Working Group on
Engineered Residual
Stress Implementation

Residual Stress Measurement Committee Annual Summary

3 April 2024

(These charts are a team product)

Eric Burba, committee lead

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Overview

Committee Logistics

- Mission Statement
- Monthly Meeting Framework
- Roster and Attendance

Update on Current and Future Projects

- Inclusion of Texture and Anisotropy into Residual Stress Measurements (Josh Ward, UDRI & James Pineault, Proto)
- Harmonization of Differing RS Measurement Datasets (James Pineault, Proto)
- Cutting Induced Plascity Modeling for Short Edge Margin Holes and the Effects of Cutting Sequence (Scott Carlson, Lockheed Martin)
- Different Cx Processes (Split Sleeve vs Split Mandrel) Residual Stress and Test Data (Scott Carlson, Lockheed Martin)
- 2x2 Working Group Update (Scott Carlson, Lockheed Martin)

Summary and Future Opportunities

Mission Statement

Provide unwavering support to ERSI stakeholders, encompassing end users and aircraft programs, as they navigate the intricate landscape of designing and executing tailored residual stress implementation initiatives.

A well-established group of professionals specializing in residual stress measurement and process modeling, we offer a comprehensive suite of services that includes:

- 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)
- Uncertainty Quantification (UQ) and Statistical Methods Relative to Residual Stress Data

https://residualstress.org/index.php?title=Residual_Stress_Characterization

Committee Roster

First Name	Last Name	Organization
Dallen	Andrew	Hill Engineering, LLC
Jeferson	Araújo de Oliveira	StressMap - Director
David	Backman	National Research Council Canada / Government of Canada
Ana	Barrientos Sepulveda	Northrup Grumman Aerospace Systems
John	Bourchard	Professor of Materials Engineering Open University - Director of StressMap
Michael	Brauss	Proto Manufacturing Inc.
Dave	Breuer	Curtiss-Wright, Surface Technologies Division
Stan	Bovid	Hepburn and Sons
Eric	Burba	U.S. Air Force (AFRL - RXC - Materials & Manufacturing Directorate)
Scott	Carlson	Lockheed Martin Aero (F-35 Service Life Analysis Group)
James	Castle	The Boeing Company (Associate Technical Fellow BR&T Metals and Ceramics)
Allen	Christopher	BAH
David	Denman	Fulcrum Engineering, LLC. (President & Chief Engineer)
Adrian	DeWald	Hill Engineering, LLC
Daniele	Fanteria	Dipartimento di Ingegneria Civile e Industriale
Eric	Greuner	LMCO
Mike	Hill	Hill Engineering, LLC
Ketih	Hitchman	FTI
Laura	Hunt	Southwest Research Institute (SwRI)
Andrew	Jones	U.S. Air Force (B-52 ASIP Structures Engineer)
Min	Liao	NRC
Eric	Lindgren	U.S. Air Force (AFRL - Materials and Manufacturing Directorate)
Marcias	Martinez	Clarkson University (Department of Mechanical & Aeronautical Engineering)
B	McGinty	MERC Mercer
Teresa	Moran	Southwest Research Institue (SwRI)
Mark	Obstalecki	U.S. Air Force (AFRL - RXCM)
Juan	Ocampo	St. Mary's University
T	Philbrick	MERC Mercer
Pete	Phillips	University of Dayton Research Institute (UDRI)
Robert	Pilarczyk	Hill Engineering, LLC
James	Pineault	Proto Manufacturing Inc.
Scott	Prost-Domasky	APE Solutions
Mike	Reedy	U.S. Navy (NAVAIR - Compression Systems Engineer)
Steven	Reif	AFLCMC/EZFS
Guillaume	Renaud	NRC
Zachary	Sanchez Archuleta	Los Alamos National Labs (LANL)
Matthew	Shultz	PCC Airframes
Lucky	Smith	SwRI
TJ	Spradlin	U.S. Air Force (AFRL - Aerospace Systems Directorate)
Marcus	Stanfield	Southwest Research Institute (SwRI)
Mike	Steinzig	Los Alamos National Labs - Weapons Engineering Q17
M	Tkokaly	Partworks
Kevin	Walker	QinetiQ
Josh	Ward	University of Dayton Research Institute (UDRI)
Michael	Worley	SwRI

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

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 contact Burba or DeWald if you would like to attend

Meeting Agenda

Characterization Committee Projects & Updates

- UQ/Risk Update (Ocampo)
- 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

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)

Outline

- Introduction
  - Mission Statement & Background
  - Residual Stress Hole Drilling
- Main Points
  - Measuring Anisotropic Elastic Constants
    - How can we Measure Anisotropy?
    - Resonant Ultrasound Spectroscopy (RUS)
    - RUS System
  - Round-Robin study of Stainless Steel Ring-Plug Specimen
    - Comparison of Hole Drilling and X-Ray Diffraction
- Summary
  - Future Work
  - Accomplishments

Mission Statement & Background

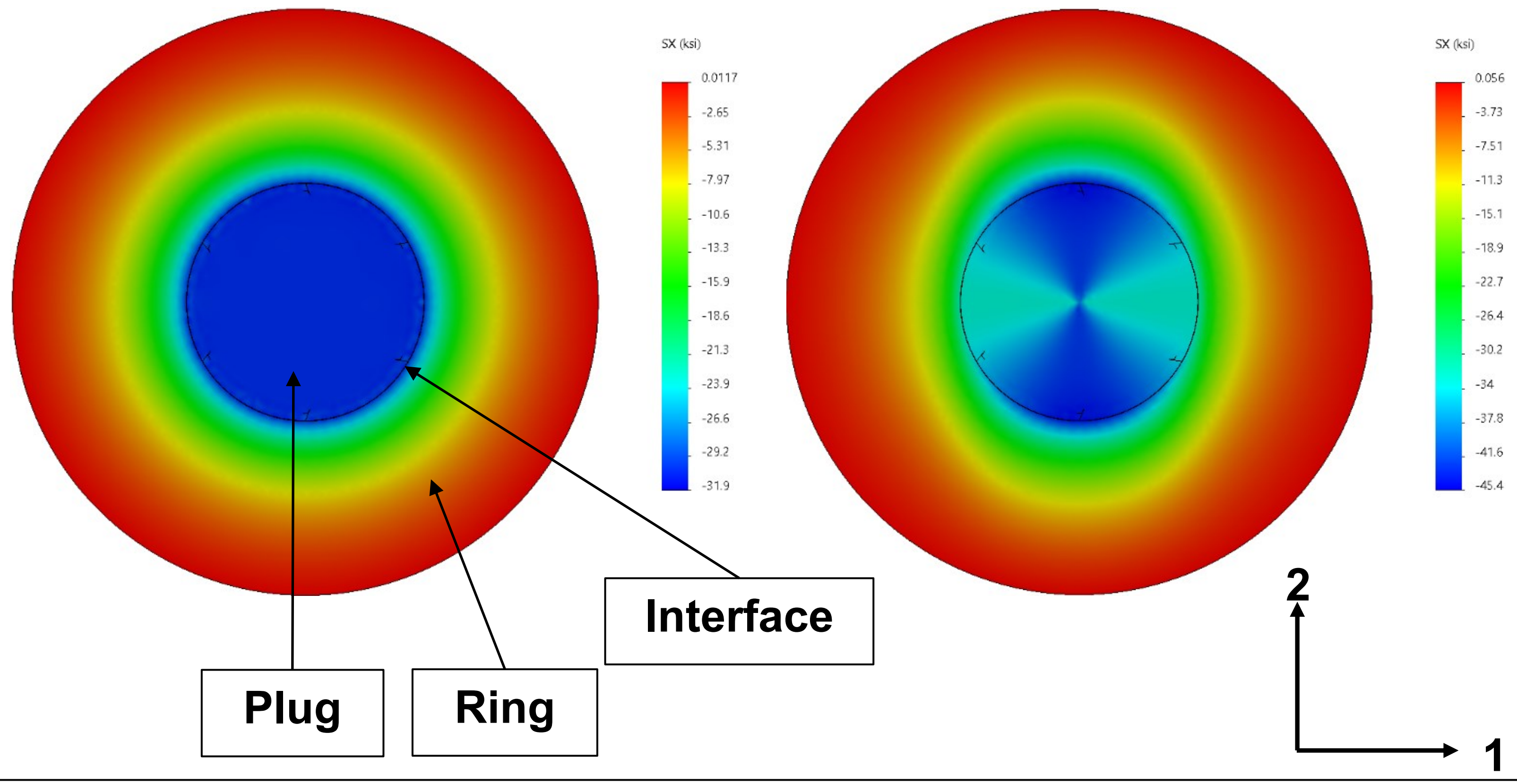
Quantify and incorporate the effects of crystallographic texture and elastic anisotropy into residual stress measurement workflows

$$\begin{bmatrix}\varepsilon_{11}\\ \varepsilon_{22}\\ \varepsilon_{33}\\ 2\varepsilon_{23}\\ 2\varepsilon_{13}\\ 2\varepsilon_{12}\end{bmatrix} = \frac{1}{E}\begin{pmatrix} 1 & -v & -v & 0 & 0 & 0\\ -v & 1 & -v & 0 & 0 & 0\\ -v & -v & 1 & 0 & 0 & 0\\ 0 & 0 & 0 & 2+2v & 0 & 0\\ 0 & 0 & 0 & 0 & 2+2v & 0\\ 0 & 0 & 0 & 0 & 0 & 2+2v \end{pmatrix}\begin{bmatrix}\sigma_{11}\\ \sigma_{22}\\ \sigma_{33}\\ \sigma_{23}\\ \sigma_{13}\\ \sigma_{12}\end{bmatrix}$$

$$\begin{bmatrix}\varepsilon_{11}\\ \varepsilon_{22}\\ \varepsilon_{33}\\ 2\varepsilon_{23}\\ 2\varepsilon_{13}\\ 2\varepsilon_{12}\end{bmatrix} = \begin{pmatrix} \frac{1}{E_1} & -\frac{v_{21}}{E_2} & -\frac{v_{31}}{E_3} & 0 & 0 & 0\\ -\frac{v_{12}}{E_1} & \frac{1}{E_2} & -\frac{v_{32}}{E_3} & 0 & 0 & 0\\ -\frac{v_{13}}{E_1} & -\frac{v_{23}}{E_2} & \frac{1}{E_3} & 0 & 0 & 0\\ 0 & 0 & 0 & \frac{1}{G_{23}} & 0 & 0\\ 0 & 0 & 0 & 0 & \frac{1}{G_{31}} & 0\\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{12}} \end{pmatrix}\begin{bmatrix}\sigma_{11}\\ \sigma_{22}\\ \sigma_{33}\\ \sigma_{23}\\ \sigma_{13}\\ \sigma_{12}\end{bmatrix}$$

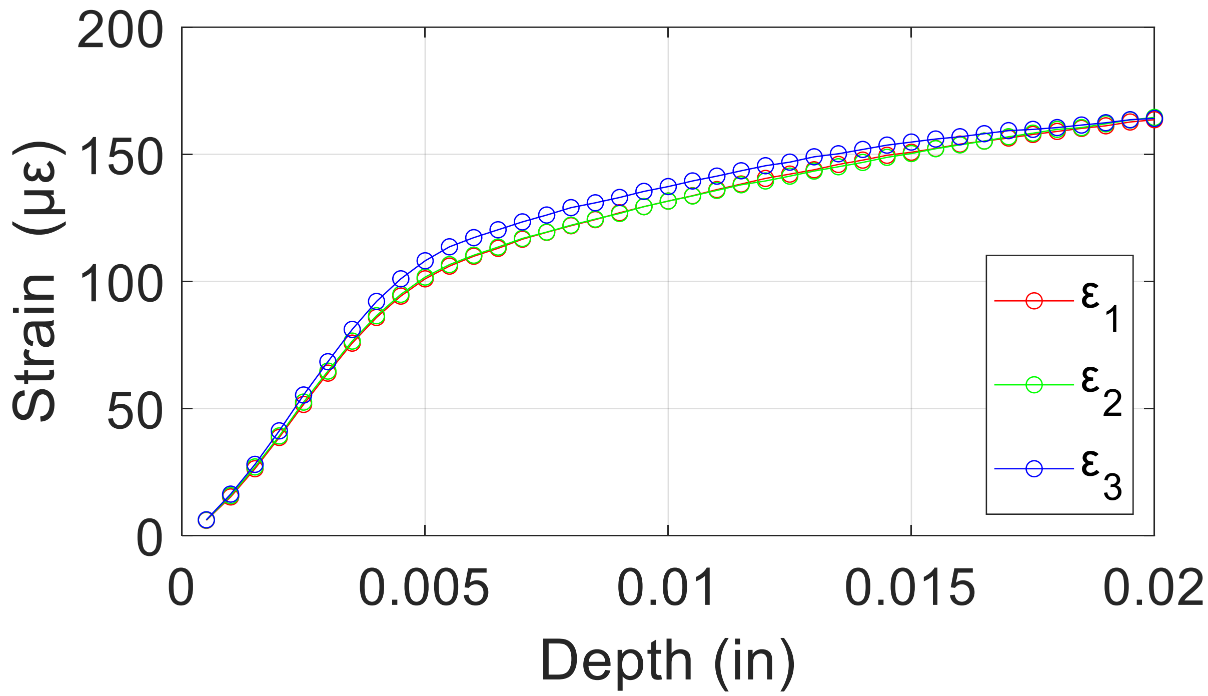
Isotropic Ring & Plug
E = 28,000 ksi

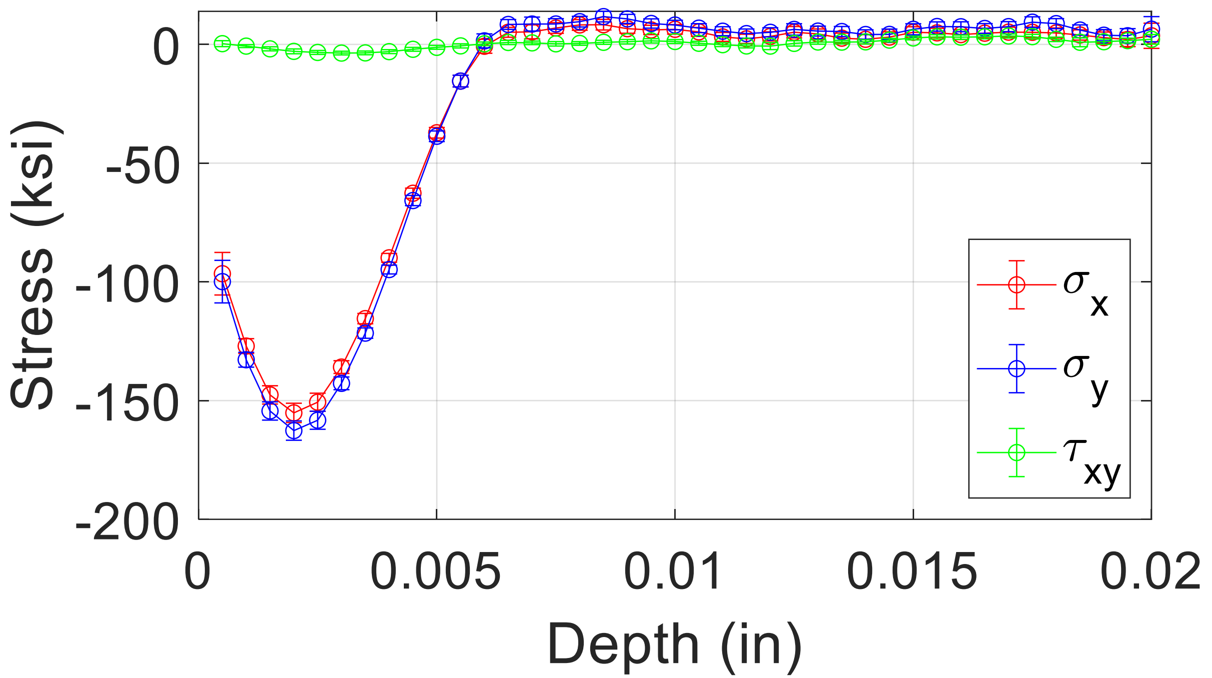
Anisotropic Ring & Plug
E_1 = 28,000 ksi E_2 = 36,400 ksi



Residual Stress via Hole-Drilling

- Incremental Hole Drilling (ASTM E837) utilizing the DART system (Hill Eng.)



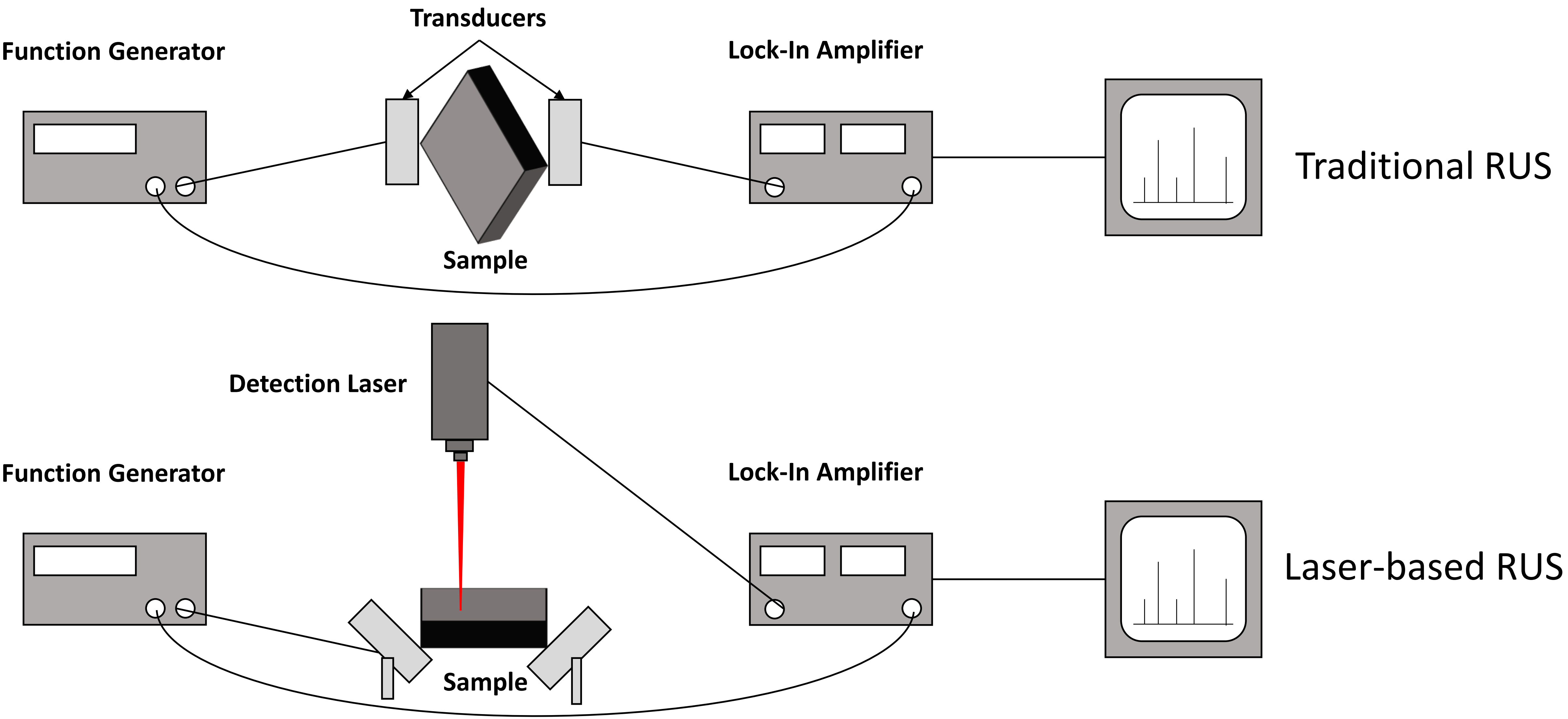


Measurement of Anisotropic Elastic Constants

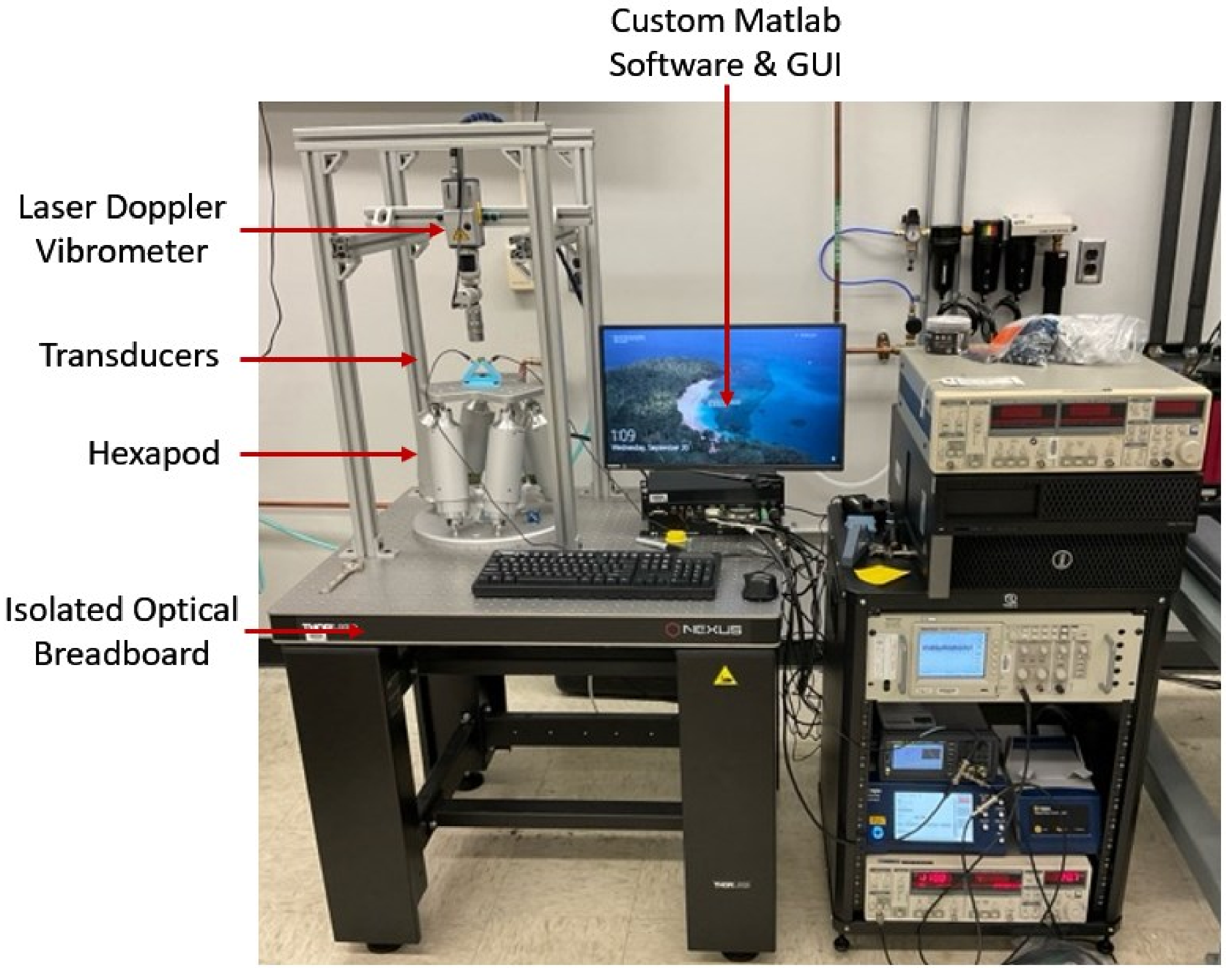
Measuring Anisotropic Elastic Constants

	Mechanical Testing	Time of Flight Ultrasound	Resonant Ultrasound Spectroscopy
Sample Cost	$1,000s	$100s	$100s
Required material	Tens of specimens (flat/round dogbone)	One small cuboid ~ 1000 mm^3	One small cuboid ~ 500 mm^3
Test Cost	$1,000s	$100s	$100s
Technical Difficulty	Requires trained technician	Requires trained technician	Requires subject matter expert to analyze results
Method Maturity			

Resonant Ultrasound Spectroscopy (RUS)

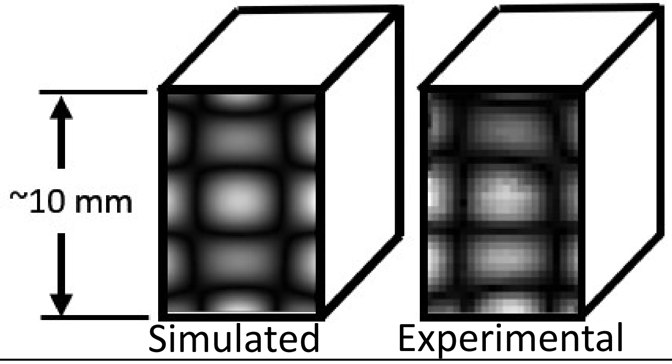


RUS System



System Capabilities

- **Rapidly measure anisotropic elastic stiffness tensor nondestructively using a small volume of material**
  - ~ 2 hr, significant savings on tension tests
  - Simple specimen preparation
- **Measures resonant frequencies and modal shapes**
- **Built in predictive models (FE & Rayleigh Ritz) and gradient descent optimizer for material constant determination**
- **Future: High temperature capabilities**
  - Modulus, Texture evolution as function of time & temperature



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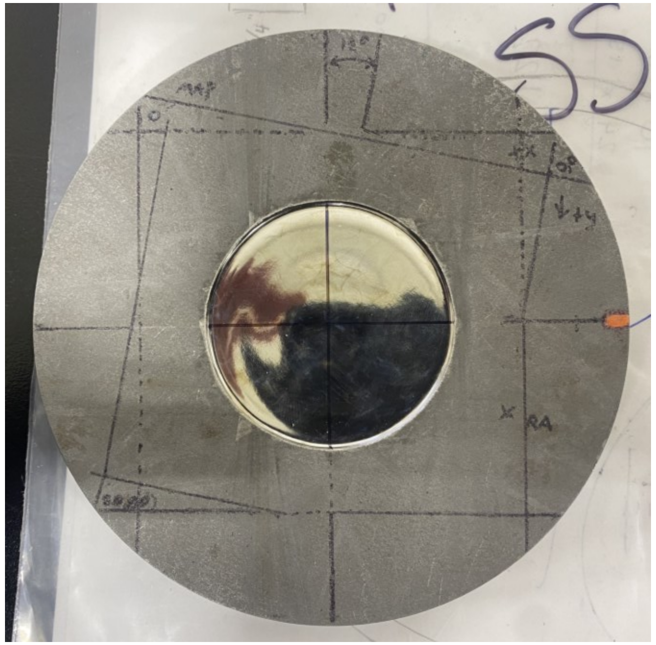
Round-Robin on 304SS Ring-Plug Specimen

- LANL fabricated and assembled Ring-Plug (304SS plug/Carbon Steel ring) for ERSI Texture Subcommittee circa 2021.
- Nominal Dimensions of Carbon Steel Ring: 4.9375” OD, 2” ID, 0.5” thick - 304SS Plug: 2” OD, 0.5” thick
- Purpose: further develop RS measurement protocols and work-flow for anisotropic materials.
- Premise: start with a presumably isotropic specimen, collect data, incorporate lessons learned on anisotropic materials in future.
- RS depth profiles collected up to 0.040” deep using RSHD on Side 1 (see holes) and XRD on Side 2 (see e-polished region).

