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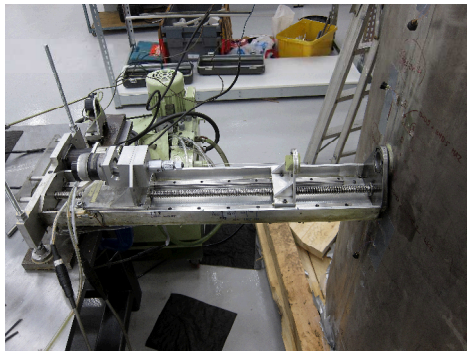
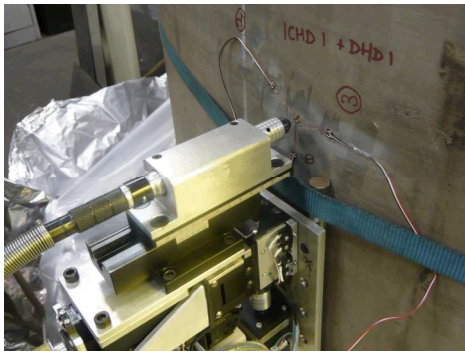

Understanding the Risk of Chloride Induced Stress Corrosion Cracking of Interim Storage Containers for the Dry Storage of Spent Nuclear Fuel: Residual stresses in typical welded containers

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Albuquerque, NM

NACE International, Corrosion 2016
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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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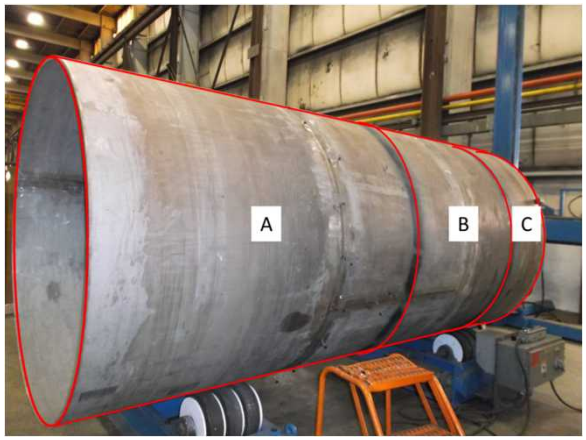
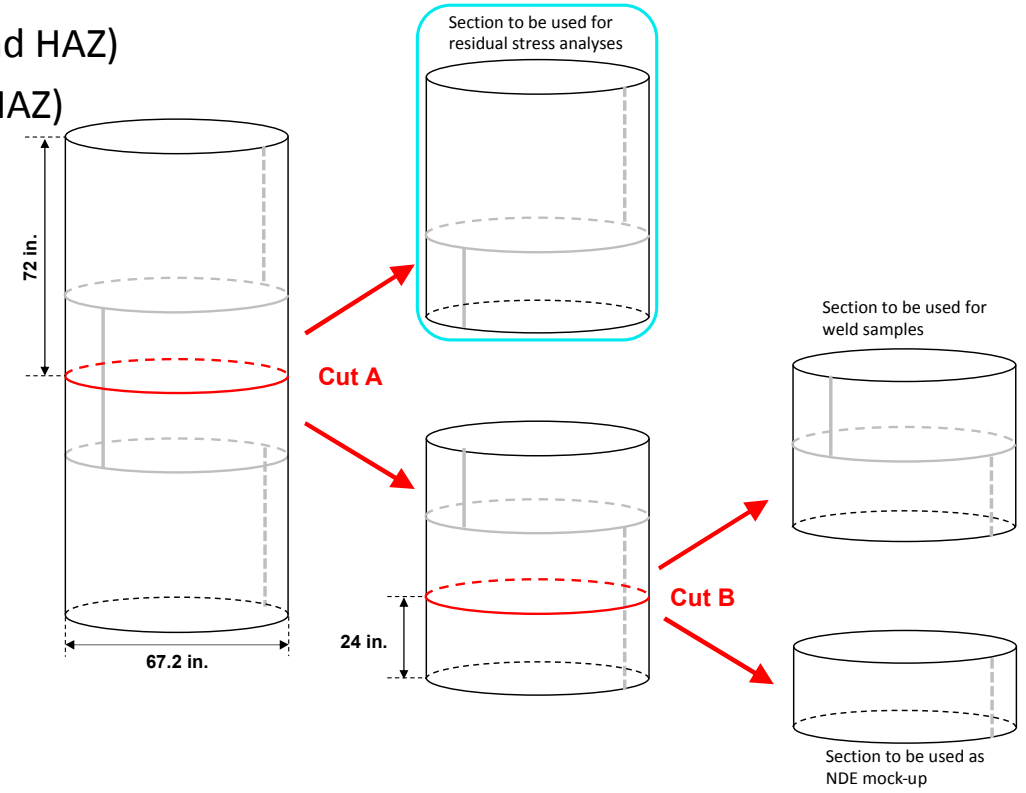
Residual Stress Measurement

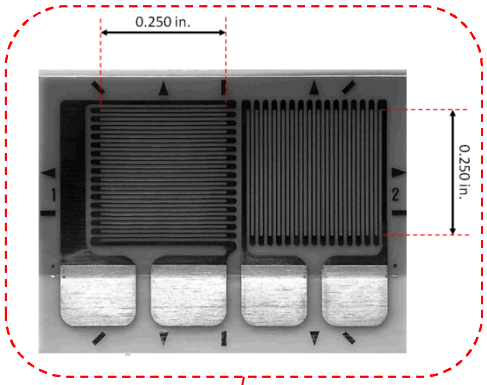
- Goal: Establish if there is sufficient through-wall tensile stresses to support SCC crack propagation
- Full-scale mockup container simulating a NUHOMS 24P container (produced at Ranor using procedures established for containers at Calvert Cliffs ISFSI)
- Series of key areas are being assessed
  - Base metal (far from welds)
  - Circumferential Weld (Centerline and HAZ)
  - Longitudinal Weld (Centerline and HAZ)
  - Weld Repair

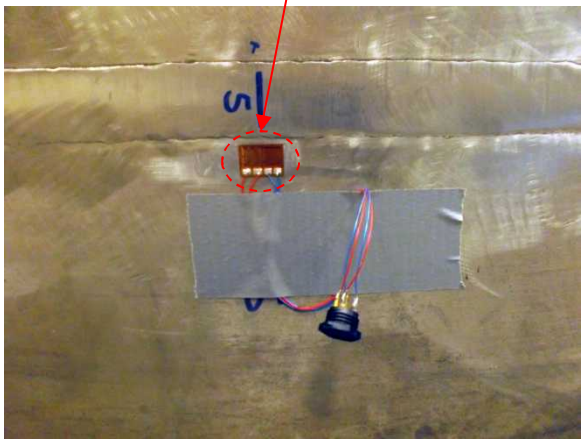


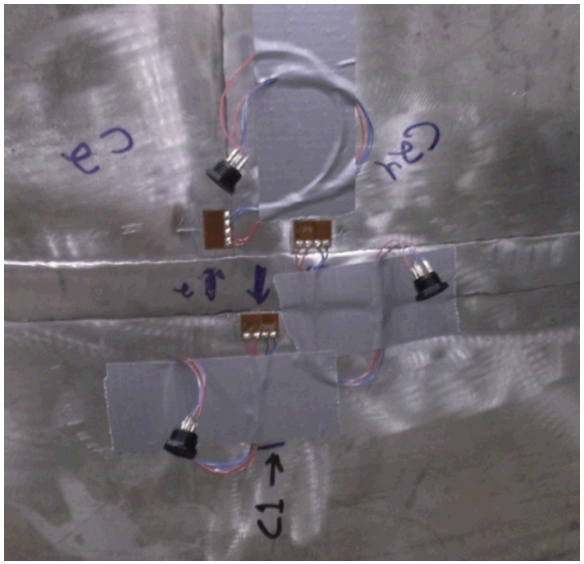


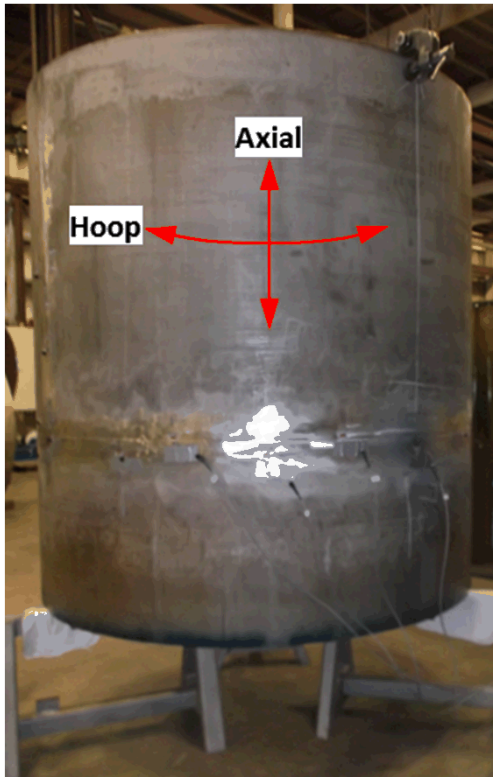
Strain Gauge Positioning

- Gauges positioned such that one grid was parallel and one perpendicular to the weld
- Positioning required that a region with no heterogeneities be identified



