

Texture and Anisotropy Sub-Team

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Recap

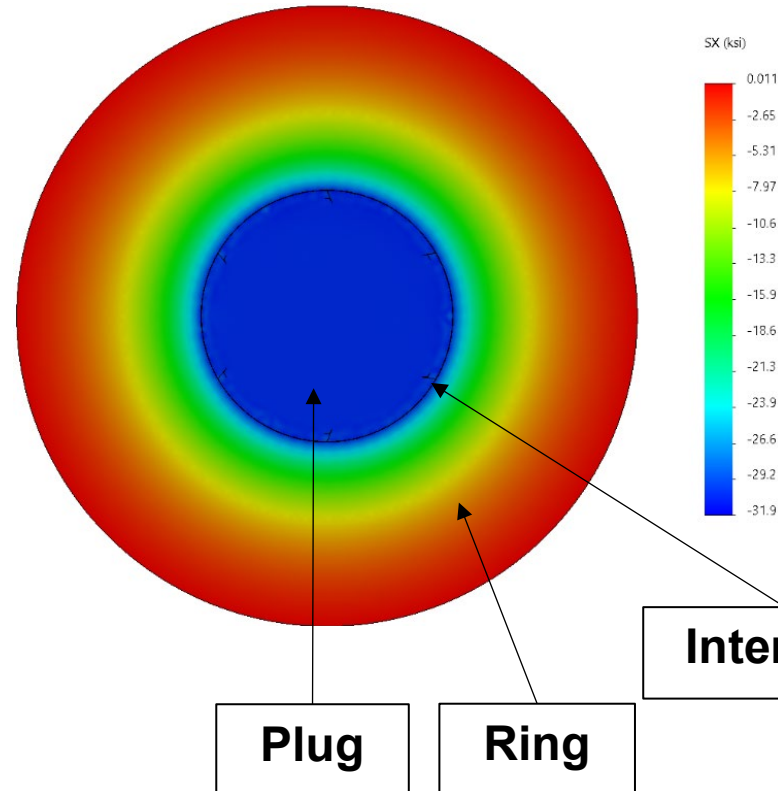
Mission Statement & Background

- 1) Quantify and incorporate the effects of crystallographic texture and elastic anisotropy into residual stress measurement workflows for both XRD and HD.
- 2) Compare accuracy of results from XRD and HD with FEA and analytical model predictions.

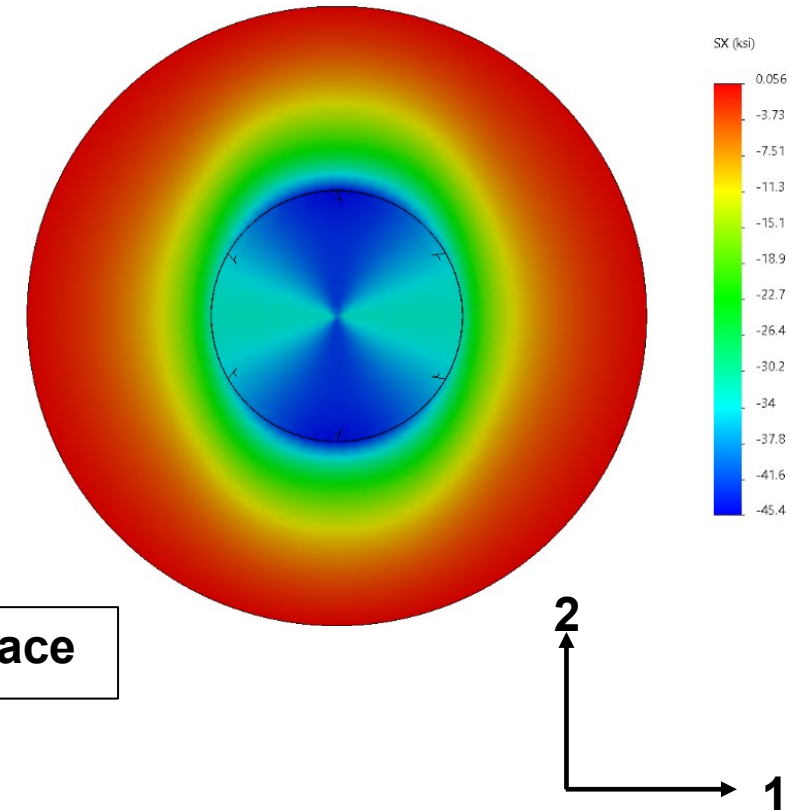
$$\begin{bmatrix} \epsilon_{11} \\ \epsilon_{22} \\ \epsilon_{33} \\ 2\epsilon_{23} \\ 2\epsilon_{13} \\ 2\epsilon_{12} \end{bmatrix} = \frac{1}{E} \begin{pmatrix} 1 & -\nu & -\nu & 0 & 0 & 0 \\ -\nu & 1 & -\nu & 0 & 0 & 0 \\ -\nu & -\nu & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2+2\nu & 0 & 0 \\ 0 & 0 & 0 & 0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

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

Isotropic Ring & Plug
E = 28,000 ksi



Anisotropic Ring & Plug
E₁ = 28,000 ksi E₂ = 36,400 ksi



Isotropic Case – A1 2024 T351 Ring and Plug Specimen

[Home](#) > [Experimental Mechanics](#) > [Article](#)

Assessing the Accuracy of Residual Stress Measurement Results on a 2024-T351 Aluminum Alloy Ring-And-Plug Specimen using X-Ray Diffraction and Incremental Hole Drilling Methods

Research paper | [Open access](#) | Published: 16 October 2025

Volume 66, pages 273–285, (2026) [Cite this article](#)

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Abstract

Background

Establishing the accuracy of residual stress measurements in aluminum alloys, such as 2024-T351, remains a topic of significant interest in the aerospace structures community. Achieving this requires a comprehensive understanding of the potential sources of error associated with each residual stress measurement methodology.

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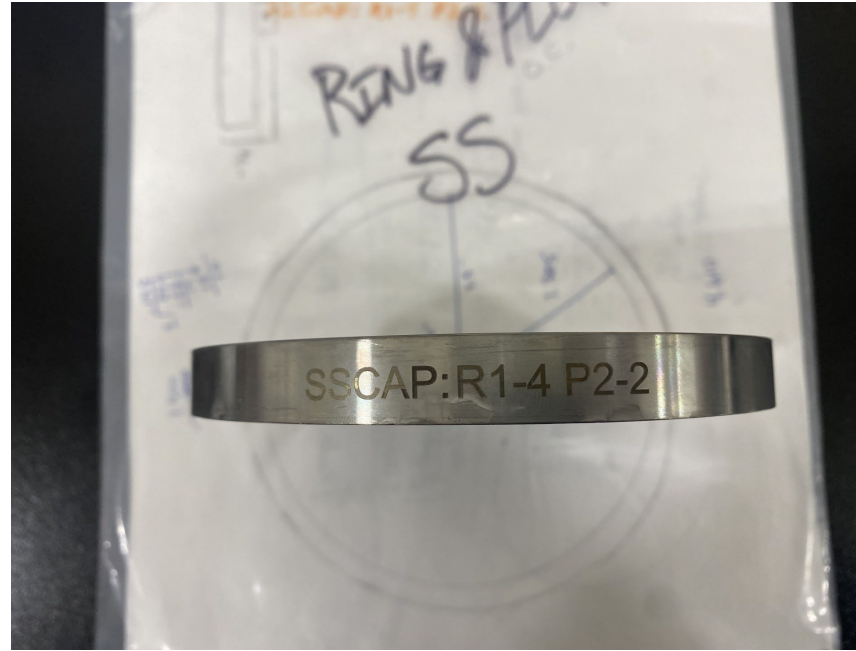
[Author information](#)

Round-Robin on 304SS Ring-Plug Specimen

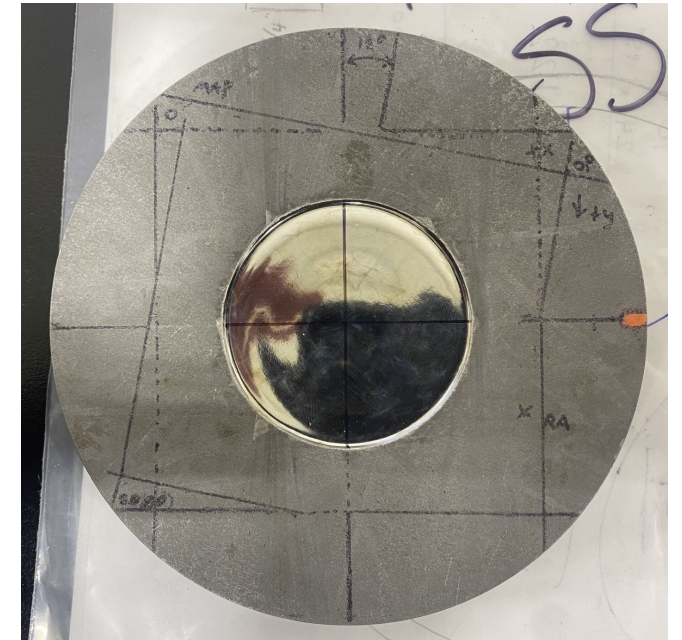
- LANL fabricated and assembled Ring-Plug (304SS plug/Carbon Steel ring) for ERSI Texture Subcommittee circa 2021.
- Nominal Dimensions of Carbon Steel Ring: 4.9375" OD, 2" ID, 0.5" thick - 304SS Plug: 2" OD, 0.5" thick
- Purpose: further develop RS measurement protocols and work-flow for anisotropic 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

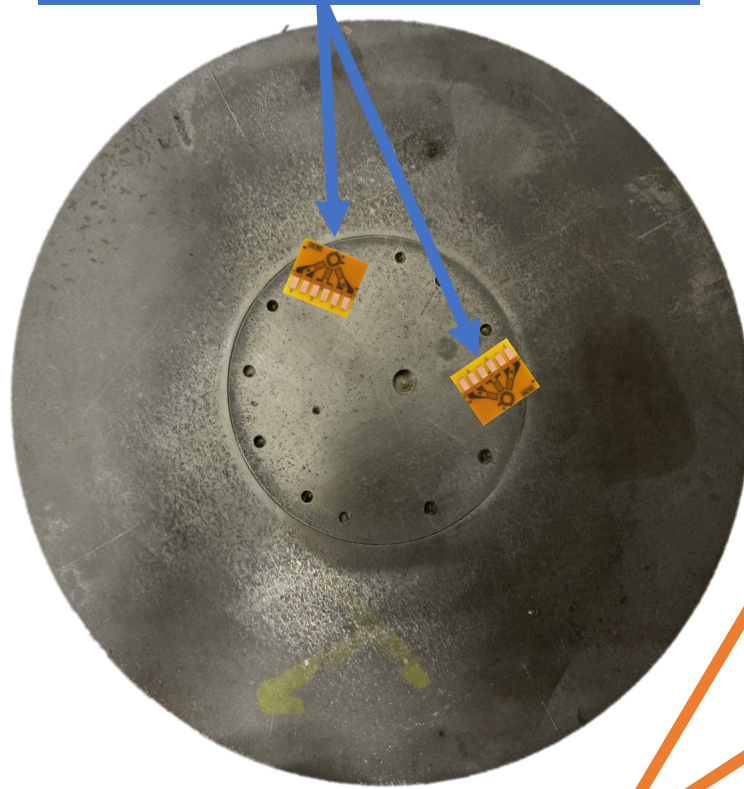


Post XRD – Side 2

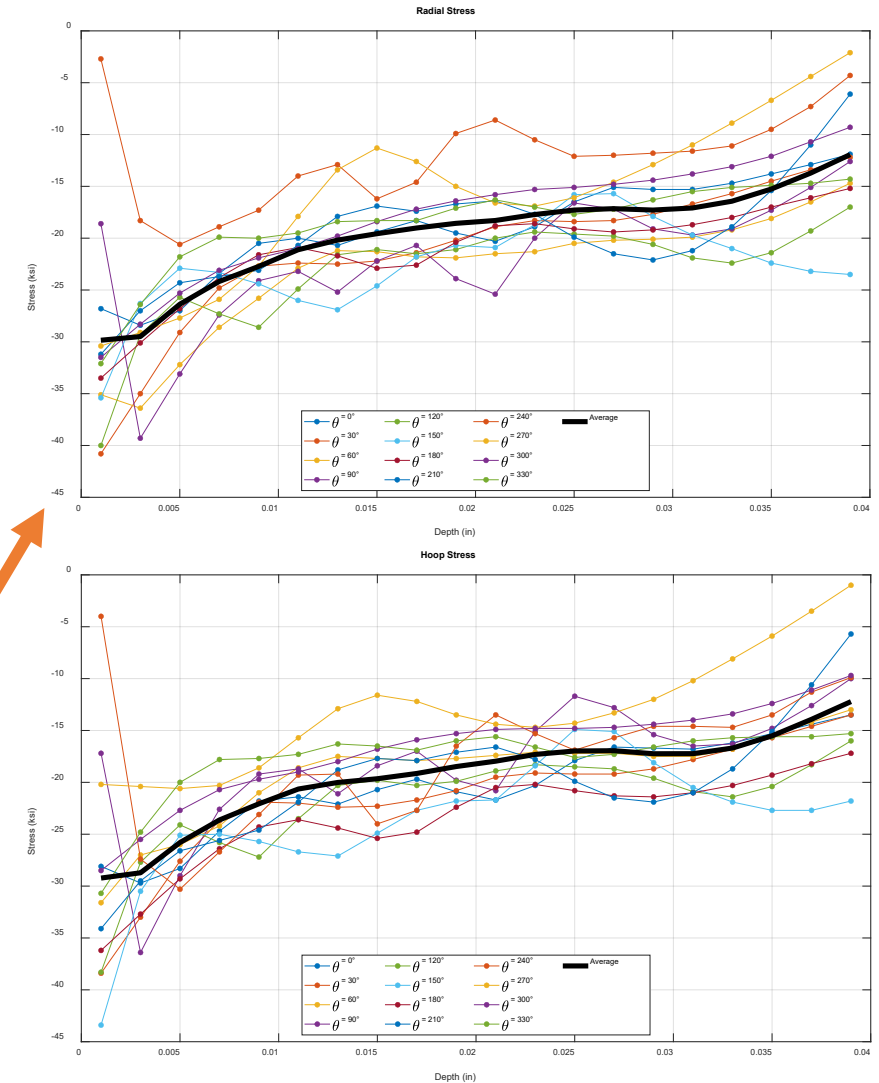
RSHD on Side 1 of 304SS Ring-Plug Specimen

- 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

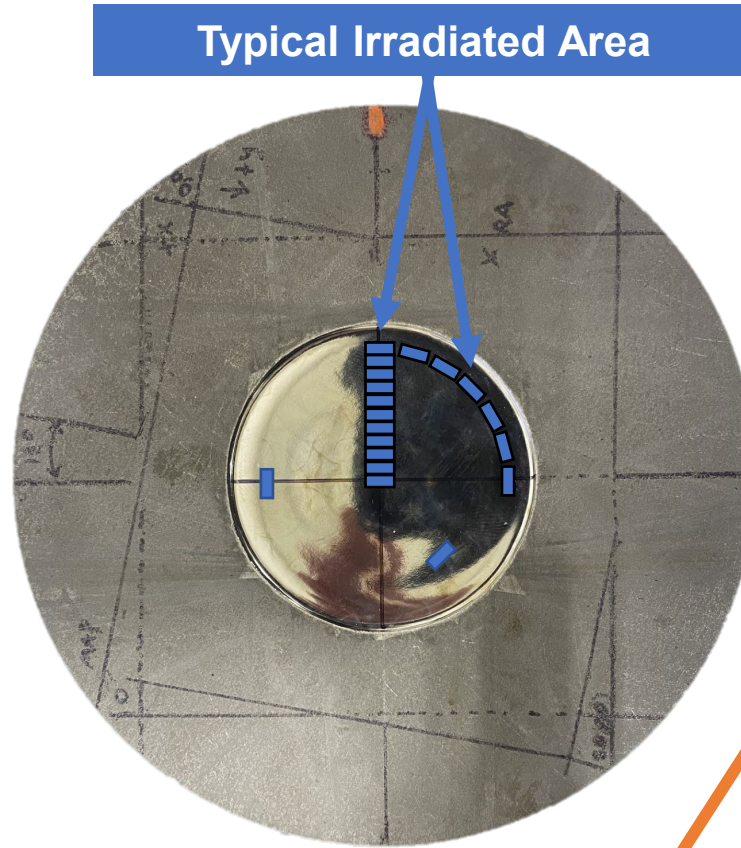


Hoop and Radial Stress vs. Depth profiles at 22 mm radial position

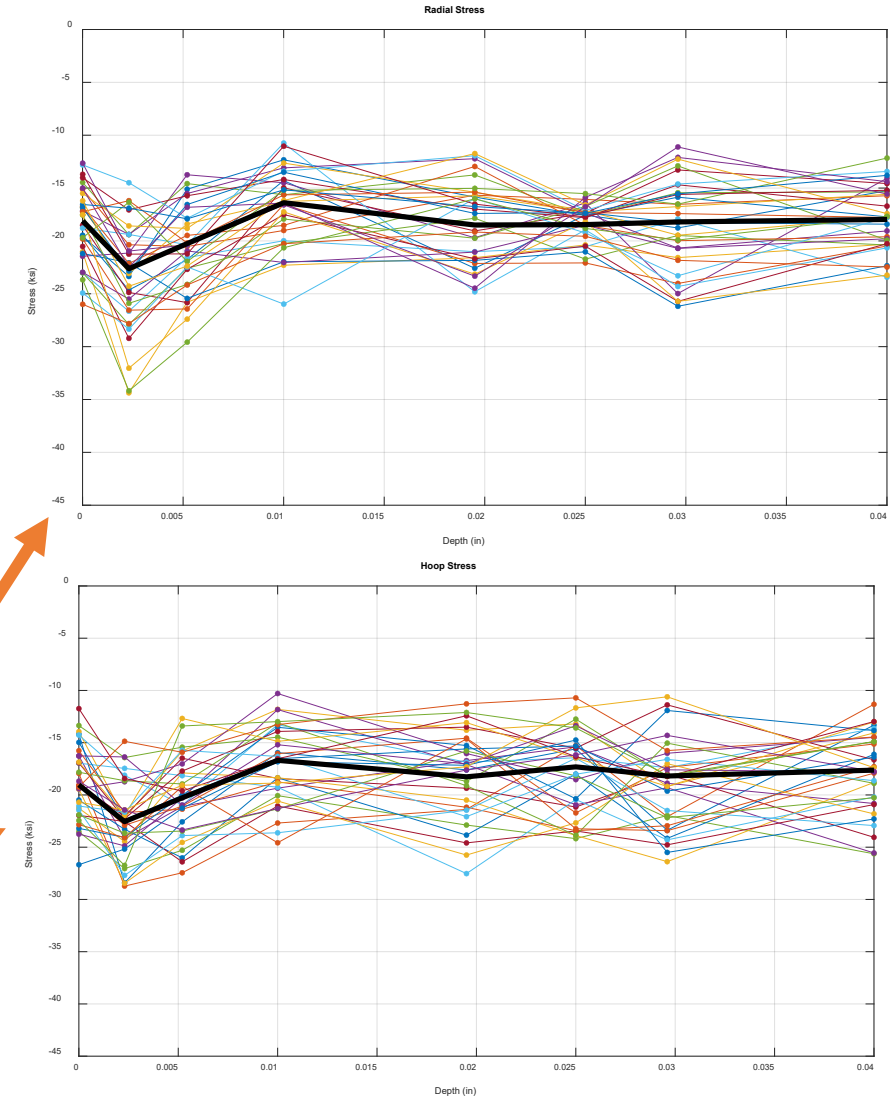


XRD on Side 2 of 304SS Ring-Plug Specimen

- 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.

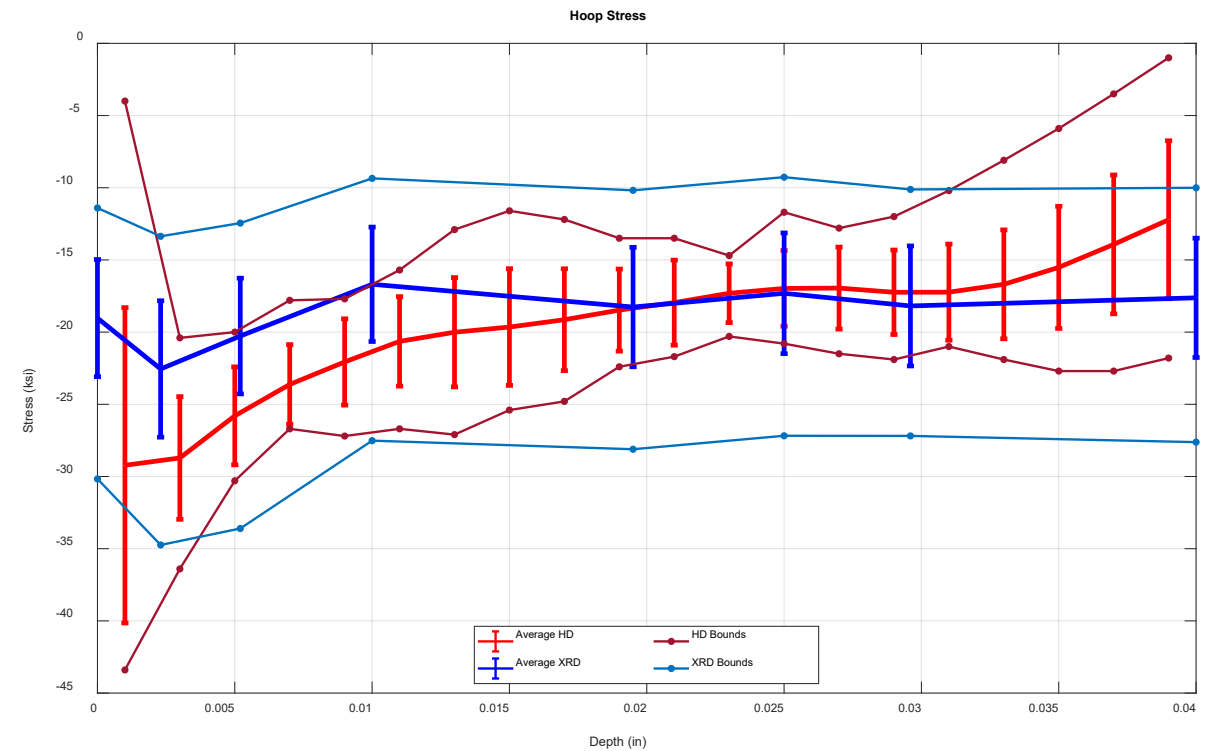
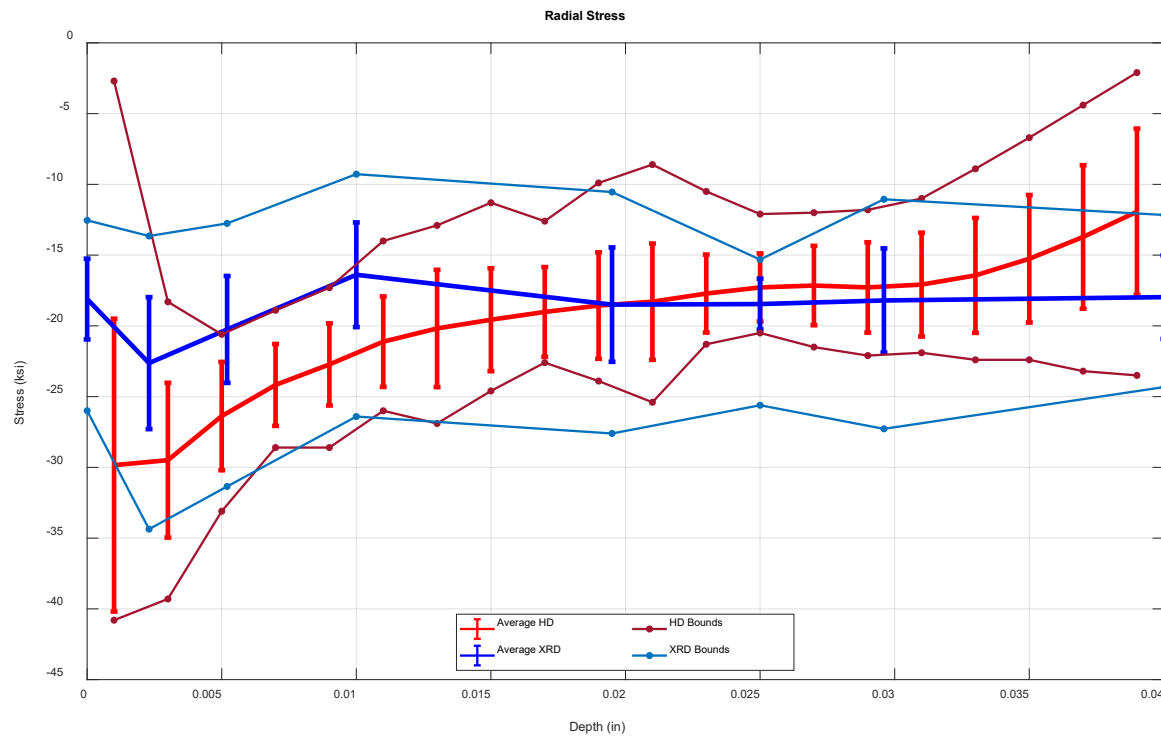


Typical Radial and Hoop Stress vs. Depth profiles – Example from R=8 mm



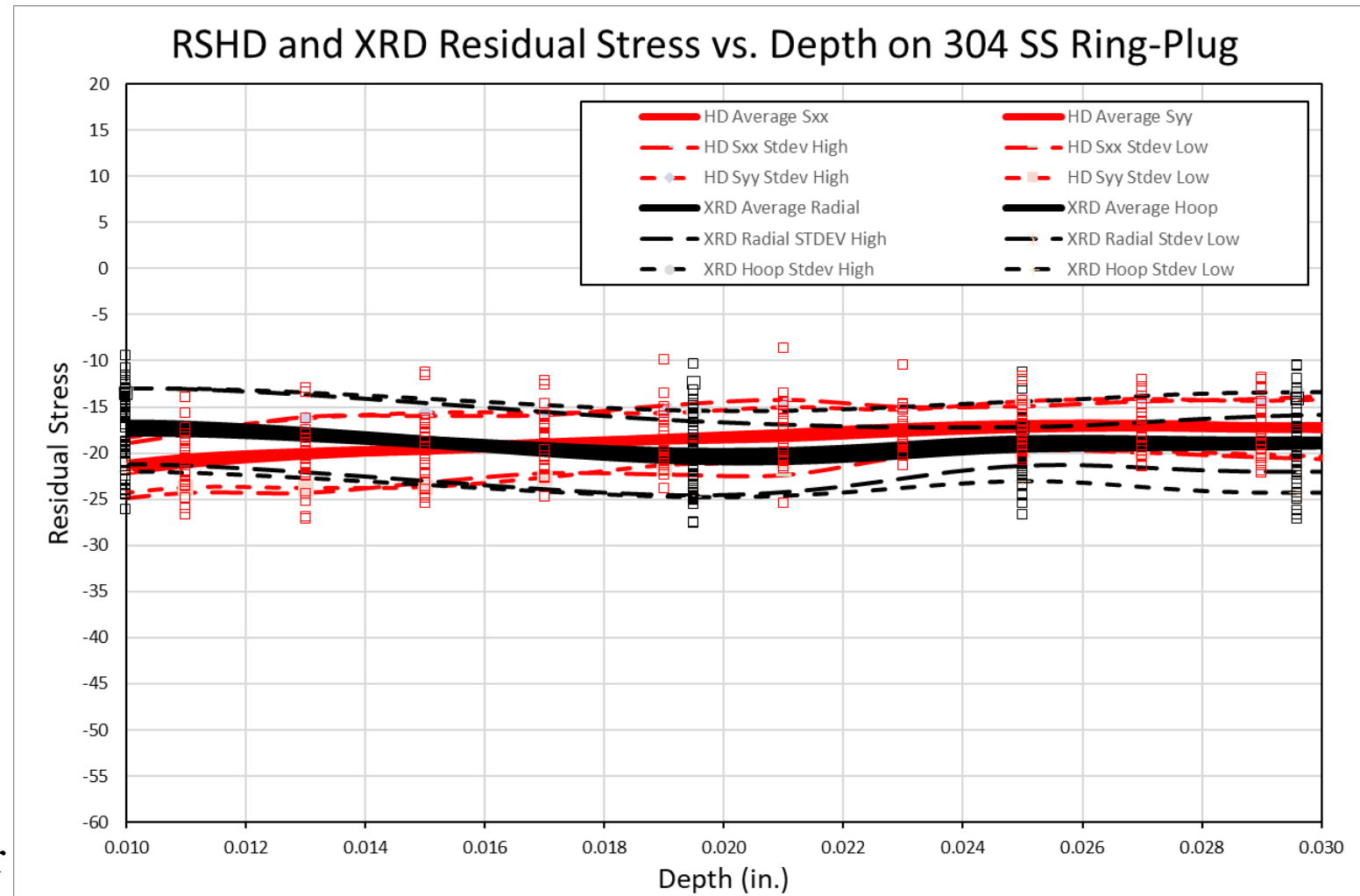
RSHD\XRD on 304SS Ring-Plug Specimen

- 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

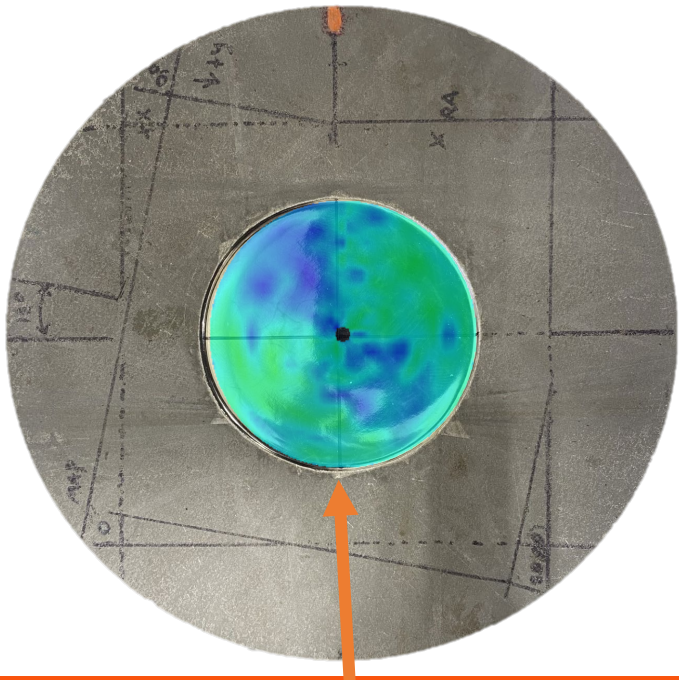


RSHD\XRD on 304SS Ring-Plug Specimen

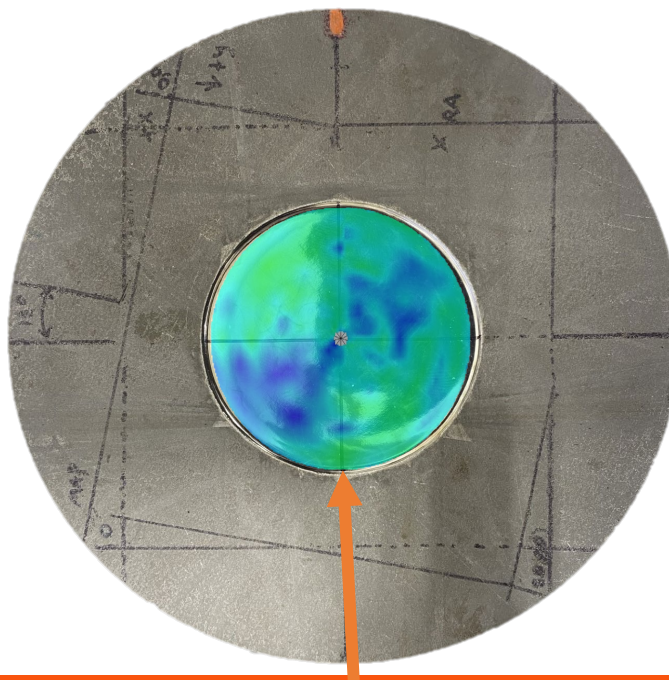
- Considered data below cold worked near surface region in the high confidence depth range for RSHD.
- XRD and RSHD results nominally equivalent despite measurements performed on opposite sides of 304SS Ring-Plug.
- Random errors one may typically expect from either RSHD or XRD shown via max/min bounds and standard deviations (nominally equivalent $\sim \pm 5$ ksi).
- 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.



