Harmonizing Contour and XRD Residual Stress Measurement Data Sets

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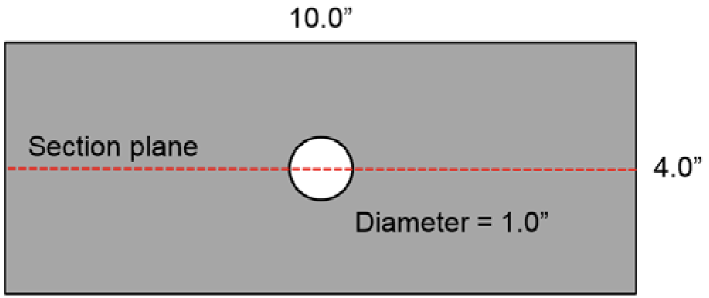
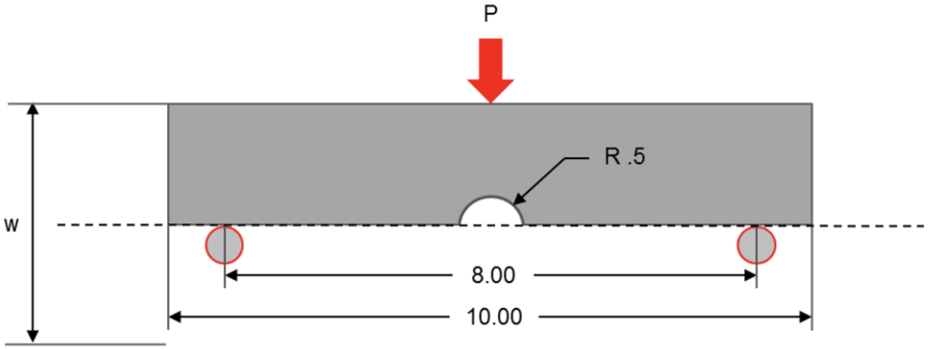
Recap on work done so far

Geometrically Large Coupons

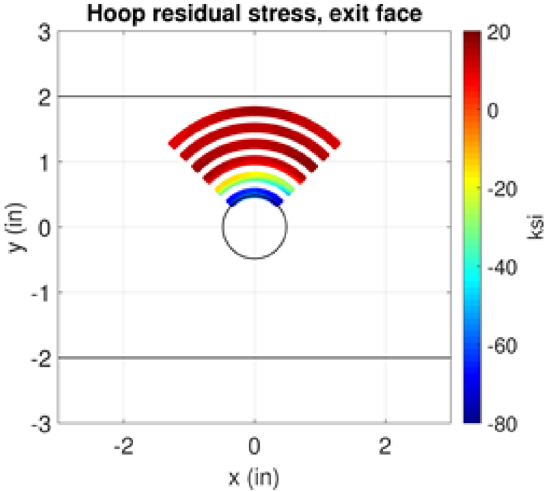
- Larger coupons scale-up the stress field to facilitate residual stress measurements using any method
- Full and split configurations
- Split configuration allows XRD access to bore ID but requires a correction for relaxation due to splitting
- XRD arc-averaging reduced to ± 45° on the face – must be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

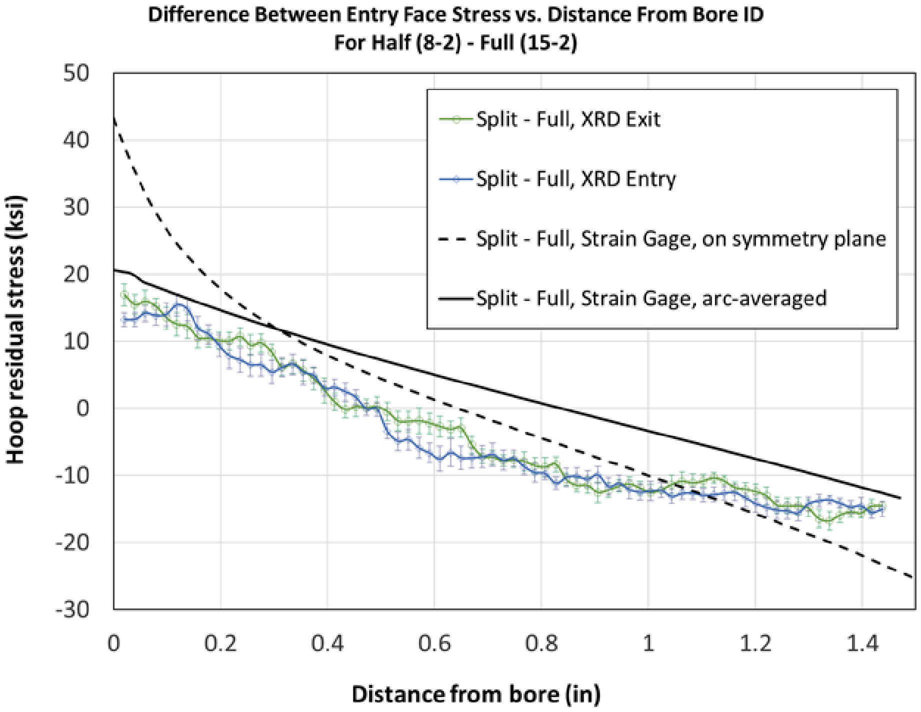




Effect of Split on Face of Geometrically Large Coupon

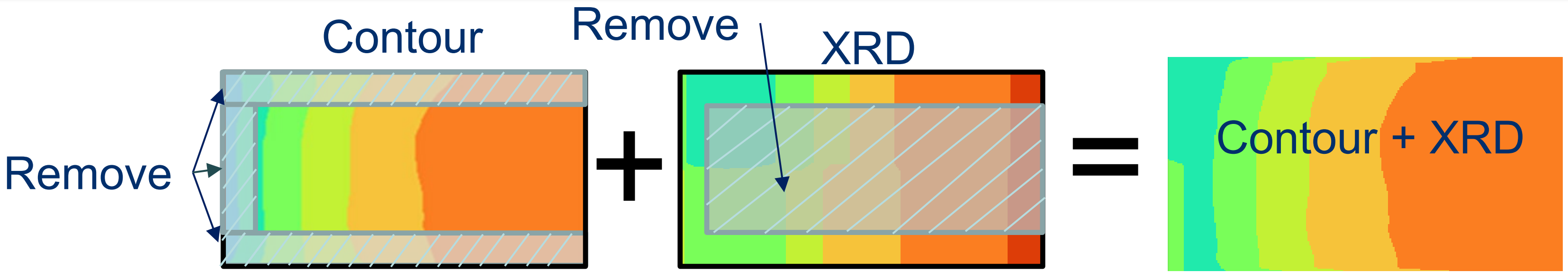
- When corrected for XRD arc averaging, the relaxation as measured by XRD vs. estimated by strain gage & FEM are more closely aligned





Opportunity to Integrate/Harmonize Datasets

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



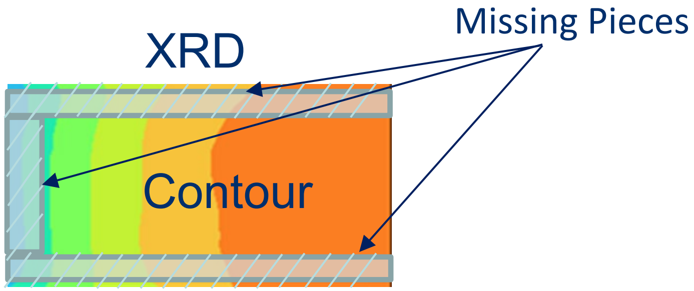
Prather, J., Carlson, S., (2023)., A Novel Approach to Integrating Residual Stress Determination Methods, Proc. 2023 Aircraft Airworthiness & Sustainment Conf., San Antonio, TX, USA.

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?**

Working With Available Data

key pieces of the puzzle were missing



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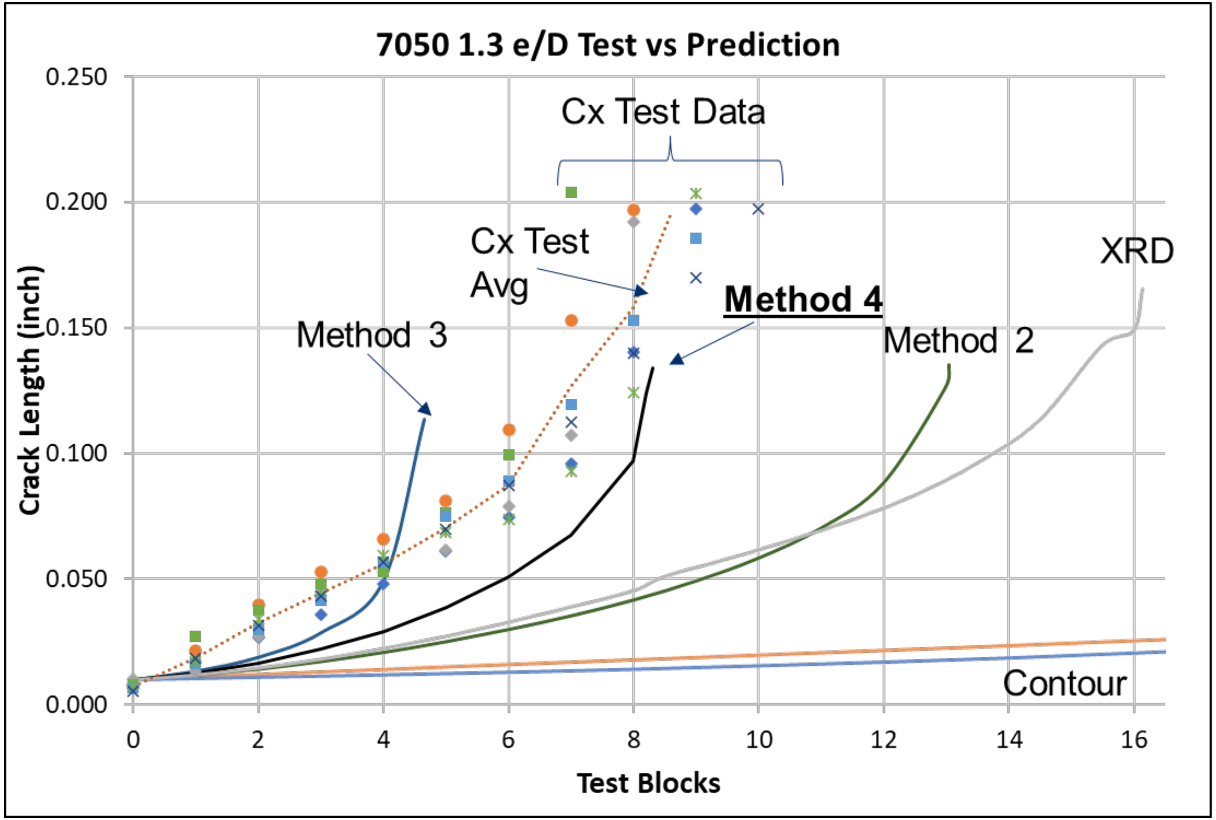
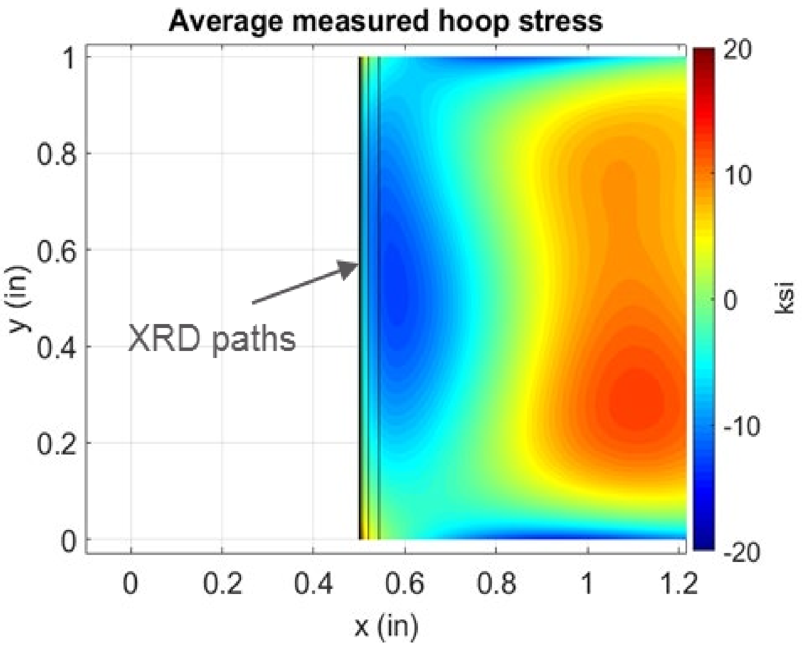


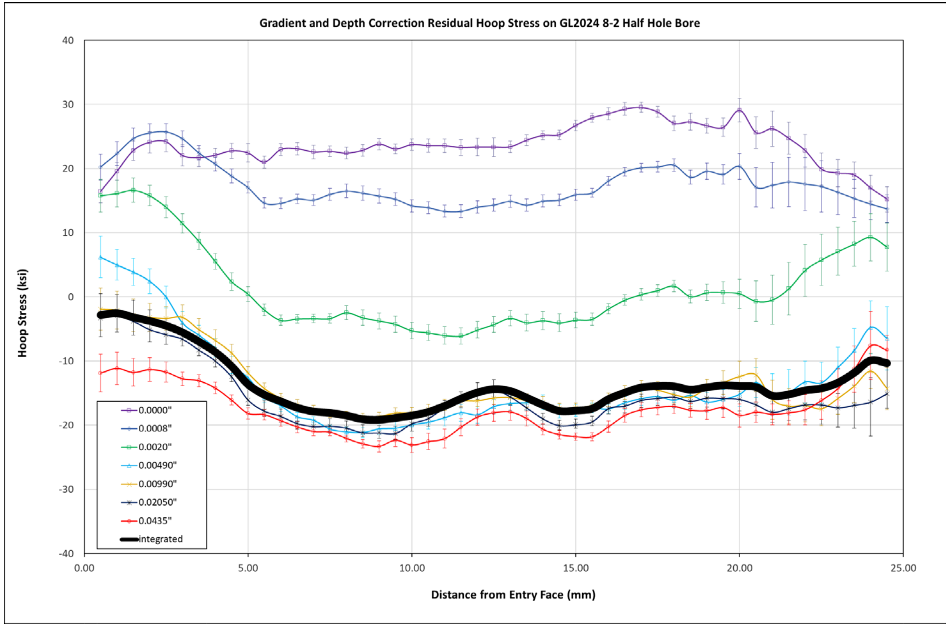
Prather, J., Carlson, S., (2023)., A Novel Approach to Integrating Residual Stress Determination Methods, Proc. 2023 Aircraft Airworthiness & Sustainment Conf., San Antonio, TX, USA

In the Bore of Split GL Coupon

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.





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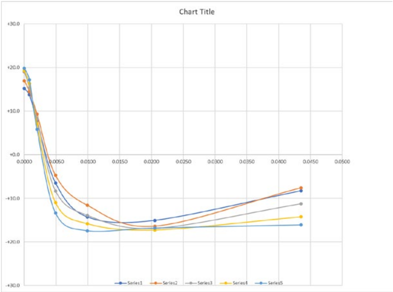
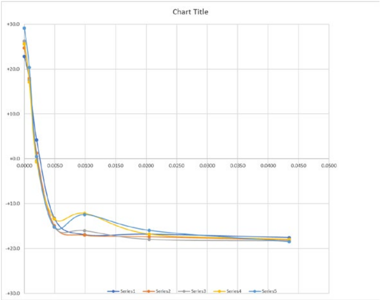
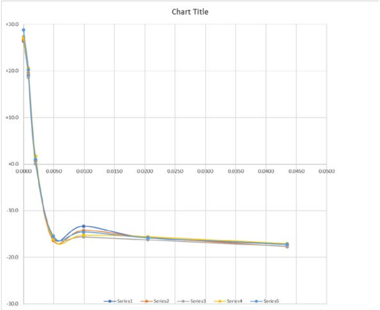
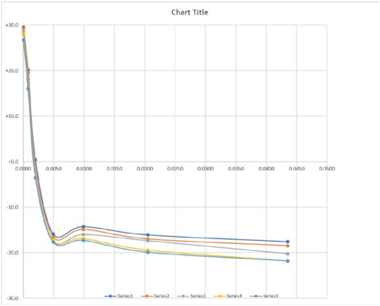
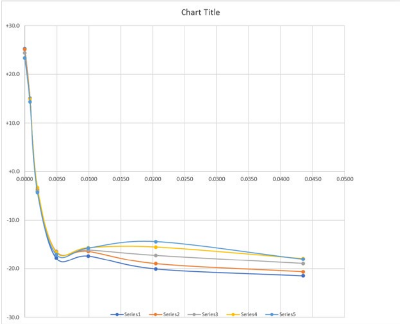
RS in Bore of Cx Hole in Geometrically Large Coupon – Depth profiles at individual points across the bore

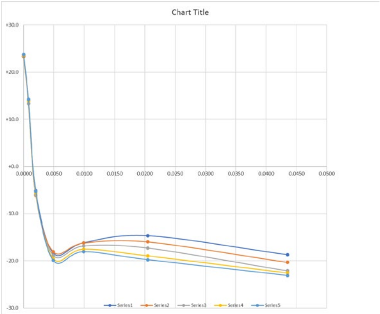


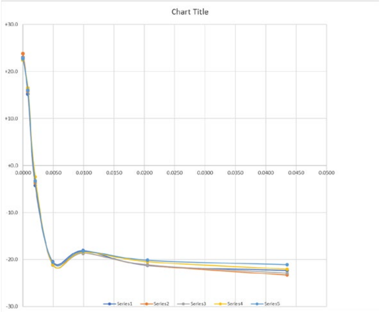


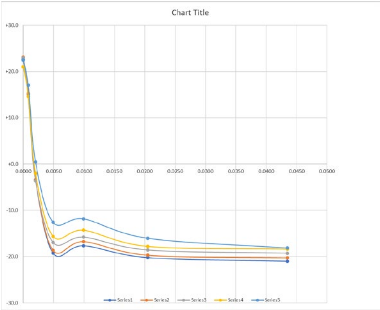












Note: Near surface cold working RS persist to about 0.010" deep

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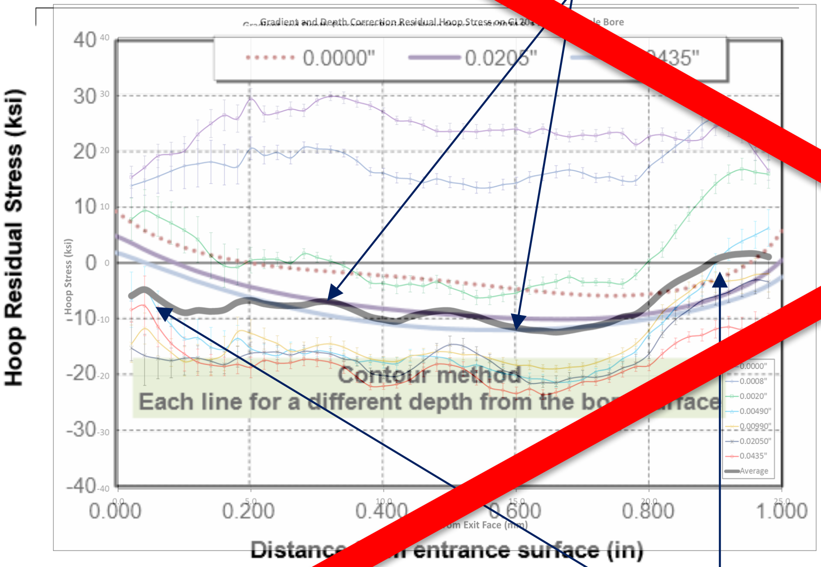
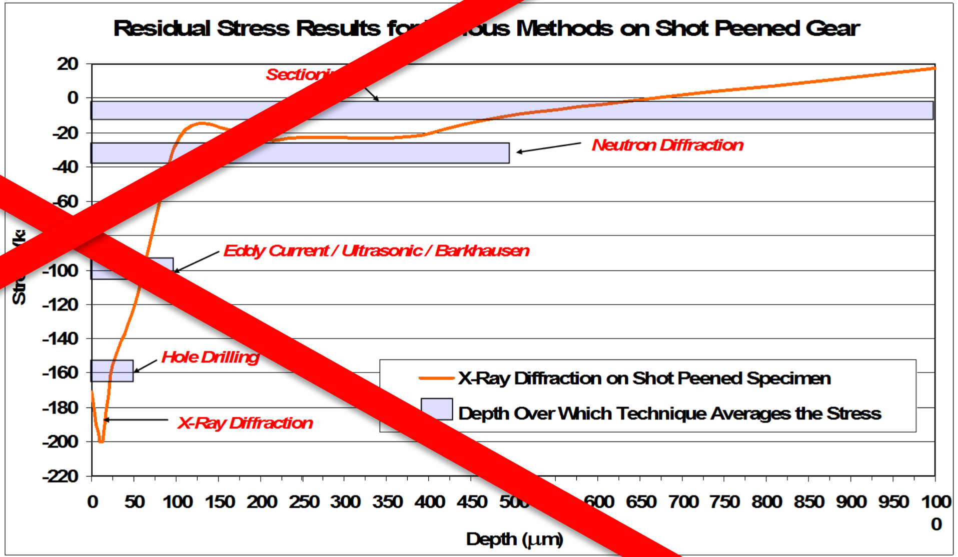
RS in Bore of Cx Hole in Geometrically Large Coupon Inter-method considerations – yes, the world is round!

"pretty good" agreement in the center





"Ok" agreement near ENT and EXT faces

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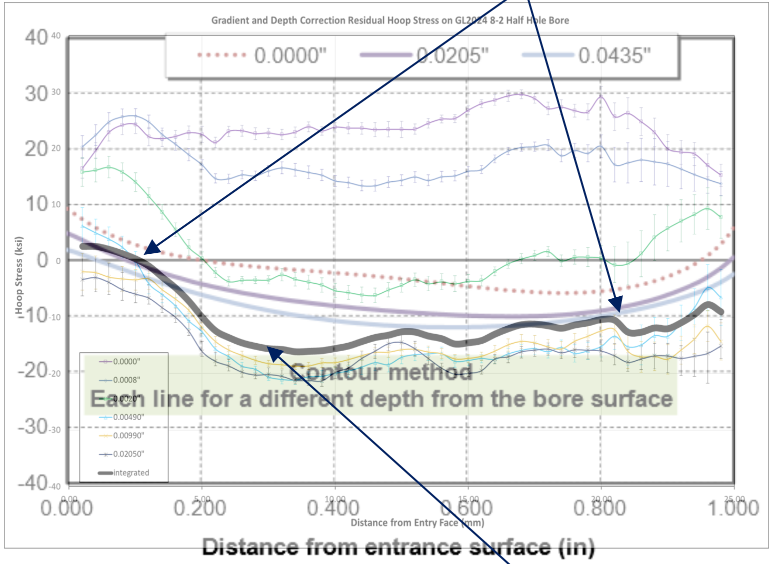
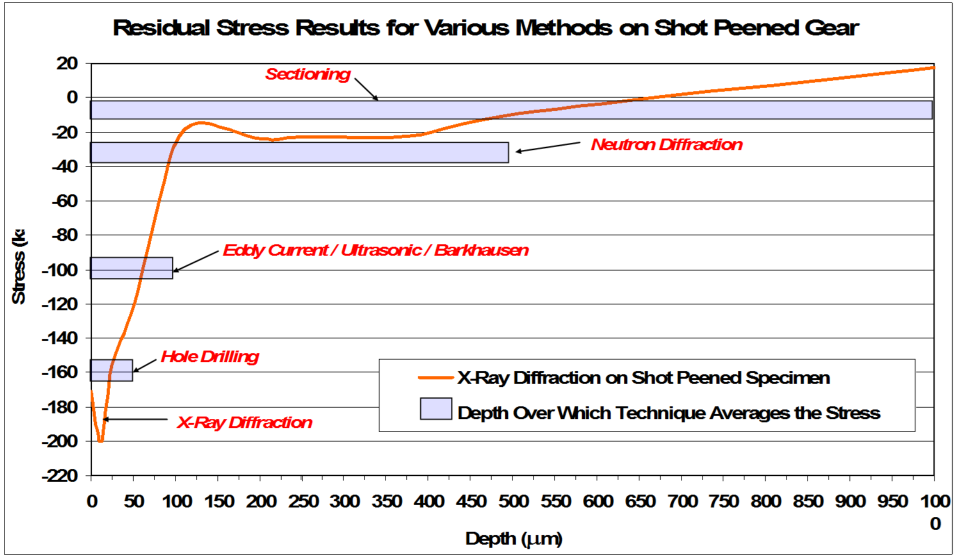
RS in Bore of Cx Hole in Geometrically Large Coupon
Inter-method considerations – yes, the world is round!

"better" agreement at entry and exit when integrating XRD data from 0.000" to 0.0205"





Compressive dip ~0.300" from Entry in XRD data

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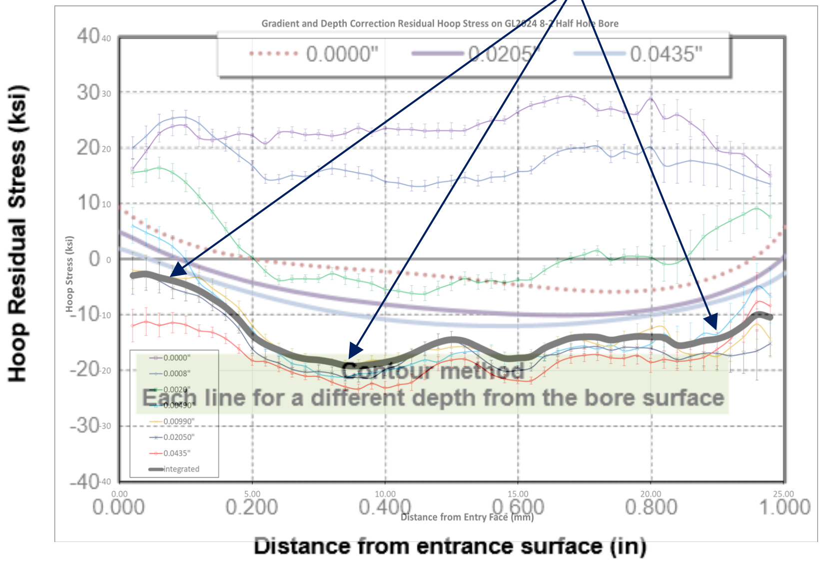
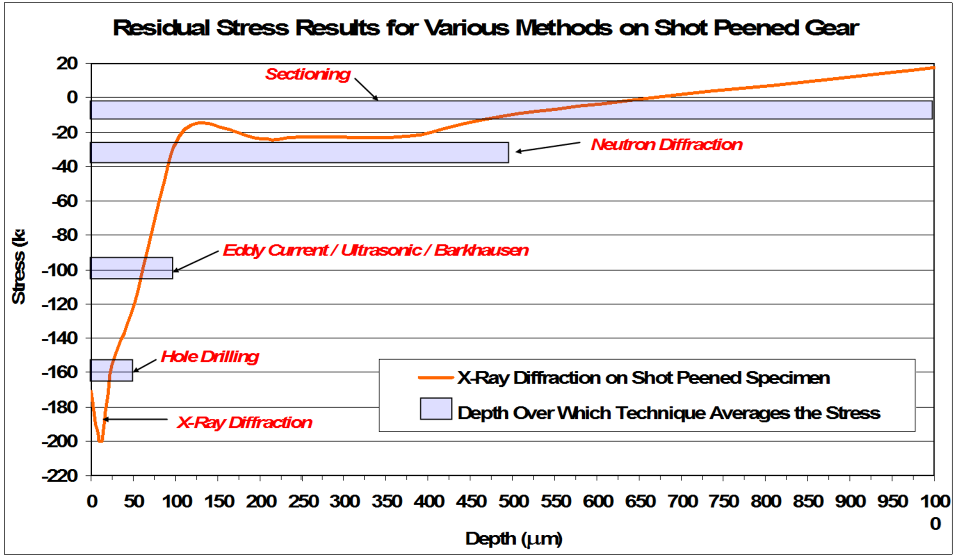
RS in Bore of Cx Hole in Geometrically Large Coupon
Inter-method considerations – yes, the world is round!

