Effect of Residual Stresses on Safe Life Predictions of Railway Axles

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- Effect of R.S. on calculated residual life
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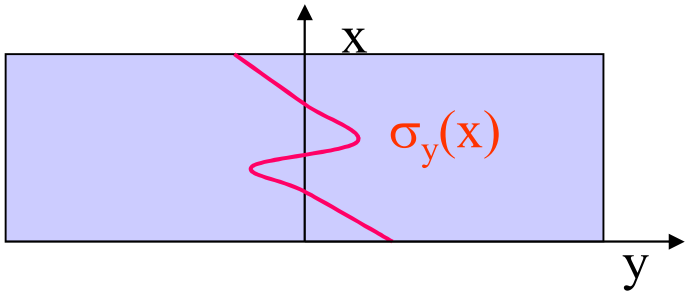
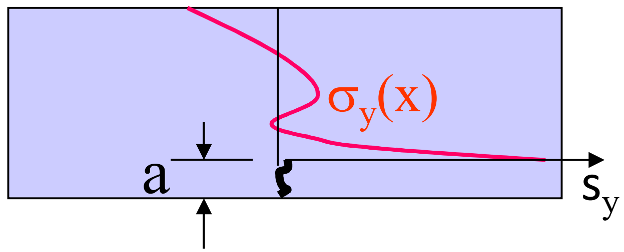
Effect of residual stress on fatigue load of a crack





SIF due to residual stress:

$$K_{Irs} = \int_0^a \sigma_y(x) \cdot h(x,a) \cdot dx$$

Total SIF:

$$K_I = K_{Iapp} + K_{Irs}$$

Fatigue crack load:

$$\Delta K = \Delta K_{app}$$

$$R(a) = \frac{K_{\min}(a) + K_{Irs}(a)}{K_{\max}(a) + K_{Irs}(a)}$$

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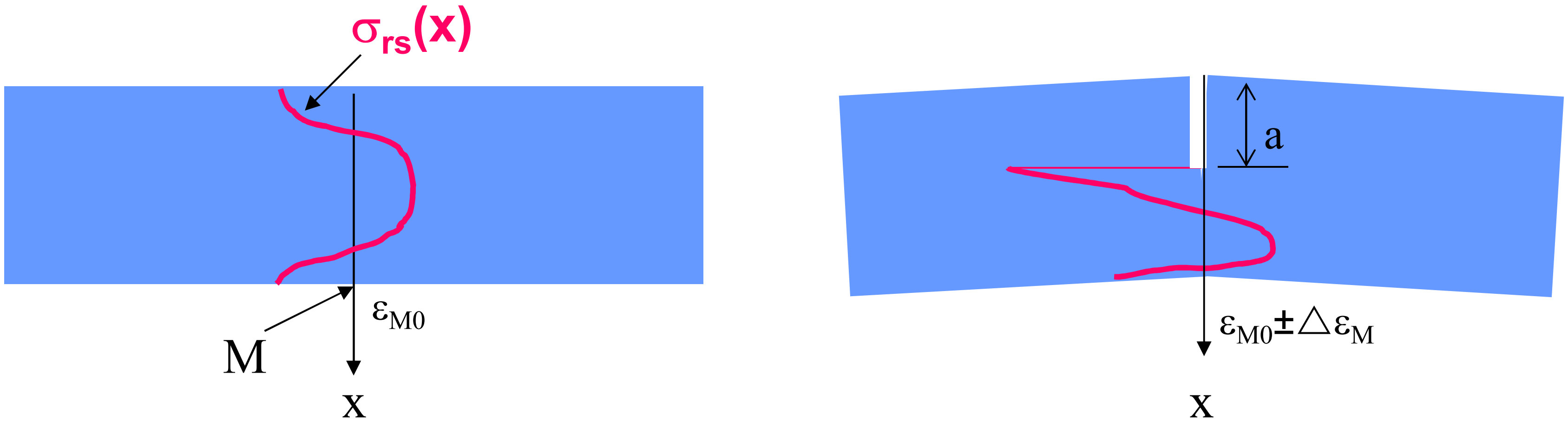
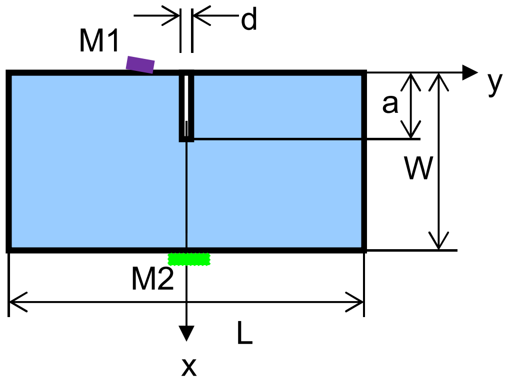
Measurement of residual stresses by the Cut-Compliance-Method

