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Title: Residual Stresses in Aluminum Clad Uranium-10 Weight % ~~Percent~~ Molybdenum Fuel Plates

Author(s): D.W. Brown, M. Okuniewski, J. D. Almer, J. S. Okasinski, B. Clausen, L. Balogh

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Residual Stresses in Aluminum Clad Uranium-10wt%Molybdenum Fuel Plates

D.W. Brown[1], M. Okuniewski[2], J. D. Almer[3], J. S. Okasinski[3], B. Clausen[1], L. Balogh[1]

[1] Los Alamos National Laboratory

[2] Idaho National Laboratory

[3] Argonne National Lab

The mission of the Global Threat Reduction Initiative (GTRI) of the National Nuclear Security Administration (NNSA) in the U.S. Department of Energy is to reduce and protect vulnerable nuclear and radiological material located at civilian sites worldwide by providing support for countries' own national programs. The GTRI Reactor Convert program converts research reactors from the use of highly enriched uranium (HEU) to low enriched uranium (LEU). The baseline fuel for conversion of high performance research reactors is aluminum clad monolithic uranium-10wt.% molybdenum (U10Mo). One bonding technique for the fuel to the cladding is hot isostatic pressing. The thermal expansion of U10Mo is roughly half that of aluminum, so a significant residual stress is expected following cooling from the pressing temperature. Finite element analysis (FEA) has been completed to calculate the residual stress and other properties under varying processing specifics, but model validation is necessary. The residual stress field was measured with 0.1mm resolution on mini fuel plates (0.25 mm thick U10Mo, 1mm thick Al-clad) in transmission with high-energy x-ray diffraction at beamline 1ID-C at the Advanced Photon Source. The entire Debye rings of five U10Mo (bcc) peaks were collected using an area detector and "caked" into 24 diffraction patterns. This was repeated with the sample normal to the beam and rotated 45° and 60° about a vertical axis to allow the full strain, and subsequently the stress tensor to be determined. In-plane compressive stresses of greater than 150MPa were observed in the U10Mo. The diffraction results will be compared to the model and the importance of the measurements at three sample orientations discussed.

RESIDUAL STRESSES IN ALUMINUM CLAD URANIUM-10WT%MOLYBDENUM FUEL PLATES

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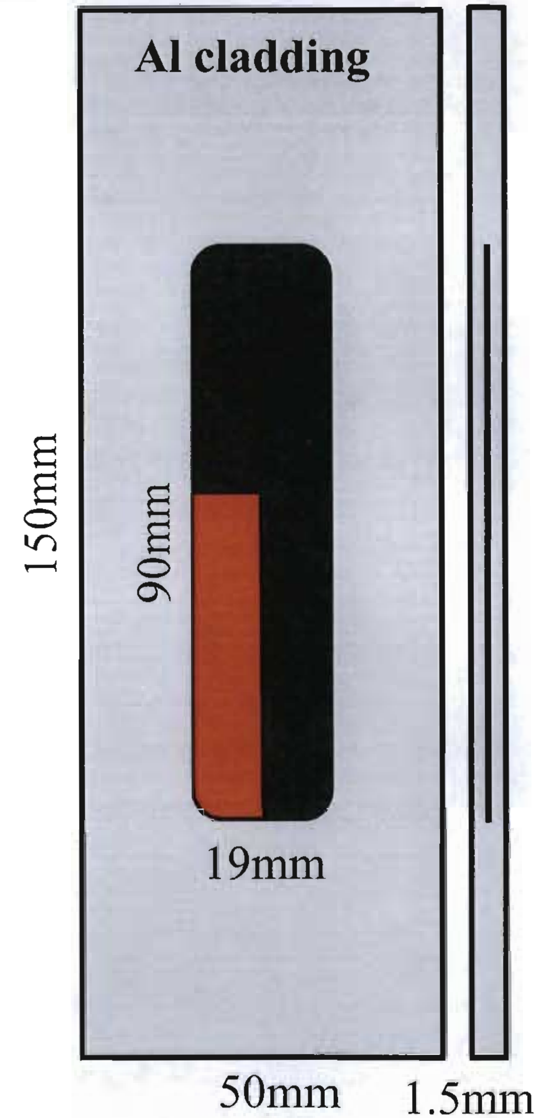
Residual Stress in Mini Monolithic U10Mo Fuel Plates

- Funded by the Reduced Enrichment for Research and Test Reactors (RERTR) program.
- Replace HEU with LEU in research reactors.
- Uranium 10wt% molybdenum foil clad with aluminum.
- CTE mismatch results in residual stresses which can cause distortions during processing and use.
    - CTE U10Mo~10×10^{-6}/C
    - CTE Al~22×10^{-6}/C
- 1.5 mm total thicknes
- 0.25mm thick U10Mo foil
- Foil was cold rolled, then HIP bonded.
- Diffraction residual stress measurements at the Advanced Photon Source.



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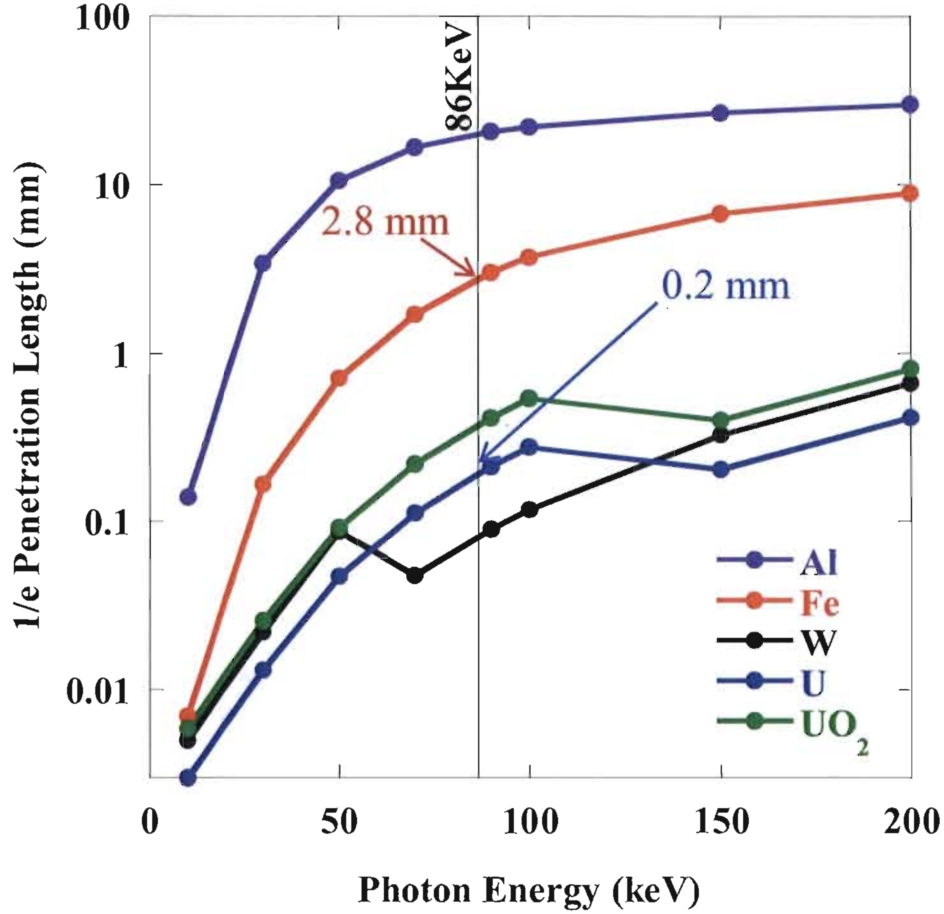
Penetration of High Energy Xrays Through High-Z Material is a Game Changer



Intensity of 3rd Generation source allows measurements at 3x, or more, the 1/e distance

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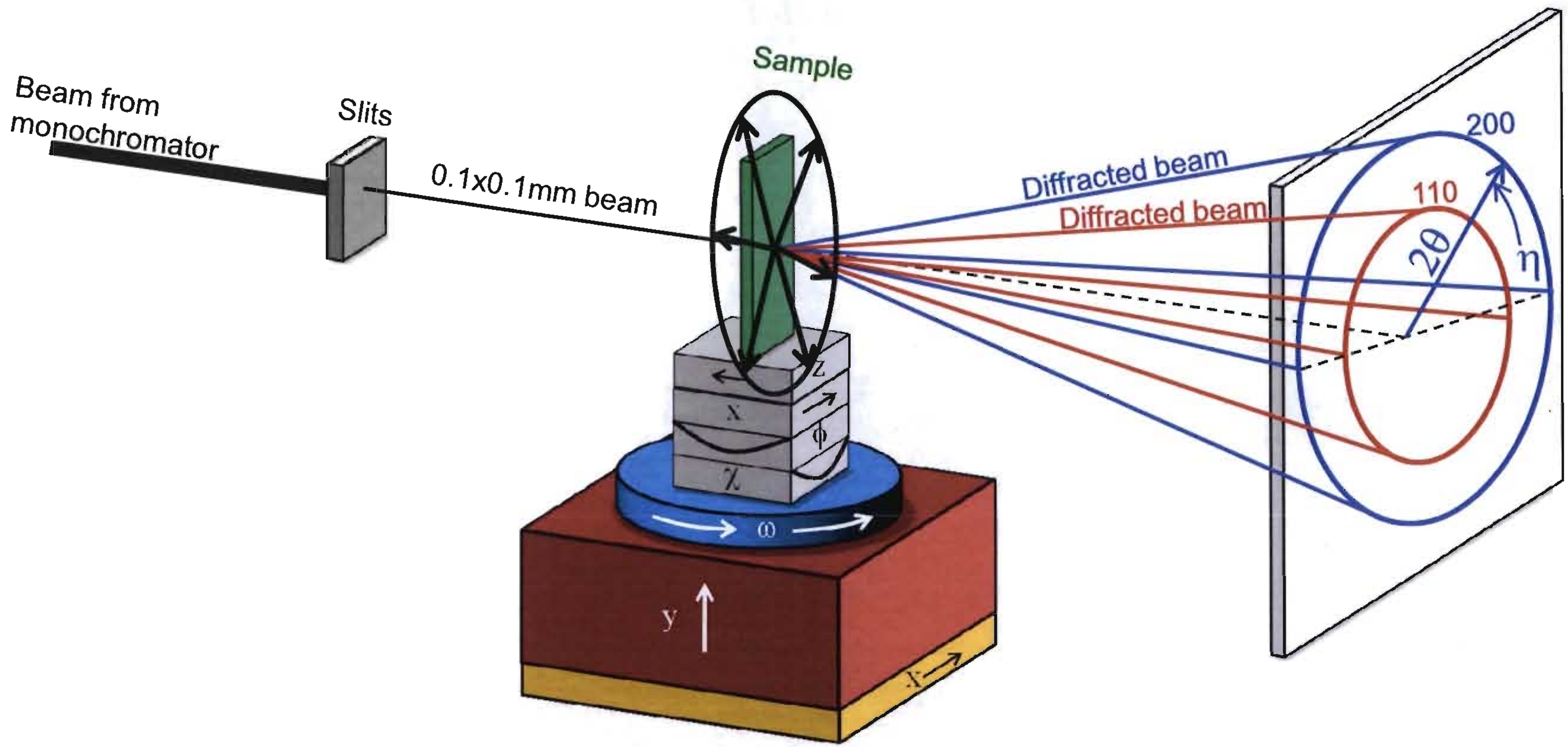
Residual Stress Measurements on 1-ID at Advanced Photon Source



