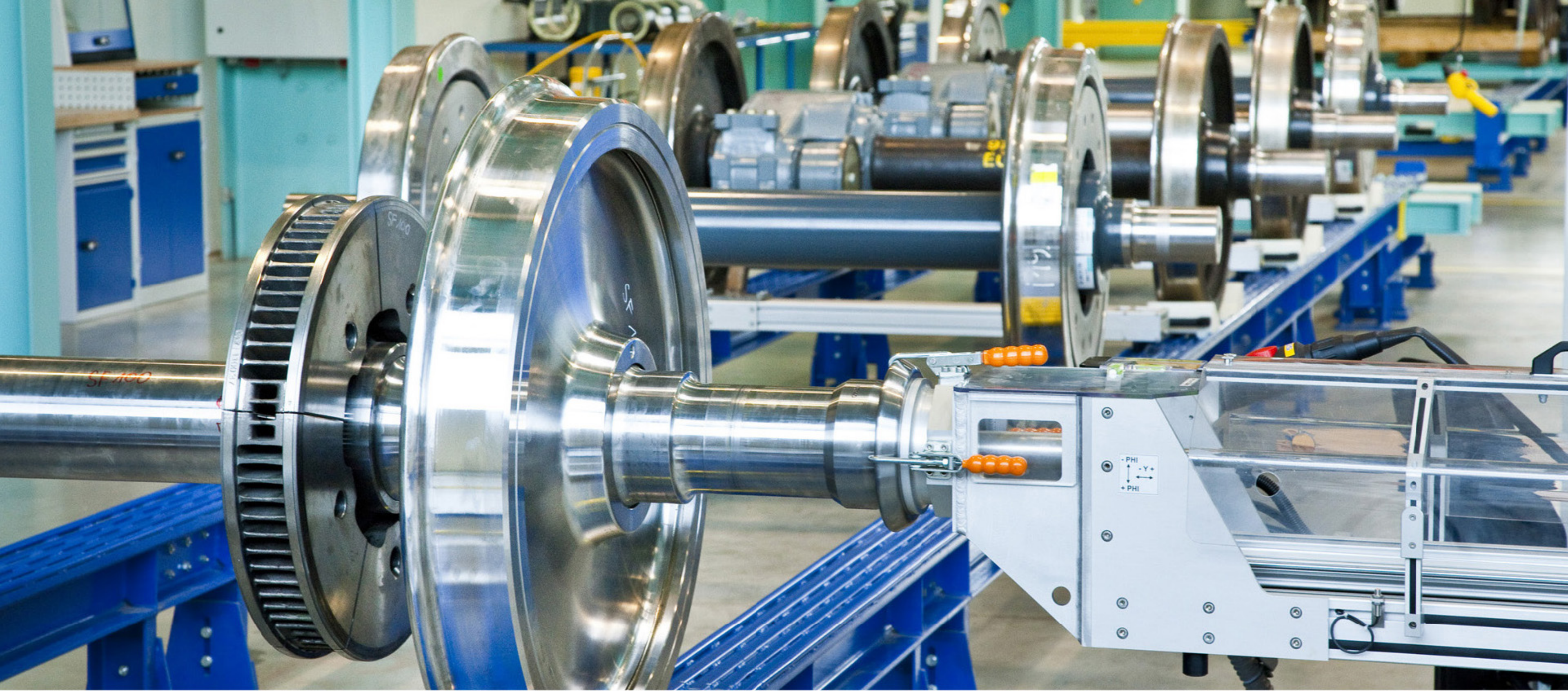


Crack closure and retardation effects – experiments and modelling

ESIS TC24 Reliability of Railway Structures, Leoben, 24.-25.10.2016

J. Maierhofer, H.-P. Gänser

EBFW-3
EisenBahnFahrWerke

Introduction / Motivation

„Safe and economic operation of railway axles“ (**EBFW2**)

Contents:

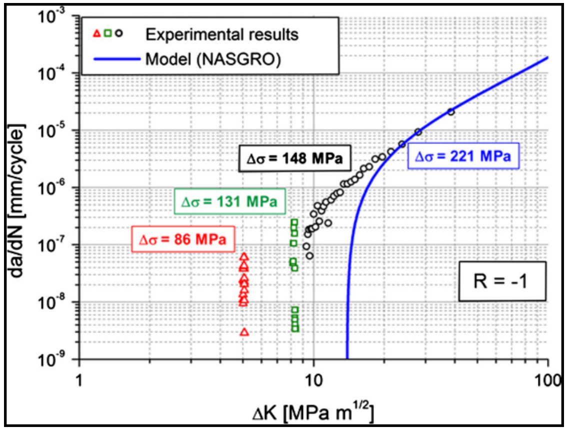
- Development of a computational method for determining the residual life and inspection intervals of railway axles by means of fatigue crack growth calculations
- Determination of fracture mechanics material parameters for axle materials
- Validation of the computational model by means of laboratory specimens and component tests on the scales 1:3 and 1:1
- Measurement of load spectra (locomotive and passenger car)
- Differences between computation and 1:1 test results showed the need for additional research → **EBFW3**

Main goal (EBFW3): **Clarification of the differences between laboratory specimen and 1:1 tests (or real components, respectively)**

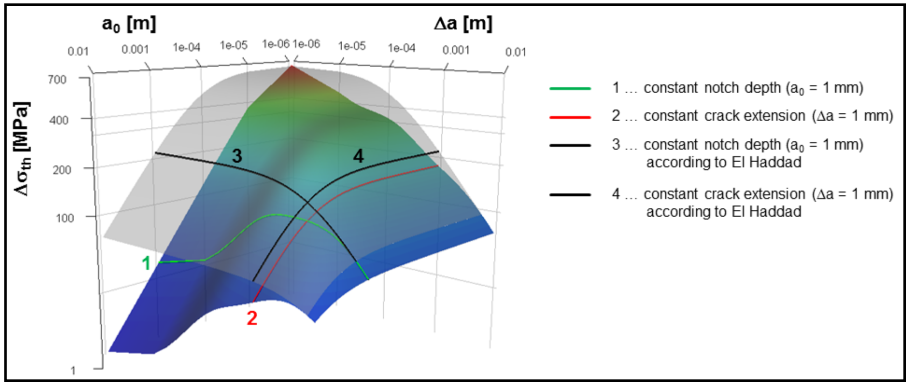
Introduction / Motivation

Current state of knowledge:

- Crack growth in real components often over-conservative
- Behaviour of short cracks[1]



- Growth of cracks emanating from deep sharp notches[2]



Even more conservative in predicting crack propagation!!

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[1] Maierhofer et al., *Modified NASGRO equation for physically short cracks,* Int. J. Fatigue, 2014.
[2] Maierhofer et al., *Modified Kitagawa-Takahashi diagram accounting for finite notch depths,* Int. J. Fatigue, 2014.

Introduction / Crack closure mechanisms

Mechanisms which can lead to a drop in the crack propagation rate[1]:

a) plasticity induced crack closure,

b) oxide induced crack closure,

c) roughness induced crack closure,

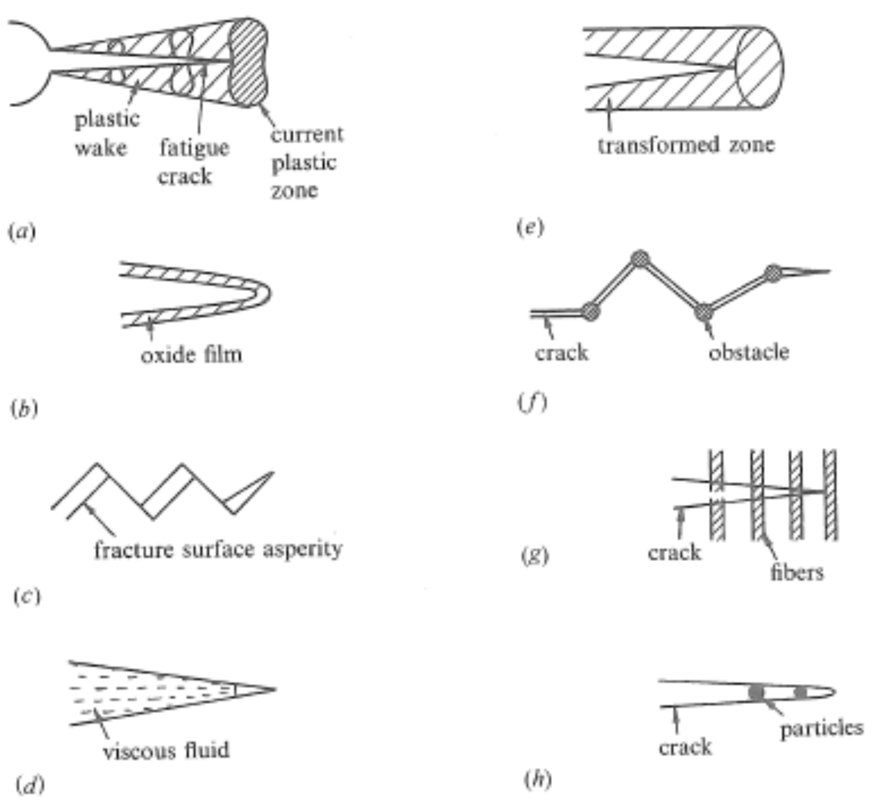
d) fluid induced crack closure,

e) transformation induced crack closure,

f) crack branching,

g) crack bridging due to fibers or

h) due to particles [Suresh, Ritchie]



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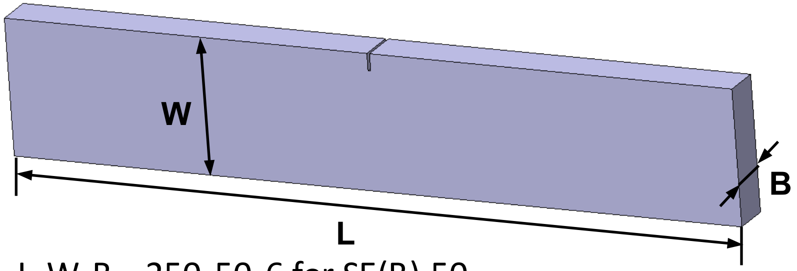
[1] Suresh, *Fatigue of Materials,* Cambridge University Press 1998.