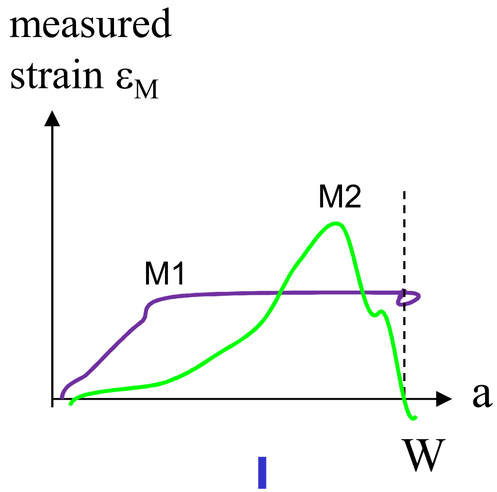
Measurement principle:



- Incremental cutting along x causes re-distribution of the stress-field in the vicinity of the cut
- The changing stress-field leads to a change of strain at the measurement location M as a funtion of cut depth a, $\varepsilon_M(a)$.
- From the meassured curve $\varepsilon_M(a)$ the original stress-distribution $\sigma_{rs}(x)$ can be evaluated by an inverse elastic analysis

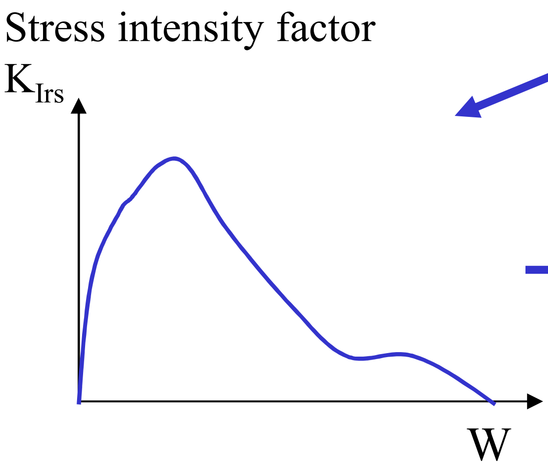
Evaluation procedure



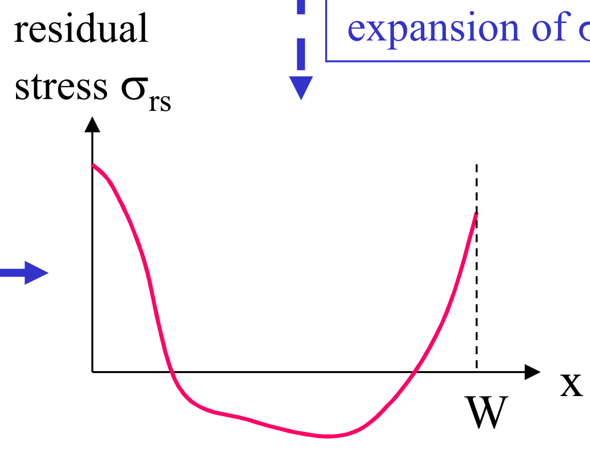


fracture mechanics

$$K_{Irs} = \frac{E'}{Z(a)} \cdot \frac{d\varepsilon_M}{da}$$



inversion by series expansion of $\sigma_{rs}(x)$



inverse analysis

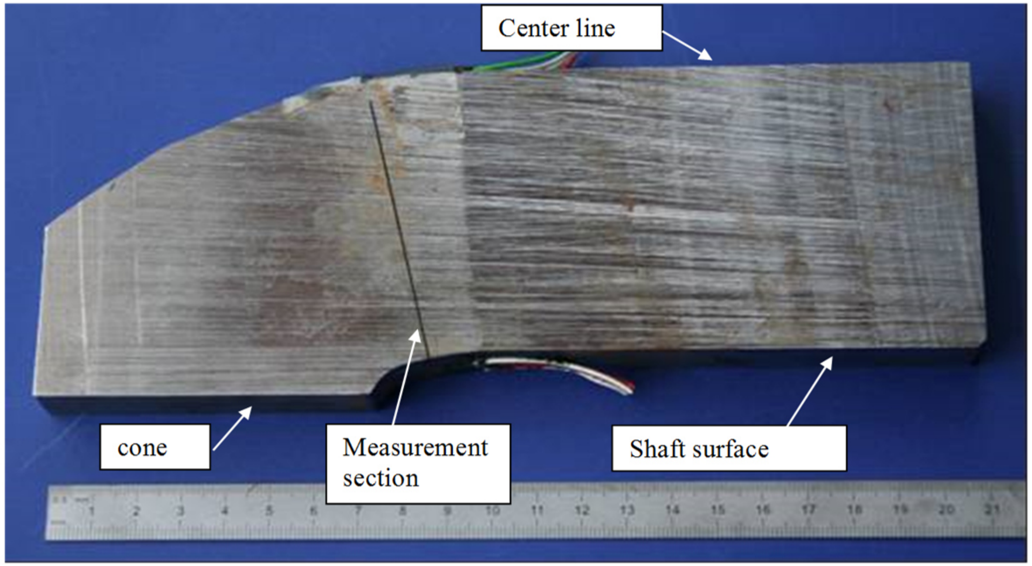
$$K_{Irs}(a) = \int_0^a h(x,a) \cdot \sigma_{rs}(x) \cdot dx$$

