Karlsruhe Institute of Technology

Hochbeanspruchte Gleit- und Friktionssysteme auf Basis ingenieurkeramischer Werkstoffe sfb 483

PROBABILISTIC ANALYSIS OF A ROLLING CONTACT FATIGUE TEST FOR SILICON NITRIDE

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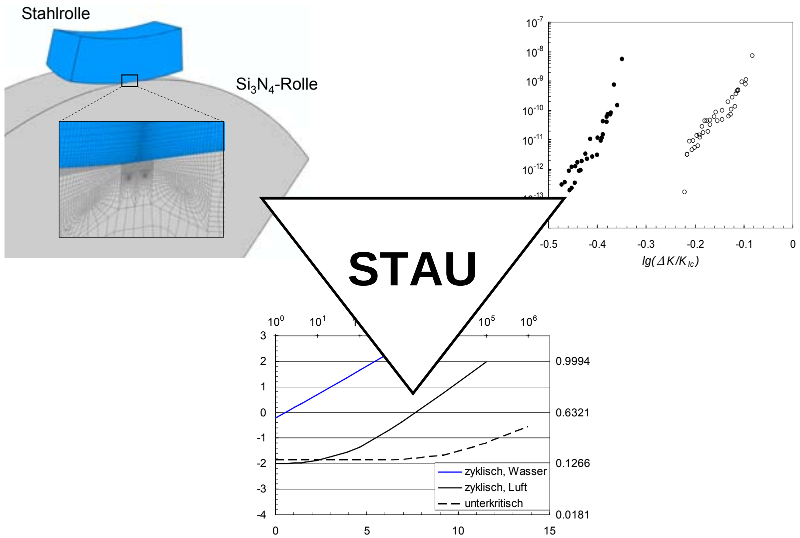
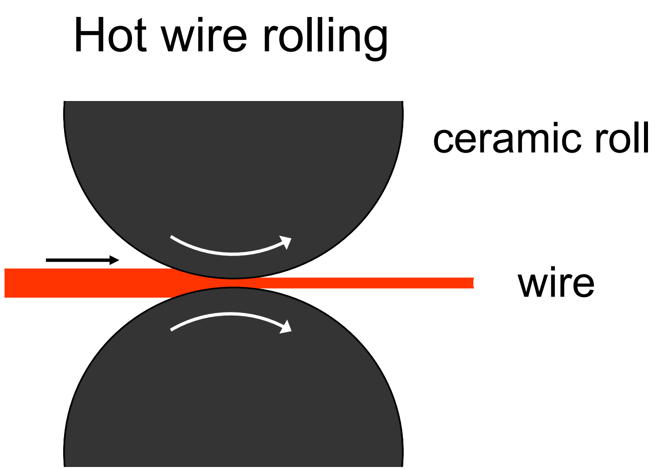


Motivation



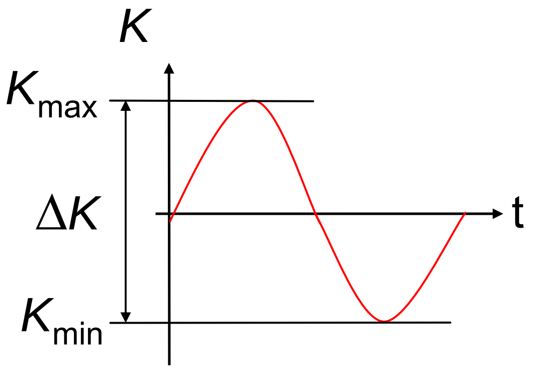
Fraunhofer Gesellschaft, IWM, Freiburg

- High strength ceramics (Si_3N_4) are used in rolling applications
- Time-dependent failure due to slow crack propagation
- Design of such components requires probabilistic methods
- Rolling contact fatigue test as model system for rolling applications

Theory: Crack propagation mechanisms

- Crack loading

$\Delta \boldsymbol{K} = K_{max} - K_{min}$ $\qquad$ $R = \dfrac{K_{min}}{K_{max}}$



Subcritical crack propagation

- Stress corrosion/ chemical reaction
- Quasi-static effect

$$\frac{\mathrm{d}a}{\mathrm{d}t} = A_S \cdot \left(\frac{K_I}{K_{Ic}} \right)^{n_S}$$

A_S ,n_S: material properties

Cyclic crack propagation (fatigue)

- Depends on load sequence
- Degradation of strengthening effects (grain bridging)

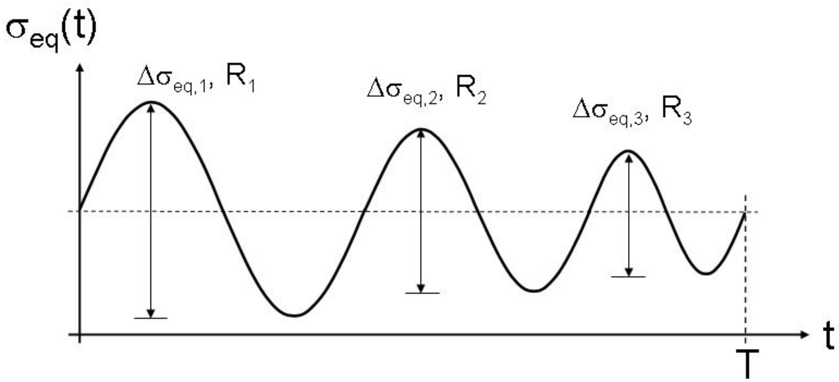
$$\frac{\mathrm{d}a}{\mathrm{d}N} = \frac{A}{(1-R)^{n-p}} \cdot \left(\frac{\Delta K_I}{K_{Ic}} \right)^{n}$$