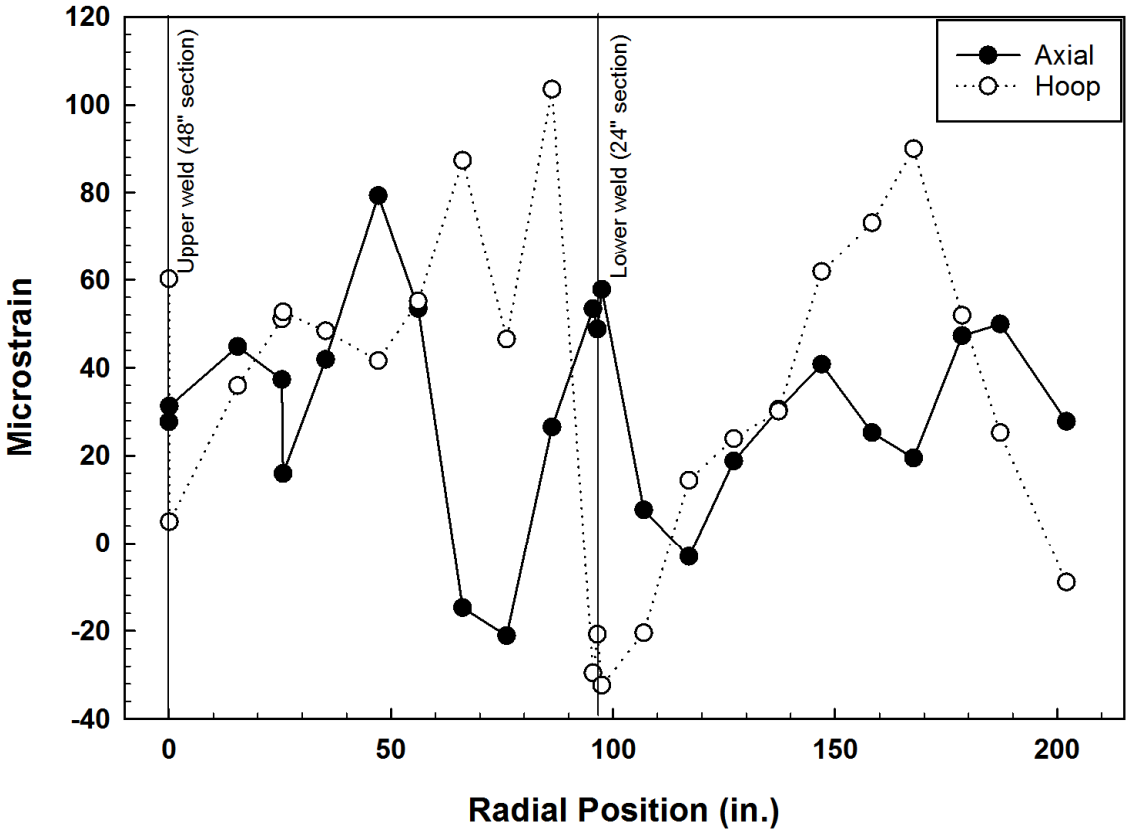


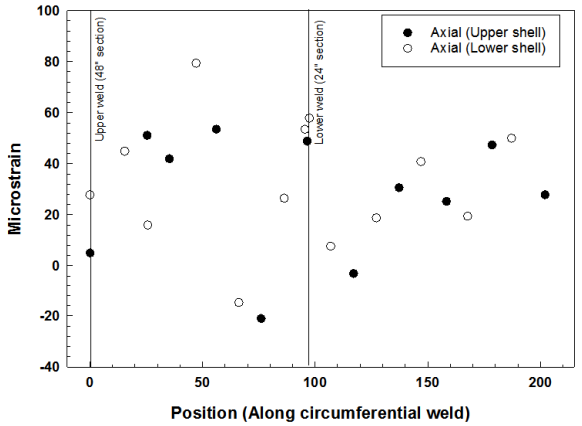


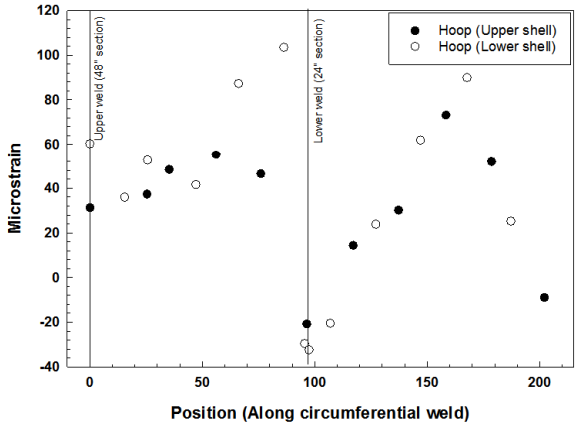


Surface Strain Gauge Data Circumferential Welds

- Minimal impact of cutting operation on the circumferential weld
  - Also assessed if measurements made on the upper vs. lower shell mattered (cut was on the lower shell)