XRD Maps on Side 2 of 304SS Ring-Plug



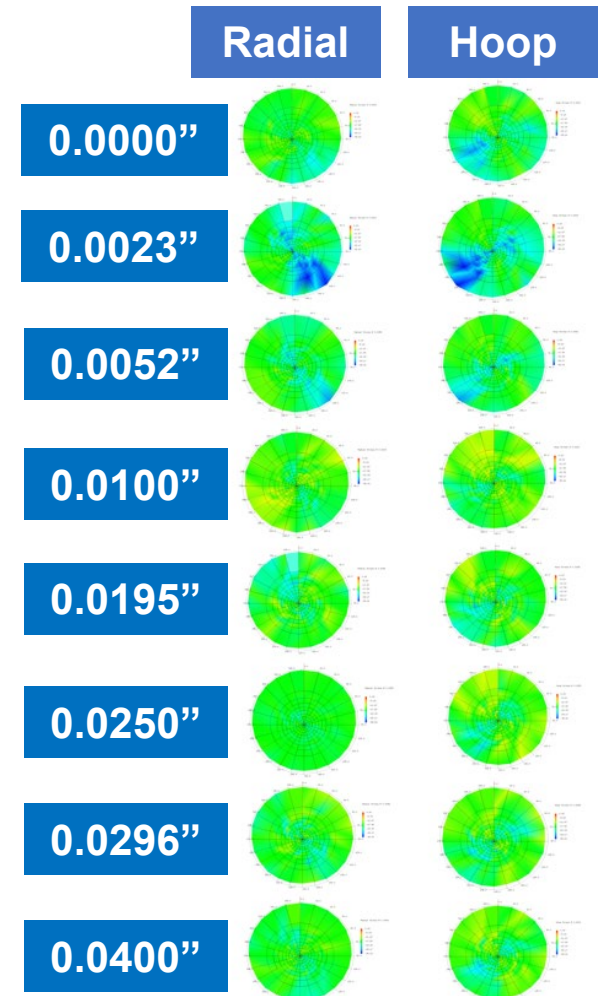
Radial Stress Map at 0.0195" deep



Hoop Stress Map at 0.0195" deep



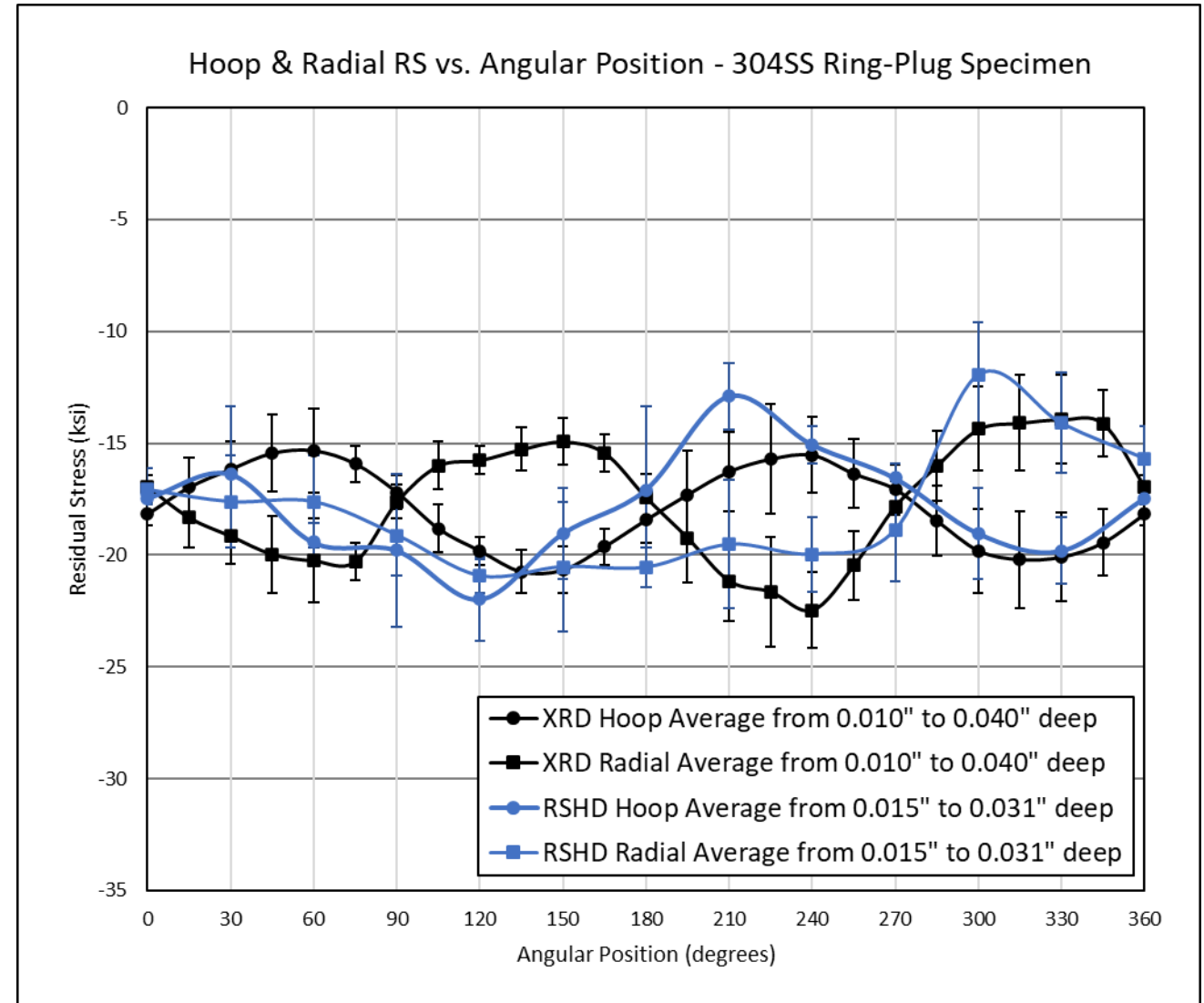
Stress [ksi]



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

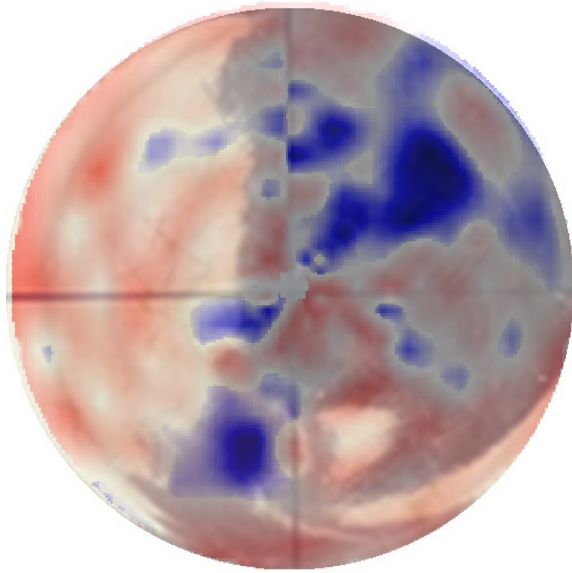
RSHD\XRD on 304SS Ring-Plug Specimen

- 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. 90° 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.

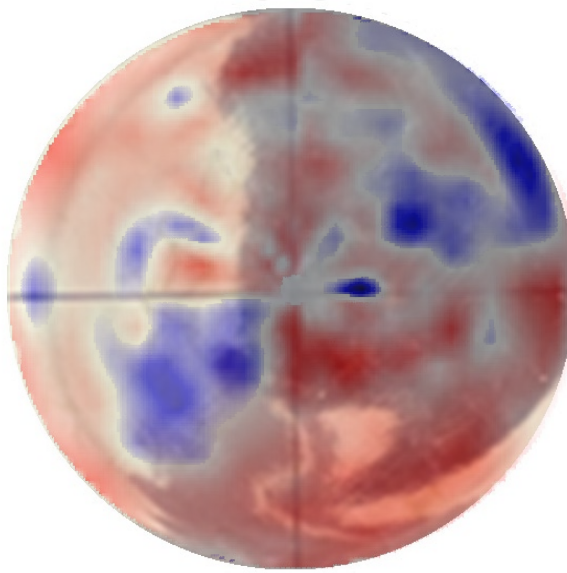


New Developments

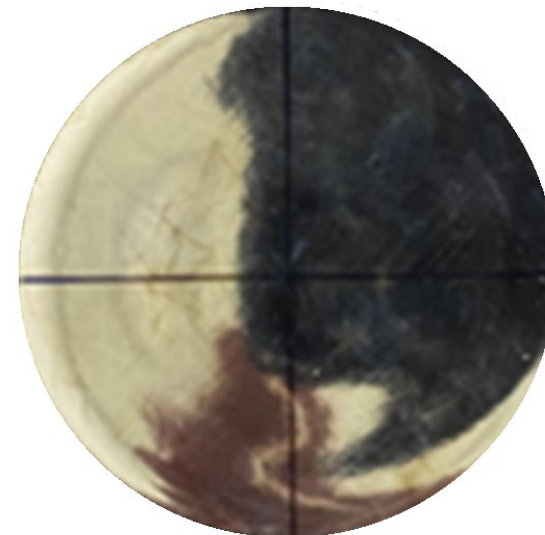
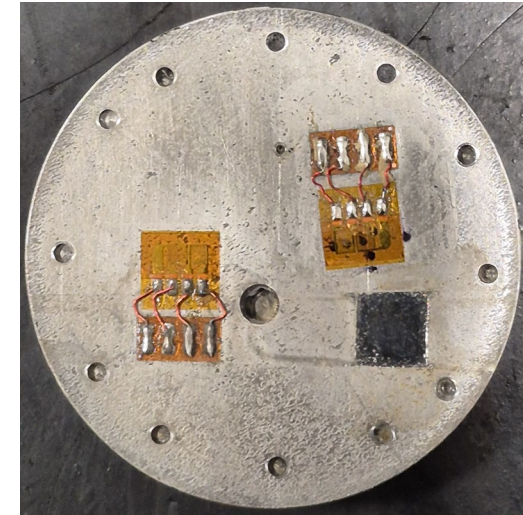
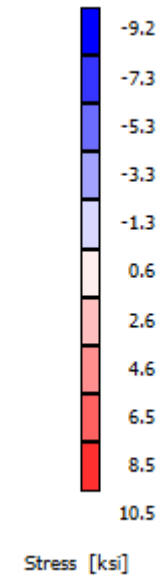
XRD Maps After Ring Removal



Radial Stress Map at 0.040" deep



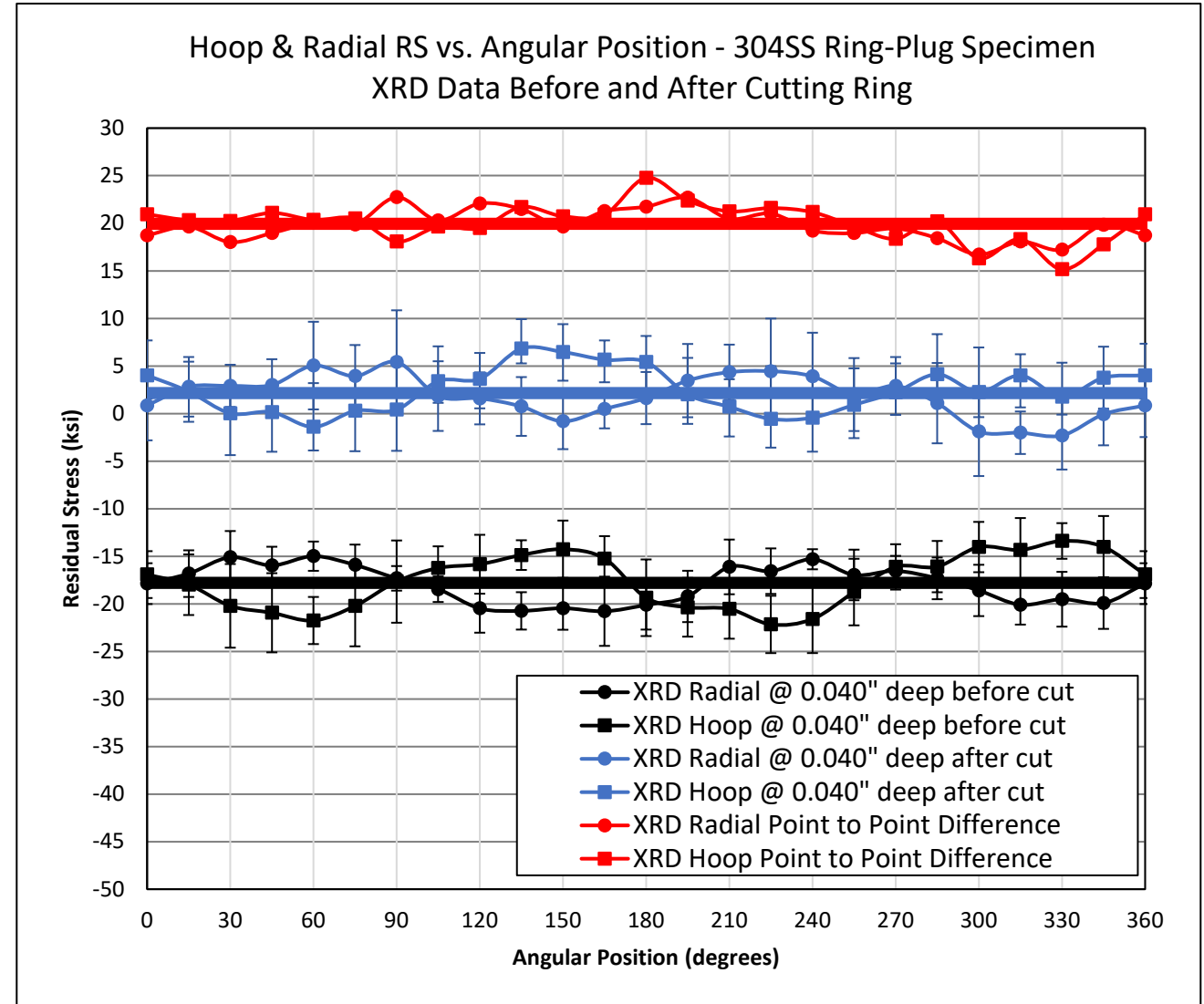
Hoop Stress Map at 0.040" deep



- XRD data collection strategy developed to facilitate analysis of anisotropic materials in upcoming experiments.
- Full field XRD RS maps indicate angular dependence on the magnitude of RS after ring removal.
- Confirms upstream fabrication residual stress, not anisotropic response to loading is the cause.

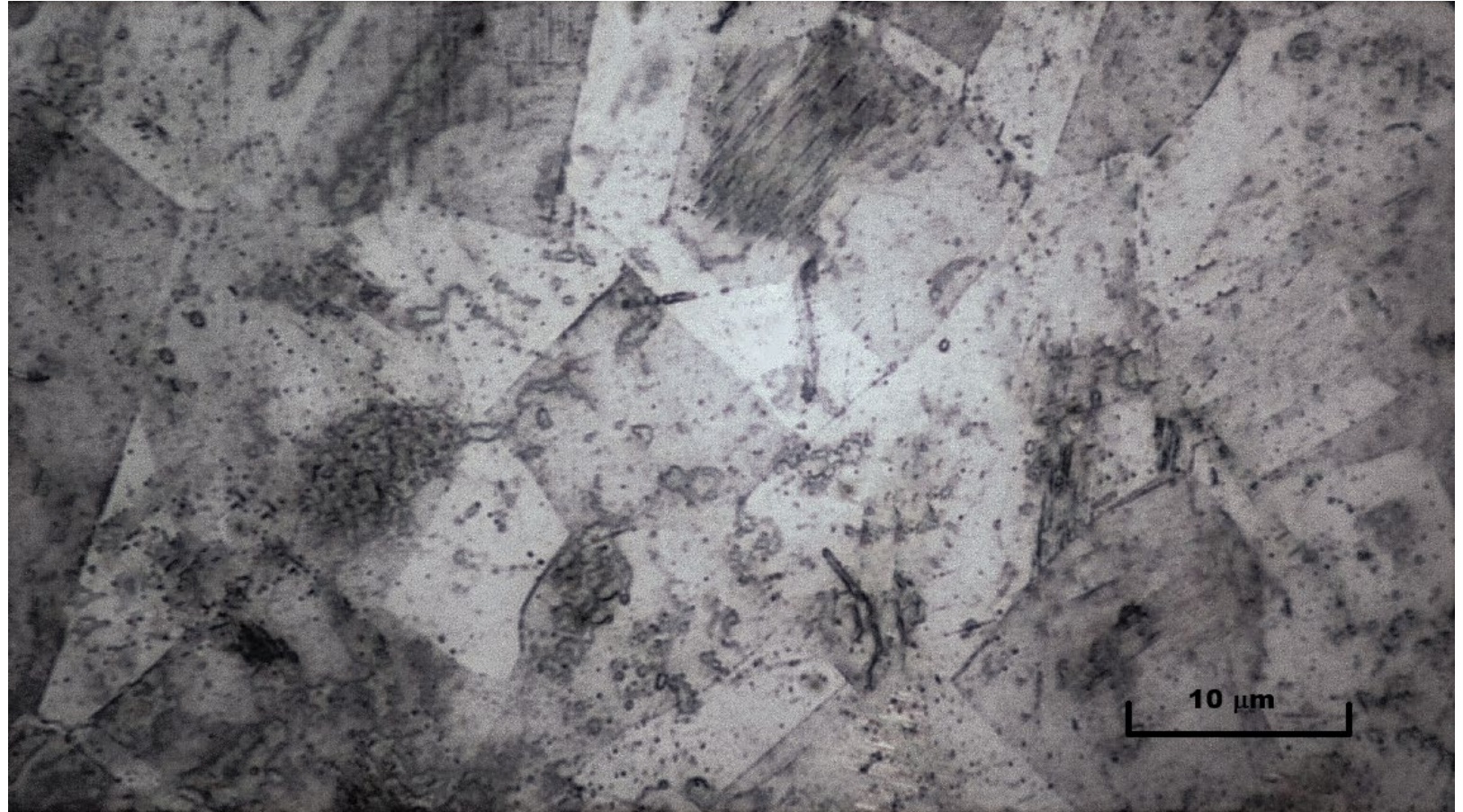
XRD on 304SS R&P Before and After Cut

- Radial dependence averaged along each given radial profile.
- Oscillatory trend observed both before and after ring removal using XRD data $\sim 90^\circ$ out of phase.
- The effect follows with sectioning indicating oscillatory behavior is due to fabrication residual stress, not anisotropy.
- Difference plot flattened – average change calculated to be -19.9 ± 2.6 ksi.
- Calculated to be $\sim 17.1 \pm 0.4$ ksi using strain gauges and book value elastic properties (to be confirmed).
- Note: Analytical modeling predicted ~ -29 ksi based dimensions and interference fit (to be confirmed) – Plasticity may account for disparity???? (TBD)



RSHD\XRD on 304SS Ring-Plug Specimen

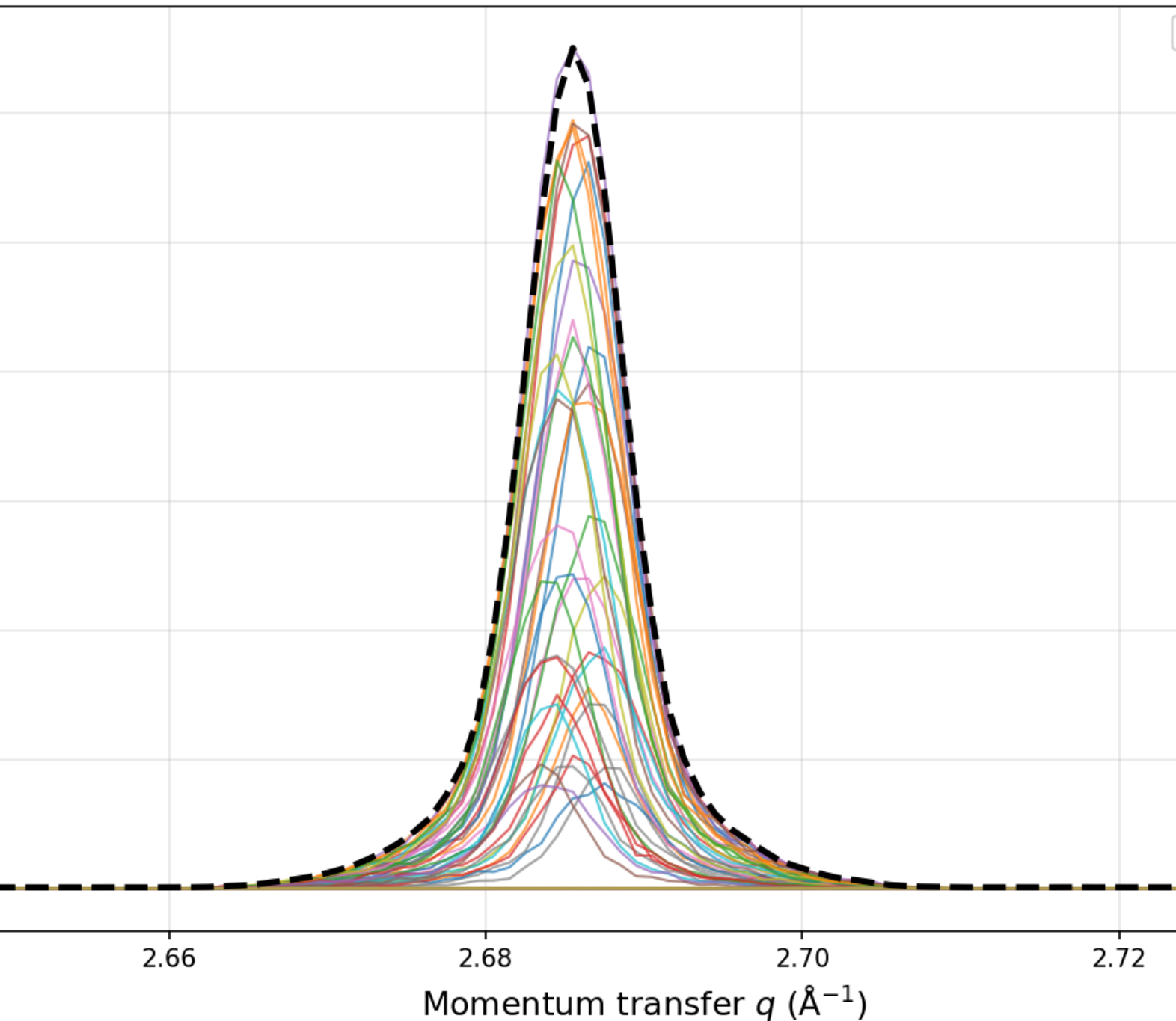
- Microstructure appears equiaxed.
- Grain size varies ~ASTM 2-10 ...ish?
- Seems to confirm the “no texture” conclusion.
- To follow up with EBSD and maybe some better micros.



Summary of Round Robin Studies

- Comparable data between RSHD and XRD for both Al 2024 T351 and 304SS ring and plug specimens, with the understanding of limitations of either method.
- Results from Al 2024 T351 ring and plug study published in Experimental Mechanics.
- Currently writing up paper on 304SS ring and plug – hope to publish late 2026 early 2027.
- Finalized workflow framework for ring-plug specimens, including data collection using RSHD and XRD to be used in anisotropic materials – use RUS and XRD pole figures to determine orientation specific elastic properties.
- With the heavy lifting of workflow complete, ring-plug specimens fabricated from anisotropic materials is the next step – probably AM Ti or Ni alloy (TBD).





**ERSI 2026,
Dayton, Ohio**

**Validation of the digital
thread for life extension
due to engineered
residual stress**

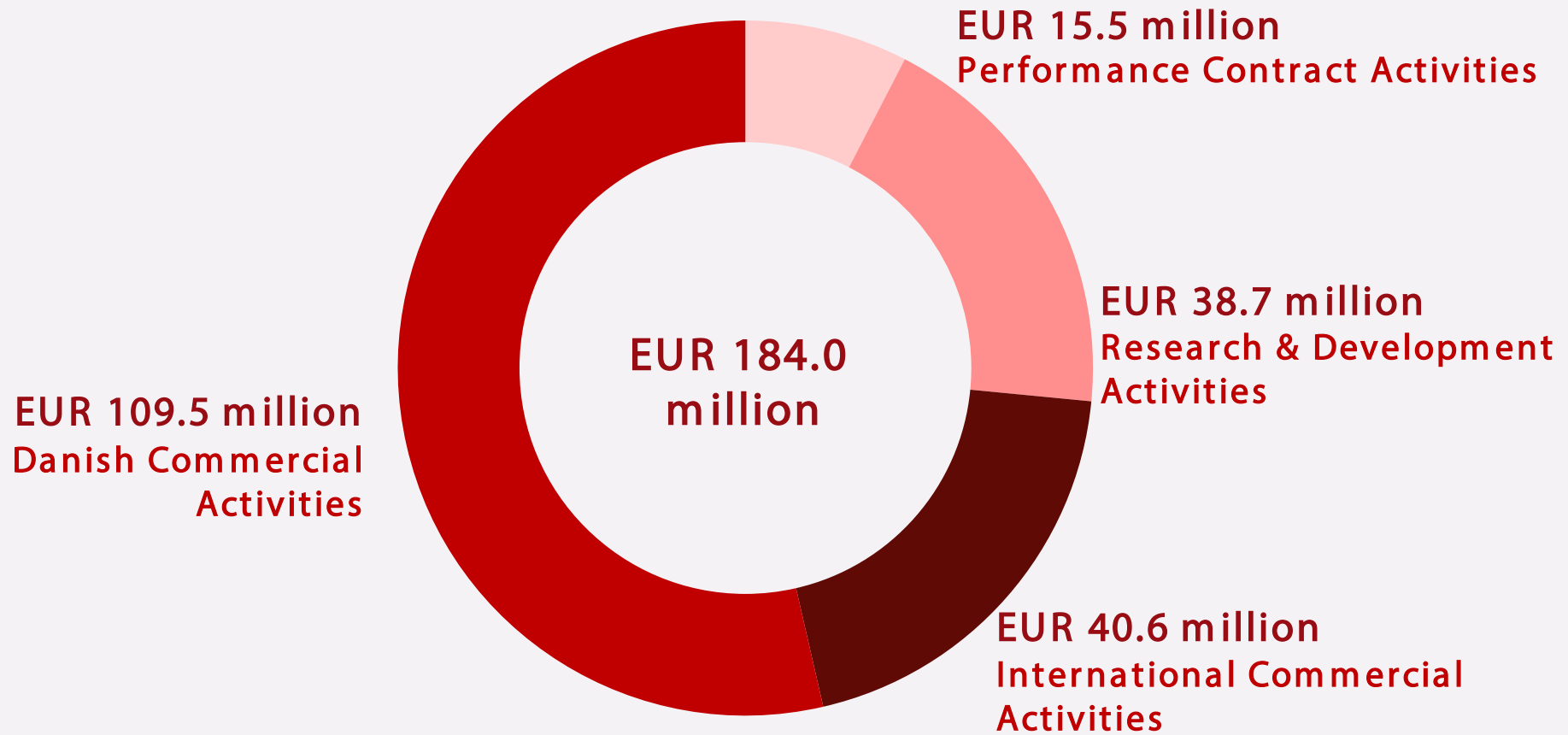


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Technology
for a better,
more resilient
future

Breakdown of group turnover in 2025



Part of the leading European RTOs

The Danish Technological Institute is a part of EUROTECH*, a group of the 10 leading Research and Technology Organizations (RTOs). In total there are 350 RTOs in Europe.

EUROTECH gathers the top management from these RTOs to develop a strategic approach to trends and dilemmas in innovation, industrial policies, and technology.

Tecnalia

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Danish Technological Institute was founded in 1906 by the visionary engineer, Gunnar Gregersen.

That makes us one of the oldest research and development institutes in the world.

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"Look ahead, ahead!

Look for the roads ahead that will pave the way for development and then place yourselves where you suspect the Institute's help will be necessary. The path will often take unknown routes and shortcuts, and detours cannot be avoided."



Gunnar Gregersen, founder of Danish Technological Institute and director from 1906-1950

A stylized, cursive signature of Gunnar Gregersen in red ink.

Our efforts are divided into five divisions

Food & Production



Building & Construction



Materials



Environmental Technology



Energy & Climate



Residual stress at DTI



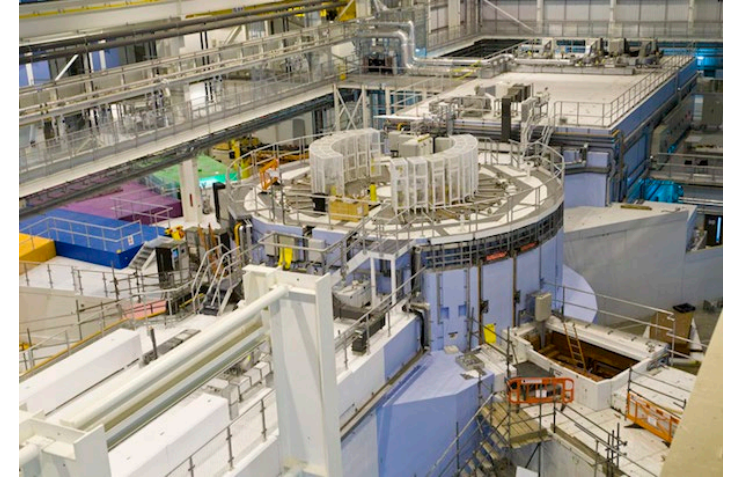
In-house lab-XRD

- X-ray diffraction-based equipment
- Surface measurements
- Non-destructive
- Portable and can measure large specimen



Destructive tests

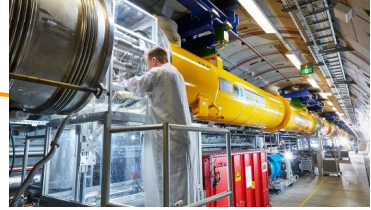
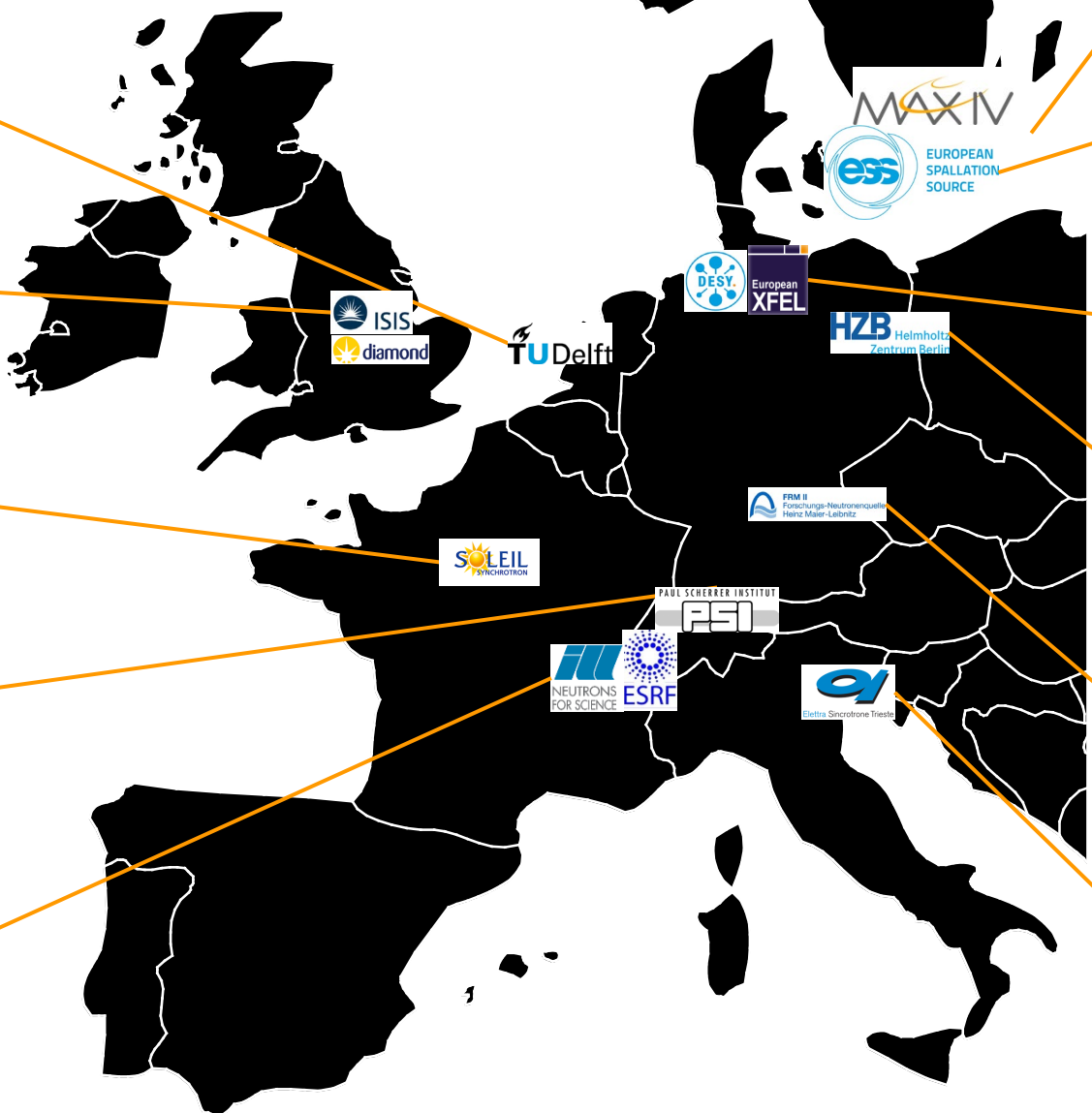
- Collaboration with many partners
- Insensitive to microstructure
- Hole boring
- Contour method
- Etc.



Large research Infrastructures

- Synchrotron & neutron radiation
- High resolution
- Depth profiles of several inches
- Leading providers of services at LRIs
- Imaging/CT services

European x-ray and neutron facilities

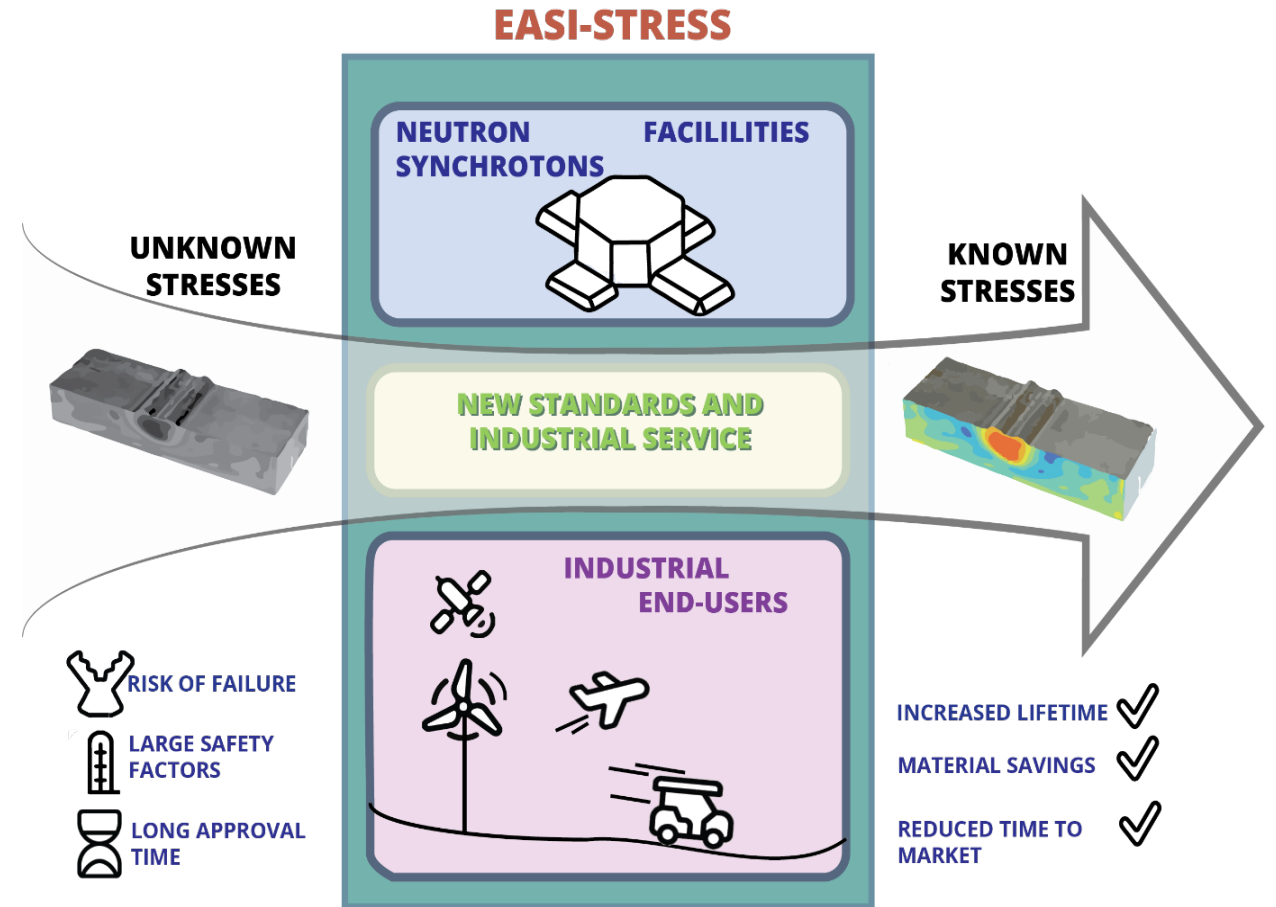


EASI-STRESS

- Harmonisation and standardisation efforts
- Setting up a sustainable industrial measurement service
- Software development for residual stress calculation
- Harmonised file-formats

DTI headed standardization efforts resulting in DS/CEN/TS 18094:2024 technical specification:

Non-destructive testing – Test method for determination of residual stress in polycrystalline materials



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 953219.



