Working Group on
Engineered Residual
Stress Implementation

Residual Stress Measurement Committee
Annual Summary

20 April 2023

(These charts are a team product)

Eric Burba, committee lead

micheal.burba.1@us.af.mil

Adrian DeWald, committee co-lead

atdewald@hill-engineering.com

Overview

Committee Logistics

- Mission and Goals
- Monthly Meeting Framework
- Roster and Attendance

Update on Current Projects

- 2inch Cx Residual Stress Determination for Process Simulation Validation (Presenter: Dr. Scott Carlson, Lockheed Martin)
- Bulk RS Measurements in Cx Geometrically Large Holes (Presenter: Dr. Mike Hill, UC Davis)
- Texture and Anisotropy Sub-Team (Presenter: Mr. Josh Ward, UDRI)

Summary and Future Opportunities

Mission Statement

ERSI – RSM Committee has experts in a wide range of residual stress measurement techniques that are available to help ERSI stakeholders (e.g., end users and aircraft programs) design and implement fit-to-purpose residual stress measurement efforts

Established group of residual stress measurement professionals available to review, define, engage, and/or document:

- Repeatability of residual stress measurement data (in lab variability)
- Reproducibility of residual stress measurement data (lab-to-lab variability)
- Inter-method residual stress comparisons (e.g. ND to x-ray to contour)
- Measurement model comparisons (e.g. for CX holes)
- UQ/Statistical methods relative to residual stress data (connect to inter-method as well as model-measurement)

Committee Goals - 2022

- Support the drafting of the Air Force Structures Bulletin, "Analytical Methods, Validation Testing, and Process Compliance Record Requirements for Explicit Utilization of Residual Stresses at Cold Expanded Fastener Holes in the Damage Tolerance Analysis of Metallic Structure"
- Review and provide feedback on the residual stress measurement section of the A-10 Best Practices document
- Assess/Quantify/Define effects of texture and anisotropy on residual stress measurement, document, and seek means to improve
- Develop and document exemplar datasets (leverage prior work and drive new work). Experimental residual stress datasets that have been implemented and published (use of 2x2 Cx hole dataset)

Committee goals for 2023-2024 to be established – see Future Opportunites

Monthly Meeting Framework

Monthly Committee Meetings

- Held on the first Wednesday of the month at 1400 Eastern
- Hosting meetings using ESRI's Zoom account
- Please contract Burba or DeWald if you would like to attend

Typical Meeting Agenda

Other ERSI Committee Updates

- Process Modeling Committee Update (DeWald)
- Risk Committee update (Ocampo)

Measurement Committee Projects & Updates

- Texture and Anisotropy Sub-Team (Obstalecki/Ward)
- Large Cx Hole Bulk Stress (Hill)
- Multi-Point Fracture Mechanics, AFRL (Burba)
- 2x2 Working Group (Carlson)

New Business

Around the Room

Roster and Attendance

✓	Jeferson	Araújo de Oliveira	StressMap - Director	44 (0) 1908 653 452	Jeferson.Oliveira@stressmap.co.uk
✓	David	Backman	National Research Council Canada / Government of Canada	(613) 993-4817	david.backman@nrc-cnrc.gc.ca
	Ana	Barrientos Sepulveda	Northrup Grumman Aerospace Systems	321-361-2049	Ana.BarrientosSepulveda@ngc.com
	John	Bourchard	Professor of Materials Engineering Open University - Director of StressMap	44(0)7884 261484	john.bouchard@open.ac.uk
	Michael	Brauss	Proto Manufacturing Inc.	(734) 946-0974	mbrauss@protoxrd.com
✓	Dave	Breuer	Curtiss-Wright, Surface Technologies Division	(262) 893-3875	Dave.breuer@cwst.com
✓	Eric	Burba	U.S. Air Force (AFRL - RXC - Materials & Manufacturing Directorate)	(937) 255-9795	Micheal.Burba.1@us.af.mil
✓	Scott	Carlson	Lockheed Martin Aero (F-35 Service Life Analysis Group)	(801) 695-7139	SCarlson01@gmail.com
	James	Castle	The Boeing Company (Associate Technical Fellow BR&T Metals and Ceramics)	(314) 563-5007	james.b.castle@boeing.com
	David	Denman	Fulcrum Engineering, LLC. (President & Chief Engineer)	(817) 917-6202	david@fulcrumengineers.com
✓	Adrian	DeWald	Hill Engineering, LLC	(916) 635-5706	atdewald@hill-engineering.com
	Daniele	Fanteria	Dipartimento di Ingegneria Civile e Industriale	(+)39.050.2217266	daniele.fanteria@unipi.it
✓	Mike	Hill	Hill Engineering, LLC	(530) 754-6178	mrhill@hill-engineering.com
	Laura	Hunt	Southwest Research Institute (SwRI)		laura.hunt@swri.org
	Andrew	Jones	U.S. Air Force (B-52 ASIP Structures Engineer)		andrew.jones.79@us.af.mil
✓	Eric	Lindgren	U.S. Air Force (AFRL - Materials and Manufacturing Directorate)	(937) 255-6994	Eric.Lindgren@us.af.mil
✓	Marcias	Martinez	Clarkson University (Department of Mechanical & Aeronautical Engineering)	(315) 268-3875	mmartine@clarkson.edu
	Teresa	Moran	Southwest Research Institue (SwRI)	(801) 777-0518	teresa.moran@swri.org
✓	Mark	Obstalecki	U.S. Air Force (AFRL - RXCM)	(937) 255-1351	mark.obstalecki@us.af.mil
✓	Juan	Ocampo	St. Mary's University		jocampo@stmarytx.edu
	Robert	Pilarczyk	Hill Engineering, LLC	(801) 391-2682	rtpilarczyk@hill-engineering.com
✓	James	Pineault	Proto Manufacturing Inc.	(313) 965-2900	xrdlab@protoxrd.com
	Mike	Reedy	U.S. Navy (NAVAIR - Compression Systems Engineer)	(301) 757-0486	michael.w.reedy1@navy.mil
	Steven	Reif	AFLCMC/EZFS	937-656-9927	steven.reif@us.af.mil
✓	TJ	Spradlin	U.S. Air Force (AFRL - Aerospace Systems Directorate)	(937) 656-8813	thomas.spradlin.1@us.af.mil
✓	Marcus	Stanfield	Southwest Research Institute (SwRI)	(801) 860-3831	marcus.stanfield@swri.org
✓	Mike	Steinzig	Los Alamos National Labs - Weapons Engineering Q17	(505) 667-5772	steinzig@lanl.gov
	Kevin	Walker	QinetiQ	+61457002775	kfwalker@qinetiq.com.au
✓	Josh	Ward	University of Dayton Research Institute (UDRI)		joshua.ward.29.ctr@us.af.mil

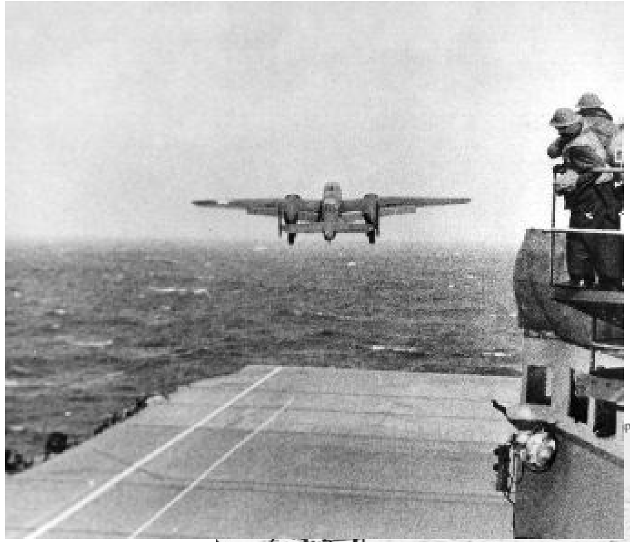
Please contact Burba or DeWald if you would like to be added or removed from this rosters

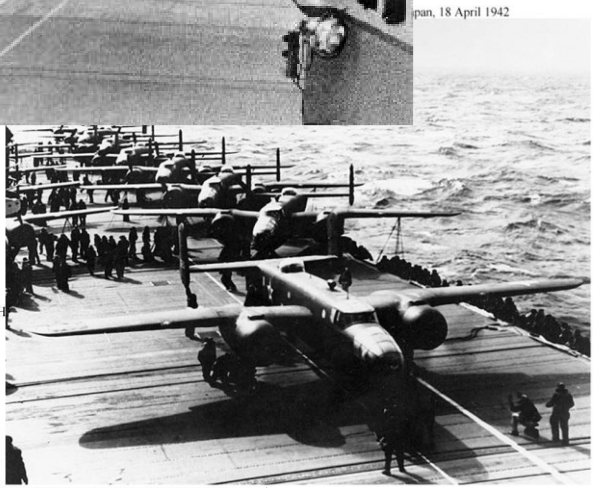
Residual Stress Determination for Cx Process Simulation Validation

Presented at the 2023 ERSI Workshop – USAF Academy, Colorado Springs, CO USA

A Little Air Force History

- On April 18, 1942 the Doolittle Raiders Took off from the USS Hornet
  - 16 B-25s were deployed to the USS Hornet
  - Raider 1 (Jimmy Doolittle's airplane) had only 467ft. of deck to take off on
  - All 16 Doolittle Raiders left Japanese air space after the bombing
    - 13 aircrews crash landed or bailed out along the Chinese coast
    - 1 aircrew landed on neutral Soviet Union soil
    - 2 aircrews were captured by the Japanese
      - Of the 10 aircrew members
        - 2 died in the crash landing
        - 3 were executed by the Japanese
        - 1 died during captivity
        - 4 were liberated in 1945
- Doolittle Raiders Continue to have a Significant Impact on the USAF





ERSI

2inch Cx Project Overview

- 2024-T351 & 7075-T651 0.25inch Thick Aluminum Plate
  - 0.25inch thick
  - 0.50inch diameter hole
  - 2inch wide

- Coupons Cxed Using Split Sleeve Cold Expansion (SsCx™) Tool Kit to the Max & Min of the Applied Expansion Range per the FTI Spec
  - 3.2% and 4.2%
  - High precision starting hole size
- One Set of Each Condition was Final Reamed for Future Use as a "Standard"
- During the Cx Process Surface Strain Measurements were Taken in "Real-Time"
  - Strain gauges installed – Installed by FTI
  - LUNA Fiber optical strain gauge – Installed and monitored by Clarkson University
  - Digital Image Correlation – Installed and monitored by SwRI

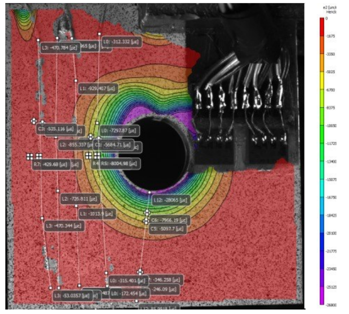
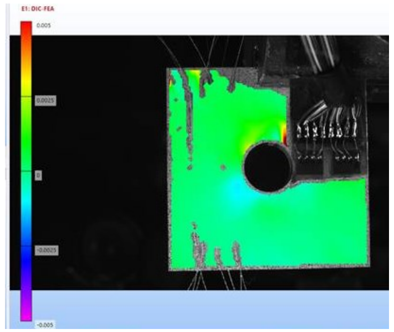
ERSI

History of Program

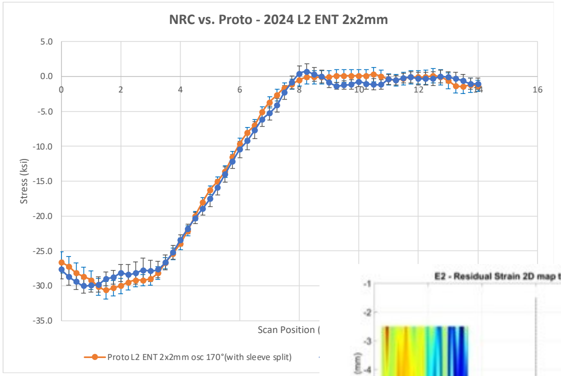
- **No Central Funding Source for all Work**
  - All Work provided at cost to the process/data owning organization – data "owned" by the group that processed the coupons
- 2016 NRC, FTI and SwRI Developed a FEA Round Robin Exercise
  - Goal was to compare state-of-the-art FEA process simulation methods and results
  - Compare results to contour method results
  - Presented at the 1st ERSI Workshop in Ogden Utah, Sept. 2016
- 2017 HOLSIP Dr. Spradlin, Dr. Martinez, Keith Hitchman and Scott Carlson Defined a Cx Process Validation Experimental Coupon Condition
  - Summer of 2017 Dr. Martinez and Marcus Stanfield performed the Cx process on 8 Aluminum coupons
- Fall of 2017 Dr. Spradlin and Carlson Traveled to Argonne NL to Perform ED-XRD on 4 of the 8 Coupons
- 2018 Through Transmission Neutron Diffraction was Performed at Coventry in UK
- Summer of 2018 Dr. Spradlin had 1 7075 Cx Coupon Processed at the CHESS EDXRD Facility
- 2019 Proto and NRC (James Pineault and Dr. David Backman) Performed an Inter-laboratory Round Robin using Surface XRD
- 2020 Neutron Diffraction was Performed on the 2024-Low Cx Coupon at JPAC (Dr. Richard Moat and Dr. Paddea)
- 2021 Neutron Diffraction was Performed on the 2024-High Cx Coupon at JPAC (Dr. Richard Moat and Dr. Paddea)
- 2021 2024-Low Cx Coupon Contour Cut at Stress-Space in UK (Prof. Bouchard)
- 2022 Neutron Diffraction of Both 7075 Cx Coupons at Oakridge National Labs (Payzant, Moat, Bouchard)
- 2023 2024-High Cx Coupon Contour Cut at 2 Difference Orientations at Stress-Space in UK (Prof. Bouchard)
- 2023 Submitted Abstracts for Surface Stress DIC Data for Process Simulation Material Model Validation and XRD Round Robin

Work Completed

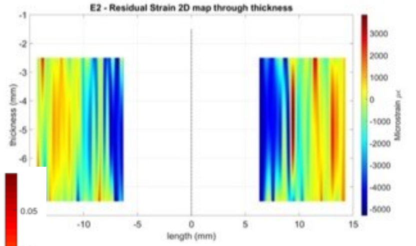
- Surface Strain Measurements During Cx Process ✓
  - Journal paper in draft form for release (focused on 2024-Low Cx level)
  - Utilizing MatchID for FEA-to-DIC comparison

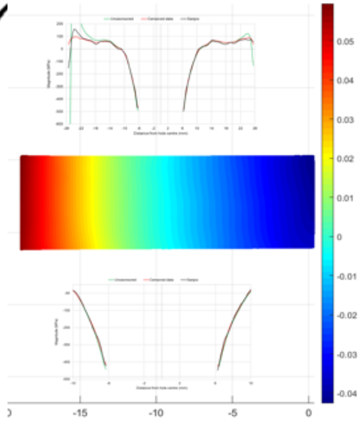



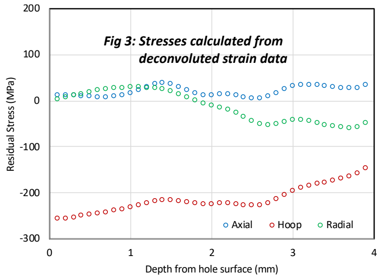
- Surface XRD Inter-Laboratory Comparison and Method Development ✓
  - Journal paper in draft for final review (All configurations presented)



- Through Thickness Measurements
  - Argonne National Lab's Synchrotron (All coupons processed) ✓
  - CHESS Synchrotron (7075 coupons processed – need data) ✓
  - JPARC and Oakridge National Lab's Neutron Diffraction (All coupons will be processed) ✓
  - Stress-Space - Contour Method (All coupons will be processed)
    - 2024 High and Low ✓



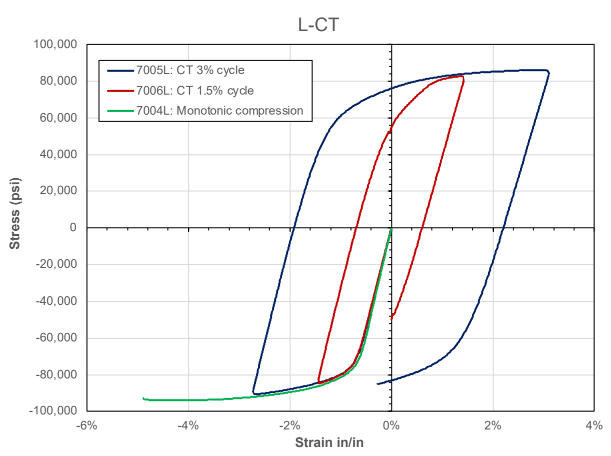




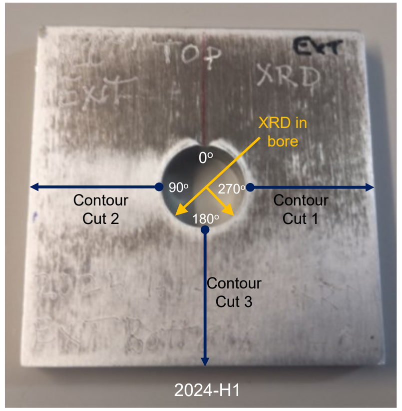
ERSI

Work In Progress

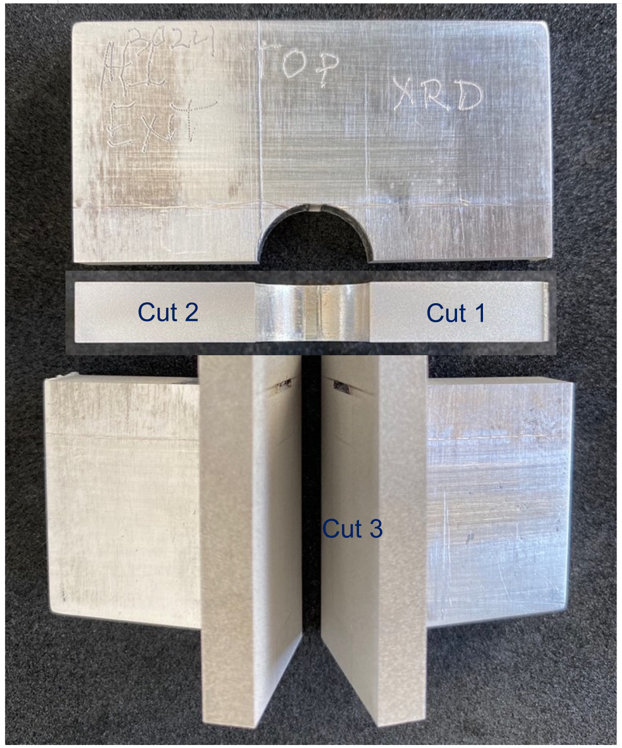
- Review Plasticity Models for FEA Simulation of Cx Process
  - Combine work from the Process Simulation round robin paper



- Processing of Neutron Diffraction Data for:
  - 2024 "High" expansion
  - Both 7075 coupons



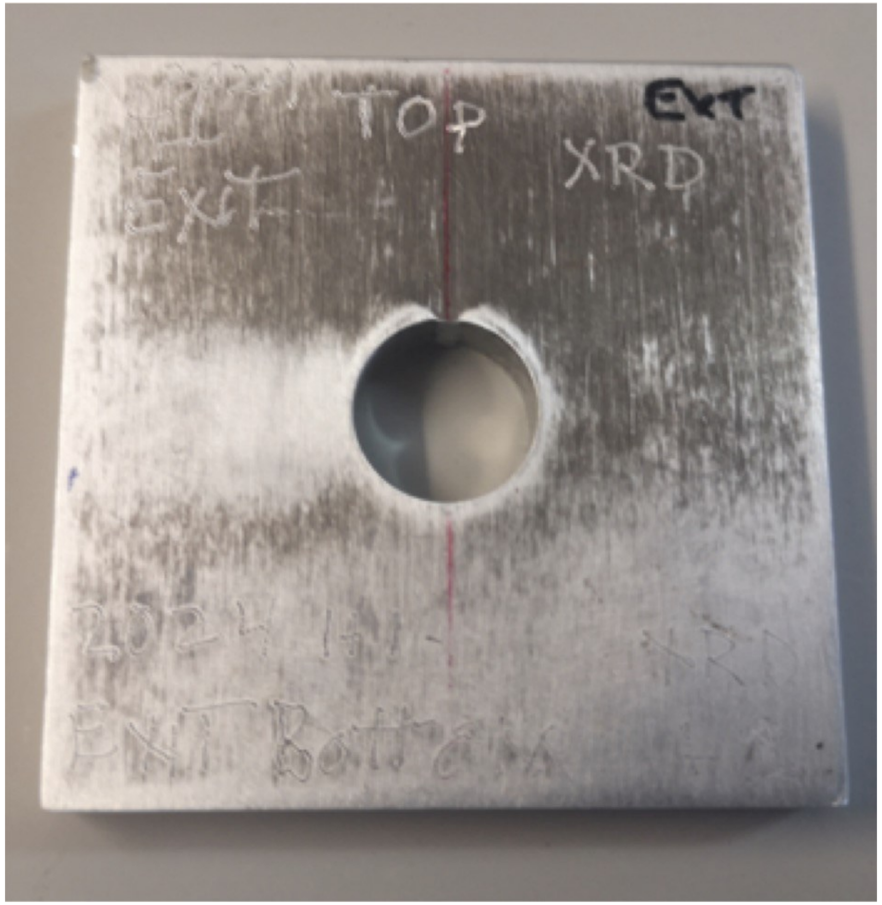
- Contour Method for Both 7075 Cx Coupons
  - Perform FEA for cutting technique
  - Perform multiple cuts on each coupon



- Develop Thru-Thickness Combination of RS Data
  - Surface XRD with Contour and Neutron Diffraction results
- Define Future Requirements for Cutting-Induced Plasticity
  - Effects of edge margin, yield strength and thickness
  - Define which side of the hole has results that are accurate

Different Data Sets for Same Case

- The 2024-H1 Conditions has Completed all Residual Stress Determination Methods, which Include:
  - Surface DIC
  - Surface XRD
    - Proto & NRC
  - Thru-Thickness Neutron Diff.
    - JPARC
  - Contour Method
    - 2 Planes
  - Hole Drilling for Rolling Stresses
  - XRD into the Hole Bore



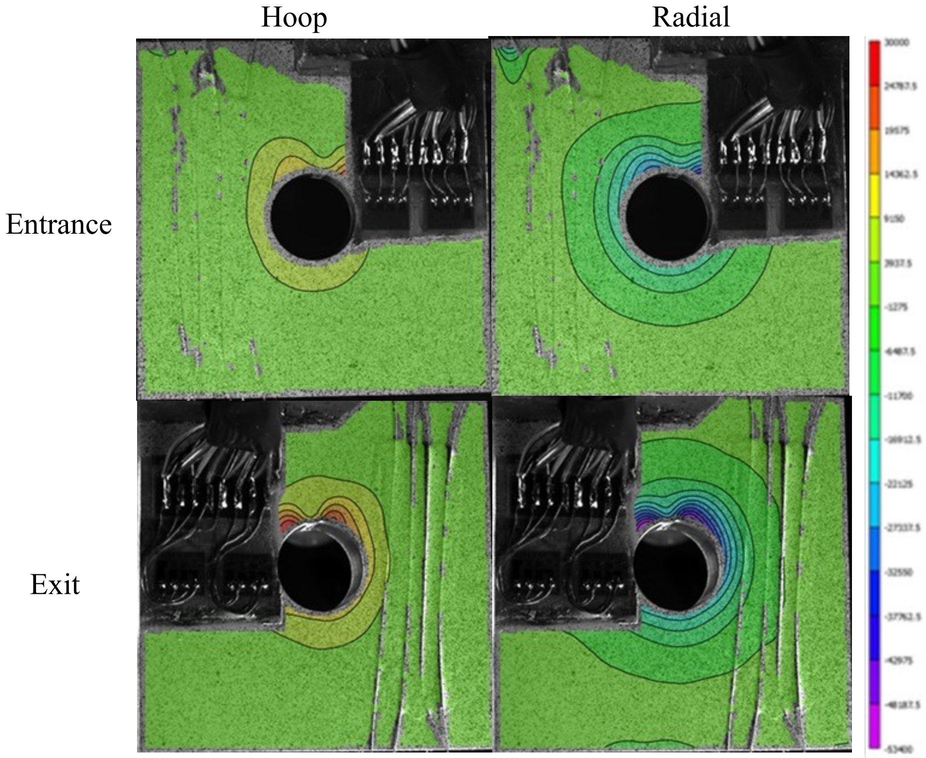
- What Do These Data Sets Look Like?
- How Can we Use them for FEA Process Simulation Validation?