- X-ray energy = 86KeV, λ=0.144Å.
- Beam cross section : 0.1mm x 0.1 mm
- Collection time at each point 0.7-1.5sec. 4 sec to save data and move sample.
- Ceria standard used for detector calibration.
- Debye cones provide diffraction vectors nearly normal to the incident beam.

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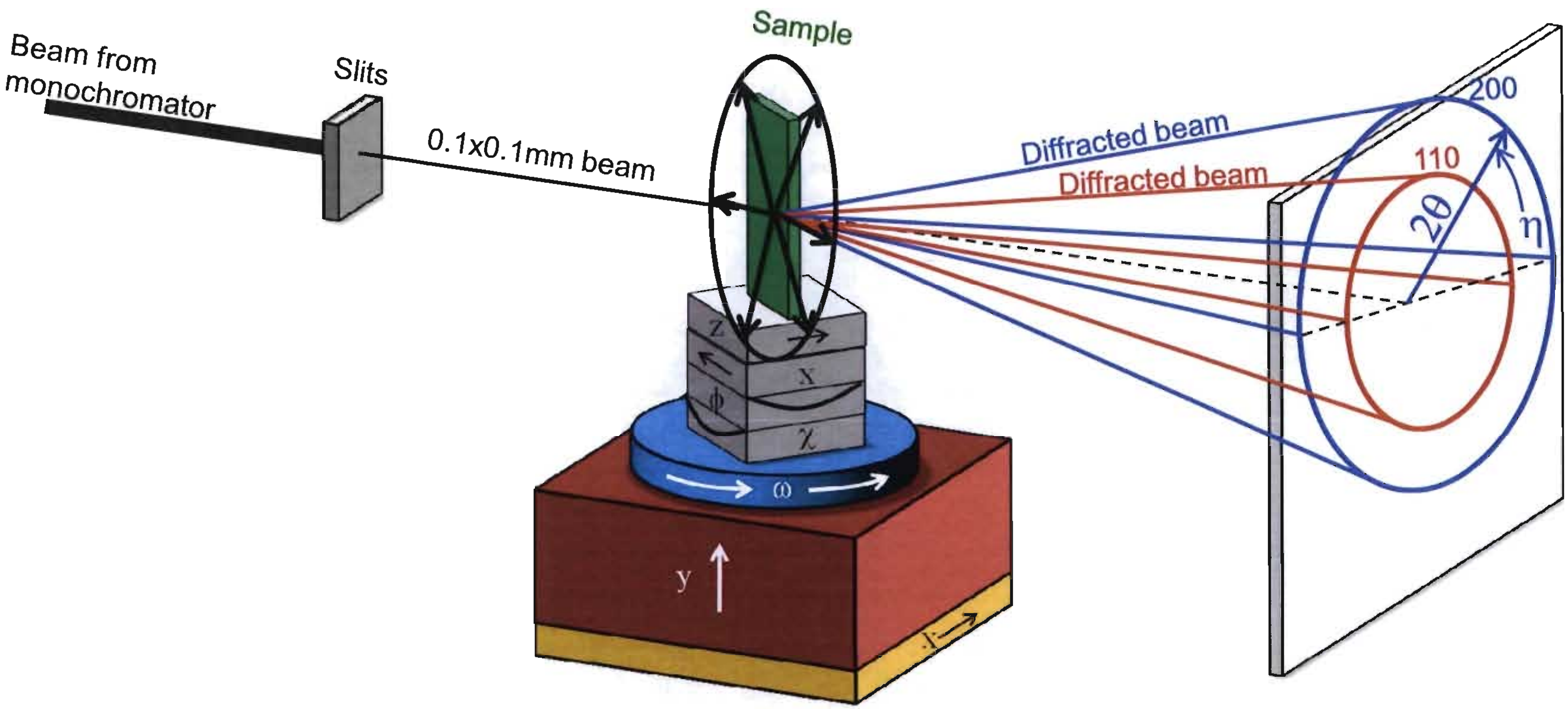
Stress Tensor is Determined by Rotating Sample About a Vertical Orientation



•Measurements at $\omega=0^{\circ}$ (beam normal to sample), 45°, and 60° allow us to determine the entire strain/stress tensor

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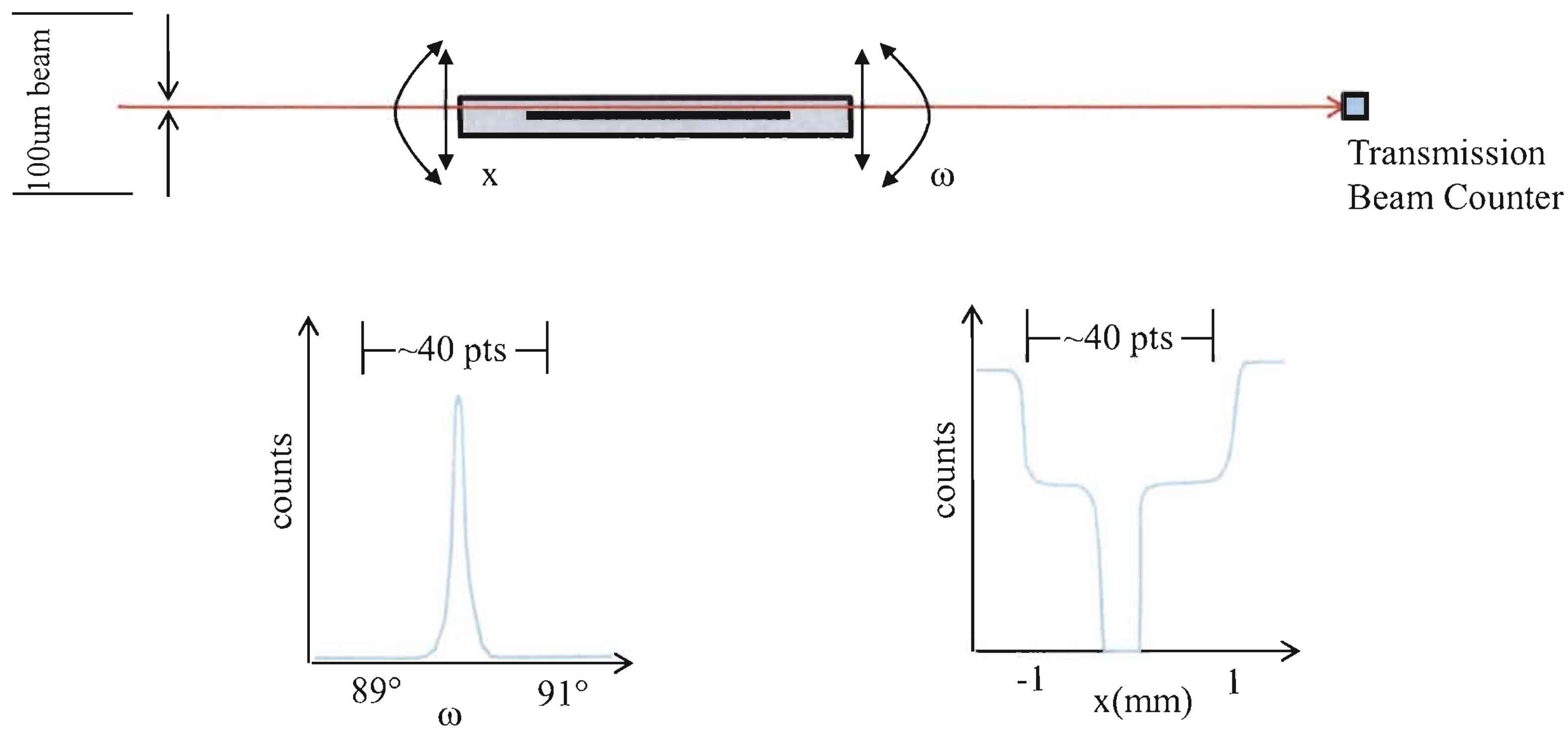
It is Critical to Align Sample Accurately in the Diffractometer



Better than 0.1mm positioning accuracy relative to the beam, corresponding to a 0.000030 strain uncertainty.

An order of magnitude less than measurement uncertainty.