Introduction / Material / Specimen preparation

Investigated material: QT steel, R_m ~ 700 MPa

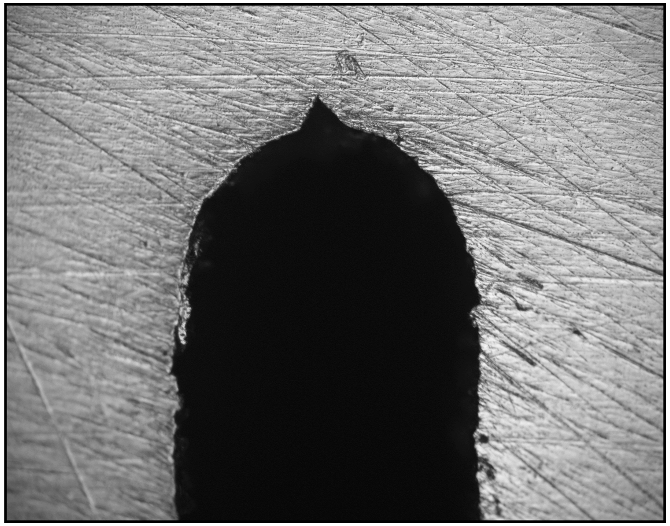


LxWxB = 250x50x6 for SE(B)-50

- Notch generation by wire electrical discharge machining
- Notch sharpening by razor blade cutting

↳ Negligibly small residual stresses after crack initiation

Razor blade cutting rig

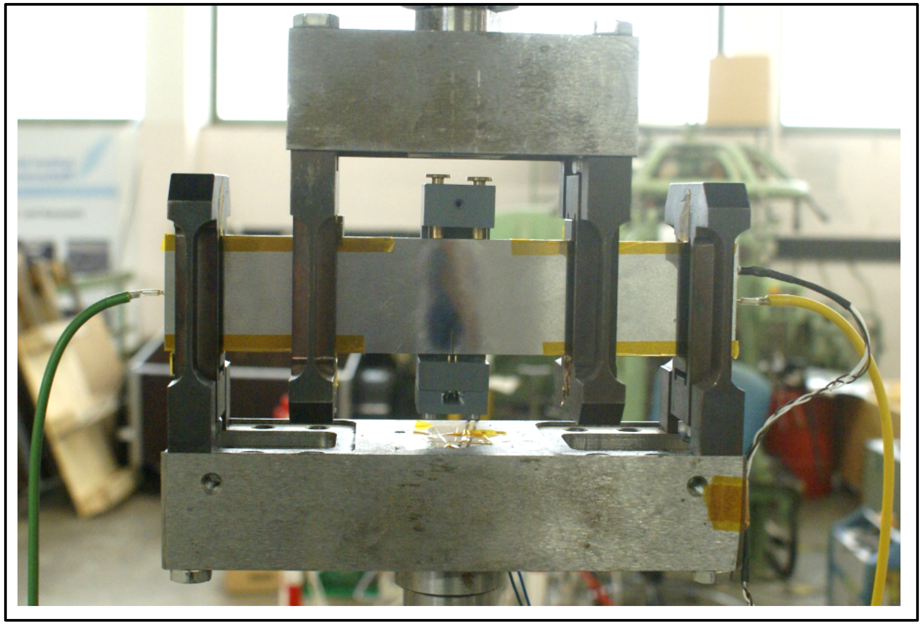


Eroded notch with razor blade cut

Introduction / Experimental setup

Resonant testing rig
(RUMUL TESTRONIC)

8-point bending mounting



- Compression precracking
  (R = 20, $\Delta K \approx 14\ \text{MPa}\sqrt{\text{m}}$)
- No crack closure effects at the start of an experiment
- Crack propagation measurement:
  direct current potential drop technique

Four main reasons for difference between laboratory specimen and 1:1 tests

1. Residual stresses

2. Overloads

3. „small“ loads

4. Downtime

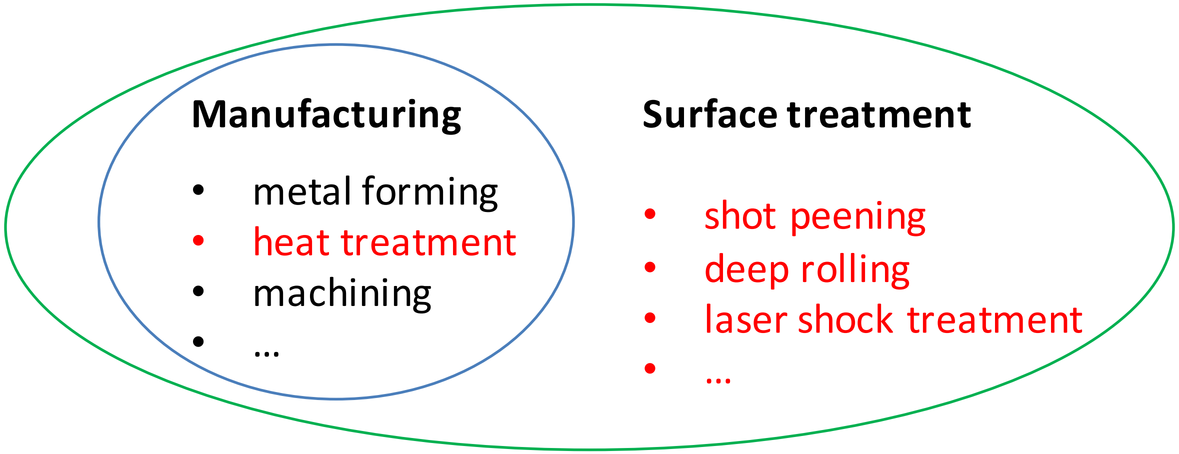
Crack retardation due to residual stresses

Difference laboratory specimen / 1:1 test:

Laboratory specimen mostly free from residual stresses!

Required for crack retardation: Residual **compressive** stresses

Origin of residual stresses in 1:1 tests and in real components:



Manufacturing

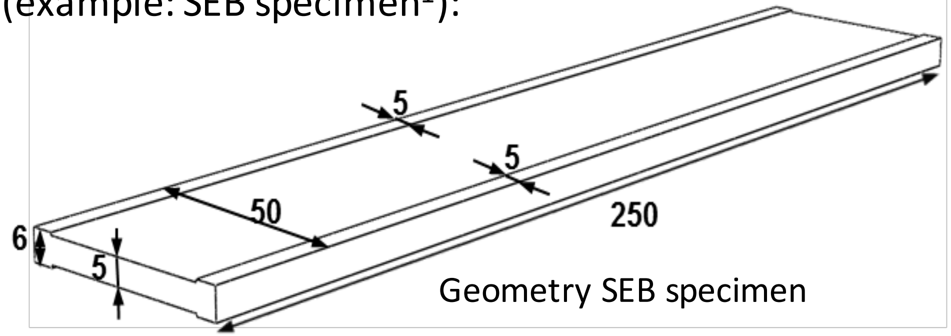
- metal forming
- heat treatment
- machining
- …

Surface treatment

- shot peening
- deep rolling
- laser shock treatment
- …

Crack retardation due to residual stresses / experiments

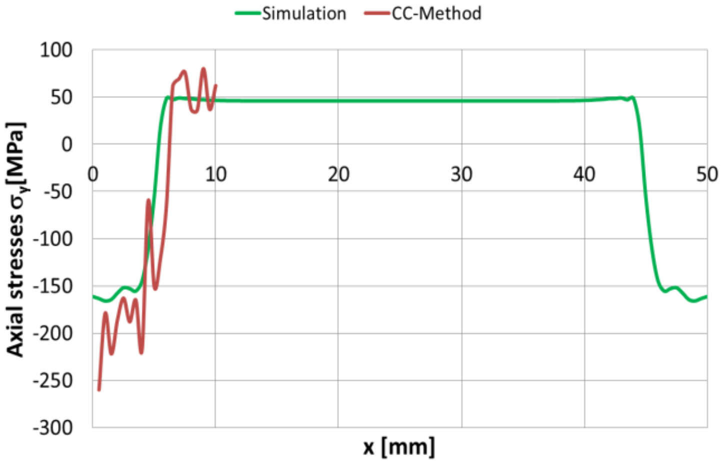
Influence of residual compressive stresses (example: SEB specimen[1]):



Geometry SEB specimen

Rolling mill

Residual stress distribution after rolling:



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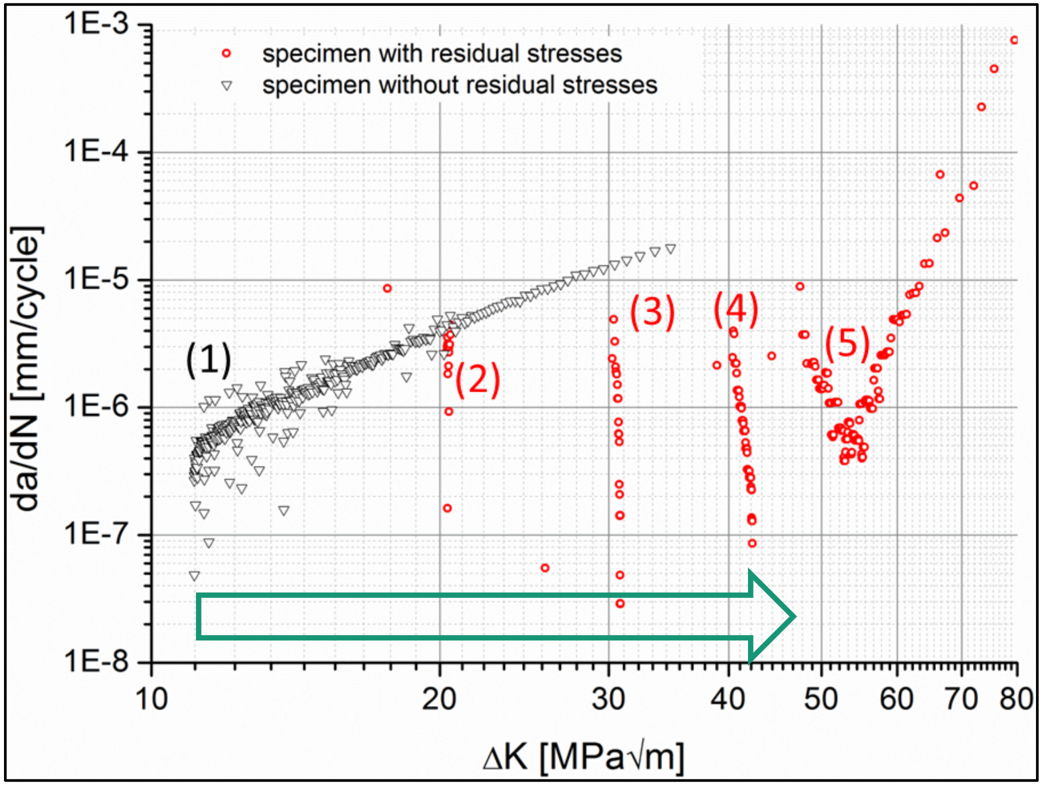
[1] Maierhofer et al., *Modified NASGRO equation for short cracks and application to the fitness-for-purpose assessment of surface-treated components,* Proceedings ECF20, 2014.

Crack retardation due to residual stresses / experiments

Influence of residual compressive stresses (example: SEB specimen[1]):



Increase of long crack growth threshold ≈ 450 %

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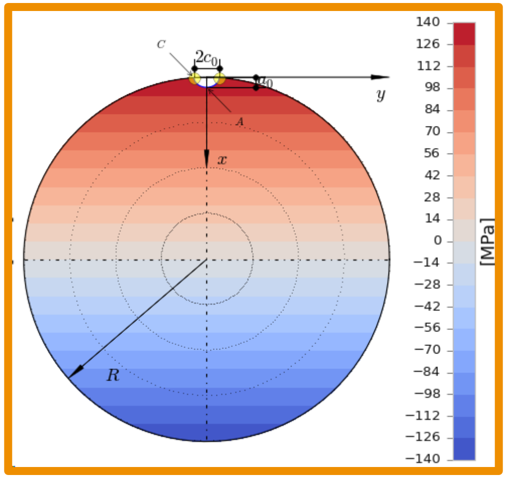
[1] Maierhofer et al., *Modified NASGRO equation for short cracks and application to the fitness-for-purpose assessment of surface-treated components,* Proceedings ECF20, 2014.