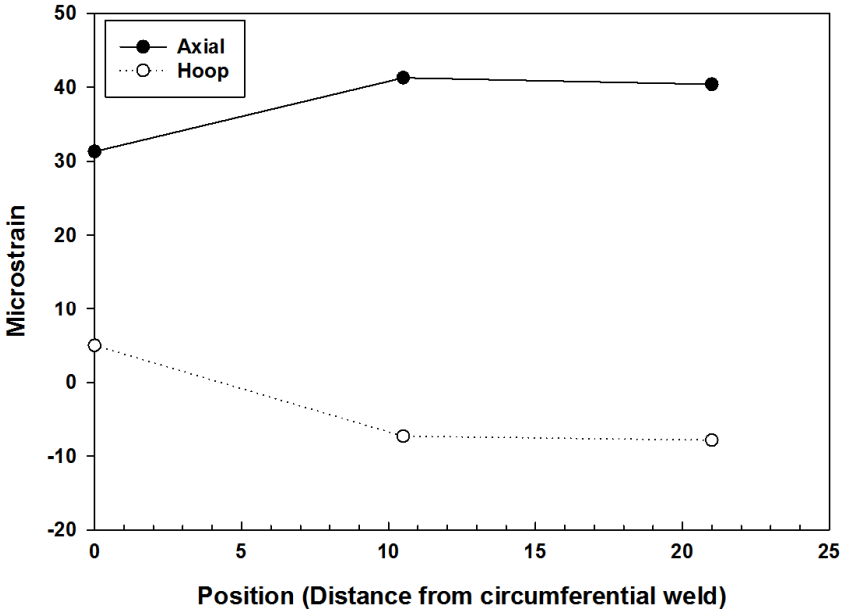


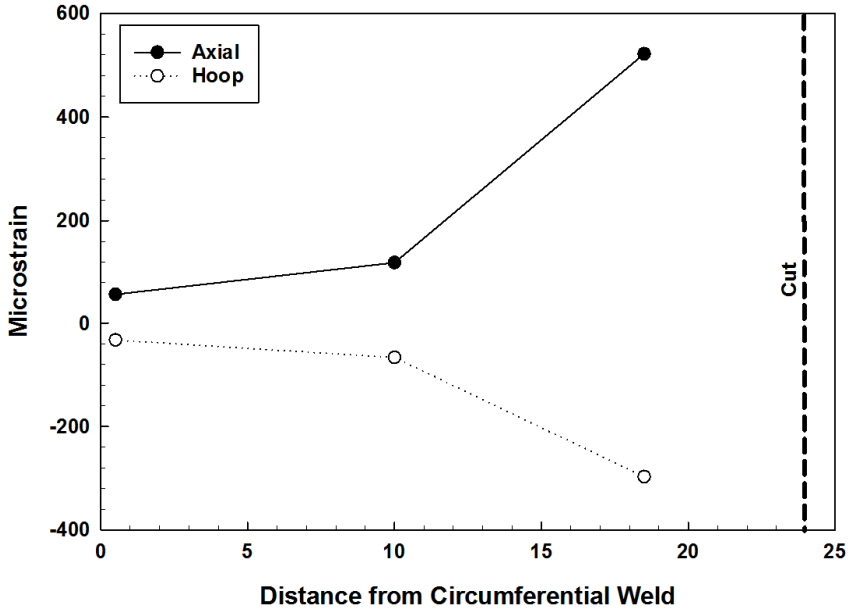




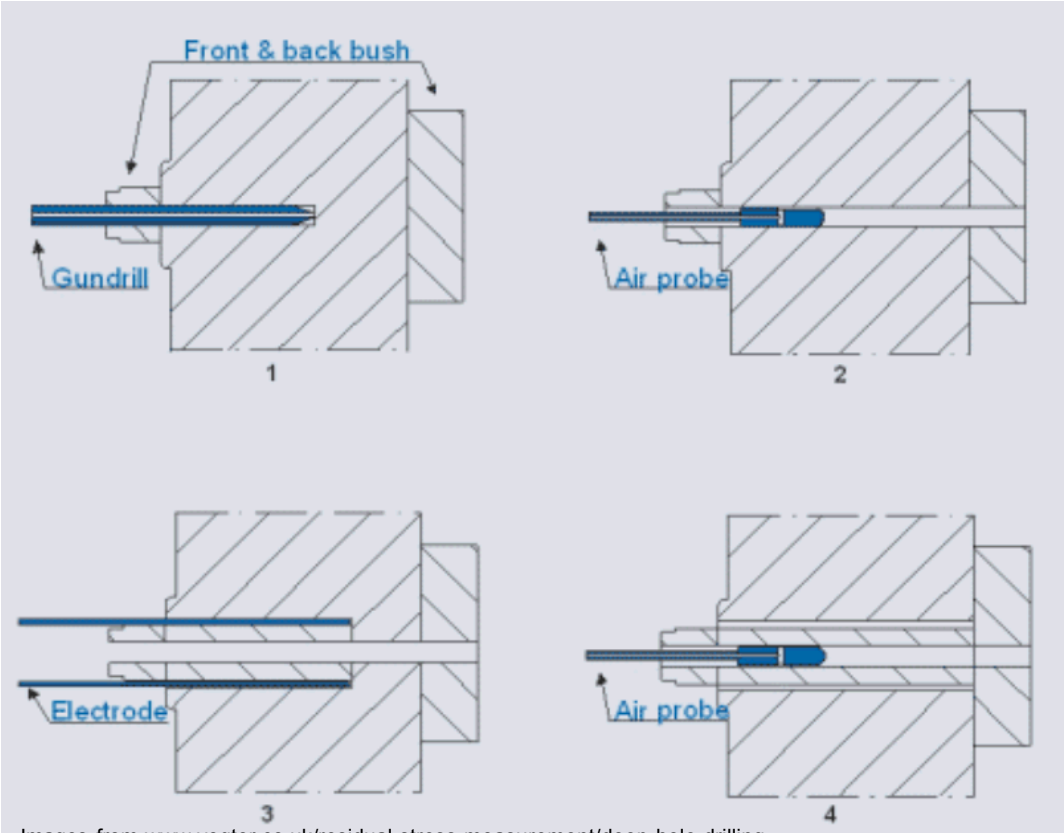
Surface Strain Gauge Data Longitudinal Welds

- Upper weld (shell which was not cut) not disturbed by the cutting operation
- Lower weld (shell which was not cut) impacted by cut
  - Some deformation of the cylinder occurred near the cut, despite the high wall thickness





Deep Hole Drilling



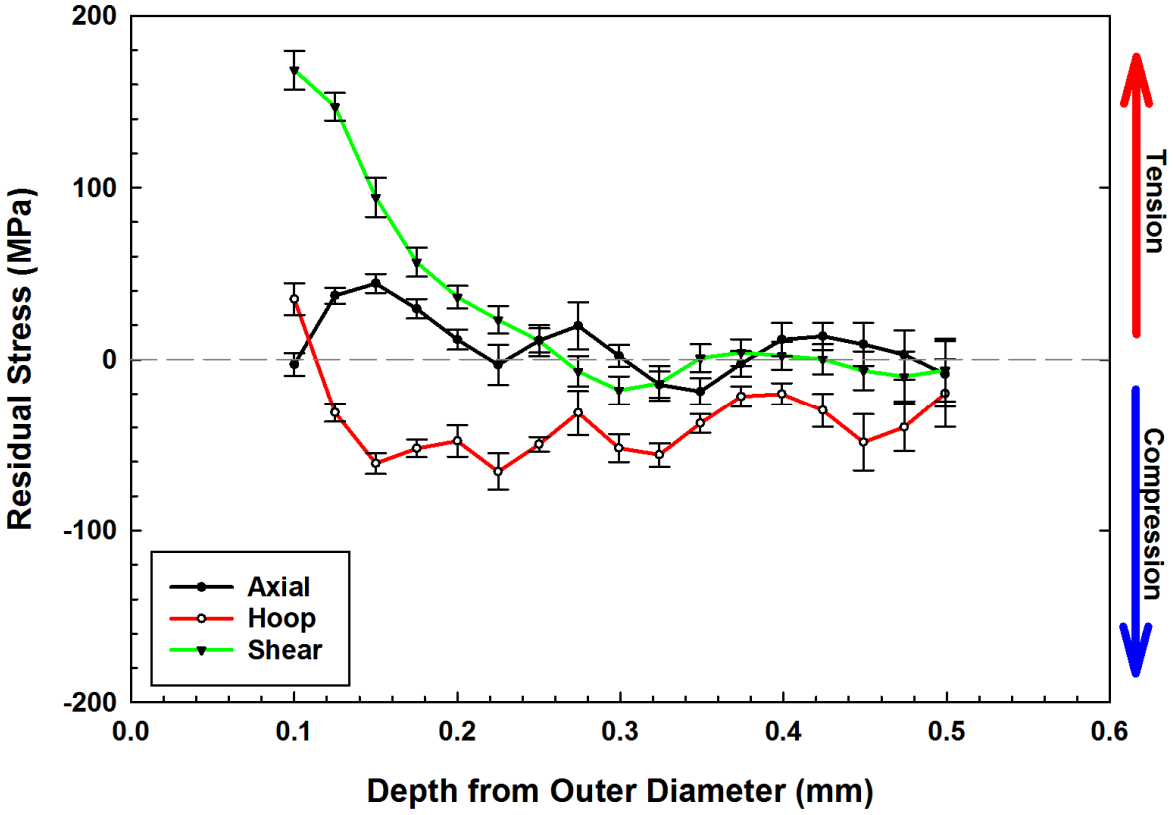
Images from www.veqter.co.uk/residual-stress-measurement/deep-hole-drilling

