Institute of Physics of Materials
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Crack closure in threshold area of railway axle steel EA4T

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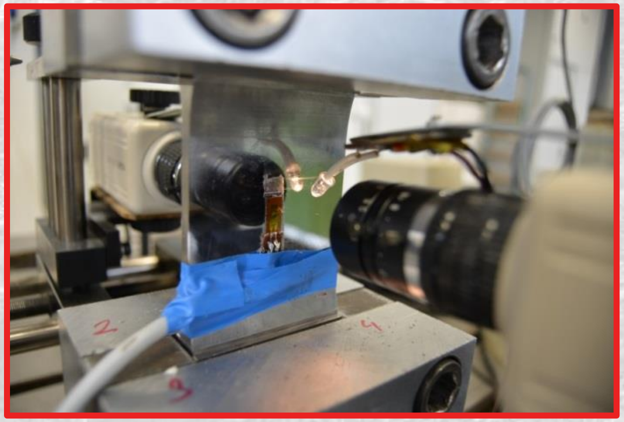
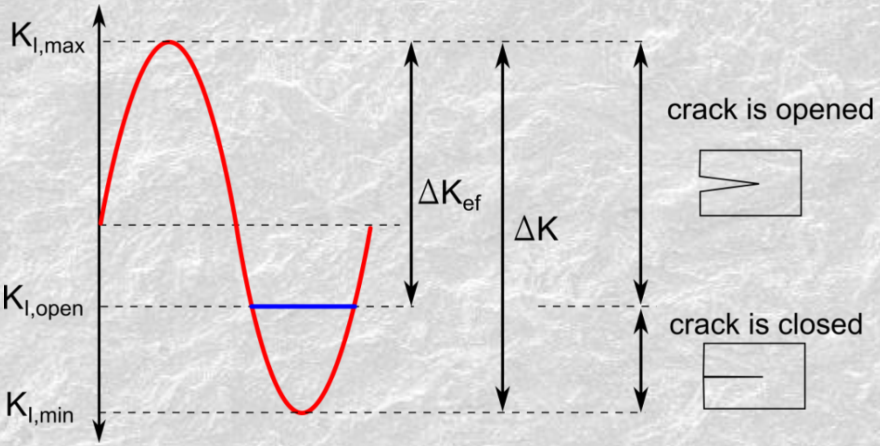
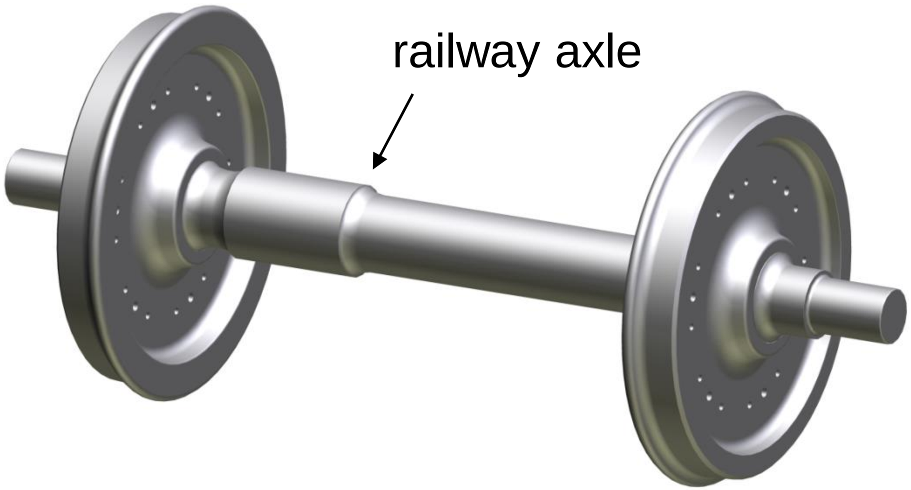




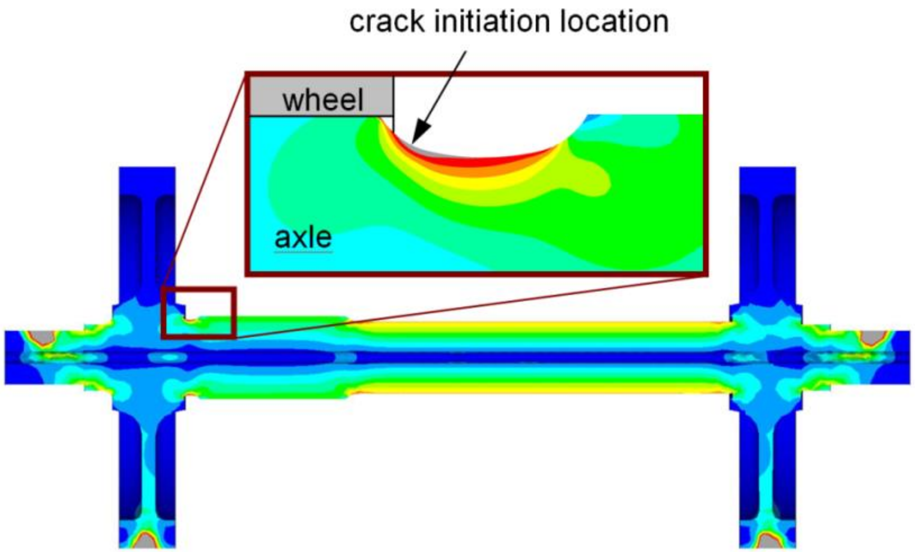
ESIS TC24 – Leoben 24th-25th October 2016

Outline

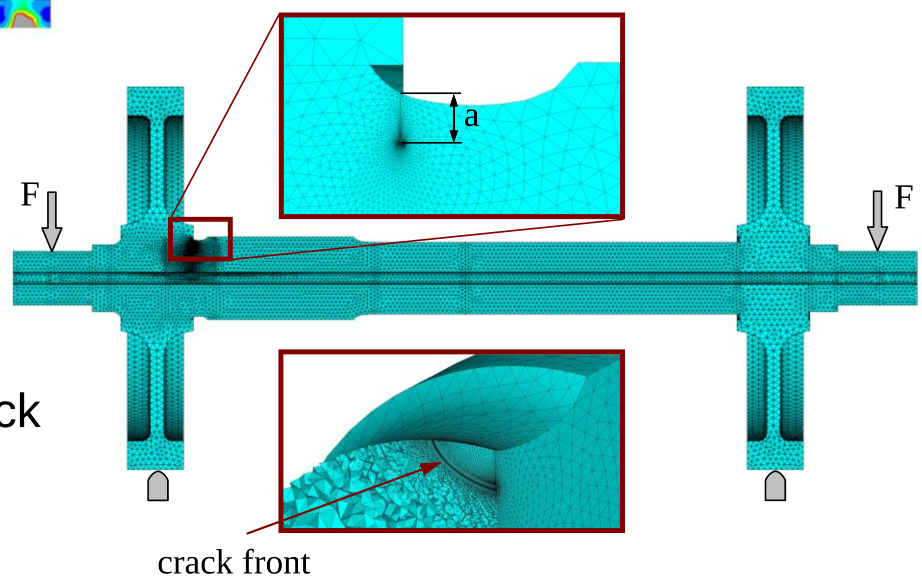
- operation stress ratio *R* of railway axles
- v-K curves measured on different stress ratios
- induced crack closures in threshold area of EA4T steel
- conclusion