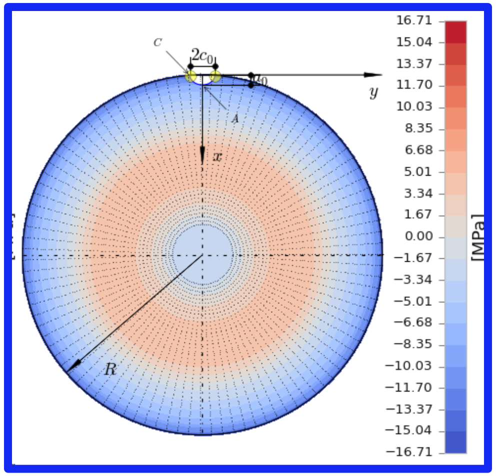
Crack retardation due to residual stresses / modelling

Consider residual stress fields in computational models by changing the mean stress:

$$\sigma_{max} = \sigma_{max,load} + \sigma_{res}$$

$$\sigma_{min} = \sigma_{min,load} + \sigma_{res}$$





$$R = \frac{\sigma_{\min}}{\sigma_{\max}}$$

$$\Delta K = K_{\max}(\sigma_{\max}) - K_{\min}(\sigma_{\min})$$

…and calculate the corresponding crack growth rate $$\frac{da}{dN} \propto \Delta K^{m}$$

Four main reasons for difference between laboratory specimen and 1:1 tests

1. Residual stresses

2. Overloads

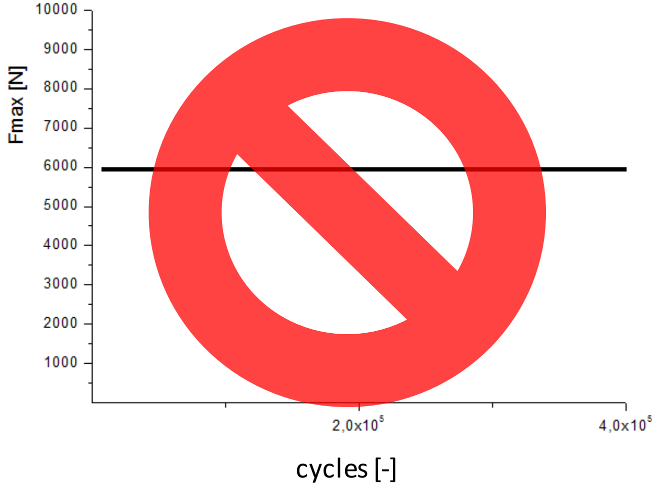
3. „small“ loads

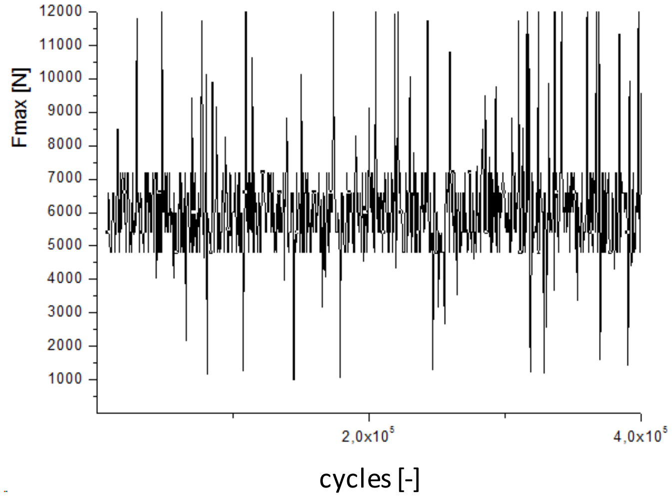
4. Downtime

Crack retardation due to overloads

Difference laboratory specimen / real component:

No constant load amplitude!





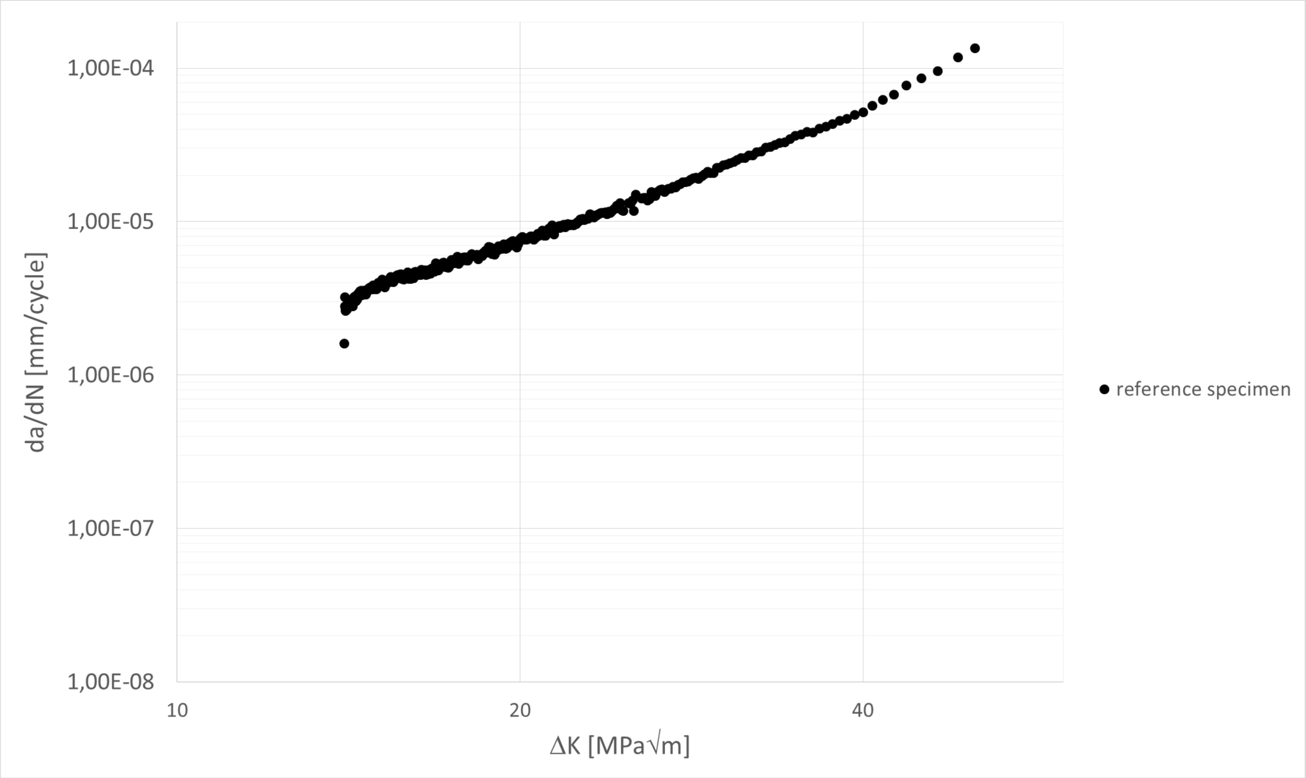
Required for lifetime enhancement : **Tension overload**

Crack retardation due to overloads / experiments

Influence of a single tensile / compressive overload

reference specimen:

- constant load (ΔF =const.), R=-0,5
- start with ΔK = 14 MPa√m
- **no overload**

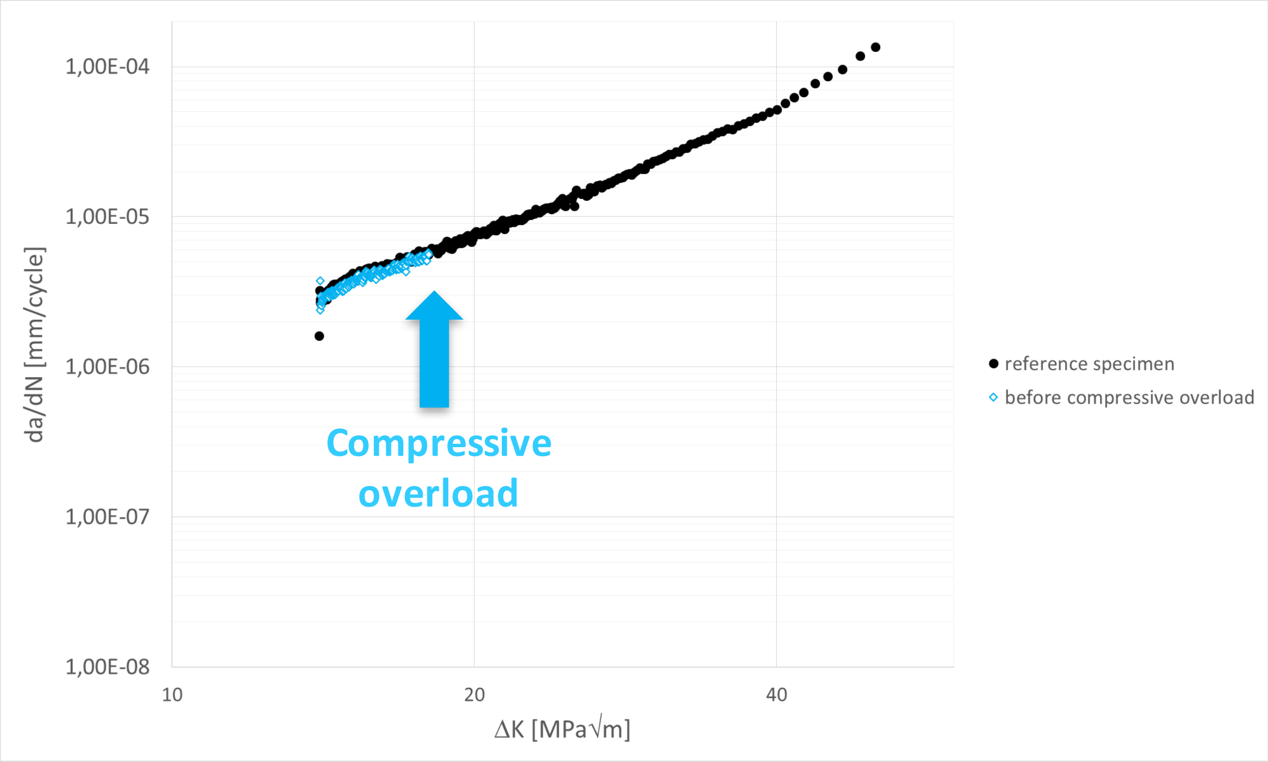


Crack retardation due to overloads / experiments

Influence of a single compressive overload

Compressive overload:

- constant load (ΔF =const.), R=-0,5
- start with ΔK = 14 MPa√m until ΔK = 18 MPa√m
- compressive overload 3 times higher than the primary load amplitude