Z(a): influence function

h(x,a): weight function

Residual stress measurements in railway axles

a) Destructive mode of application:



Through-the-thickness measurement by an axial slice

b) Semi-destructive mode:

Near-surface measurement

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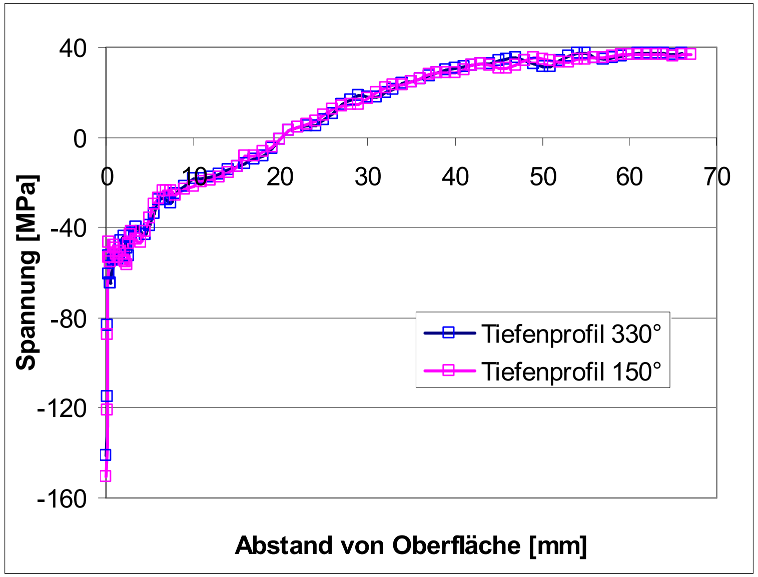
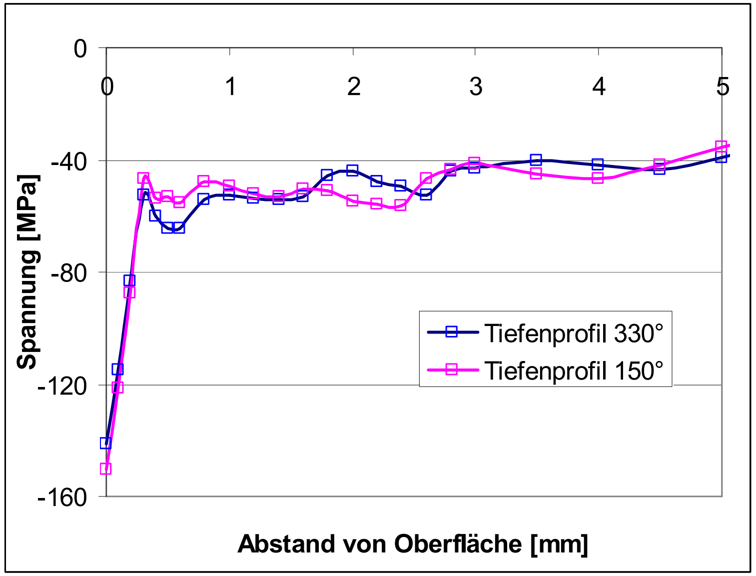
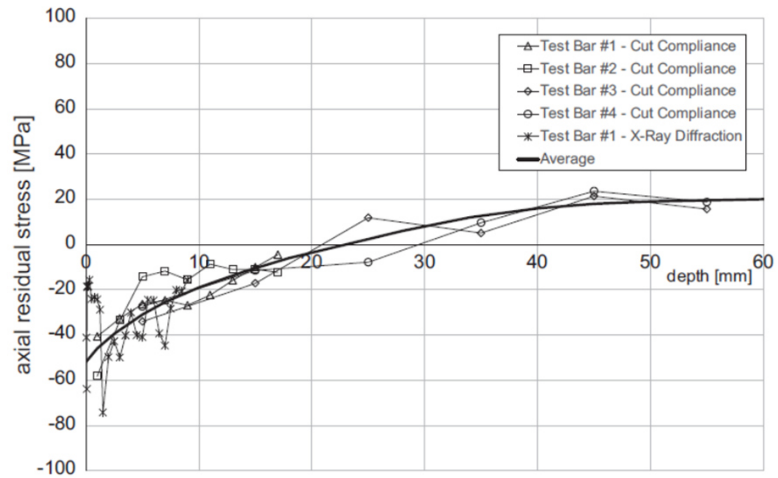
Measured residual stress distribution





For comparison:

Results from Gänser et.al, IJF, 2016:



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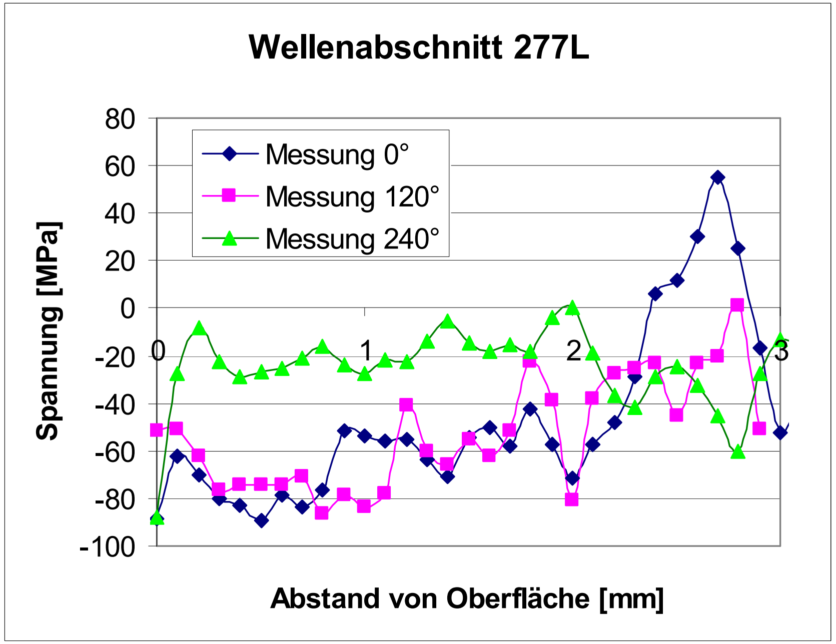
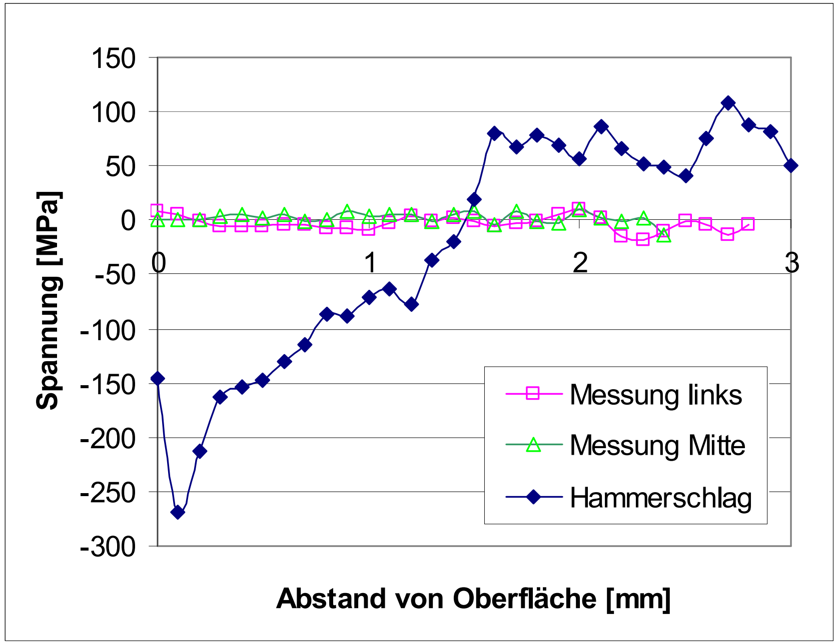
Examples of near-surface stress profiles





Variability of residual stress profiles along cercumference

For comparison:

- Residual stress profiles after stress relieving (red and green curves)
- due to to a slight manual impact by a steel hammer (blue curve)