A ,n ,p: material properties

Theory: Failure probability

Weibull Theory

- Integration over component surface/ volume and flaw orientation
- Equivalent stress σ_{eq}: local failure criterion



Subcritical crack propagation

$$P_f = 1 - \exp\left[-\frac{1}{A_0} \int_A \frac{1}{2\pi} \int_\alpha \left(\max_{t \in [0,T]} \left\{ \left(\frac{\sigma_{eq}(t)}{\sigma_0} \right)^{n_S - 2} + \frac{\sigma_0^2}{B} \int_0^t \left(\frac{\sigma_{eq}(t')}{\sigma_0} \right)^{n_S} dt' \right\} \right)^{\frac{m}{n_S - 2}} d\alpha \, dA \right]$$

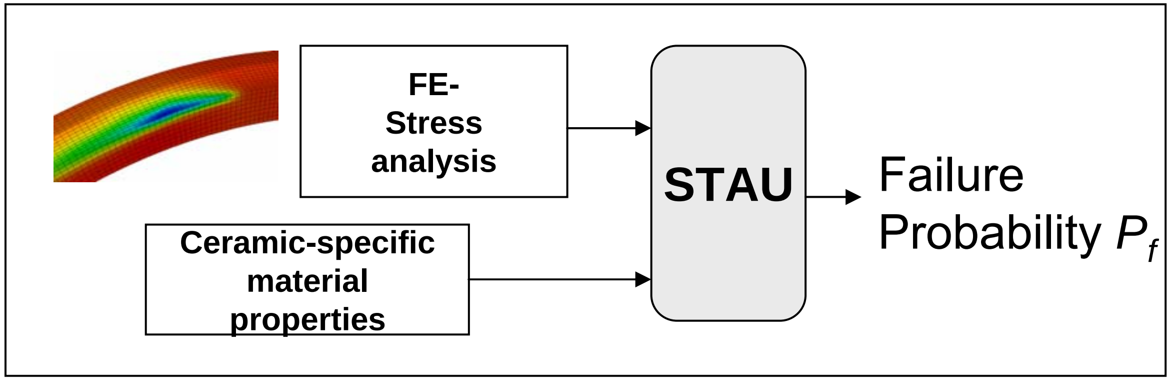
Time/Cycle dependent load history

Cyclic crack propagation

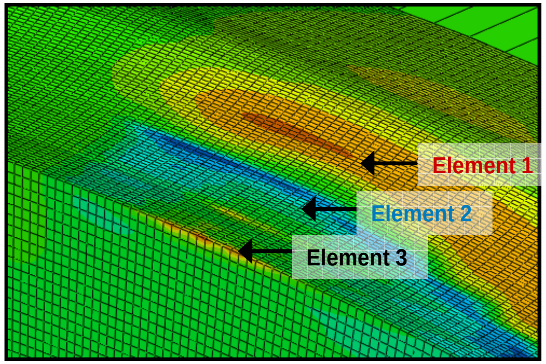
$$P_f = 1 - \exp\left[-\frac{1}{A_0} \int_A \frac{1}{2\pi} \int_\alpha \left(\max_{\eta \in [N_1, N_K]} \left\{ \left(\frac{\sigma_{eq,\max}(\eta)}{\sigma_0} \right)^{n - 2} + \frac{\sigma_0^2}{B} \int_{N_1}^{\eta} \left(\frac{\sigma_{eq,\max}(N')}{\sigma_0} \right)^{n} (1 - R(N'))^p \, dN' \right\} \right)^{\frac{m}{n-2}} d\alpha \, dA \right]$$