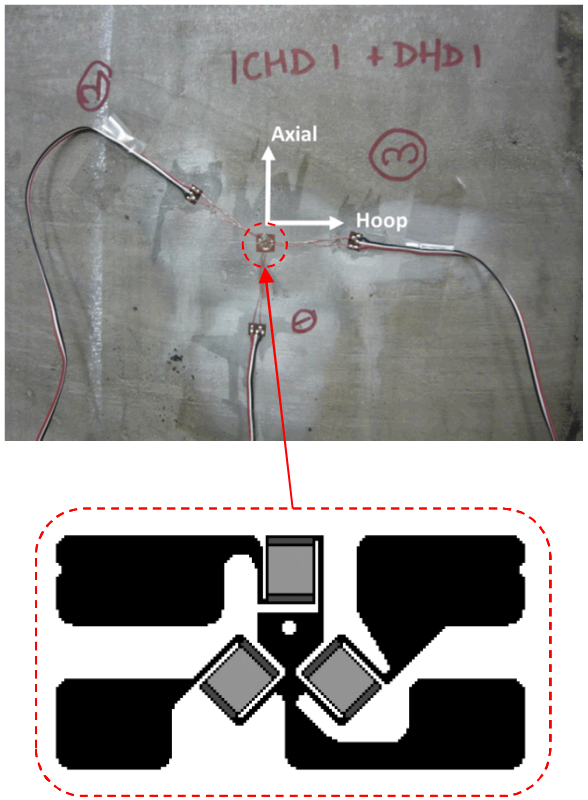
- Hole precisely drilled through region to be characterized
- Air probe used to measure the inner diameter of the hole as a function of position
- EDM used to cut core around the hole, relaxing the constraint placed by the surrounding material
- Air probe used to measure the resulting distortion of the hole inner diameter
- Stress state calculated from displacements
- Complicated when stresses are high (requires modified technique)

- Get one dimensional map of initial stress state without cutting up structure
- Semi-destructive, labor intensive ($)

Near Surface Stresses Assessed Via Incremental Center Hole Drilling

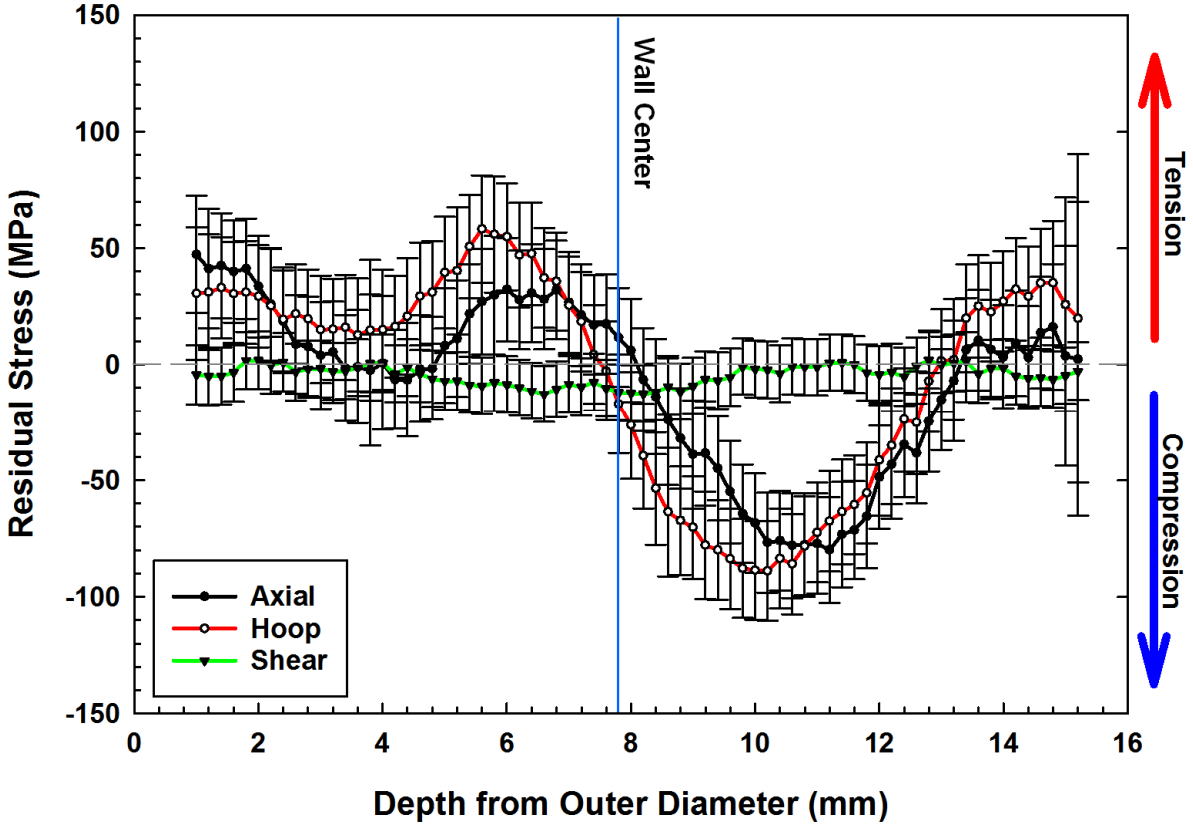
- DHD is not able to resolve strains accurately very near the metal surface (first 0.5mm or so)
- iCHD used to make these measurements

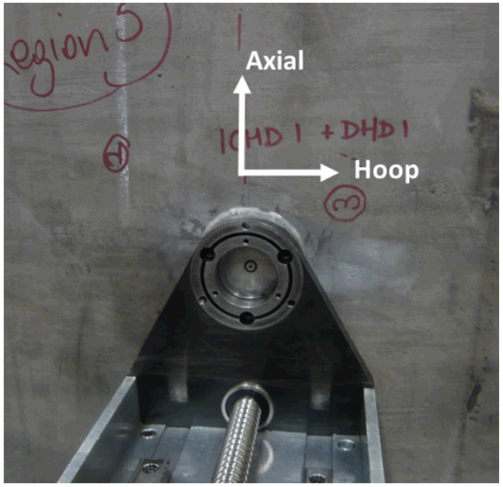




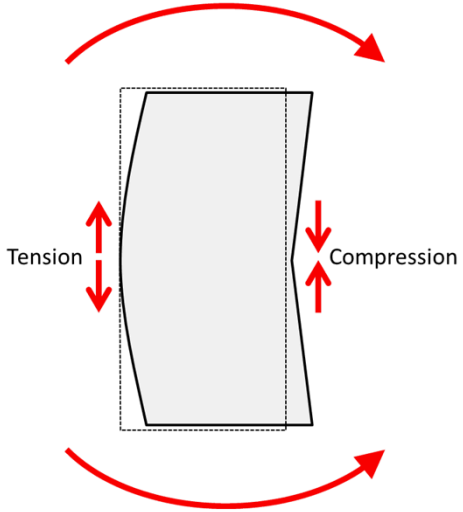
Residual Stresses in the Base Metal Far from Welds

- Stress state consistent with forming process
  - Stresses on OD tensile
  - Stresses in ID compressive
  - Consistent with bending process used to form