Critical position of fatigue crack

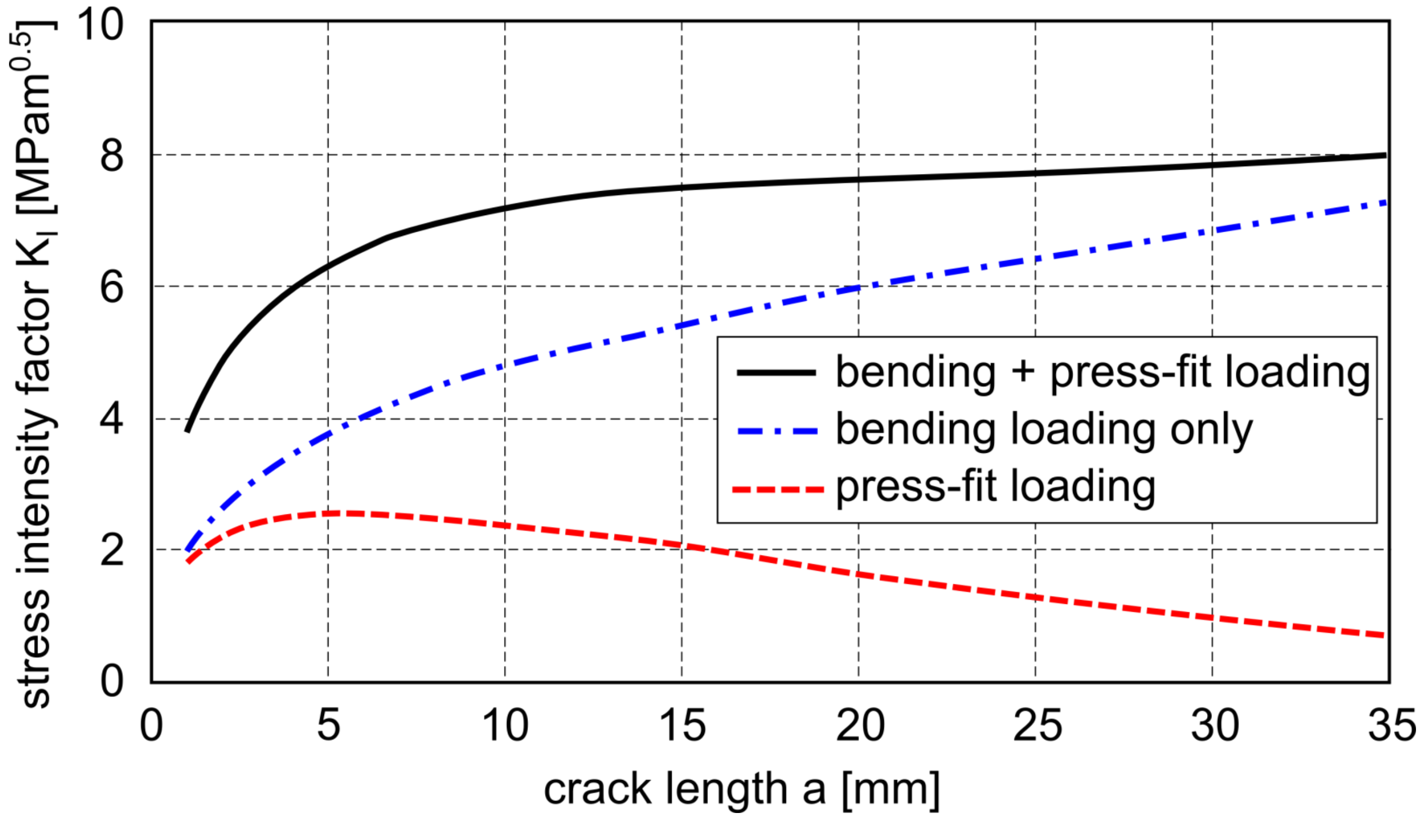


stress intensity



a numerical model of axle with crack

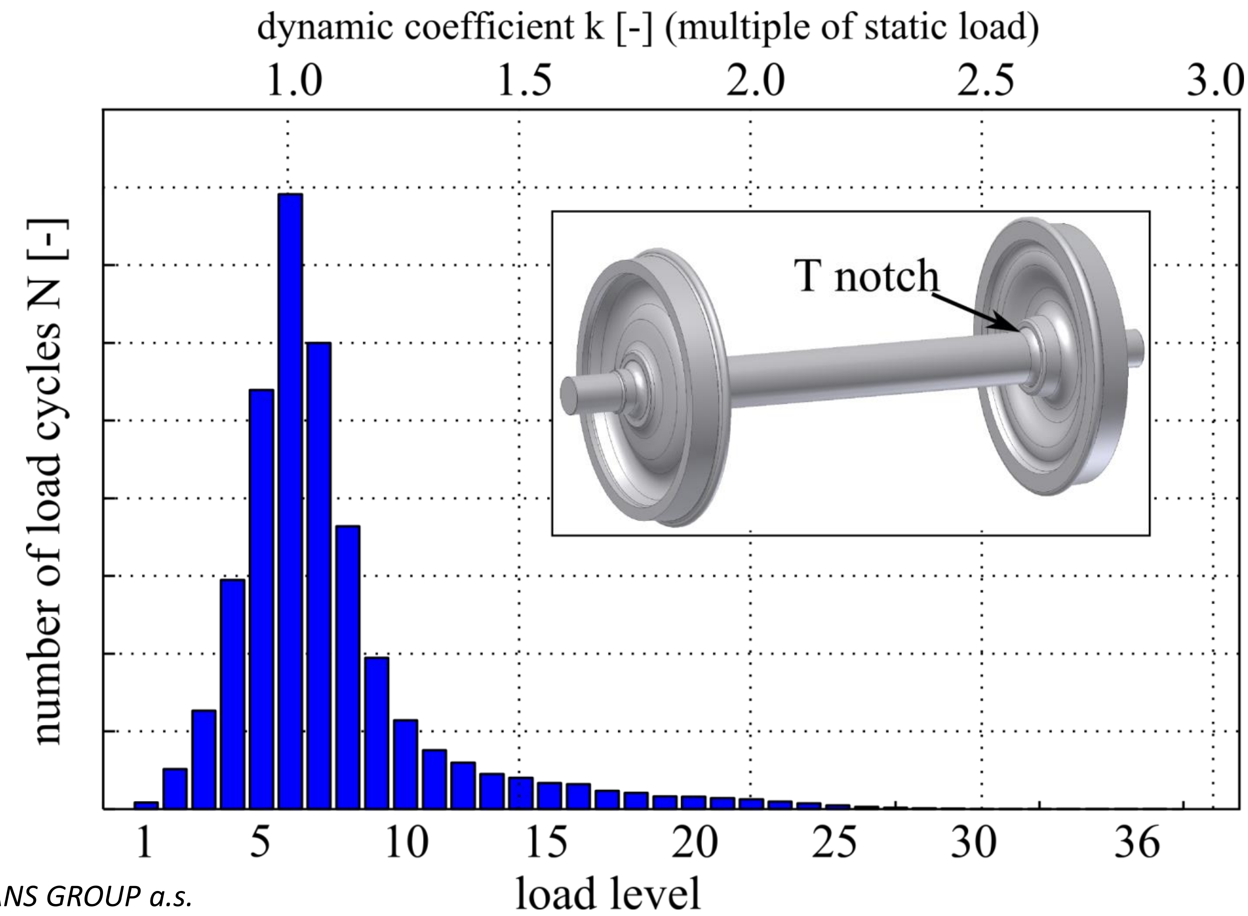
Stress intensity factor at the critical position



$$K_{I,total} = K_{I,bending} + K_{I,press\ fit}$$

for given crack length a:
the stress intensity factor caused by bending moment **is not constant**.

Load spectrum

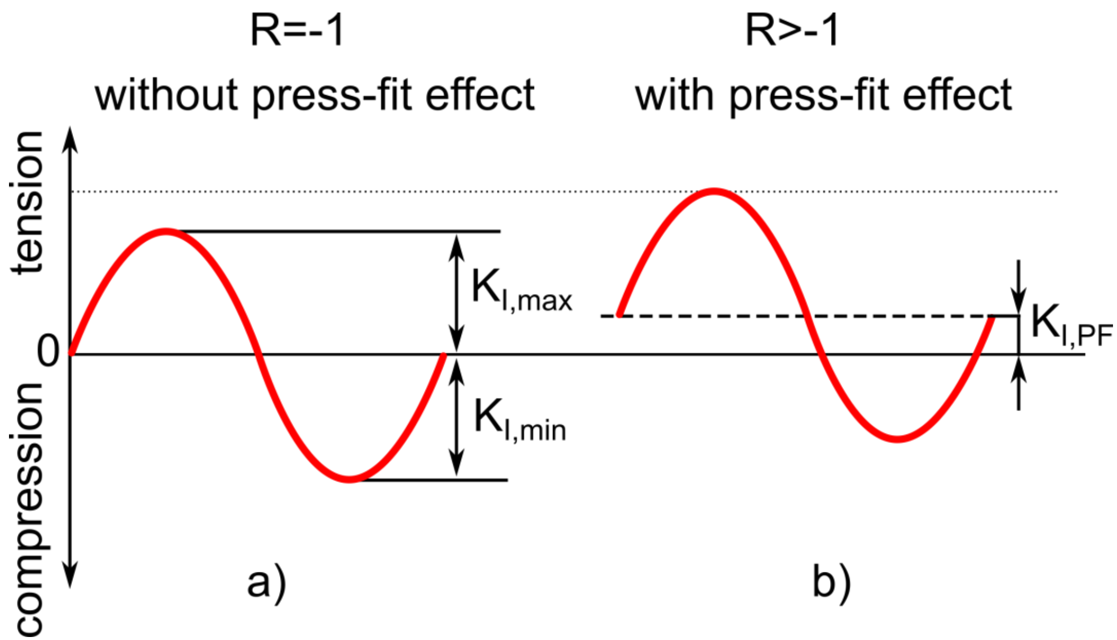


Source: BONATRANS GROUP a.s.

load for general cycle:

$$\boldsymbol{K_{I,total} = k.K_{I,bending} + K_{I,press\ fit}}$$

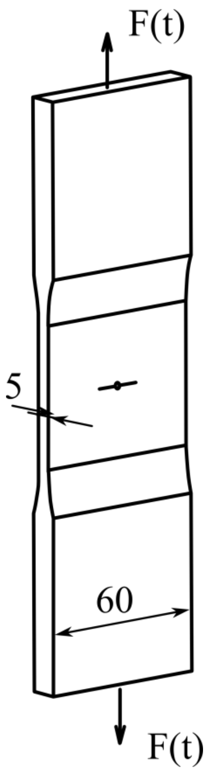
Stress ratio R

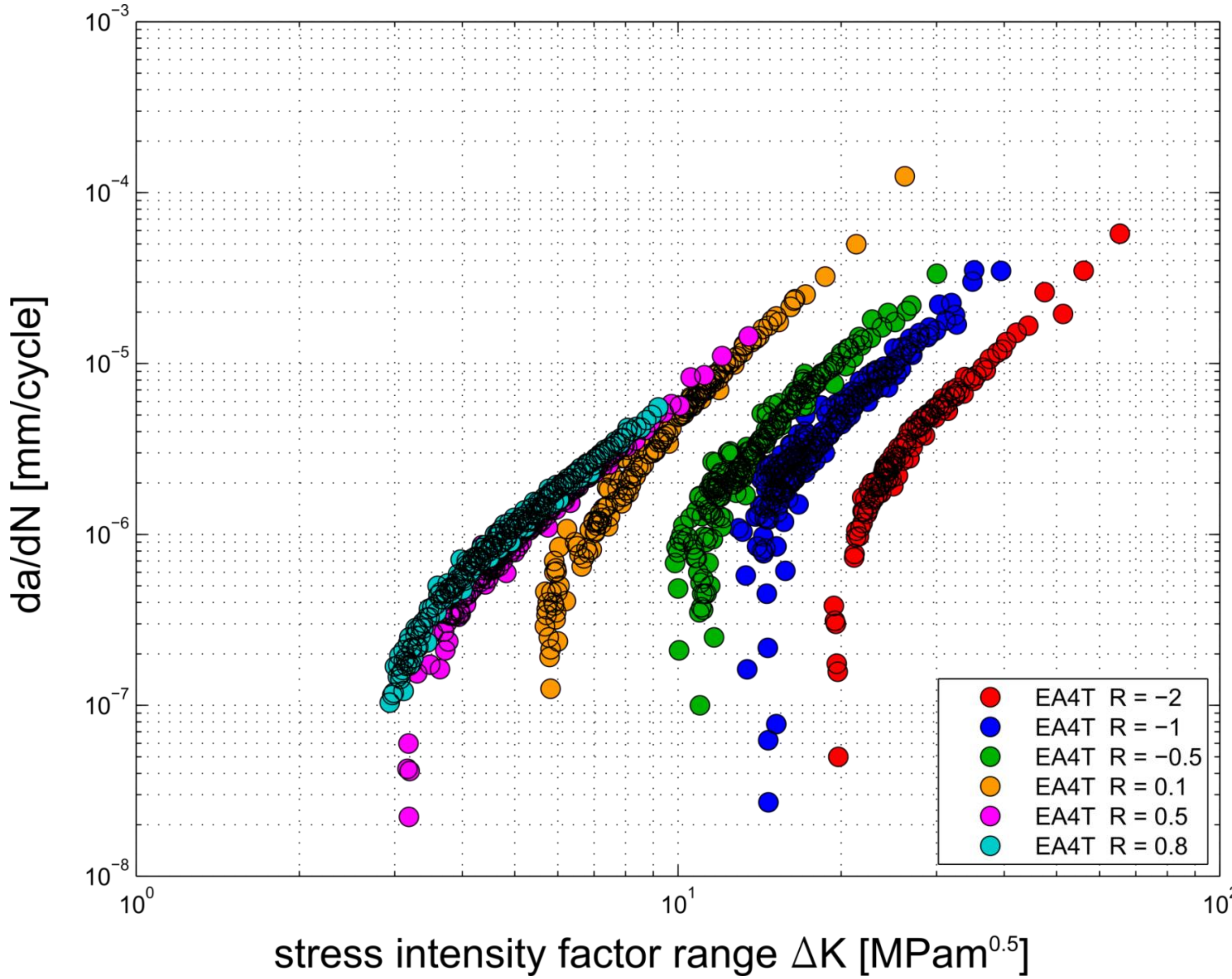


$$R(a,k) = \frac{K_{I,min}}{K_{I,max}} = \frac{K_{I,press\ fit}(\mathrm{a}) - \mathrm{k}.K_{I,bending}(a)}{K_{I,press\ fit}(\mathrm{a}) + \mathrm{k}.K_{I,bending}(a)}$$

