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Analysis of Material Defects in Relation to Different Damage Mechanisms

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stle Nashville
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Agenda

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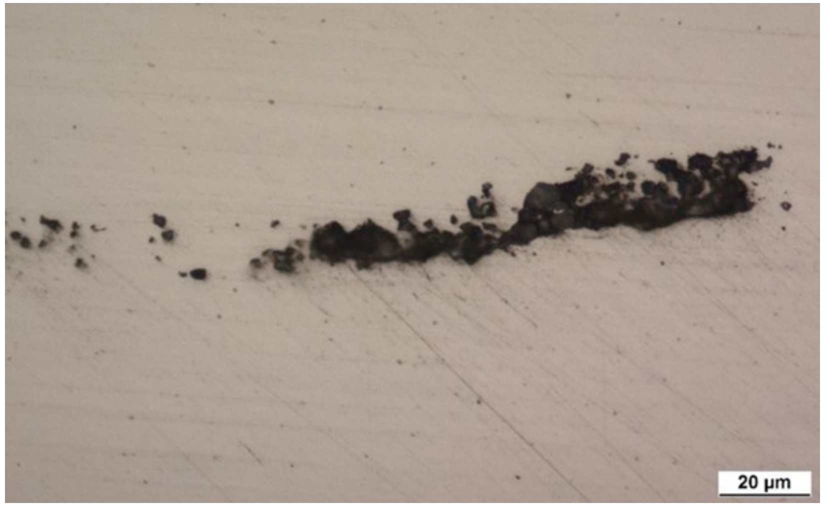
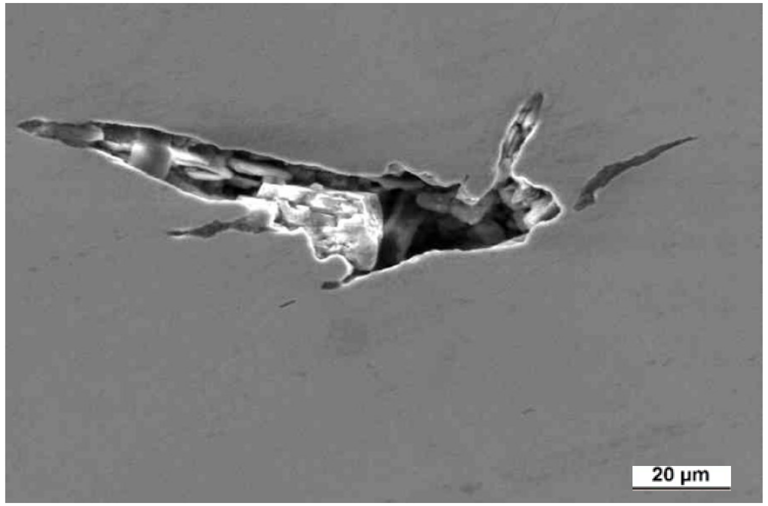
Inclusions in clean steel





Inclusions in technical steels are not avoidable, even in clean steels.

Inclusions in clean steels consist typically of few large particles and lots of small ones.

Inclusions are generally stress raisers in the material with a major impact on fatigue strength.
(Influence of type, size, shape, depth, orientation, bonding, void formation, density, ...)

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Classification of inclusions

Type A – MnS Stringers

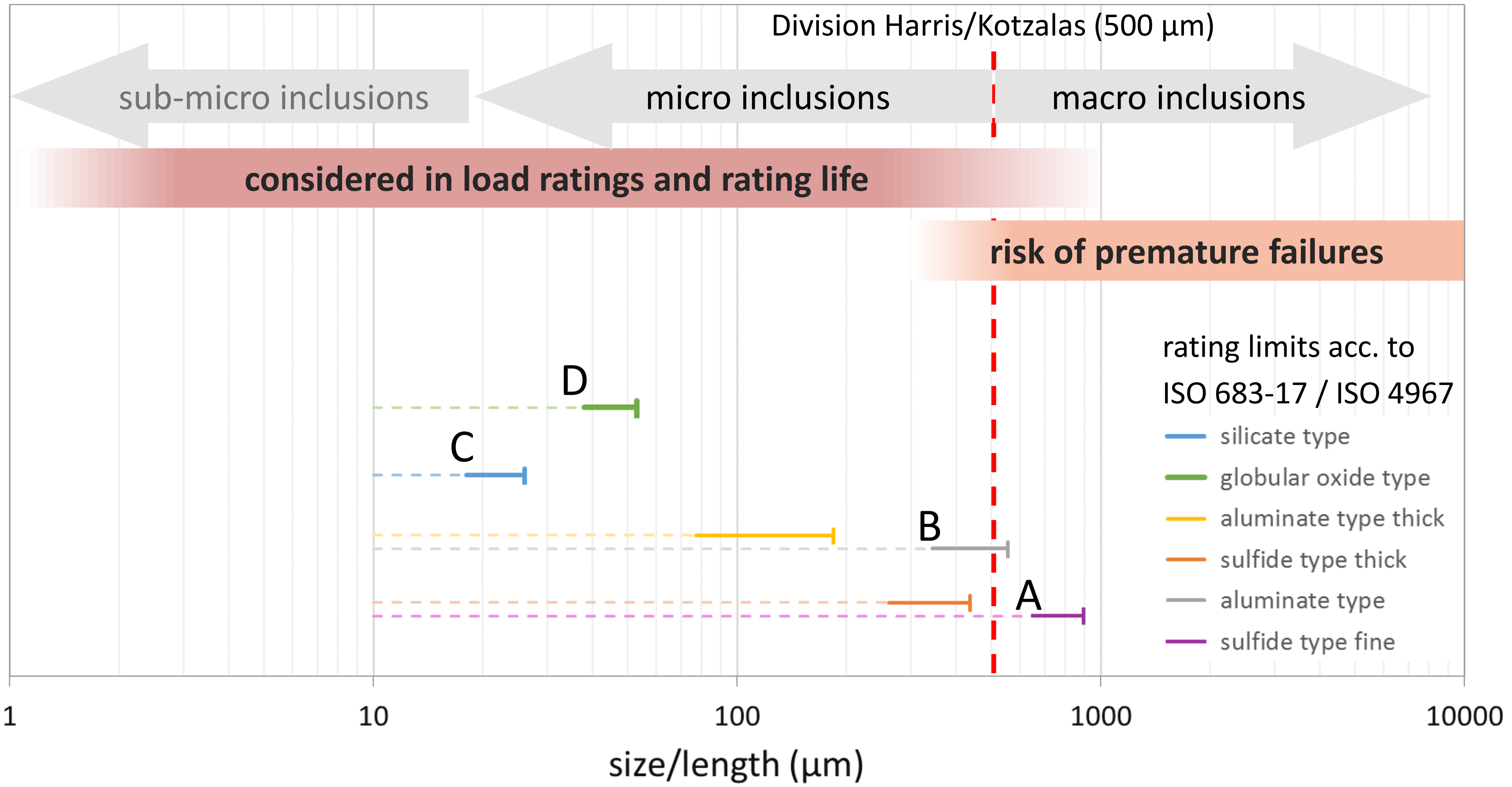
Type B – Aluminia Stringers

Type C – Silicate Stringers

Type D – Globular Oxides

ISO 683-17 determines requirements for the microscopic assessment of content of NMIs in ball and roller bearing steels.

ISO 4967 determines the rating limits for the requirements.



[ASTM E45 / Harris, Kotzalas: Rolling Bearing Analysis, 5th ed.]

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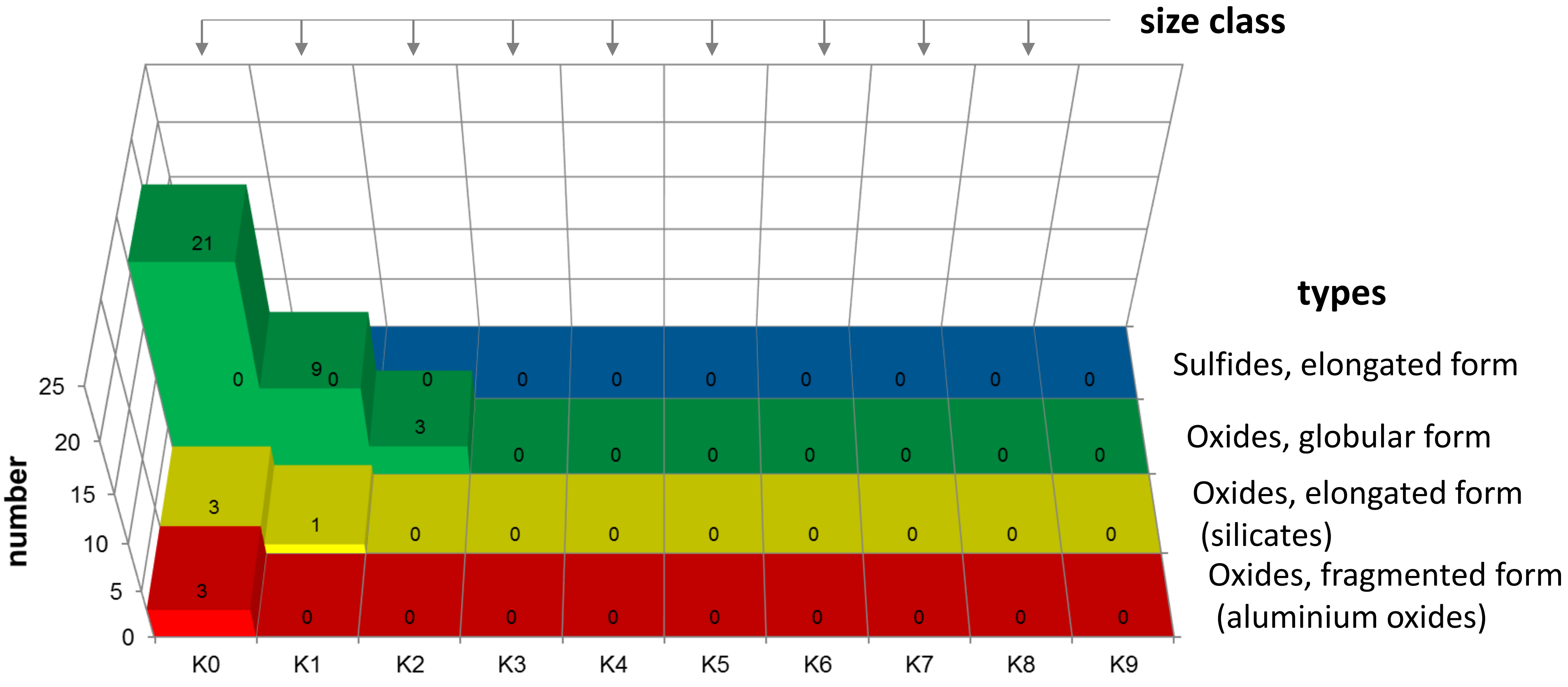
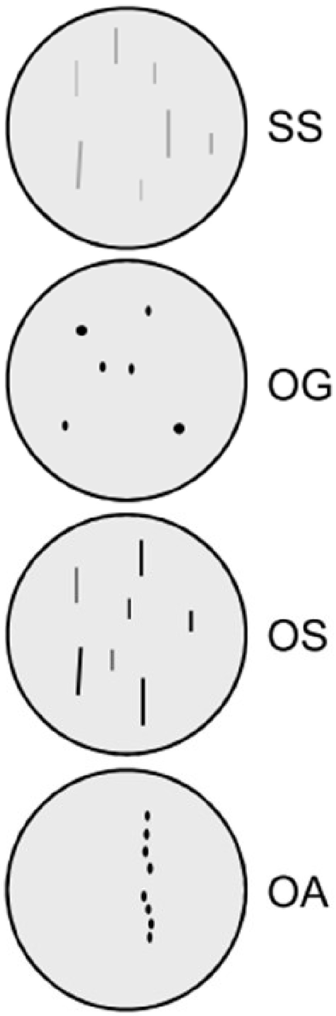
Rating of inclusions according to DIN 50602





	K0	K1	K2	K3	K4	K5	K6	K7	K8	K9
OA	3	0	0	0	0	0	0	0	0	0
OS	3	1	0	0	0	0	0	0	0	0
OG	21	9	3	0	0	0	0	0	0	0
SS	0	0	0	0	0	0	0	0	0	0

