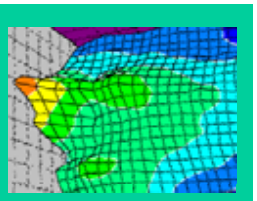
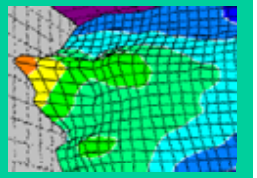


Structural Health Monitoring an Großanlagen unter Anwendung von Multisensorsystemen und fraktalbasierten Auswerteverfahren

Jürgen Schreiber

Fraunhofer Institut für
Zerstörungsfreie Prüfverfahren
Institutsteil Dresden



Introduction

Challenge:
Characterisation of the material damage state without baseline

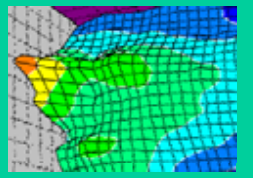
Save and economic service of
safety relevant industrial components

Reliable evaluation of the fatigue damage , forecasting of the residual life time

Maximal usage of the whole service life time, definition of actions

Search for suitable NDT-methods
either for
regular inspection
or

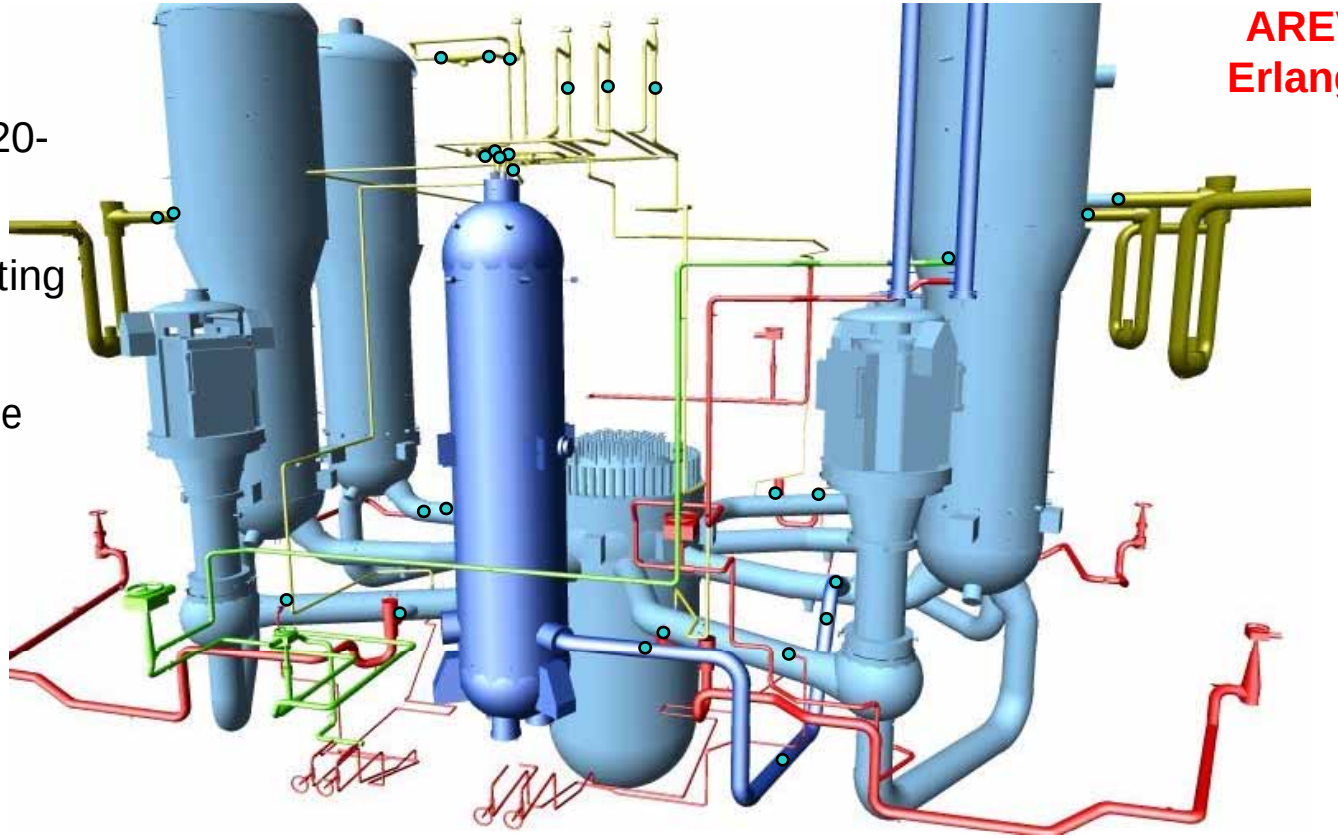
Structural Health Monitoring



Introduction

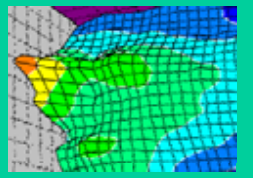
Fatigue Monitoring in nuclear power plants

Up to 150 thermocouples in 20-50 measurement sections
plus signals of existing operational instrumentation
for residual life time estimation



AREVA Erlangen

Materials damage ← → Safty



Introduction

Components of brown coal open cast mining

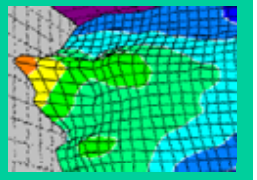
System of strain gauges are displaced to control load and to assess the service strength

Vattenfall Europe Cottbus

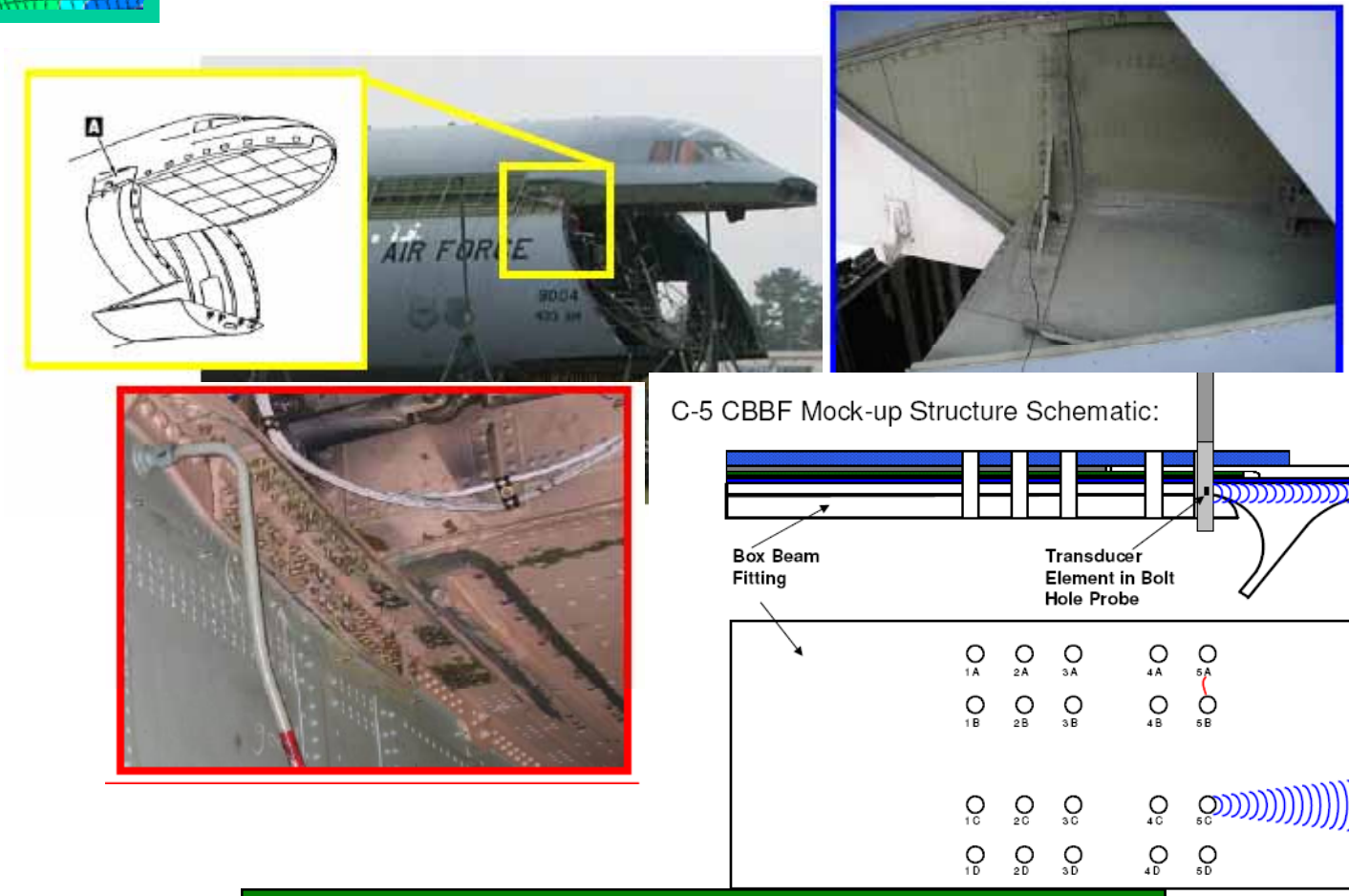
Cyclic load

Aging

Materials damage ← → Residual service life time ?

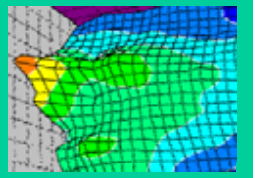


Introduction



Materials damage ← → Actions?

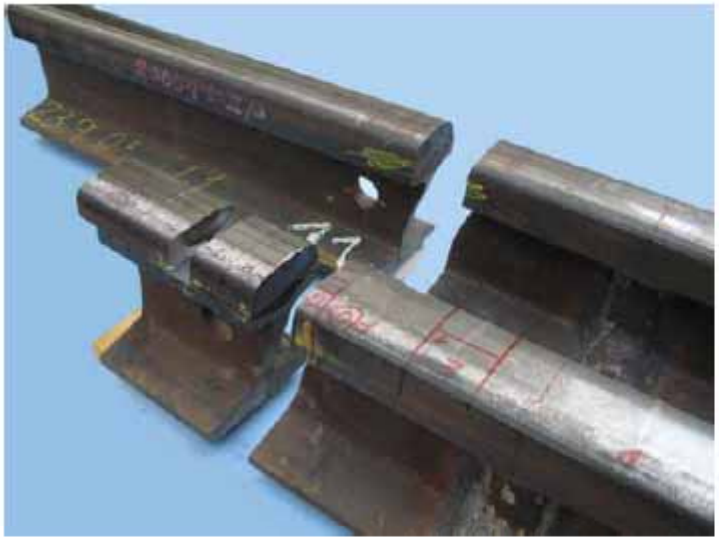
Fraunhofer IZFP Institut Zerstörungsfreie Prüfverfahren



Introduction

Integrity of Railway Structures

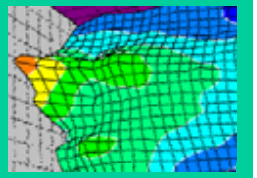
Wiener Linien



strain gauge

Tests with mobile eddy current sensor system for crack inspection

Rolling Contact Fatigue ← → Repairing in time before cracking

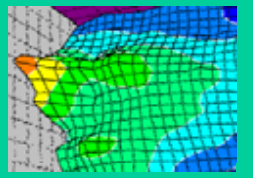


Introduction

Available NDT-methods

- Micro-thermography: Crack indicator, but too week signals from deformation structure
- US-backscattering: Multiple scattering and long propagation path strongly mask the effect of deformation meso-structures, while cracks are seen well.
- Acoustic emission: Low effect of plastic deformation, signals only due to force changes
- Potential sensor: Weak sensitivity for deformation, only crack indication
- Optical methods: Dirty surface prevent simple application
- Eddy current: Good for crack indication, but deformation?
- Barkhausen noise: Testing locally, simple and continuous noise excitation, magnetic parameters sensitive to stress and microstructure.