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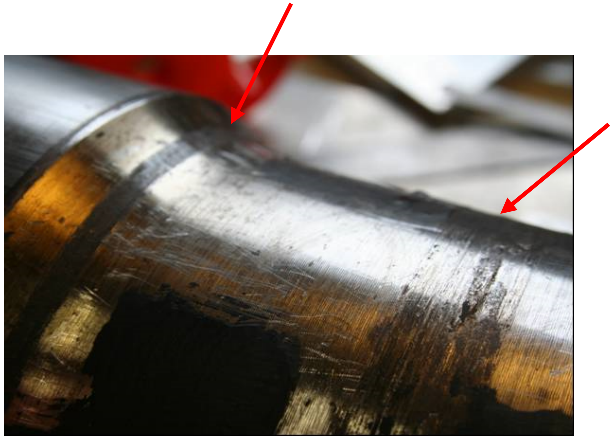
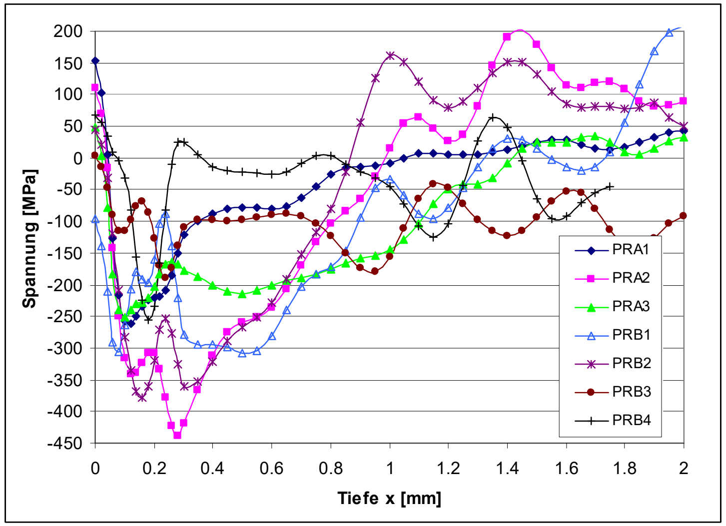
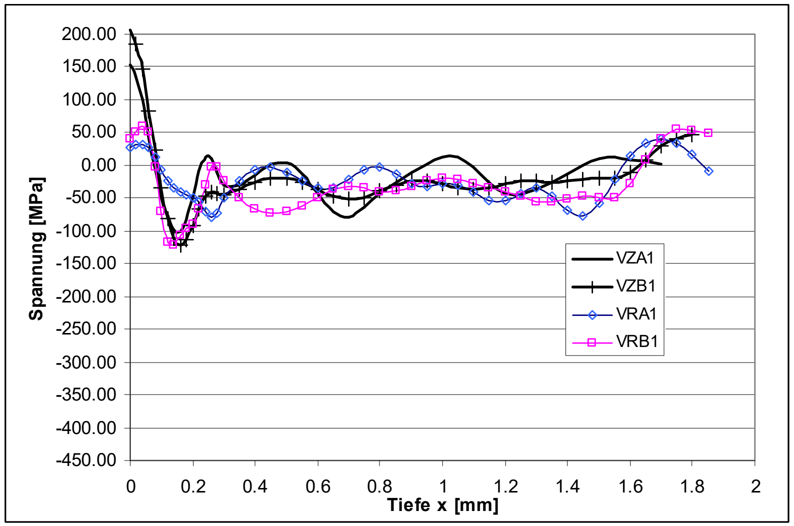
Examples of near-surface stressprofiles



Axle with visibel traces of contact with friction



Stress profiles in regions of friction



Stress profiles at locatuins unaffected by friction

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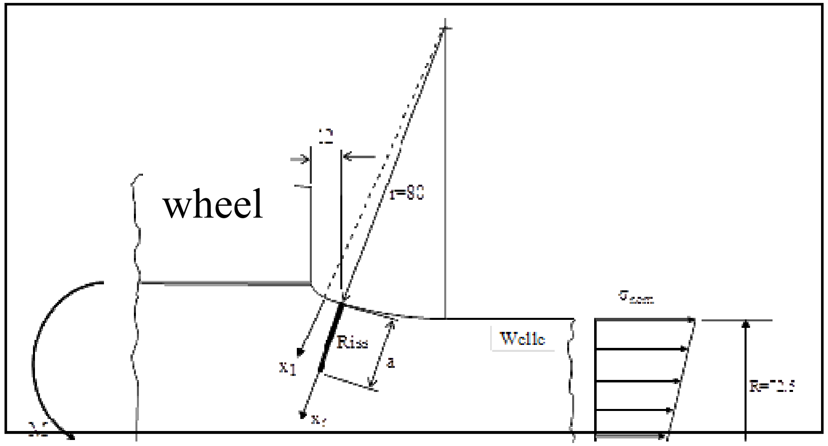
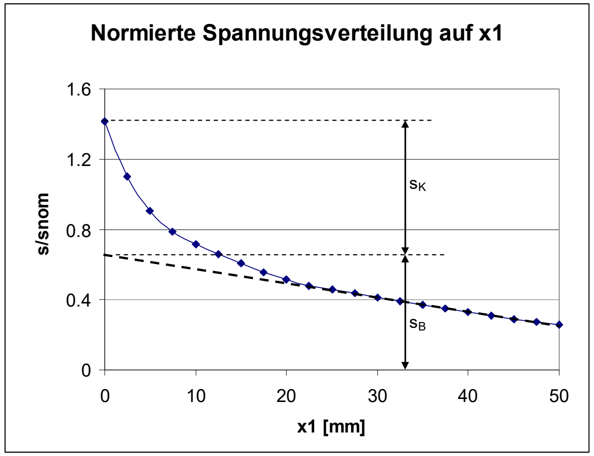
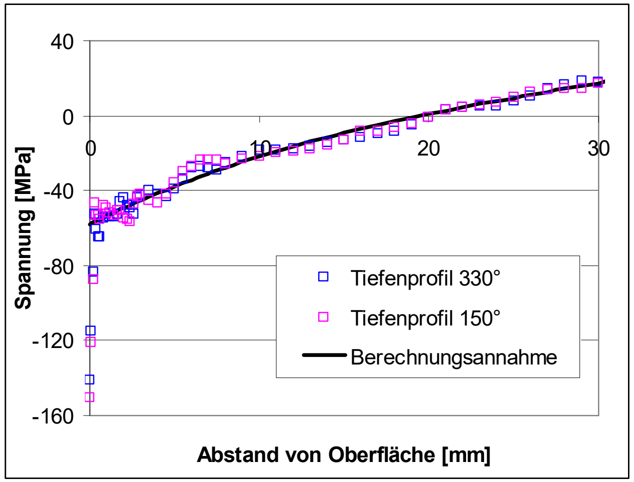
Stresses at location of maximum service stress

