FRM II
Forschungs-Neutronenquelle
Heinz Maier-Leibnitz

ACCELERATE Research2Business Online-Workshop: Residual Stress Analysis

Tuesday 9 Mar 2021, 10:00 → 14:05 Europe/Berlin

Residual stress analysis with neutron diffraction

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MLZ is a cooperation between:

outline

Why neutrons?

RS with neutron diffraction - *howto*

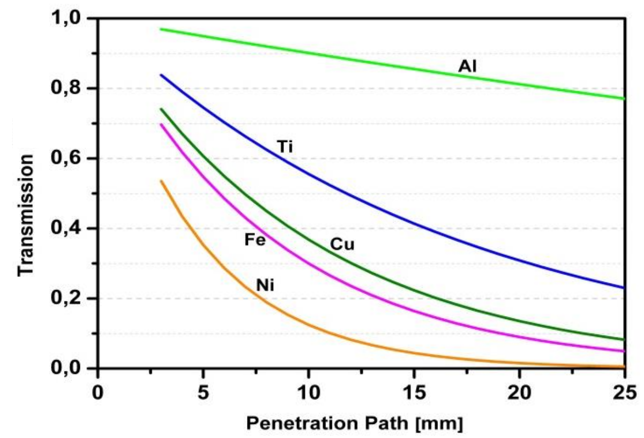
Examples

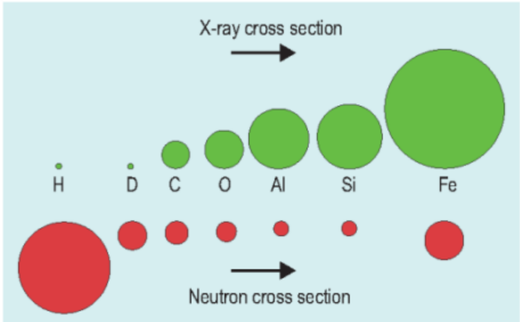
Summary

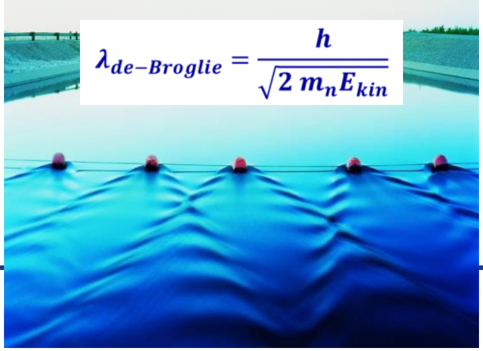
Neutron methods for materials science

Why use neutrons?

- **Neutral** → high penetration depth → large samples and/or sample environment (furnaces, cryostats, magnets, etc.) can be used
- **Scattering cross sections independent of atomic number** → detection of light elements, distinction of neighbouring elements
- **Scattering cross section depends on nucleus** → isotopes can be distinguished (i.e. H/D)
- **Neutrons have wavelength** → in the range of atomic distances and can yield information on crystal structures



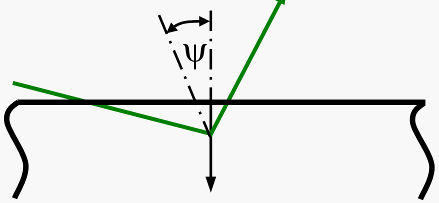




information depth

Surface

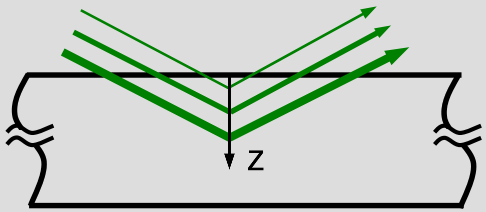
angular dispersive X-ray-Methods



Energy range ≈ 5 – 17 keV
Information depth (steel) ≈ 15 µm

Intermediate Range

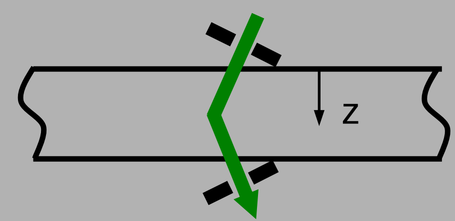
e.g.: ED X-ray diffraction



Energy range ≈ - 60 ... 150 keV
Information depth (steel) ≈ 150 µm

Volume

Neutron diffraction
High energy synchrotron diffraction



Information depth (steel) ≈ 10-20 mm

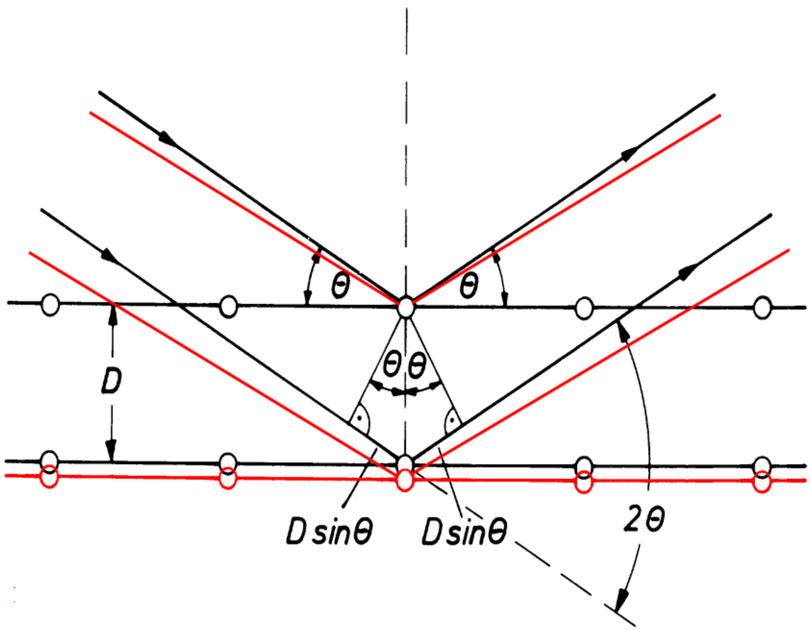
Note: New neutron methods allow to fill the gap ≈ 150µm .. 1mm

