FRM II
Forschungs-Neutronenquelle
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Neutron Diffraction in NeT

Michael Hofmann

(1) Introduction and who is participating?

(2) Neutron diffraction

(3) Residual stress “measurement” using neutron diffraction

(4) Examples of some NeT Task Groups & lessons learned

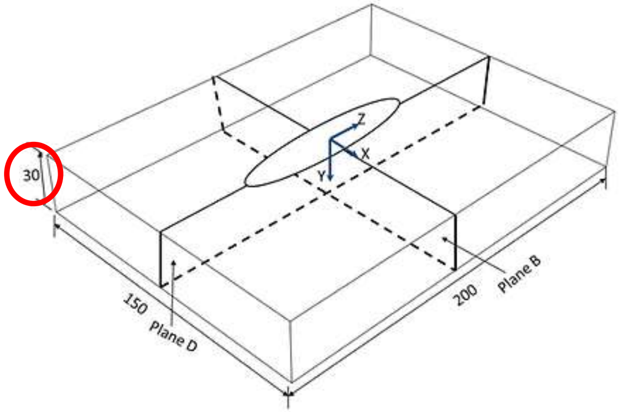
(5) Summary

Introduction

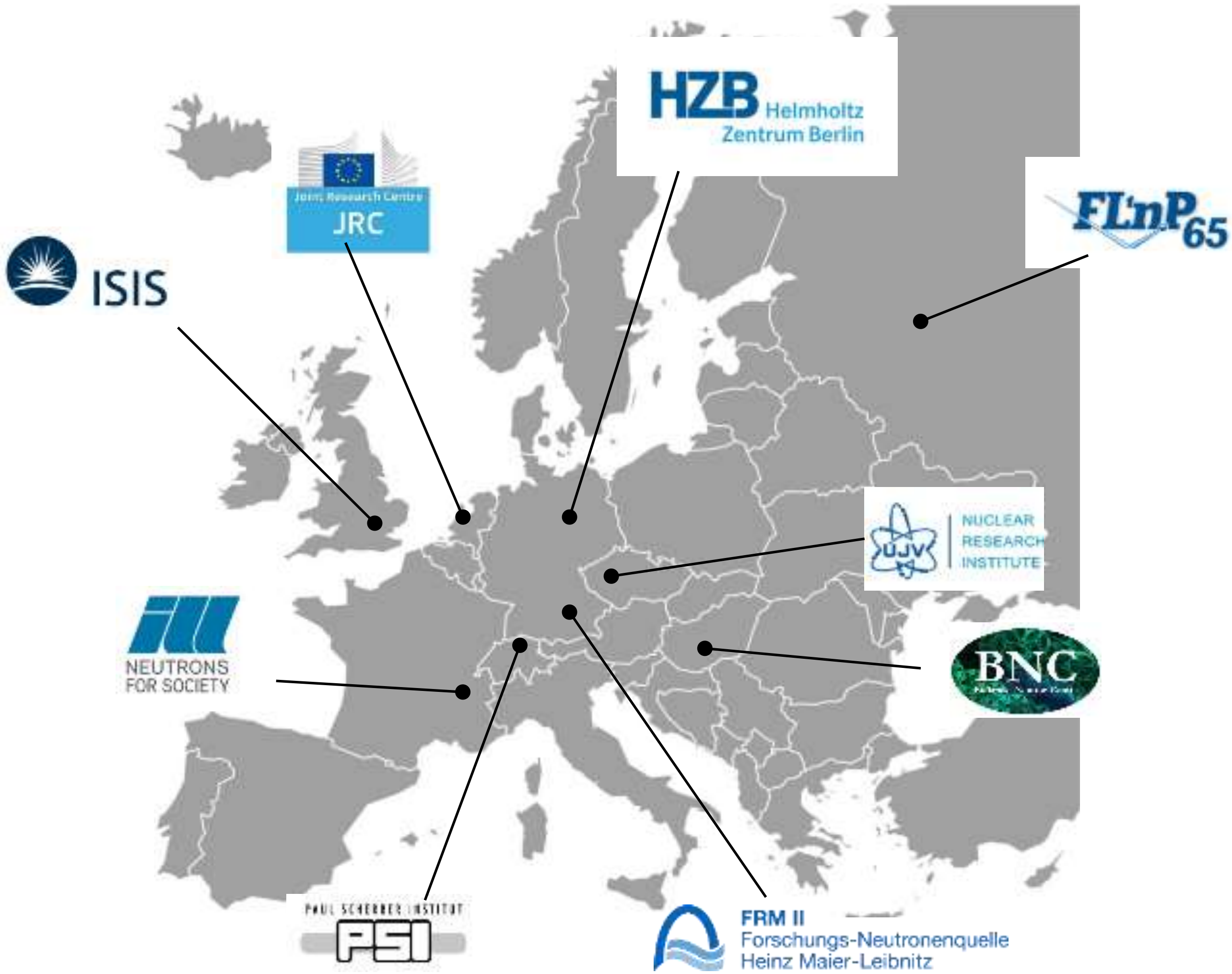
- NeT mission is to develop techniques and standards for the reliable characterisation of residual stresses in structural welds.
- For each problem a Task Group (TG) is formed which undertakes measurements, simulations and interpretation of the results.
- Neutron diffraction measurements to determine **residual stress** at the heart of almost every task group within NeT.

Example from TG 8

Measurements were done on large and thick model samples.