What can we learn from standard Barkhausen noise measurements?



State of the art in NDT

Barkhausen noise parameter versus fatigue

stress controlled (R=0; f=3 Hz, stop at necking)

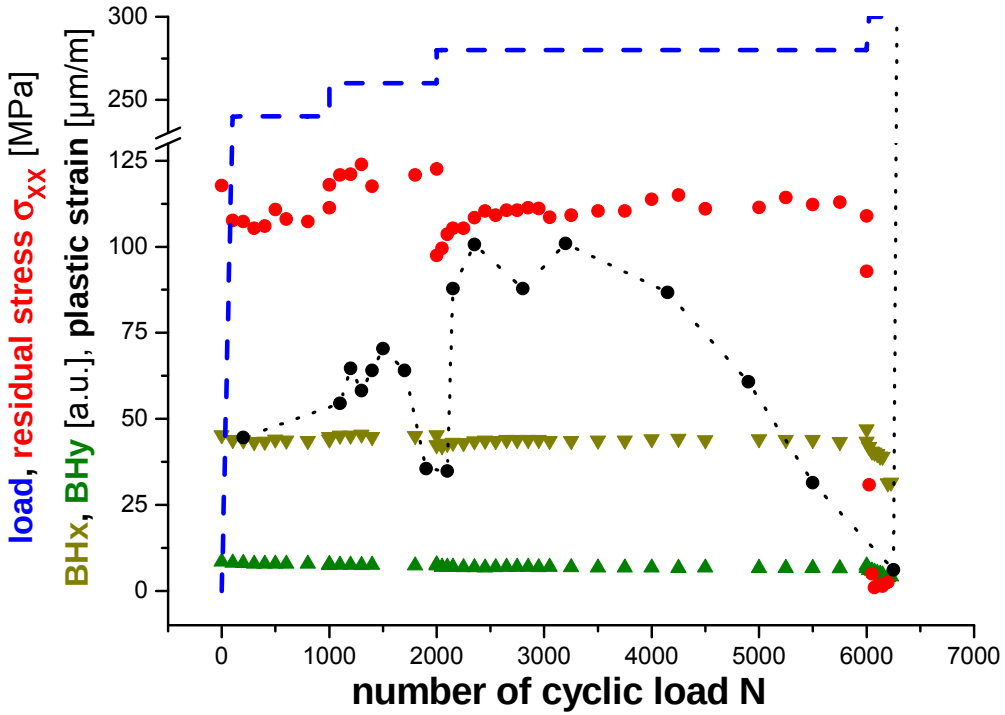
a) N=0-1000, σ_a=240MPa

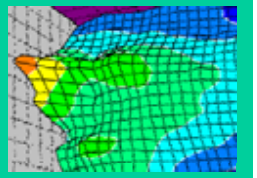
b) N=1000-2000, σ_a=260MPa

c) N=2000-6000, σ_a=260MPa

c) N=6000-6229, σ_a=300MPa

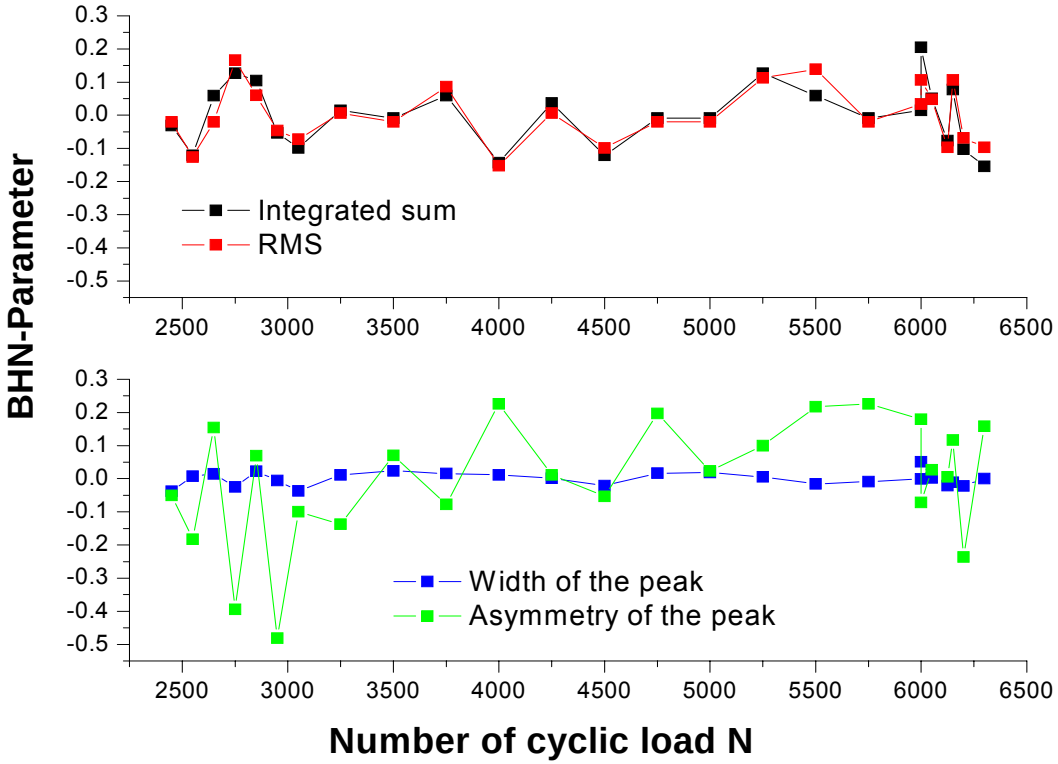
Material: 15NiCuMoNb5 (WB 36)

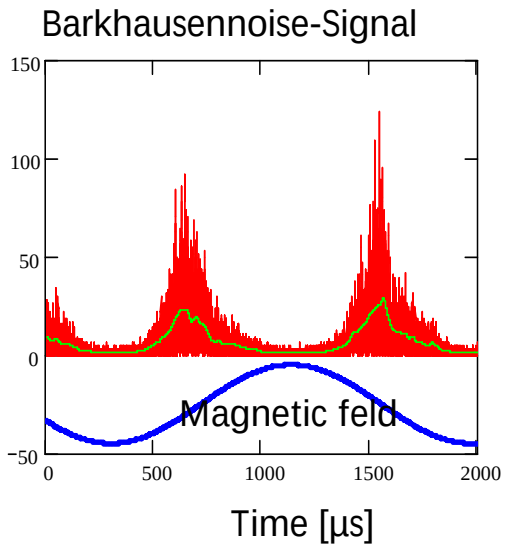




State of the art in NDT

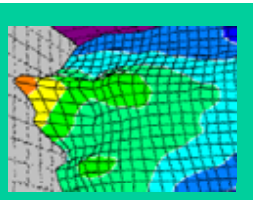
Barkhausen noise parameter versus fatigue



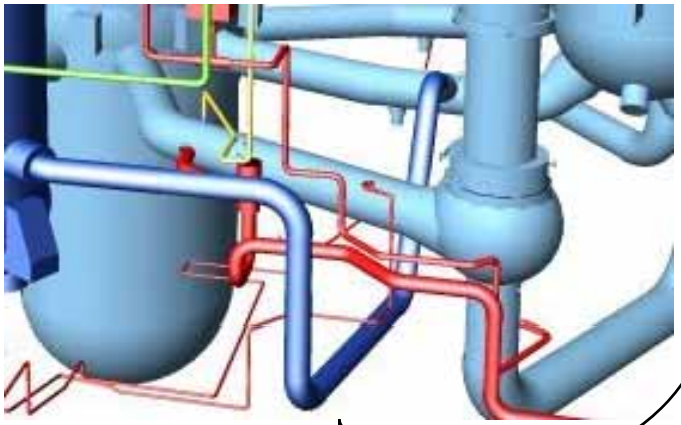


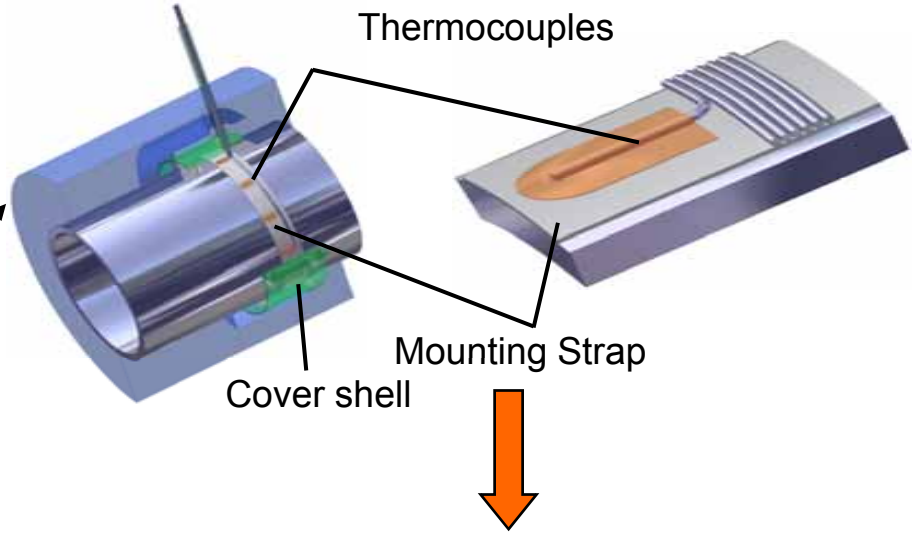
Resume:

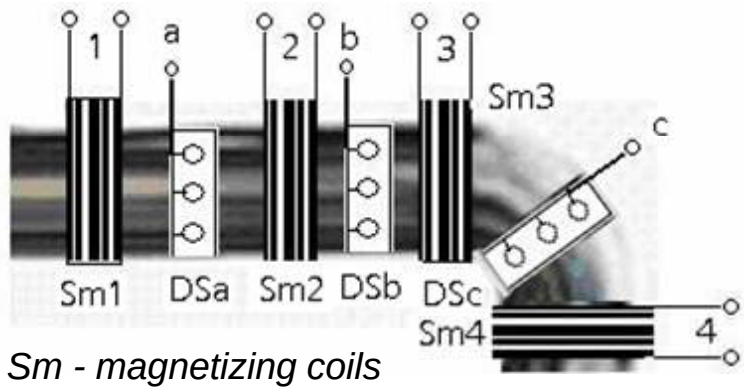
This method is not able to estimate the actual stage of fatigue!