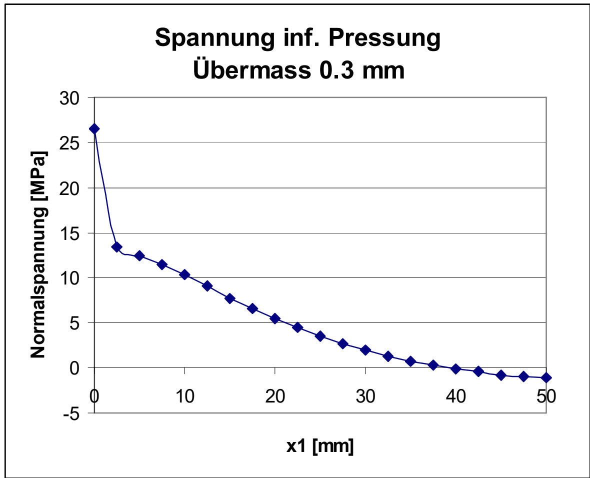




Stress due to service load

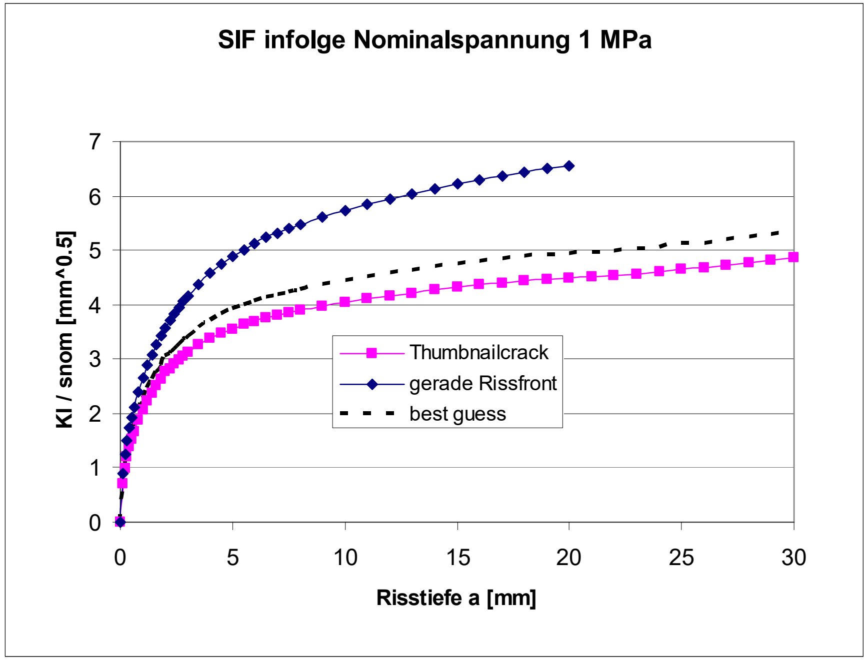


Residual stress

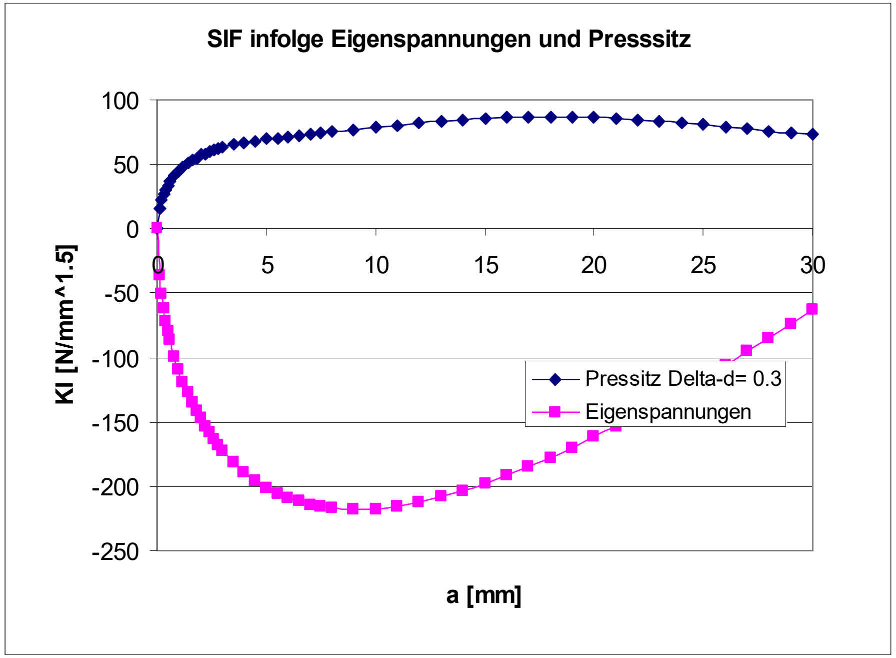


Stress due to press-fitting of wheel

Stress intensity factors for surface cracks at critical location



$K_I(a)$ due to primary stresses (normalized)