Post HD – Side 1

Edge View

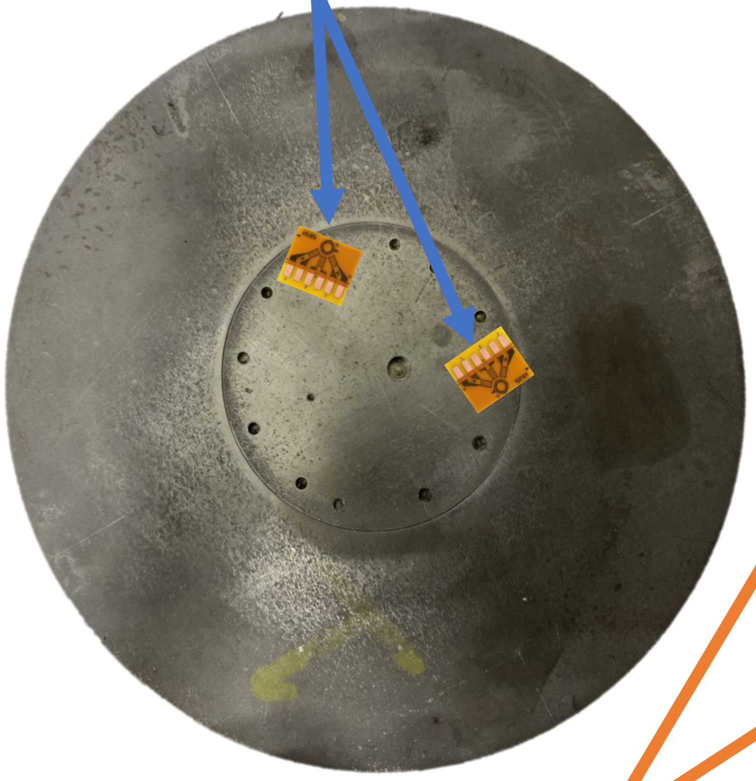


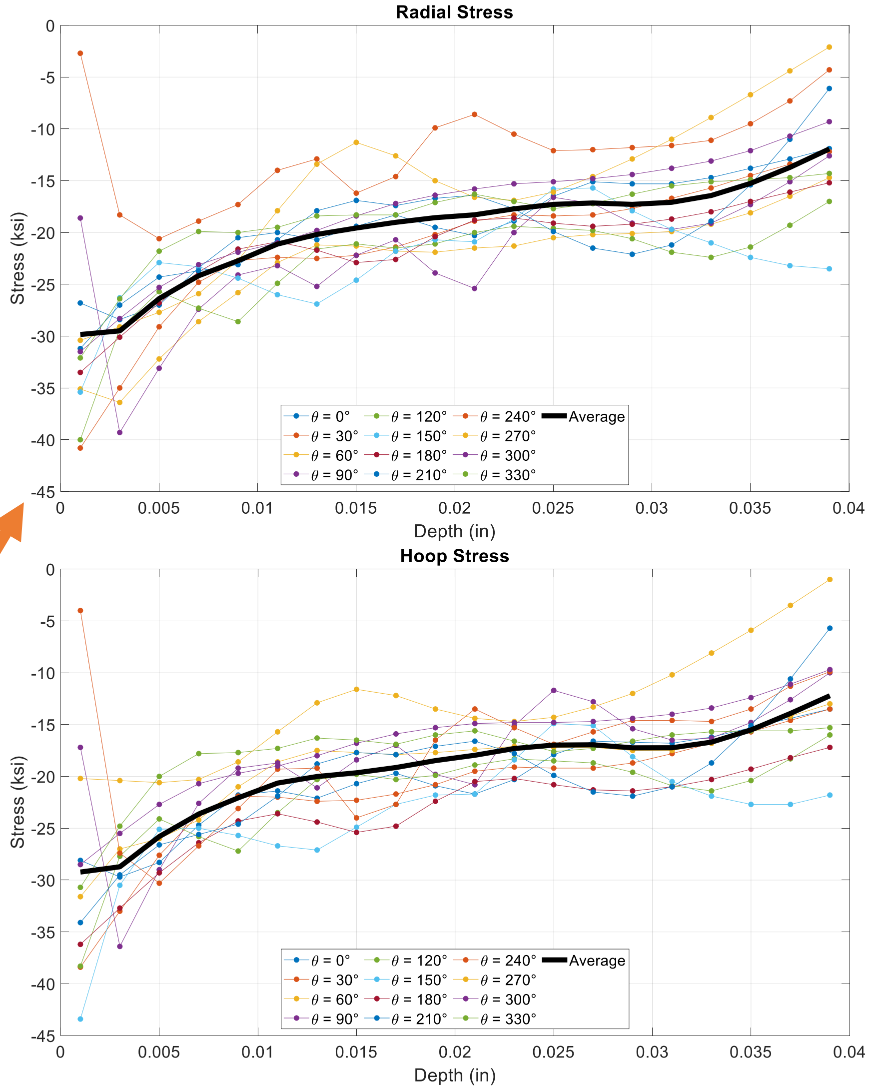
Post XRD – Side 2

RSHD on Side 1 of 304SS Ring-Plug Specimen

- RSHD work performed at AFRL.
- 12 standard size (0.08"Ø hole) HD measurements performed 30° apart around the plug at the 22 mm radial position
- Oriented with σ_{xx} in radial direction and σ_{yy} in hoop direction
- Depth profiles indicate a surface RS gradient is present likely due to upstream cold work applied to 304SS cold rolled sheet/plate.
- Comparable average between radial (σ_{xx}) and hoop (σ_{yy}) stress as expected on ring-plug configuration.

Typical Rosette Placement



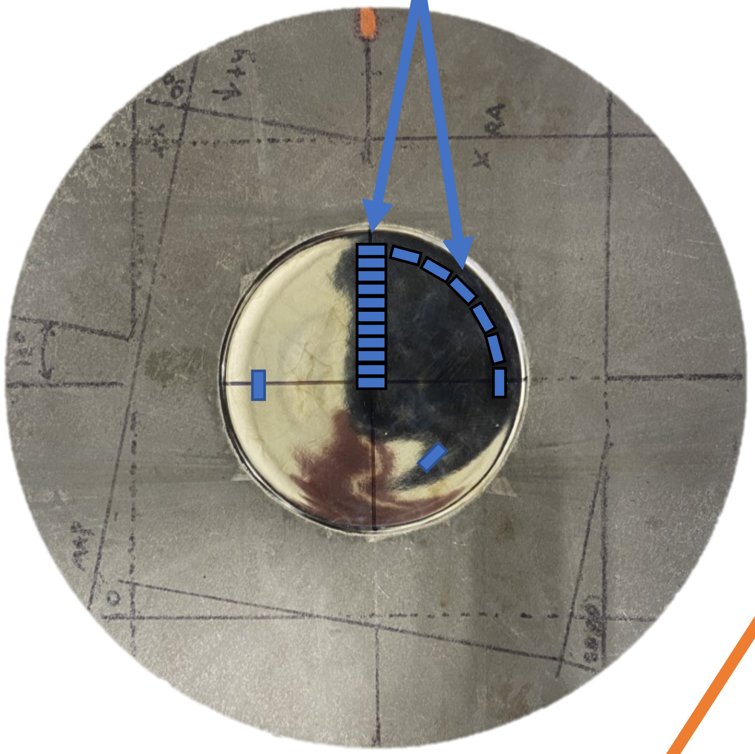


Hoop and Radial Stress vs. Depth profiles at 22 mm radial position

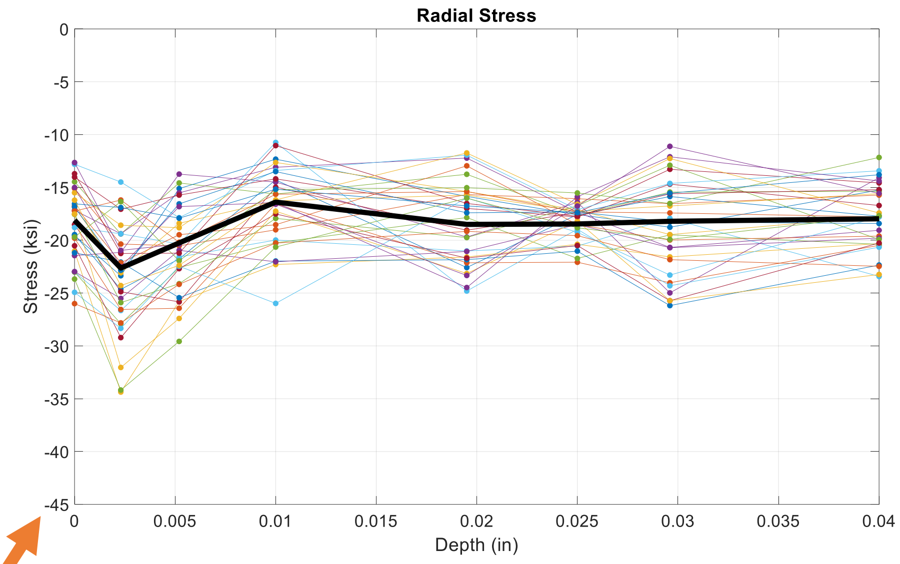
XRD on Side 2 of 304SS Ring-Plug Specimen

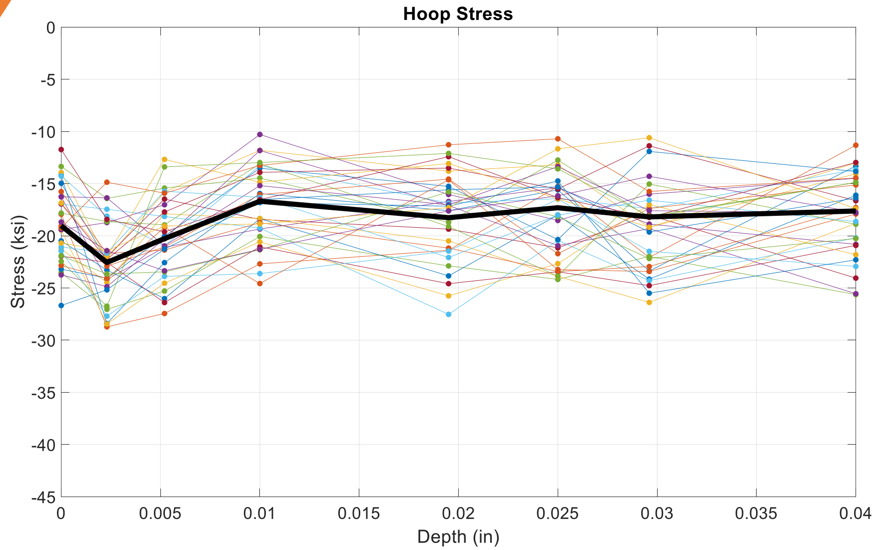
- XRD work performed at Proto.
- 264 locations used for XRD at **15° intervals** and **2 mm radial increments** (some examples of irradiated area highlighted in blue boxes).
- Depth profiles indicate a surface RS gradient is present likely due to upstream cold work applied to 304SS cold rolled sheet/plate.
- Comparable average between radial (σ_{xx}) and hoop (σ_{yy}) stress as expected on ring-plug configuration.

Typical Irradiated Area

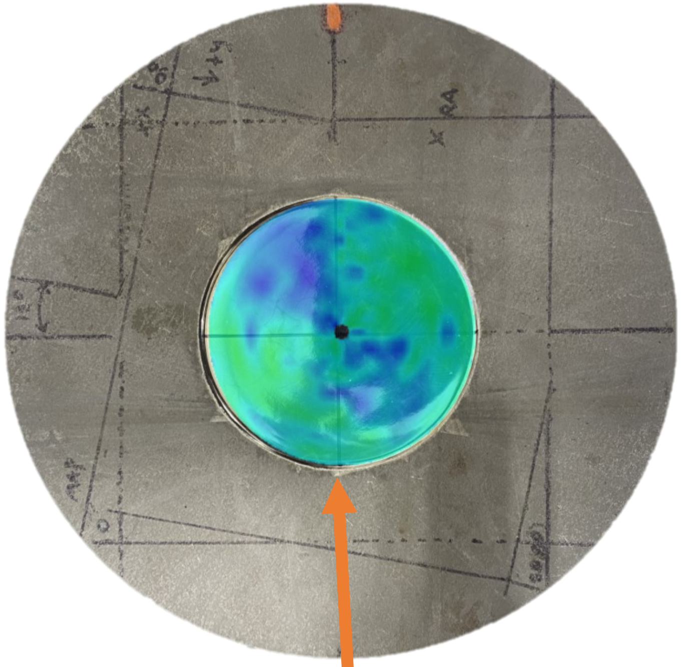


Typical Radial and Hoop Stress vs. Depth profiles – Example from R=8 mm

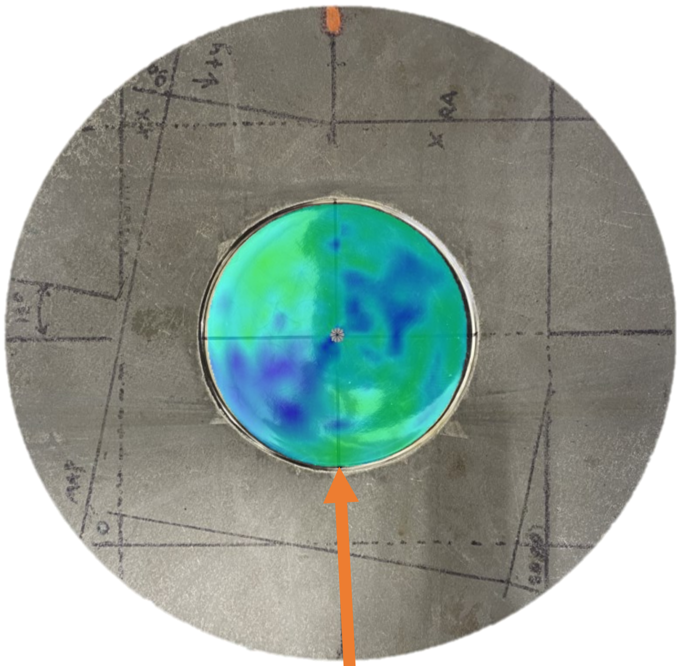




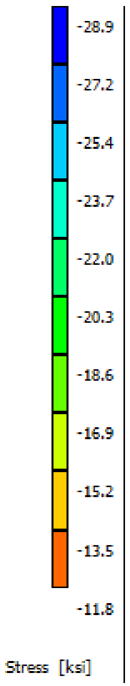
XRD Maps on Side 2 of 304SS Ring-Plug

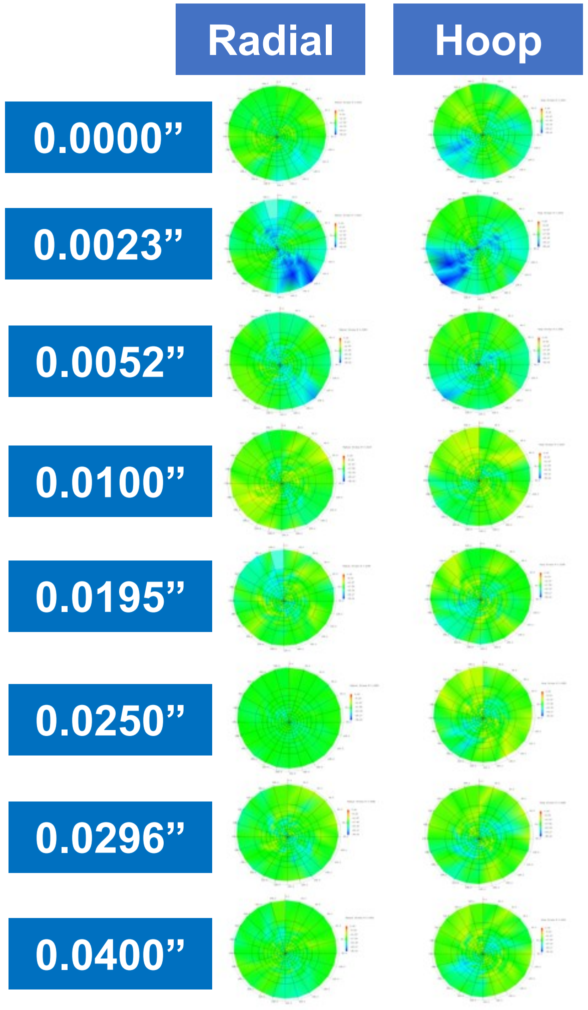


Radial Stress Map at 0.0195” deep



Hoop Stress Map at 0.0195” deep



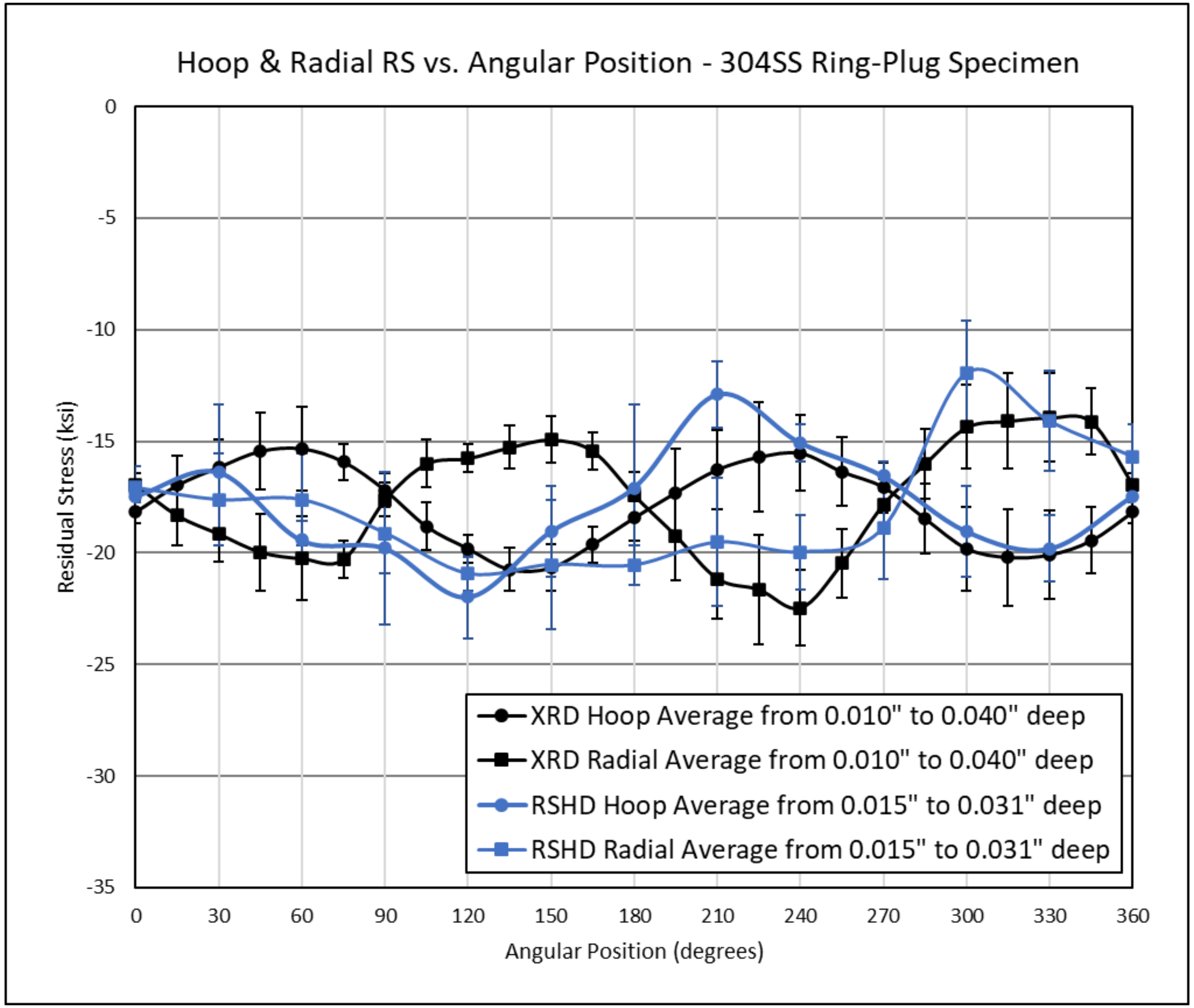


Note: color scale on above RS maps different than one shown above left

- Full field XRD RS maps indicate angular dependence on the magnitude of RS.
- Radial and Hoop RS maps “mirror images” indicating possible dependence on a) upstream fabrication residual stress, and/or b) anisotropic response to loading.
- Effect persists from near surface to maximum sampled depth of 0.040”.
- XRD data collection strategy developed to facilitate analysis of anisotropic materials in upcoming experiments.

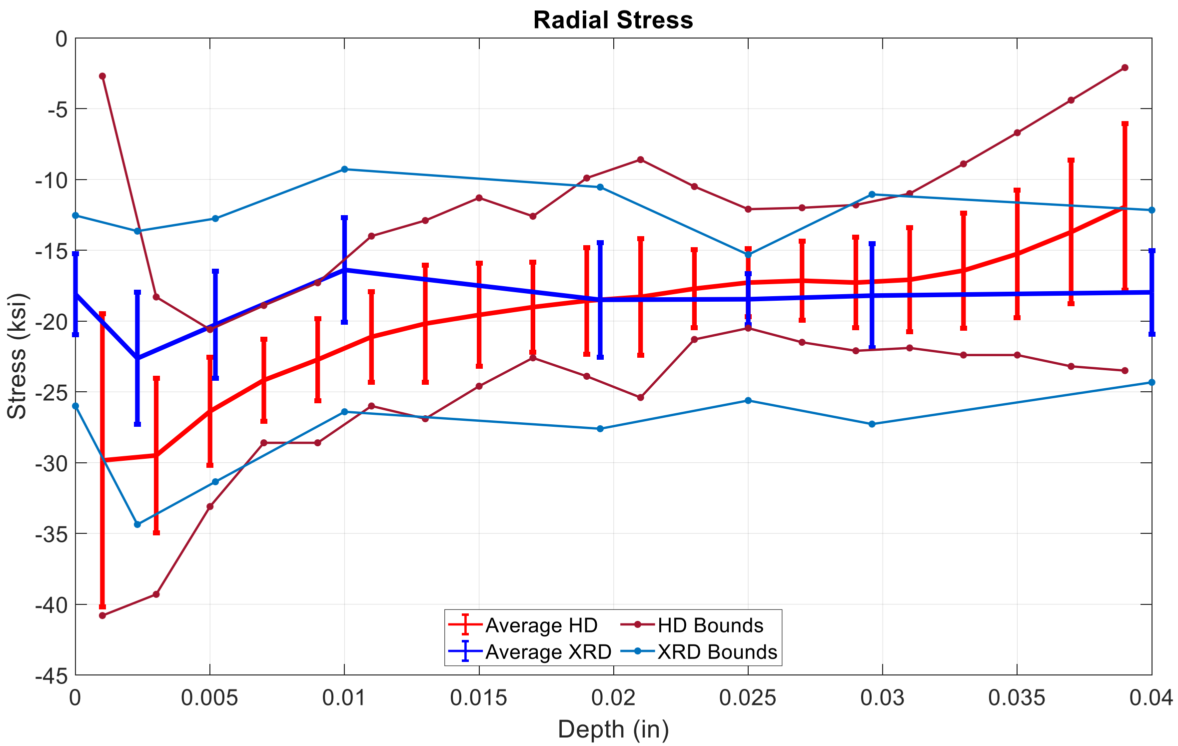
RSHD\XRD on 304SS Ring-Plug Specimen

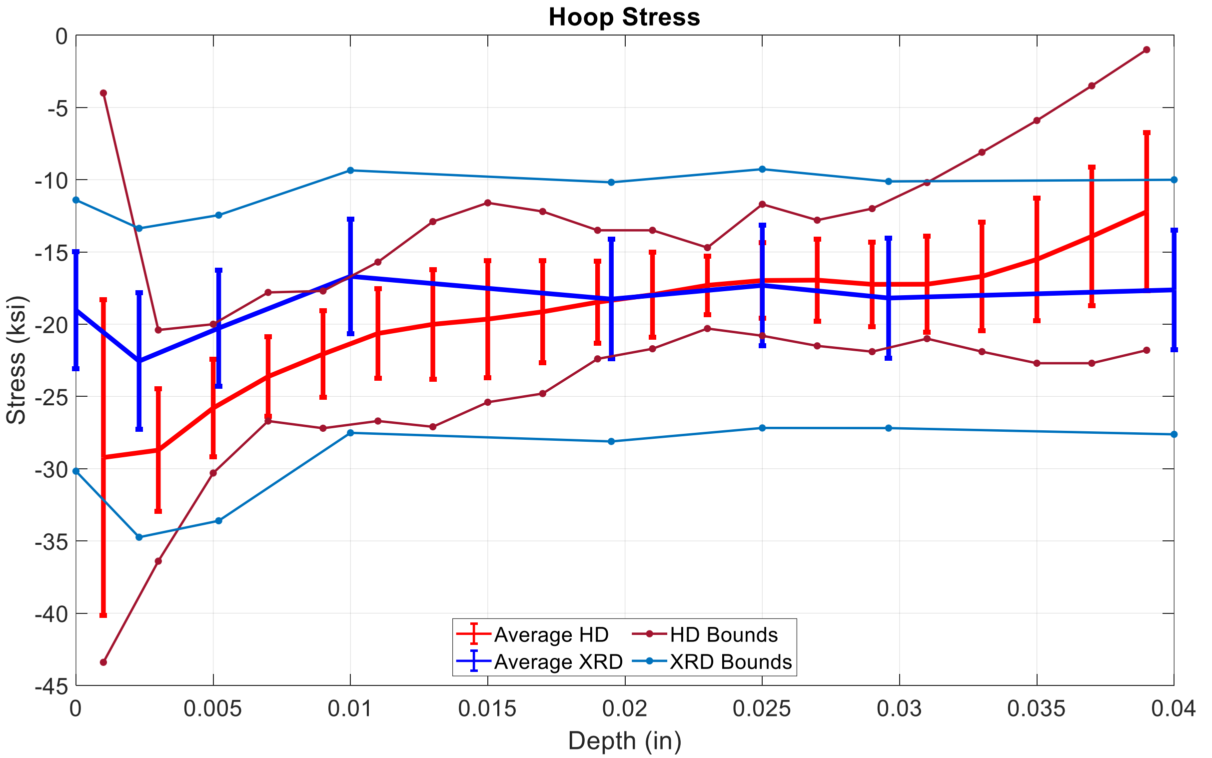
- Average residual stress below cold worked layer plotted versus angular position for both RSHD and XRD.
- Clear oscillatory trend observed in both RSHD and XRD data (as seen in XRD full field polar maps i.e. 90º out of phase).
- Effect of upstream fabrication residual stresses and/or anisotropy to be investigated:
  - a) micro/macro etching to determine rolling direction of 304SS plate.
  - b) perform EBSD/RUS to determine anisotropic characteristics
- Strain gauge and remove plug from ring to confirm interference RS applied as compared to designed interference at time of assembly.



RSHD\XRD on 304SS Ring-Plug Specimen

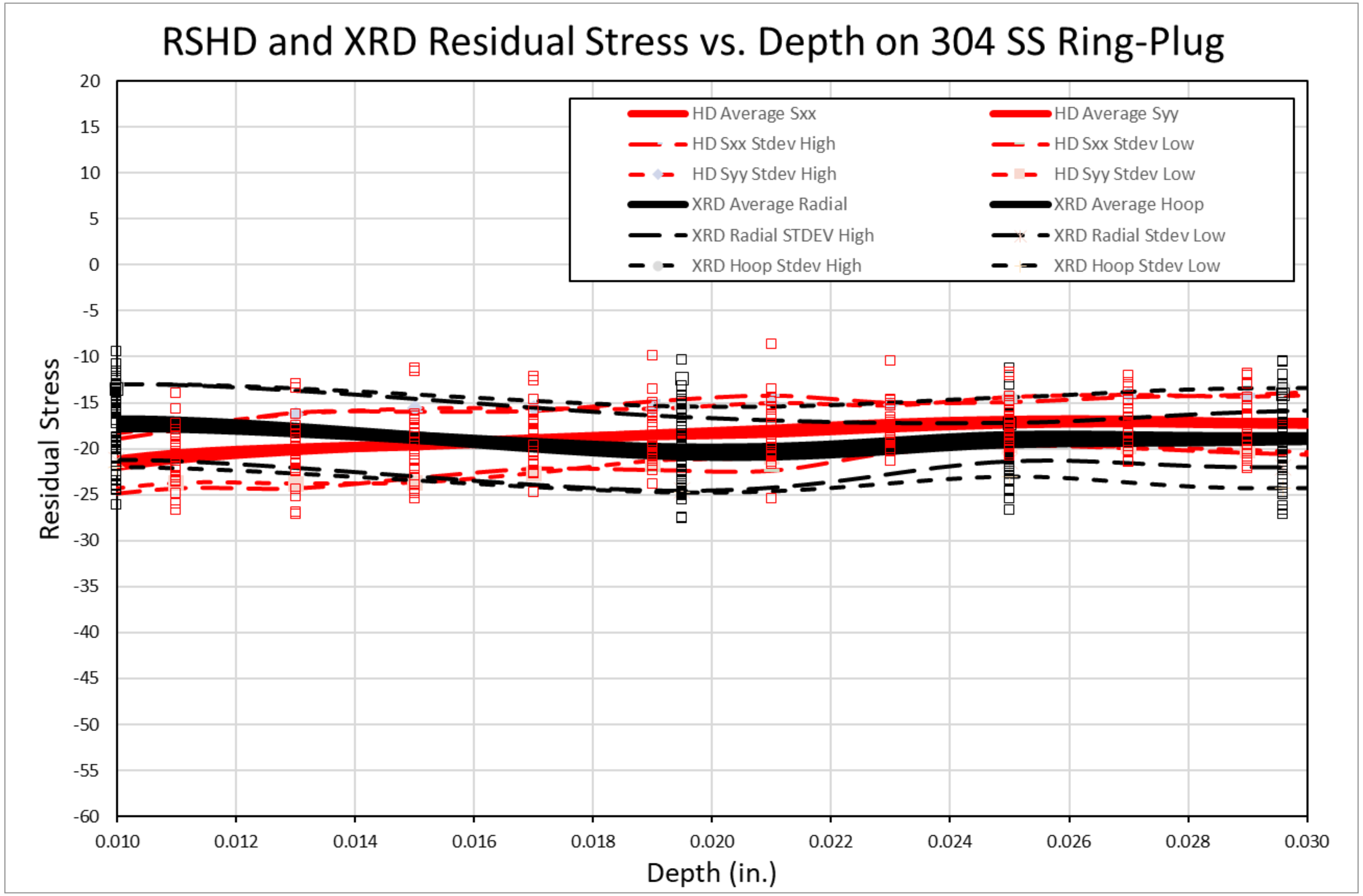
- Average residual stress versus depth from surface for RSHD and XRD
- Error bars calculated from standard deviation of all locations at a specific depth
- Bounds representative of minimum and maximum values at each depth (any location) for each method





RSHD\XRD on 304SS Ring-Plug Specimen

- Considered data <u>below</u> cold worked near surface region in the high confidence depth range for RSHD.
- XRD and RSHD results nominally equivalent despite measurements performed on opposite sides of 304SS Ring-Plug.
- Random errors one may typically expect from either RSHD or XRD shown via max/min bounds and standard deviations (nominally equivalent ~ ± 5ksi).
- Real baseline RS variances can be a factor as per observed oscillatory data.
- Underscores the need for statistically significant data sets (i.e. multiples) when grain size is relatively coarse using either RSHD or XRD.