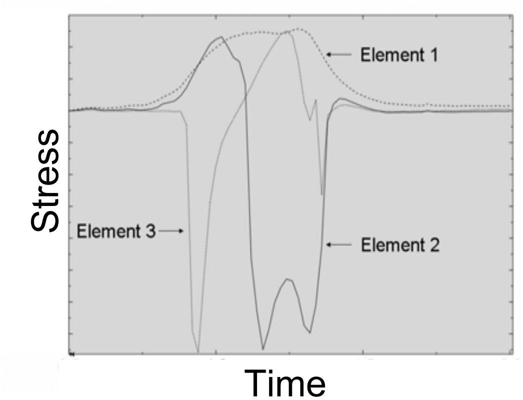
Theory: Numerical evaluation

STAU[1]: Finite-Element Postprocessor for reliability assessment of ceramics



Reliability analysis for rolls ➔ Complex load history must be considered





[1] *H. Riesch-Oppermann, M. Härtelt, O. Kraft, Int. J. Mat. Res. 99 (2008)*

Results: Material parameters Si_3N_4-SL200

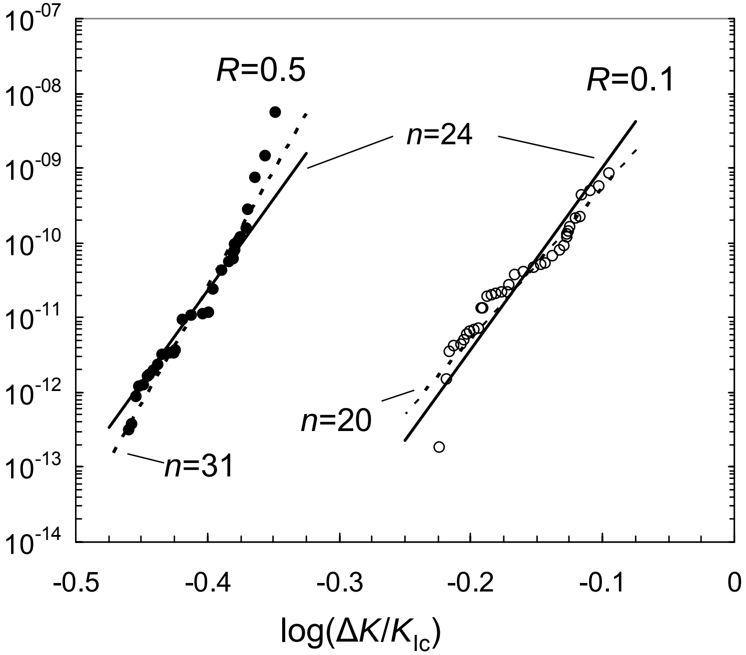
- Strength

σ_{4PB}=1044 MPa
m=11.5

- Subcritical crack growth

n=42, A_S=10^{-6} m/s
Lube and Dusza, *J.Eur.Ceram.Soc.*, 27(2-3),2007

- Cyclic fatigue parameters (air)



Härtelt et al., *J Am Ceram Soc*, 2011, in press

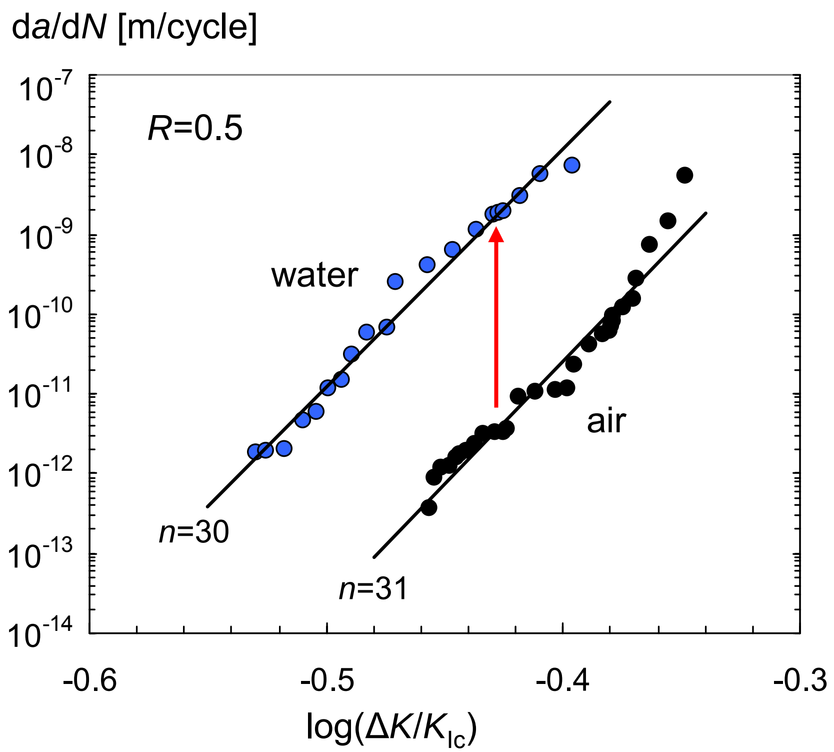
- Crack growth exponent n depends on load ratio R (n=20,31)
- Curves must be represented by common exponent n:

$$\frac{da}{dN} = \frac{A}{(1-R)^{n-p}} \cdot \left(\frac{\Delta K_I}{K_{Ic}}\right)^n$$

n=24, p=2.2, A=$3\cdot10^{-8}$ m/cycle

Results: Material parameters Si_3N_4

- Cyclic fatigue parameters (water)

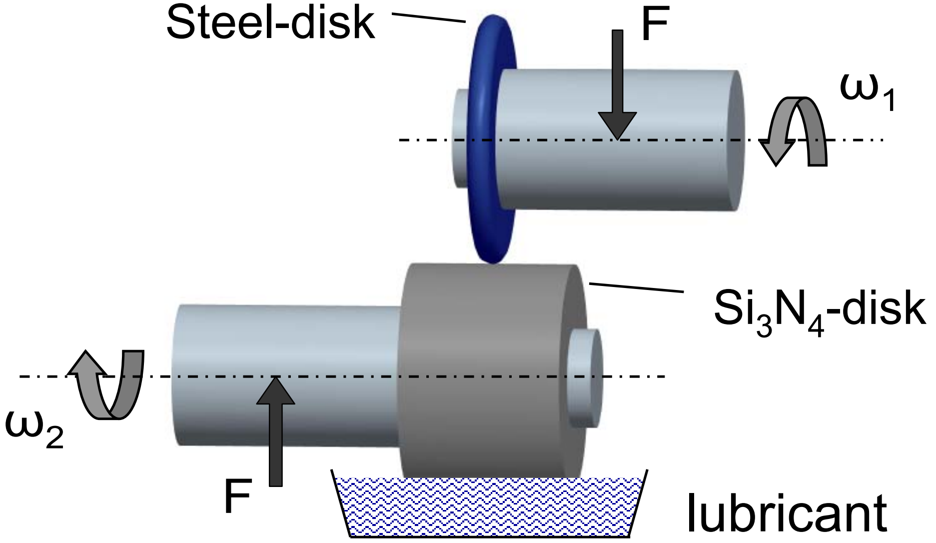


- Water enhances fatigue effect!
- Measurements for R=0.5: n=29.9
- Parameters are evaluated assuming p=2.2 (air):