- showed railway axle R from -1 to 0.2.
- some railway axles with large negative residual stresses →R<-1
- stress ratio with high R (e.g. R=0.8 → closure free stress ratio)

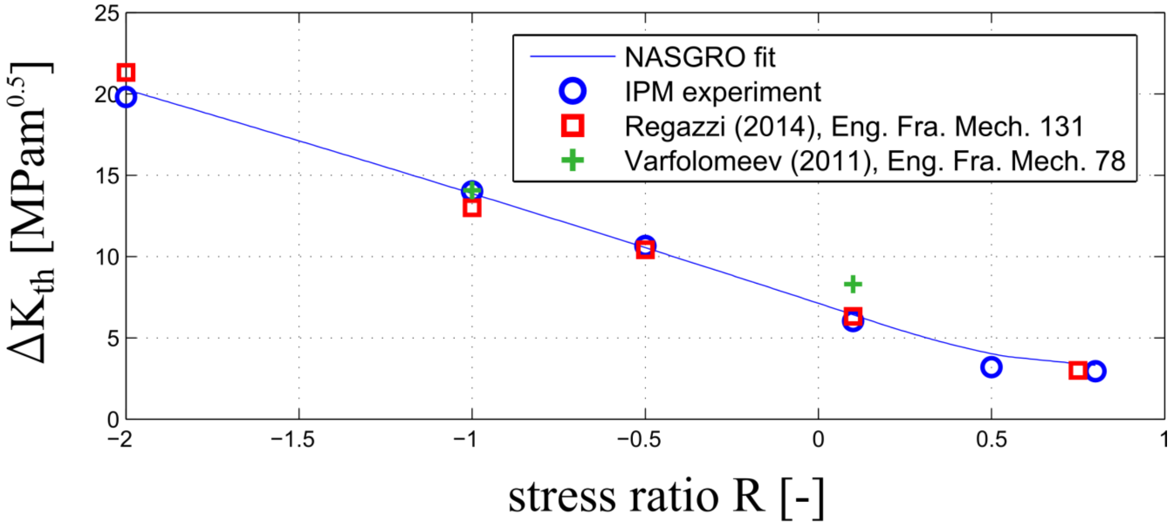
da/dN-ΔK curve - EA4T steel



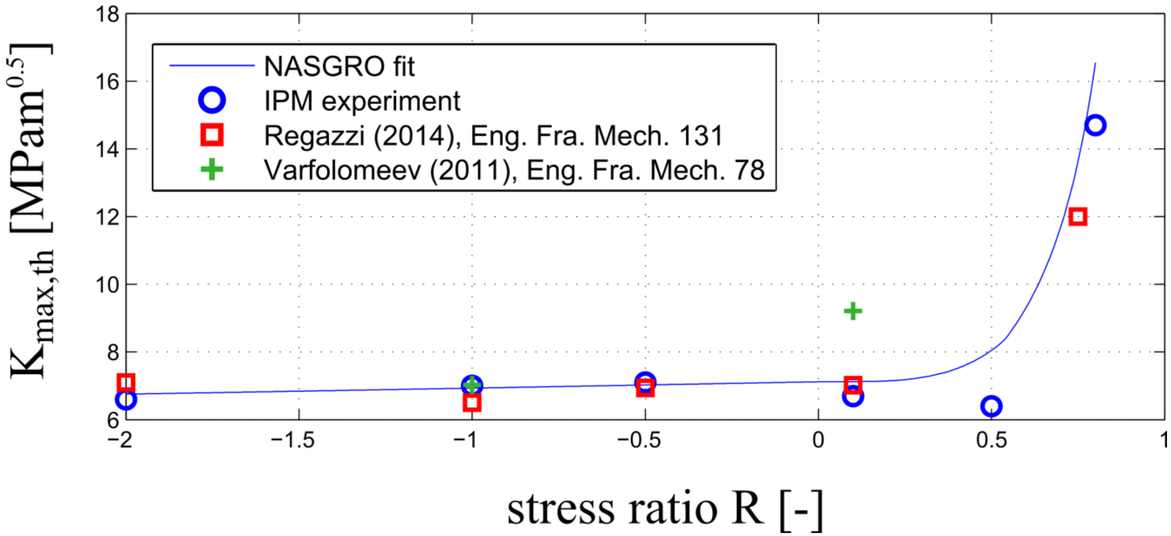


Comparison of thresholds of EA4T steel

ΔK
expression



K_{max}
expression

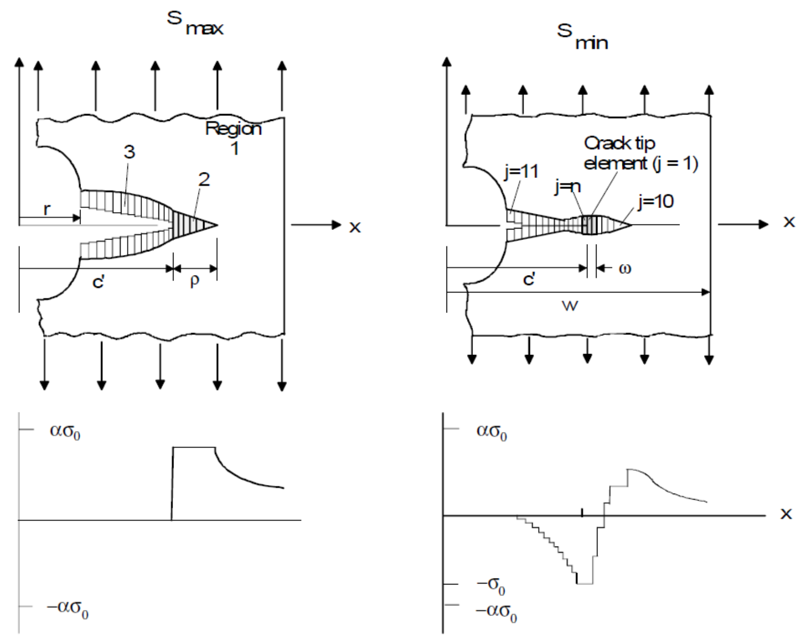


NASGRO

$$\frac{da}{dN} = C\Bigg[\underbrace{\left(\frac{1-f}{1-R}\right)}_{U}\Delta K\Bigg]^n \frac{\left(1-\dfrac{\Delta K_{th}}{\Delta K}\right)^p}{\left(1-\dfrac{K_{max}}{K_c}\right)^q}$$

$$\Delta K_{ef} = U\Delta K$$

$$f = \frac{K_{op}}{K_{max}} = \begin{cases} \max\left(R,\ A_0 + A_1R + A_2R^2 + A_3R^3\right) & R \geq 0 \\ A_0 + A_1R & -2 \leq R < 0 \end{cases}$$



(a) Maximum stress (b) Minimum stress

icients are given by:

f

$$A_0 = \left(0.825 - 0.34\alpha + 0.05\alpha^2\right)\left[\cos\left(\tfrac{\pi}{2} S_{max} / \sigma_0\right)\right]^{1/\alpha}$$

$$A_1 = (0.415 - 0.071\alpha) S_{max} / \sigma_0$$

$$A_2 = 1 - A_0 - A_1 - A_3$$

$$A_3 = 2A_0 + A_1 - 1.$$

ΔKth

$$\Delta K_{th} = \Delta K_1^* \left[\frac{1-R}{1-f[R]}\right]^{(1+RC_{th}^p)} / (1-A_0)^{(1-R)C_{th}^p}\ ,\ R \geq 0$$

