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Title: Comparing residual stress measurements using diffraction and mechanical techniques

Author(s): DeWald, Adrian T.
Hill, Michael R.
Prime, Michael B.
Clausen, Bjorn
Brown, Donald W.
Sisneros, Thomas A.

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Comparing residual stress measurements using diffraction and mechanical techniques

Adrian T. DeWald
Hill Engineering, LLC

Michael R. Hill
University of California, Davis

Michael B. Prime, Bjørn Clausen,
Donald W. Brown, and Thomas A. Sisneros
Los Alamos National Laboratory

Hill Engineering, LLC
Engineering structural integrity

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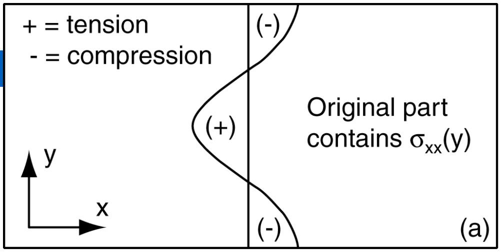
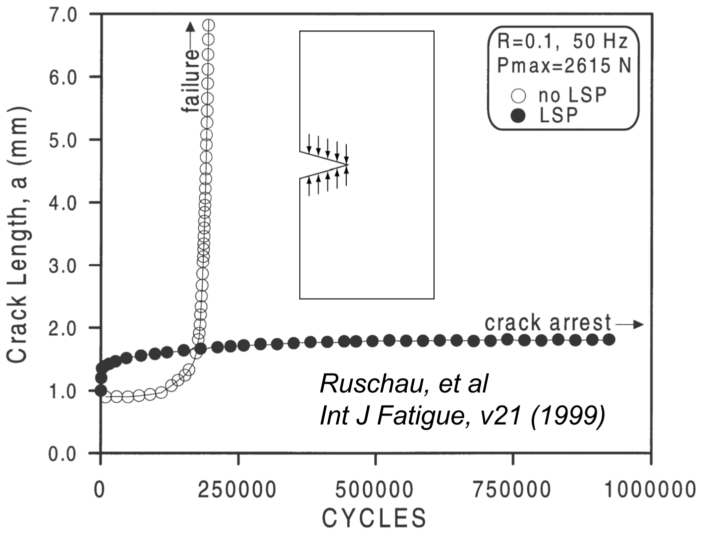
Background on residual stress

- Residual stresses are stress remaining within a body after outside forces removed
  - Must satisfy equilibrium
    - Forces & moments sum to zero on every plane
- Common RS sources
  - Material processing (e.g., quench)
  - Welding
  - Surface treatments
  - Cold working
- Residual stresses play a significant role in many failure mechanisms
  - Tensile RS → decrease performance
  - Compressive RS → increase performance





Accurate understanding of residual stress required for proper design

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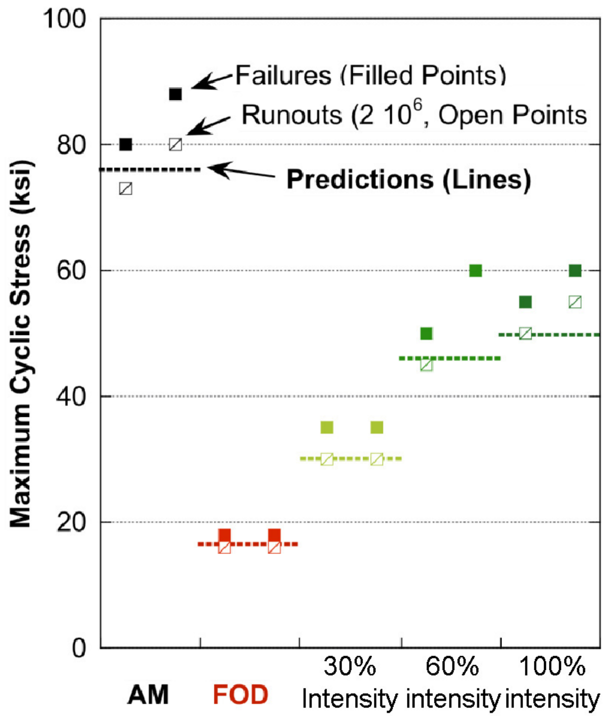
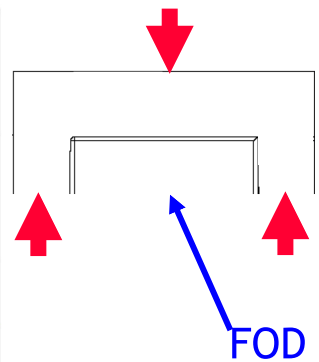
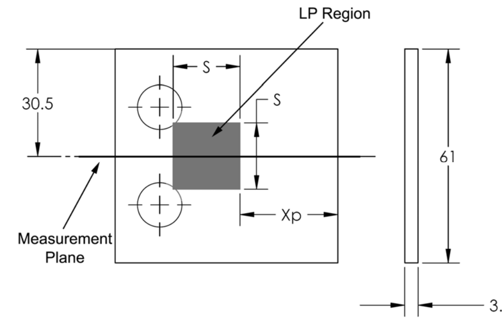
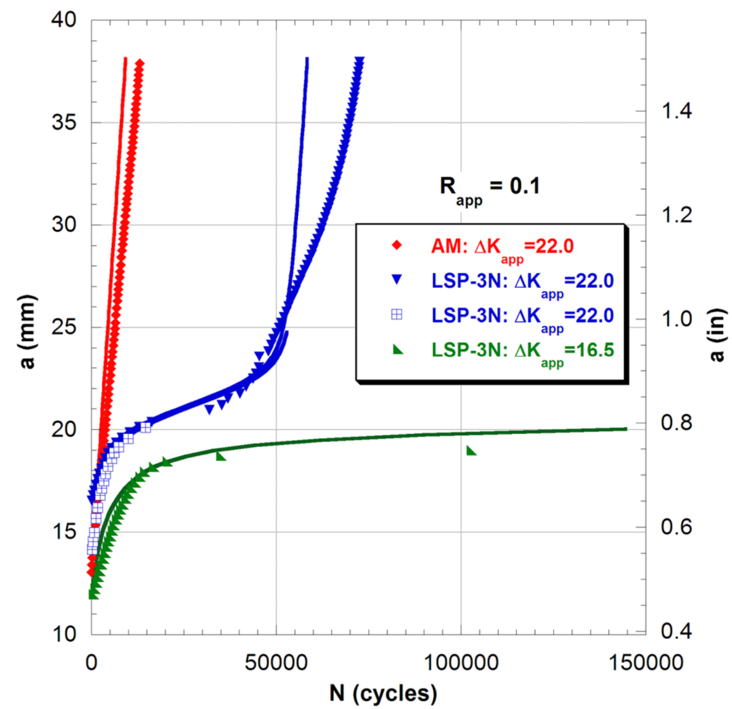
Residual stress effects on fatigue

- Residual stress combines with applied stress to affect fatigue performance









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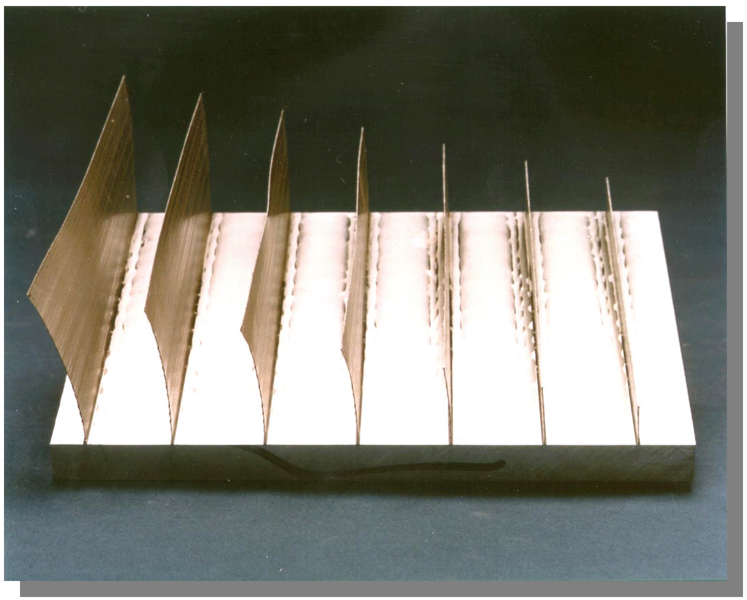
Residual stress effects on distortion

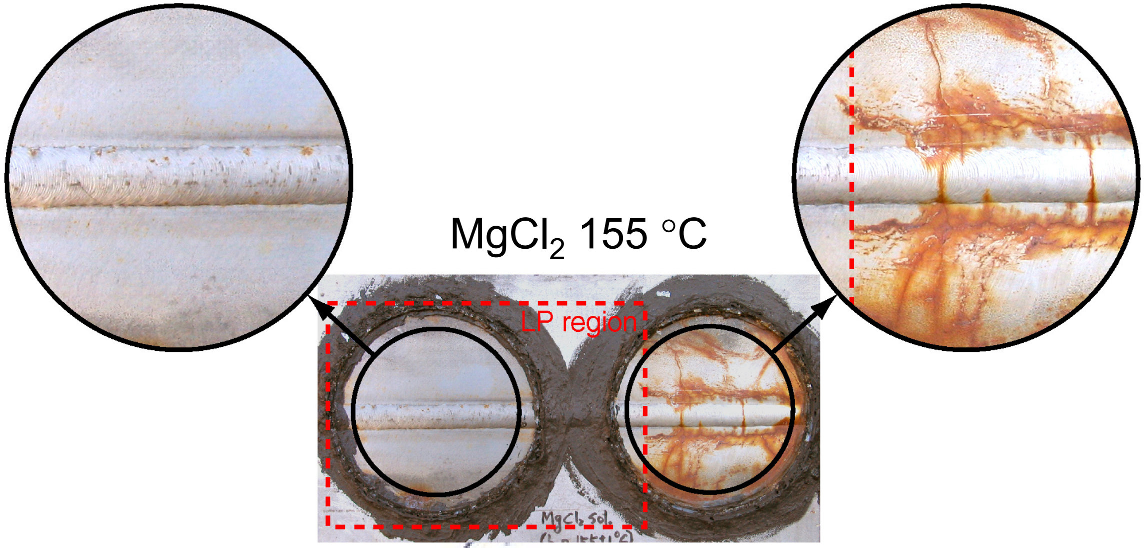
- **Bulk residual stresses can have a significant impact on distortion of thin-walled components**
  - Even low-level bulk stress can cause significant distortion
    - Large amount of material removed
    - Long length scales