Neutron centres active in NeT



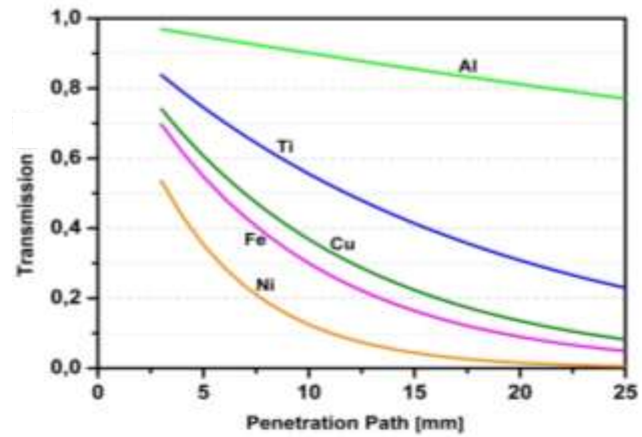
Outside Europe

Australian Government
ANSTO

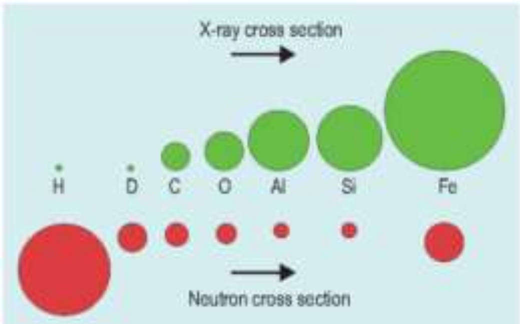
OAK RIDGE
National Laboratory

Why neutrons?

- **Neutral** → high penetration depth → large samples and/or sample environment (furnaces, cryostats, magnets, etc.) can be used

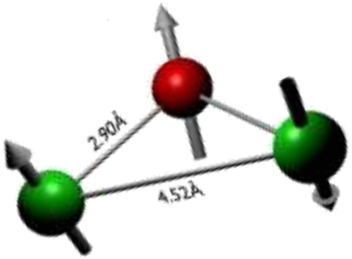


- **Scattering cross sections independent of atomic number** → detection of light elements, distinction of neighbouring elements

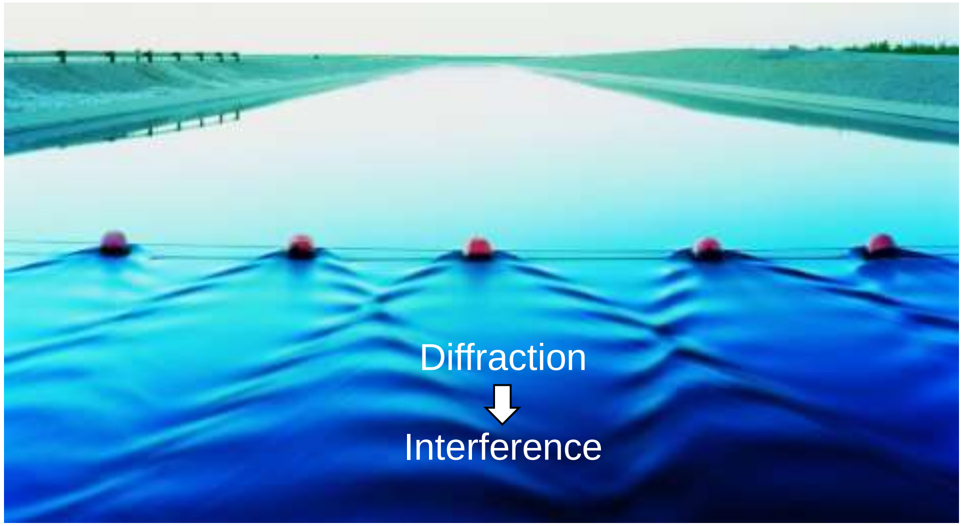


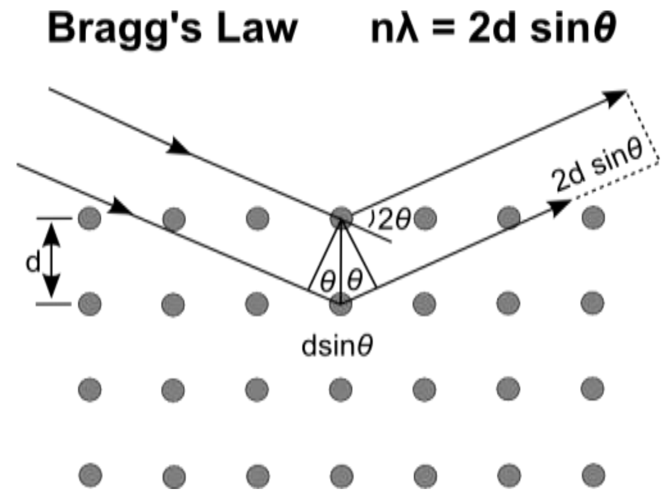
- **Scattering cross section depends on nucleus** → isotopes can be distinguished (i.e. H/D)

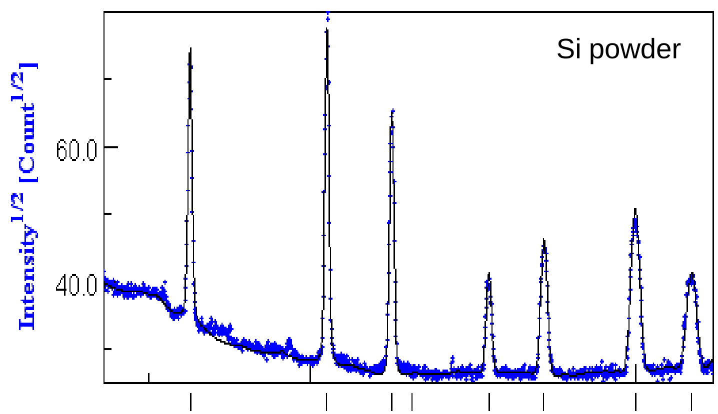
- **Magnetic moment** → information on magnetic structures