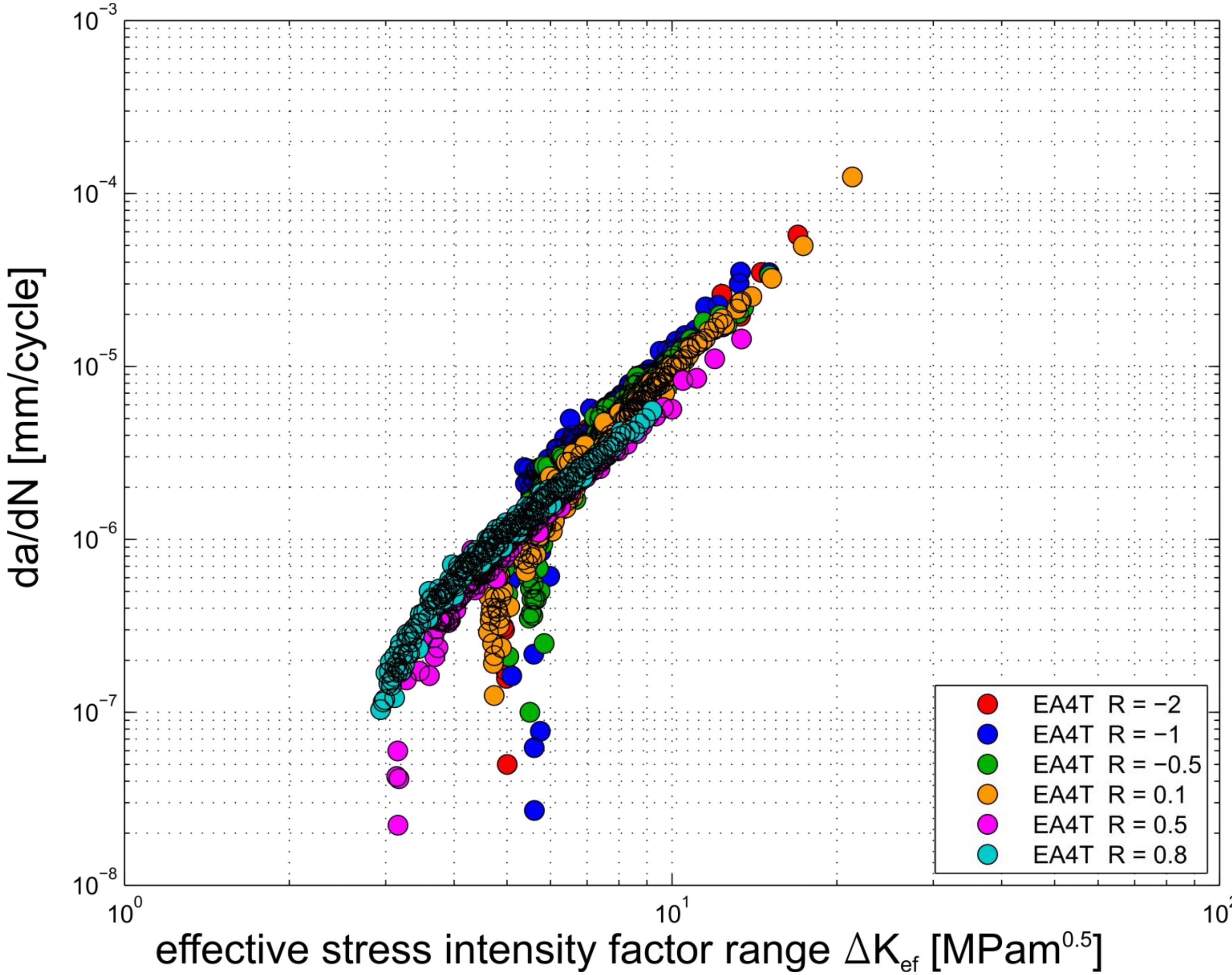
$$\Delta K_{th} = \Delta K_1^* \left[\frac{1-R}{1-f[R]}\right]^{(1+RC_{th}^m)} / (1-A_0)^{(C_{th}^p - RC_{th}^m)}\ ,\ R < 0$$

in which

$$\Delta K_1^* = \Delta K_1 \left[\frac{a}{a+a_0}\right]^{1/2}$$

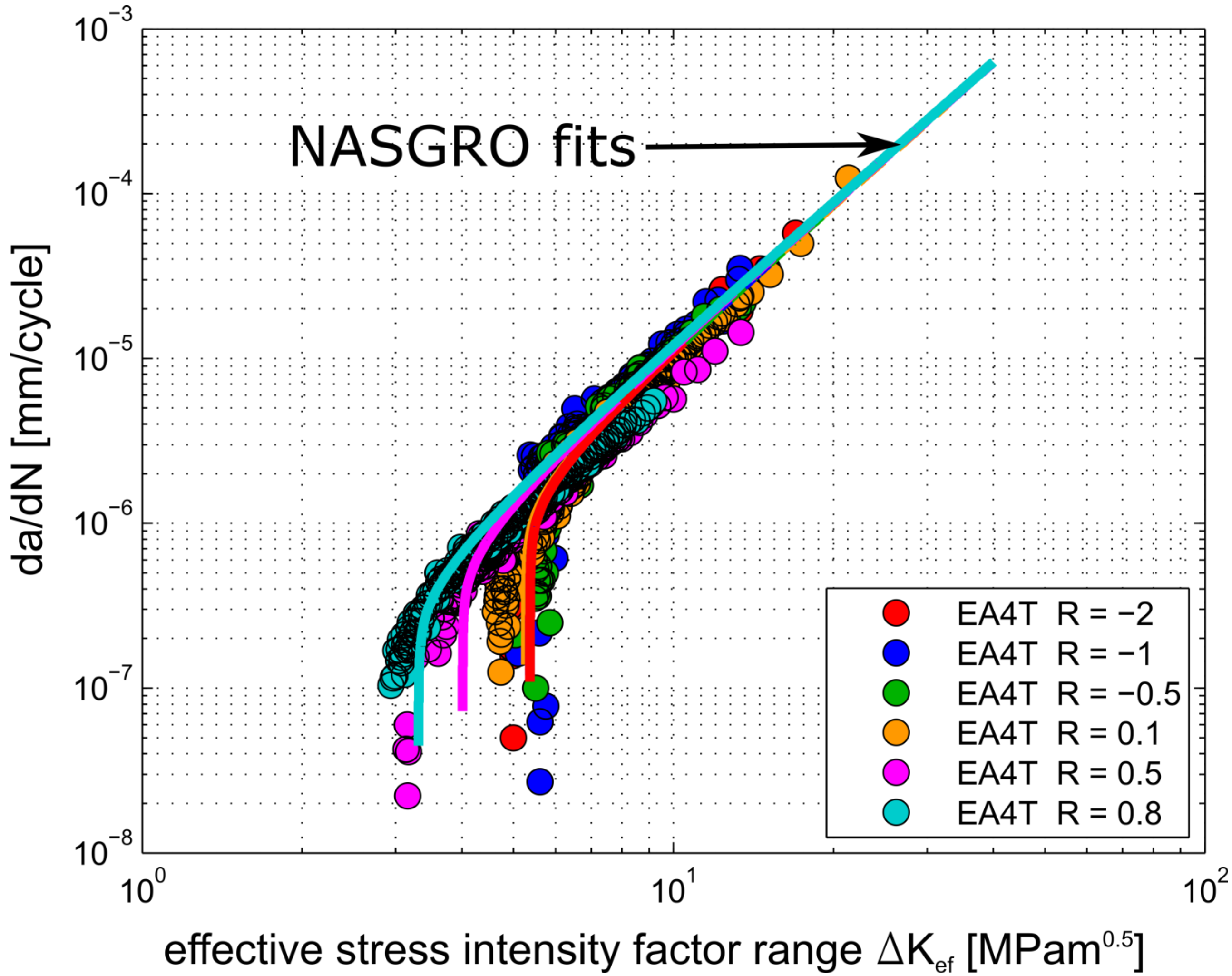
SOURCE: NASGRO, Fracture Mechanics and Fatigue Crack Growth Analysis Software, Reference manual, 2002.

v-ΔKef curve - EA4T steel



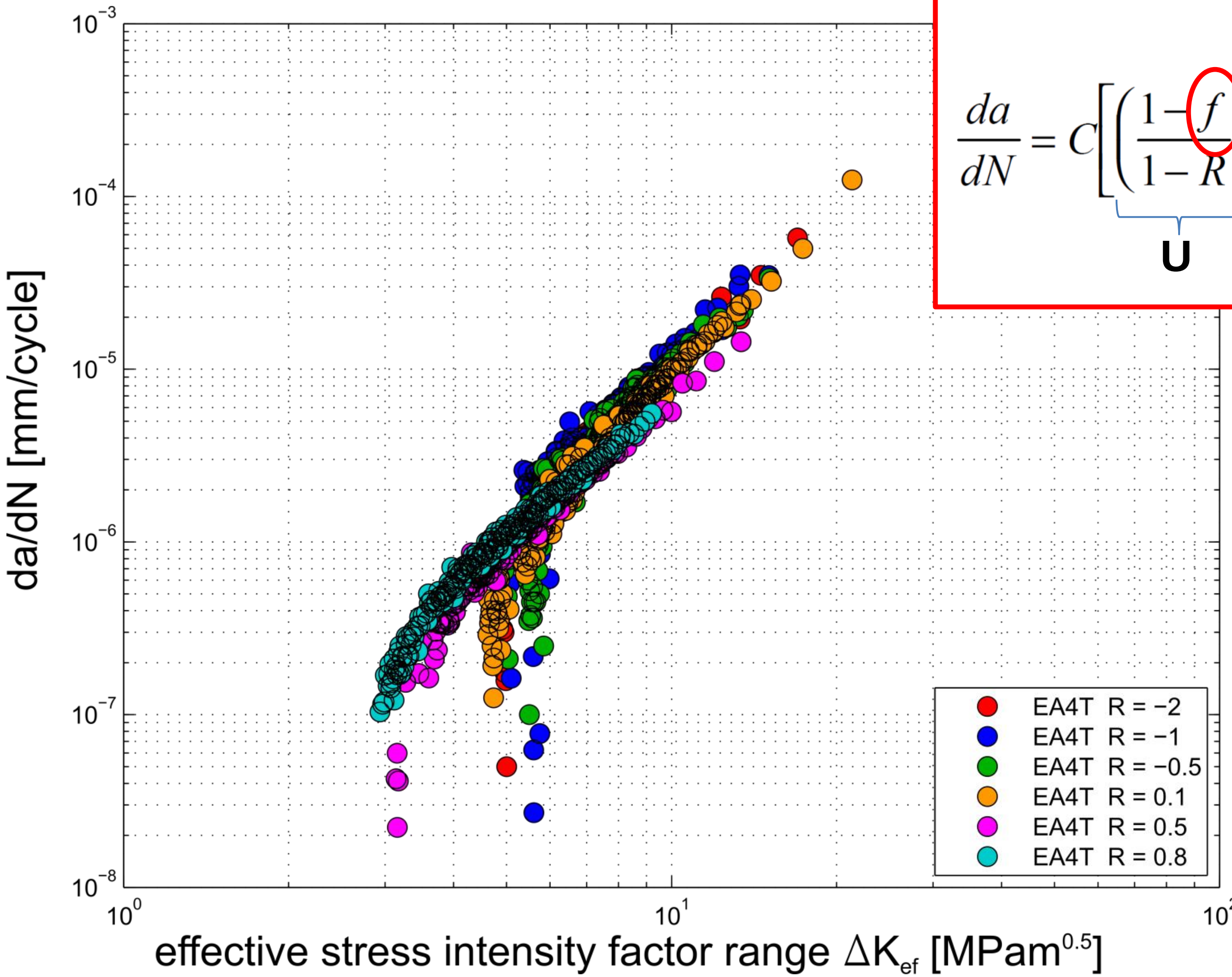
$$\Delta K_{ef} = U\Delta K$$

v-ΔKef curve - EA4T steel



$$\Delta K_{ef} = U \Delta K$$

v-ΔKef curve - EA4T steel



$$\frac{da}{dN} = C\left[\underbrace{\left(\frac{1-f}{1-R}\right)}_{U}\Delta K\right]^n \frac{\left(1-\frac{\Delta K_{th}}{\Delta K}\right)^p}{\left(1-\frac{K_{\max}}{K_c}\right)^q}$$