Photos curtsey Boeing

Stress corrosion cracking

- Recipe for stress corrosion cracking
  - Susceptible material
  - Corrosive environment
  - Tensile stress
- Elimination of tensile residual stress stops SCC
- 304 Stainless steel weld
  - LSP region of weld
  - Expose two sections to $MgCl_2$ 155 °C



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Residual stress effects on fracture

- Bulk residual stresses can lead to spontaneous fracture

Photo: Ryszard Szymani, Wood Machining Institute

Photo: Mark Newborn, Alcoa

Residual stress measurement

- Residual stress measurement is challenging
  - Impossible to "see" residual stress
  - Requires indirect measurement
    - Measure something else (e.g., strain release) and "infer" residual stress
- Variety of accepted RS measurement methods
  - Each method has advantages and disadvantages
  - "Best method" depends on specific application

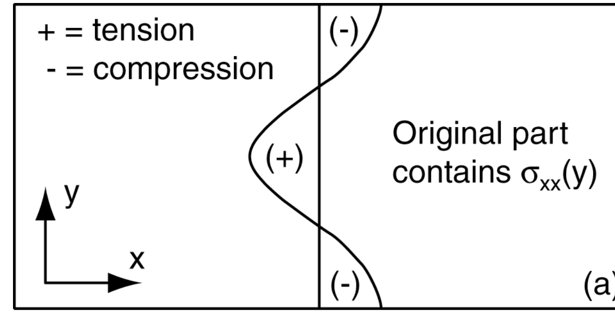
Selection of RS measurement technique	
Depth of RS measurement	Required accuracy
Magnitude of stress gradients	Spatial variation of RS
Number RS components	Material property variations
Geometry	Application specific concerns
Destructiveness	Required equipment
Measurement time	Cost
Portability	Required expertise
Material handling	

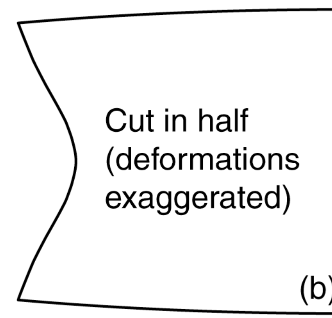
No residual stress measurement will be exact…one way to estimate bounds is to compare multiple techniques

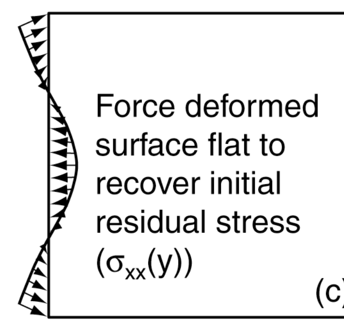
Contour method overview

- Contour method steps (illustrated for 2D body)
  - Part contains unknown RS (a)
  - Cut part: stress release ⇒ deformation (b)
  - Measure deformation of cut surfaces
  - Apply reverse of average deformation to FE model of body (c)
  - Map of RS normal to surface determined
  - Same procedure holds for 3D

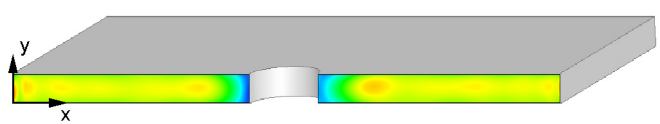
Cut → measure → FEM → residual stress







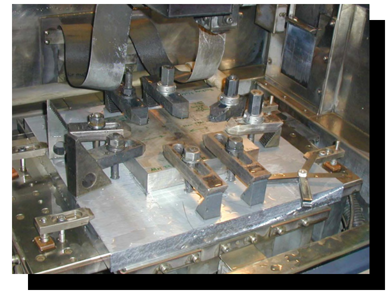
- Contour method can generate a 2D map of residual stress normal to a plane



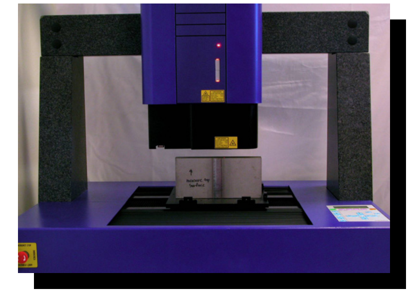
Contour method example

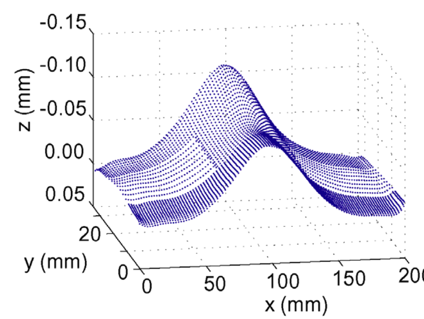
- Cut the part
  - Wire EDM typical
  - Clamp part to rigid backing plate
- Measure surface deformation
  - CMM or laser scanner typical
  - Measure a grid of points on both cut surfaces
- Analyze experimental data
  - Filter out noise
  - Average data from both surfaces
- Compute residual stress
  - FE model
  - Displacement boundary condition

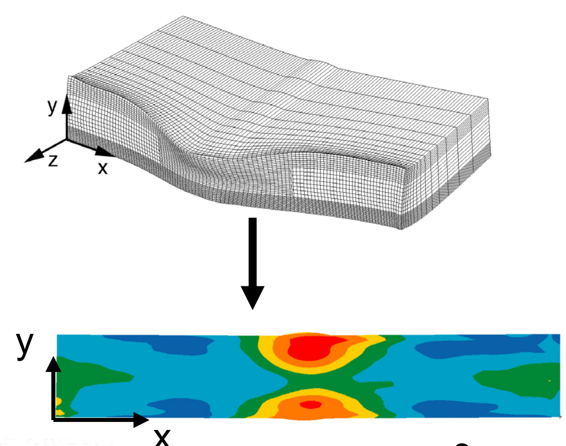
EDM cut



Surface measure

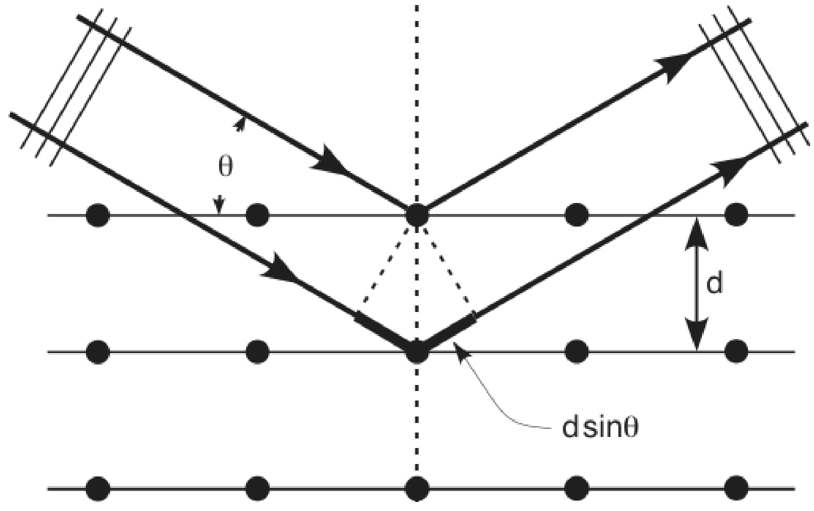






Diffraction methods principle

- Subject a crystalline material to incident radiation
- Radiation will diffract off of crystal lattice planes via Bragg's law
  - $\lambda = 2d\sin\theta$
- Gives you lattice spacing d
- Compare with unstressed lattice spacing d_0
- Get elastic strains
- Calculate stress
- Requires statistics - average over many diffracting grains



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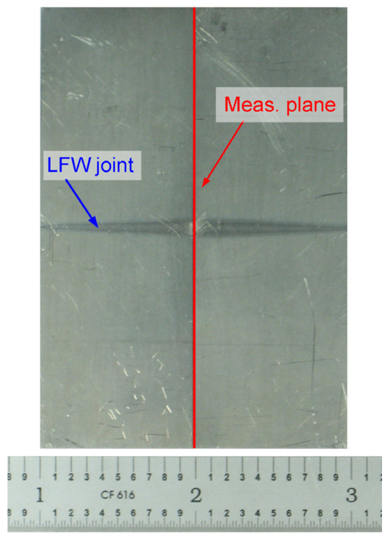
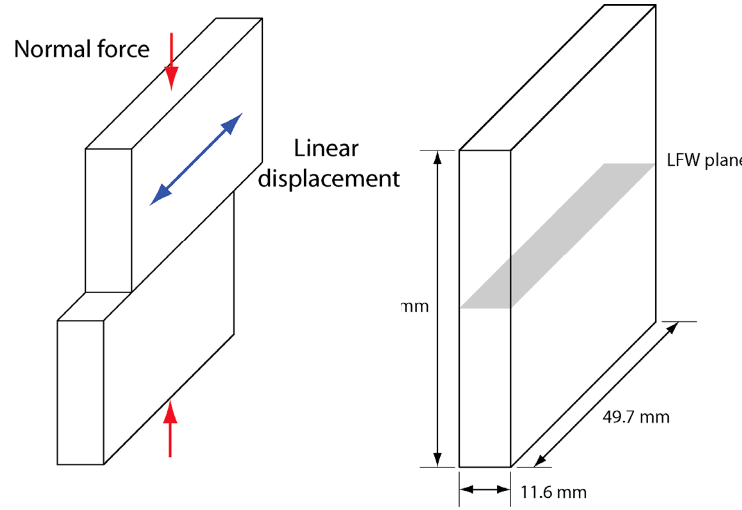
$$\varepsilon_i = \frac{d \;\; - d^0}{d^0}$$