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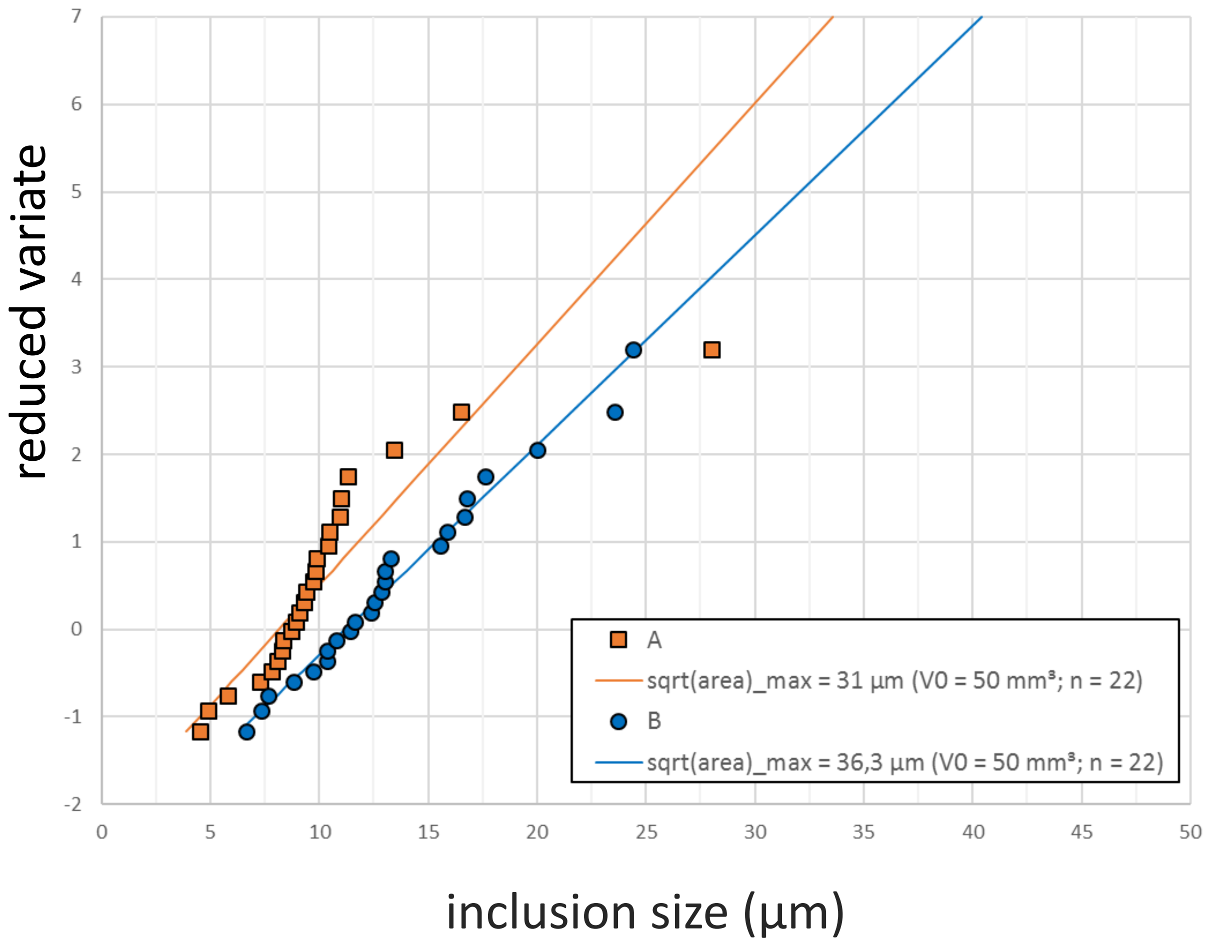
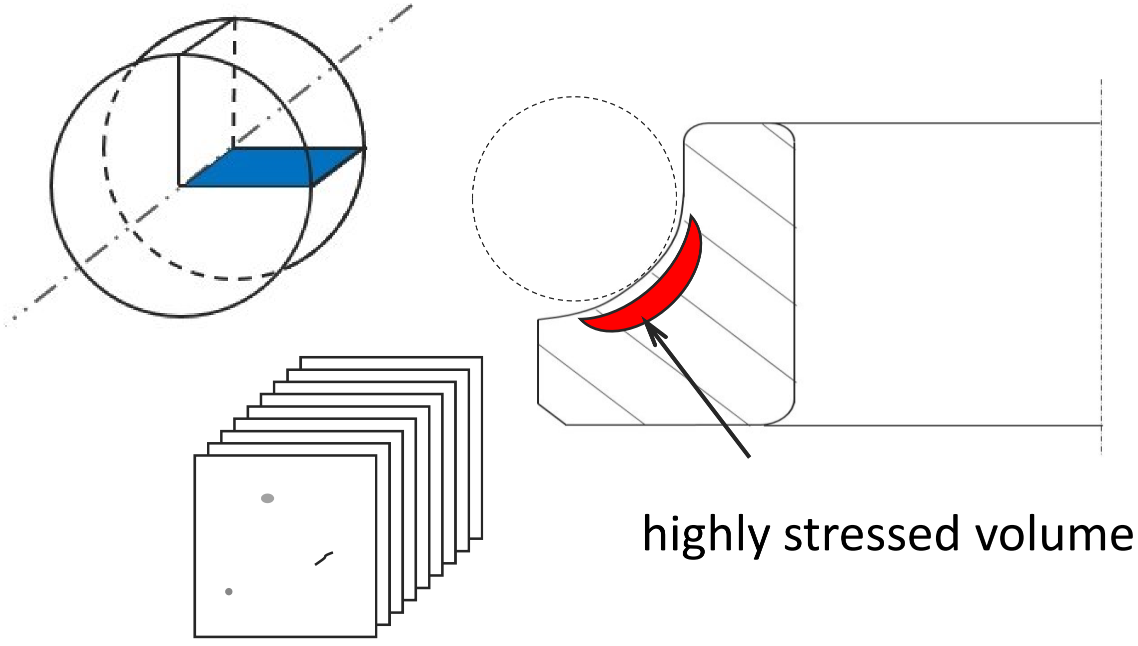
Challenge: prediction of inclusion properties (number, size, orientation, ...) in a component

e.g. statistics of extreme values





Impact of manufacturing methods and processes as well as size and position of stressed volume.

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1 Introduction

2 Rating of inclusions

3 **Subsurface fatigue**

4 White etching cracks (WECs)

5 Summary

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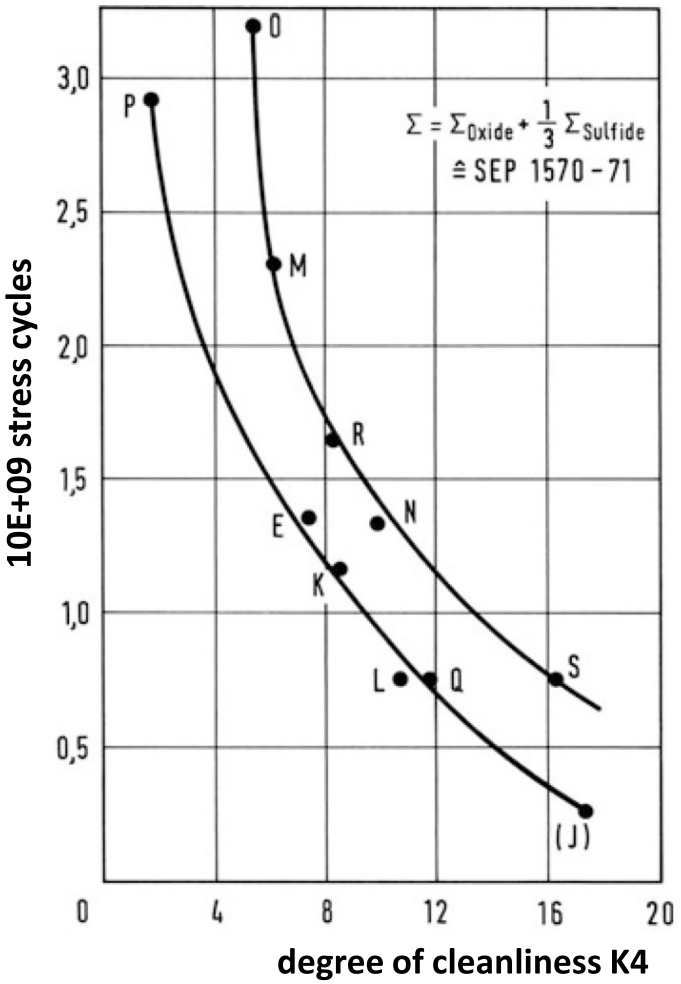
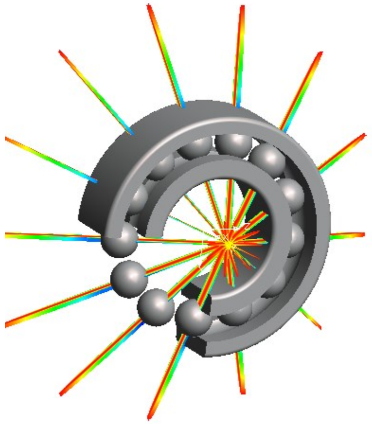
Impact of inclusions on operating life



Bearing: 7205B
Test rig: L17
p_0 = 2600 MPa (IR)



[Source: Schlicht 1978]

Micro inclusions → considered in rating life

Macro inclusions → risk of premature failures

<u>Questions:</u>

Impact on rating life – adequate cleanliness?

Where are macro inclusions of which size acceptable?

→ prediction by analysis?

Analysis options

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ISO 281 (valid for typical rolling bearing material)

STLE life factors (melting practice)

[Zaretsky 1992]

Finite Element Analysis

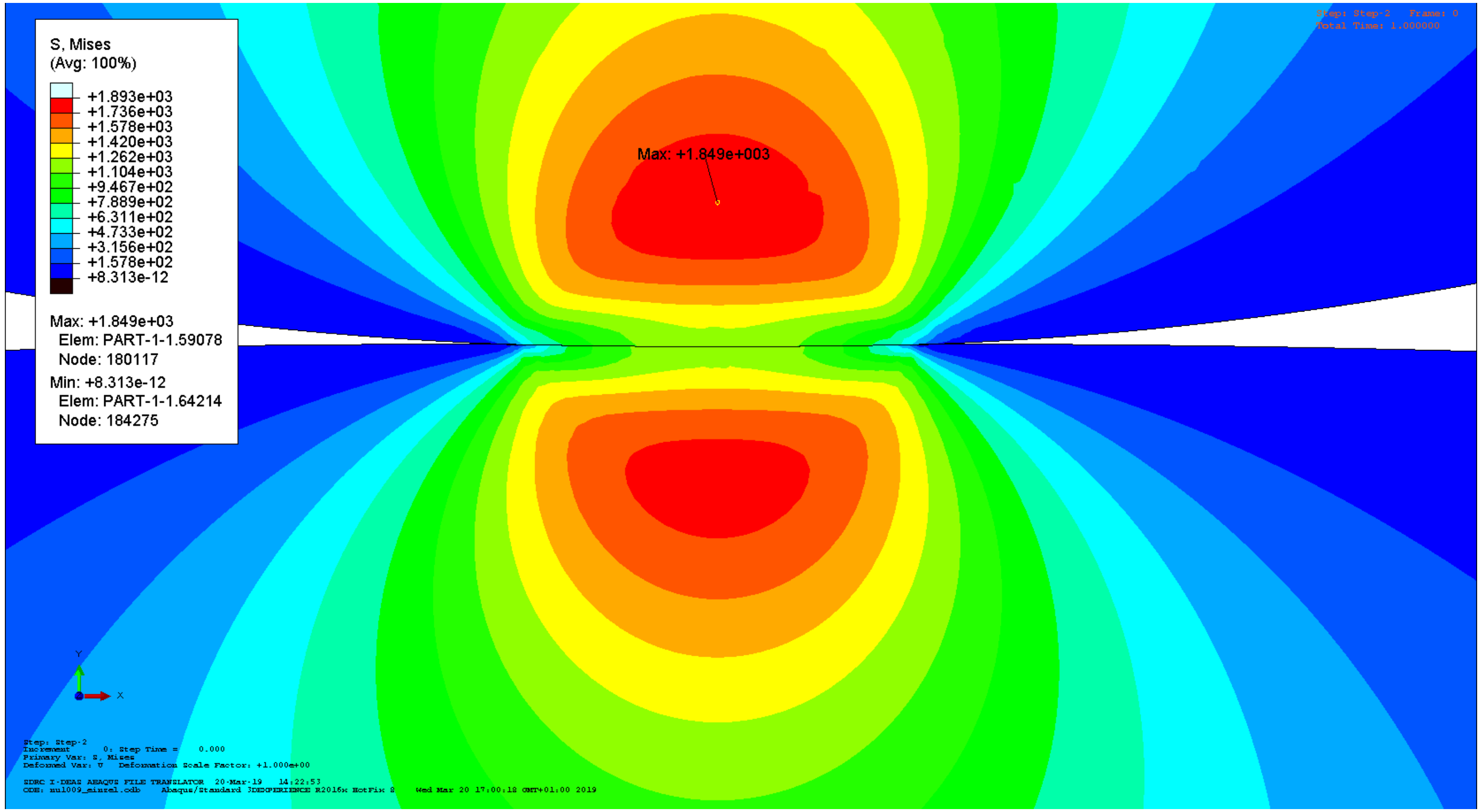
[Böhmer 1993, Melander 1997, Alley 2010, Burkart 2012, Lai 2018, ...**]**

Voronoi FE model

[Jalalahmadi et al. 2011]

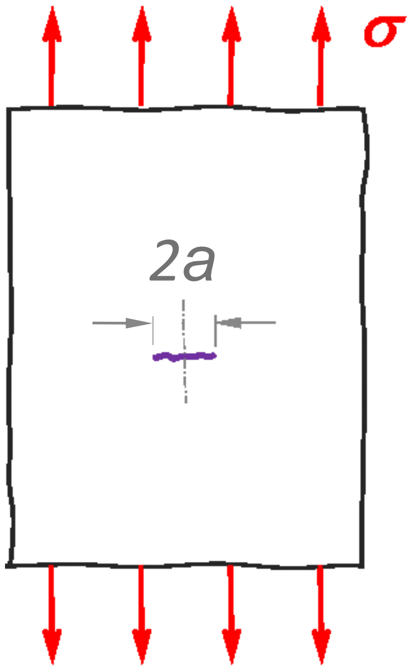
Fracture Mechanics

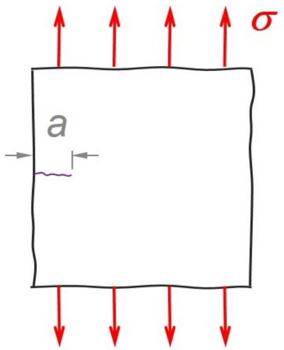
[Kaneta et al. 1986, Murakami et al. 1989, Tarantino et al. 2011, Lewis, Tomkins 2012, Mazzu 2013, Donzella et al. 2015, ...]



Linear Elastic Fracture Mechanics (LEFM) approach

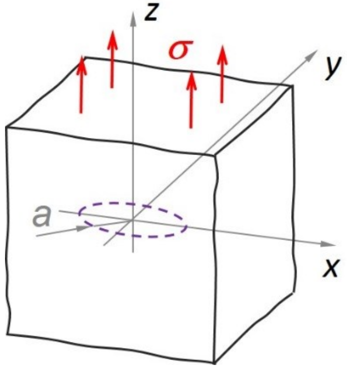
Assumption: inclusions can be analyzed as small cracks.