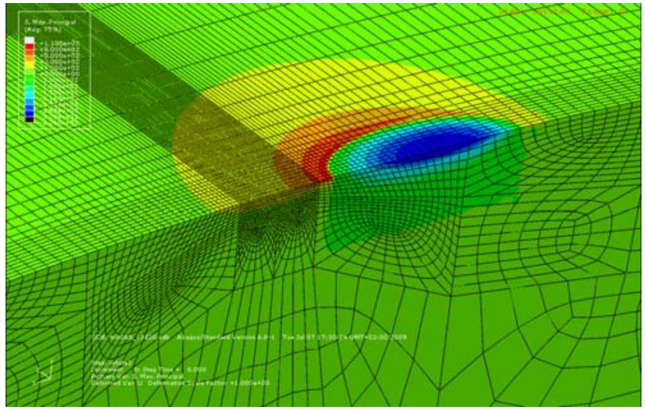
$$\frac{\mathrm{d}a}{\mathrm{d}N} = \frac{A}{(1-R)^{n-p}} \cdot \left(\frac{\Delta K_\mathrm{I}}{K_\mathrm{Ic}} \right)^n$$

n=29.9, p=2.2, $A=5\cdot 10^{-5}$ m/cycle

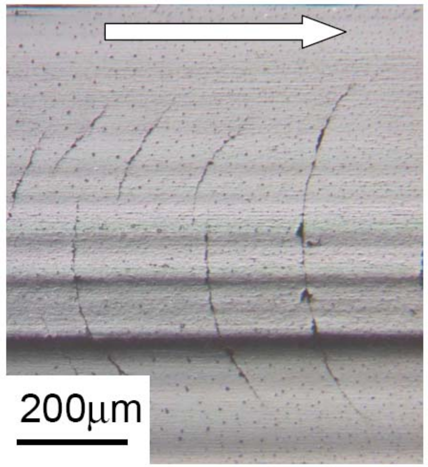
Results: Rolling contact fatigue (RCF) test