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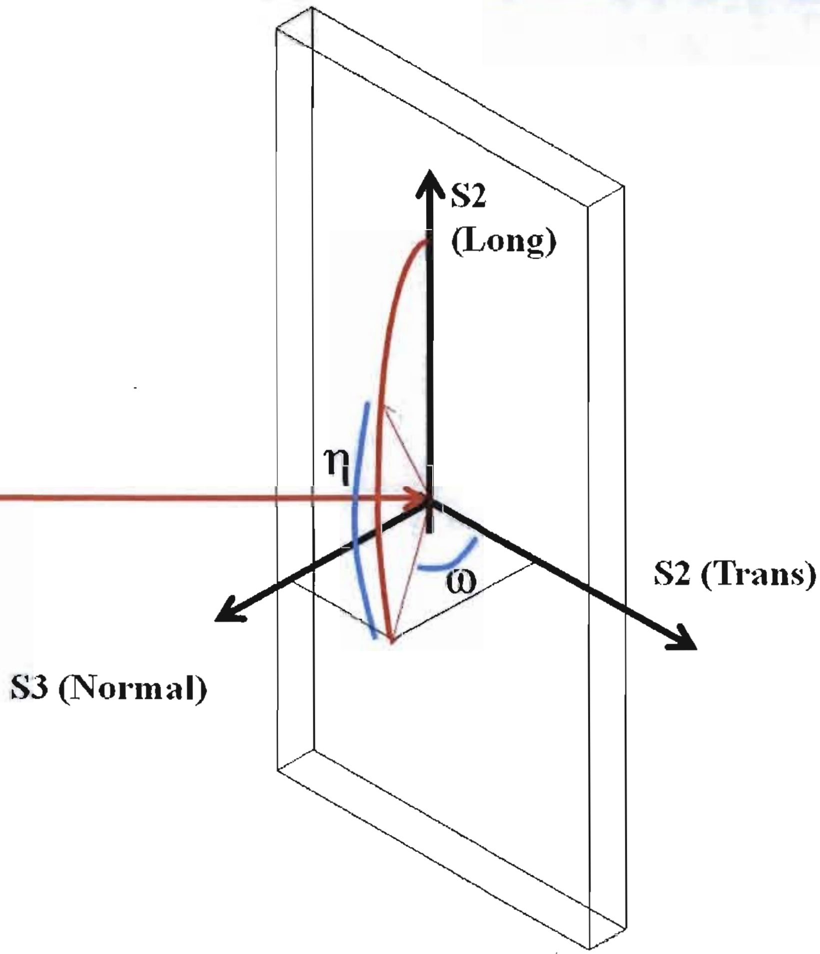
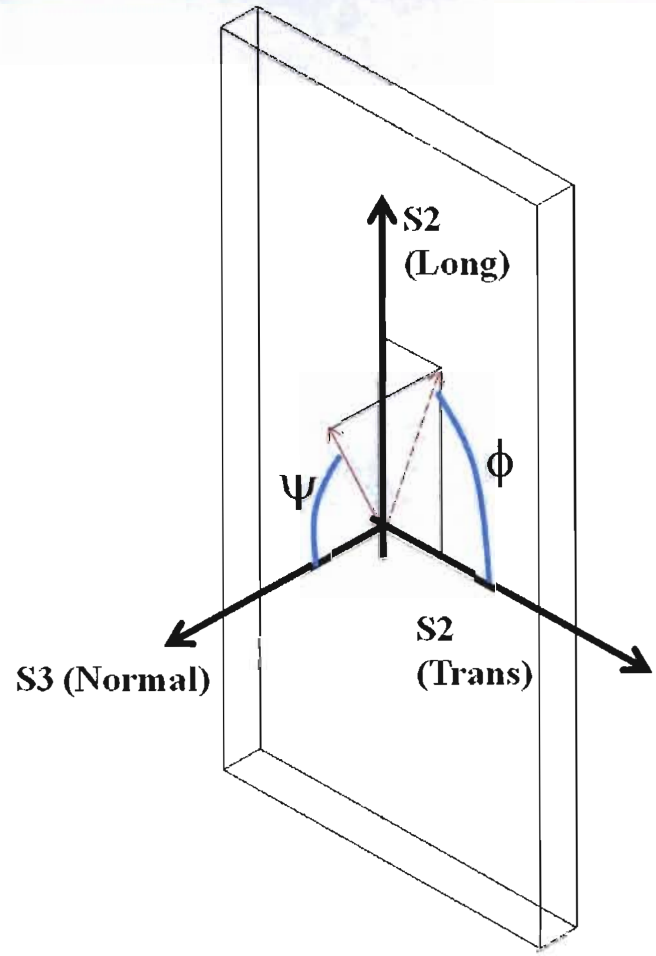
Sample vs. Laboratory Coordinate Systems





$$\cos\psi = \cos\theta_B \cos\eta \sin\omega + \sin\theta_B \cos\omega$$

$$\tan\phi = \frac{\cos\theta_B \sin\eta}{\cos\theta_B \cos\eta \cos\omega - \sin\theta_B \sin\omega}$$

$$\theta_B \approx 2^\circ$$

$$0 \le \eta \le 360$$

$$\omega = 0^\circ, 45^\circ, 60^\circ$$

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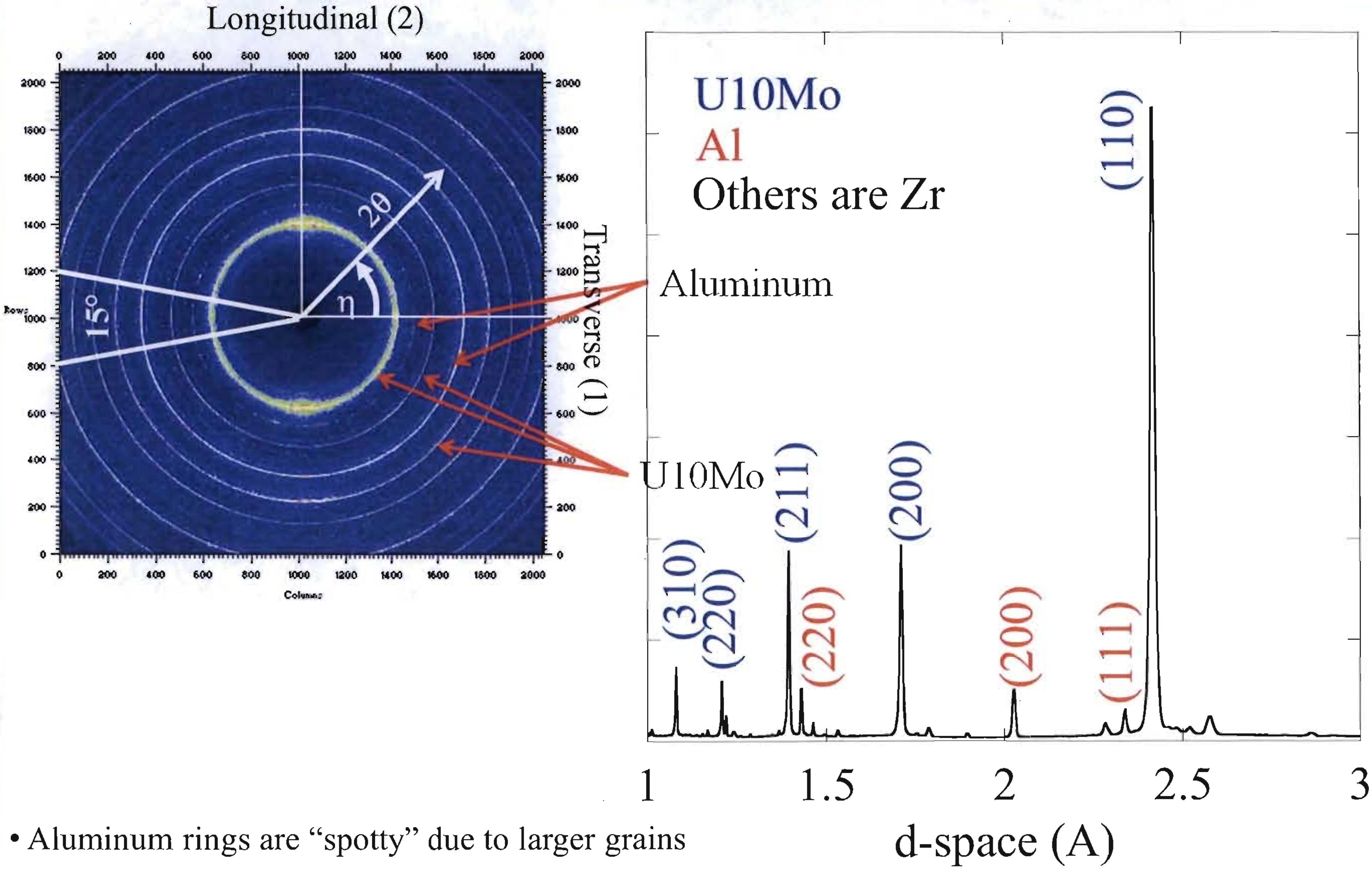
2-D Detector Provides Lattice Parameters in a Plane



- Aluminum rings are "spotty" due to larger grains
- Note texture in U10Mo, the (110) is strong along the original rolling direction.
- Rings are "caked" into 24 1-d diffraction patterns .
- 3 sample orientations w = 0° (normal to beam), 45° and 60°.