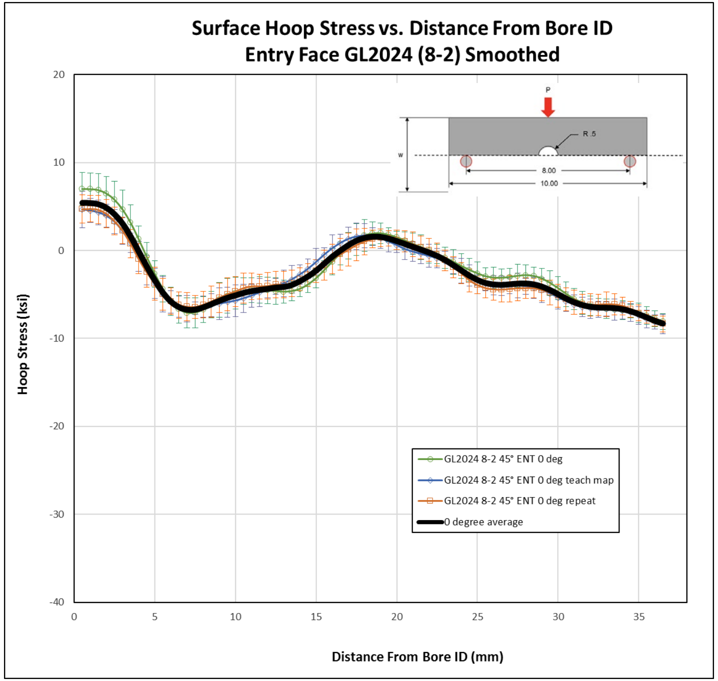
Slightly more compressive when integrating XRD data from 0.000” to 0.0435”

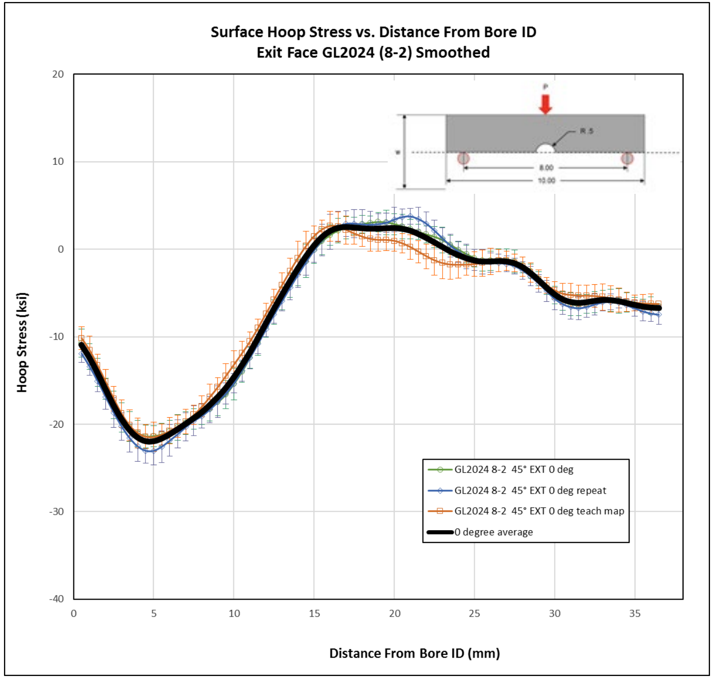




On Entry and Exit Faces at the Surface Only on Split GL

RS on Faces of Geometrically Large Coupon - Split





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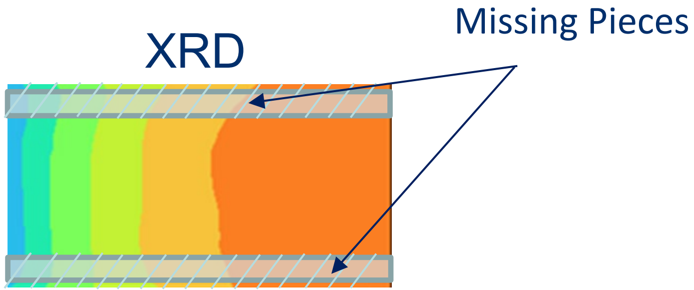
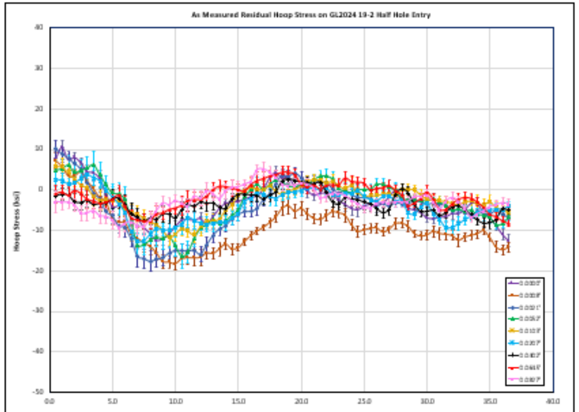
Missing Data for Split GL

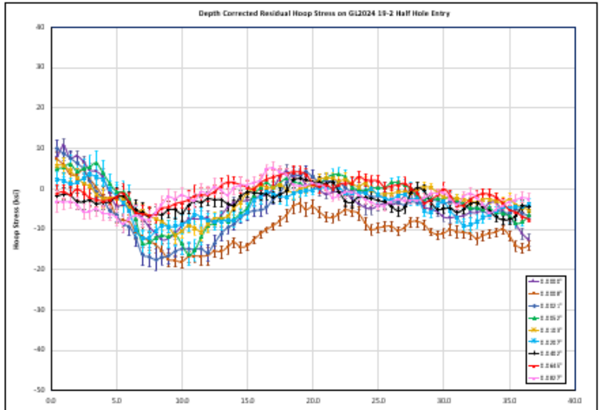


New XRD Data

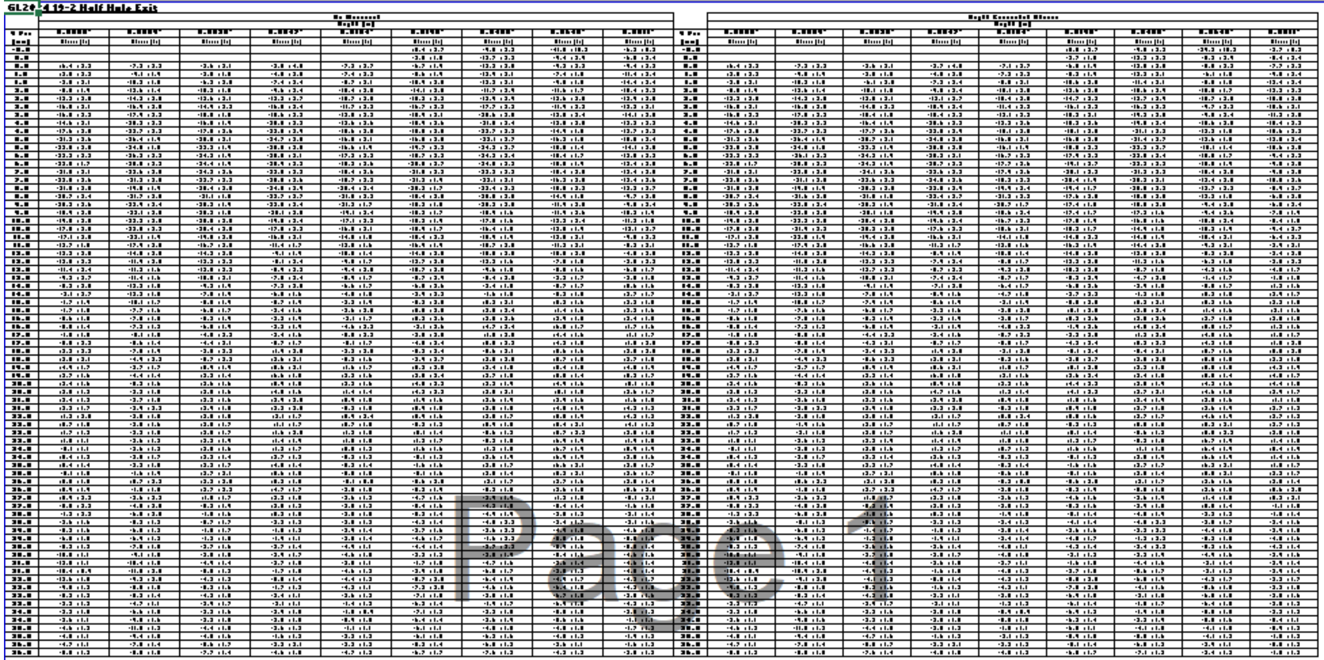
Entry Face
0.000" to 0.080" deep

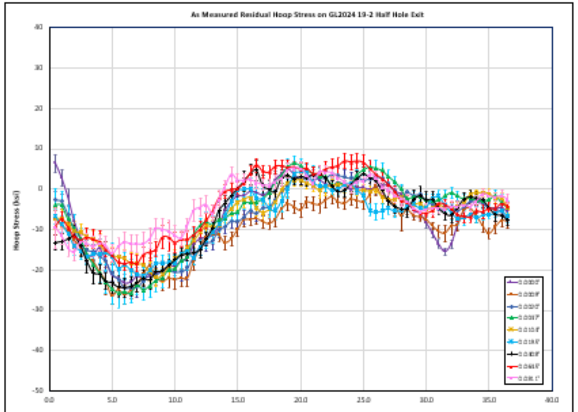
GL2024 19-2 Half Hole Entrance (etch side)

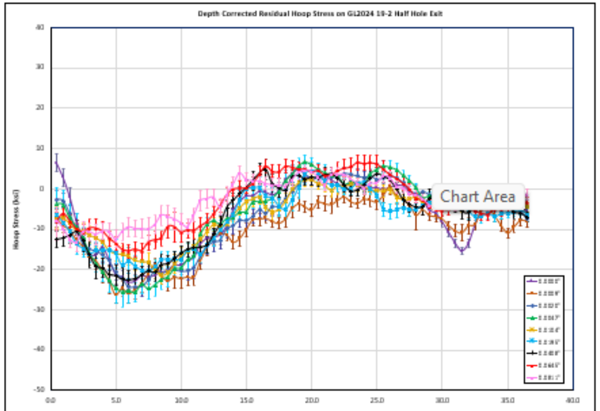




Exit Face
0.000" to 0.080" deep



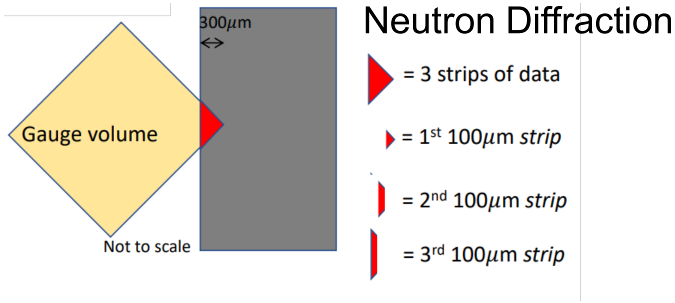




Dataset improvements using <u>deconvolution</u> methods

The original idea came from Richard Moat using overlapping data sets using ND via a “large” spot with “small” profile step increments

M1=S1, M2=(S1+S2)/2, M3=(S1+S2+S3)/3, etc…



Solve the series of equations to obtain solutions for each Sn value.

This approach was attempted with XRD however in several instances the grain size issue for the first few increments where the beam is “overhanging” resulted in large errors.

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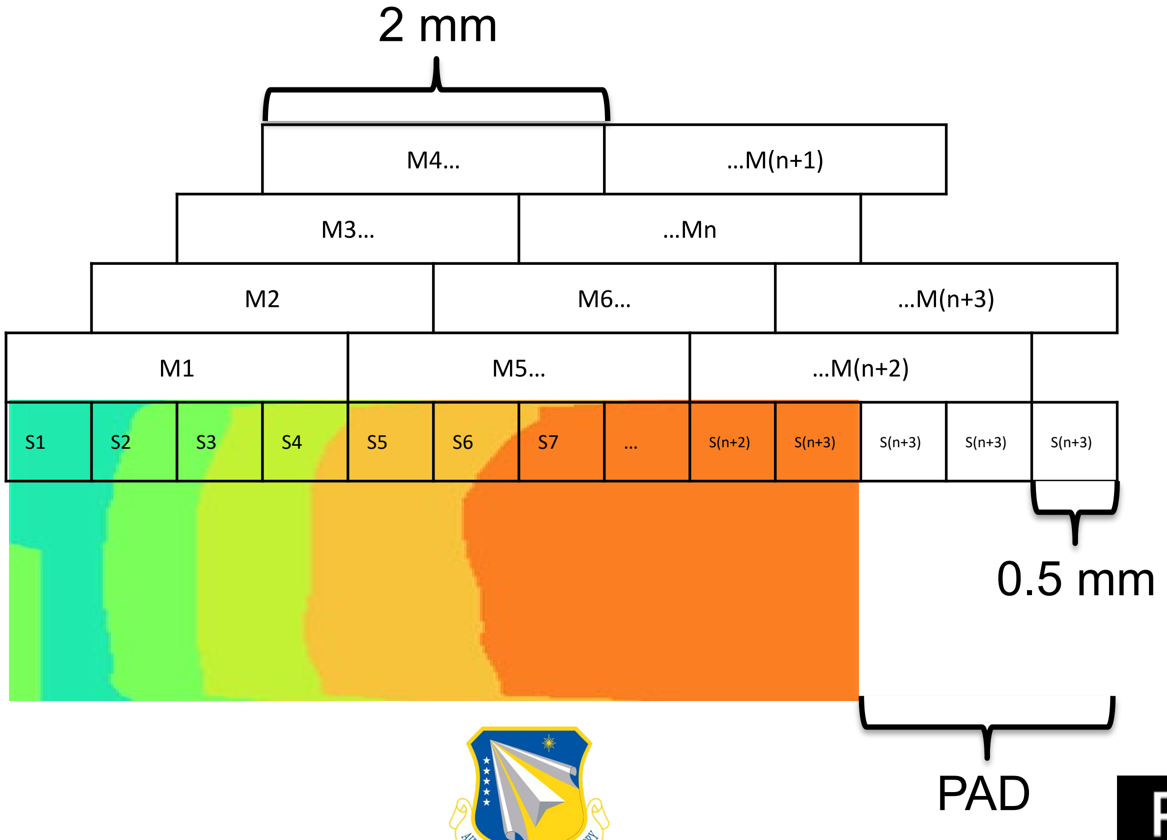
Alternate Approach to Deconvolution of GL Data

Data were collected using 0.5 mm increments and a 2 mm spot.



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Alternate Approach to Deconvolution

By "padding" the array at the end of the data set where it is approximately linear far from the hole, a sufficient number of equations can be obtained for a direct solution.

M(n+3)=[S(n+3)+S(n+3)+S(n+3)+S(n+3)]/4, **M(n+2)**=[S(n+2)+S(n+3)+S(n+3)+S(n+3)]/4, **M(n+1)**=[S(n+1)+S(n+2)+S(n+3)+S(n+3)]/4 **are the extra 3 equations** …then continue with **M(n)**=[S(n)+S(n+1)+S(n+2)+S(n+3)]/4, **M(n-1)**=[S(n-1)+S(n)+S(n+1)+S(n+2)]/4, etc…

Solve the series of equations to obtain solutions for each Sn value
Other methods are also possible i.e. Moore-Penrose Inverse

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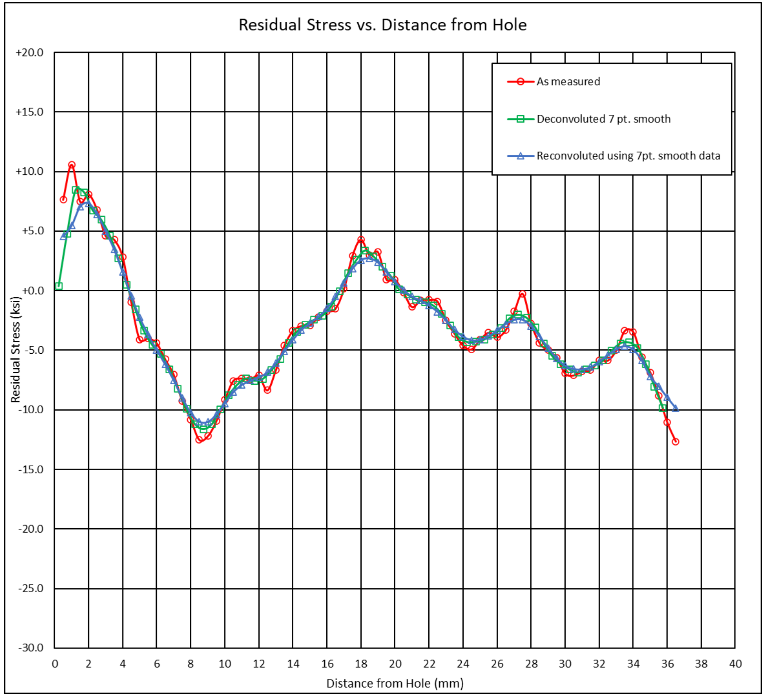
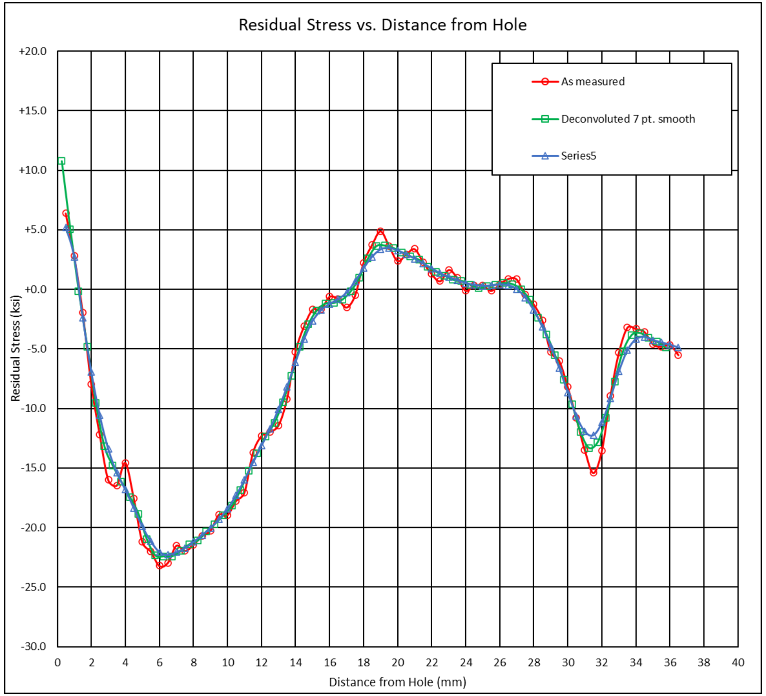
Padded Array Approach to Deconvolution

Entry 0.000" deep



Exit 0.000" deep



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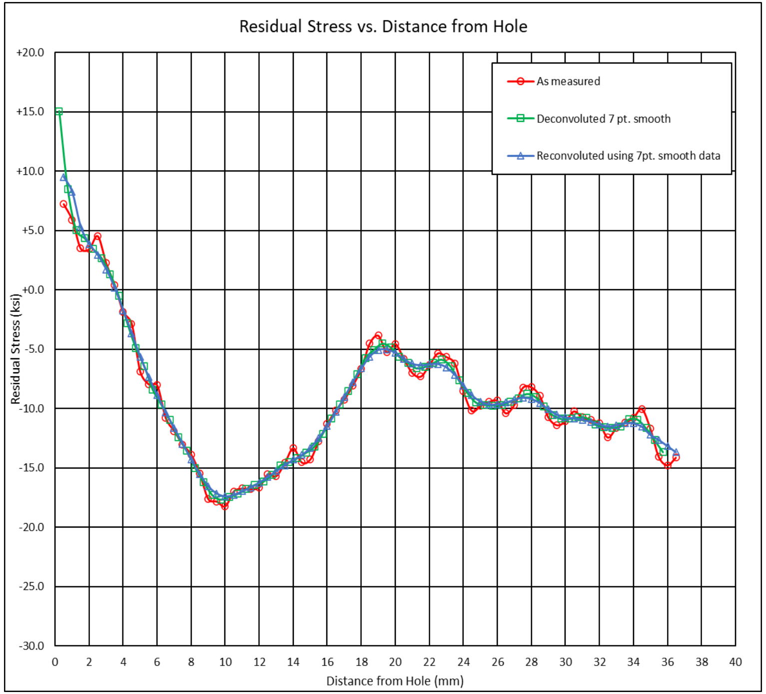
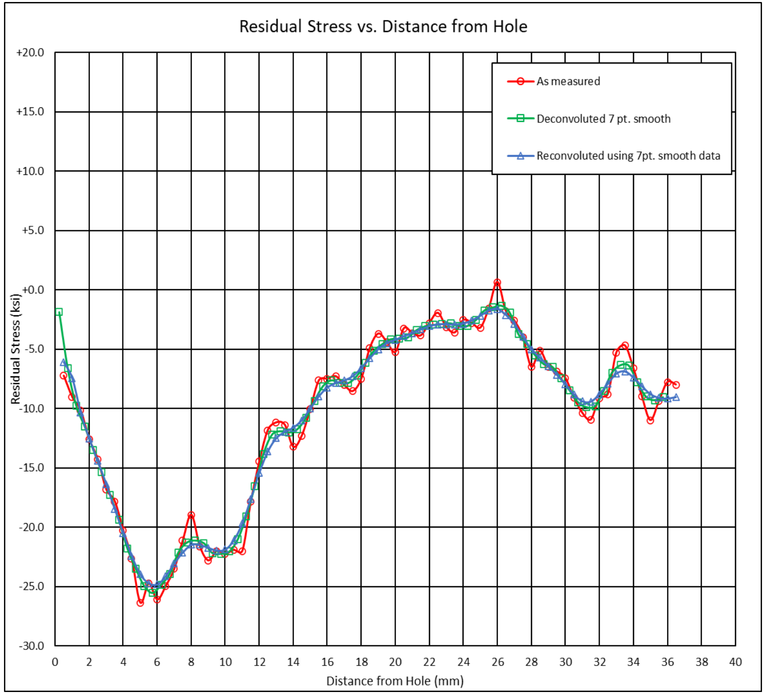
Padded Array Approach to Deconvolution

Entry 0.0008" deep



Exit 0.0009" deep



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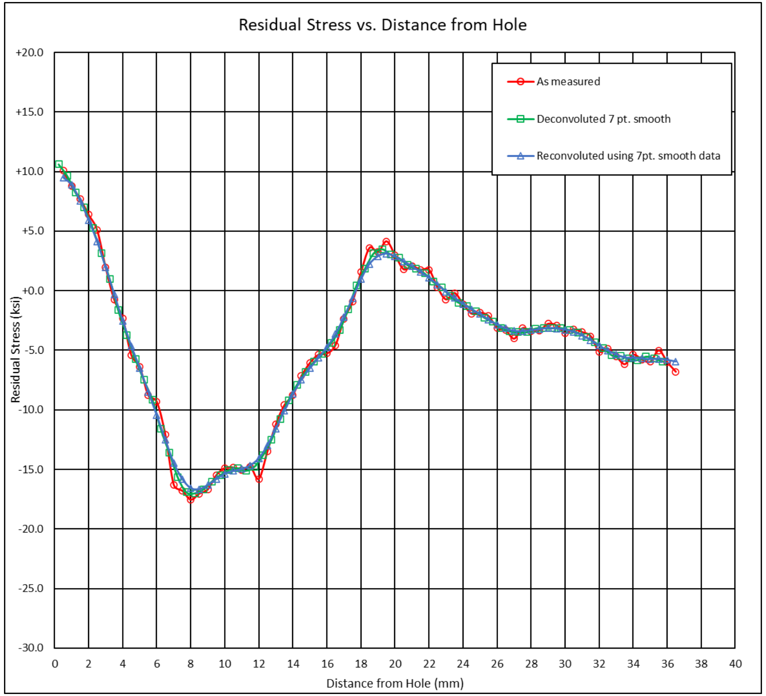
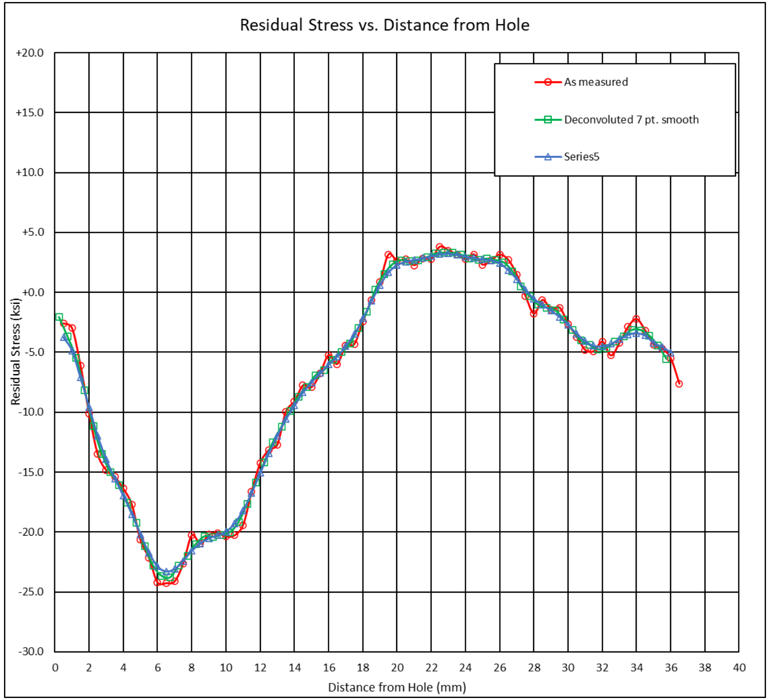
Padded Array Approach to Deconvolution

Entry 0.002" deep



Exit 0.002" deep



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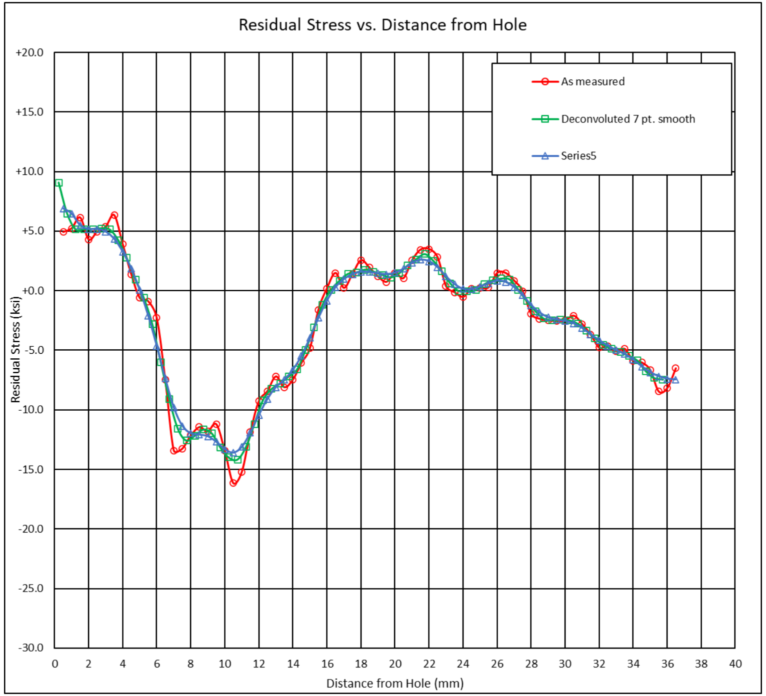
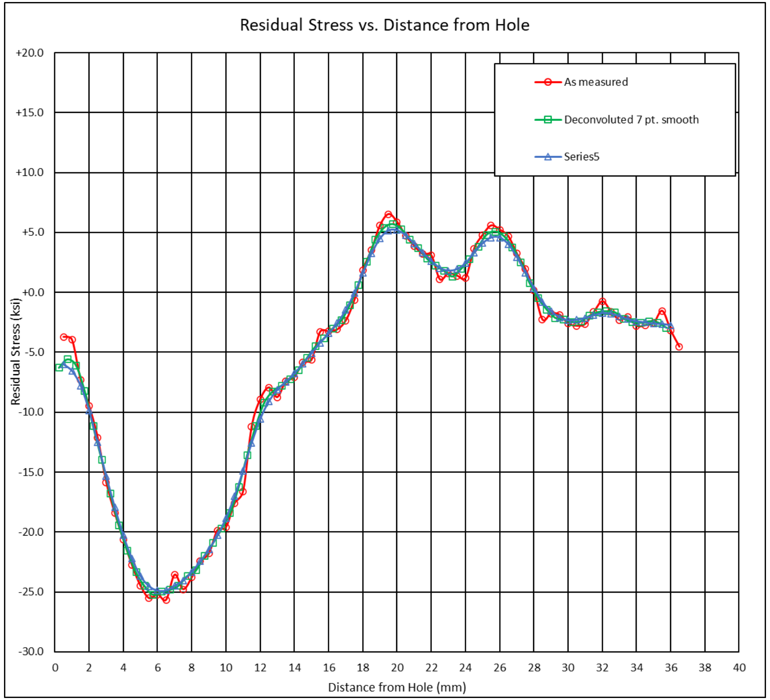
Padded Array Approach to Deconvolution

Entry 0.005" deep



Exit 0.005" deep



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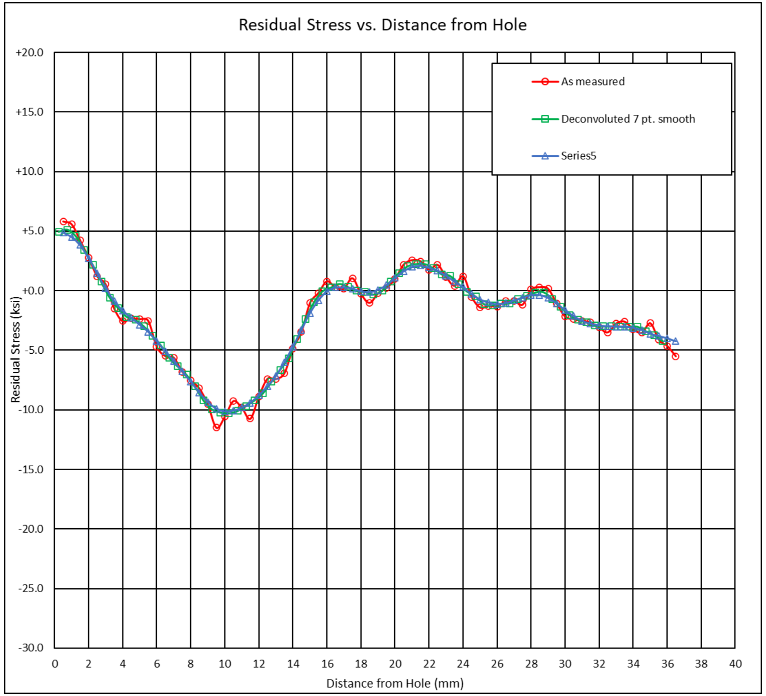
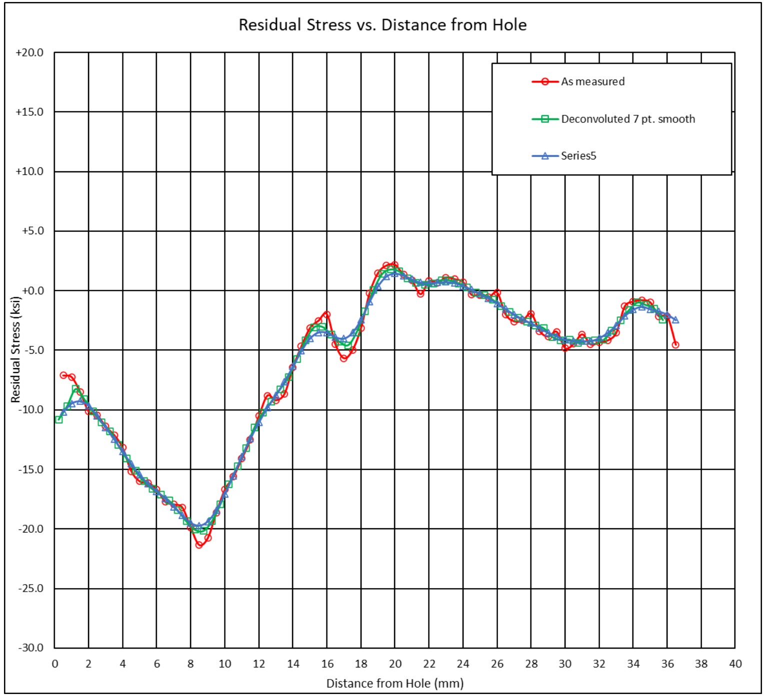
Padded Array Approach to Deconvolution

Entry 0.010" deep

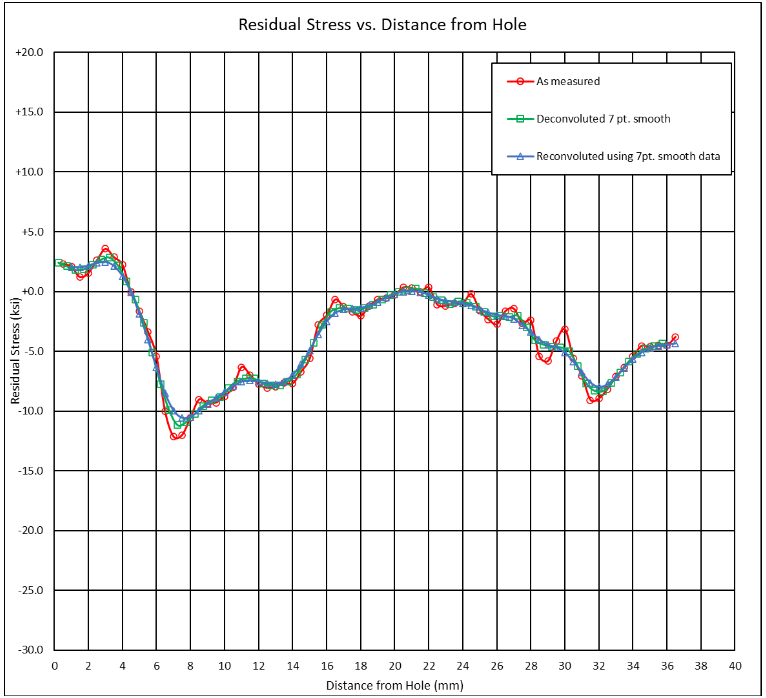


Exit 0.010" deep

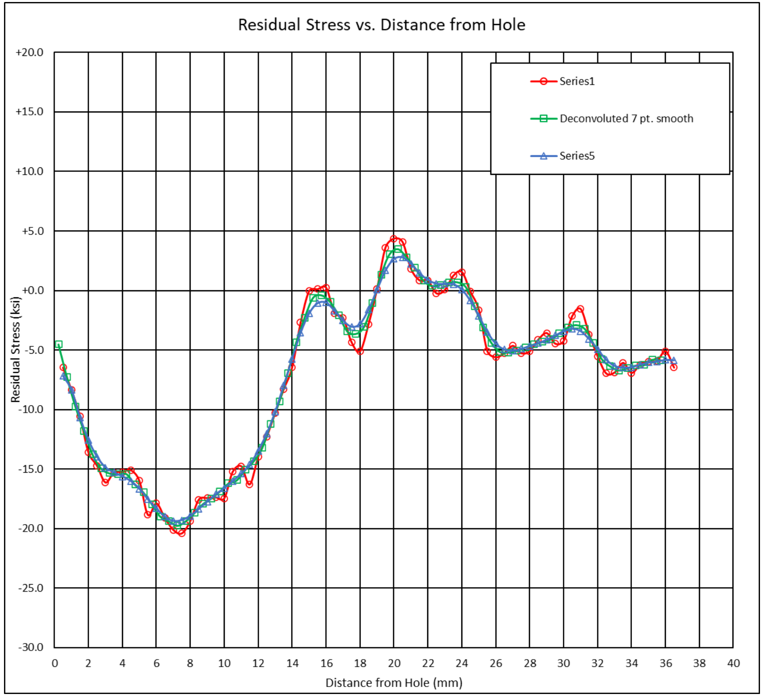


Padded Array Approach to Deconvolution

Entry 0.020” deep



Exit 0.020” deep



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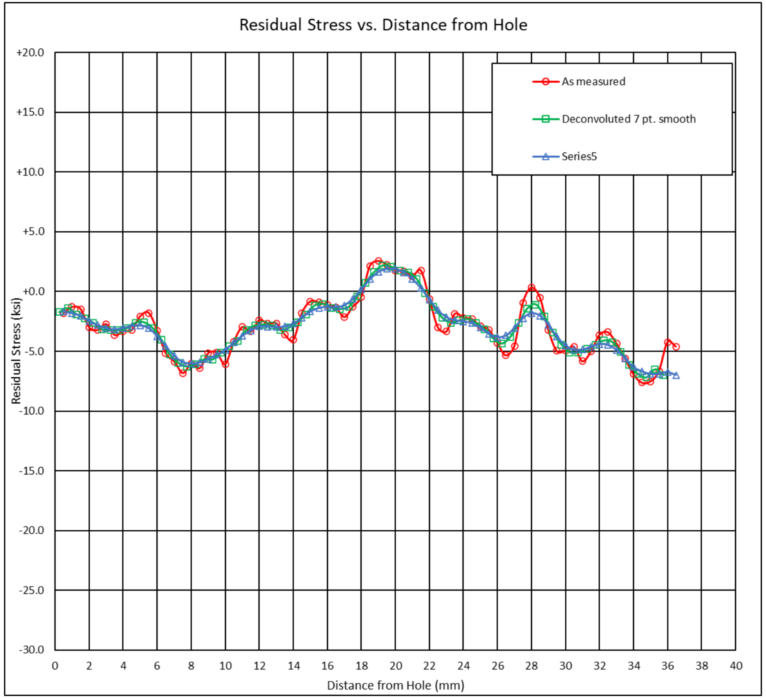
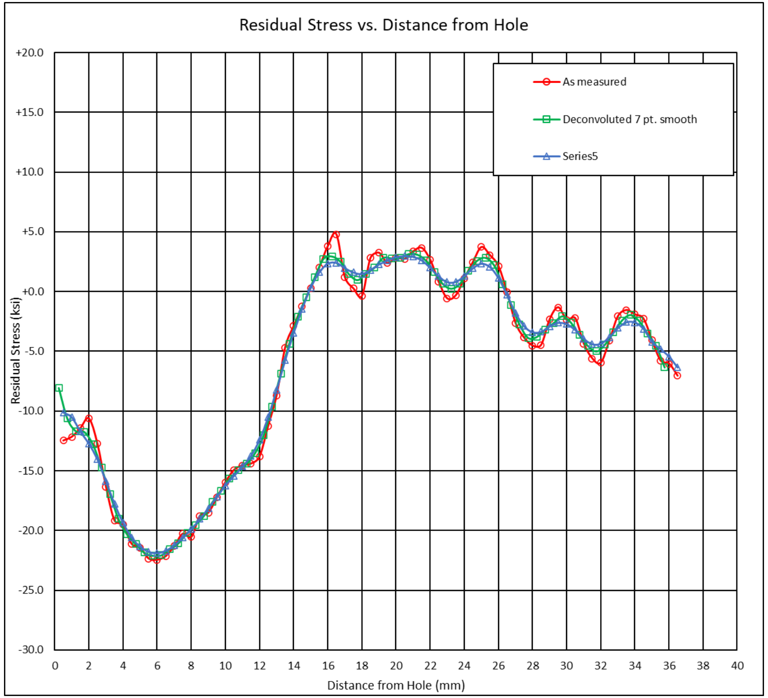
Padded Array Approach to Deconvolution