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EASI-STRESS: consortium

RTOs and
Universities



DANISH
TECHNOLOGICAL
INSTITUTE
(Coordinator)



The University of Manchester



Advanced Research Infrastructures



Centre for
Energy Research

Standardisation
Body



DANSK STANDARD

Industry



edf



TEKNOLOGISK
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The VULCAN machine

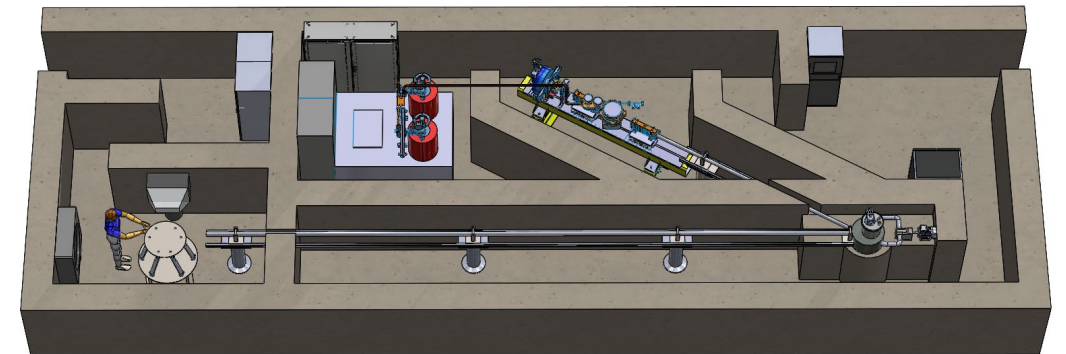
Design of ultra compact neutron source for industrial residual stress measurement

Neutron-based diffraction is

- Inherently non-destructive
- Applicable to all crystalline materials
- Able to measure stresses several inches into steel

However, facilities are quite large and have limited access. E.g. the European Spallation Source costs around 3 billion dollar for 15 instruments.

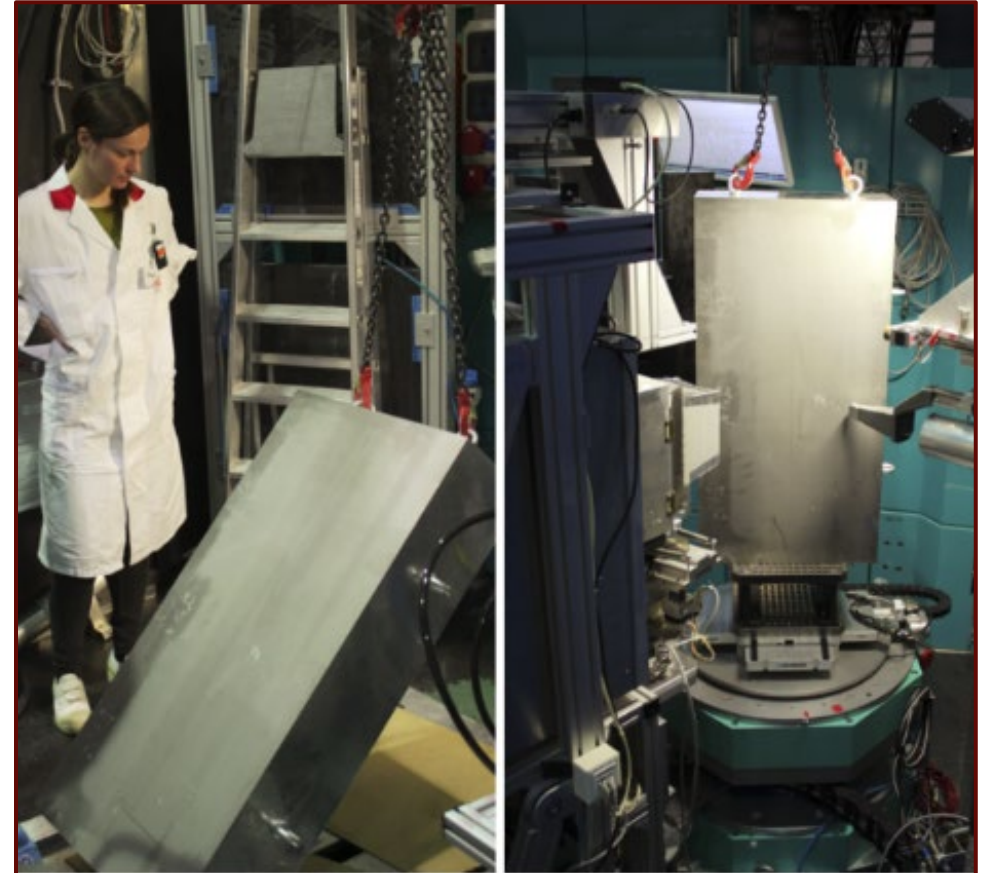
As part of a publicly funded project, we have designed the VULCAN machine. Residual stress dedicated neutron source that can be installed in a large lab.



Vision

Vision

- High confidence RS data close to the bore hole edge in three directions
- Develop protocols and methods for determining near-bore surface RS
- Enhance the ability to predict failure and crack growth
- Establish SsCx at DTI



Samples

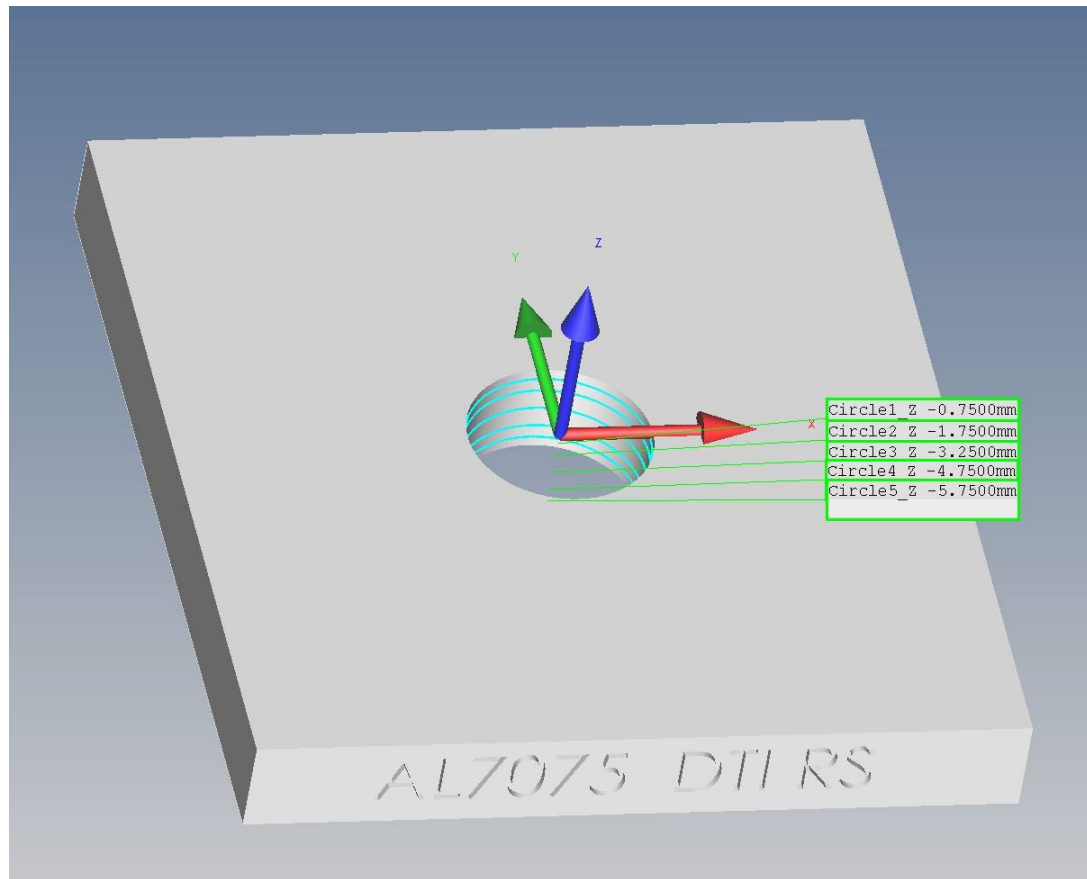
- Al 2024, 7075, 7050
- High and low expansion
- Reamed and unreamed
- 24 specimens in total



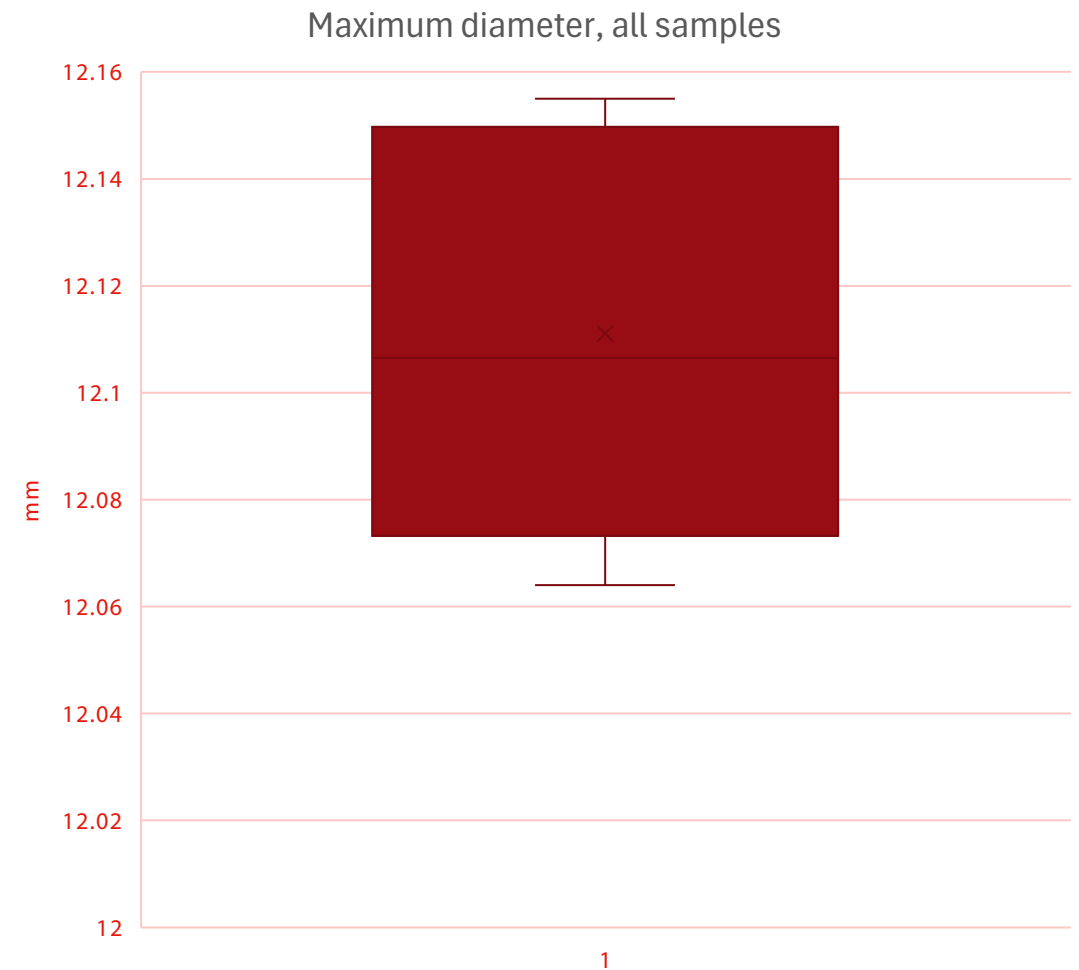
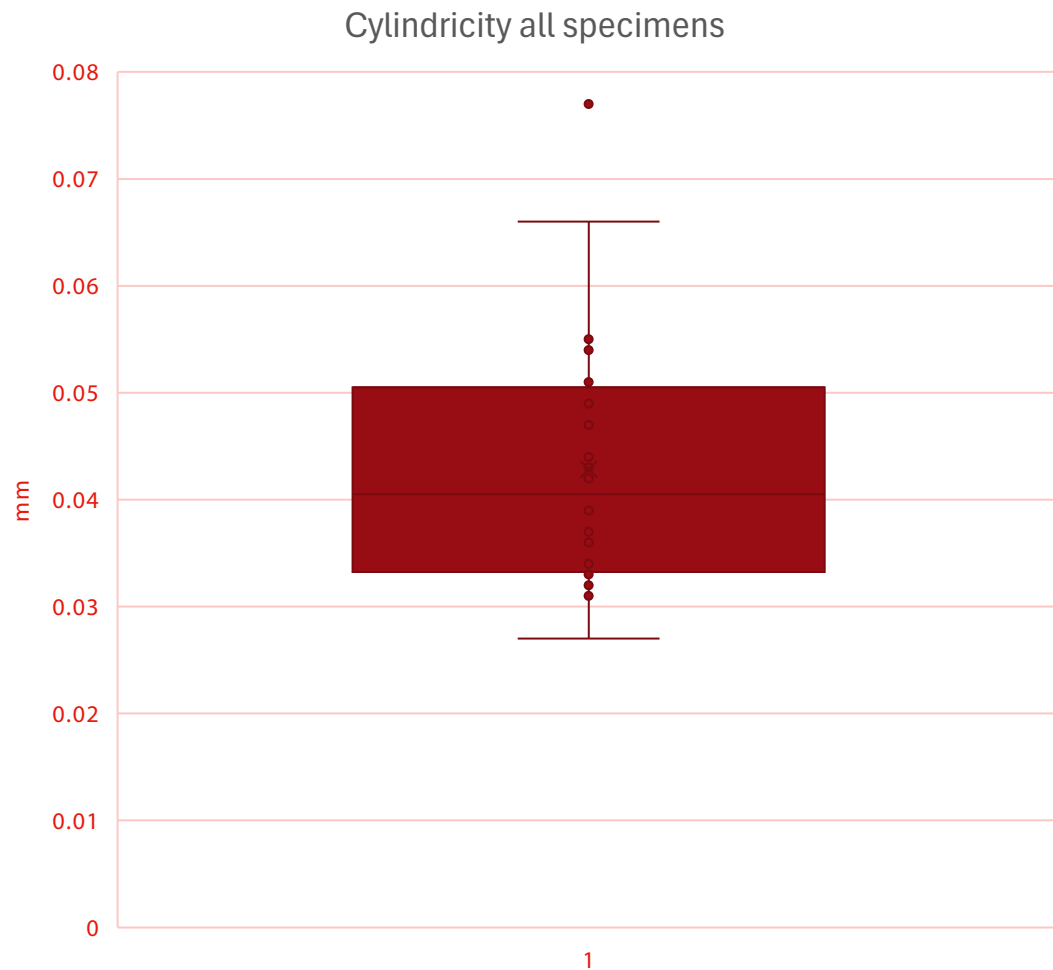
Challenges and methods

- High degree of texture and large elongated grains
- Strain free reference
- High confidence surface measurements in three directions
- Measuring the texture, adding rotation/oscillation, supporting destructive analyses, wave length- and energy dispersive methods
- McStas simulation of gauge volume
- Deconvolution of the gauge volume
- Two-three independent, fundamentally different measurement methods
- Extensive hole metrology before and after cold expansion

Initial metrology

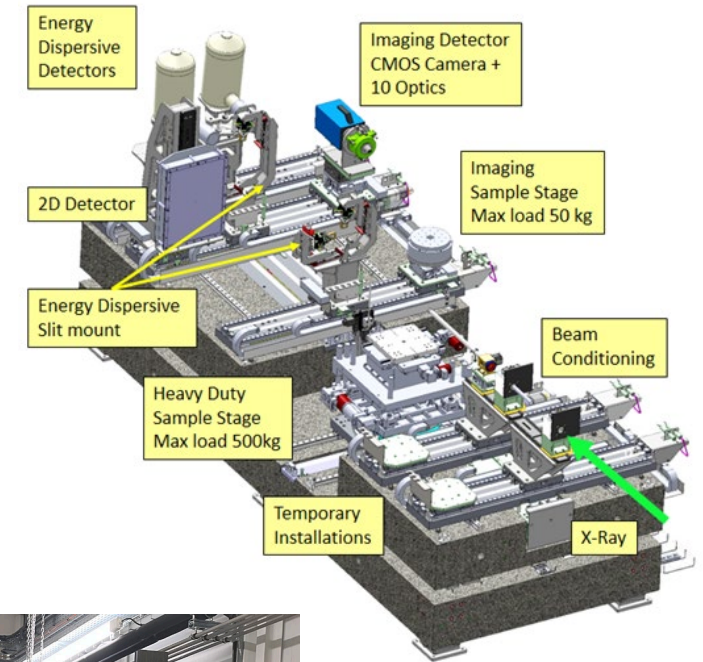


Initial metrology

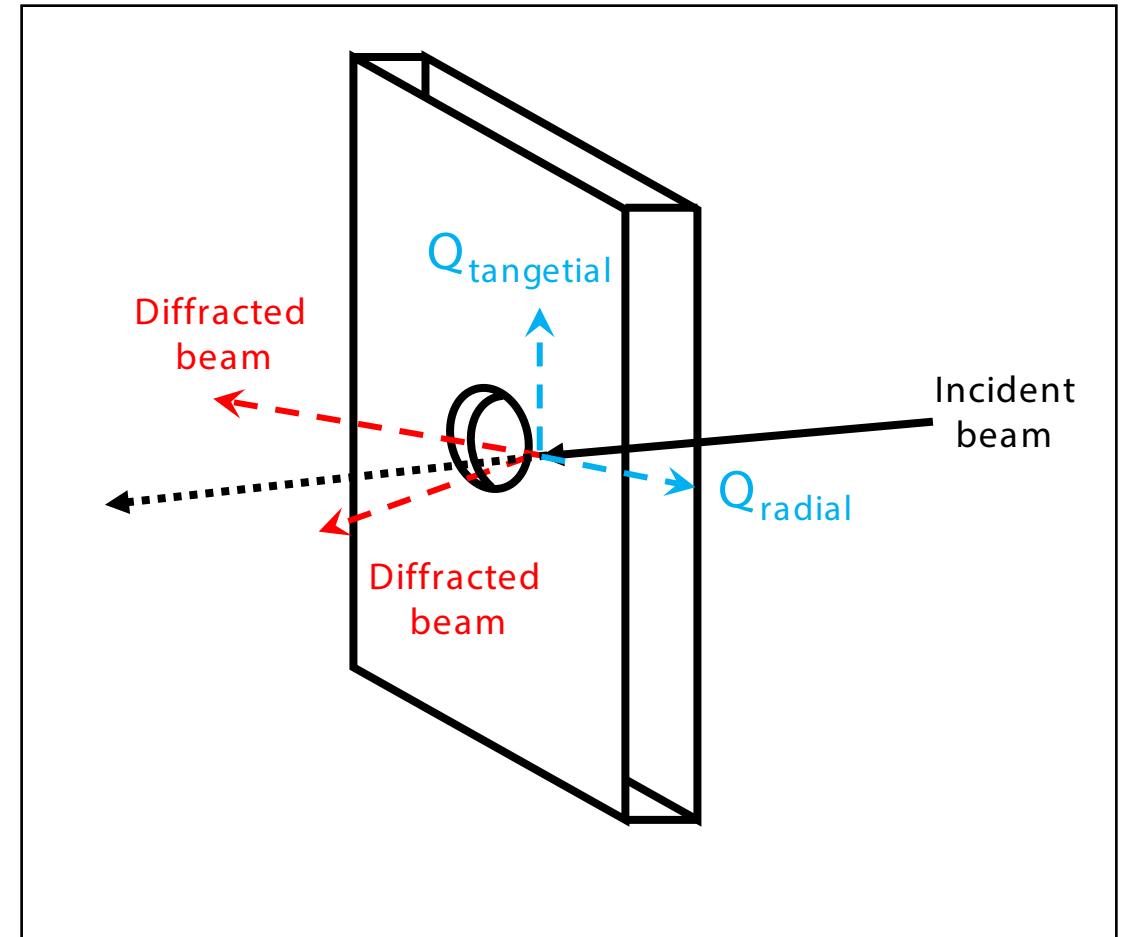
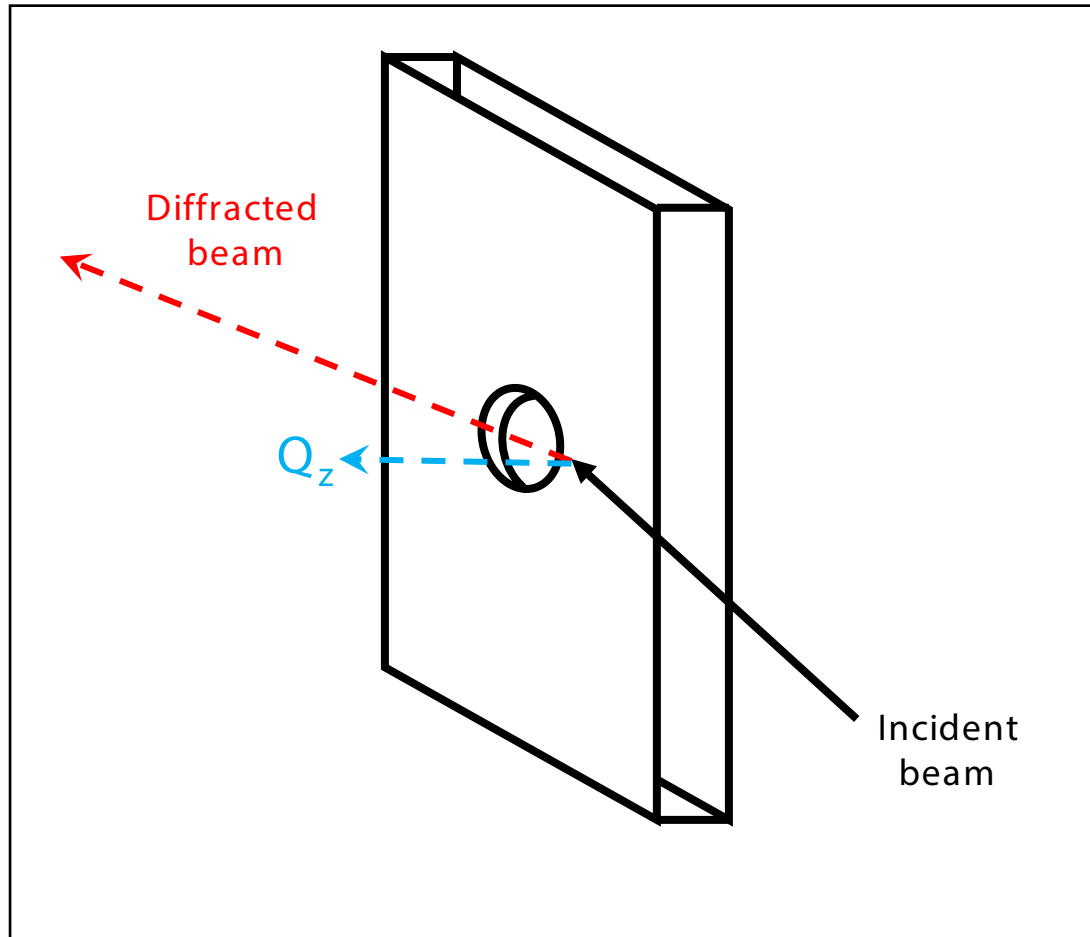


ED-XRD

- Beamline: ESRF ID15A
 - Energy dispersive x-ray diffraction using white beam radiation
 - Energy Range
 - 20-500 keV
 - Beam size
 - 0.1 mm – 8 mm
- Sample mounting: Euler cradle + XYZ stage



Experimental setup (ED-XRD)



ND

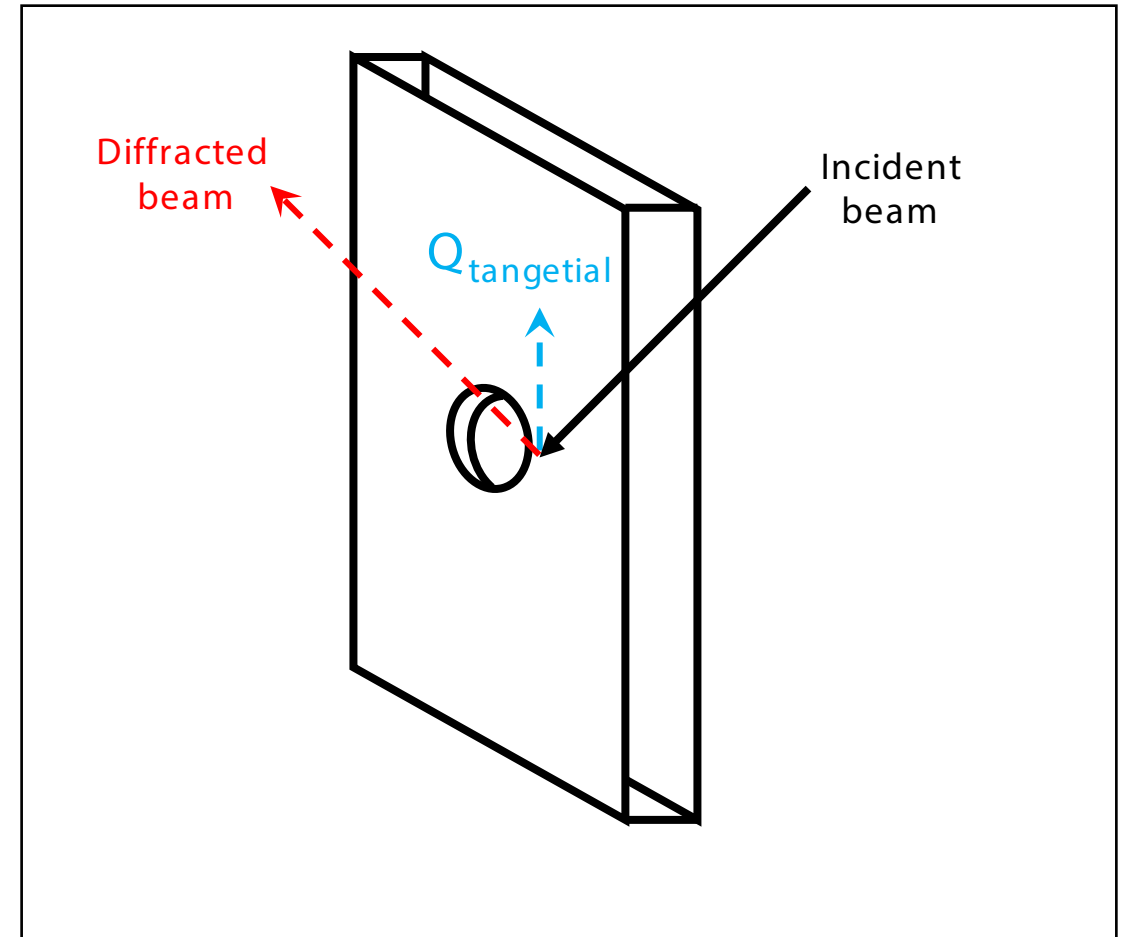
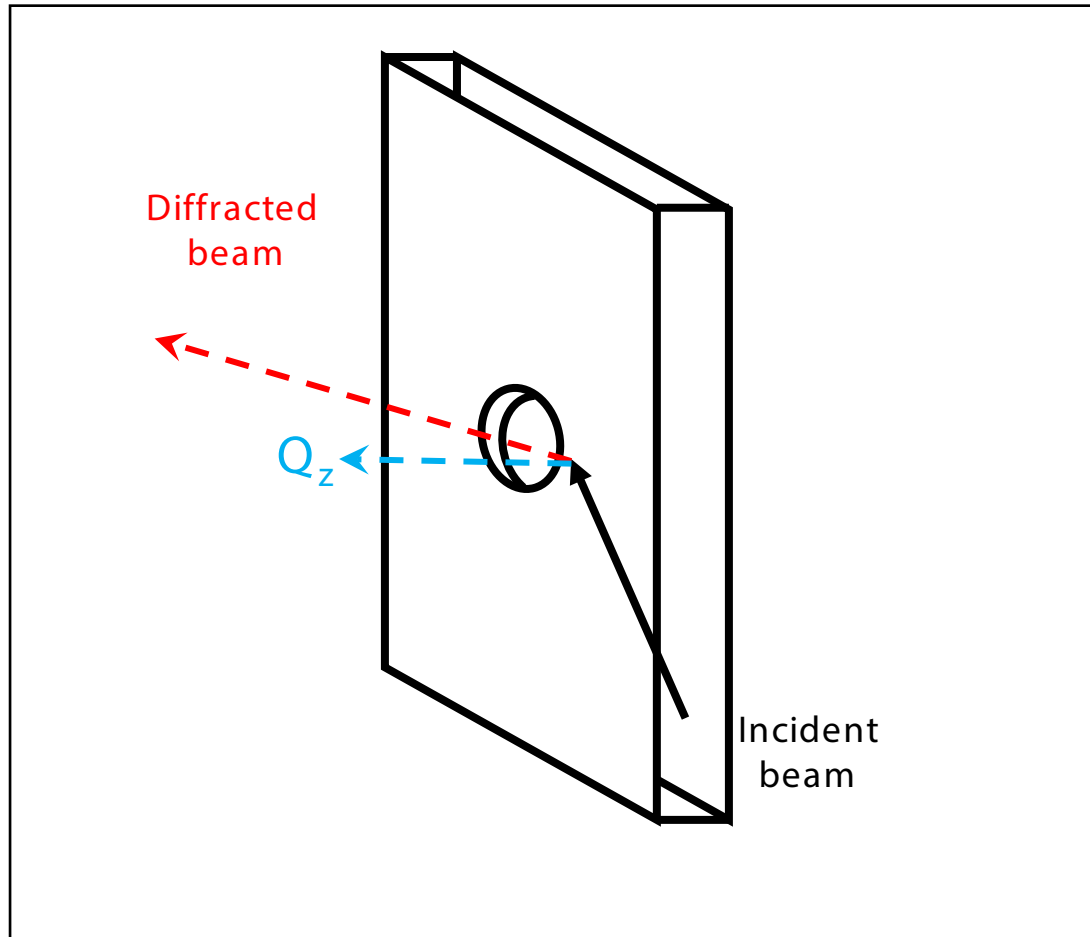
- Engin-X?
- Time of flight
- Detectors:
- $2\theta = \pm 90^\circ$ diffraction banks, ZnS scintillators
- 2θ range: 76° to 104°
- Vertical range: $\pm 21^\circ$

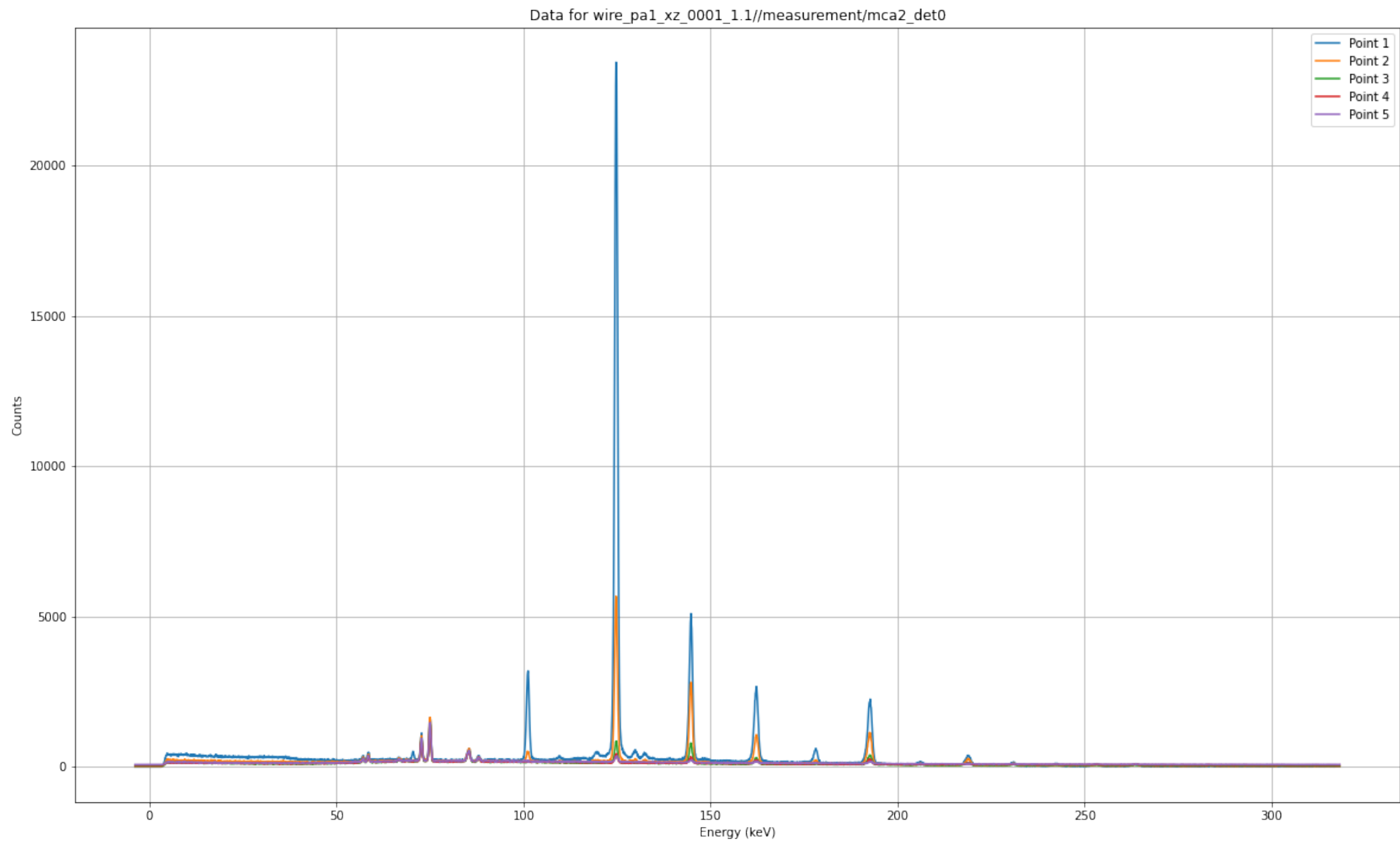
Incoming beam collimation:

- Vertical: 0.2 to 20 mm
- Horizontal: 0.2 to 10 mm



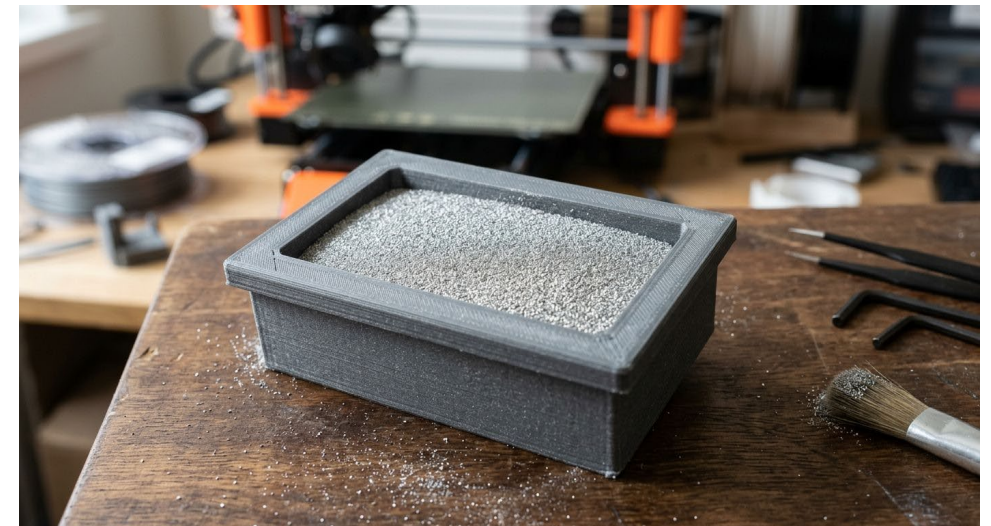
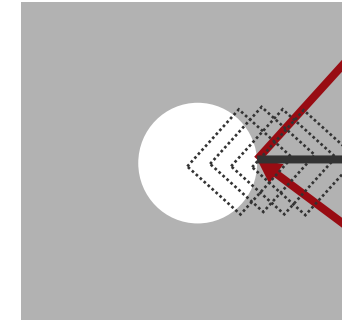
Experimental setup (ND)

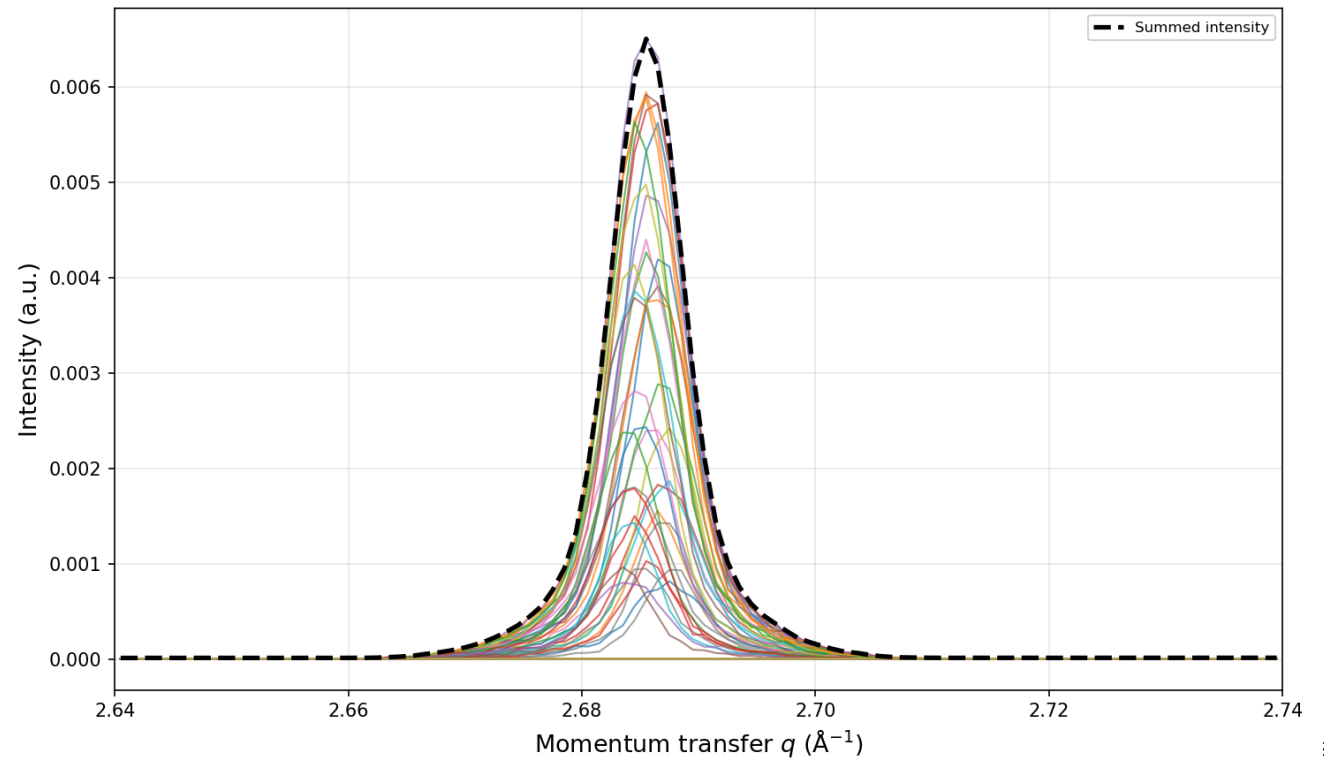
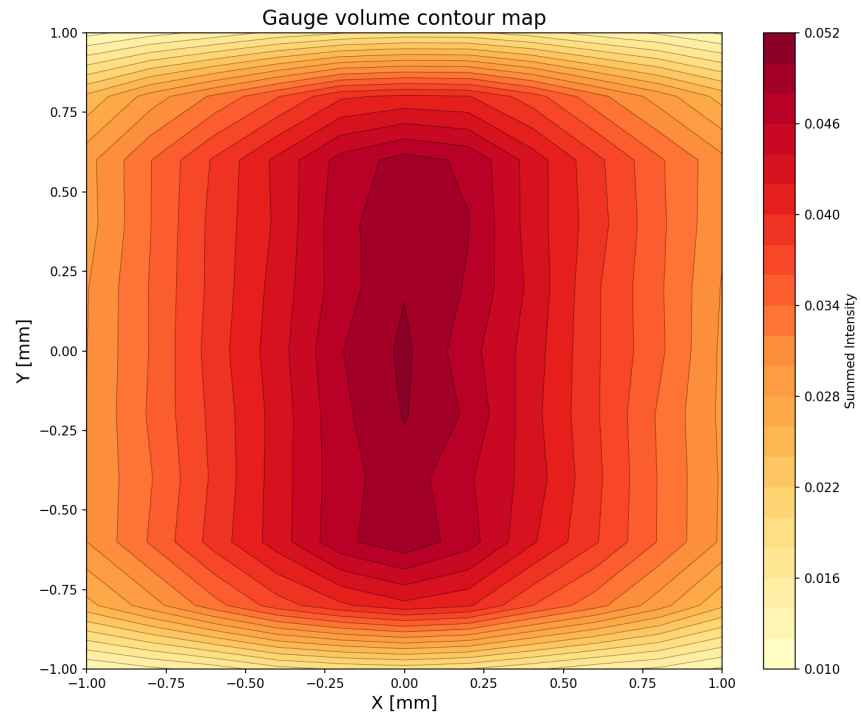
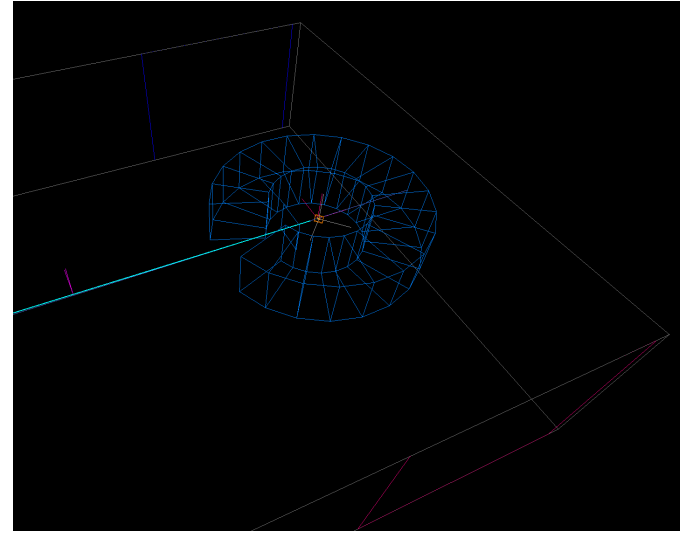
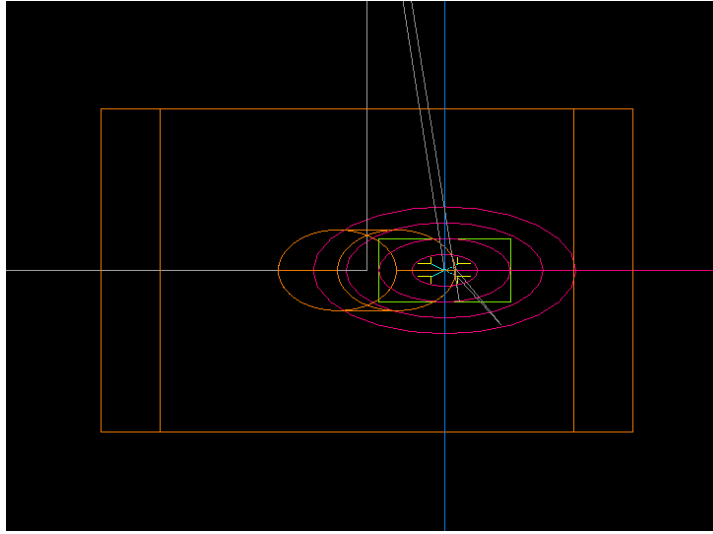
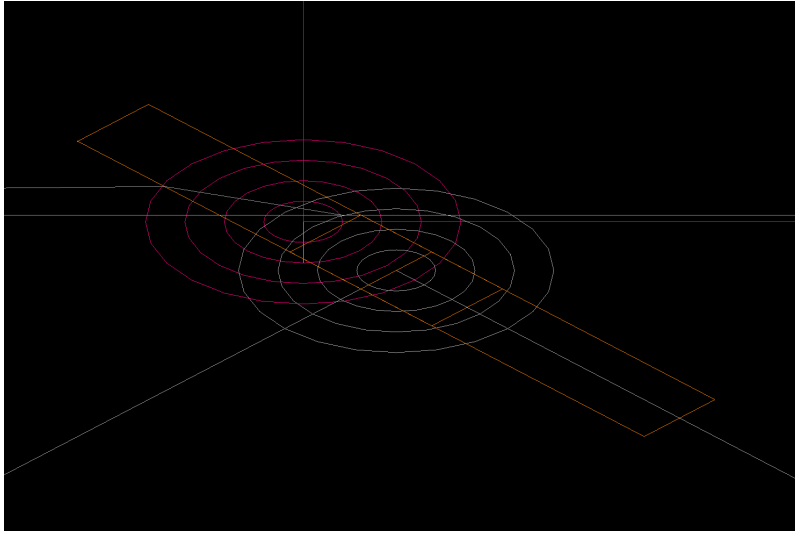


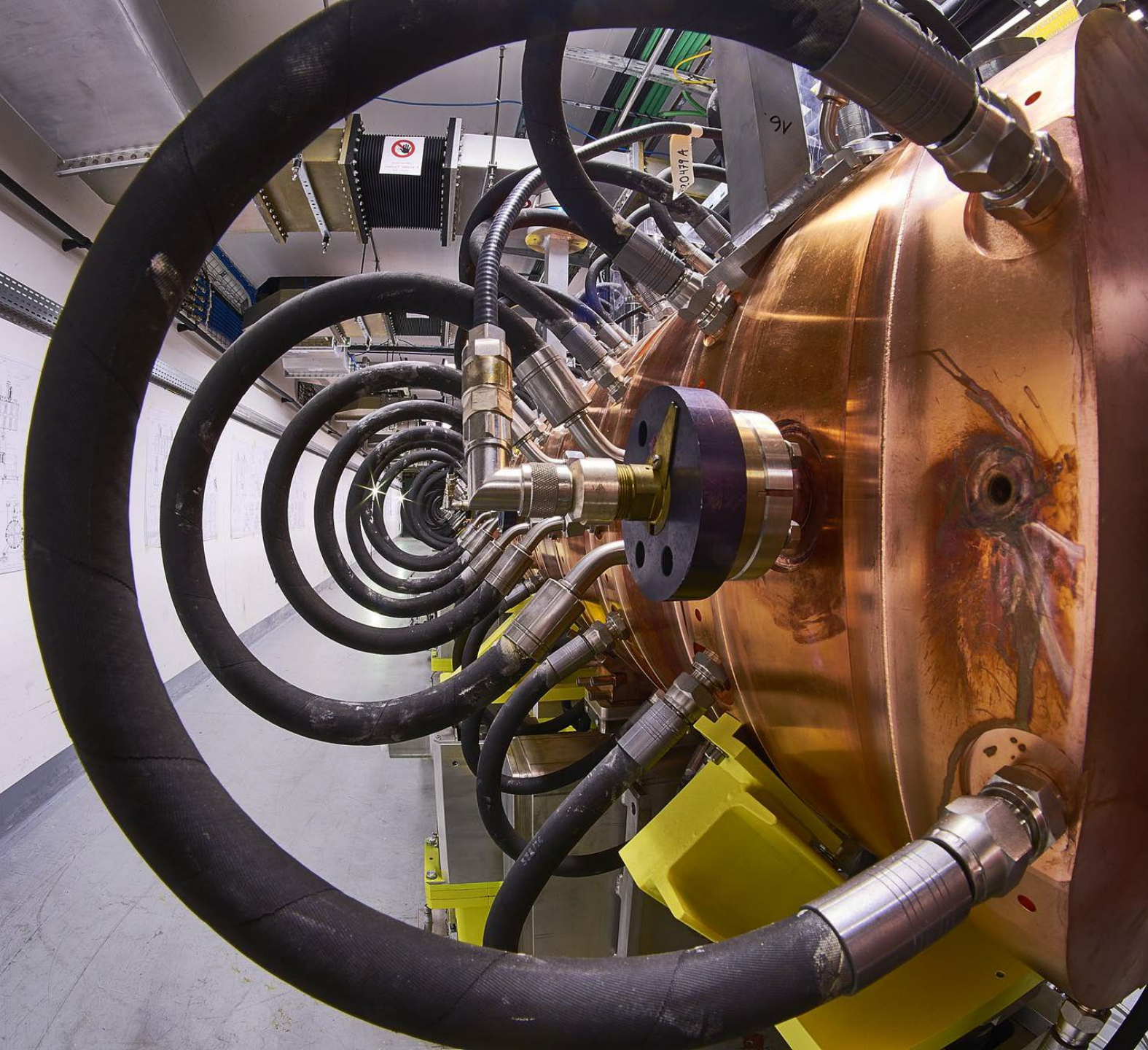


Deconvolution and simulation

Challenges	Mitigations
Statistic noise	Good statistics + accepting uncertainties
Guage volumes do not have well defined boundaries.	Accepting uncertainties. This error can in principle be estimated through simulations.
Texture	Use energy dispersive instruments and rotate sample
Attenuation and multiple scattering causes errors on the foil approach.	Use simulations to quantify error
Guage volumes do not overlap for all geometries	Select geometries







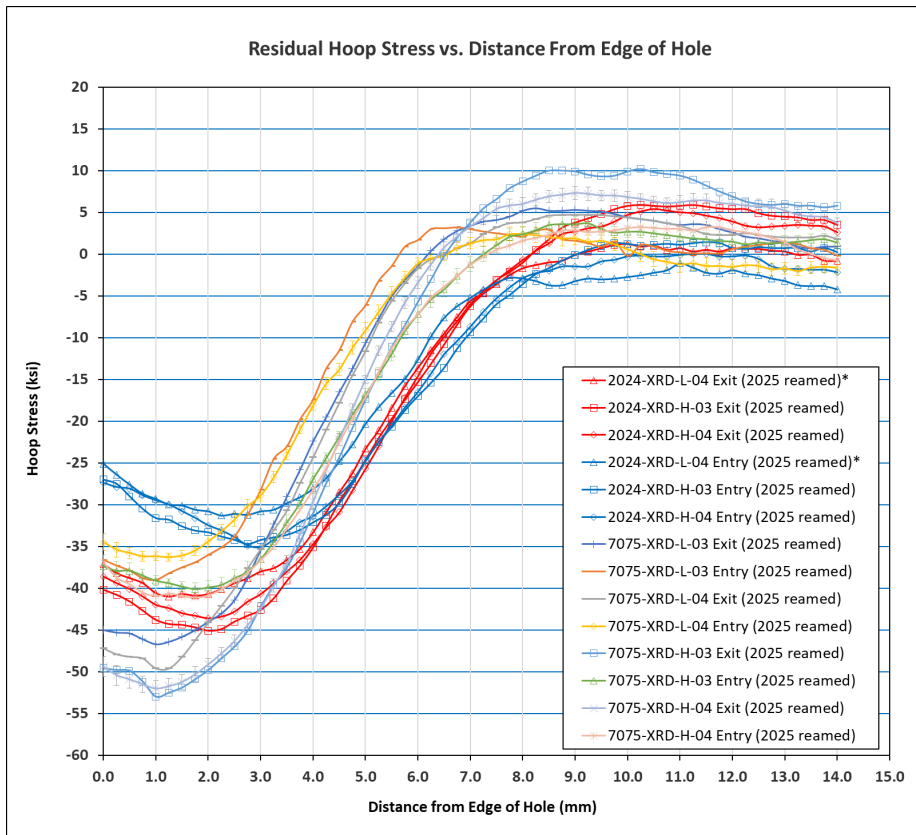
Thank you for your time!

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Nikolaj Zangenberg
Director
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New data for 2024-T351 and 7075-T651

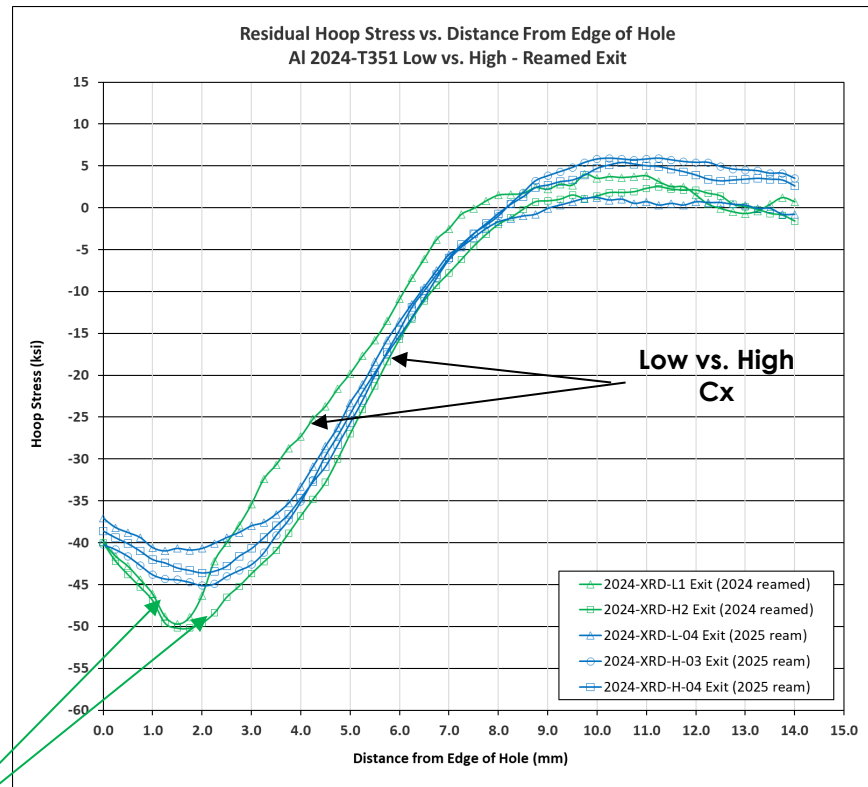
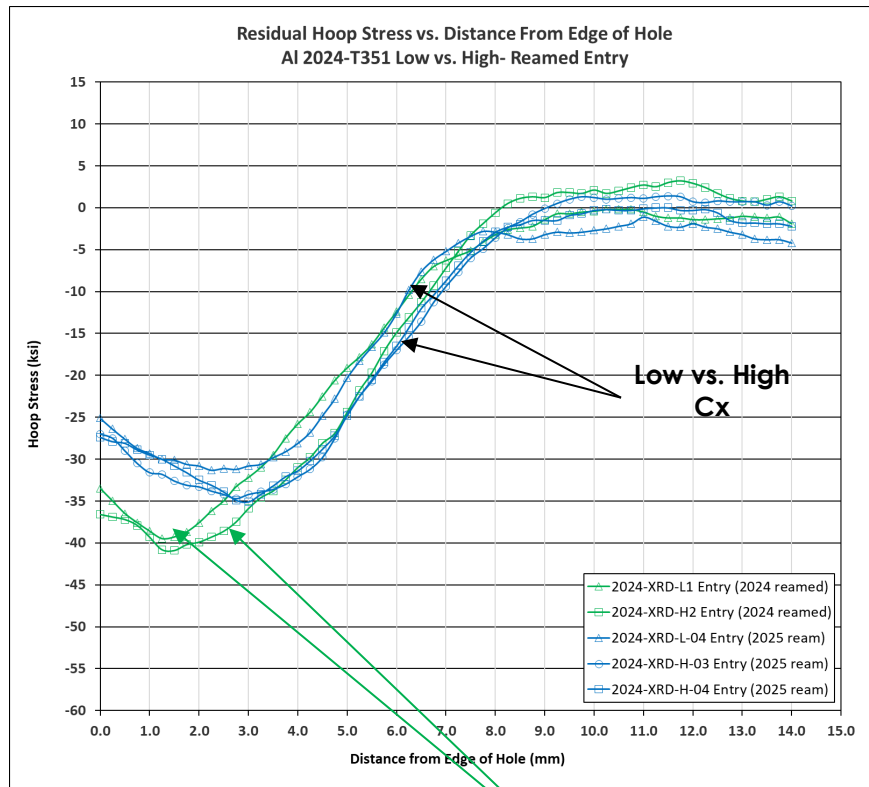
RS on surface faces of 2x2 Coupons



Note: All holes are in the new data set were in the “reamed” condition – more specifically, circularly interpolated using a mill rather than a conventional reamer.

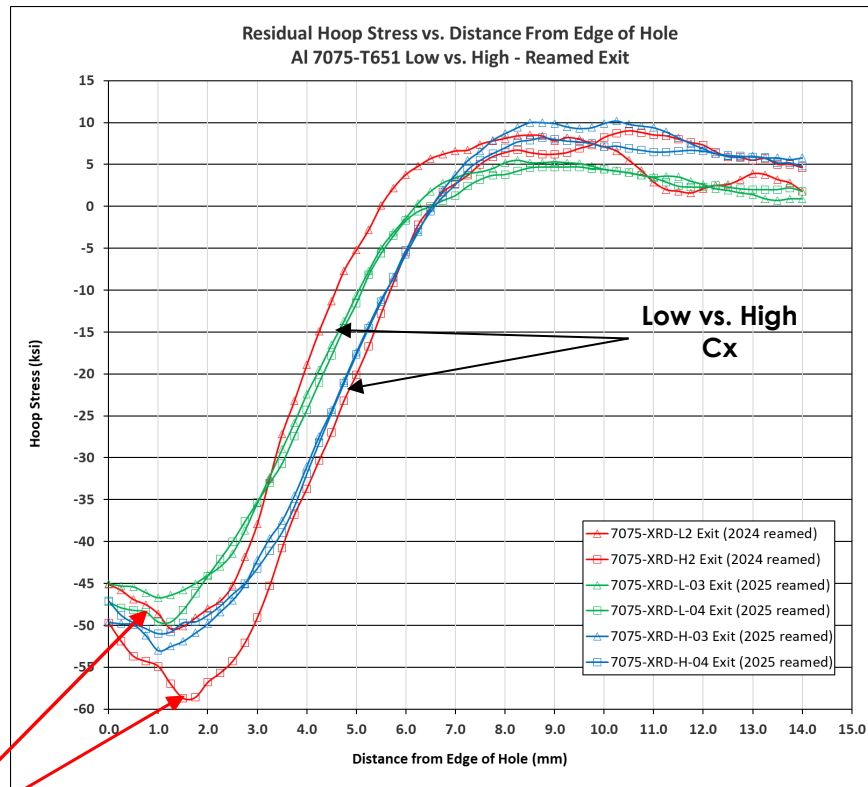
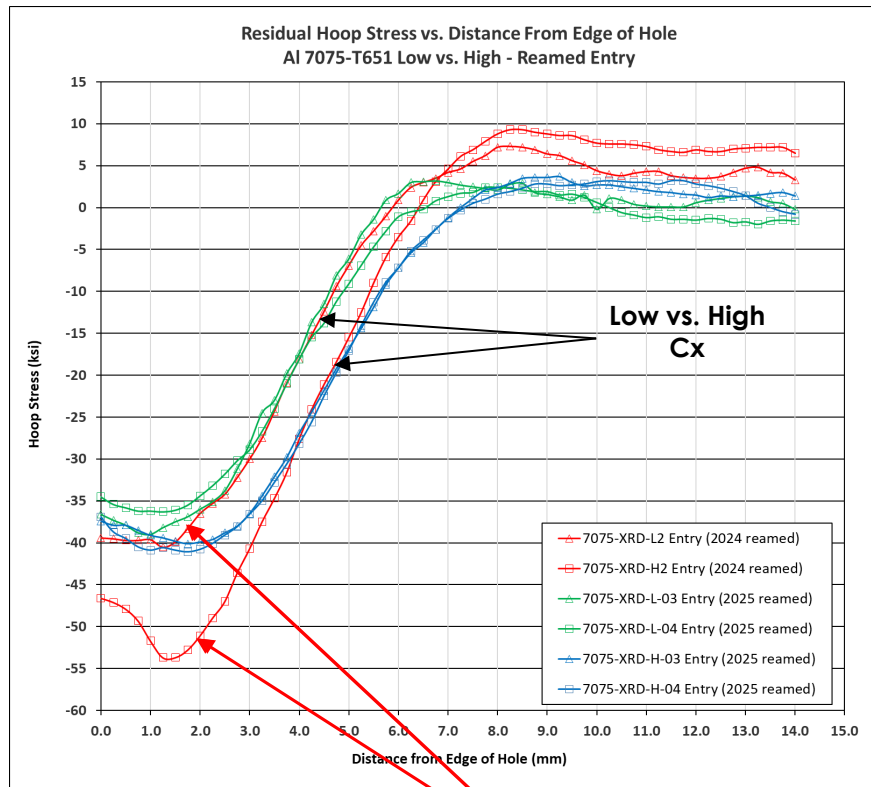
Low Cx vs. High Cx (Reamed Condition)

AI 2024-T351 (Reamed) - Low Cx vs. High Cx



With Reamer

Al 7075-T651 (Reamed) – Low Cx vs. High Cx



With Reamer

Discussion

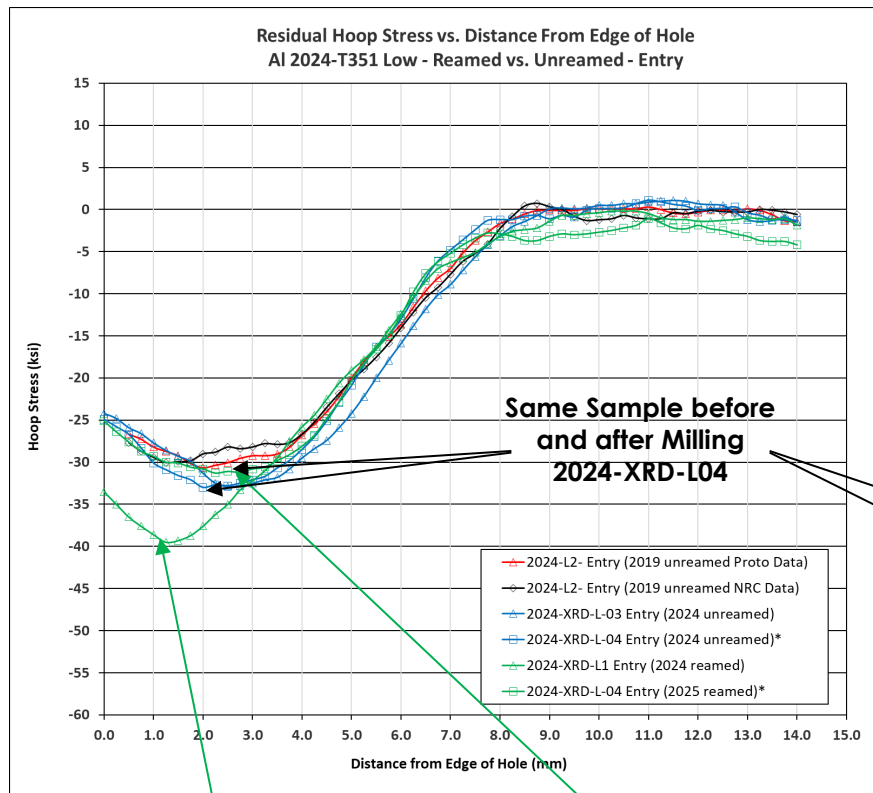
In the Reamed condition, “Low” and “High” range of “in-spec” Cx interference results in different RS fields – Expected.

The effect is more pronounced in 7075-T651 as compared to 2024-T351 in the “Reamed” condition.

RS field varies using Reamer vs. Milling with Circular Interpolation!??

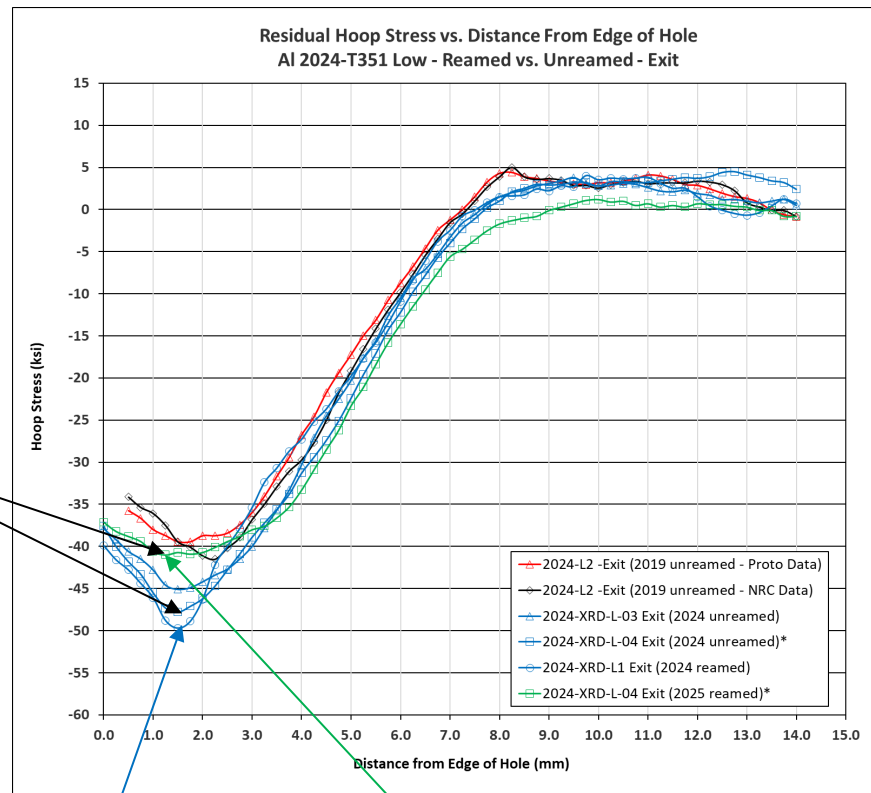
Reamed vs. Un-reamed (Low and High Cx Conditions)