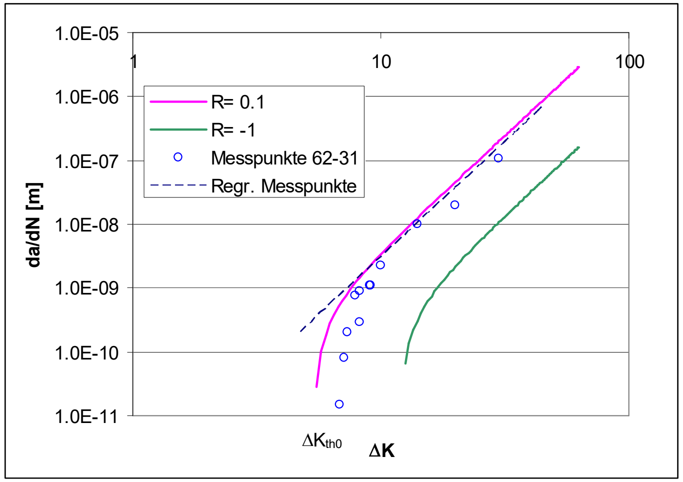
$K_I(a)$ due to residual stresses (red) and due to press-fitting (blue)

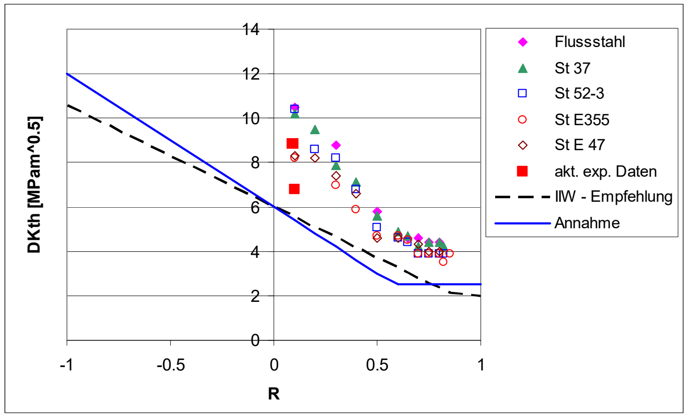
Calculation of crack growth in service

$$\frac{da}{dN} = C(R=0)\cdot(\Delta K_{eff}^{n} - \Delta K_{th}^{n})$$

$$K_{eff} = K_{max} = \frac{\Delta K}{1-R}$$

$$R = \frac{-\sigma_{nom}\cdot k_{Nom}(a) + K_{Res}(a) + K_{Ei}(a)}{\sigma_{nom}\cdot k_{Nom}(a) + K_{Res}(a) + K_{Ei}(a)}$$





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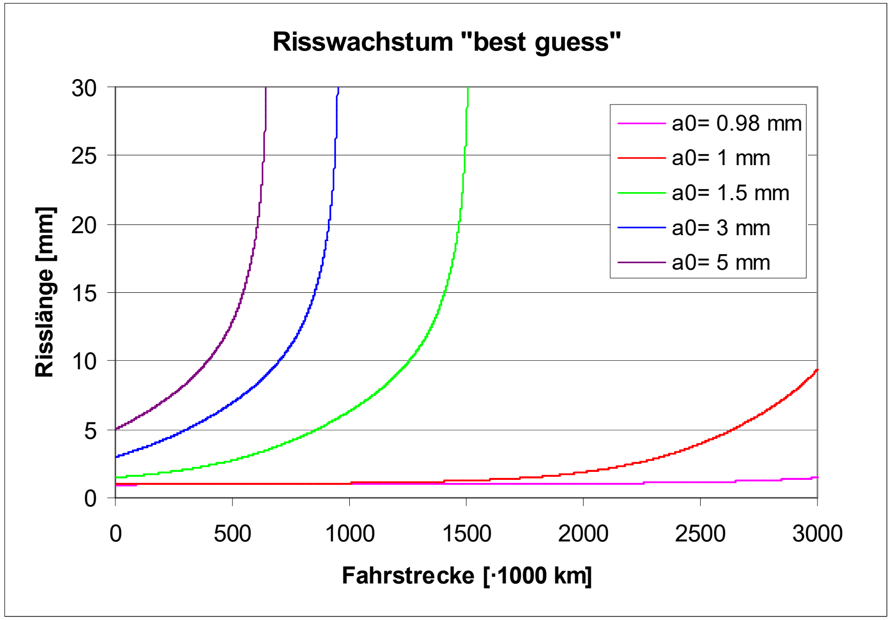
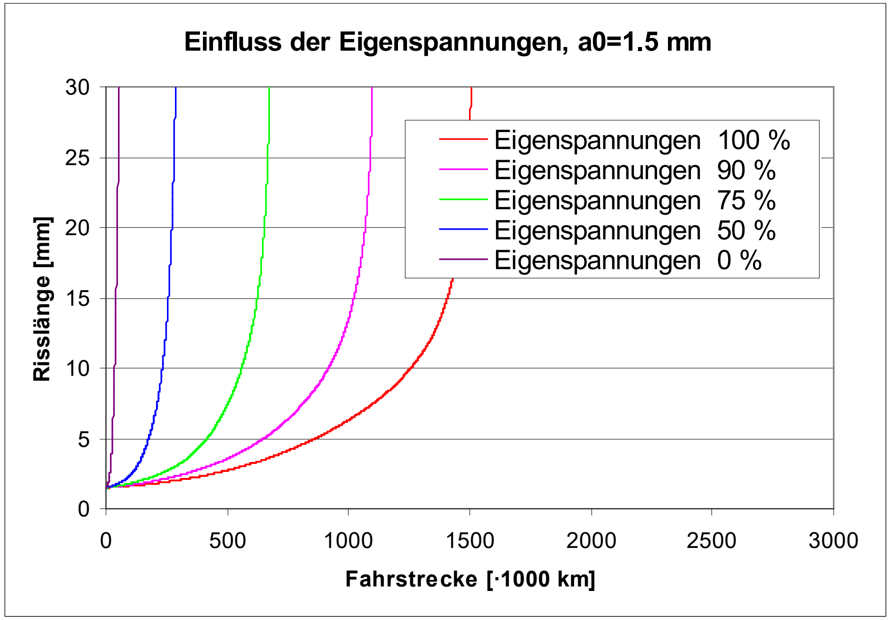
Results