Entry 0.040" deep



Exit 0.040" deep



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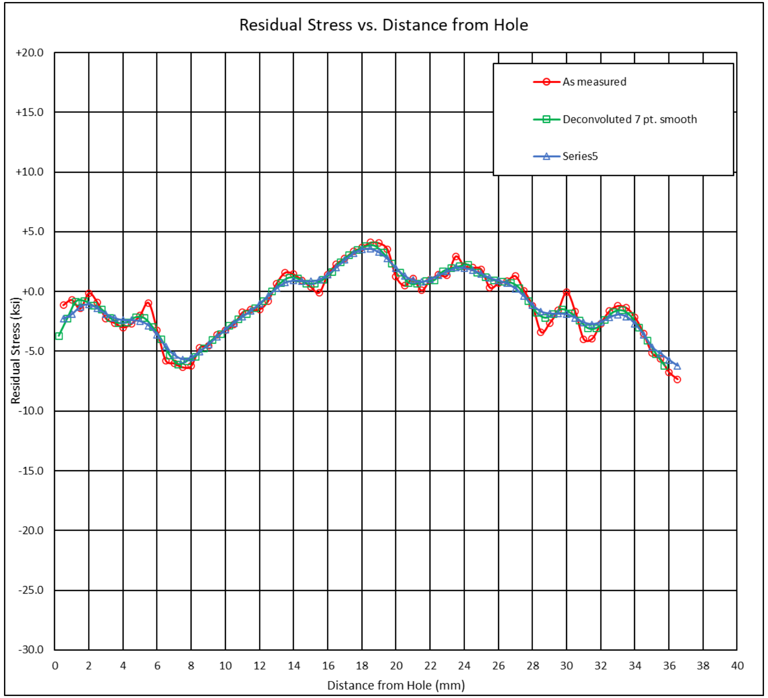
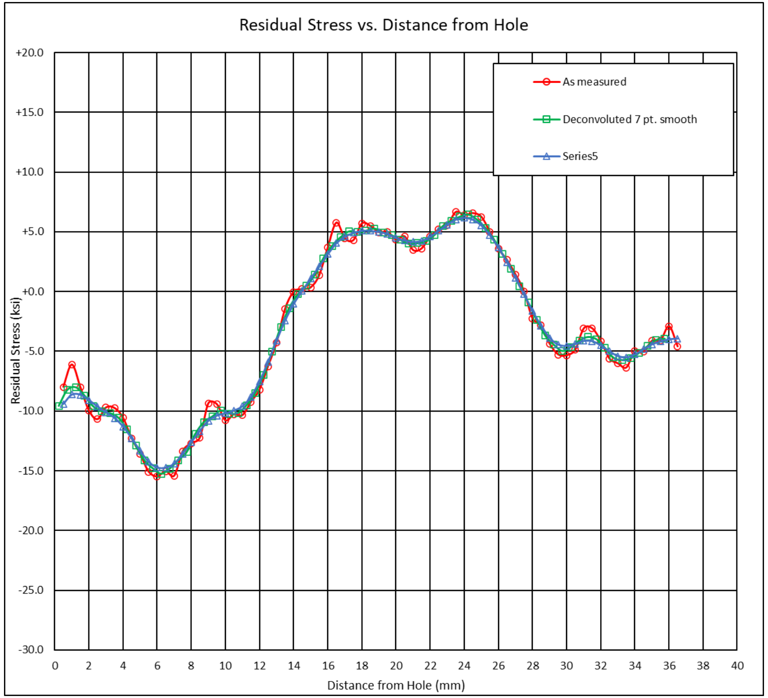
Padded Array Approach to Deconvolution

Entry 0.060” deep



Exit 0.060” deep



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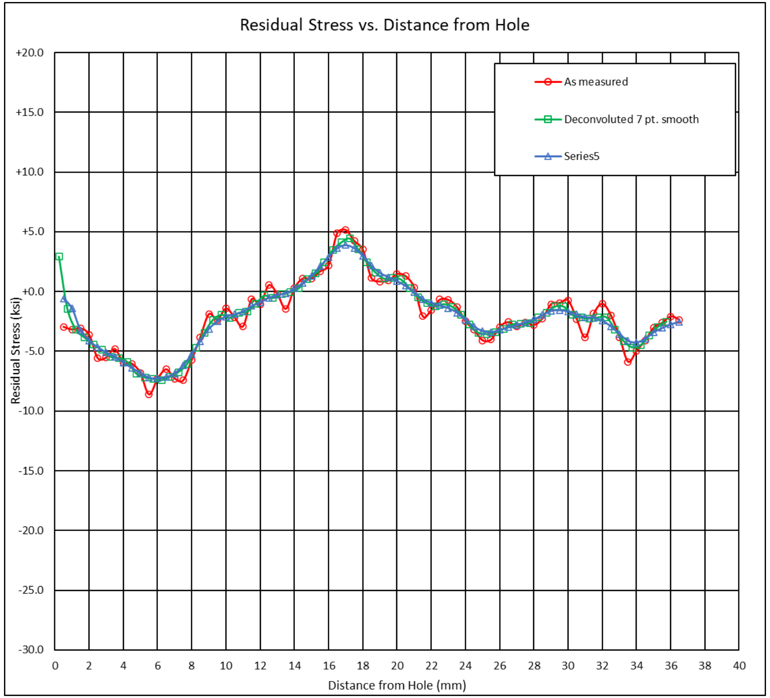
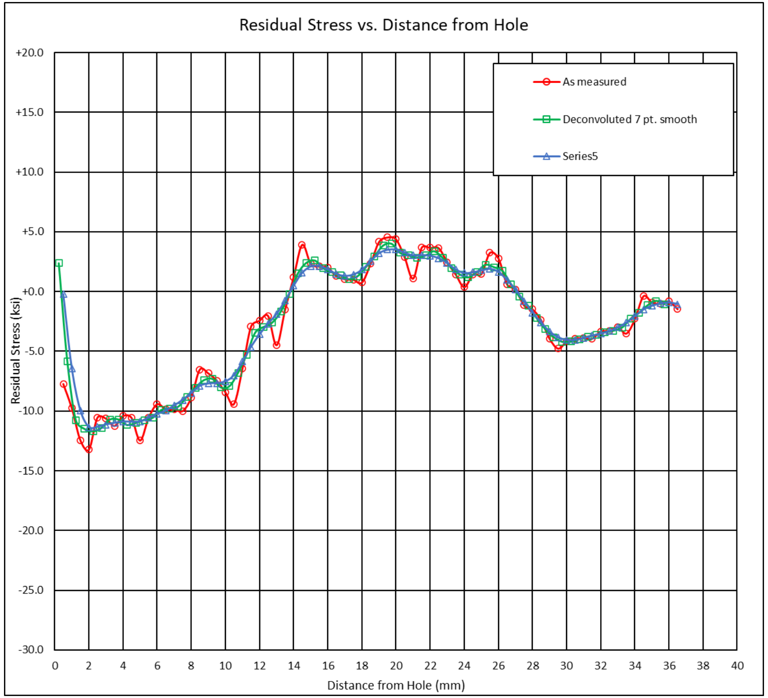
Padded Array Approach to Deconvolution

Entry 0.080" deep



Exit 0.080" deep



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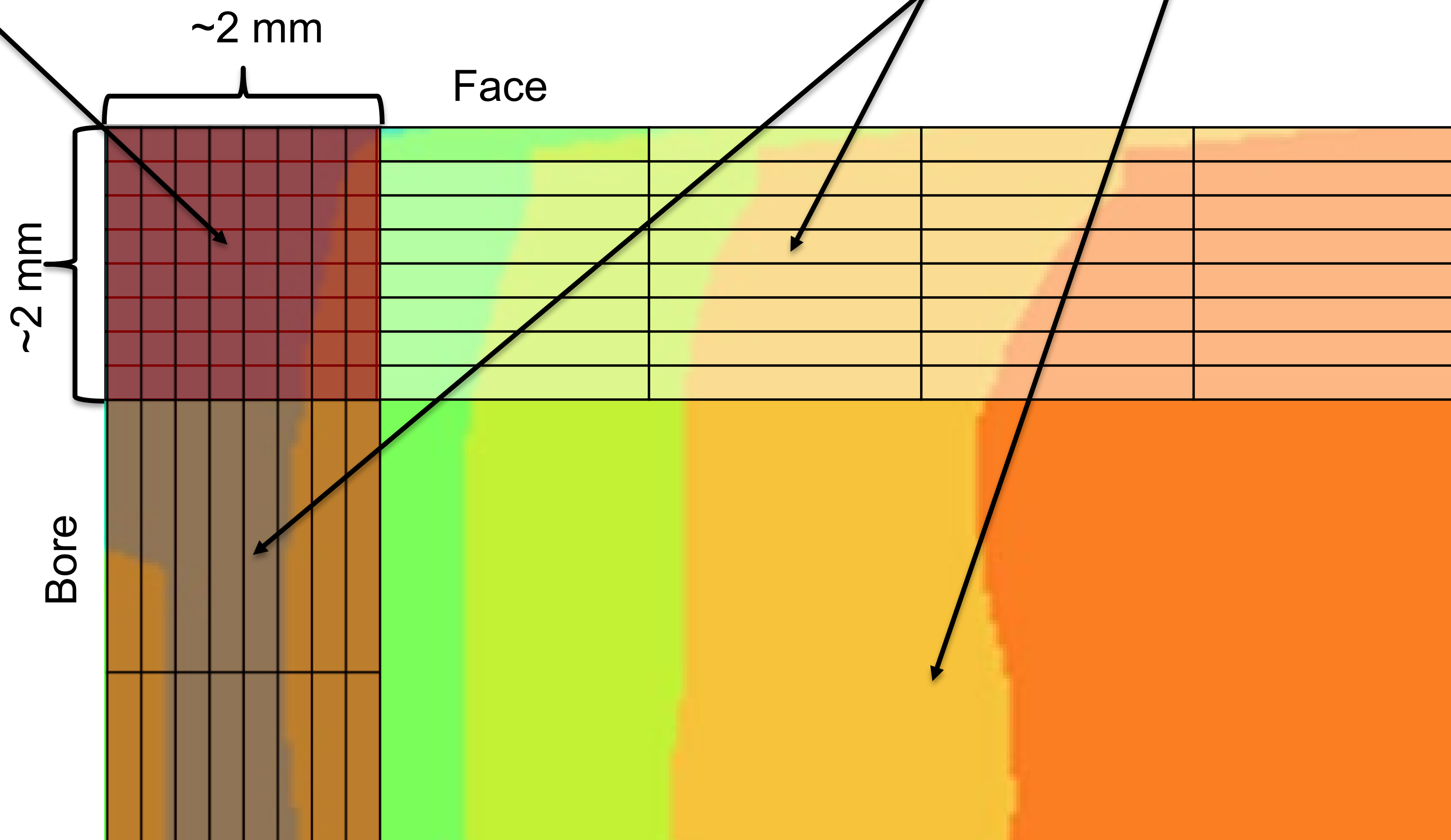
What Does Deconvolution Bring to the Table?

1) In this case a sampling region 0.5 mm vs. 2.0 mm wide
2) The potential to make this region smaller still (i.e. the 0.5 mm step selection was arbitrary).
3) Smaller regions translate into smaller step sizes which do translate into increased data collection time, but when data collection is automated, who cares?
4) There might be a limit to the minimum step size - what that limit would be is currently unknown?

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

Question: How do we merge XRD and Contour data?

Question: Might shed some light on micro-slitting results?



Summary

1) All XRD and Contour data have been collected on the GL coupon
2) Need to merge data sets – select mesh – interpolate where needed
3) Provide data with GL coupon geometry & latest corner crack loading to FCG model predictions folks (blind study).
4) After blind predictions are made, compare FCG predictions to known corner crack loading FCG rates for the GL coupon configuration and loading.
5) 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 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 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 potential but needs to be further investigated (i.e. the blind study that comes at the end).

Thank you

Review of 2inch Cx “Standard” Residual Stress Coupon Program

2025 ERSI Workshop – Layton, UT

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Co-Authors Include:
James Pineault (Lockheed Martin)
Sanjoo Paddea (StressSpace, Ltd.)
Dave Backman (NRC-Canada)

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2inch Cx Project Overview

- 2024-T351 & 7075-T651 0.25inch Thick Aluminum Plate
  - 0.25inch thick
  - 0.50inch diameter hole
  - 2inch wide
- Coupons Cxed Using Split Sleeve Cold Expansion (SsCx™) To[illegible] M of the Applied Expansion Range per the FTI Spec
  - 3.2% and 4.2%
  - High precision starting hole size
- One Set of Each Condition was Final Reamed for Future Use as a “Standard”
- During the Cx Process Surface Strain Measurements were Taken in ”Real-Time”
  - Strain gauges installed – Installed by FTI
  - LUNA Fiber optical strain gauge – Installed and monitored by Clarkson University
  - Digital Image Correlation – Installed and monitored by SwRI
- <u>Machined “New” Set of 2inch Cx Coupons Following Identical Manufacturing Process</u>
  - <u>No RS methods applied during the Cx process</u>
  - <u>New coupons will be final reamed to 0.50inc final diameter</u>

History of Program

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

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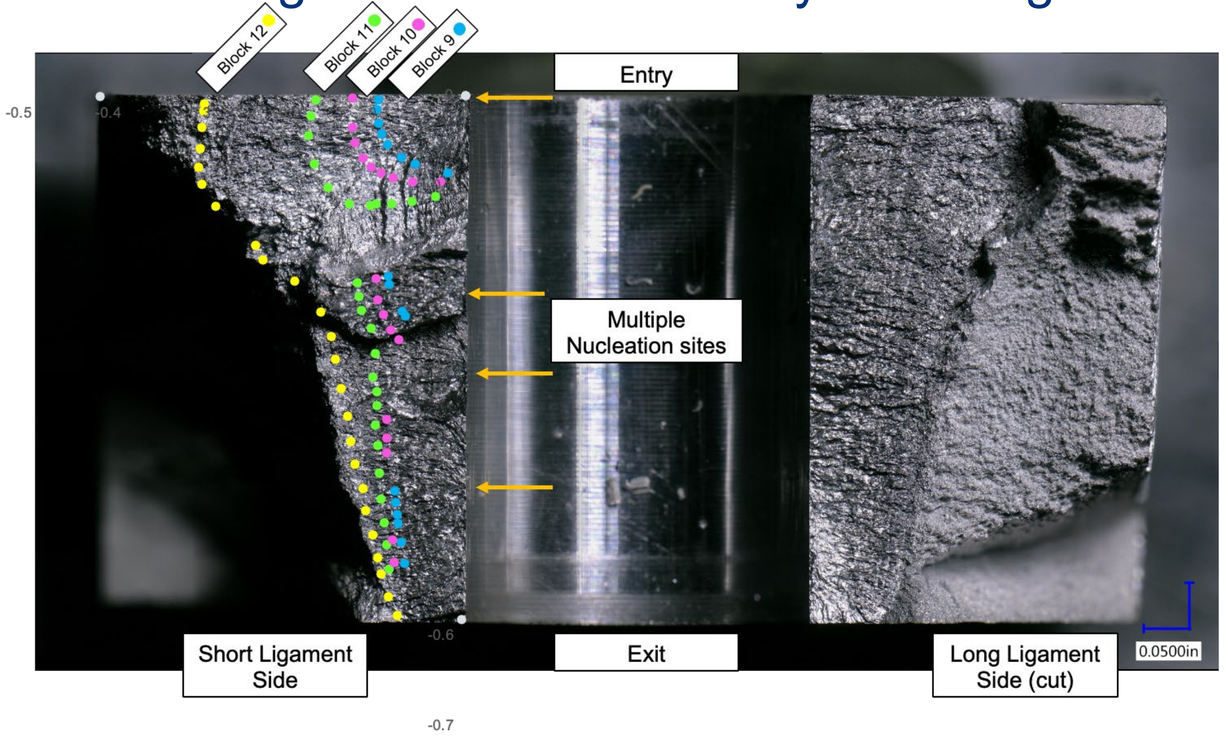
State of Program

- 2024 Began work on in-bore XRD work at Proto – Started with 2024-L2
  - Will be presented today
- 2024 Performed In-Bore Incremental Hole Drilling (IHD) on 2024-H1 Coupon
- 2024 Began “Near-bore” DIC Work with NRC
- 2024 Created another set of 2inch Cx “High” and “Low” Coupons from same lot of material – Used exact same Cx process per drawings in 2016
- 2025 Performed Surface XRD on Set of Original Reamed Coupons
- 2025 Performing Final Ream on New Set of Test Coupons – Will have 3 sets of final reamed coupons in “High” and “Low” applied expansion levels
- 2025 Plan to Perform Surface XRD on “New” Final Reamed Sets
- 2025 Plan to Perform Contour Method on Both Sets of Final Reamed Coupons
- 2025-2026 Develop Residual Stress Condition to Provide Analysis Group to Compared to Test Data in “Low” Applied Expansion (APES Testing Work)
- 2024-2026 Working with Danish Technical Institute (DTI) to Develop Robust ED-XRD and ND Methods for Near-Bore RS Data
  - Starting point will be 2inch Cx “Standard” Coupons in 2024-T351 and 7075-T651

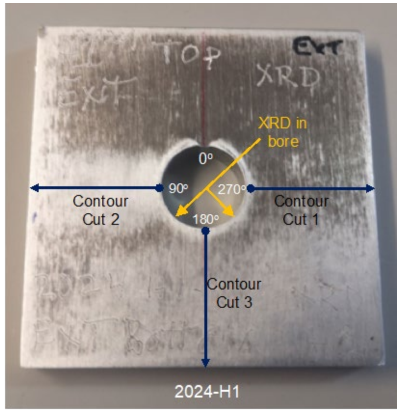
Updates from 2inch Cx ”Standards”

- RS Characterization Committee Continues to See “Near-Bore” Residual Stresses to be Critical to Capture the Initial Cracking Phase and Thus Total Life
  - No single RS characterization method can provide the “full picture” of the RS state
- Naturally Occurring Cracks in SsCx Holes Form “Quickly” then Slam on the Brakes
  - Community needs to move towards testing with naturally occurring cracks and not EDM notches
  - Many struggles come from validating models with naturally occurring cracks – we need to though!



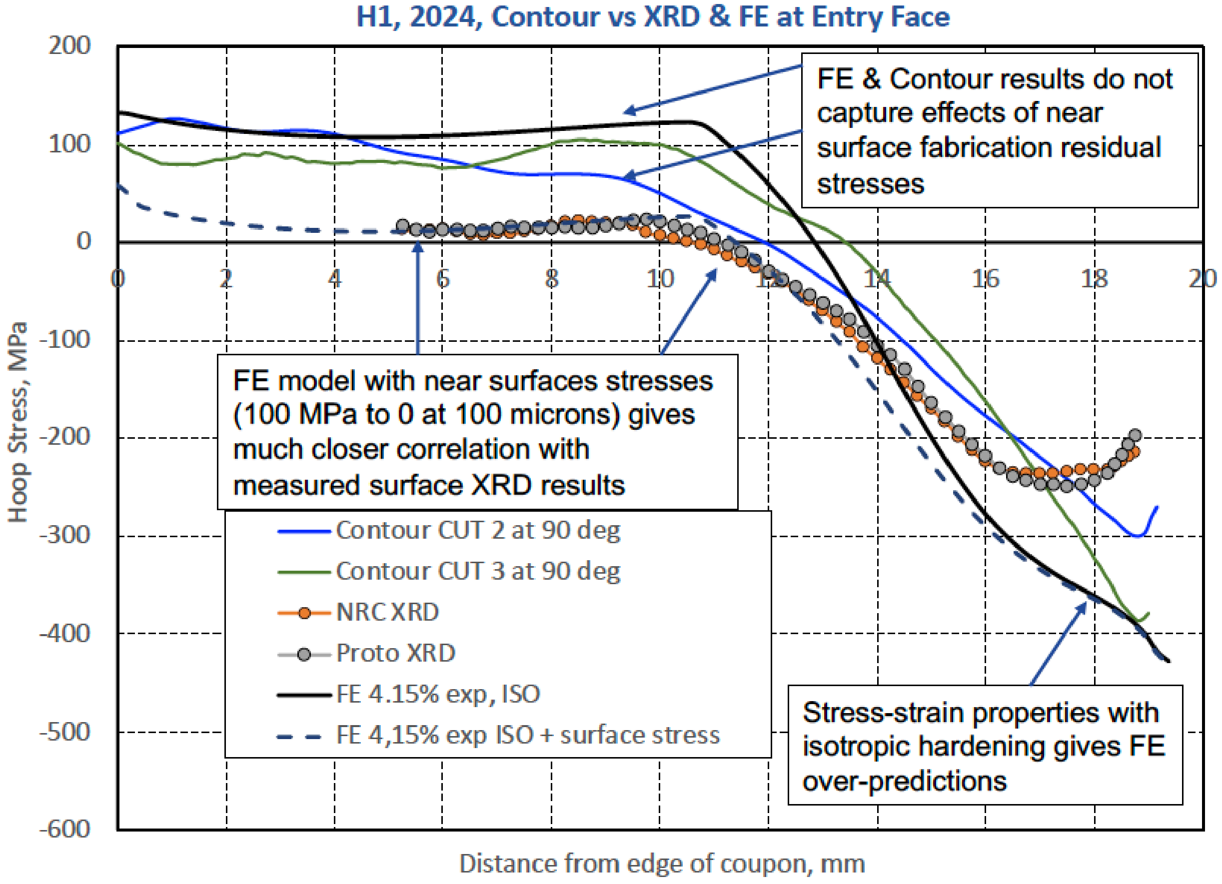
Lessons We're Learning

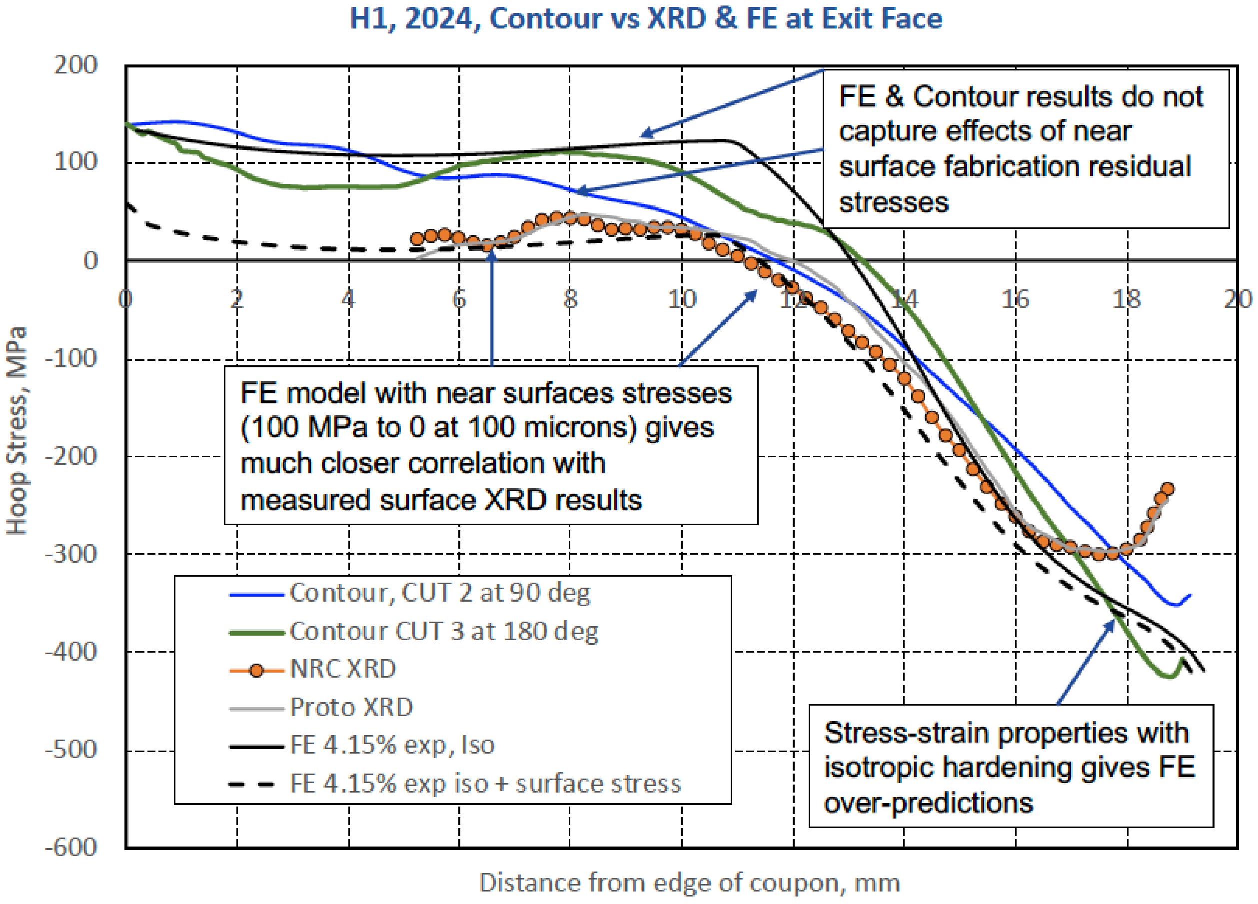
- Near-Bore DIC is Showing Us New Things!
  - XRD, ED-XRD, Neutron Diff., Contour Method all assumed the RS field was symmetric around the hole, except for at the "split"
    - XRD rotates the coupon to capture enough grains, same with ED-XRD, Neutron
    - Contour cuts have assumed that due to cutting 1 side has less error
      - Idea was to cut 3 and 9 O'clock and then have a "stress-free" cut at 6 O'clock and that would be most accurate



Initial Method for Combining RS Data

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





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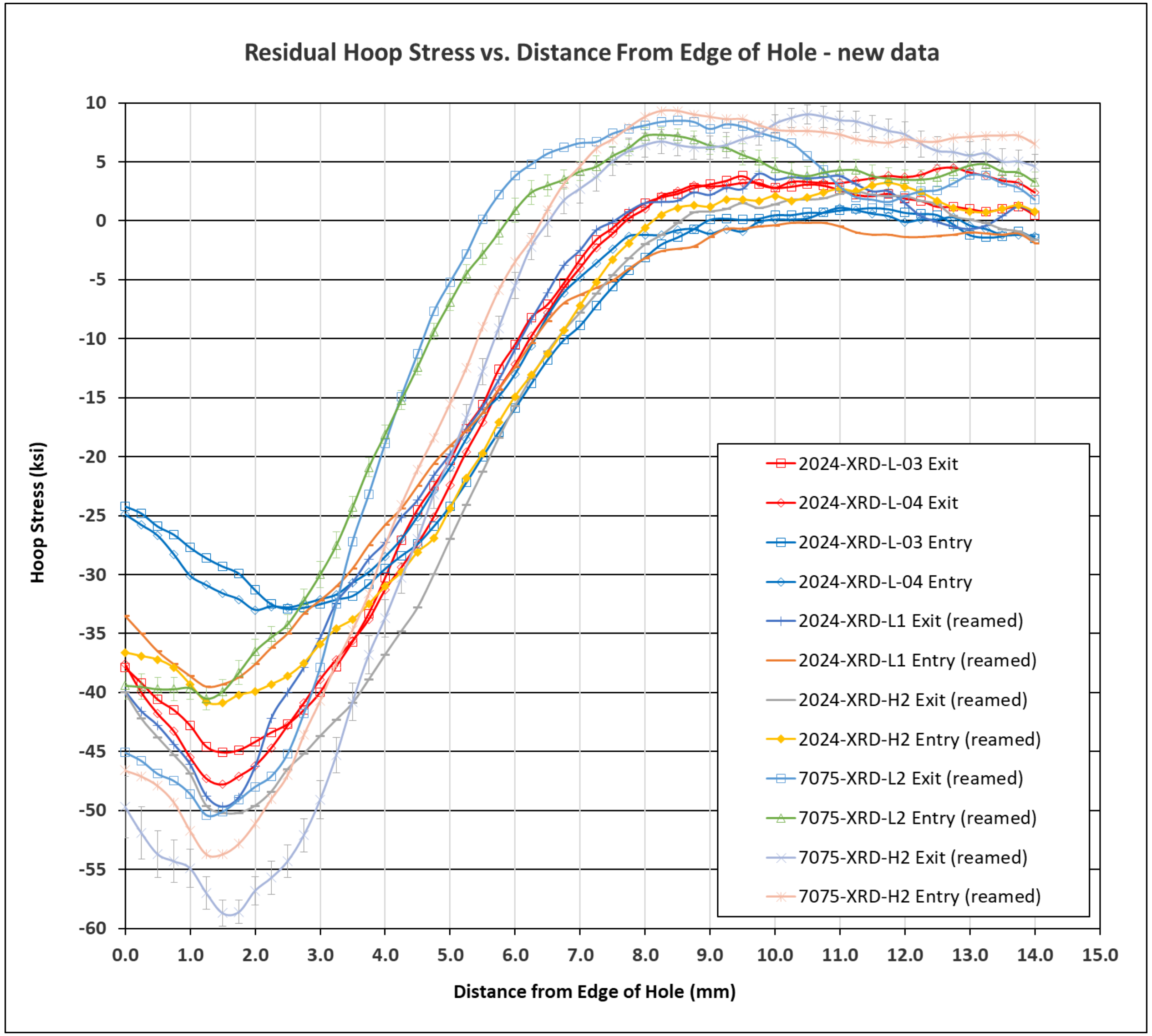
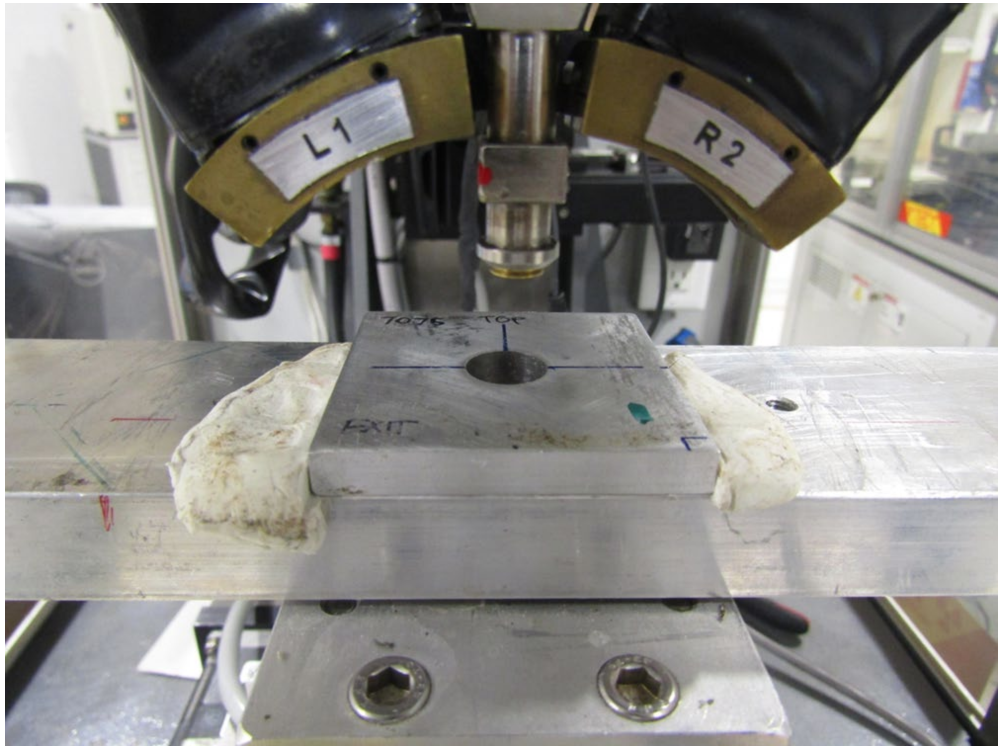
RS on surface faces of 2x2 Coupons new data for 2024-T351 and 7075-T651