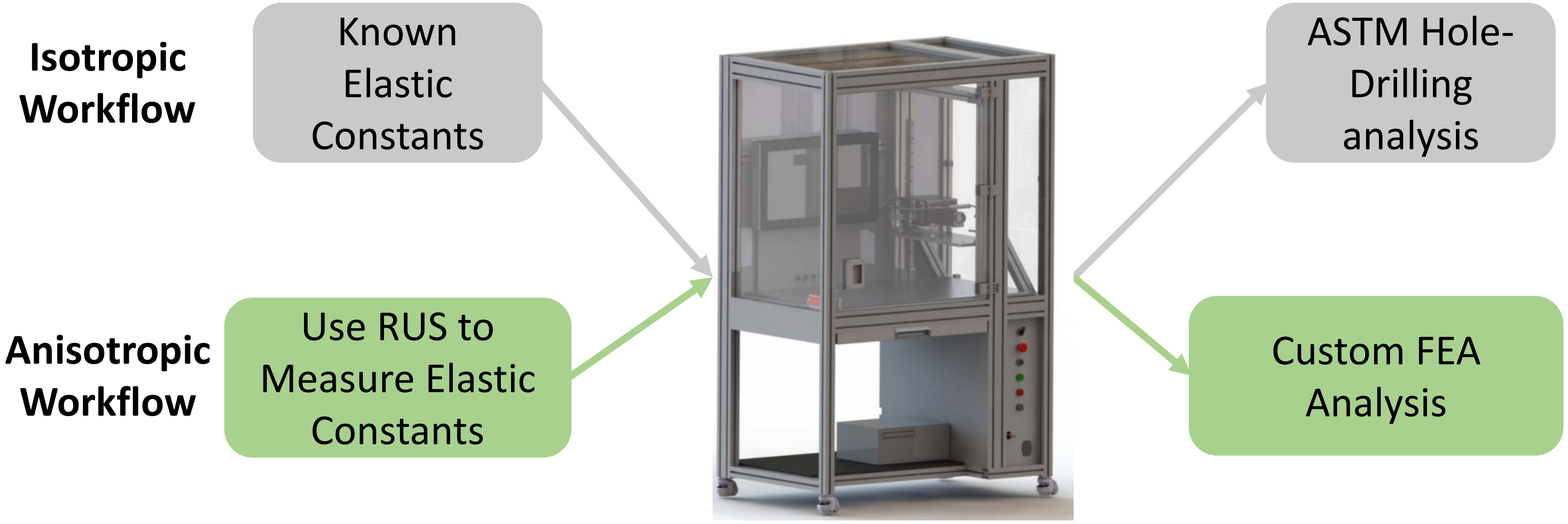


Summary of Round Robin

- Comparable data between RSHD and XRD, with the understanding of limitations of either method
- Finalized workflow for ring-plug specimens, including data collection using RSHD and XRD
- With the heavy lifting of workflow complete, ring-plug specimens fabricated from anisotropic materials is the next step

Future Work

- Validation of RUS inversion algorithm by comparing to traditional mechanical testing
- Looking at additively manufacturing samples with high degrees of anisotropy for residual stress measurement
- Writing up the round-robin measurements of aluminum ring-plug discussed last year
- Derive/Design a workflow to incorporate elastic anisotropy into RSHD



Accomplishments

- Conducted two round-robin studies of ring-plug samples
- Conducted residual stress hole-drilling (RSHD) measurements on textured ring-plug sample
- Developed an FEA tool to simulate RSHD

Harmonizing Contour and XRD Residual Stress Measurement Data Sets

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The Proposed Approach
(recap on work done so far)

A Novel Approach to Integrating Residual Stress Determination Methods

2023 Aircraft Airworthiness & Sustainment Conference

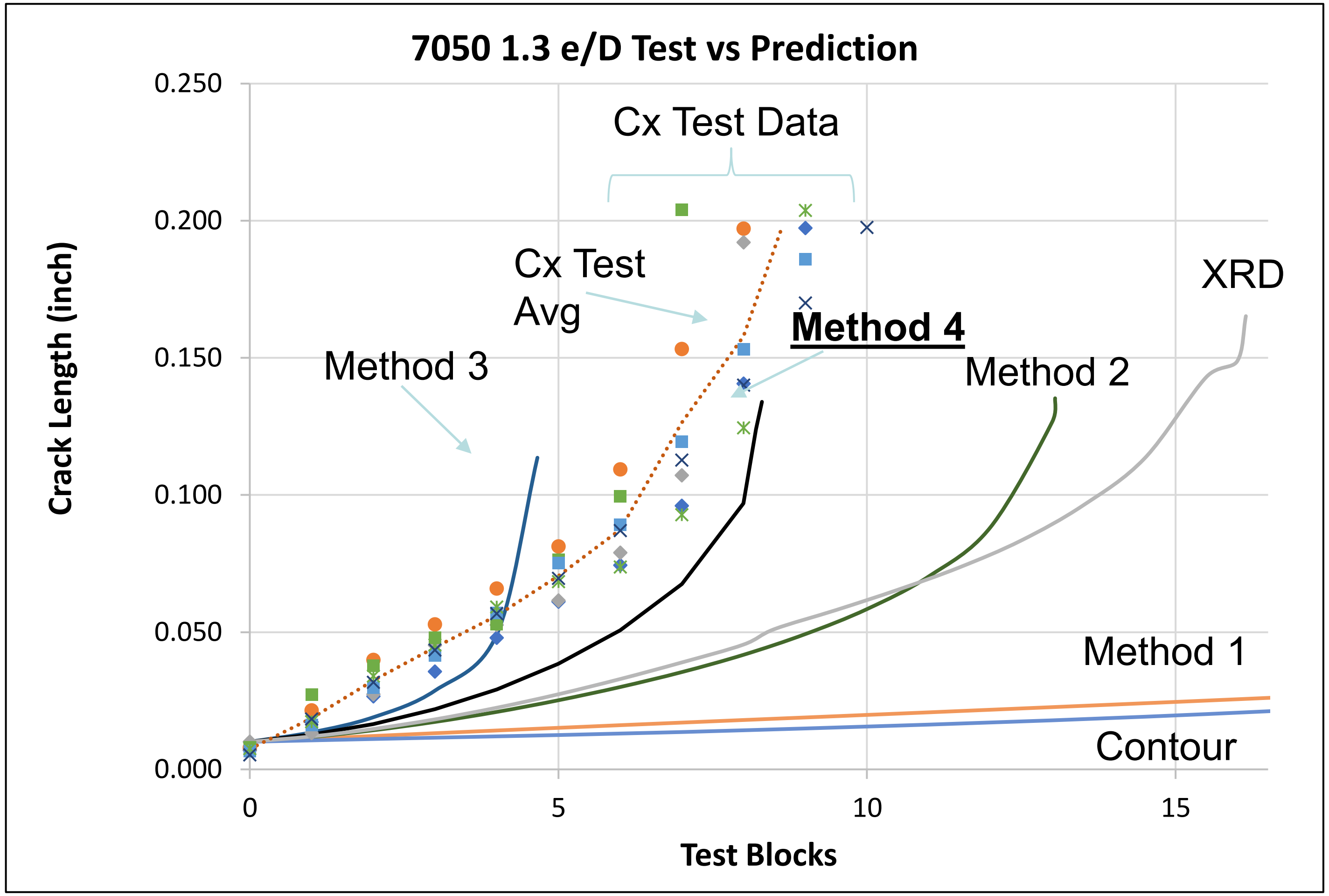
30 August 2023

James Prather: Presenter
Dr. Scott Carlson: Co-Author
F-35 Service Life Analysis Group

LOCKHEED MARTIN

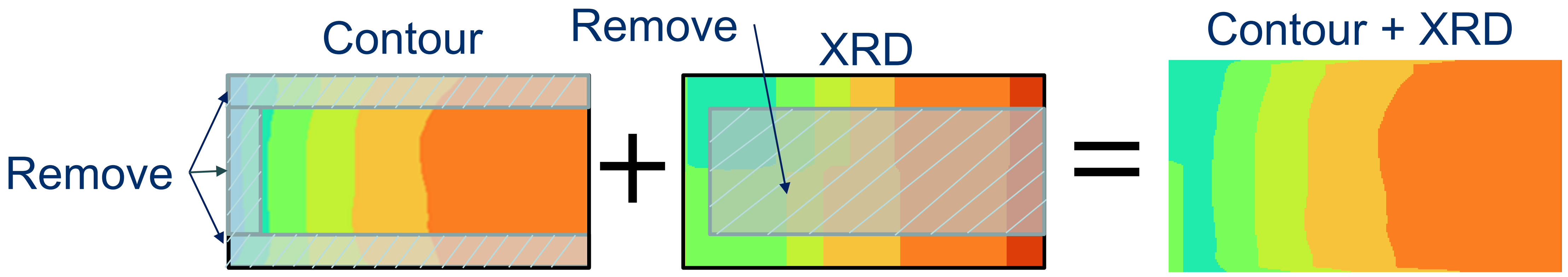
FCG Life Predictions: XRD and Contour (All 4 Methods)

- **Same LEFM-based FCG analysis applied using each method's resultant residual stress profile as input**
  - Both XRD alone and Contour alone are unconservative
  - Both Methods 1 and 2 are unconservative
  - Method 3 is slightly conservative
  - Method 4 closely predicts the average test life and would provide reasonable initial and recurring inspection intervals



Integrating Datasets

(But I still like Method 2 in principle)

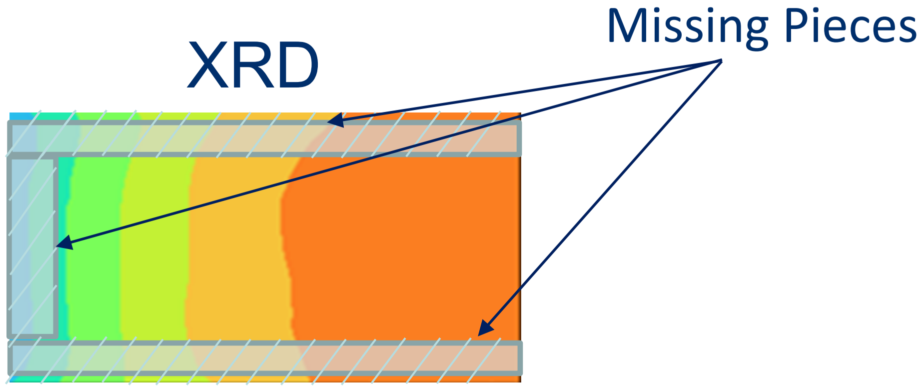


"Stitching" the datasets together where research literature claims they are most accurate

Leverages benefits of each method while removing areas of limitations

Why was Method 2 Unconservative?

I would posit some of the key pieces of the puzzle were missing?



We need these missing pieces of data.

The Proposed Approach
For Proof of Concept: Leverage Data Sets Already Available on GL Coupons

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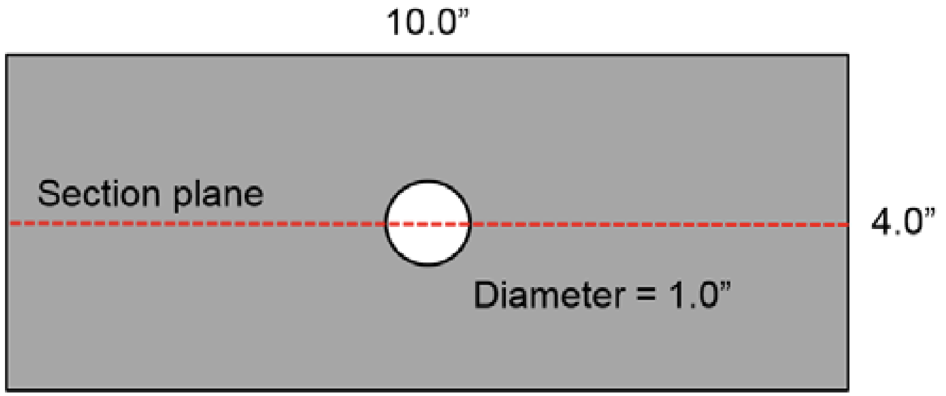
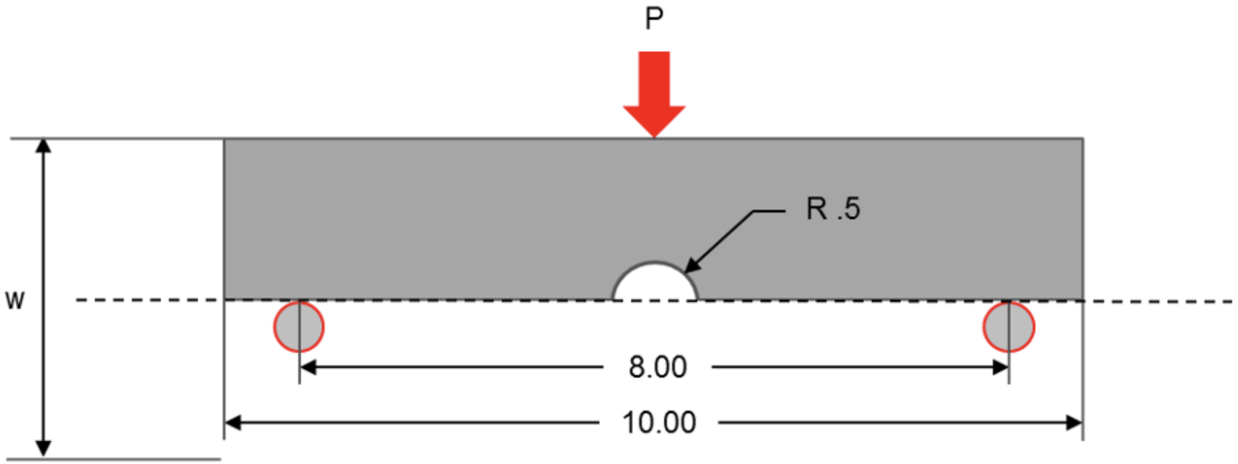
Case Study #1 - Geometrically Large Coupons

- Larger coupons scale-up the stress field to facilitate residual stress measurements using any method
- Full and split configurations
- Split configuration allows XRD access to bore ID but requires a correction for relaxation due to splitting
- XRD arc-averaging reduced to ± 45° on the face – must be accounted for if coupon is split.





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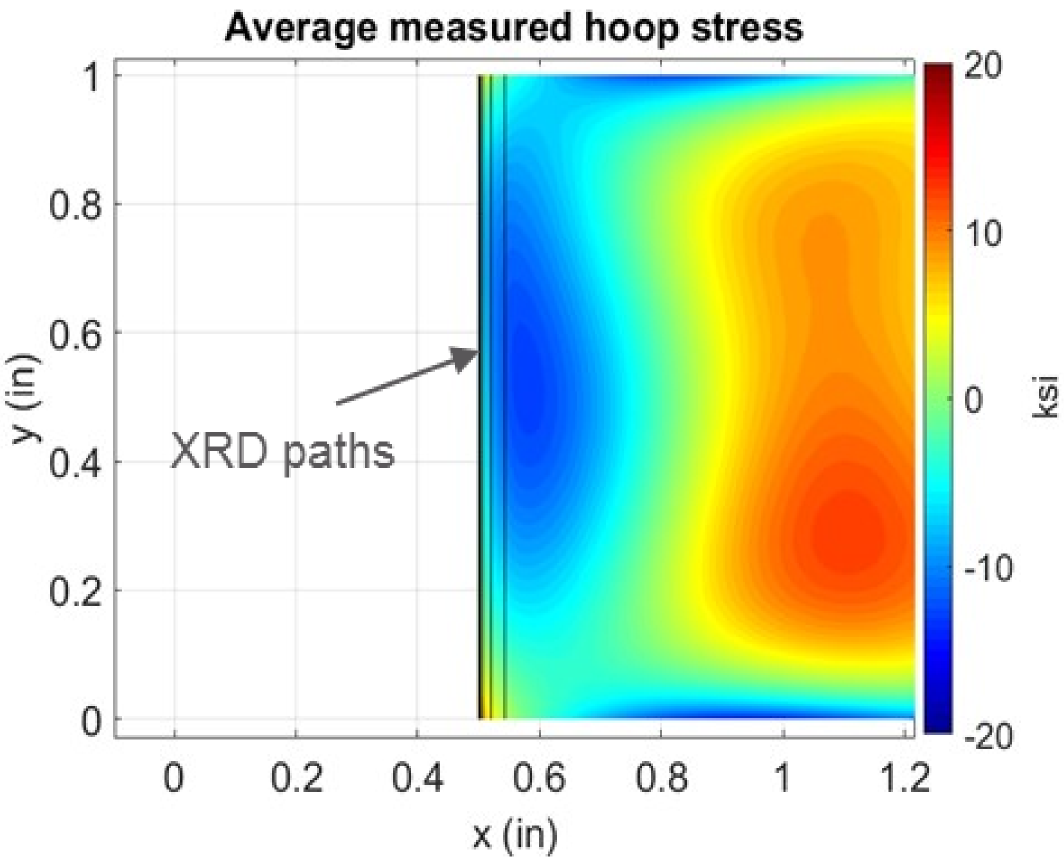
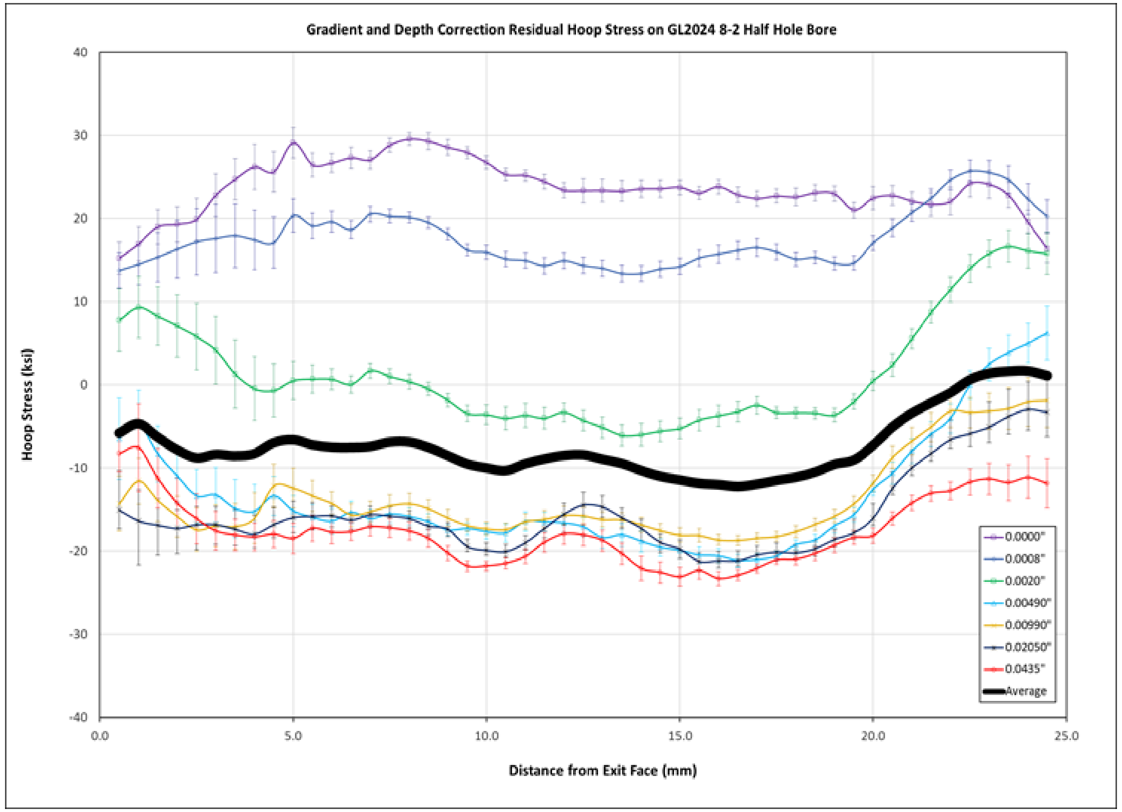
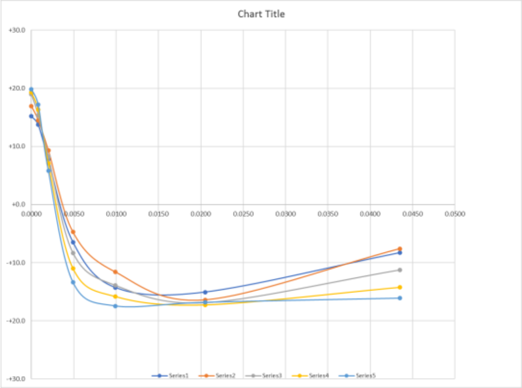
RS in Bore of Cx Hole in Geometrically Large Coupon

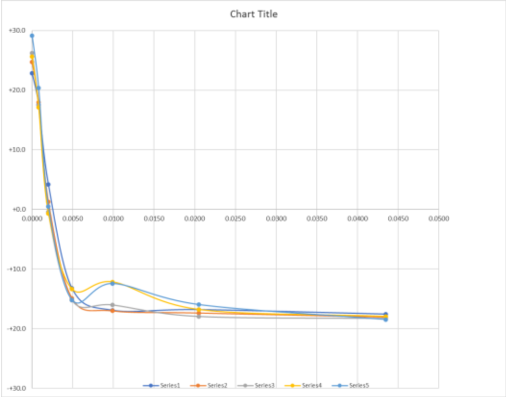
- Once a correction is available for splitting coupons for access to the bore, residual stresses can be measured via XRD – this correction can be obtained by either Contour data, strain gage data, or both.
- XRD + electropolishing can be used to get data on the bore to be stitched together with the Contour data.

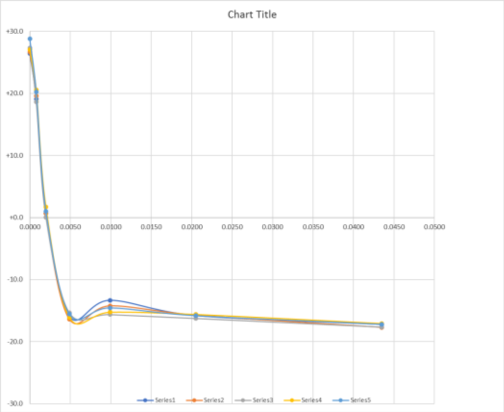


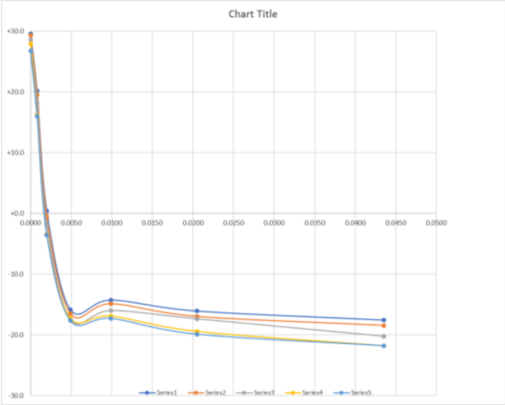


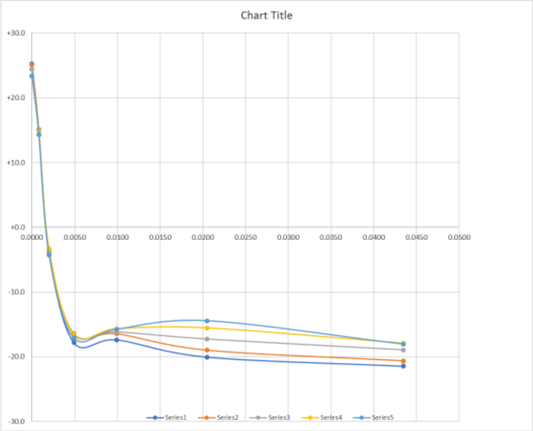
RS in Bore of Cx Hole in Geometrically Large Coupon – Depth profiles at individual points across the bore