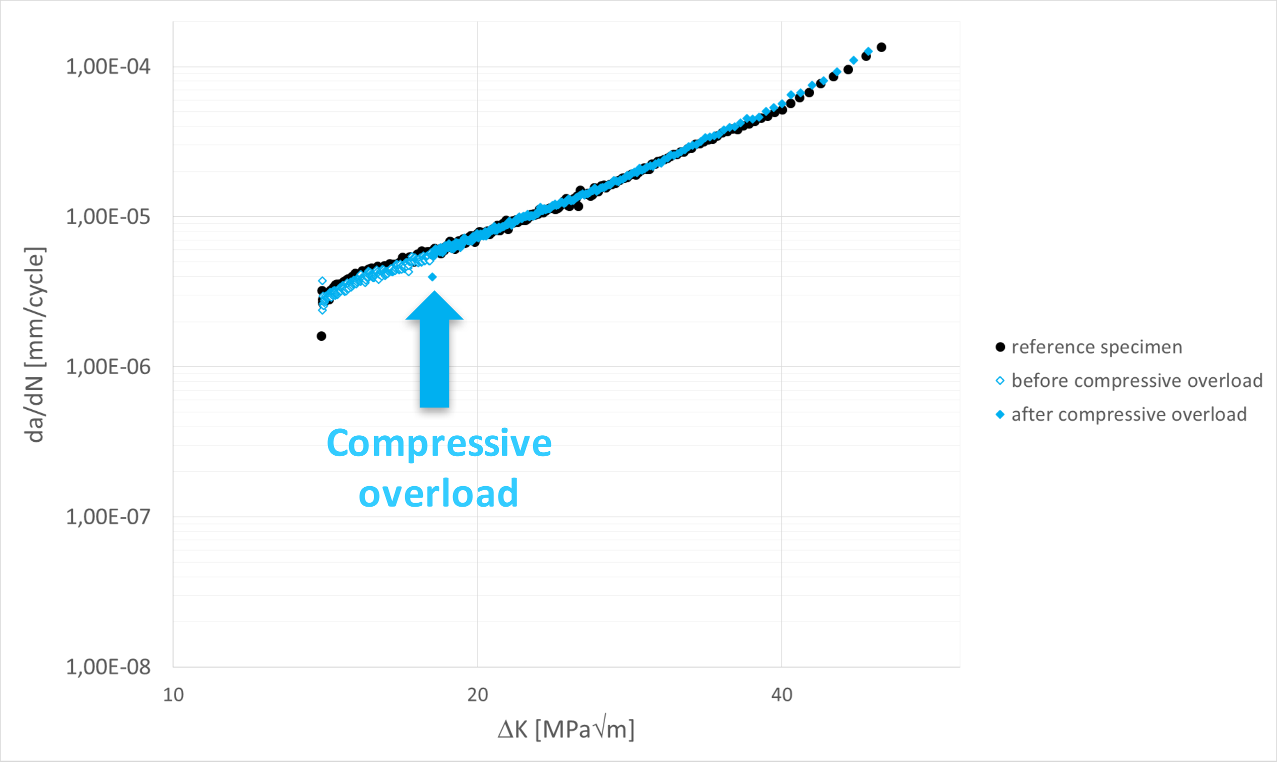


Crack retardation due to overloads / experiments

Influence of a single compressive overload

Compressive overload:

- constant load (ΔF =const.), R=-0,5
- start with ΔK = 14 MPa√m until ΔK = 18 MPa√m
- compressive overload 3 times higher than the primary load amplitude
- again apply primary load amplitude until final fracture of the specimen



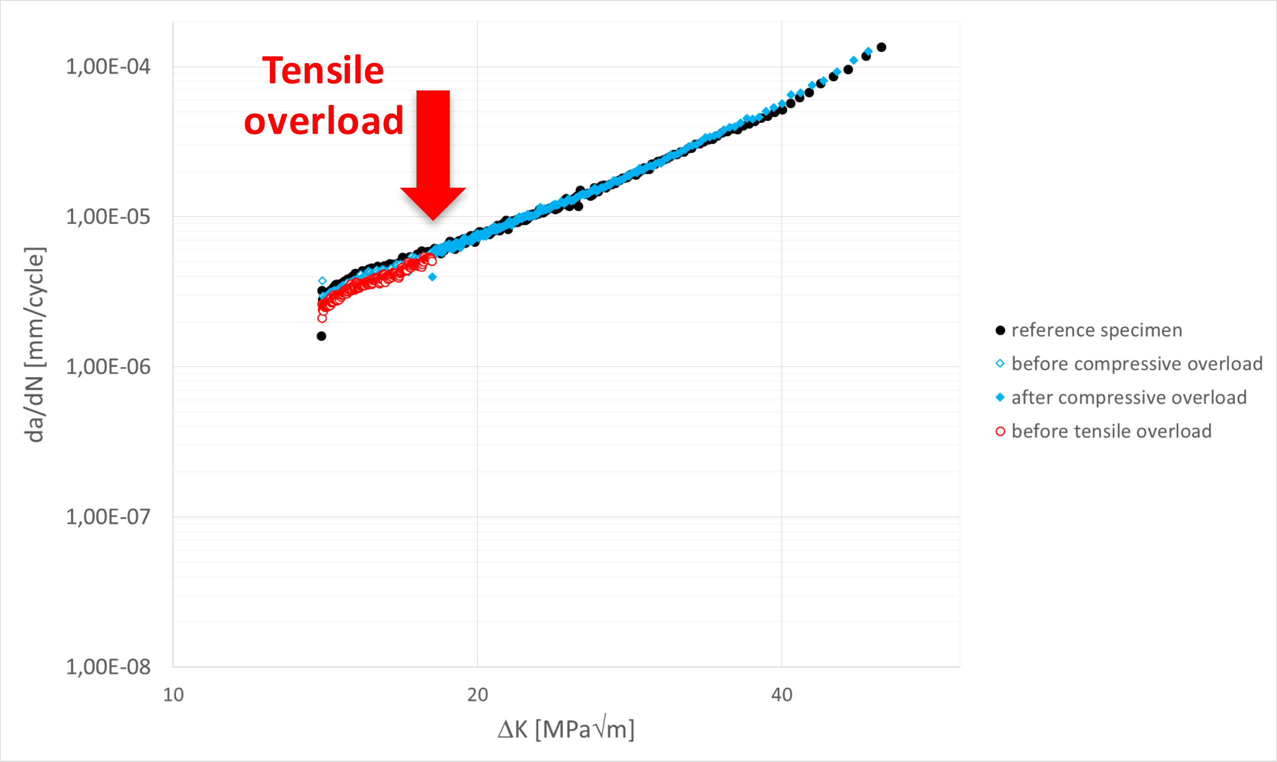
No influence of compressive overloads on the crack propagation rate (valid for long cracks and small scale yielding conditions)

Crack retardation due to overloads / experiments

Influence of a single tensile overload

Tensile overload:

- constant load (ΔF =const.), R=-0,5
- start with ΔK = 14 MPa√m until ΔK = 18 MPa√m
- tensile overload 3 times higher than the primary load amplitude

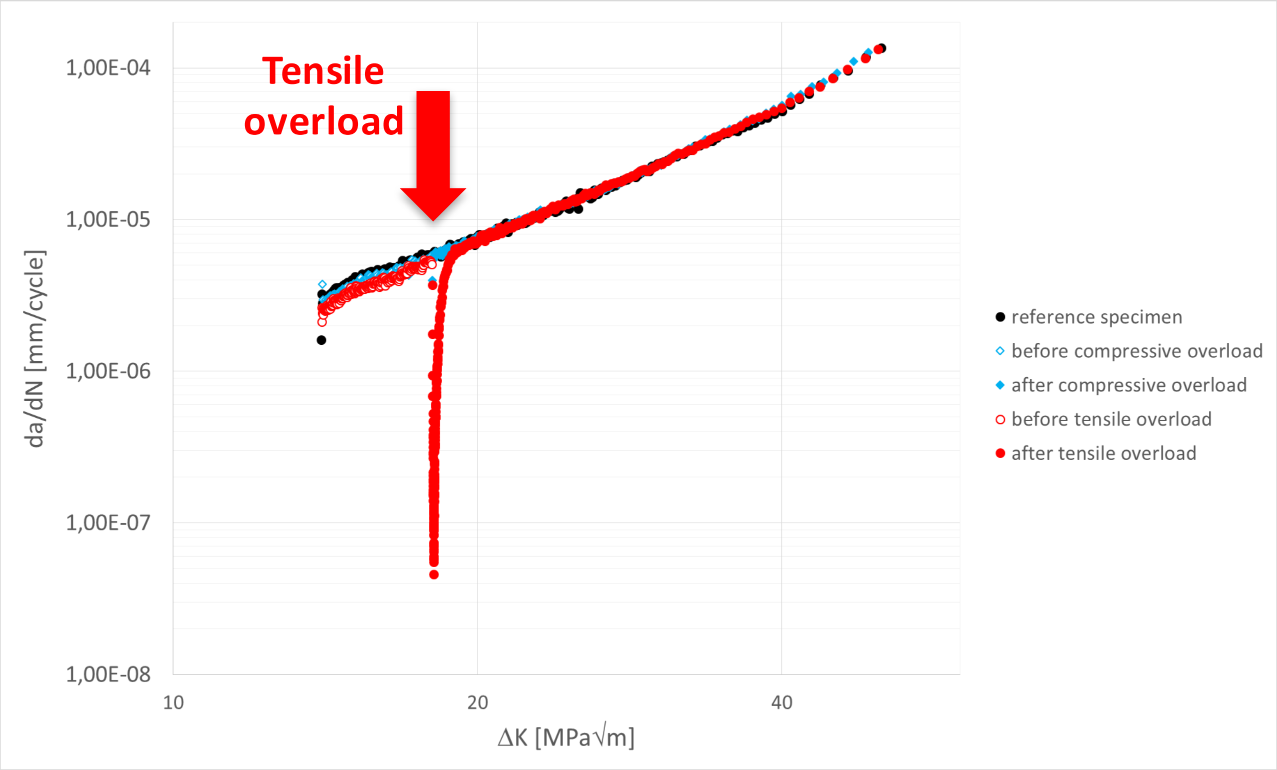


Crack retardation due to overloads / experiments

Influence of a single tensile overload

Tensile overload :

- constant load (ΔF =const.), R=-0,5
- start with ΔK = 14 MPa√m until ΔK = 18 MPa√m
- tensile overload 3 times higher than the primary load amplitude
- again apply primary load amplitude until final fracture of the specimen