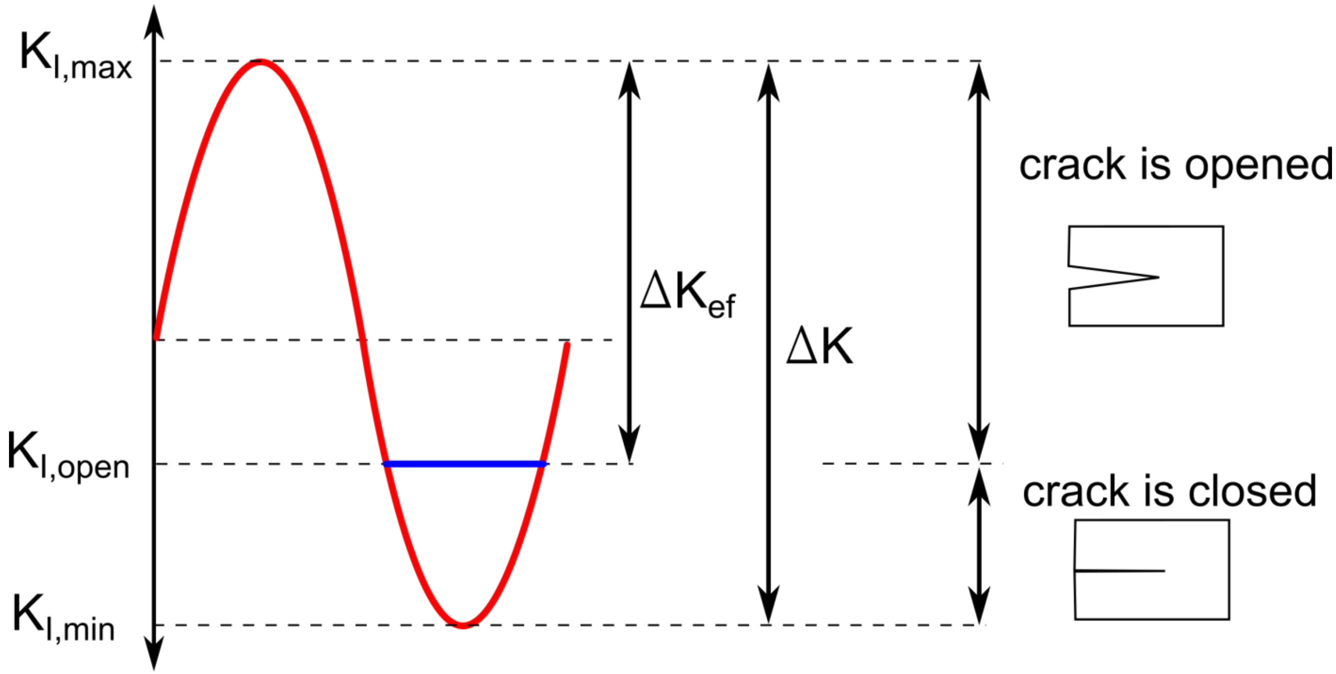
$$\Delta K_{ef} = U\Delta K$$

Bifurcation of

$$da/dN - \Delta K_{ef}$$

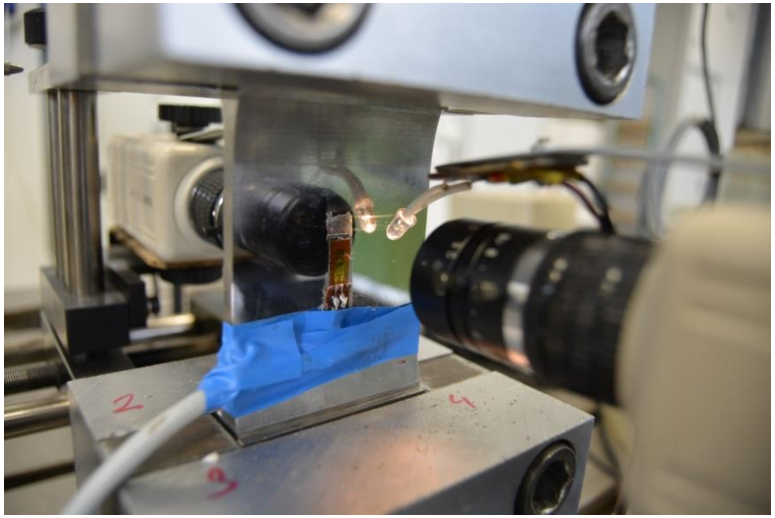
curves in threshold area?

Experimental determination of closure function U

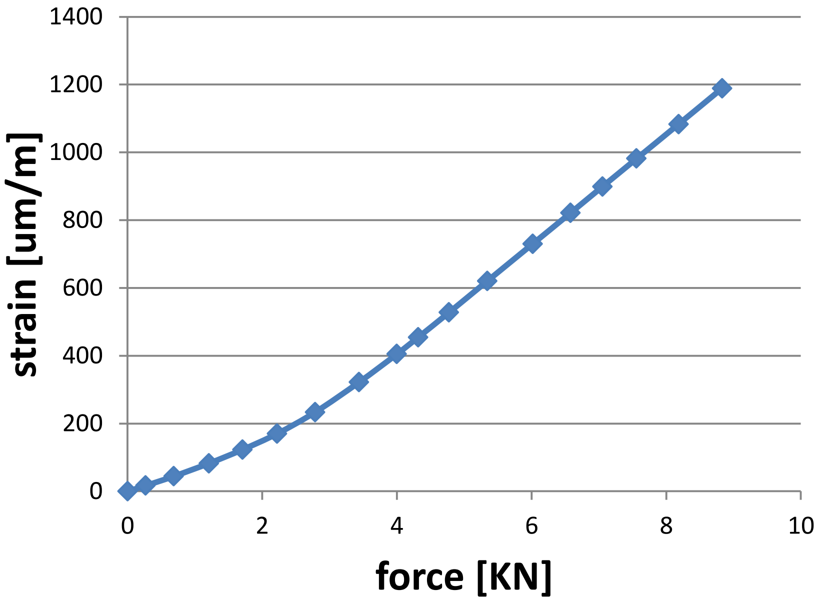


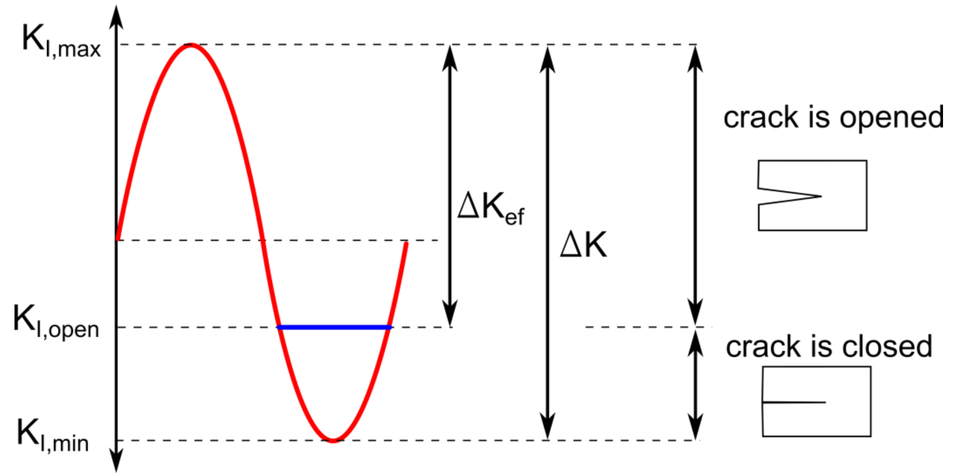
$$U = \frac{K_{max} - K_{open}}{K_{max} - K_{min}}$$

$$\Delta K_{ef} = U \Delta K$$



Experimental determination of closure function U

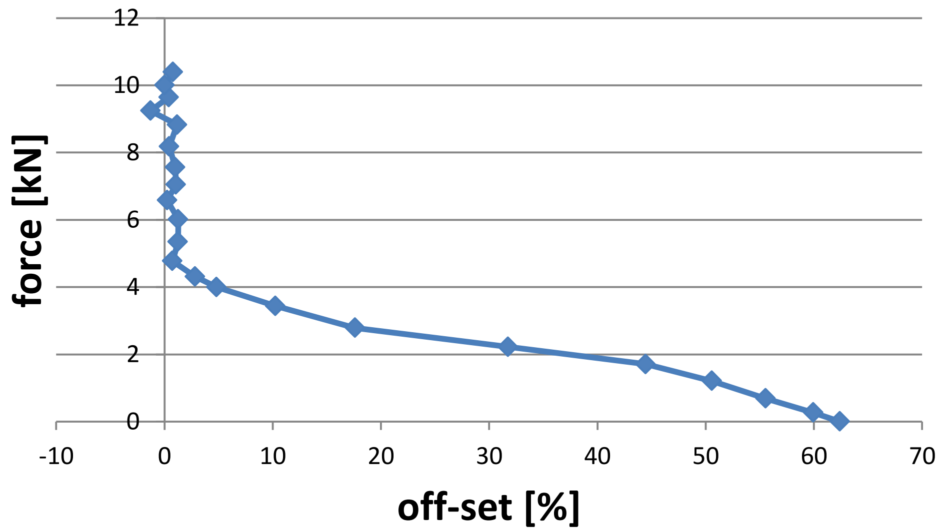




Determination of *U* according to ASTM E647 standard (4% off-set)

$$U = \frac{K_{\max} - K_{open}}{K_{\max} - K_{\min}}$$

$$\Delta K_{ef} = U \Delta K$$



Experimental determination of closure function U

function *U* determined by:

a) NASGRO

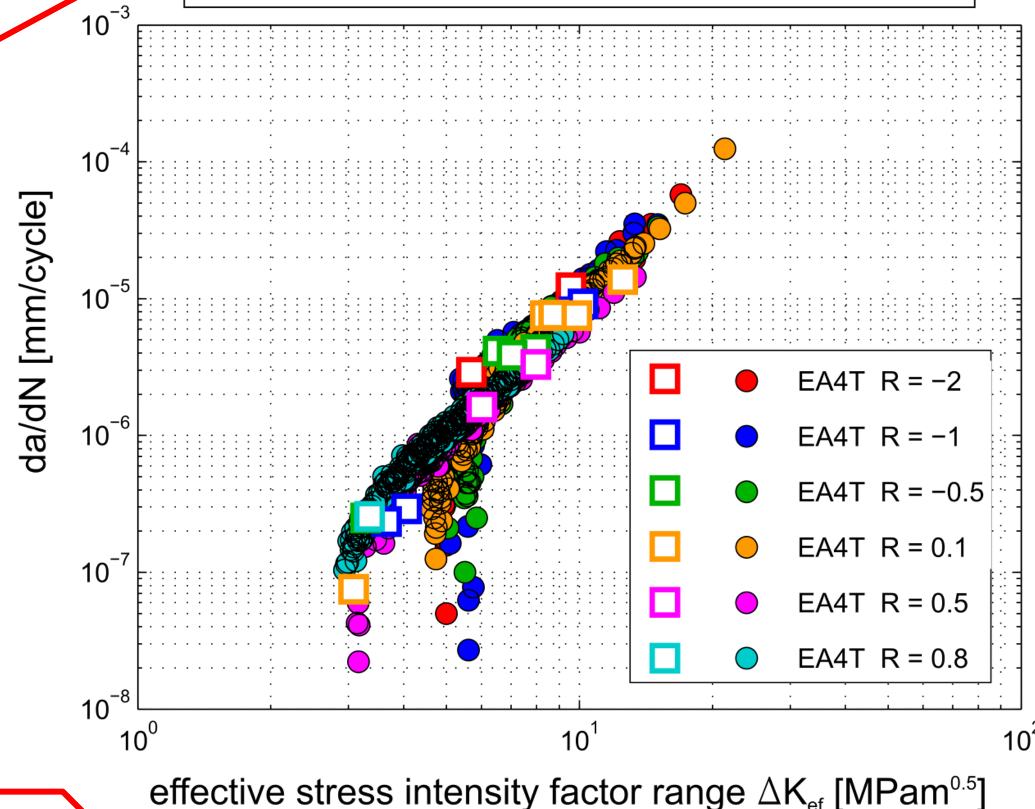
$$\Delta K_{ef} = U_{NASGRO} \Delta K$$

b) experimental measurement

$$\Delta K_{ef} = U_{measurement} \Delta K$$

points determined by NASGRO model
(based on Newman strip yield model)
just - plasticity induced crack closure

points determined by experimental measurement
all regimes of induced crack closure



$$U_{NASGRO} = \frac{1-f}{1-R}$$

function *f* does not represent crack closure in threshold area of EA4T!

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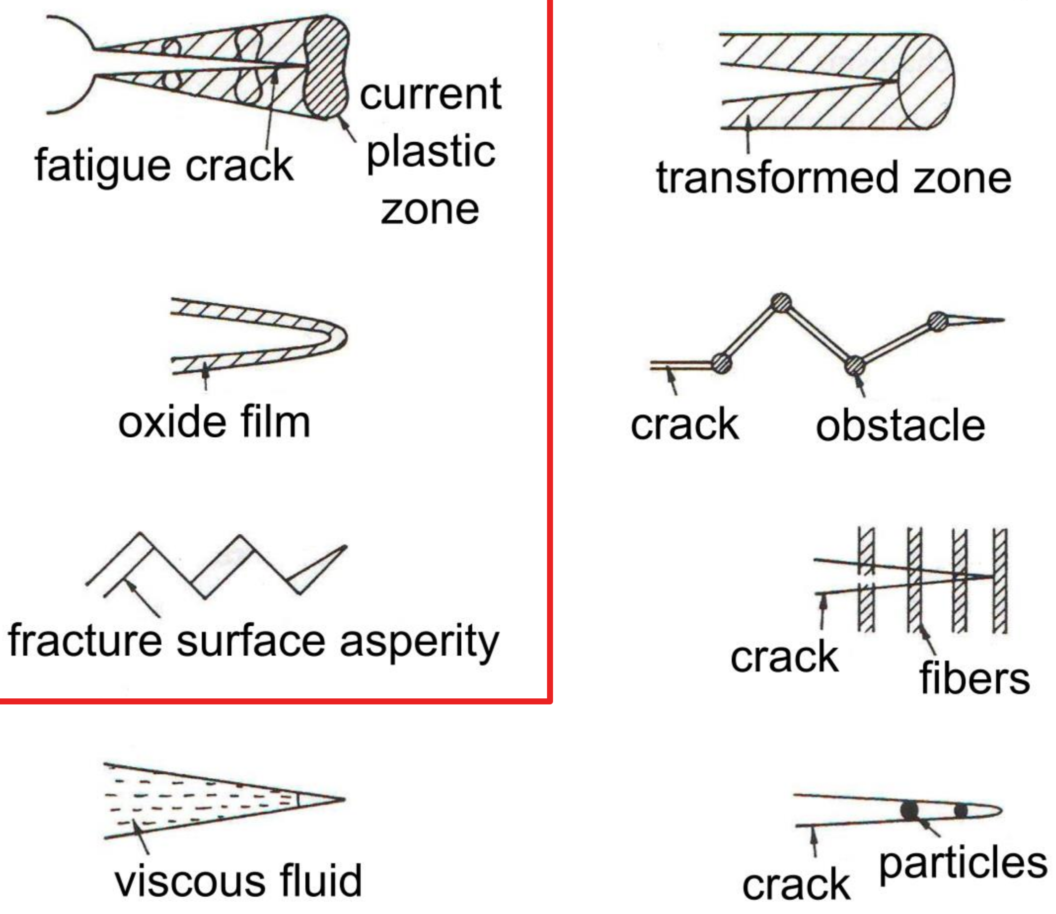
Mechanisms of crack closure



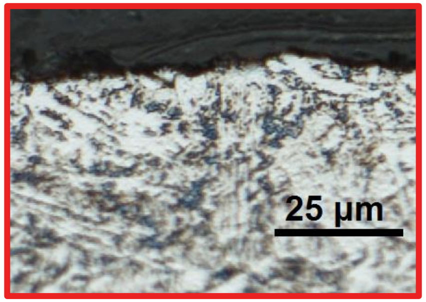
Source: Suresh, Fatigue of Materials

Roughness induced crack closure

Theoretical size of the plastic zone for threshold loading:

$$r_{PZ} = \frac{1}{3\pi}\left(\frac{K_{max,th}}{\sigma_y}\right)^2 = \frac{1}{3\pi}\left(\frac{7\ MPam^{0.5}}{400\ MPa}\right)^2 = 32\ \mu m$$

Microstructural parameter (distance between microstructural barriers):



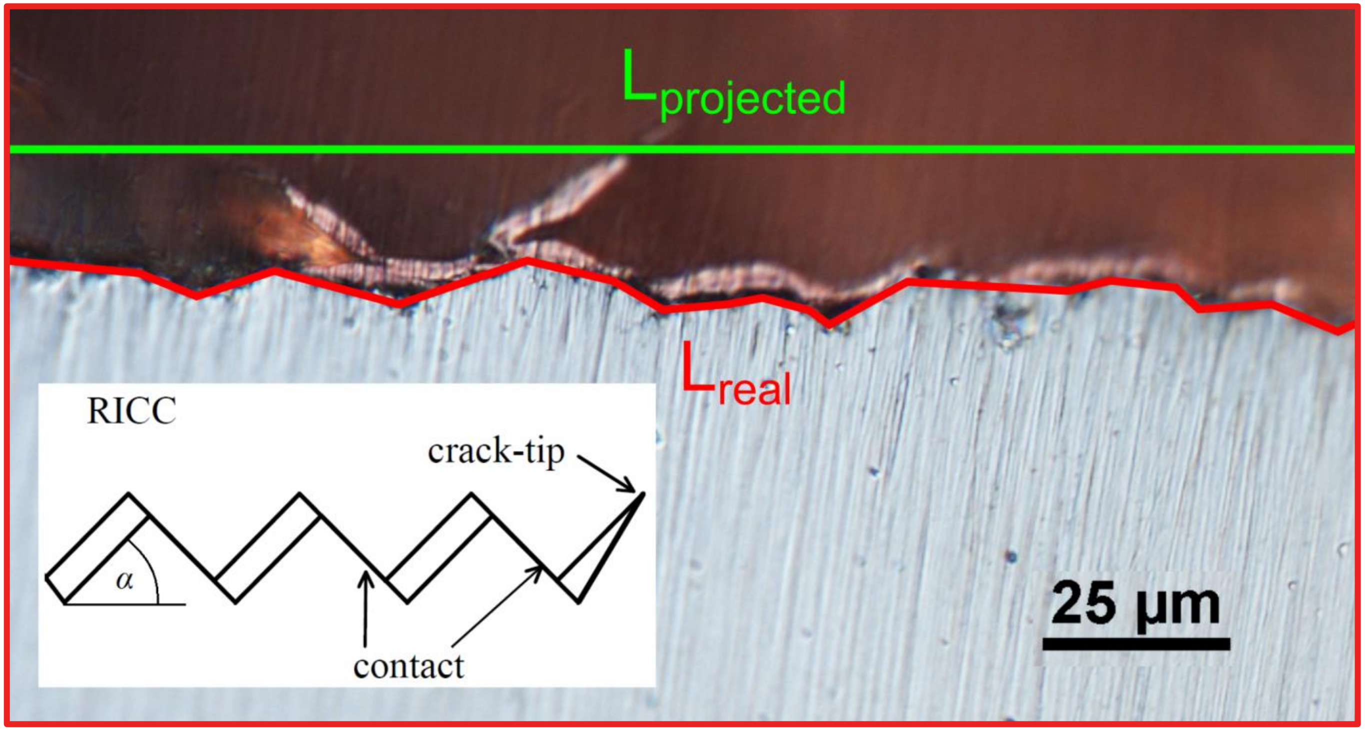
$$d_m \approx 4\ \mu m$$

Size ratio:

$$S_R = \frac{d_m}{r_{PZ}} = \frac{4}{32} = 0.125 < 1$$

The plastic zone is several times larger than the microstructural parameter
-> **low fracture surface roughness**

Roughness induced crack closure (RICC)