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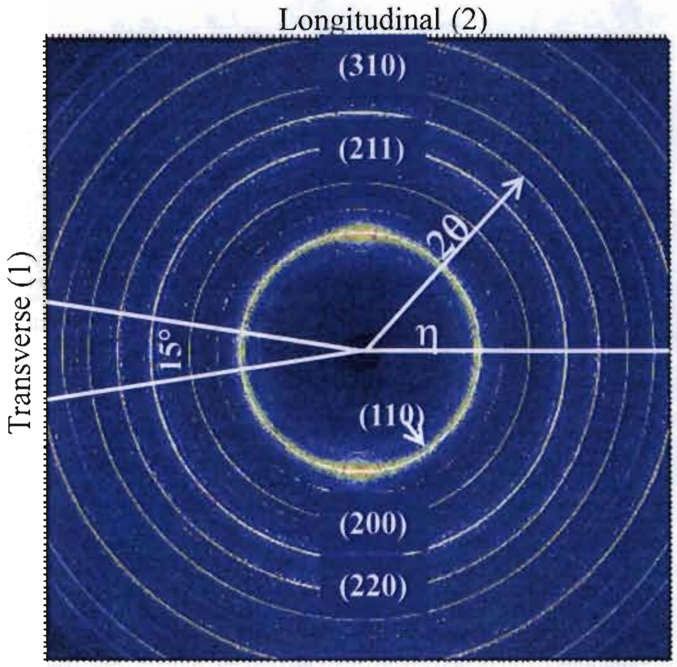
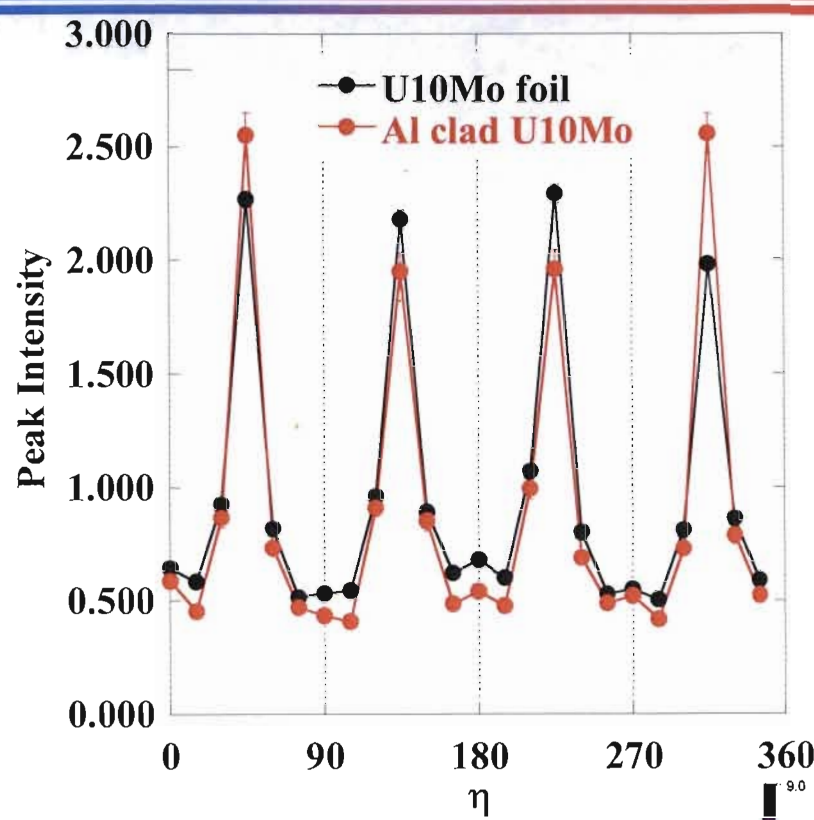
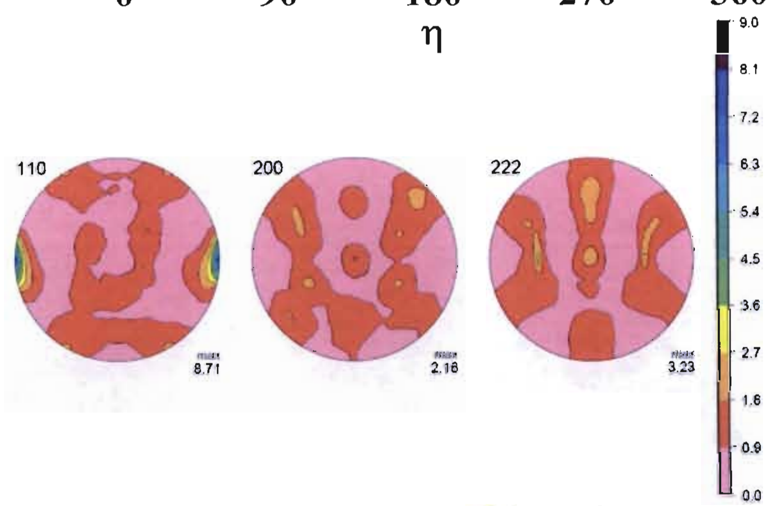
Texture is Apparent in Intensity Variation of Rings







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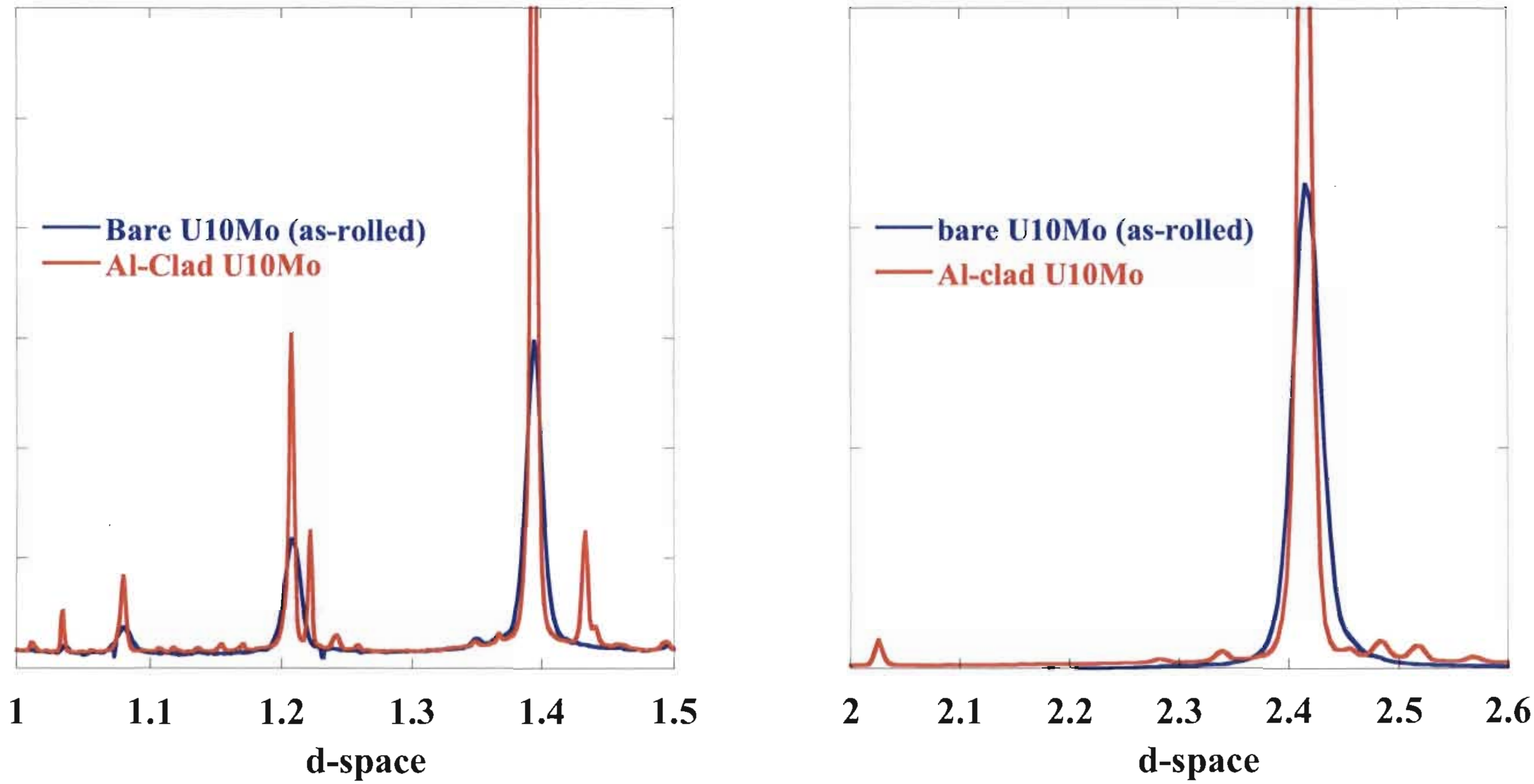
Annealing of U10Mo Foil During Bonding Evident in Decrease in Peak Width



- Narrowing of peak with HIP'ing tells us the microstructure has annealed.
- Shift of the peak likely due to chemistry change, probably moly segregation during HIP'ing.

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Find d_0 by Assuming Normal Stress Components are Zero Far From Edge

Assume isotropic mechanical properties : $\varepsilon_{ij} = \frac{1+\nu}{E}\sigma_{ij} - \delta_{ij}\frac{\nu}{E}\sigma_{kk}$