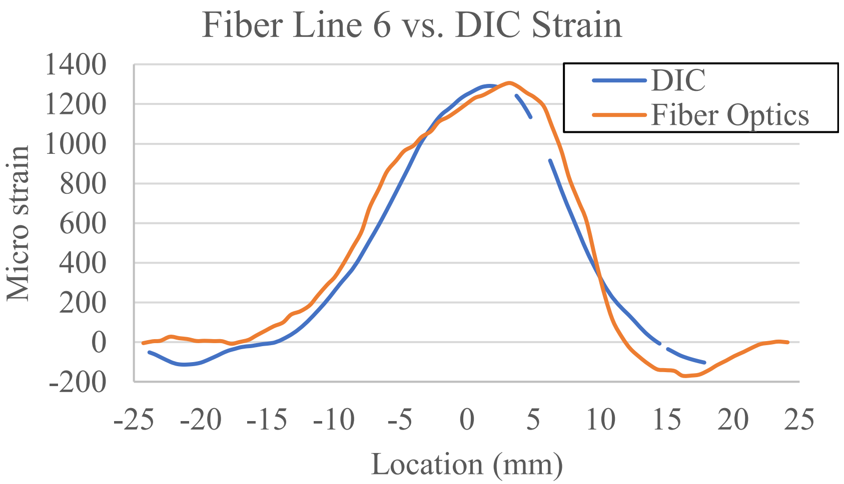
ERSI

Cx Processing DIC Data vs. Strain Gauge

- During Cx Processing Real-Time DIC, LUNA Fiber Optics and Strain Gauges Captured Full-Field Strains
  - Limited ability to capture strains "at the edge of the hole" due to DIC and Cx processing factors
  - Goal was to validate DIC as the "standard" for surface strain results for FEA validation purposes

Strain Comparison: Gage vs. DIC			
Location	**Gage**	**DIC**	**%Diff**
1	0.003571	0.003573	0.05%
2*	-0.005699	-0.005684	0.26%
3	0.000984	0.000969	1.54%
4	-0.000459	-0.000430	6.43%
*Adjusted for 13.6 degree split rotation			

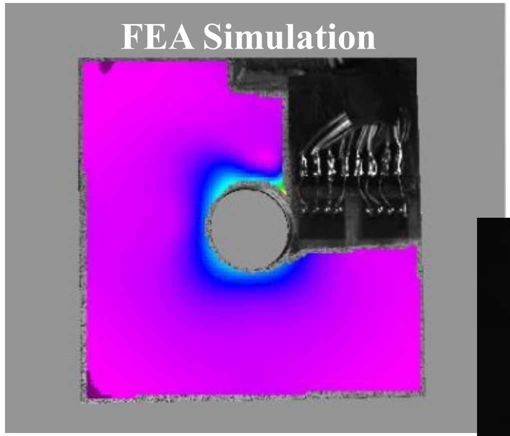


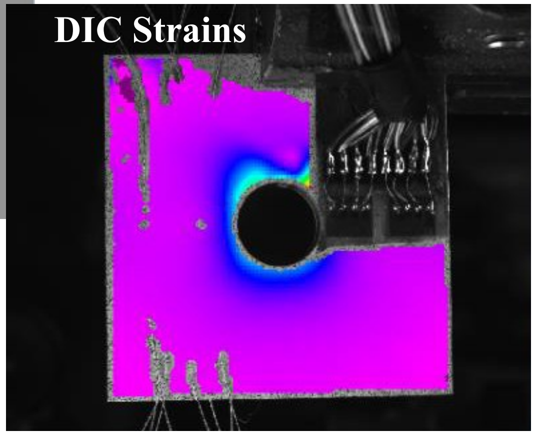


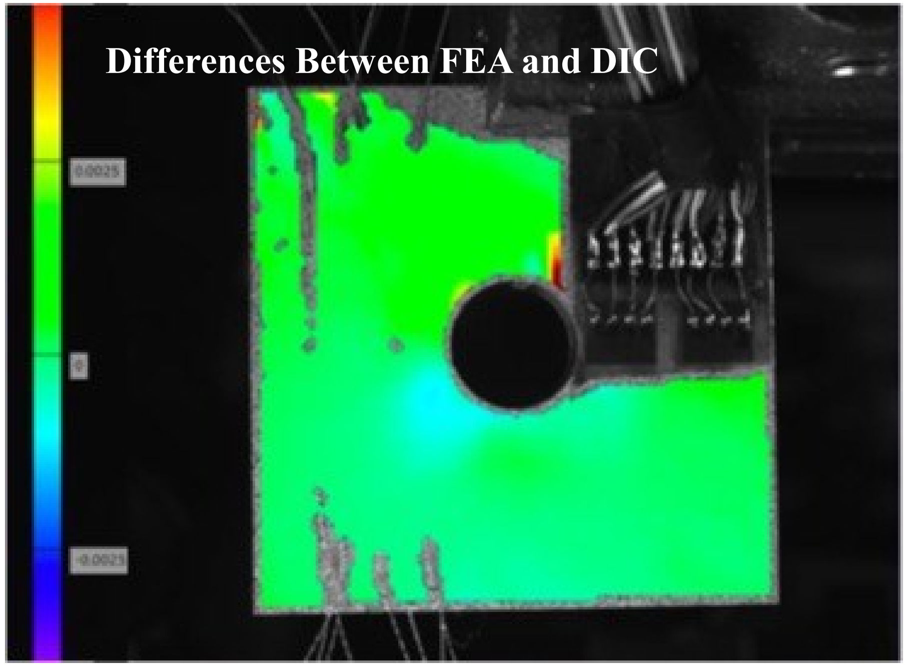
ERSI

Application of MatchID

- MatchID Allows for the Alignment and Direct Nodal Comparison of DIC Data to FEA Surface Stresses
  - FEA process simulations were performed by FTI using 3 different material models
    - Kinematic
    - Isotropic
    - Combined
  - MatchID was performed at NRC to comparison of DIC strain measurement data to FEA simulations

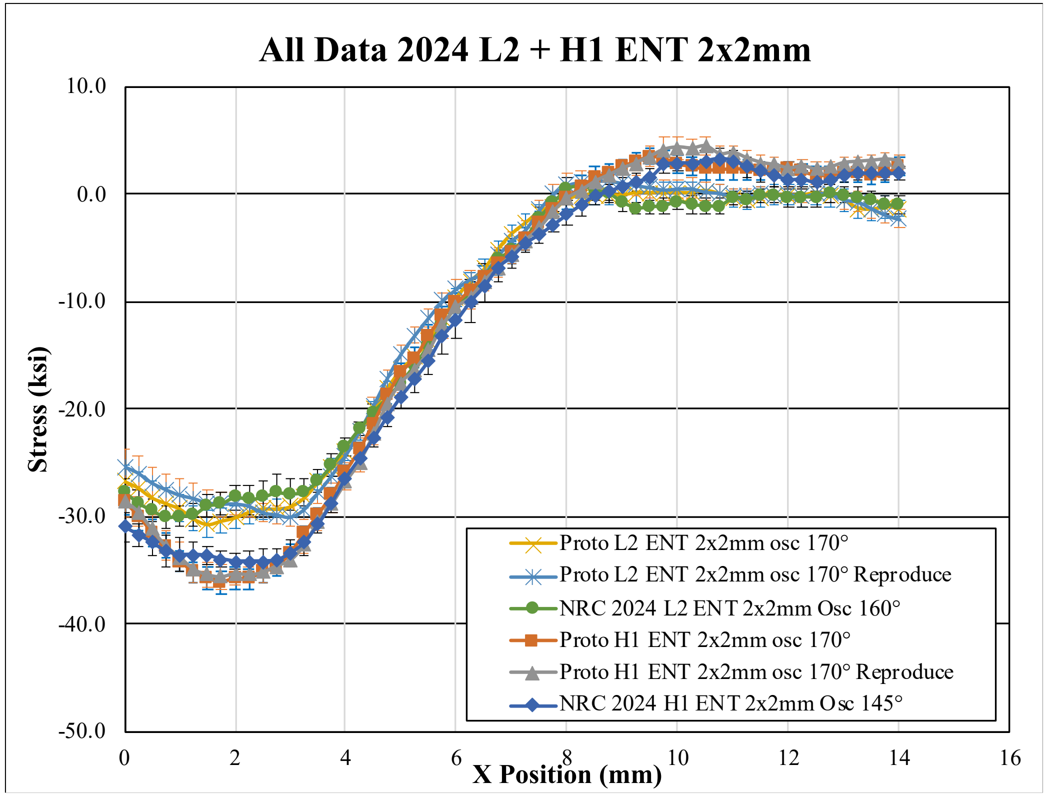


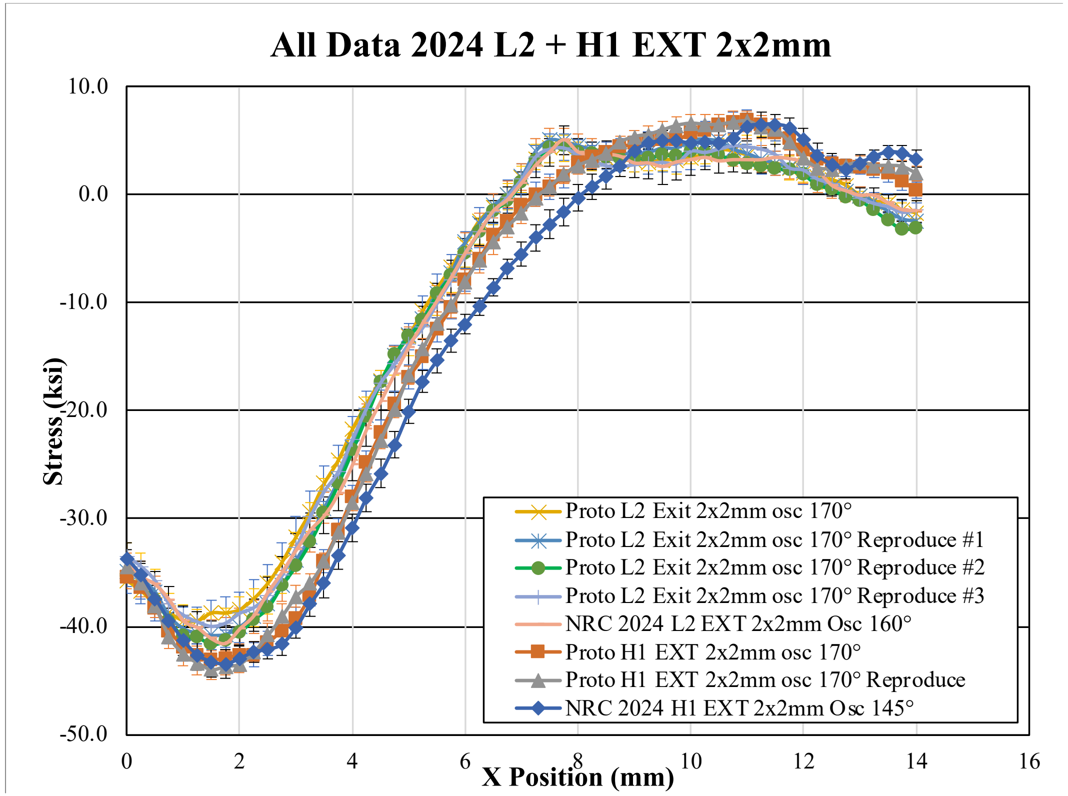




Surface XRD Round Robin Results

- Proto and NRC Performed Independent XRD Experiments on All 2inch Cx Un-Reamed Test Coupons (2024-High & Low + 7075 High & Low)
  - Development of state-of-the-art methodology for more accurate XRD measurements at Cx holes through the rotation of the coupon around the center of the hole
  - Allows for the capture of more grains but within the same stress gradient





ERSI

Neutron Diffraction Preliminary Results

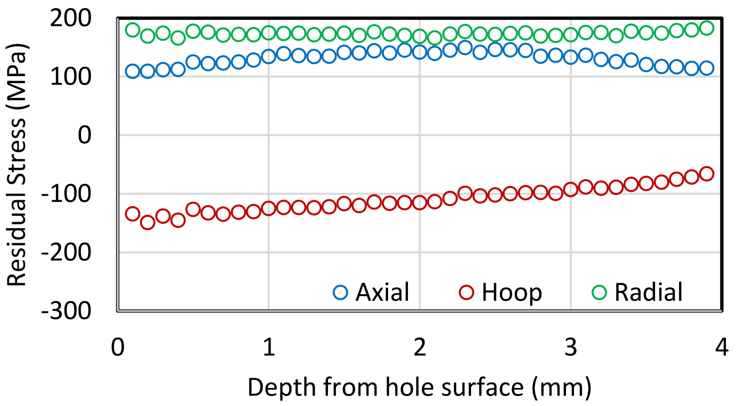
- Dr. Richard Moats Oversaw all Experiments with Deconvolution Data Analysis Approach Being Validated Prior to Application to Cx Data
  - 2024 Coupons at JPARC
  - 7075 Coupons at Oak Ridge NL

Neutron diffraction doesn't have the spatial resolution to reliably resolve much below ~1mm.

Using a step size smaller than the gauge size presents a complex convolution of spatially smoothed stresses and the nonuniform strain response of different regions of the gauge volume.

To deconvolute the raw data collected using a 100μm step size with a 2x2mm gauge size, the following steps are required.

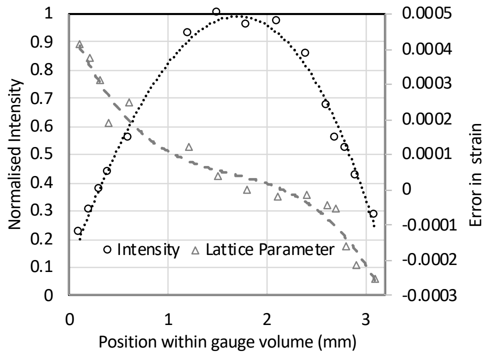
1. Collect lattice strains in 3 orthogonal direction with a step size of 100μm positioned at the centre of the thickness



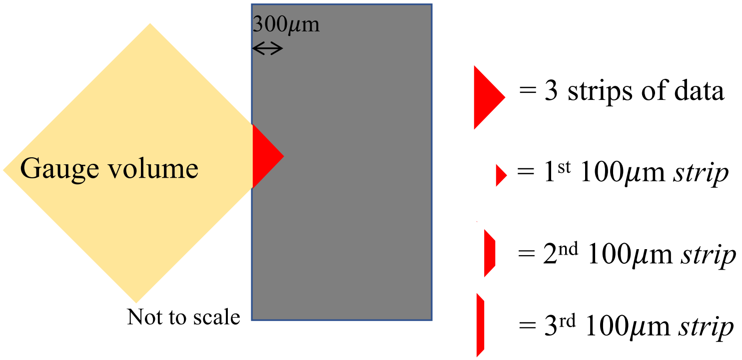
This yields highly smoothed, but clearly incorrect results (radial direction must be close to 0 MPa at the surface)

2. Map the contribution and effective error in strain across the gauge volume by scanning a 100μm thick foil

Fig 2: Intensity & error in lattice strain for 100μm slices of gauge volume



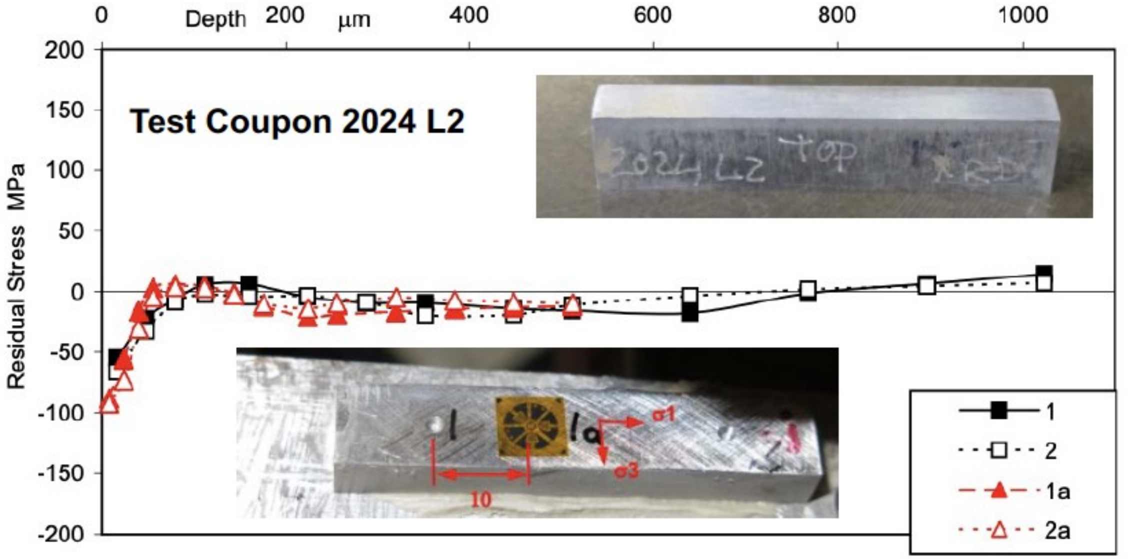
3. For each 100 μm slice of gauge volume calculate the contribution & effective shift in strain by fitting polynomials to the above curve



ERSI

Questions Asked About Rolling Stresses

- Both Materials were Manufactured from Rolled 0.25inch Plate
  - Rolling process introduces compressive residual stresses at the surface
  - Could these impact the accuracy of other residual stress determination methods



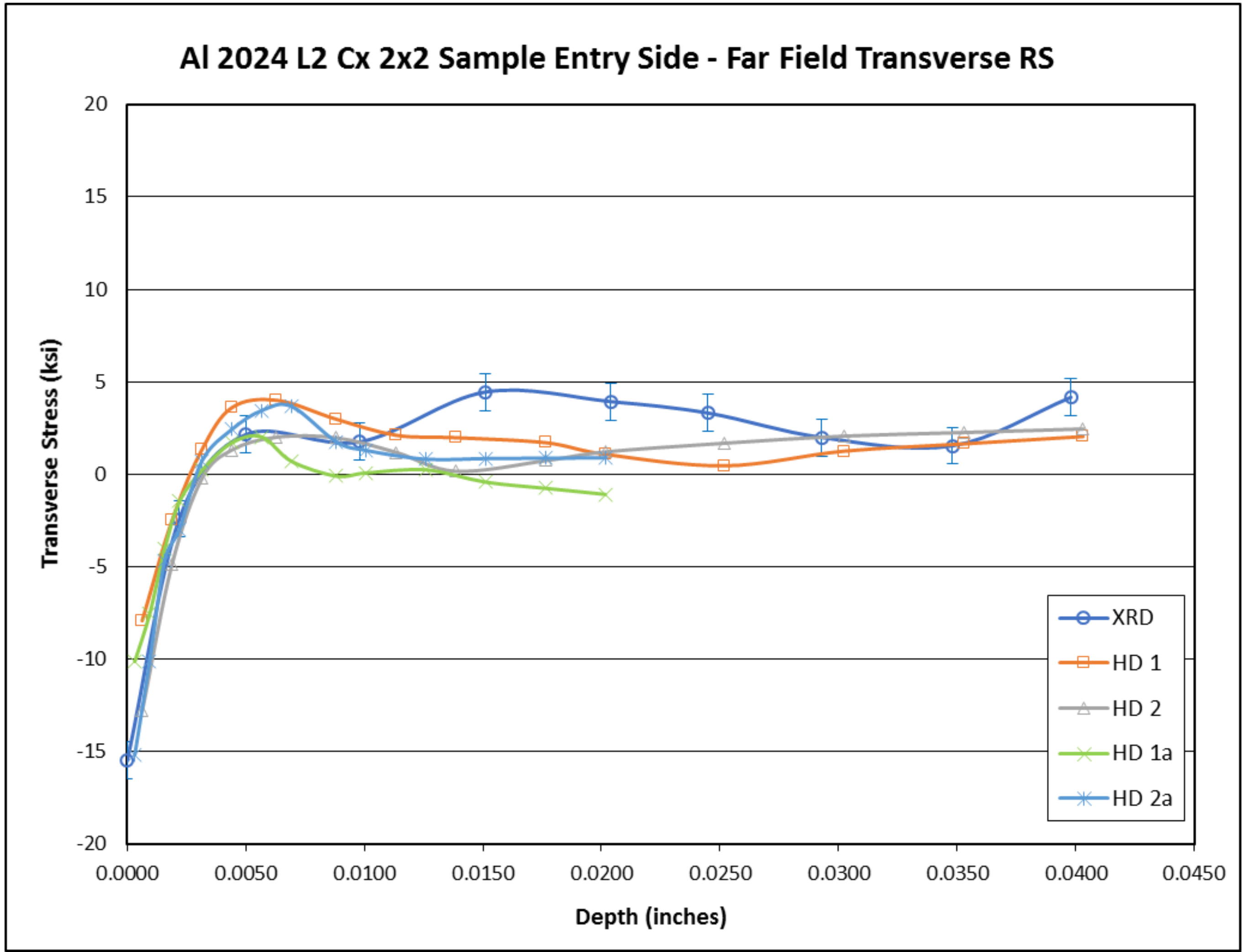
Distributions of longitudinal stresses vs depth

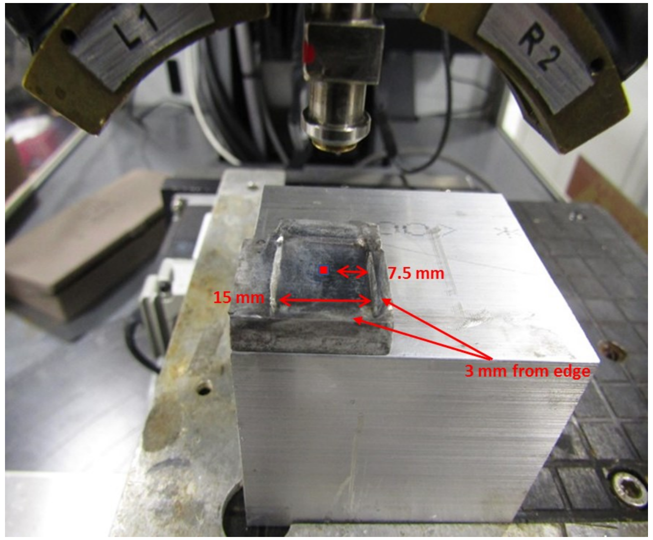
- HD Showed Compressive RS of Approx. -100MPa (-14.5ksi) at the Surface and Fall to 0ksi at Approx. 100 microns (0.004inch)
  - These rolling stresses interact with the Cx process at the surface
  - These stresses may be one reason why XRD and Contour results are different since Contour can't capture these gradients

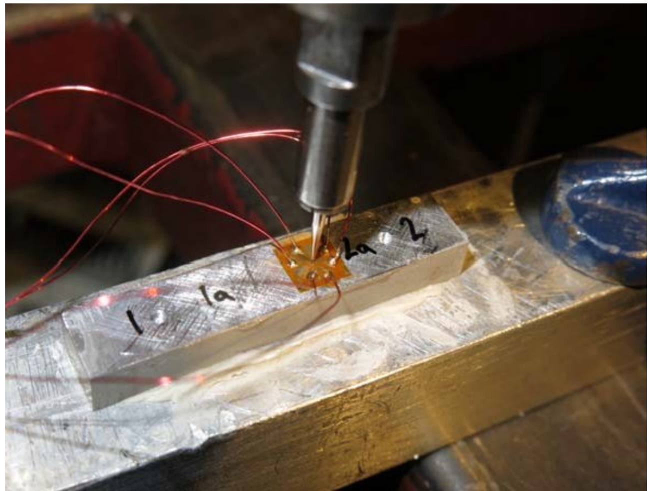
ERSI

Rolling Stresses Answered

- Confirmation of Rolling Stresses via XRD
  - Proto performed in-depth XRD via electro-polishing to confirm Holl Drilling results



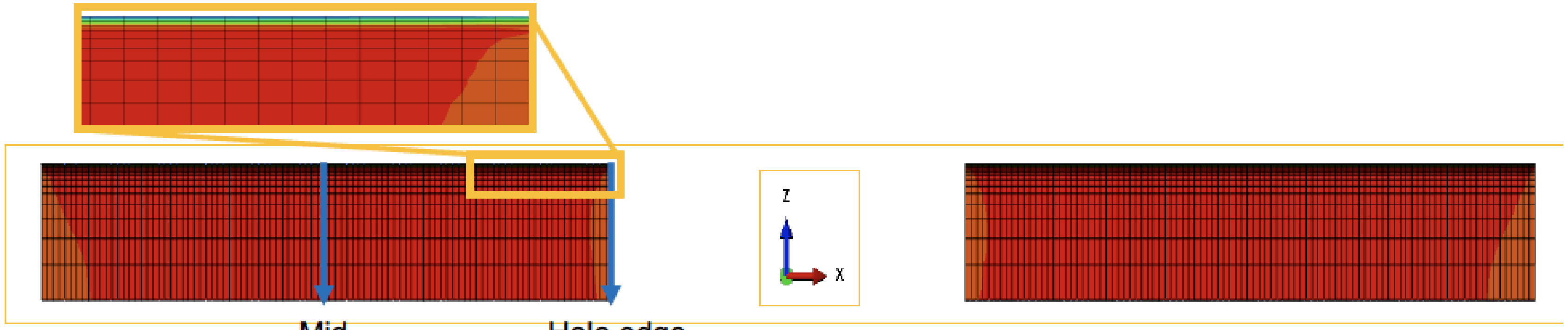


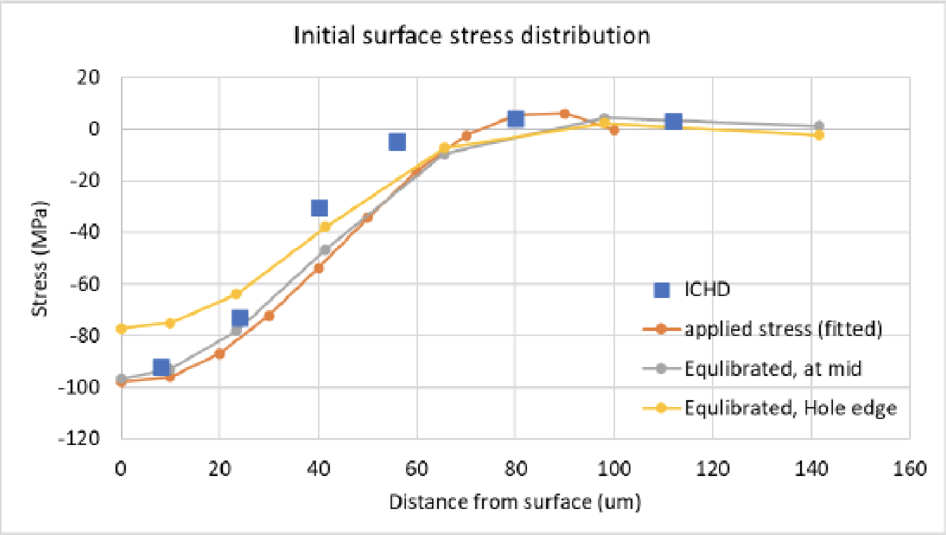


ERSI

Initial Method for Combining RS Data

- Stress-Space and Open University Developing Methodology for Combining RS Data for the 2024-H1 Condition
  - Surface XRD + HD



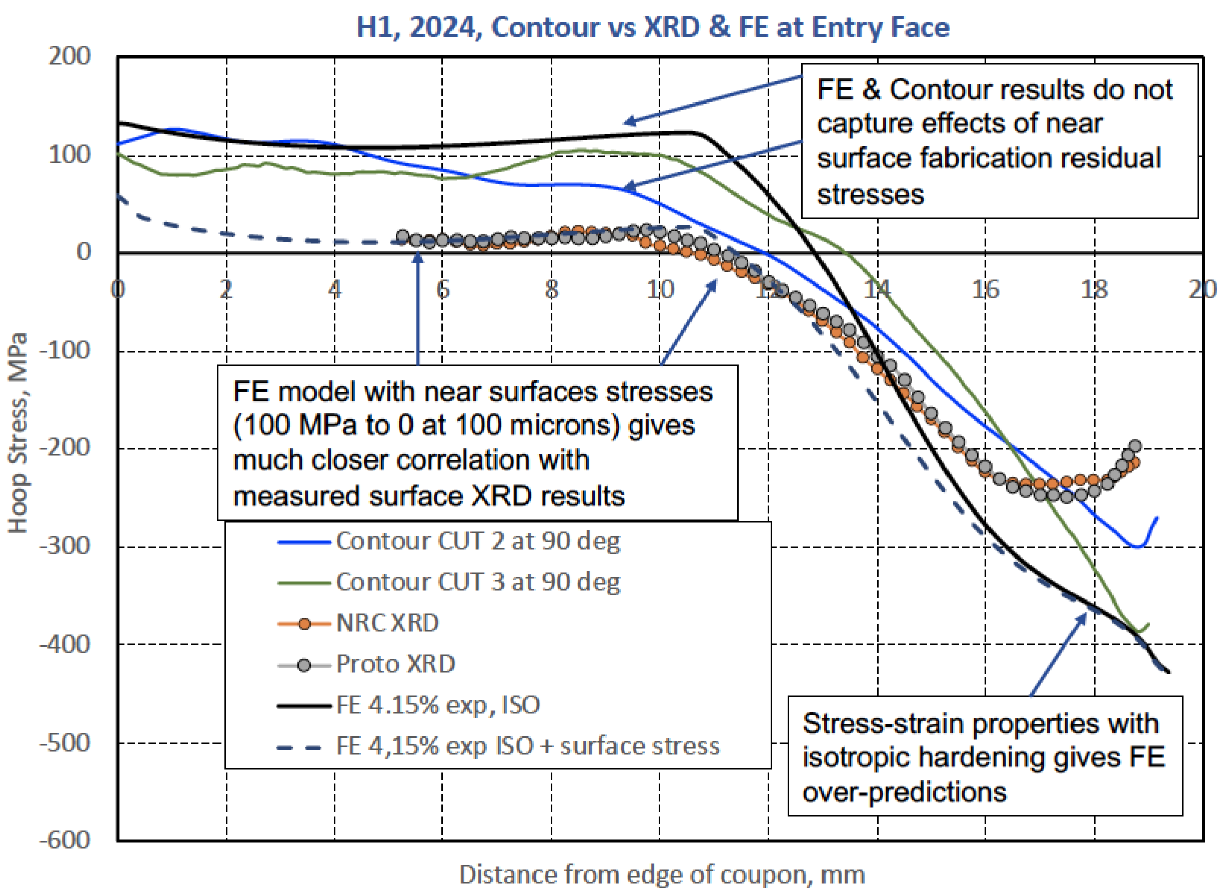


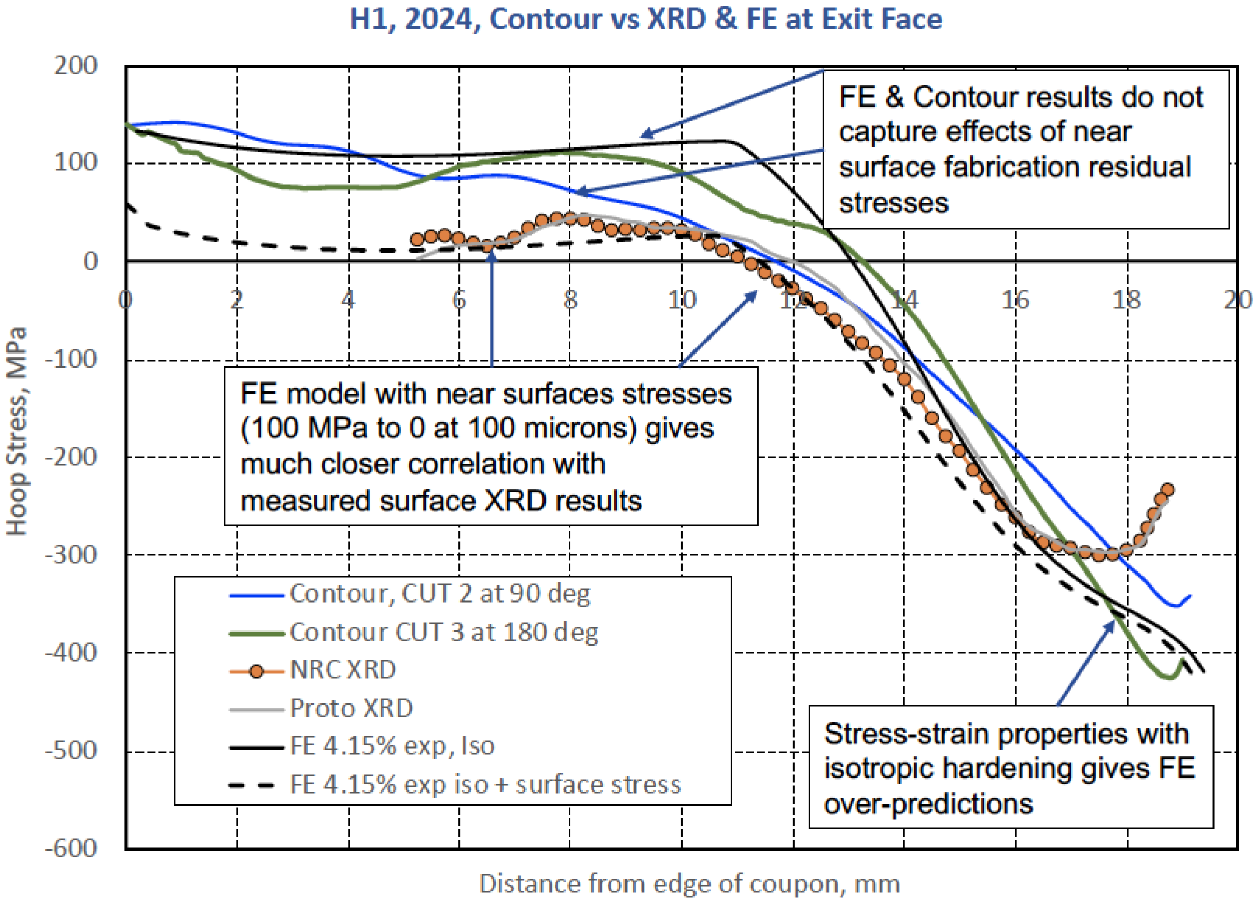
- Single bias mesh along the z direction from 0.01 mm at top surface to 0.8 mm at the bottom surface (with applied z symmetry boundary condition)
- The measured stress data were fitted to a function which was applied as an initial stress to a depth of 100 microns from the top surface.
- Then an equilibrium step was applied.