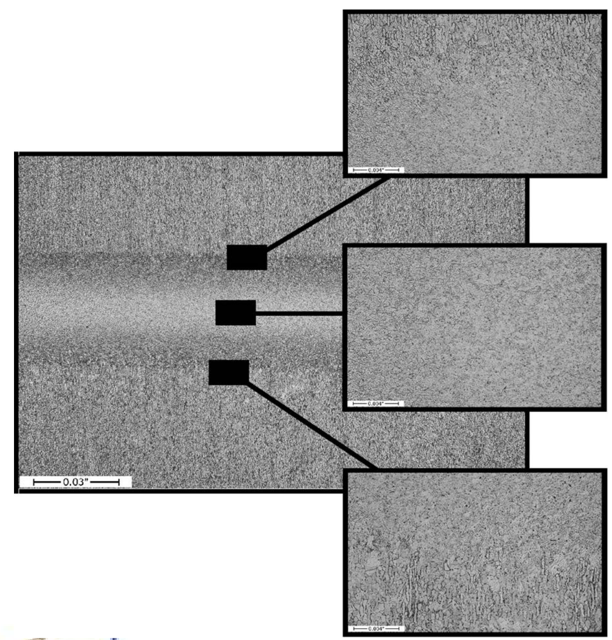
$$\sigma_i = \frac{E(1-\nu)}{(1+\nu)(1-2\nu)}\left[\varepsilon_i + \frac{\nu}{1-\nu}(\varepsilon_j + \varepsilon_k)\right]$$

Example: linear friction weld specimen

- Test specimen construction
  - Two blocks of Ti-6Al-4V
  - Join using LFW
  - Remove flash
  - Polish and etch surface







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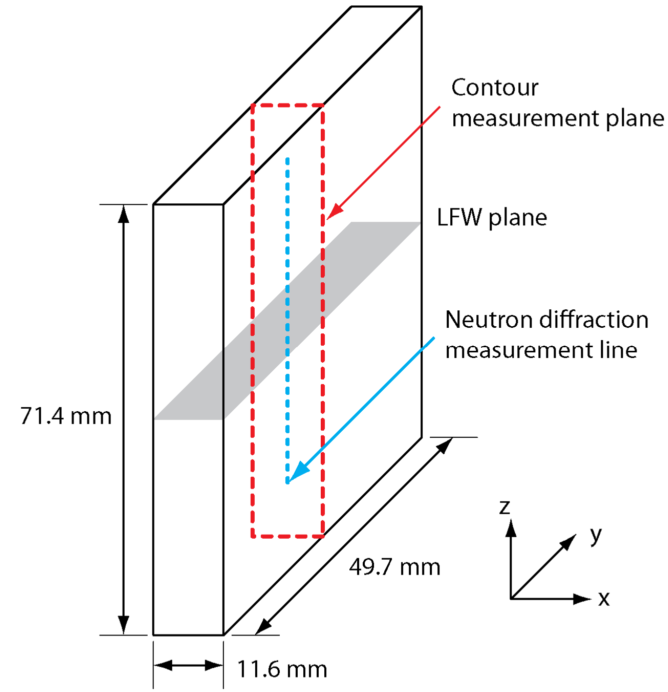
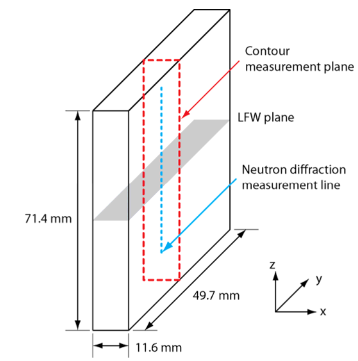
Measurement details

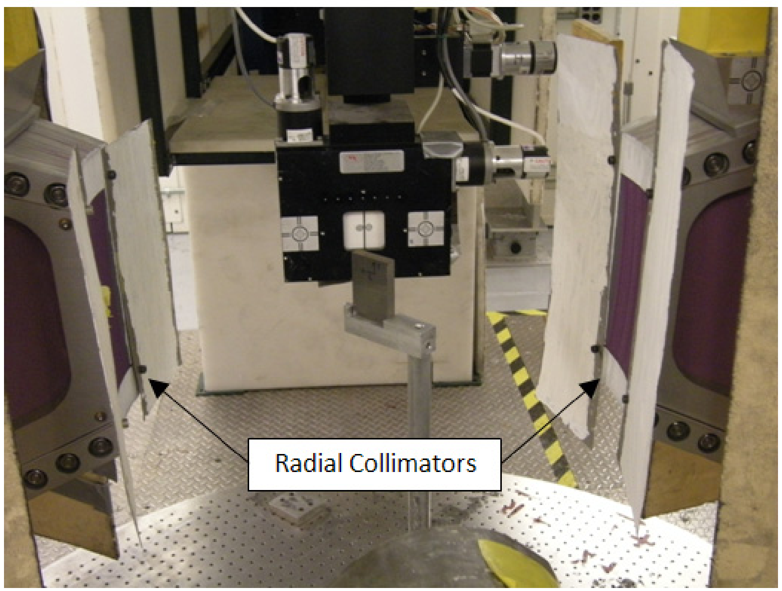
- Neutron diffraction measurements along line
- Contour measurement over plane(s)