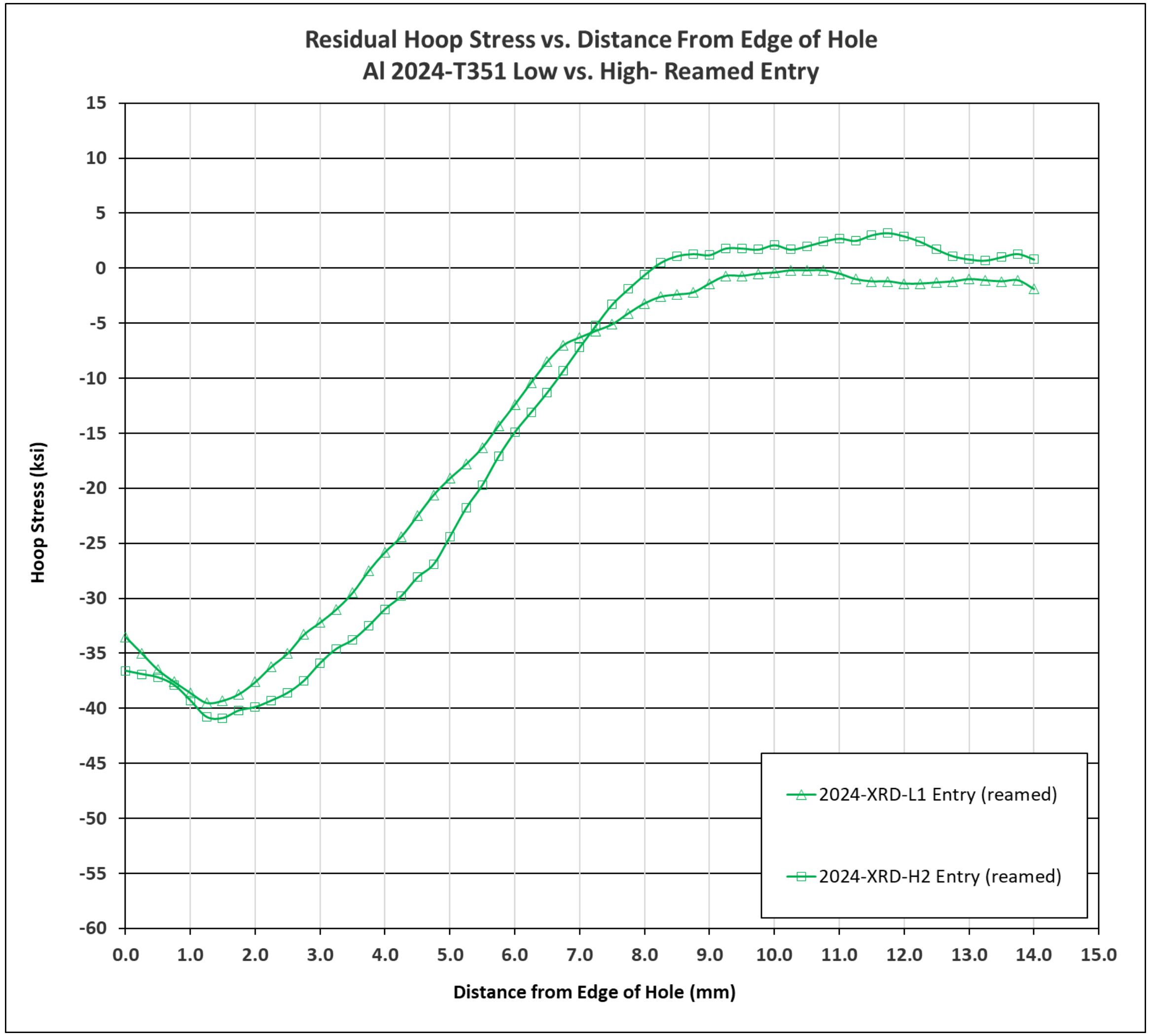


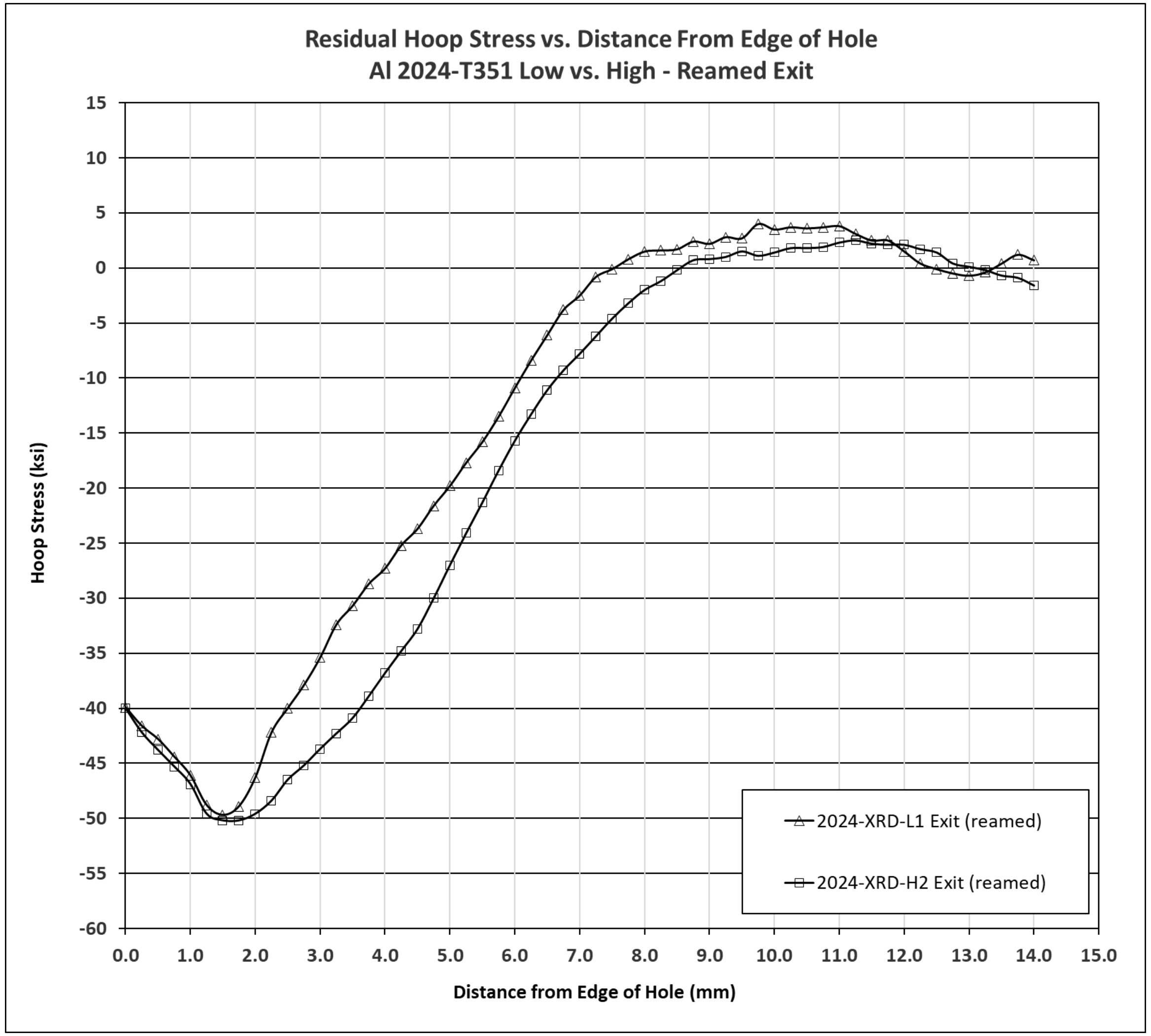


Note: Holes are "Un-reamed" unless specified as "(reamed)" in plot legends.

Low Cx vs. High Cx (Reamed Condition)

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





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X-RAY DIFFRACTION

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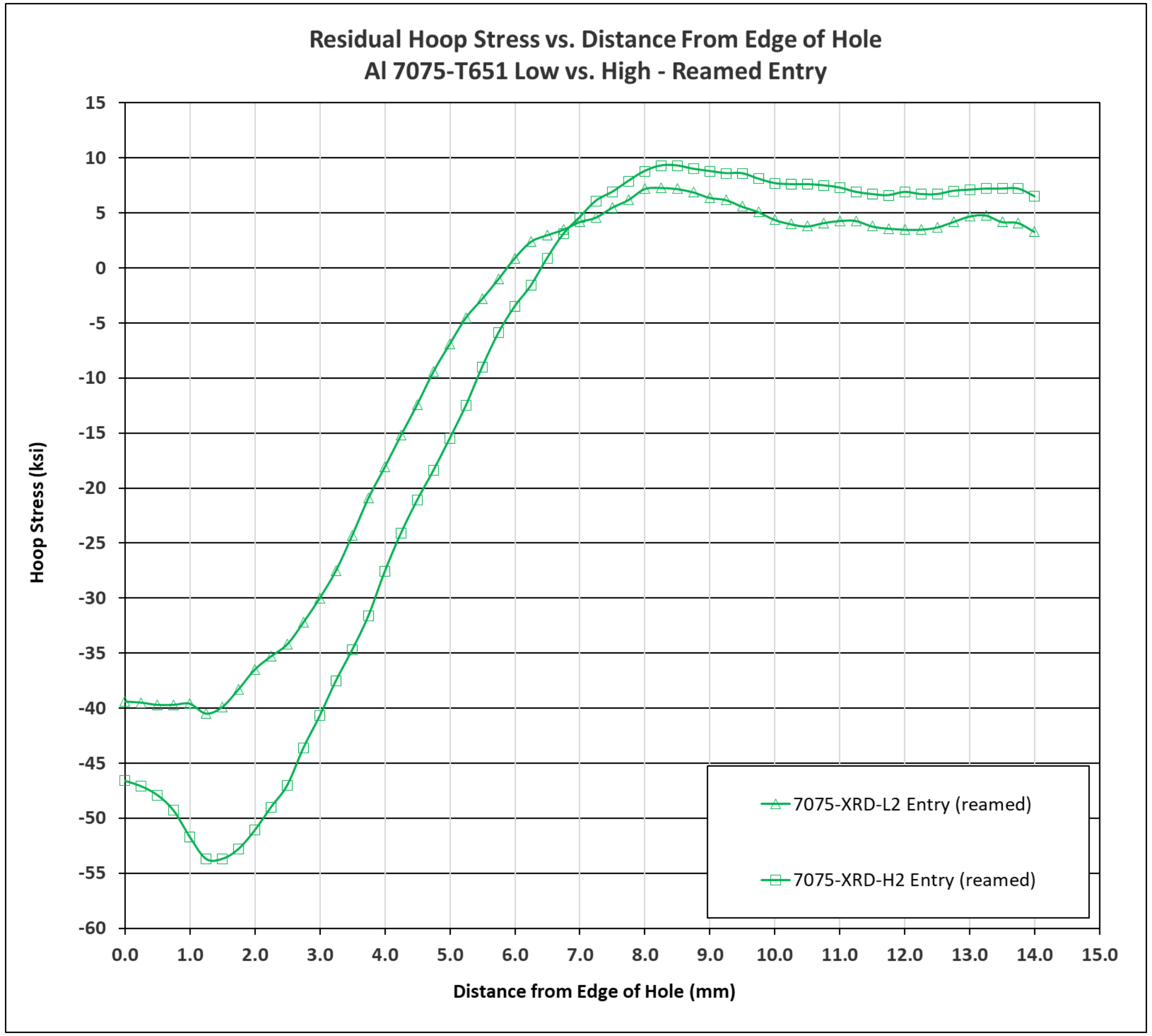
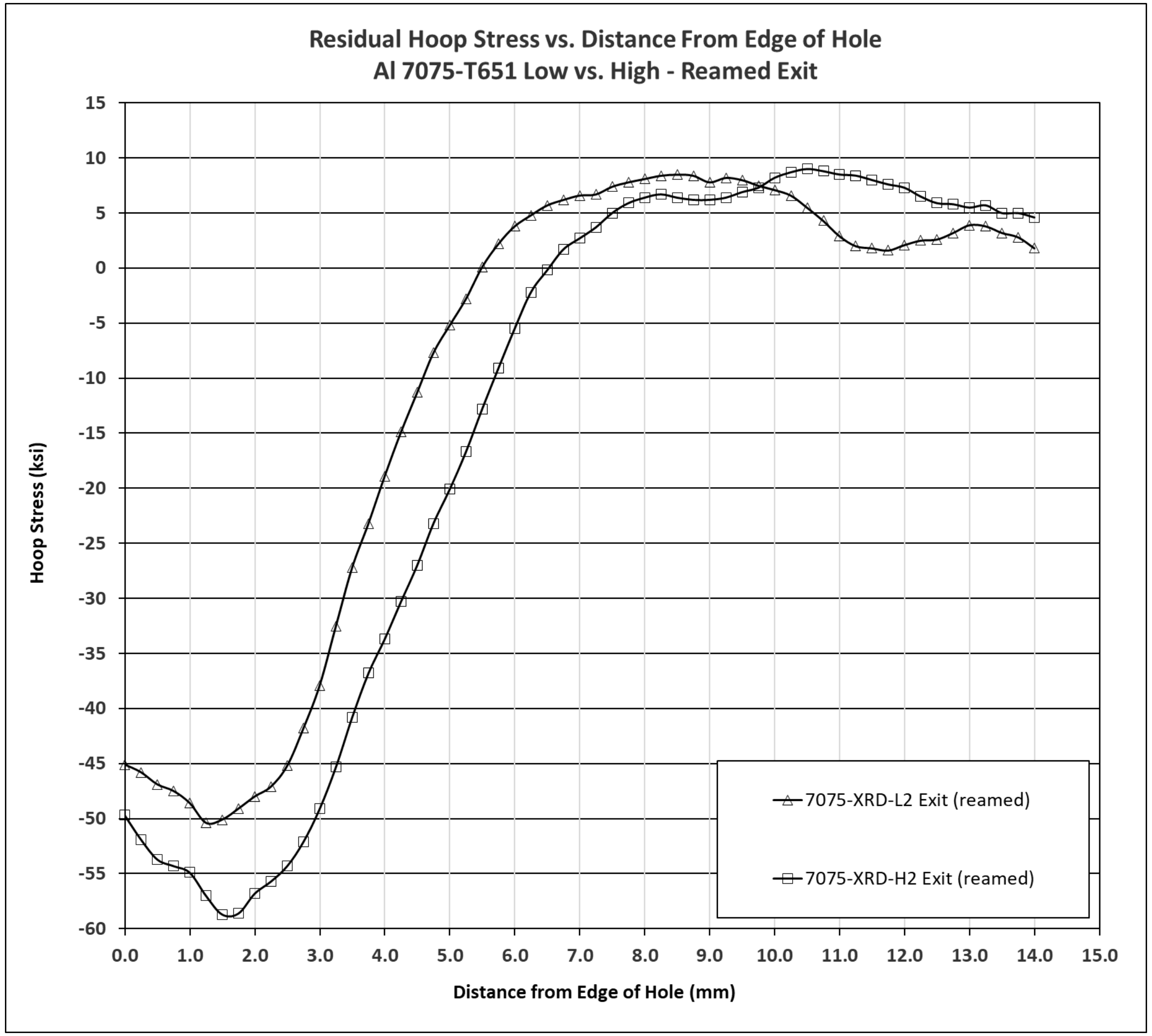
Al 7075-T651 (Reamed) – Low Cx vs. High Cx





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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 - Expected? Anyone? Buehler?

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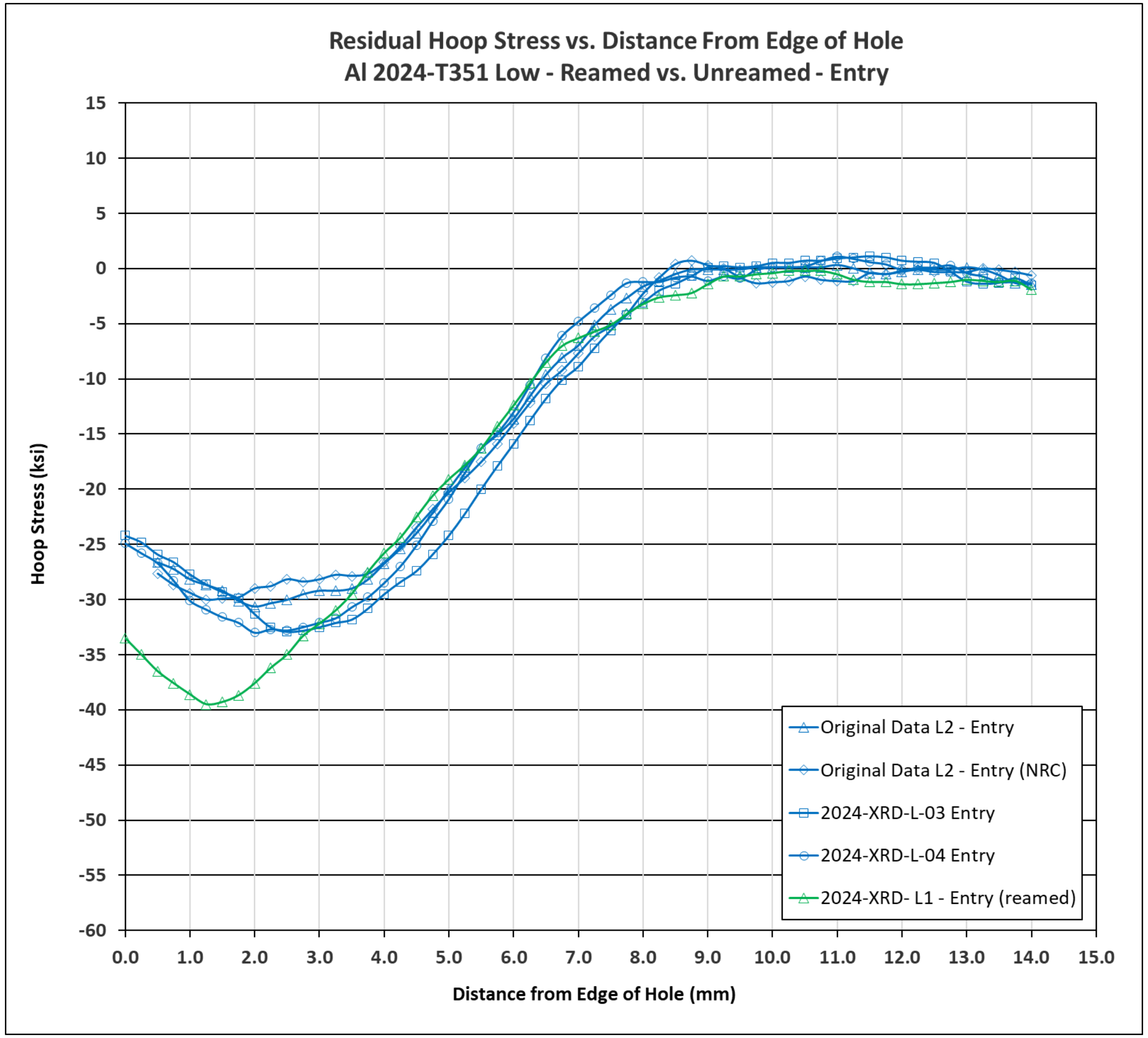
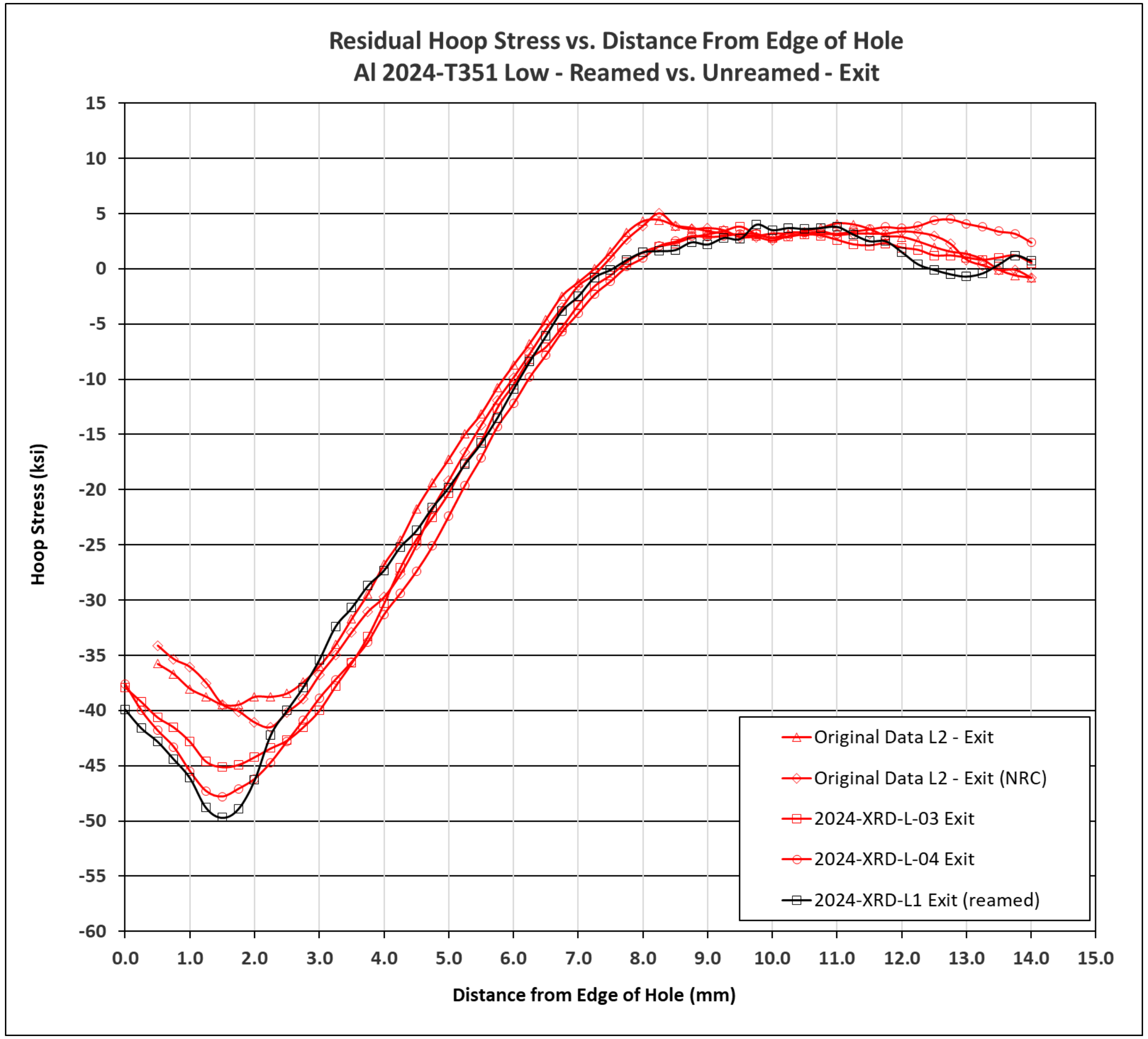
Reamed vs. Un-reamed
(Low and High Cx Conditions)

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





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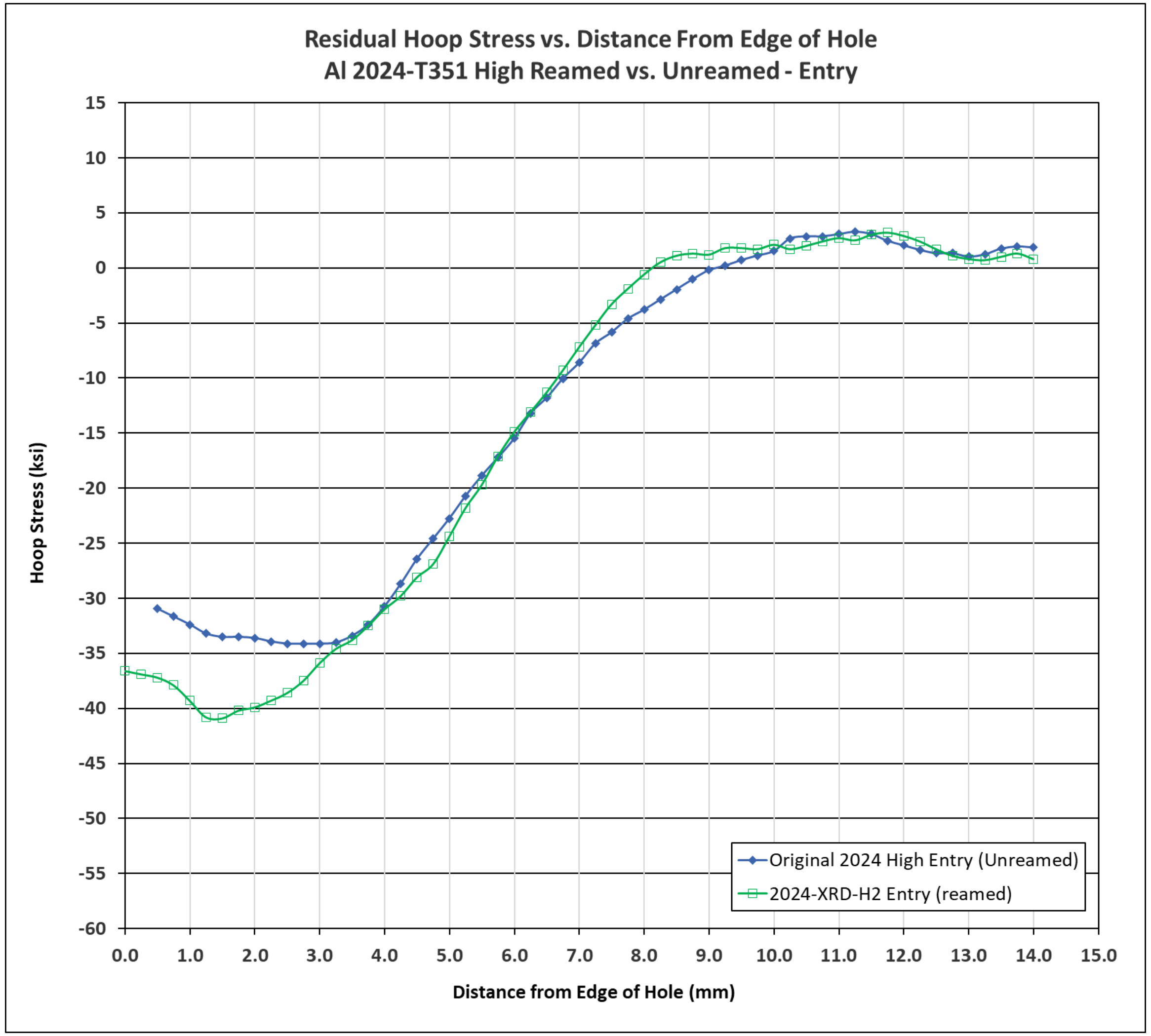
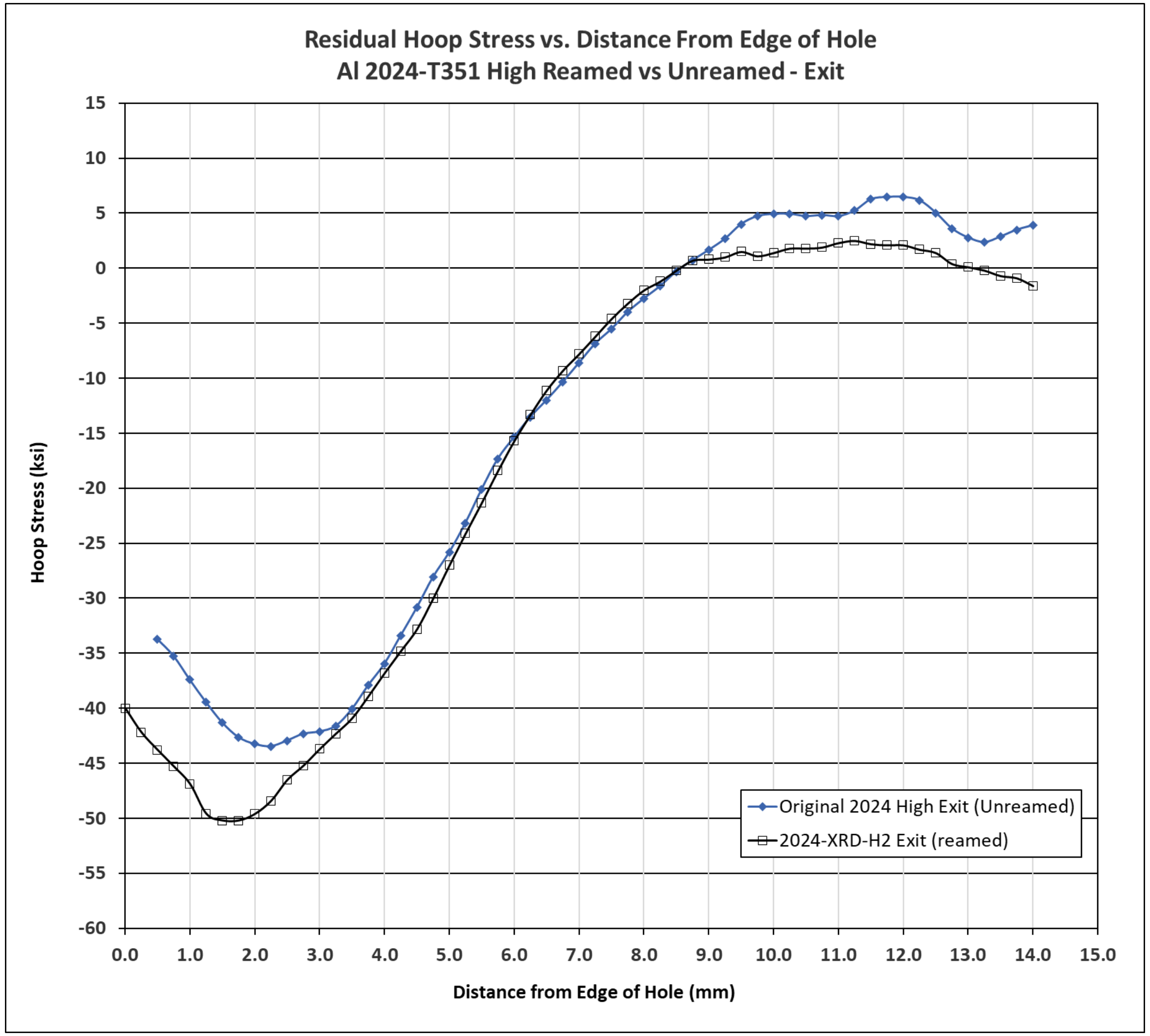
Al 2024-T351 High Cx - Reamed vs. Un-reamed