Effect of initial crack depth on residual life



Effect of residual stress on residual life

Conclusions

- Residual stresses have a tremendous effect on crack-growth rate under rotating bending
- Accounting for residual stresses is indispenable in residual life calculations of railway axles
- If there are significant compressive stresses at depth 1 mm – 10 mm, the near-surface residual stresses (depth < 0.5 mm) are not crucial.
- Typical (reliable) residual stress distributions should be known for the materials and fabrication procedures of axles in question
- Details of the da/dN-modelling in the near-threshold regime and crack closure are of key importance
- It is likely that there is an interaction between residual stress and crack-closure effects, particularly for R<0. It should be accounted for in the crack-growth laws

⇨ Revisiting fundamentals of fatigue crack growth (such as Paris' law or NASGROW-equation) is advisable.

Revisiting Paris'law

Paris'law (empirical): $\frac{\Delta a}{\Delta N} = C(R) \cdot \Delta K^{m}$

Analytical relation: $\frac{\Delta a}{\Delta N} = C_i \cdot \frac{E}{R_{p0.2}} \cdot \frac{(\delta_{max} - \delta_{min})^2}{\delta_{cf} - \delta_{max}}$ with $\delta = \frac{K_I^2}{m \cdot E \cdot R_{p0.2}}$

Simplified version: $\frac{\Delta a}{\Delta N} = C_\delta \cdot \Delta\delta^{m} = C_\delta \cdot (\delta_{max} - \delta_{min})^{m}$

or in terms of SIF: $\frac{\Delta a}{\Delta N} = C_K \cdot (K_{max}^2 - K_{min}^2)^{m}$

Most important factors that corrupt transferability:
- Residual stresses
- Crack closure

Revisiting crack closure effects

Extension of crack-growth law to include crack closure:

$$\frac{\Delta a}{\Delta N} = C_\delta \cdot \left(\delta_{max} - \delta_{op\ pl} - \delta_{th\ int}\right)^m$$

in terms of SIF:

$$\frac{\Delta a}{\Delta N} = C_K \cdot \left(K^2_{max\ tot} - K^2_{op\ pl} - K^2_{th\ int}\right)^m$$

crucial for transferability

with:

$$K_{max\ tot} = K_{max} + K_{res} \qquad \Delta K_{th\ int} = E \cdot \sqrt{b}$$

$$K_{op\ pl} = f(R_{eff}) \cdot K_{max\ tot} \qquad R_{eff} = \frac{K_{op\ remote}}{K_{max\ tot}} \quad (> 0)$$

Remote crack closure:

$$K_{op\ remote} = m \cdot E \cdot R_{p0.2} \cdot \left(\delta_{corr} + \delta_{rough} + \delta_{pl\ max}\right) \qquad (> 0!\ )$$

Corrosion-induced | Roughness-induced | Plasticity-induced

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Effect of residual stress and geometry on crack closure

Geometry
stress state (3D)
$R=K_{min/tot}/K_{max/tot}$
load sequence

local closure

$$K_{op\,p} = K_{max\,tot} \cdot f(R_{eff})$$

crack growth

remote closure

$$K_{op\,remote}$$

$$K_{max\,tot} = K_{max} + K_{res}$$

$$R_{eff} = \frac{K_{op\,remote}}{K_{max\,tot}}$$

1:1-tests,
field experience

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