Neutron centres in Europe

- With dedicated instrumentation for strain scanning.
- Most have liaison office and grant special routes for access for industry.
- MLZ (TUM, HZG, FZJ): Diffractometer STRESS-SPEC

from: www.lens-initiative.org

How to measure „stress“



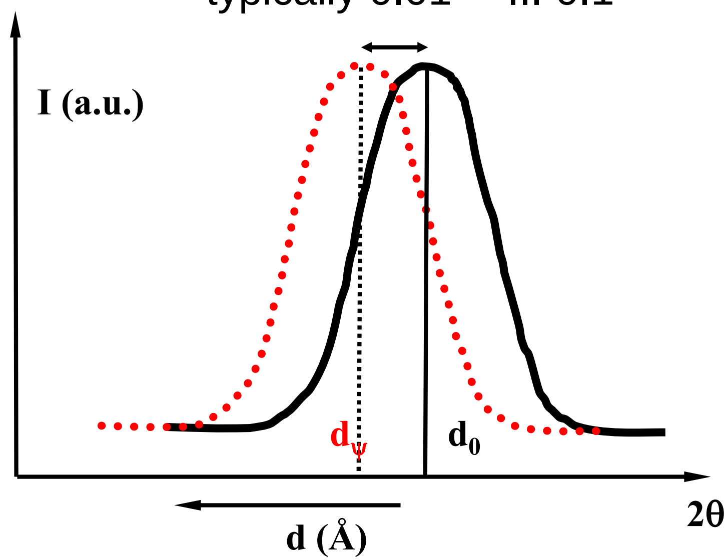
$\lambda = 2d \sin\theta$

Angular resolution:

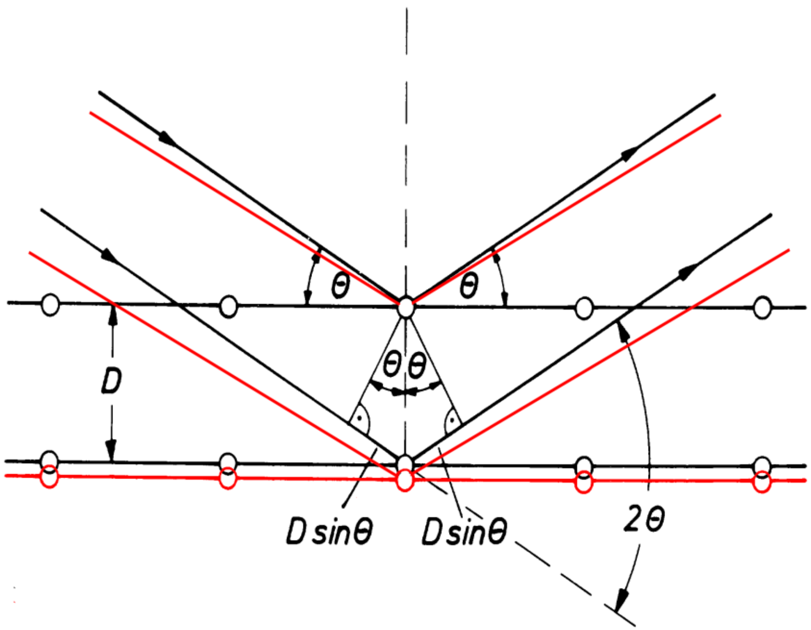
< 0.01° for $\Delta d \sim 1 \times 10^{-4}$

Spatial resolution:

depends on stress gradient, (~mm^3)



How to measure „stress“



$\boxed{\lambda = 2d \sin \theta}$

Scattering angle (sample) + **Reference value**

2θ $\qquad$ $2\theta_0$

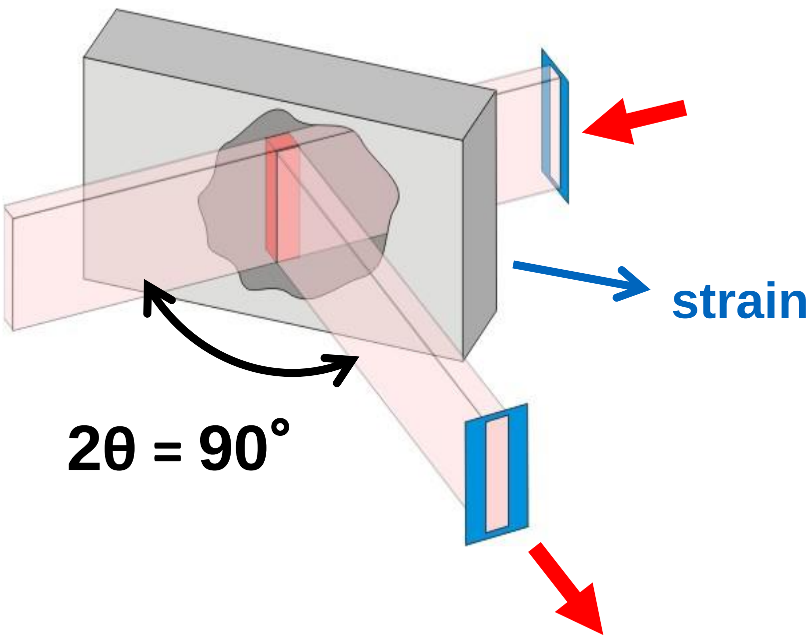
$$\varepsilon_{hkl} = \frac{d_{hkl} - d_{0,hkl}}{d_{0,hkl}} = \frac{\sin(\theta_{0,hkl})}{\sin(\theta_{hkl})} - 1$$