Bending Force

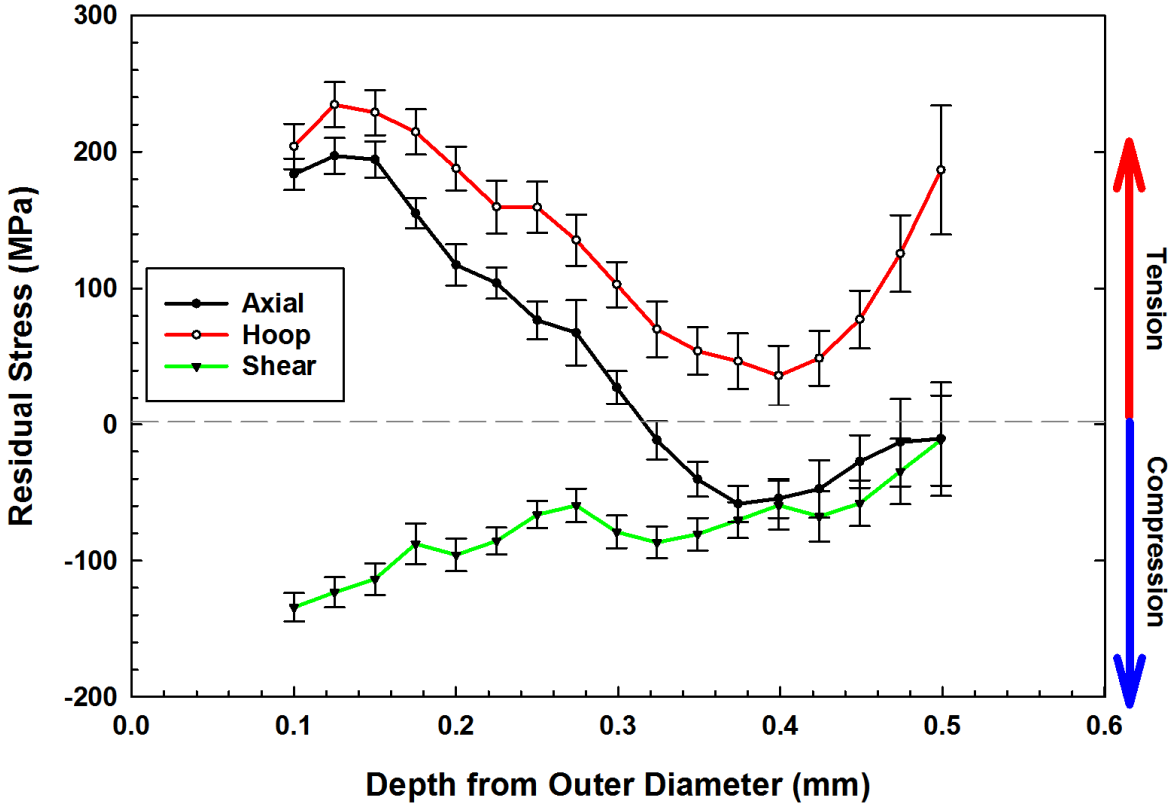


Bending Force

Note – locations where temporary supports have been welded and removed will be different…

Residual Stresses in Circumferential Weld (Centerline)

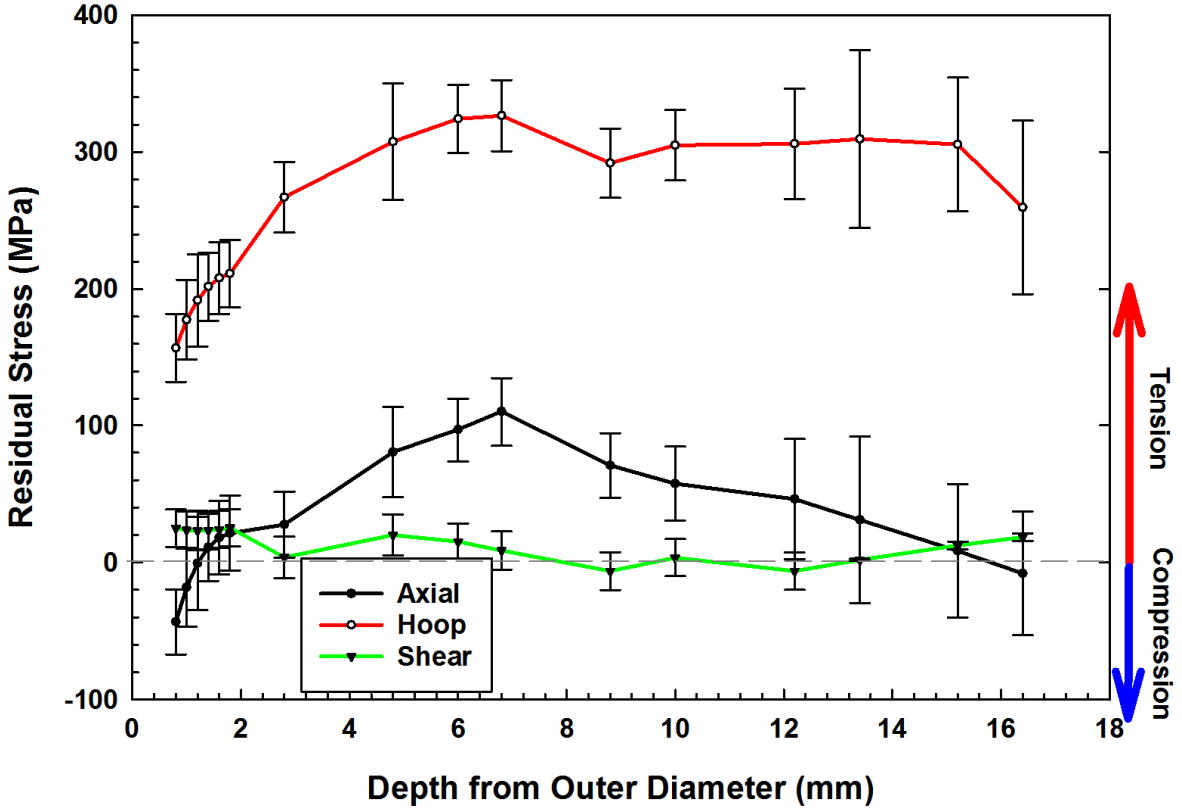
- iCHD used to assess stress state in region very close to the surface of the container (on the OD)



- **Both axial and hoop stresses strongly tensile near surface**
- **iCHD measurements likely to exhibit some positional variability**
  - Single test location
  - Consider qualitatively

Residual Stresses in Circumferential Weld (Centerline)

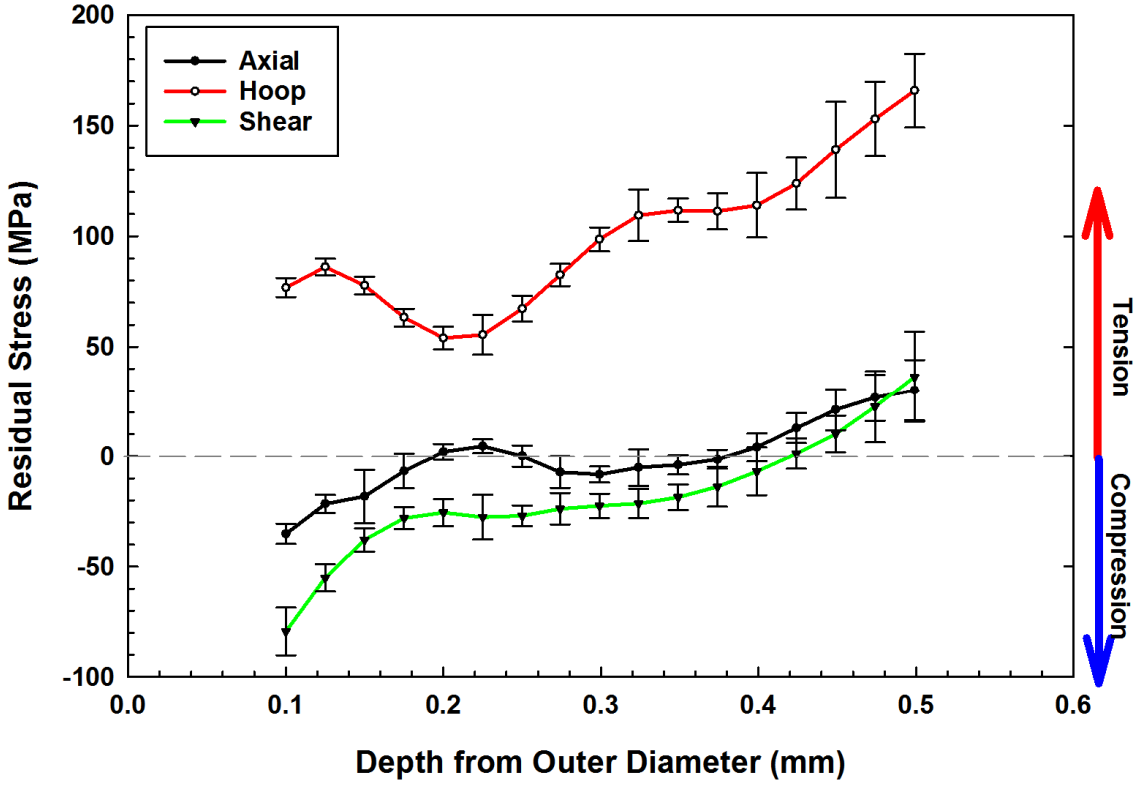
- Due to large stresses present in weld, material will yield as the core is cut for traditional DHD – as a result, incremental DHD measurements are made