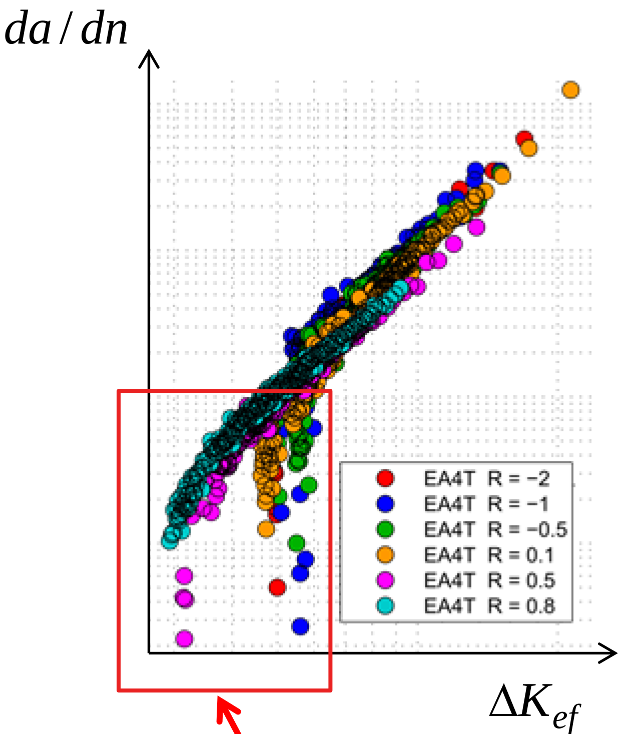


$$R_L = \frac{L_{real}}{L_{projected}} = 1.079$$

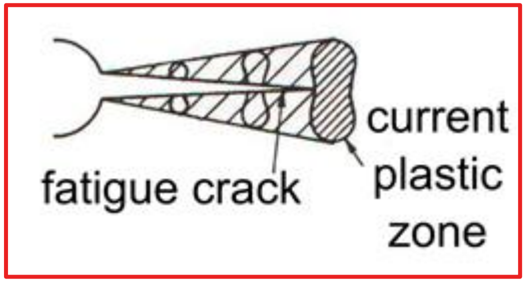
$$R_L = \frac{1}{\cos\alpha} \Rightarrow \boxed{\alpha = 22^\circ}$$

→ **low effect of RICC**

Induced crack closure (ICC)

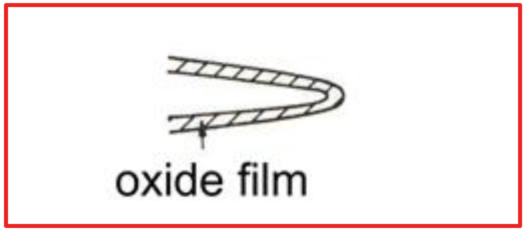


Bifurcation of curves in threshold area?



Plasticity ICC
considered by NASGRO

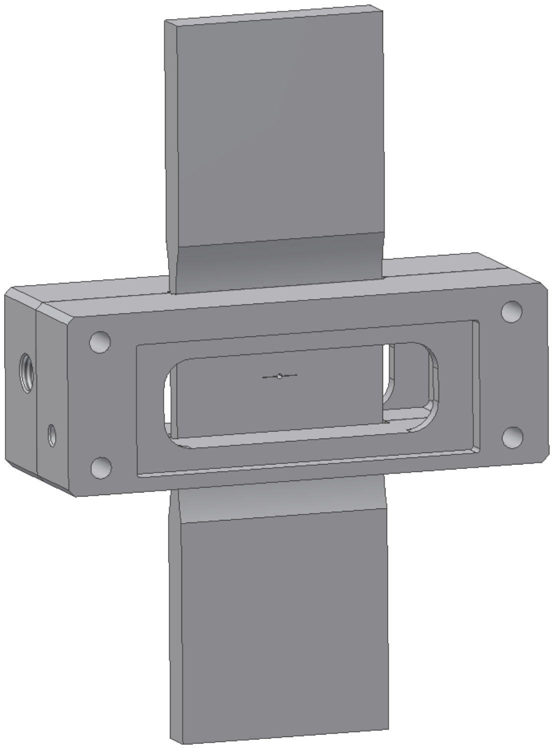
Roughness ICC
low effect



Oxide ICC
significant effect ???

Oxide induced crack closure (OICC)

chamber used for
reduction of humidity



1) standard laboratory conditions:

- room temperature (circa 25°C)
- relative humidity: 30-40%

2) conditions with chamber:

- room temperature (circa 25°C)
- relative humidity: **11%** (specimen 1)
- relative humidity: **18%** (specimen 2)

Effect of reduced humidity (stress ratio R = -1)

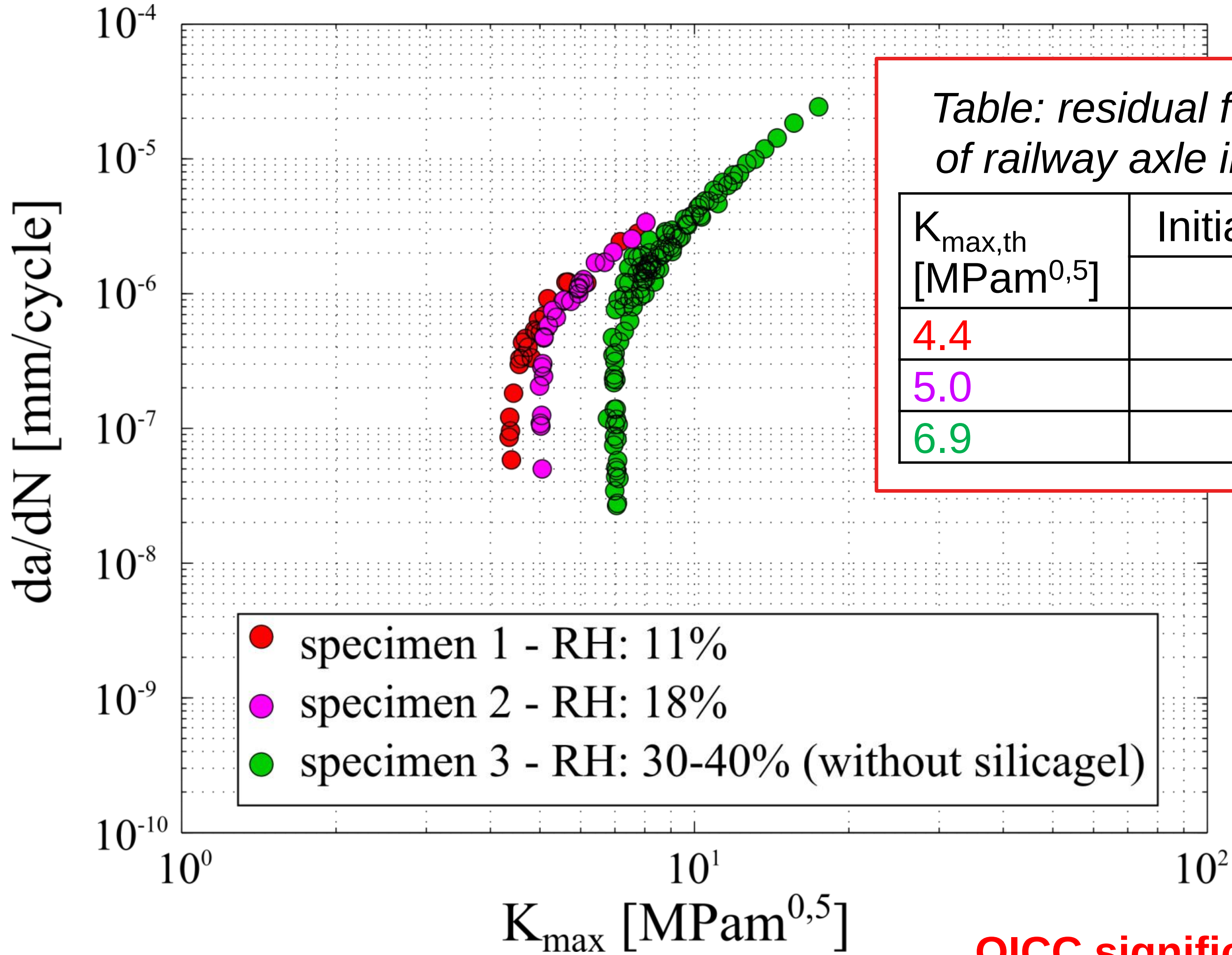
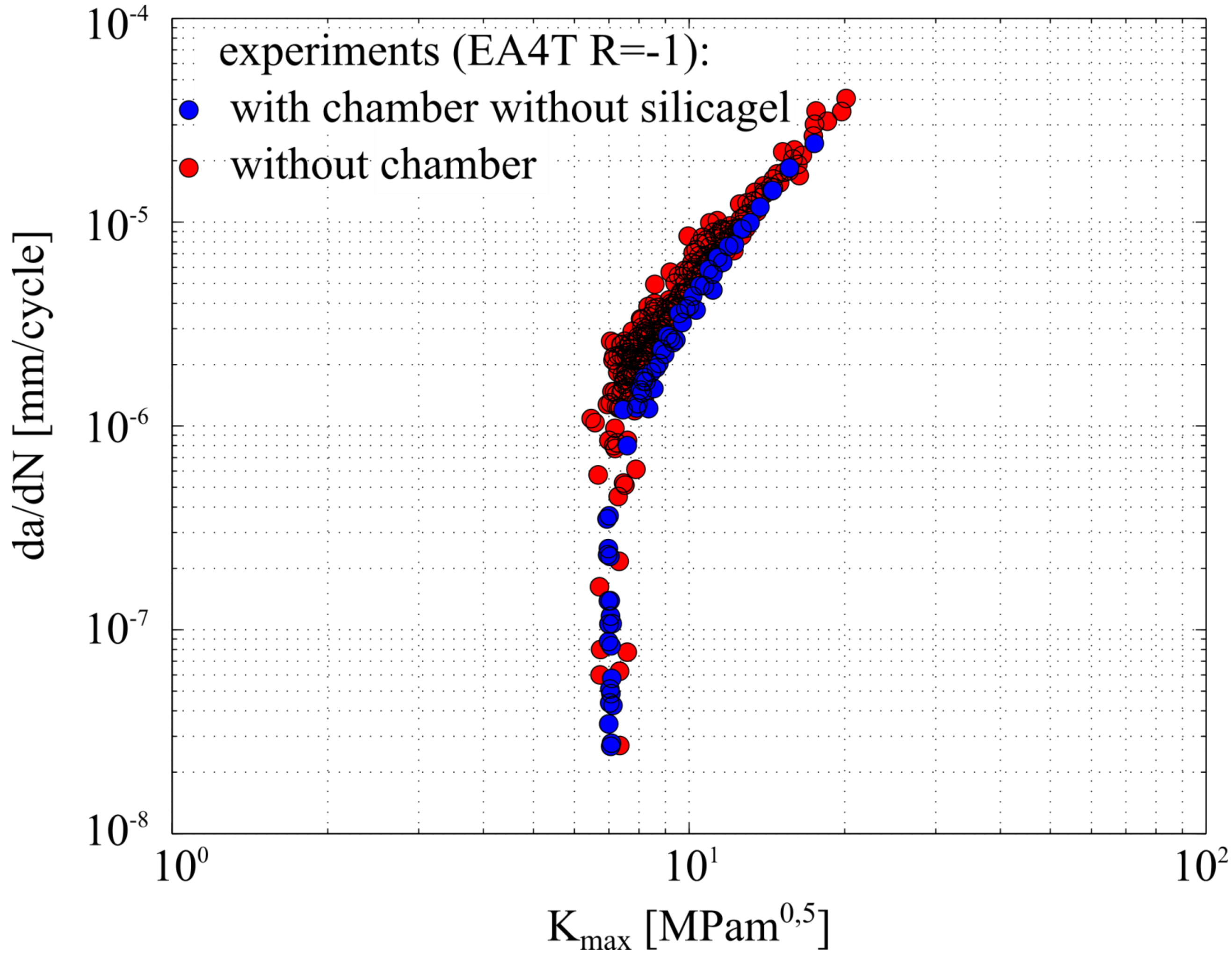