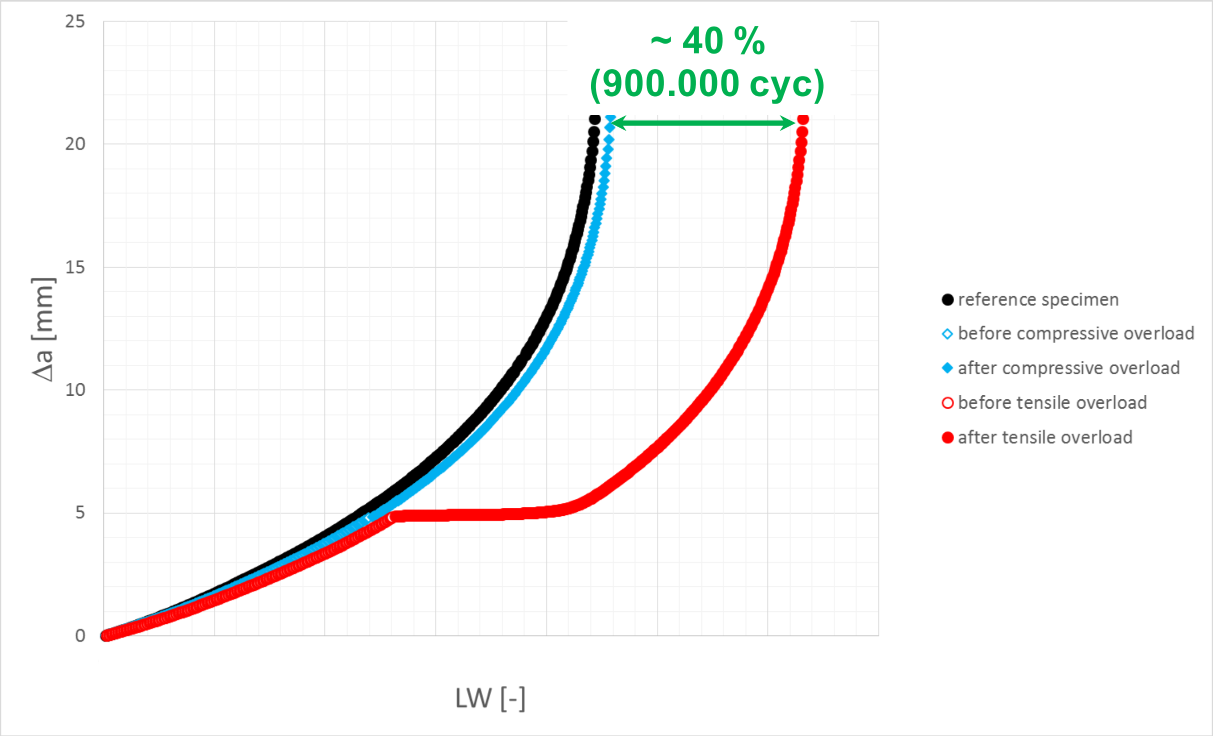
Significant influence of tensile overloads on the crack propagation rate (valid for long cracks and small scale yielding conditions)

Crack retardation due to overloads / experiments

Influence of overloads on the crack growth behaviour of long cracks:

Compressive overload: no influence on crack growth / lifetime

Tensile overload: significant retardation of the crack propagation rate; increase of lifetime



Crack retardation due to overloads / modelling

Approximate description of overload induced crack retardation by means of the Willenborg-Gallagher-Hughes model:

- effective load ratio: $R_{\mathrm{eff}} = \dfrac{K_{\mathrm{min}} - K_{\mathrm{r}}}{K_{\mathrm{max}} - K_{\mathrm{r}}}$

- SIF due to overload induced residual stresses in front of the crack tip:

$$K_{\mathrm{r}} = \Phi \cdot \left[K_{\mathrm{max,OL}} \left(1 - \frac{\Delta a}{Z_{\mathrm{OL}}} \right)^{1/2} - K_{\mathrm{max}} \right]$$

- Size of overload influence zone depends on overload:

$$Z_{\mathrm{OL}} = L_{\mathrm{OL}} (K_{\mathrm{max}} - \Delta K_0)^{p_{\mathrm{OL}}}$$

Four main reasons for difference between laboratory specimen and 1:1 tests

1. Residual stresses

2. Overloads

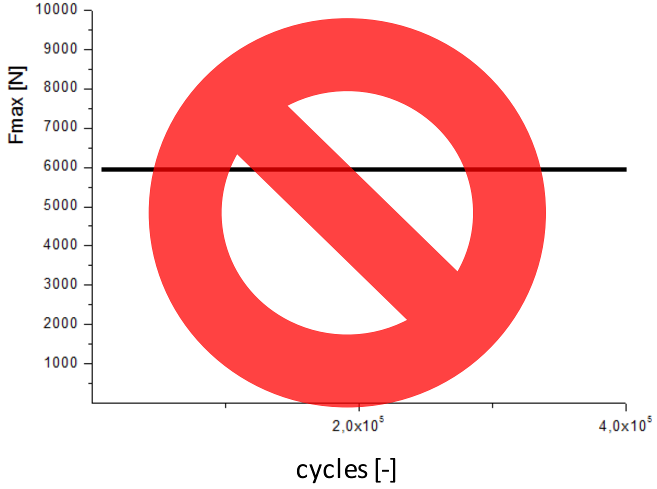
3. „small“ loads

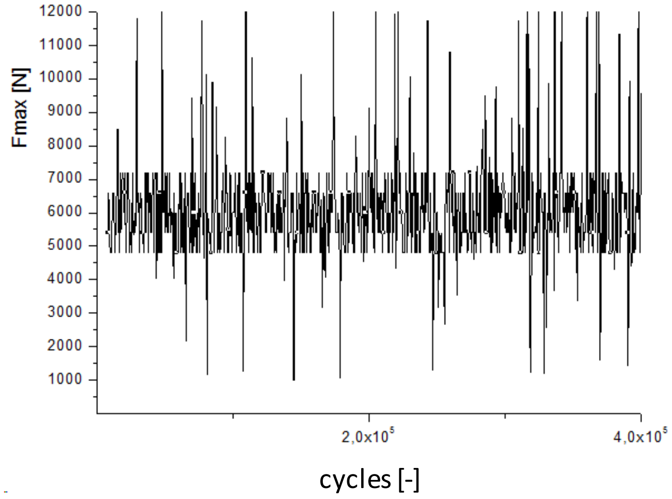
4. Downtime

Crack retardation due to „small“ loads

Difference laboratory specimen / real component:

No constant load amplitude!





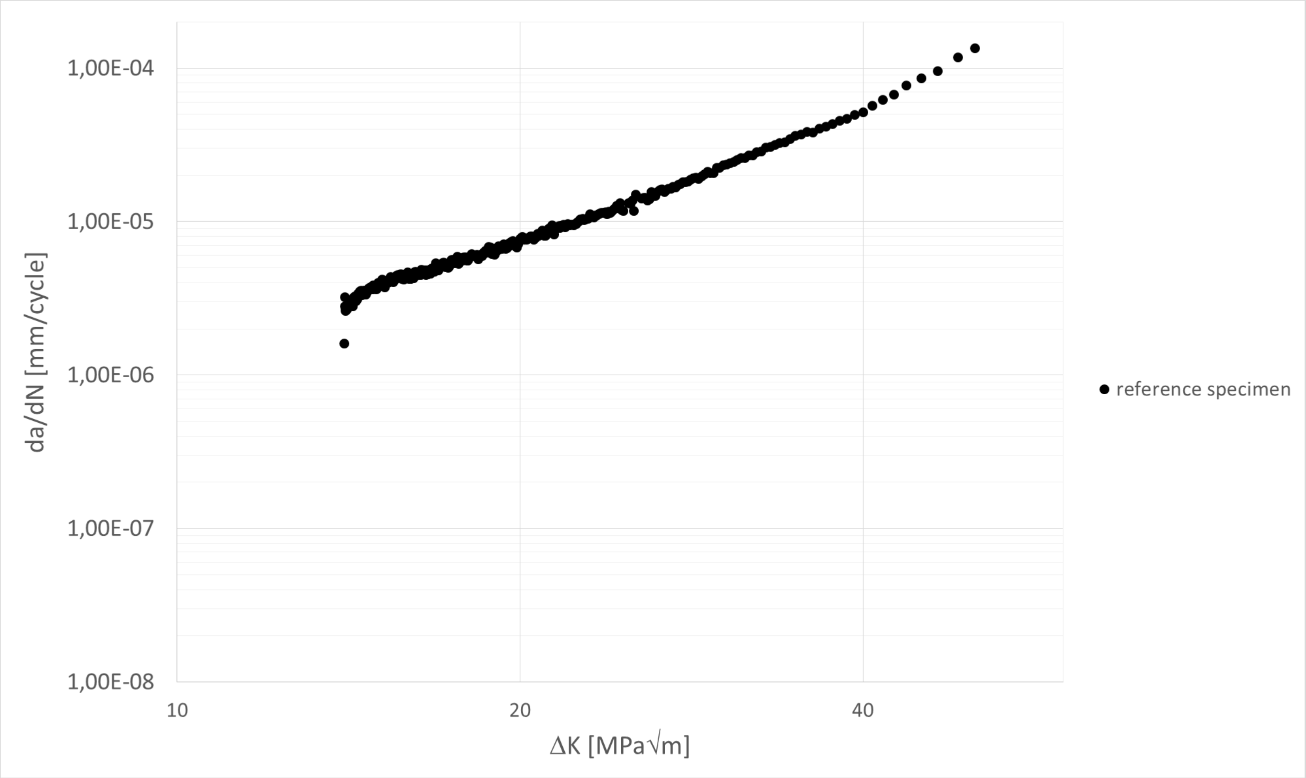
Required for lifetime enhancement : **quite a few small loads**

Crack retardation due to small loads / experiments

Influence of small loads

reference specimen:

- constant load (ΔF =const.), R=-0,5
- start with ΔK = 14 MPa√m
- **no small loads → no build-up of oxide layer**

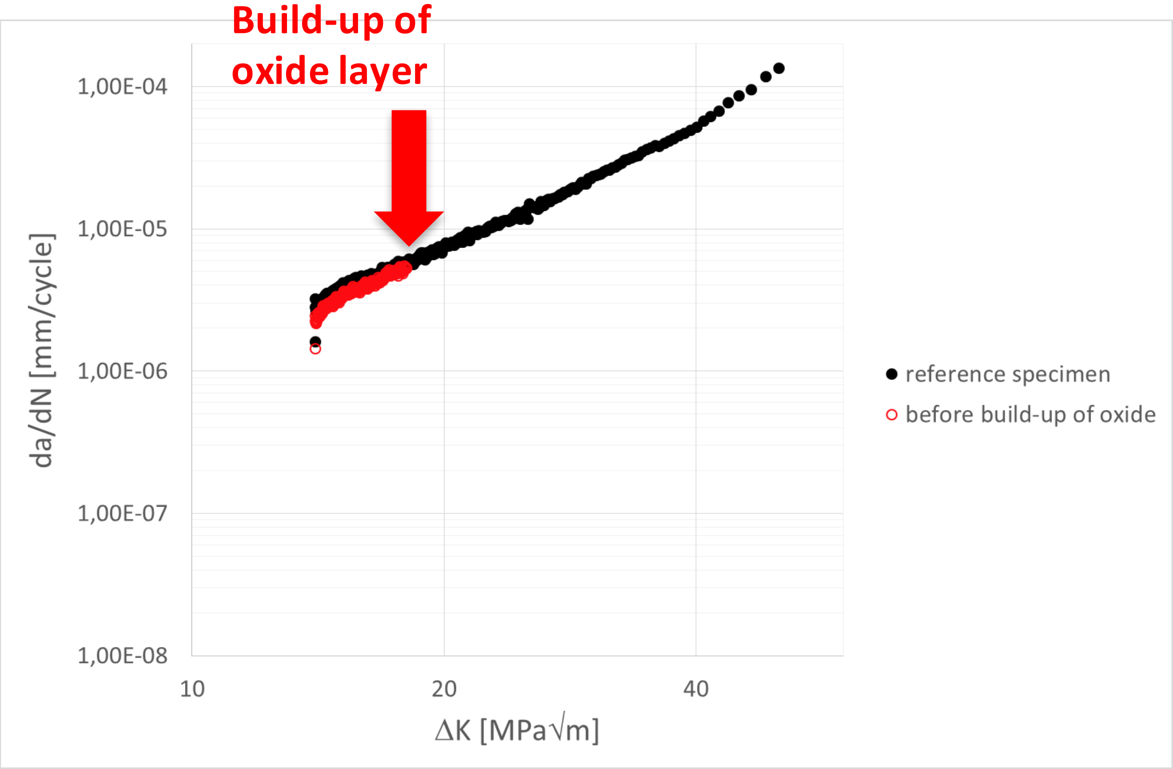


Crack retardation due to small loads / experiments

Influence of small loads

Build-up of oxide layer:

- constant load (ΔF =const.), R=-0,5
- start with ΔK = 14 MPa√m until ΔK = 18 MPa√m
- build-up of oxide layer with 9 MPa√m (≈34·10^6 cycles)

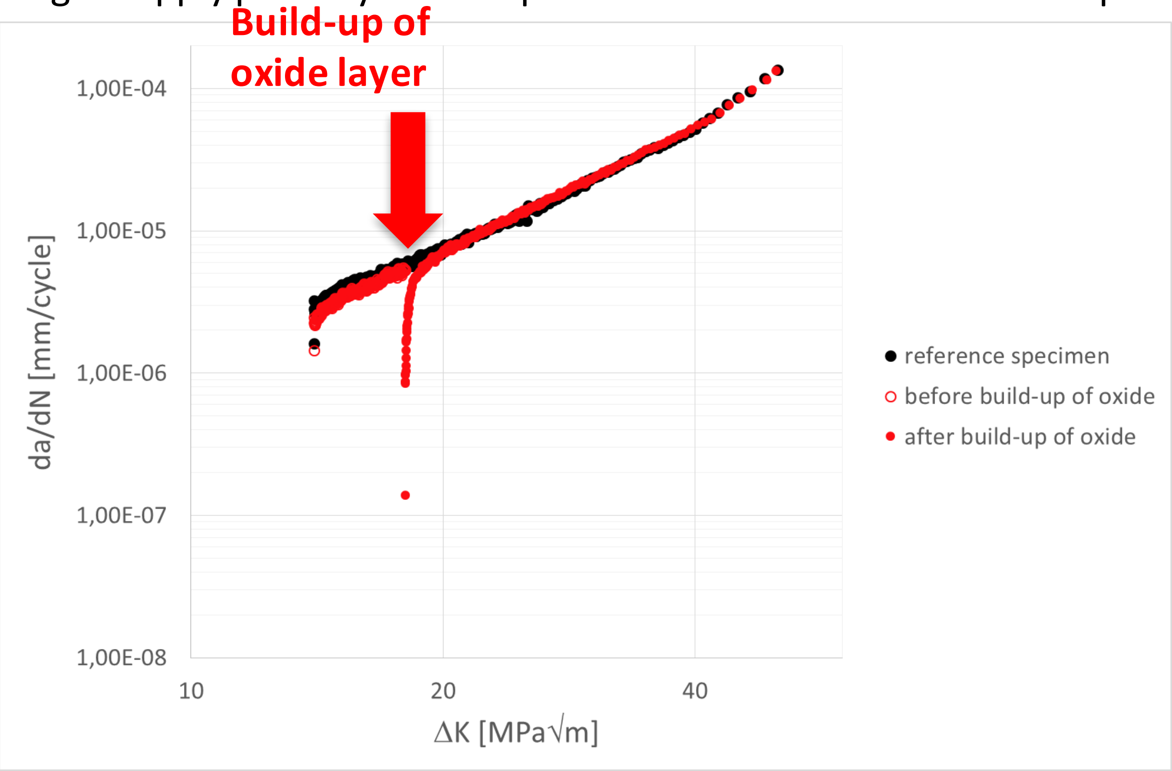

Build-up of oxide layer

Crack retardation due to small loads / experiments

Influence of small loads

Build-up of oxide layer:

- constant load (ΔF =const.), R=-0,5
- start with ΔK = 14 MPa√m until ΔK = 18 MPa√m
- build-up of oxide layer with 9 MPa√m (≈ 34·10^6 cycles)
- again apply primary load amplitude until final fracture of the specimen



Build-up of oxide layer

Crack retardation due to small loads / fracture surface analysis

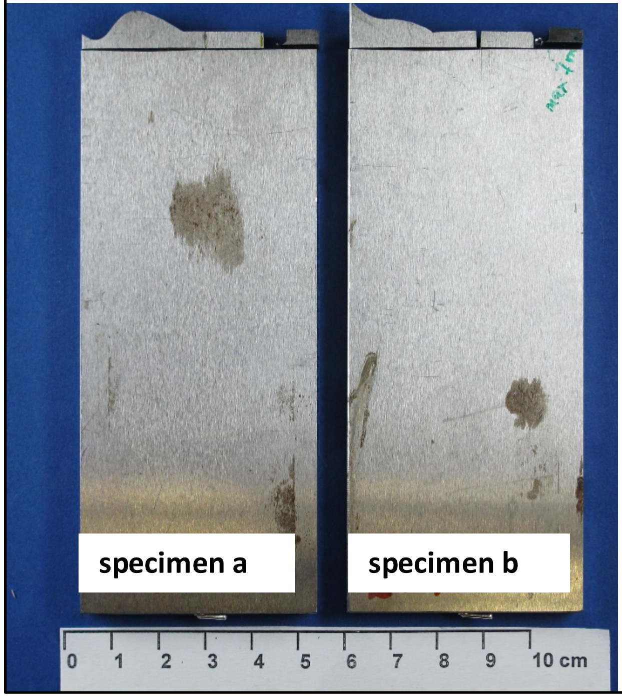
Investigation of two specimens using an IonSlicer

specimen a: $\Delta K_{\text{oxide}} = 7\ \text{MPa}\sqrt{\text{m}}$, 200.000 load cycles

specimen b: $\Delta K_{\text{oxide}} = 9\ \text{MPa}\sqrt{\text{m}}$, 33.000.000 load cycles

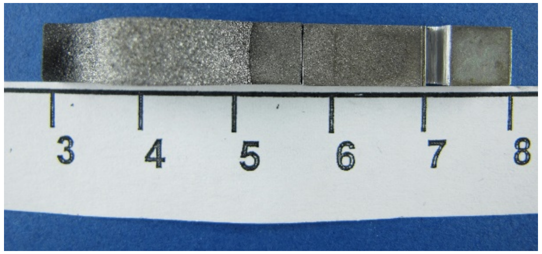
Specimen preparation:

Sampling from SEB specimens



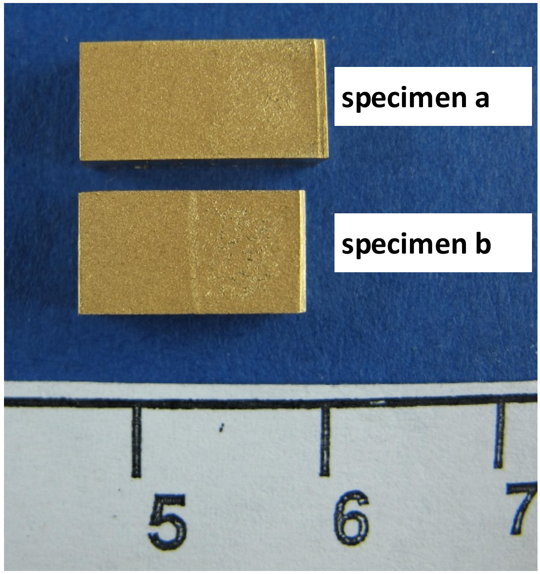
Fracture surface

specimen a



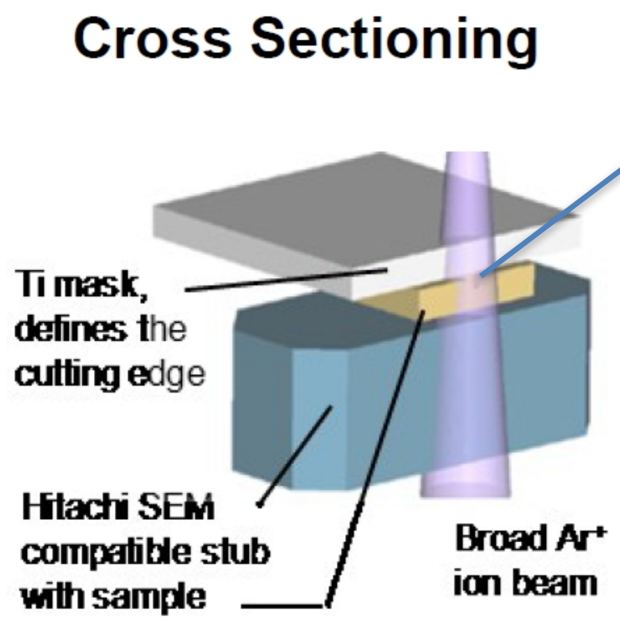
specimen b

Fracture surface –
after applying a thin gold layer

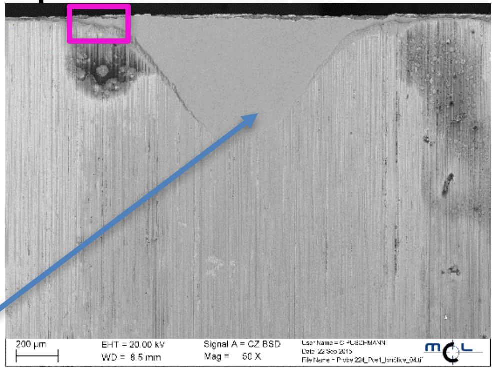


Crack retardation due to small loads / fracture surface analysis

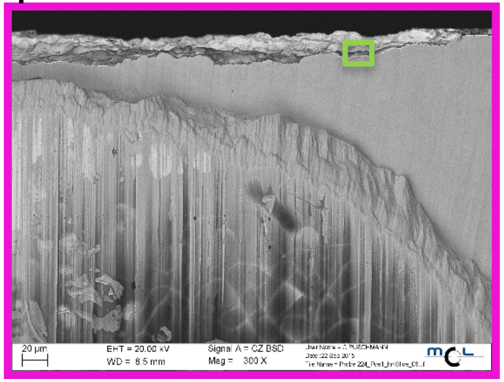
Working principle of an IonSlicer:



specimen a



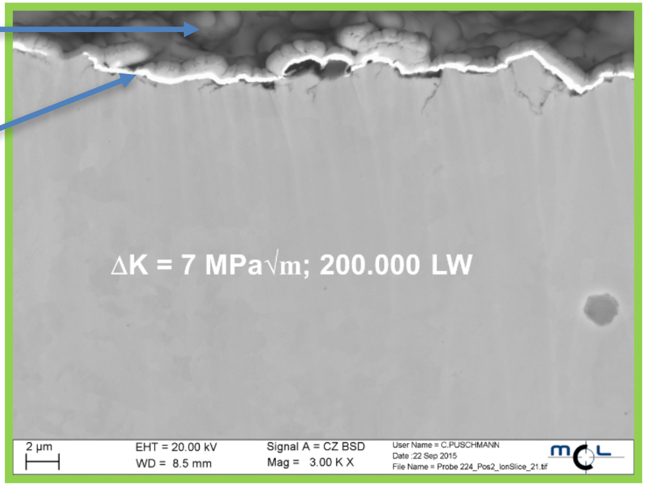
specimen a



specimen a

removed material

gold layer (white line)