ERSI

Initial Method for Combining RS Data

- Rough 1st Cut at FEA Process Simulation Validation via Combined RS Data





ERSI

Effect of Cutting Sequence for Contour Data

- Learning that Cutting Sequence Can Have Dramatic Influence on Residual Stress State
  - Residual Stress Database used an average of the “Left” and “Right” side of the hole
    - This is likely introducing significant errors into the residual stress data used at the edge of the hole
  - One 1 side of the hole will have “accurate” residual stresses due to cutting induced plasticity at the edge of the hole
- Recommend Performance of a Cutting Induced Plasticity FEA Simulation Prior to Cutting Cx Holes
  - In 7085 and 7050 we have learned that the cutting sequence may need to be changed due to:
    - Edge margin
    - Thickness
    - Material yield strength
- Recommend Review of the Residual Stress Database to Remove Incorrect Data and Perform Averaging Again
  - May need to perform FEA simulation to determine which side is most accurate

Future Work

- Complete and Submit Surface Strain & XRD Round Robin Papers to ASM Mat. Eng. and Processes Special Edition
  - Abstracts were accepted, time to “Band Together”
- Complete Data Processing of Neutron Diffraction Experiments
  - Richard Moats and Prof. Bouchard working through data reduction of all 4 Neutron Diff. data
- Complete Contour Method on 7075 “Low” and “High” Test Coupons
- Develop Journal Papers on Through-Thickness Comparisons
  - Neutron vs. Contour
- Develop Method for Coupling Residual Stress Methods for Near-Surface and Away-from-Surface Stress Fields
  - Potential to use Neutron or XRD data near the bore of the hole and Contour data away from the hole

Questions??

Not Sure Which Looks More Tired

What happens after 6 years of work and:

- Traveling to 4 Countries
- Being Shot with High Energy X-rays (ED-XRD)
- Surface X-rays (XRD)
- Neutrons (Neutron Diff)
- Sectioned with a Wire EDM, 3 times (Contour)
- Electro-Polished and Shot with X-rays in the hole (XRD)

ERSI

ERSI

Working Group on Engineered Residual Stress Implementation

Bulk RS Measurements in Cx Geometrically Large Holes

Presenter: Dr. Mike Hill, UC Davis

Mechanical and Aerospace Engineering
University of California, Davis

Determination of Residual Stress and Strain Fields During Cold Expansion Processing Using Complementary Diffraction Techniques

Nicholas A. Bachus, Donald W. Brown, Chris Budrow, Micheal E. Burba, Bjørn Clausen, Adrian T. DeWald, J.Y. Peter Ko, Kelly E. Nygren, Mark Obstalecki, Robert T. Pilaczyk, Renan L. Ribeiro, Paul A. Shade, Matthew Shultz, Michael R. Hill

Distribution Statement A. Approved for public release: distribution unlimited. Ref. AFRL-2023-1025

LA-UR-23-21858

Challenge with Air Force Legacy Aircraft

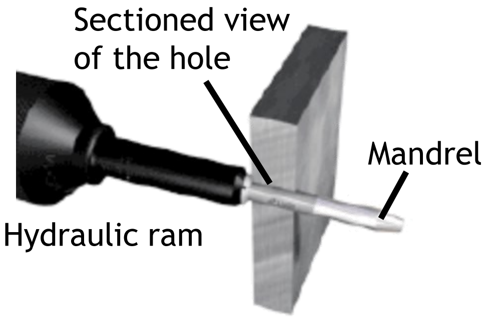
- The current airframes are aging, and solutions must be developed to extend their life expectancy
- Fatigue crack growth is a leading cause for airframe retirement and is why decelerating crack growth is so attractive
- Careful engineering implementation of residual stress can help decelerate crack growth
  - Residual stress is an equilibrium stress field (2nd order tensor) within a component in the absence of external loading

https://www.flickr.com/photos/usairforce/

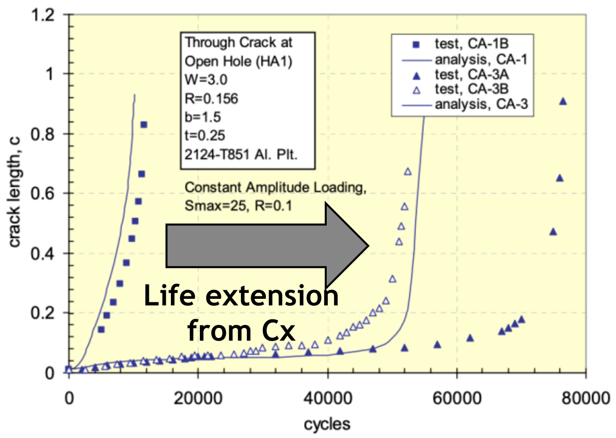
Defense.gov

Cold Expansion Process

- The Engineering Residual Stress Implementation (ERSI) group was formed to validate the Cold Expansion (Cx) process as a means of extending the fatigue life of structural components containing fastener holes
- The Cx process forces an oversized mandrel through an undersized hole causing plastic deformation which induces compressive residual stress near the hole bore
- Compressive residual stress slows crack growth (well documented in the literature)

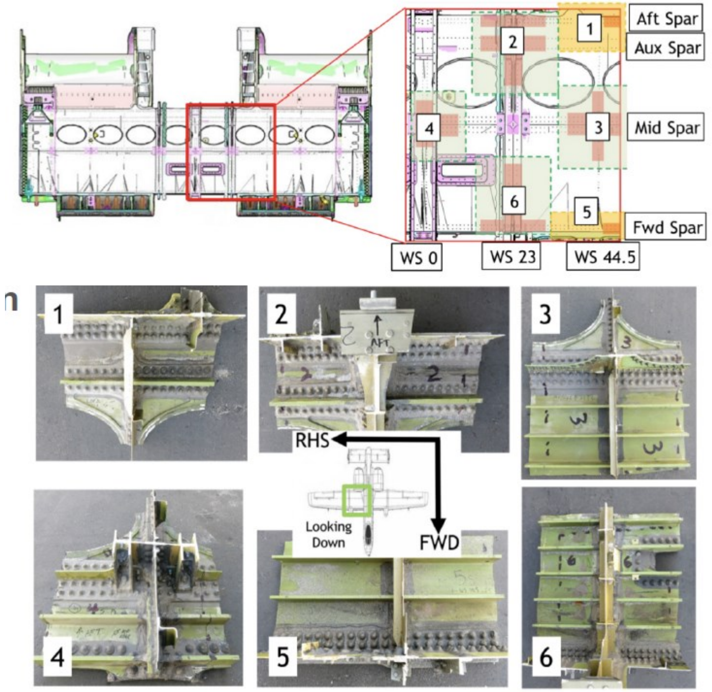


Fatigue Technology



D. Ball and M. Doerfler 2003

Wing bulkhead sections containing numerous fastener holes processed with Cx

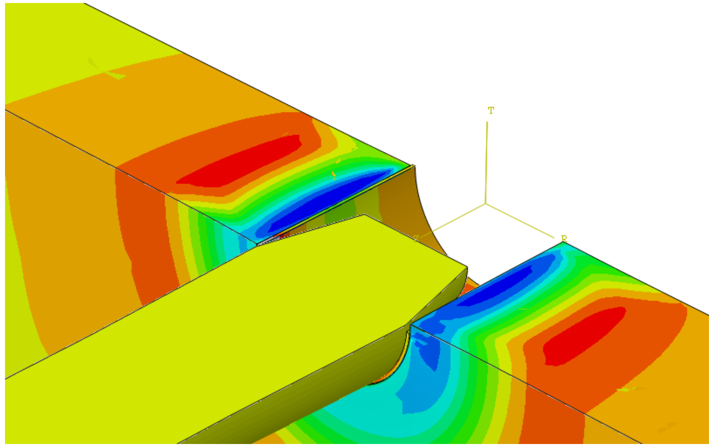


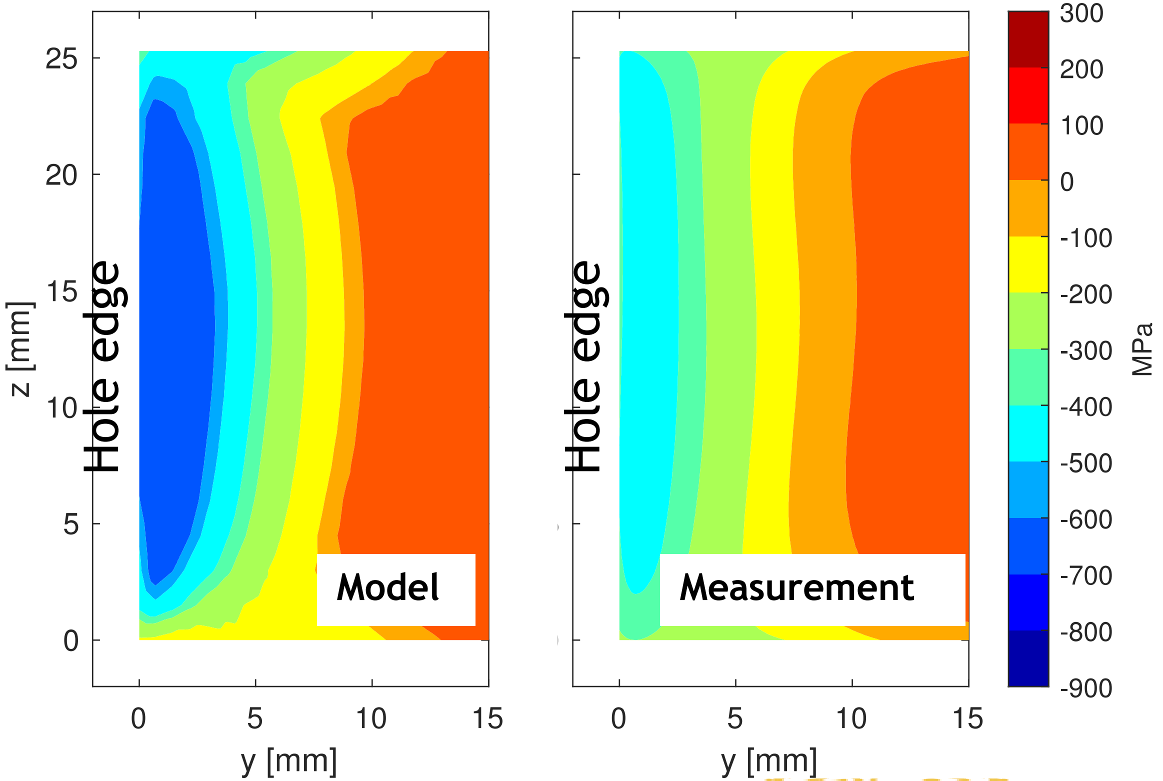
Pilarczyk, ASIP Conference 2018

Process Modeling and Historical Measurements

- To explicitly credit Cx with airframe life extension, engineers need accurate models to predict residual stress fields
- An elastic-plastic process model was previously developed using finite element software to incrementally displace the mandrel through the hole and observe the resulting residual stress state
- A prior validation campaign showed an over estimation of compressive residual stress near the hole edge
  - Overestimate of roughly 50% of maximum measured residual stress would lead to gross overestimation of Cx process benefit if used to predict structural fatigue life
- A lot of work has been published on modeling, residual stress measurements, and comparisons, but we believe an exemplar data set is required to encourage further model development

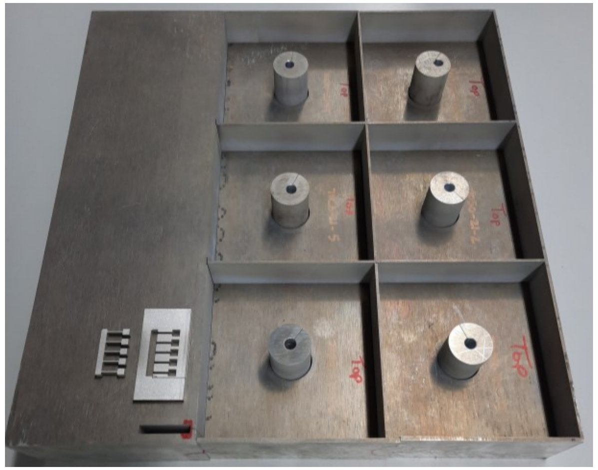
Sectioned view of the process model at a late time step



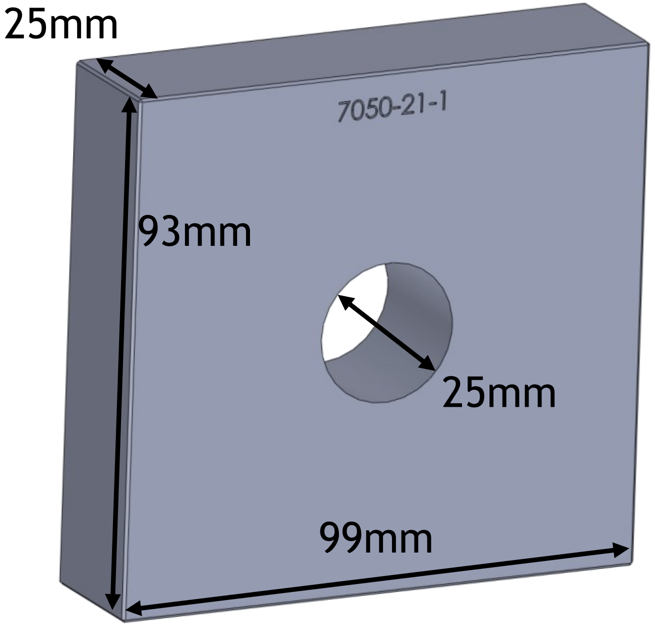


Specimen Preparation

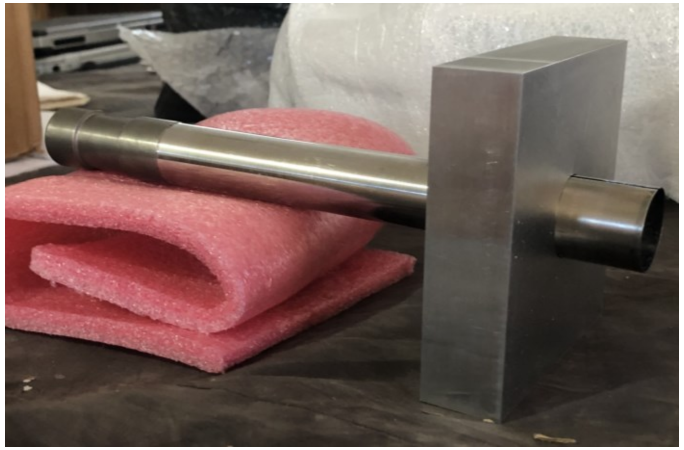
- Multiple specimens were extracted from a single 50mm thick rolled AA7050-T7451 plate (solution heat treated, stretch stress relieved, artificially aged)
- Extracted specimen dimensions were 99mm (L) x 93mm (LT) x 25mm (ST)
- To qualify models at multiple Cx processing time step, two processed conditioned were developed for this initial study
  - 100% Cx processed specimen
  - 50% Cx processed specimen, where the mandrel was held in place by friction



100% Cx processed



50% Cx processed

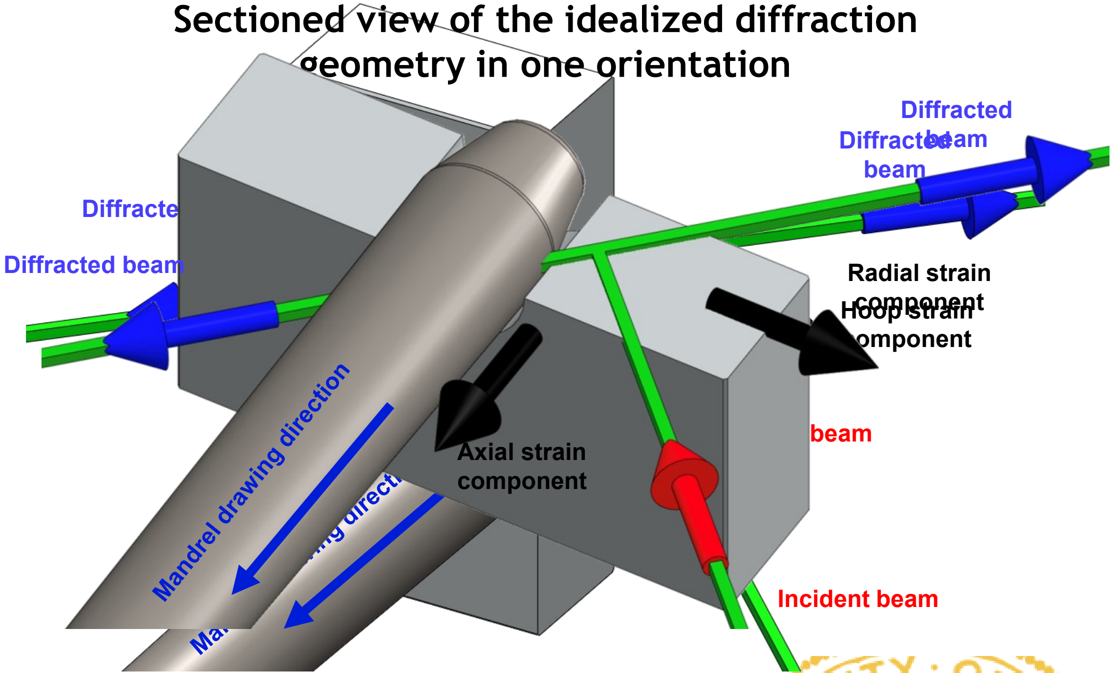


Neutron Diffraction Measurements

- ❑ **Neutron diffraction measurements were conducted on the SMARTS instrument at the Los Alamos National Laboratory**
- ❑ **SMARTS capabilities include**
  - ➢ Two detector banks at ± 90 degrees for typical engineering strain component determination
  - ➢ $0.5 - 7.5$Å incident neutron spectrum for full diffraction pattern analyses
  - ➢ 250KN load frame, a vacuum furnace with in-situ loading capabilities, Leica laser absolute tracking system and Romer laser scanner, back scatter detector banks dislocation density measurements from line profile analysis
- ❑ **Determined 3 orthogonal normal strain components along the axial, hoop, and radial directions**
- ❑ **Isotropic Hooke's law was then used to compute the normal residual stress components**

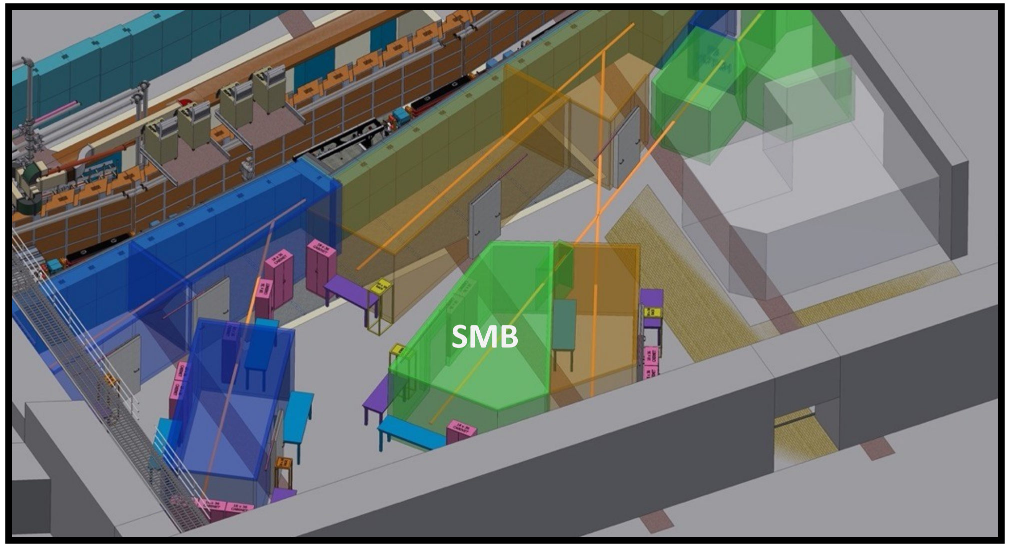
OSTI.gov

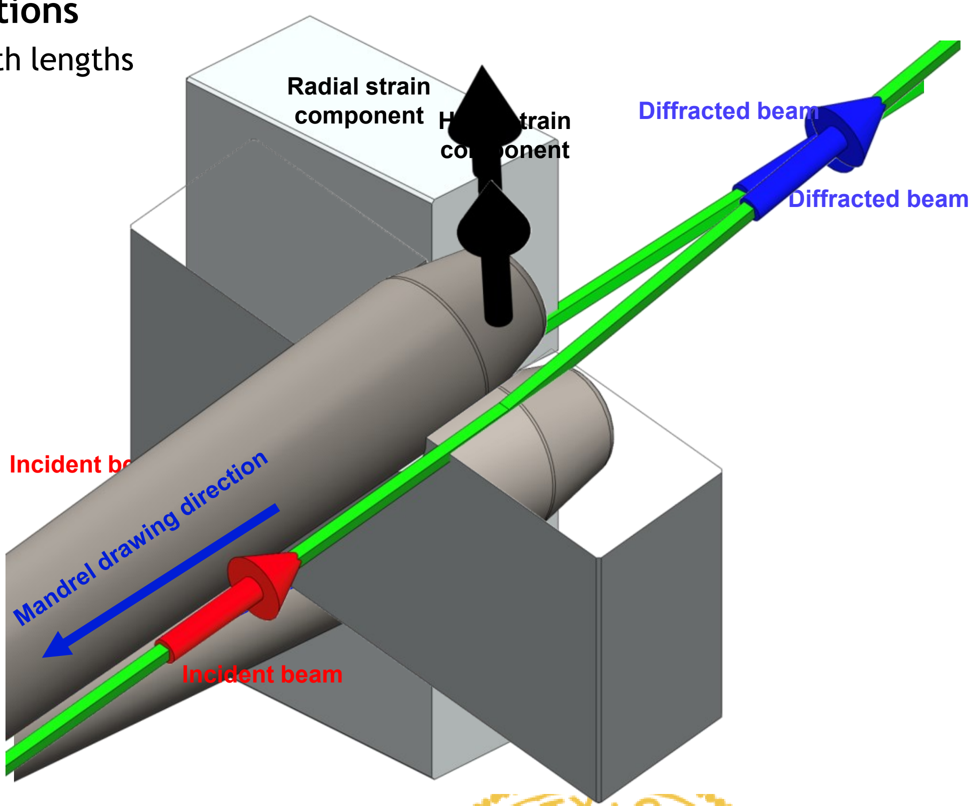
Sectioned view of the idealized diffraction geometry in one orientation



X-ray Energy Dispersive Diffraction Measurements

- X-ray energy dispersive diffraction measurements were conducted at the CHESS Structural Materials Beamline which is currently sponsored by the Air Force Research Laboratory (AFRL)
- Structural Materials Beamline capabilities include
  - Single detector bank at $2\theta = 6.46$
  - White beam incident X-ray spectrum
  - Kuka 6-axis robot arm for sample positioning
- Determined 2 normal strain components along the hoop and radial directions
  - Axial strain component measurements were not conducted due to the extreme path lengths

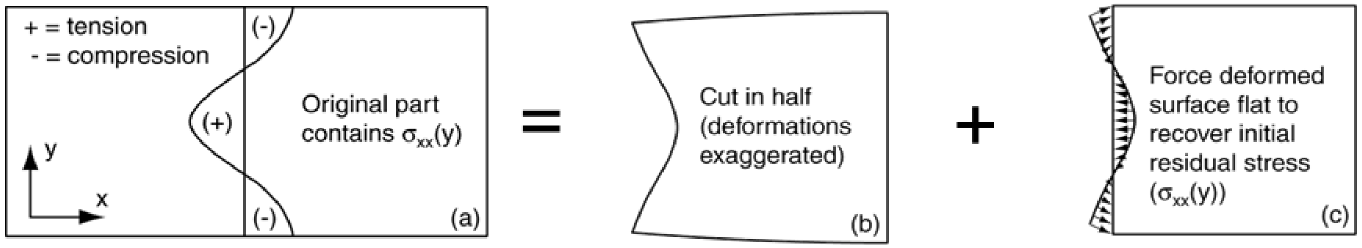




Contour Method Measurements of Residual Stress

- A single hoop stress measurement was made along the same plane as the neutron and X-ray diffraction measurements
- The contour method determines a single component of residual stress normal to a plane of interest
- Comprises cutting a part along a plane of interest and measuring the resulting normal deformation
  - Cutting a residual stress bearing body introduces a traction free surface and to satisfy equilibrium the residual stress field redistributes resulting in deformation
  - The normal deformation is applied to a linear elastic finite element analysis as a boundary condition to compute the residual stress field within the plane
  - Provides a 2D map of residual stress normal to the plane of interest