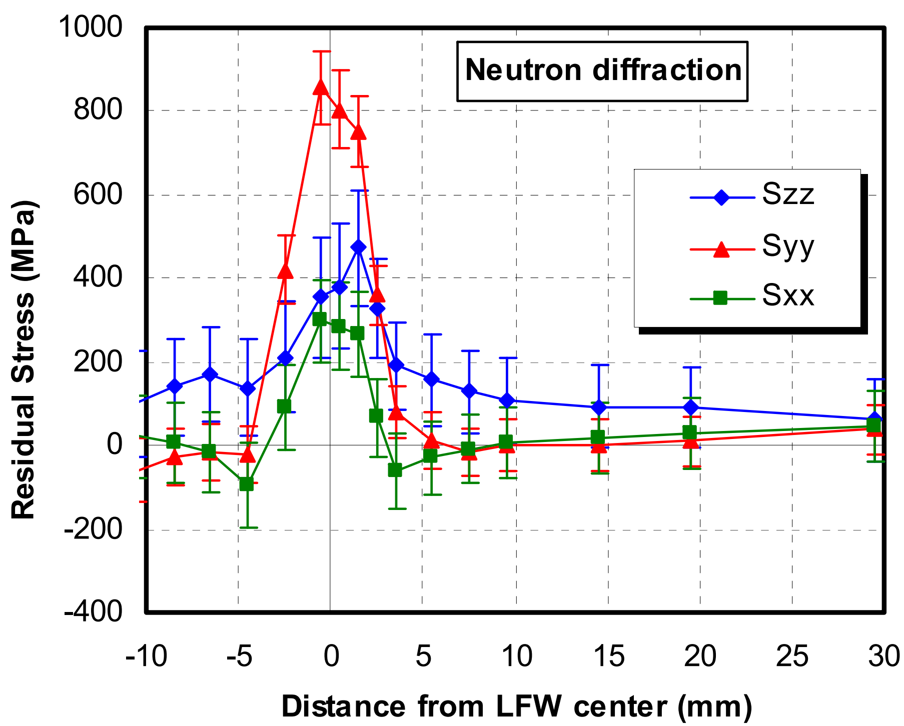


Neutron diffraction experimental details

- SMARTS beamilne
  - 2 mm x 2 mm x 2 mm gage volume
  - 16 measurement points

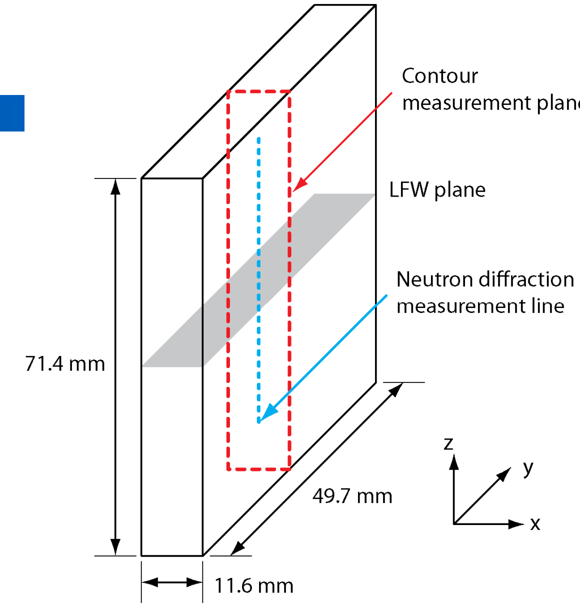


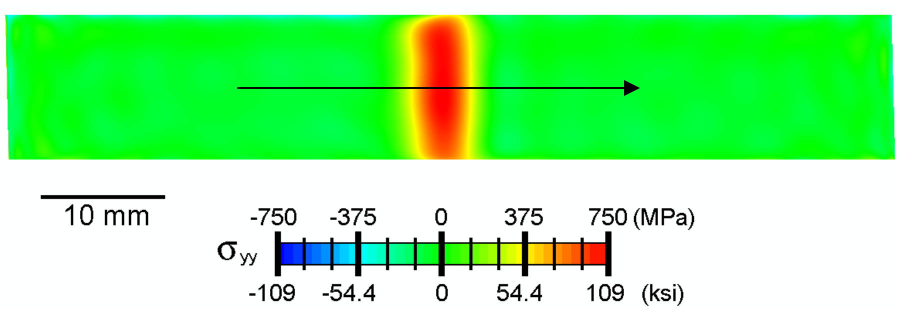


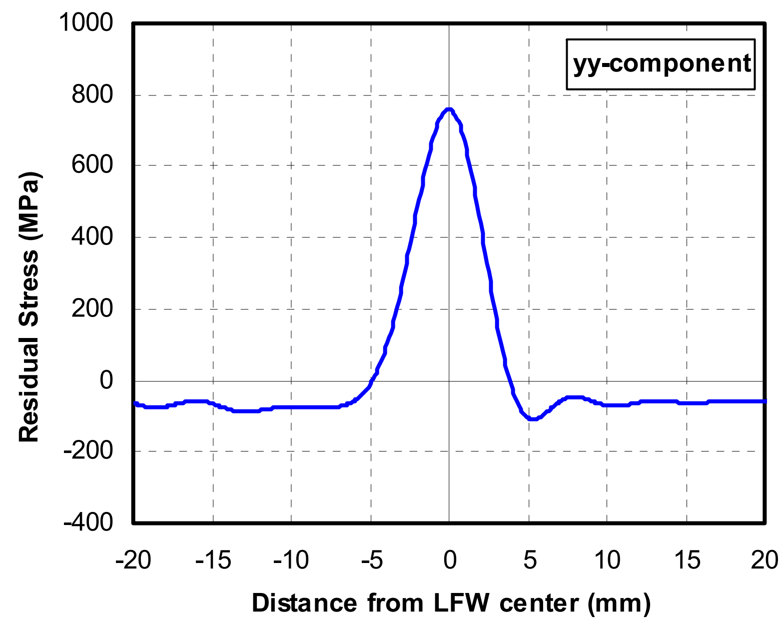


Contour method results

- Summary of results from contour method measurement
  - 2D map of long-direction stress
  - High magnitude tensile stress near LFW joint
  - Near-zero stress elsewhere

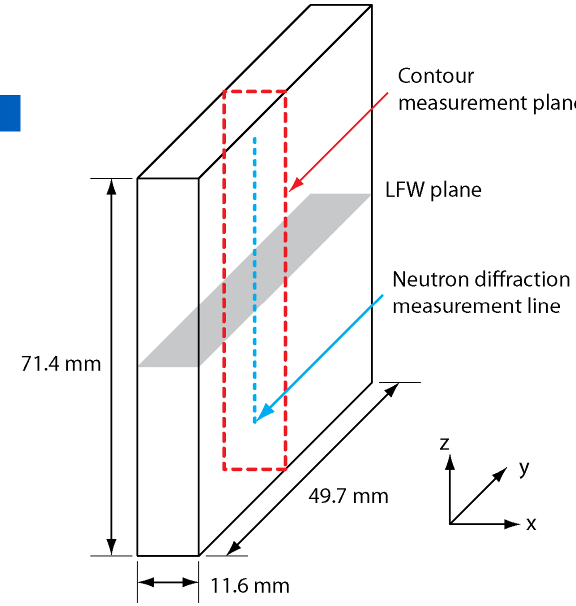


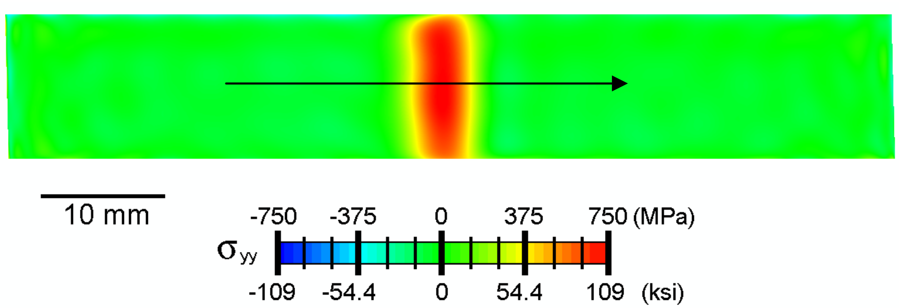


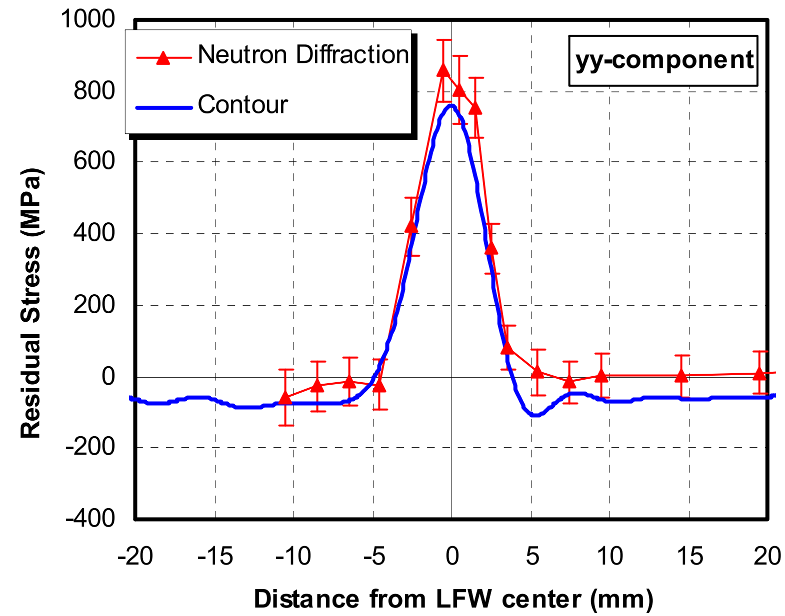


Comparison

- Neutron diffraction
  - Single line, 3 stress components
- Contour method
  - 2D map, single stress component
- Compare region of overlap
  - Similar peak magnitude (800 MPa vs 750 MPa)
    - Contour method is slightly lower
  - Similar peak width

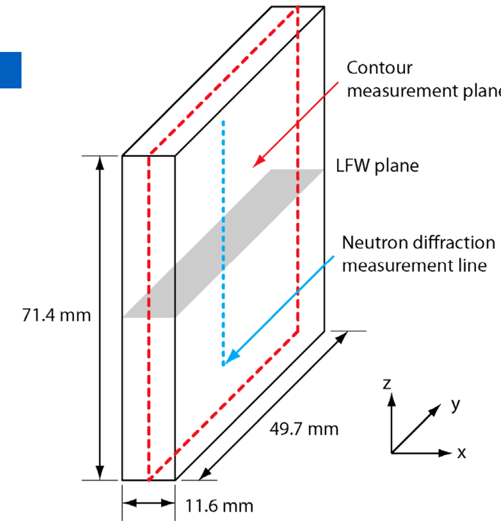


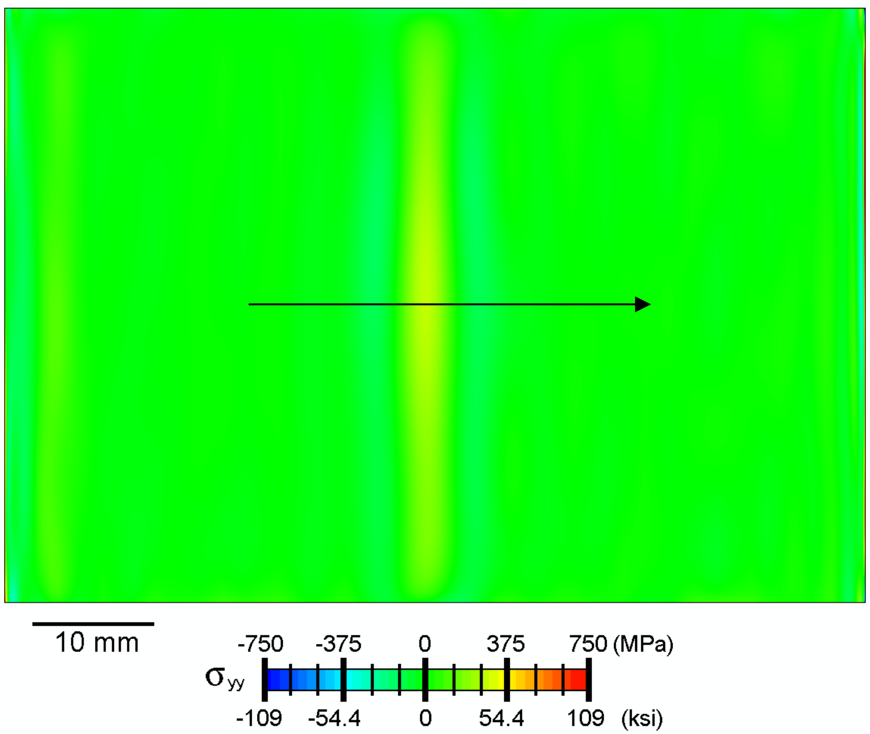


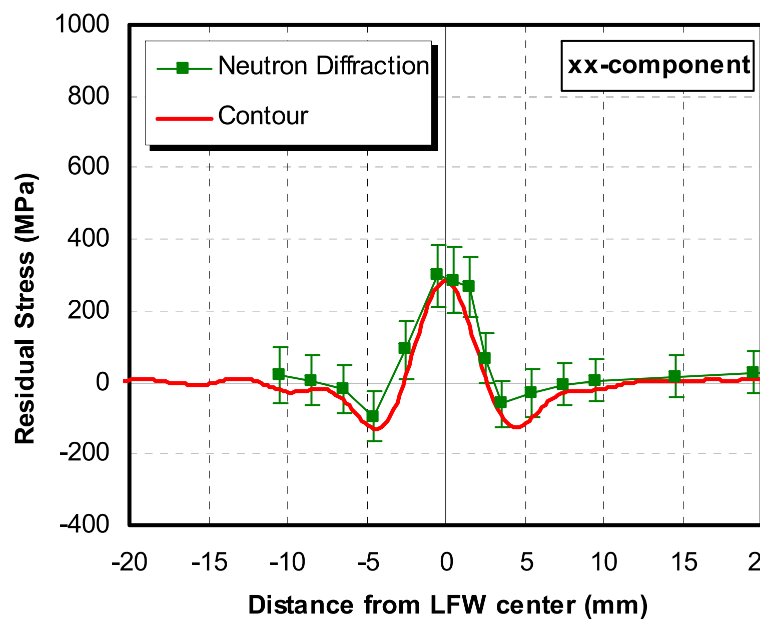


Another stress component

- Measure xx-direction stress using contour method on ***different*** (but similar) specimen
- Compare with neutron diffraction results
  - Similar good agreement in peak magnitude and width