New developments in NDT for SHM

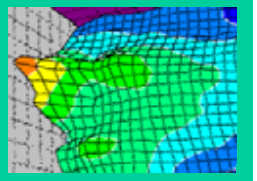




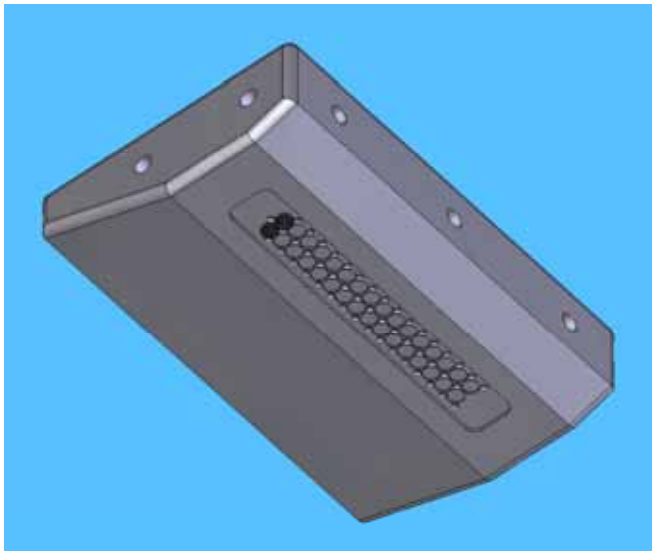


Multi-sensor systems to detect time characteristics of materials response to thermo-mechanical load

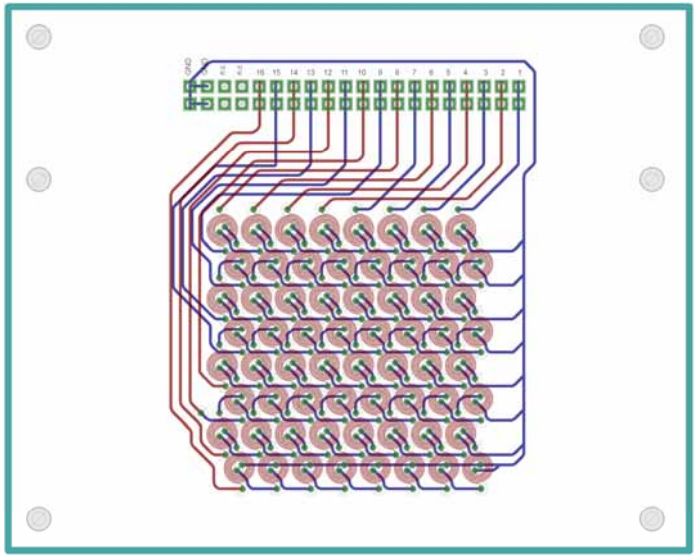
Sm - magnetizing coils
DS - detecting sensors for Barkhausen noise



New developments in NDT for SHM

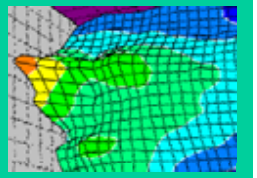


Concept of 16-element eddy current line array developed at IZFP-Dresden.



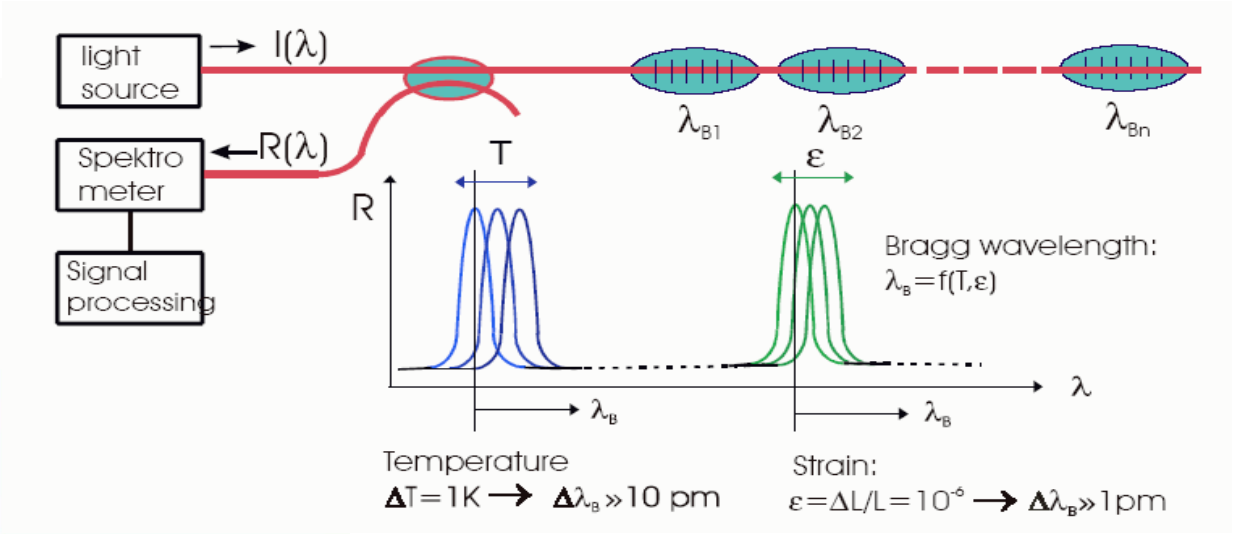
Schematic of 64-element two-dimensional eddy current array planned as foil sensor system

Array sensor system to detect Structural varying eddy current ("Grain noise")



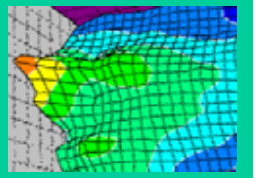
New developments in NDT for SHM

FBG sensor pads with strain and temperature sensors



Scheme of fibre Bragg grating sensor (see IPHT, Bartelt)

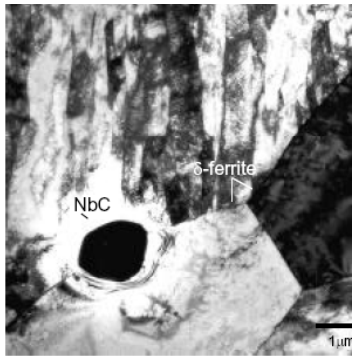
Meander type fiber Bragg grating sensor system for space-time characteristics of load as well as materials damage



Mesoscopic deformation structures

It is possible now to measure very much, however, what is the key information for the assessment of materials damage?

Micro



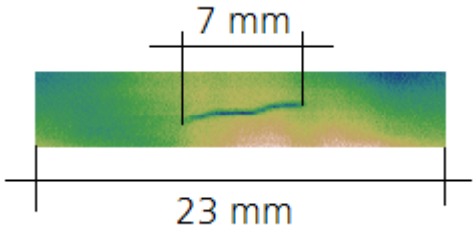
TEM-Image

Meso

Panin-Idea:

Mesomechanics

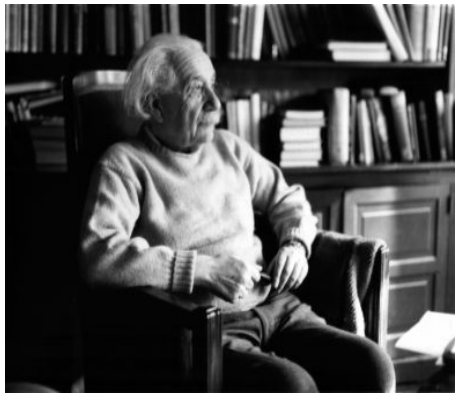
Macro



CT-Image of fatigue crack

Eine wirklich gute Idee erkennt man daran, dass ihre Verwirklichung von vorneherein ausgeschlossen erscheint.

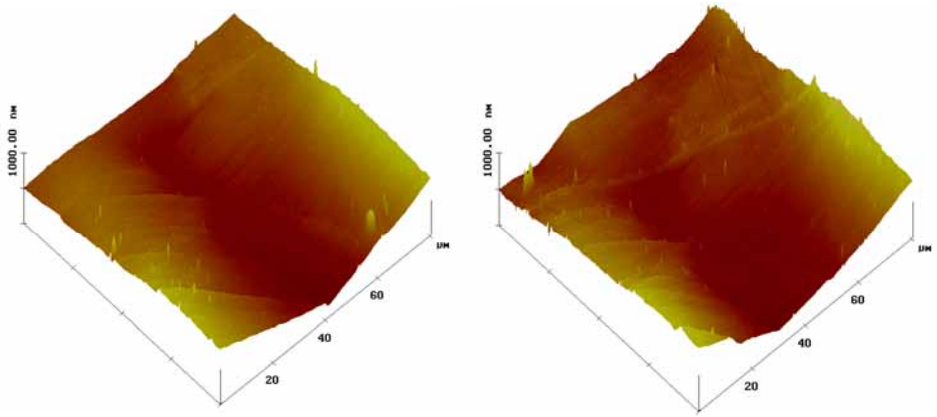
Albert Einstein (1879 - 1955)



Mesoscopic deformation structures

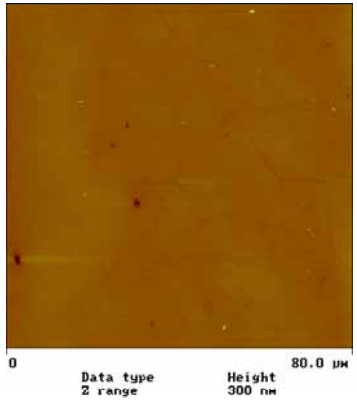
Austenitic sample

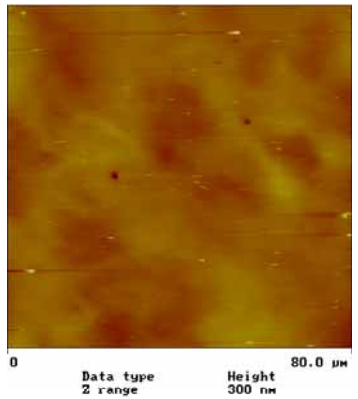
Ferritic sample

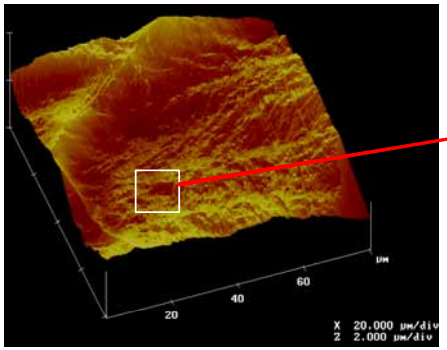


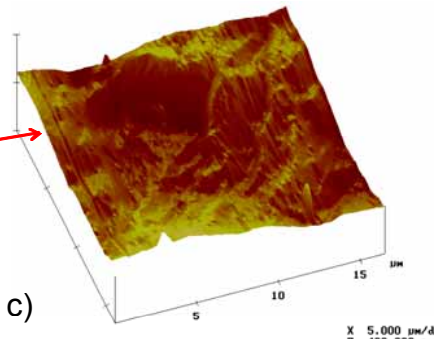
a)

b)

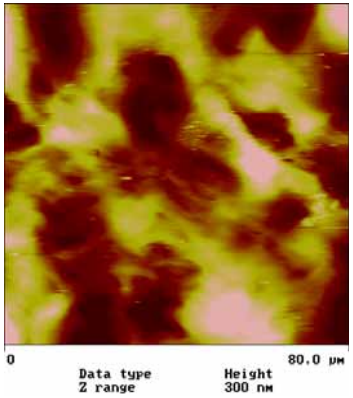


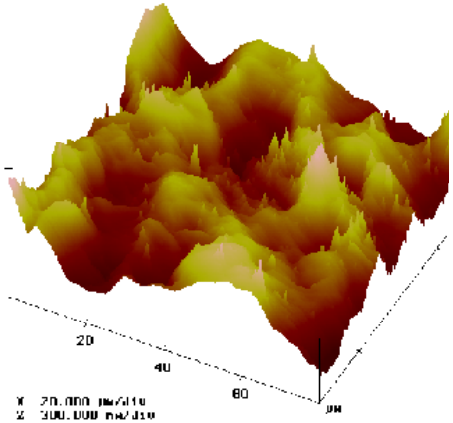






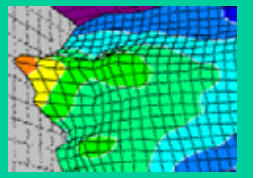
c)





a) N = 2000, b) N = 7000, c) N = 13000

What does characterise these structures?