Stress distribution



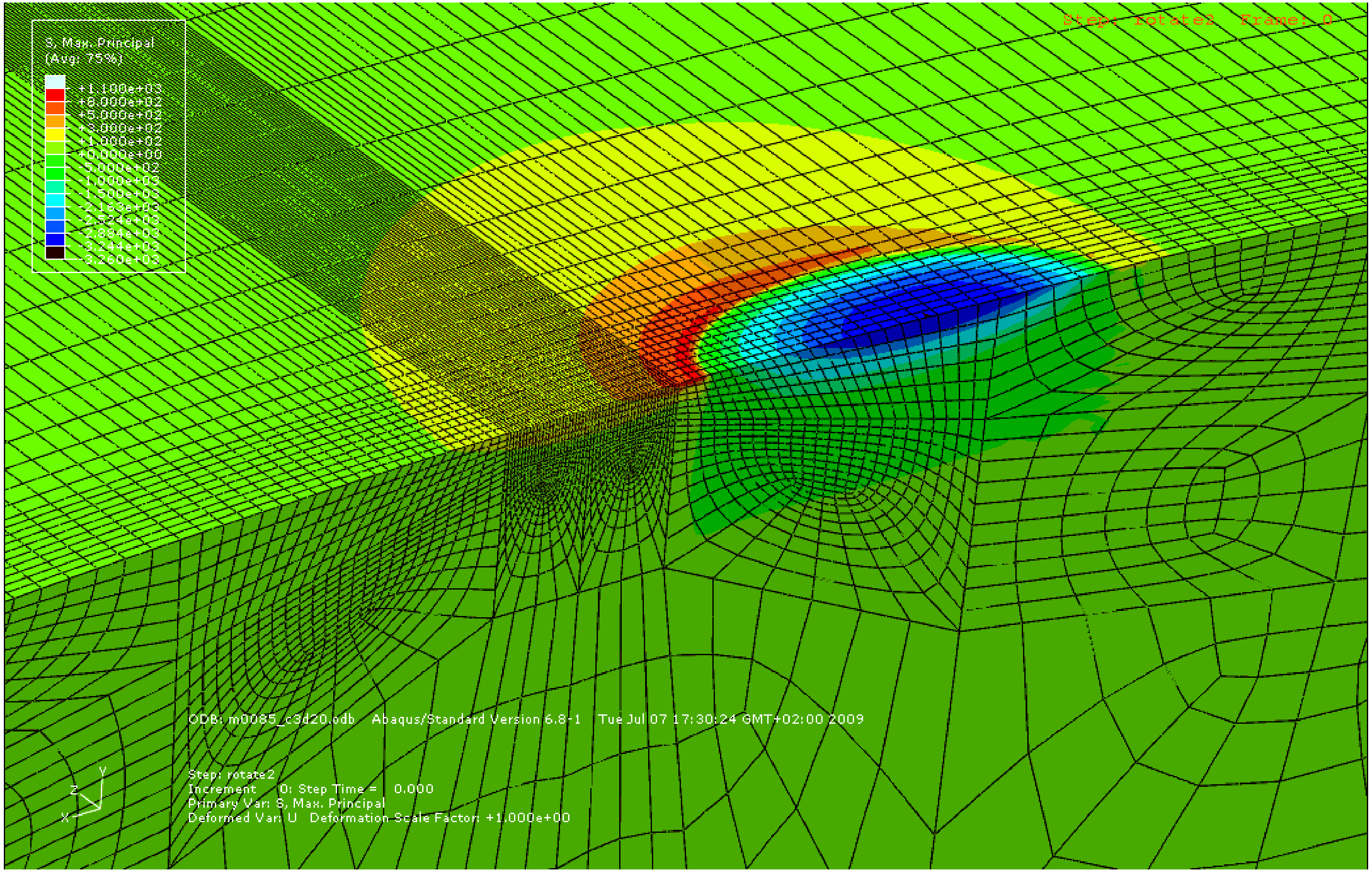
Damage after 10^5 rotations



- lubricant: friction coefficient μ=0.085
- F=1700N
- relative slip: ~22%
- max. principal stress: ~1100 MPa

RCF tests: Iyas Khader, Fraunhofer Institute IWM, Freiburg

Results: Rolling contact fatigue (RCF) test



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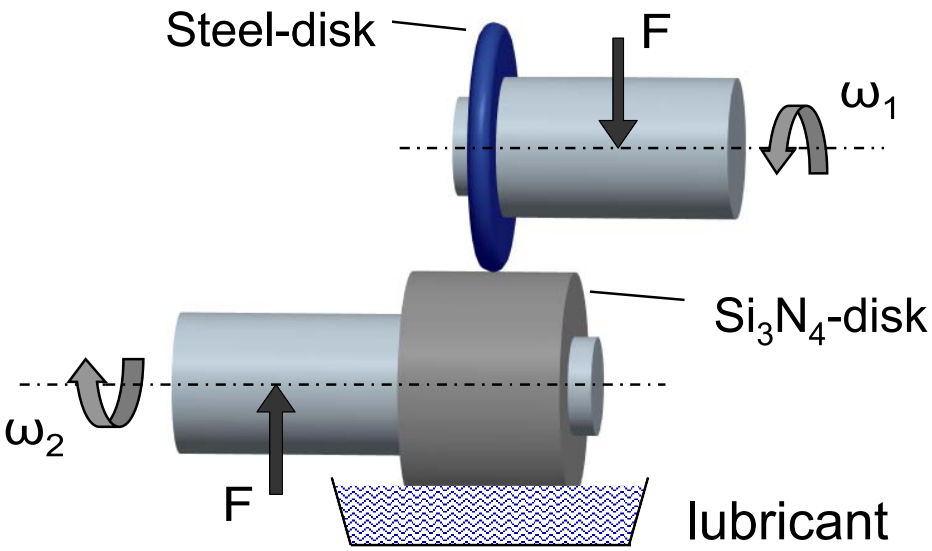
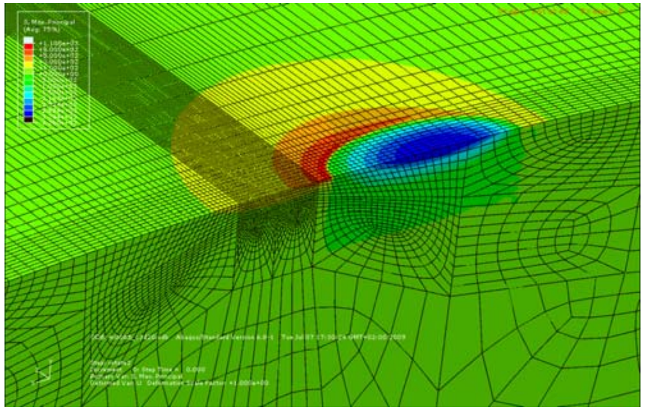


Stress distribution



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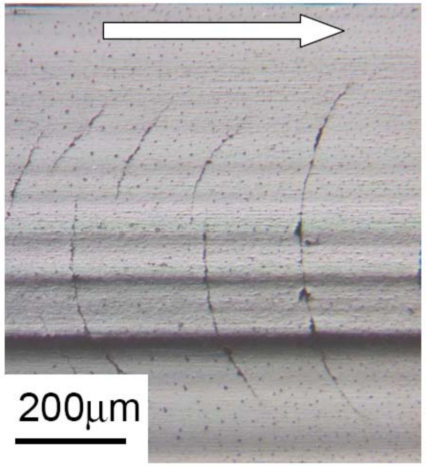