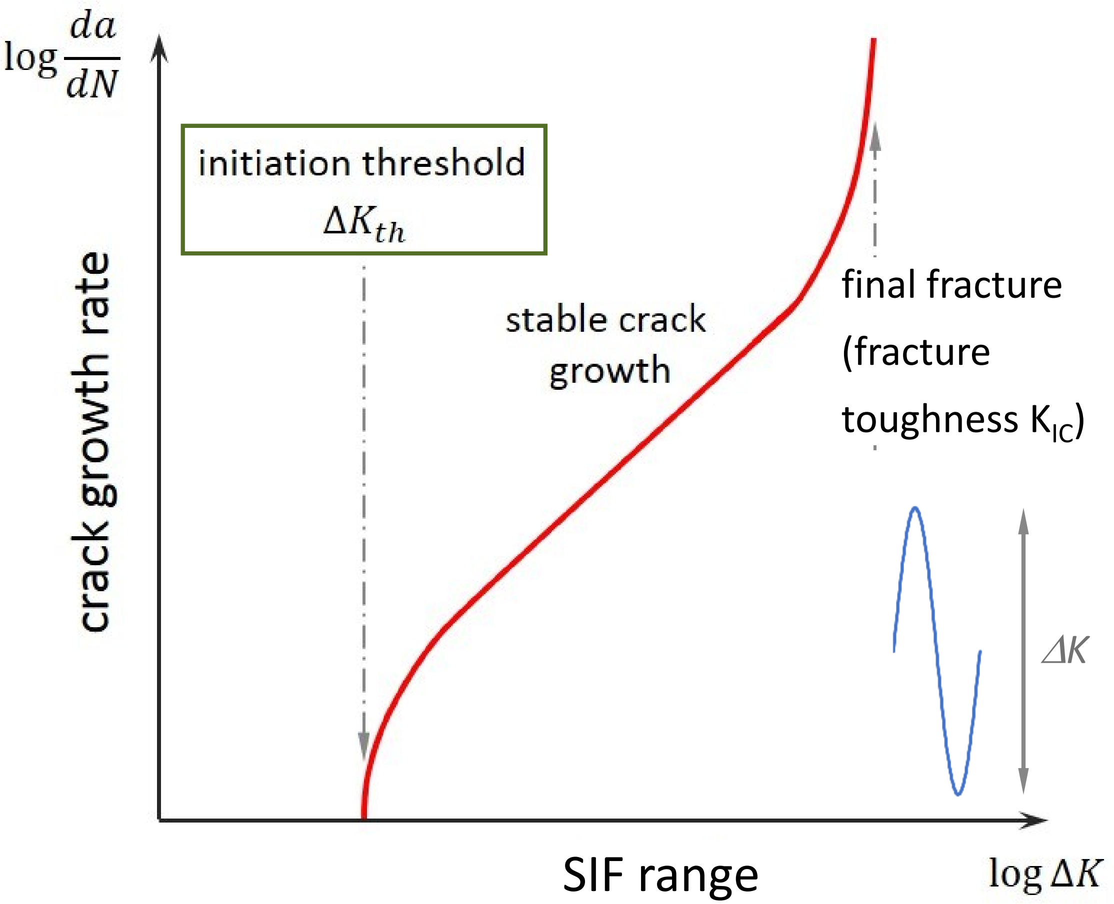




$Y = 1.12$

$Y = \frac{2}{\pi}$





Stress intensity factor (SIF):

$$K = Y \cdot \sigma \cdot \sqrt{\pi \cdot a}$$

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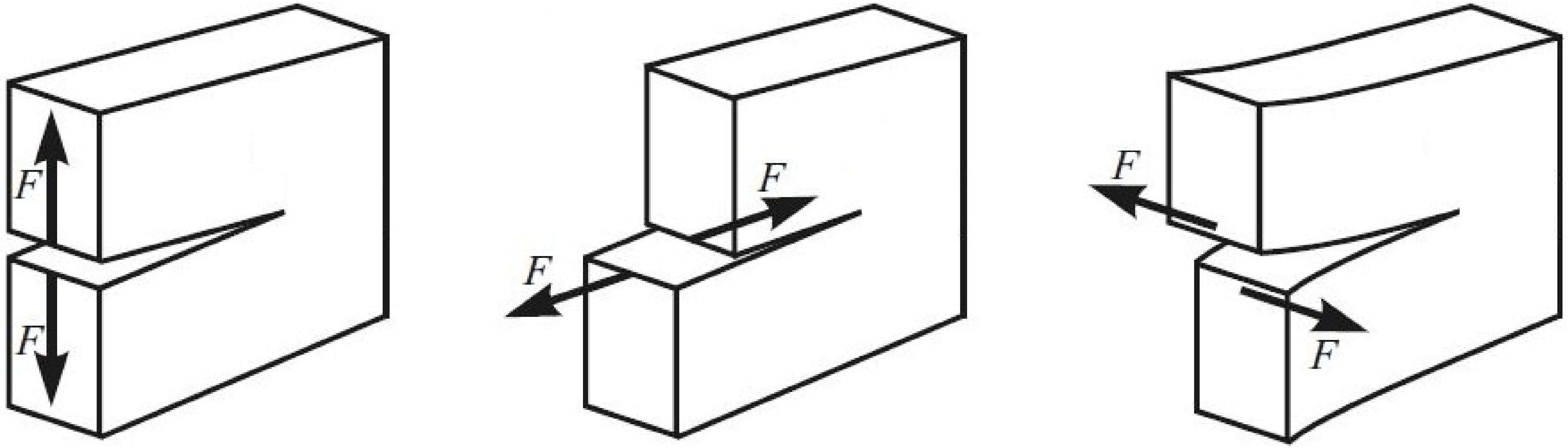
Fracture modes of loading



Mode I
(normal to the crack)

Mode II
(in-plane shear)

Mode III
(out-of-plane shear)

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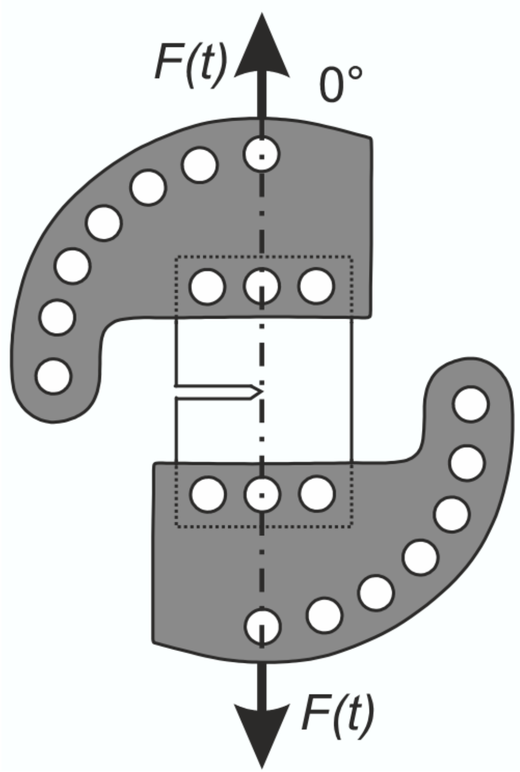
Application of LEFM

Successful application in many technical fields

(aerospace, pressure vessels and piping systems of power plants, turbines, pipelines, railway vehicles, steel structures, welded components, ...)

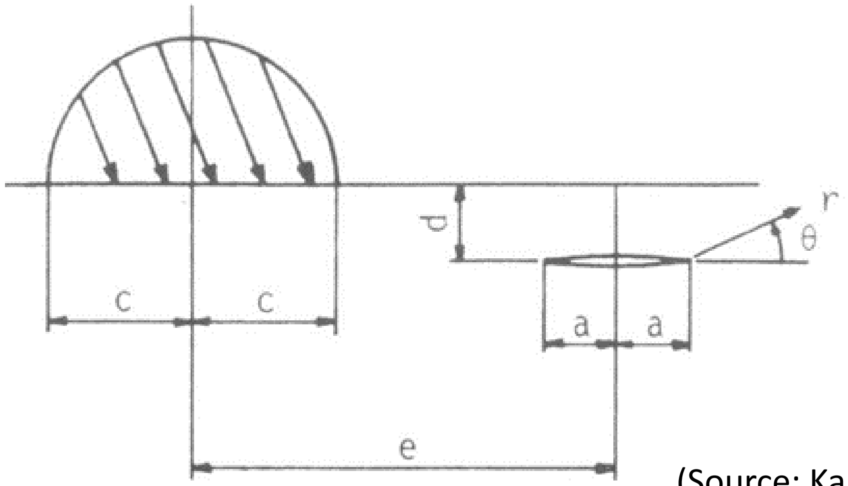
Several papers with application of FM to RCF

[Kaneta et al. 1986, Murakami et al. 1989, Lewis, Tomkins 2012, Tarantino et al. 2011, Mazzu 2013, Donzella et al. 2015, ...]



Two challenges in RCF:

- complex stress state
- short crack behavior



(Source: Kaneta 1986)

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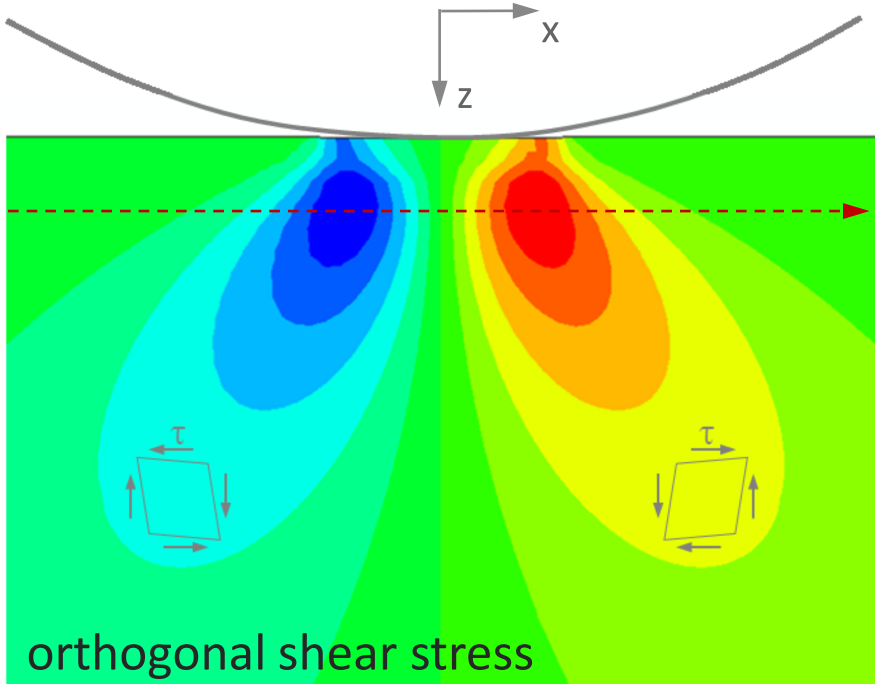
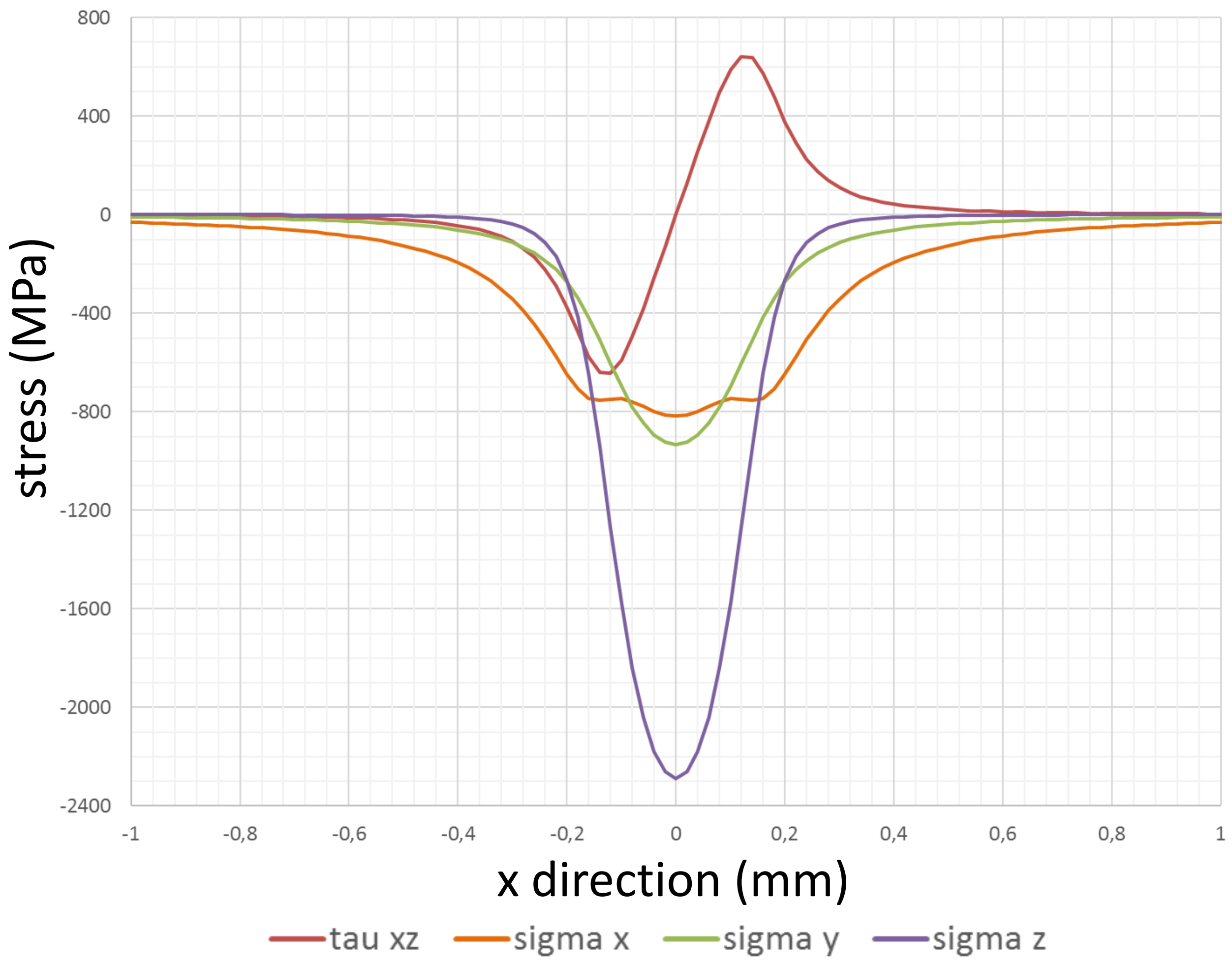
Multiaxial stress state