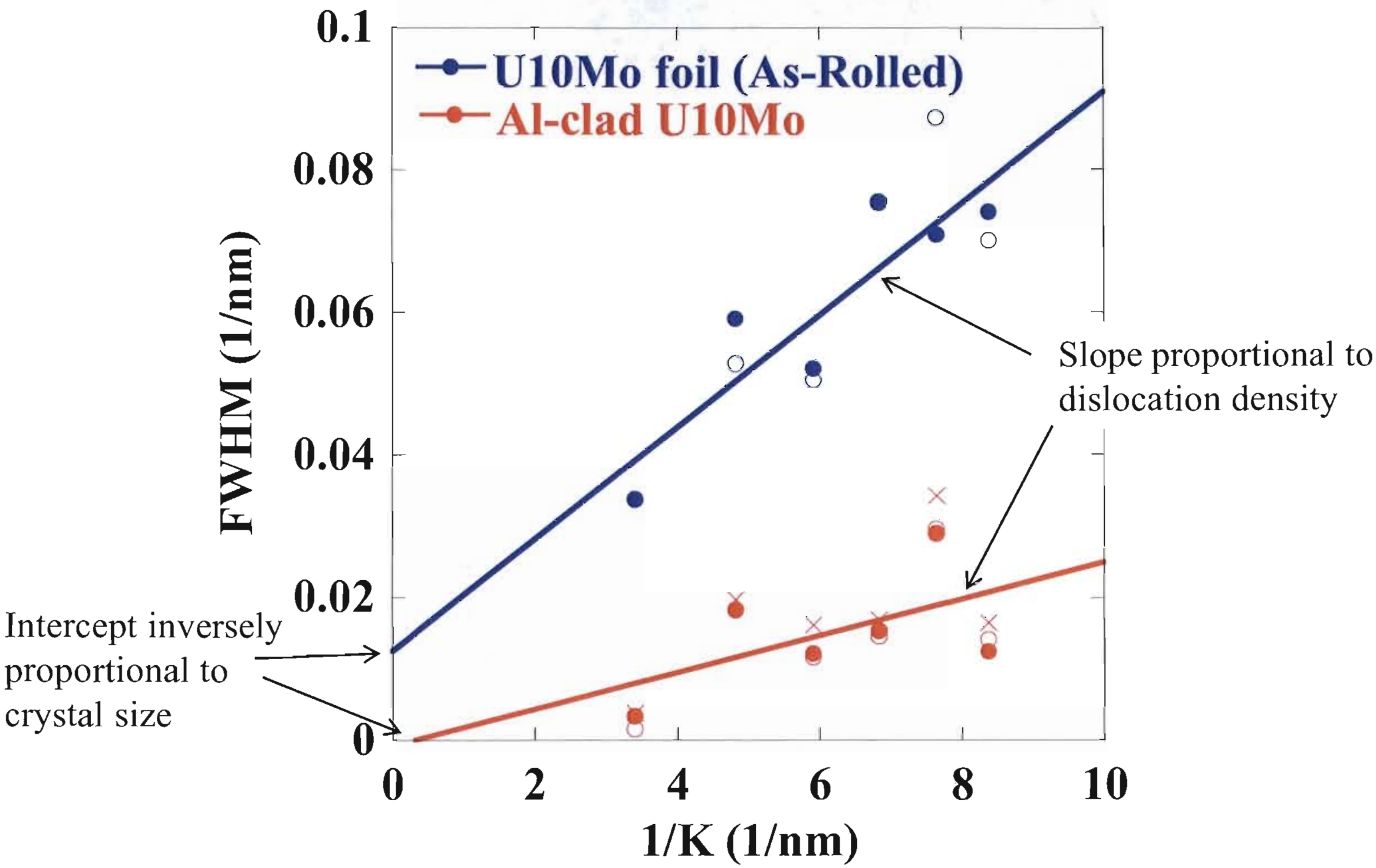
$$\varepsilon(\varphi,\psi) = \frac{d(\varphi,\psi)-d_0}{d_0} = \frac{1+\nu}{E}\left\{\sigma_{11}\cos^2\phi + \sigma_{12}\sin 2\phi + \sigma_{22}\sin^2\phi\right\}\sin^2\psi +$$

$$\frac{1+\nu}{E}\left\{\sigma_{13}\cos\phi + \sigma_{23}\sin\phi\right\}\sin 2\psi + \frac{1+\nu}{E}\sigma_{33} - \frac{\nu}{E}\left\{\sigma_{22} + \sigma_{22} + \sigma_{33}\right\}$$

Set $\sigma_{33} = \sigma_{13} = \sigma_{23} = 0$

$$\frac{d(\varphi,\psi)-d_0}{d_0} = \frac{1+\nu}{E}\left\{\sigma_{11}\cos^2\phi + \sigma_{12}\sin 2\phi + \sigma_{22}\sin^2\phi\right\}\sin^2\psi - \frac{\nu}{E}\left\{\sigma_{11} + \sigma_{22}\right\}$$

Peak Broadening Analyzed to Yield Dislocation Density and Crystal Size



- Bare U10Mo foil $\rho = 60 \times 10^{14}/m^2$
- Al-Clad U10Mo $\rho = 6 \times 10^{14}/m^2$
- Crystallite size in foil ~100nm

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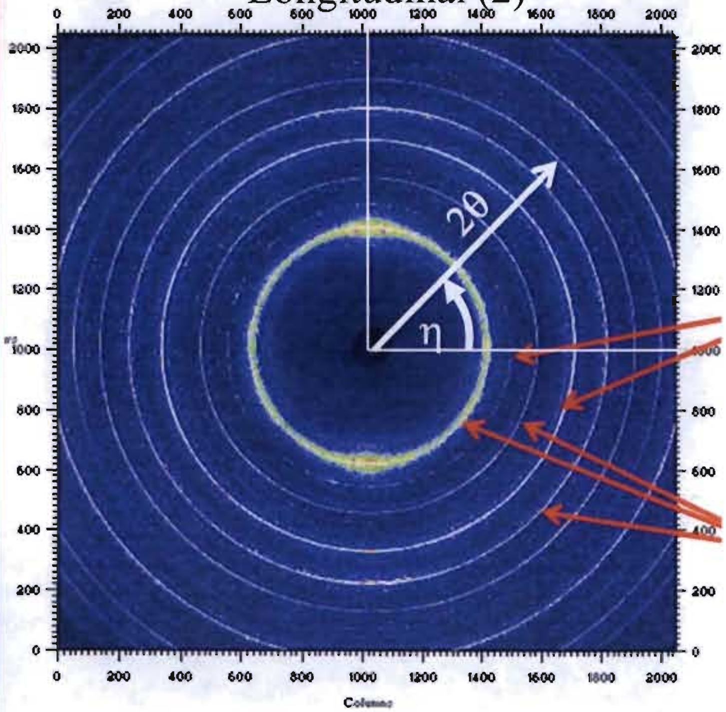
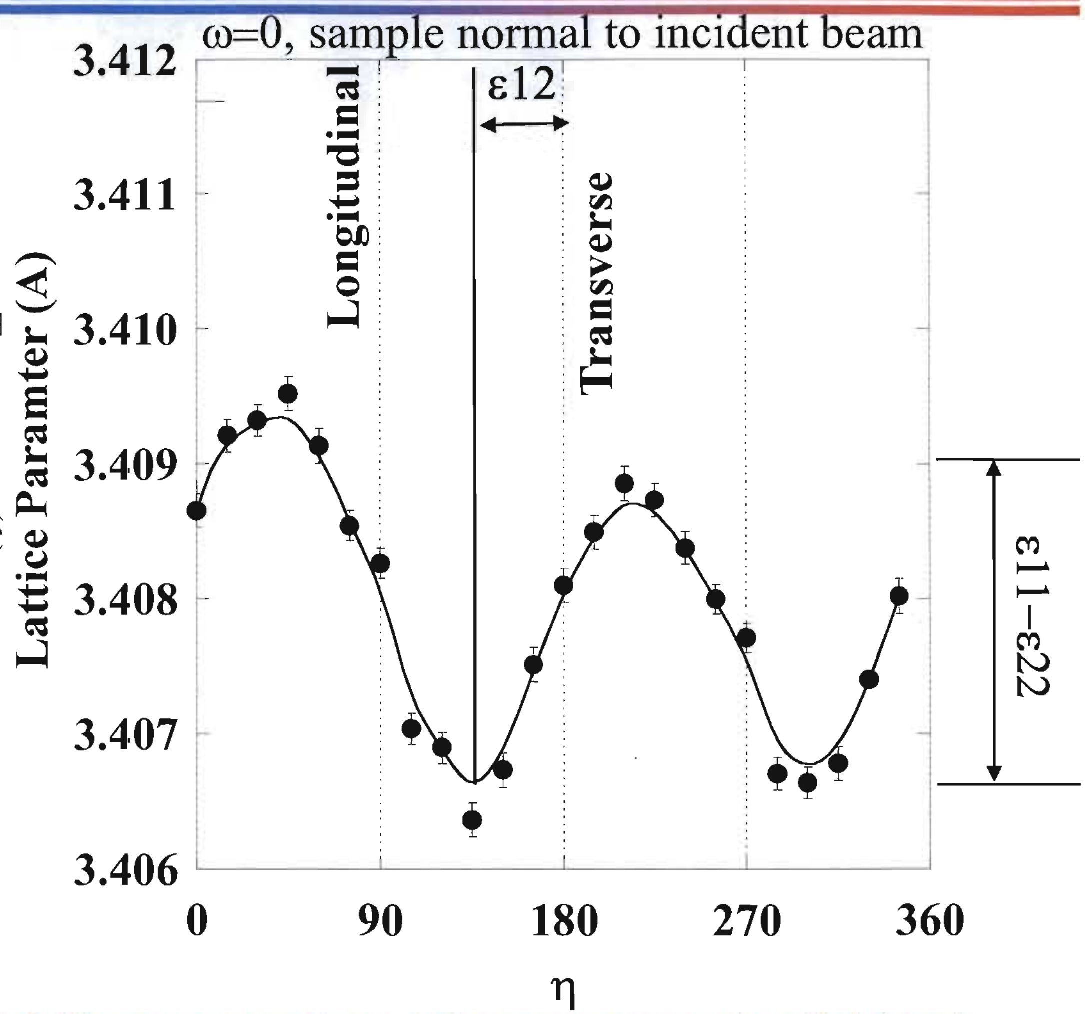
Shape of Diffraction "Rings" Tells About Stress State





6 fitting parameters, 72 measurements of *d* (ϕ,ψ)

$$\varepsilon(\varphi,\psi) = \frac{d(\varphi,\psi) - d_0}{d_0}$$

$$= \varepsilon_{11}\cos^2\phi\sin^2\psi + \varepsilon_{22}\sin^2\phi\sin^2\psi + \varepsilon_{33}\cos^2\psi +$$

$$\varepsilon_{12}\sin 2\phi\sin^2\psi + \varepsilon_{23}\sin\phi\sin 2\psi + \varepsilon_{13}\cos\phi\sin 2\psi$$