Neutron diffraction

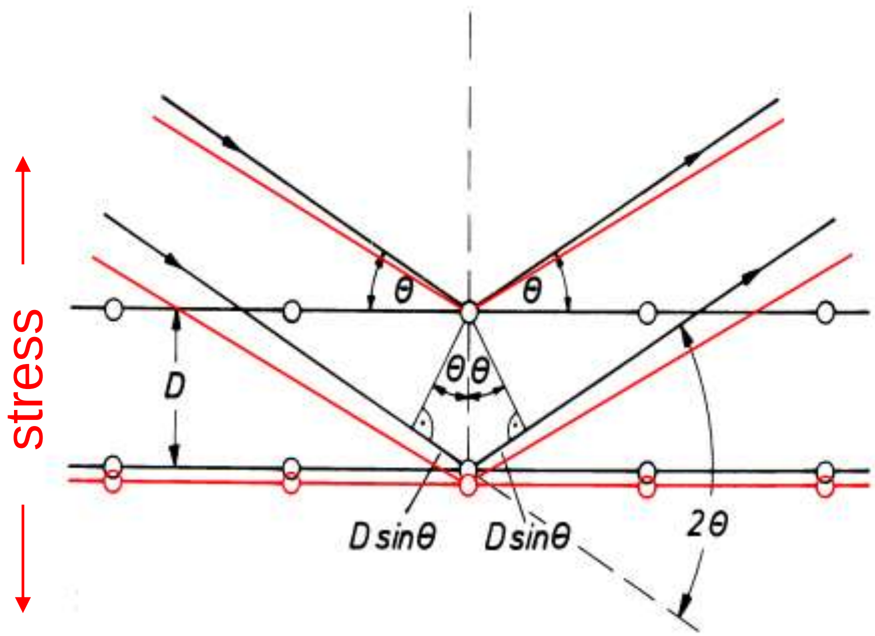






Crystalline phases give characteristic diffraction patterns

- 2θ Position → unit cell, **strain**
- Intensity → phase analysis, texture, atomic positions
- Profile → grain size, defects, dislocations



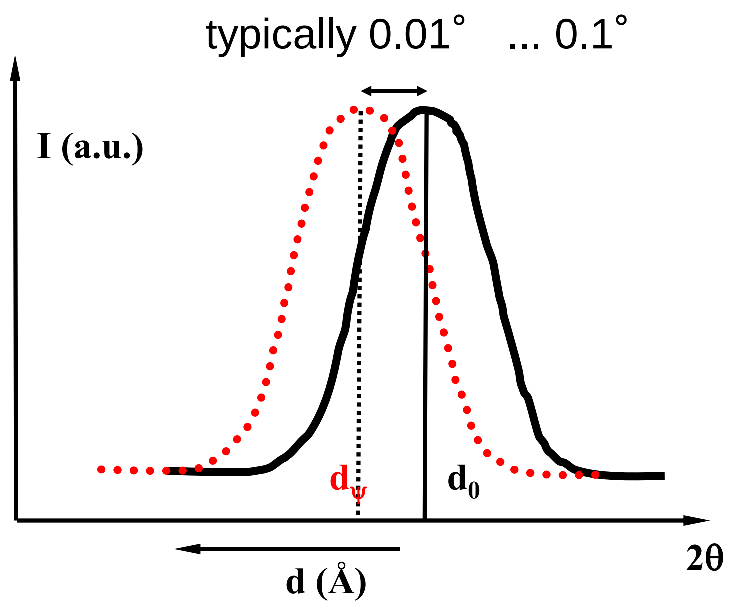
λ = 2d sin θ

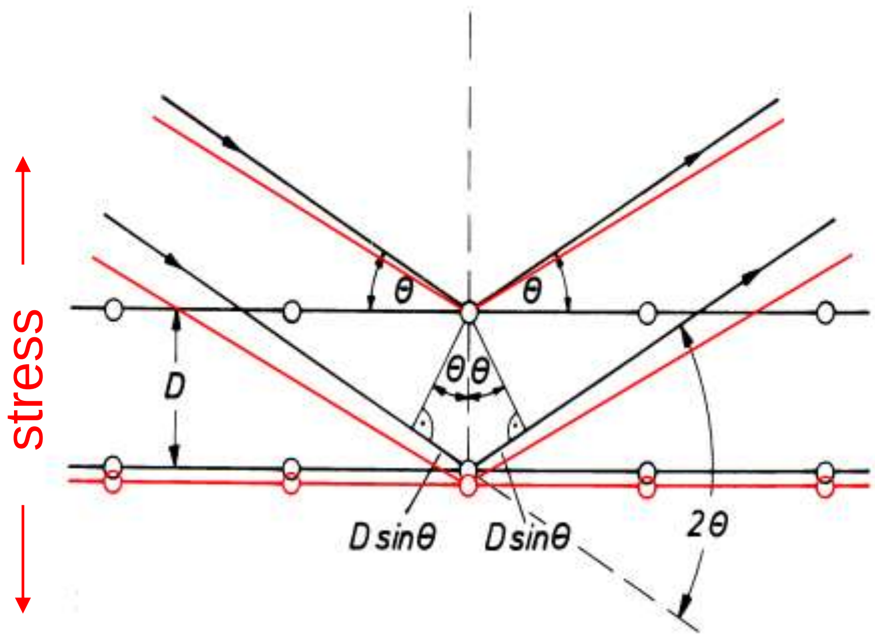
Angular resolution:

< 0.01° for Δd ~ 1 × 10^{-4}

Spatial resolution:

depends on stress gradient, < 1 mm^3





$\lambda = 2d \sin\theta$

Scattering angle (sample) 2θ **+** **Reference value** (= stress free) $2\theta_0$