Mesoscopic deformation structures

Theoretical und experimental basis

Mesomechanics (Panin, since 82)

Plastic deformation: Gliding locally due to stress concentrators accompanied by rotation of neighbouring grains → formation of closed structures (new structure elements) → hierarchical structure

- Dislocation pattern (Micro)
- Slip band formation (Meso I)
- Folded multi-bands (Meso II)

Suggestion:
Scaling behaviour of micro-meso-structure may characterise fatigue, fractal dimension D_F as a measure of damage?

Depinning Models ("self-organising criticality" 90ies)

(avalanches, sand pile, domain motion)
Distribution of jump heights, duration and energy as well as the power spectrum for Barkhausen noise in amorphous magnets:

$D(s) \sim s^{\alpha}$, $P(k) \sim k^{\beta}$ → scaling behaviour

Symmetry arguments point at 3 universal classes:

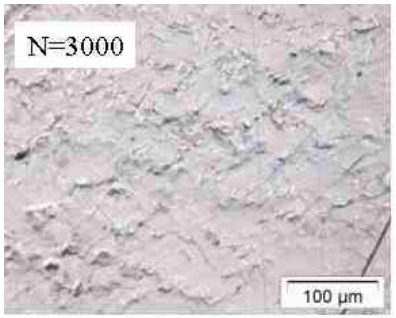
- α 1 ≈ 1.70 ⇒ 3D domains , dipole-dipole-interaction
- α 2 ≈ 1.44 ⇒ 2D domains in local fields
- α 3 ≈ 1.30 ⇒ 2D multi-domains in local fields

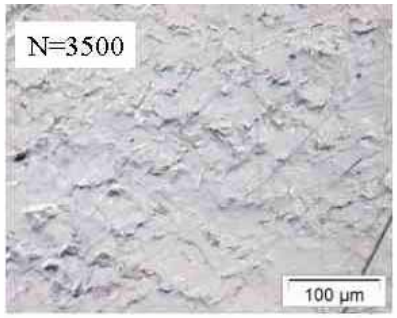
However, continuous transformation between the structures are obtained experimentally.
There are similarities between deformation and magnetic structures!

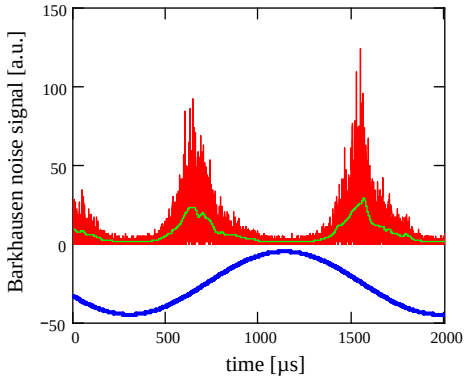
Scaling behaviour

Mesoscopic deformation structures

Scaling behaviour?







Topography $Z(R_i)$ or time signal $S(t)$

$$Z(\lambda R_i) \sim \lambda^H Z(R_i)$$

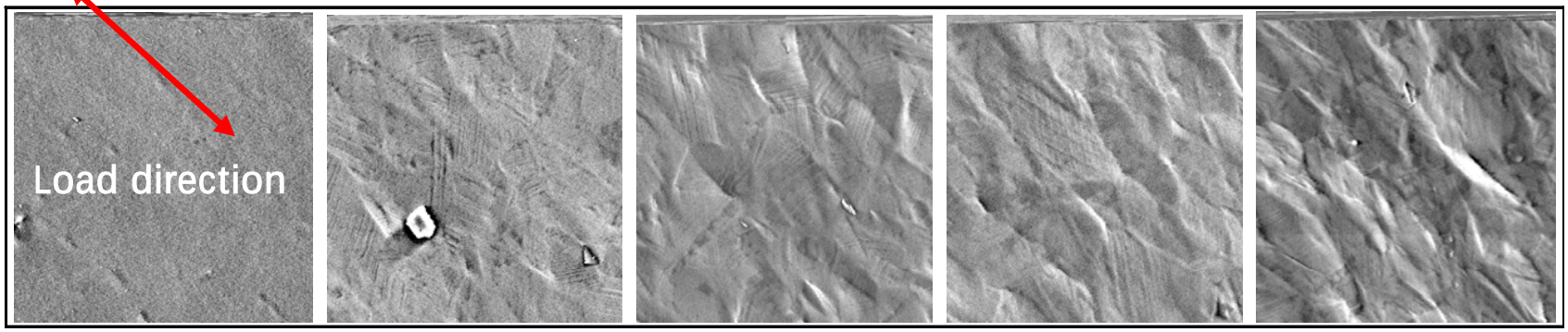
$$S(\lambda t_i) \sim \lambda^H S(t_i)$$

Fractal dimension: $D_F^{(r)} = 3 - H^{(R)}$ or $D^{(t)}_F = 2 - H^{(t)}$,

Area, length: $F(s) \sim s^{H-1}$,

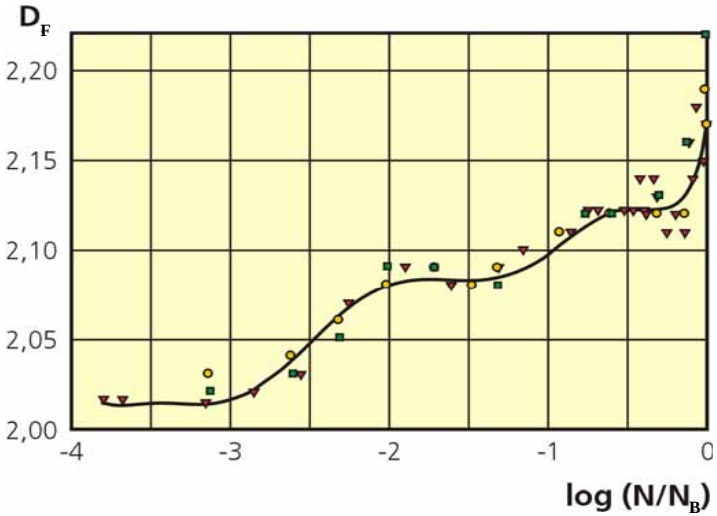
Correlation function: $C(\tau) = \langle |S(t+\tau)-S(t)|^2 \rangle_t \sim \tau^{2H}$

Mesoscopic deformation structures



Online SEM-Images

Panin, Kuznetsov, Schreiber (1998)



X6 CrNiTi 18 10

σa ~ 240, 250, 260 MPa

$\Delta D_{F21} = 0.07$

$\Delta D_{F32} = 0.04$

What is a suitable NDT-method?

Mesoscopic deformation structures

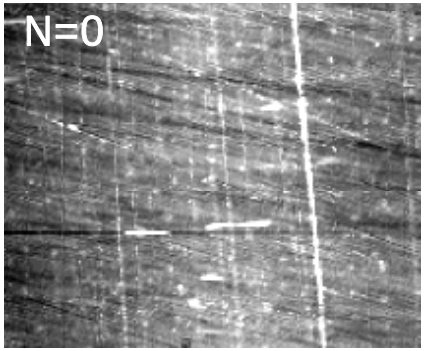
Topography and micro-magnetic structures