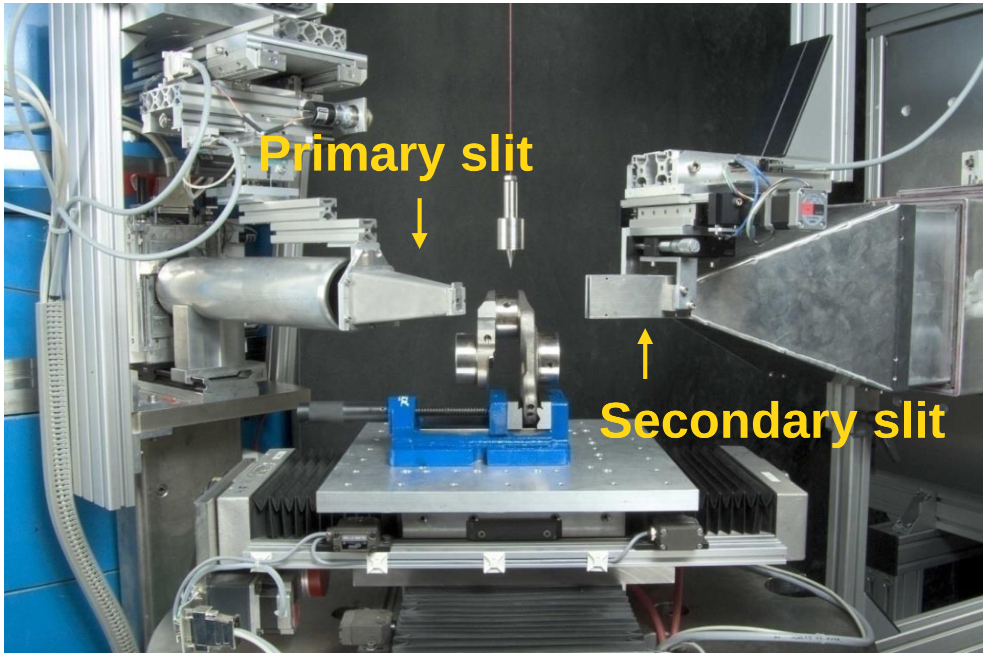
Hooke's Law
$\sigma_{ij} = c_{ijkl}\ \varepsilon_{kl}$

Isotropic case
c_{ijkl} : E, ν

Local stress tensor

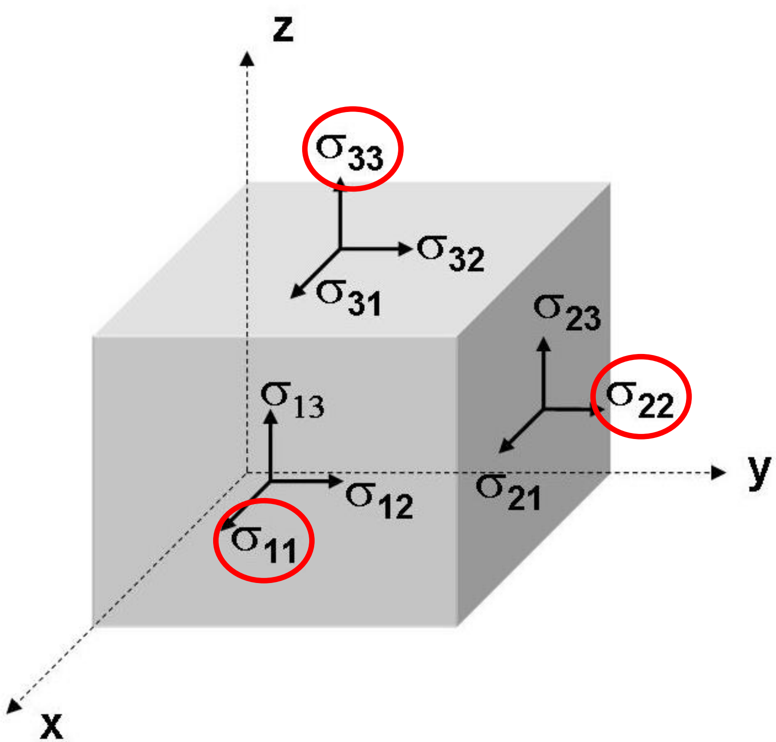
Gauge volume definition at a neutron diffractometer





How to measure „stress“ – stress tensor

$$\sigma_{ii} = \frac{E}{1+\nu}\left(\varepsilon_{ii} + \frac{\nu}{1-2\nu}(\varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33})\right)$$



Frequently:

Main axis

➔ just ε_{11}, ε_{22}, ε_{33}

➔ just 3 measured directions

Stress Direction (Example: Composite casting Steel-Aluminium)