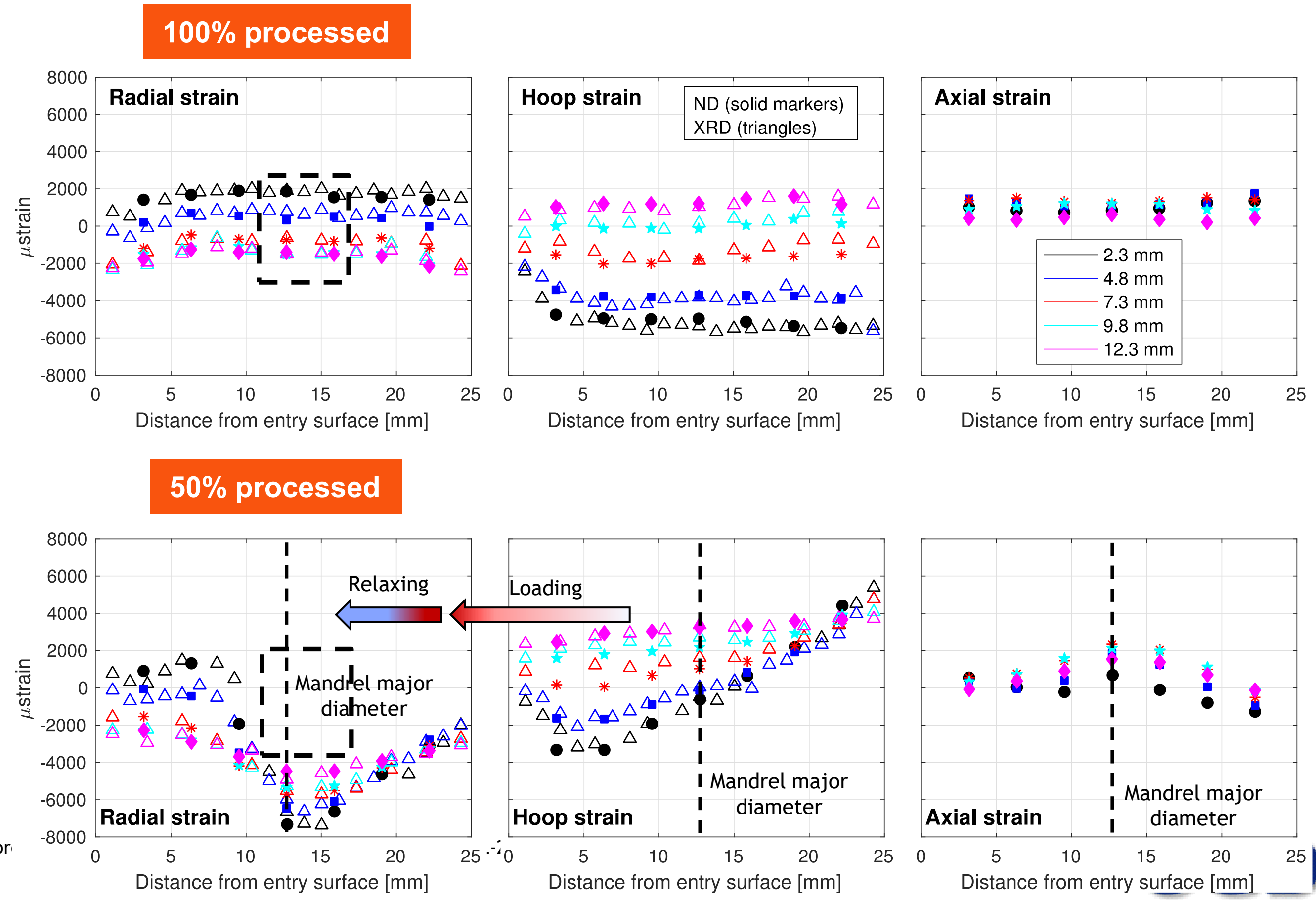
Contour method

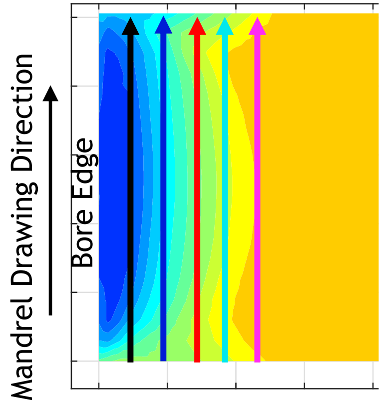


Prime 2001

Elastic Residual Strain Comparison

- Excellent agreement is seen between the XRD (triangles) and the ND (circles) elastic strain measurements
- The 100% Cx sample shows high magnitudes of hoop compressive strain near the hole bore edge in addition to slight tensile radial strain (typical to published results). The axial strain is near zero and slightly tensile
- The 50% Cx sample also shows exceptional agreement between XRD and ND measurements especially near the sharp gradients present in the radial strain field
  - This agreement if vital for furth qualifying the process model (please stick around for the following presentation from Professor Michael R. Hill for discussion of the modeling results)

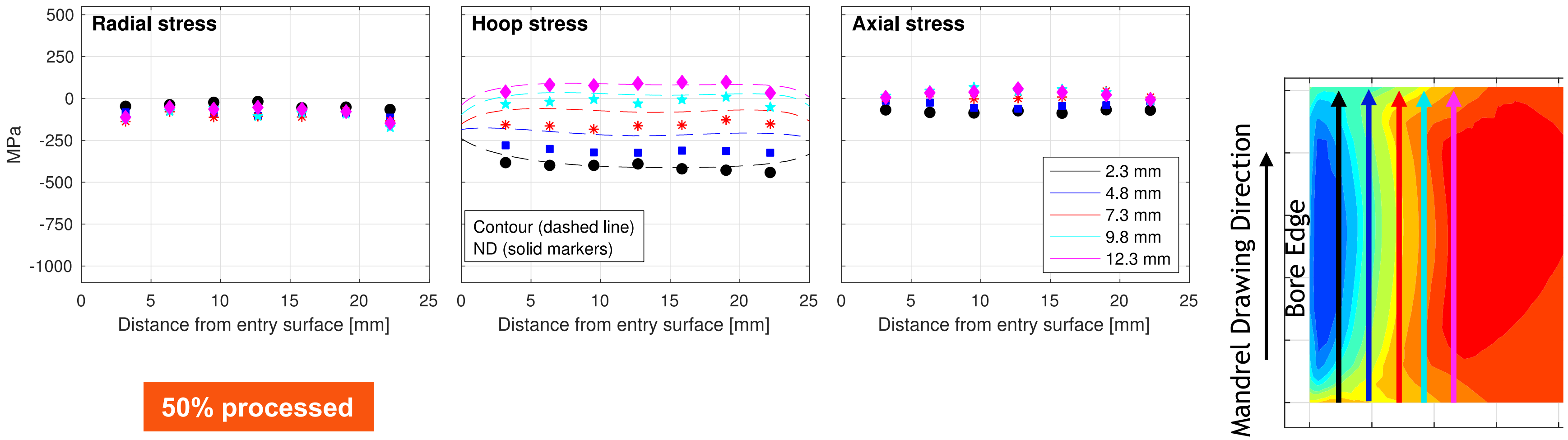




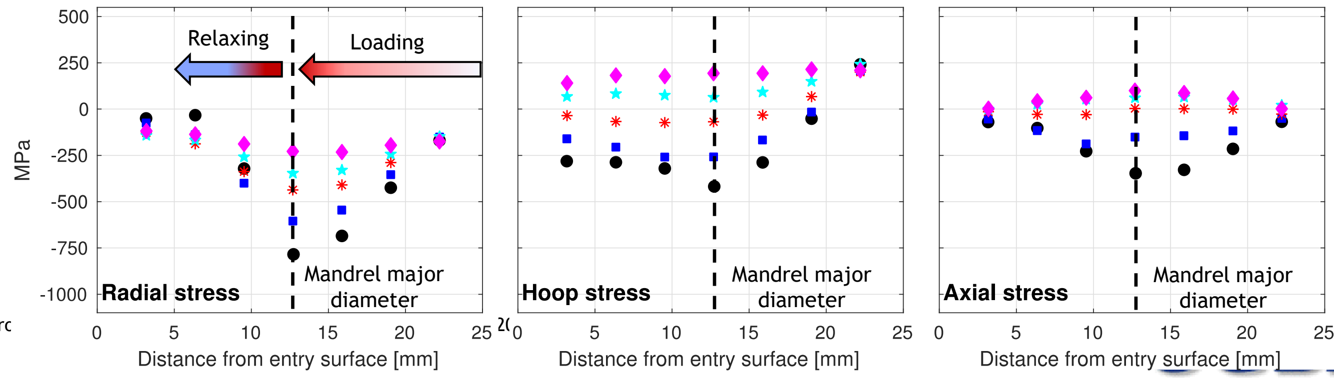
Residual Stress Comparison

- Good agreement is seen between the ND and and CM measurements of the hoop residual stress component in the 100% Cx sample
- The 50% Cx sample displays a nearly hydrostatic stress state near the hole bore edge at the position of the mandrel major diameter (12.7 mm)

100% processed

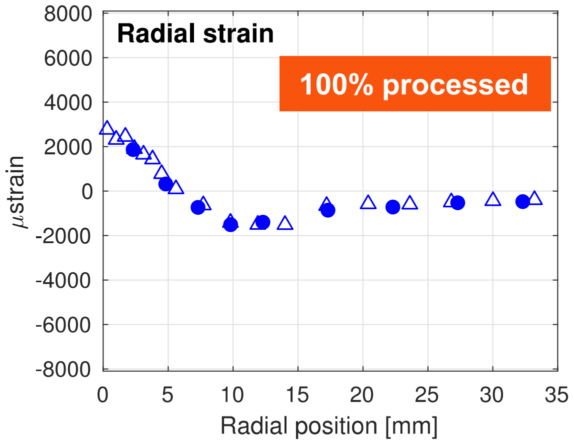


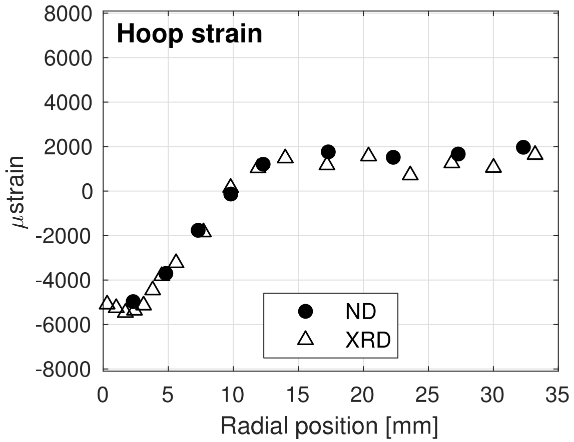
50% processed

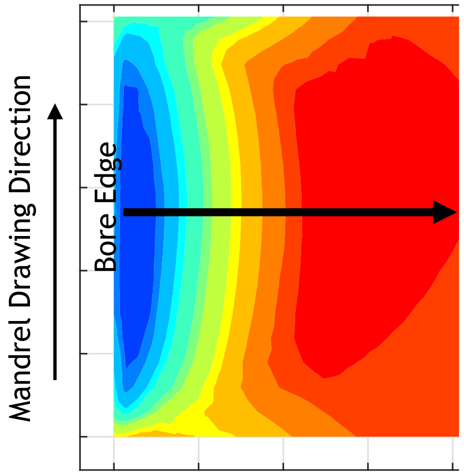


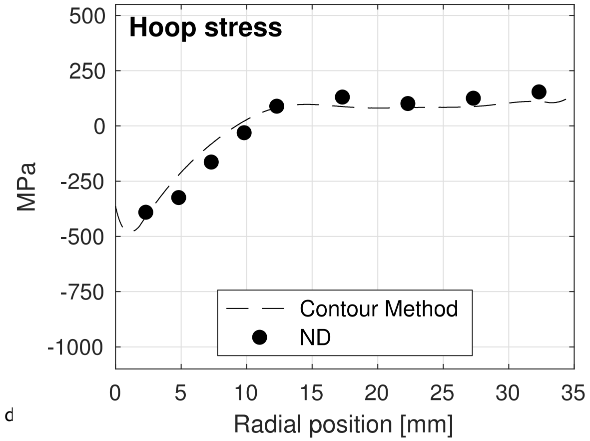
Comparing measurement techniques

- The elastic strain measurements compare well within measurement uncertainty near the bore and bulk regions
- Residual stress measurements techniques are just outside each uncertainties, with better correlation in the bulk region
  - We think this is due to the finite ND measurement volume over high stress gradients



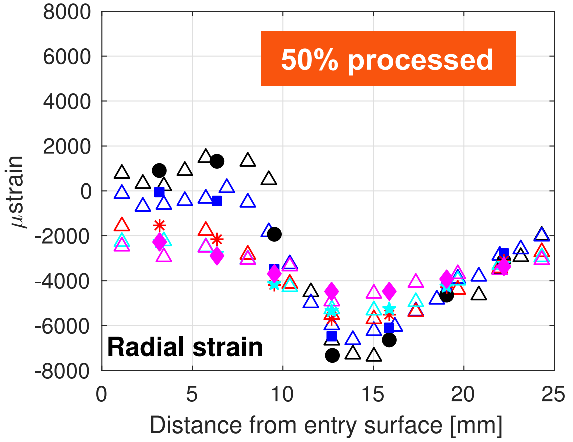


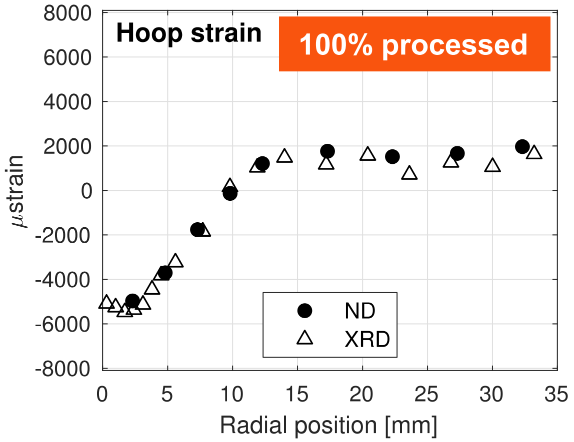


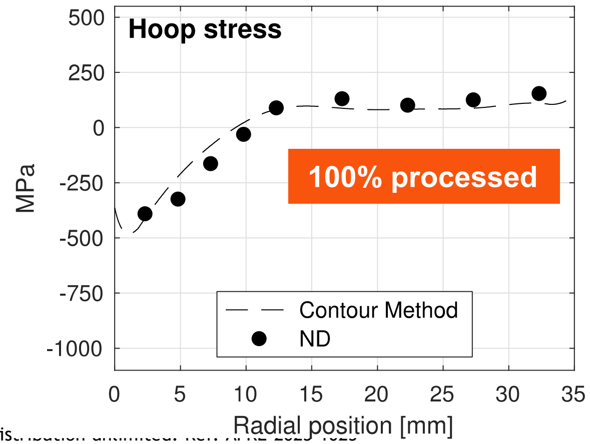


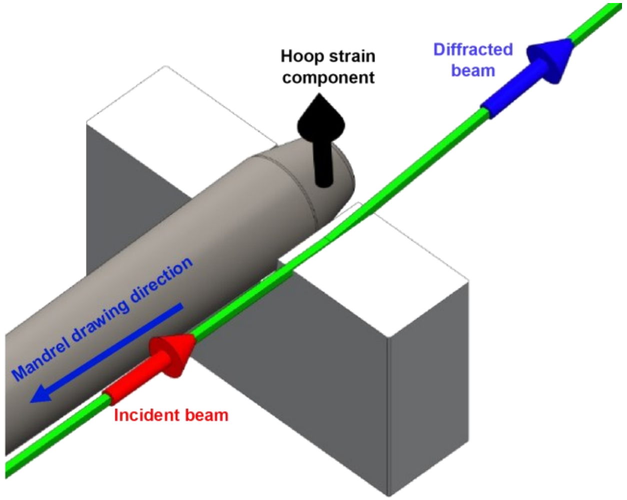
Concluding remarks

- Comparable results are seen between the diffraction and mechanical based measurement techniques in the 50% and 100% Cx processed samples giving confidence in the residual elastic strain and stress fields for future model validation
- Diffraction techniques offer indispensable perception into the Cx process through the 50% processed sample
  - Neutron diffraction allows for simple stress determination
  - XRD's reduced measurement gage volume offers higher spatial resolution near the hole bore









UCDAVIS

10:35 AM
Bulk Residual Stress and Strain Measurements Near Geometrically Large Holes for Improving Cold Expansion Process Models:

Michael Hill[1]; Nicholas Bachus[1]; Donald Brown[2]; Chris Budrow[3]; Michael Burba[4]; Bjørn Clausen[2]; Adrian DeWald[5]; J.Y. Peter Ko[6]; Kelly Nygren[6]; Mark Obstalecki[4]; Robert Pilarczyk[5]; Renan Ribeiro[5]; Paul Shade[4]; Matthew Shultz[7]; [1]University of California Davis; [2]Los Alamos National Laboratory; [3]Budrow Consulting LLC; [4]Air Force Research Laboratory; [5]Hill Engineering, LLC; [6]Cornell High Energy Synchrotron Source; [7]Fatigue Technology, Inc

Thank you for your attention

Any questions?

ERSI

Working Group on
Engineered Residual
Stress Implementation

Bulk Residual Stress and Strain Measurements Near Geometrically Large Holes for Improving Cold Expansion Process Models

Michael R. Hill[1], Nicholas A. Bachus[1,2], Donald W. Brown[2], Chris Budrow[3], Michael E. Burba[4], Bjørn Clausen[2], Adrian T. DeWald[5], J.Y. Peter Ko[6], Kelly E. Nygren[6], Mark Obstalecki[4], Robert T. Pilarczyk[5], Renan L. Ribeiro[5], Paul A. Shade[4], Matthew Shultz[7]

[1] Mechanical and Aerospace Engineering, University of California, Davis
[2] Los Alamos National Laboratory
[3]Budrow Consulting LLC
[4] Air Force Research Laboratory
[5] Hill Engineering LLC
[6]Cornell High Energy Synchrotron Source
[7] Fatigue Technology Inc

(14 authors from 7 organizations)

Distribution Statement A Approved for public release: distribution is unlimited. AFRL-2023-1095 LA-UR-23-22540

Team

Organized under ERSI Residual Stress Measurement Subgroup

Contributors:

- Hill Engineering (HE)
  - Renan Ribeiro, Bob Pilaczyk, Adrian DeWald
- US Air Force Research Lab (AFRL)
  - Eric Burba, Mark Obstalecki, Paul Shade
- Fatigue Technologies (FTI)
  - Matt Shultz
- Los Alamos National Lab (LANL)
  - Don Brown, Bjørn Clausen
- Cornell High Energy Synchrotron Source (CHESS)
  - Chris Budrow, Kelly Nygren, Peter Ko
- University of California, Davis (UC Davis)
  - Nick Bachus, Mike Hill

Background and Objectives

Background:

- Existing prior data for large (D = 25.4 mm) Cx holes in 7075-T651
  - Residual stress measurements (contour)
  - Residual stress outputs from nonlinear process model
- Disagreement between measurement results and model outputs

Objectives:

- Fabricate coupons for measurements in D = 25.4 mm Cx holes
  - Samples cut from 7050-T7451 50.8 mm (2 inch) thick plate (AFRL)
  - 100% processed and 50% processed (FTI)
- Develop process model outputs for coupon conditions (Hill Engineering)
- Assess bulk RS in coupons
  - Neutron Diffraction (ND) at SMARTS (LANL, UCD)
  - Synchrotron X-ray Diffraction (EDXRD) (CHESS, AFRL, UCD)
  - Contour (Hill Engineering)
- Compare model outputs to measurement data (UCD and all)

Expected outcomes:

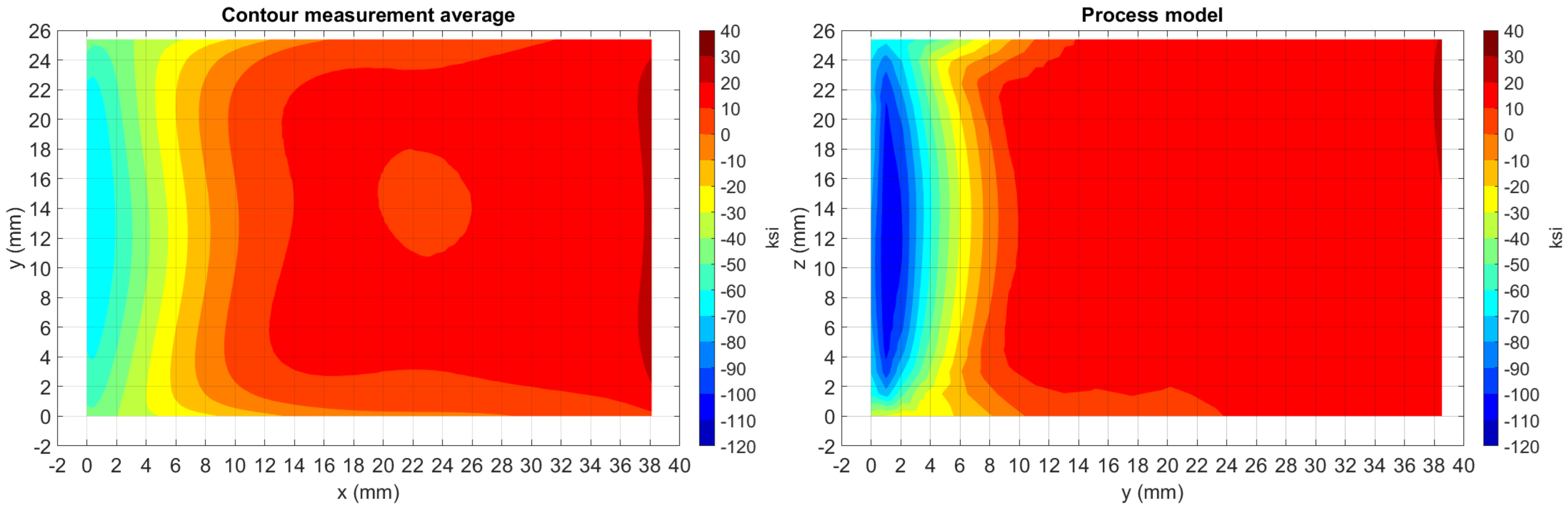
- Use data for process model improvements
- Share data with community (Conference presentation, Journal publication)

Prior work: Measurement and model comparisons

Contour maps of the hoop residual stress below

- Results shifted to start at the hole edge
- Dimensions in mm, stress in ksi (same color scale)
- Significantly higher magnitude of residual stress from model compared to measurement average

7075-T651



Samples for experiments

Samples reflect the conditions in the prior charts, but are in a new material and geometry

Material is AA7050-T7451 plate, 50.8 mm (2 inch) thick

- Widely used high-strength aluminum alloy

Sample geometry (mm)

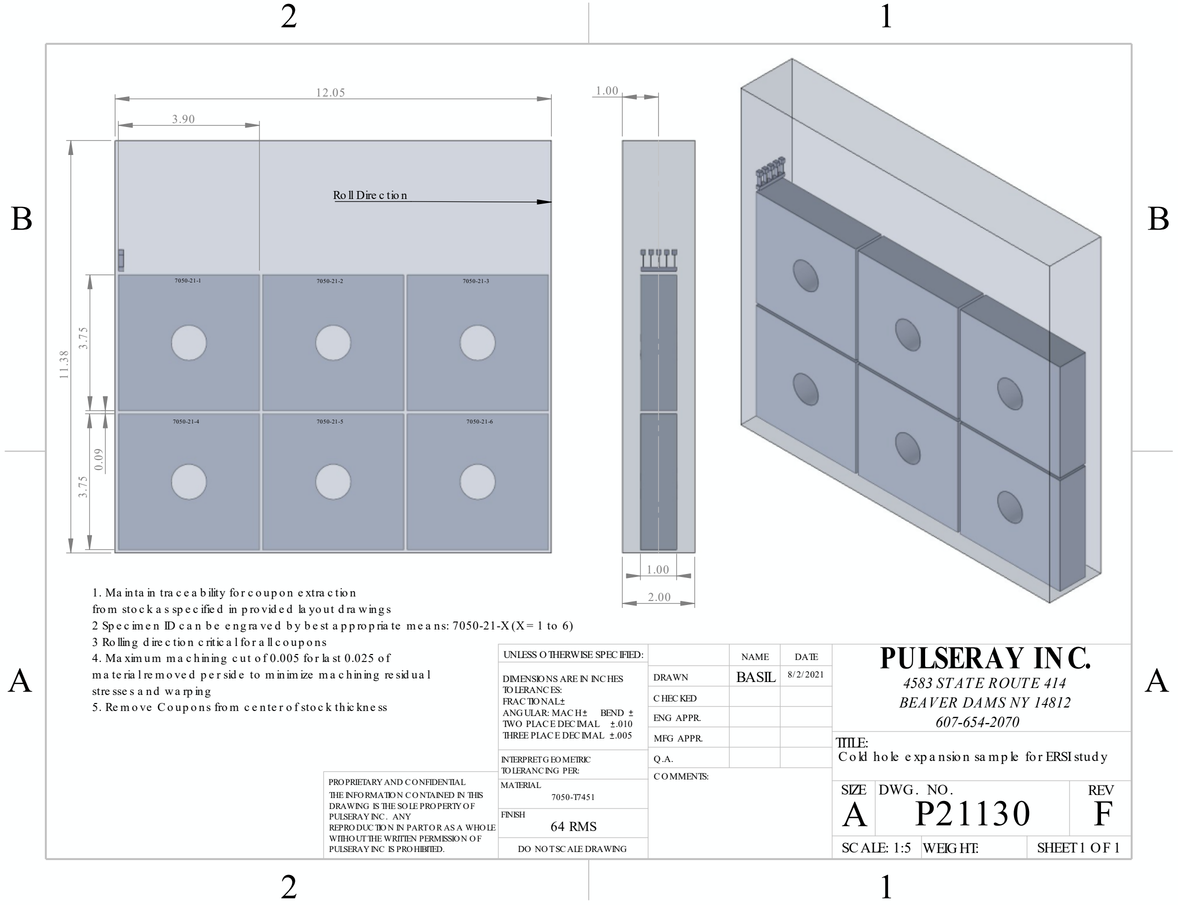
- Plates, L = 99 (along L), W = 95 (along LT), and T = 25.4 (along ST)
  - 25.4 dimension at plate mid-thickness to reduce texture
- Centered hole, D = 25.4

Fabricated 6 samples (AFRL)

- 7050-21-1 to 7050-21-6

Processing (FTI)

- Cx to 3.43 to 3.45% (see data)
- 7050-21-1: 100% Cx (ND complete)
- 7050-21-2: 100% Cx
- 7050-21-3: 50% Cx (ND complete)



Processed samples upon arrival at LANL

7050-21-1 – 100% CX (ND, EDXRD, Contour)

7050-21-2 – 100% CX (Spare)