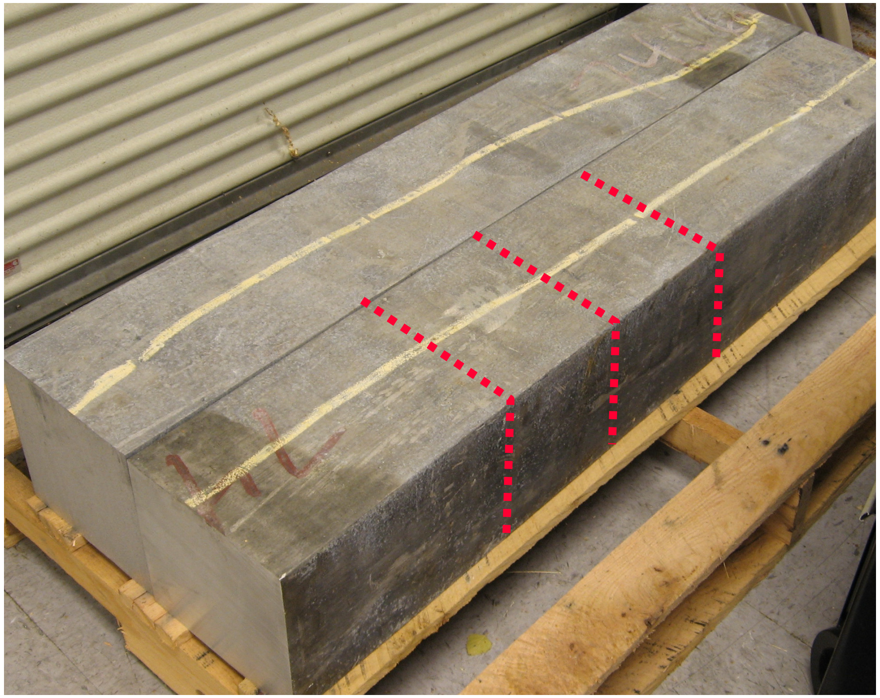






Example: aluminum forging

- **Measure longitudinal residual stress in aluminum forging**
  - Aluminum 7050-T74
    (as quenched, no stress relief)
  - 8” x 8” cross section (approximate)
  - This time, two adjacent pieces from “long” forging
    - 8” long pieces



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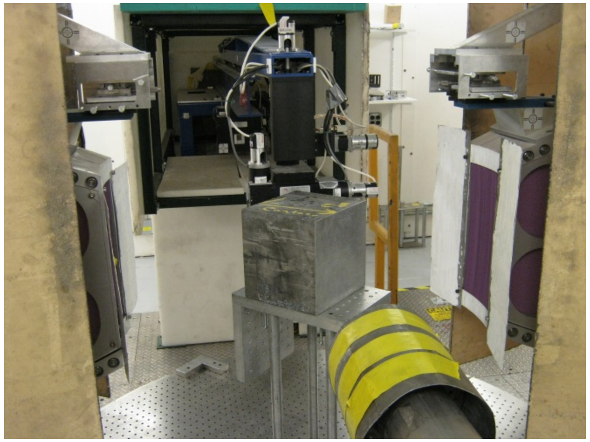
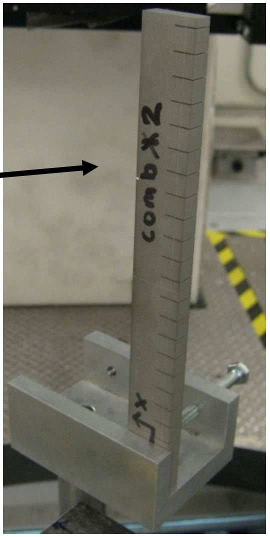
Neutron diffraction experimental details

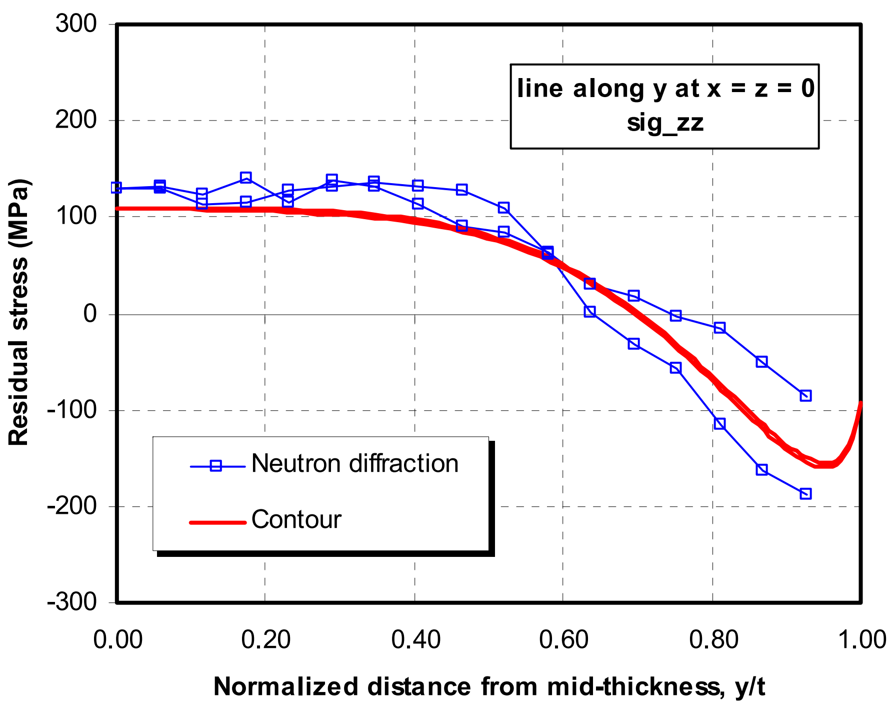


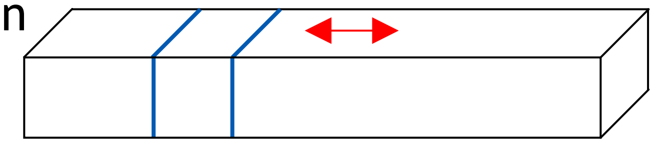
- **SMARTS beamline (LANL)**
- **Measured 2 orientations to get 3 strain components**
  - 5 × 5 × 4 mm sampling volume
- **Only 5% neutron penetration in thick part**
  - ~120 hours to measure ~80 points along 3 lines
  - Full 2D map not practical
- **Spallation source - multiple reflections, fit to Rietveld refinement**
- **Measured unstressed lattice spacing on comb specimens**
  - Large d0 variations – adds uncertainty
- **Texture up to 10 × random**
  - Adds uncertainty

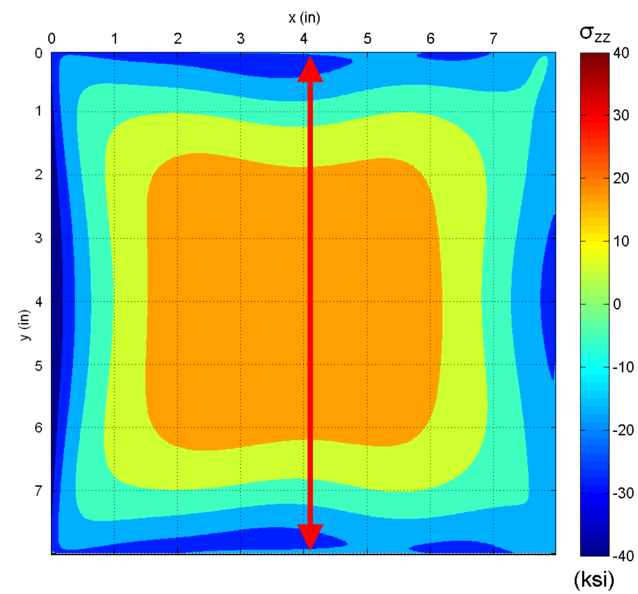


Compare measured residual stress

- Compare long direction stress
  - Similar shape, good agreement overall
  - Neutron diffraction shows slightly higher tension in core
    - ~ 130 MPa vs ~ 110 MPa (15%)
  - Neutron diffraction shows higher variation
    - Likely noise due to difficult experiment