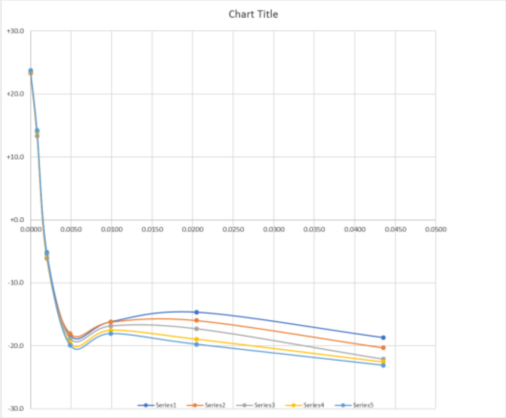


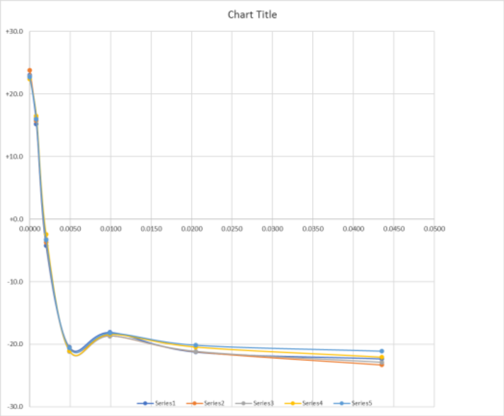


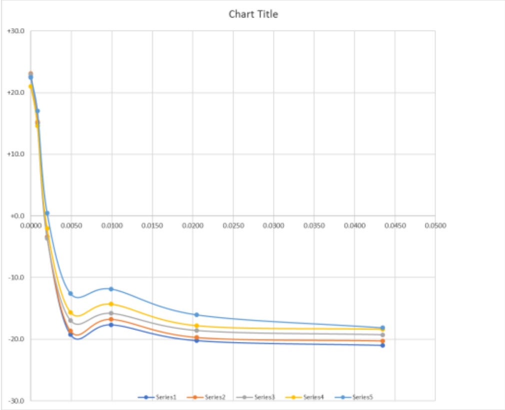












Note: Near surface cold working RS persist to about 0.010” deep

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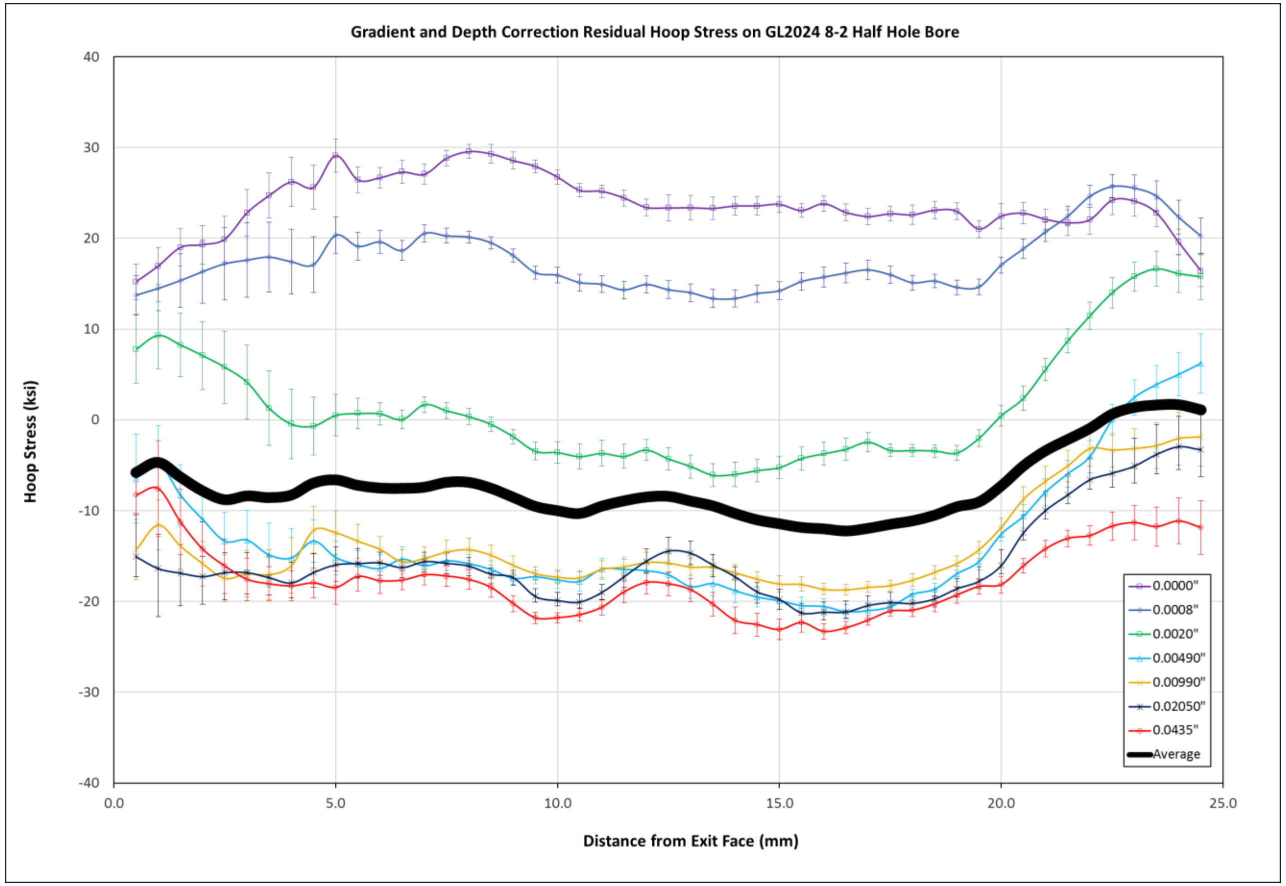
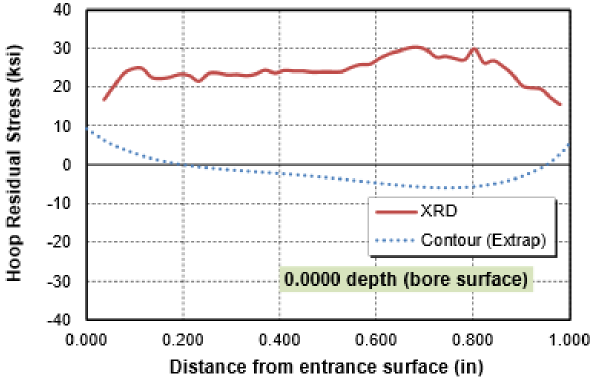
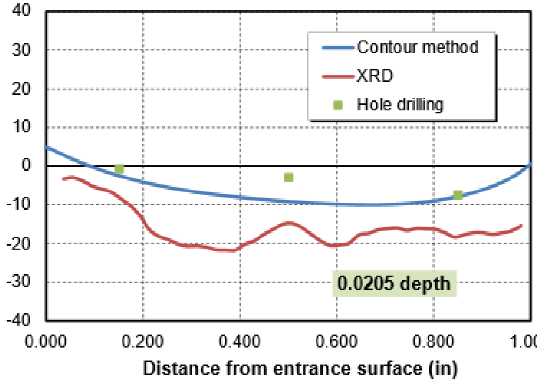
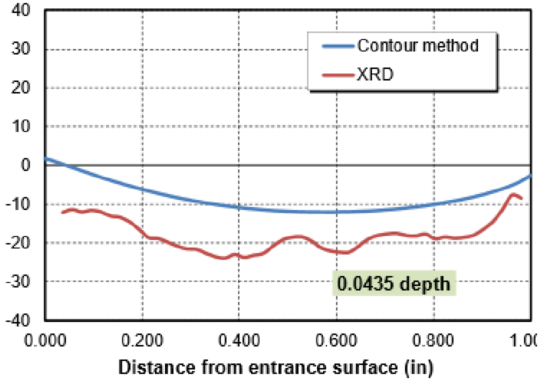
X-RAY DIFFRACTION

RS in Bore of Cx Hole in Geometrically Large Coupon XRD, Contour & Hole Drilling









PROTO X-RAY DIFFRACTION

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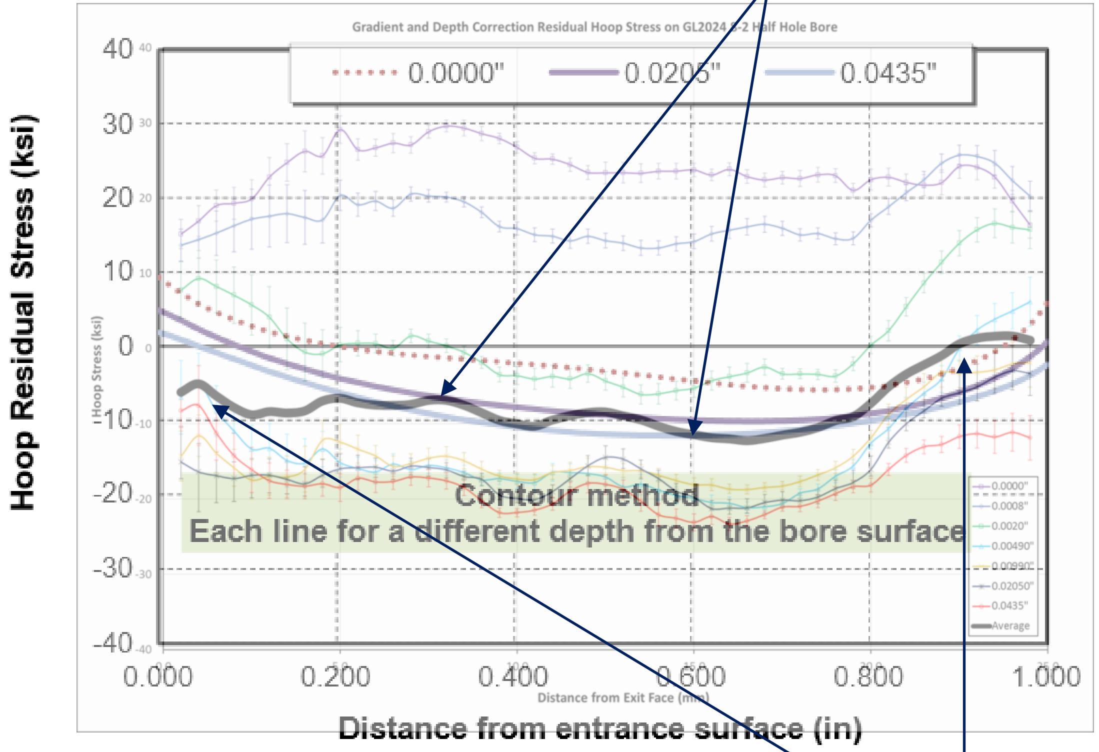
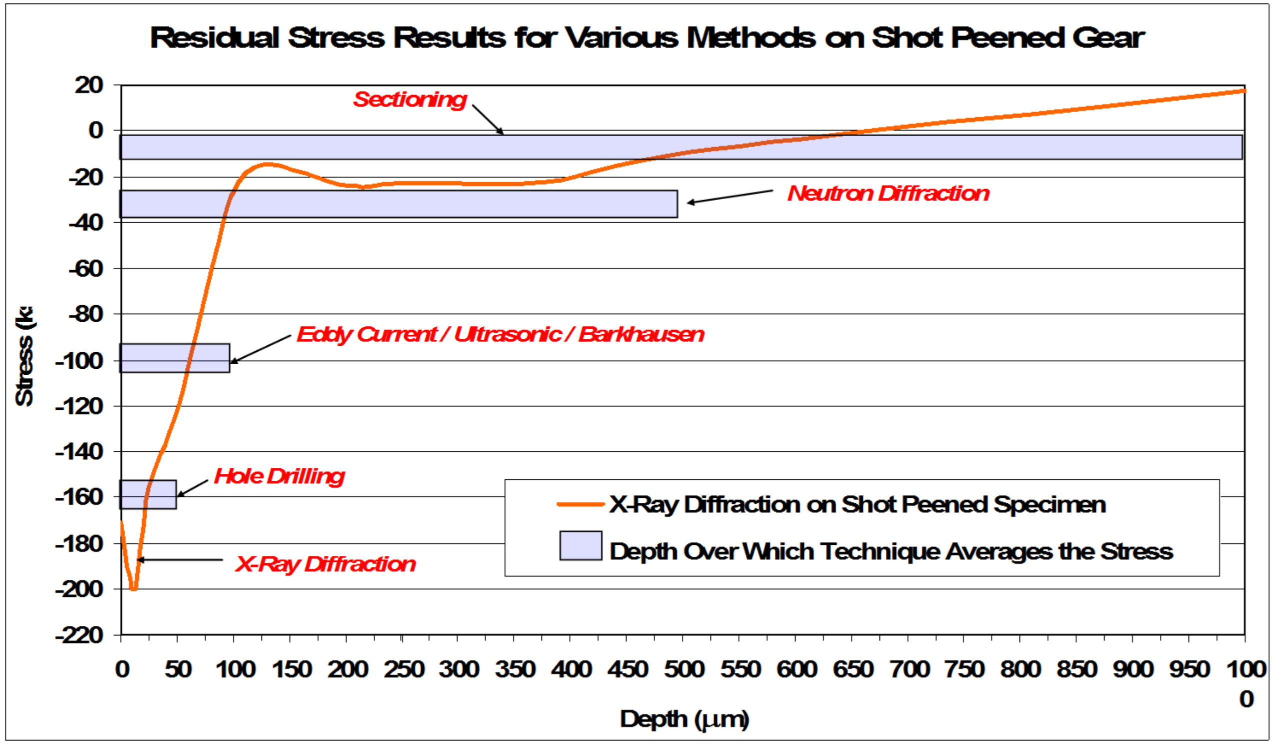
RS in Bore of Cx Hole in Geometrically Large Coupon
Inter-method considerations – yes, the world is round!

"pretty good" agreement in the center





"Ok" agreement near ENT and EXT faces

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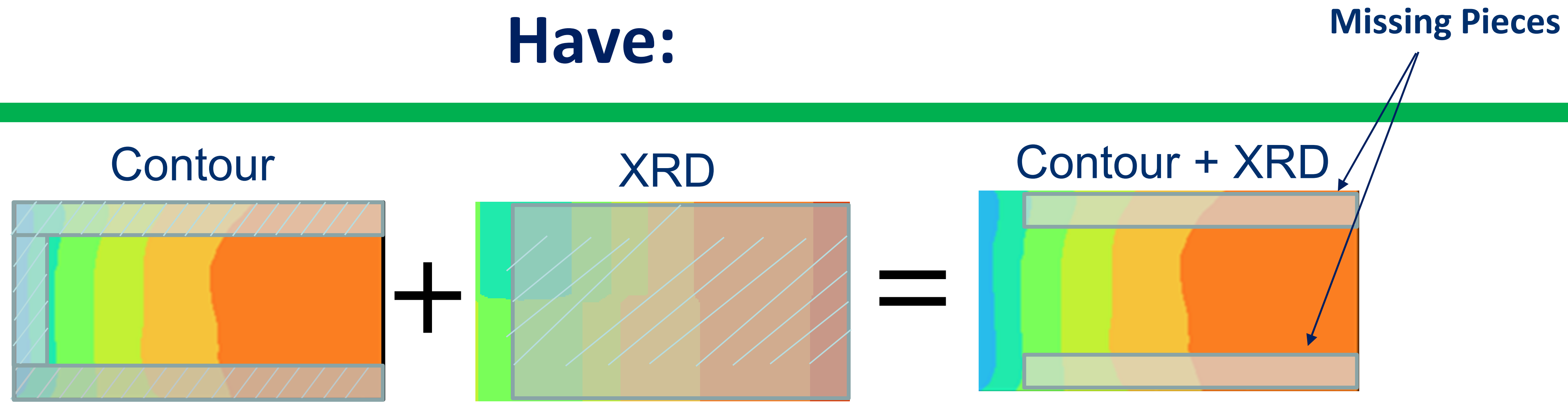
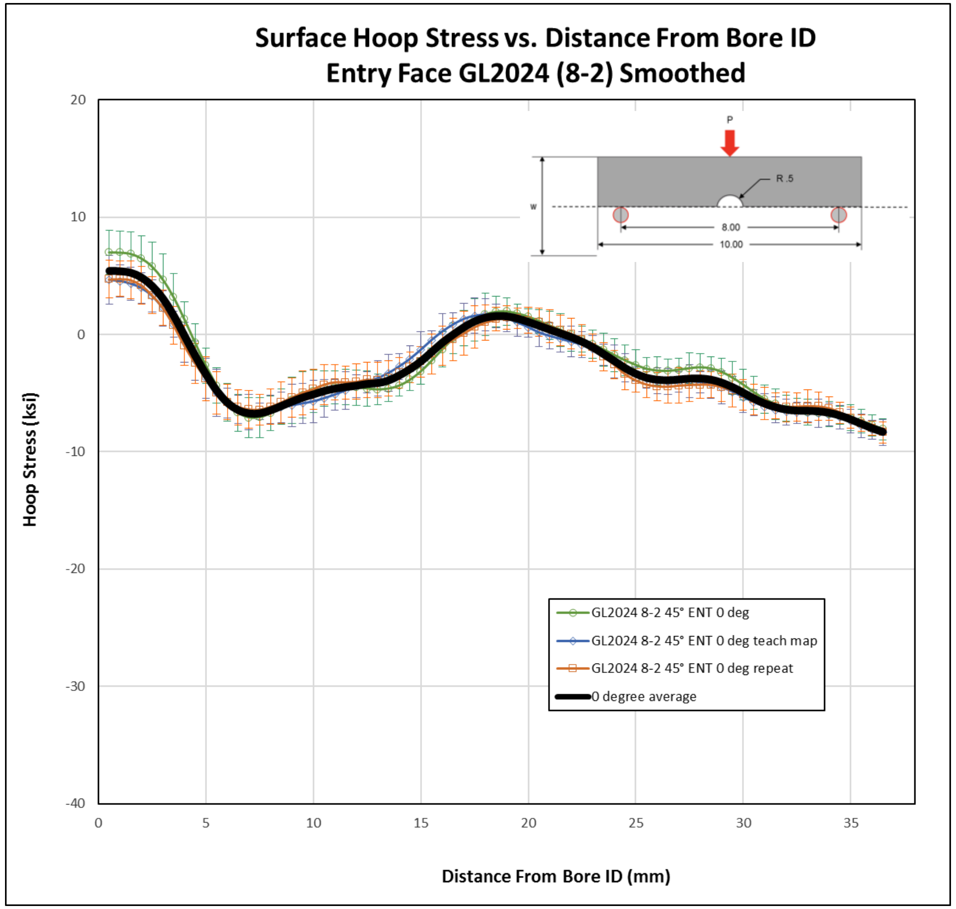
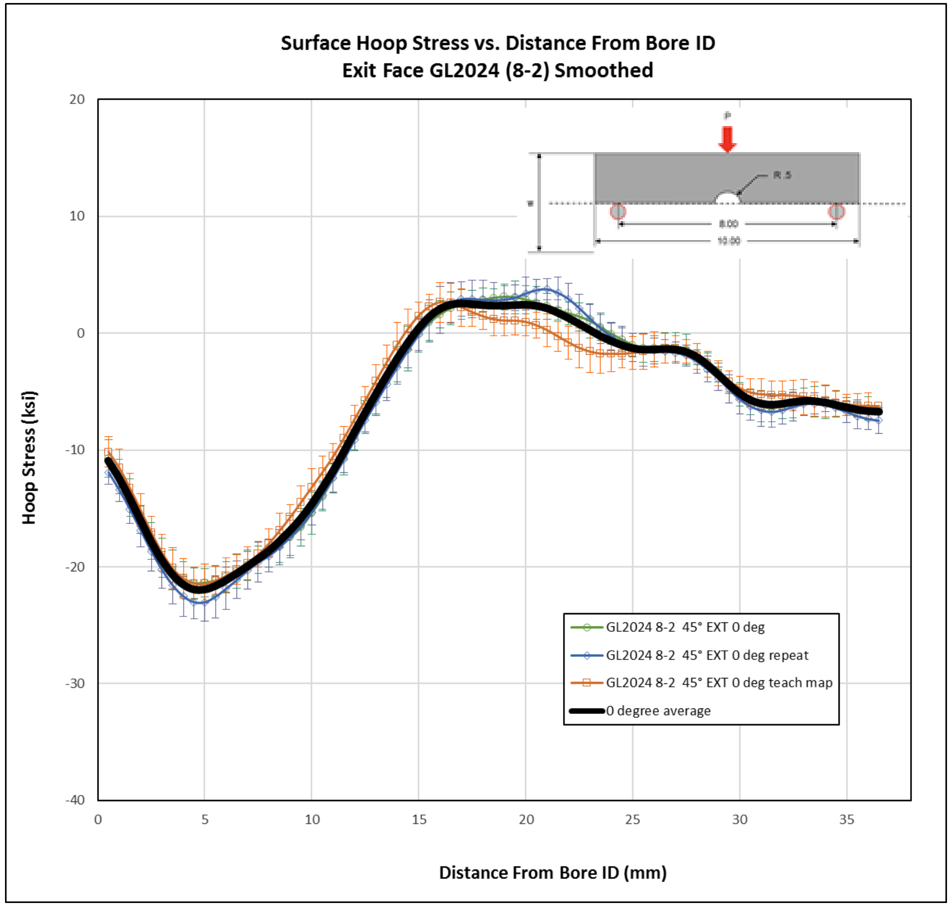
X-RAY DIFFRACTION

Method 2 - With XRD Bore ID Data, We Now Have:



RS on Faces of Geometrically Large Coupon - Split





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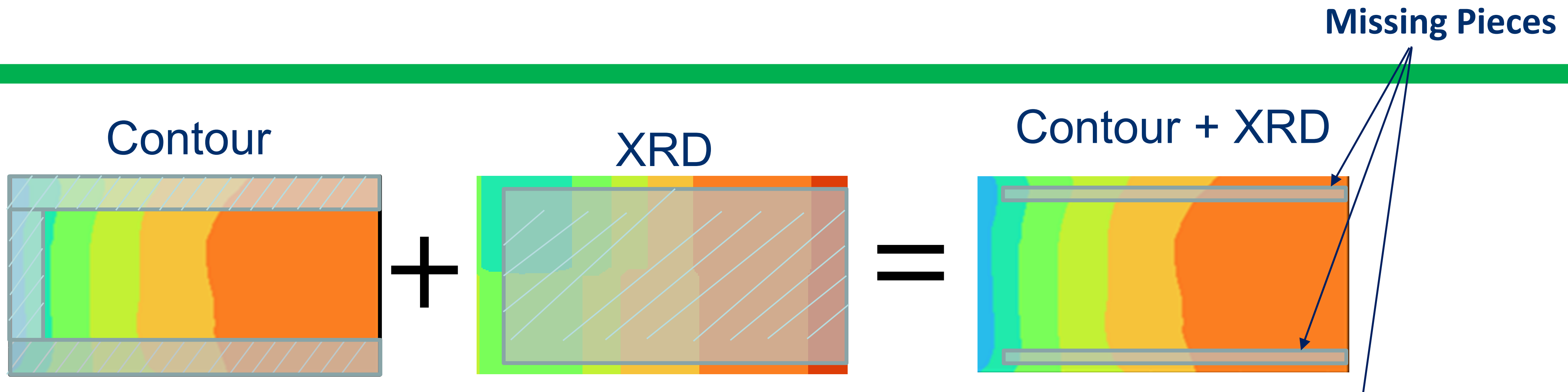
X-RAY DIFFRACTION

Method 2 -With XRD Bore ID & Face Data, We Will Have:



… and the coupon from which to obtain the last pieces of the puzzle.

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Predict. Test. Perform.

PROTO
X-RAY DIFFRACTION

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The Proposed Approach (moving forward):

1) Proto to collect final data sets required to create a full field harmonized XRD + Contour RS data set.
2) Provide XRD & Contour data with GL coupon geometry & latest corner crack loading to FCG model predictions folks (blind study).
3) After blind predictions are made, compare FCG predictions to known corner crack loading FCG rates for the GL coupon configuration and loading.
4) Afford FCG model prediction folks the opportunity to revise chosen data harmonizing methods if required and re-analyze.

- Hill Engineering will provide the relevant Contour RS data, the loading and coupon information, and measured corner crack loading FCG rates after blind predictions are made.
- Proto will provide the XRD RS data.

Challenges:

1) Codify/formalize a method by which the splitting of coupons to access the bore can be corrected – leverage available Contour data and/or introduce strain gage or deformation data to account for relaxation where necessary.
2) Account for arc averaging in XRD data as may be required due to grain size where necessary and improve deconvolution methods to get optimal spatial resolution (i.e. Moate and Sprauel methods)
3) Codify/formalize methods of harmonizing XRD & Contour RS data sets for FCG predictions.
4) Note: crack growth work done to date has limitations, because the analyses are two-point analyses(?) that can be biased regardless of the data being used for residual stress.
5) The “Proposed Approach” appears to have <u>potential</u> but needs to be further investigated (i.e. the blind study that comes at the end).

FYI: 2x2 Group is working on a similar approach – more on that to come

Effects of Cutting Sequence & Restraint on Contour Method Residual Stress Determination in Cx Coupons

2024 ERSI Workshop – San Antonio, TX

LOCKHEED MARTIN

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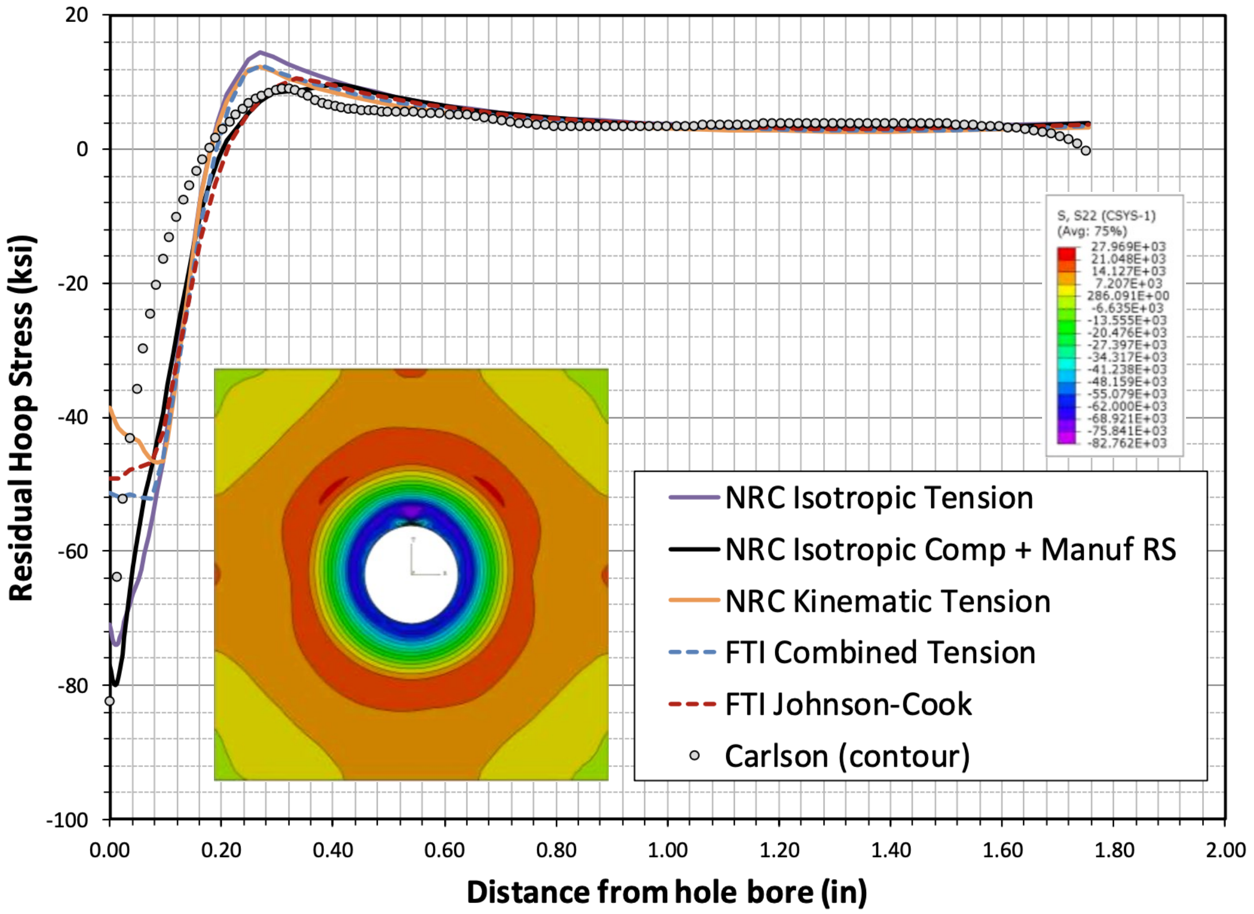
  - www.stress-space.com
- Ho Kim - ho.kim@open.ac.uk

stress-space Ltd

esa business incubation centre UK

Cx Stress Characterization Requirements

- It is required to determine, with high certainty, the distribution of hoop residual stress approaching the bore of a cold expanded hole in order to take full benefit of the ”engineered residual stress” condition.



- A 2016 NRC-FTI-SwRI benchmark exercise comparing Cx residual stress predictions with average contour method data showed significant discrepancies in Cx stress profiles up to 5 mm (0.2”) from the bore.

- Characterizing the residual stress field of interest by modelling and measurement remains challenging today!

Factors Affecting Cx Residual Stresses

- Test coupon geometry (representing the structure of interest).
  - Dimensions
  - Hole diameter
  - Edge margin
- Manufacturing history
  - Consequences of rolling (surface residual stresses and material texture)
- Material
  - Elastic properties
  - First cycle non-linear stress-strain behaviour under multi-axial loading
- Loading
  - Level of cold expansion introduced
  - Cx process design

The Contour Method (CM)

- The CM offers the prospect of determining cross-sectional maps of hoop residual introduced by the Cx process in laboratory fatigue test coupons
- But the accuracy of CM residual stress profiles can be compromised by:

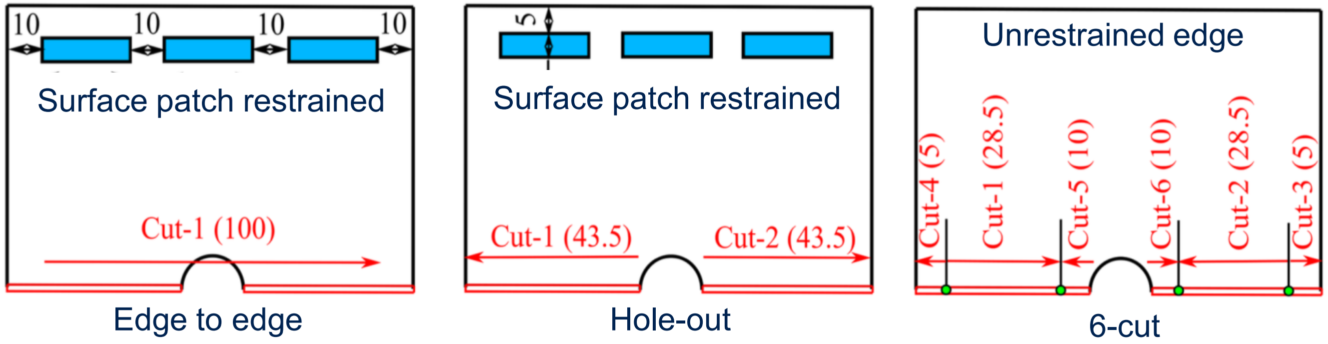
1. Cutting induced plasticity (CIP) error
2. Cutting induced elastic error (referred to as bulge error)
3. Cutting wire anomalies when exiting a sample
4. Wire feed entry/exit cutting artefacts
5. Wire EDM cutting anomalies (breaks, barrelling, steps, instabilities etc)
6. Metrology and data processing methods

- Factors 4 to 6 can be mitigated by good measurement practice
- Factors 1 to 3 can be managed, and potentially mitigated, by controlling the **contour cutting sequence** and **boundary conditions**

CM Accuracy Assessment - Detailed

- Simulate the residual stress field introduced by the Cx process for the specific coupon design, manufacturing history, cold expansion and materials of interest.
  - Create 3D FE model of coupon and perform an elastic-plastic stress analysis for a uniform through-thickness radial expansion applied to the bore of the hole. This introduces a representative residual stress profile at mid-thickness and a surface average profile.
- Perform a series of elastic-plastic FE analyses simulating progressive CM cutting of the modelled Cx coupon in order to predict plastic strains (PEEQ) introduced along the cut path and the surface displacement.
  - Compare PEEQ profiles from different CM cutting sequence/boundary conditions.
  - Apply the predicted surface deformation profile to an elastic FE model of one half of the coupon to simulate the CM determined stress profile. Compare this profile with the initial simulation of the Cx stress field to quantify any error.