- multiaxial stress state
- **shear stress** assumed to be critical

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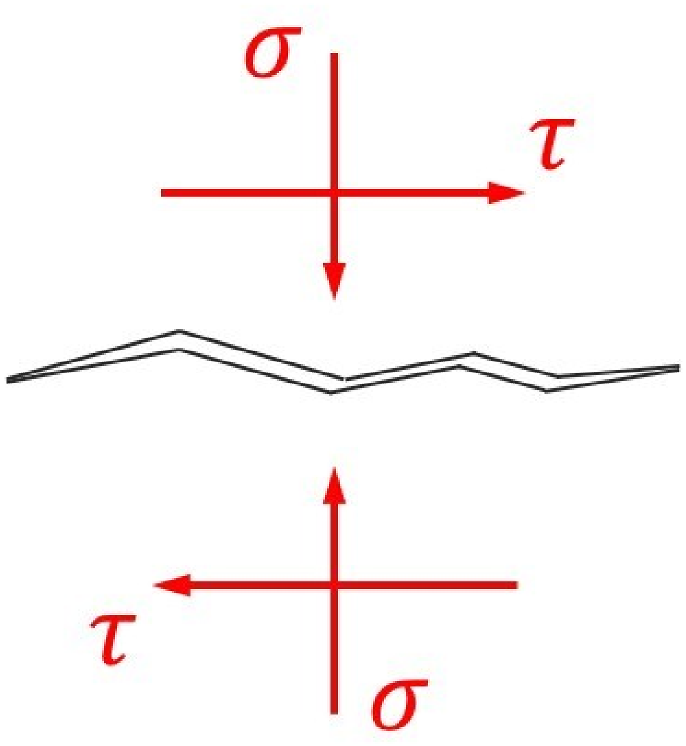
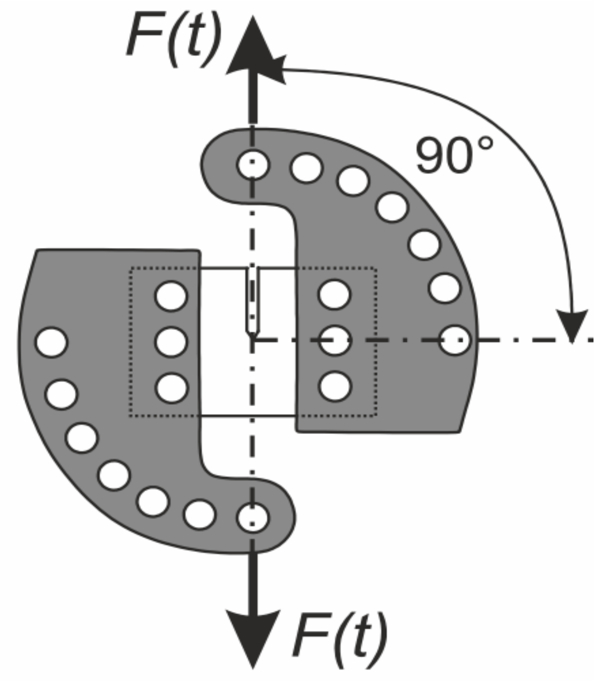
Determination of Mode II threshold

Influence of **crack face friction** and superimposed normal stress.

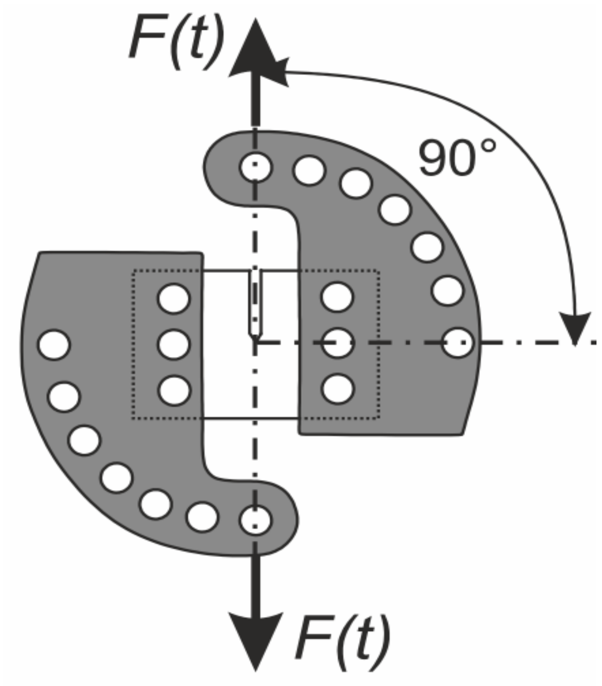


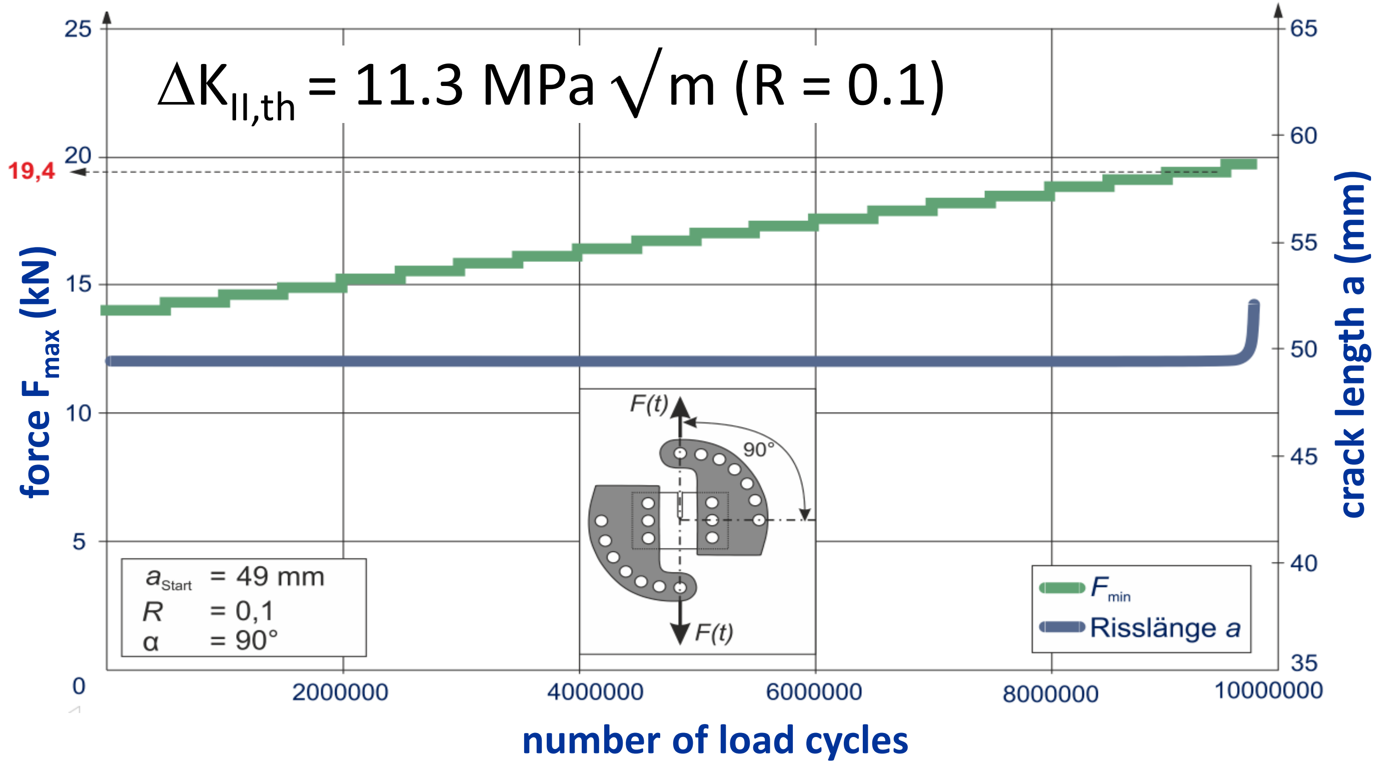
Mode II test with compact tension shear specimen (100Cr6).



Determination of Mode II threshold

Mode II test with compact tension shear specimen (100Cr6)





U. Paderborn 2018

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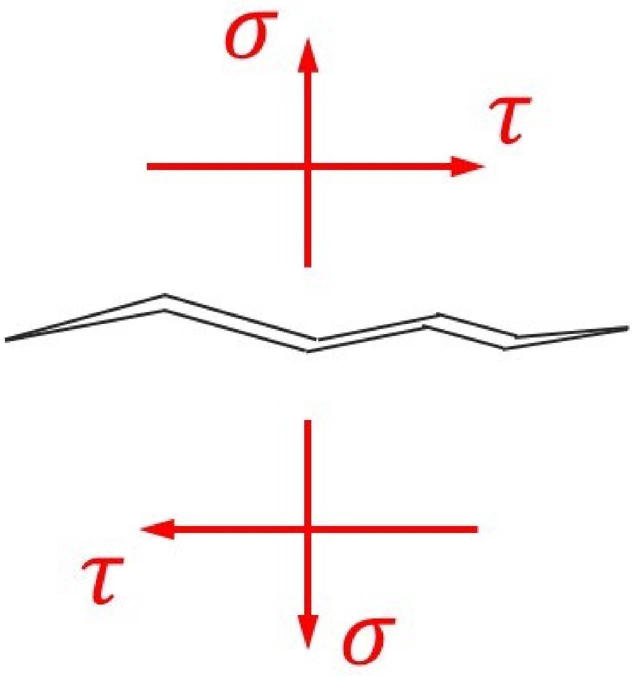
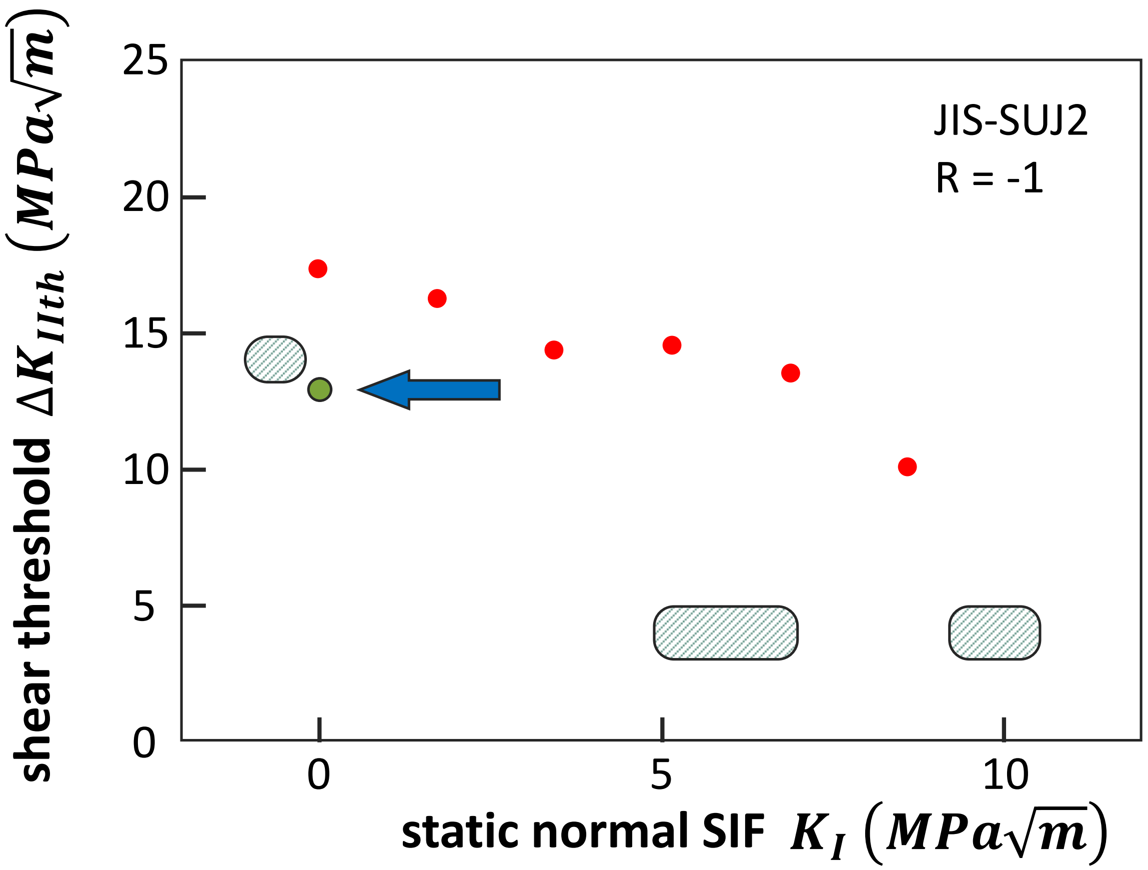
Published Mode II threshold results

Published results (R = -1)

(Source: Okazaki 2017)





$\Longrightarrow \Delta K_{II,th} = 13\ MPa\sqrt{m}$ (R = -1)

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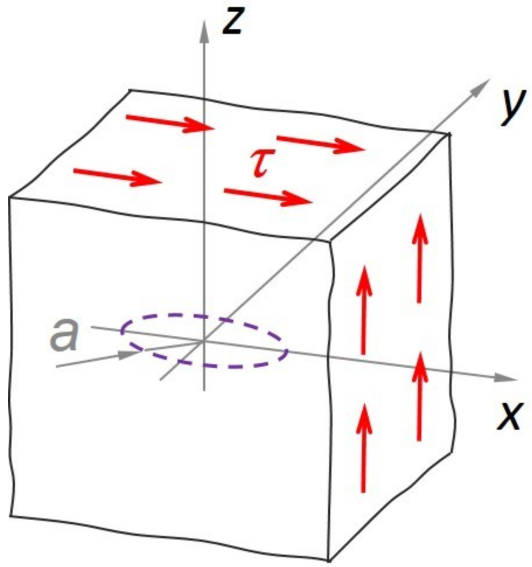
Short Crack Behaviour: Kitagawa-Takahashi diagram



$$\Delta K_{II} = Y \cdot \Delta\tau \cdot \sqrt{\pi \cdot a}$$

$$\Rightarrow \Delta\tau = \frac{\Delta K_{II}}{Y\sqrt{\pi \cdot a}}$$

with $\Delta K_{IIth} \Rightarrow$ fatigue limit depending on crack size (LEFM):