15 NiCuMoNb 5

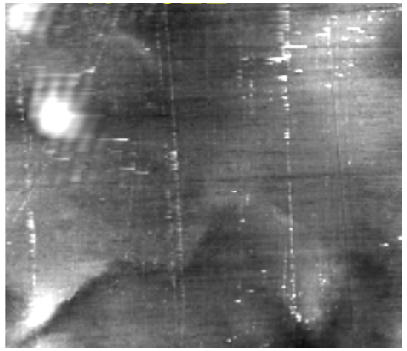
Fatigue experiment

ε_a = 0.7 %, dε /dt = 3 %/min

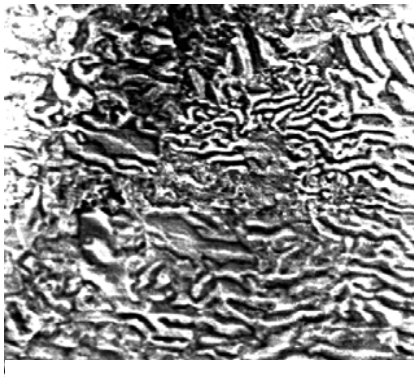
AFM-Topography



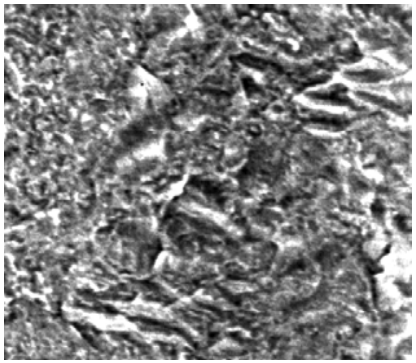
N = 622, D_F = 2.53



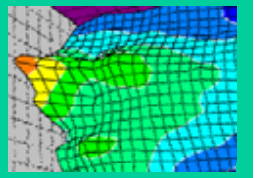
Mesostructures



MFM-Image

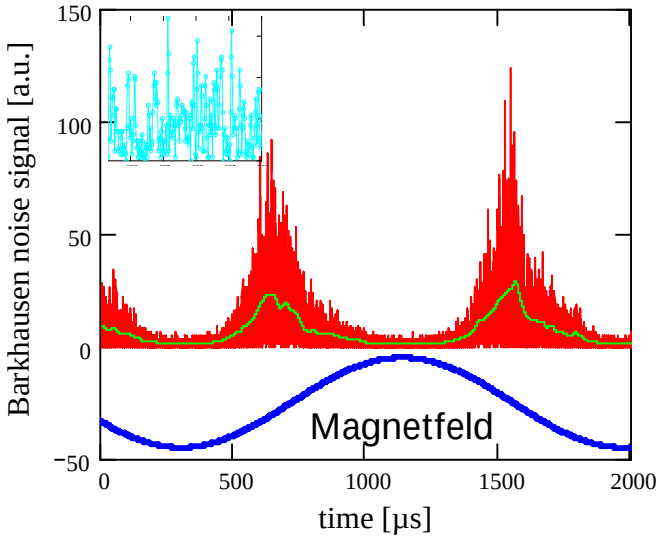


D_F = 2.50



Fractal analysis of Barkhausen noise

Magnetic Barkhausen noise

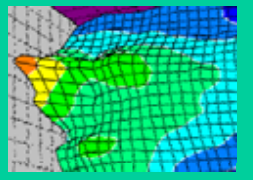


Integral parameters

1. Integrated Amplitude
2. RMS-value
3. Asymmetry (Moments)

Time series

1. Distribution of chumps
2. Powerspectrum
3. Correlation function



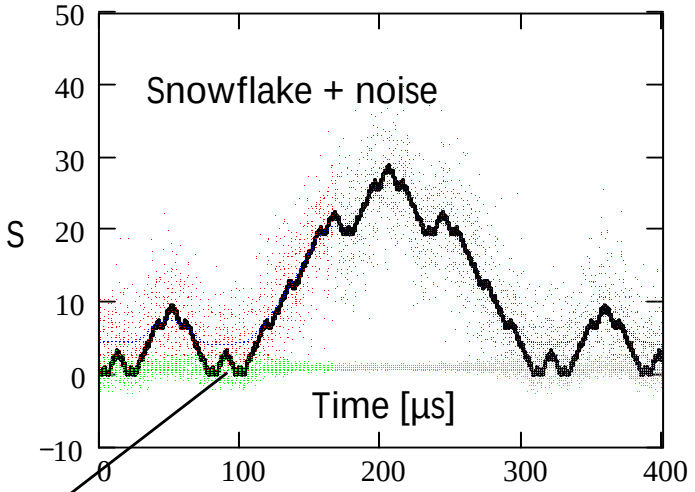
Fractal analysis of Barkhausen noise

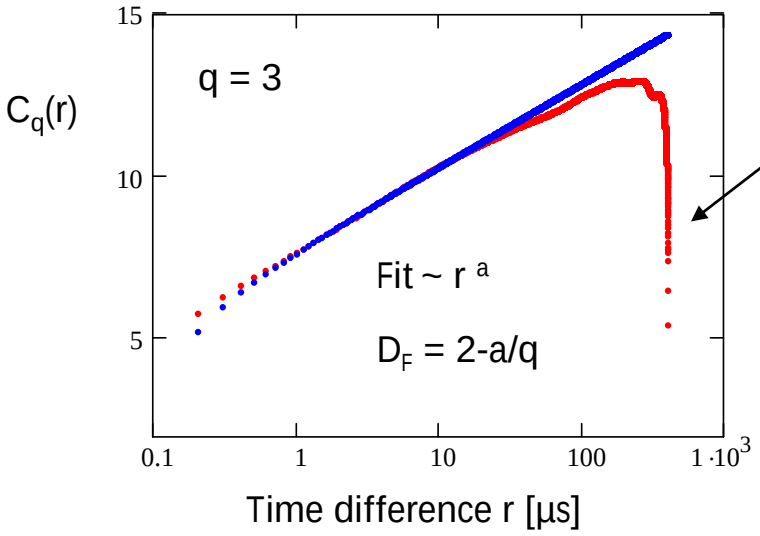
Simulation of real fractals:

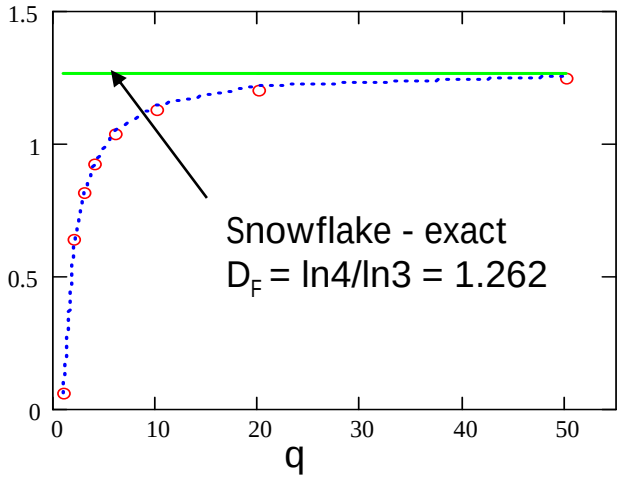
Finite time series and *random noise*

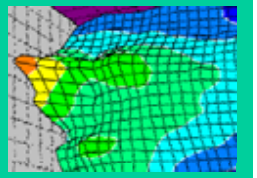
$$C_q(r) := \sum_{i=1}^{N-r} \frac{\left(\left|S_{i+r} - S_i\right|\right)^q}{N - r}$$

Analysis for the integrated time series





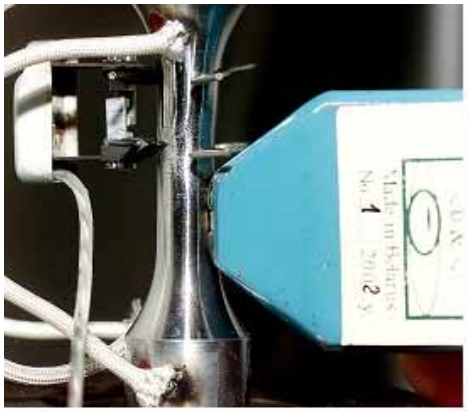


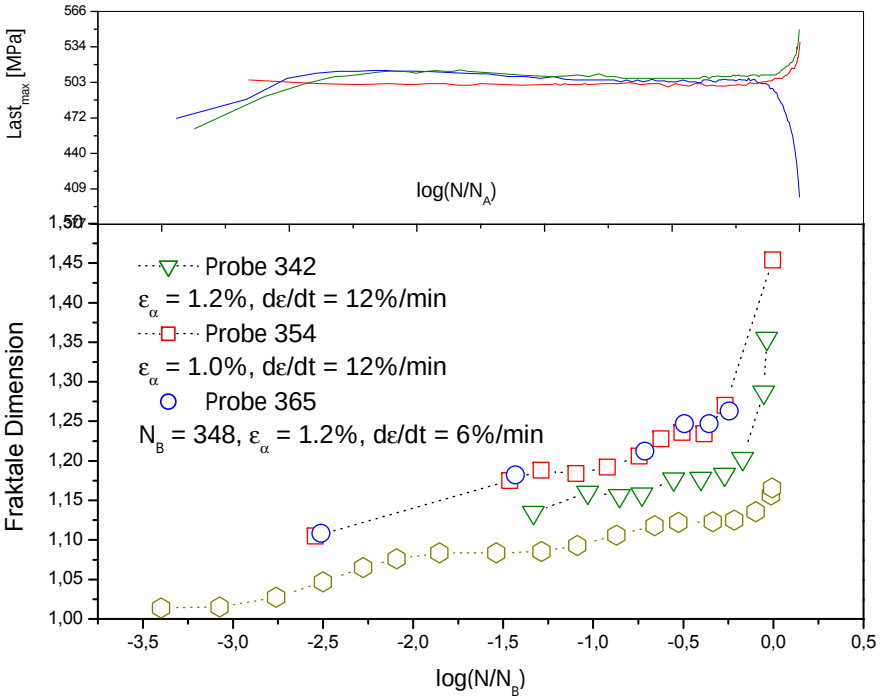


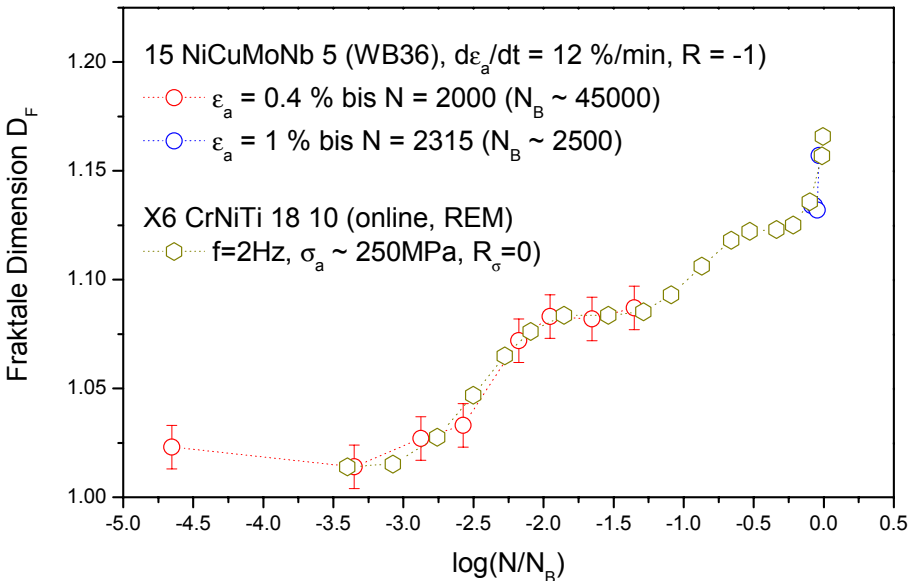
Fractal analysis of Barkhausen noise

Online fatigue experiments
(variable strain amplitude
and strain rate)

15 NiCuMoNb 5



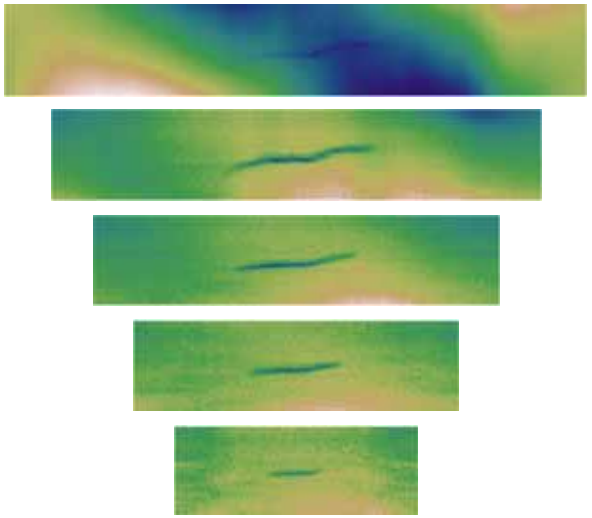




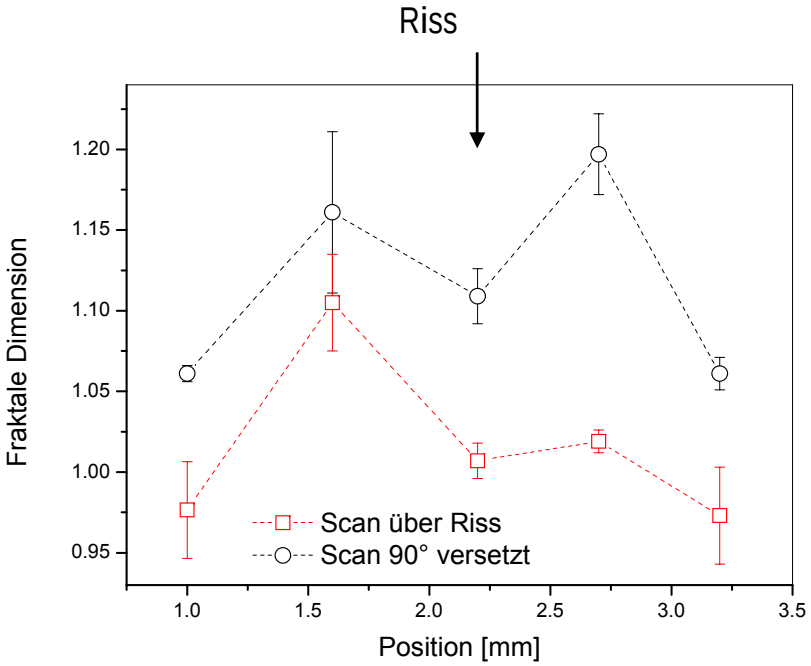
$\Delta D_F(1 \rightarrow 2) = 0.082$ (Topografie: 0.07)
$\Delta D_F(2 \rightarrow 3) = 0.045$ (Topografie: 0.04)