7050-21-3 – 50% CX (ND, EDXRD)

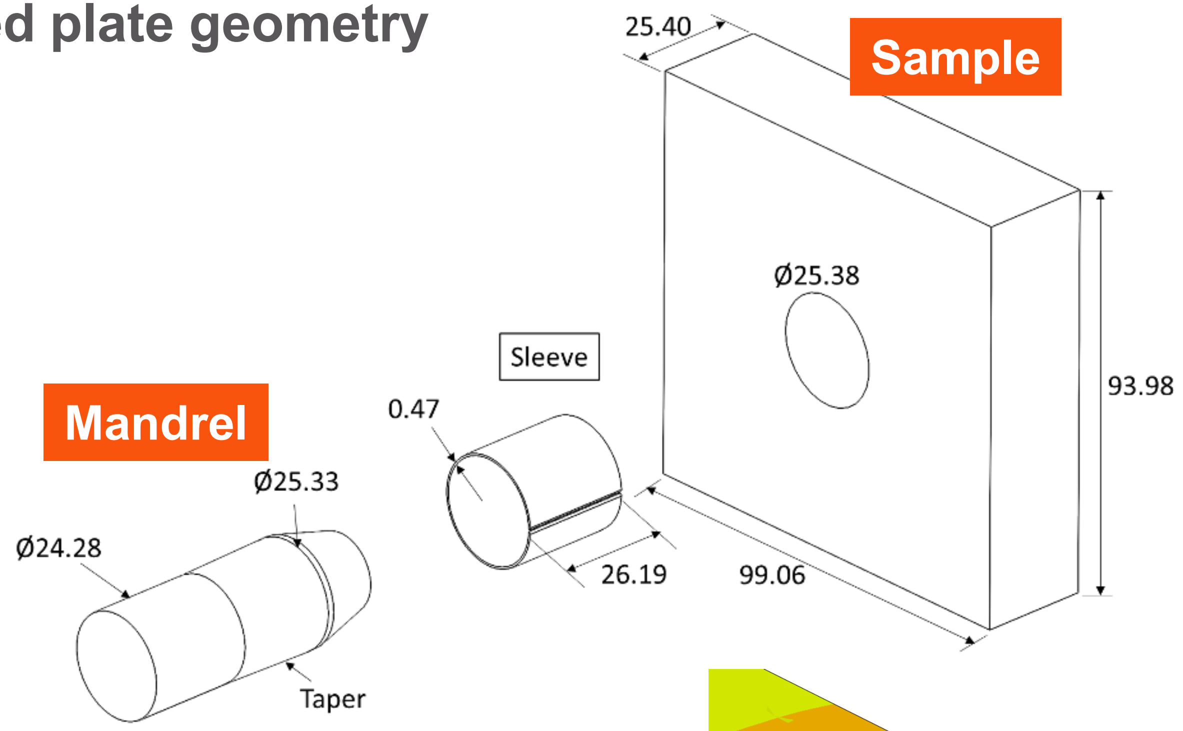
Numerical Simulation of Cx

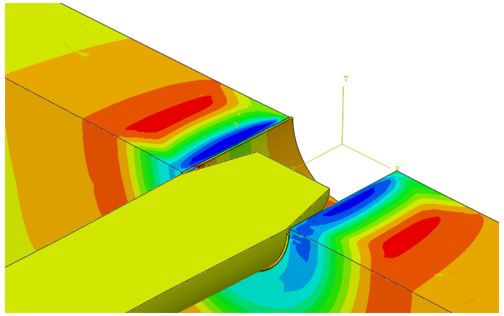
Samples: well-known material, tightly controlled plate geometry

Used finite element method

- Three bodies: sample, sleeve, mandrel
- Non-linear contact with friction
- Elastic plastic model for the sample material
  - Typical isotropic metal plasticity model
    - J_2 yield criterion and associative flow rule
    - Isochoric plasticity
    - Isotropic hardening
- Small time steps to follow the development of deformation, strain, and stress fields with mandrel motion

Note: prior work shows that these models tend to over-predict retained residual stress





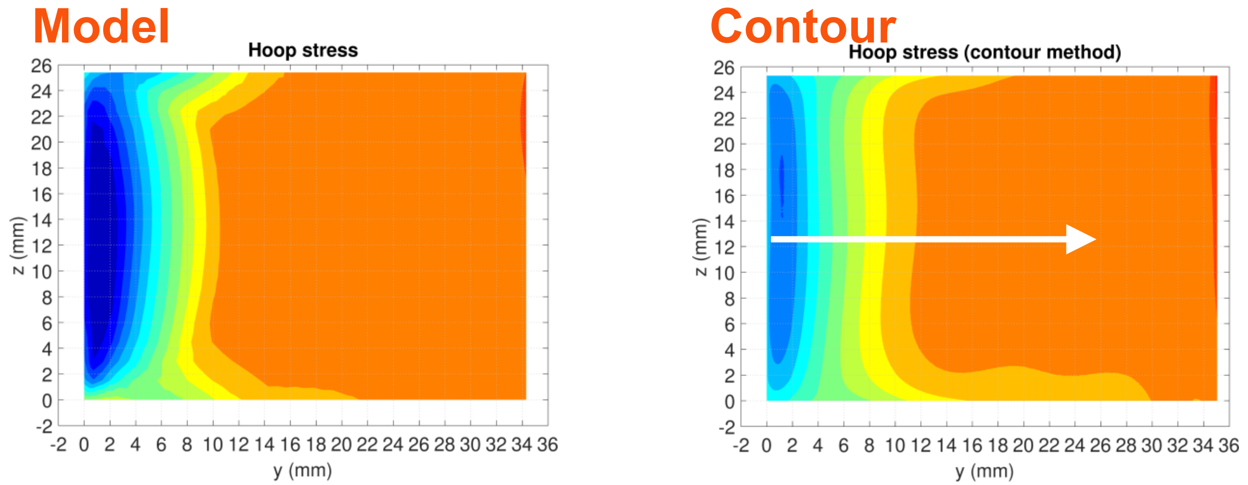
Section view of the process model at a late time step

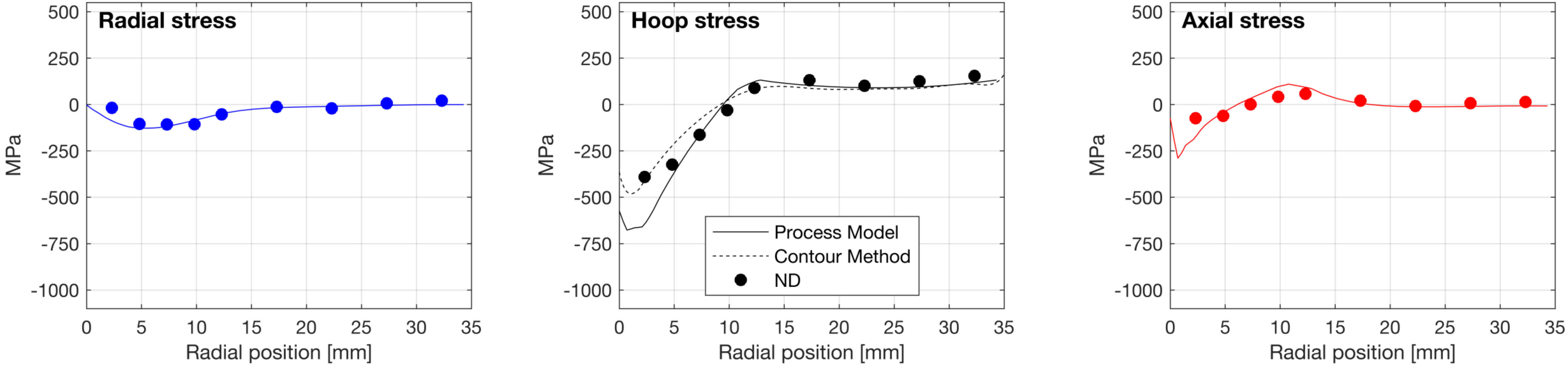
Comparisons at 100% (process complete) (Stress vs. r, z = T/2)

Model vs Contour measurement

Line plots for Model, Contour, ND measurements below

- Radial, hoop, and axial stress components





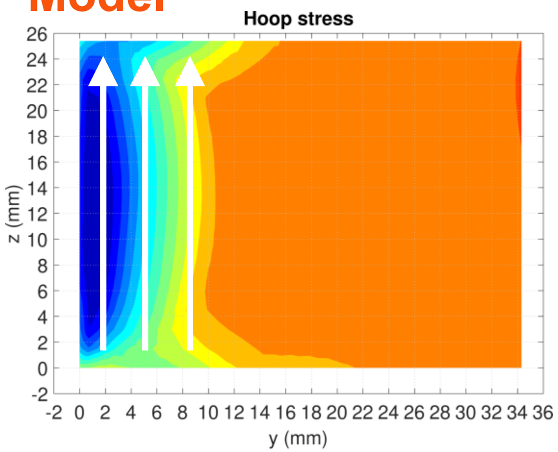
Comparisons at 100% (process complete) (Stress vs z, various r)

Model vs Contour measurement

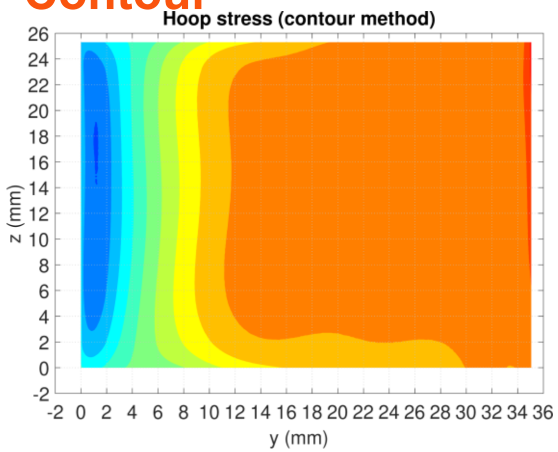
Line plots for compare Model, Contour, ND data

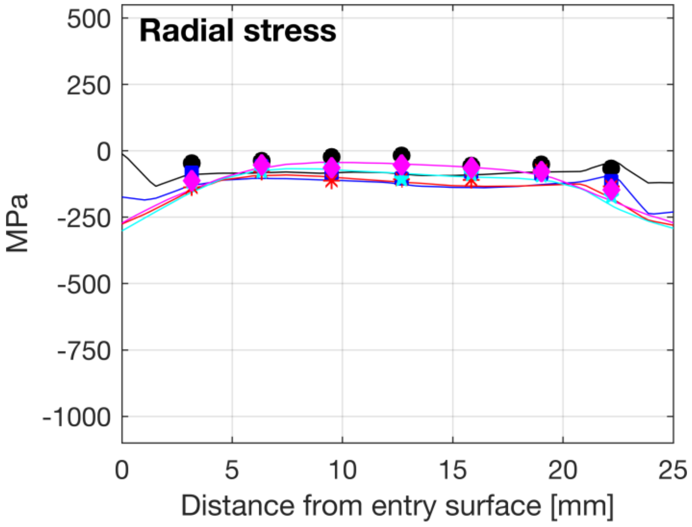
- Radial stress
- Hoop stress
- Axial stress

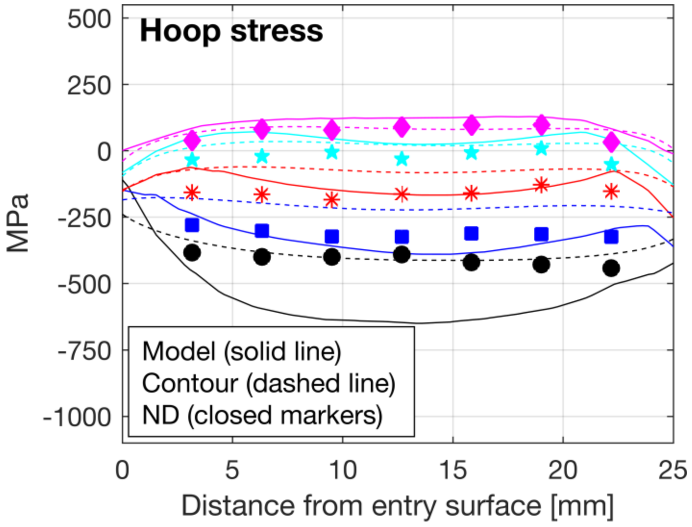
Model

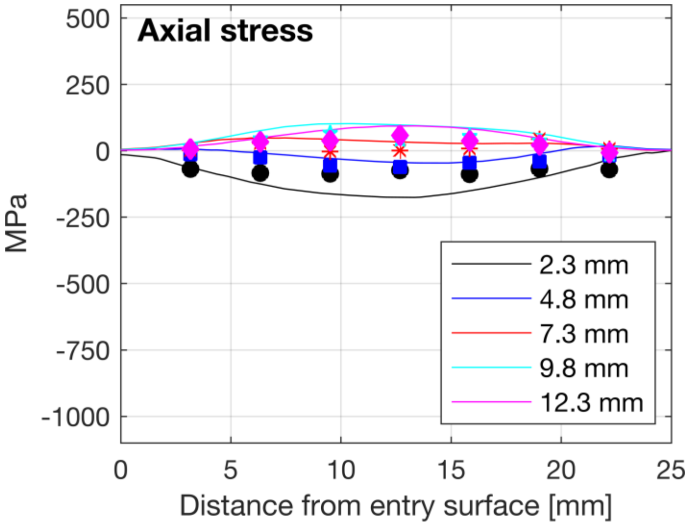


Contour









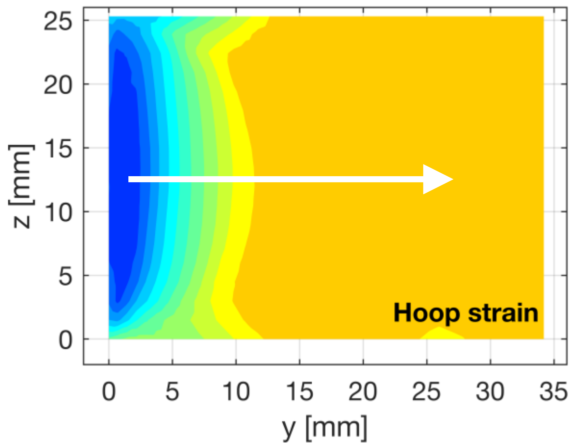
Comparisons at 100% (process complete) (Strain vs. r, z = T/2)

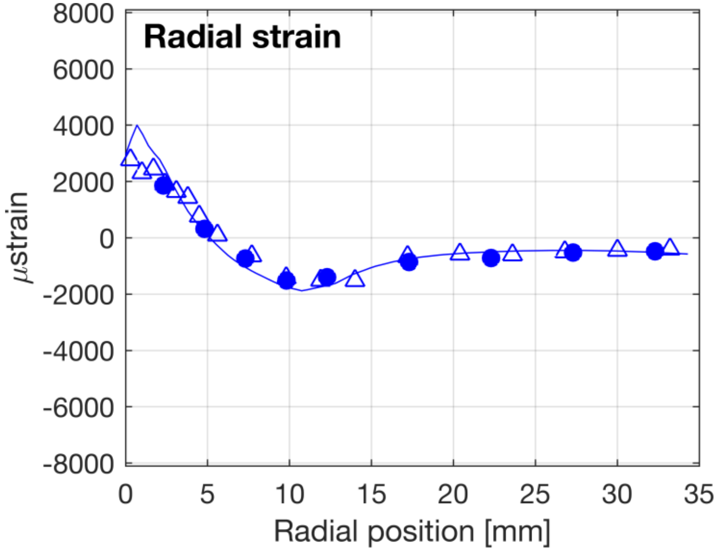
Model shows hoop strain field

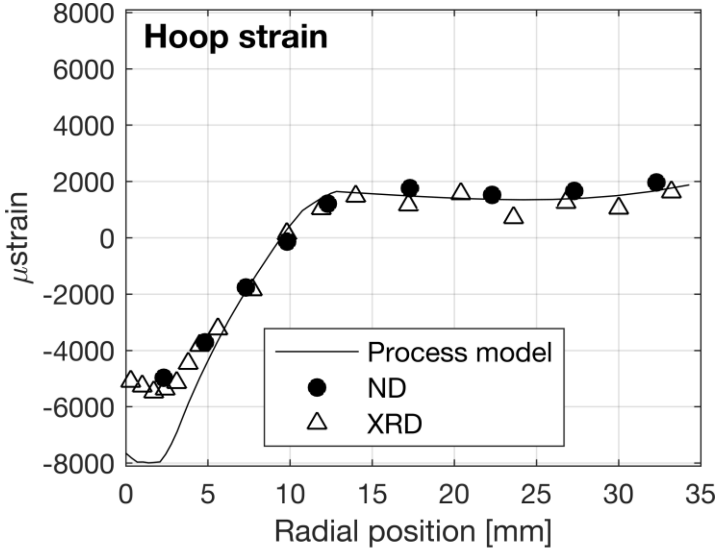
Line plots for Model, ND, and EDXRD measurements below

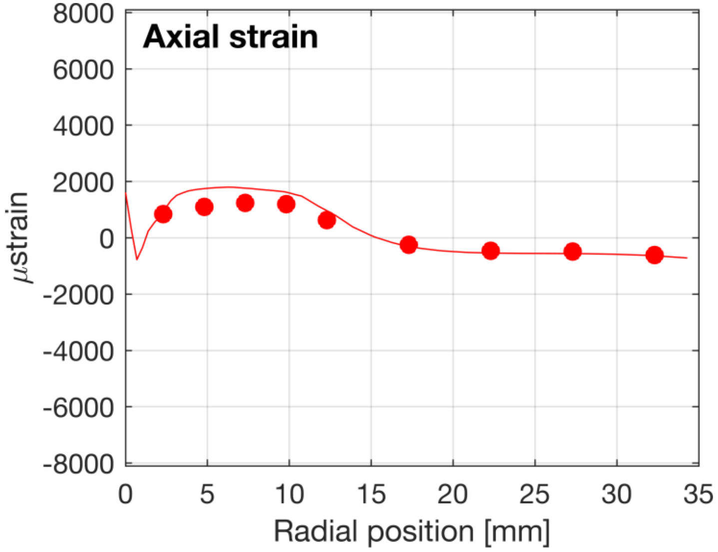
- Radial, hoop, and axial stress components

Model







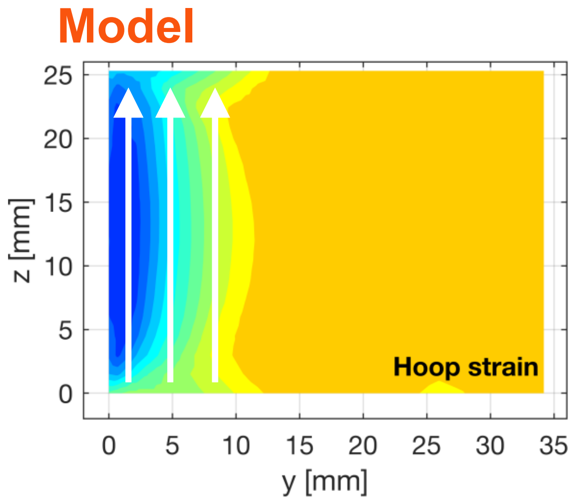


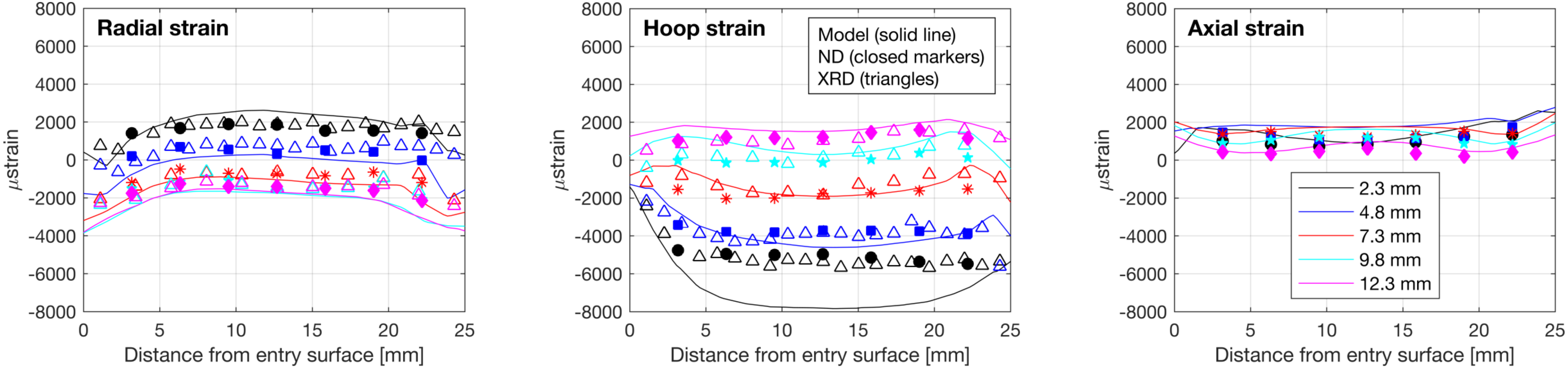
Comparisons at 100% (process complete) (Strain vs z, various r)

Model shows hoop strain field

Line plots for Model, ND, and EDXRD measurements below

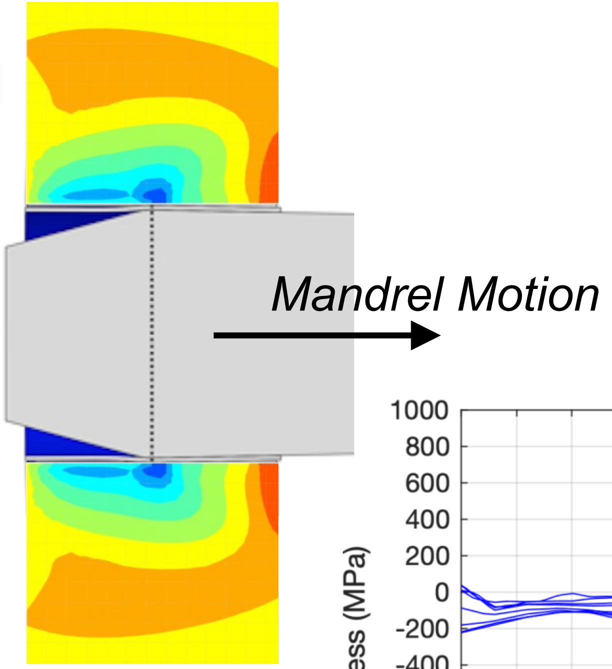
- Radial, hoop, and axial stress components

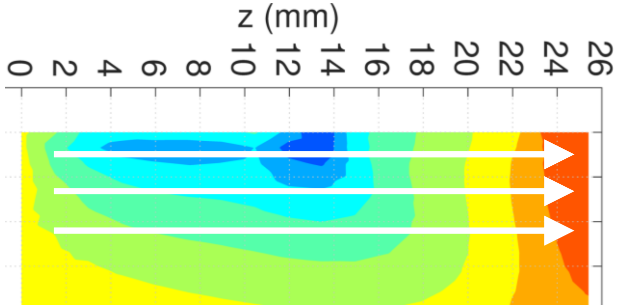


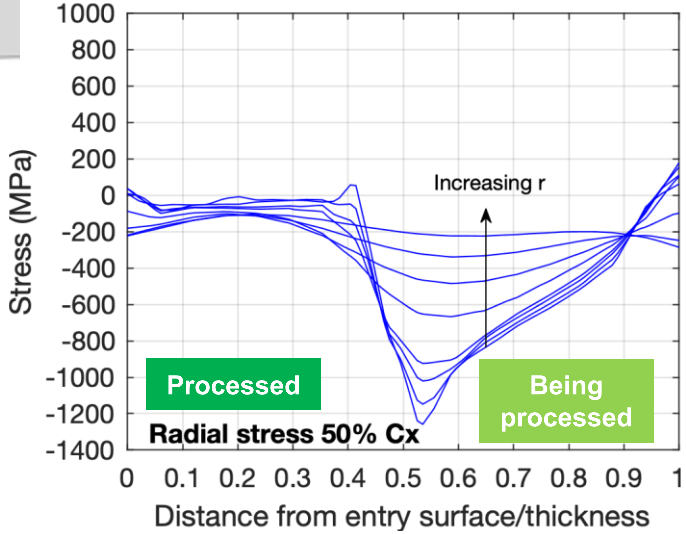


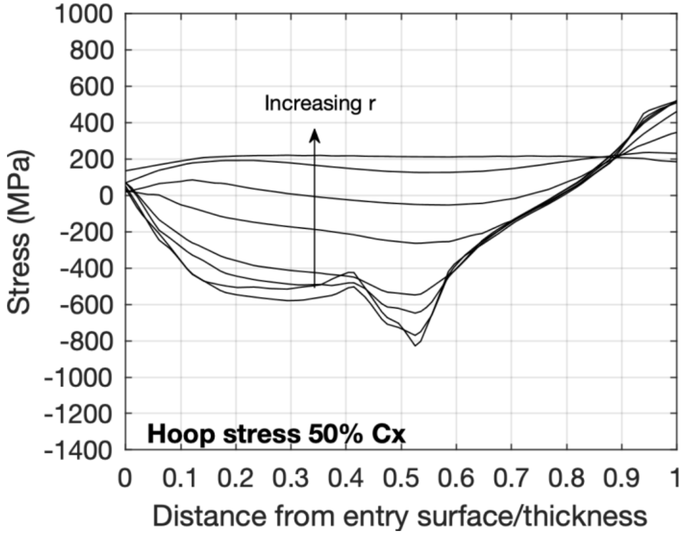
Model output spatial field at 50% processed (fixed time)

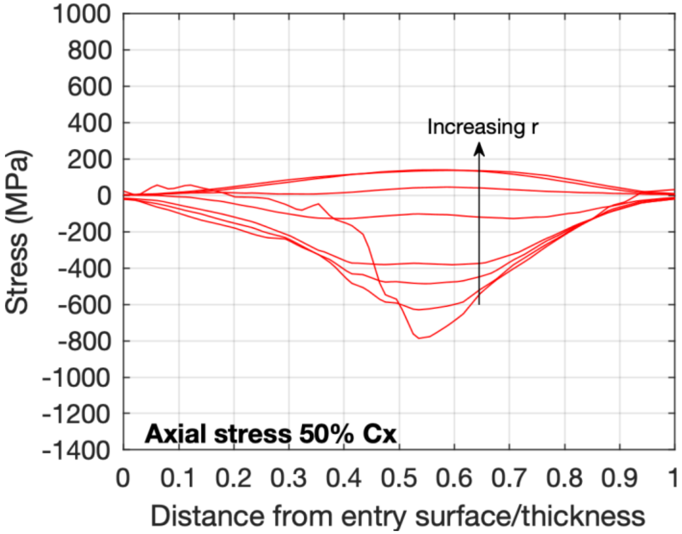
Stress field versus axial position, lines for range of radial positions