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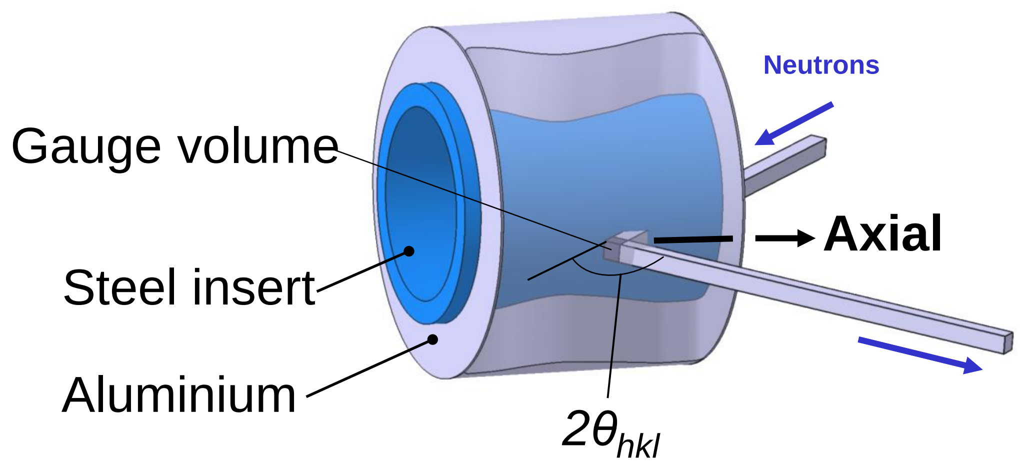
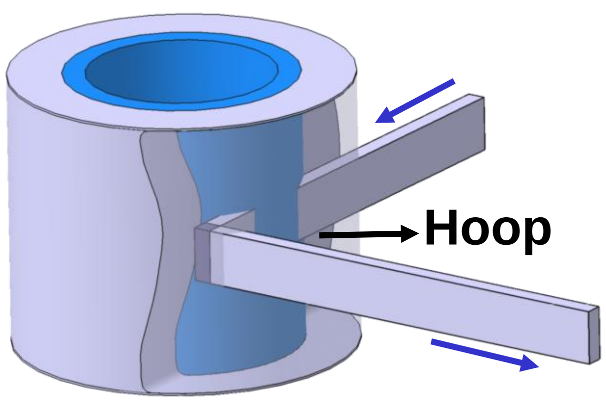
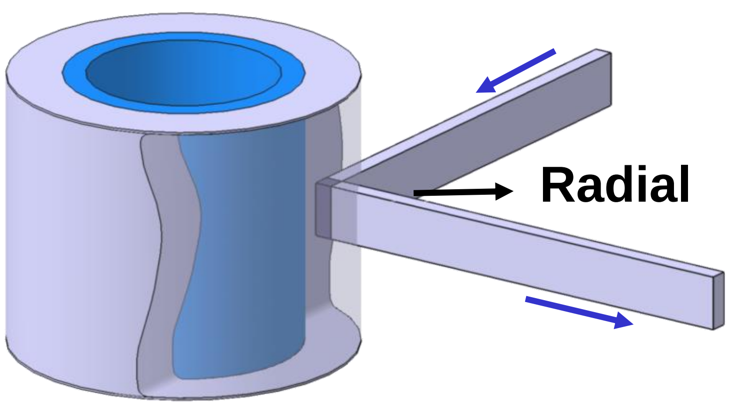


	Steel	Aluminium
Lattice plane	Fe(211)	Al(311)
$2\theta_{hkl}$	~91.3°	~86.7°
Direction	Gauge volume [mm^3]	
Axial	1x1x1	2x2x2
Radial / Tang.	1x10x1	2x10x2





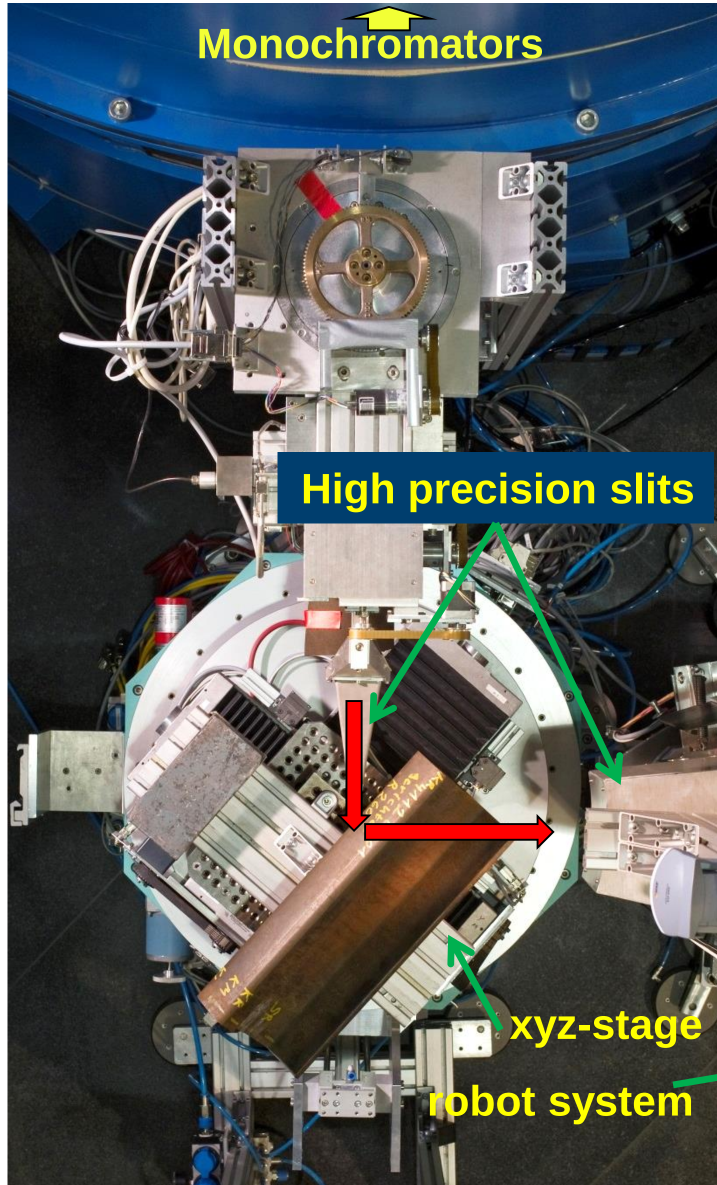
Our neutron diffractometer

3 Monochromators

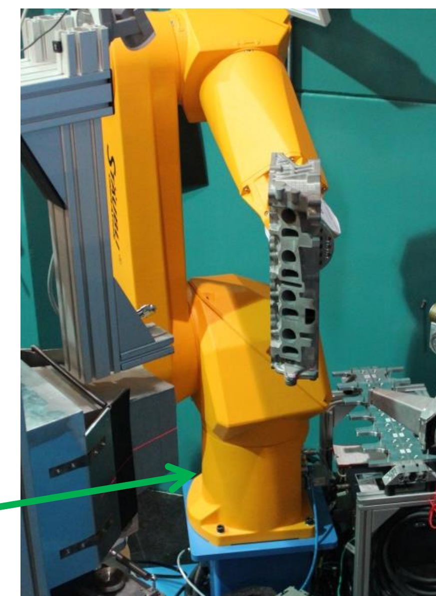
- Si(400)
- Ge(311)
- PG(002)