Fractal analysis of Barkhausen noise

Effect of cracks on D_F



Computer-Tomography

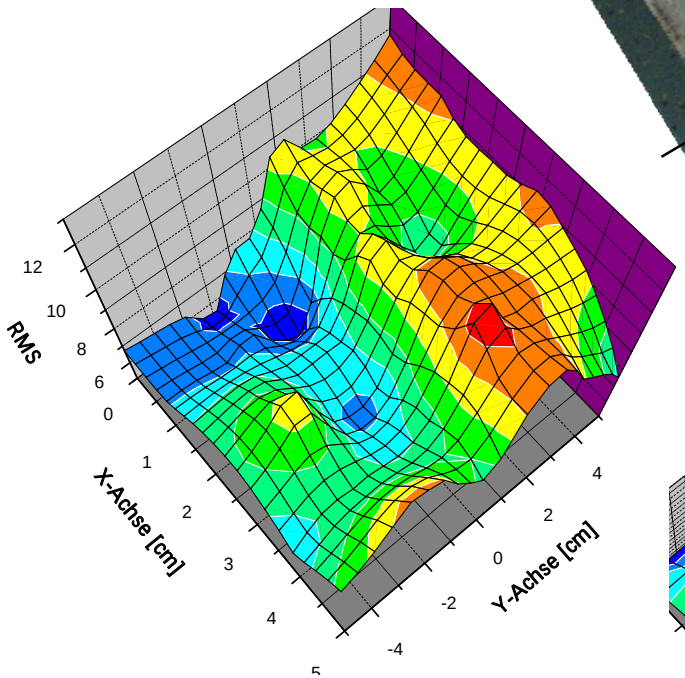


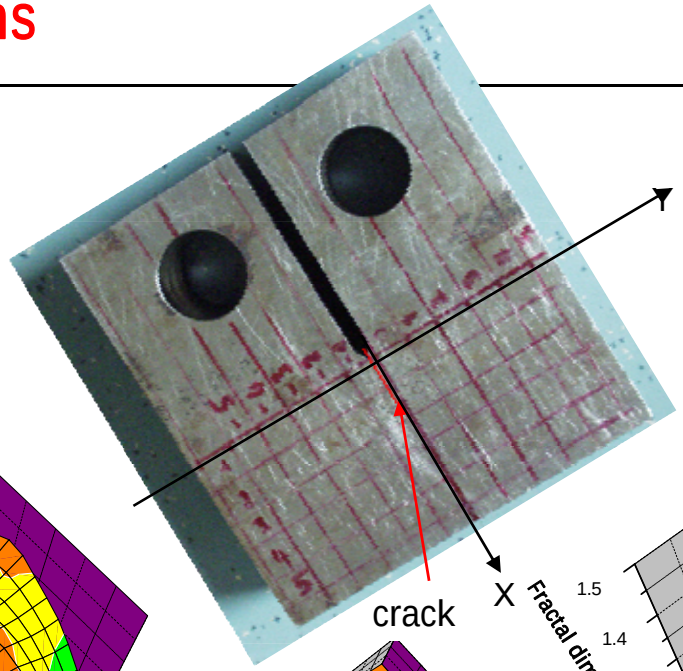
Applications

CT-sample
like a component

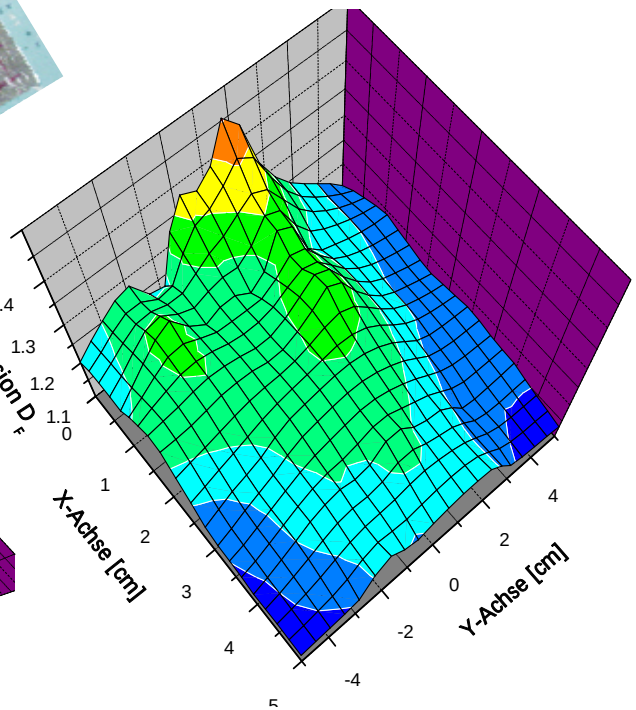
22 **NiMoCr** 37

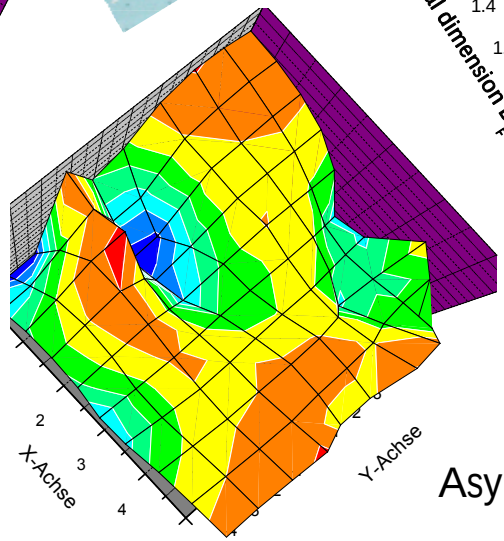
RMS ~ Residual stress





Fractal dimension



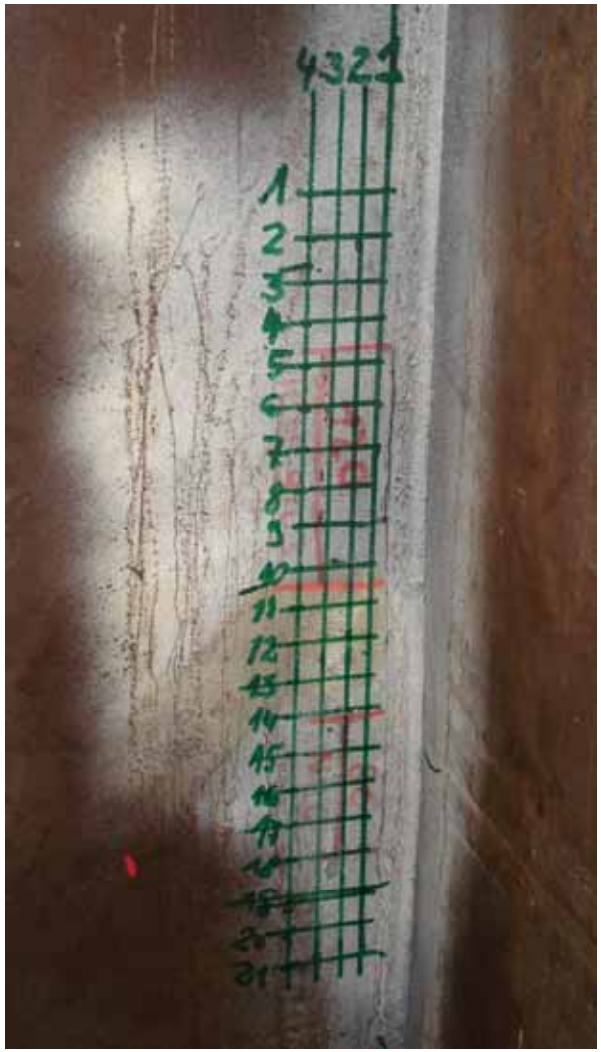


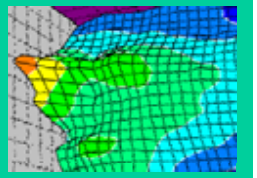
Asymmetry parameter

Applications

Brown coal open cast mining

Support of the 600 m long bridge F60

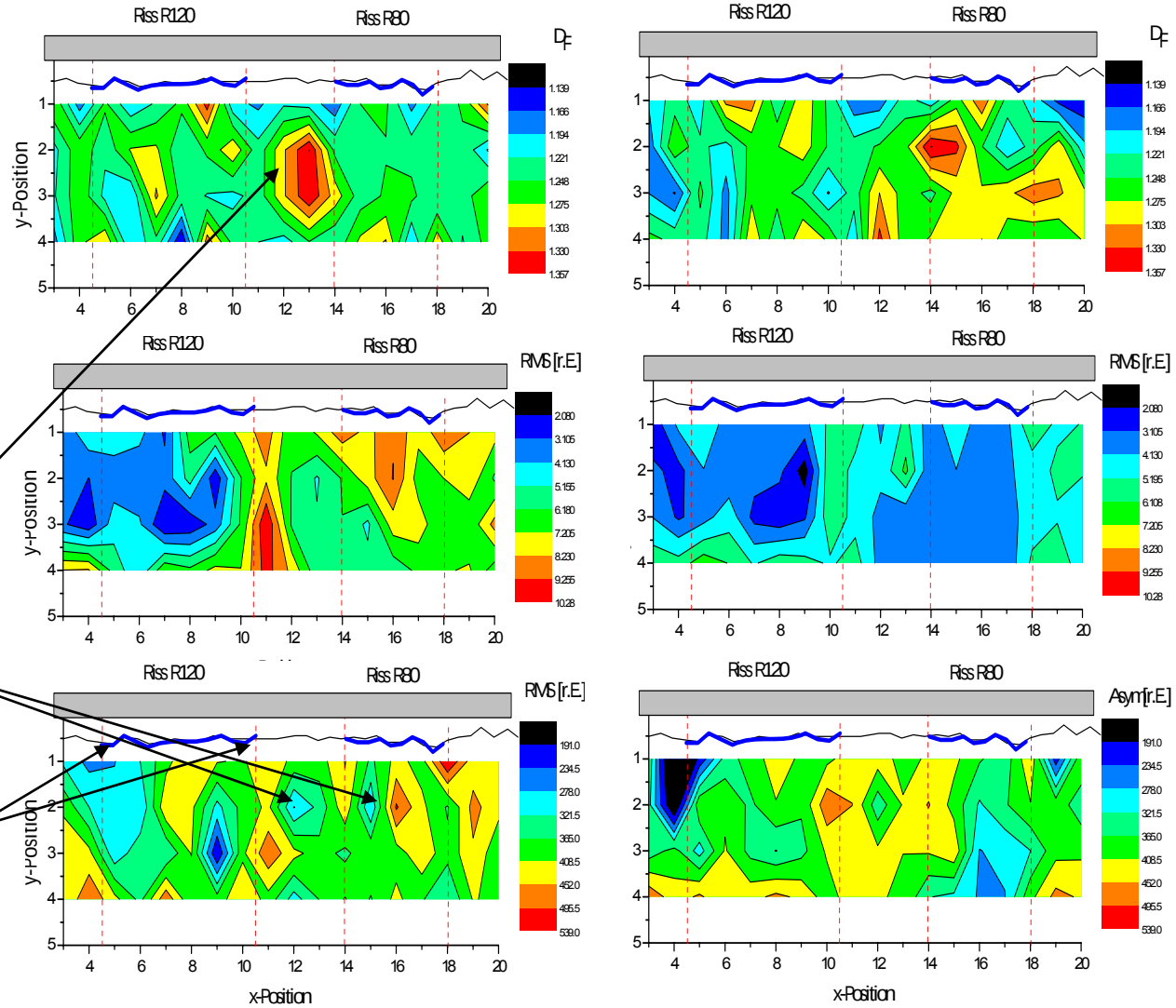




Applications

Along the crack

Perpendicular direction



D_F

RMS

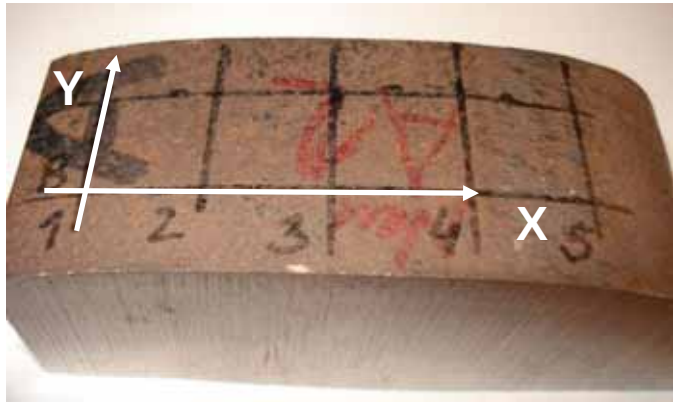
Asym

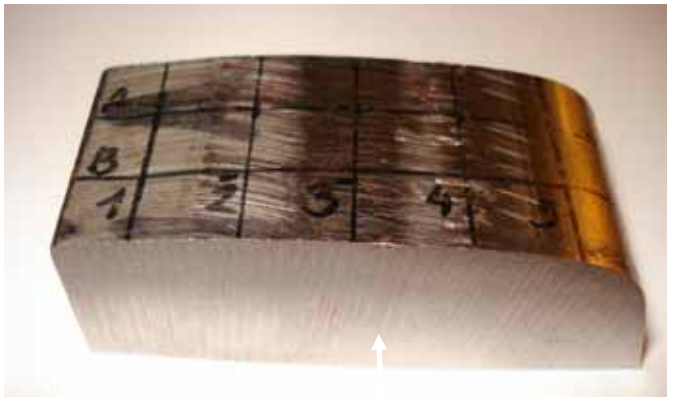
Beginning cracks?