Assessment Results for ERSI (5x4)" Coupons

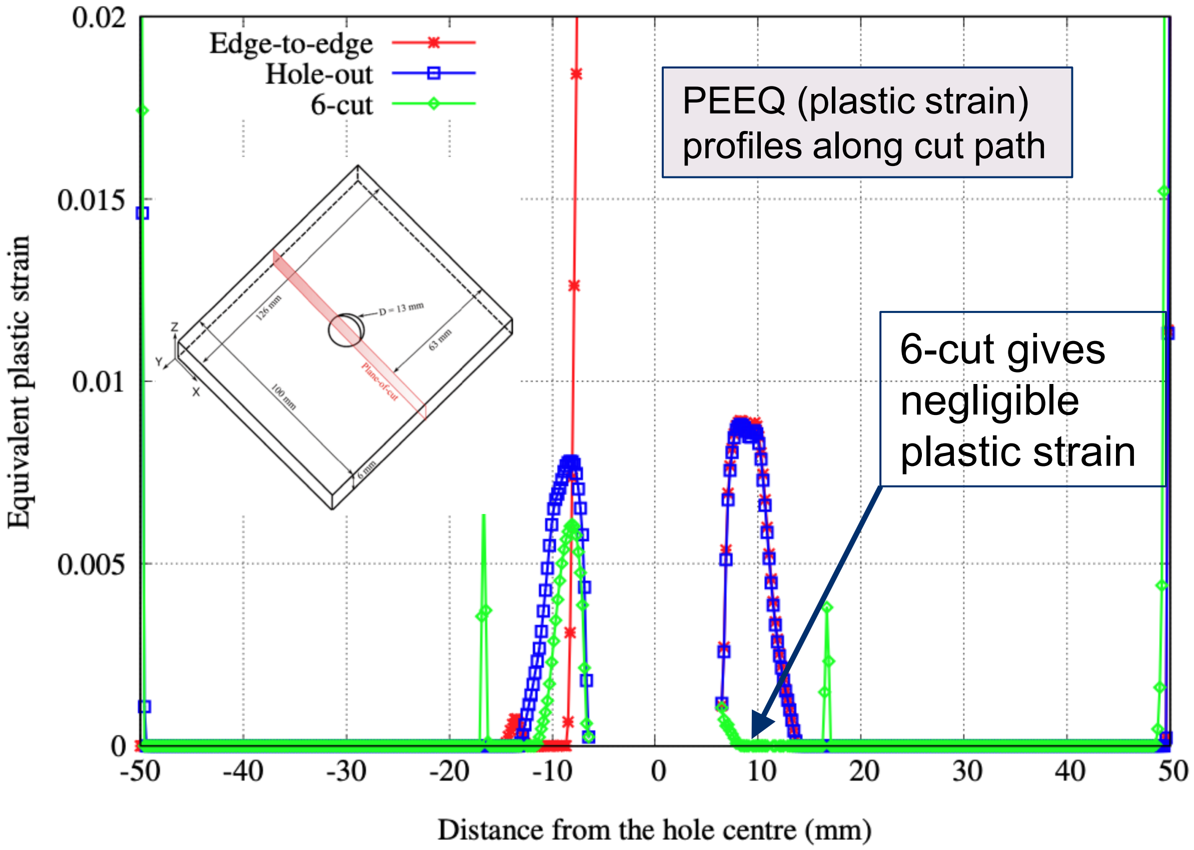


https://doi.org/10.1007/s11340-021-00756-z

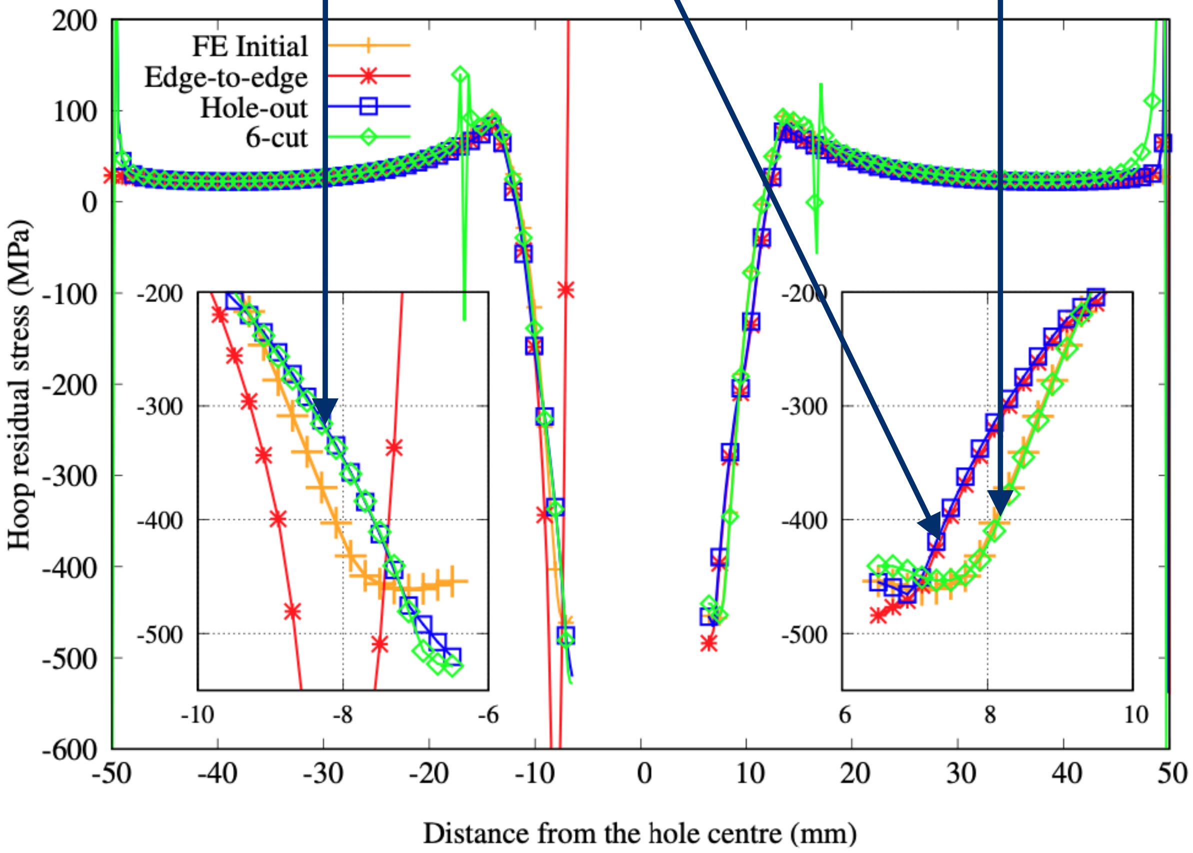
6-cut and hole-out best on LHS

Hole-out 2nd best on RHS

6-cut gives accurate RHS stress profile

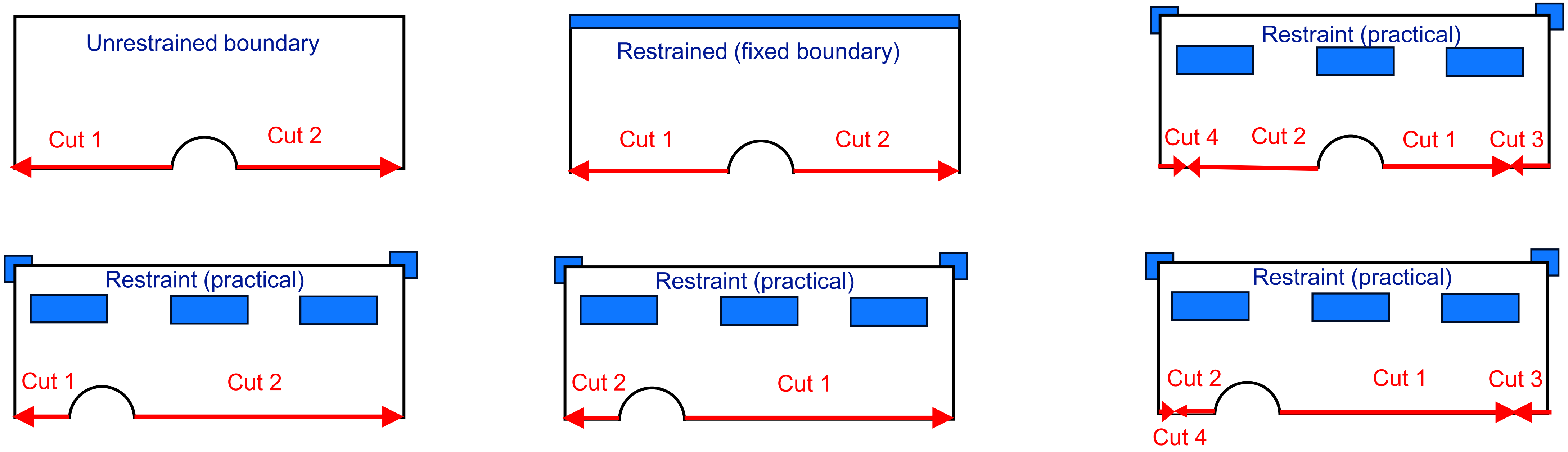


6-cut gives negligible plastic strain



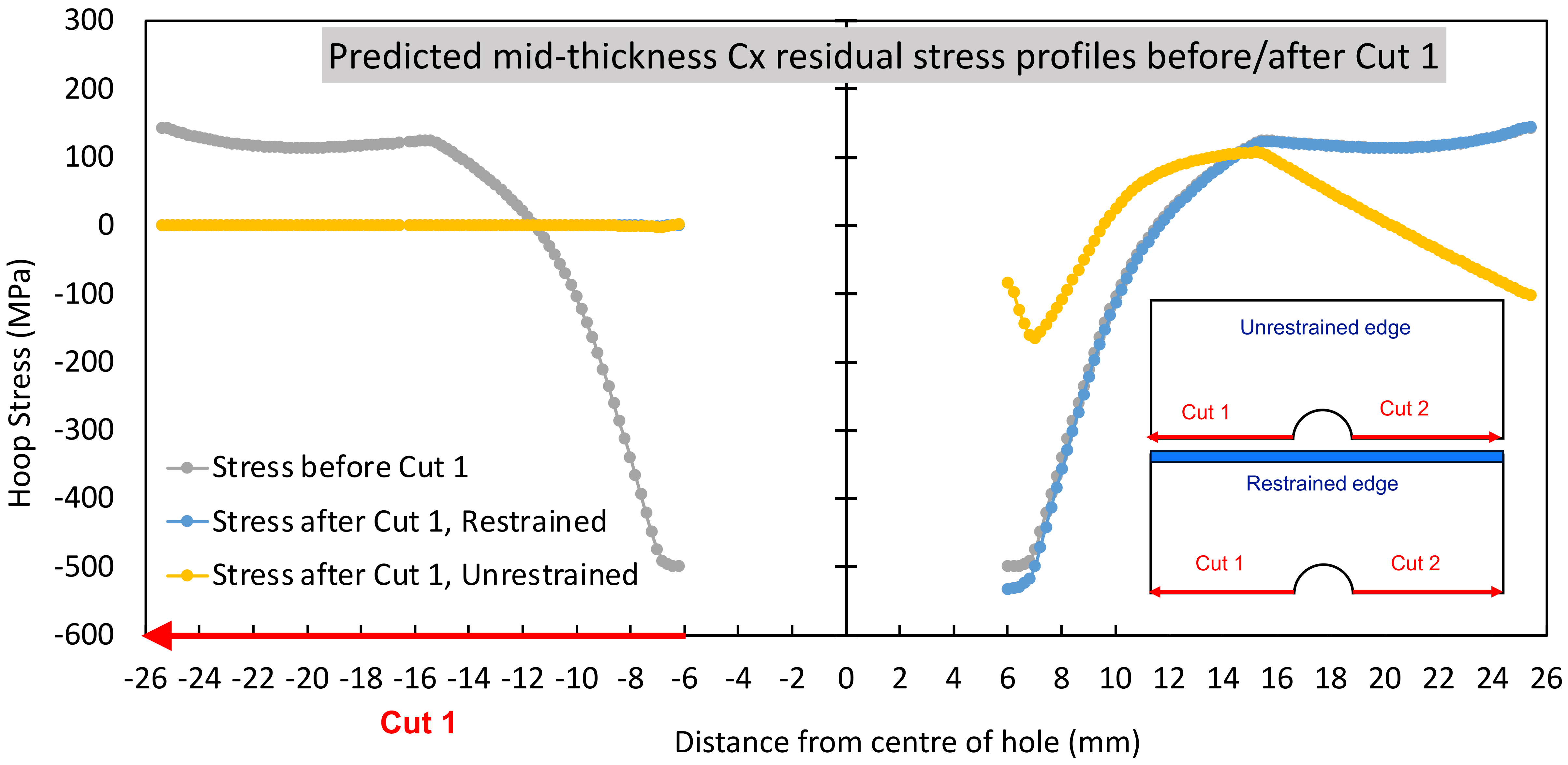
CM Cut Sequencing and Restraint

- Cutting induced plasticity (CIP) arises when stresses ahead of the CM wire EDM cut (a blunt crack) exceed the material yield strength.
- The cut SIF can be used to help select the cutting sequence and coupon boundary conditions that will minimize CIP in the region of interest that can introduce stress errors.

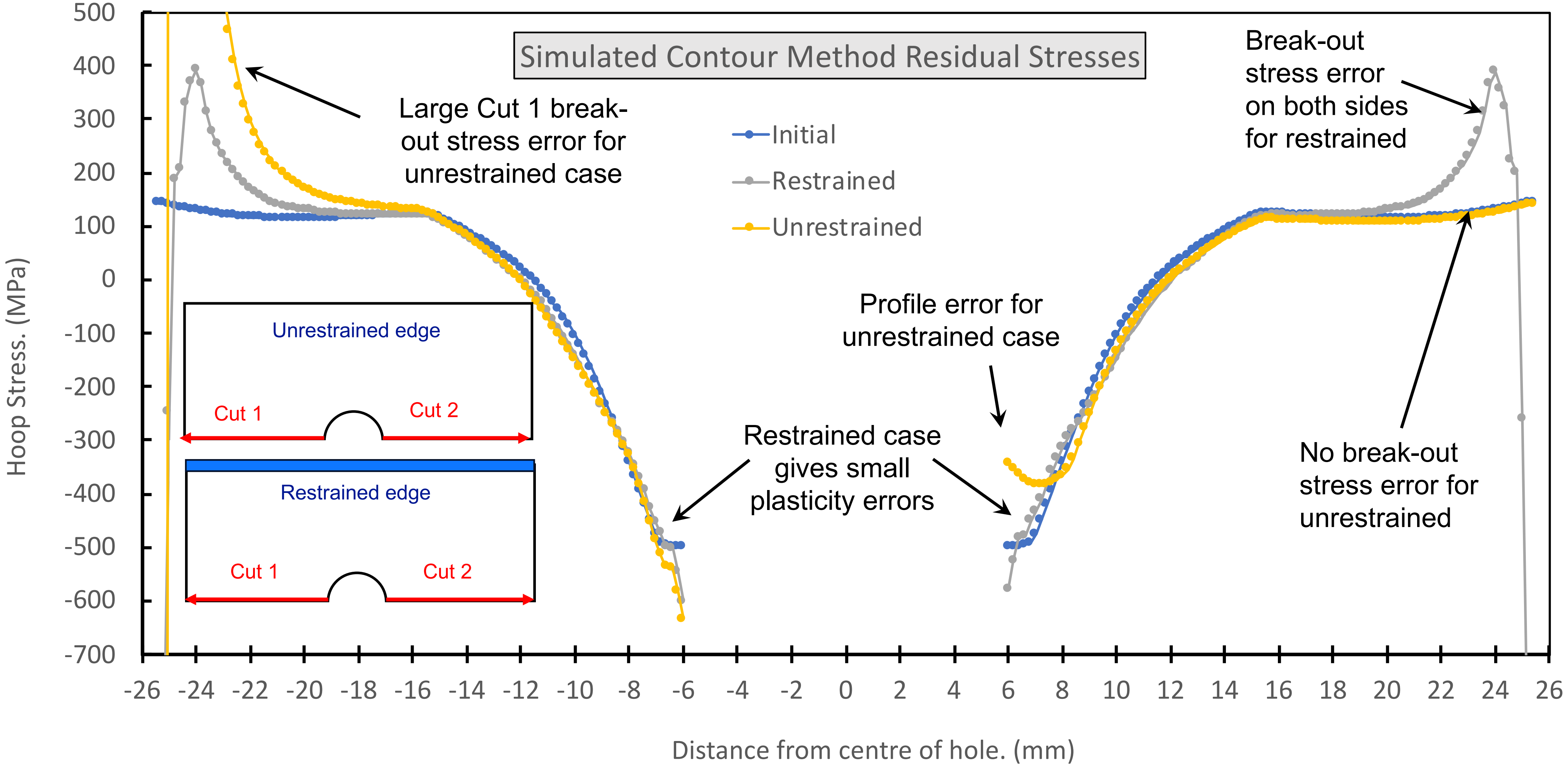


Illustrating some CM cut sequence and coupon restraint options for symmetric and short edge margin coupons

Predicted Stresses in ERSI Coupon 2024 H1

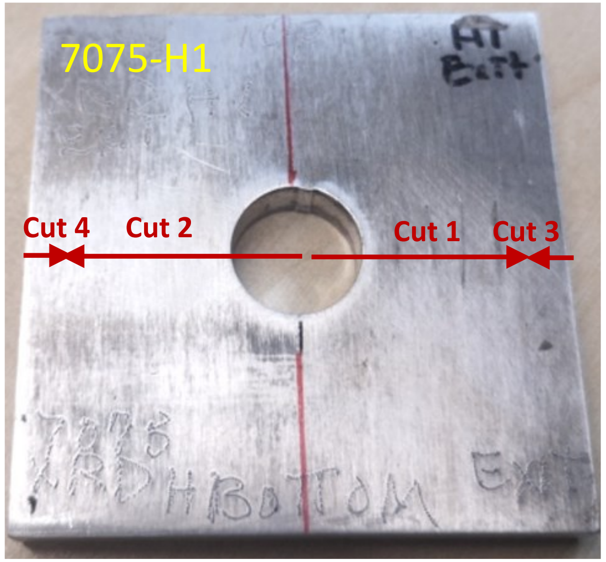


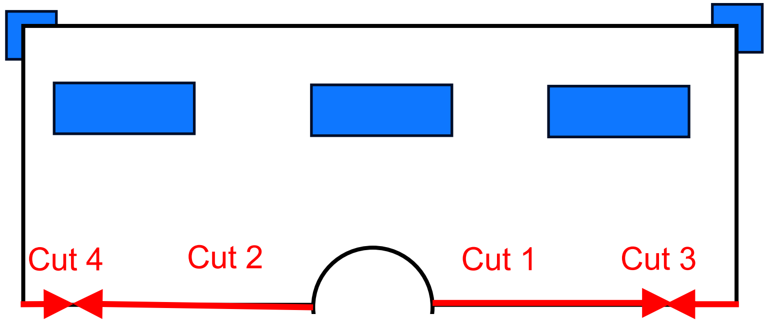
Detailed Prediction of CM Stress Profile

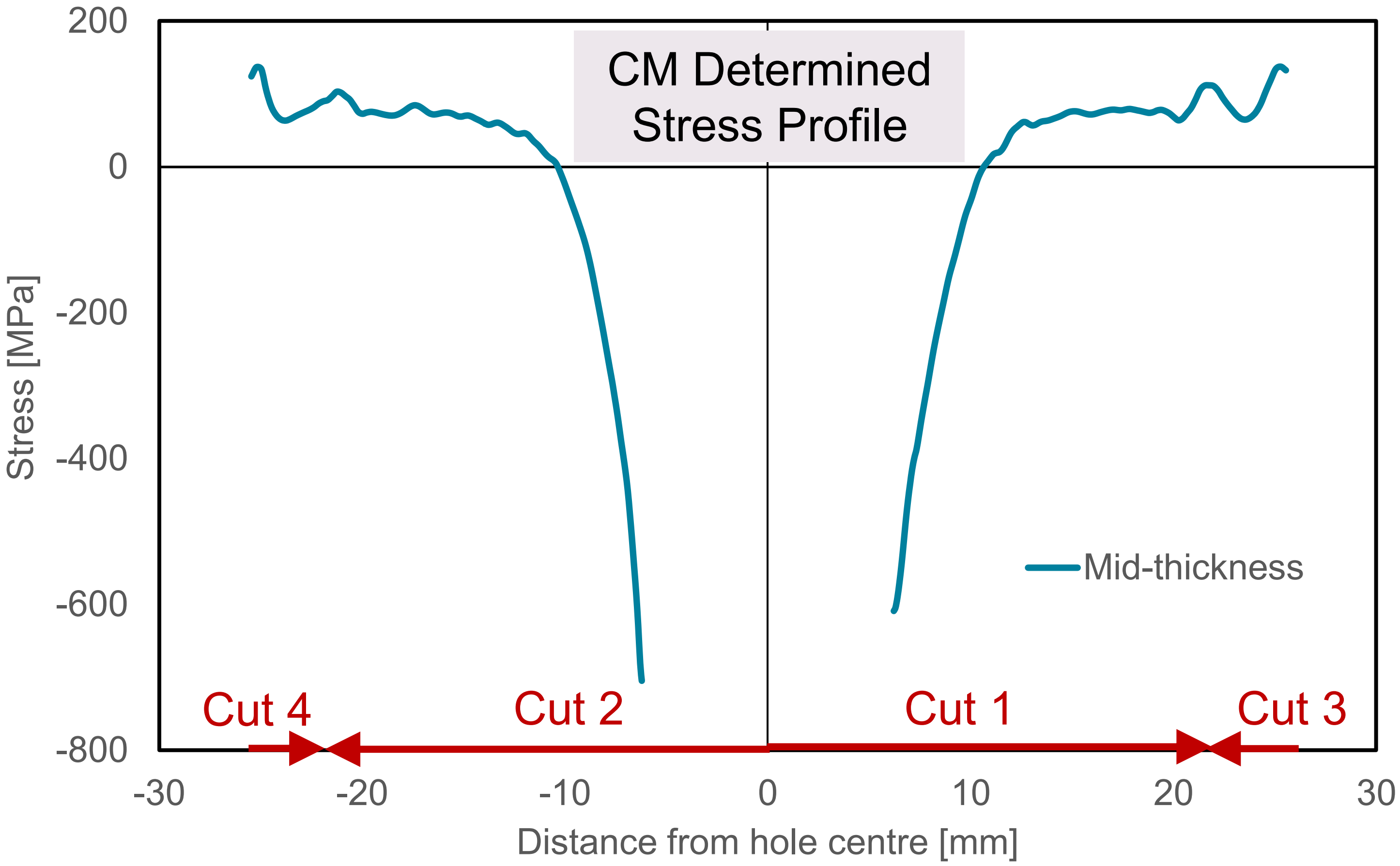


Application of Findings to ERSI 7075-H1

- Fully restrained case is predicted to give most accurate stresses approaching the hole bore.
- Accuracy of stresses near "break-out" can be improved by using a 4-pass cut sequence.







Other Considerations

- The practicality of cutting sequences must be assessed (e.g. the 6-cut sequence is impractical for 2 x 2 inch coupons).
- Avoid cutting sequences where the wire exits the coupon at or near the region of interest (i.e. at the hole). This is because very high stresses and plasticity develop ahead of the cut prior to break-through generating CM displacement and stress errors.
- The practicality of applying restraint conditions during wire EDM cutting of coupons must be considered.
- The smallest dia wire should be used for EDM cutting as this reduces elastic bulge errors (which can be significant in the region of interest).
- Its possible to correct CM determined stress profiles for elastic bulge errors.

Insights into the Testing of Sleeveless Cold Expansion Processes *(Why we must be specific and "words mean stuff")*

2024 ERSI Workshop – San Antonio, TX

Presented by: Scott Carlson
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Acknowledgements

- Brian Yeang (LM Drilling Tech) – Brian.Yeang@lmco.com
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Tool EDTI Engineering

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PROTO X-RAY DIFFRACTION

Agenda for Presentation

- Motivation for Sleeveless Cx Implementation
- Mechanics of Sleeved vs. Sleeveless Cx Processes
- FEA Simulations of Residual Stress Profiles
  - XRD results of Ent. and Ext. surfaces
- Effects of Applied Expansion on Crack Growth Life
  - Crack growth life differences in original matrix
    - Nominal vs. Tailored applied expansion levels
- Effects of Expansion Methods on Cracking Morphology
  - “Entrance” and “pinning” effects on crack formation and propagation

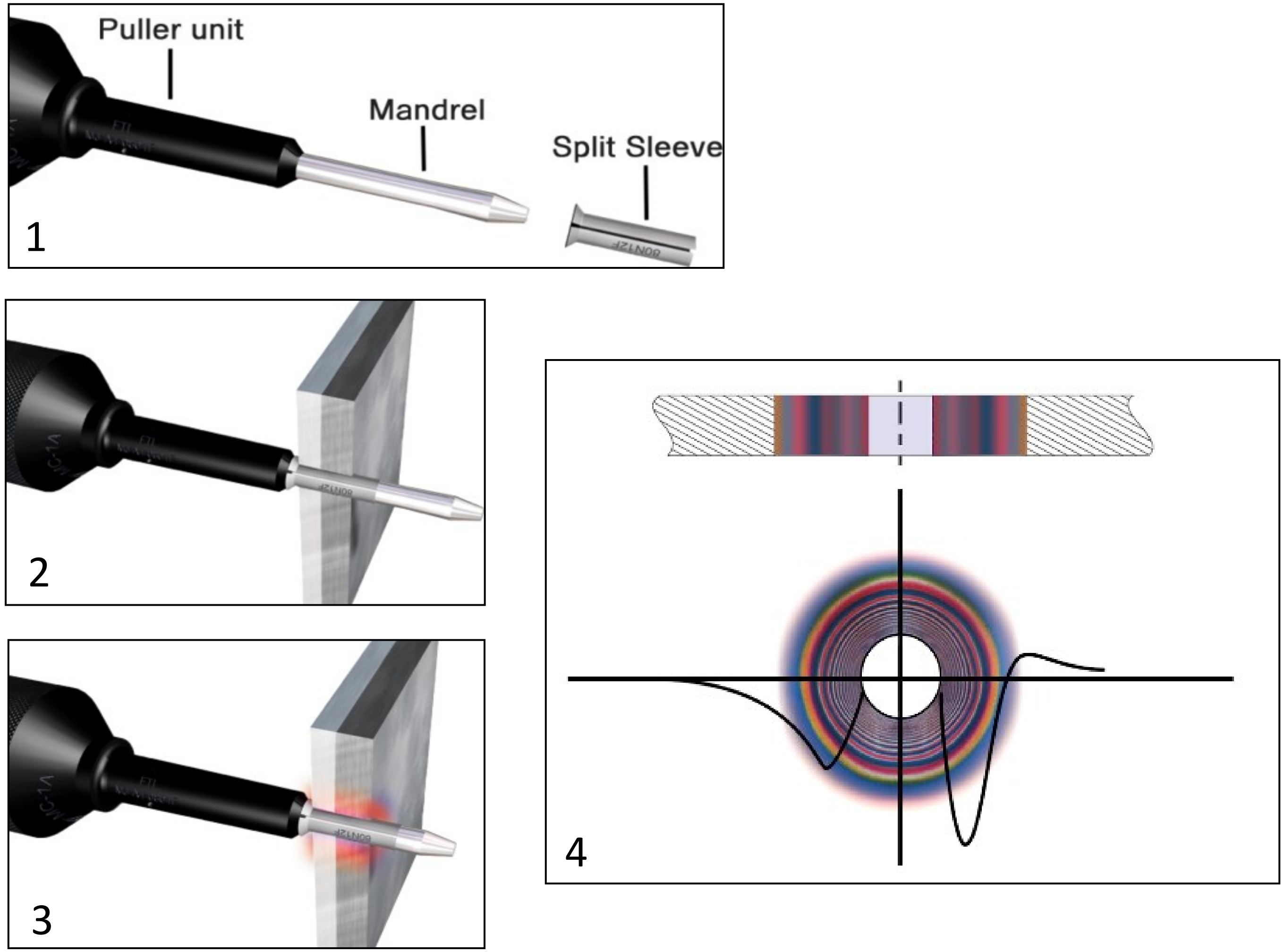
Motivation for Sleeveless Cx Process

- Cx is Often Used During Production to Meet Life Requirements
- Potential for Automation of Cold Expansion Process
  - Very challenging to have a robot insert the split sleeve
    - Sleeveless would allow a "one-step" Cx process
    - Would eliminate the sleeve clocking requirement
  - Application of the Cx process requires significant touch hrs.
    - Multiple steps during the drilling and reaming process
    - Requires additional de-stack and deburr steps
    - Clocking orientation for the sleeve can require Eng. Approval
- Unlocks the Potential to Drill, Cx and Ream with 1 Tool
  - Dramatic decrease in process time for manufacturing

Split Sleeve Cx (SsCx) Process

Split Sleeve Cold Expansion

- Legacy Cold Expansion process first conceptualized in 1969
- Proprietary lubricated split sleeve is key component in the process
  1. The split sleeve is slipped onto the mandrel, which is attached to the hydraulic puller unit.
  2. The mandrel and sleeve are inserted into the hole with the nosecap held firmly against the workpiece.
  3. When the puller is activated, the mandrel is drawn through the sleeve, radially expanding the hole.
  4. Residual Compressive stresses induced from the split sleeve cold expansion process improve in-service fatigue life.