AI 2024-T351 Low Cx - Reamed vs. Un-reamed



With Reamer

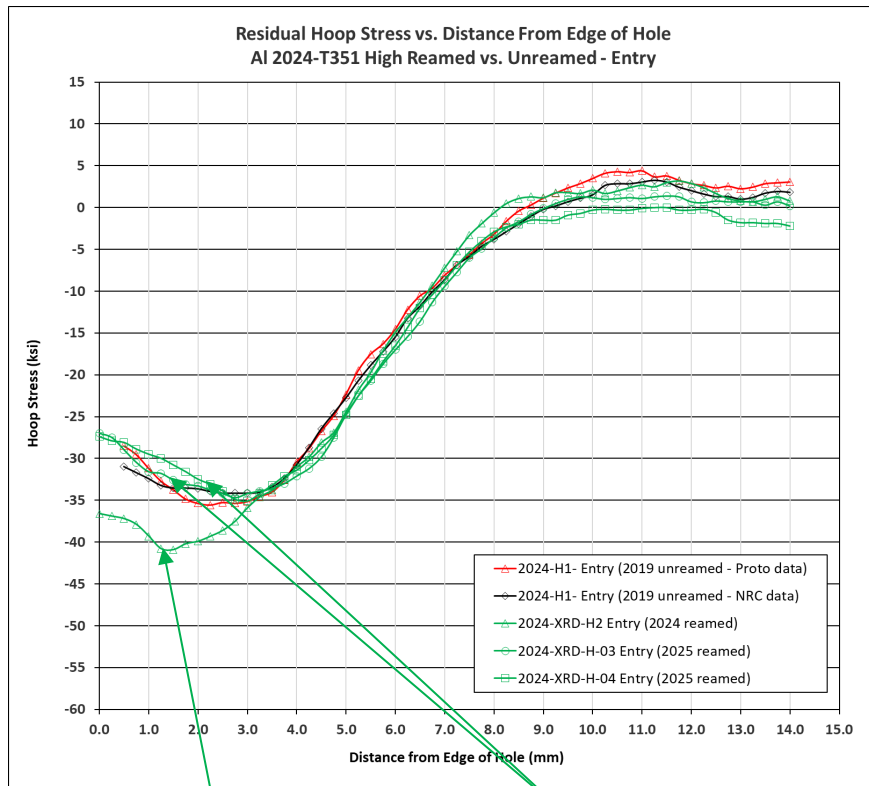
With Mill



With Reamer

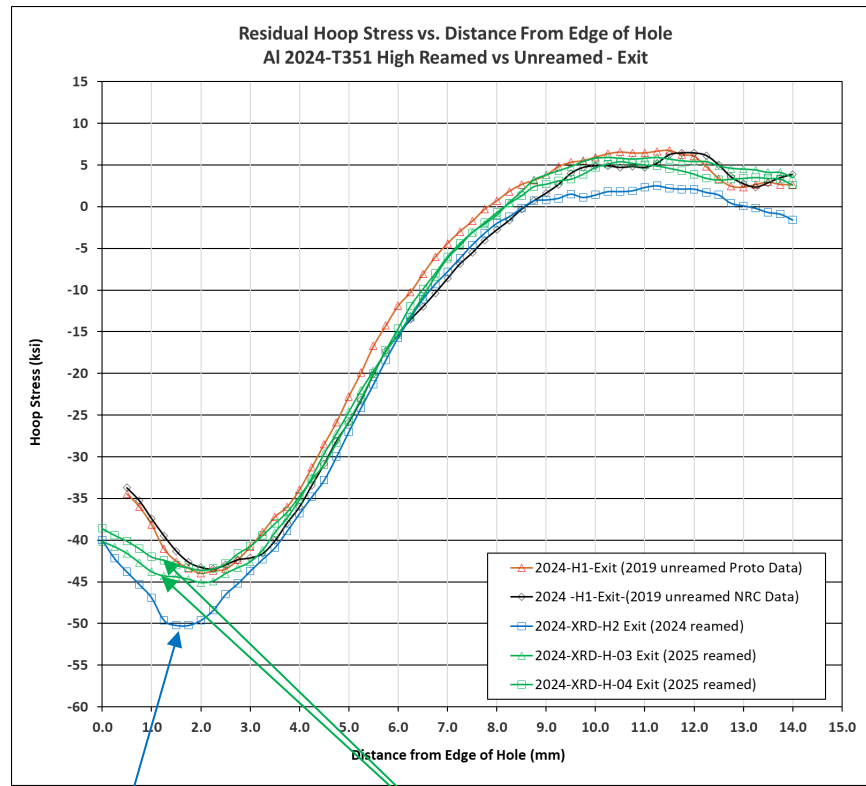
With Mill

AI 2024-T351 High Cx - Reamed vs. Un-reamed



With Reamer

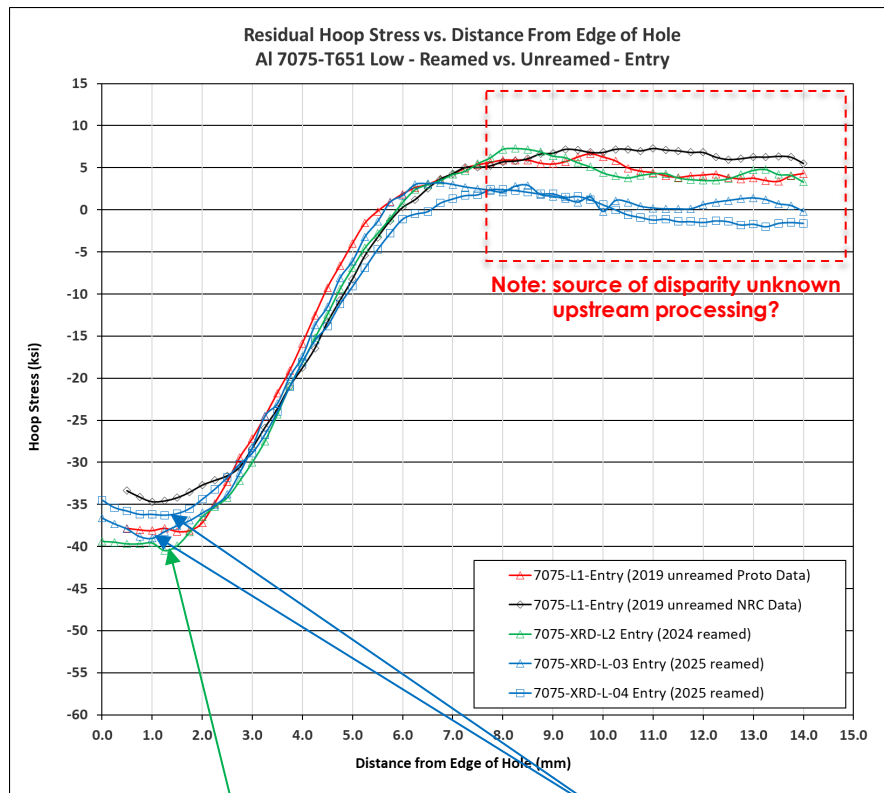
With Mill



With Reamer

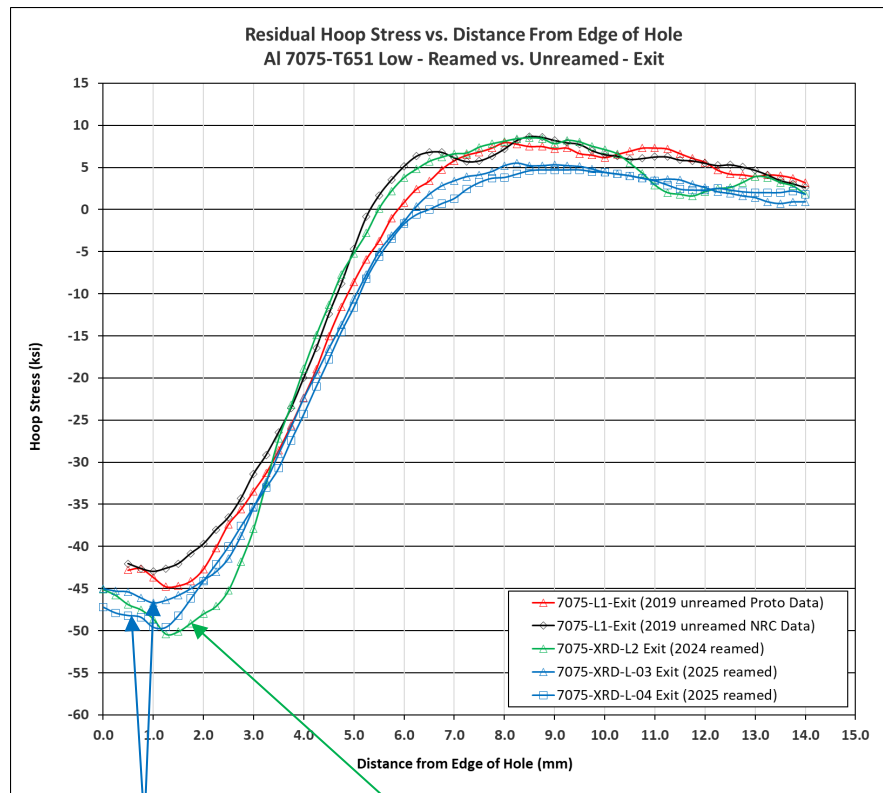
With Mill

AI 7075-T651 Low Cx- Reamed vs. Un-reamed



With Reamer

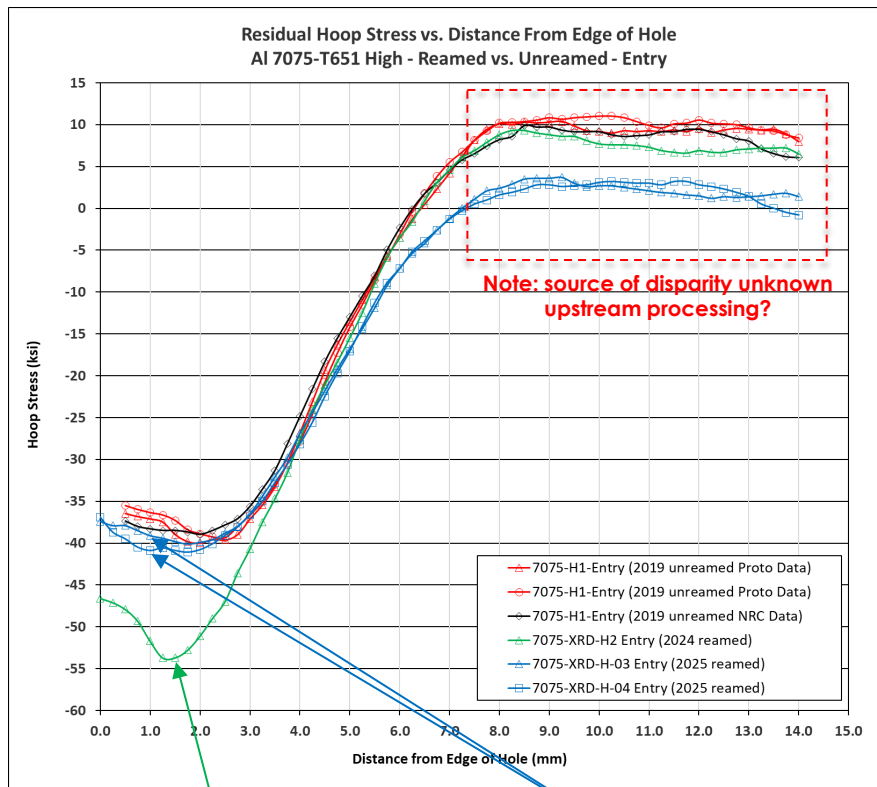
With Mill



With Mill

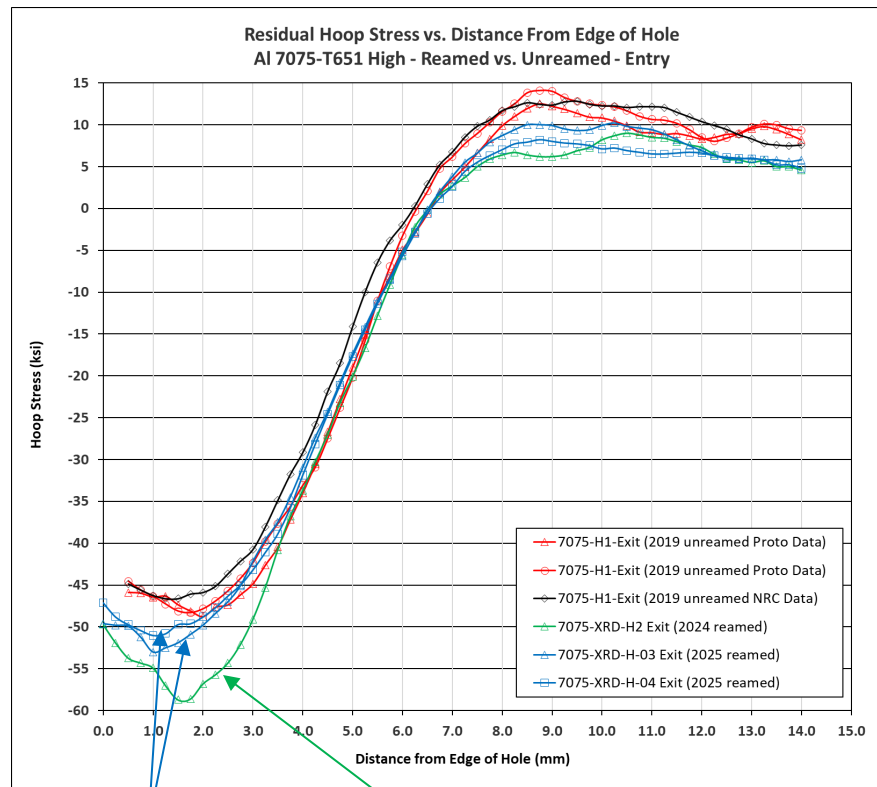
With Reamer

Al 7075-T651 High Cx- Reamed vs. Un-reamed



With Reamer

With Mill



With Mill

With Reamer

Discussion

- Low vs. High Cx separation as expected with 1 exception
- Reaming has a small effect on persistence of compressive field with increasing distance from the hole.
- Effect of Reaming has a greater effect localized to edge of hole – results in increased compressive RS maxima.
- The method of reaming appears to change the stress field near the hole i.e. Reaming (relatively large) vs. Milling with Circular Interpolation (smaller effect).
- Trends hold true for both “Low” and “High” Cx.
- Trends hold true for both 7075-T651 and 2024-T351.
- Effect greatest on 7075-T651 High.

Moving Forward on 2x2 coupons

- 1) Focus on Contour and XRD measurements in bore for reamed condition moving forward.
- 2) Why? Carlson has fatigue data for reamed condition
- 3) Leverage lessons learned on GL coupon.
- 4) Develop corrections for bending “post-Contour” for XRD bore measurements.
- 5) Employ deconvolution techniques as required
- 6) Continue to develop framework for Contour + XRD harmonization.
- 7) Perform Validation Round Robin.
- 8) ASK: Can ERSI Analysis Committee establish a round robin for the GL Baseline condition? RS Committee will provide the RS Data for Phase 2.

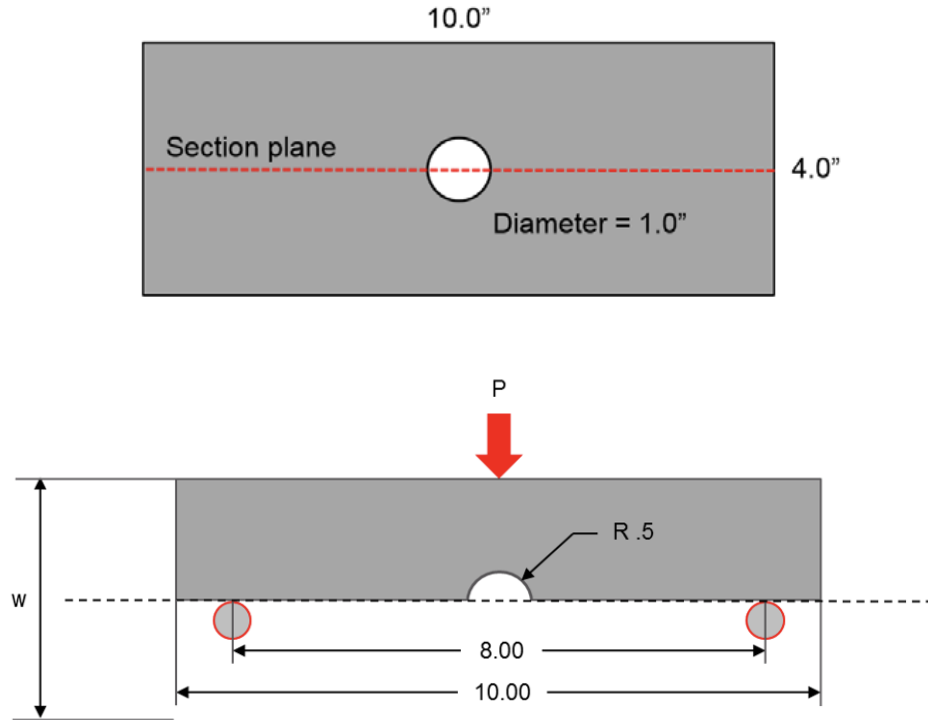
Thank You

Harmonizing Contour and XRD Residual Stress Measurement Data Sets

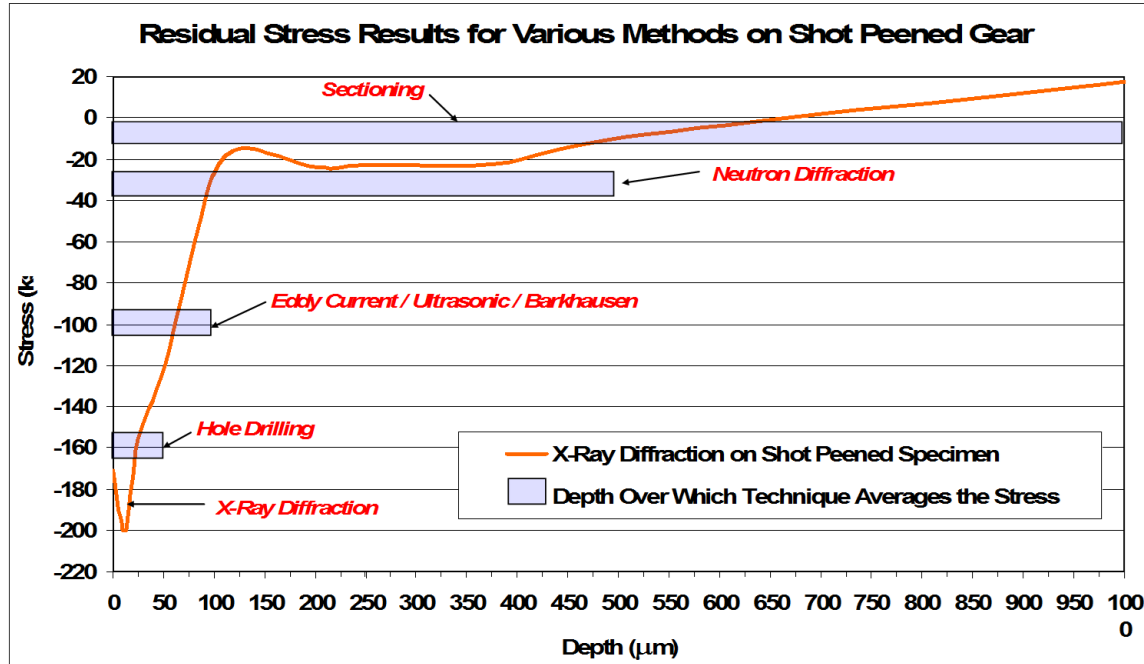


Geometrically Large Coupons

- 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 $\pm 45^\circ$ on the face – must be accounted for if coupon is split.

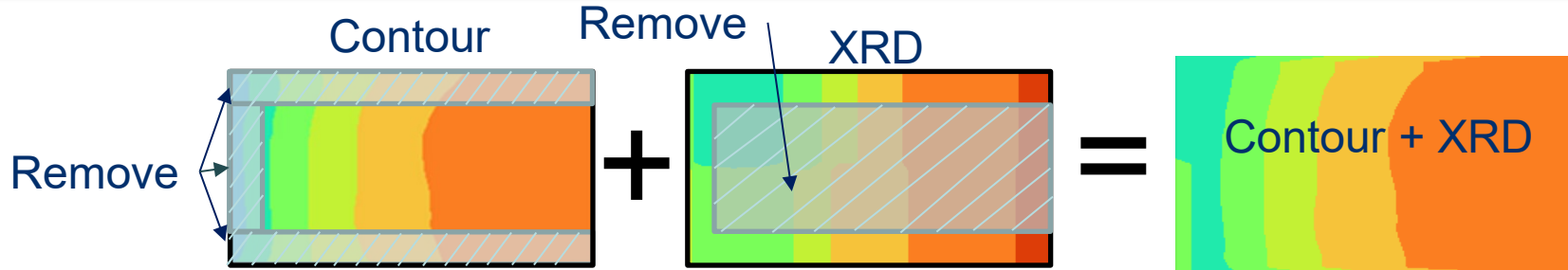


Different RS measurement methods sample different depths better than others – why not take advantage of the strengths of each?



Opportunity to Integrate/Harmonize Datasets

A proposed idea: “Stitch” datasets together to leverage benefits of each method, address limitations

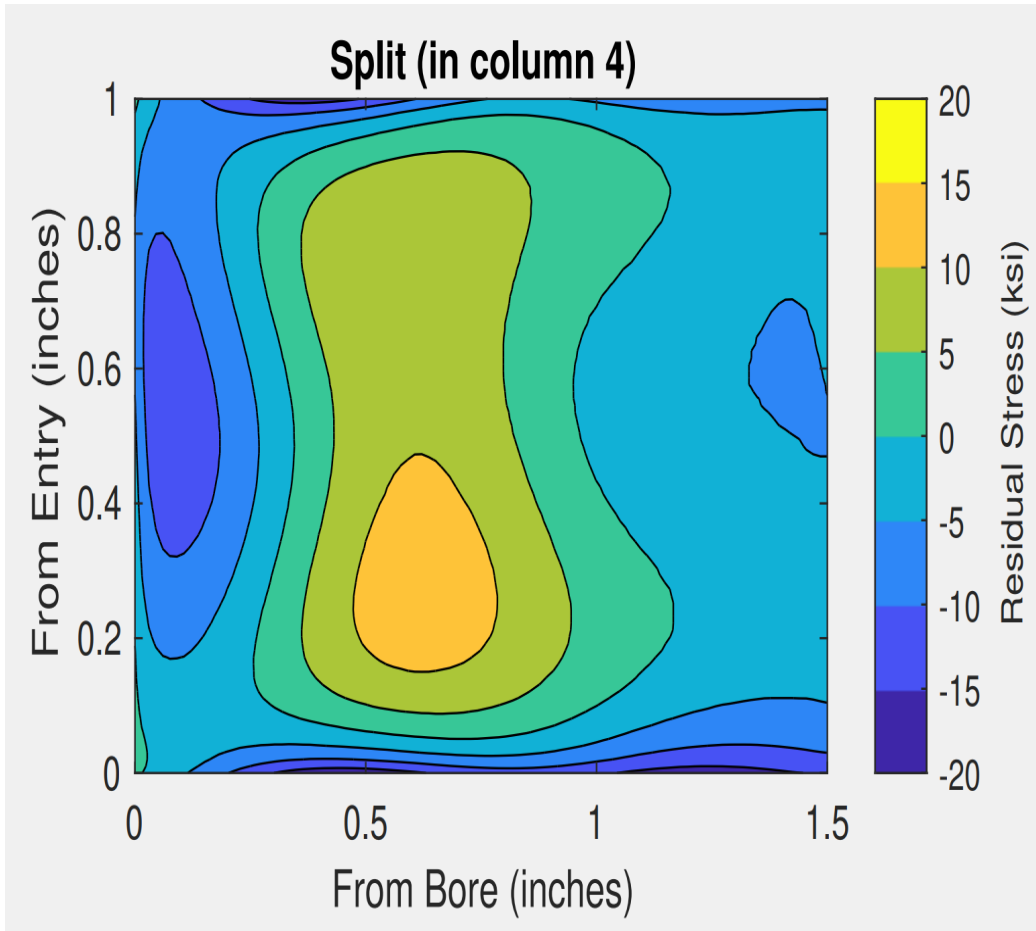


Prather, J., Carlson, S., (2023)., A Novel Approach to Integrating Residual Stress Determination Methods, Proc. 2023 Aircraft Airworthiness & Sustainment Conf., San Antonio, TX, USA.

Questions:

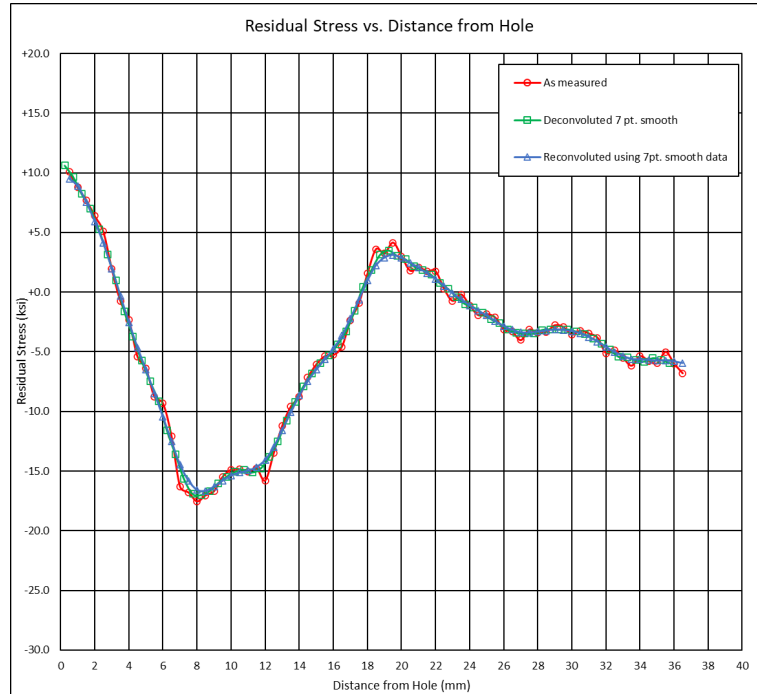
- Would this approach add value (e.g., improve understanding of fatigue crack growth behavior)?
- What methods would be used for measurements?
- What methods would be used for stitching?

GL2024-6-1 Contour data in Split Configuration

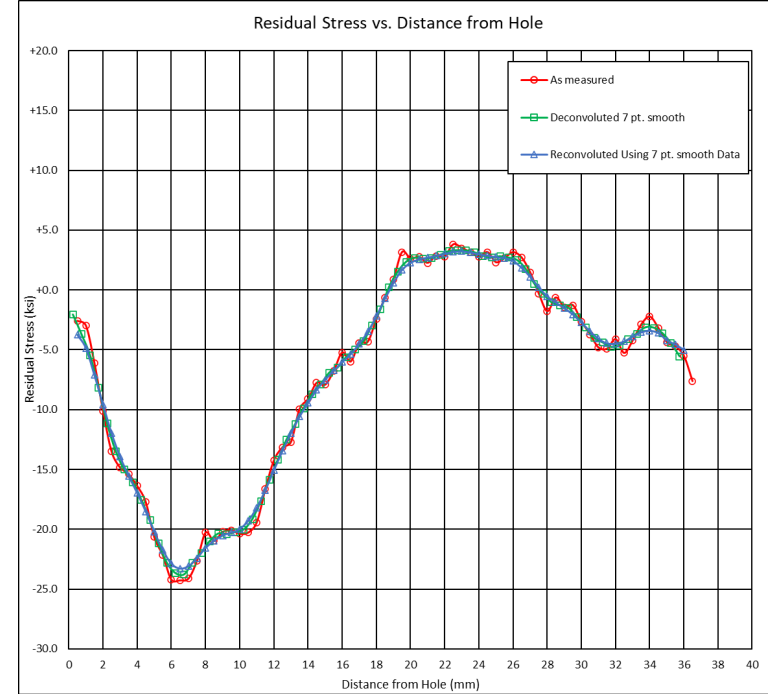


GL2024-6-1 XRD data in Split Configuration (sample)

Entry Face 0.002" deep

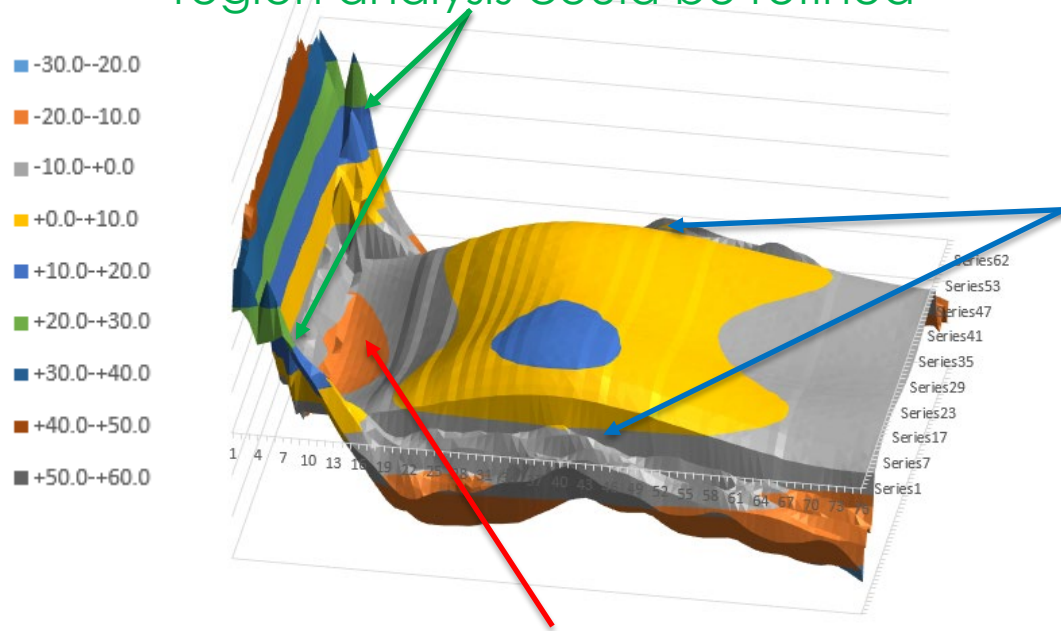


Exit Face 0.002" deep



Draft Harmonized XRD + Contour Plot

Entry and Exit corners provide interesting results – overlapping region analysis could be refined



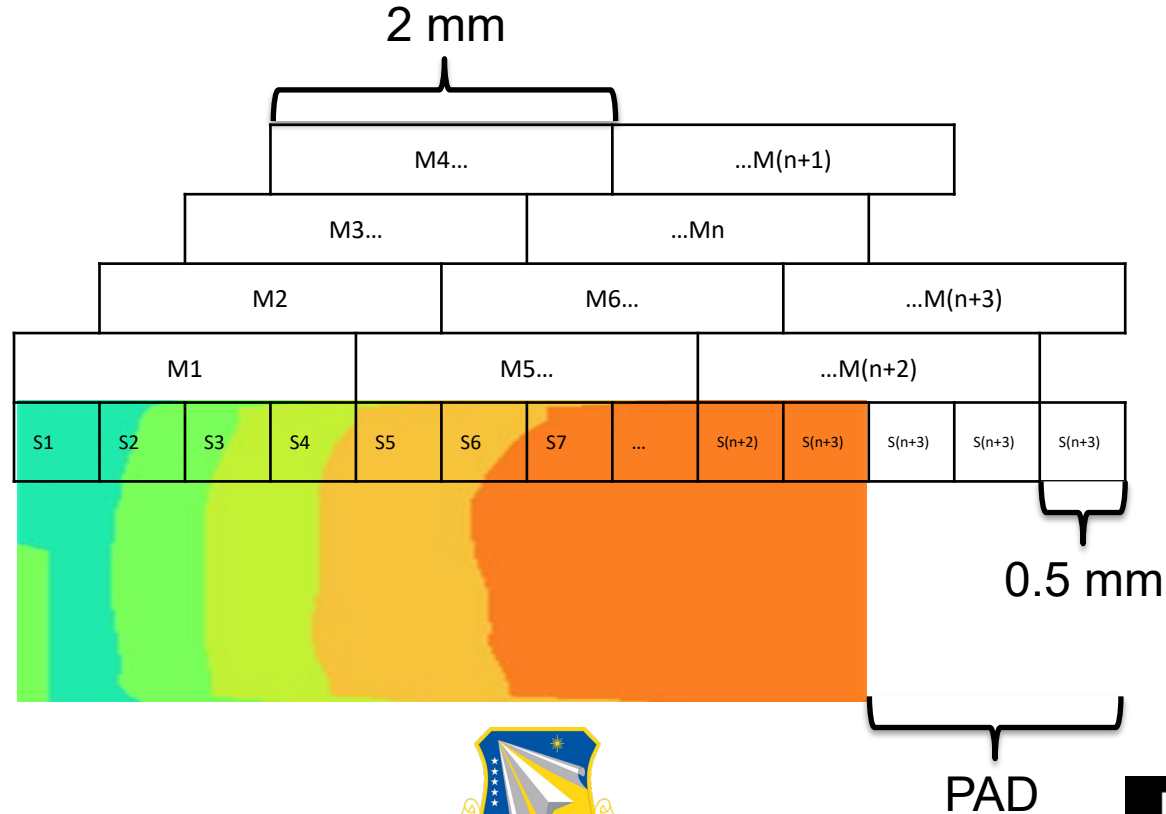
Contour RS interpolated from higher resolution dataset to match XRD – this process could be refined.

Contour/XRD dataset interface along the axis away from the hole ID not perfect could be smoothed – delta ranges from ~1-10 ksi depending on distance – could be related to arc-averaging during XRD data collection?

Contour/XRD dataset interface along bore has a surprisingly smooth transition – the world is round!

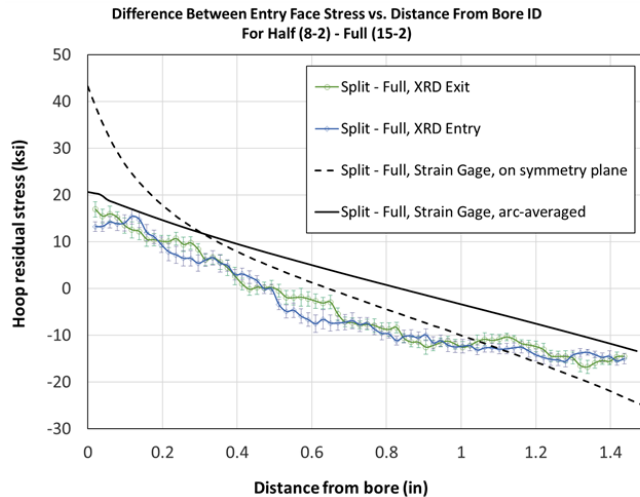
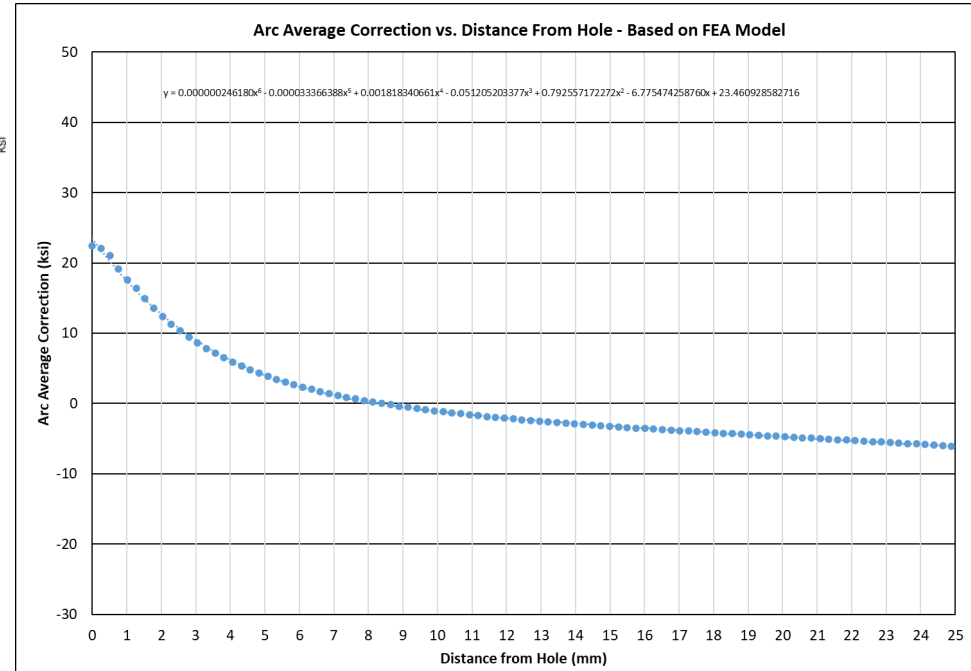
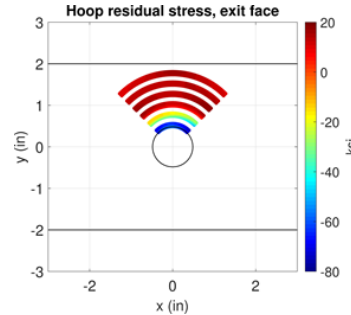
Areas That May Need Further Development/Fine Tuning

Fine Tune Deconvolution Method - Padded array approach seems to work – might be critical in smaller geometries - TBD



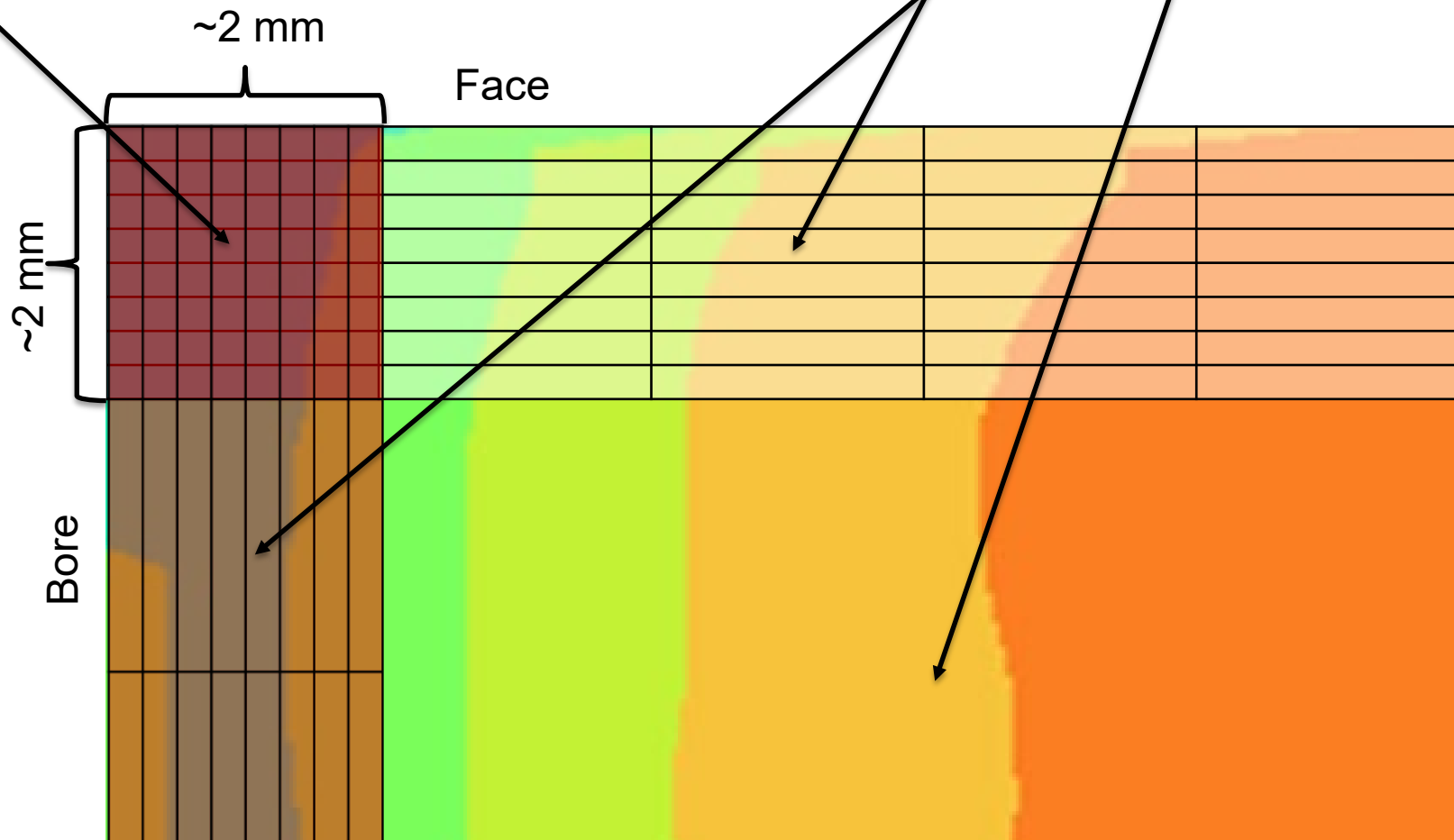
Develop Approach to Arc Averaging Correction for XRD Data

When corrected for XRD arc averaging, the relaxation as measured by XRD vs. estimated by strain gage & FEM are more closely aligned – ultimately need to put the split back together using Contour data.