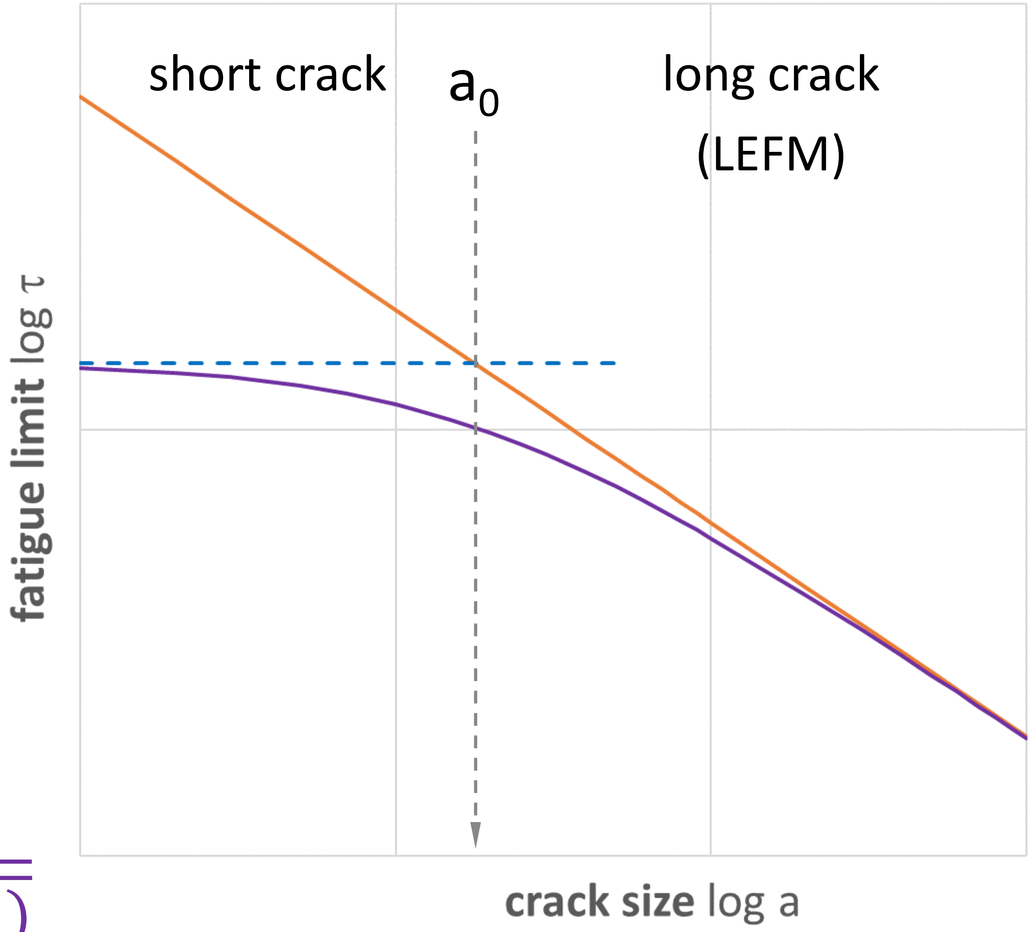
$$\tau_w = \frac{\Delta K_{IIth}}{2 \cdot Y\sqrt{\pi \cdot a}}$$

fatigue limit w/o crack:

$$\tau_{w\,max} \approx \frac{1.5}{\sqrt{3}} HV$$

El Haddad transition:

$$\tau_w = \frac{\Delta K_{IIth}}{2 \cdot Y\sqrt{\pi \cdot (a + a_0)}}$$



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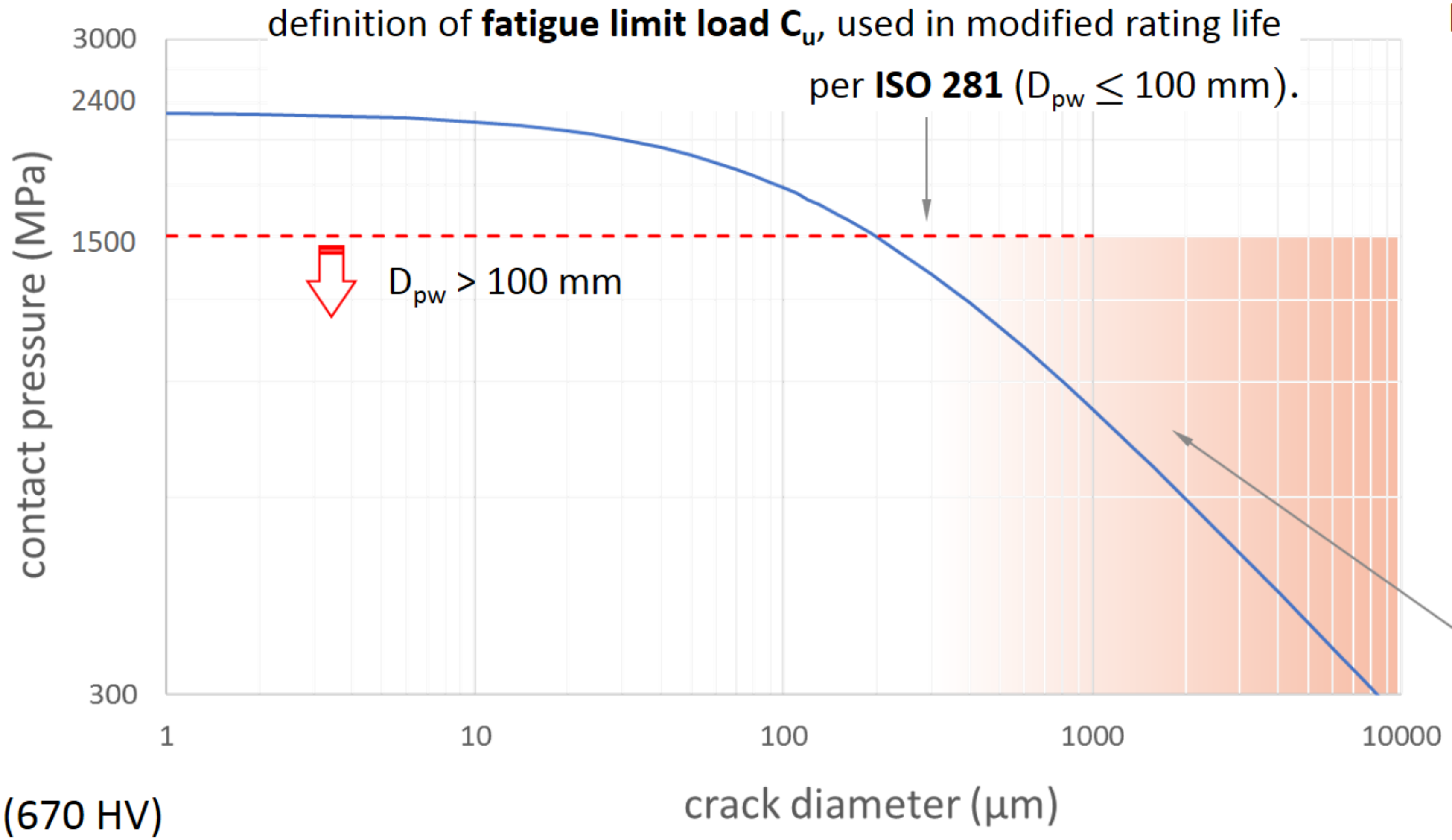
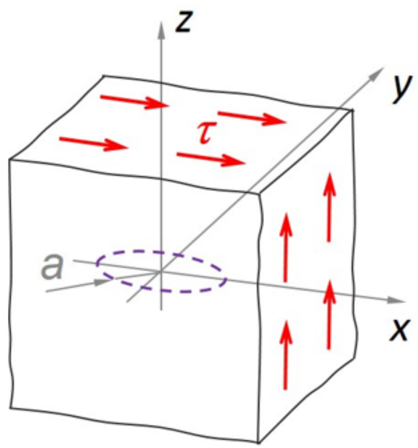
Kitagawa-Takahashi diagram for Mode II fatigue (penny shaped crack)



(670 HV)

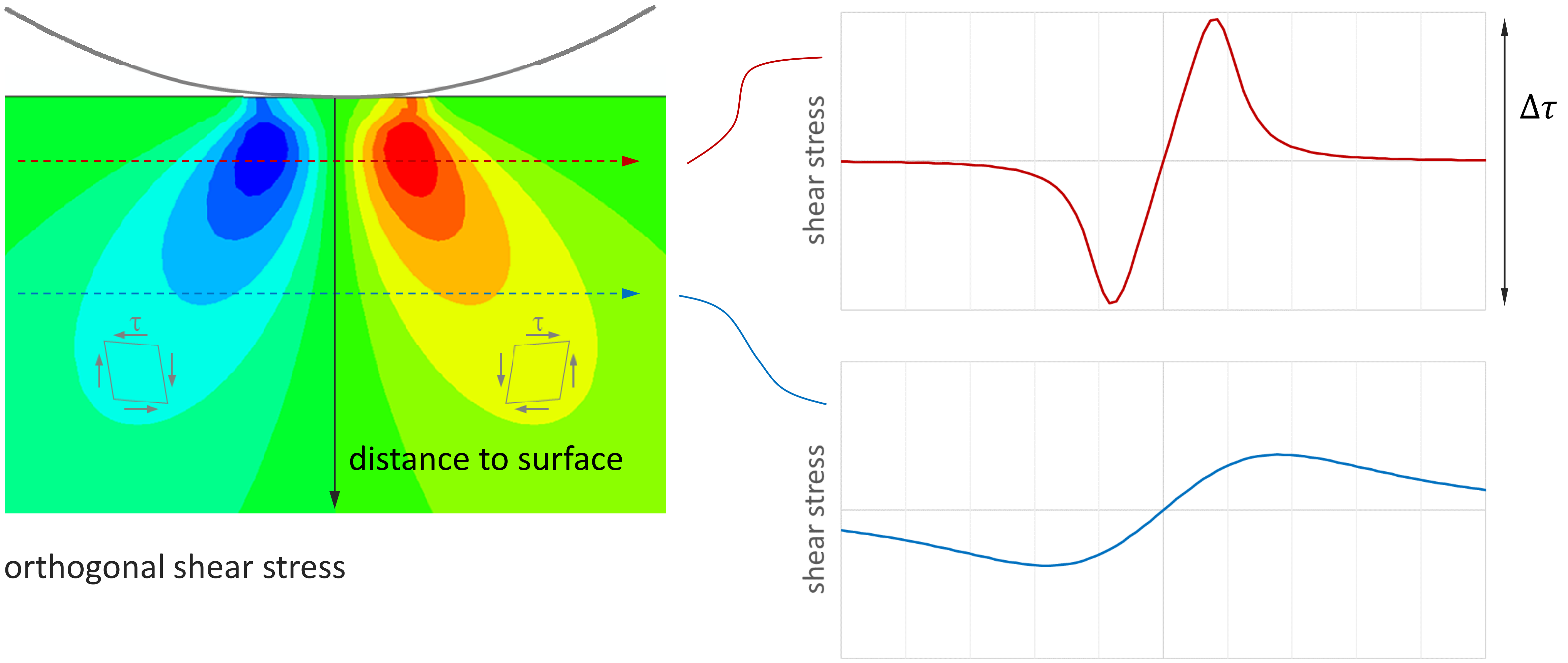
Penny-shaped crack:

$$p_{0\,lim} = \frac{2\,\Delta K_{IIth}}{0.75\sqrt{\pi \cdot (a + a_0)}}$$



Exclusion of macro inclusions using ultrasonic inspection (e.g. acc. to WPOS).

Mode II approach for RCF



orthogonal shear stress

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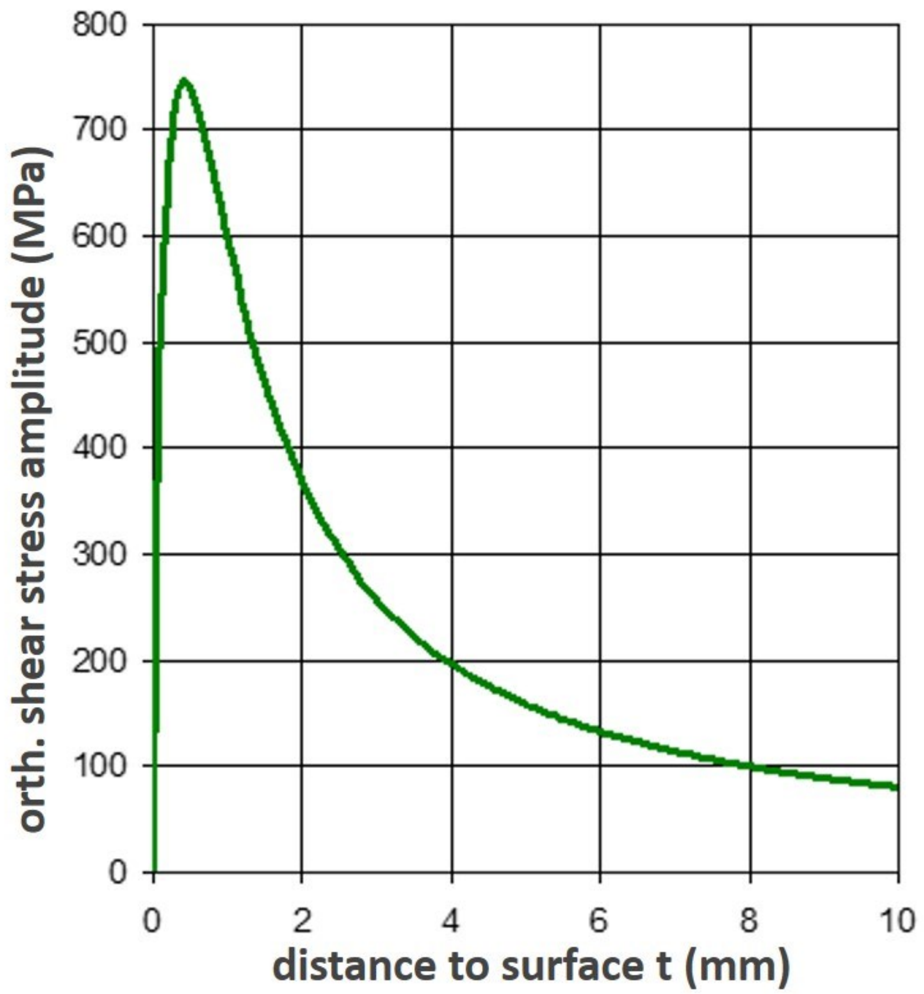
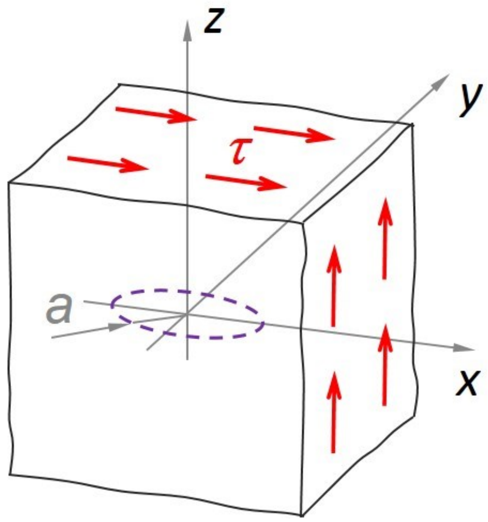
Mode II approach for RCF