- **DHD near surface, iDHD in bulk**
- **Hoop stress strongly tensile through wall**
- **Axial stress compressive at surfaces, tensile through bulk**
- **Single measurement location**

Residual Stresses in Circumferential Weld (HAZ)

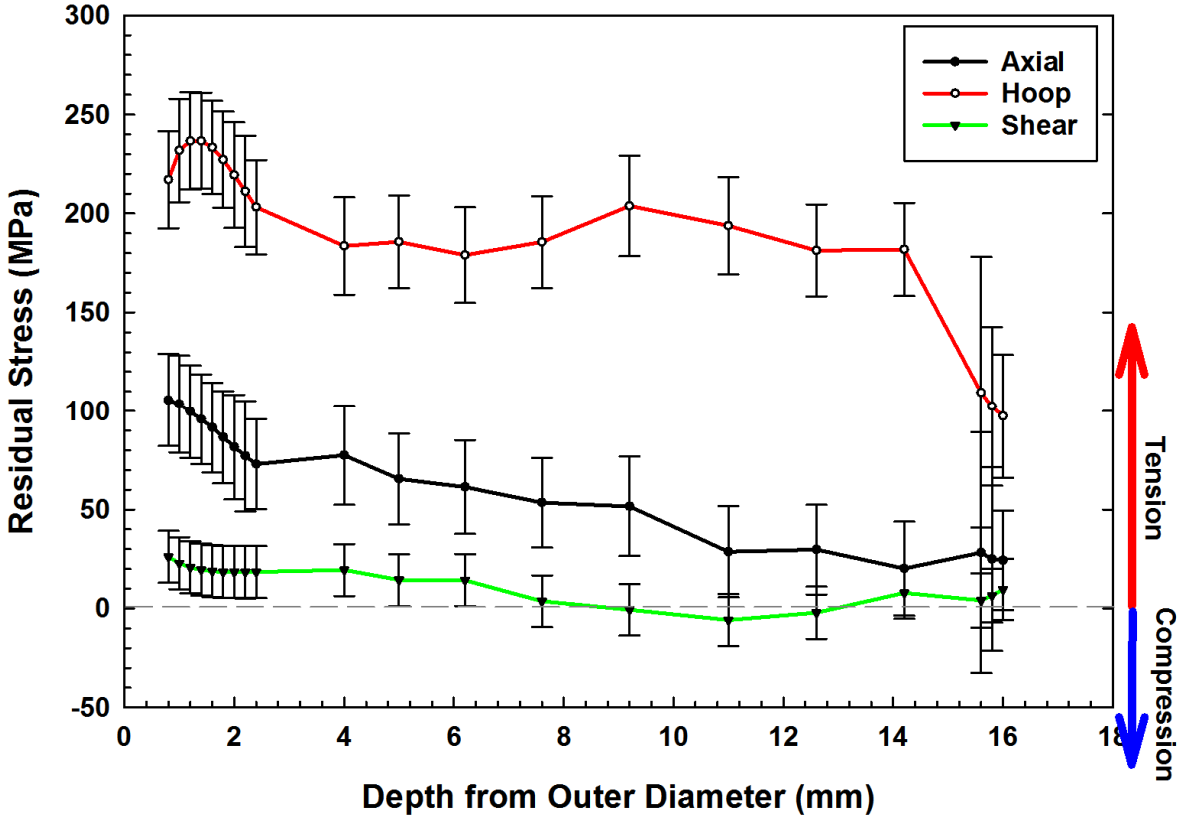
- Looking at 4mm from weld toe
- iCHD used to assess stress state in region very close to the surface of the container (on the OD)



- **Hoop stress tensile at surface, increasing with depth**
- **Axial stress low and slightly compressive, becoming tensile with depth**
- **iCHD measurements likely to exhibit some positional variability**
  - Single test location
  - Consider qualitatively

Residual Stresses in Circumferential Weld (HAZ)

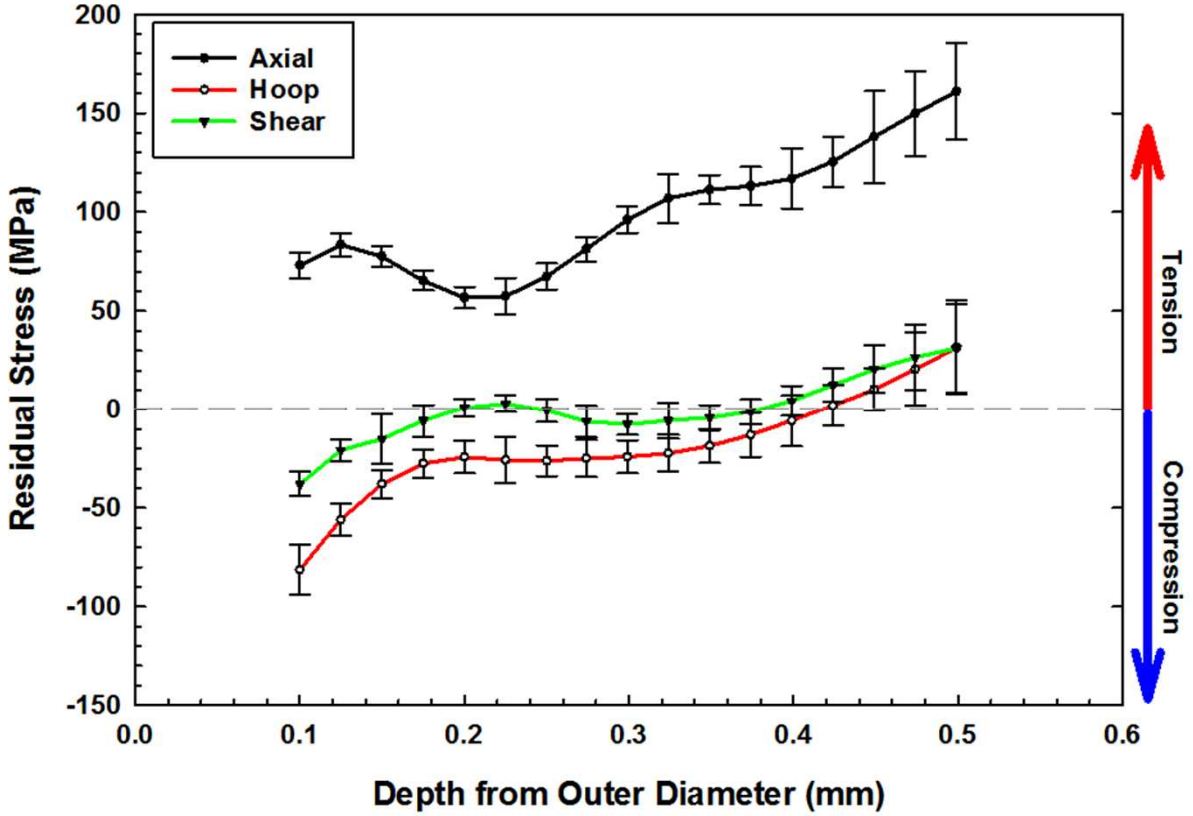
- Due to large stresses present in weld, material will yield as the core is cut for traditional DHD – as a result, incremental DHD measurements are made



- **DHD near surface, iDHD in bulk**
- **Hoop stress strongly tensile through wall**
- **Axial stress lower in magnitude, but tensile through thickness**
- **Single measurement location**

Residual Stresses in Longitudinal Weld (Centerline)