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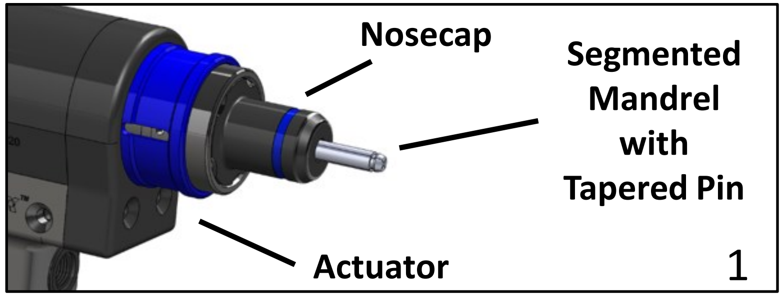
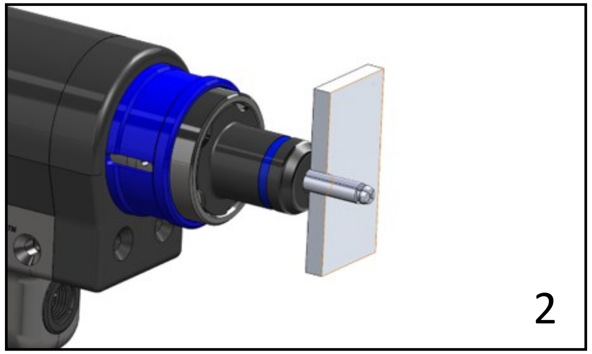
SmartCx (SmCx) Process

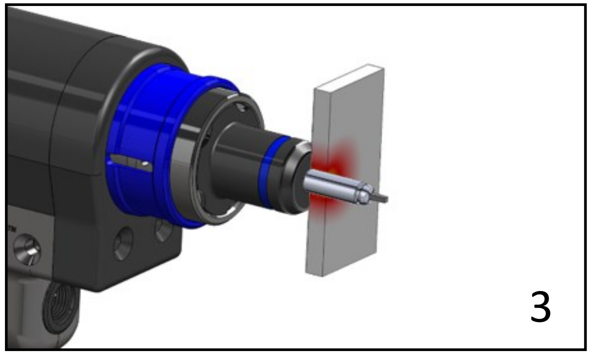
SmartCx Cold Expansion

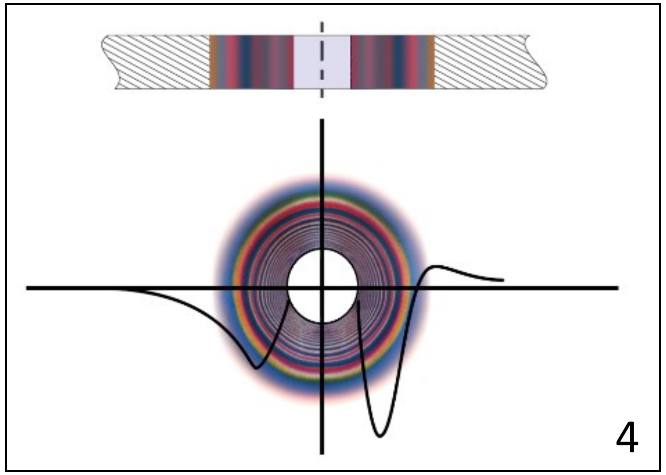
- New Cx process to provide a variable expansion, “sleeveless” solution for Cold Expansion
- Proprietary segmented expansion mandrel is the key component in the process:

1. The segmented mandrel and tapered pin are attached to the actuator and “tuned” to the required expansion.
2. The segmented mandrel is inserted into the hole with the nosecap held firmly against the workpiece.
3. When the actuator is activated, the piston pushes the tapered pin into the segmented mandrel, causing the mandrel segments to spread outward, radially expanding the hole.
4. Residual Compressive stresses induced from the SmartCx cold expansion process improve in-service fatigue life.









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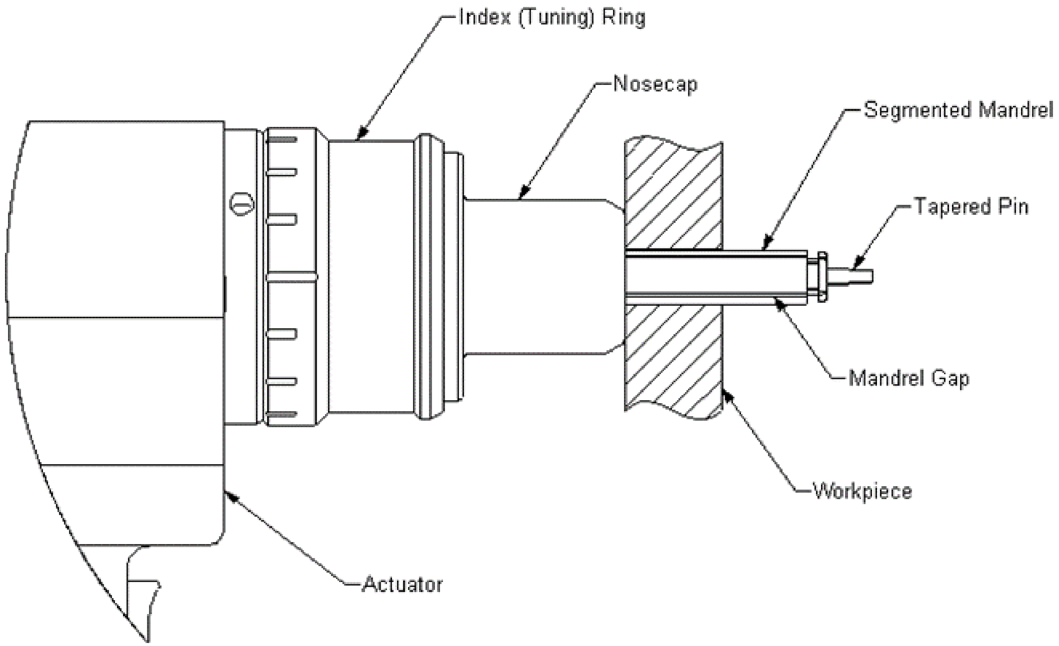
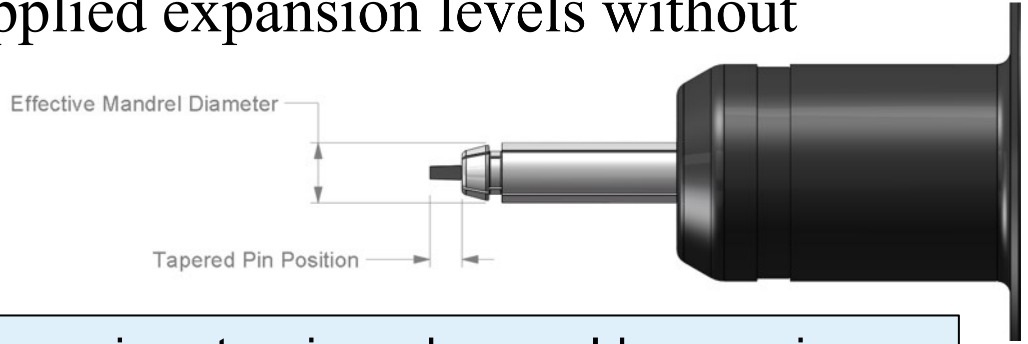
SmartCx Adjustable Expansion

Applied Expansion is variable by adjusting a “tuning” ring on the tool. Adjustments change the position of the segmented mandrel relative to the tapered pin, thus changing the Effective Mandrel Diameter.

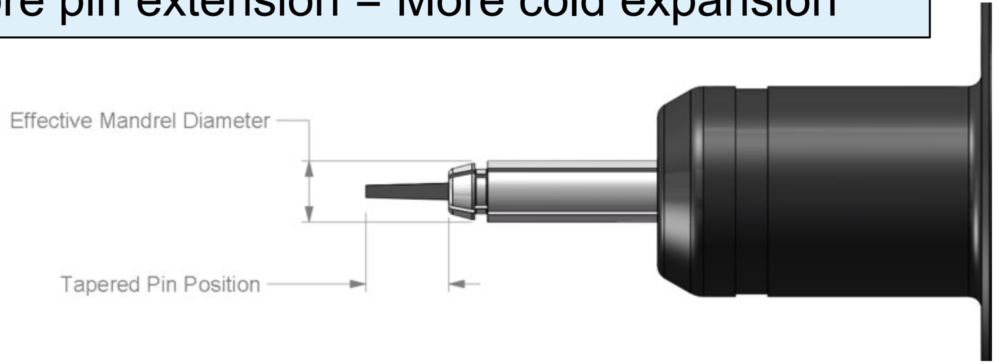
- “Tuning” the mandrel diameter supports various applied expansion levels without changing mandrels





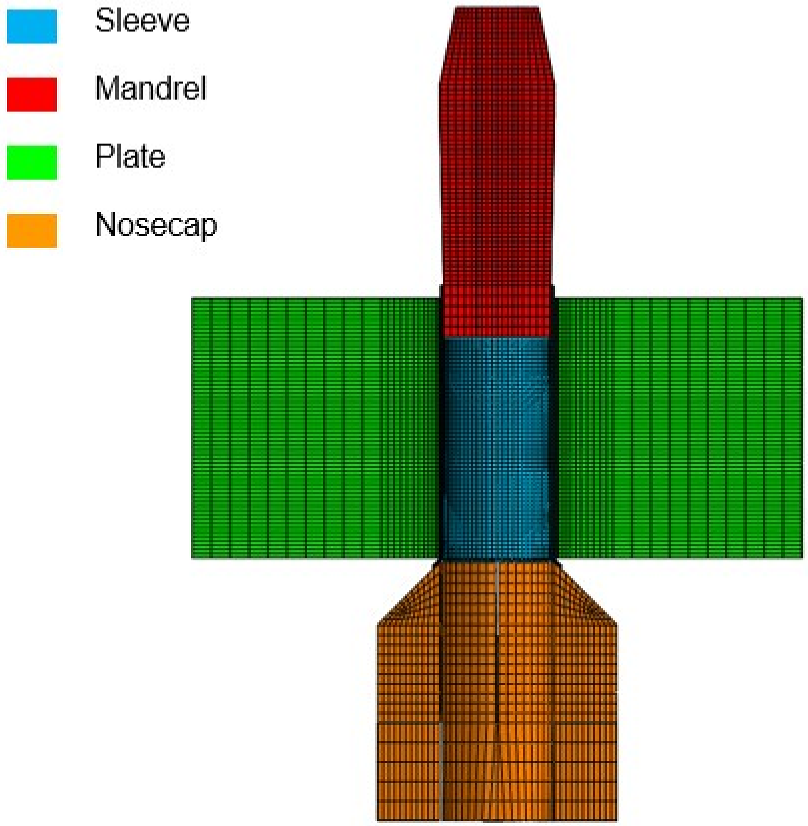
Less pin extension = Less cold expansion

More pin extension = More cold expansion



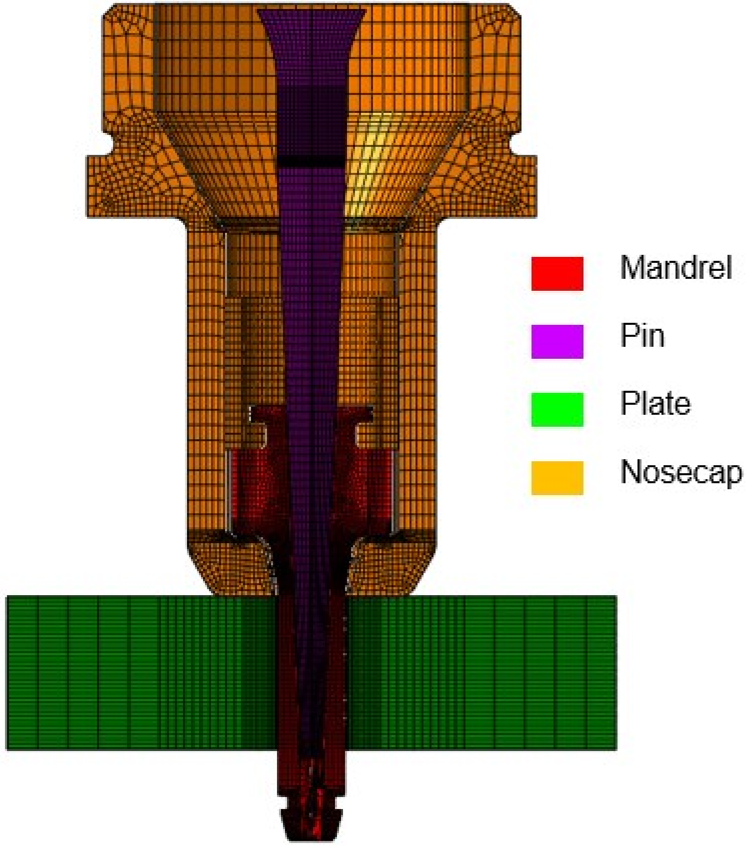
Process Modeling Comparison

SsCx



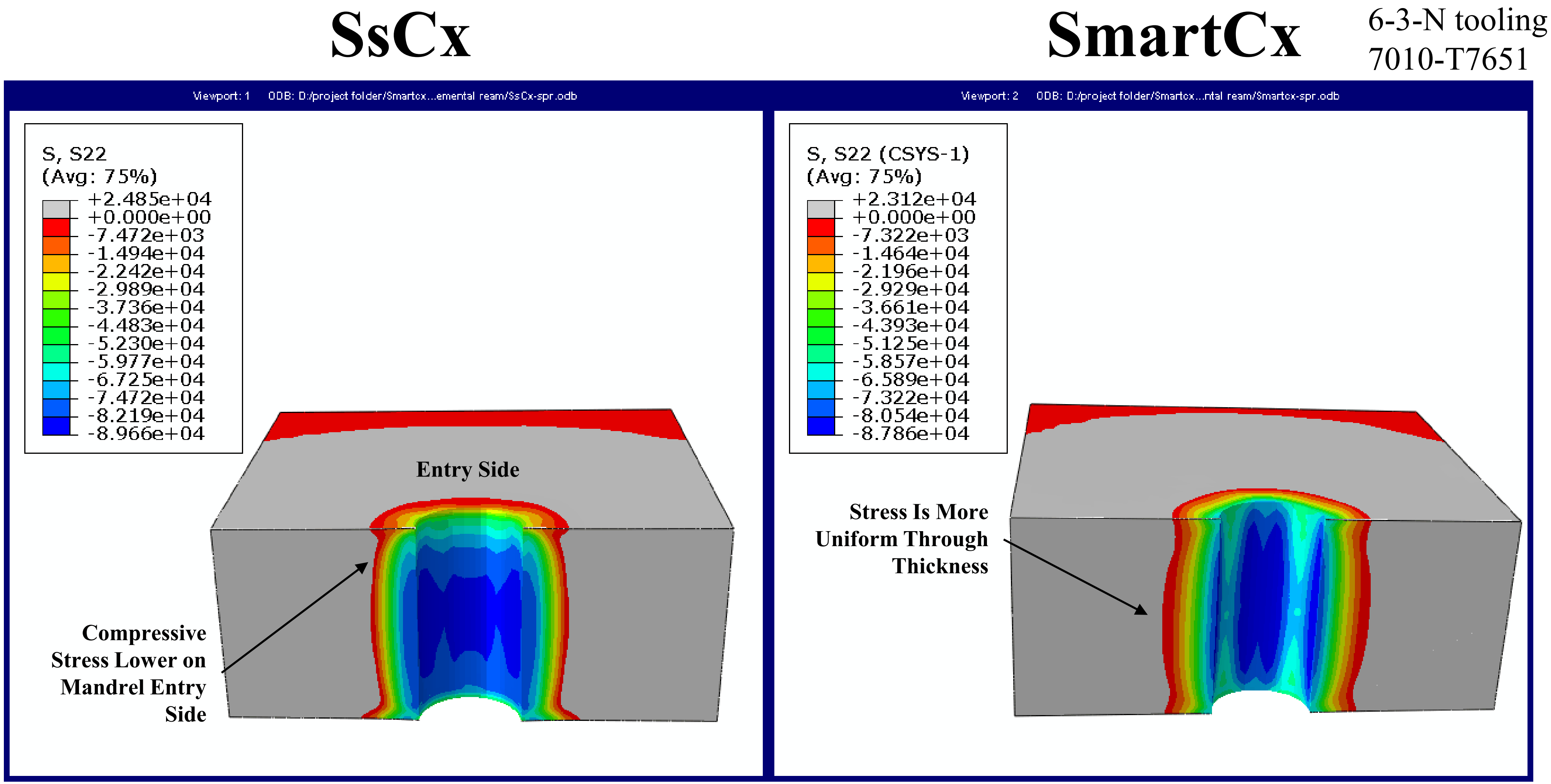
Parameters
6-3-N tooling (or equivalent)
7010-T7651

SmartCx



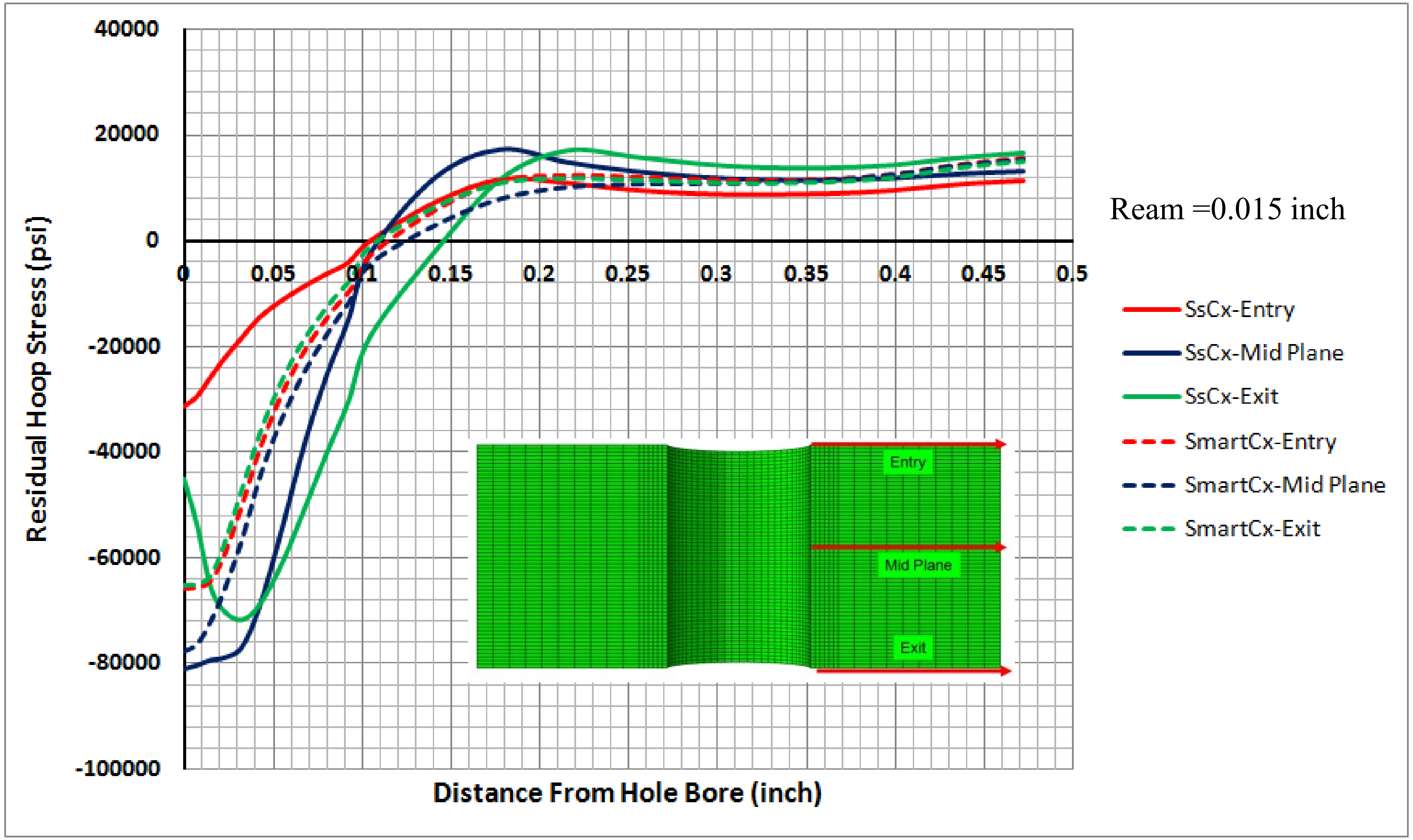
Process Modeling Comparison - Example

Parameters
6-3-N tooling (or equivalent)
7010-T7651



Post-Ream Compressive Hoop Stress (psi) – Contour Plot

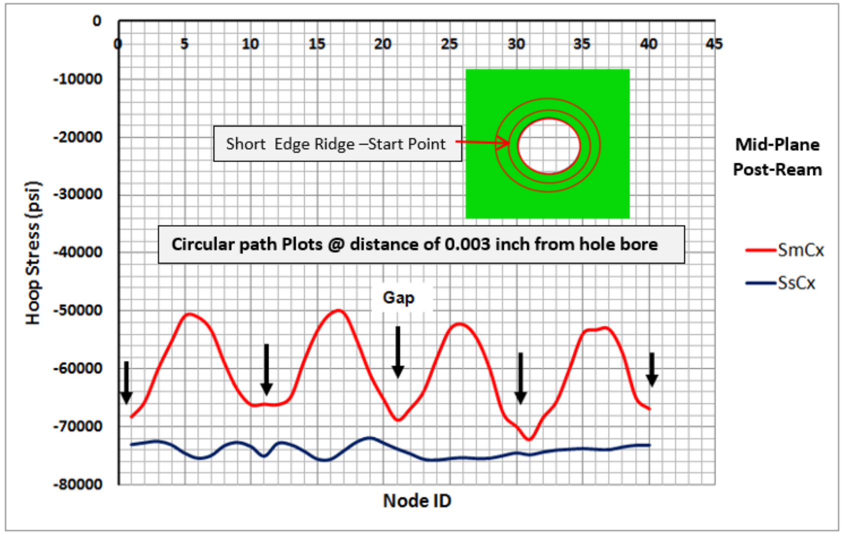
Process Modeling Comparison - Example



<u>Parameters</u>

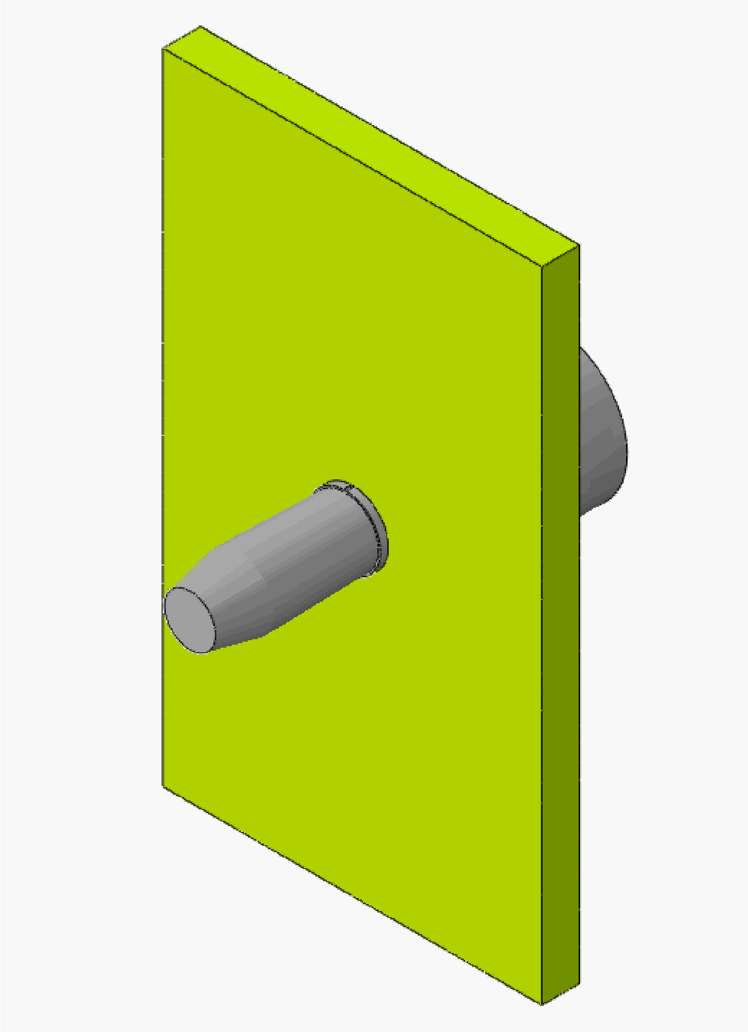
6-3-N tooling (or equivalent)