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

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

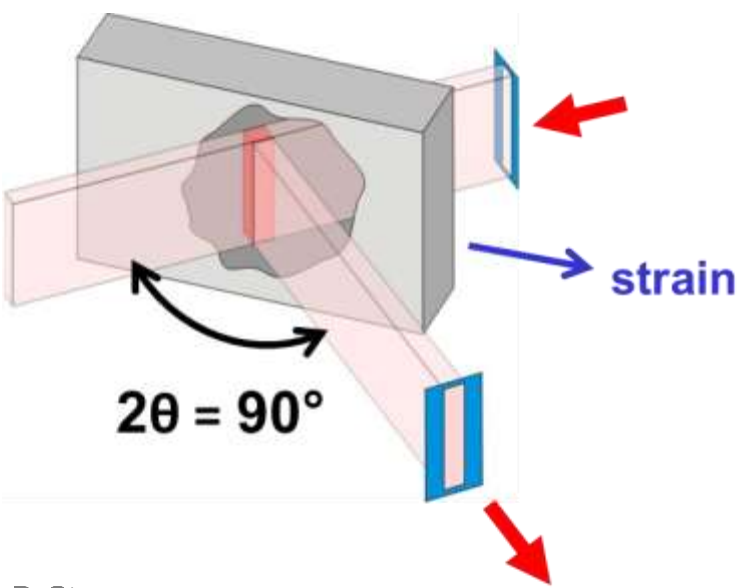
Isotropic case
c_{ijkl} : E, ν

Local stress tensor
=
Complete stress state at that point

Pecularities of the measurements

- spatial resolved
- small gauge volumes (GV)

- sample needs to be measured at the same GV position in different orientations



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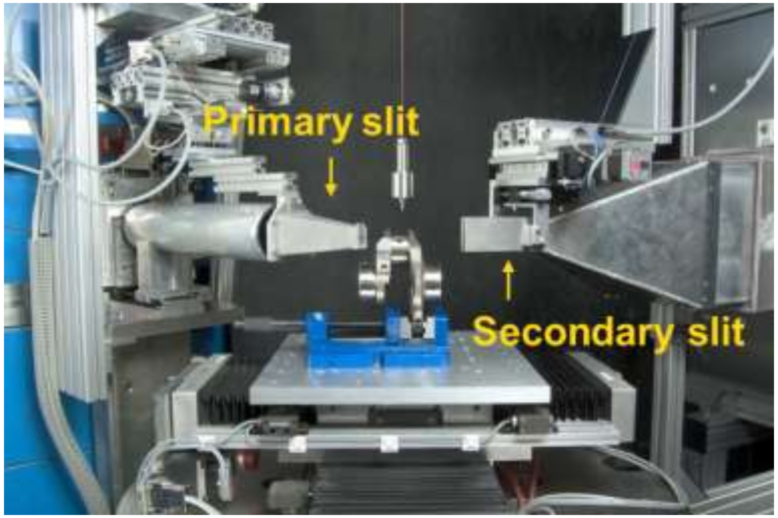
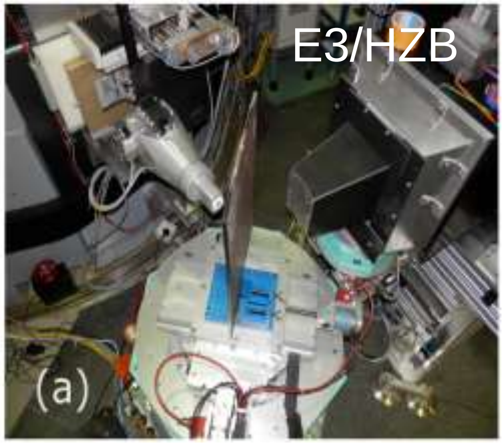
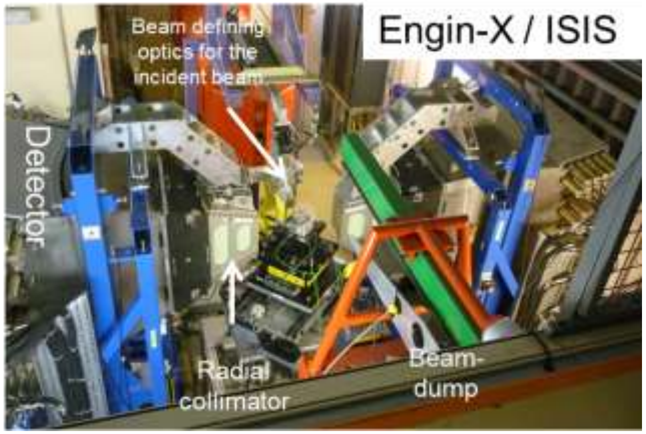
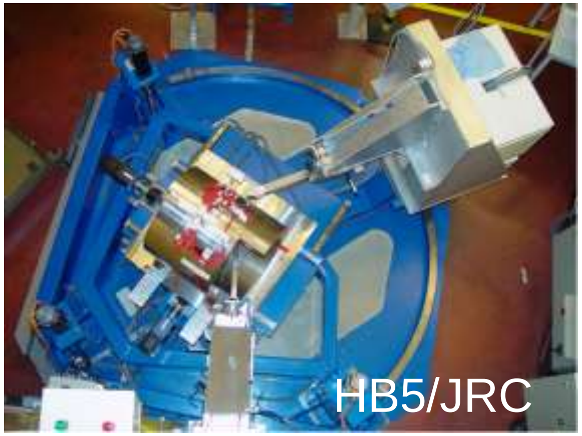