Fatigue versus power crack?

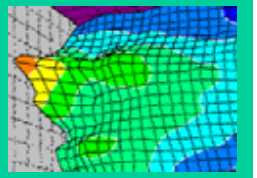
Applications

First results for “Wiener Linien” rails





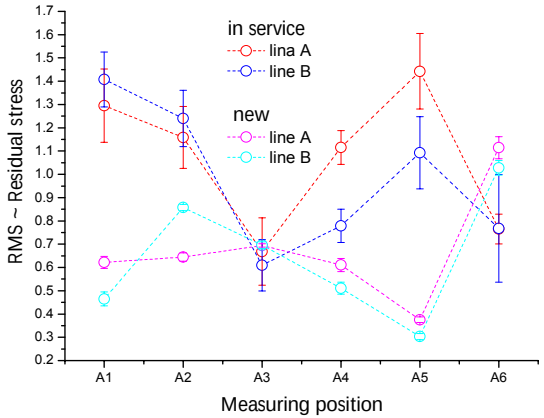
Y ~ roling direction



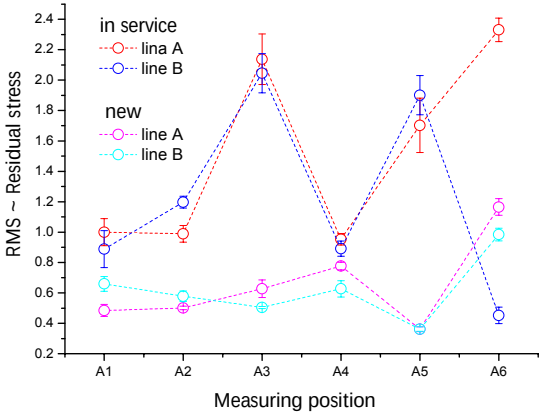
Applications

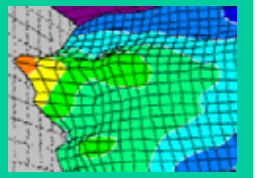
RMS ~ Residual stress

Perpendicular direction



Roling direction

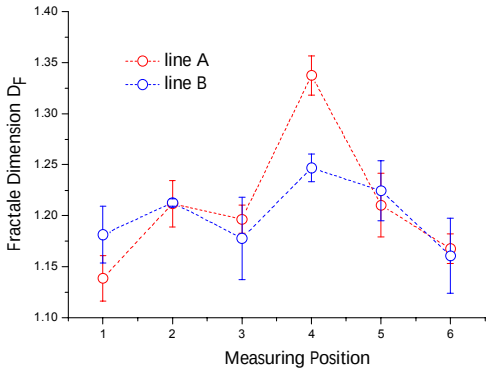


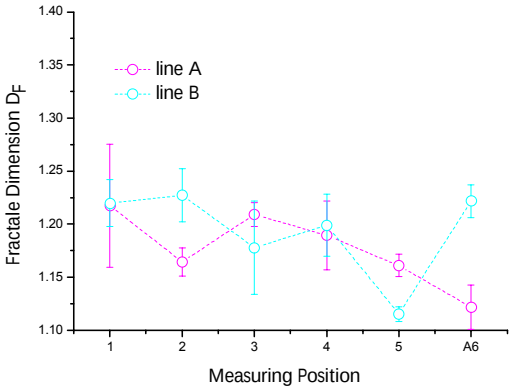


Applications

D_F ~ Fatigue damage

Perpendicular direction

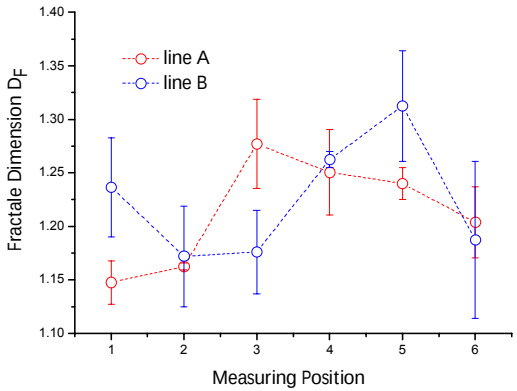


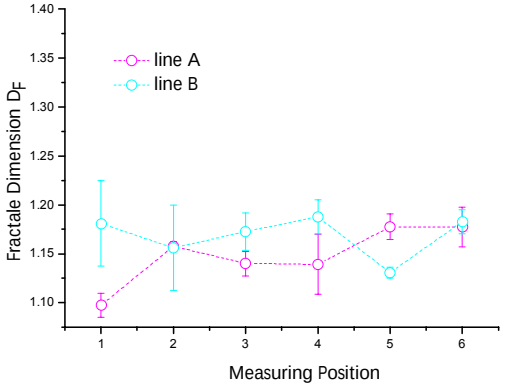


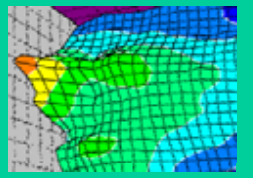
in service

new

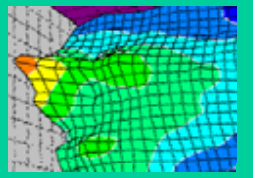
Roling direction





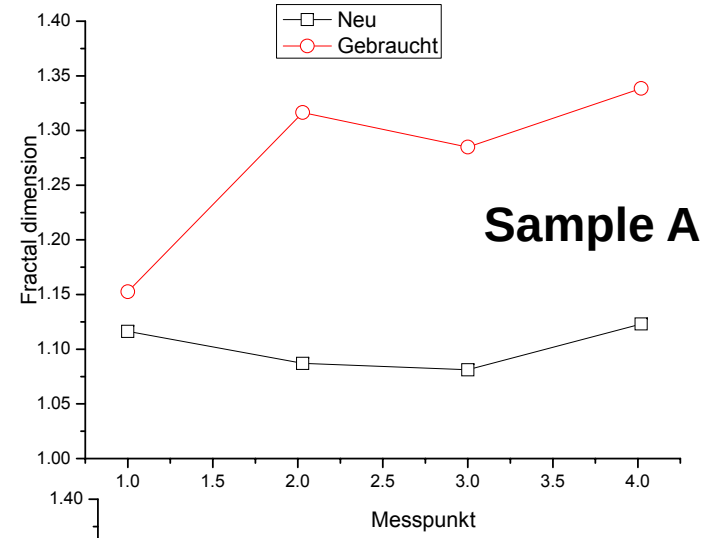


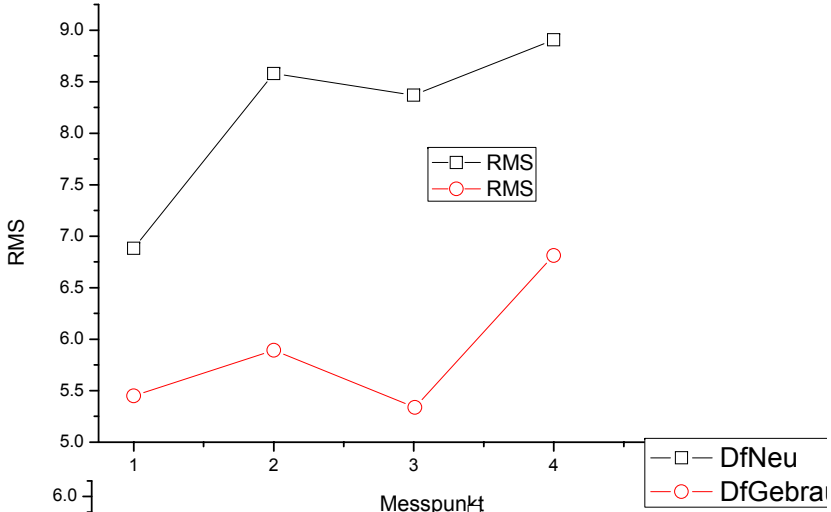
Further applications

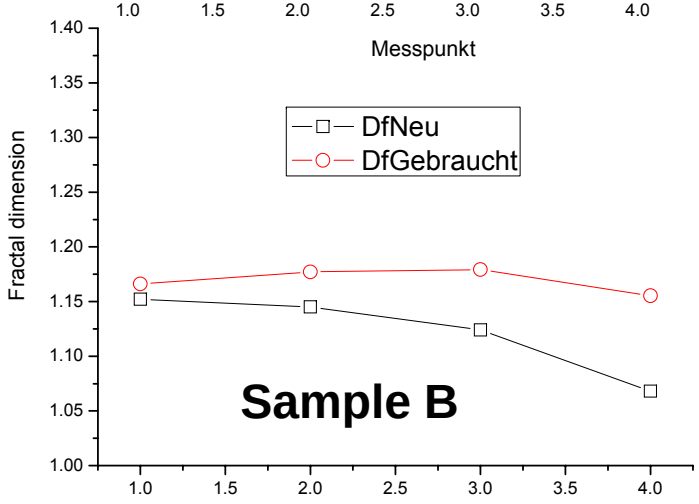


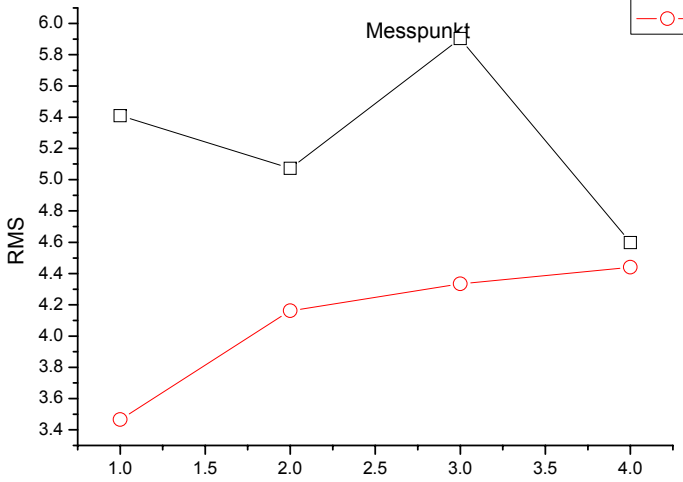
Further applications

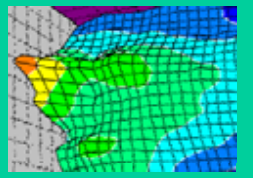
Fractal dimension of Barkhausen noise







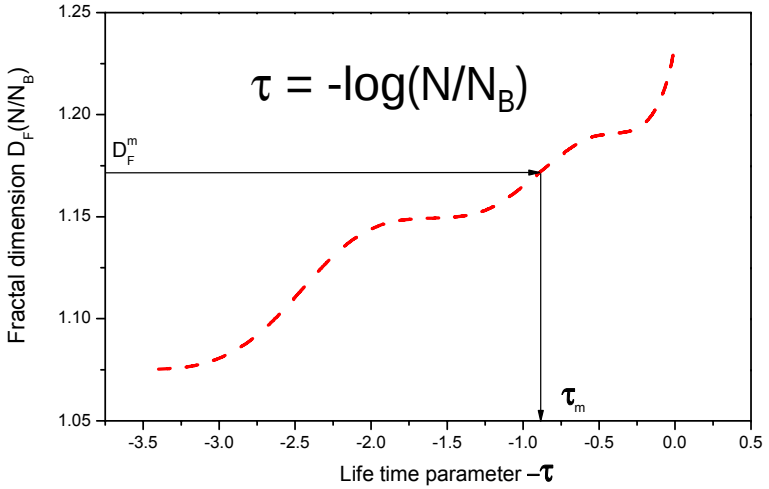




Outlook

Estimation of residual life

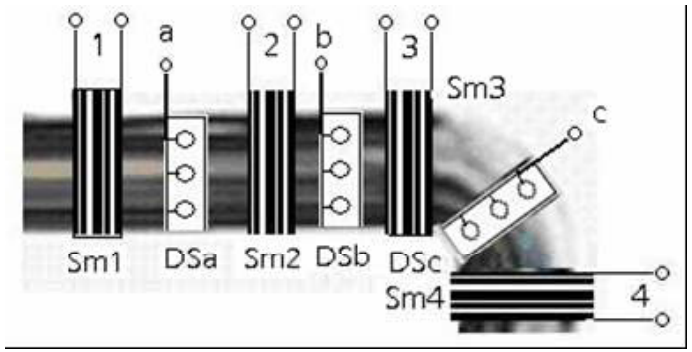
$D_F(N/N_B)$-function independent on N_B and R → universal curve!



DMS → Load collectives +Wöhler-curve → N_B, $\alpha(\Delta ti) = \Delta N(\Delta ti)/\Delta ti$

$$T_m = 1/M(m) \sum_{i=1}^{M(m)} \frac{N_B^m}{\alpha(\Delta t_i)} (1 - \exp(-\tau_m))$$

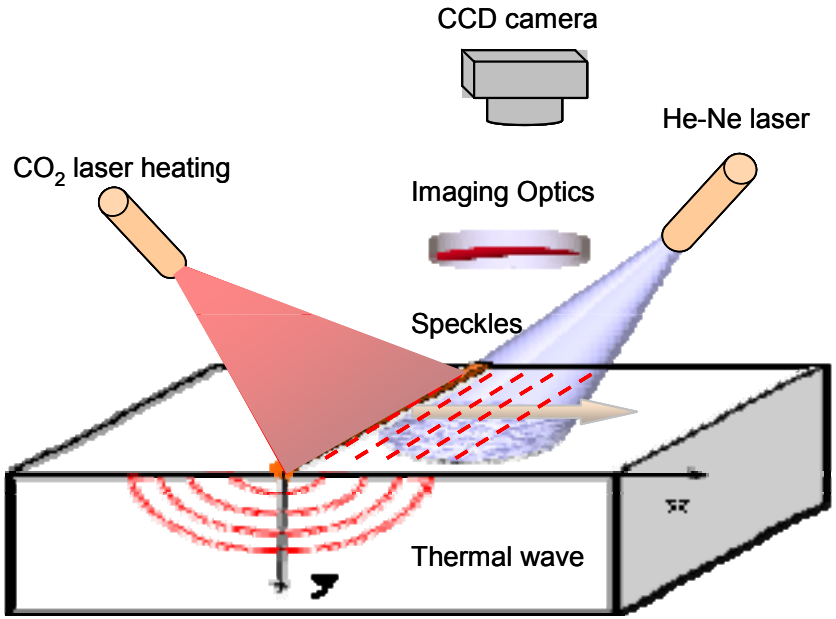
Residual service life time

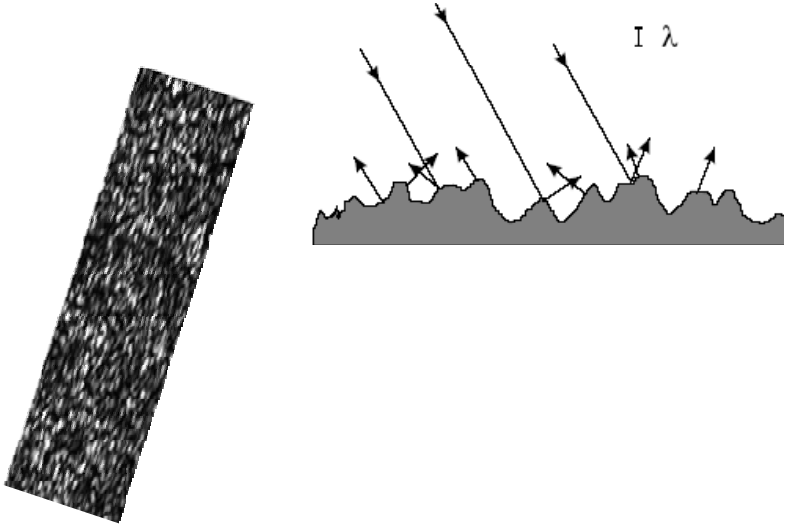


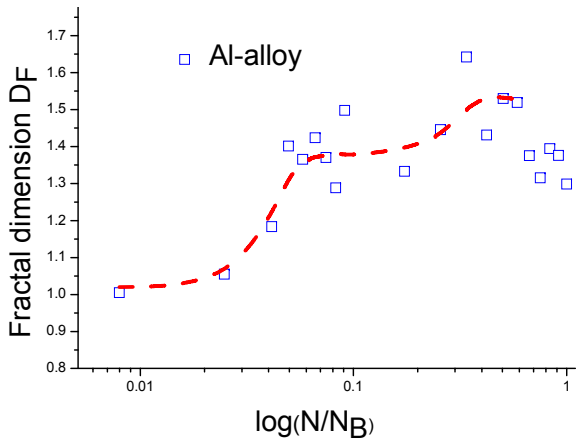
Outlook

Nonmagnetic materials

Time resolved Speckle-Photometry

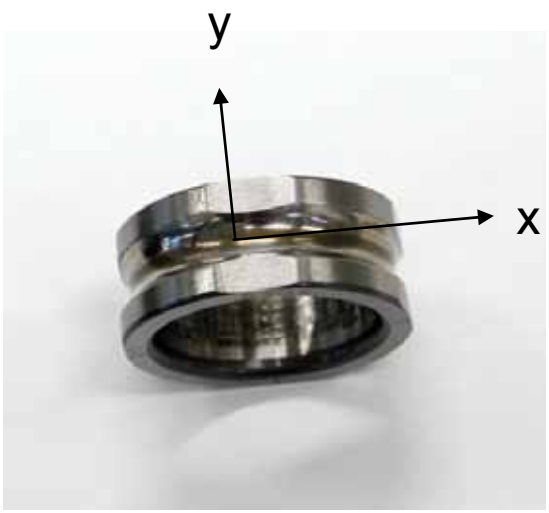






Outlook