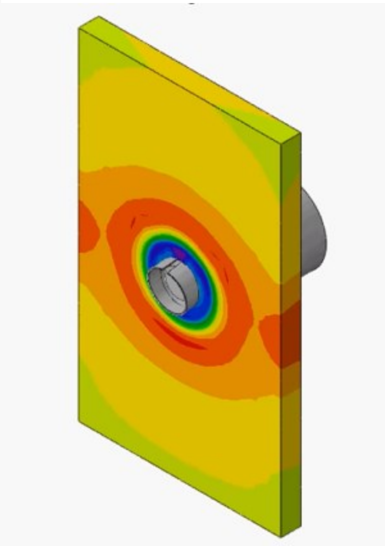
7010-T7651



Process Modeling Animations

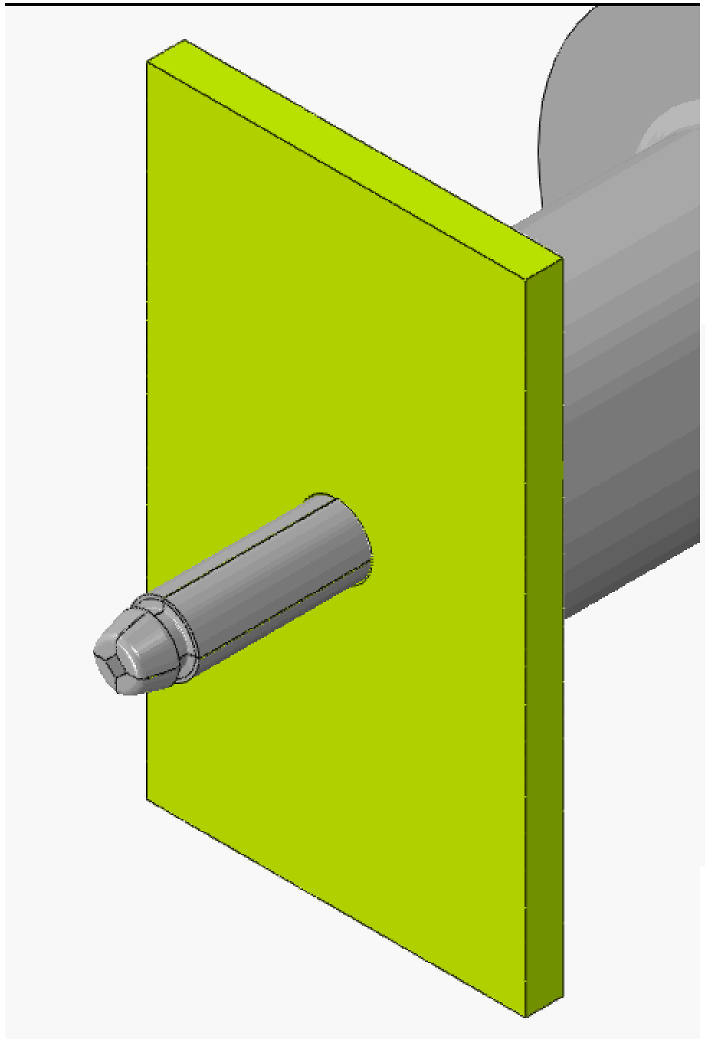
SsCx

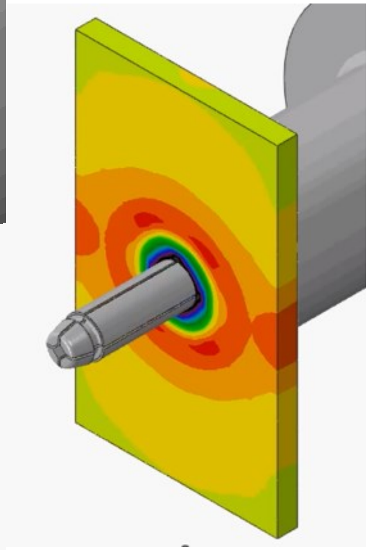




Parameters
6-3-N tooling (or equivalent)
7010-T7651

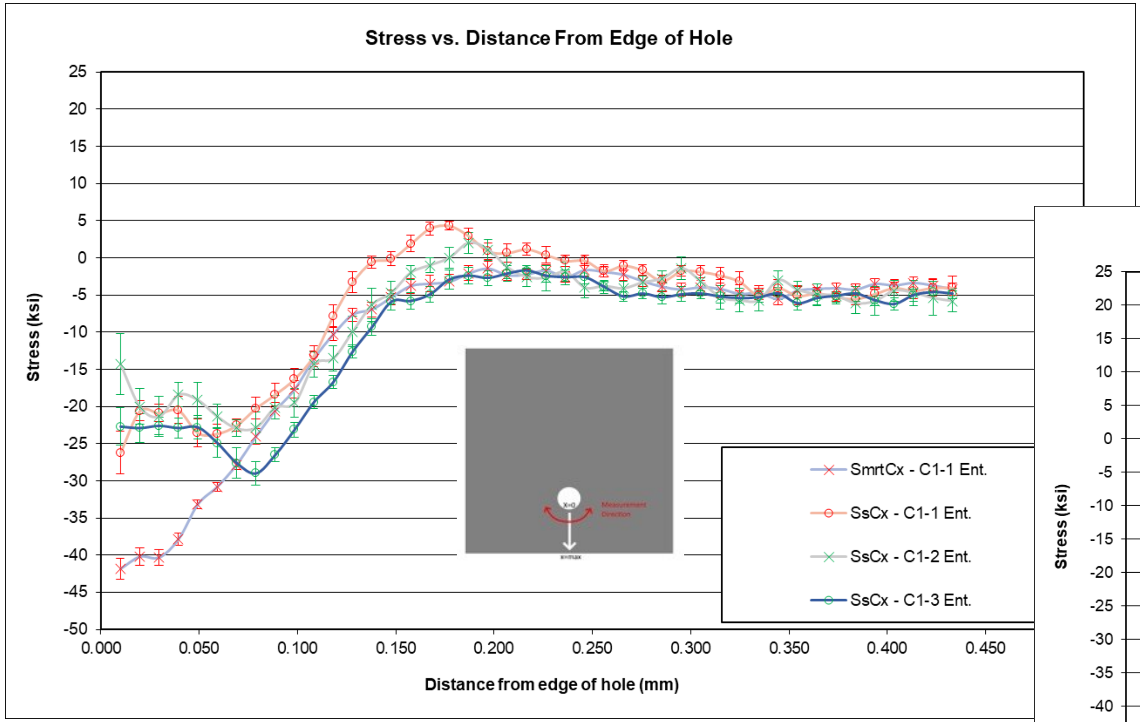
SmartCx

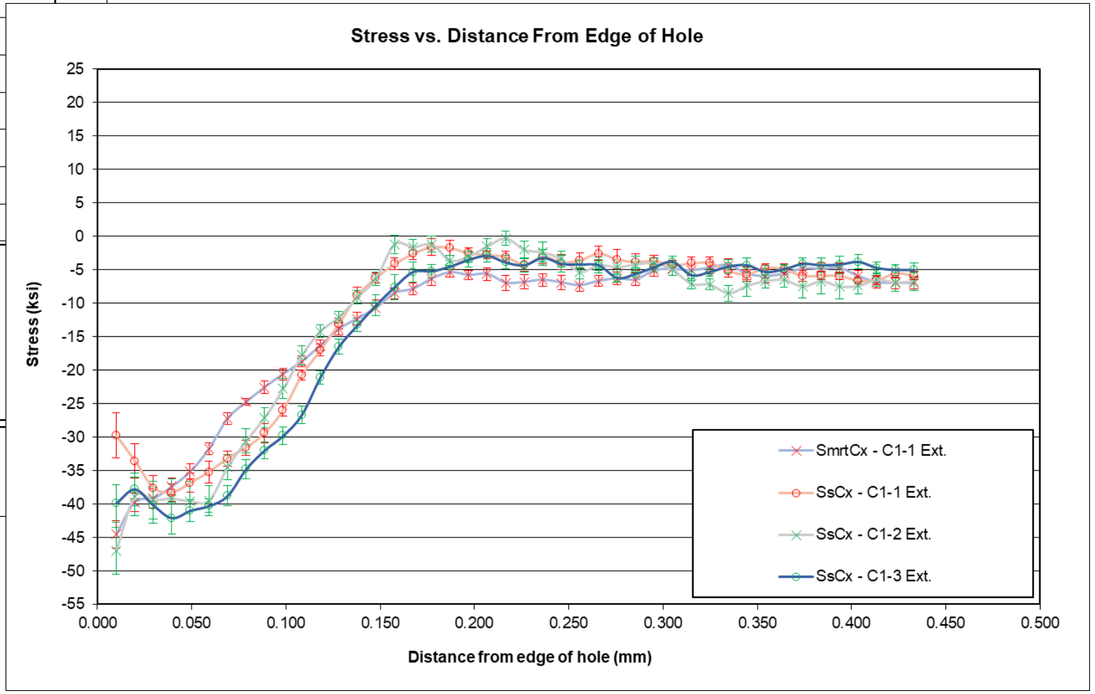




XRD Surface Residual Stress Differences

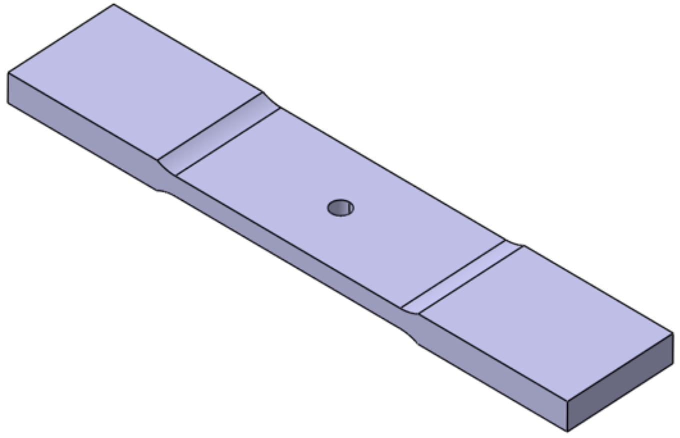
- Xray Diffraction Surface Stresses were Determined for a Range of Conditions that were Processed via SmartCx™ and SsCx™

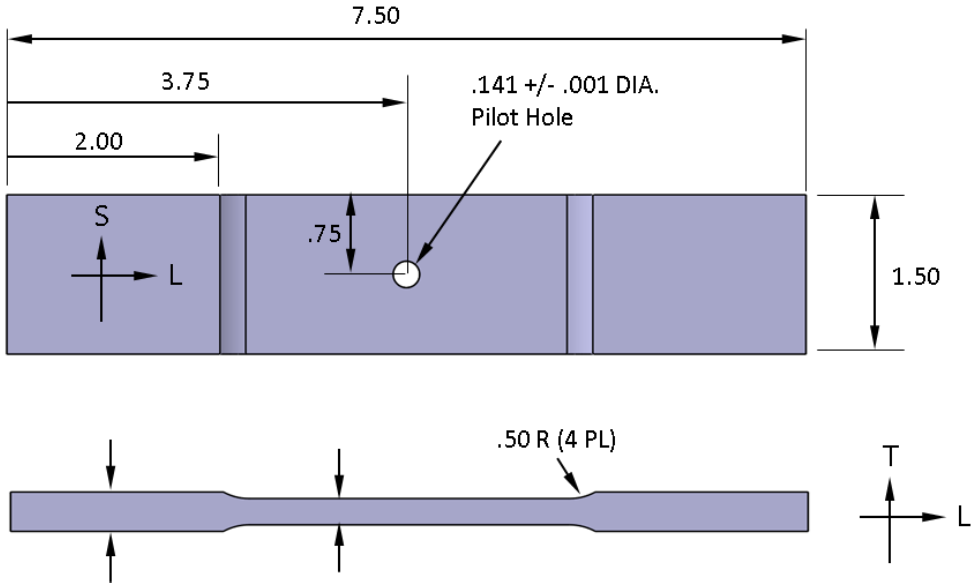




Purpose of Initial Sleeveless Evaluation

- Fatigue Testing Performed using Constant Amplitude, R=0.1, Smax = 23ksi
  - Purpose was to assess feasibility of a Sleeveless Cx process for future implementation
  - Coupons EDM Notched using plunge corner notch, avg. length = 0.025inch
  - Pre-Cracked to surface length = 0.035inch
  - Then final reamed to standard starting hole diameter
  - Imposed Marker Banding post repeatable "Block"
    - Used DST-G's Constant Amplitude Marker Band (CAMB) sequence
    - No post-test fractographic evaluation has been performed on these coupon sets yet





Effect of "Tuning" Applied Expansion

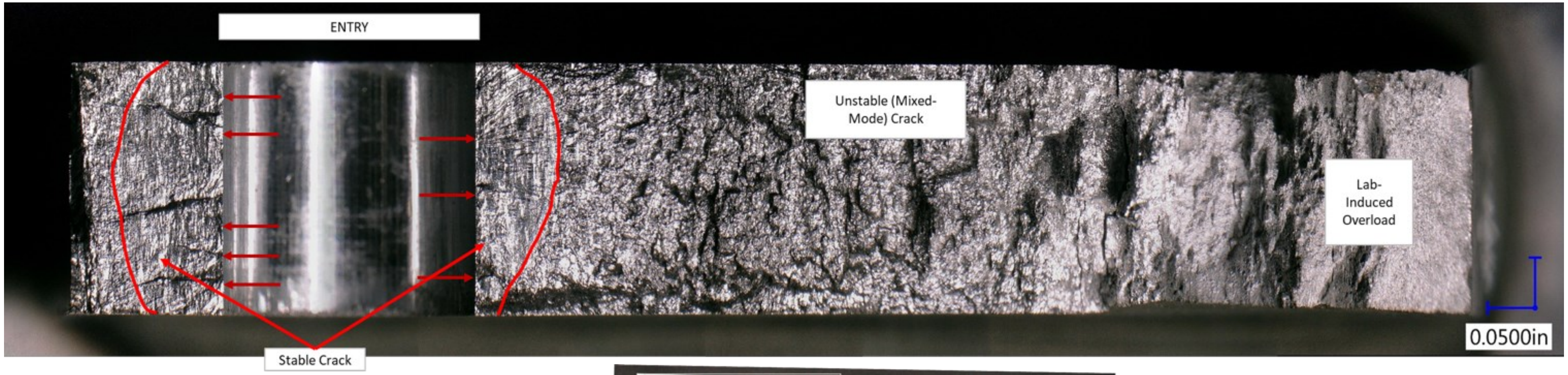
- Initial Testing Performed Using 6-3-N "Low" Retained Expansion Levels per the SsCx™ Tooling
  - Hypothesis was that if the level of retained Cx hole retention could be managed across methods that results would be similar
    - With sleeveless Cx processes it's not possible to determine applied expansion due to the retraction of the tool during the Cx process
  - Method or "tuning" was based off of some level of trial and error after first measuring pre and post Cx hole diameters
    - How you measure makes a difference and so you want to have confidence in the method and stick with it
- Initial Results at "Standard" Retained Expansion Levels did Not Meet or Exceed the SsCx™ Life
- Pursued Tuning of Hole Diameter and Tooling Settings to Match Retained Expansion

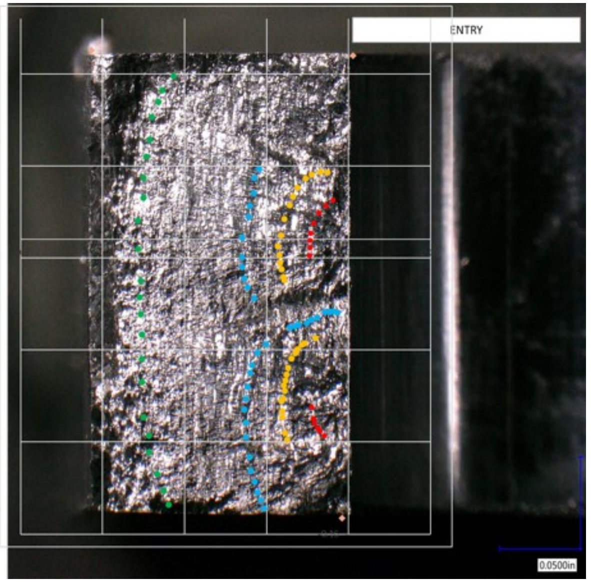
Fatigue Crack Test Results

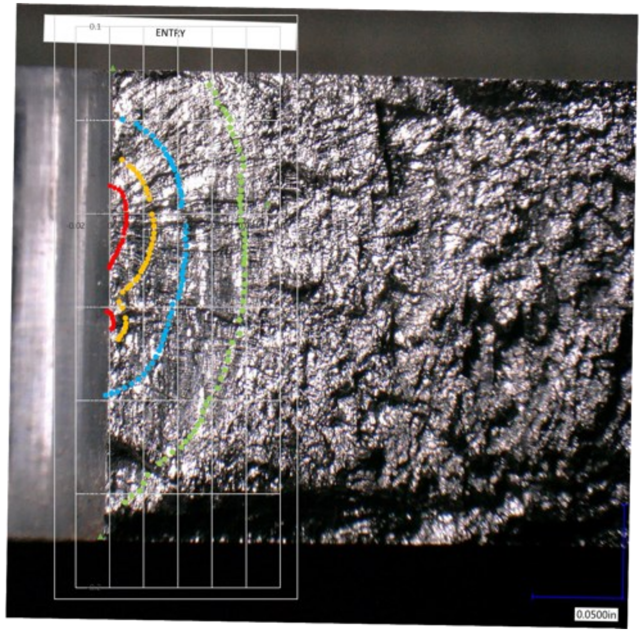
Cx Process	Average Life for Pre-Cracking	Std on Pre-Crack Life	Weibull Characteristic Life for Pre-Cracking	N90/90 Life for Pre-Cracking	Average Life Post Final Ream	Std on Life Post Final Ream	Weibull Characteristic Life Post Final Ream	N90/90 Life Post Final Ream
Baseline	9,701	1,029	10,094	3,900	17,508	1,700	18,253	6,155
SsCx	203,937	84,368	235,407	6,200	46,212	4,398	47,899	27,200
V1 SM1-STD	91,133	27,900	100,104	22,400	35,959	6,878	37,882	13,700
V2 SM1-STD	121,998	26,682	132,146	41,300	38,426	12,172	42,476	8,300
V2 SM1-TND	480,634	108,599	523,332	77,500	39,426	9,326	42,587	13,400
V1 SM1-TND	216,900	45,666	233,333	77,000	61,808	6,991	64,513	36,900
V2 SM1-MAX	519,848	66,414	546,027	228,500	53,331	7,806	59,400	20,100

QF Results of SmrtCx™ vs. SsCx™

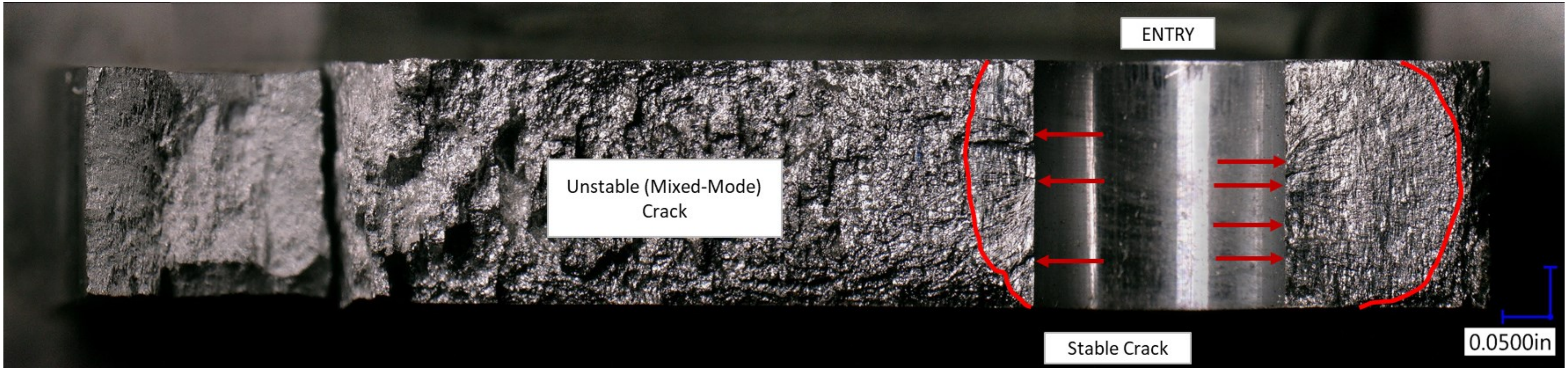
- Maybe Use Data from the "C" Matrix

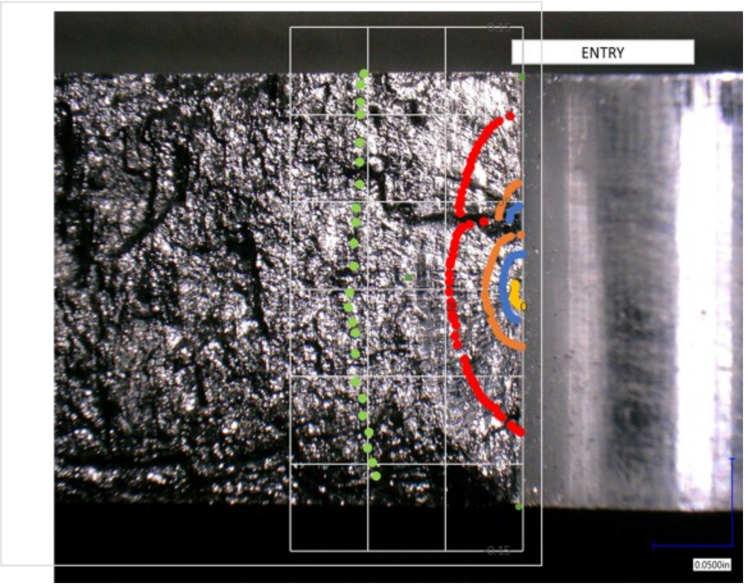


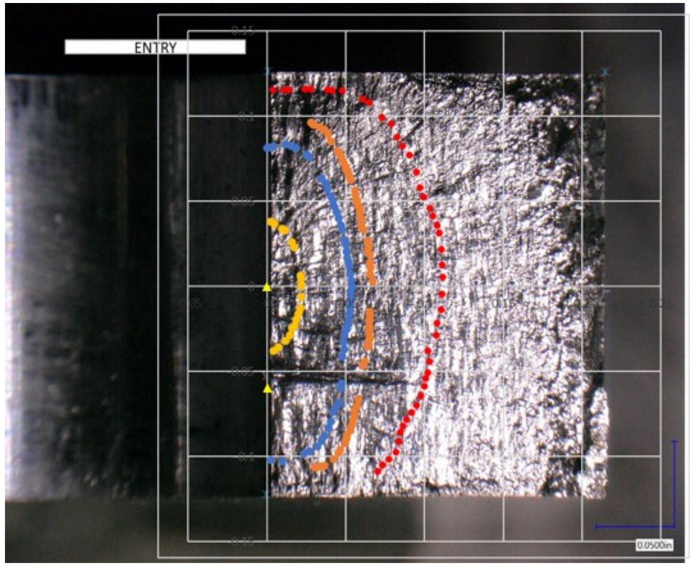




QF Results of SmrtCx™ vs. SsCx™







Lessons Learned

- Split Mandrel Cold Expansion Methods Currently Have Limited Applicability
  - Due to materials and pulling forces
- Due to Tolerance Stack-ups in Sleeveless-Style Assemblies "Tuning" Retained Expansion Useful
  - Not possible to use applied expansion
  - This may be challenging if drawing/spec require updates/revisions for starting hole size
- In Sleeveless Cx Methods Cracks can Form All Along the Bore
  - Limited "pinning" due to higher compression near Exit surface
  - Can form a thru-crack faster than SsCx™ process
    - This has implications in NDI and other Holistic aspects

Additional Comments or Questions

Continuation of active work

Bring us your problems!

Extra Slides

Harmonizing Contour and XRD Residual Stress Measurement Data Sets

HILL ENGINEERING
Predict. Test. Perform.

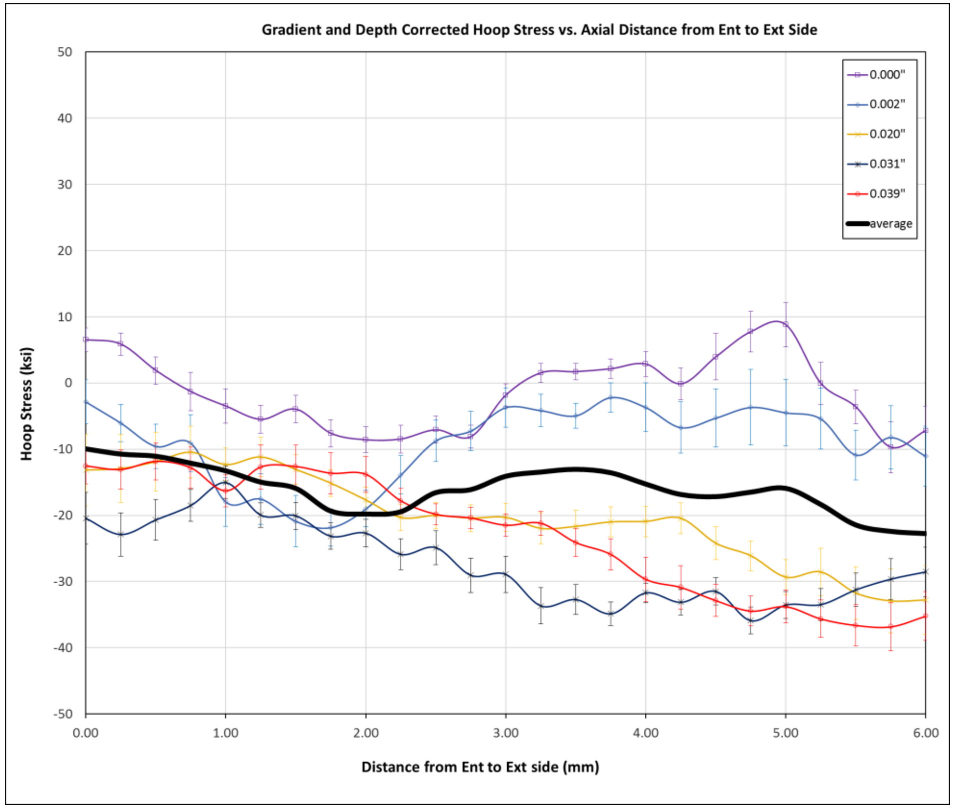
PROTO
X-RAY DIFFRACTION

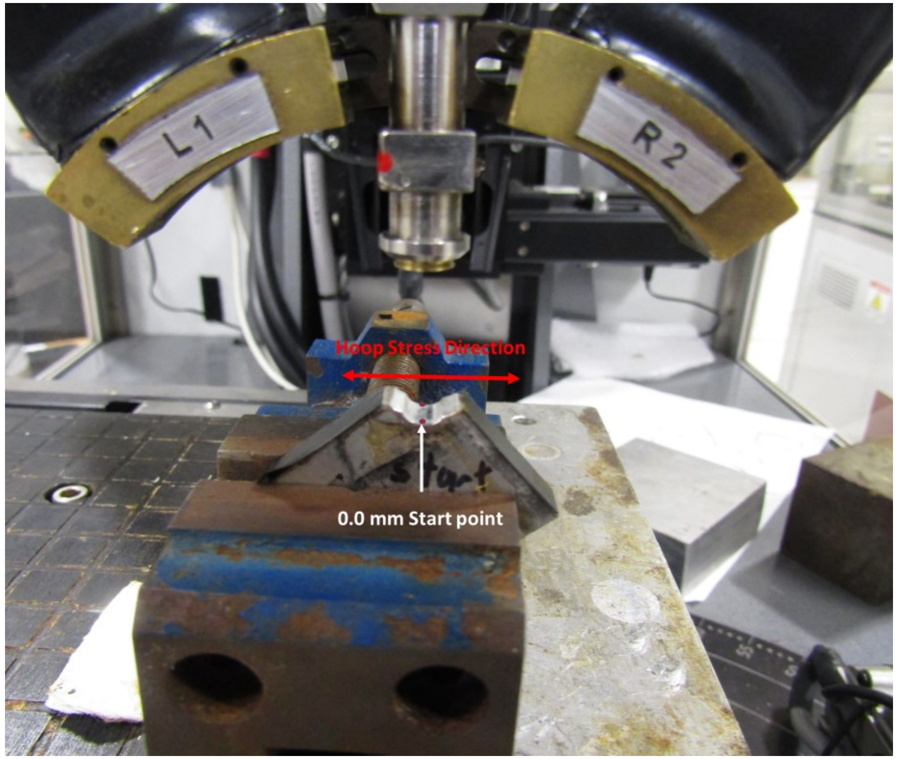
AIR FORCE RESEARCH LABORATORY

LOCKHEED MARTIN

RS in bore of 2024-T351 Low Expansion Cx 2"x 2" Coupon

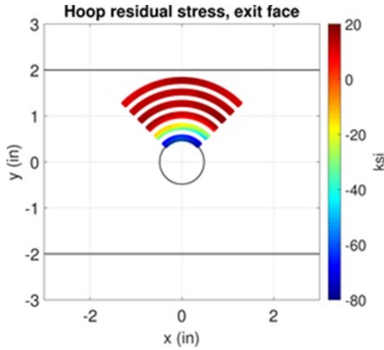
- Similarly, data was collected on the bore of a 2x2 Cx Hole coupon.
- Depth profiles via electropolishing were collected to bridge the gap between XRD and Contour data – correction required for splitting to access to the bore.
- Steep near surface stress gradients can be captured rather than averaging near surface.