Slit system + sample table at STRESS-SPEC

Diffractometers for strain determination







The NeT Task Groups
(in which diffraction methods play a key role)

increase in complexity

TG1: Single bead on austenitic steel plate

TG4: 3 pass slot weld in austenitic steel

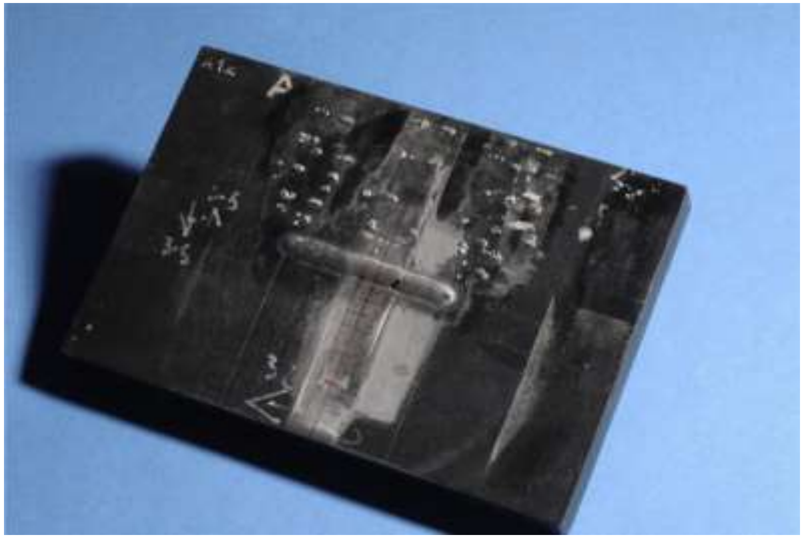
TG5: Edge welded beam of ferritic steel
Phase transformations

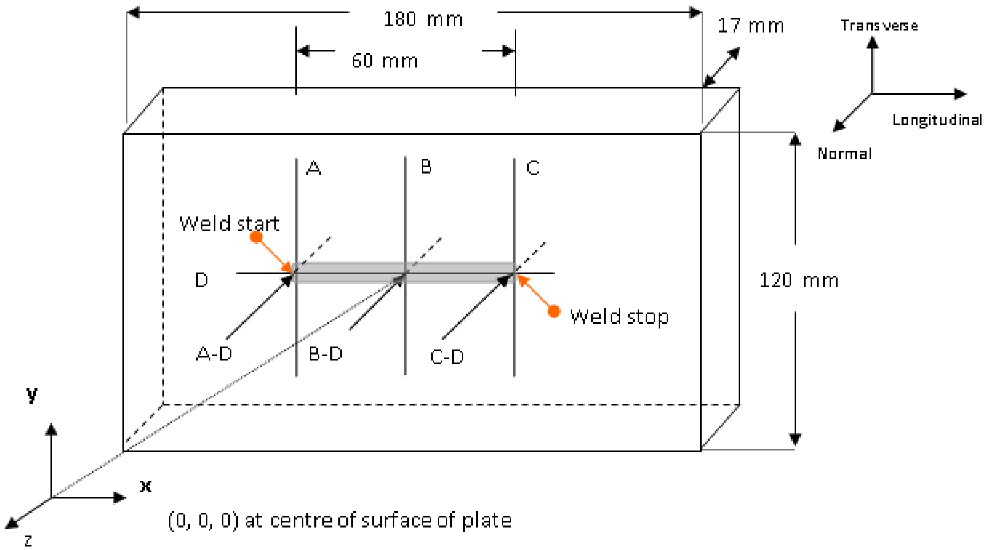
TG6: 3 pass slot weld in Ni alloy
Dissimilar filler and base material

TG8: Letterbox dissimilar metal weld on ferritic steel
Thick geometry plate (30 mm)

TG9: WLAM additive manufactured beams (stainless steel)

TG1 – single bead on plate



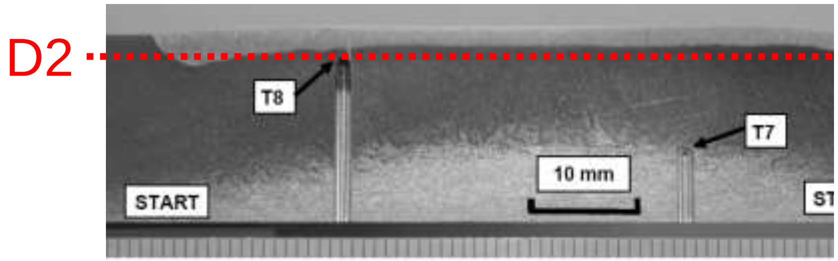


Benchmark problem of a single weld bead laid down on the top surface of an austenitic steel plate

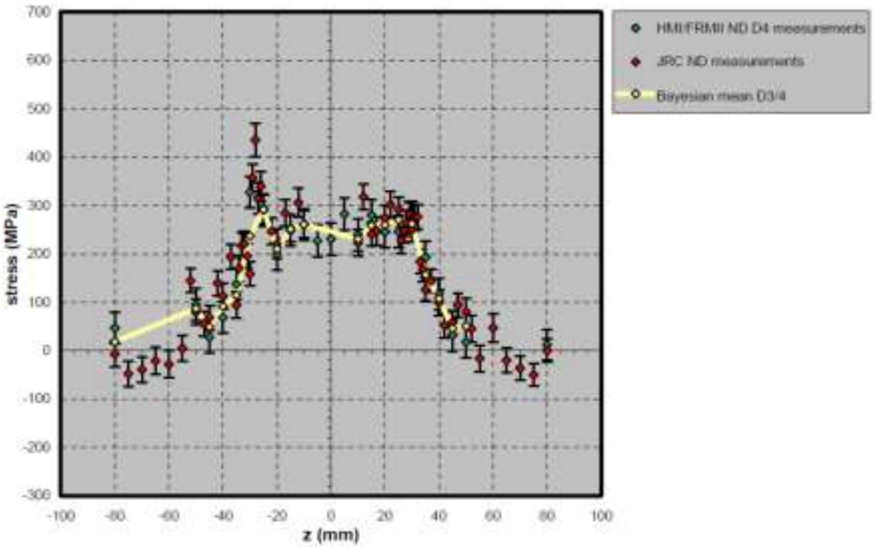
- Austenitic steel AISI 316L
- Simple geometry
- Several samples produced nominal the same
- No d0 reference values