Crack retardation due to small loads / fracture surface analysis

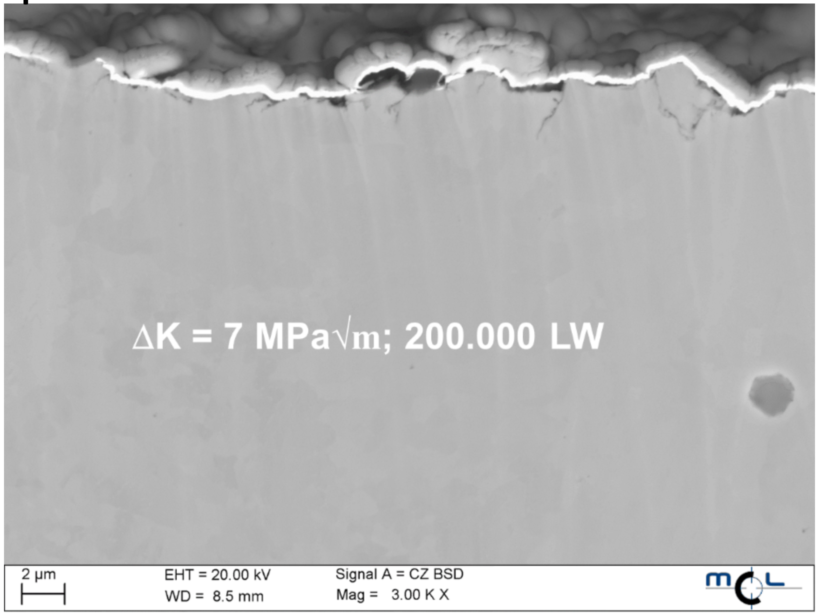
Comparison of the two oxide layers:

- oxide layer of specimen b significantly thicker

→ thickness of oxide layer depending on

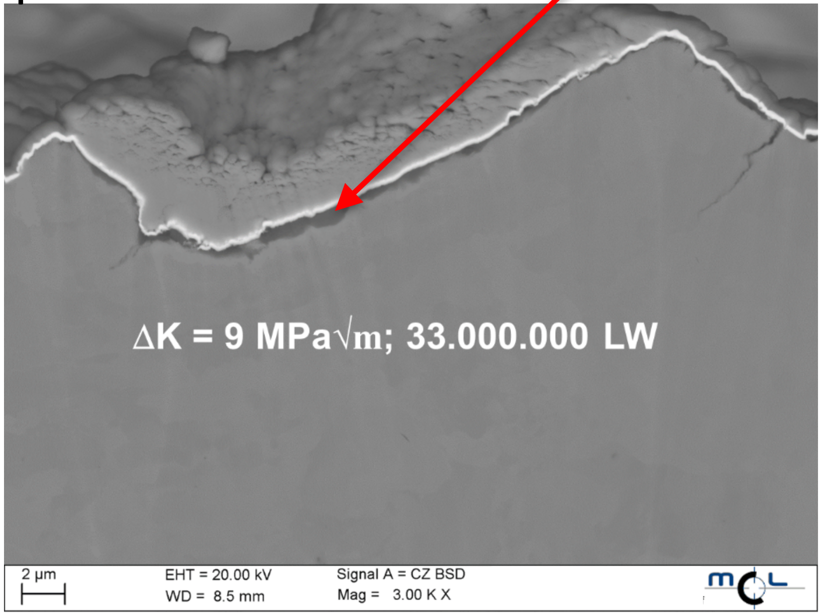
1. number of applied load cycles and
2. load amplitude (of the small loads)

specimen a



specimen b

oxide layer
(dark-grey area)



Crack retardation due to small loads / modelling

The area of influence Z_{0x} of small loads and therefore the thickness of the oxide layer depends on the number of load cylces and the corresponding load amplitude :

$$Z_{\mathrm{ox}} = L_{\mathrm{ox}} (1+R)^{s_{\mathrm{ox}}} \Delta K_{\mathrm{ox}}^{p_{\mathrm{ox}}} N_{\mathrm{ox}}^{q_{\mathrm{ox}}}$$

Modelling of the oxide induced crack retardation by increasing the crack growth threshold:

$$\Delta K_{\mathrm{th,ox}} = K_{\mathrm{ox}} (1+R)^{r_{\mathrm{ox}}} \Delta K_{\mathrm{ox}}^{m_{\mathrm{ox}}} N_{\mathrm{ox}}^{m_{\mathrm{ox}}}$$

Four main reasons for difference between laboratory specimen and 1:1 tests

1. Residual stresses

2. Overloads

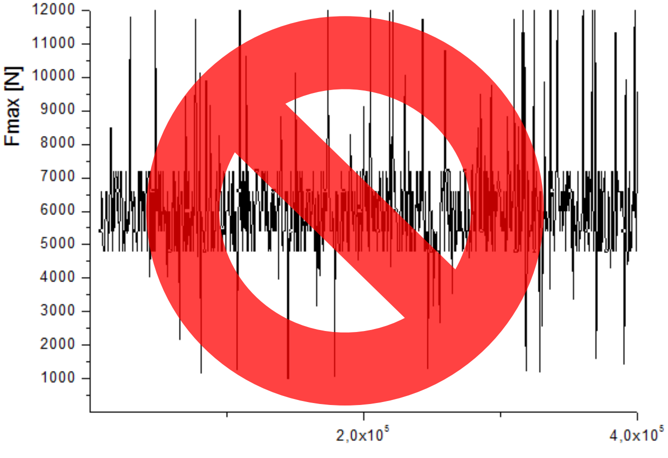
3. „small“ loads

4. Downtime

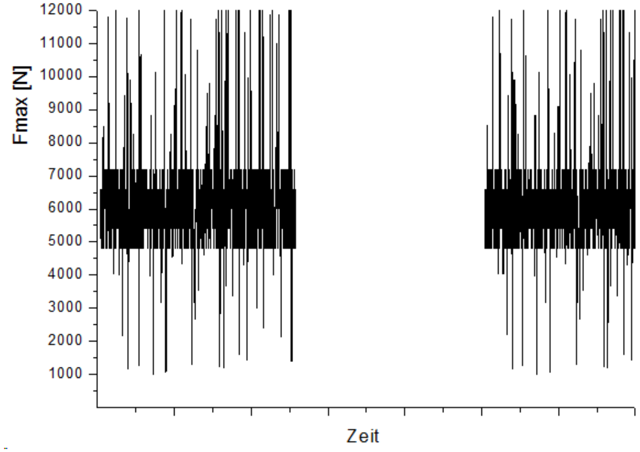
Crack retardation due to downtime

Difference laboratory specimen / real component:

No downtime in laboratory specimen!



cycles [-]



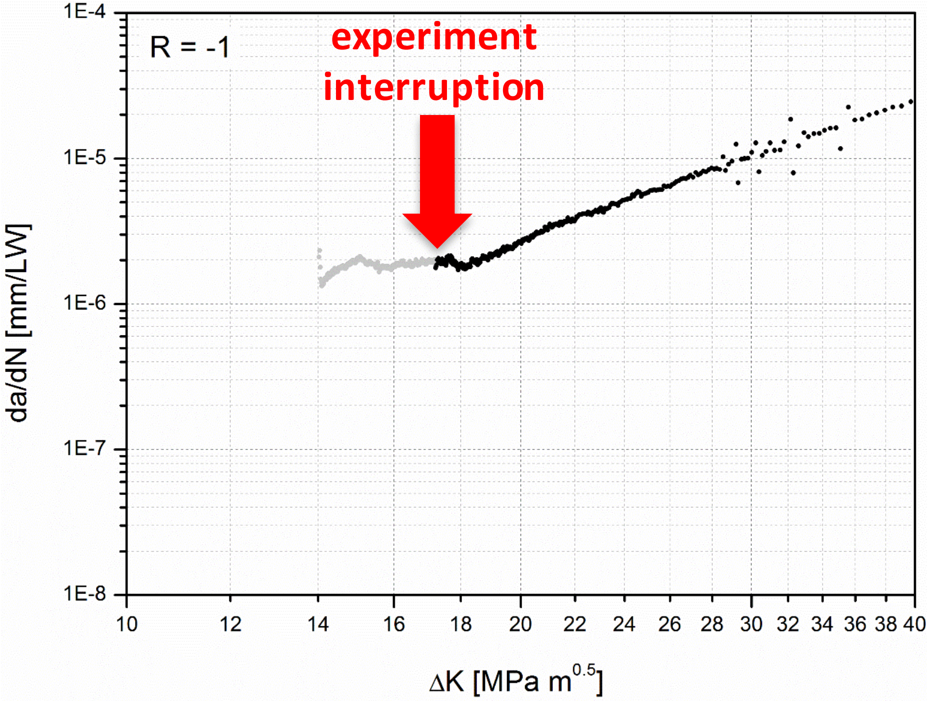
cycles [-]

Crack retardation due to downtime / experiments

Influence of downtime

Test procedure:

- constant load (ΔF =const.), R=-1
- start with ΔK = 14 MPa√m
- after ΔK = 17,2 MPa√m was reached, experiment was stopped, the specimen removed, again clamped in the testing rig and restarted with primary load amplitude

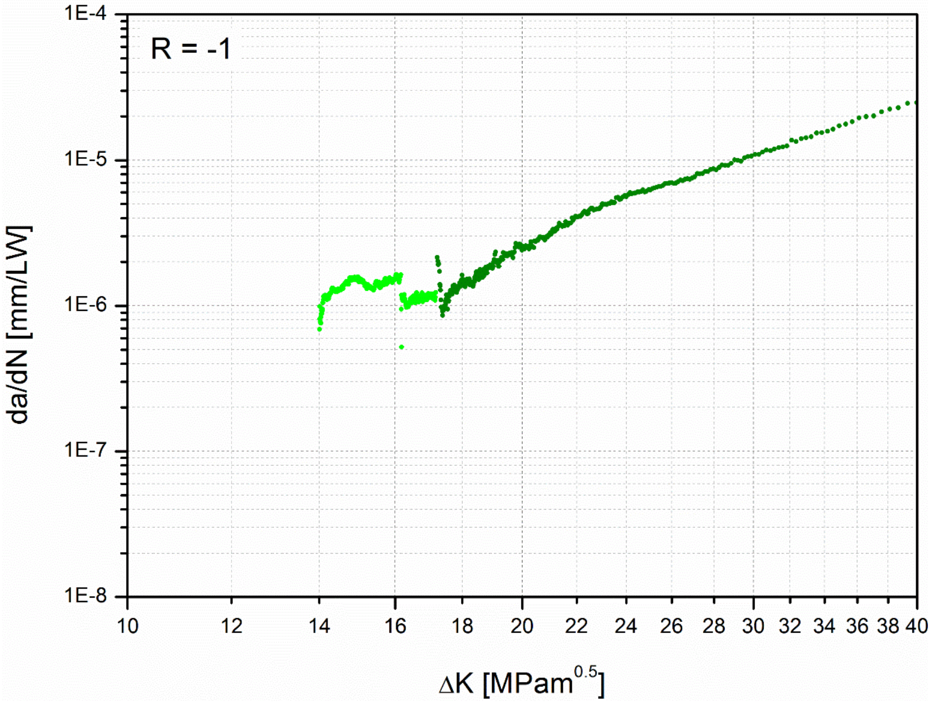


Crack retardation due to downtime / experiments

Influence of downtime

Test procedure:

- constant load (ΔF =const.), R=-1
- start with ΔK = 14 MPa√m
- after ΔK = 17,2 MPa√m was reached, experiment was stopped and the specimen removed
- after **two weeks in ambient air** the experiment was again clamped in the testing rig and restarted with the primary load amplitude

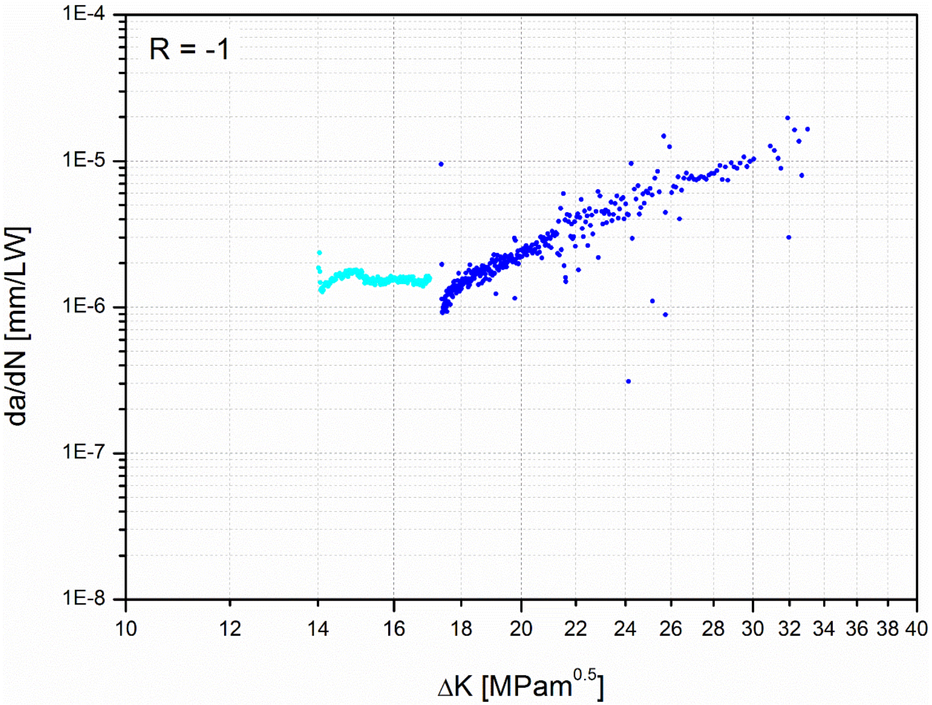


Crack retardation due to downtime / experiments

Influence of downtime

Test procedure:

- constant load (ΔF =const.), R=-1
- start with ΔK = 14 MPa√m
- after ΔK = 17,2 MPa√m was reached, experiment was stopped and the specimen removed
- after **two weeks in water** the experiment was again clamped in the testing rig and restarted with the primary load amplitude

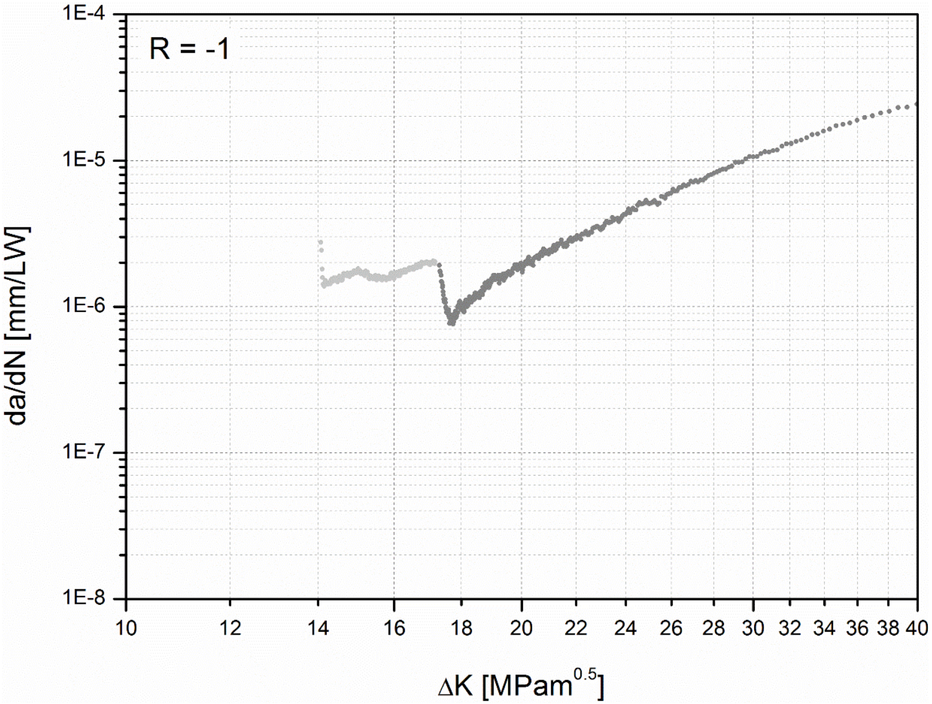


Crack retardation due to downtime / experiments

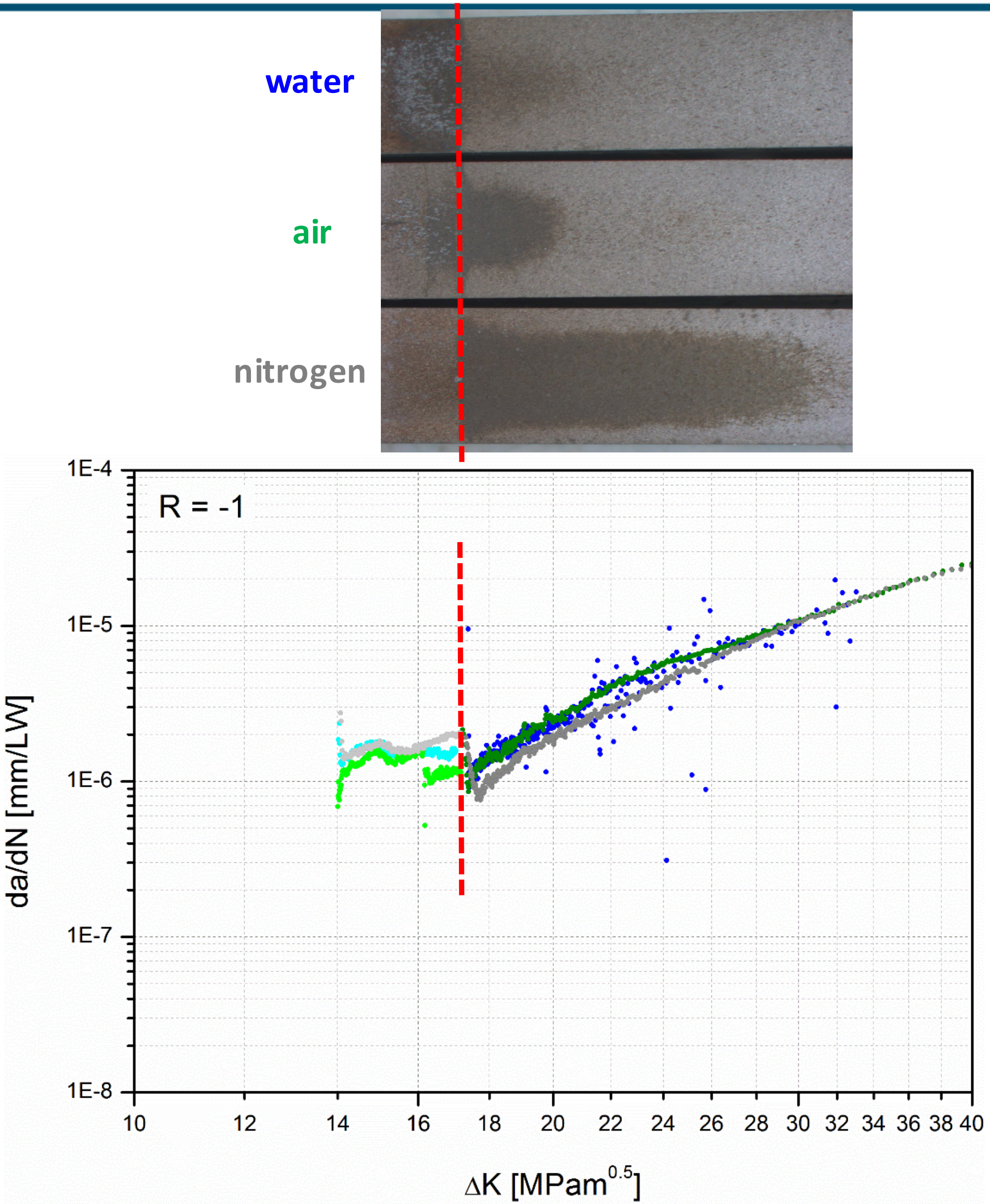
Influence of downtime

Test procedure:

- constant load (ΔF =const.), R=-1
- start with ΔK = 14 MPa√m
- after ΔK = 17,2 MPa√m was reached, experiment was stopped and the specimen removed
- after **two weeks in liquid nitrogen** the experiment was again clamped in the testing rig and restarted with the primary load amplitude



Crack retardation due to downtime / fracture surface analysis



Summary

Four main reasons for difference between laboratory specimen and 1:1 tests (or real components, respectively):

1. **Residual stresses**
    - Residual compressive stresses decrease the crack growth rate and lead to higher lifetimes
    - In small scale specimens there are often no residual stresses left
2. **Overloads**
    - Tensile overloads can lead to a significant retardation of crack growth
    - Compressive overloads have no effects (for long cracks and small scale yielding)
3. **Small loads**
    - Depending on the applied load and number of cyles a build-up of oxide layer can occur → crack closure increases and therefore the crack growth rate decreases
    - Small loads are often not considered during testing („omission“)
4. **Downtime**
    - Influence on crack growth in the near-threshold region

Acknowledgement

Financial support by the Austrian Federal Government (in particular from Bundesministerium für Verkehr, Innovation und Technologie and Bundesministerium für Wissenschaft, Forschung und Wirtschaft) represented by Österreichische Forschungsförderungsgesellschaft mbH and the Styrian and the Tyrolean Provincial Government, represented by Steirische Wirtschaftsförderungsgesellschaft mbH and Standortagentur Tirol, within the framework of the COMET Funding Programme is gratefully acknowledged.

Projektpartner

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Thank you for your attention!

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