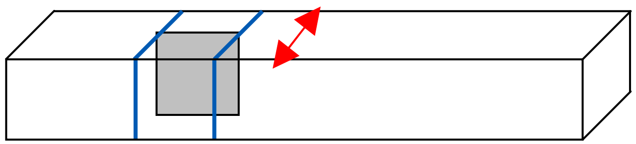


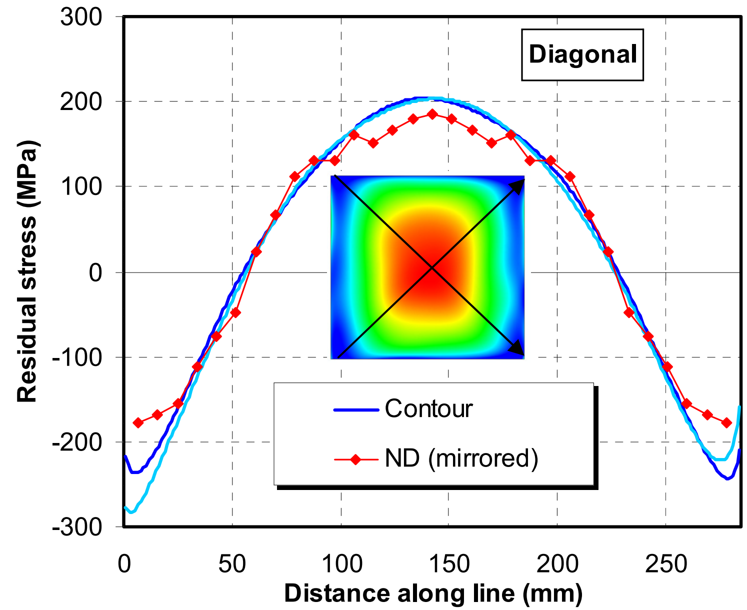


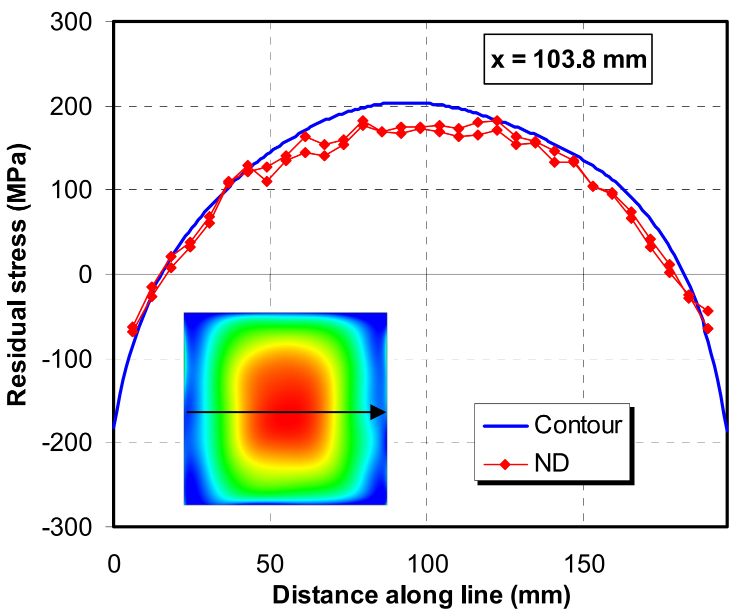


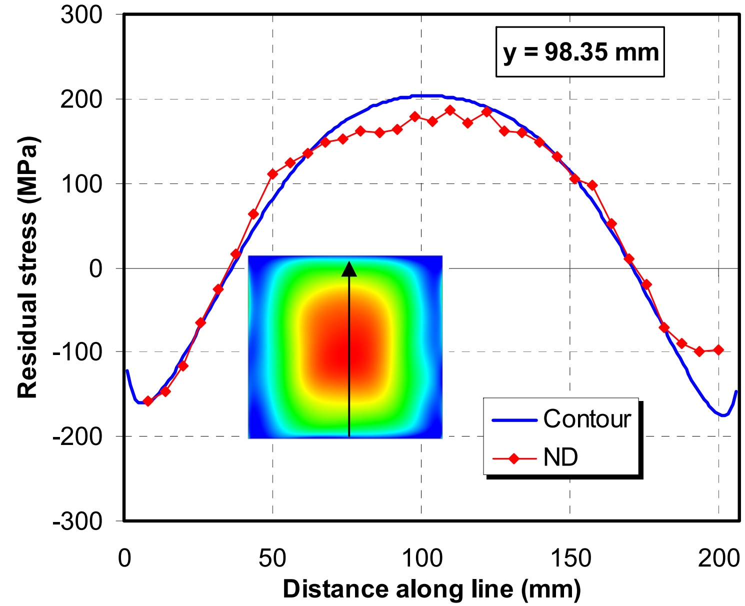
Compare measured residual stress

- Transverse stress at mid-width
  - Similar shape, good agreement
  - Contour method shows slightly higher tensile stress in core
    - ~ 200 MPa vs ~ 175 MPa (12%)



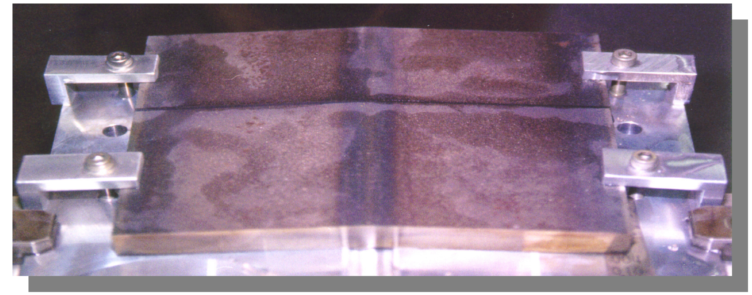






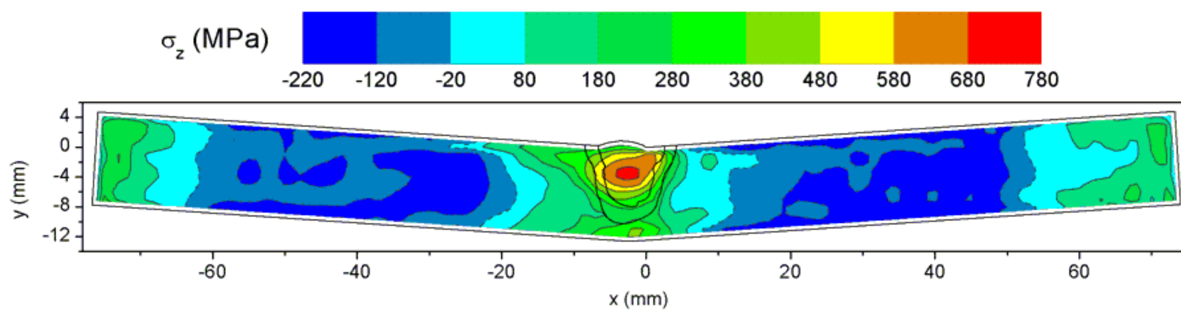
Example: welded steel plate

- Continuously welded plate
  - Steel: BS 4360 50D (ferritic)
  - 12.5 mm thick
  - 12 pass TIG weld



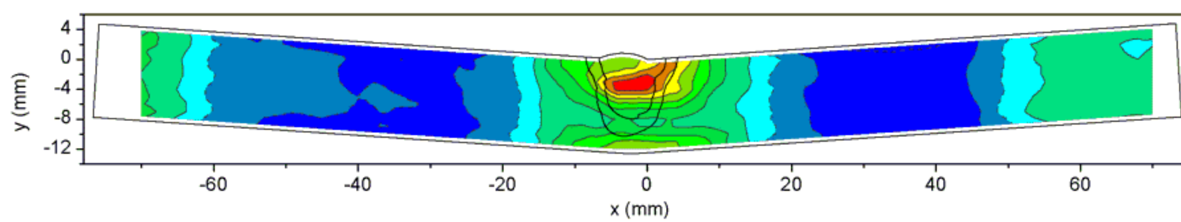
- Results for contour and neutron diffraction

Contour method



Contour method using laser contouring. Uncertainty estimated at ± 24 MPa.

Neutron diffraction

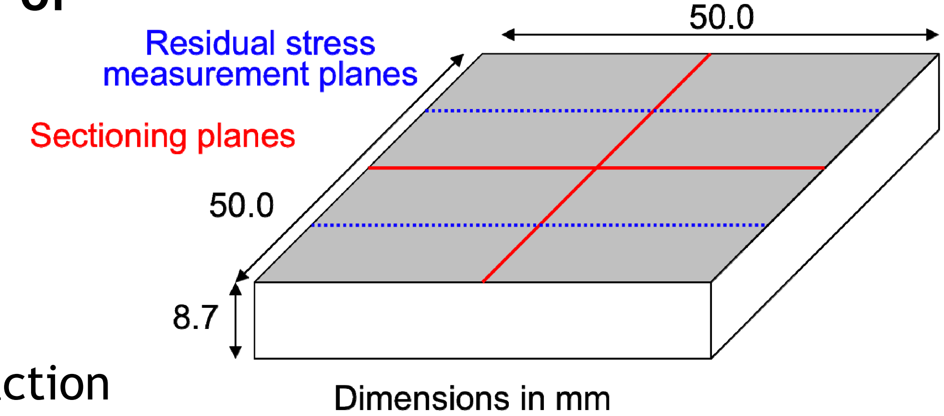


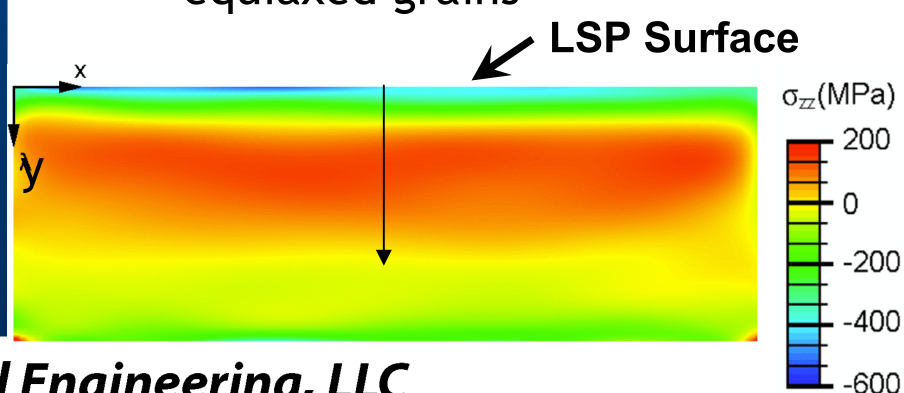
Neutron diffraction. Uncertainty estimated at ± 35 MPa.