Question: How do we merge Face and Bore XRD data?

Question: How do we merge XRD and Contour data?



Notional Round Robin Plan

- 1) Create a baseline model (excluding RS) and run a prediction to validate inputs.
- 2) “Harmonize” contour and XRD data for input to the fracture mechanics analysis.
- 3) Add the “harmonized” RS input from step 2 to the validated fracture mechanics analysis from step 1
- 4) Iterate on steps 2 and 3 until a reasonable prediction is achieved.

For the round robin, steps 2-4 should be blind, but not necessarily step 1. If step 1 is blind, then the round robin results may be confounded by inputs that have nothing to do with the RS, i.e. provide participants with the fatigue test results of the non-cold-expanded baseline cases, then participants can validate that their baseline model is providing an accurate solution (step 1). This to ensure that the round robin results focus solely on incorporating the RS field.

Does that sound agreeable?

Summary

- 1) XRD and Contour datasets have been collected on a GL coupon**
 - 2) A “Notional Round Robin Plan” has been developed (blind)**
 - 3) Once complete, afford FCG model prediction folks the opportunity to revise chosen data harmonizing and analysis 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 Moving Forward:

- 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 to “unsplit” coupons – we think we know how to do this.
- 2) Account for arc averaging in XRD data as may be required due to grain size where necessary and improve deconvolution methods if required – we think we know how to do this as well.
- 3) Framework to be validated via Round Robin study.
- 4) Codify/formalize methods of harmonizing XRD & Contour RS data sets for FCG predictions moving forward i.e. 2 x 2 coupons.
- 5) ASK: Can ERSI Analysis Committee establish a round robin for the GL Baseline condition? RS Committee will provide the RS Data for Phase 2.

Thank you

ERSI – Near-Bore Analysis upon Cold Expansion through Digital Image Correlation Techniques

March 24, 2026

Lockheed Martin Corporation & APES Inc

Dr. Scott Carlson

Mr. David Mauldin

Mr. James Prather

Dr. Thomas Mills

National Research Council Canada

Dr. David Backman

Mr. Milan Djordjevic

Dr. Guillaume Renaud

Dr. Gang Qi

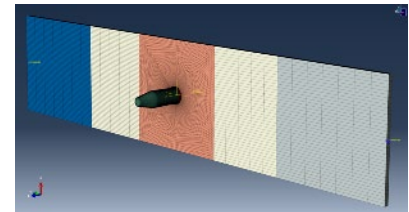
Mr. John Hoogenraad

Presentation Overview

- 1) Purpose of Near-bore DIC work
- 2) Limitations of Previous Work on 2" SsCx RS Coupons
- 3) RS Coupon Matrix
- 4) DIC Setup
- 5) Comparison of Near-Bore Strains for the SsCx condition
- 6) Comparison of Near-Bore Strains for the Final Ream Condition
- 7) Initial Fatigue Results
- 8) Lessons Learned
- 9) Next steps

Purpose of Near-Bore DIC Work

- Near-bore strains poorly quantified, characterized, and validated in FEM
 - Accurate characterization of residual stresses (RS) through strain data needed for accurate FEM and impact maximization of SsCx
- Collect DIC data through automated SR-DIC to characterize strain fields
- Different coupon configurations
 - SsCx/Ream
 - Entry/Exit



Limitations of Previous Work (Manual SR-DIC)

Manual SR-DIC

- ~ 8 hours/coupon
- Inherent variance in tile positioning

Automated SR-DIC

- ~ 1.5 hours/coupon, with possibility to decrease further
- robust and consistent tile positioning
- Larger test program made available

Overview & Limitations of Previous Testing

Magnification with 3D-DIC: 25 pixel/mm [vs 383 pix/mm currently]

Previously strains measured up to ~900 micron from edge [vs 170 micron]

Model validation process levelled FEA and DIC data

Full field subtraction showed no clear difference between FEA& DIC data

Match ID: Processing Method & Philosophy

•Directly determining differences between DIC & FEA data has drawbacks

- DIC data has spatial resolution limited by camera/lens setup
- FEA model can adaptively increase nodal resolution in areas of strain concentration
- Differences between DIC & FEA data not always indicative of problems with FEA model

•MatchID Comparison Philosophy

- Put FEA and DIC data on the same basis for comparison
- FEA nodal displacements used to numerically DISTORT reference speckle pattern
- DIC algorithm (with experimental Subset/Step Size/Filter parameters) used for analysis
- FEA comparison focuses on REF image correlated with FEA distorted speckle
- DIC-FEA subtractions are now on the same basis and can be compared accurately

•Validate FEM results by comparing them to DIC results

[1] Assessment of measuring errors in DIC using deformation fields generated by plastic FEA. *Optics and lasers in engineering*, 47 (7-8), 747-753 (2009)

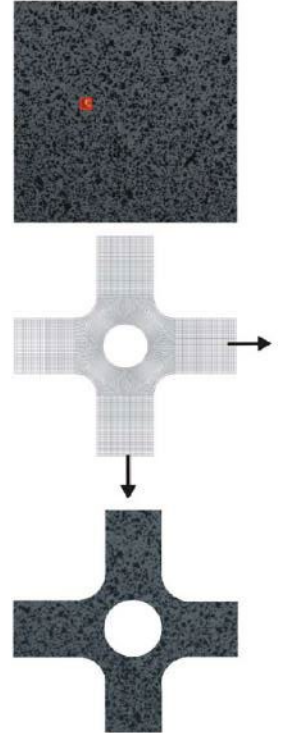


Fig. 1. Distorted reference speckle pattern[1]

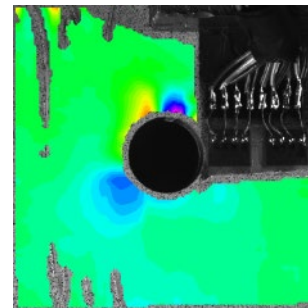
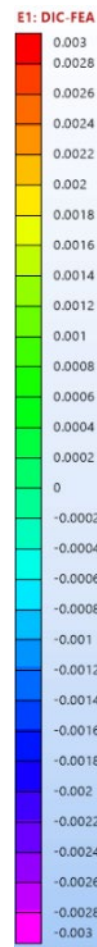
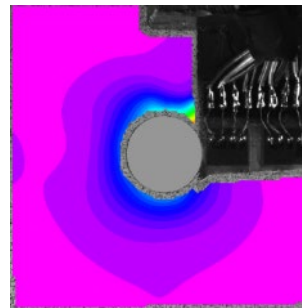
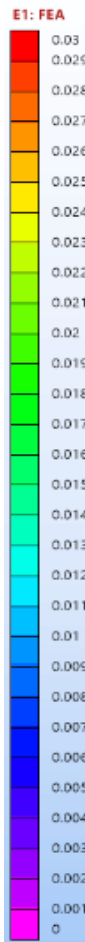
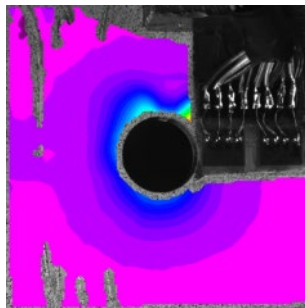
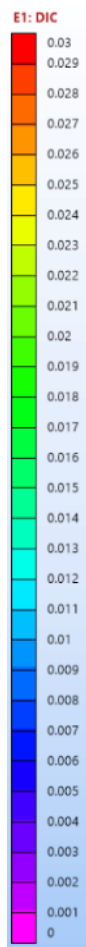
ENTRY

DIC

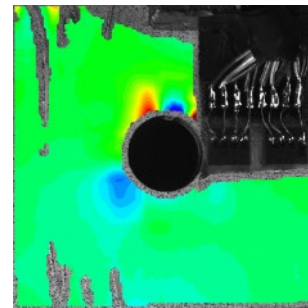
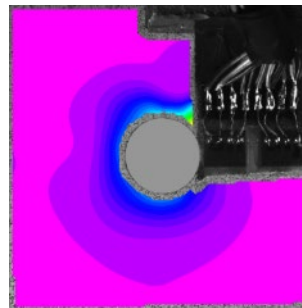
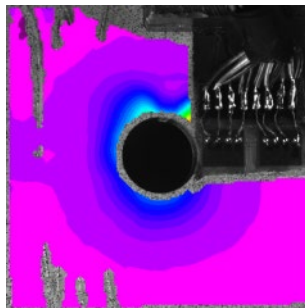
FEA

DIC - FEA

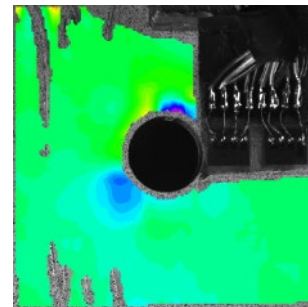
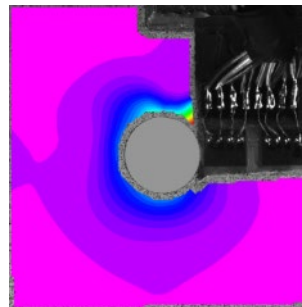
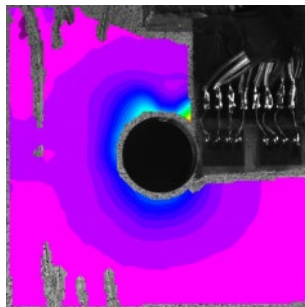
CHABOCHE
(a)



KINEMATIC
(b)



ISOTROPIC
(c)



		Average Difference Magnitude ($\mu\epsilon$)	Standard Deviation ($\mu\epsilon$)
ENTRY	CHABOCHE	264	311
	KINEMATIC	286	344
	ISOTROPIC	235	270
EXIT	CHABOCHE	558	911
	KINEMATIC	471	959
	ISOTROPIC	454	718

RS Test Matrix and SsCx Stages

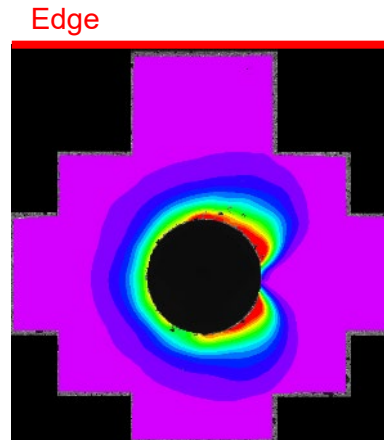
Test Matrix Variables:

- Hole size
- Edge Distance : Diameter
- Thickness
- Expansion Level

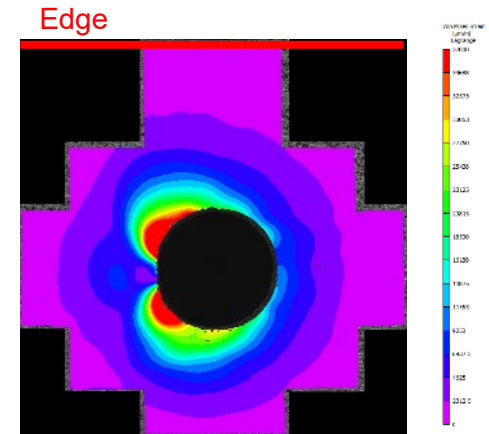
Bore Size	e/d	Thickness [in]	Expansion Level
4N	1.5	0.125	2.2%
6N	1.75	0.25	1.8%
8N	2	0.375	1.8%

Stages of Data Collection:

- Reference Image
- SsCx
- Reamed
- (Deburred)



SR-DIC: 4N-2.0-.25T Entry
(Reamed)



SR-DIC: 4N-2.0-.25T Exit
(Reamed)

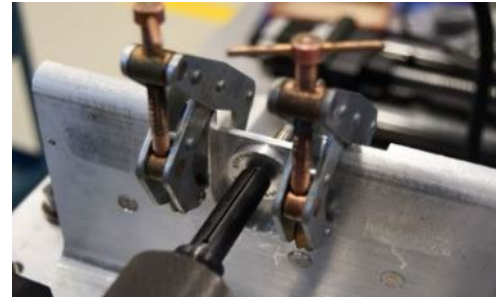
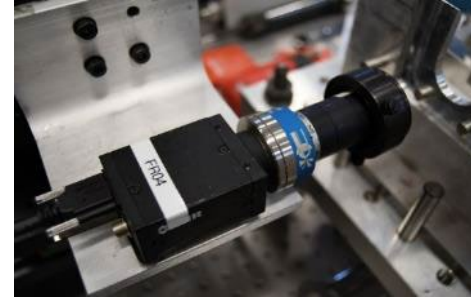
SR-DIC Setup

High Magnification 2D DIC

- Scale: 383px/mm

Translation Stages + Automation

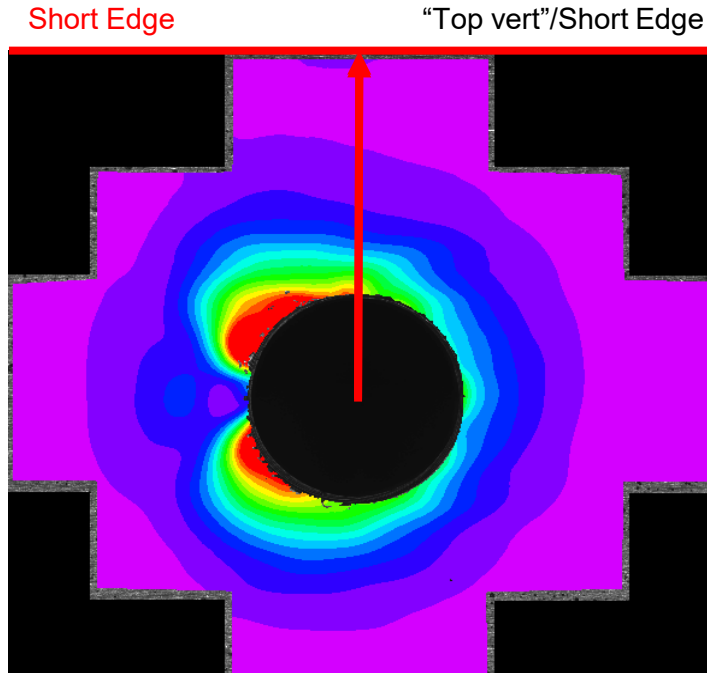
- Consistent displacements (± 10 micron)



PROCESSING STEPS AND LEGEND

Entrance and Exit Sides

Processing Steps: Radial Strain Extractions (ev and e1)



Processing Steps:

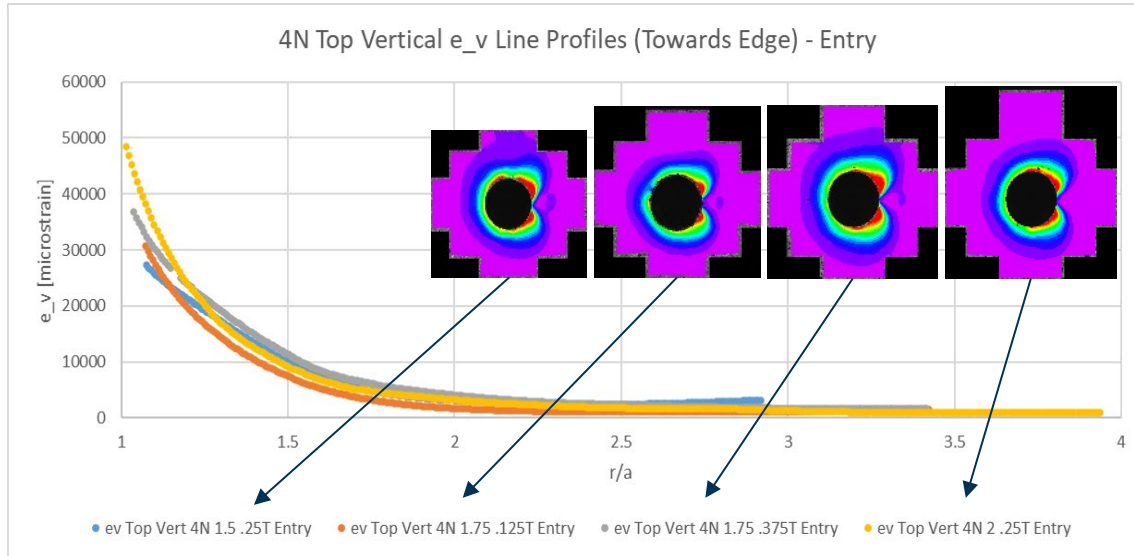
- Line profiles plotted for $r/a > \text{argmax}(\{|e_i|\})$

Dimensionless parameter r/a :

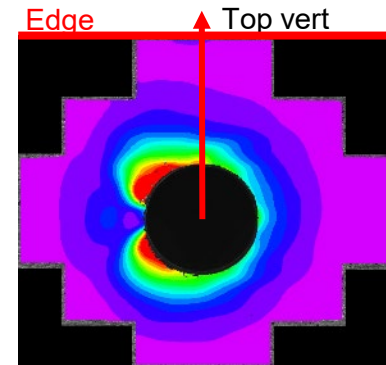
r = radial distance

a = radius of expanded/reamed hole

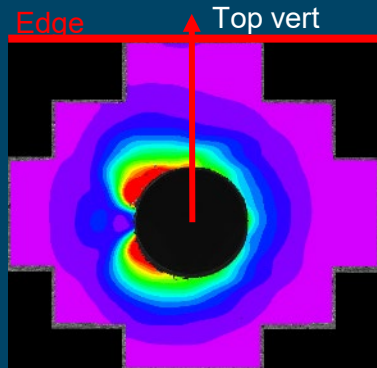
Legend: Radial Von Mises Strain Extractions



Legend for Profile Direction



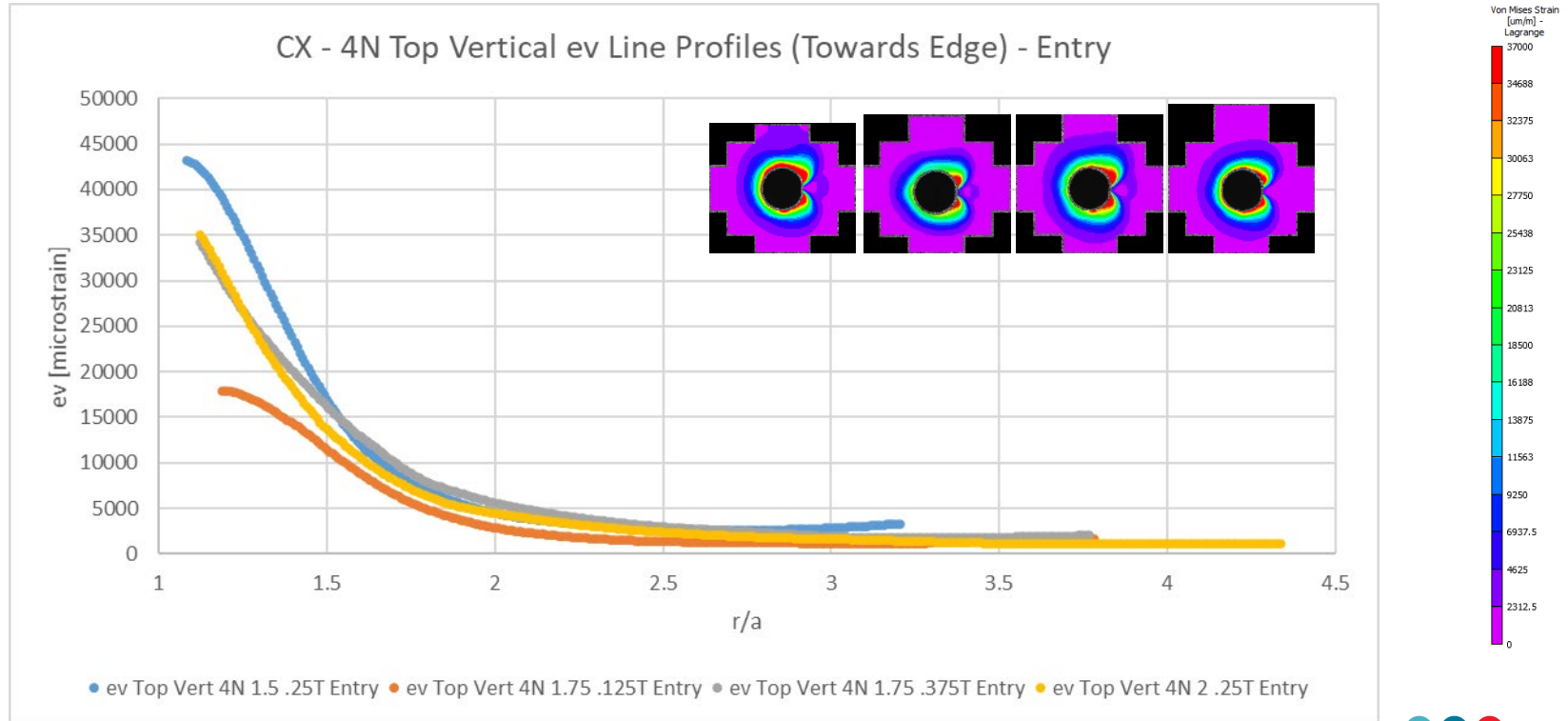
SHORT EDGE SSCX PROFILES (TOP VERT)



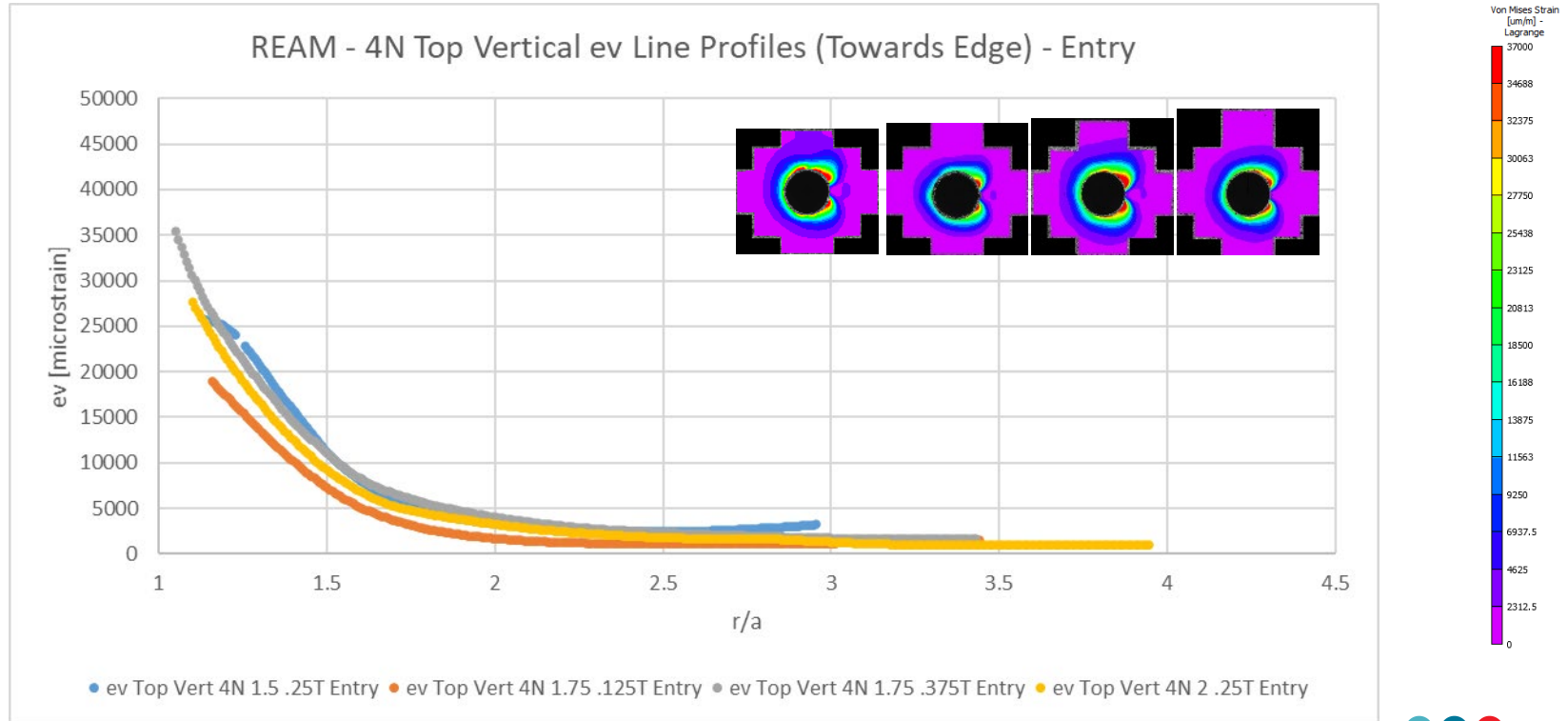
4N DATA SSCX AND REAM DATA

$e_{\text{von mises}} (e_v)$: Entrance and Exit Short Edge Profiles

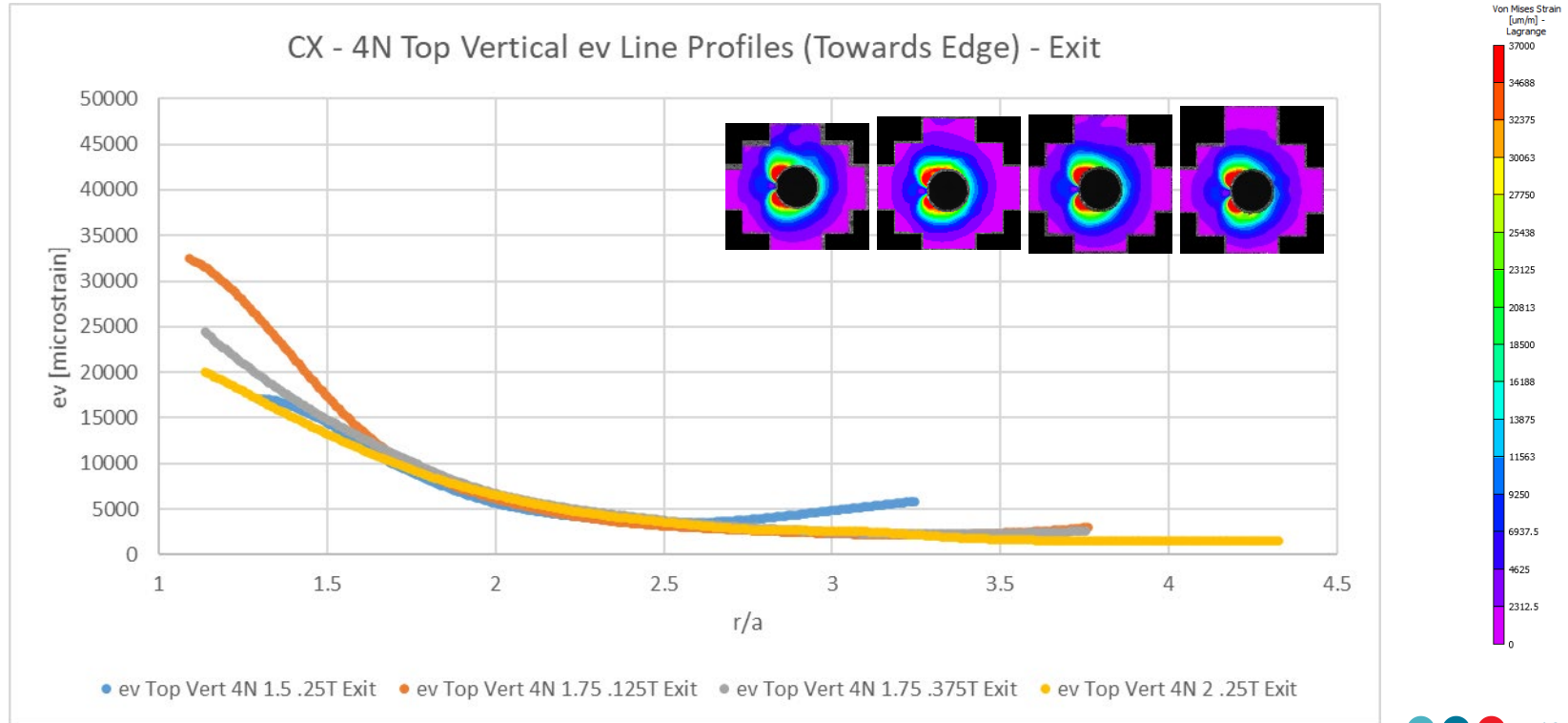
Entrance ev – 4N SsCx Line Profile along Short Edge



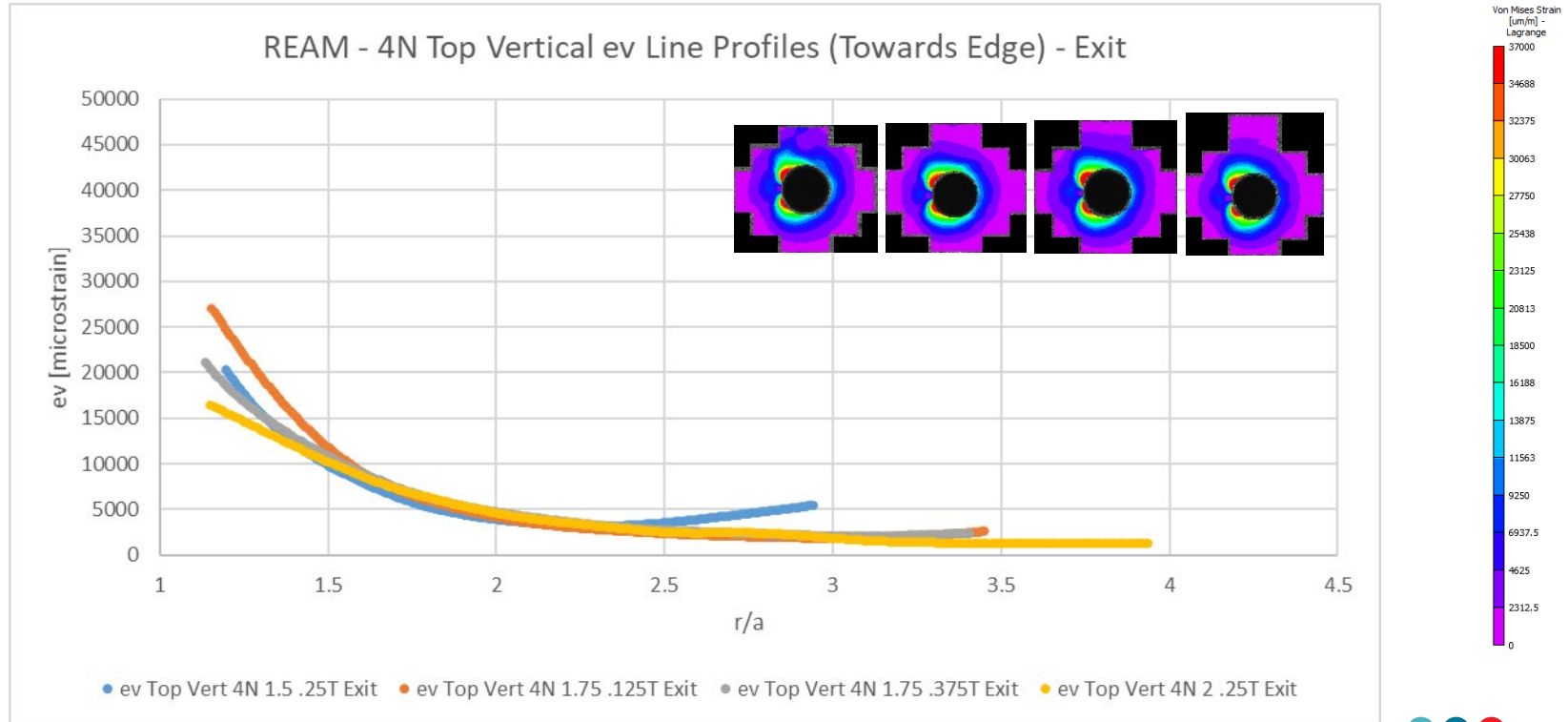
Entrance ev – 4N Ream Line Profile along Short Edge