Table: residual fatigue lifetime of railway axle in load blocks:

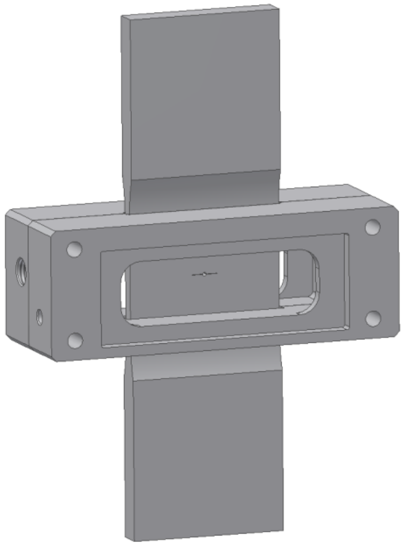
$K_{max,th}$ [$MPam^{0,5}$]	Initial crack length	
	1 mm	2 mm
4.4	51	40
5.0	70	43
6.9	3904	104

OICC significant effect!!!

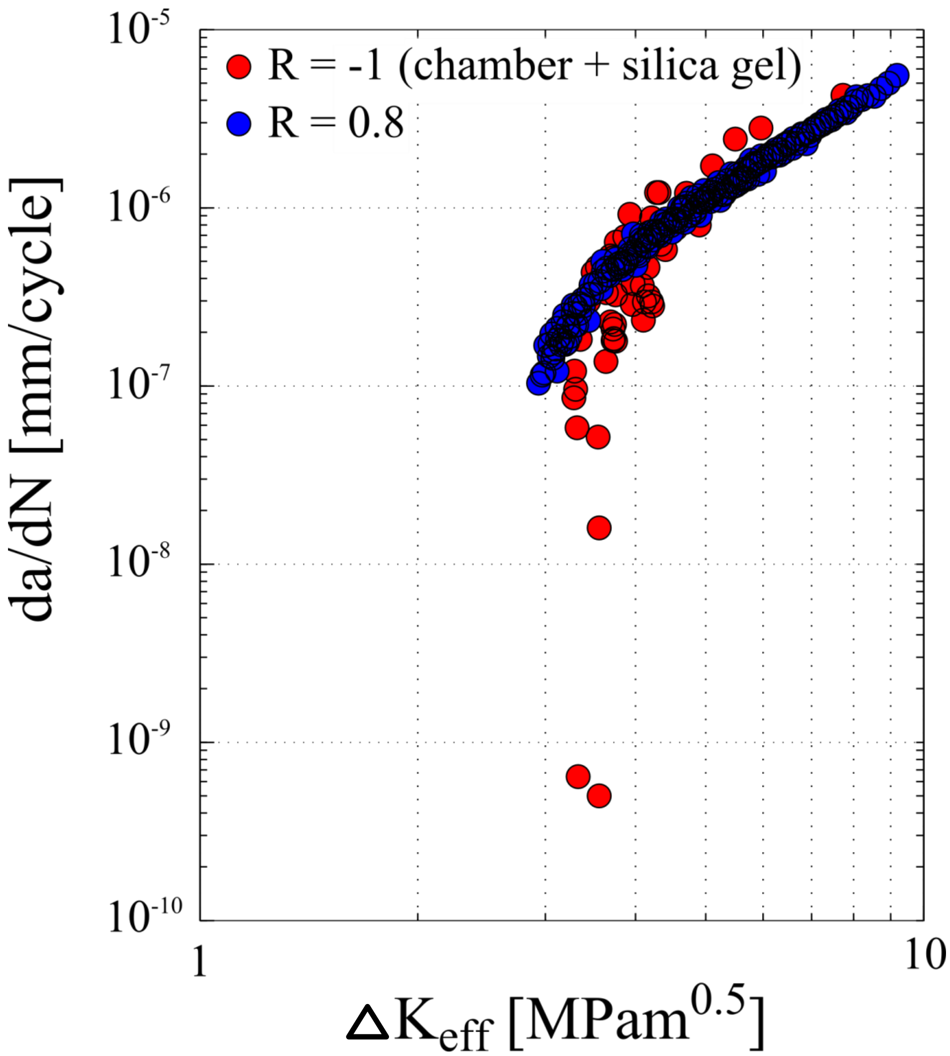
No influence of chamber



chamber used for reduction of humidity



Effective stress intensity factor



R = 0.8 → closure free stress ratio

R = -1
with considering of:
- plasticity induced crack closure (NASGRO)
- reduction of oxide induced crack closure by reduction of relative humidity to 11%

slight difference in thresholds could be explained:
- oxide induced crack closure is not fully reduced
- roughness induced crack is small, but still present.

Estimation of distribution of ICC in dry air RH 11%

$$\Delta K_{ef} = K_{\max,th} - K_{OP}$$

$$\rightarrow K_{OP} = K_{\max,th} - \Delta K_{ef}$$

$$K_{\max,th} = 4.4\ MPam^{0.5}$$

$$\Delta K_{ef,NASGRO} = 3.4 MPam^{0.5}$$

$$\Delta K_{ef} = 2.9 MPam^{0.5}$$

$$K_{OP} = K_{OP,PICC} + K_{OP,RICC} + K_{OP,OICC}$$

$$K_{OP,PICC} = K_{\max,th} - \Delta K_{ef,NASGRO} = 4.4 - 3.4 = 1.0\ MPam^{0.5}$$

$$K_{OP,OICC} = 0\ MPam^{0.5}$$

$$K_{OP,OICC} + K_{OP,RICC} = \Delta K_{ef,NASGRO} - \Delta K_{ef}$$

$$K_{OP,RICC} = \Delta K_{ef,NASGRO} - \Delta K_{ef} - K_{OP,OICC} = 3.4 - 2.9 - 0 = 0.5\ MPam^{0.5}$$

estimated results of induced crack closure

type of induced crack closure		value	amount of closure
Plasticity	$K_{OP,PICC}$	1.0 $MPam^{0.5}$	67%
Roughness	$K_{OP,RICC}$	0.5 $MPam^{0.5}$	33%
Oxide	$K_{OP,OICC}$	0.0 $MPam^{0.5}$	0%

Estimation of distribution of ICC in lab air RH 30-40%

$$\Delta K_{ef} = K_{\max,th} - K_{OP}$$
$$\rightarrow K_{OP} = K_{\max,th} - \Delta K_{ef}$$

$$K_{\max,th} = 6.9\ MPam^{0.5}$$
$$\Delta K_{ef,NASGRO} = 5.3 MPam^{0.5}$$
$$\Delta K_{ef} = 2.9 MPam^{0.5}$$

$$K_{OP} = K_{OP,PICC} + K_{OP,RICC} + K_{OP,OICC}$$

$$K_{OP,PICC} = K_{\max,th} - \Delta K_{ef,NASGRO} = 6.9 - 5.3 = 1.6\ MPam^{0.5}$$

$$K_{OP,RICC} = 0.5\ MPam^{0.5}$$

$$K_{OP,OICC} + K_{OP,RICC} = \Delta K_{ef,NASGRO} - \Delta K_{ef}$$

$$K_{OP,OICC} = \Delta K_{ef,NASGRO} - \Delta K_{ef} - K_{OP,RICC} = 5.3 - 2.9 - 0.5 = 1.9\ MPam^{0.5}$$

estimated results of induced crack closure

type of induced crack closure		value	amount of closure
Plasticity	$K_{OP,PICC}$	1.6 $MPam^{0.5}$	40%
Roughness	$K_{OP,RICC}$	0.5 $MPam^{0.5}$	12%
Oxide	**$K_{OP,OICC}$**	**1.9 $MPam^{0.5}$**	**48%**

Conclusion

- The work was focused on fatigue crack **growth in railway axle steel EA4T**.
- Railway axles are subjected to **variable stress ratio** during operation loading.
- The **threshold value is important parameter** for determination of residual fatigue lifetime of railway axle.
- The **threshold value is significantly influenced by crack closure mechanisms**.
- NASGRO describes only **plasticity induced crack closure**.
- In threshold area of EA4T there are **another sources of crack closure** (**oxide** + roughness). **The oxide induced crack closure is the most dominant crack closure in threshold area (for air with common humidity)!!!**
- **Effect of low humidity (railway axles operate in different conditions) should be considered** in calculations of residual fatigue lifetime of railway axles (trains operate in various conditions).

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More information can be found in our published paper:

P. Pokorný, T. Vojtek, L. Náhlík, P. Hutař

Crack closure in near-threshold fatigue crack propagation in railway axle steel EA4T

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http://www.sciencedirect.com/science/article/pii/S0013794416307196

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