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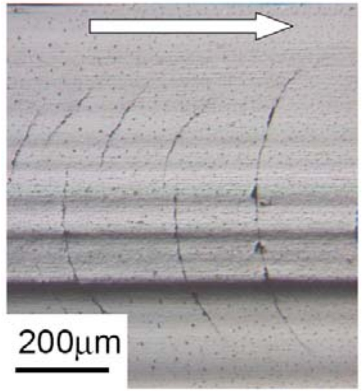
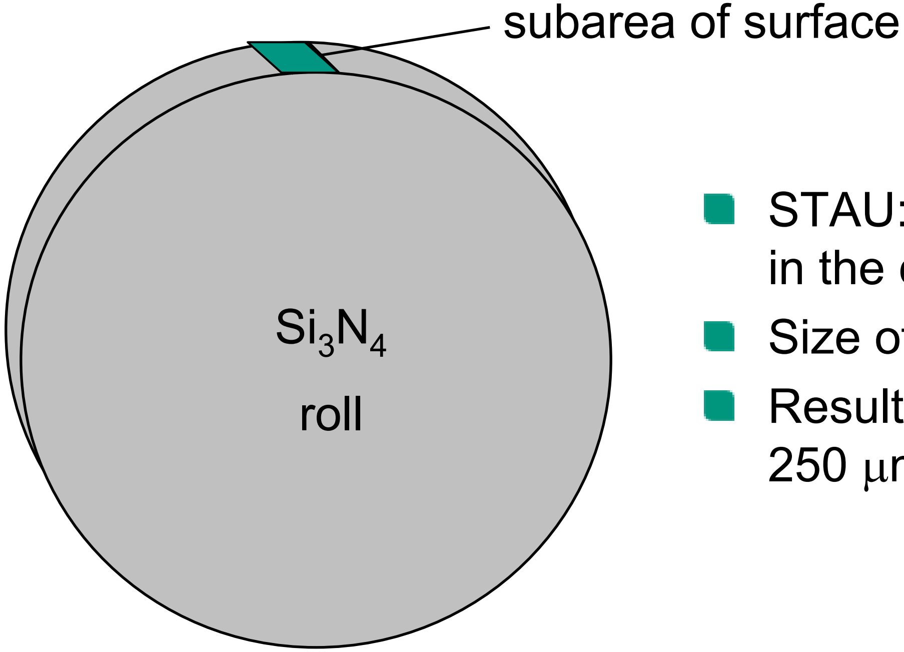
Results: STAU analysis

- Contact damage: initiation of macroscopic flaws
- Predicting of a certain flaw density on the surface

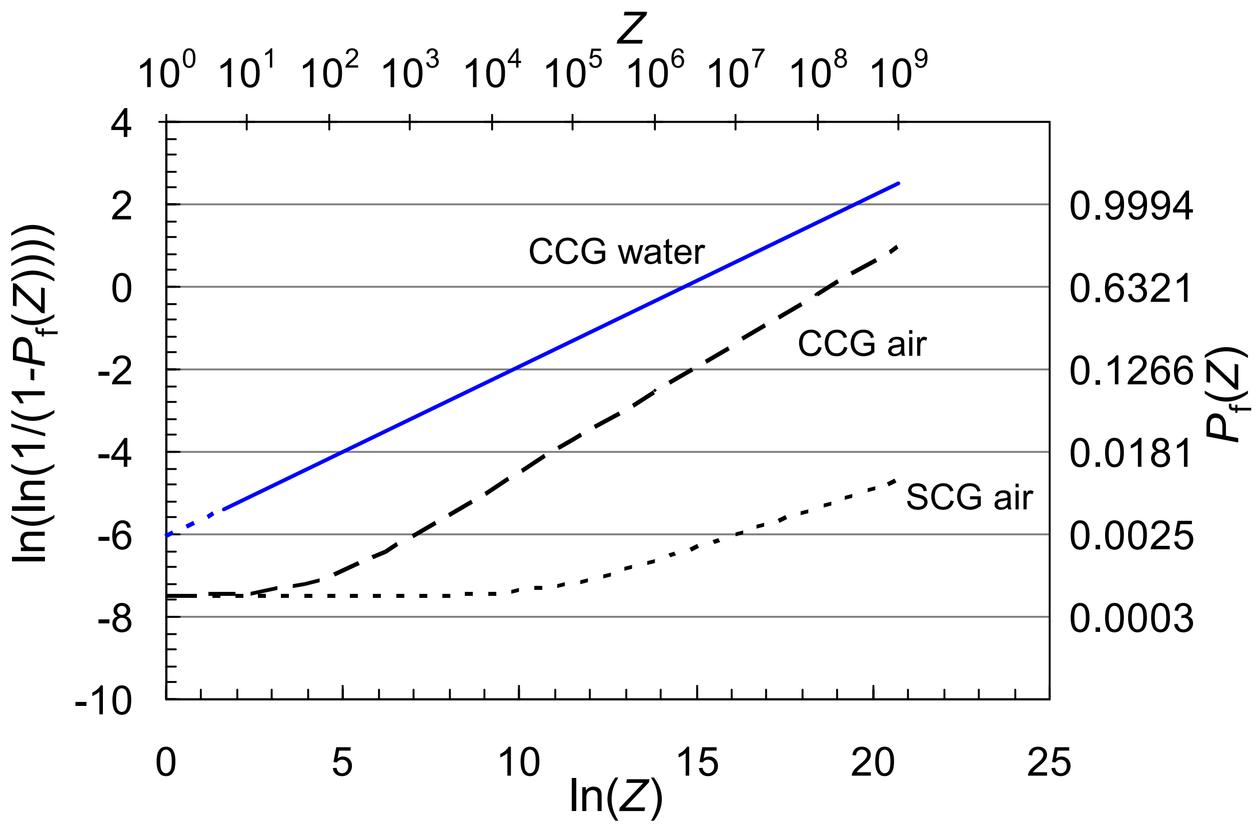




- STAU: probability of the initiation of <u>one</u> flaw in the considered subarea
- Size of subarea ↔ crack density
- Results refer to crack density of 1 crack per 250 µm along the circumference