Exit ev – 4N SsCx Line Profile along Short Edge



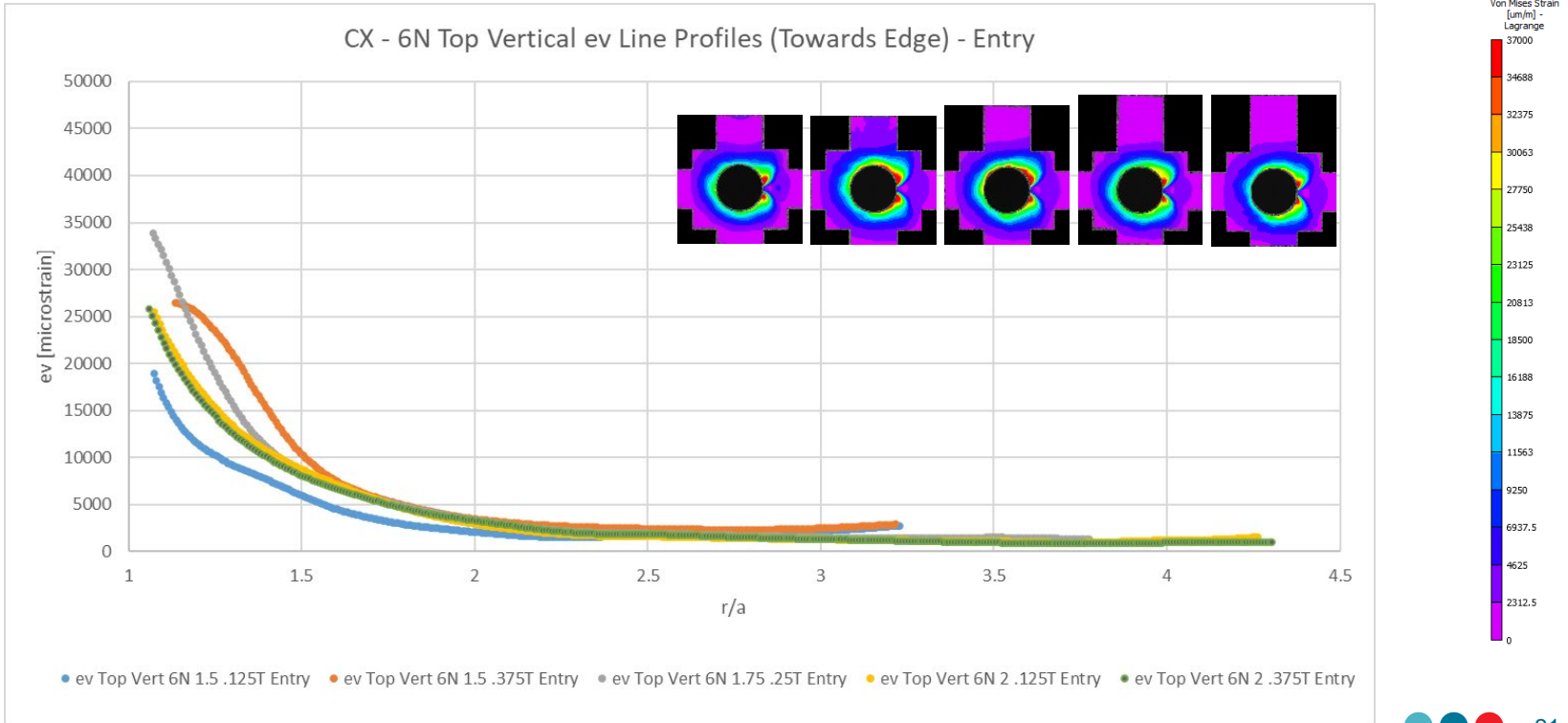
Exit ev – 4N Ream Line Profile along Short Edge



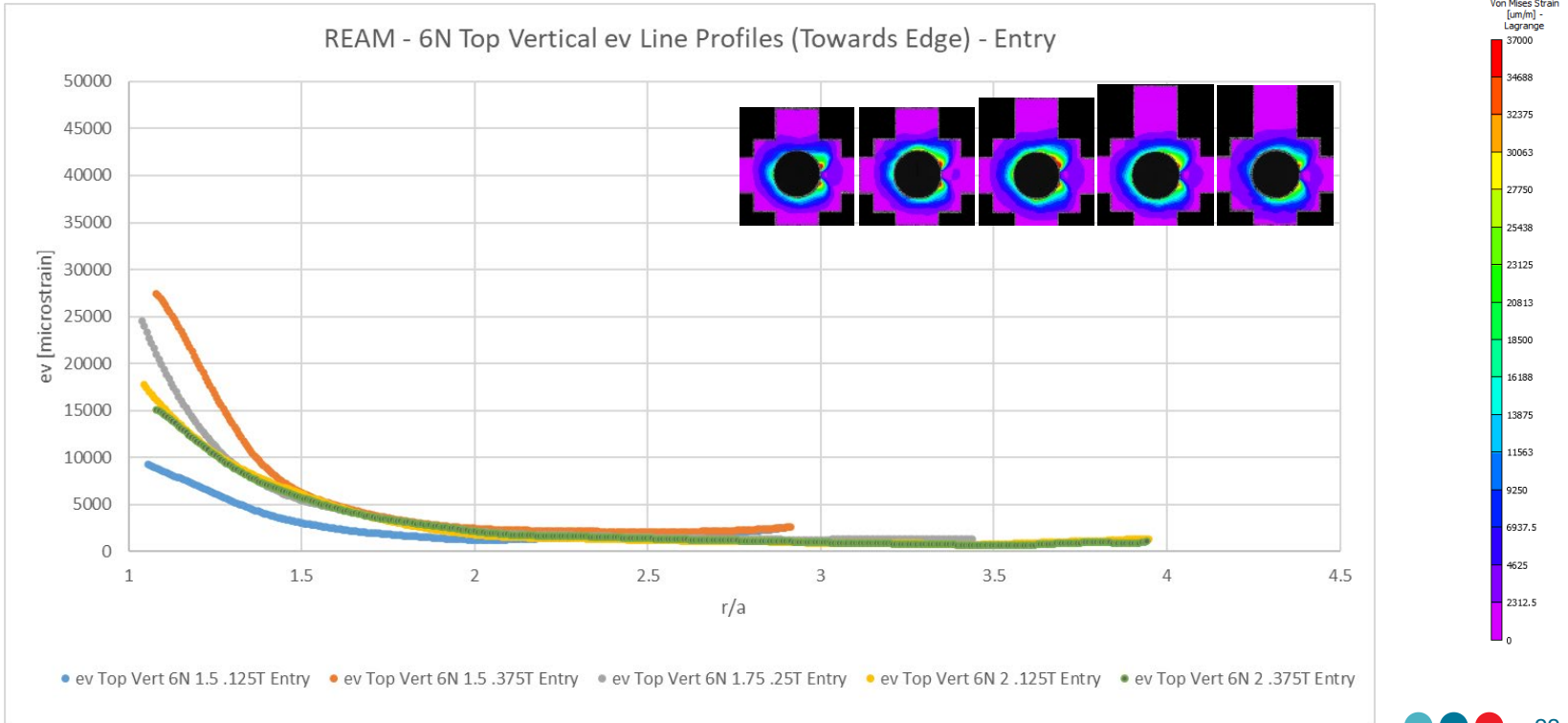
6N DATA SSCX AND REAM

$e_{\text{von mises}} (e_v)$: Entrance and Exit Short Edge Profiles

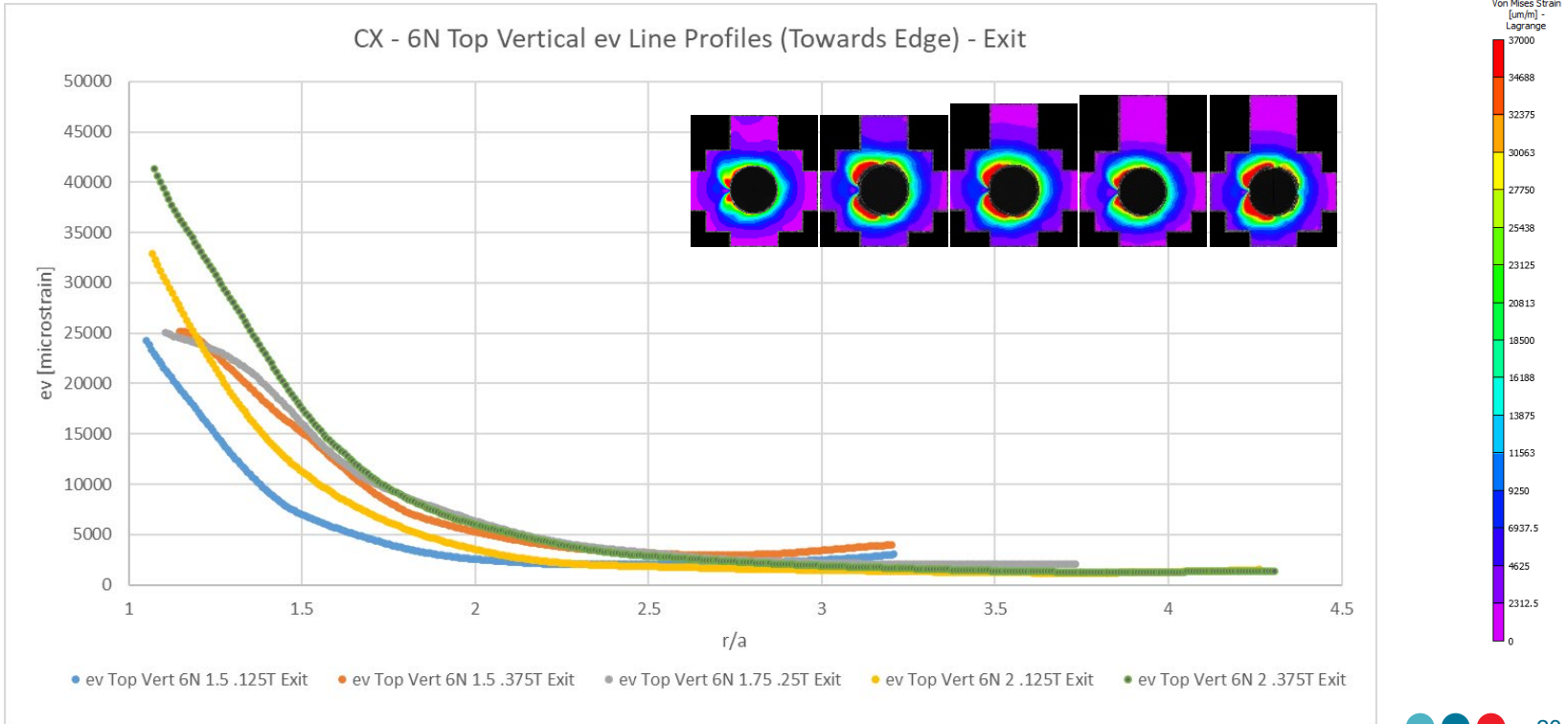
Entrance ev – 6N SsCx Line Profile along Short Edge



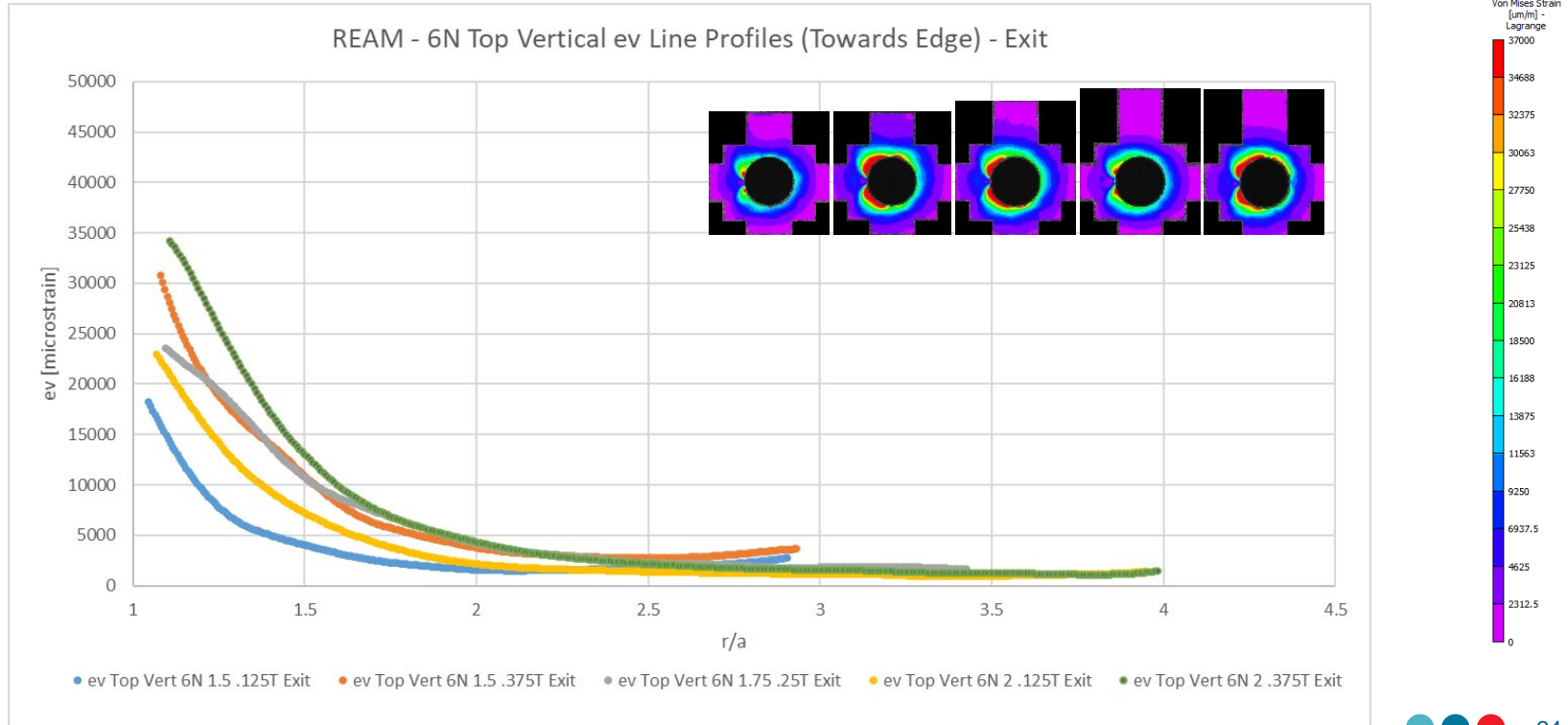
Entrance ev – 6N Ream Line Profile along Short Edge



Exit ev – 6N SsCx Line Profile along Short Edge



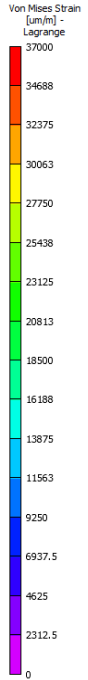
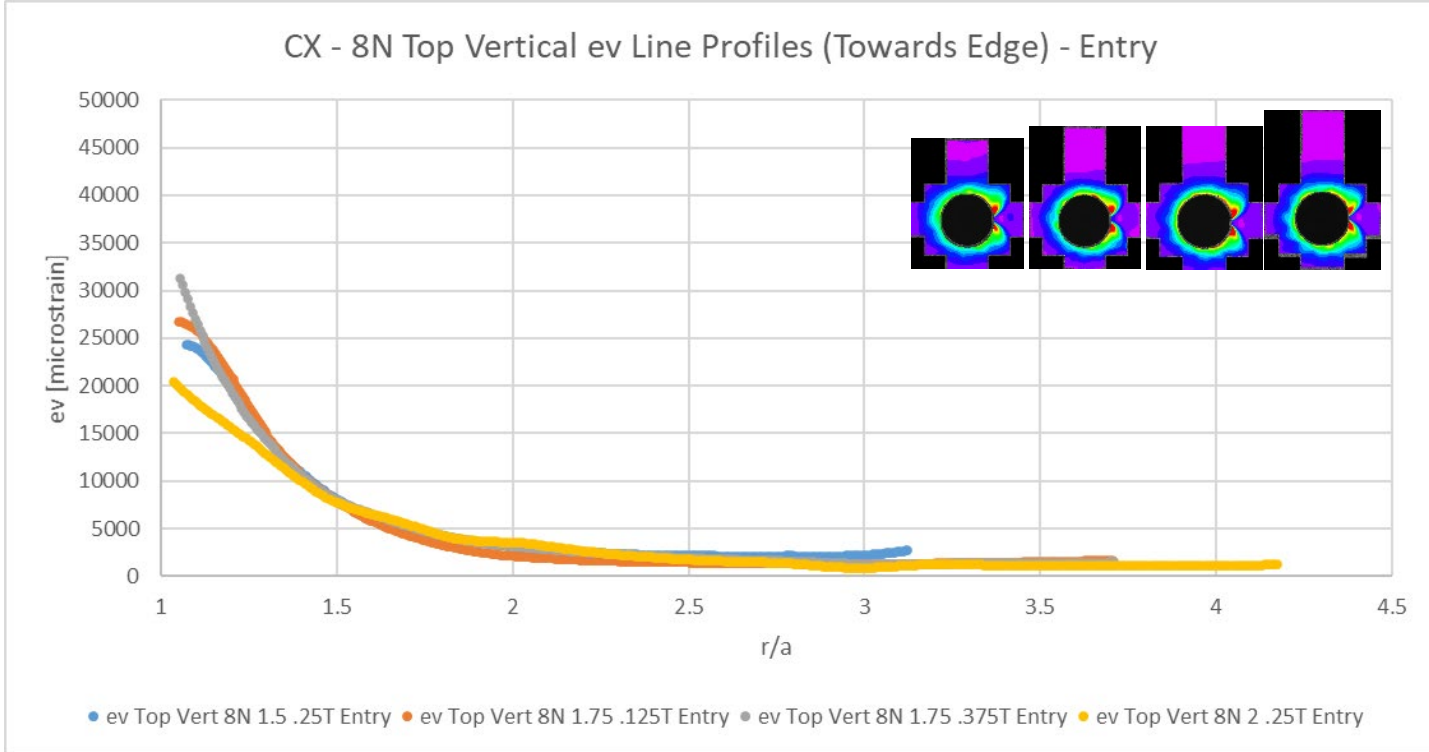
Exit ev – 6N Ream Line Profile along Short Edge



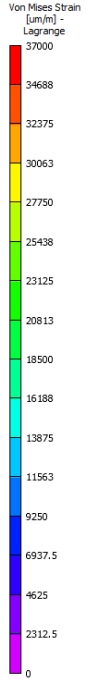
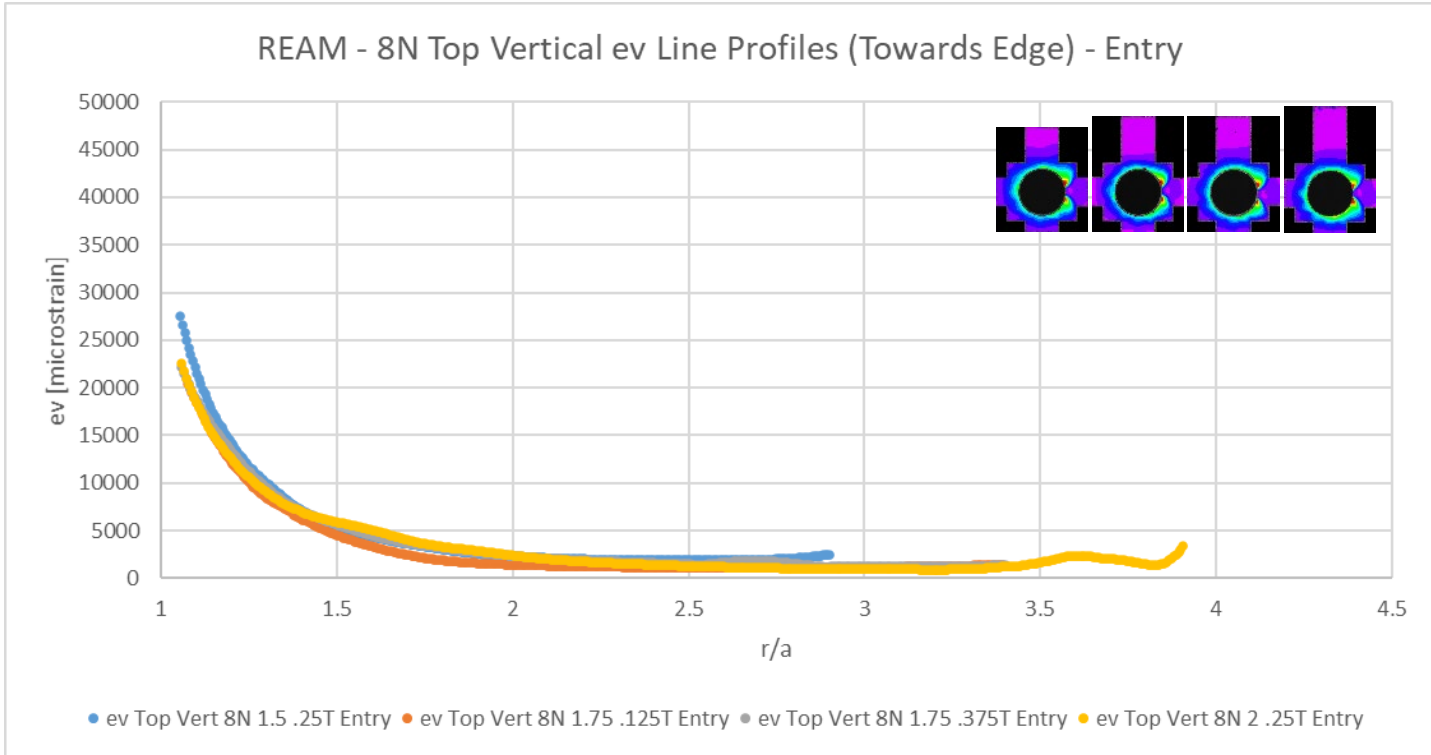
8N DATA SSCX AND REAM

$e_{\text{von mises}} (e_v)$: Entrance and Exit Short Edge Profiles

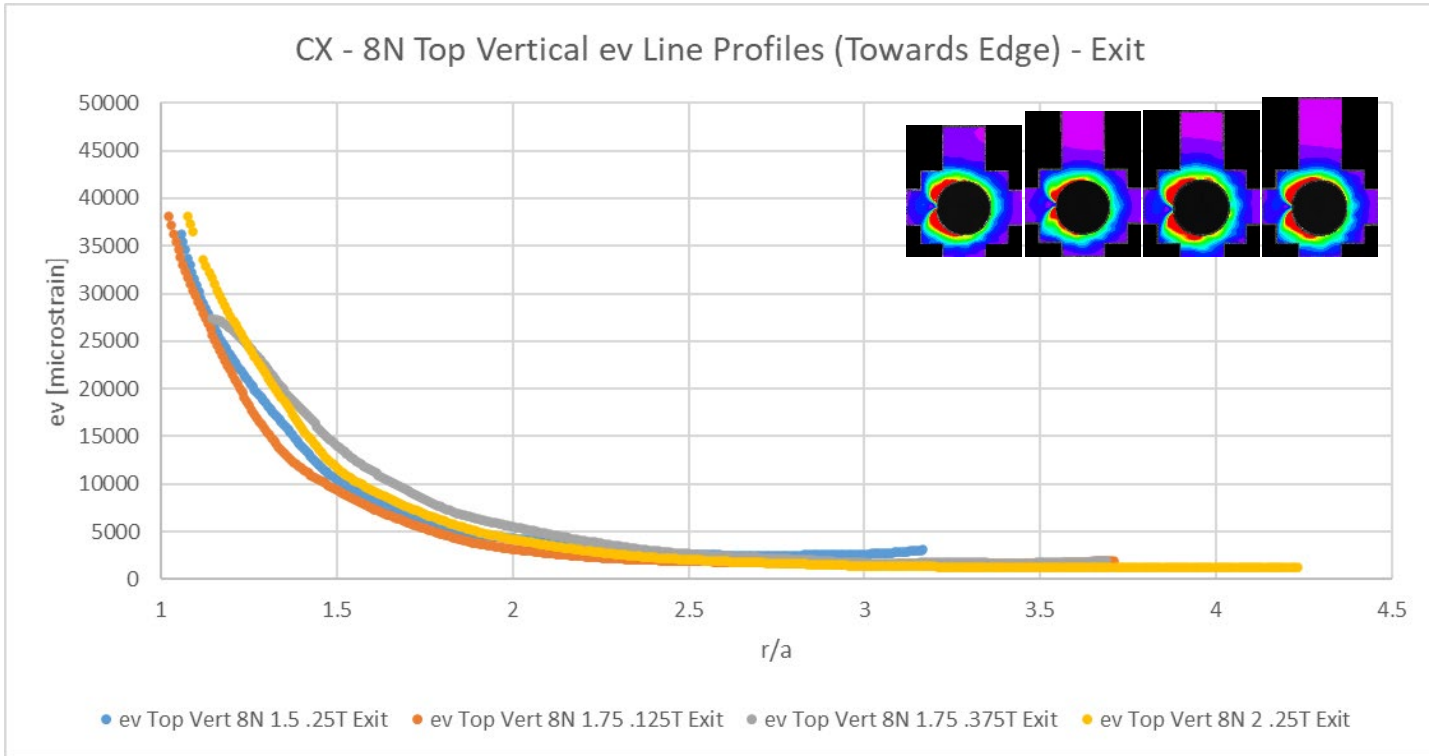
Entrance ev – 8N SsCx Line Profile along Short Edge



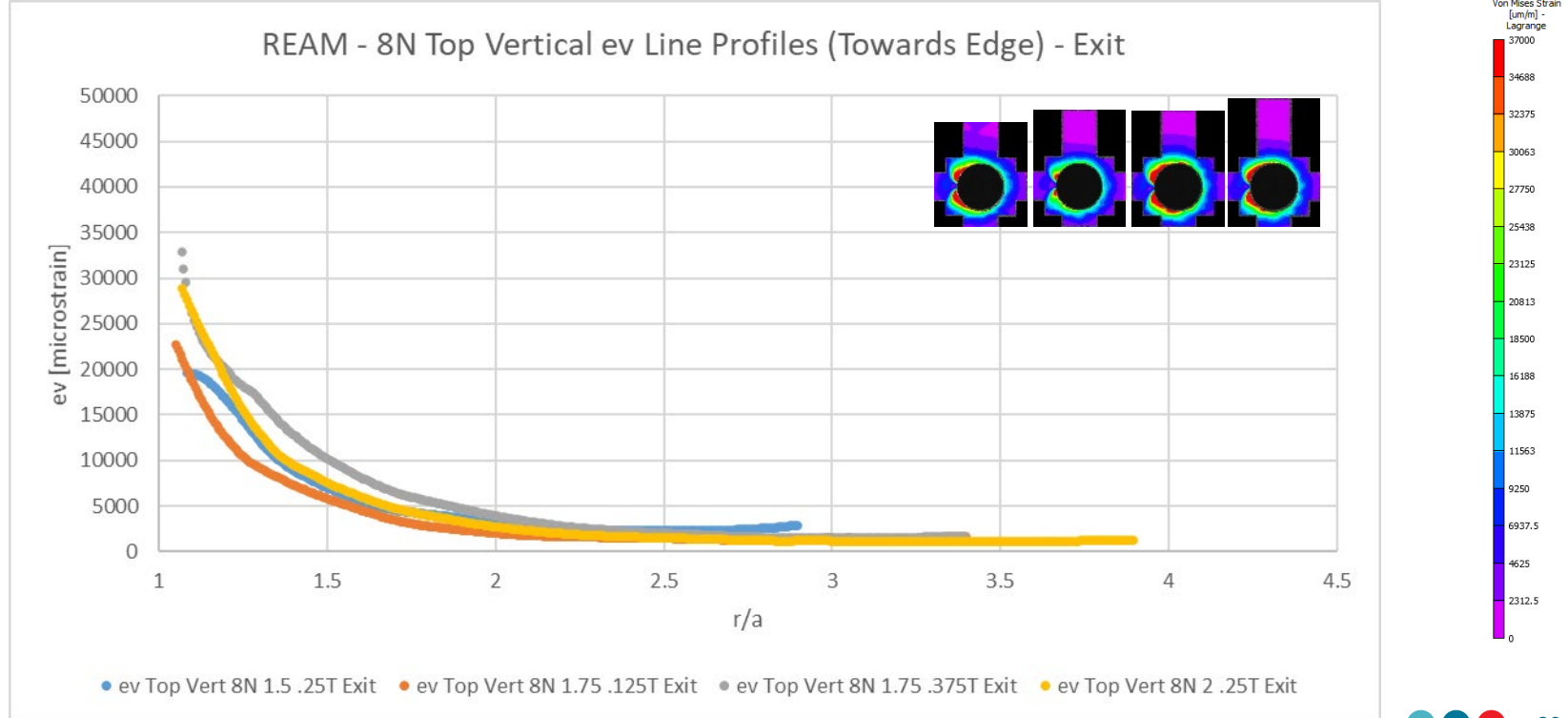
Entrance ev – 8N Ream Line Profile along Short Edge



Exit ev – 8N SsCx Line Profile along Short Edge



Exit ev – 8N Ream Line Profile along Short Edge

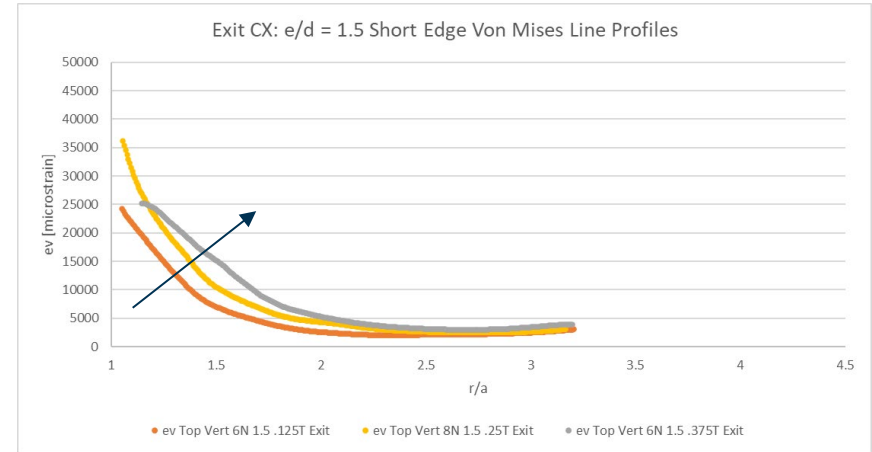
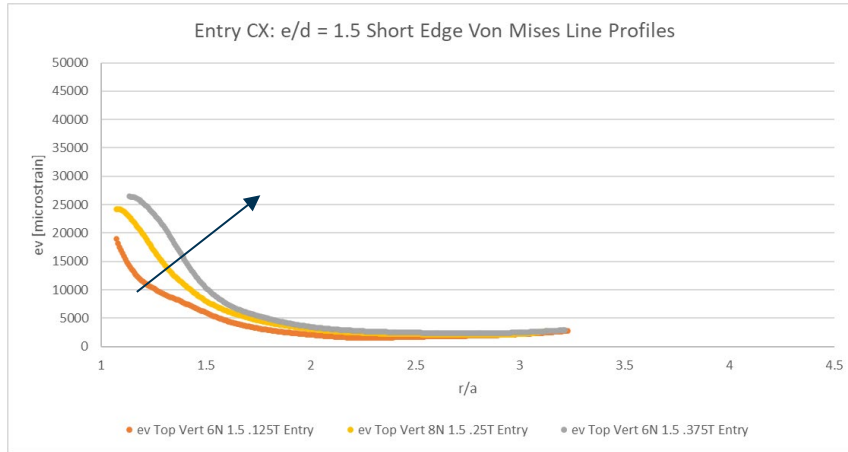


DISCUSSION

EDGE DISTANCE (E/D) EFFECTS

EDGE DISTANCE (E/D) - 1.5

e/d 1.5 CX Entry and Exit – 4N Excluded

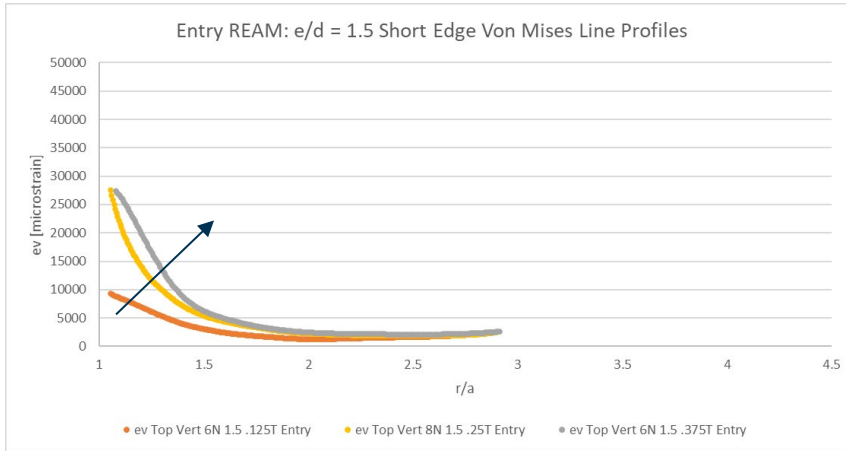


Entry CX: e/d = 1.5 Short Edge Von Mises Line Profiles

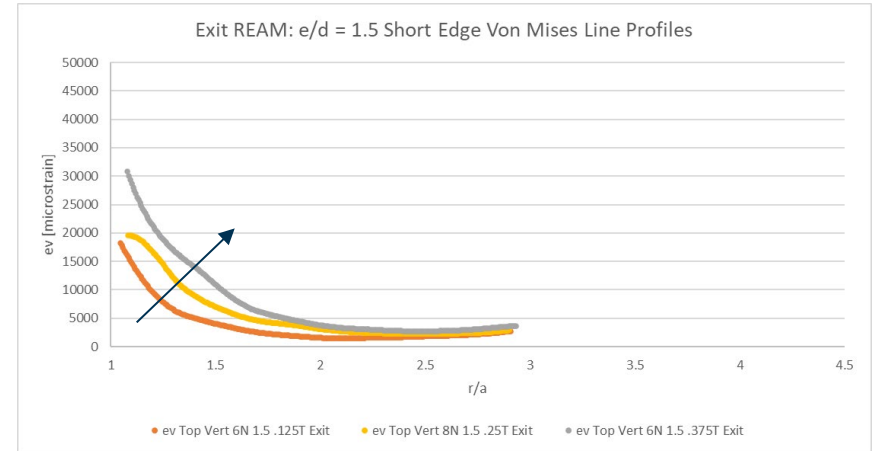
Exit CX: e/d = 1.5 Short Edge Von Mises Line Profiles