Penny-shaped crack under shear:

$$\Delta K = 0.75\, \Delta\tau \sqrt{\pi\,(a + a_0)}$$



$\Longrightarrow$ critical crack size f(t):

$$2\, a_{crit}(t) = \frac{2}{\pi}\left(\frac{\Delta K_{IIth}}{0.75 \cdot \Delta\tau(t)}\right)^2 - 2\, a_0$$

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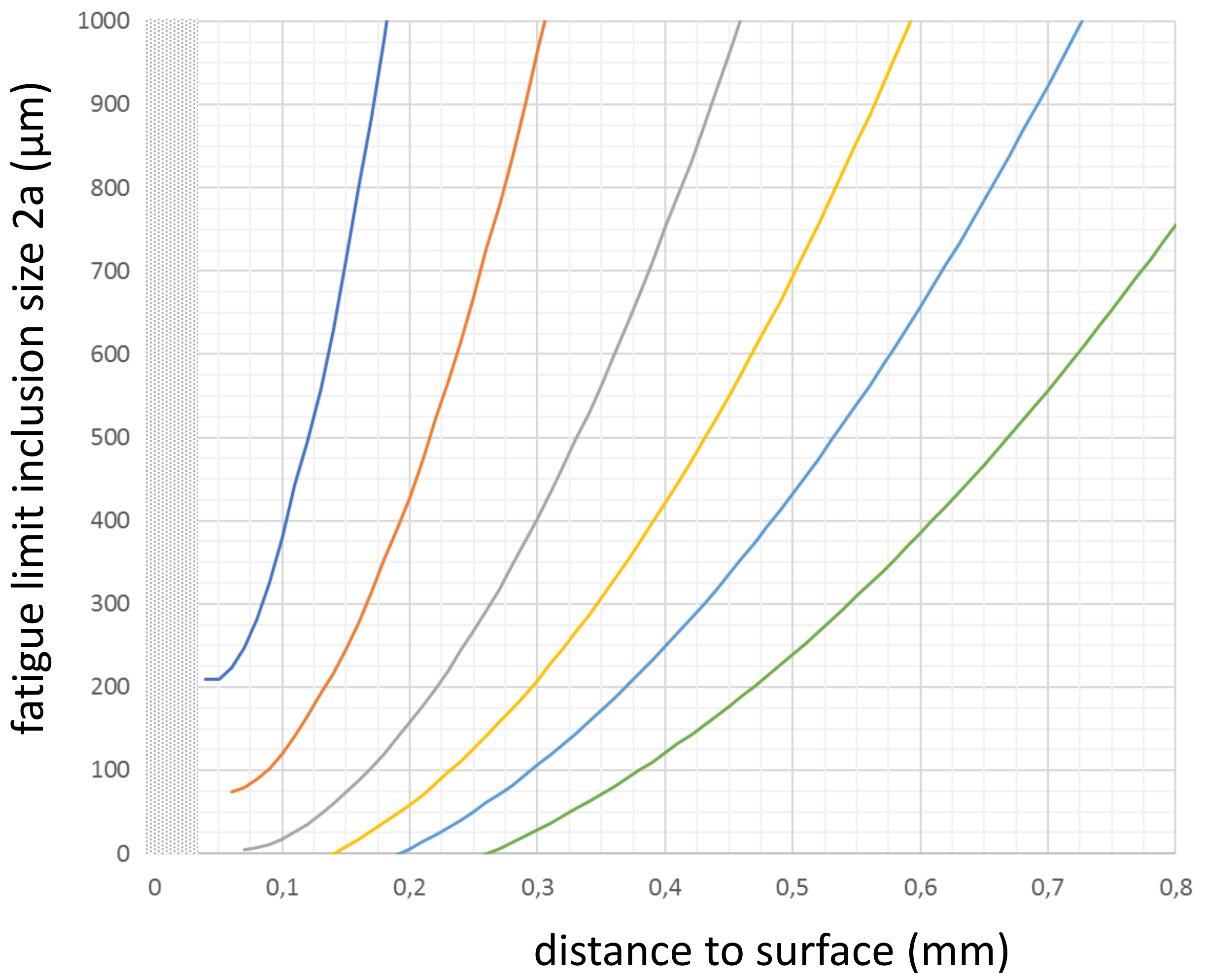
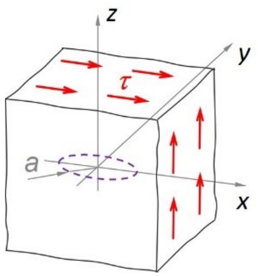
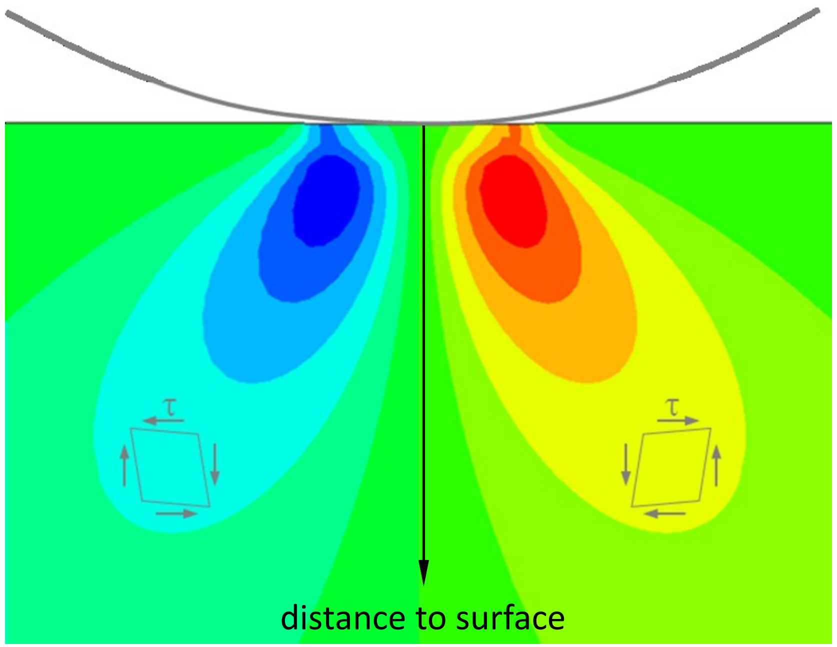
Fatigue limit estimation for Mode II (penny shaped crack)







$$2a_{crit} = \frac{2}{\pi}\left(\frac{\Delta K_{IIth\ LC}}{0.75 \cdot \Delta\tau}\right)^2 - 2a_0$$

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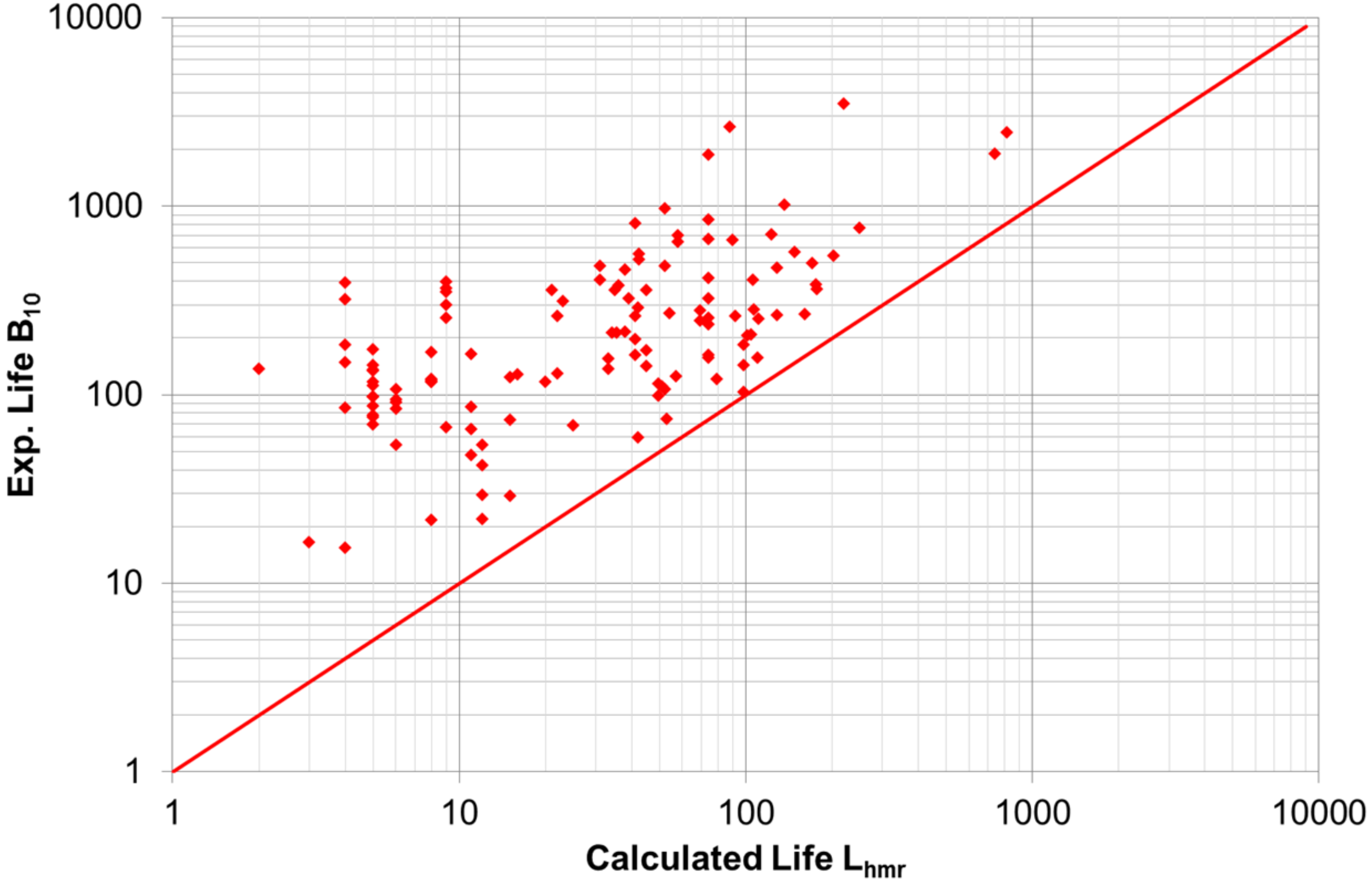
Evaluation of ISO/TS 16281 modified reference rating life calculation



129 tests 2011 – 2016

(full size life tests with 20+ samples)

Rating life calculation according to ISO/TS 16281 offers a safe approach for operating life prediction.

Mode I or mixed mode approach

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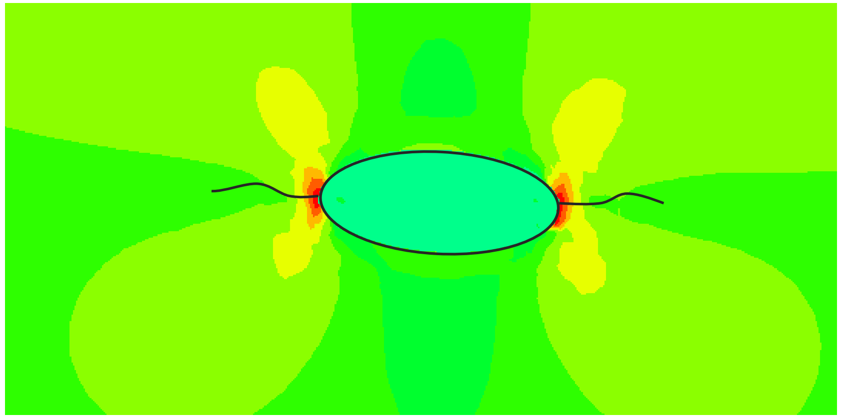
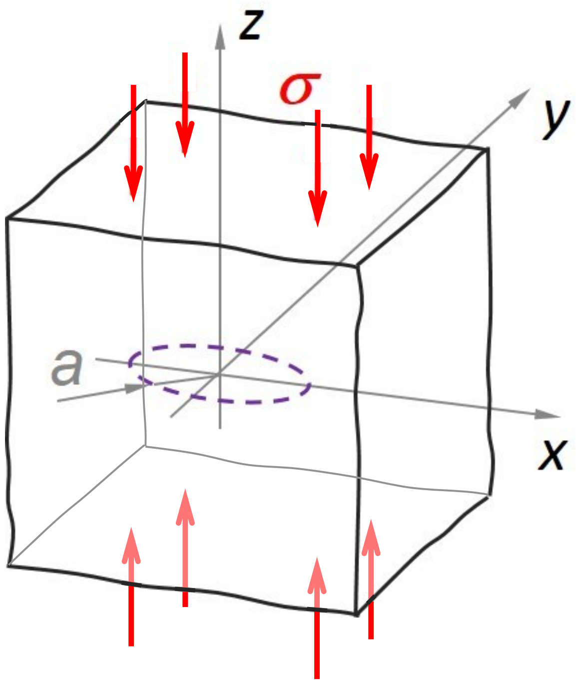
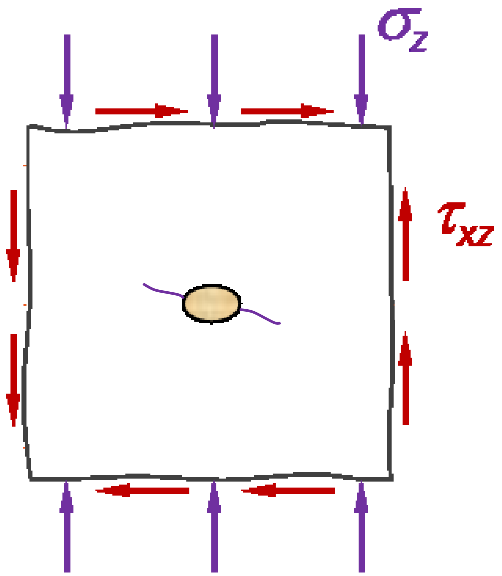
Assumption: cracks can grow under **Mode I** compression or compressive **mixed mode**.