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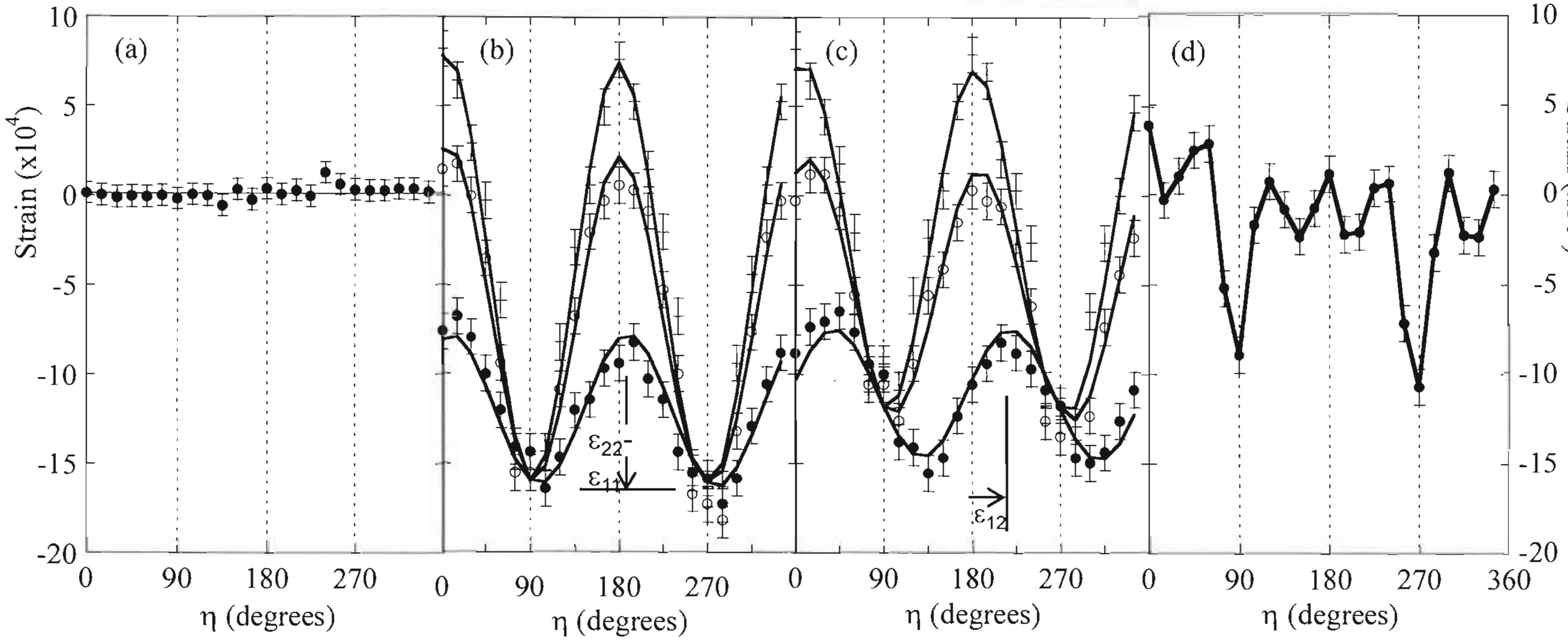
Some Things You Can Discern From the Raw Strain Data



Calibrant : Proves we can measure 0 stress

Offset from 0 and 180 suggests shear strain

Non-physical strains in as-rolled material, suggests something else is going on.

X=2.8 Y=13.0 3829   X=1.5 Y=5 3176

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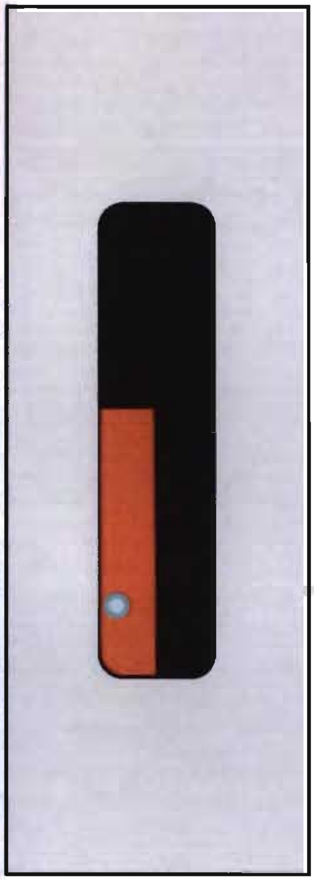
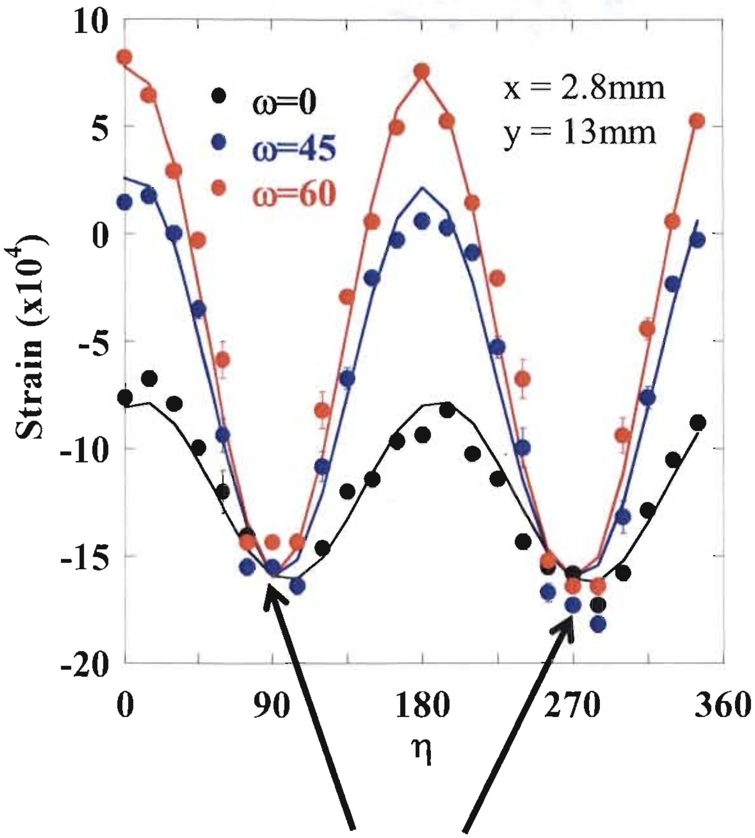
Tensor Equation Fits Measured Strains Very Well





$$\varepsilon = \begin{Bmatrix} -8.1 & 1.4 & -0.5 \\ 1.4 & -16.0 & 1.0 \\ -0.5 & 1.0 & 12.8 \end{Bmatrix} \times 10^{-4}$$

$$\pm \begin{Bmatrix} 0.3 & 0.3 & 0.3 \\ 0.3 & 0.2 & 0.3 \\ 0.3 & 0.3 & 0.4 \end{Bmatrix}$$

- At η=90 °,270°, ω does not matter.
- At this point strain should not (and does not) depend on ω.

  This was not forced !

  Increases confidence in positioning accuracy.

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Residual Strains Determined With 0.100mm Resolution

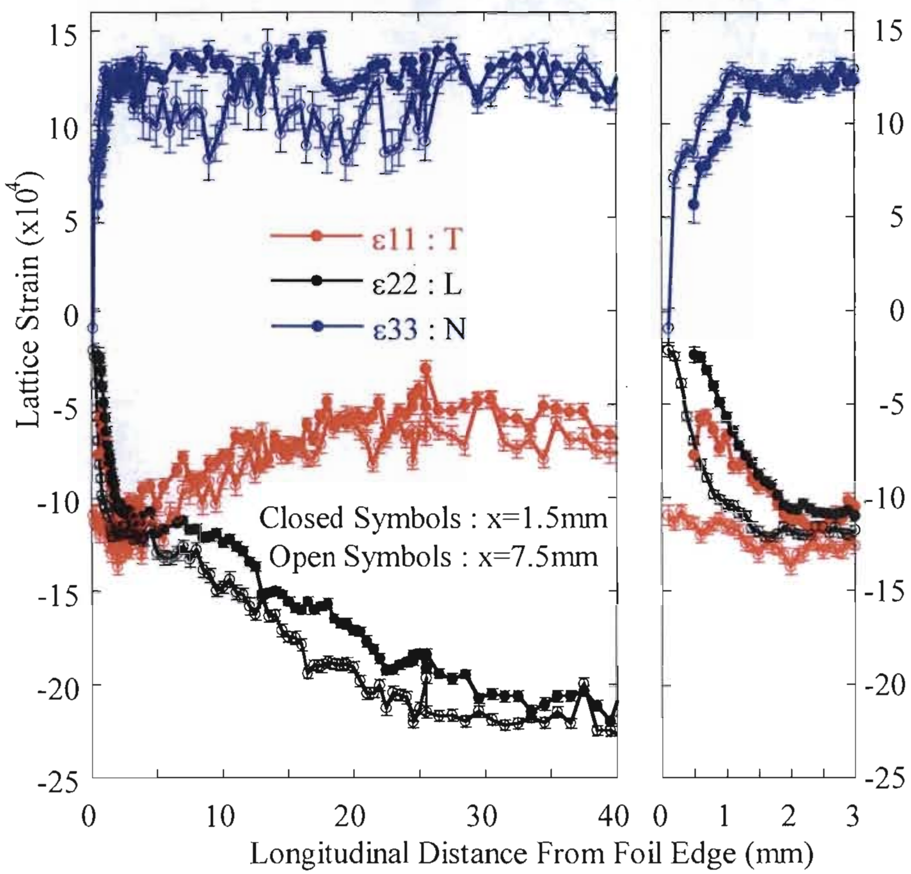

Figure 5. (a.) Residual strains as a function distance from the short edge, y, on lines at x=1.5mm and 7.5mm. (b.) Expansion of the first 3mm to highlight the strong strain gradient near the foil edge.