Excluding 4N (higher expansion ratio), strains increase with thickness

e/d 1.5 Ream Entry and Exit – 4N Excluded



Entry REAM : e/d = 1.5 Short Edge Von Mises Line Profiles

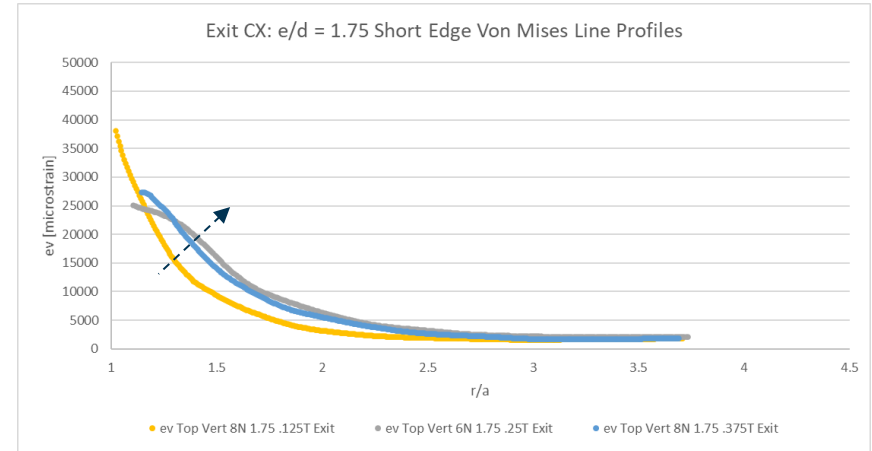
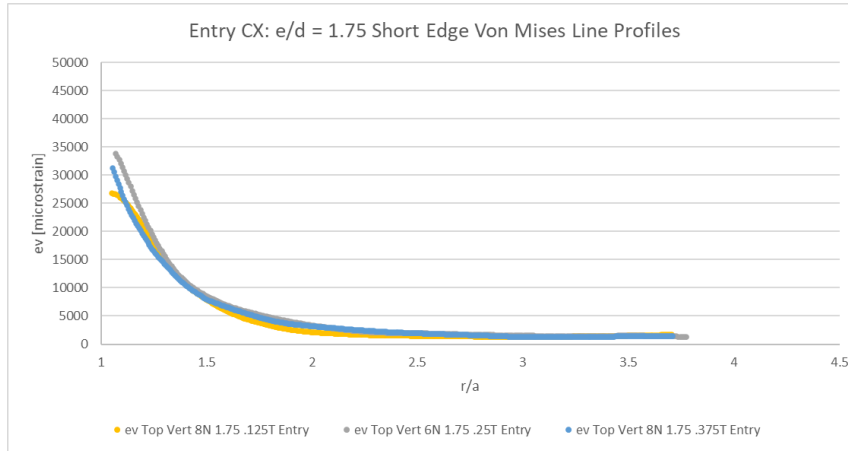


Exit REAM : e/d = 1.5 Short Edge Von Mises Line Profiles

Excluding 4N (higher expansion ratio), strains increase with thickness

EDGE DISTANCE (E/D) - 1.75

e/d 1.75 CX Entry and Exit – 4N Excluded

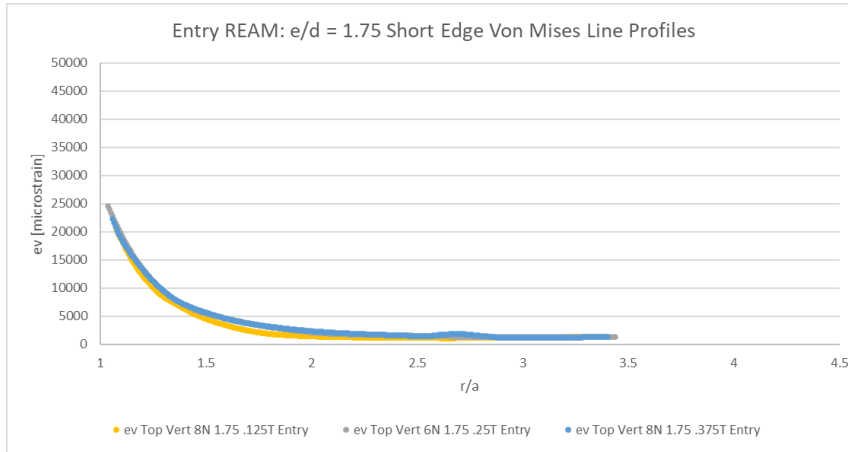


Entry REAM : e/d = 1.75 Short Edge Von Mises Line Profiles

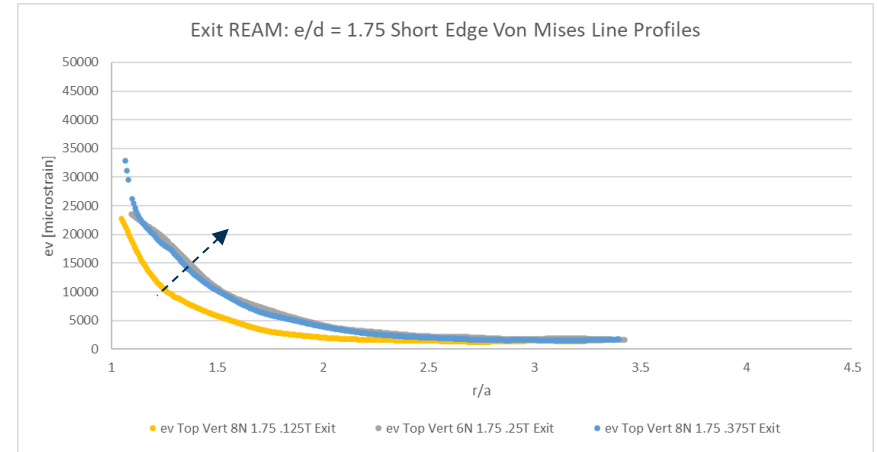
Exit REAM : e/d = 1.75 Short Edge Von Mises Line Profiles

- Strain profiles as a function of thickness only marginal (on Exit face)
- Entry face very uniform

e/d 1.75 REAM Entry and Exit – 4N Excluded



Entry REAM : e/d = 1.75 Short Edge Von Mises Line Profiles

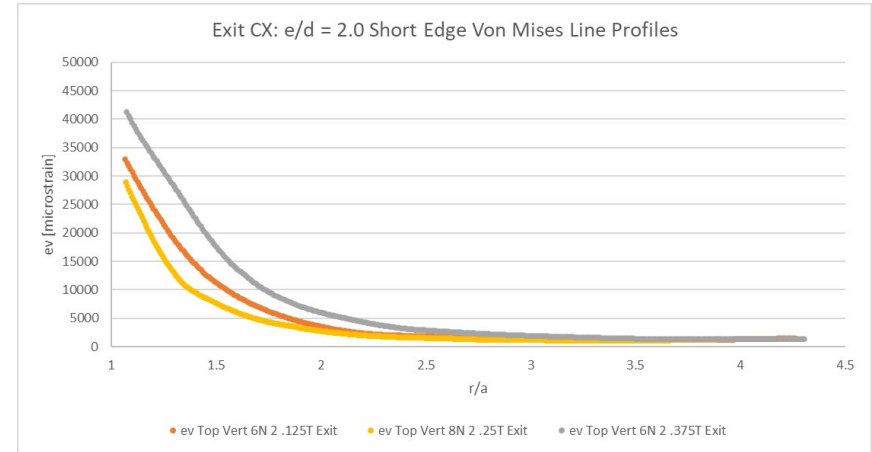
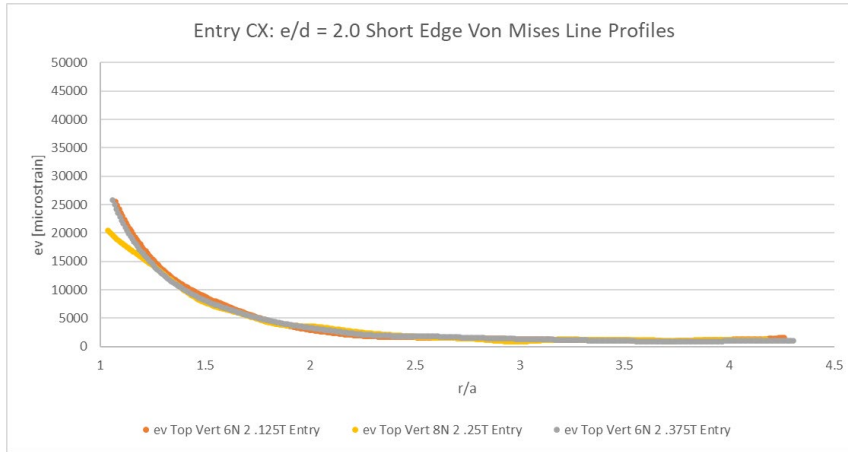


Exit REAM : e/d = 1.75 Short Edge Von Mises Line Profiles

- Strain profiles as a function of thickness only marginal (on Exit face)
- Entry face very uniform

EDGE DISTANCE (E/D) – 2.0

e/d 2.0 CX Entry and Exit – 4N Excluded

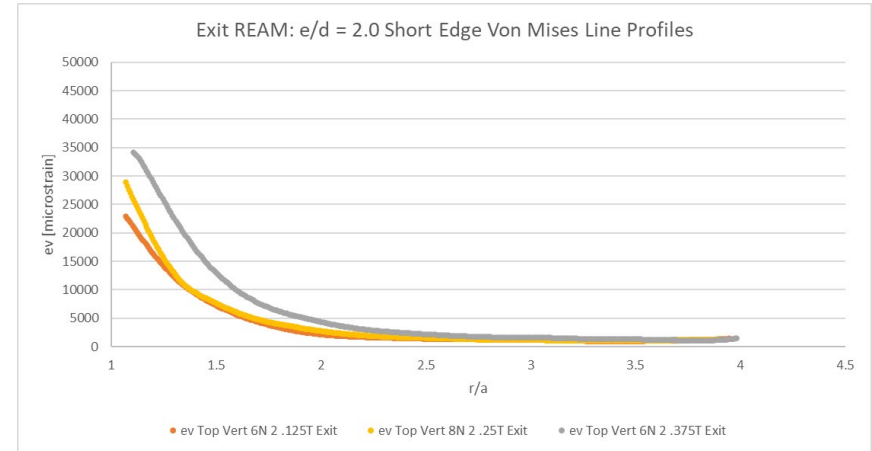
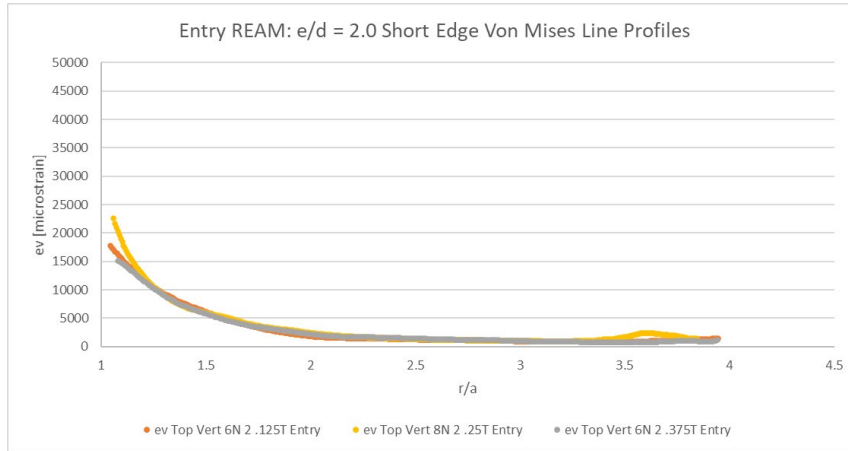


Entry REAM : e/d = 2.0 Short Edge Von Mises Line Profiles

Exit REAM : e/d = 2.0 Short Edge Von Mises Line Profiles

- No obvious relation between strain and thickness
- Entry face very uniform

e/d 2.0 REAM Entry and Exit – 4N Excluded



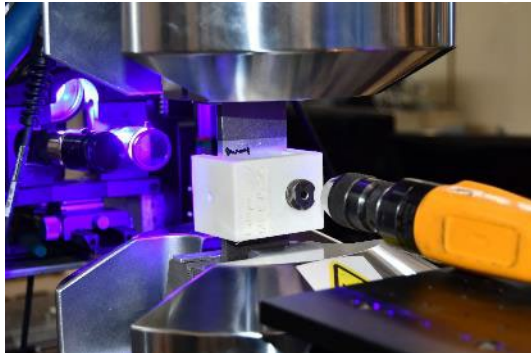
Entry REAM : e/d = 2.0 Short Edge Von Mises Line Profiles

Exit REAM : e/d = 2.0 Short Edge Von Mises Line Profiles

- No obvious relation between strain and thickness
- Entry face very uniform

INITIAL FATIGUE TESTING

In-Situ SsCx Fatigue Experiment: Test Setup



In-situ SsCx Fatigue Experiment

- SsCx/Ream/Debur/Metrology
- F-35 Spectrum Loading (8 blocks/life)
- CAMB's & High-Mag 3D-DIC between blocks

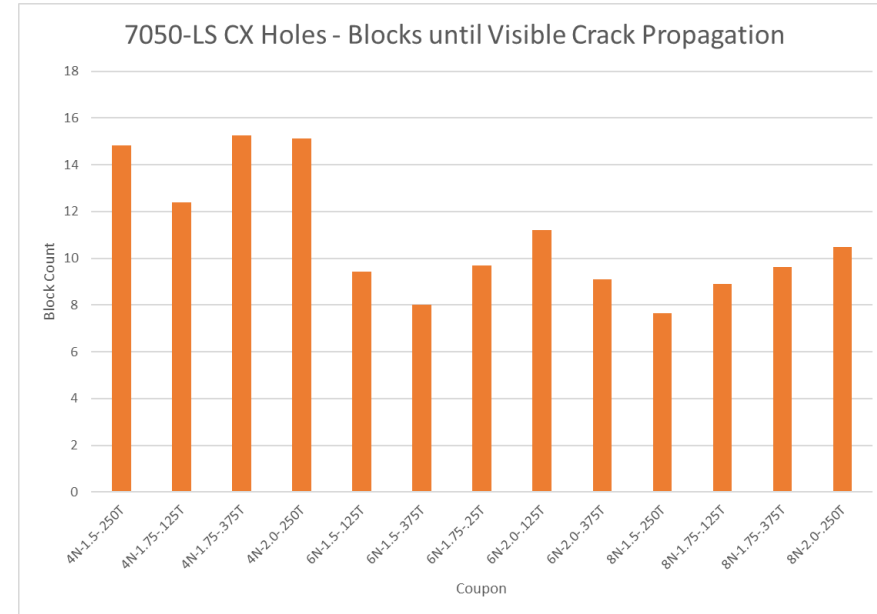
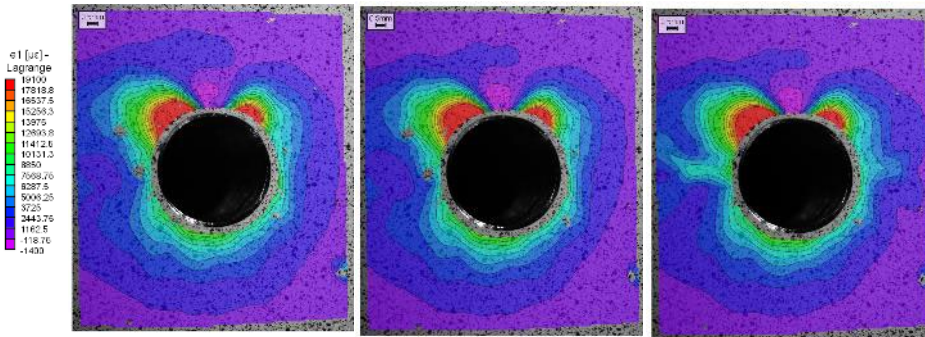
Deliverables

- Developed novel in-situ DIC for fatigue
- Developed method for detecting onset of nucleation (to be confirmed via quantitative fractography)
- Nucleated and propagated crack to allow for QF

Results: In-Situ SsCx Fatigue Experiment

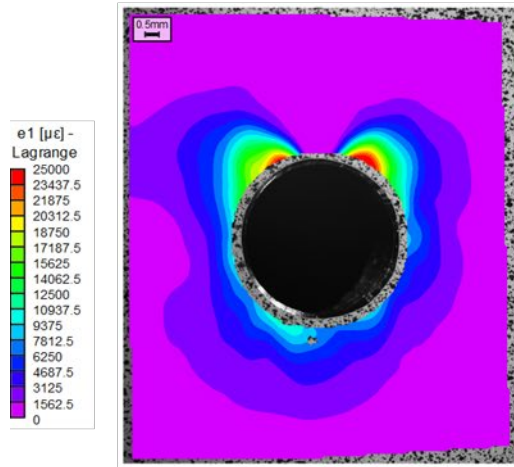
In-situ SsCx Fatigue Experiment

- DIC to detect crack formation
- Cycling stopped once crack propagated close to edge

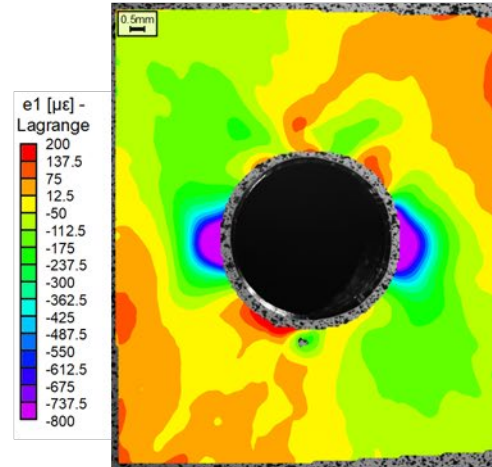


Change in ϵ_1 Cold Expansion Strain upon Initial Cycles

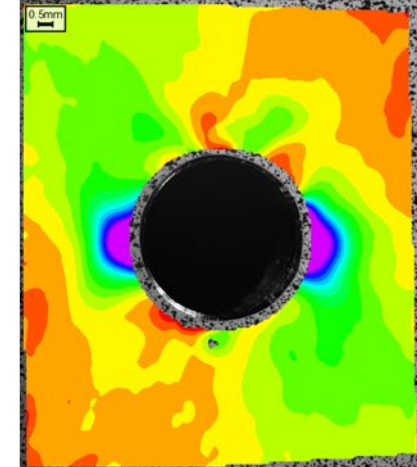
4N-1.75-.125T



Post-Deburr ϵ_1 Strain Field



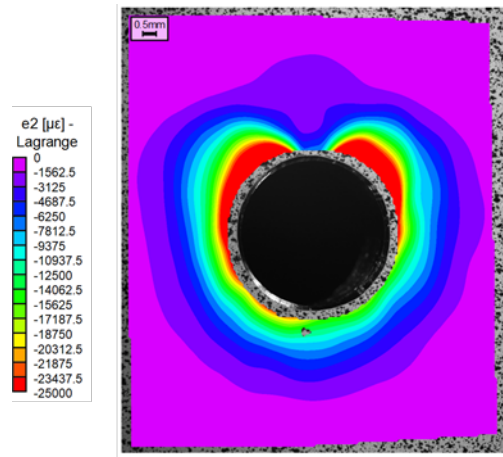
End of Block 1 – Change in ϵ_1



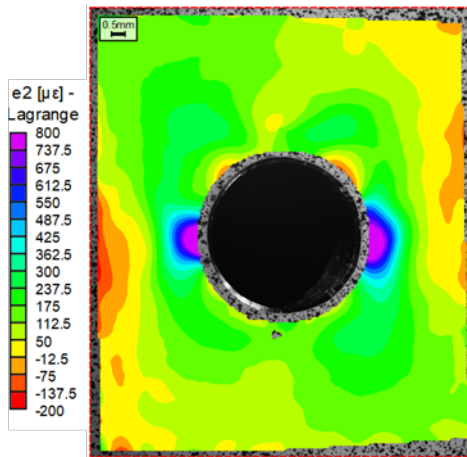
End of Block 4 – Change in ϵ_1

Change in e2 Cold Expansion Strain upon Initial Cycles

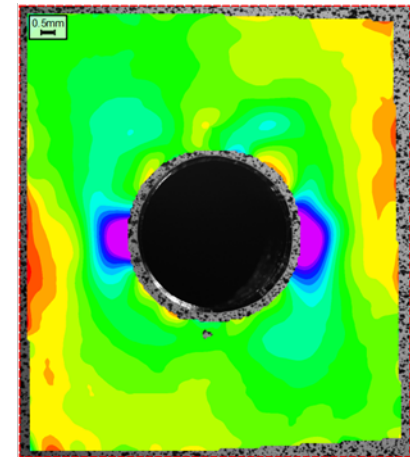
4N-1.75-.125T



Post-Debur e2 Strain Field



End of Block 1 – Change in e2



End of Block 4 – Change in e2

Discussion: DIC for Detecting Nucleation

Novel crack detection method

- Utilize difference in strain field (SsCx – BLOCK N image)
- Examined peak strain location
- Sudden change appeared to indicate precede visible crack
- Needs to be confirmed via fractography

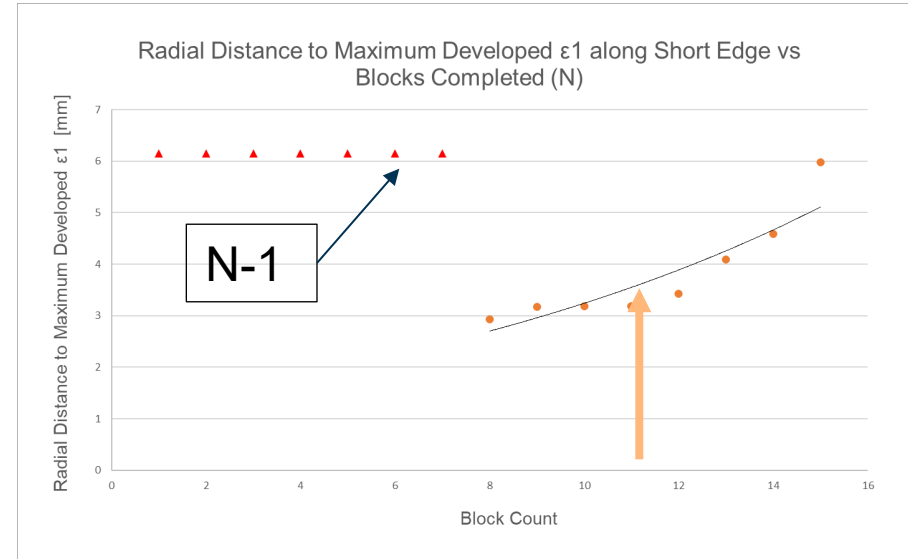
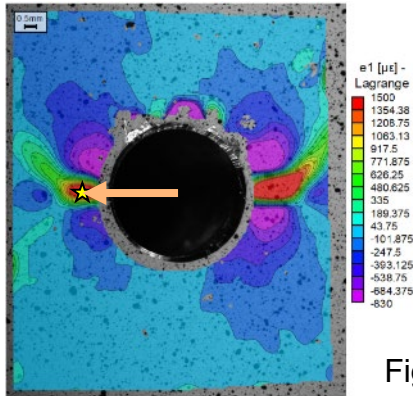
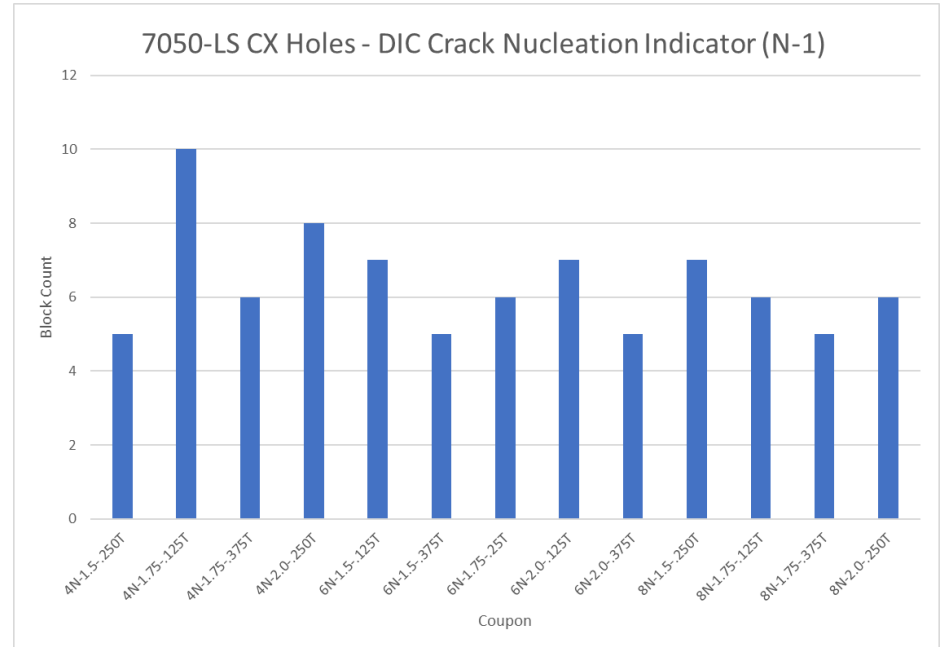


Figure 10: DIC 4N-1.75-.375T (After 12 Blocks)

Discussion: Estimated Cycles to Nucleation

Novel crack detection method

- **Needs to be confirmed via fractography**
- Crack nucleation in bore is not detectable BUT this method may offer enhanced sensitivity vs normal DIC



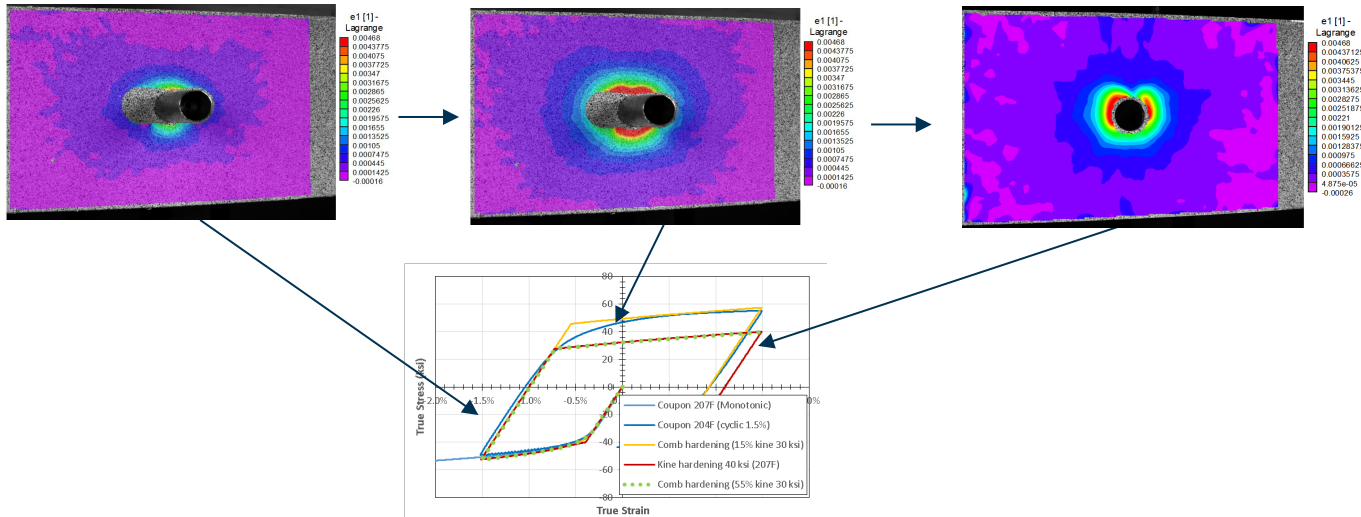
OVERALL TRENDS

OVERALL TRENDS

- SR-DIC enables simultaneous capture of far-field and near-bore strain profiles
- For $e/D = 1.5$, strain increases with thickness (8N and 6N)
- For $e/D = 1.75$, strain increases with thickness ONLY for Exit face
- For $e/D = 2.0$, no relation between strain and thickness
- Reaming generally reduces strain profile variability and generally alleviates near-bore “curvature”
- As e/D decreases the strain at the far-field increases (independent of thickness)
- Exit strains higher than Entrance generally r/a between 1.5 – 2
- All 8N Profiles more self-consistent
 - Could relate to 8N coupons having greater amount of material at edge ‘e’ (compared to corresponding 4N and 6N coupons)

Next Steps

- Manual SsCx process allows for interim strain capture during mandrel pull.
- This data contains elastic, elastic-plastic and plastic data
- May allow for more robust material model validation



Thank you

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Extra Slides

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Task 3: Metrology

- Pre cold work (CX), post CX, and post ream & Deburr metrology
- Min-Max metrology obtained with ball gauges
- Single Measurements obtained with Hologic



Fatigue Coupon Metrology Summary (TC and CA)

Hole Size and State	Target Hole Diameter [in]	Average [in]	Standard Deviation [in]
4N Min Pre CX	0.1705	0.1701	0.0001
4N Max Pre CX		0.1706	0.0001
4N Min CX		0.1744	0.0001
4N Max CX		0.1753	0.0001
4N Min Ream + Deburr	0.193	0.1926	0.0001
4N Max Ream + Deburr		0.1928	0.0001
6N Min Pre CX	0.2275	0.2275	0.0001
6N Max Pre CX		0.2278	0.0001
6N CX		0.2314	0.0001
6N Ream + Deburr	0.253	0.2523	0.0003
8N Pre CX	0.2855	0.2856	0.0001
8N CX		0.2905	0.0001
8N Ream + Deburr	0.3125	0.3156	0.0003

Task 1: Abaqus Model Development and Validation

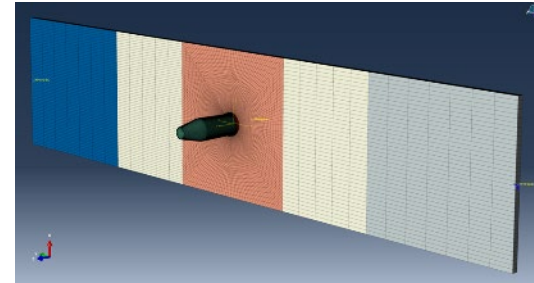
Abaqus Simulation FEM Results

Input Parameters:

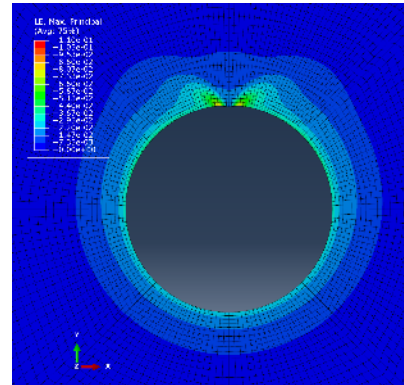
- Geometry (Plate Length, Width, Thickness, Diameter...)
- Material (Stress-strain curves)
- Other (Friction, Mesh)

Deliverable:

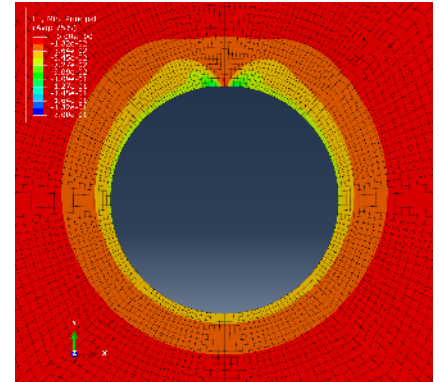
- Validation against MARC model



Abaqus Model Setup



Entrance – Max Principal Strain



Entrance – Min Principal Strain

Additional SsCx Test Programs

Aluminum Alloys – Fastener Holes

- 7050-T7451 & 7085-T7452
 - Investigate Fatigue & Crack Growth Benefits of SsCx at "Short" e/Ds
 - 1.5, 1.3, 1.1 edge margins
 - 0.25inch thick with a 0.25inch diameter hole
 - Machined from center half of 2.5inch, 3.5inch, 8.0inch thick plate (for forging it's out of representative thicknesses)
 - Naturally occurring cracks
 - "Low" applied expansion
 - Multiple fighter spectrum applied
 - Wing Root Bending
 - Upper Fuselage
 - Horizontal Tail
 - Fully Reversed
 - Investigate Effect of Pre-Crack Sequence and SsCx (Ref. SB-17)
 - Drill->SsCx->EDM Notch->Pre-Crack->Final Ream
 - Drill->EDM Notch->Pre-Crack->SsCx->Final Ream
 - Investigate Effect of Sleeve Orientation to Loading Direction
 - Align split sleeve at 12 O'clock and 9 O'clock

Aluminum Alloys – Fastener Holes

- 7085-T7452 Forging
 - Design of Experiments (DoE) test matrix developed to cover 50+ different SsCx hole configurations in wing-to-body area
 - 13 Unique conditions designed to cover three “levels”
 - Thickness
 - Hole Diameter
 - Edge Margin
 - Same loading spectrum + CAMBS (lwr. wing skin, near landing gear)
 - Naturally occurring cracks
 - Allows for use of DoE mathematical model to predict performance within the design box
 - Can we use this type of approach to develop a mathematical model for predicting performance at SsCx holes?
 - RS coupons machined and surface XRD performed

Aluminum Alloys – Fastener Holes

- 7050-T7451
 - Multi-phase DIC During SsCx & Final Ream + RS Determination + Fatigue Testing
 - Purpose to develop a group of conditions for FEA and Prediction validation
 - Machined form center half of 3.5inch thick plate
 - 3 thicknesses
 - 3 hole diameters
 - 3 edge margins
 - Capture RS using:
 - DIC during SsCx + final ream
 - Surface XRD
 - Contour
 - In-Bore XRD
 - K_{sol} (Back Extrapolation)
 - Fatigue testing using
 - 2 spectrum types (tension-tension, tension-compression)
 - High and Low stress levels

Aluminum Alloys – Web Penetrations

- 7050-T7451 & 7085-T7452
 - Quantify the Fatigue & Crack Growth Life Improvements for SsCx Application
 - Define parameters that can be normalized to reduce test matrix
 - Can we test a 1inch diameter hole to represent a 2inch diameter hole?
 - How do we design test coupons to capture stiffness effects of vertical and horizontal stiffeners within unitized structural design?
 - Manufacturing processes are different for Production vs. Mod
 - Production Suppliers usually leave the web thicker when performing the SsCx process and then perform a final machining step
 - Mod performs SsCx at nominal thickness (with or without a backing plate??)
 - Previous work for countersunk holes shows that post-machining of RS material changes the RS state, crack location and propagation morphology!
 - No final ream is performed post-SsCx on web penetrations (unless required tubing hook-ups)
 - Perform testing to determine if leaving the split sleeve impacts fatigue and crack growth life
 - Residual stress captured for each configuration

Titanium Alloys – Web Penetrations

- Ti-6Al-4V Beta Annealed ELI
 - Perform similar testing to that in Aluminum alloys
 - Fatigue + Residual Stress characterization