- type of inclusion
- bonding
- void or gap occurence
- residual stresses



$$\Delta K_I = \frac{2}{\pi} \cdot \Delta\sigma \cdot \sqrt{\pi \cdot a}$$



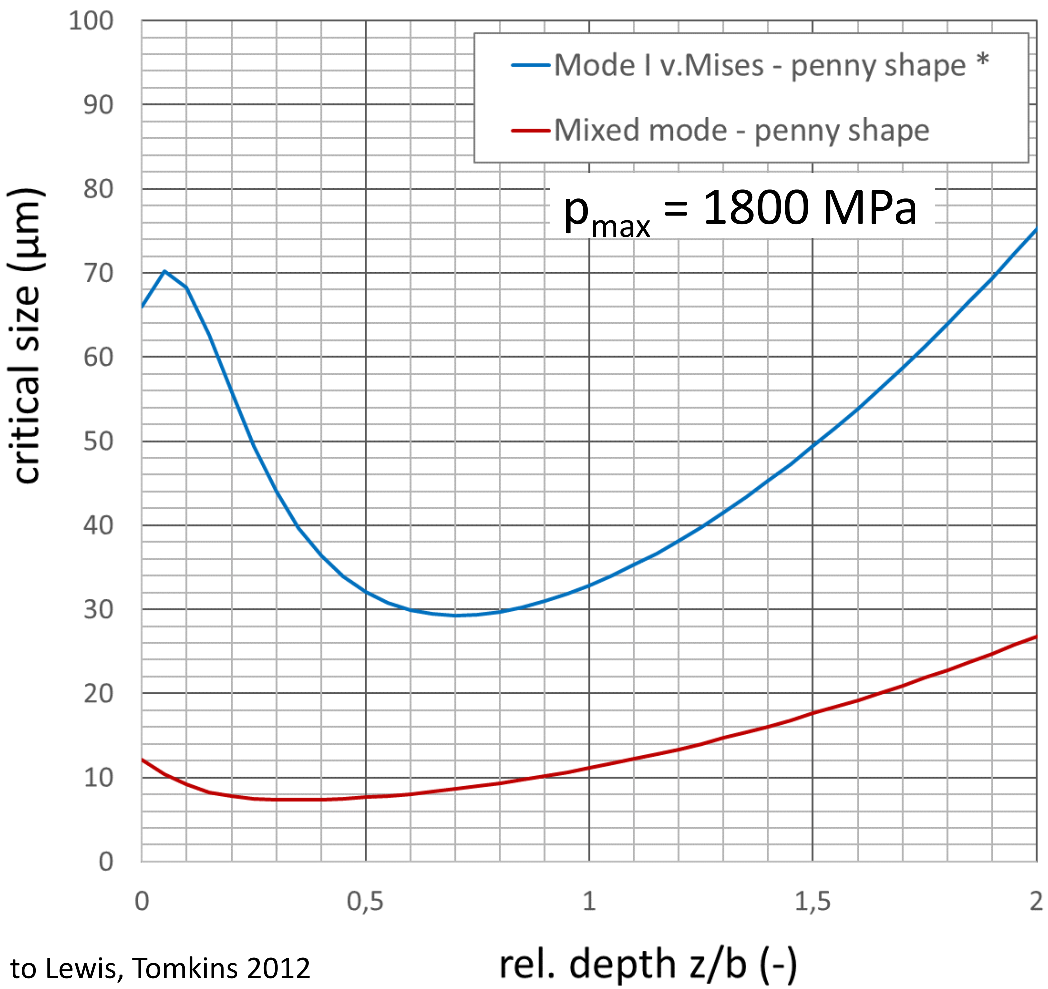
$$\Delta K_V = \frac{\Delta K_I}{2} + \frac{1}{2}\sqrt{\Delta K_I^2 + 5.336\Delta K_{II}^2}$$

(acc. to Richard/Sander 2016)

Mode I or mixed mode approach – butterfly generation

Assumption: cracks can grow under mode I compression or mixed mode.

Effect decreases with increasing distance from inclusion -> **crack arrest** => **butterfly**!



* acc. to Lewis, Tomkins 2012

Mode I or mixed mode approach – butterfly generation

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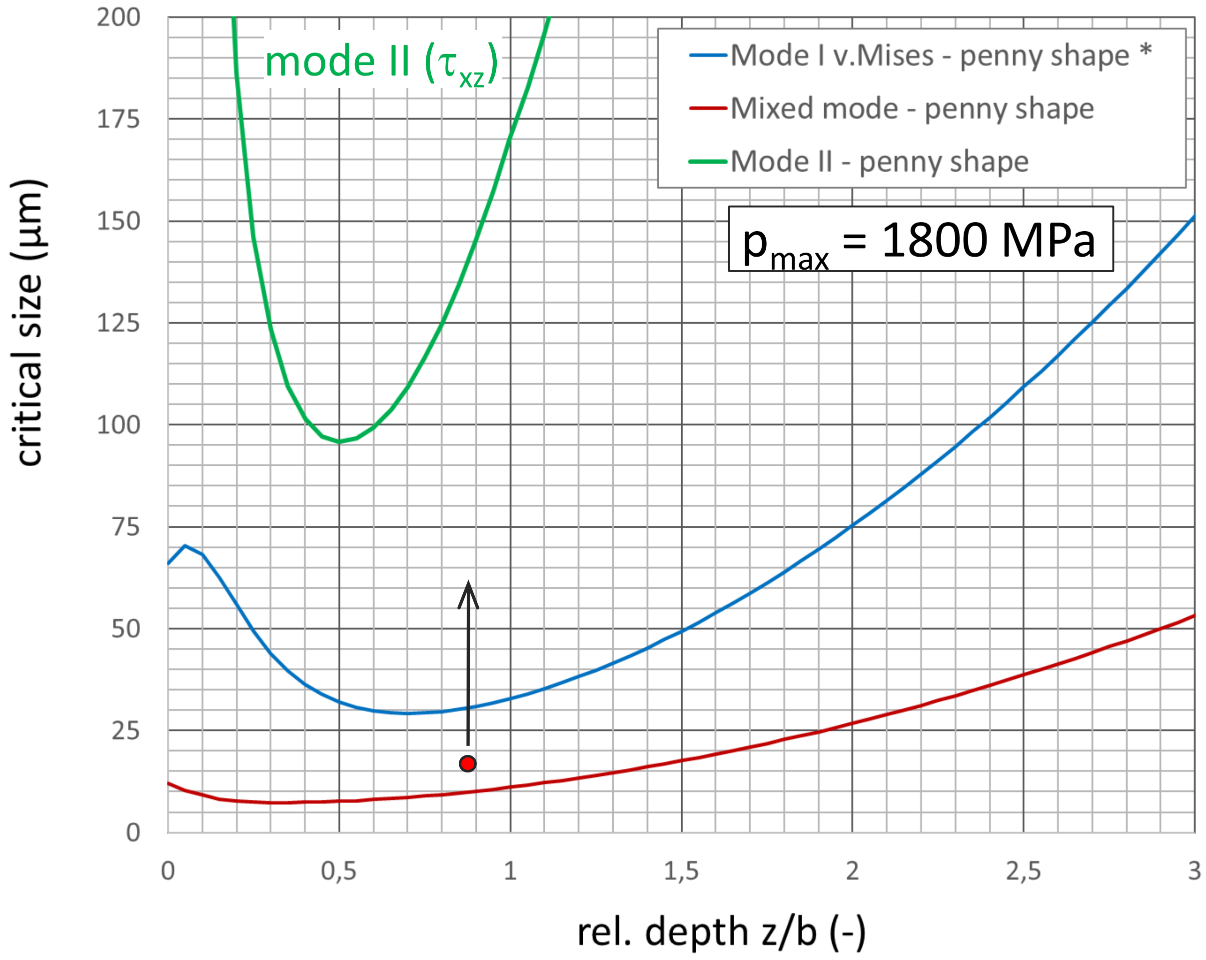

mode I based on v.Mises equiv. stress

(acc. to Lewis, Tomkins 2012)

mixed mode (σ_z and τ_{xz})

Butterfly generation more likely even for moderate loads.

Crack arrest when butterfly size beneath mode II criteria.

Simulation of crack propagation - pros

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Issues:

- crack kinking behavior
- crack face friction
- crack growth rate
- influence of residual stresses
- mixed-mode behavior
- ...

=> ongoing research!

Crack parameters:
- length 2a = 20 µm
- angle β = 0°
- depth t = 150 µm
- coeff. of friction **µ = 0.0**

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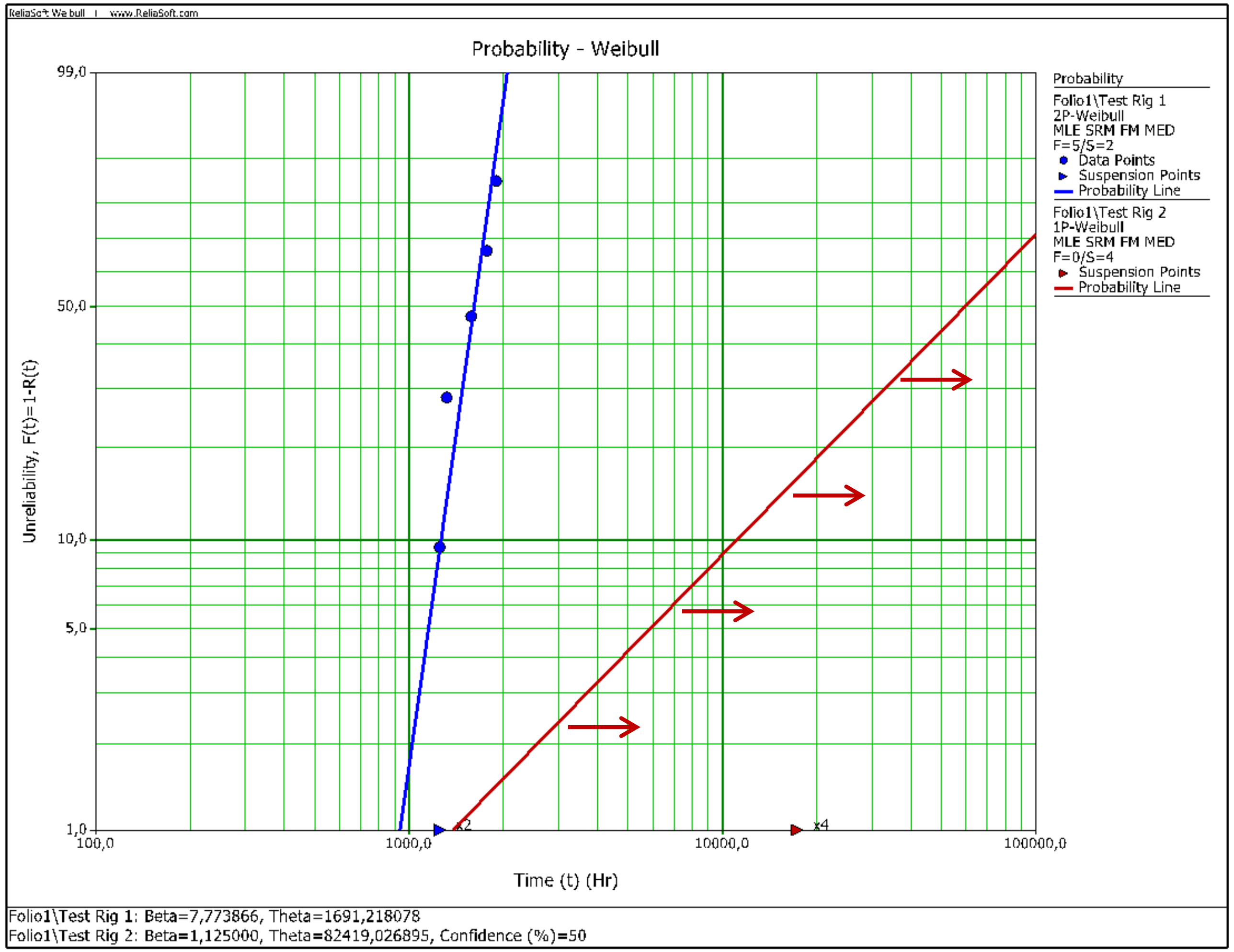
WEC characteristics

WECs can lead to **premature failure** at e.g. 1% -20% of calculated rating life.

WECs can occur in rings and rolling elements of **all bearing types** in greased as well as in oil-lubricated bearings.

Typically a steep rise of failure probability occurs.

[Holweger 2015, Loos 2016, Kruhoeffer 2017, Franke 2017]



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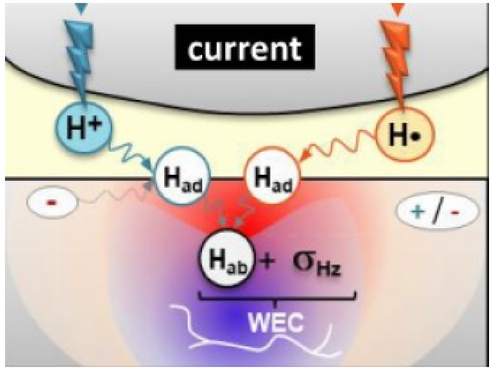
WEC generation: stress - strength

Stress
- stress and strain state
- lubrication conditions

- hydrogen release
- hydrogen diffusion



Strength
- microstructure
- diffusible hydrogen content

WEC critical conditions
- electric current
- frictional energy
- corrosion
- lubricant chemistry
- ...