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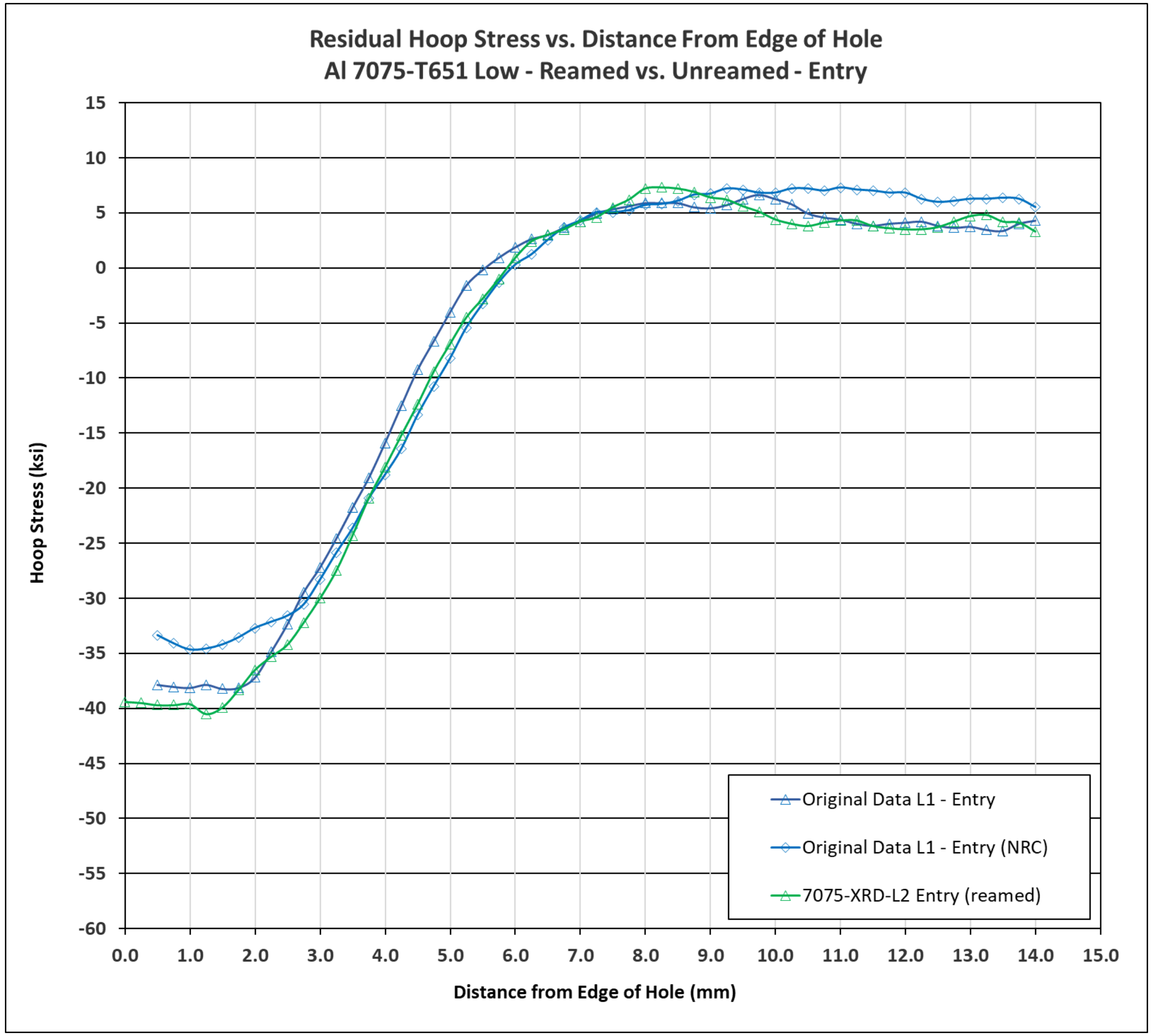
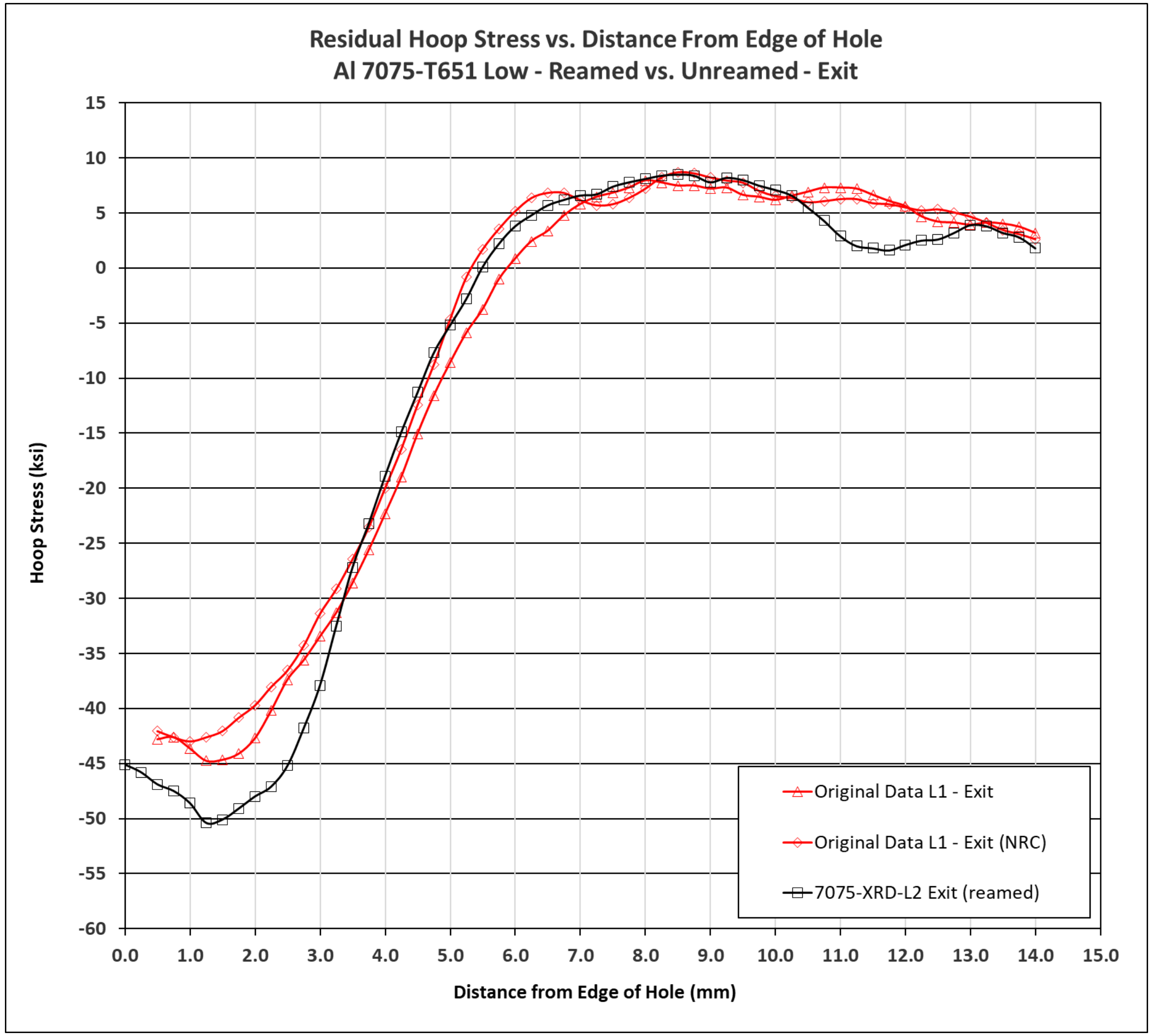
Al 7075-T651 Low Cx- Reamed vs. Un-reamed





PROTO X-RAY DIFFRACTION

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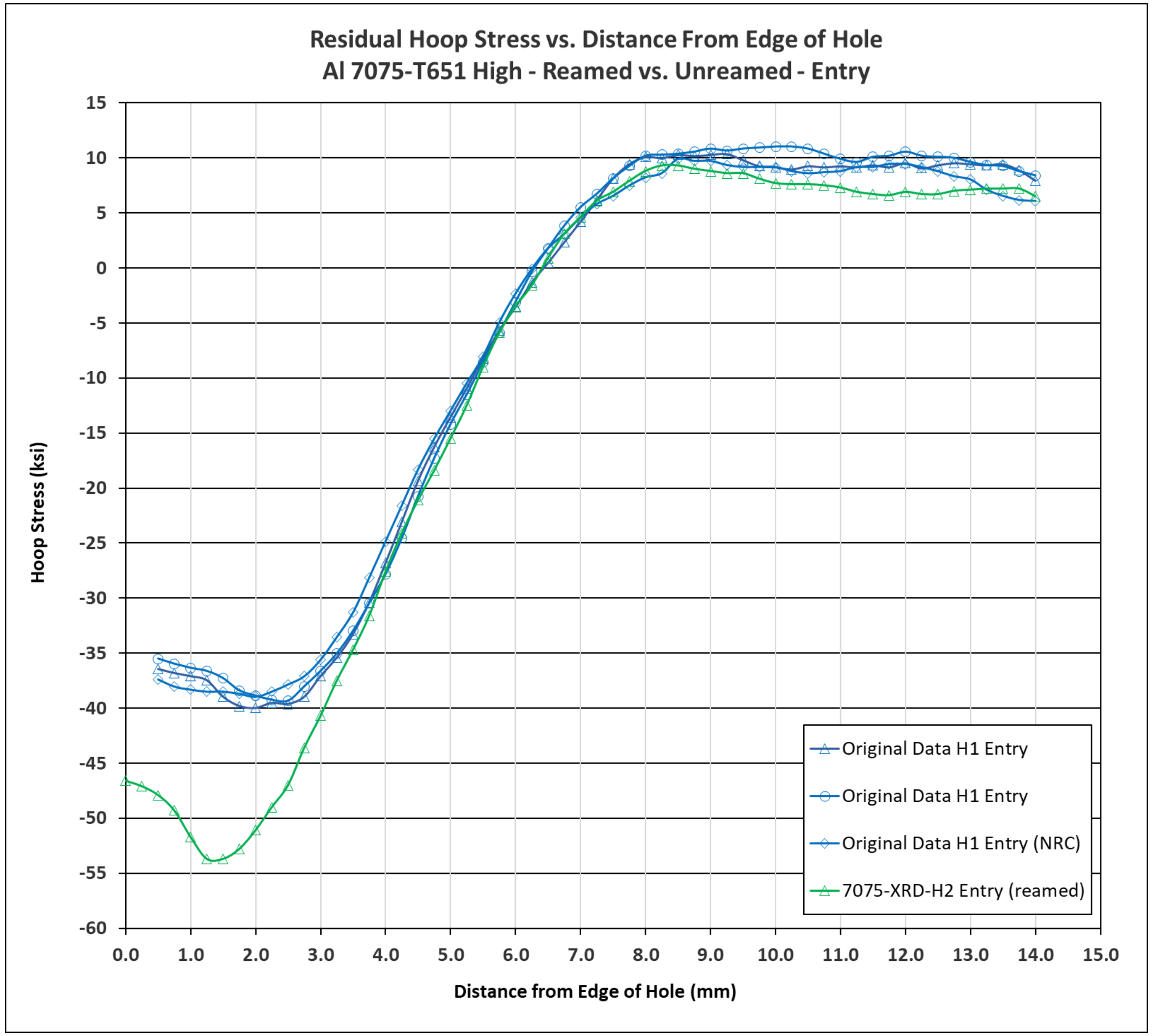
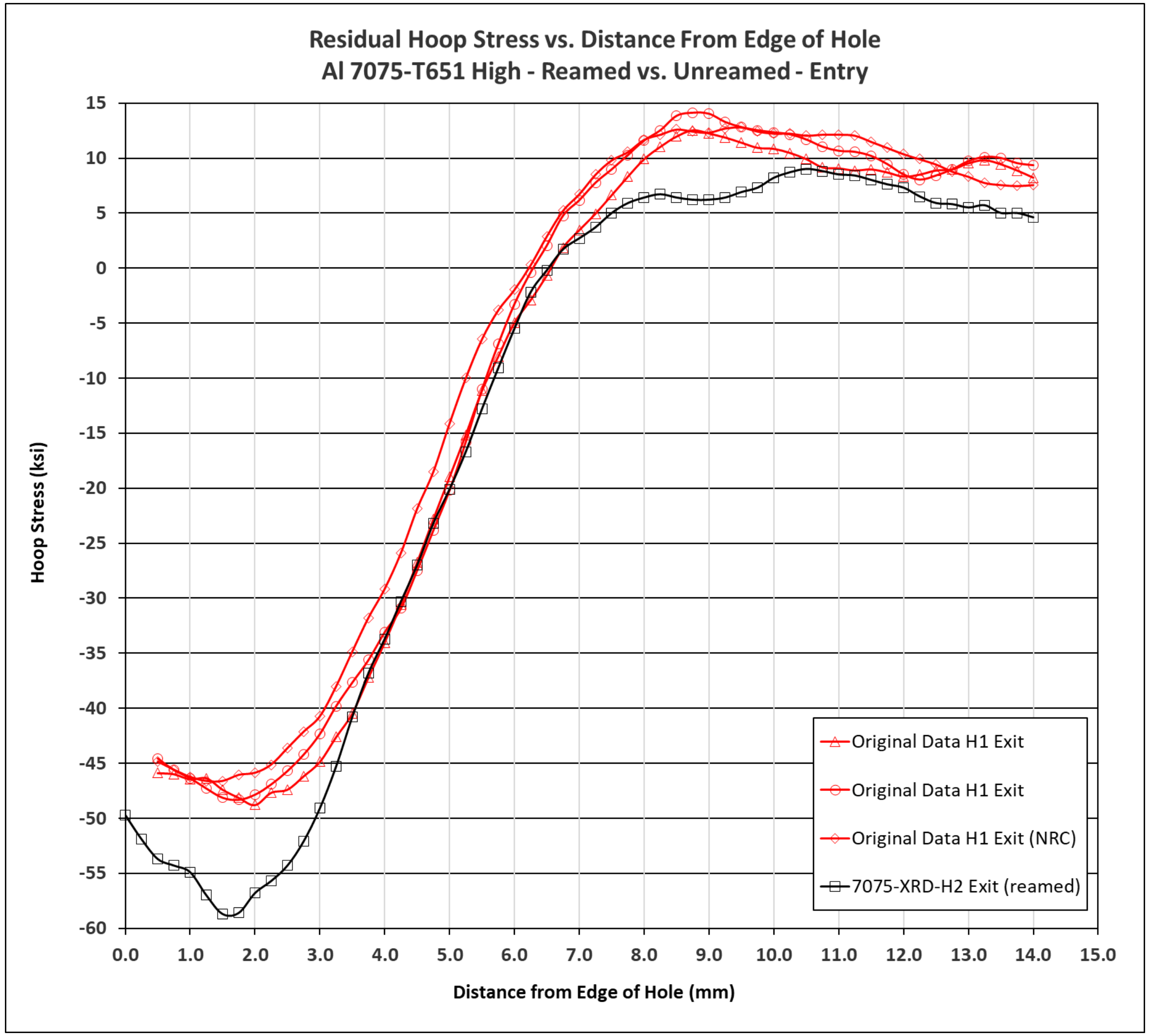
Al 2024-T351 Low & High Cx - Reamed vs. Un-reamed





PROTO X-RAY DIFFRACTION

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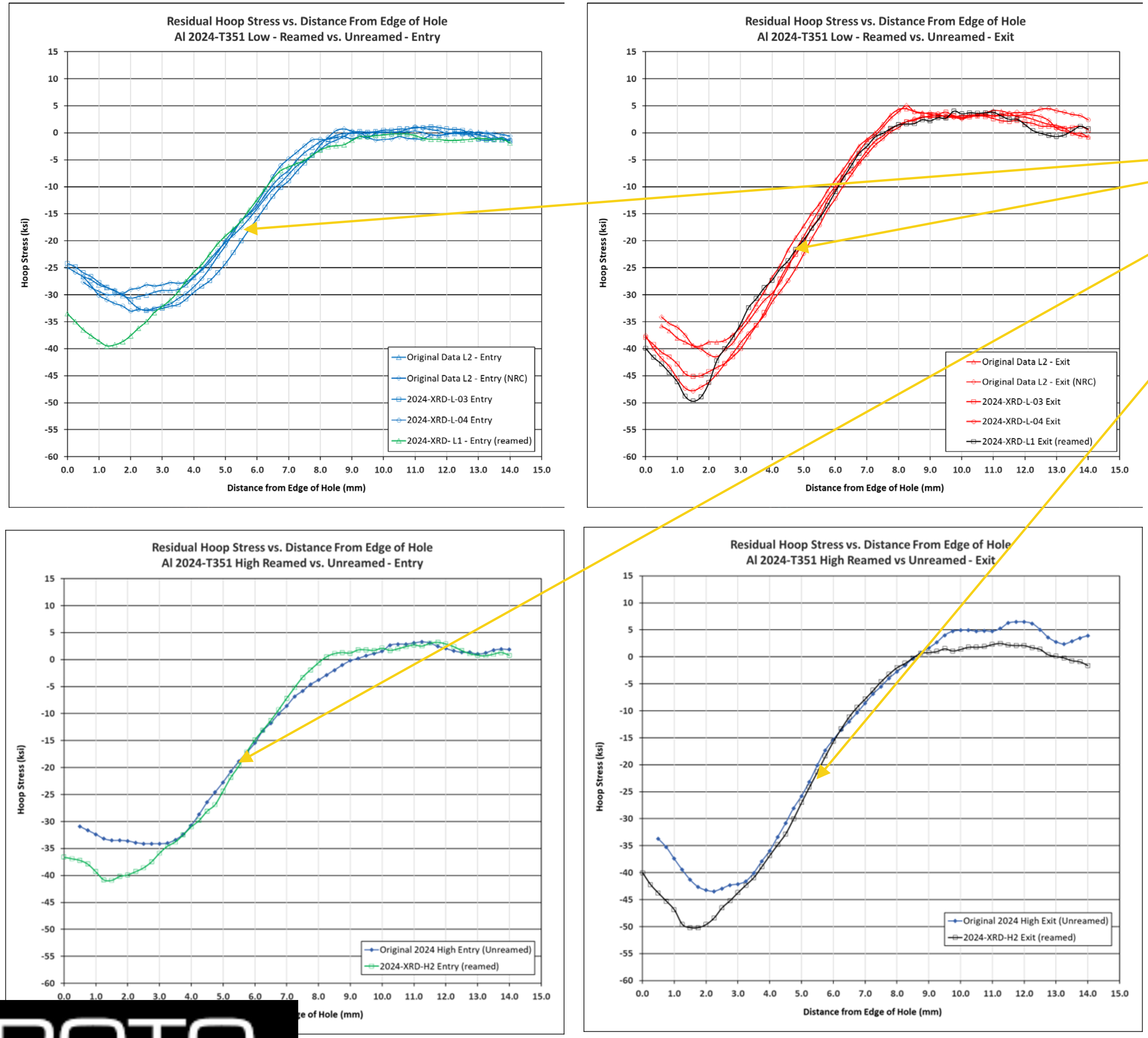
Al 2024-T351 Low & High Cx - Reamed vs. Un-reamed



Reaming has a small effect on persistence of compressive field with increasing distance from the hole

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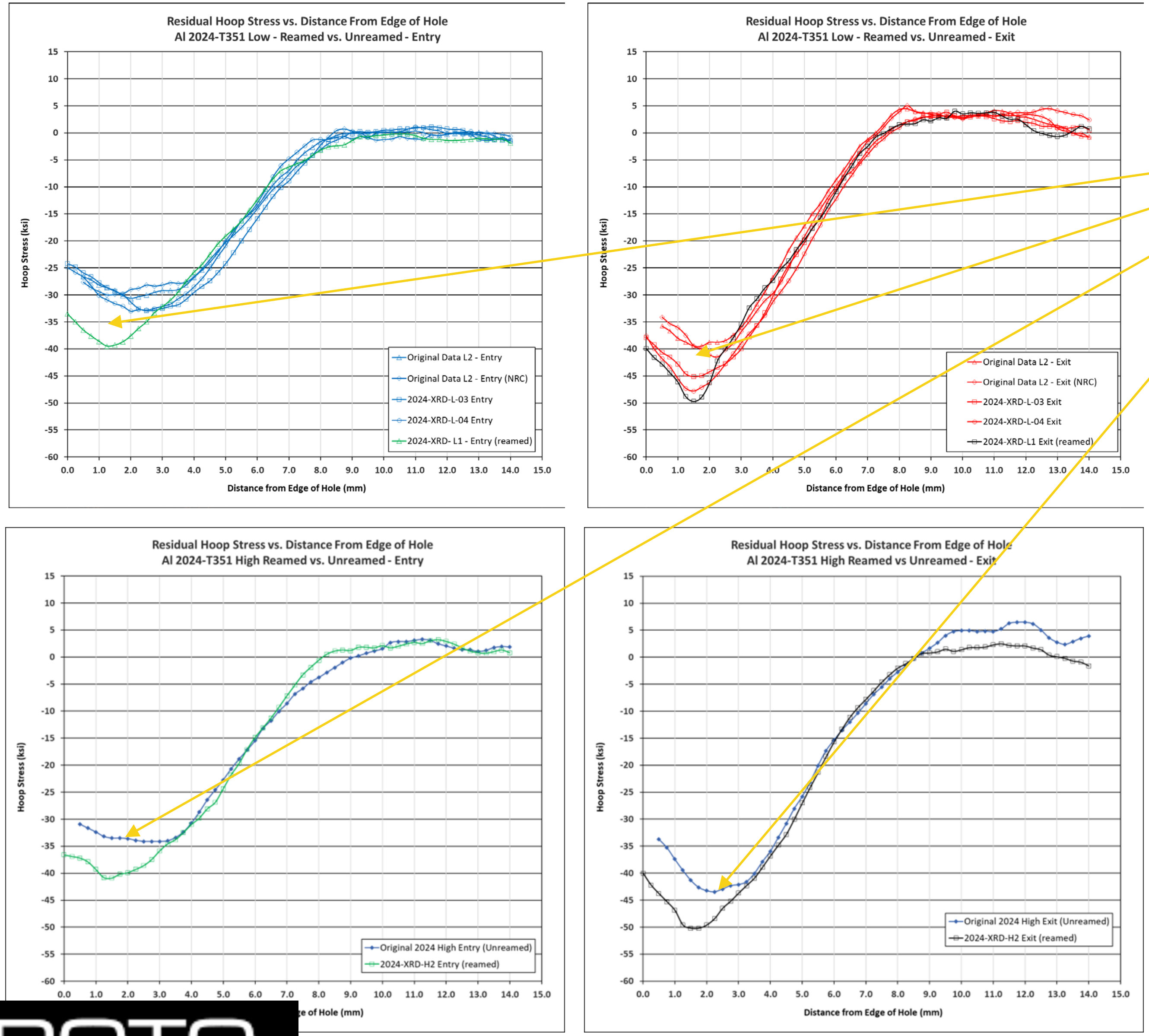
Al 2024-T351 Low & High Cx - Reamed vs. Un-reamed



Effect of Reaming more localized to edge of hole – results in increased compressive RS maxima

PROTO X-RAY DIFFRACTION

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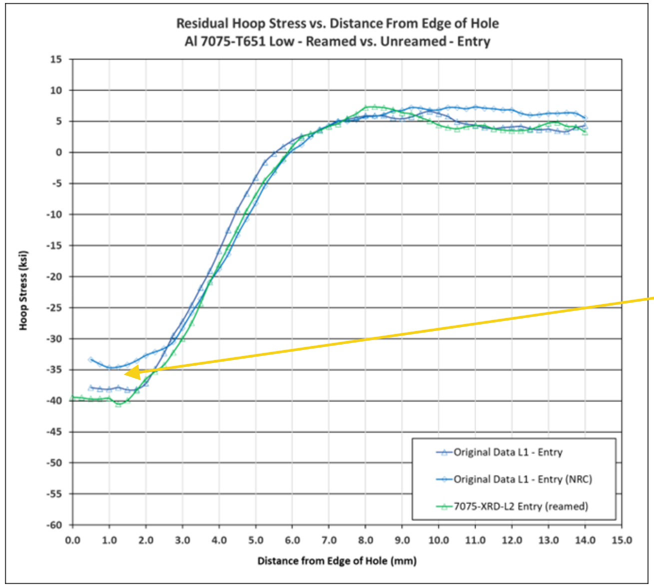
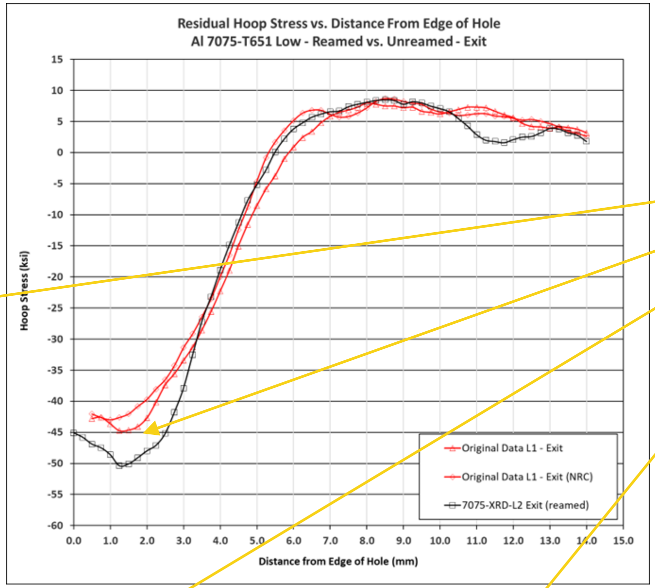
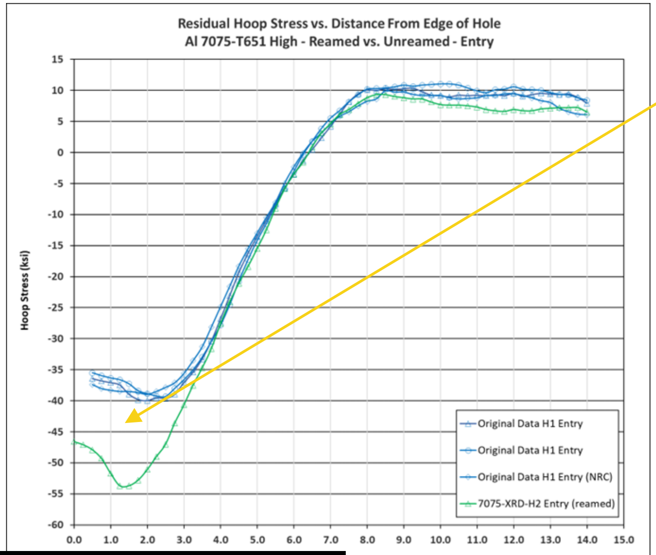
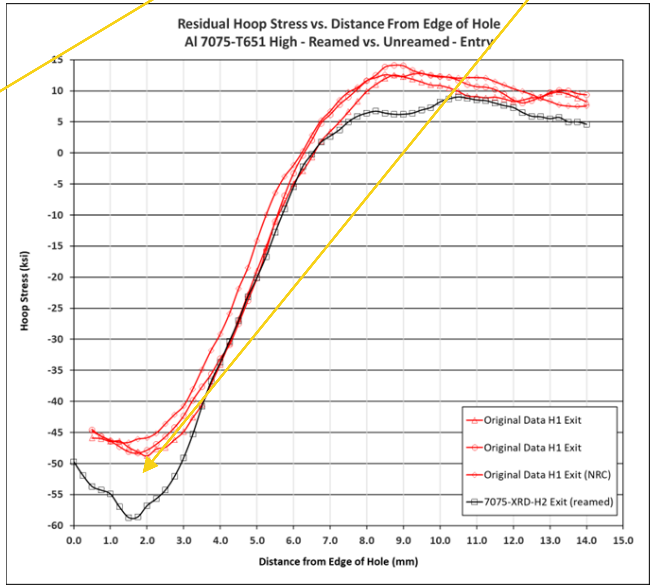
Al 7075-T651 Low & High Cx - Reamed vs. Un-reamed









Effect of Reaming more localized to edge of hole – results in increased compressive RS maxima

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Discussion

Reaming has a small effect on persistence of compressive field with increasing distance from the hole.

Effect of Reaming more localized to edge of hole – results in increased compressive RS maxima.

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.