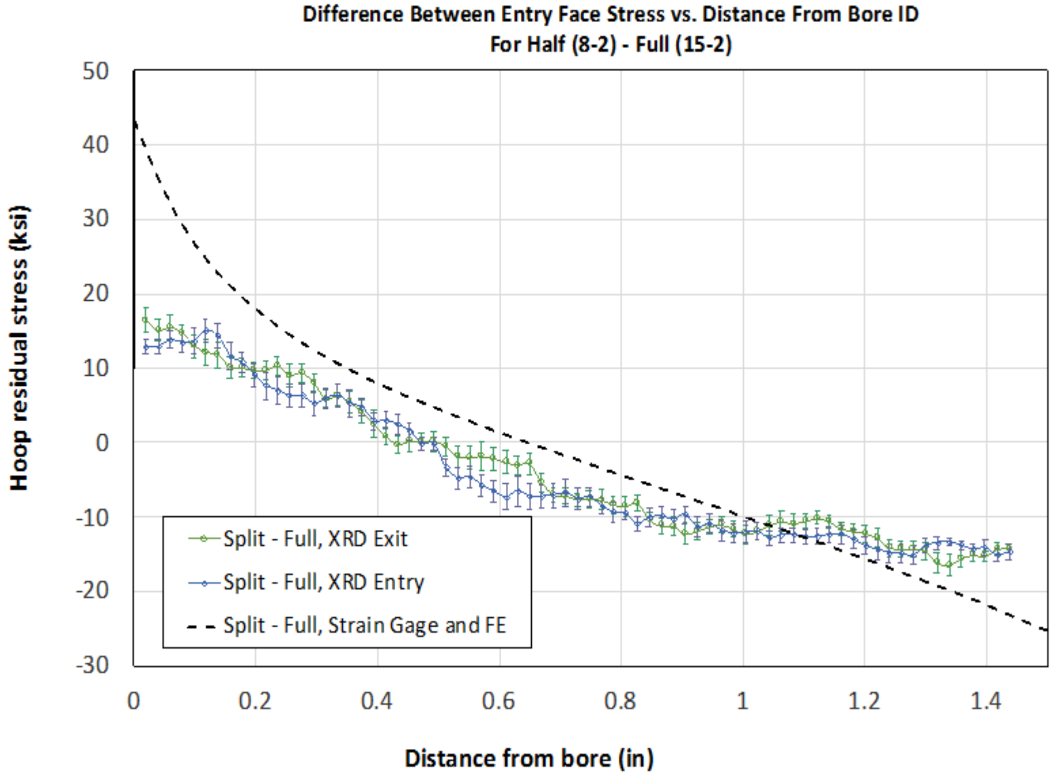


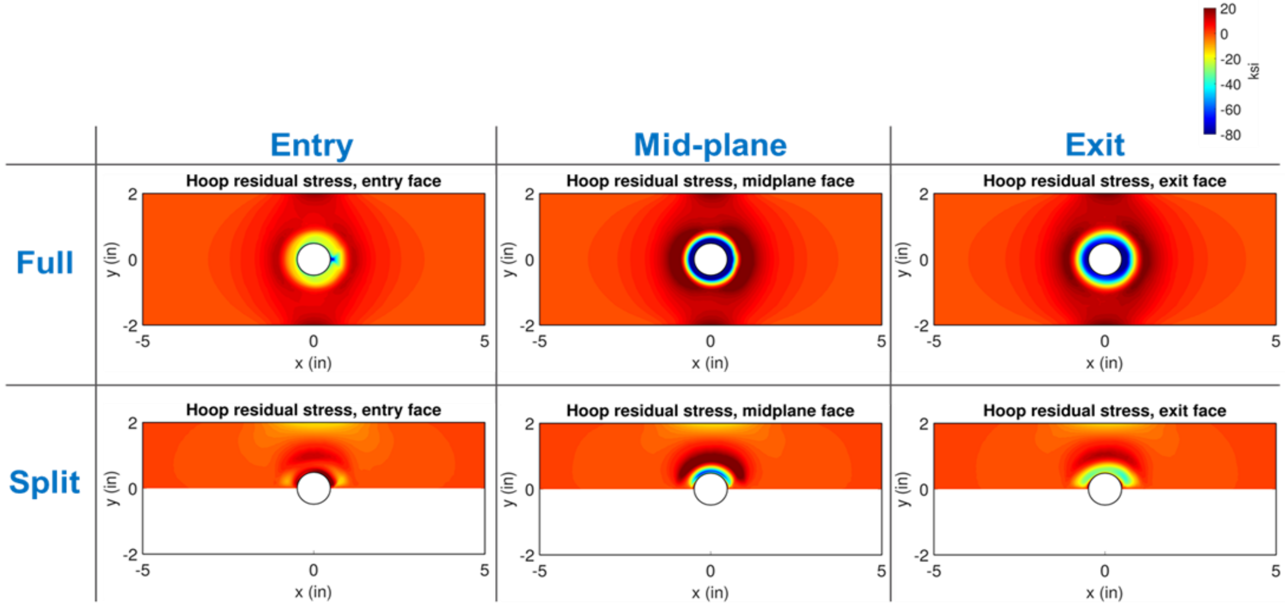


Effect of Split on Geometrically Large Coupon

- The difference between RS in full and split configurations was looked at to determine effect – the effect was significant – green and blue XRD data.
- This relaxation was then compared to that estimated by strain gage & FEM.
- The results were different, especially near the bore – thought to be due to XRD arc averaging – modeling was used to determine the effect of arc-averaging.

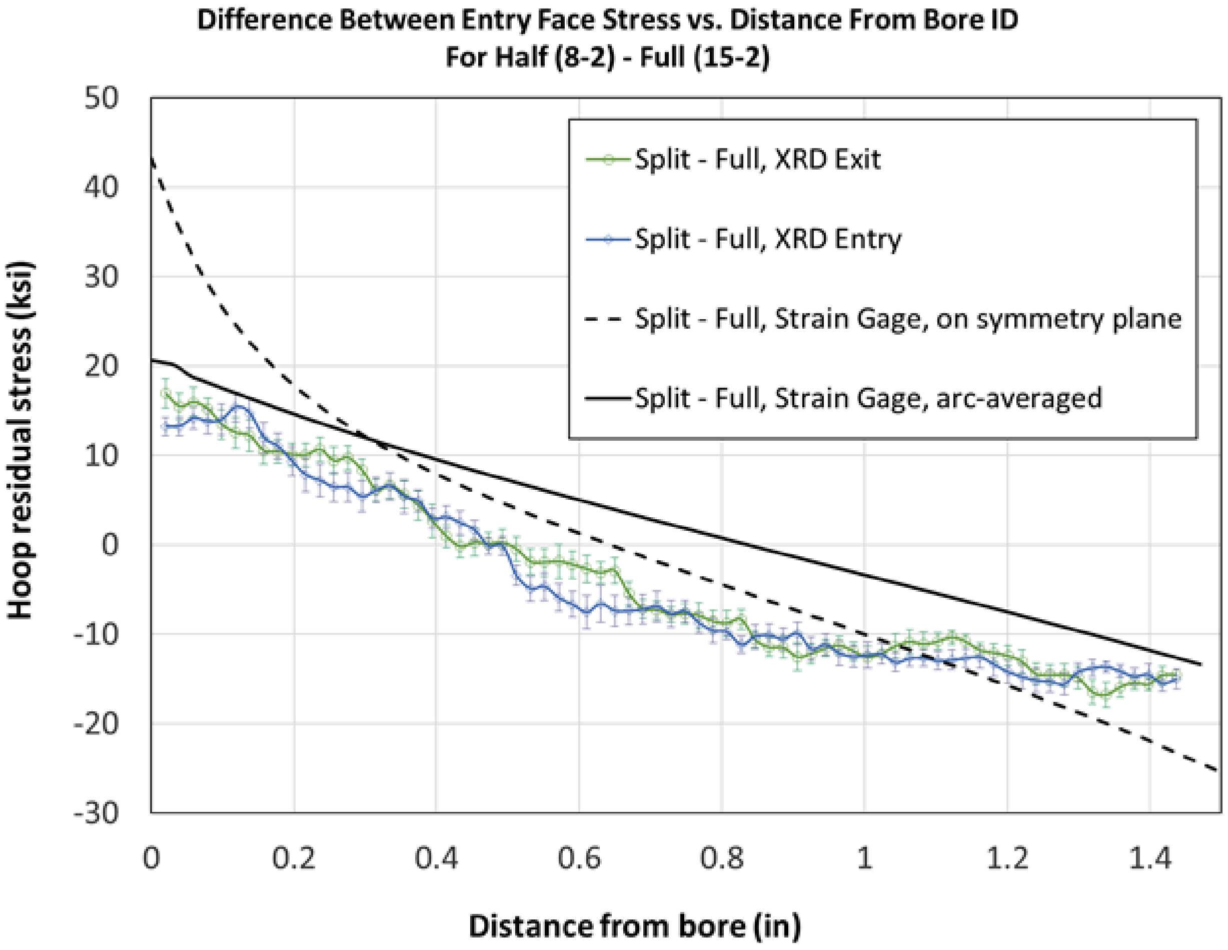




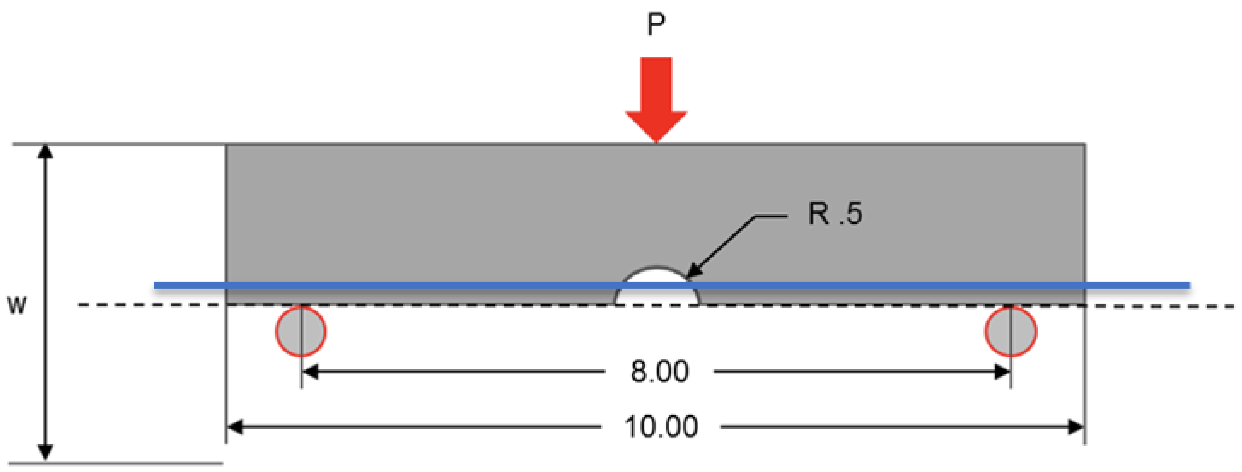


Effect of Split on Face of Geometrically Large Coupon

- When corrected for XRD arc averaging, the relaxation as measured by XRD vs. estimated by strain gage & FEM are more closely aligned

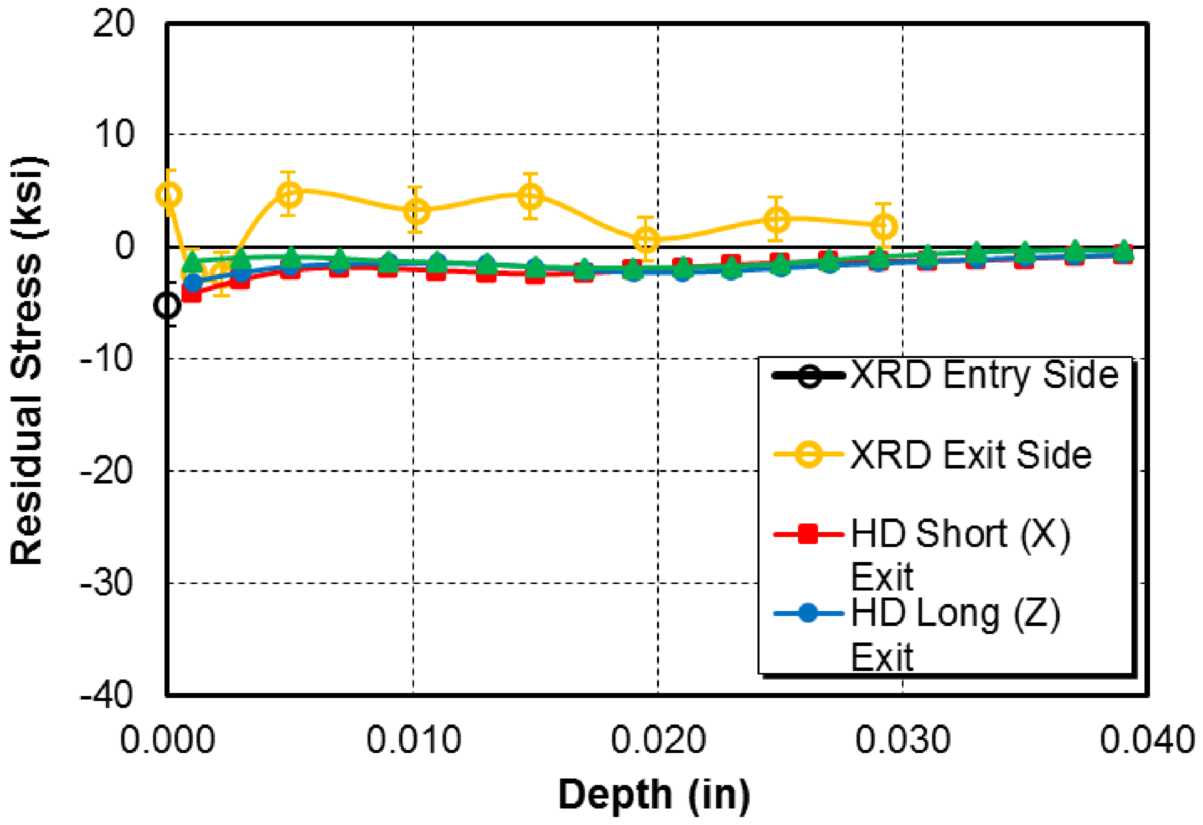


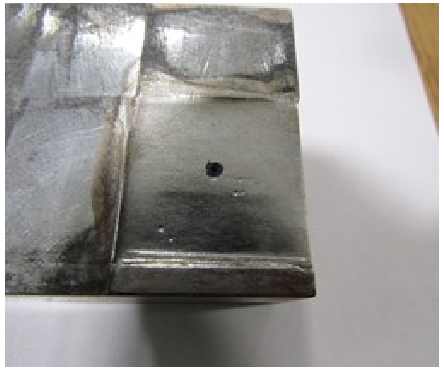
Case Study: Can we measure RS in the bore of Geometrically Large Cx Hole Coupons?



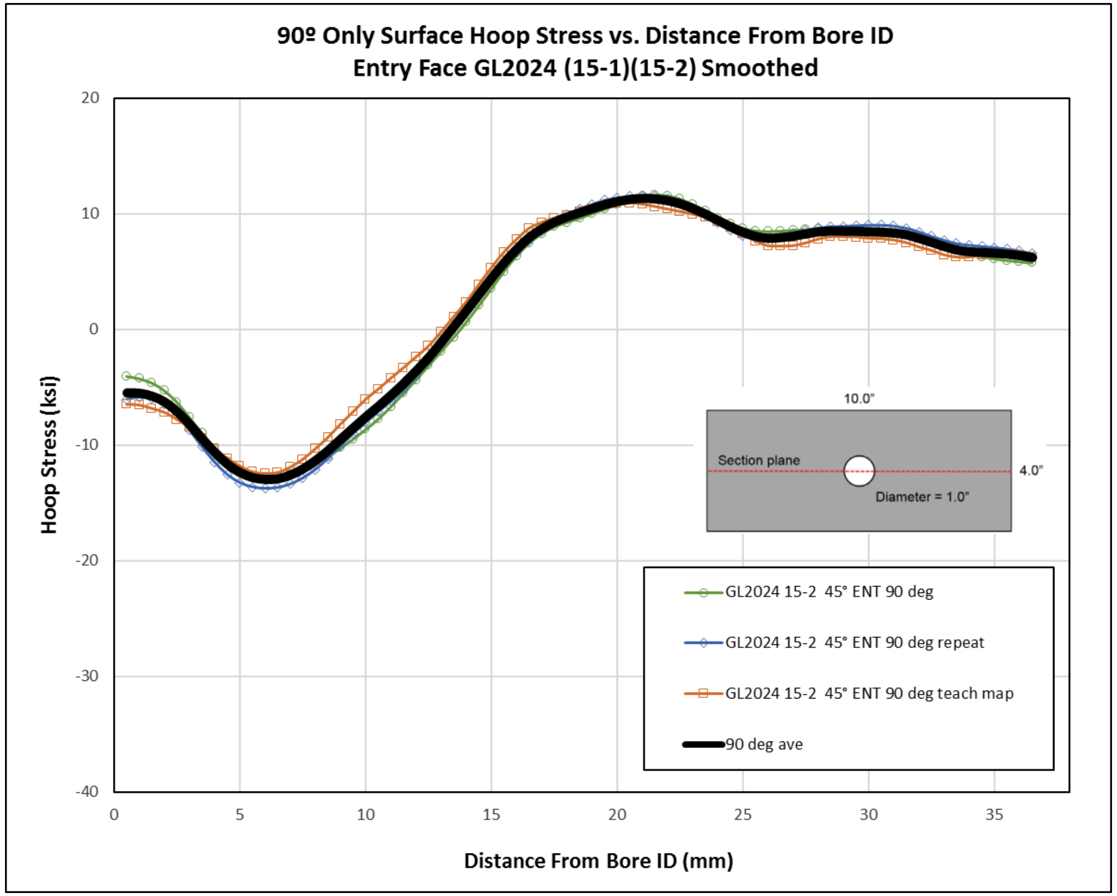
Far Field RS on Face of Geometrically Large Cx Coupon

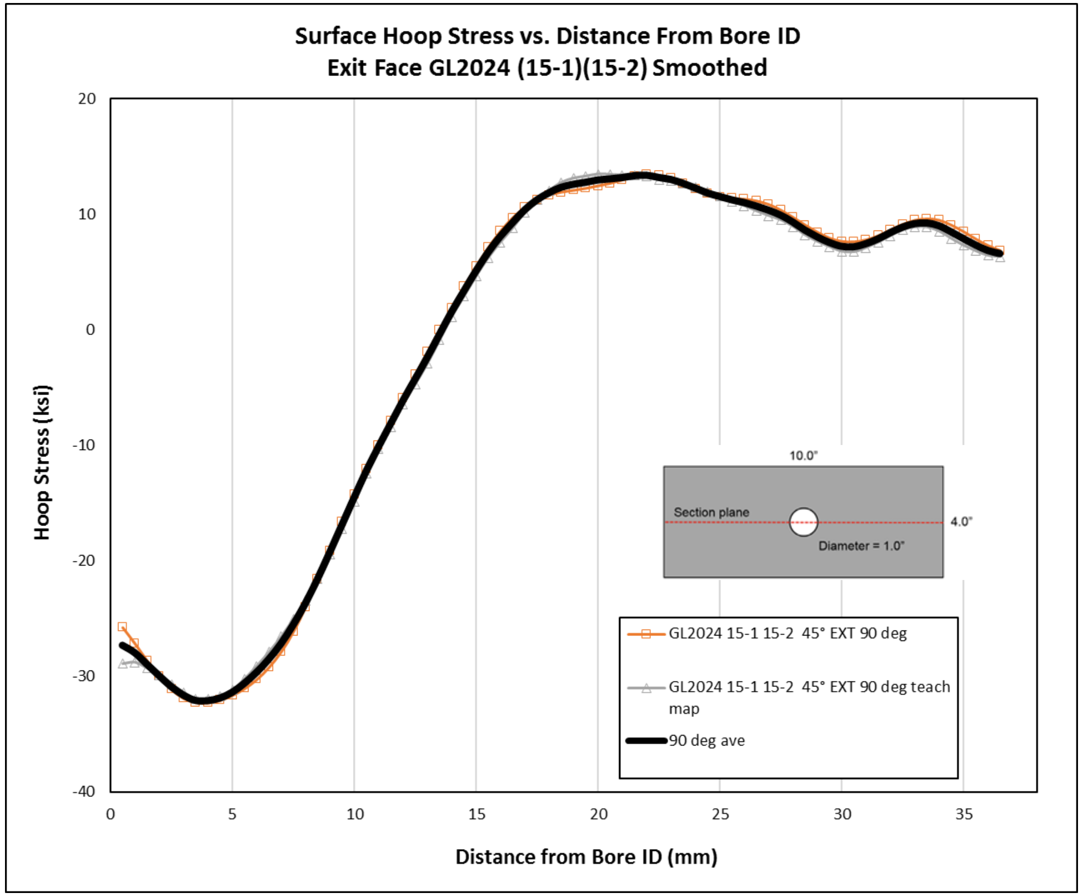
- Far field near surface RS measurements collected via XRD and HD indicate the magnitude of upstream processing RS to be low





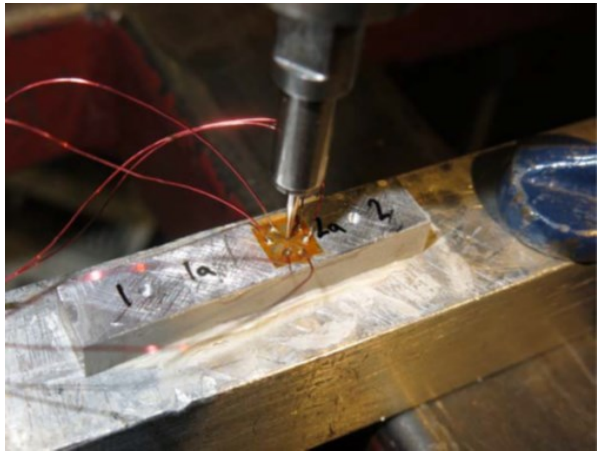
RS on Face of Geometrically Large Coupon

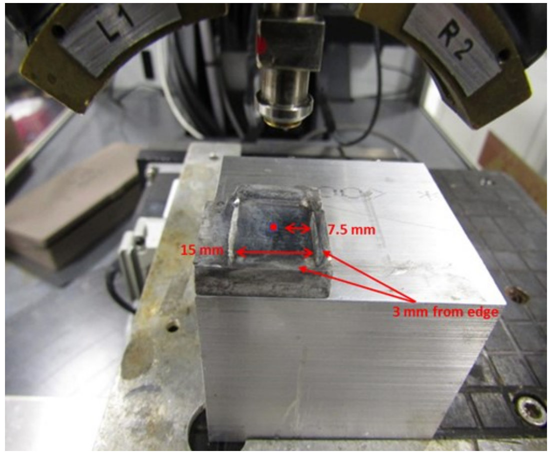


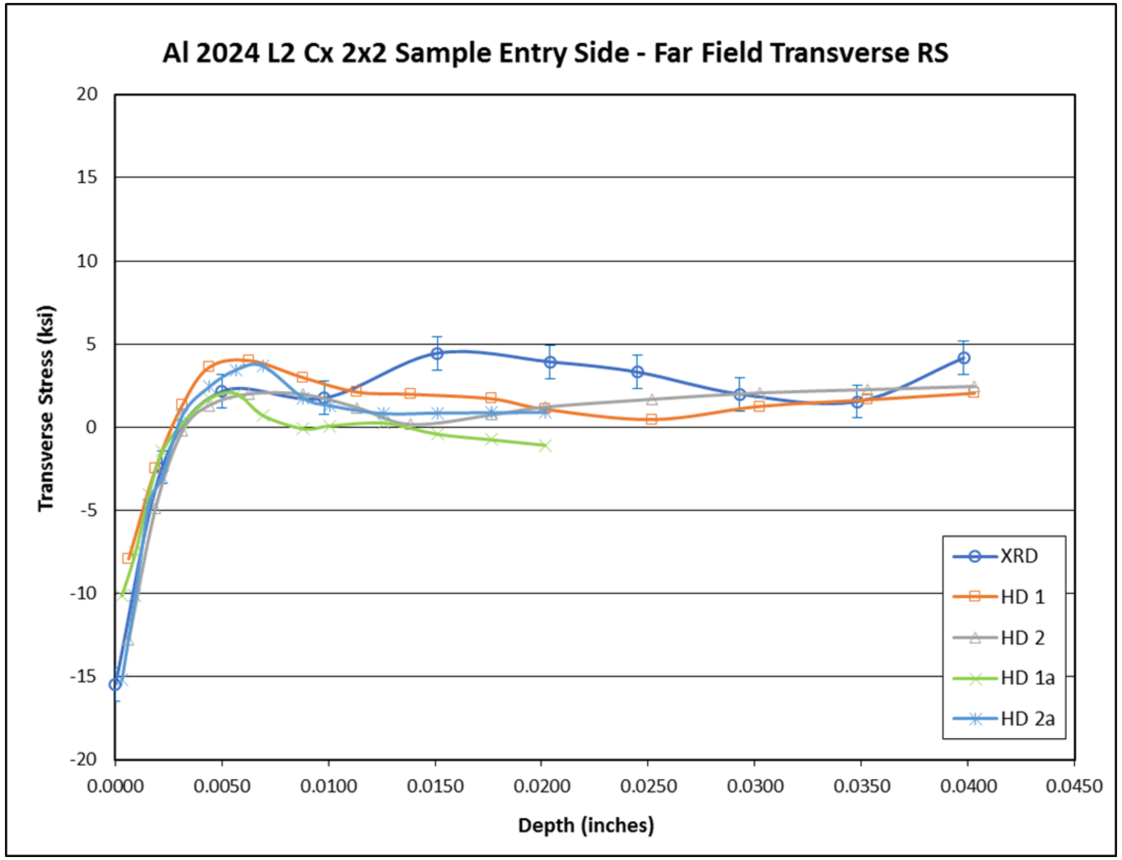


Far Field RS on Face of 2 x 2 Cx Hole Coupon

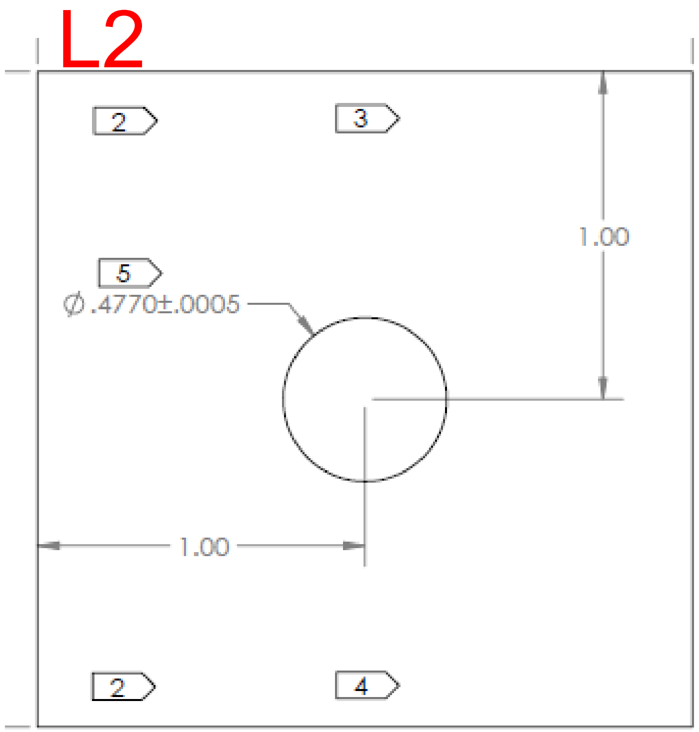
- Al 2024 L2 Cx Sample Far Field Transverse RS on Entry Side measured using XRD and HD
- RS measurements collected via XRD and HD to determine upstream processing RS.







Case Study #2: Can we measure RS in the bore of a 2024-T351 Low Expansion Cx 2" x 2" Coupon?



Takeaways

- XRD can be used to determine if Cx was applied to the right level on either coupons, or in the field on aircraft.
- XRD is able to pick up steep near surface stress gradients, especially in tricky areas like the bore of a Cx hole.
- Near surface bore ID measurements might explain why Cx vs. non-Cx holes crack propagate at nearly the same rate for the first few thou.
- A path forward to harmonize/splice XRD, Contour, HD, ND, etc. data sets such that the strengths of each can be exploited i.e. these are complimentary techniques.
- It is important to do your homework with regards to far field RS, grain size effects, gradient effects, elastic properties of the material, etc. i.e. use best practices!!!