M. Smith *et al*, Int. J. Pres. Ves. Pip. **120-121** (2014) 93-140

TG1 – single bead on plate



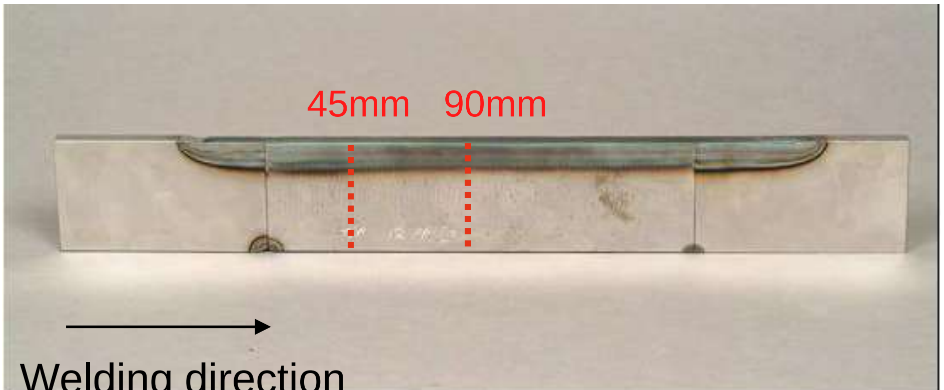
Side view on weld, measurement line 2 mm below surface



- ➢ Accurate positioning and error reporting absolutely essential
- ➢ Extensive and very complete measurement data sets → allowed to do statistical analysis (Bayesian)
- ➢ Used to correlate different results form different measurement methods and provided a sound basis for the numerical simulations
- ➢ TG1 samples are available and were used to test (and calibrate) other neutron strain scanners

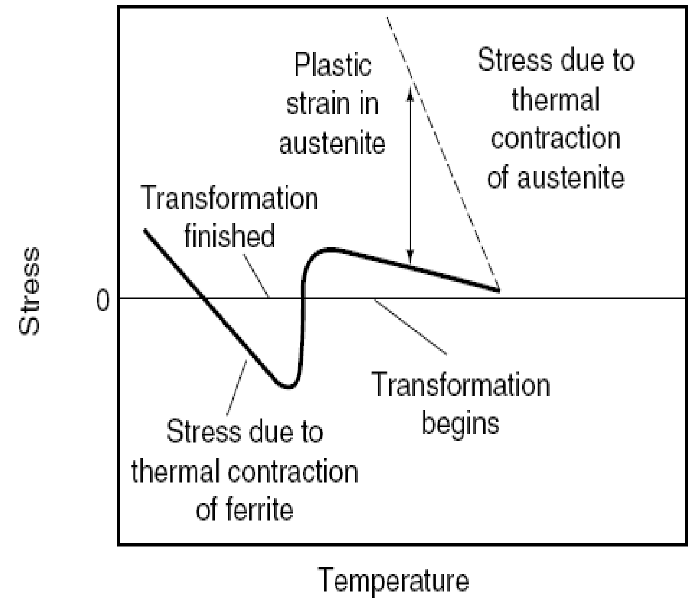
M. Smith *et al*, Int. J. Pres. Ves. Pip. **120-121** (2014) 93-140

TG5 - single autogenous weld on ferritic plate



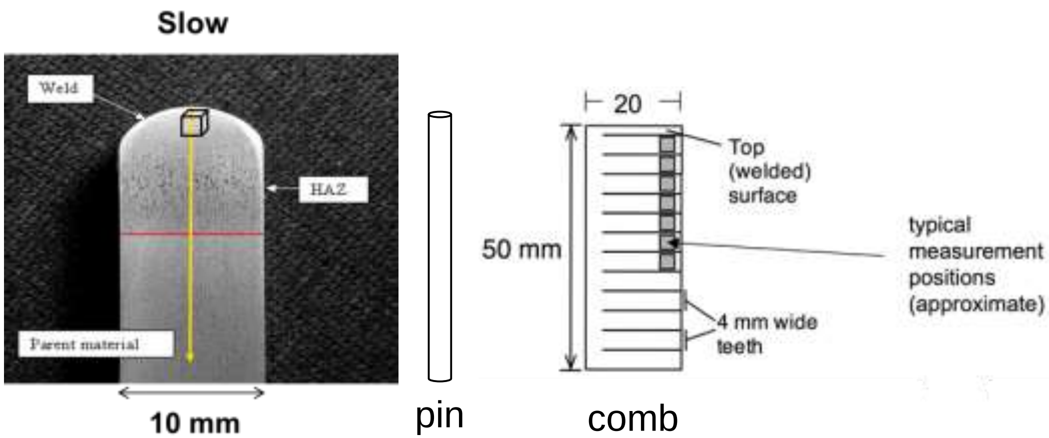
- The TG5 edge-welded beam specimen provides a simple validation case for modelling of weld residual stresses in ferritic steels.
- In the TG5 specimen the heat flow is approximately 1-dimensional
- Phase transformation need to be considered

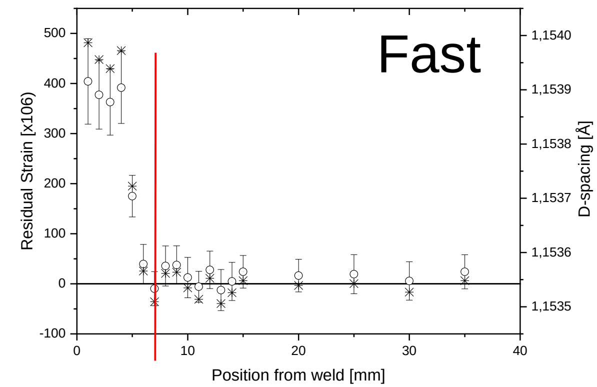
Phase transformations – Residual stresses