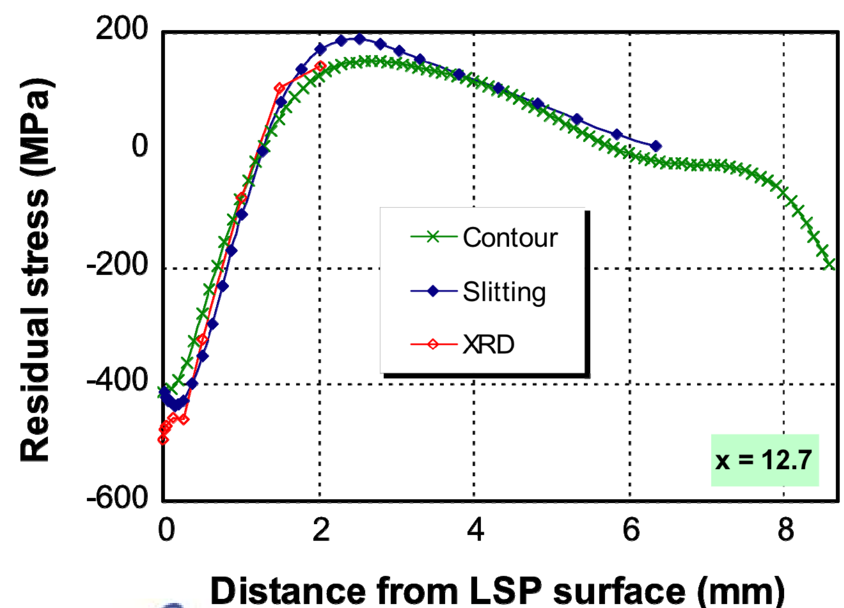
M. B. Prime, R. J. Sebring, J. M. Edwards, D. J. Hughes, P. J. Webster, "Laser Surface-Contouring and Spline Data-Smoothing for Residual Stress Measurement," *Experimental Mechanics*, **44**(2), pp. 176-184, 2004.

Example: laser shock peened plate

- Uniformly LSP entire surface of titanium alloy plate
- Cut into 4 block coupons
  - Each 25 x 25 x 8.7 mm
- Measure residual stress
  - Slitting, Contour, X-ray diffraction
- Good agreement in methods
  - Residual stress field that meets assumptions of methods
  - Uniform microstructure, equiaxed grains







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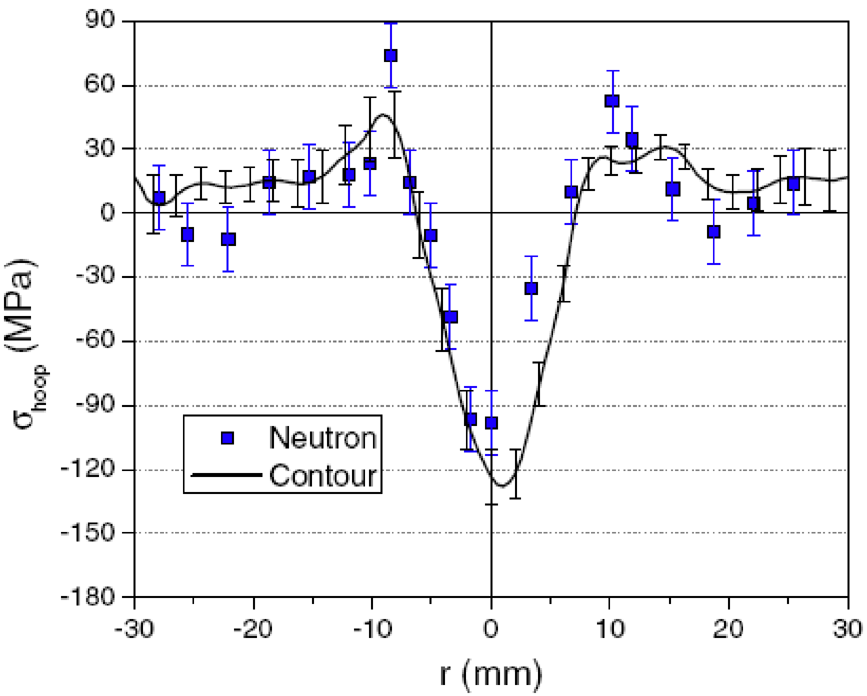
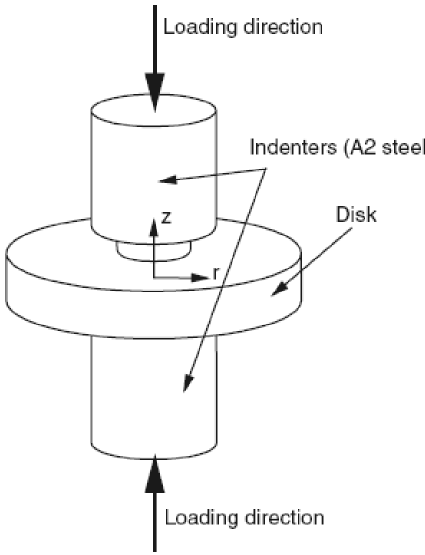
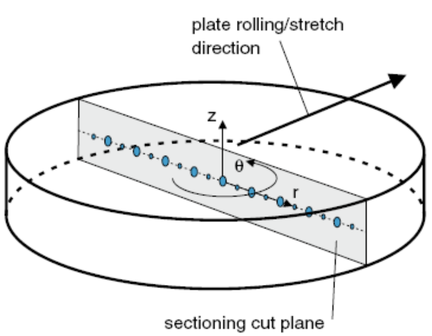
Example: cold compressed disk

- **AA2024-T351 disk**
  - Compress in center to induce residual stress
- **Compare contour and neutron diffraction**
  - Similar data trends
  - Contour shows slightly higher compression







P Pagliaro and MB Prime et. al, Exp. Mech., 2010 DOI 10.1007/s11340-010-9424-5.

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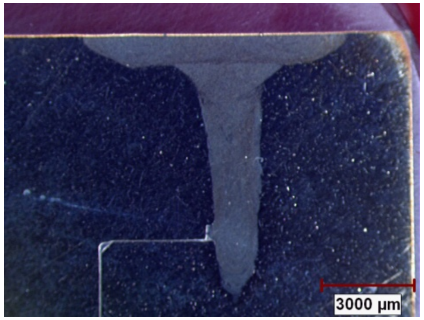
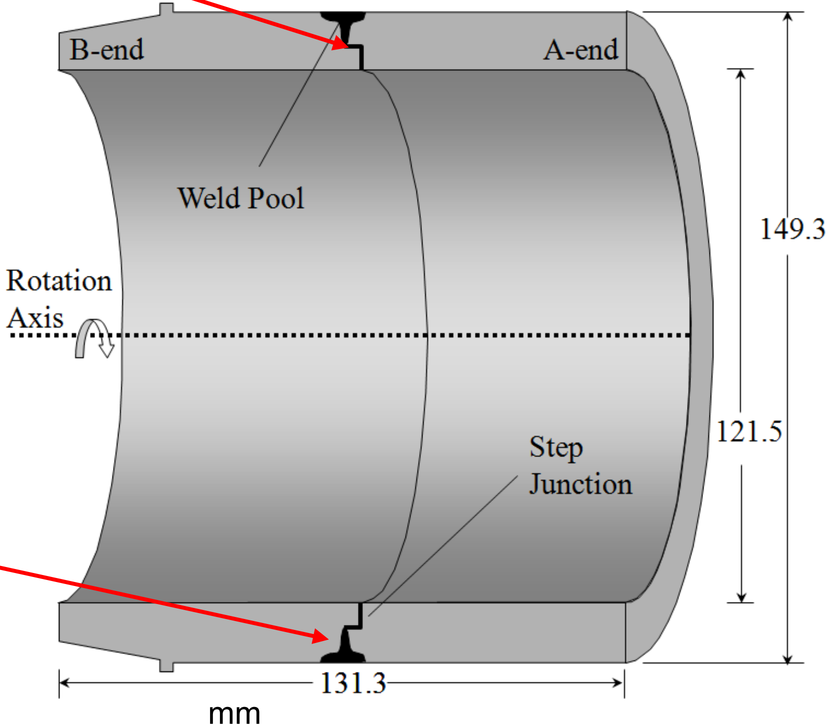
Example: partial-penetration girth-weld

- Circumferentially welded depleted uranium cylinder
- Stepped butt joint
- Single pass E-beam weld partial penetration
  - Leaves unfused partial joint
- Cosmetic de-focused top pass