An increased hydrogen content leads to a fundamental reduction of the endurance limit

(Murakami 2013, Hamada 2006, Karsch 2012, ...)

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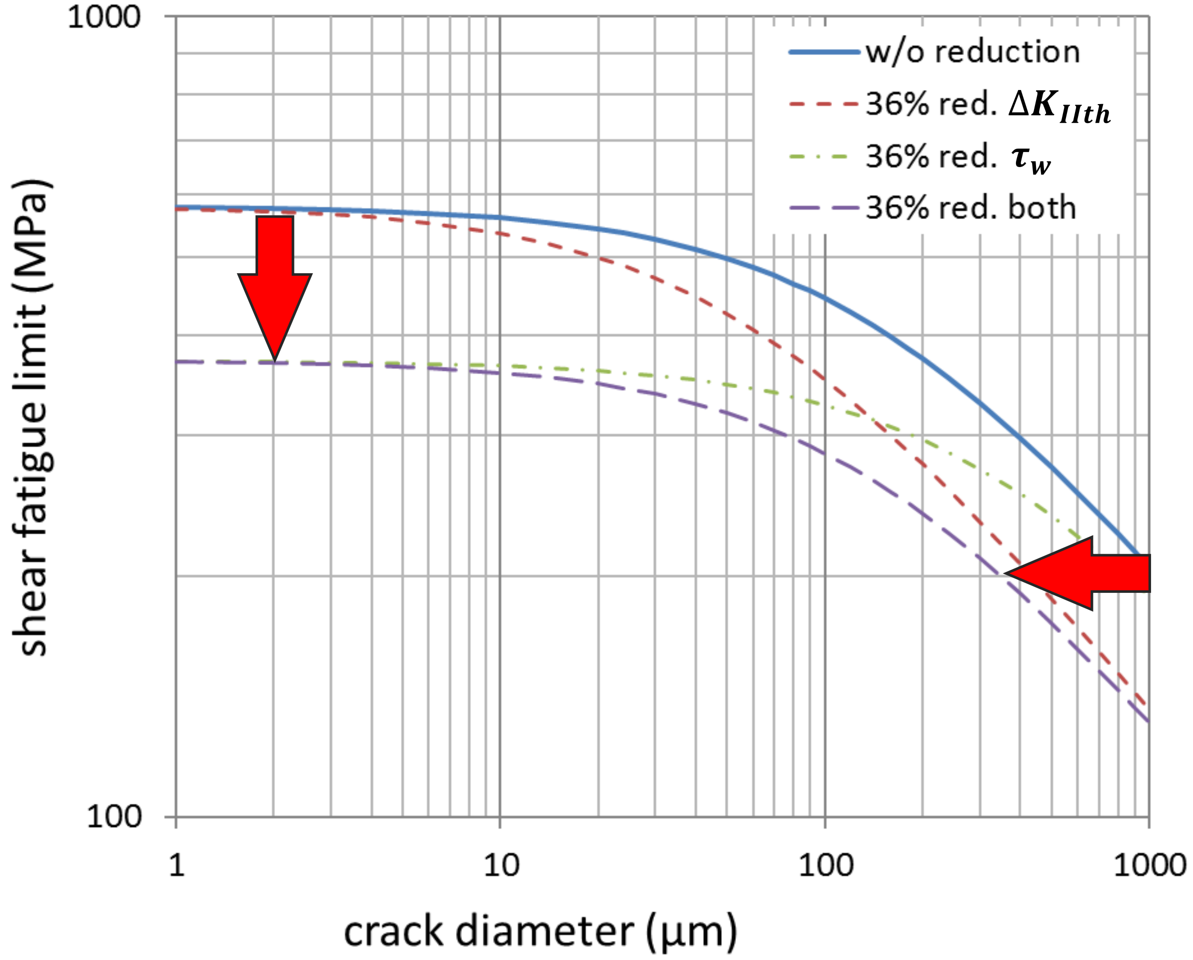
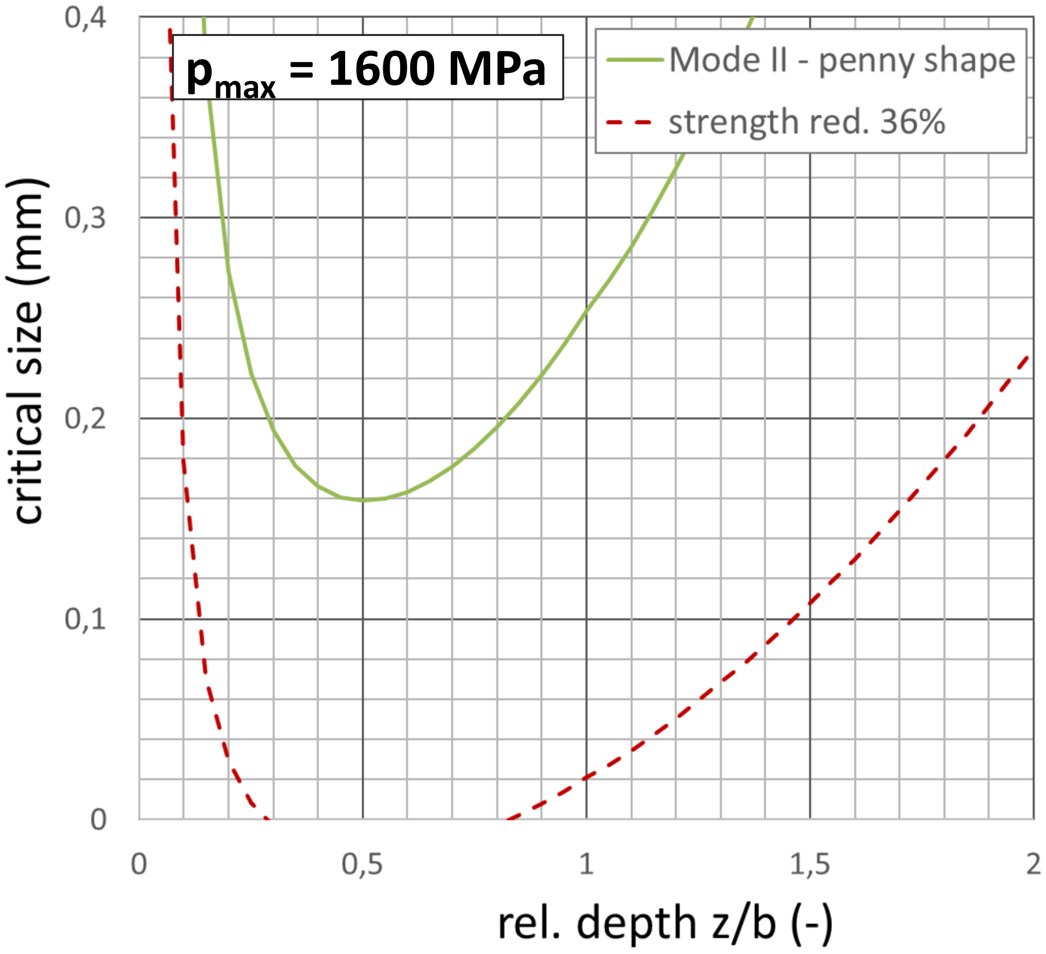
Reduction of material properties by hydrogen





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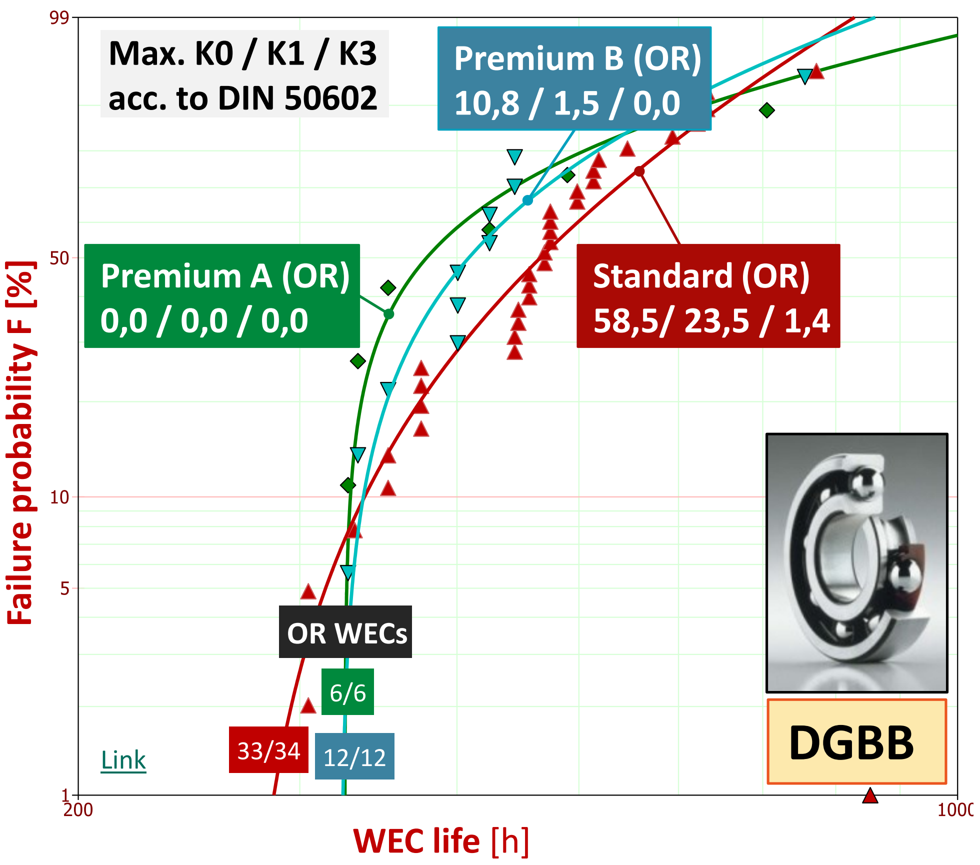
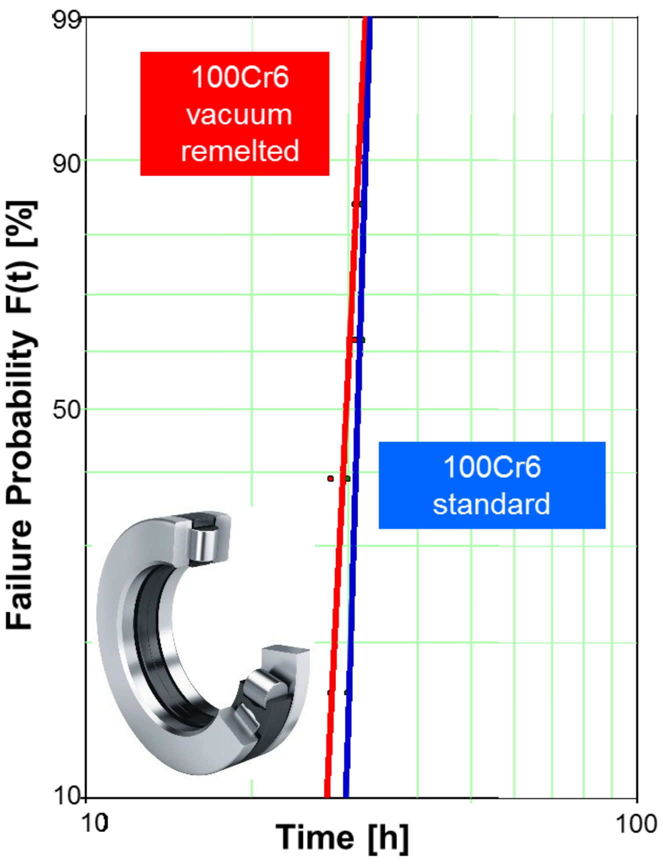
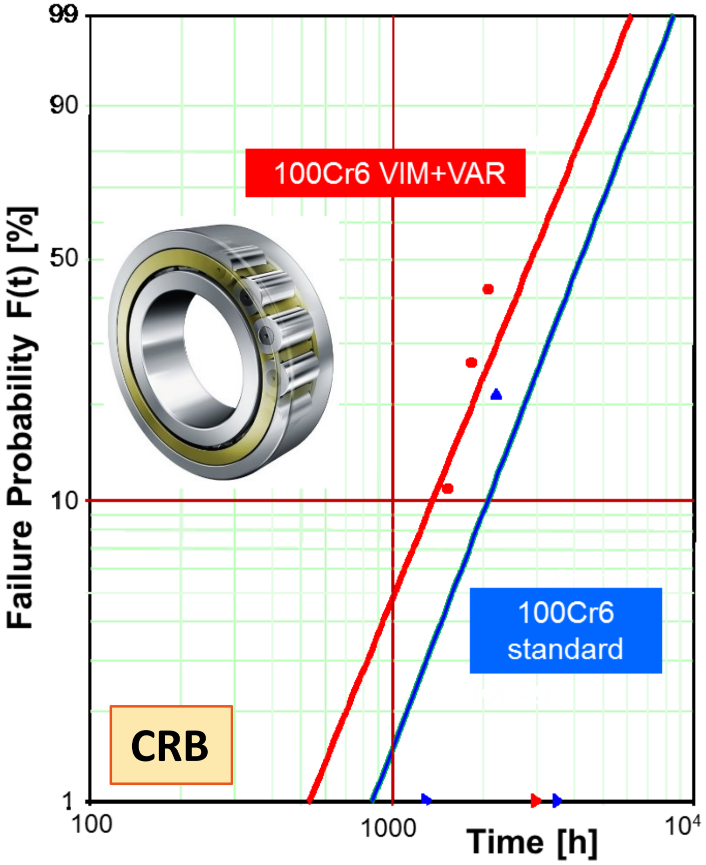
Experience from WEC test rigs







None of Schaeffler's tests has shown a significant influence of the technical steel cleanliness on WEC.

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Summary and conclusion

- **Non-metallic inclusions cannot be avoided in technical steel production, this is considered in the generally used life rating methods.**
- **Fracture mechanics can offer a reasonable approach for the evaluation of inclusions.**
- **White etching cracks are an independent damage mechanism characterized by premature fatigue and typically a small scatter of time to failure.**
- **The cleanliness of the steel has no significant influence on WEC failures on different test rigs.**

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