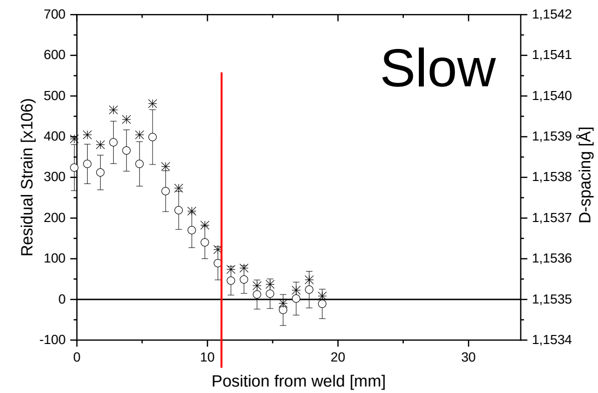
After: H.K.D.H. Bhadeshia, in „Handbook of Residual Stress and Deformation of Steel

TG5 - single autogenous weld on ferritic plate



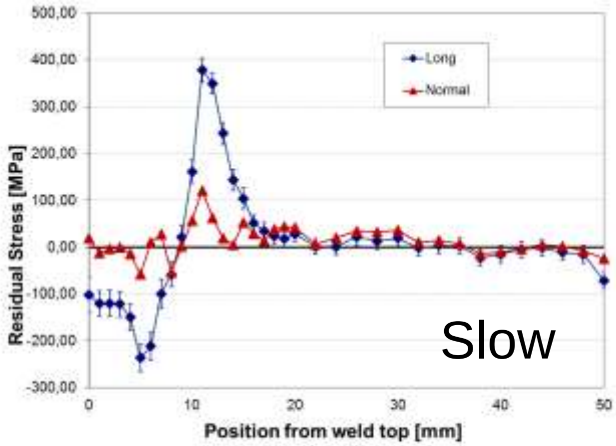


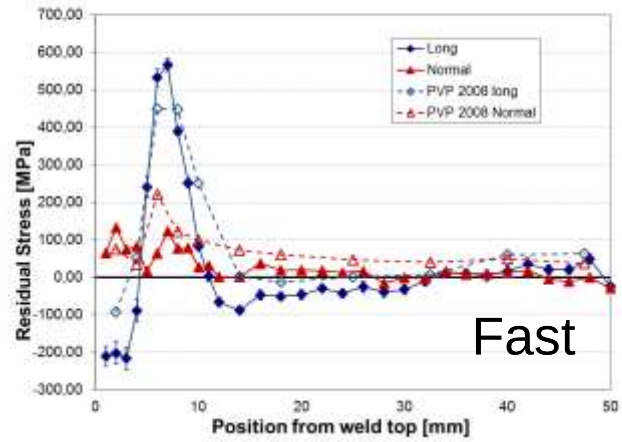
- Two different welding speeds
- Large d0 gradients
- Adequate reference samples, need to be perfectly aligned



A.P. Warren *et al*, Mat. Sci. Forum **524-525** (2006) 827-832

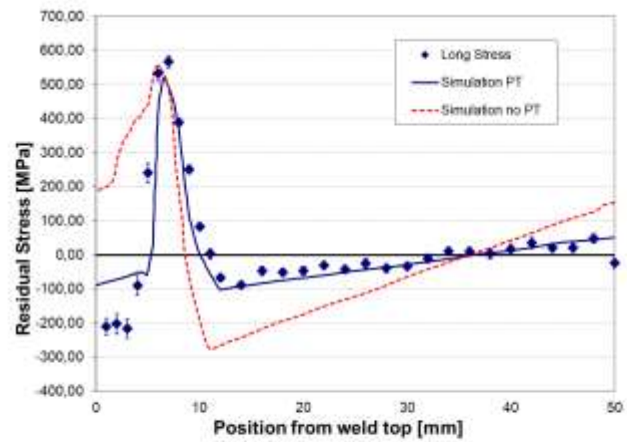
TG5 - single autogenous weld on ferritic plate





- Different welding processes produce different cooling rates → different ferrite phases and accordingly different residual stresses

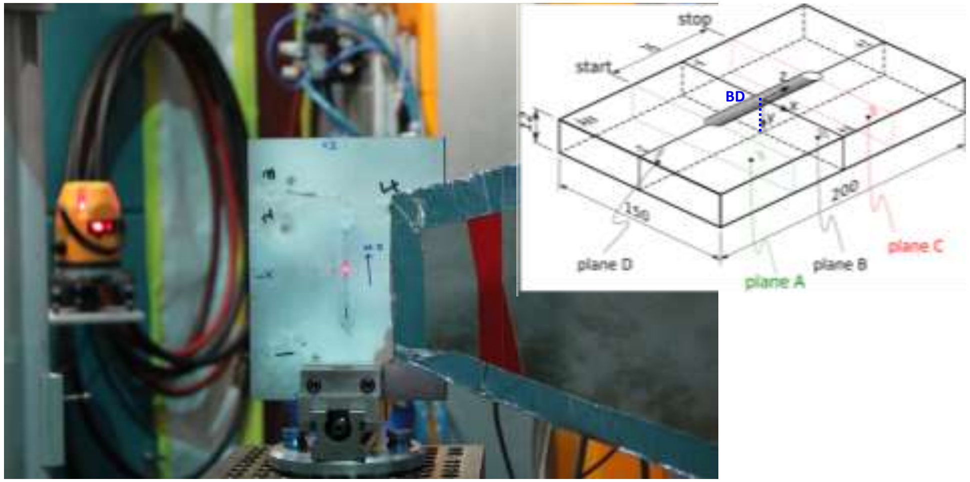
- Combs proved difficult to align and resulted in somewhat unrealistic ~50 MPa positive normal stresses