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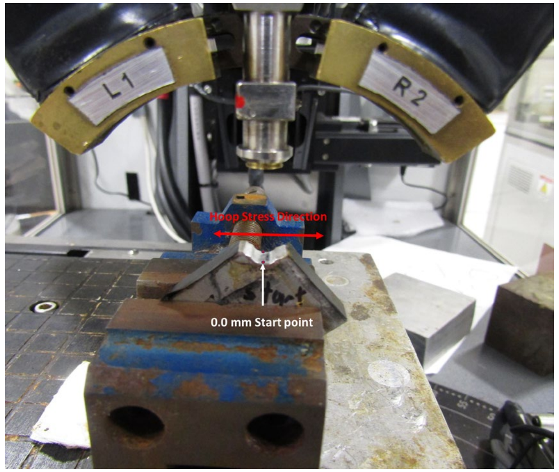
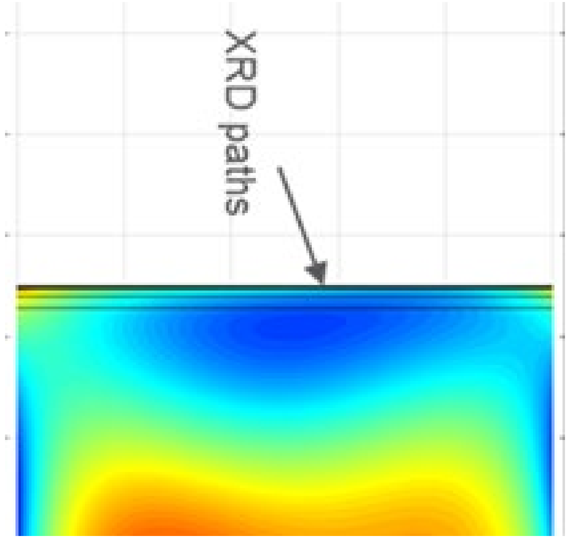
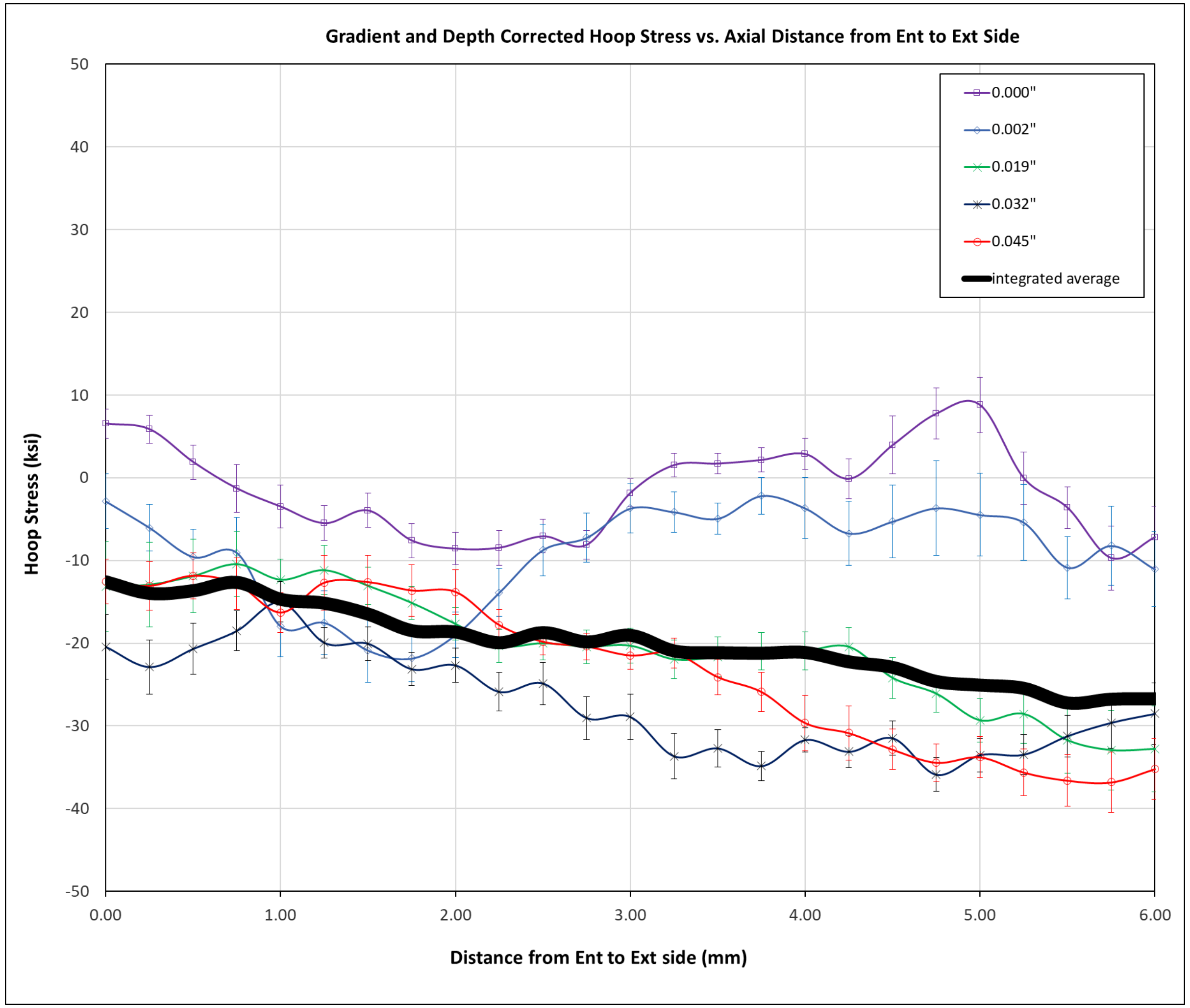
RS in Bore of 2 x 2 Cx Hole – 2024-T351 High (Un-reamed)

- Feasibility of bore RS measurements on 2x2 coupons
- XRD profiles across the bore from Entry to Exit
- Electropolish entire layer and repeat
- Results must be corrected for bending due to contour cut
- Integrated average over 0.045” should correlate with ~1mm sampling







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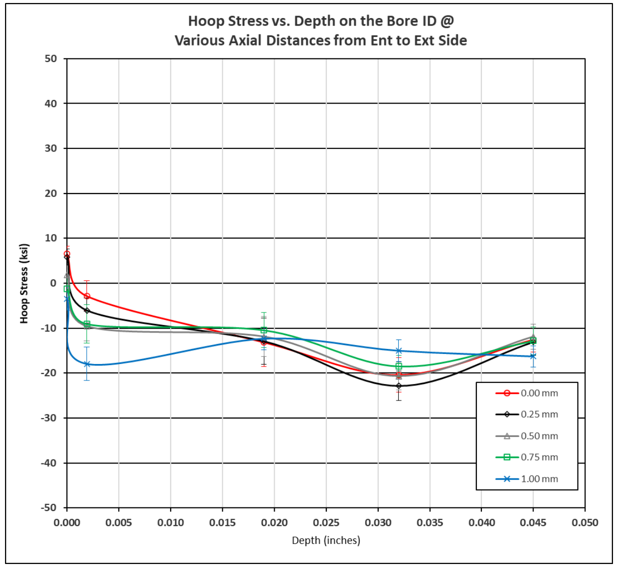
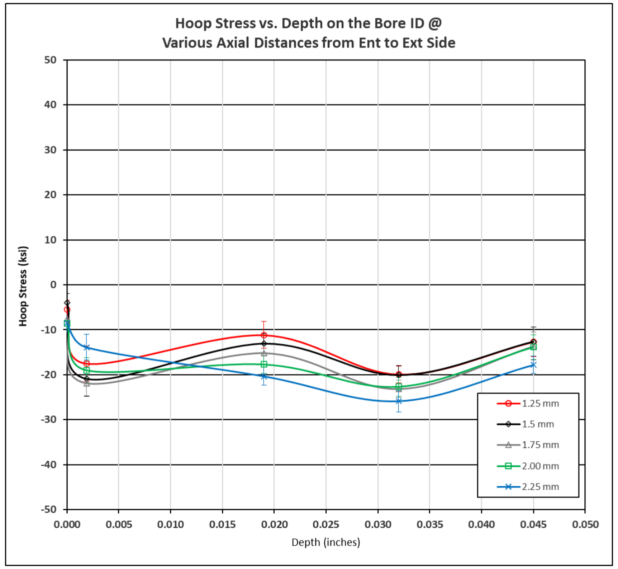
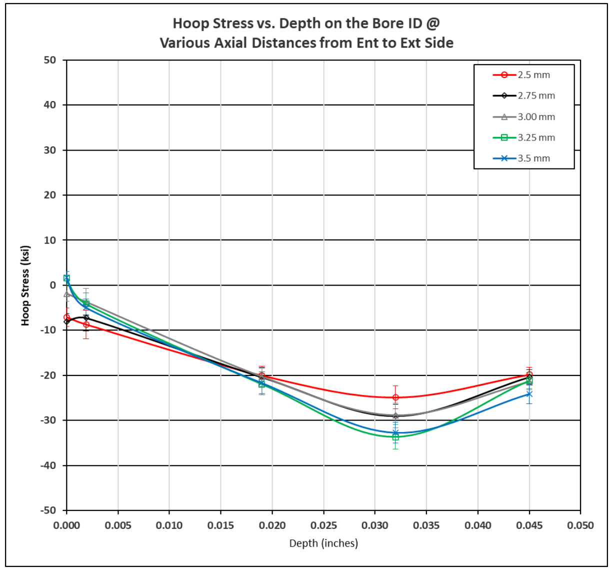
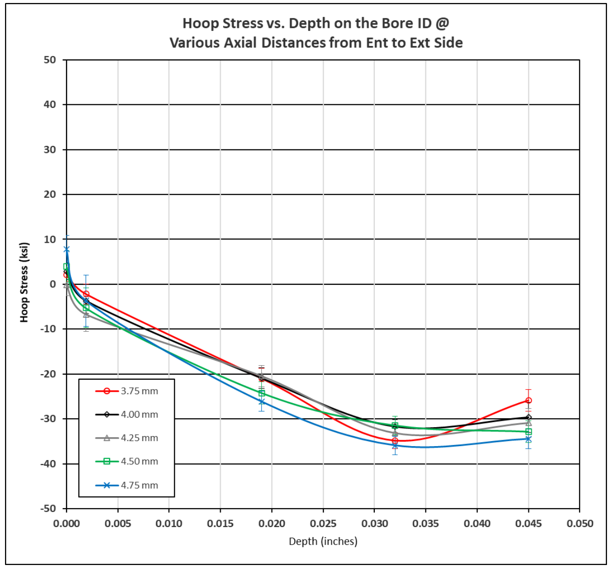
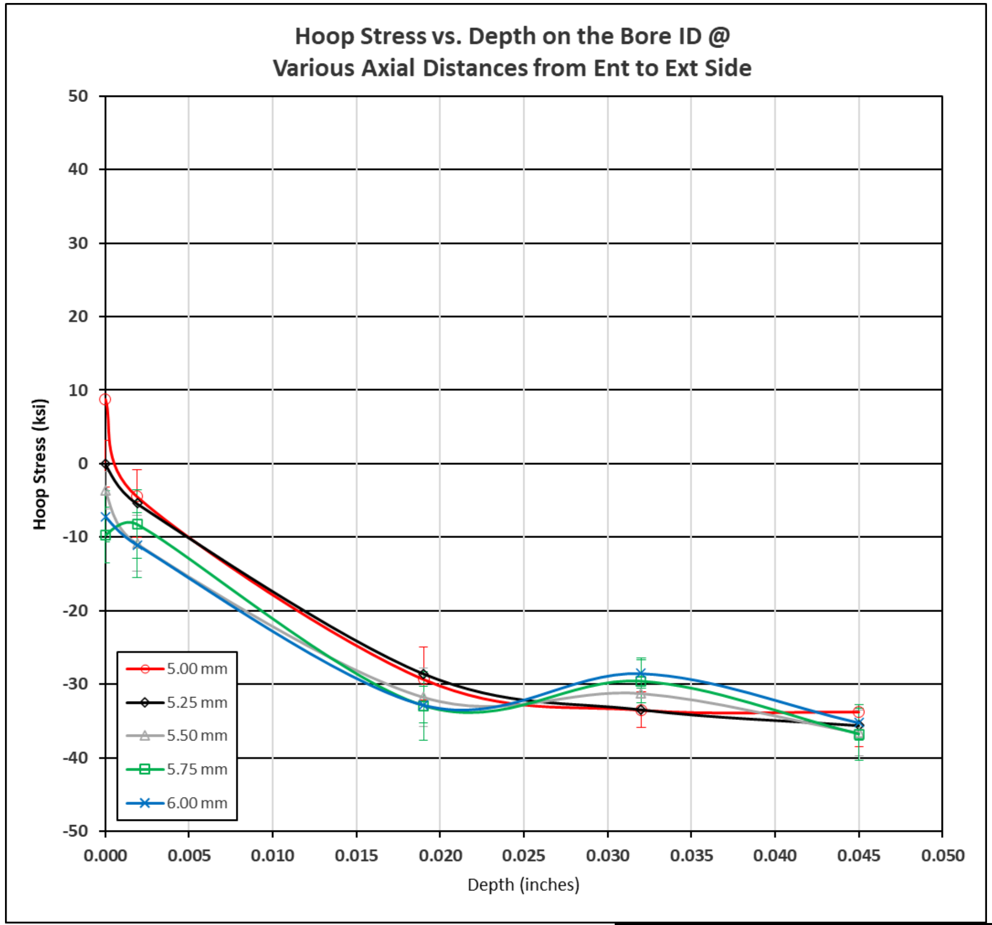
RS depth profiles at individual points across the bore 2 x 2 Cx Hole – 2024-T351 High (Un-reamed)











Note: near surface cold working RS persist to ~ 0.025” deep

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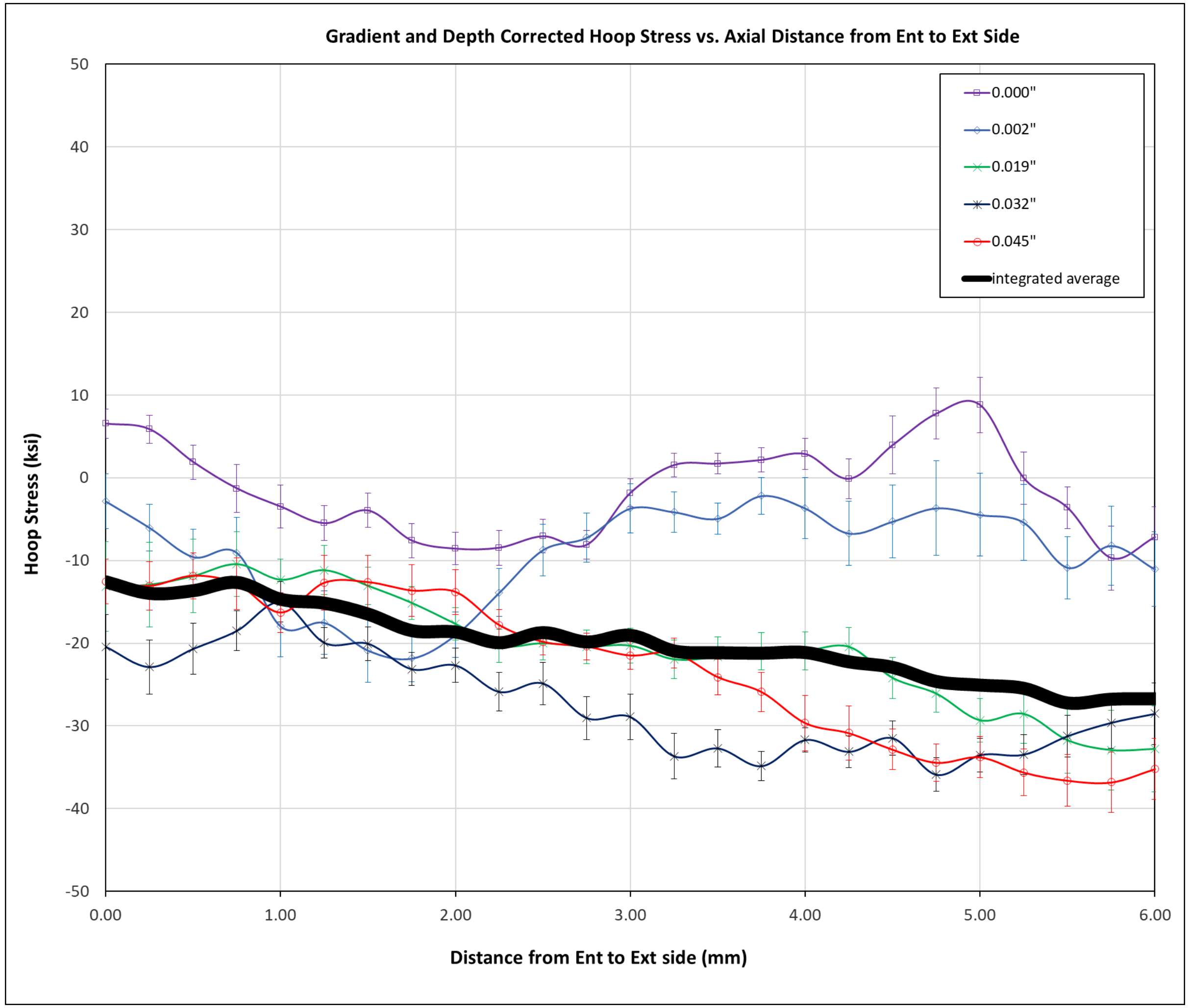
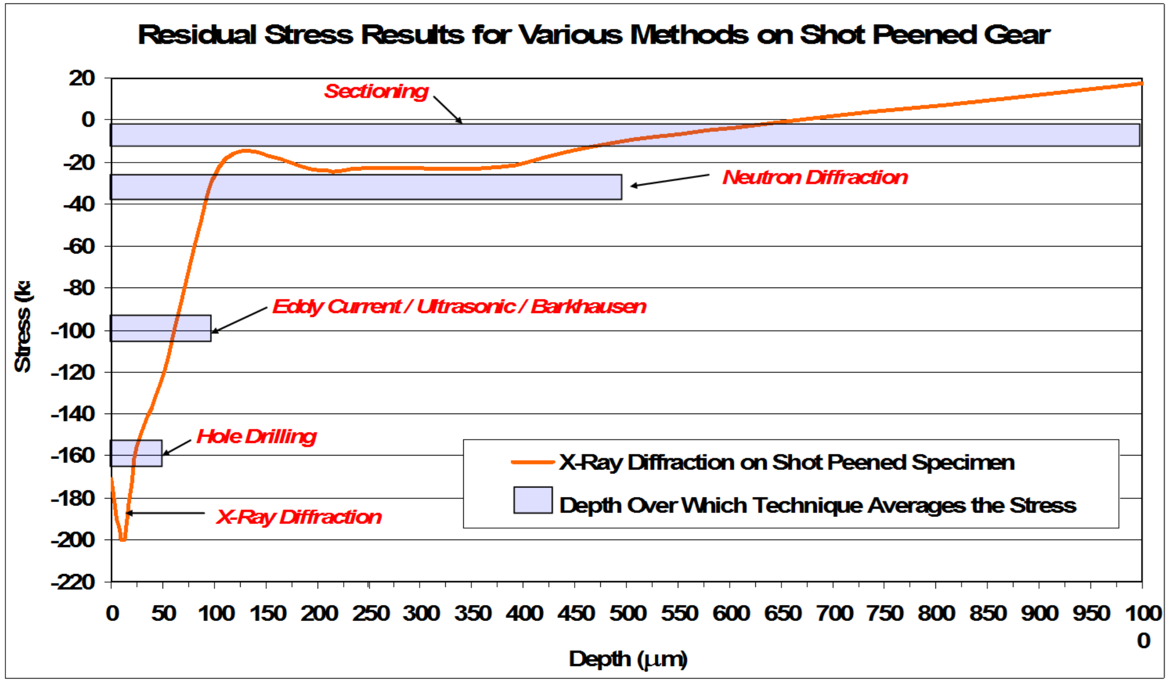
RS in Bore of Cx Hole Inter-method harmonization





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Discussion

RS measurements in bore of 2x2 coupons are feasible.

XRD profiles across the bore from Entry to Exit via electropolishing entire layer and repeating process

Results must be corrected for bending due to contour cut

Inter-method considerations - integrated average over 0.045” should correlate with ~1mm sampling

Conclusions

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1) In the Reamed condition, "Low" and "High" range of acceptable Cx interference results in different RS fields – Expected.
2) The effect is more pronounced in 7075-T651 as compared to 2024-T351 in the "Reamed" condition - Expected? Anyone? Buehler?
3) Reaming has a small effect on persistence of compressive field with increasing distance from the hole.
4) Effect of Reaming more localized to edge of hole – results in increased compressive RS maxima.
5) Trends hold true for both "Low" and "High" Cx and for both 7075-T651 and 2024-T351. Effect greatest on 7075-T651 High.
6) RS measurements in bore of 2x2 coupons are feasible.
7) XRD profiles across the bore from Entry to Exit via electropolishing entire layer and repeating process
8) Results <u>must</u> be corrected for bending due to contour cut
9) Inter-method considerations - integrated average over 0.045" should correlate with ~1mm sampling

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Moving Forward on 2x2 coupons

1) Focus on Contour and XRD measurements in 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) Continue to develop framework for Contour + XRD harmonization.

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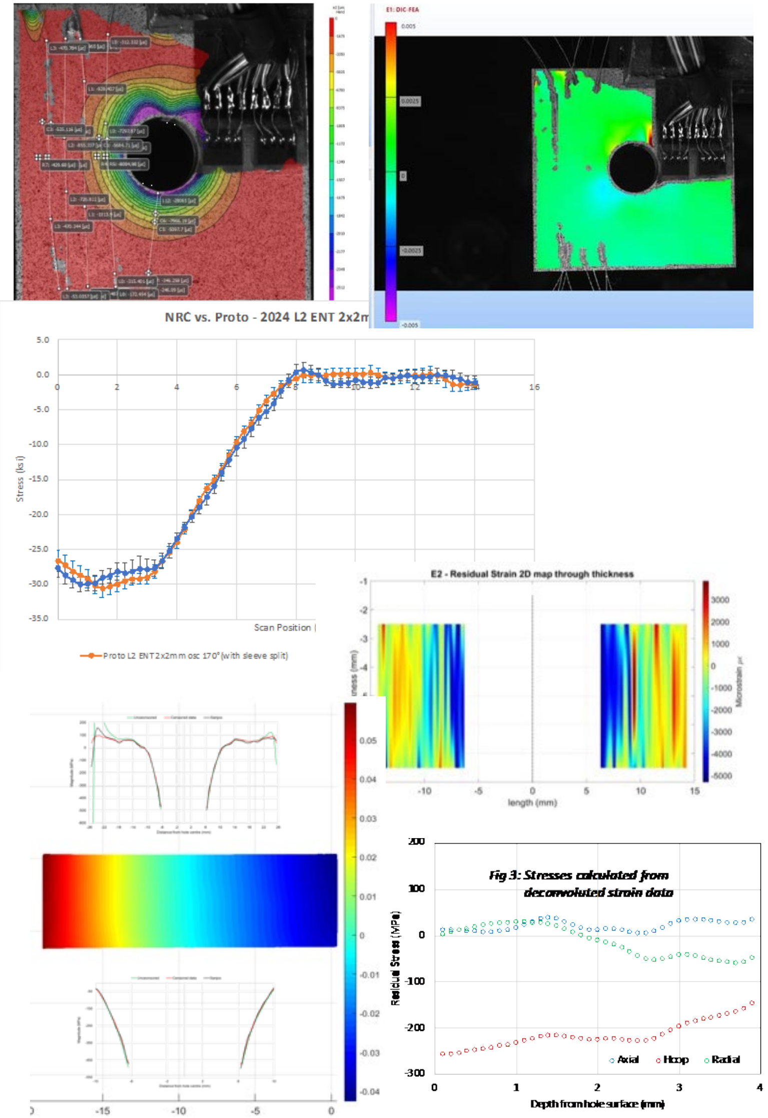
Thank You

Work Completed

- Surface Strain Measurements During Cx Process
  - Journal paper in draft form for release (focused on 2024-Low Cx level)
  - Utilizing MatchID for FEA-to-DIC comparison
- Surface XRD Inter-Laboratory Comparison and Method Development
  - Journal paper in draft for final review (All configurations presented)
- Through Thickness Measurements
  - Argonne National Lab's Synchrotron (All coupons processed)
  - CHESS Synchrotron (7075 coupons processed – need data)
  - JPARC and Oakridge National Lab's Neutron Diffraction (All coupons will be processed)
  - Stress-Space - Contour Method (All coupons will be processed)
    - 2024 High and Low



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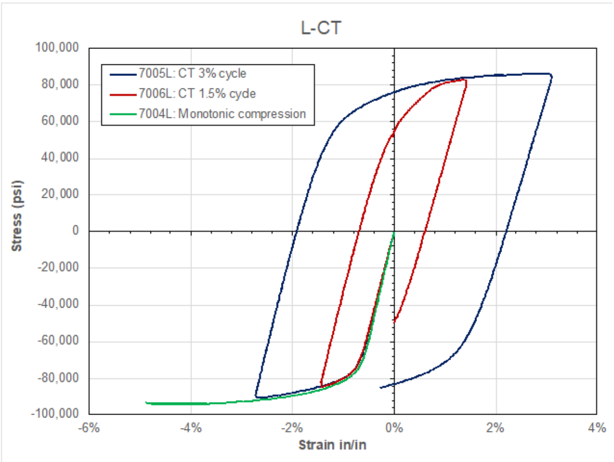
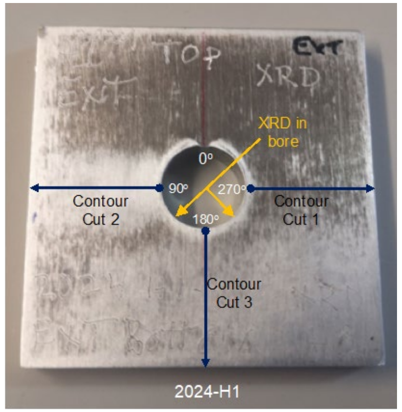
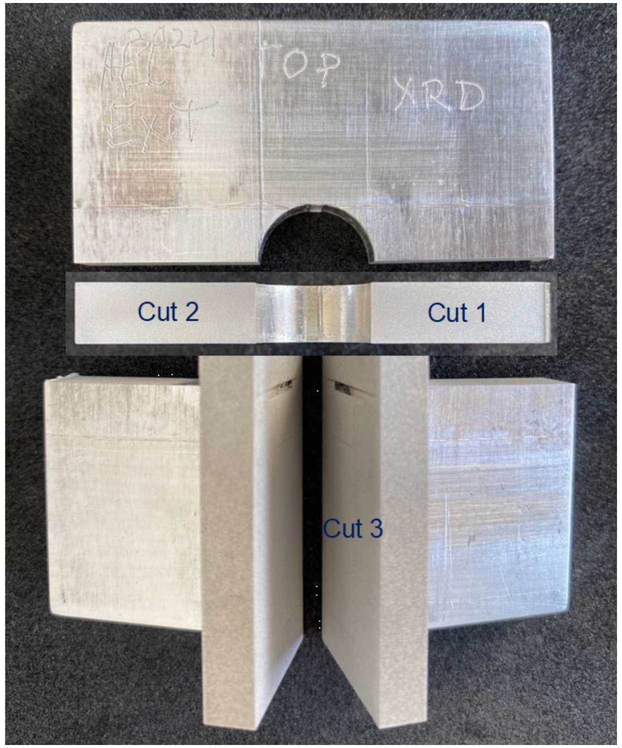
Work In Progress

- Review Plasticity Models for FEA Simulation of Cx Process
  - Combine work from the Process Simulation round robin paper
- Processing of Neutron Diffraction Data for:
  - 2024 “High” expansion
  - Both 7075 coupons
- Contour Method for Both 7075 Cx Coupons
  - Perform FEA for cutting technique
  - Perform multiple cuts on each coupon
- Develop Thru-Thickness Combination of RS Data
  - Surface XRD with Contour and Neutron Diffraction results
- Define Future Requirements for Cutting-Induced Plasticity
  - Effects of edge margin, yield strength and thickness
  - Define which side of the hole has results that are accurate







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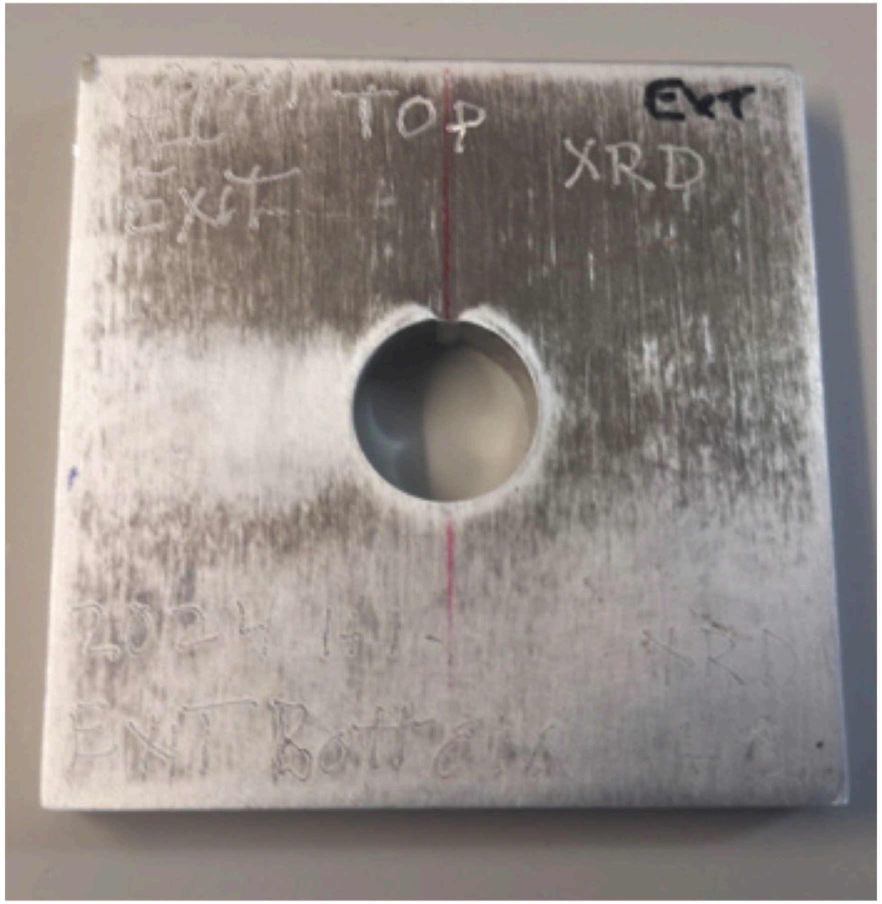
Different Data Sets for Same Case

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

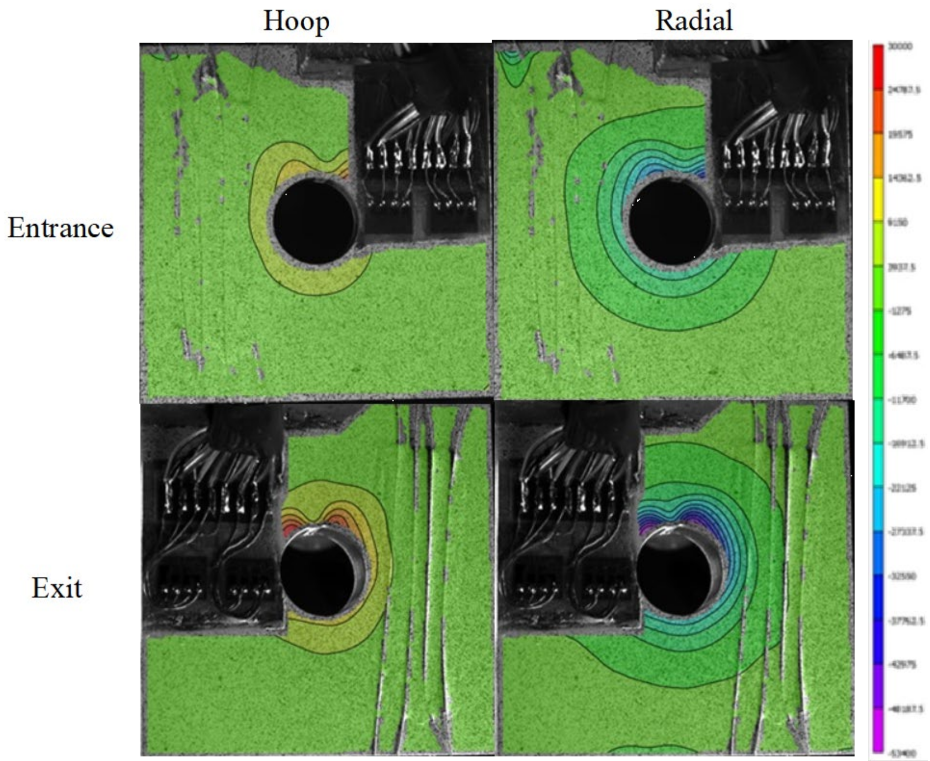


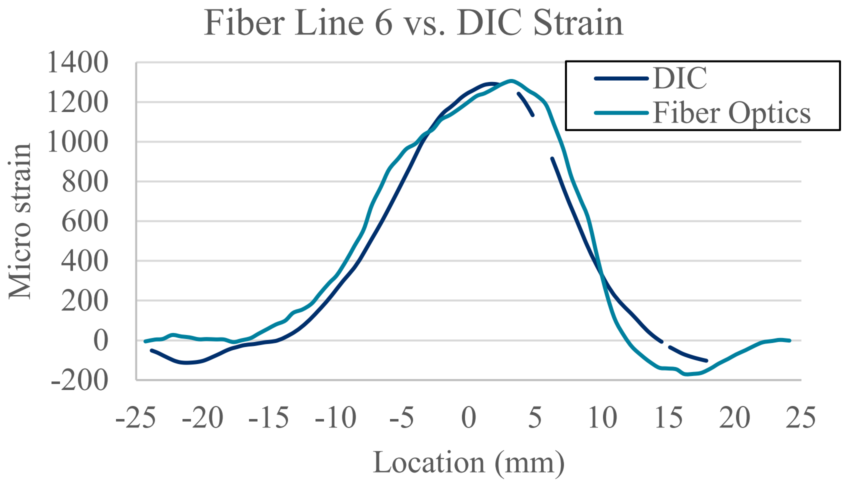
- What Do These Data Sets Look Like?
- How Can we Use them for FEA Process Simulation Validation?