Results: Failure probability

- Probability to initiate one macroscopic crack every 250 µm



- Weibull function

$$P_{\mathrm{f}} = 1 - \exp\left[-\left(\frac{Z}{N_0} \right)^m \right]$$

m – slope of the curve

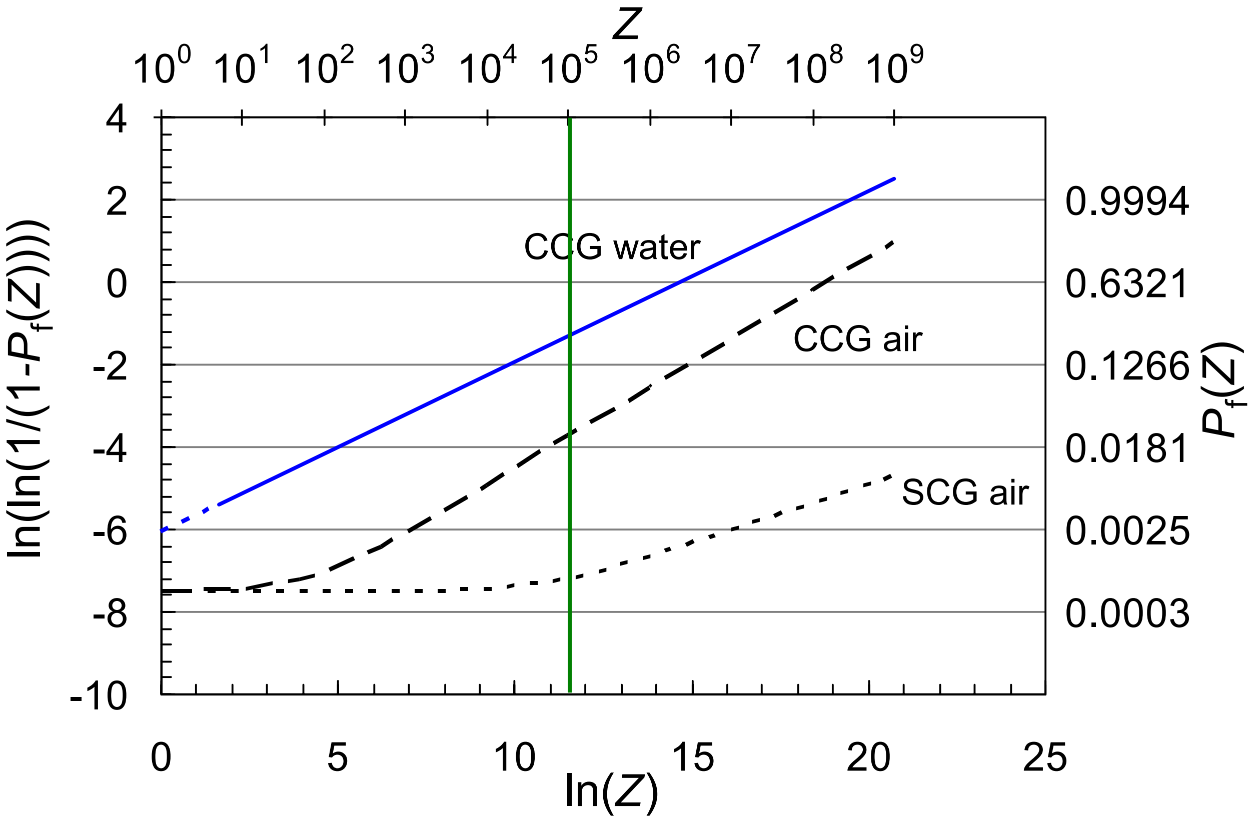
N_0 - characteristic lifetime (63%-quantile)

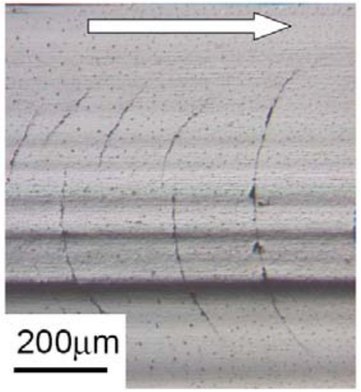
Z – no. of rotations

- Highest failure probability obtained for fatigue parameters in water.