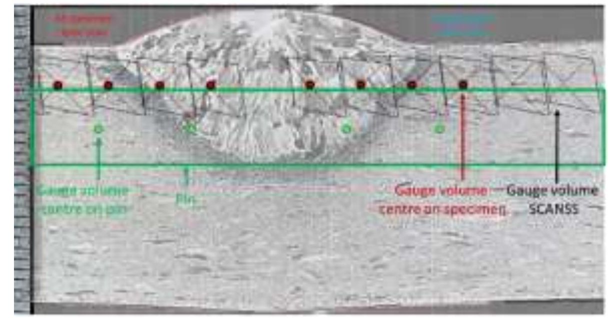


PVP 2008 = Proceedings of the 2008 ASME Pressure Vessels and Piping Conference

Simulation: IHI cooperation

TG6 – Inconel plate

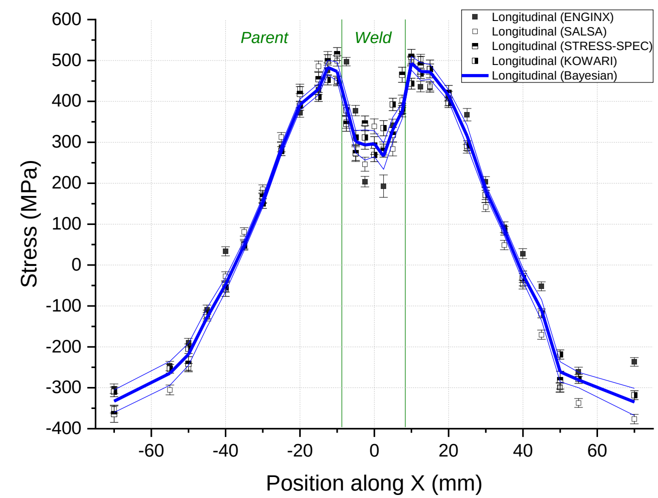




View across weld (plane B), coarse grains in weld region

Issues

- Base metal Ni Alloy 600, filler Alloy 82 → d0 gradients
- Positioning due to distortions + accurate alignment of pins
- Good agreement between measurements & a plane stress assumption seems to work reasonably well

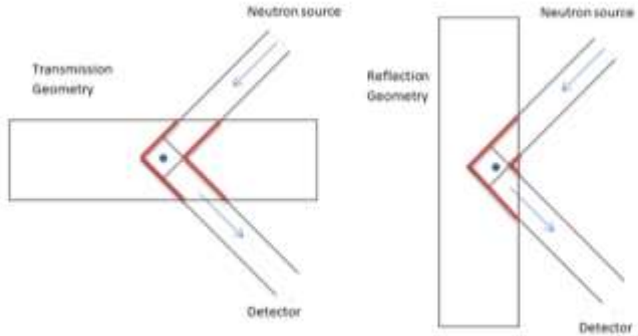


V.Akrivos *et al*, J. Appl. Cryst. **53** (2020) 1181-1194

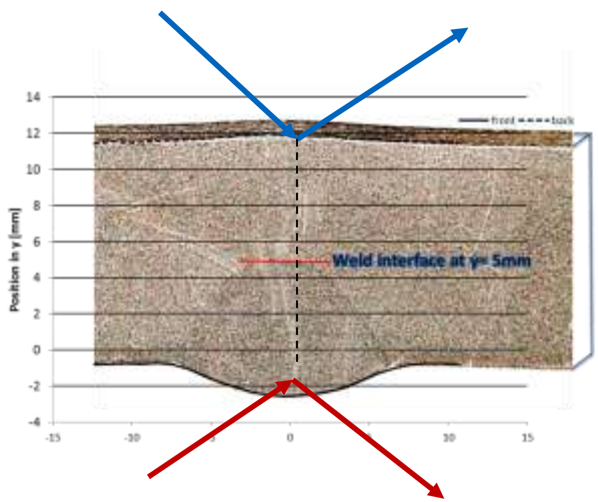
TG6 – Inconel plate

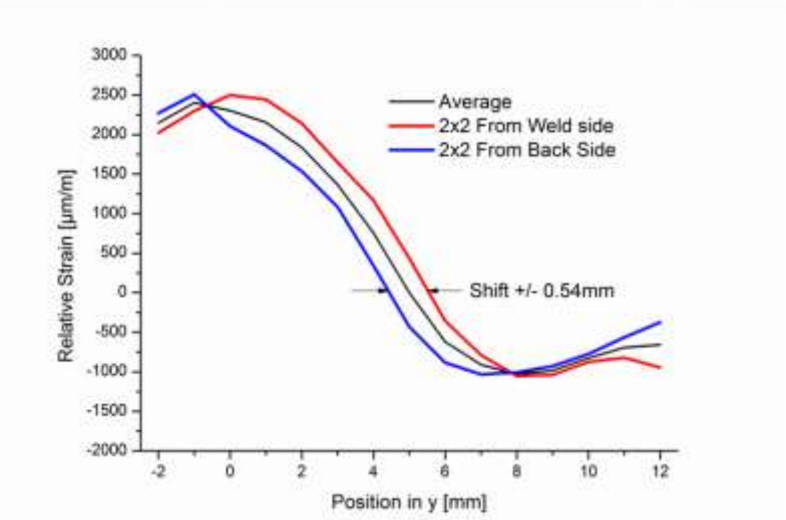
Additional obstacle

- Steep strain gradient + high absorption in Ni
- Apparent shift of GV centre leads to high strain errors
- Needs to be corrected (or averaged), otherwise incorrect stress values



Shift in centre of scattering from GV





R.C Wimpory *et al*, Mat. Perf. Char. **7** (2018) 488-502

Summary

- Residual Stress determination using Neutron diffraction essential for almost every NeT project

- Large amount of data in NeT projects elucidated and helped to resolve key problems with the method
  - d0 gradients
  - positioning (absorption shifts, reference samples …)
  - true error estimation

- Despite of sometimes complex issues with the samples very good agreement of data → <u>Gold standard of experimental validation</u>

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