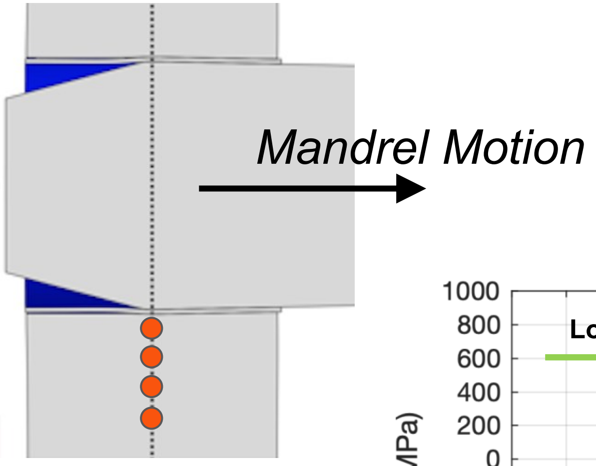


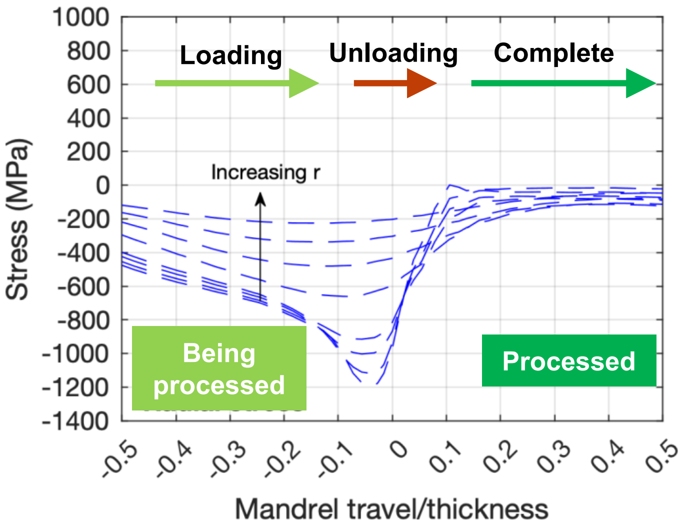


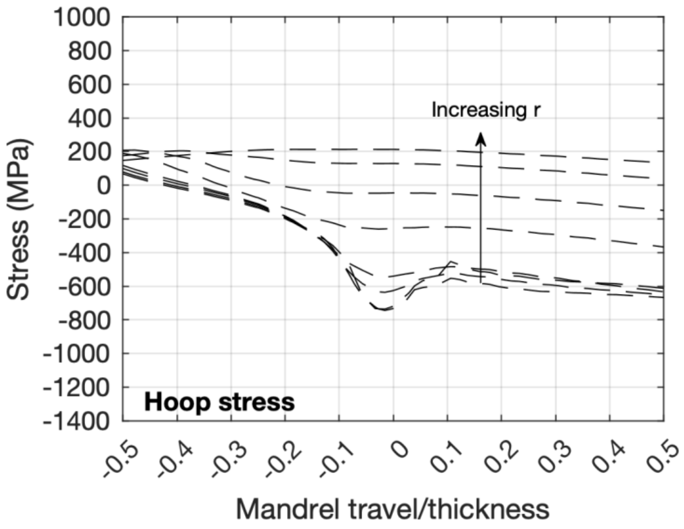


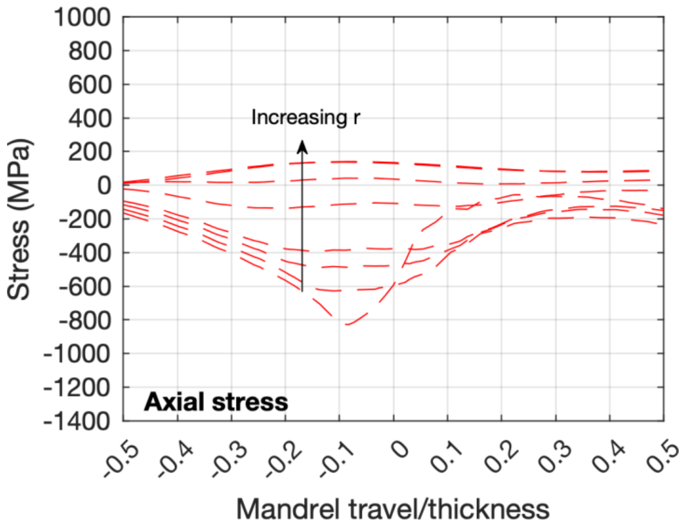
Model output versus time at z = T/2 (fixed locations, various r)

Stress field versus mandrel travel, lines for range of radial positions

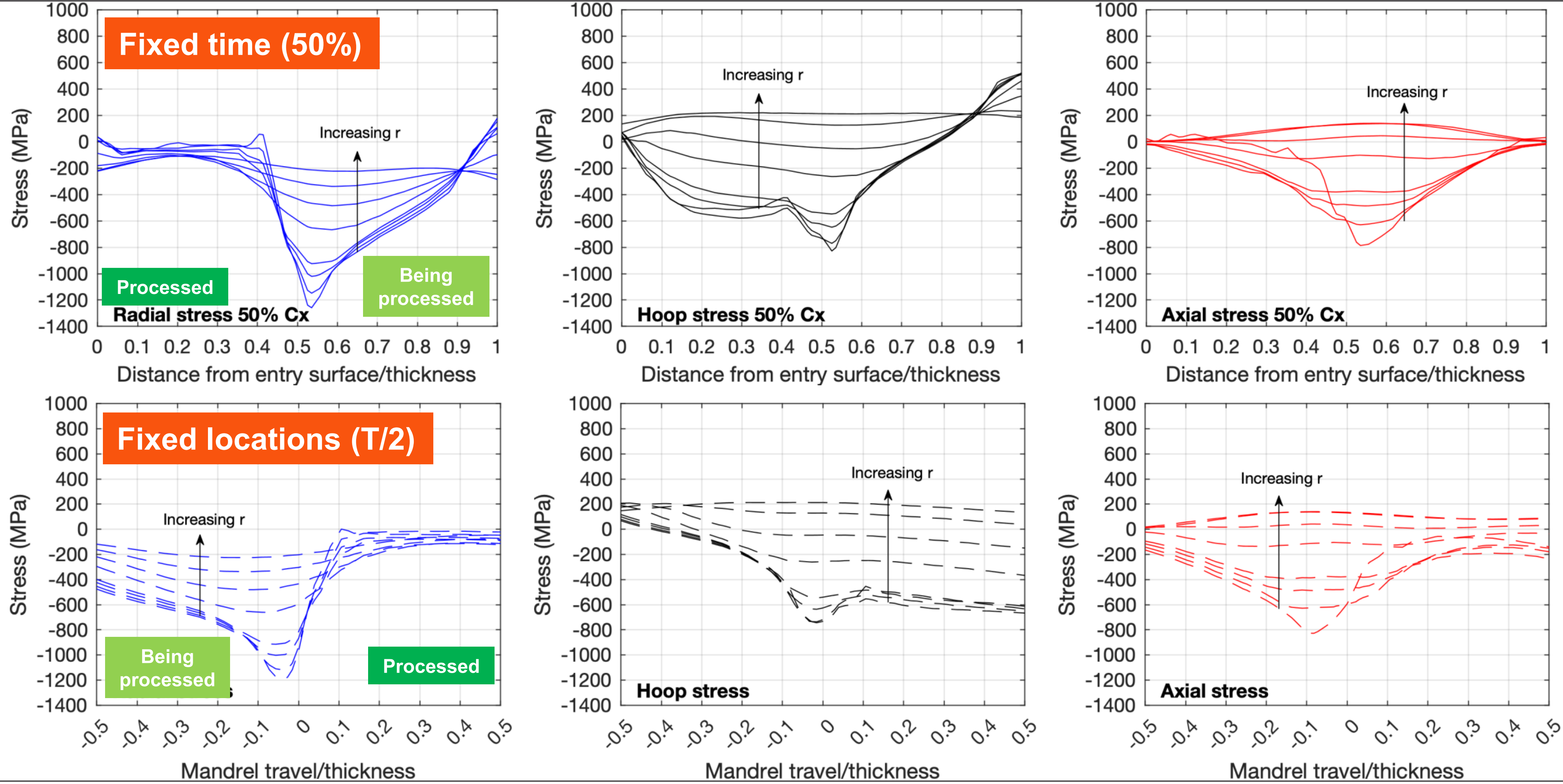








Model outputs at 50% time compared to time variation at T/2



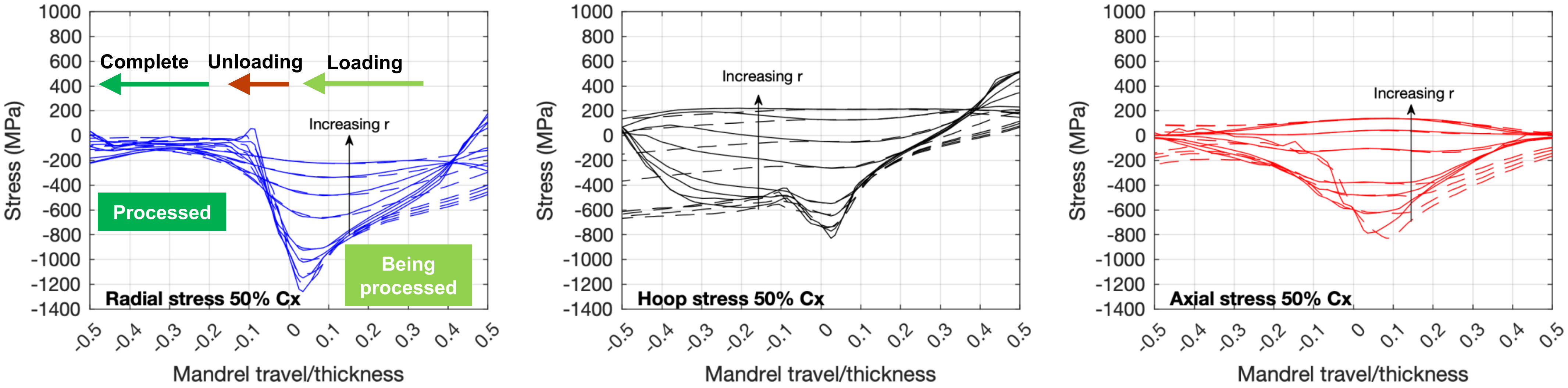
Model output overlay: at 50% time and versus time at T/2

Solid lines are at fixed time: spatial variation at 50% processed

Dashed lines are at fixed locations: temporal variation at z = T/2 (plotted backward)

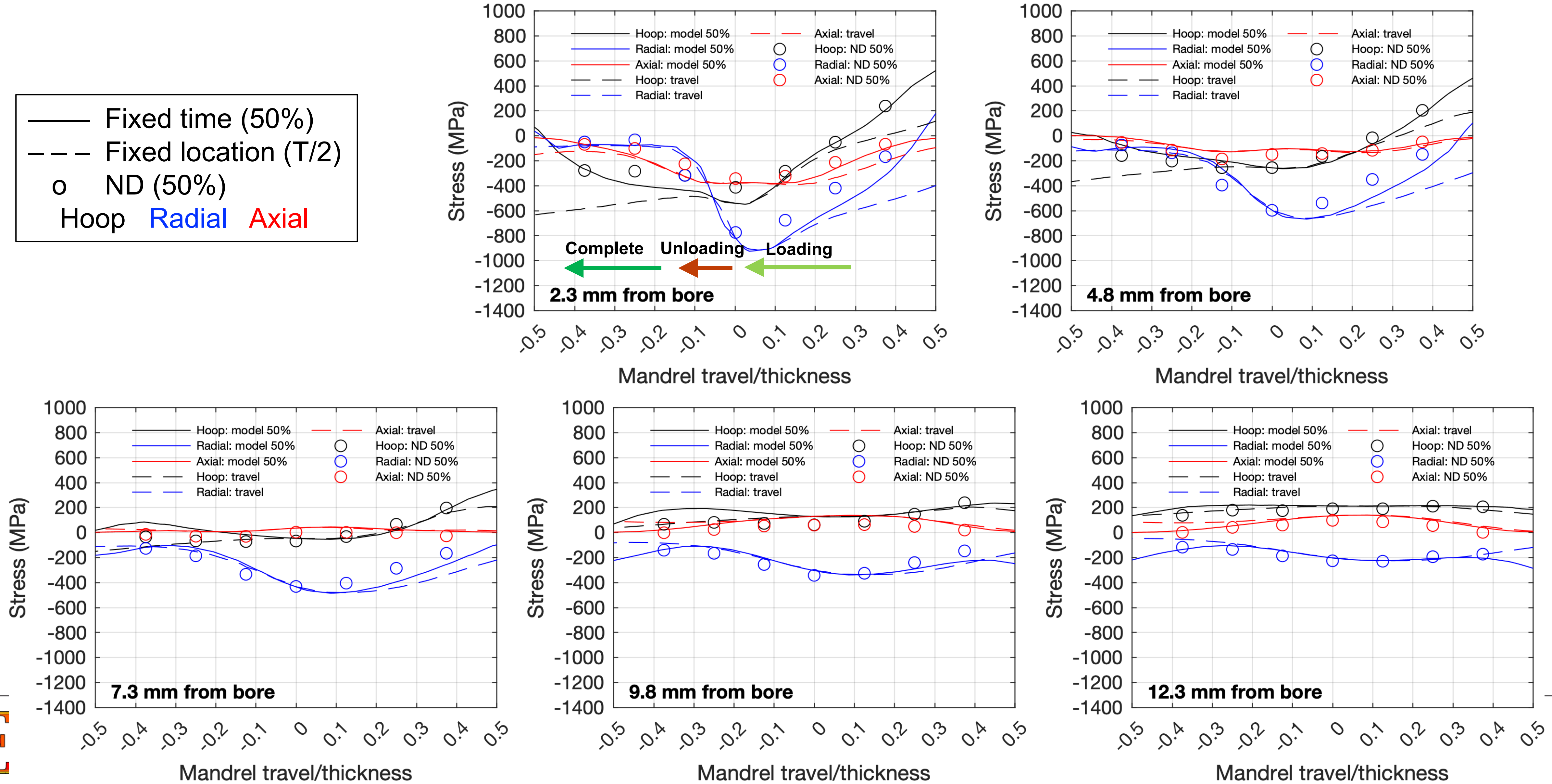
Region near mid-thickness where the two sets of trends are very similar

- Measurement at 50% time almost as good as a time-resolved test (*in situ* process experiment)

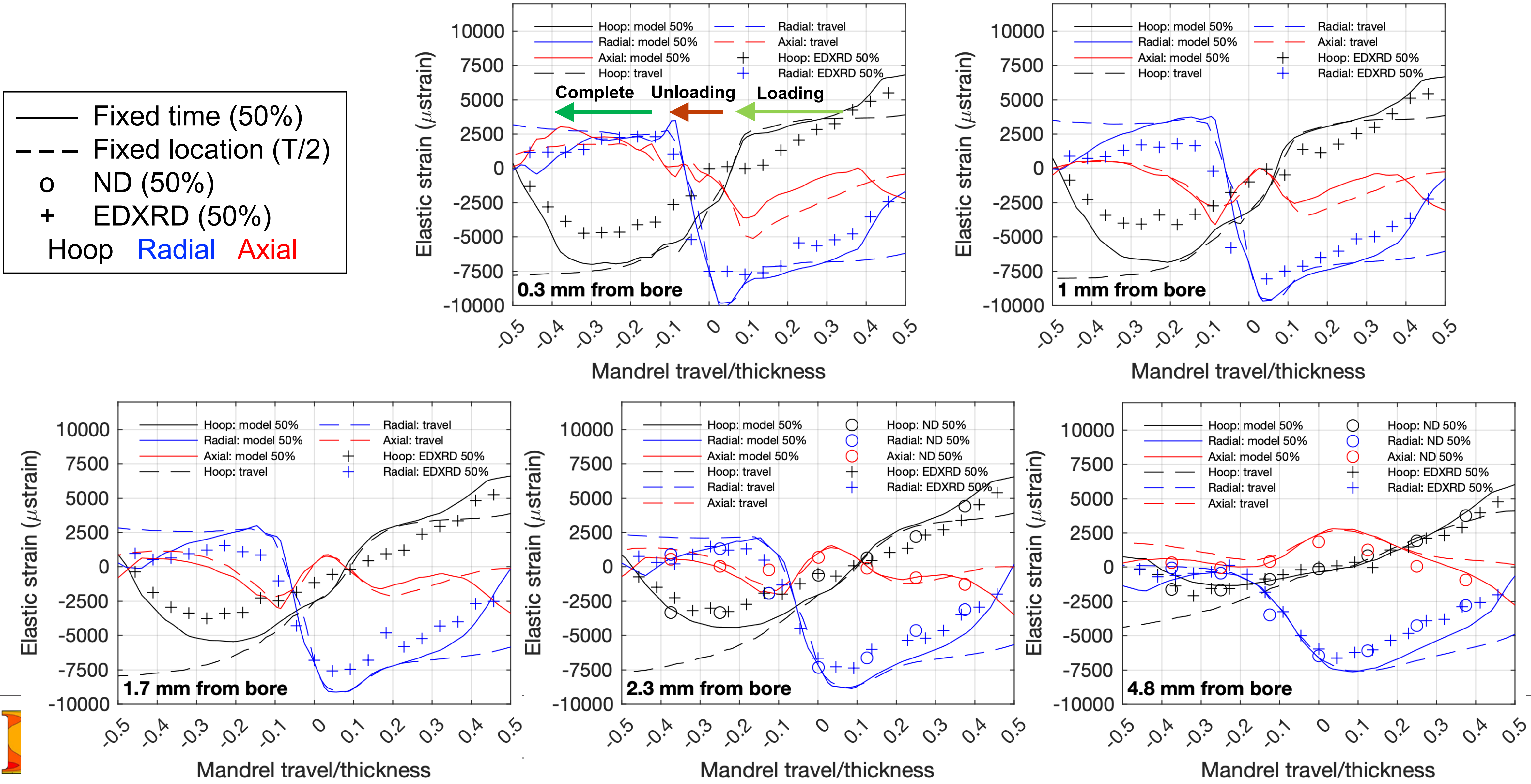


Comparisons of model outputs to 50% measurement data (Stress)

Fixed time (50%)
Fixed location (T/2)
o ND (50%)
Hoop Radial Axial



Comparisons of model outputs to 50% measurement data (Strain)



Summary

A set of samples were made to support model validation for cold expanded (Cx) holes

- Two configurations were assessed, a fully processed sample (100%), and a half-processed sample (50%)

Measurements of residual stress were performed using three diverse techniques

- Neutron diffraction (ND), Energy dispersive x-ray diffraction (EDXRD), and Contour method (CM)

Measurement data are consistent across all techniques

- Residual strains from ND and EDXRD are in agreement
  - For both 100% and 50% processed samples
- Residual stresses from ND and CM are in agreement
  - For 100% processed samples

Each technique had particular advantages

- ND provided three orthogonal strain and stress components (radial, hoop, and axial)
- EDXRD enabled high spatial resolution and data near the free surface (0.3 mm from edge)
- CM provided a 2D map of the hoop residual stress across the entire plane of measurement

Model outputs exhibit discrepancy compared to the measurement data

- Close to the hole bore, hoop stress and strain from the model are 40% higher than from measurement

Data for the 50% sample showed that discrepancies appear during the loading phase of Cx and then persist during unloading and at process end

- Material behavior appears to differ from the assumed plasticity model (isochoric, J_2 flow theory) during Cx loading

The present data can support development of an improved constitutive model applicable to Cx

Texture and Anisotropy Sub-Team

Team:

Joshua Ward (AFRL)
Mark Obstalecki (AFRL)
Eric Burba (AFRL)
Mike Hill (Hill Engineering)
Mike Steinzig (LANL)
Zachary Sanchez (LANL)

James Pineault (Proto)
Kyle Johnson (Sandia)
Philip Reu (Sandia)
D. Michael Autenrieth (Sandia)
Dan Moser (Sandia)

Mission Statement & Background

Quantify and incorporate the effects of crystallographic texture and elastic anisotropy into residual stress measurement workflows

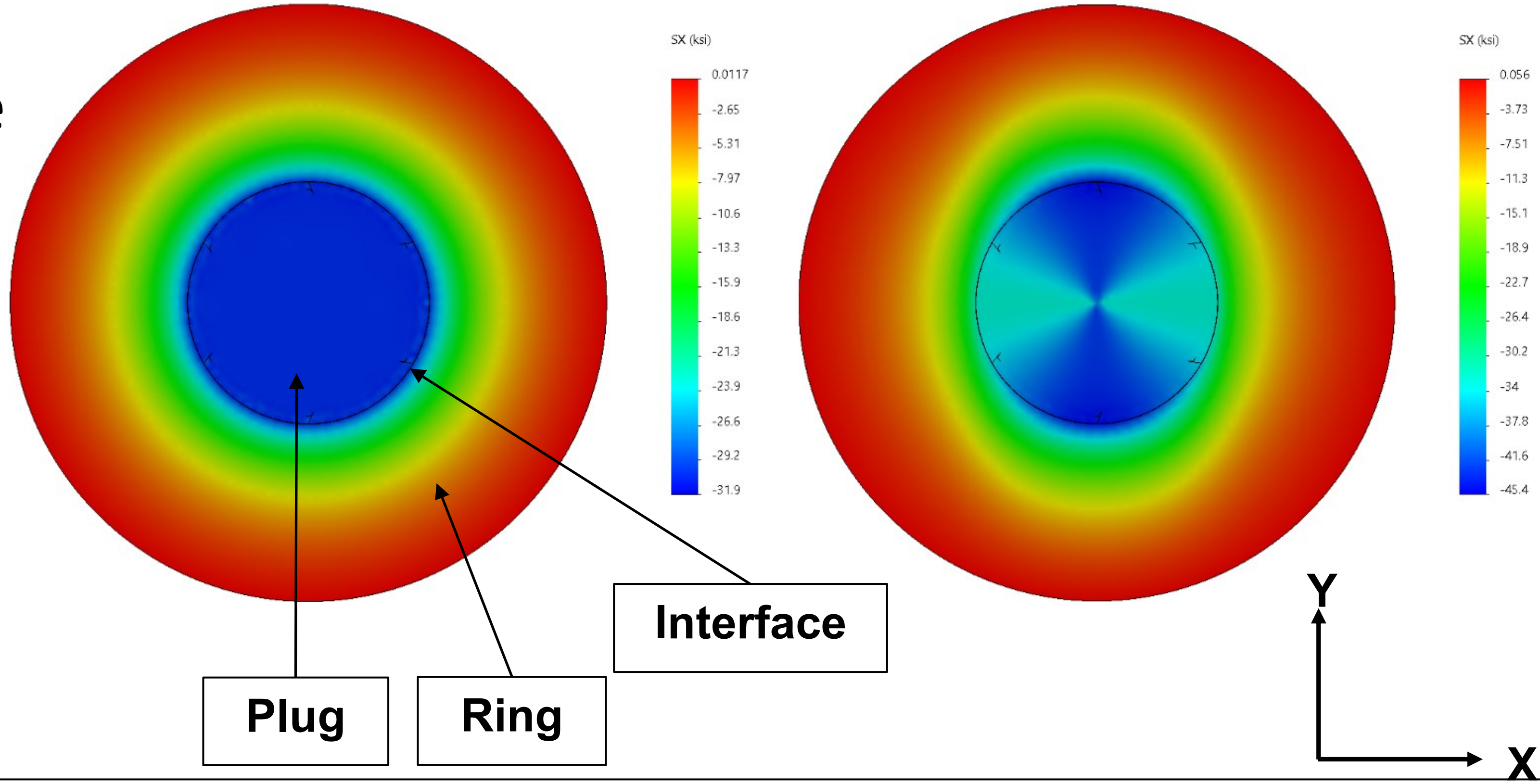
- Focused on RS hole drilling
- Ring and Plug sample

$$\begin{bmatrix}\sigma_{11}\\\sigma_{22}\\\sigma_{33}\\\sigma_{23}\\\sigma_{13}\\\sigma_{12}\end{bmatrix}=\begin{pmatrix}C_{11}&C_{12}&C_{12}&0&0&0\\C_{12}&C_{11}&C_{12}&0&0&0\\C_{12}&C_{12}&C_{11}&0&0&0\\0&0&0&C_{44}&0&0\\0&0&0&0&C_{44}&0\\0&0&0&0&0&C_{44}\end{pmatrix}\begin{bmatrix}\varepsilon_{11}\\\varepsilon_{22}\\\varepsilon_{33}\\2\varepsilon_{23}\\2\varepsilon_{13}\\2\varepsilon_{12}\end{bmatrix}$$

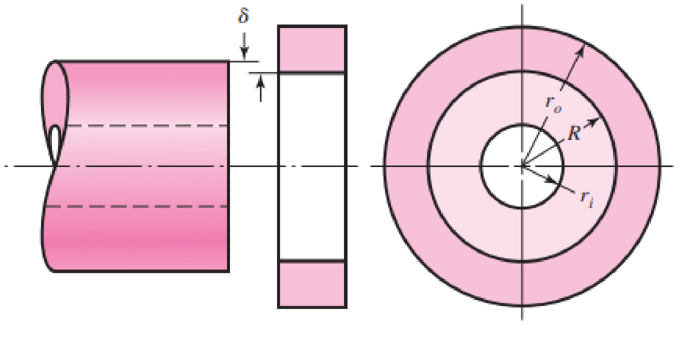
where $C_{44} = 0.5(C_{11}-C_{12})$

$$\begin{bmatrix}\sigma_{11}\\\sigma_{22}\\\sigma_{33}\\\sigma_{23}\\\sigma_{13}\\\sigma_{12}\end{bmatrix}=\begin{pmatrix}C_{11}&C_{12}&C_{13}&C_{14}&C_{15}&C_{16}\\C_{21}&C_{22}&C_{23}&C_{24}&C_{25}&C_{26}\\C_{31}&C_{32}&C_{33}&C_{34}&C_{35}&C_{36}\\C_{41}&C_{42}&C_{43}&C_{44}&C_{45}&C_{46}\\C_{51}&C_{52}&C_{53}&C_{54}&C_{55}&C_{56}\\C_{61}&C_{62}&C_{63}&C_{64}&C_{65}&C_{66}\end{pmatrix}\begin{bmatrix}\varepsilon_{11}\\\varepsilon_{22}\\\varepsilon_{33}\\2\varepsilon_{23}\\2\varepsilon_{13}\\2\varepsilon_{12}\end{bmatrix}$$

$E_x = E_y = 28{,}000$ ksi | **$E_x = 28{,}000$ ksi $E_y = 36{,}400$ ksi**



Ring and Plug Sample Definition



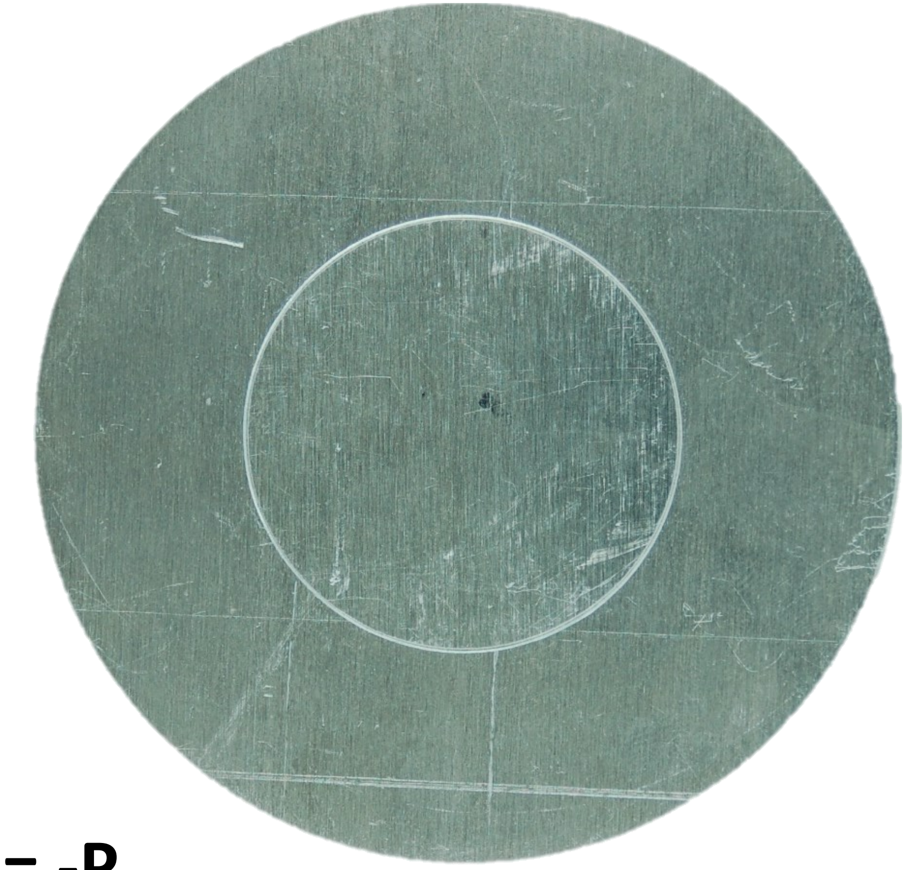
$$\sigma_h = \frac{P_i r_i^2 - P_o r_o^2 - r_i^2 r_o^2 \frac{P_o - P_i}{R^2}}{r_o^2 - r_i^2}$$

$$\sigma_r = \frac{P_i r_i^2 - P_o r_o^2 + r_i^2 r_o^2 \frac{P_o - P_i}{R^2}}{r_o^2 - r_i^2}$$

$$P = \frac{\delta}{R\left[\frac{1}{E_o}\left(\frac{R_o^2 + R^2}{R_o^2 - R^2} + v_o\right) + \frac{1}{E_i}\left(\frac{R_i^2 + R^2}{R_i^2 - R^2} + v_i\right)\right]}$$