+ $2\theta_M = 35^\circ \; -110^\circ$
+ high flux (8×10^7 n/cm²/s)

- **Optimise:**
  Flux – resolution
- **λ = 1.0 ~ 2.4 Å**
- **$2\theta = 90^\circ$ possible**
  (cubic gauge volume!)
- **Gauge volume**
  (0.2 ~ 125 mm³)



+ Additional equipment:
  - *Tensile rig*
  - *Furnaces*
  - *Dilatometer*

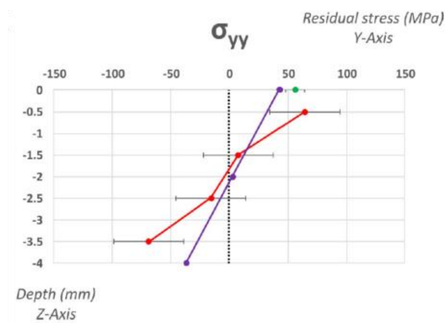


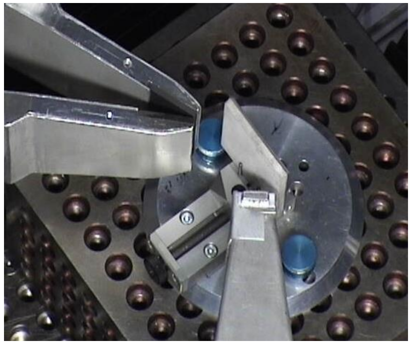
Industrial projects - Tests

EADS, Audi, SKF, DaimlerChrysler, ALFING Maschinenfabrik Alfing Kessler GmbH, ABB, MAN, MTU Aero Engines, VW, DVS SLV München, ROTAX, ZEISS, Rolls Royce, Diamonde Quiller

SINE2020 projects @ STRESS-SPEC

Brazed Al_2O_3-ZrO_2 / WC plate (*)