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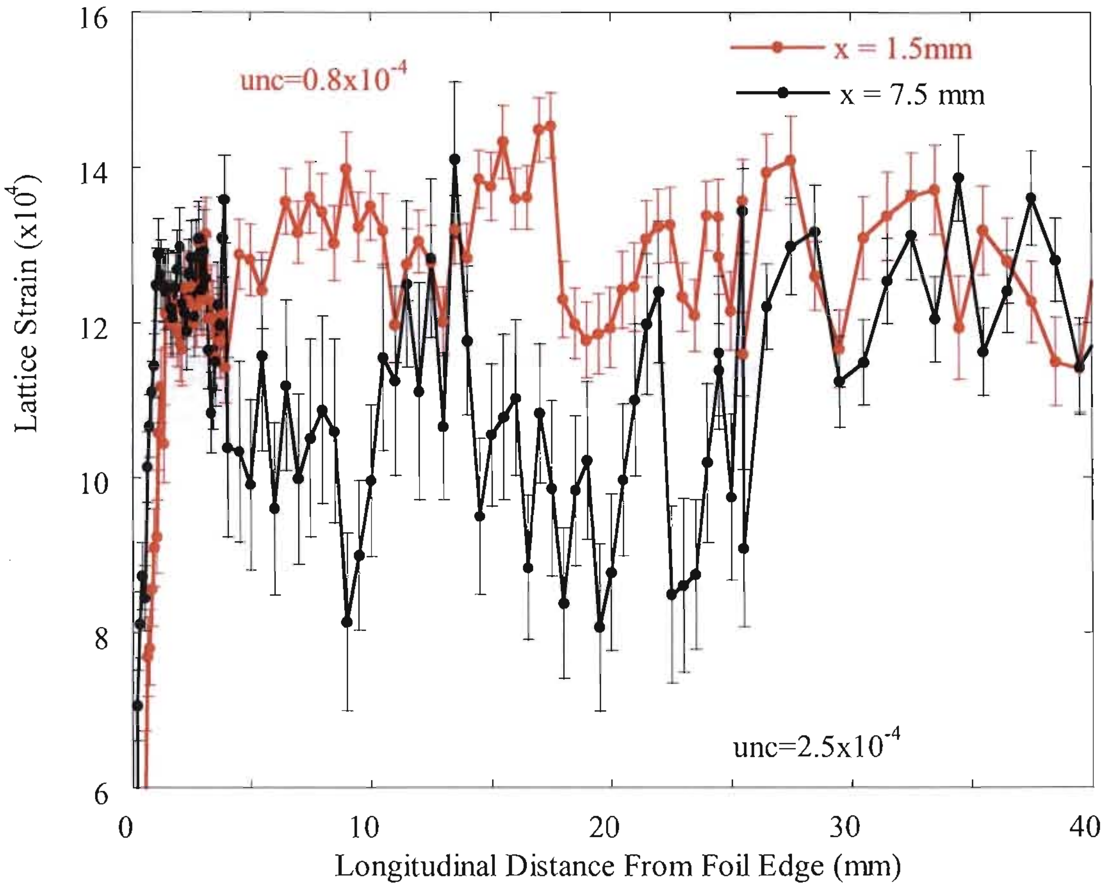
Extent of Sample Rotations Greatly Effects Strain Uncertainty



In area where only 2 orientations were measured, uncertainty increases x3.

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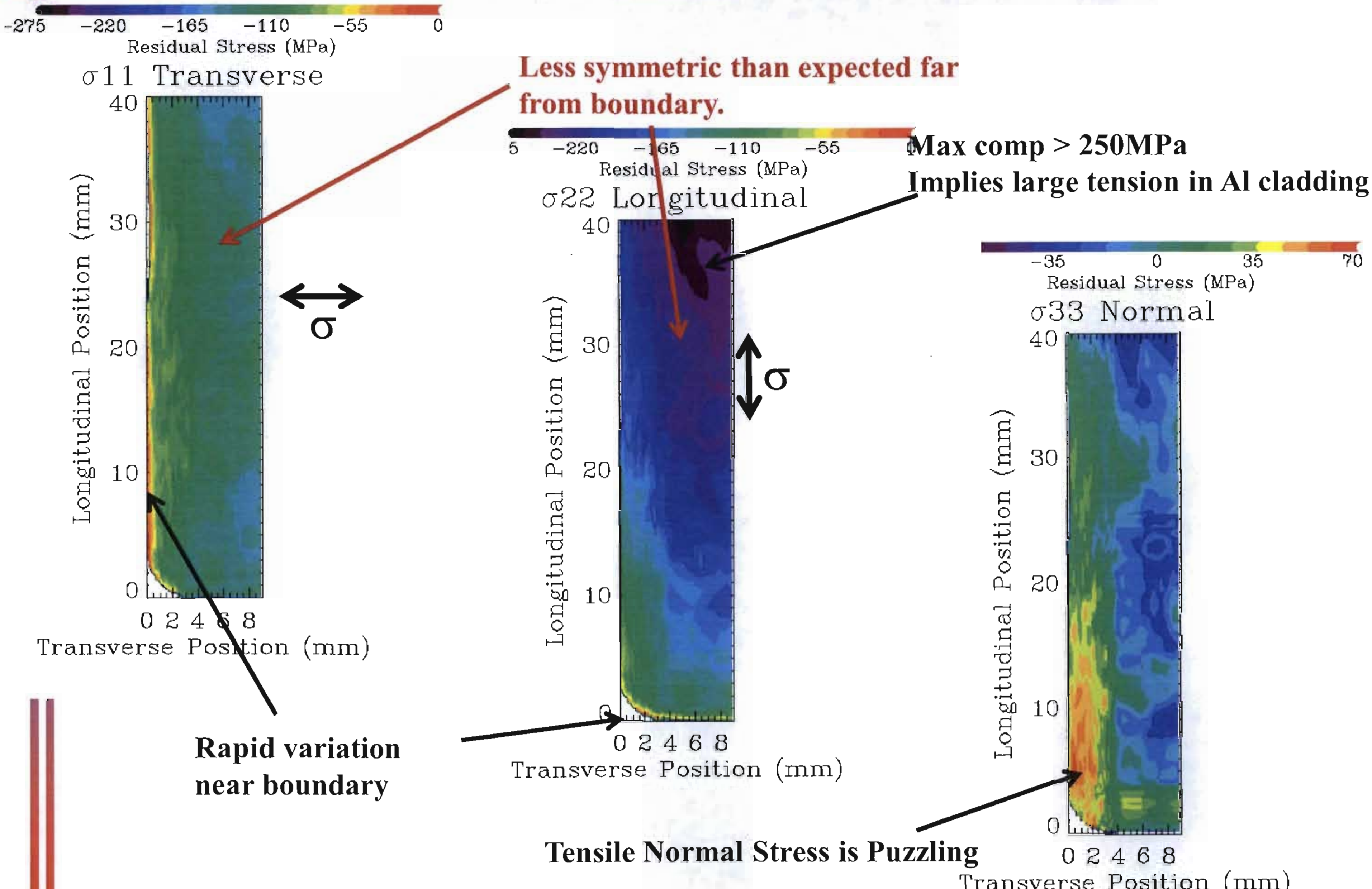
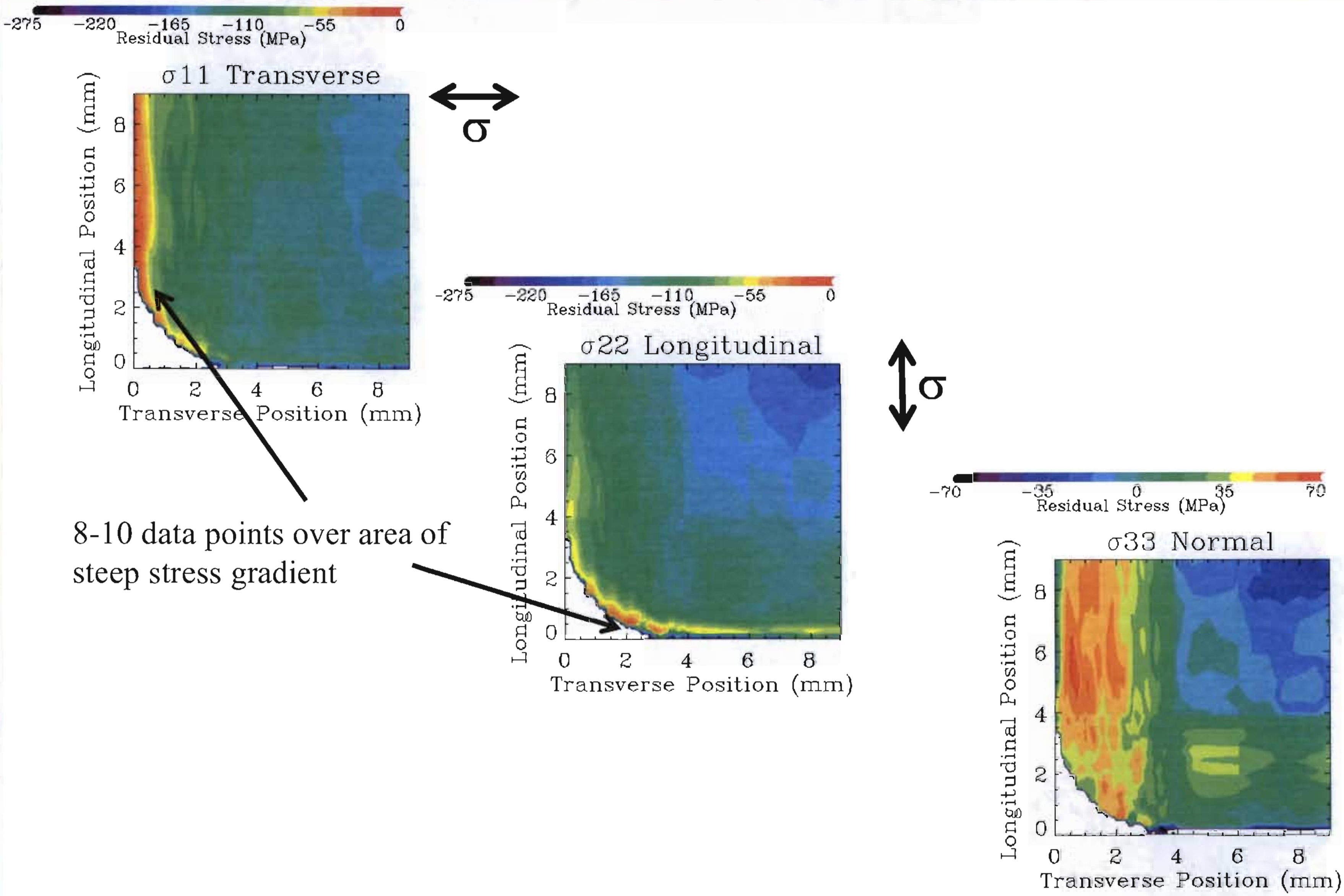
Residual Stress Tensor Mapped Over ¼ of Foil