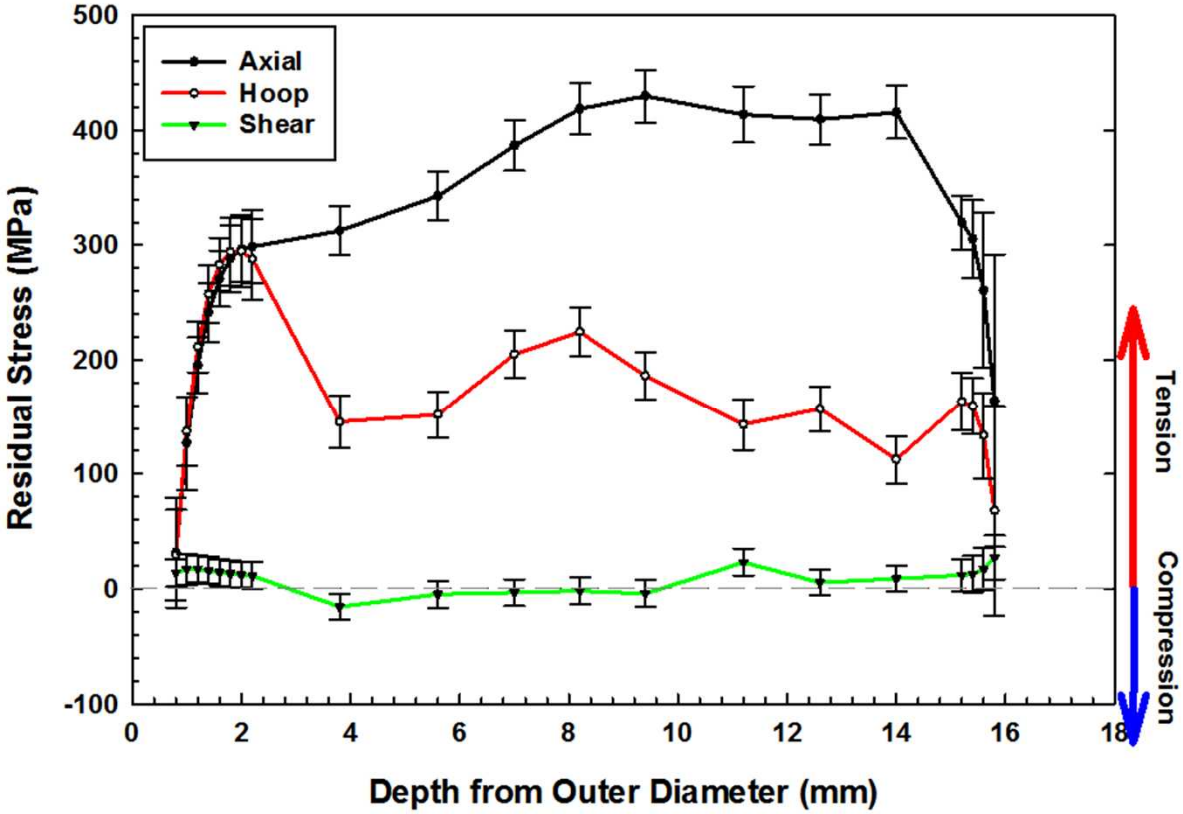
- iCHD used to assess stress state in region very close to the surface of the container (on the OD)



- **Axial stresses strongly tensile near surface**
- **iCHD measurements likely to exhibit some positional variability**
  - Single test location
  - Consider qualitatively

Residual Stresses in Longitudinal Weld (Centerline)

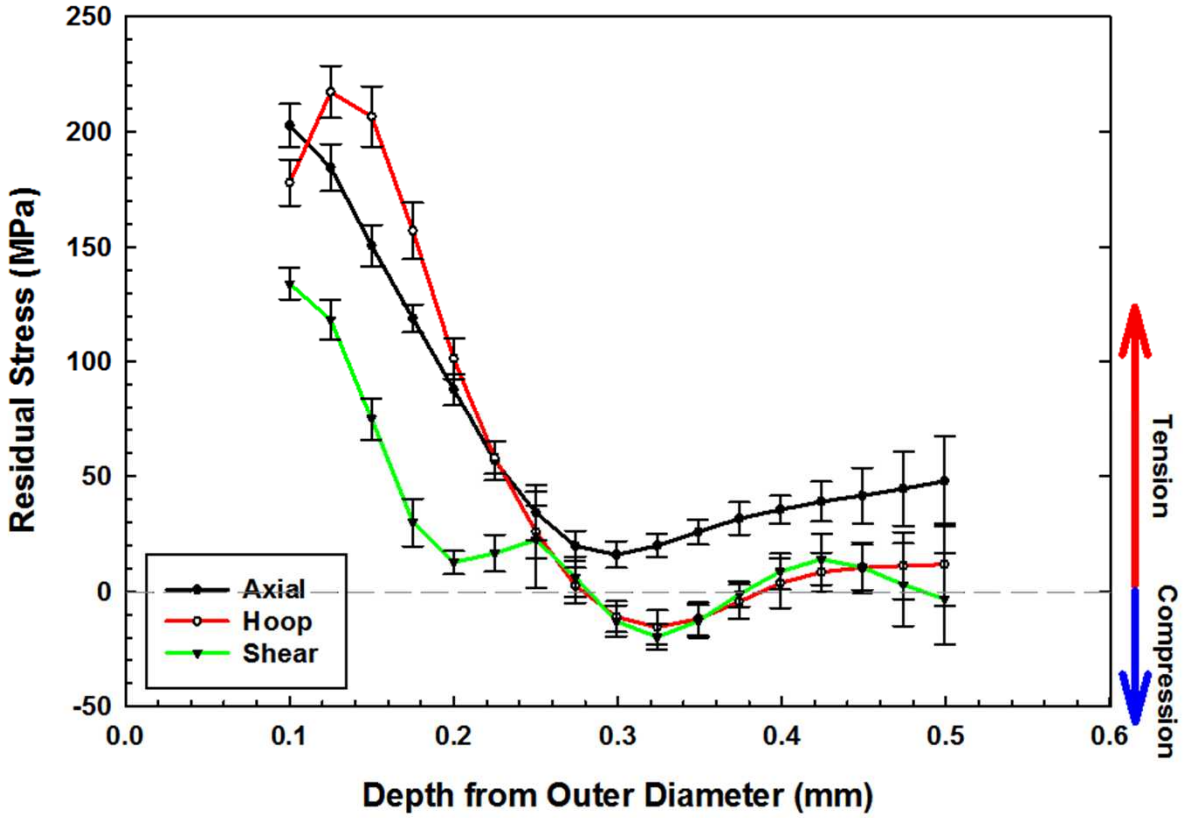
- Due to large stresses present in weld, material will yield as the core is cut for traditional DHD – as a result, incremental DHD measurements are made



- **DHD near surface, iDHD in bulk**
- **Axial stress strongly tensile through wall**
- **Hoop stress lower in magnitude, but tensile through thickness**
- **Single measurement location**

Residual Stresses in Longitudinal Weld (HAZ)

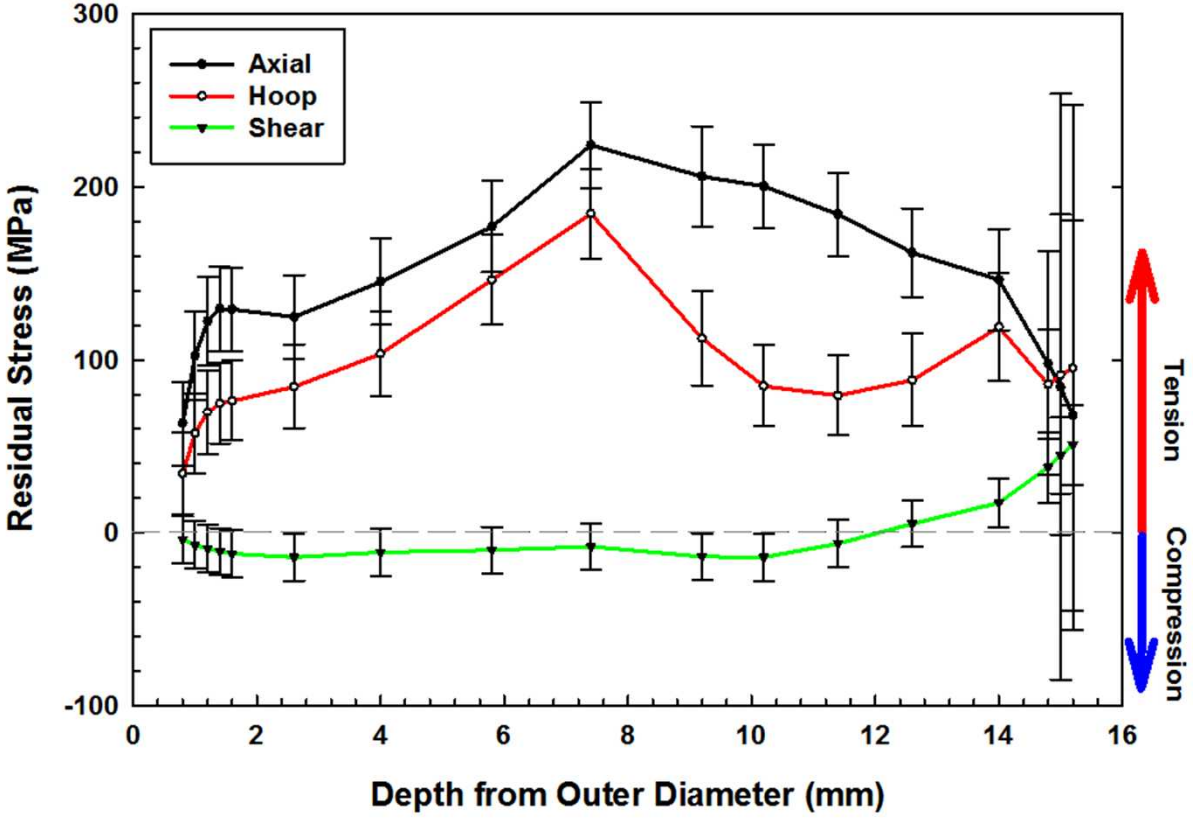
- Looking at 4mm from weld toe
- iCHD used to assess stress state in region very close to the surface of the container (on the OD)