Inside the plug, assuming $R_i = P_i = 0$

$\sigma_h = \sigma_r = -P$



- $E_o = E_i =$ 10,600 ksi
- $V_o = V_i$ = 0.28
- R = 1”
- R_o = 2”
- δ = 0.00355”

$\sigma_{Analytical}$ = -13.2 ksi

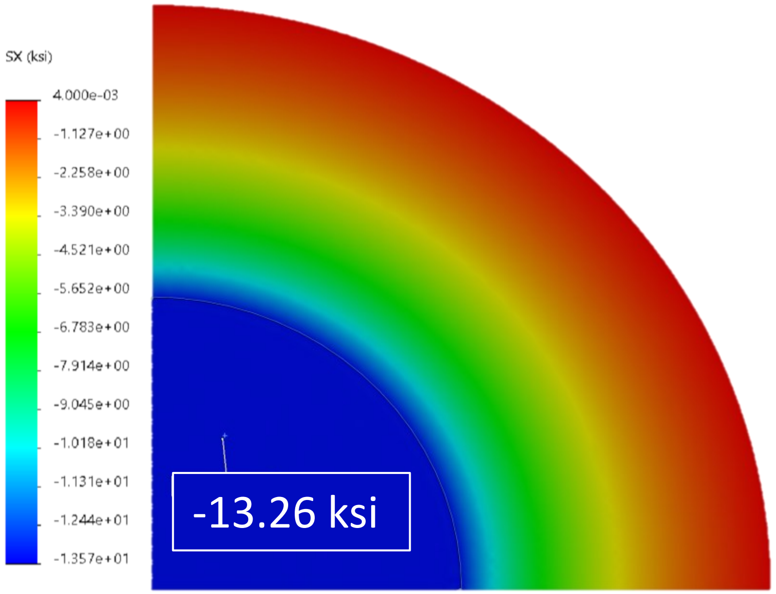
Residual Stress Measurement Technique Comparison

- Round Robin Measurements
  - Residual Stress Hole Drilling (HD) (ASTM E837)
  - X-Ray Diffraction (XRD) (ASTM E915, E1426, and SAE H5784)
  - Electronic Speckle Pattern Interferometry (ESPI)
- Aluminum 2024-T351, assumed to be elastically isotropic

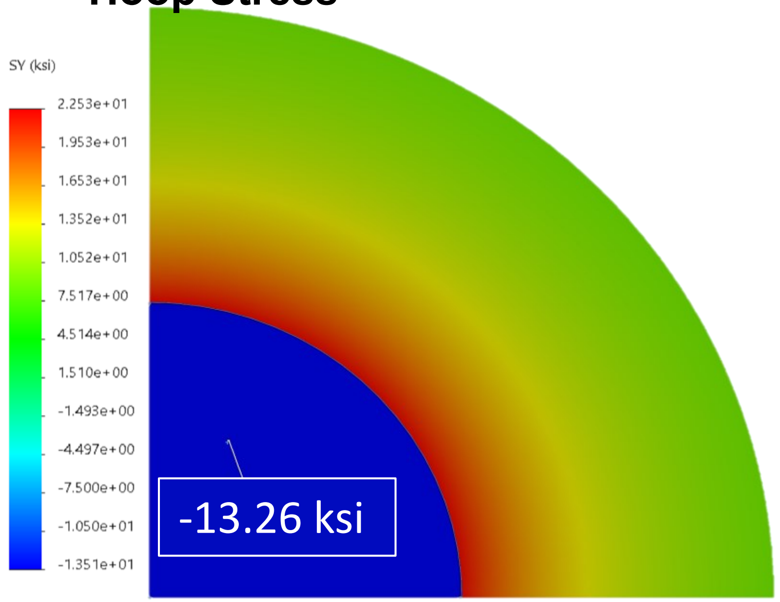
$\sigma_{Simulated}$ = -13.26 ksi

Technique	Elastic Constant	Value
HD / ESPI	E	10,600 ksi
	v	0.33
XRD	XEC_{RD}	7,832 ksi
	XEC_{TD}	7,907 ksi

Radial Stress

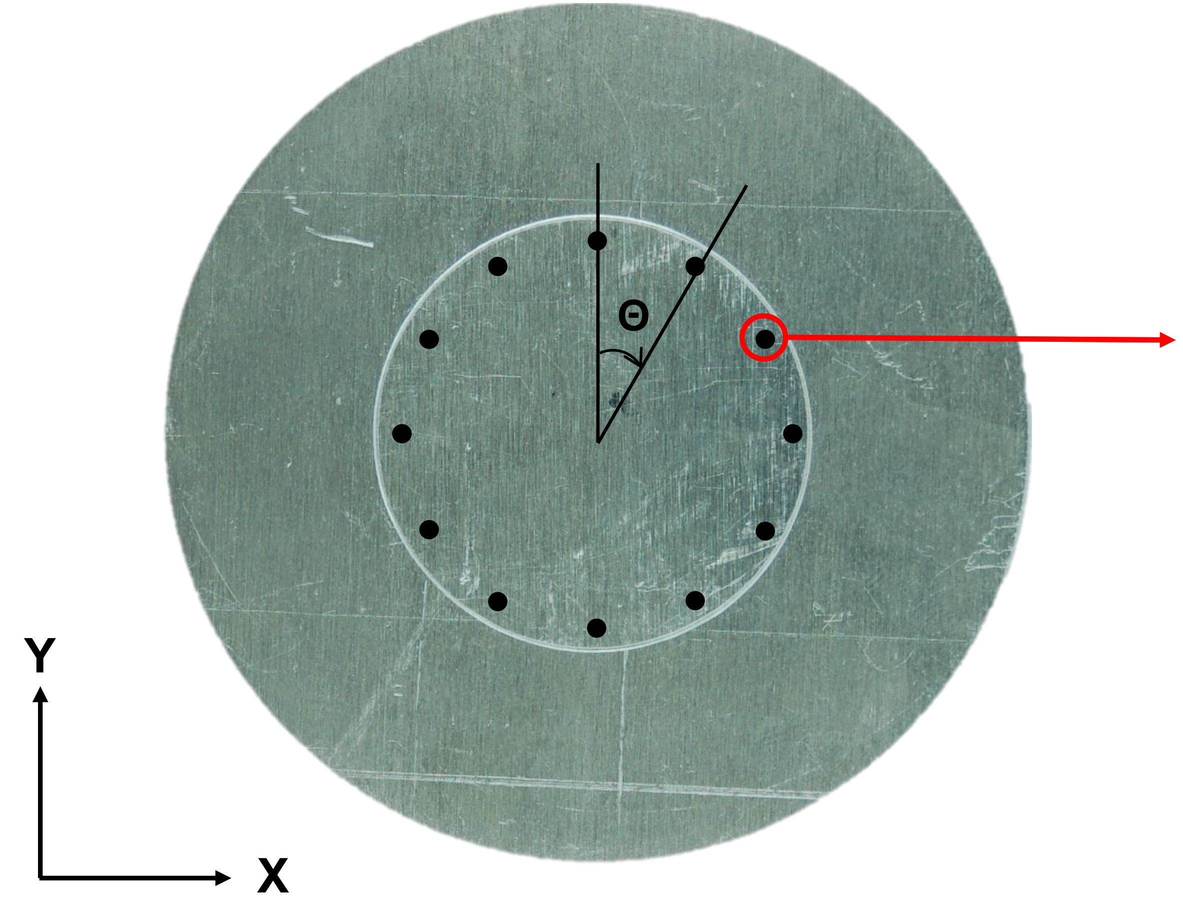


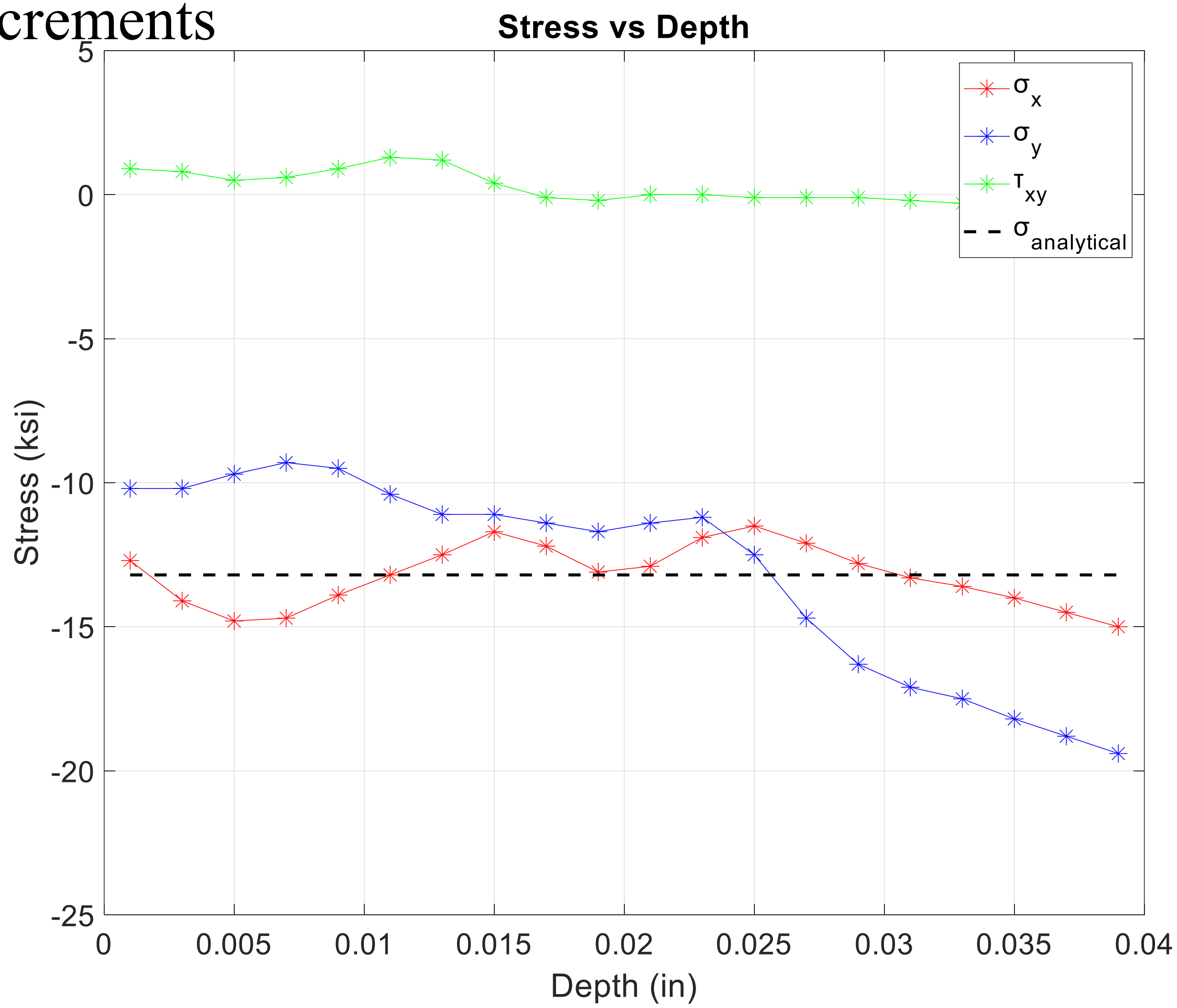
Hoop Stress



Hole Drilling Method - AFRL

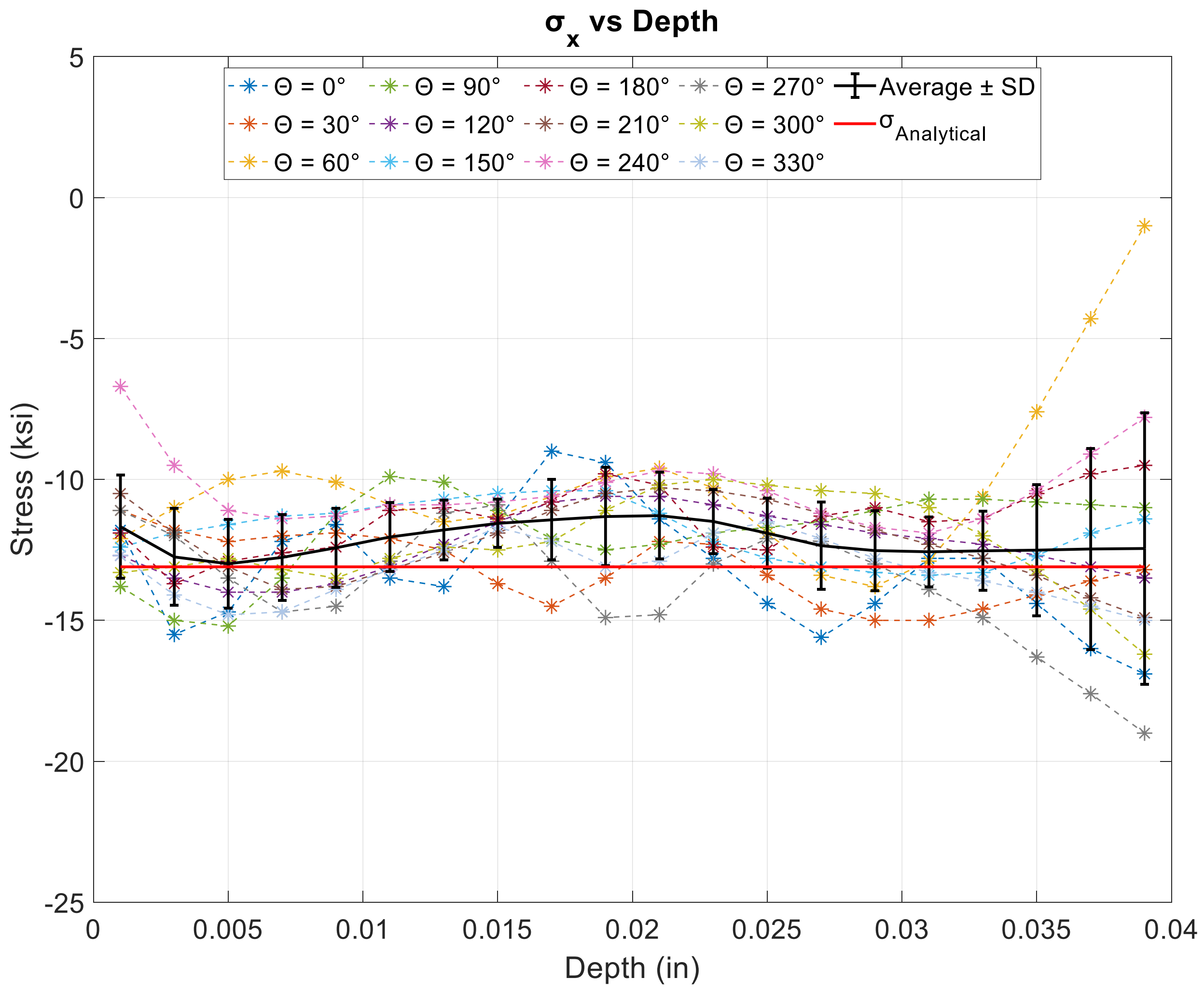
- Measurements made using DART (US Patent 10,900,768) (Appendix A)
- Total of 12 measurements made at 30° increments

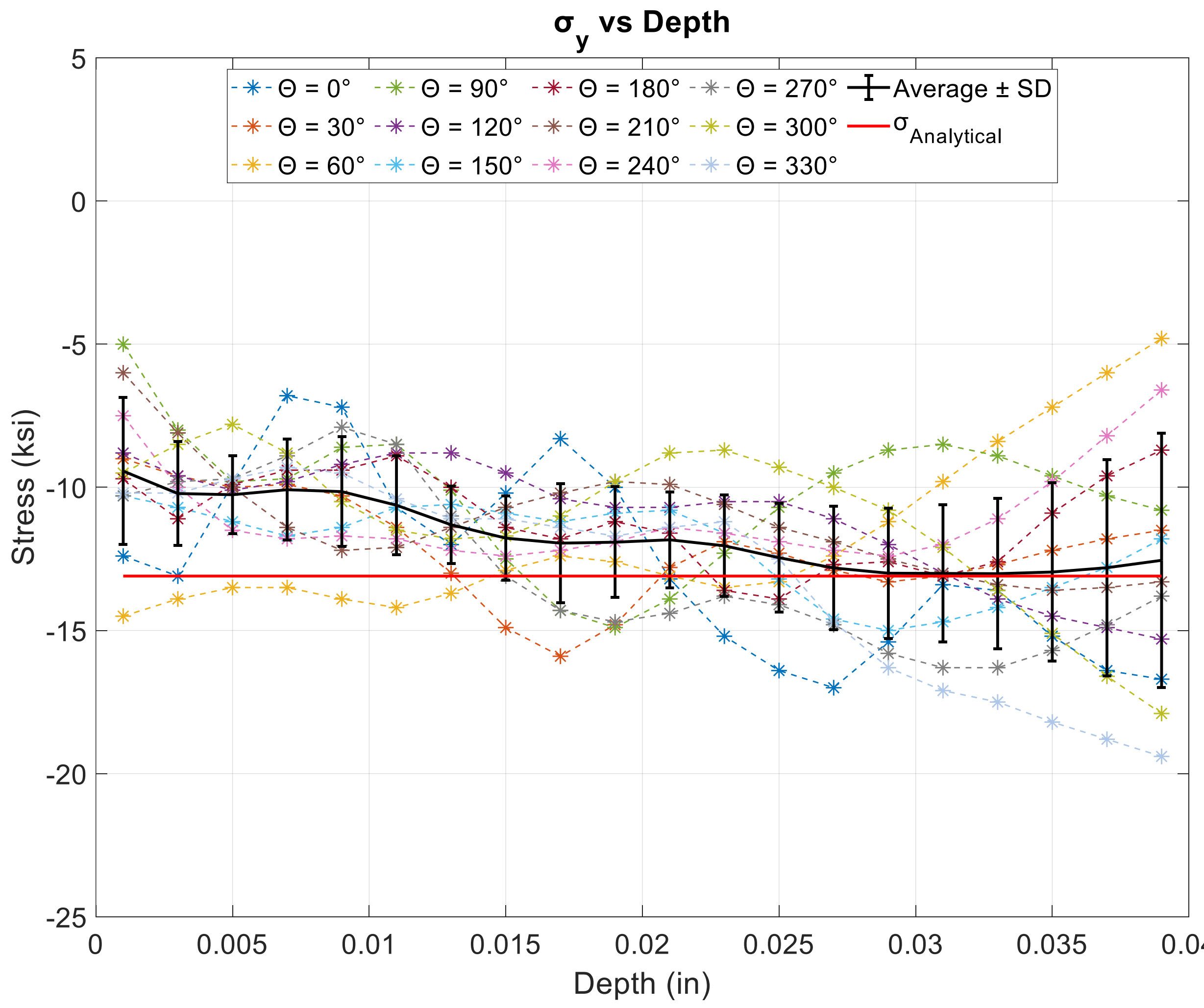




Distribution Statement A. Approved for public release: distribution unlimited.