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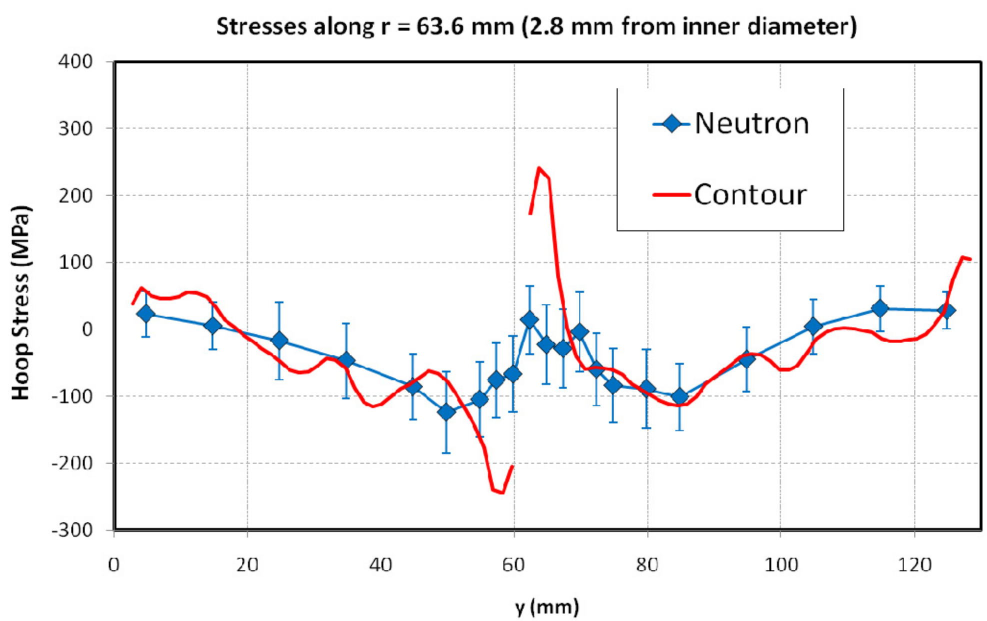
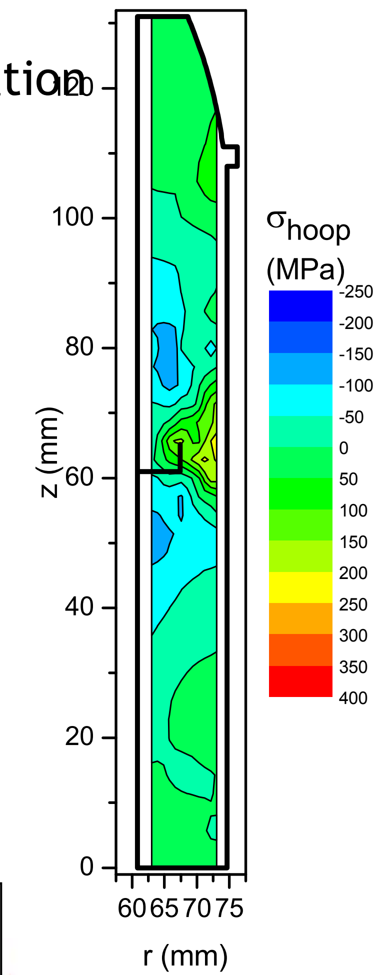
Compare measured residual stress

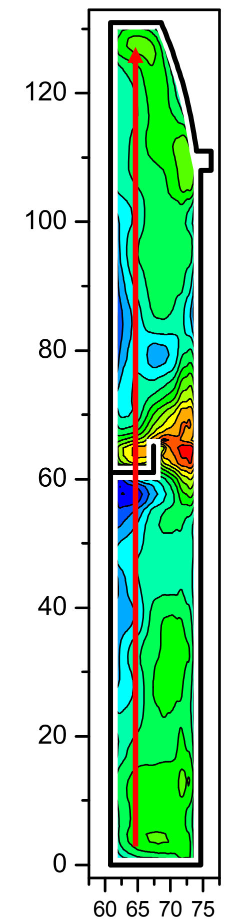
- Contour method gives similar but higher stresses than neutron results
- However, not a direct comparison
  - Contour measured stress at one angular location
  - Neutron is averaged over circumference



Neutron



Contour



DW Brown, TM Holden, B Clausen, MB Prime, TA Sisneros, H Swenson, J Vaja (2011), "Critical Comparison of Two Independent Measurements of Residual Stress in an Electron-Beam Welded Uranium Cylinder: Neutron Diffraction and the Contour Method." Acta Materialia 59 (3):864-873

Comparison of contour and neutron diffraction

- **Contour method is a 2D mapping technique**
  - Can't only measure at a single point
- **Neutron diffraction is a "pointwise" technique**
  - Can measure at many points to create a map
- **Very different measurement concepts/physics**
  - Displacements and deformation versus diffraction and lattice spacing
- **Range of applicable part sizes**
  - Contour probably extends a little farther on both ends in terms of allowable cross section size
    - Maximum thickness is very material dependent for ND
  - Neutron diffraction facilities can more easily accommodate large parts (in terms of handling)
- **Measured stress component(s)**
  - Neutron diffraction measures 3 orthogonal components (multiple set-ups)
    - Can measure multiple stress components over same line/plane
  - Contour only measures component normal to surface of cut
    - Multiple cuts to measure multiple stress components…but not the same thing

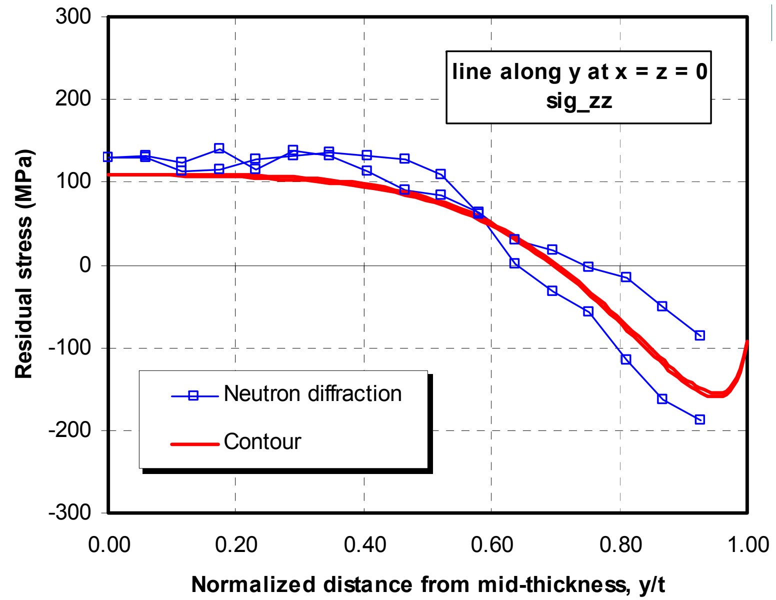
General comparisons

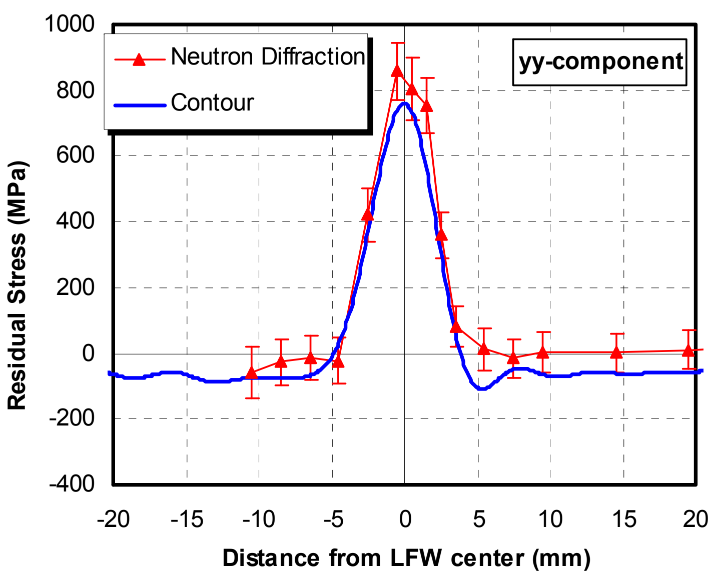
- **Measurement is difficult…choose method carefully**
  - Comparing results from different techniques is often useful
  - Correlation between different techniques builds confidence
- **For a straightforward measurement using good experimental technique it is possible to achieve strong correlation between different techniques**
  - Contour method and neutron diffraction comparisons shown here tended to have on the order of +/- 10 % maximum variance and +/- 5% RMS variance (for the best cases)
  - Highest variance tends to be observed at the most “difficult” locations
    - Near the surface
    - Near high stress gradients
- **Variance can increase significantly as measurement becomes more challenging (or use of improper method / technique)**

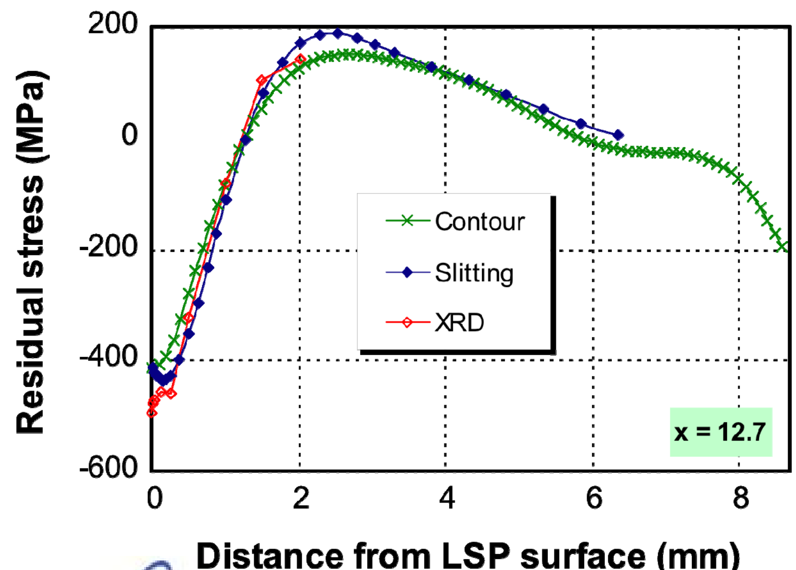
Thank you

Hill Engineering, LLC
3035 Prospect Park Drive, Suite 180
Rancho Cordova, CA 95670

Adrian T. DeWald
(916) 635-5706
atdewald@hill-engineering.com







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