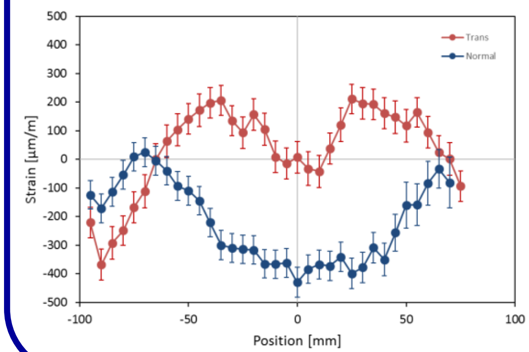


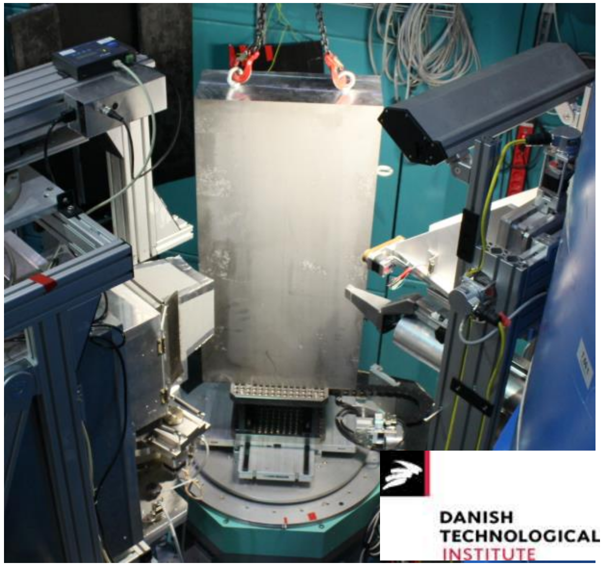


https://www.diamonde.fr/

RS in Al 7075-T6 plates

- 100 × 50 × 20 cm^3
- 285 kg





(*) F. Contrato et al, Int. J. Appl. Ceram. Technol. **17** (2020) 990

Industrial projects - Standards

ICS > 19 > 19.100

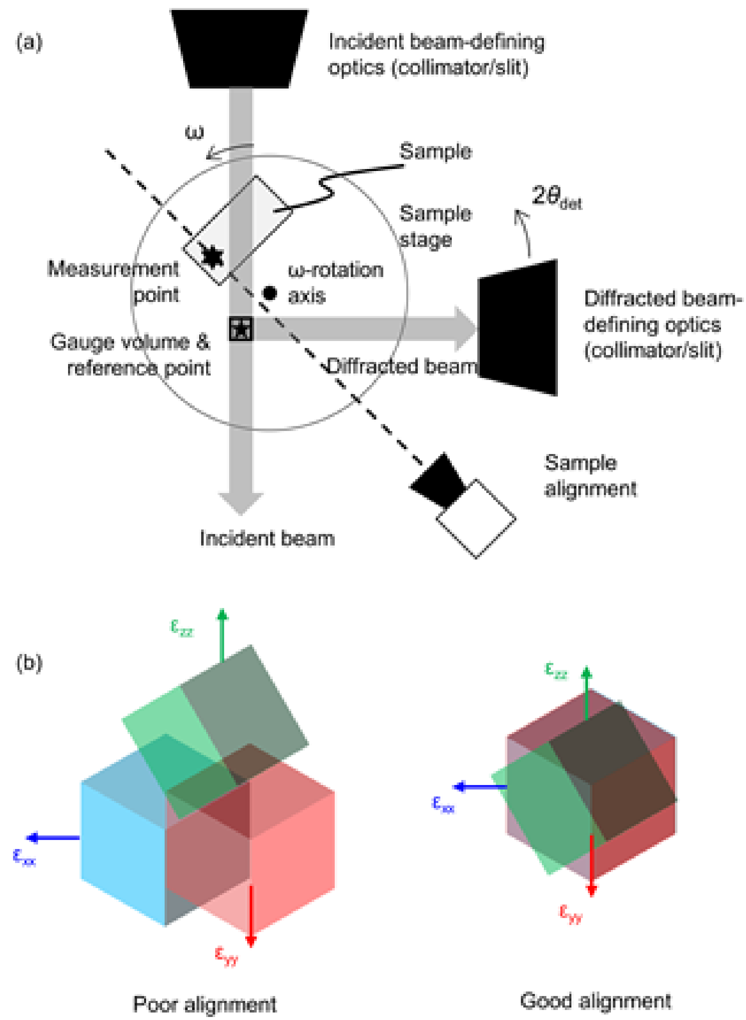
ISO 21432:2019

Non-destructive testing — Standard test method for determining residual stresses by neutron diffraction

New ISO standard serves as best practice guide for proprietary research

NEUTRON QUALITY LABEL

Leading European neutron centres (F, UK & D) have adopted a further calibration protocol to ensure high accuracy through a Neutron Quality Label (i.e. standardized reporting and positioning routines)



R. Ramadhan et al, NIMA 2021 *(in press)*

outline

What do we measure?

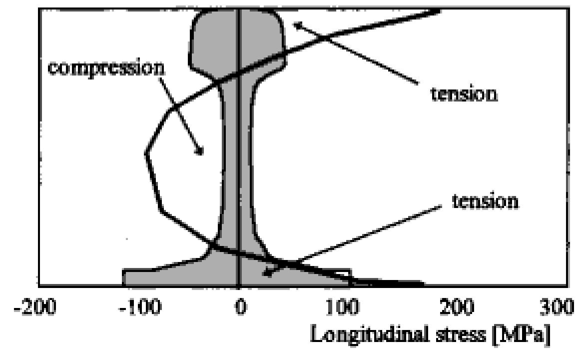
RS with neutron diffraction - Howto

Examples

Summary

Residual stresses – Large samples

Roller straightening device
Fa. Koch H&K Industrieanlagen



Expected RS state in longitudinal direction of the rail after straightening

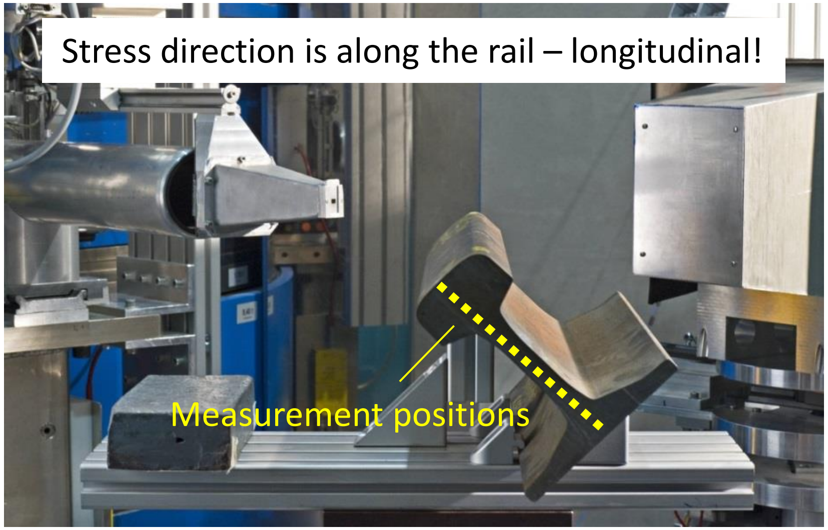
Motivation:

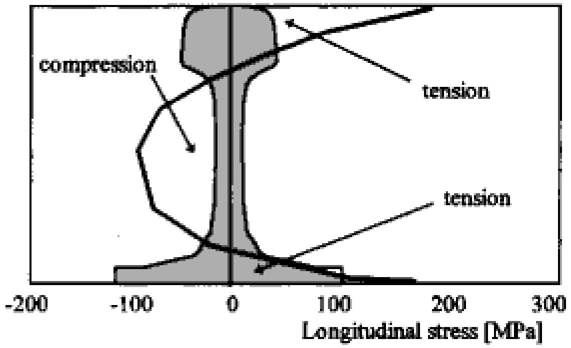
Roller straightening is the last process step in production of rails. Residual stresses (RS) introduced should be kept as low as possible (< 250 MPa at the foot, EN 13674, 2008)

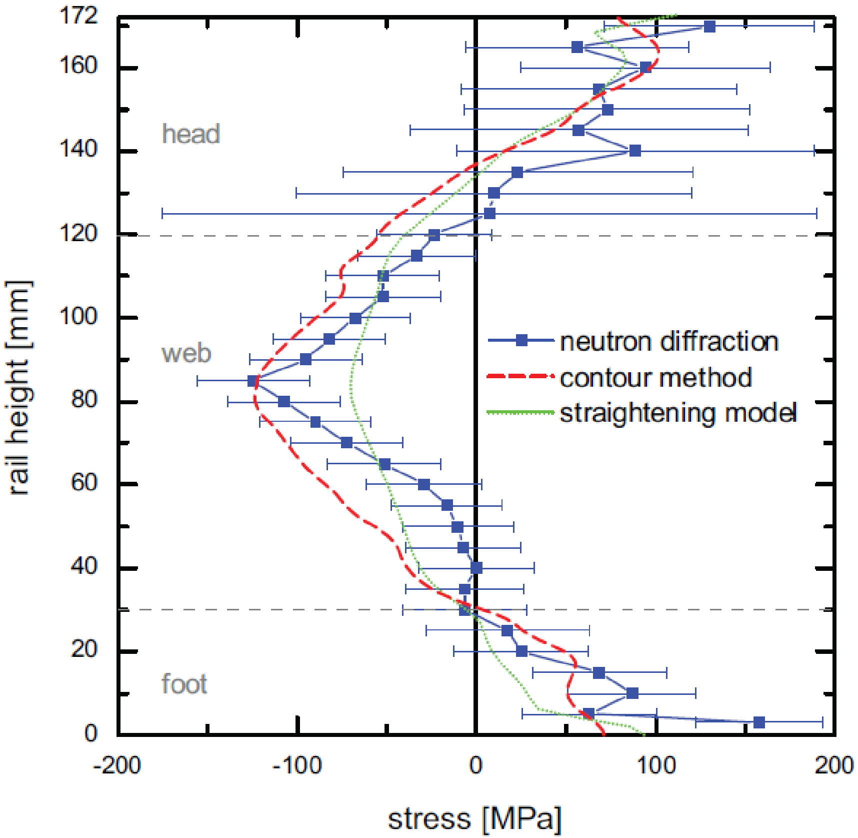
Aims:

Determination of RS state for comparison with FEM and validation of destructive methods (Contour-Method)

Residual stresses – Large samples







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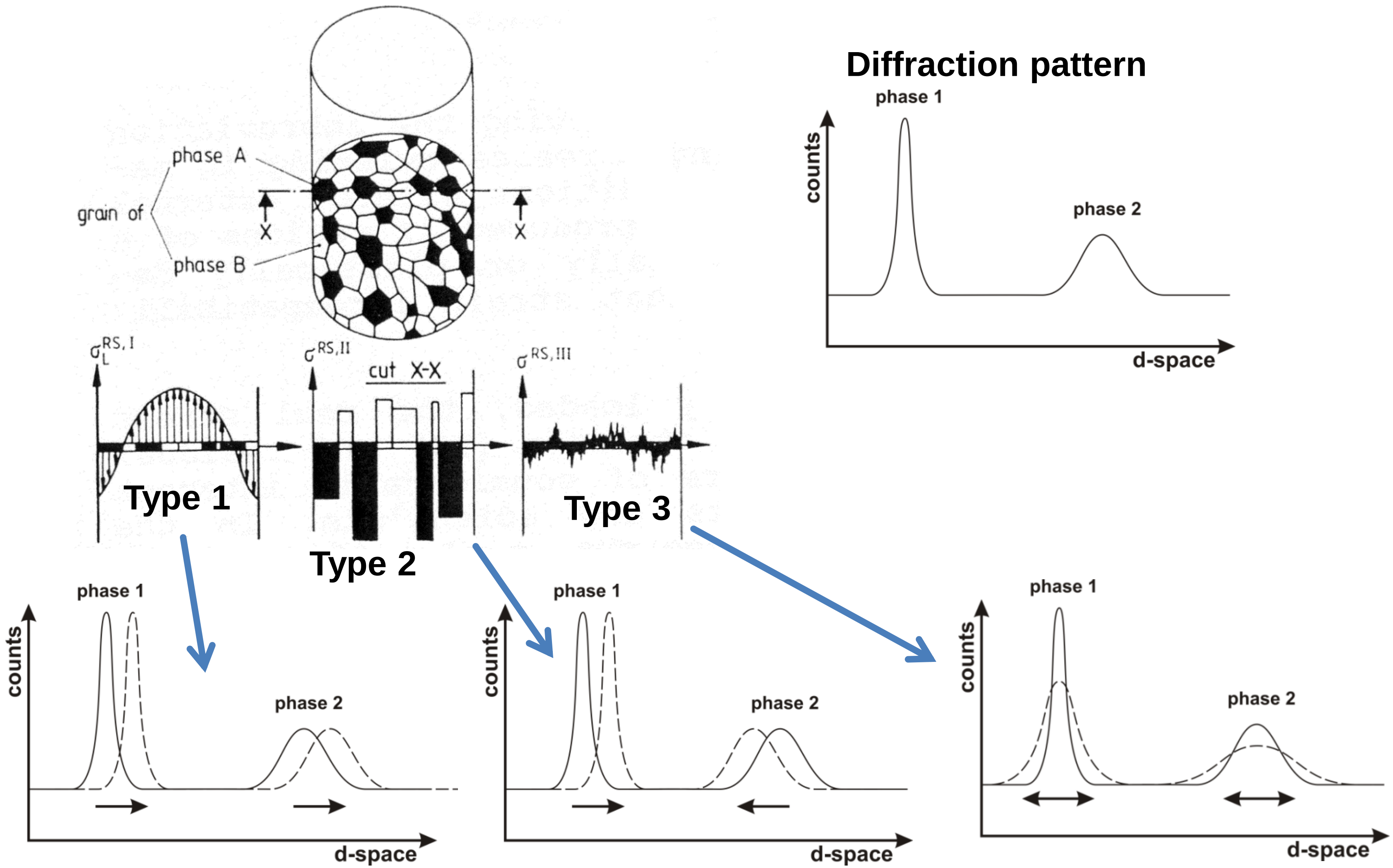
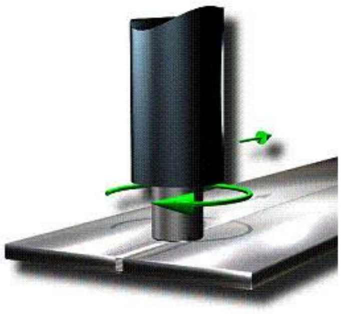
Residual stresses in heterogeneous materials



Residual Stresses (RS) in Metal Matrix Composites (MMC)

- ✓ high stiffness & strength
- ✓ good resistance to creep
- ✓ low thermal expansion
- ✓ better dimension stability

- X poor formability
- X **poor weldability**



Friction Stir Welding (FSW)