Expansion of Data Near Edge Highlights Rapid Variation of Stresses



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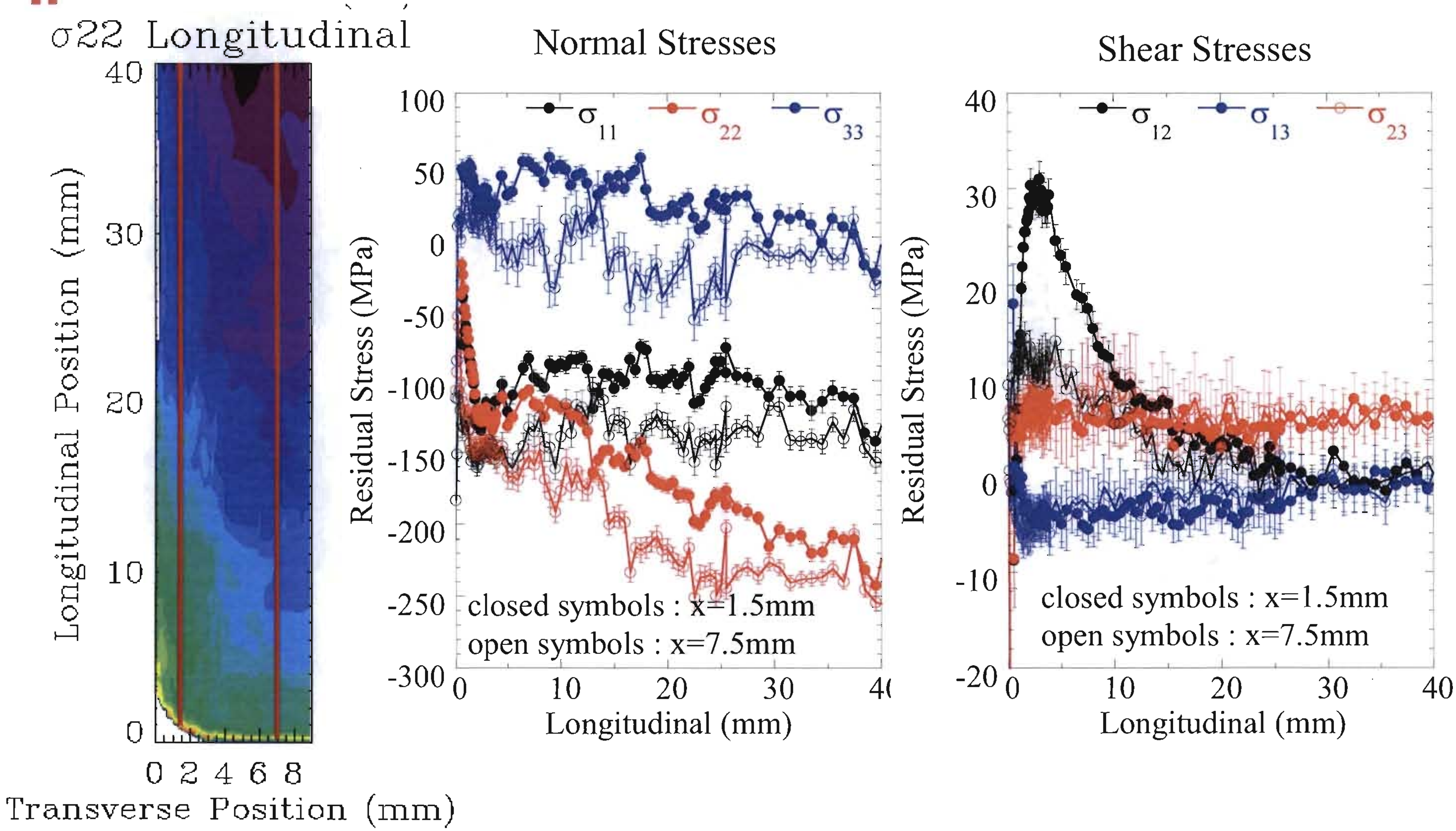
Residual Stress in Mini Monolithic U10Mo Fuel Plates



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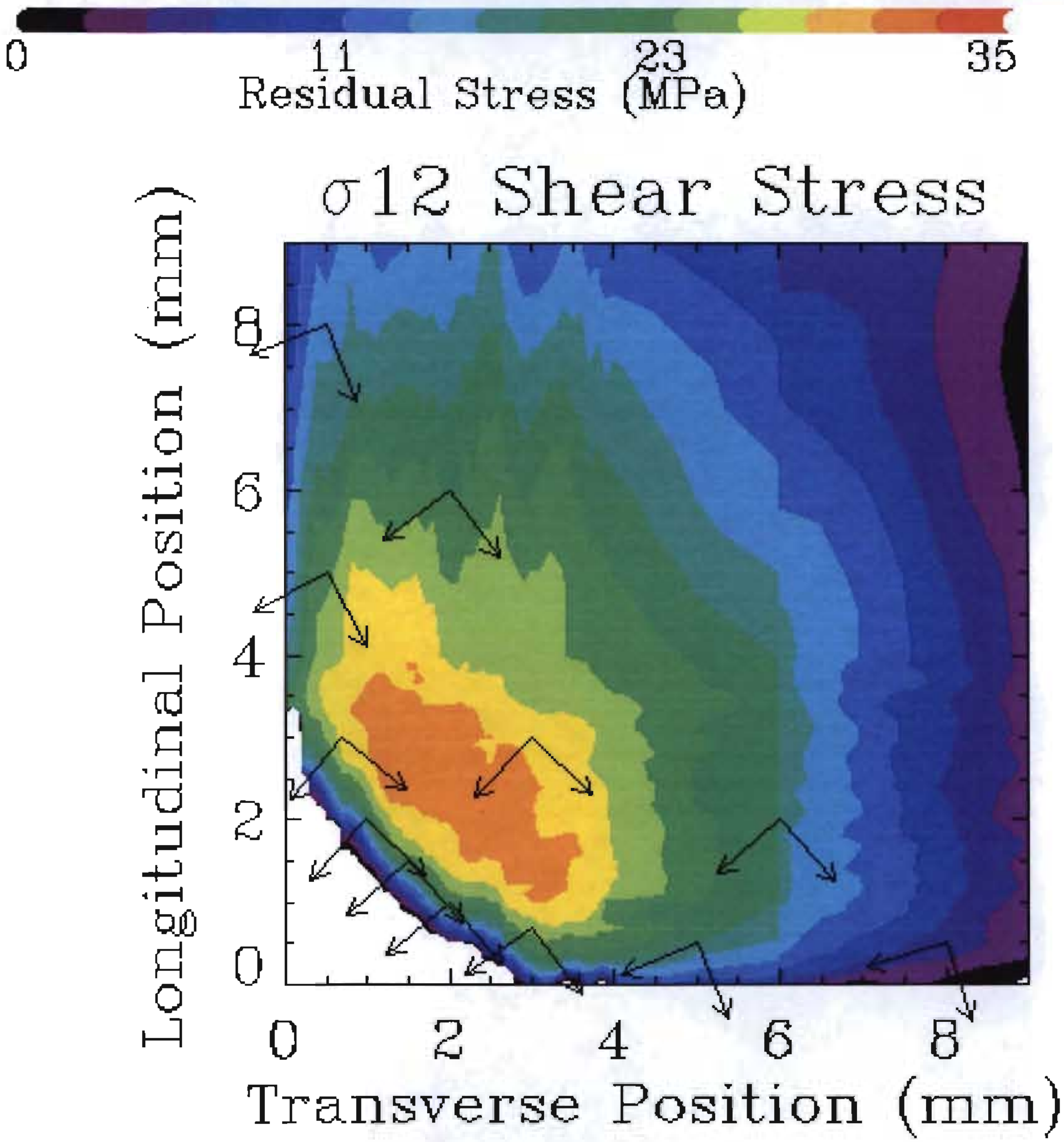
Shear Stress Indicates Principle Axis Are Rotating



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Summary

- High energy xrays can be used to characterize microstructure of bulk samples, even with high Z.
  - Demonstrated residual stress, dislocation density, and texture measurements in Al-clad Uranium 10wt% Molybdenum fuel plates.
- ~250 MPa compressive residual stress in U10Mo foil.
  - Suggests a yield level tensile stress in Aluminum cladding.
- Tensile residual stress in normal direction indicates plastic deformation (probably in Aluminum) during cooling.
- Rapid approach of transverse components to zero at edges suggests foil is not bonded on lateral edges.
- Rotation of stress tensor in corner suggests same.
- Asymmetry of stress field (longitudinal vs. transverse directions) is consistent with constraints during HIP'ing.
- Dislocation density of 60 x $10^{14}/m^2$ in as-rolled foil. Reduce by 10x during HIP'ing. Properties of foils, in particular yield strength are likely different then assumed.
- Strong rolling texture in U10Mo foil.

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