Cx Processing DIC Data vs. Strain Gauge

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

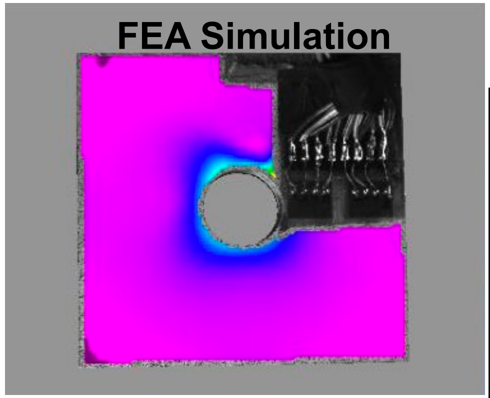
Strain Comparison: Gage vs. DIC			
Location	**Gage**	**DIC**	**%Diff**
1	0.003571	0.003573	0.05%
2*	-0.005699	-0.005684	0.26%
3	0.000984	0.000969	1.54%
4	-0.000459	-0.000430	6.43%
*Adjusted for 13.6 degree split rotation			

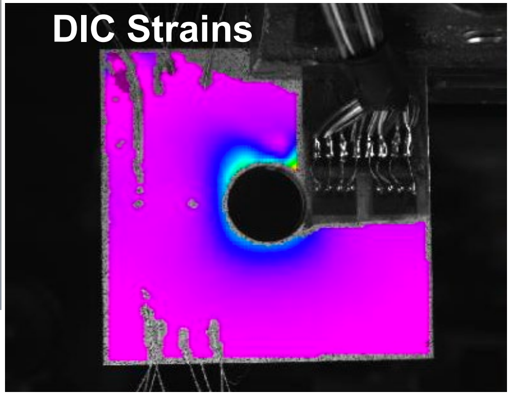


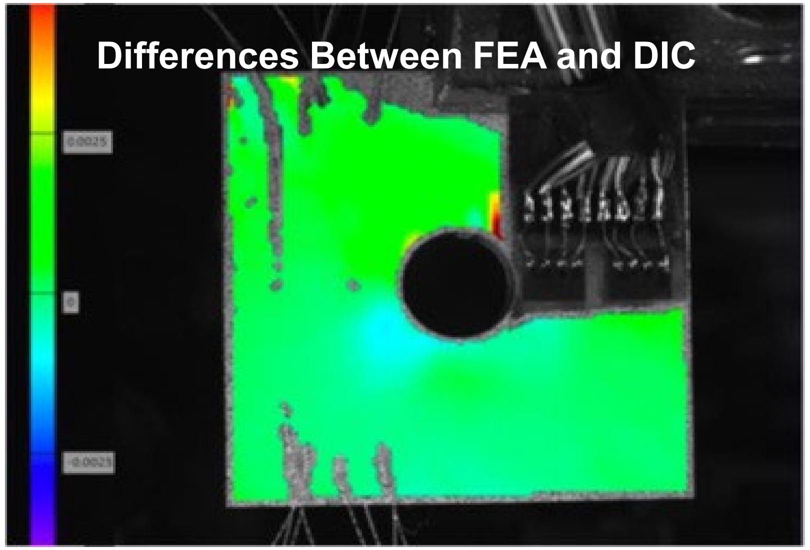


Application of MatchID

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

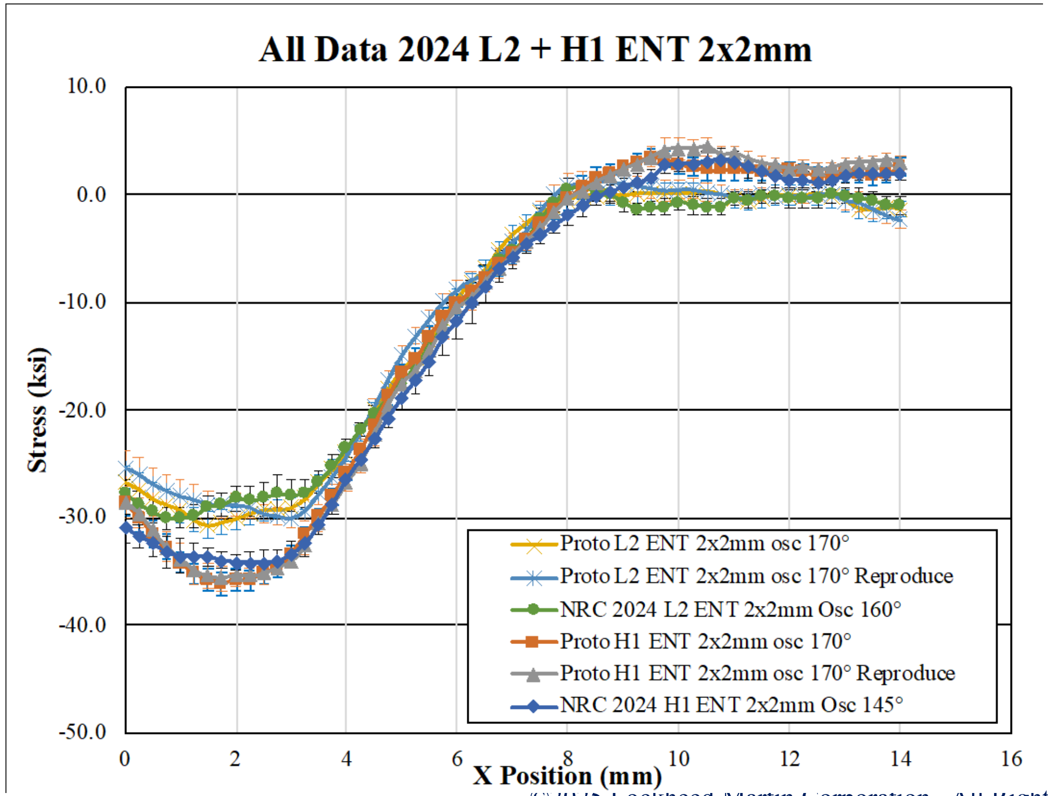


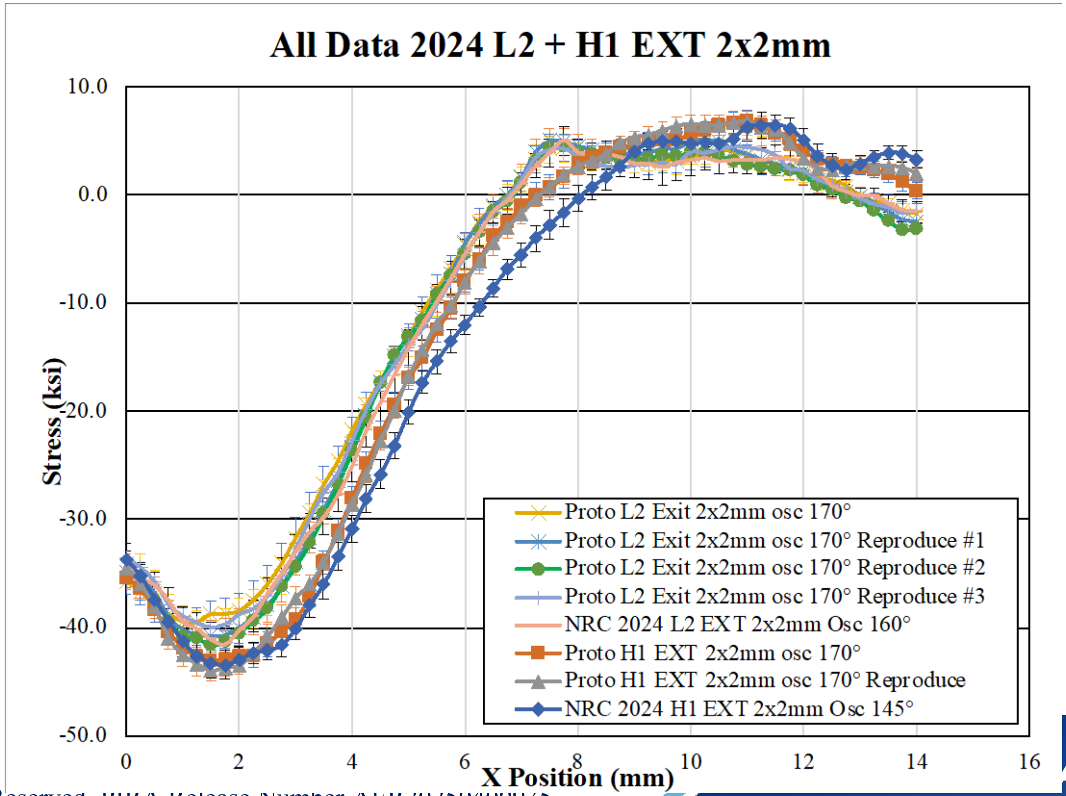




Surface XRD Round Robin Results

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





Neutron Diffraction Preliminary Results

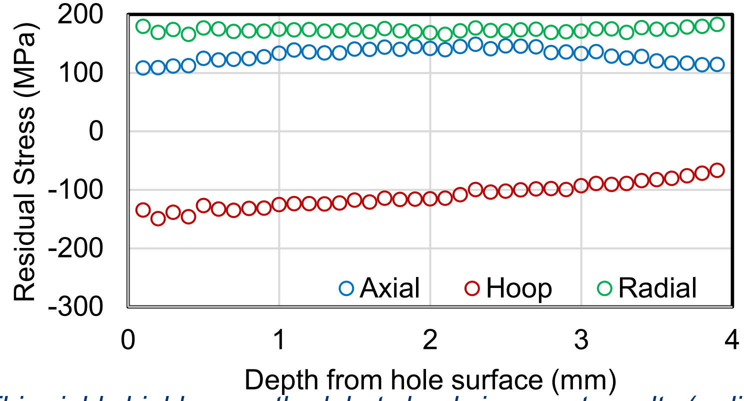
- Dr. Richard Moats Oversaw all Experiments with Deconvolution Data Analysis Approach Being Validated Prior to Application to Cx Data
  - 2024 Coupons at JPARC
  - 7075 Coupons at Oak Ridge NL

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

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

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

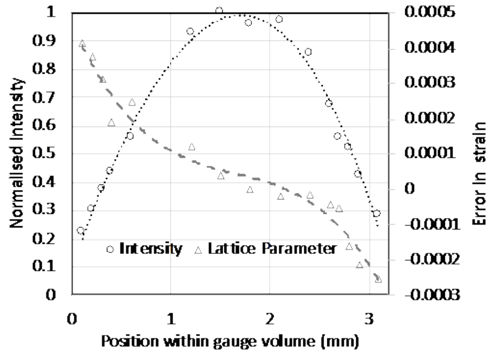
1. Collect lattice strains in 3 orthogonal direction with a step size of 100μm positioned at the centre of the thickness



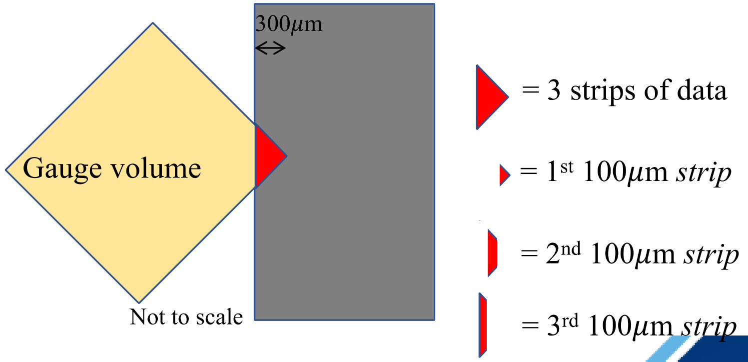
This yields highly smoothed, but clearly incorrect results (radial direction must be close to 0 MPa at the surface)

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

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



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



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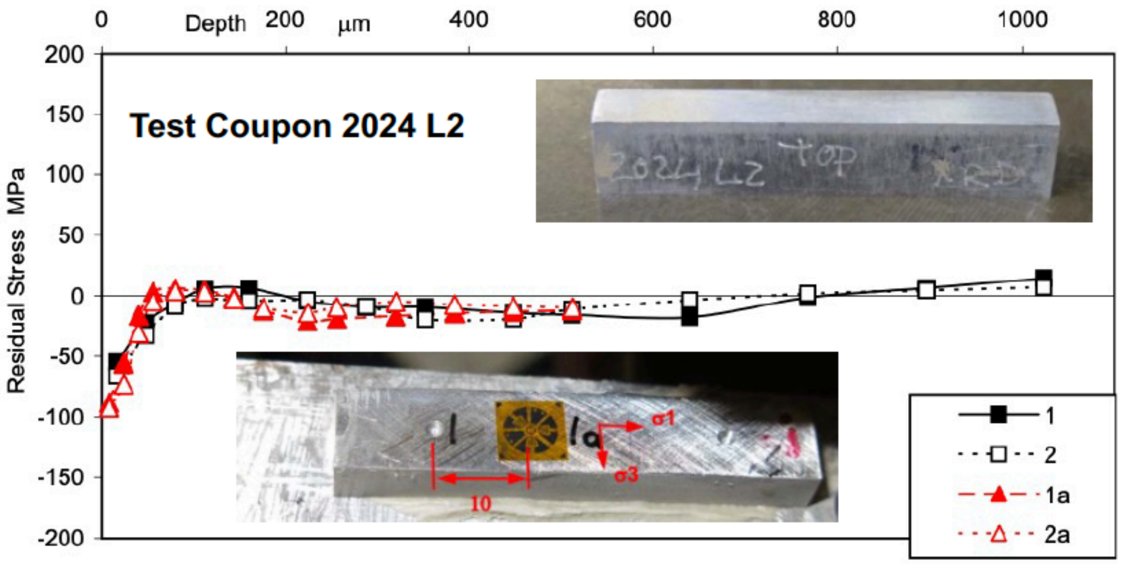
Questions Asked About Rolling Stresses

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

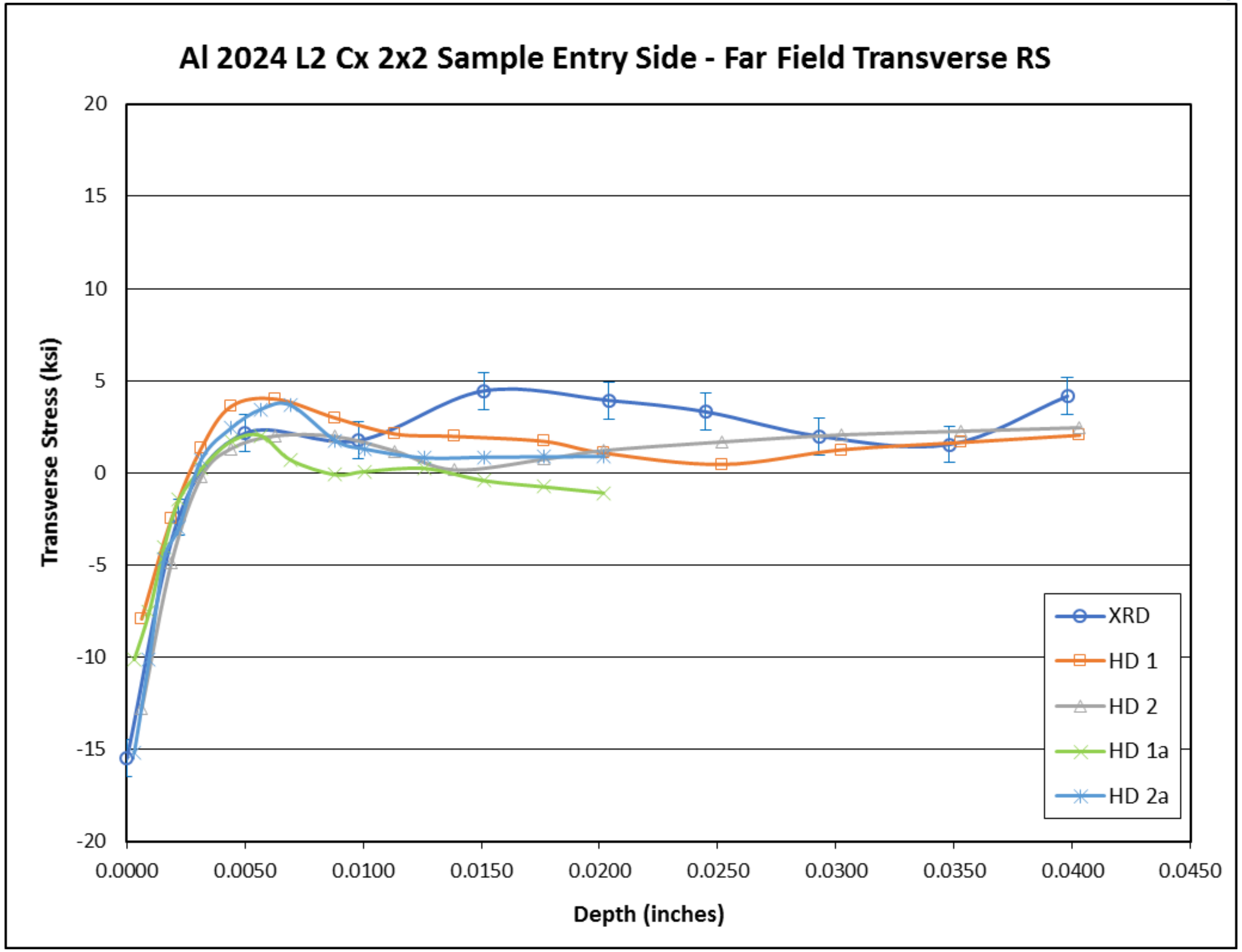


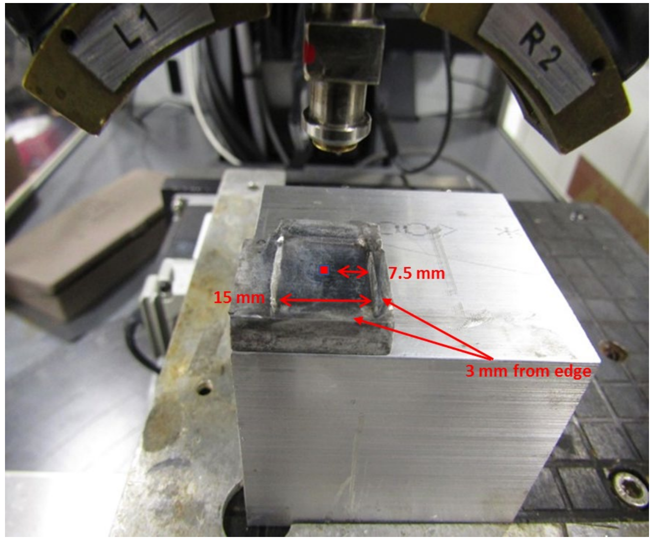
Distributions of longitudinal stresses vs depth

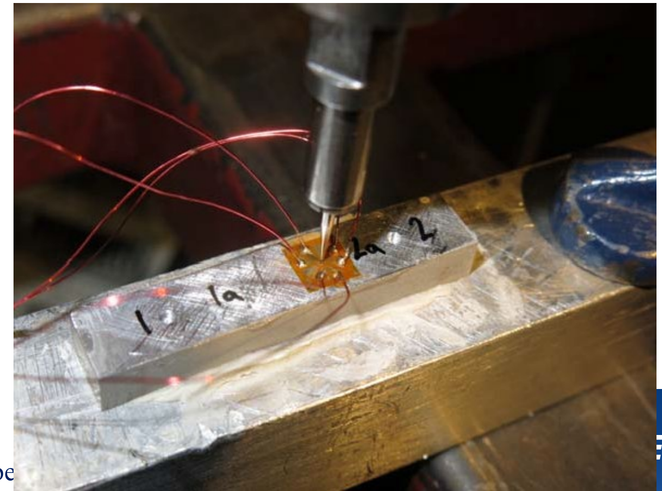
- HD Showed Compressive RS of Approx. -100MPa (-14.5ksi) at the Surface and Fall to 0ksi at Approx. 100 microns (0.004inch)
  - These rolling stresses interact with the Cx process at the surface
  - These stresses may be one reason why XRD and Contour results are different since Contour can't capture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

Rolling Stresses Answered

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







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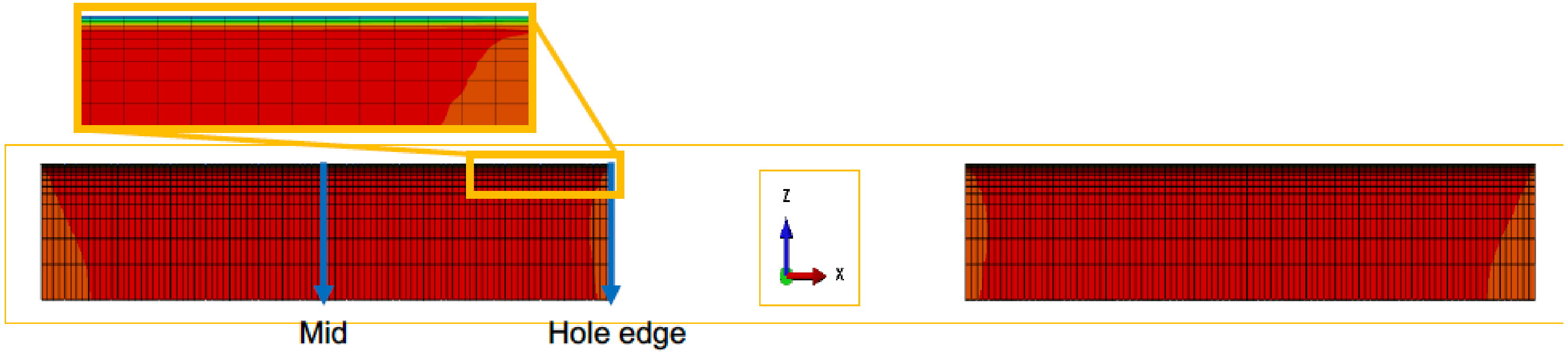
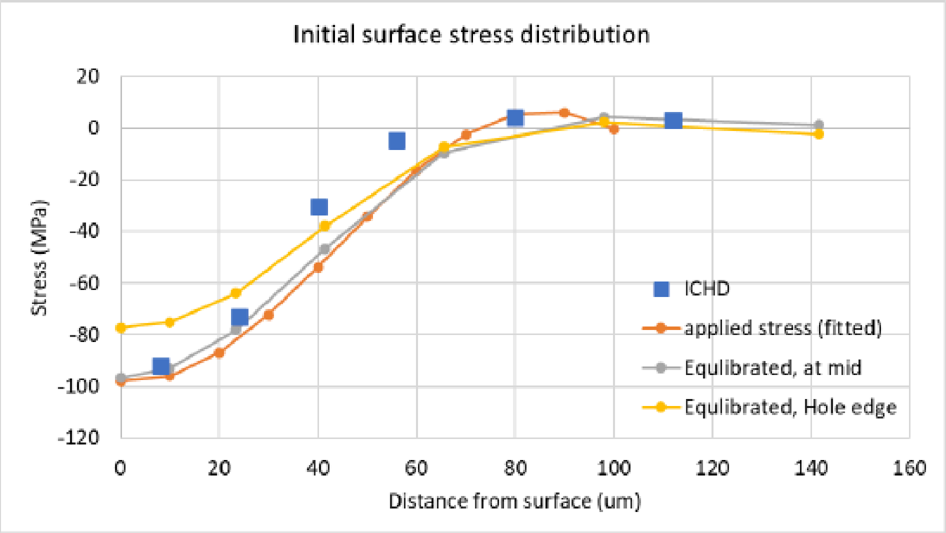
Initial Method for Combining RS Data

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





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

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Thank You
Questions/Comments?

Application of Retained Expansion as Critical Measurement Factor for Crack Growth Performance in Split Mandrel Screening Testing

2025 ERSI Workshop

May 1, 2025 – Layton Utah, USA

Scott Carlson (Lockheed Martin)
Brian Yeang (Lockheed Martin)
Matt Shultz (FTI)
Keith Hitchman (FTI)

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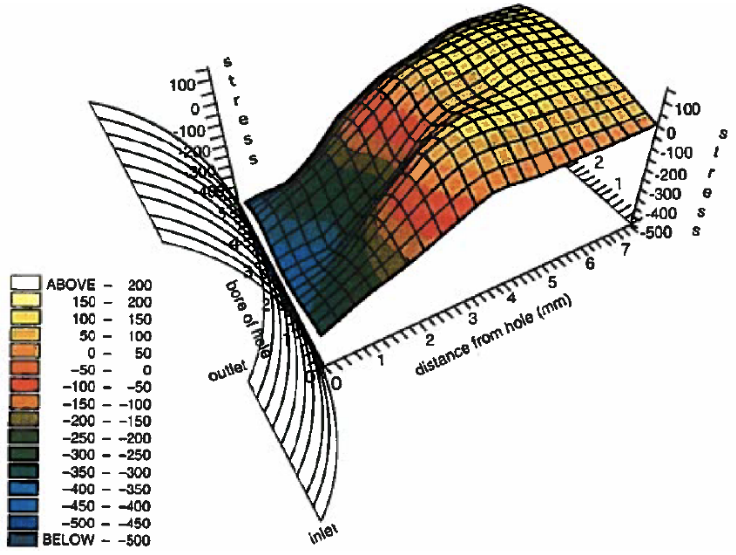
Agenda



- **Project Overview**
- **Split Mandrel Tooling Discussion**
  - *Conventional Split Mandrel and SmartCx^{TM} intro*
- **Test Program Purpose and Hypothesis**
  - *Hypothesis – Retained expansion can be the best "tuning" metric for Cx processes and crack growth performance*
  - *Coupon Design and Cx Process Flow*
  - *Test Matrix and Data Collection*
- **Results**
  - *Pre-Crack & Total Life Comparisons*
  - *Residual Stress Comparisons SsCx^{TM} vs. SmartCx^{TM}*
- **Lessons Learned**
  - *Orientation of splits*
  - *EDM notch size*
  - *Pre-crack results vs. Post-ream results*

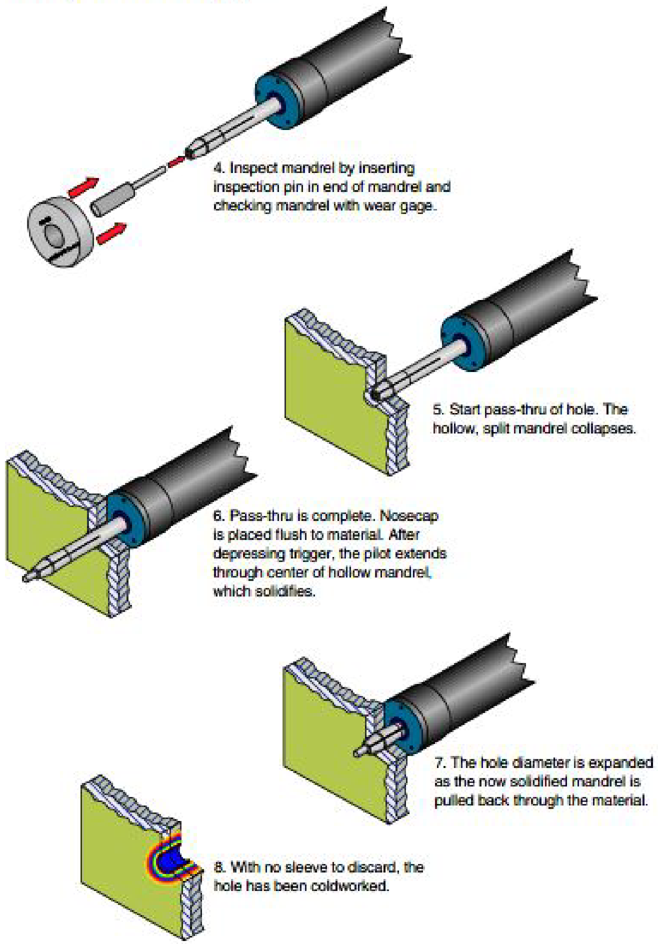
Project Overview

- **Increased Automation and Production Time Reduction Demands**
  - *SsCx™ is utilized within Production and requires multiple, time-consuming steps*
  - *Potential to utilize automation to combine hole drilling thru composite skin and Cx of sub-structure*
- **SsCx™ Process is Extremely Difficult to Automate**
  - *Orientation of sleeve is very difficult*
- **ProdOps Funded Initial Screening of Sleeveless Cx Processes**
- **Sleeveless Cx Processes Must be "As Good or Better Than" the SsCx™ Established Allowables**
  - *Testing performed with EDM notched coupons*
- **2 Types and Manufactures of a Sleeveless Cx Processes**
  - *Fatigue Tech. Incorp. & West Coast Industries*

Split Mandrel Tooling & Cx Processes

- **FTI & WCI Split Mandrel Processes**
  - *4-split mandrel is inserted into the hole*
  - *Drive a <u>straight pin</u> is pushed thru mandrel*
  - *Lub is forced into mandrel*
  - *Mandrel and pin are pulled back thru hole*

1. Drill start hole with start drill.
2. Ream hole to proper starting size with start hole reamer.
3. Verify start hole with hole gage.



9. Inspect coldworked hole with hole gage.
10. Ream hole to final size with piloted reamer.
11. Inspect final reamed hole with hole gage. Countersink if necessary.

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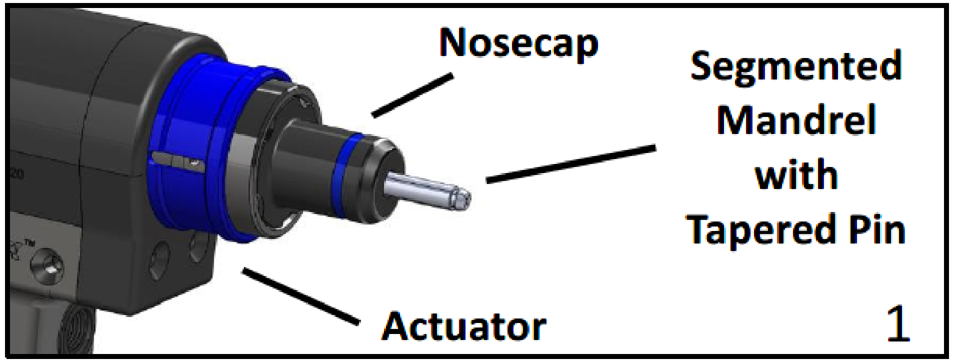
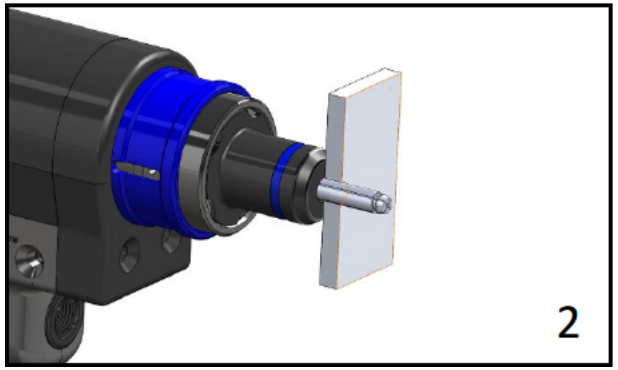
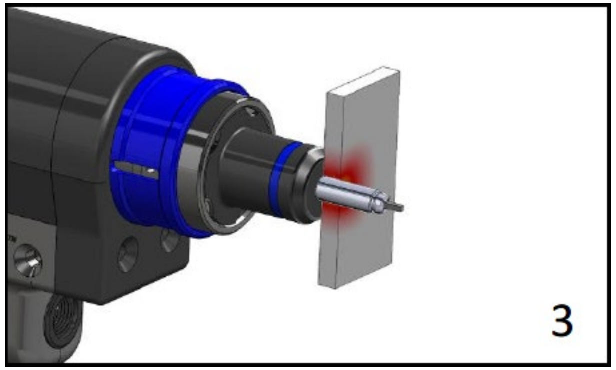
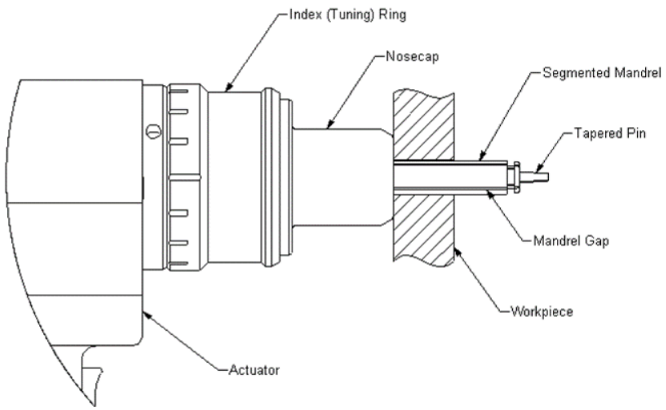
SmartCx^{TM} by FTI

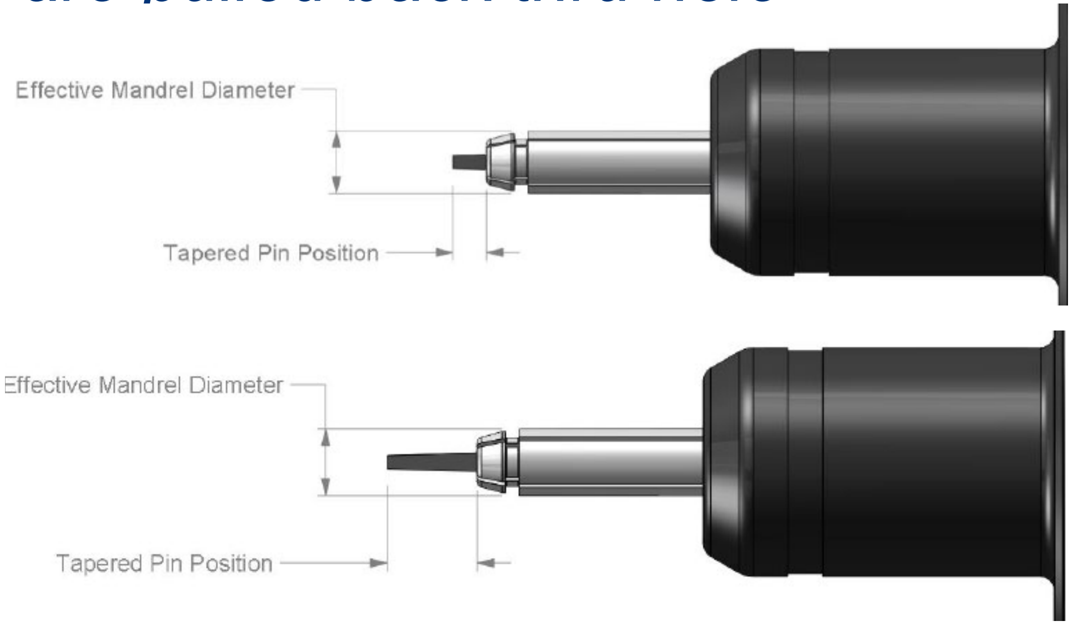
- **SmartCx^{TM} Process and Tooling**
  - *4-split mandrel is inserted into the hole*
  - *Drives a tapered pin thru split mandrel*
    - **Allows for adjustment of applied expansion**
  - *Lub is forced into mandrel*
  - *Mandrel and pin are pulled back thru hole*