Results: Failure probability

- Relation with experimental crack density after 10 h

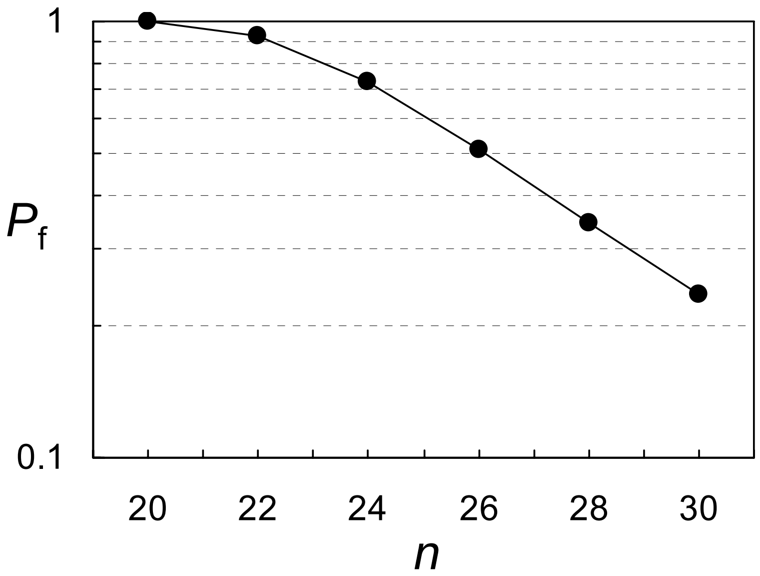


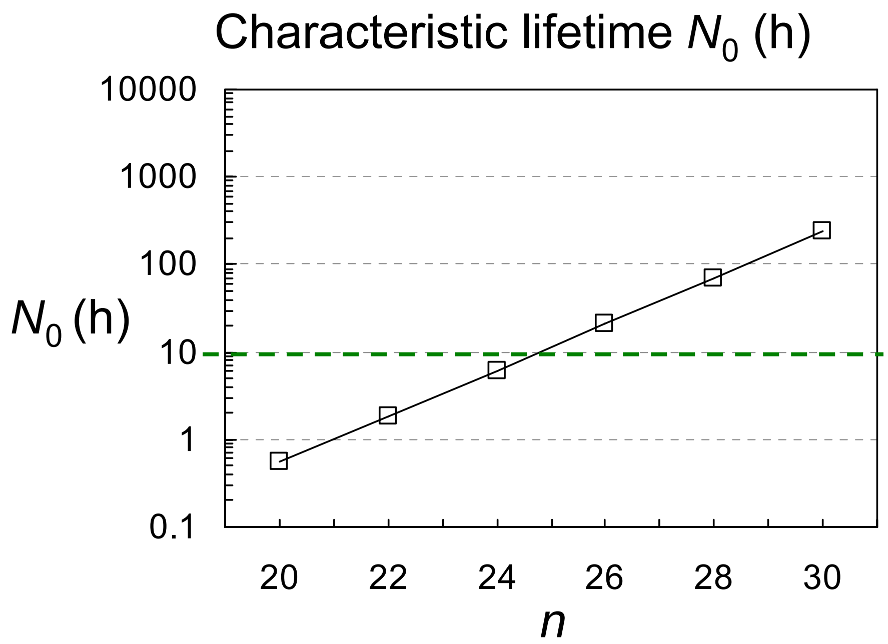


- Initiation probability low for parameters in (air)

Results: Parametric study

- Influence of crack growth exponent *n*

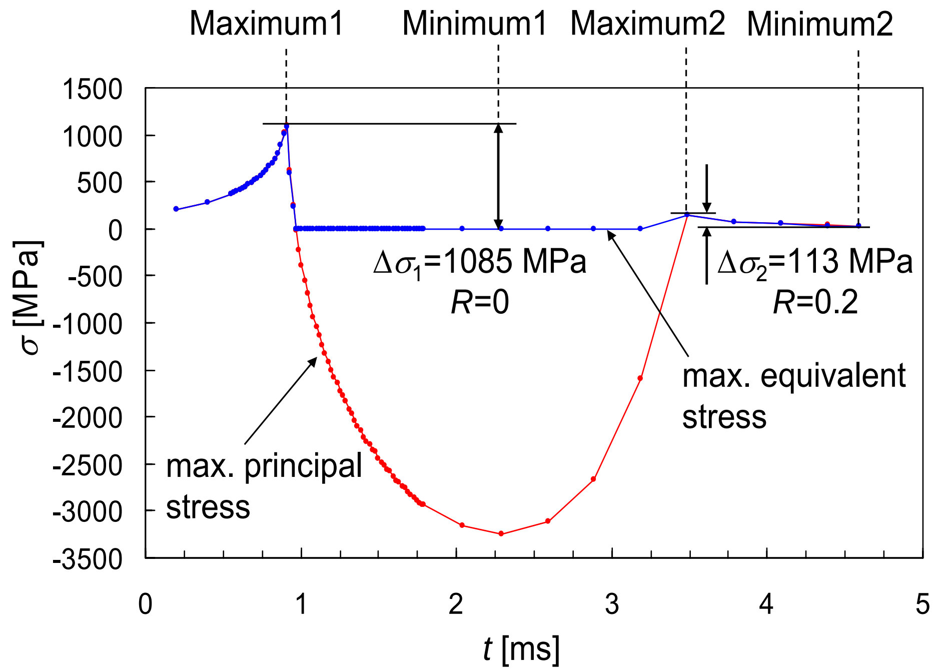




- Crack growth exponent has a strong influence on the results:
  For n<25, crack initiation probability is >70%;
  Characteristic lifetimes are below 10 h

Discussion

- Agreement with experimental results for lower *n*-values if water parameters are used



- Stress history: R=0 dominates

➔ Using a lower n value (n≈20) in the case of water.

- Limitations of the analysis scheme:

- Stress gradients in the range of natural flaws
- Interaction of macroscopic cracks
- Wear

Summary

- STAU as general tool for reliability assessment under complex loading
- prediction of evolving crack patterns on roll surface is possible
- sensitivity to crack growth parameters is challenging

Acknowledgements

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Deutsche Forschungsgemeinschaft DFG

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