Fractal dimension D_F as a function of running time



3 000 MPa, T = 60 °C

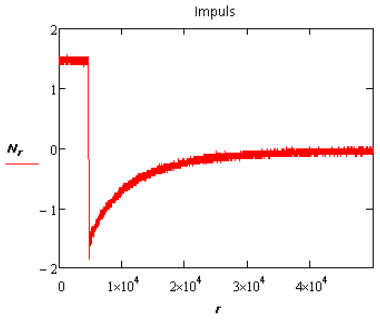
Direction	x-axes along roling trace	y-axes
100 h	1.059	1.18
200 h	1.129	1.083
300 h	1.37	1.265
400 h	1.126	1.349

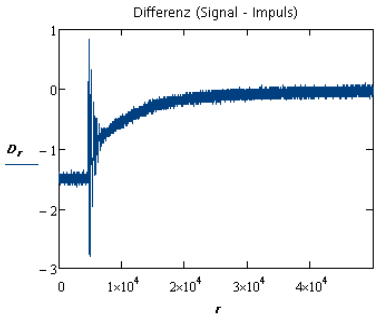
Outlook

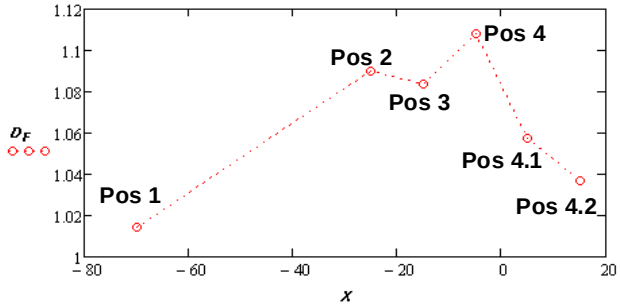
Eddy current relaxation

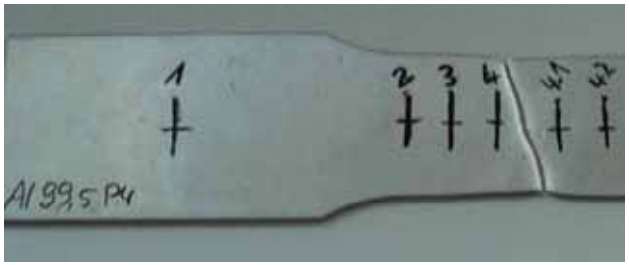
$$\langle j(t)\rangle = \langle j(to)\rangle - (\langle j(to)\rangle - \langle j(t \rightarrow \infty)) (1 - R(t\text{-}to))$$

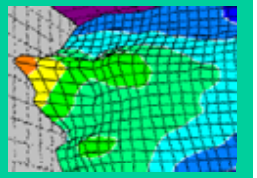
$$R(t\text{-}to) = \langle \Delta j(t)\, \Delta j(to)\rangle / \langle \Delta j2\rangle \quad and \quad \Delta j(t) = j(t) - j(t \rightarrow \infty)$$











Conclusion

- SHM – characterization of materials damage before cracking and without baseline! Fractal analysis of deformation structure → new working concept based on D_F!

- For steel D_F increases with fatigue damage, however, the appearance of cracks and the stress release can locally reduce D_F.

- as a function of cyclic load number was found. Symmetry arguments point at the existence of three universality classes.

- The fractal analysis of the offers the possibility to introduce the fractal concept into the inspection practise. Besides of D_F the RMS-value of Barkhausen noise has to be measured in order for crack indication

- Search is ongoing for similar approach to nonmagnetic materials (eddy current noise, Speckle-Photometry), it looks promising!

- IZFP is now developing a special device "FrakDim" with optimized working regime including fast soft ware. Specialized sensors will be manufactured.

Than you very much !