FSW introduces large RS due to heating + deformation

RS state in weld is complicated, because it

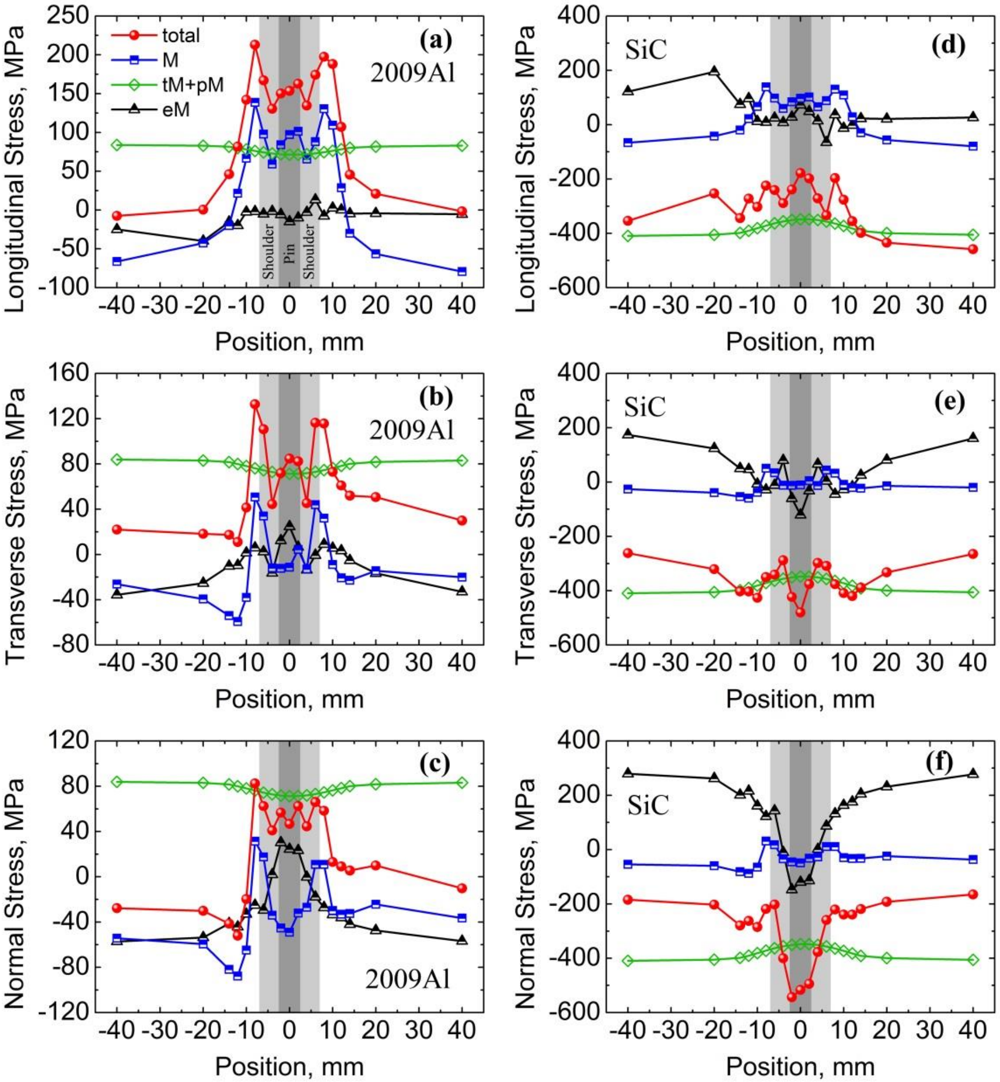
- **includes macro & microscopic RS due to elastic mismatch, thermal misfit and plastic misfit;**
- **is tough to be measured in MMCs due to difficulties in obtaining unstrained reference parameters (d_0).**

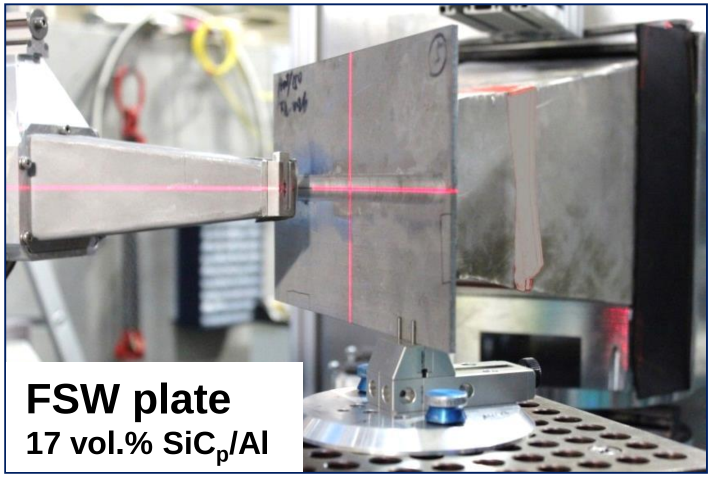
⬇

Reliable experimental method to determine macro and microscopic RS in MMCs using neutron diffraction

X. X. Zhang et al., Acta Mater. **87** (2015) 161-173
X. X. Zhang et al., Mat. & Des. **115** (2017) 364-378

RS: Micro- and Macro





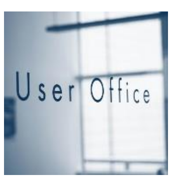
With neutron diffraction all macro & microstrain components can be determined for each phase!

Input for multiscale FEM model for process optimisation

X. X. Zhang et al., Acta Mater. **87** (2015) 161-173
X. X. Zhang et al., Mat. & Des. **115** (2017) 364-378

Summary and how to get beamtime

- Neutron is a powerful tool for RS analysis, especially for large engineering components
- Most of today facilities have a dedicated strain scanner and offer beamtime
    1. Proprietary research (via industrial liaison office) - *usually also some test beamtime for feasibility tests*
    2. Official proposal system – i.e. selected on scientific merit (*NO costs involved here*)



https://mlz-garching.de/user-office

Thanks for your attention!