- **Both Axial and Hoop stress tensile at surface, decreasing with depth**
- **iCHD measurements likely to exhibit some positional variability**
  - Single test location
  - Consider qualitatively

Residual Stresses in Longitudinal Weld (HAZ)

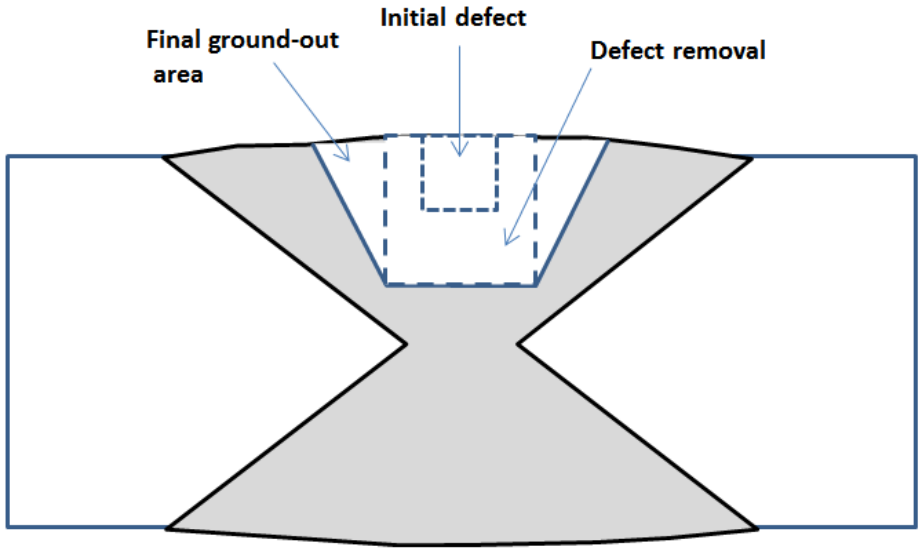
- Due to large stresses present in weld, material will yield as the core is cut for traditional DHD – as a result, incremental DHD measurements are made



- **DHD near surface, iDHD in bulk**
- **Axial stress strongly tensile through wall**
- **Hoop stress lower in magnitude, but tensile through thickness**
- **Single measurement location**

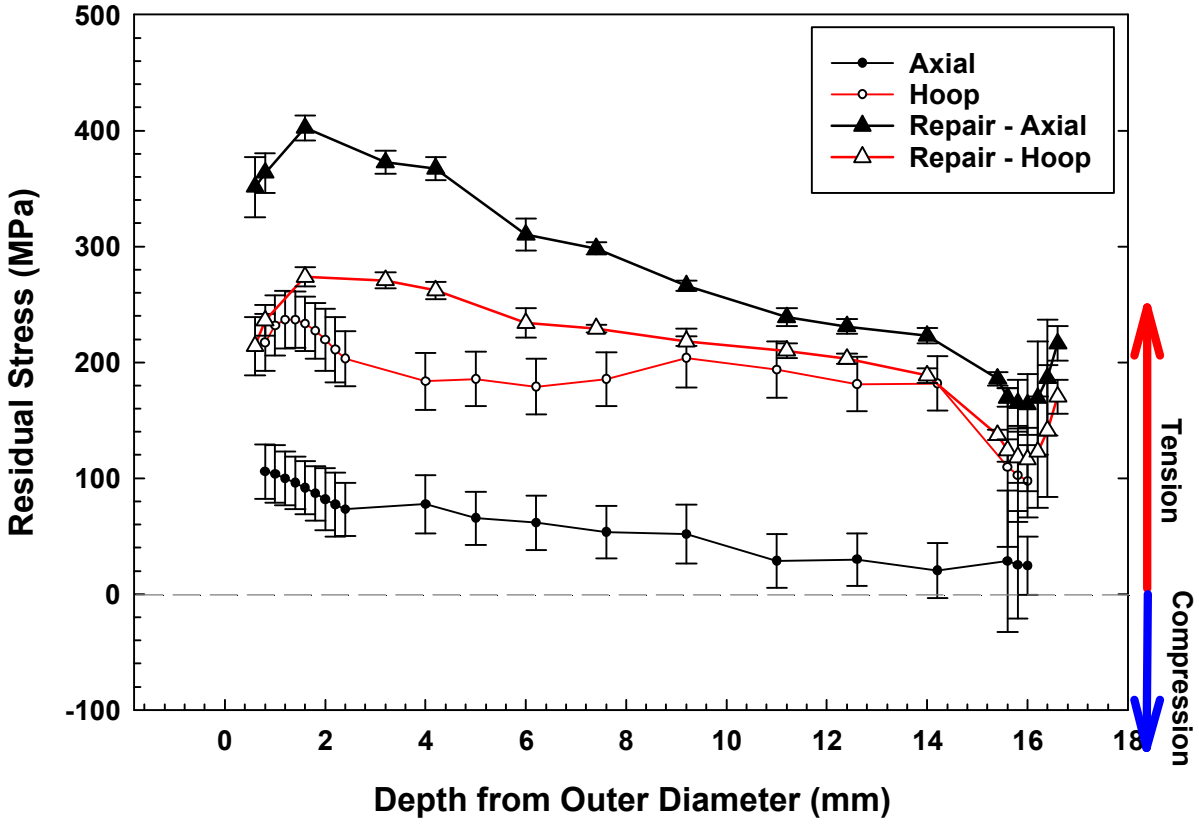
Weld Repairs on Circumferential Welds

- Welds were fabricated via submerged arc welding using a well defined protocol/schedule – very low defect density
- Manufacturer (Ranor) created a repair typical for this type of weld (simulating a local defect due to entrained slag at a weld stop/start point, etc.)
- mock defect into the container by drilling a 1/8” diameter hole partially into the center of the weld root. They then went back and “removed” that defect, by drilling out additional material using a ¼” drill, after which they ground the edges of the site such that the opening of the hole was approximately 0.5” wide. Repair completed via TIG.



Residual Stresses in Repair: Circumferential Weld (HAZ)

- Dramatic increase in magnitude of stresses, particularly in the axial direction, when a repair is made



- DHD near surface, iDHD in bulk
- Hoop stress increased in region of weld repair
- Axial stress dramatically increased in weld repair
- Similar observation on opposite side of weld

Summary and Future Direction

- Far from the welds, the residual stresses are tensile on the OD, then compressive on the ID.
- Circumferential welds are strongly tensile through thickness, with the largest stress being parallel with the weld direction
  - Still tensile perpendicular to the weld…
- Longitudinal welds are also strongly tensile through thickness, with the largest stresses parallel to the weld direction
  - Larger in magnitude than the circumferential weld
  - Tensile stresses also exist through thickness perpendicular to the weld
- Contour measurements remain to be completed, as well as an evaluation of the magnitude of the plastic strain along the weld fusion zone