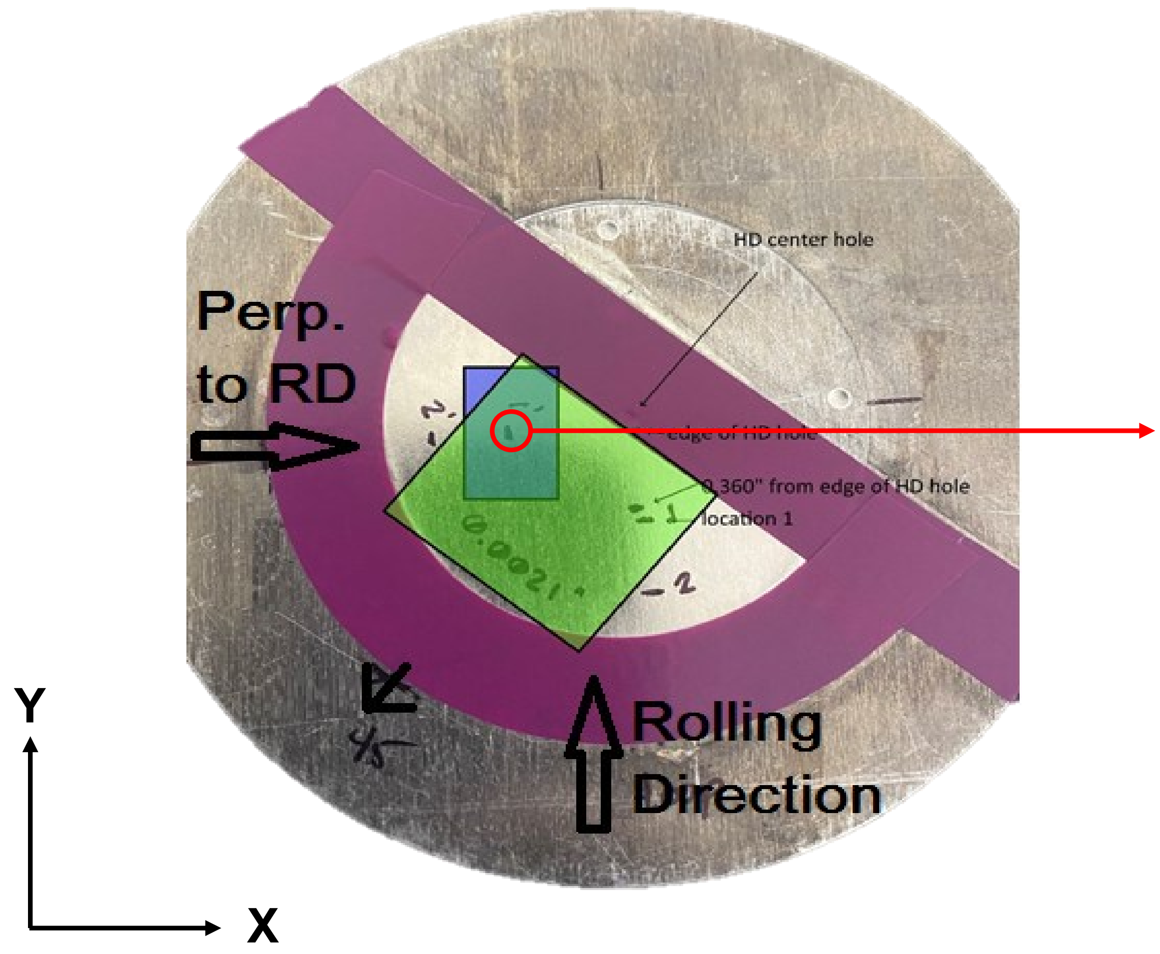
All 12 Hole Drilling Stress Profiles

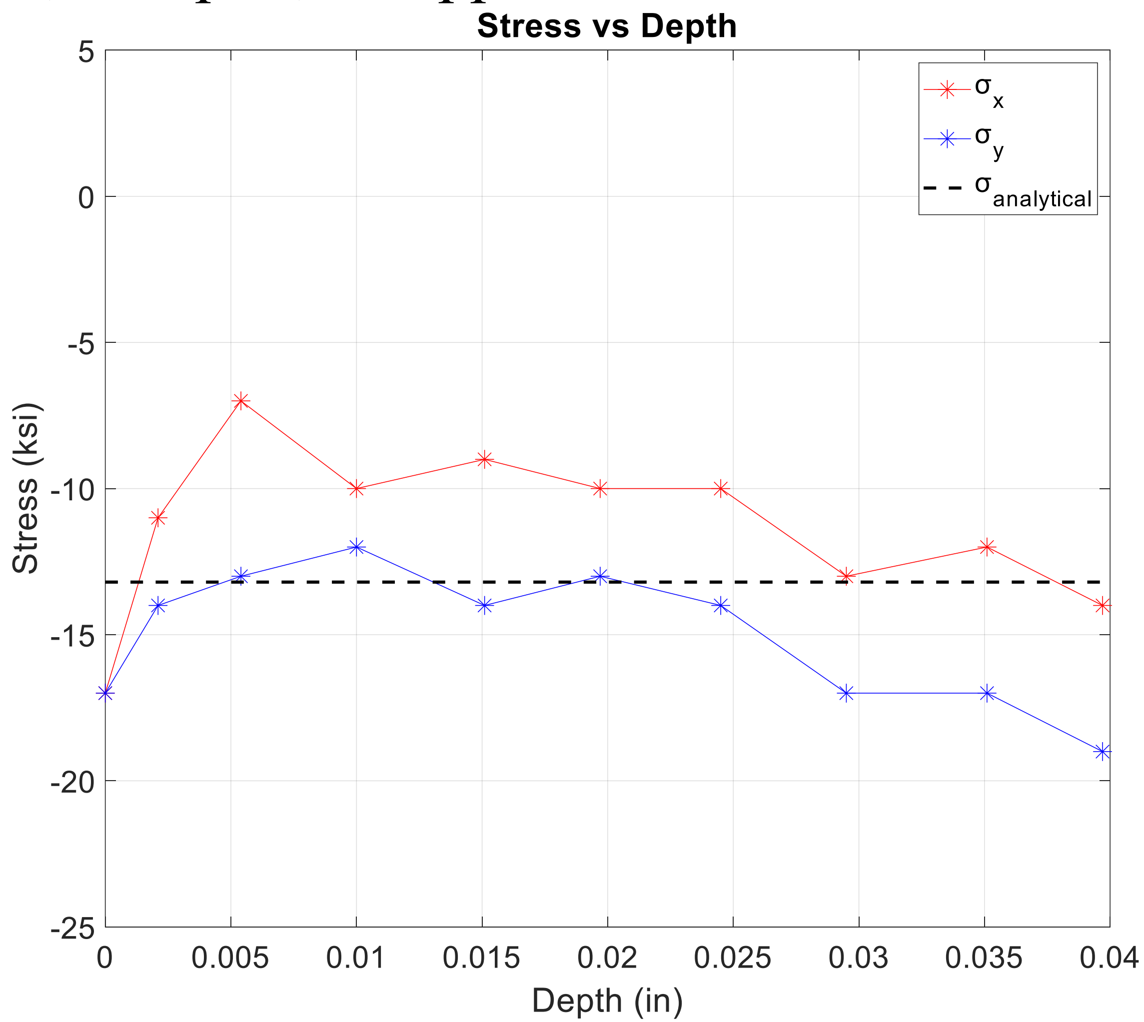




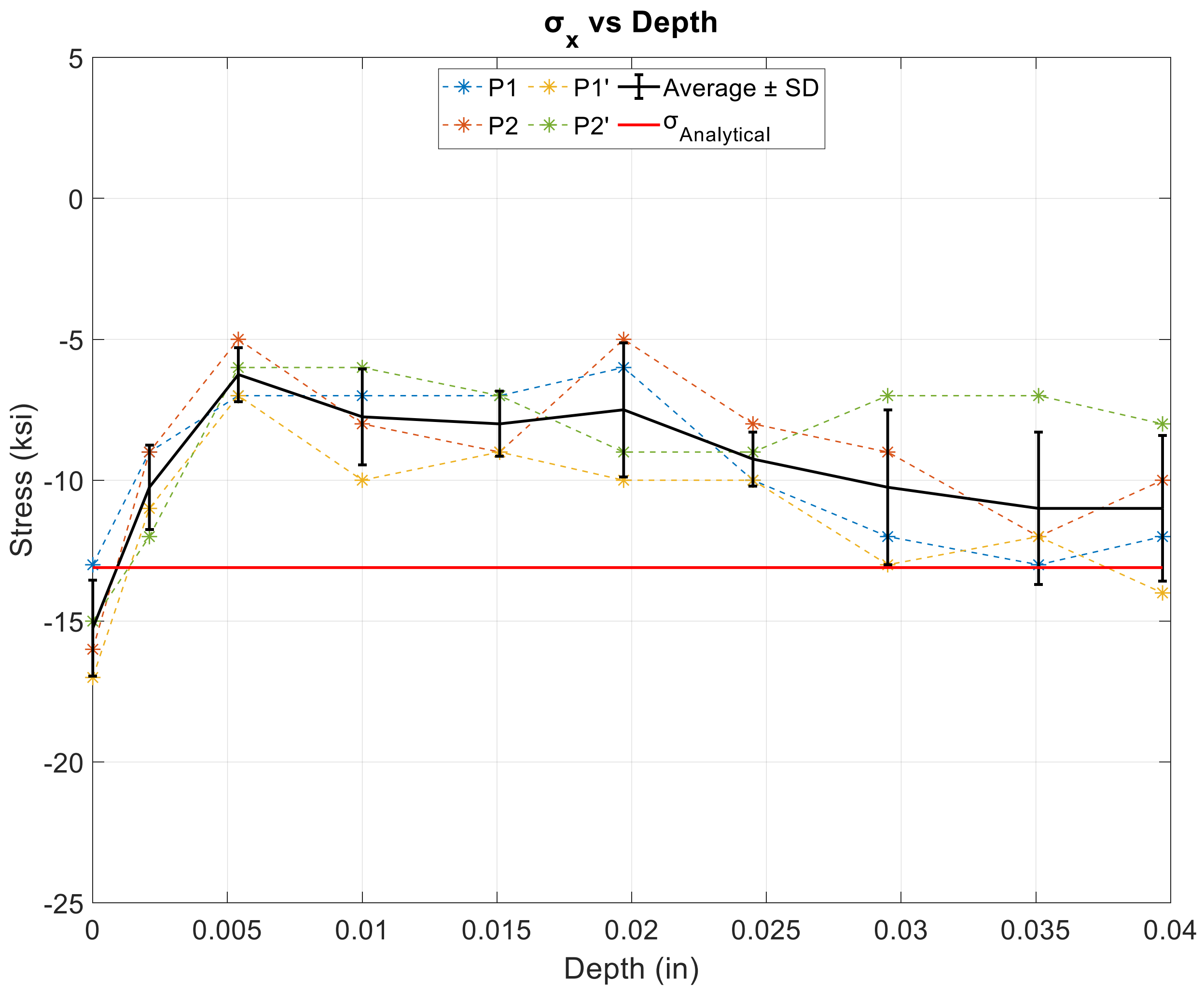
X-Ray Diffraction – Proto Manufacturing

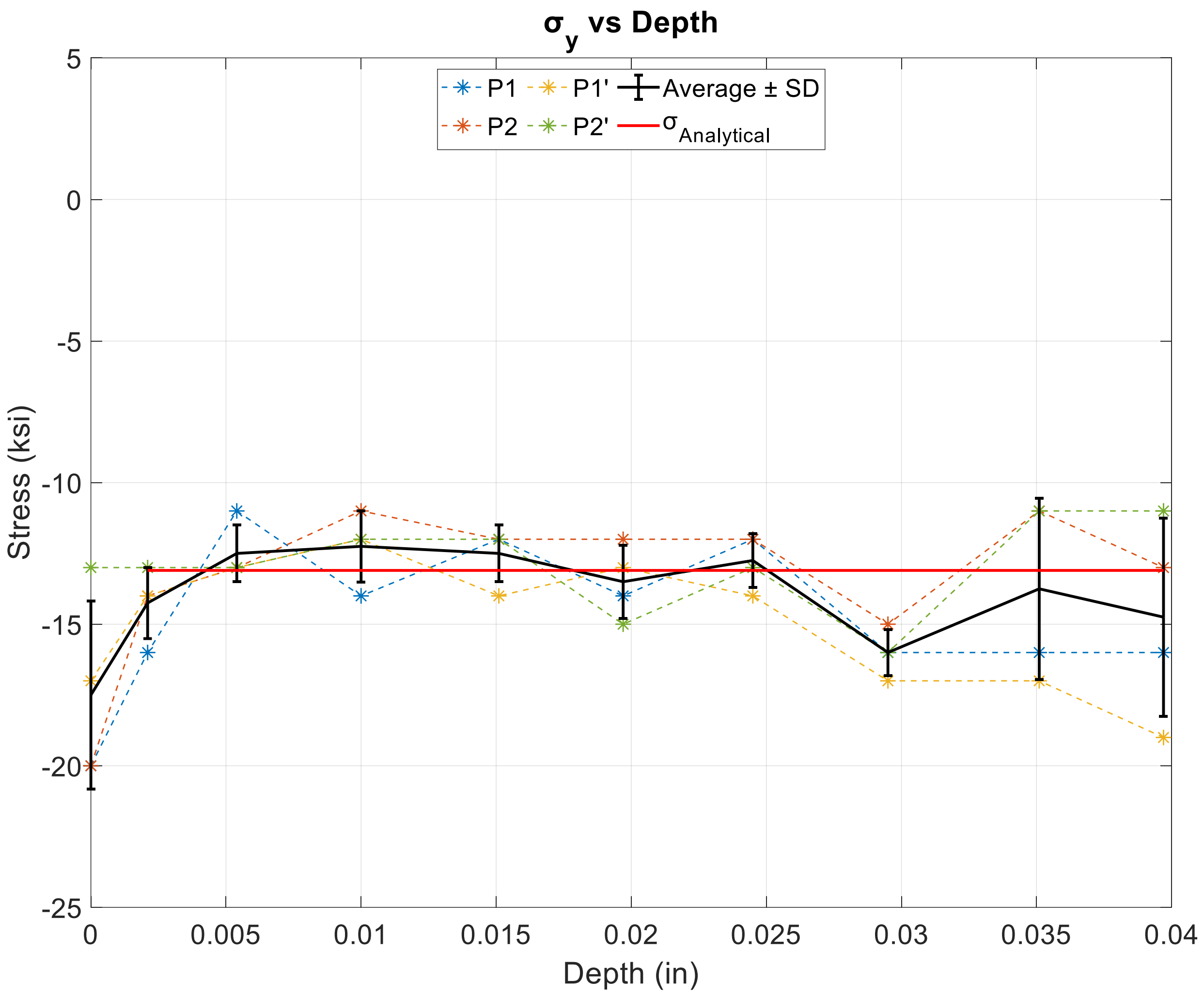
- 4 locations at 2 different radii, 90°apart, on opposite face as HD





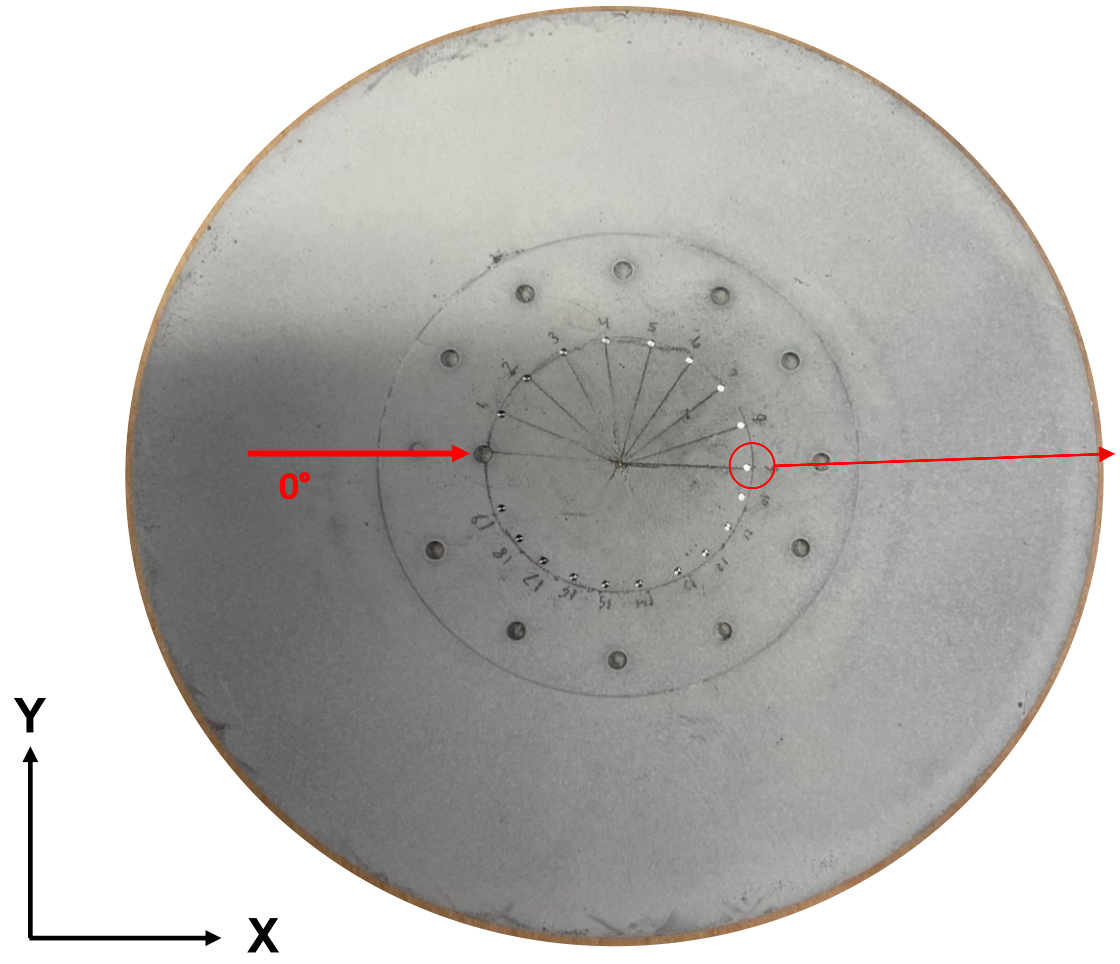
All 4 X-Ray Diffraction Stress Profiles

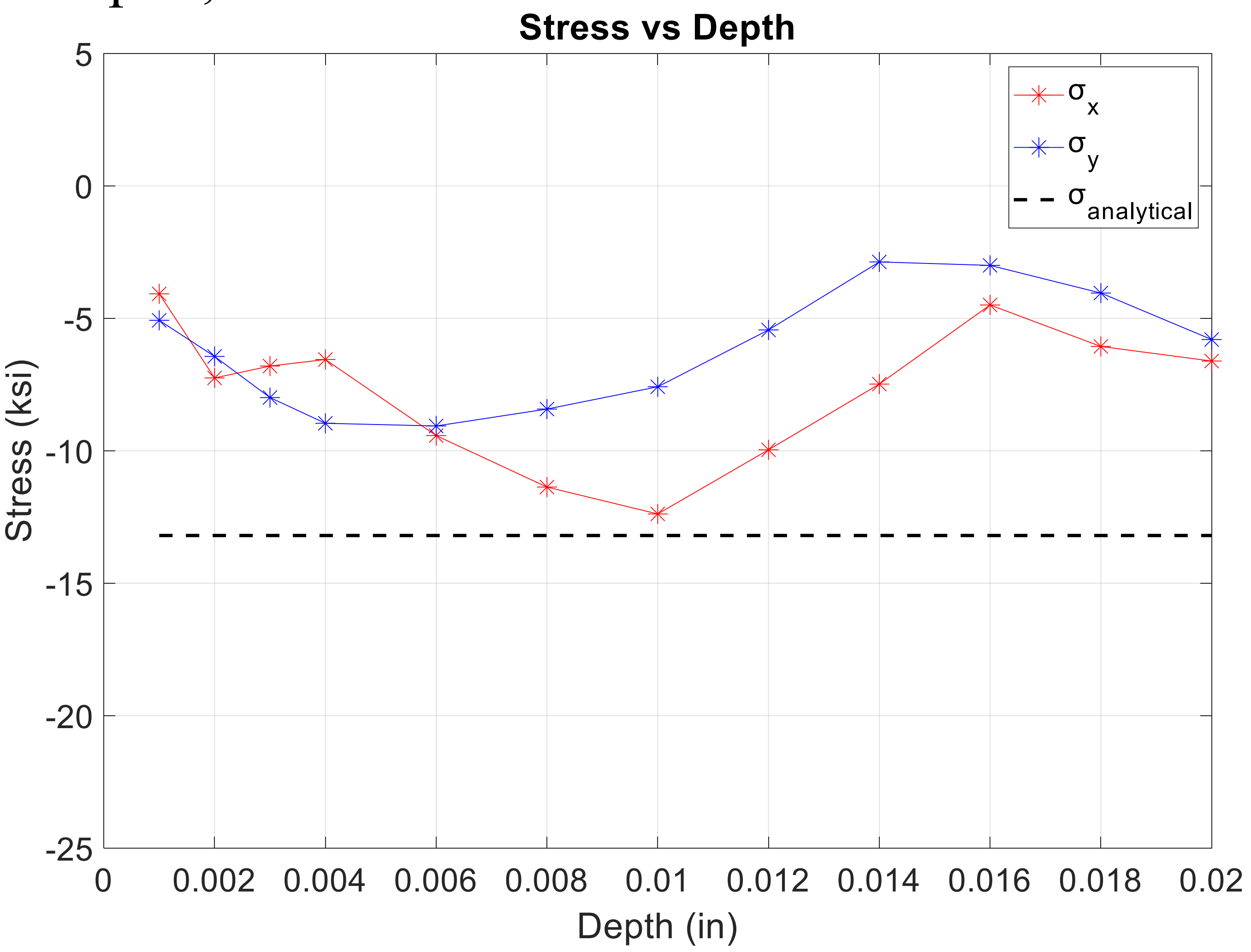




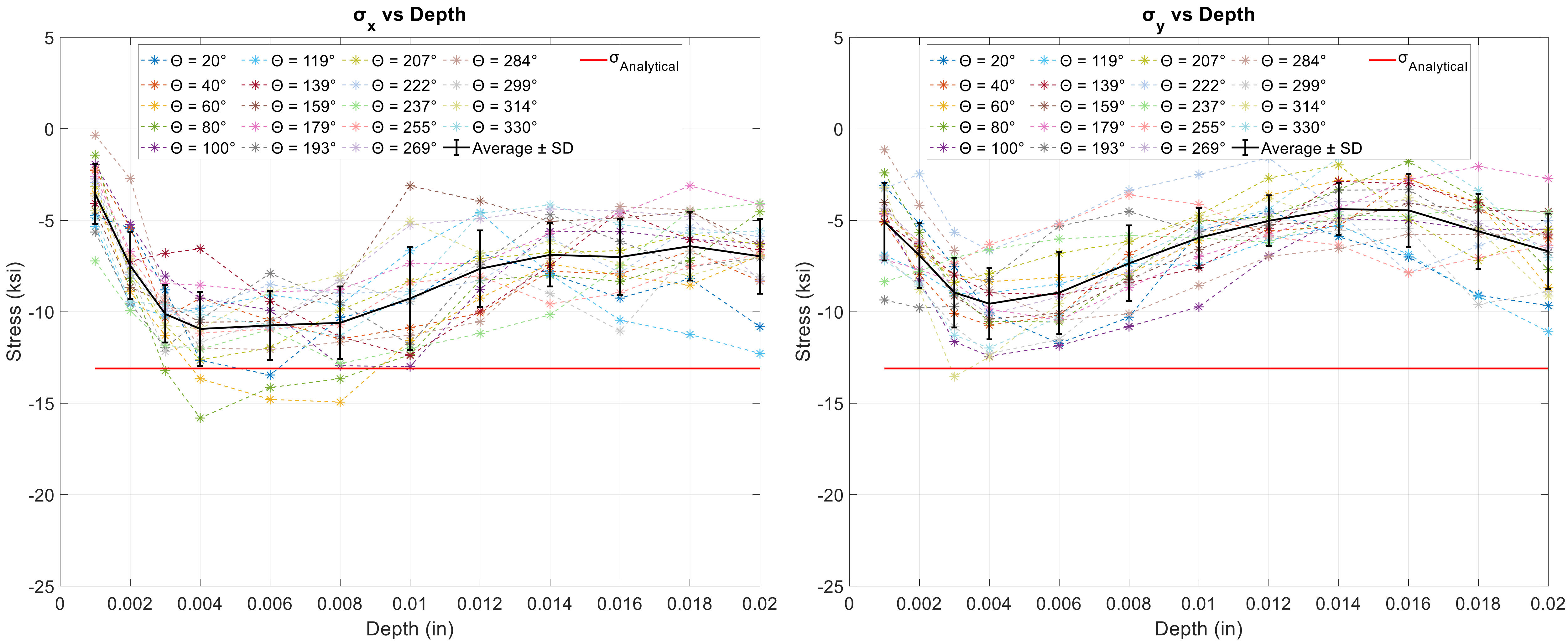
ESPI (Prism) – Sandia National Laboratories

- 19 locations between 14-20°apart, made on same face as HD

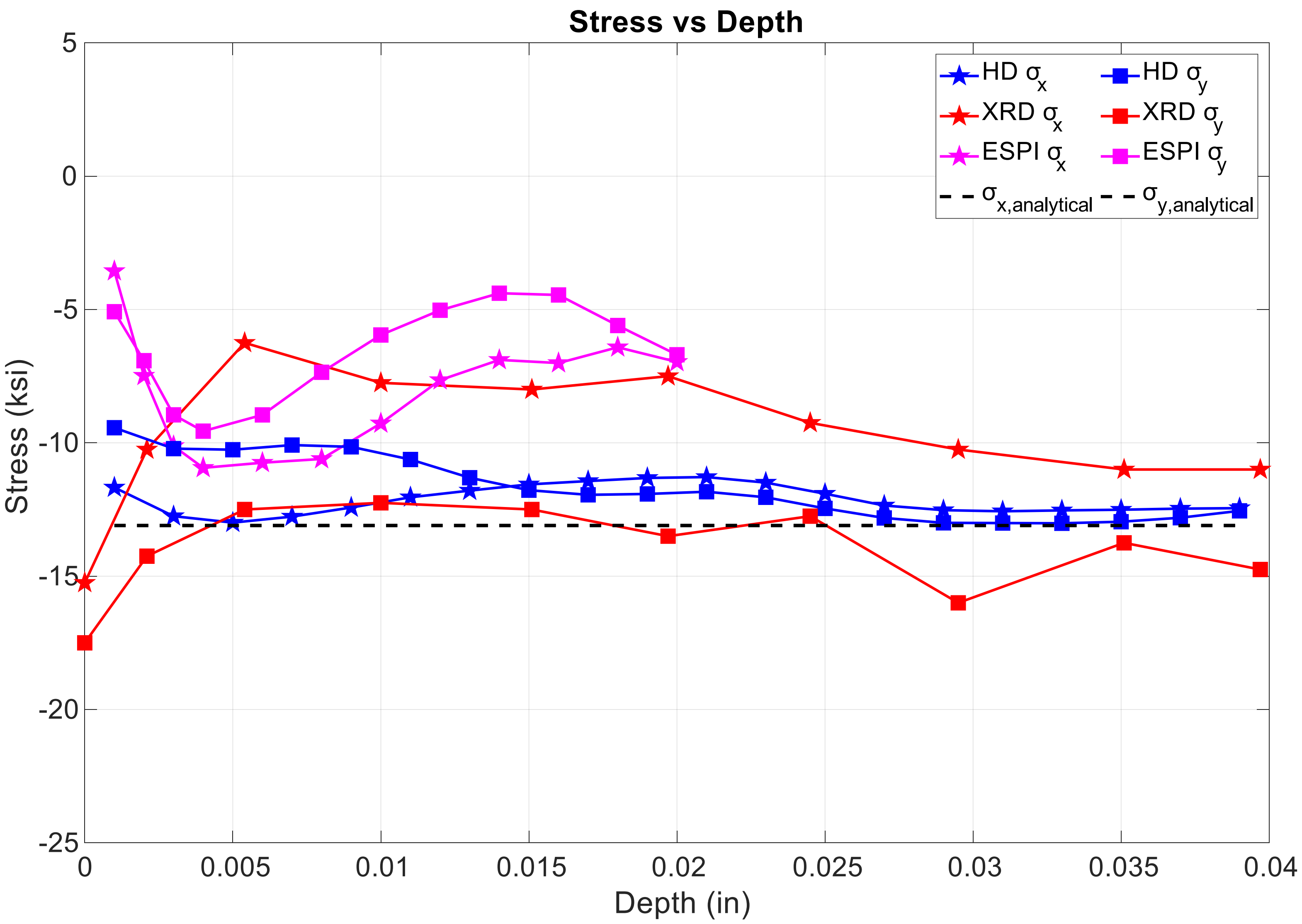




All 19 ESPI Stress Profiles



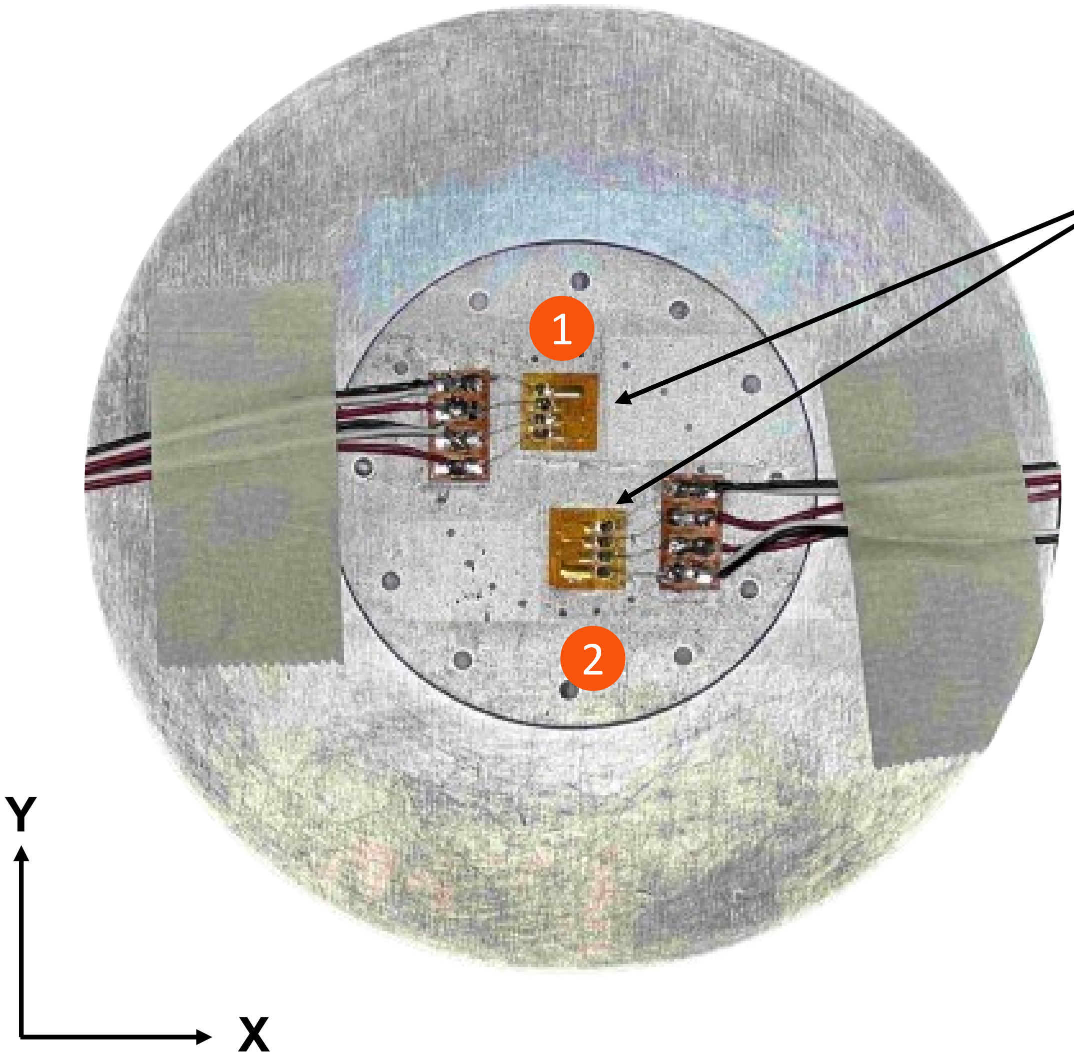
Round Robin Summary

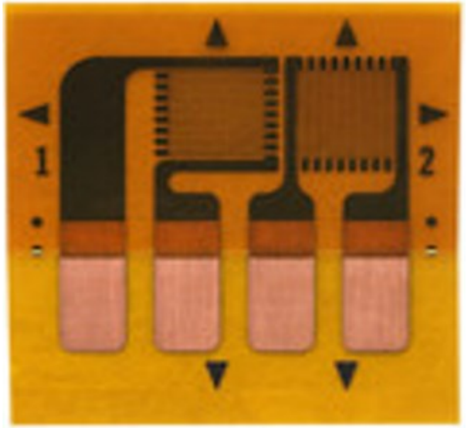


$$\Delta\sigma = \sigma_{analytical} - \bar{\sigma}$$

Method	σ	Δσ (ksi)
HD	σ_x	1.0
	σ_y	1.4
XRD	σ_x	3.5
	σ_y	0.9
ESPI	σ_x	5.0
	σ_y	6.5

Stress Measured from Ring Removal





Gage #	$\Delta\varepsilon_x$ ($\mu\varepsilon$)	$\Delta\varepsilon_y$ ($\mu\varepsilon$)
1	773.2	789.8
2	748.3	750.4

Method	Ring Removal	HD	XRD	ESPI
σ_x (ksi)	-12.1	-12.1	-9.7	-8.1
σ_y (ksi)	-12.1	-11.7	-14.0	-6.6

Summary

- Highlighted the variability of residual stress measurement techniques
- Comparable results for the three techniques
- Elastically isotropic samples provide a good baseline for the development and comparison of elastically anisotropic samples

Future Work

- Utilizing RUS quantify anisotropic elastic constants of textured brass for ring and plug assembly design
- Conduct residual stress measurements on ring and plug sample manufactured of elastically anisotropic material
- Build framework to simulate incremental hole drilling for experimental comparison
- Conducting similar round robin measurements for steel ring and plug sample
- For more information regarding this work check out “Effects of Elastic Anisotropy on Residual Stress Measurements Performed Using the Hole-Drilling Technique” being published this summer

Appendix A

Device for

Automated

Residual Stress

Test

Courtesy of:

Hill Engineering

Appendix A

LXRD

Stress Analyzer

Courtesy of:

Proto Manufacturing

Future Opportunities

Bring us your problems!

Continuation of active work

New! Residual Stress Characterization Committee

- RS Measurement
- RS Process Simulation
- Uncertainty Quantification