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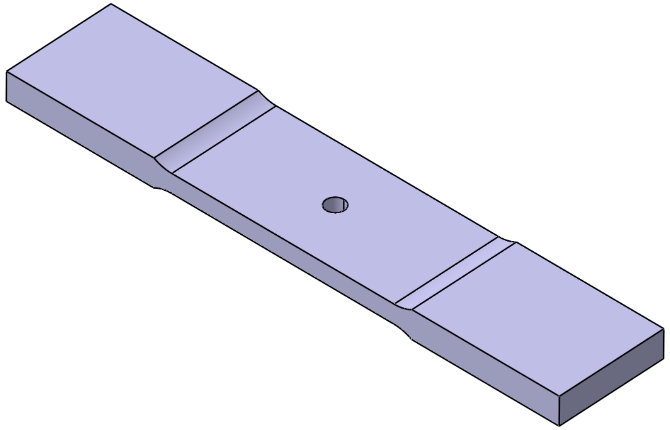
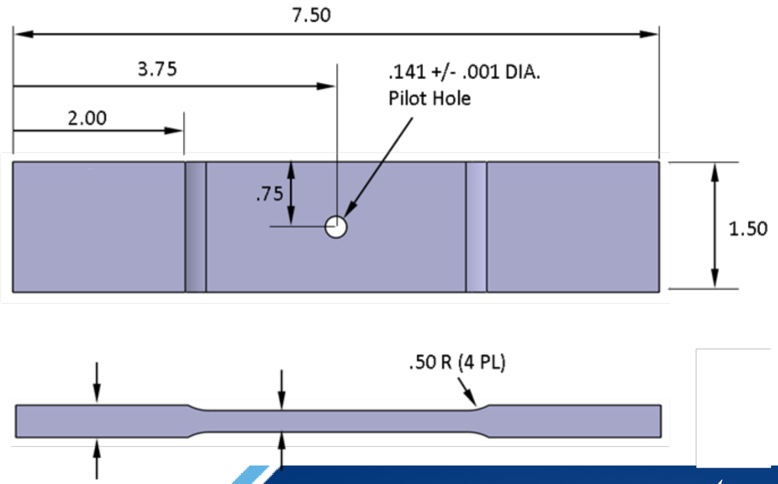
Test Program Overview

- **Perform Constant Amplitude, Tension Dominated Testing in 7050-T7451 Plate, 5 Replicates per Process + Baseline**
  - *R=0.1, Max Stress = 23ksi*
  - *0.025inch corner EDM Notch*
  - *Starting hole diameter = 0.2275inch (FTI 6-3-N)*
  - *Final hole diameter = 0.265inch*
- **Pre-Cracking Sequence**
  - *Get hole to pre-Cx diameter*
  - *Cx hole*
    - **Split Sleeve at 12 O'clock**
    - **Split mandrel at 12, 3, 6, and 9 O'clock**
  - *EDM notch*
  - *Pre-crack to 0.055inch from edge of hole*
  - *Perform final ream*
  - *Finish testing at 23ksi*





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Testing Hypothesis for Retained Expansion

- **All Cx Tooling has Standardized Starting Hole Diameters**
- **Split Mandrel Tooling Collapses During Cx Due to Tolerance Gapes**
  - *A reduced level of applied/retained expansion will have a direct impact on performance*
- **For Production it's Possible to Acquire Custom Tooling at Higher Levels of Expansion**
- **Modifying the Starting Hole Diameter Simulates this Custom Tooling Effect**
- **Success = "As good or better than" SsCx^{TM} Performance**
  - *Pre-crack cycles and post-final ream testing considered*

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Hole Metrology for Cx Holes Isn't Easy

- **Starting Hole Diameters Measured via Ball Gauge at 12 and 3 O'clock on Both Mandrel Entrance and Exit Surfaces**
  - *Holes machined in CNC using circular interpolation and had very little variance*
- **Post Cx Hole Diameters is Difficult to Measure Due to Presence of Split/Splits**
  - *SsCx^{TM} with a single split is more manageable*
  - *Split Mandrel processes with 4 splits becomes more complicate to align*
    - **Makes precise retained expansion levels challenging to nail down**
- **Performing Metrology on Keyence Presents Unique Challenges for Defining Edge of Hole**

Test Matrix & Pre-Test Metrology Results

Coupon Name	Manufactured ID	Cx Process	Pre-EDM Hole Diameter Requirement (inch)	Avg. Pre-Cx Ent. Hole Diameter (inch) (12)	Avg Pre-Cx Ext. Hole Diameter (inch) (12)	Avg. Pre-Cx Ent. Hole Diameter (inch) (3)	Avg Pre-Cx Ext. Hole Diameter (inch) (3)	Avg. Post-Cx Hole Diameter (inch) (12)	Avg. Post-Cx Hole Diameter (inch) (3)	Avg. Retained Expansion Ent. (%)	Avg. Retained Expansion Ext. (%)	EDM Notch Length (inch)
7050-B-01	7050Cx-01	Baseline	0.2275+/- 0.0005inch	0.2276	0.2274	0.2277	0.2274	N/A	N/A	N/A	N/A	0.027
7050-B-01												
7050-B-02	7050Cx-02											0.023
7050-B-02												
7050-B-03	7050Cx-03											0.023
7050-B-03												
7050-SsCx-01	7050Cx-04	SsCx		0.2279	0.2274	0.2278	0.2274	0.2319	0.2319	1.74%	1.98%	0.023
7050-SsCx-01												
7050-SsCx-02	7050Cx-05											0.025
7050-SsCx-02												
7050-SsCx-03	7050Cx-06											0.024
7050-SsCx-03												
7050-SsCx-04	7050Cx-07											0.024
7050-SsCx-04												
7050-SsCx-05	7050Cx-08											0.026
7050-SsCx-05												
7050-SM-01	7050Cx-09	SMCx		0.2277	0.2274	0.2279	0.2274	0.2313	0.2313	1.37%	1.88%	0.030
7050-SM-01												
7050-SM-02	7050-Cx10											0.029
7050-SM-02												
7050-SM-03	7050-Cx11											0.029
7050-SM-03												
7050-SM-04	7050-Cx12											0.029
7050-SM-04												
7050-SM-05	7050-Cx13											0.030
7050-SM-05												
7050-SMCx-01	7050-Cx14	SmrtCx-Std		0.2279	0.2271	0.2278	0.2271	0.2302	0.2302	1.05%	1.36%	0.027
7050-SMCx-01												
7050-SMCx-02	7050-Cx15											0.026
7050-SMCx-02												
7050-SMCx-03	7050-Cx16											0.025
7050-SMCx-03												
7050-SMCx-04	7050-Cx17											0.025
7050-SMCx-04												
7050-SMCx-05	7050-Cx18											0.025
7050-SMCx-05												

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Test Matrix & Pre-Test Metrology Results

Coupon Name	Manufactured ID	Cx Process	Pre-EDM Hole Diameter Requirement (inch)	Avg. Pre-Cx Ent. Hole Diameter (inch) (12)	Avg Pre-Cx Ext. Hole Diameter (inch) (12)	Avg. Pre-Cx Ent. Hole Diameter (inch) (3)	Avg Pre-Cx Ext. Hole Diameter (inch) (3)	Avg. Post-Cx Hole Diameter (inch) (12)	Avg. Post-Cx Hole Diameter (inch) (3)	Avg. Retained Expansion Ent. (%)	Avg. Retained Expansion Ext. (%)	EDM Notch Length (inch)
7050-SMCx-Mx-01		SmrtCx-Tuned	0.2275+/-0.0005inch	0.2281	0.2273	0.2278	0.2274	0.2314	0.2315	1.54%	1.87%	
7050-SMCx-Mx-01	7050-Cx19											0.024
7050-SMCx-Mx-02												
7050-SMCx-Mx-02	7050-Cx20											0.024
7050-SMCx-Mx-03												
7050-SMCx-Mx-03	7050-Cx21											0.025
7050-SMCx-Mx-04												
7050-SMCx-Mx-04	7050-Cx22											0.024
7050-SMCx-Mx-05												
7050-SMCx-Mx-05	7050-Cx23											0.023
7050-SMCx-Mx-06												
7050-SMCx-Mx-06	7050-Cx39											0.015
7050-SMCx-Mx-07												
7050-SMCx-Mx-07	7050-Cx40											0.014
7050-Sm-01		SMCx (Tune)		0.2265	0.2264	0.2265	0.2265	0.2304	0.2303	1.44%	1.96%	0.024
7050-Sm-01	7050Cx-24											
7050-Sm-02												0.023
7050-Sm-02	7050-Cx25											
7050-Sm-03												0.021
7050-Sm-03	7050-Cx26											
7050-Sm-04												0.023
7050-Sm-04	7050-Cx27											
7050-Sm-05												0.024
7050-Sm-05	7050-Cx28											
7050-SmrtCx(TunO)-01		SmrtCx-Max		0.2276	0.2273	0.2277	0.2275	0.2304	0.2303	1.44%	1.96%	0.019
7050-SmrtCx(TunO)-01	7050Cx-29											
7050-SmrtCx(TunO)-02												0.020
7050-SmrtCx(TunO)-02	7050-Cx30											
7050-SmrtCx(TunO)-03												0.018
7050-SmrtCx(TunO)-03	7050-Cx31											
7050-SmrtCx(TunO)-04												0.018
7050-SmrtCx(TunO)-04	7050-Cx32											
7050-SmrtCx(TunO)-05												0.022
7050-SmrtCx(TunO)-05	7050-Cx33											

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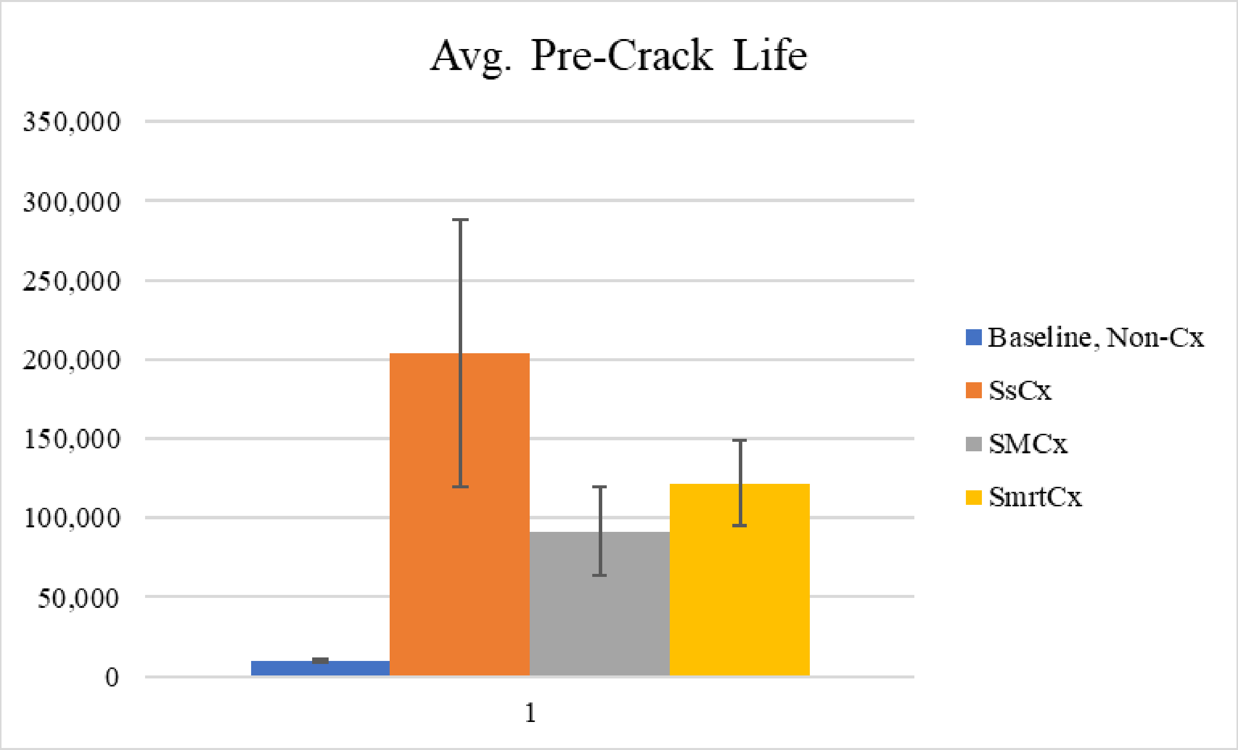
Test Matrix and Pre-Crack & Final Lives

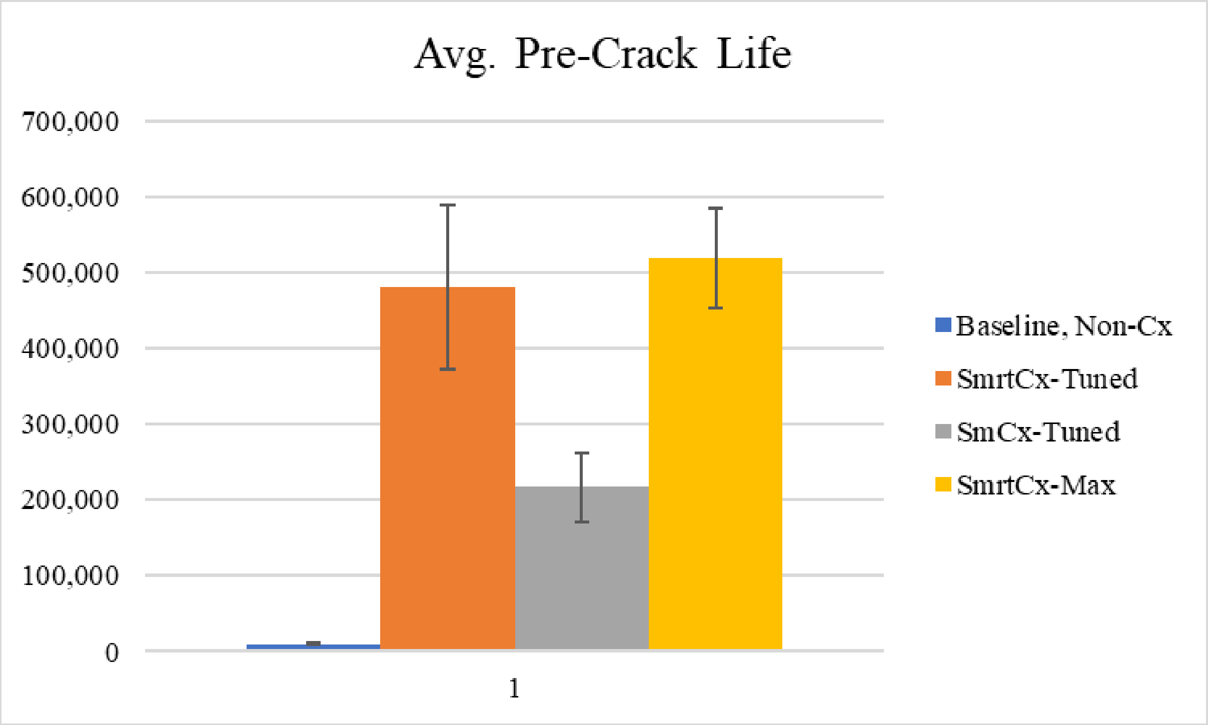
Coupon Name	Manufactured ID	Cx Process	Pre-Crack Surface Length From Notch (inch)	Average Life for Pre-Cracking	Std on Pre-Crack Life	Final Ream Diameter Requirement (inch)	Average Life Post Final Ream	Std on Life Post Final Ream
7050-B-01	7050Cx-01	Baseline	0.030	9,701	1,029	0.2650±0.004inch	17,508	1,700
7050-B-01								
7050-B-02	7050Cx-02		0.032					
7050-B-02								
7050-B-03	7050Cx-03		0.030					
7050-B-03								
7050-SsCx-01	7050Cx-04	SsCx	0.030	203,937	84,368		**46,212**	**4,398**
7050-SsCx-01								
7050-SsCx-02	7050Cx-05		0.030					
7050-SsCx-02								
7050-SsCx-03	7050Cx-06		0.029					
7050-SsCx-03								
7050-SsCx-04	7050Cx-07		0.122					
7050-SsCx-04								
7050-SsCx-05	7050Cx-08		0.034					
7050-SsCx-05								
7050-SM-01	7050Cx-09	SMCx	0.034	91,133	27,900		**35,959**	**6,878**
7050-SM-01								
7050-SM-02	7050-Cx10		0.052					
7050-SM-02								
7050-SM-03	7050-Cx11		0.030					
7050-SM-03								
7050-SM-04	7050-Cx12		0.030					
7050-SM-04								
7050-SM-05	7050-Cx13		0.030					
7050-SM-05								
7050-SMCx-01	7050-Cx14	SmrtCx-Std	0.048	121,998	26,682		**38,426**	**12,172**
7050-SMCx-01								
7050-SMCx-02	7050-Cx15		0.030					
7050-SMCx-02								
7050-SMCx-03	7050-Cx16		0.030					
7050-SMCx-03								
7050-SMCx-04	7050-Cx17		0.031					
7050-SMCx-04								
7050-SMCx-05	7050-Cx18		0.036					
7050-SMCx-05								

Test Matrix and Pre-Crack & Final Lives

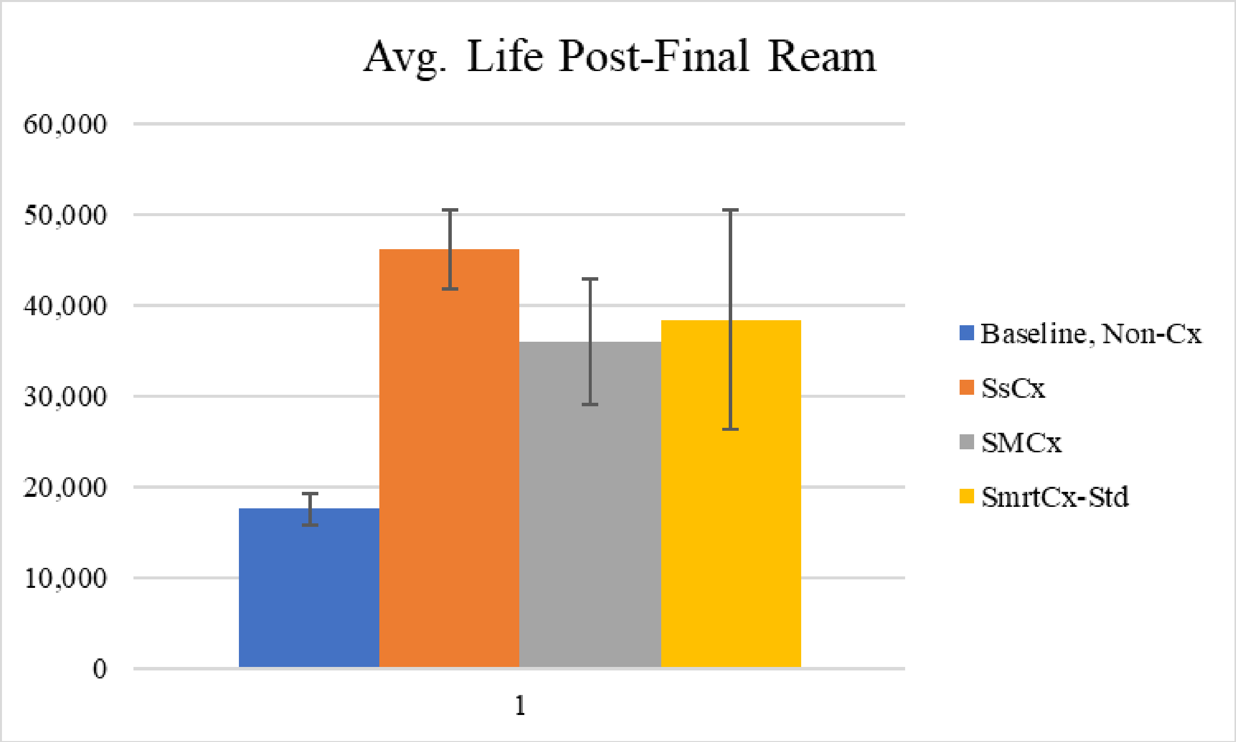
Coupon Name	Manufactured ID	Cx Process	Pre-Crack Surface Length From Notch (inch)	Average Life for Pre-Cracking	Std on Pre-Crack Life	Final Ream Diameter Requirement (inch)	Average Life Post Final Ream	Std on Life Post Final Ream
7050-SMCx-Mx-01		SmrtCx-Tuned		480,634	108,599	0.2650±0.004inch	**39,426**	**9,326**
7050-SMCx-Mx-01	7050-Cx19		0.010					
7050-SMCx-Mx-02								
7050-SMCx-Mx-02	7050-Cx20		0.030					
7050-SMCx-Mx-03								
7050-SMCx-Mx-03	7050-Cx21							
7050-SMCx-Mx-04								
7050-SMCx-Mx-04	7050-Cx22		0.038					
7050-SMCx-Mx-05								
7050-SMCx-Mx-05	7050-Cx23		0.021					
7050-SMCx-Mx-06								
7050-SMCx-Mx-06	7050-Cx39		0.027					
7050-SMCx-Mx-07								
7050-SMCx-Mx-07	7050-Cx40		0.028					
7050-Sm-01		SMCx (Tune)	0.0299	216,900	45,666		**61,808**	**6,991**
7050-Sm-01	7050Cx-24							
7050-Sm-02			0.0336					
7050-Sm-02	7050-Cx25							
7050-Sm-03			0.031					
7050-Sm-03	7050-Cx26							
7050-Sm-04			0.033					
7050-Sm-04	7050-Cx27							
7050-Sm-05			0.03					
7050-Sm-05	7050-Cx28							
7050-SmrtCx(TunO)-01		SmrtCx-Max	0.03192	519,848	66,414		**53,331**	**7,806**
7050-SmrtCx(TunO)-01	7050Cx-29							
7050-SmrtCx(TunO)-02			0.0522					
7050-SmrtCx(TunO)-02	7050-Cx30							
7050-SmrtCx(TunO)-03			0.03574					
7050-SmrtCx(TunO)-03	7050-Cx31							
7050-SmrtCx(TunO)-04			0.0321					
7050-SmrtCx(TunO)-04	7050-Cx32							
7050-SmrtCx(TunO)-05			0.0335					
7050-SmrtCx(TunO)-05	7050-Cx33							

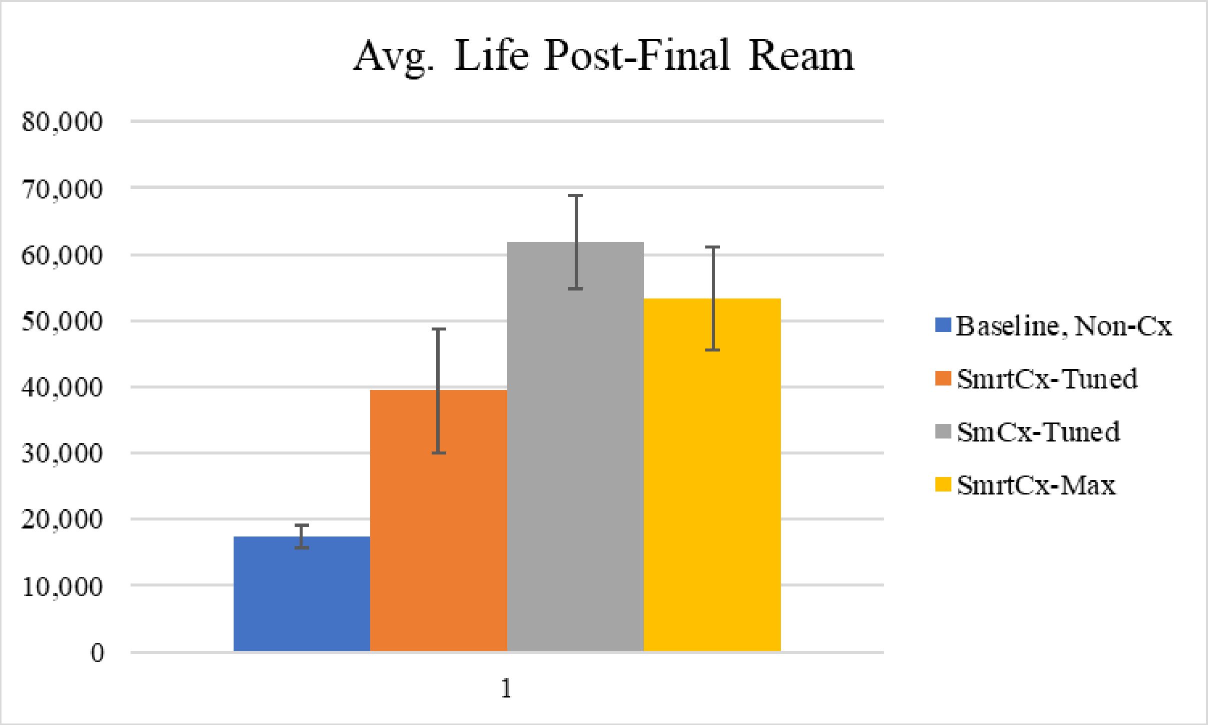
Pre-Crack Lives





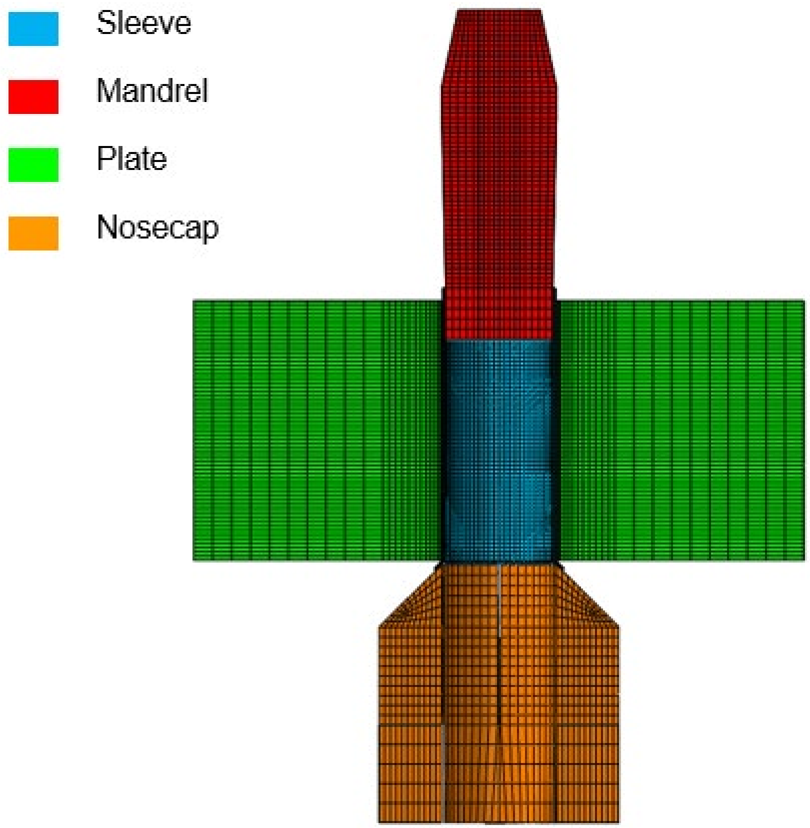
Post-Final Ream Lives





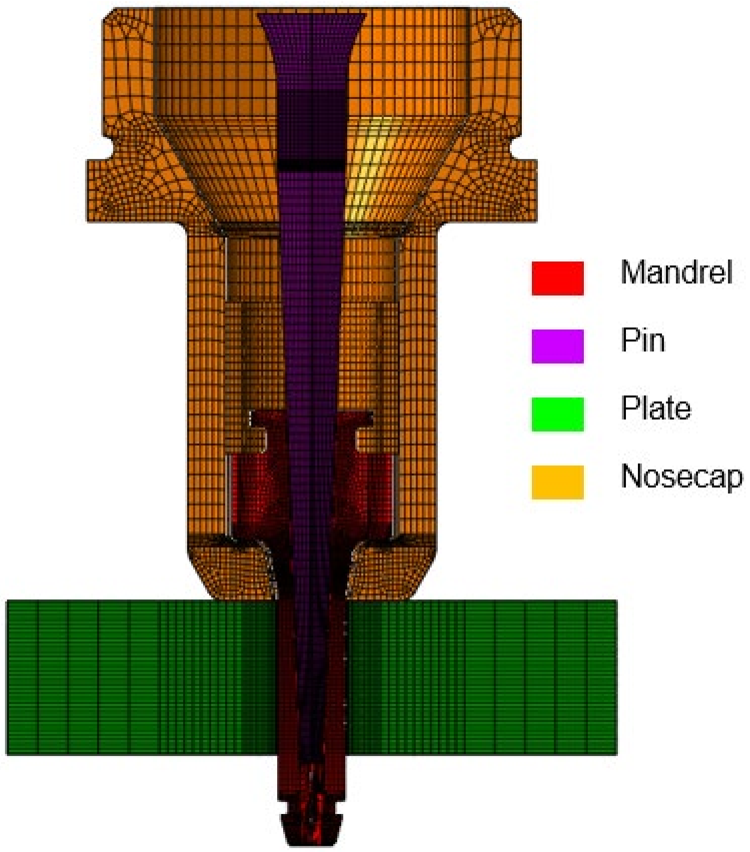
Process Model Comparison

SsCx



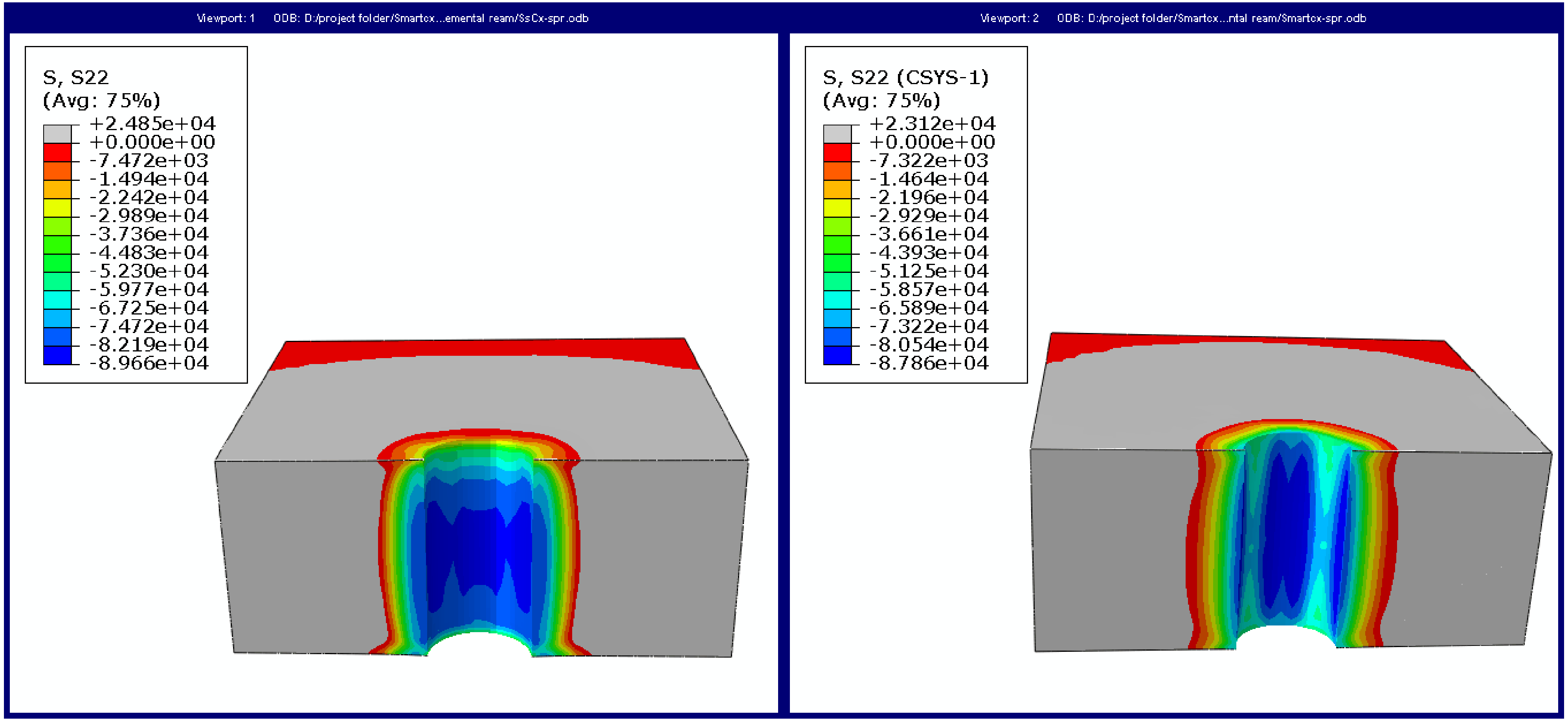
Parameters
6-3-N tooling (or equivalent)
7010-T7651

SmartCx



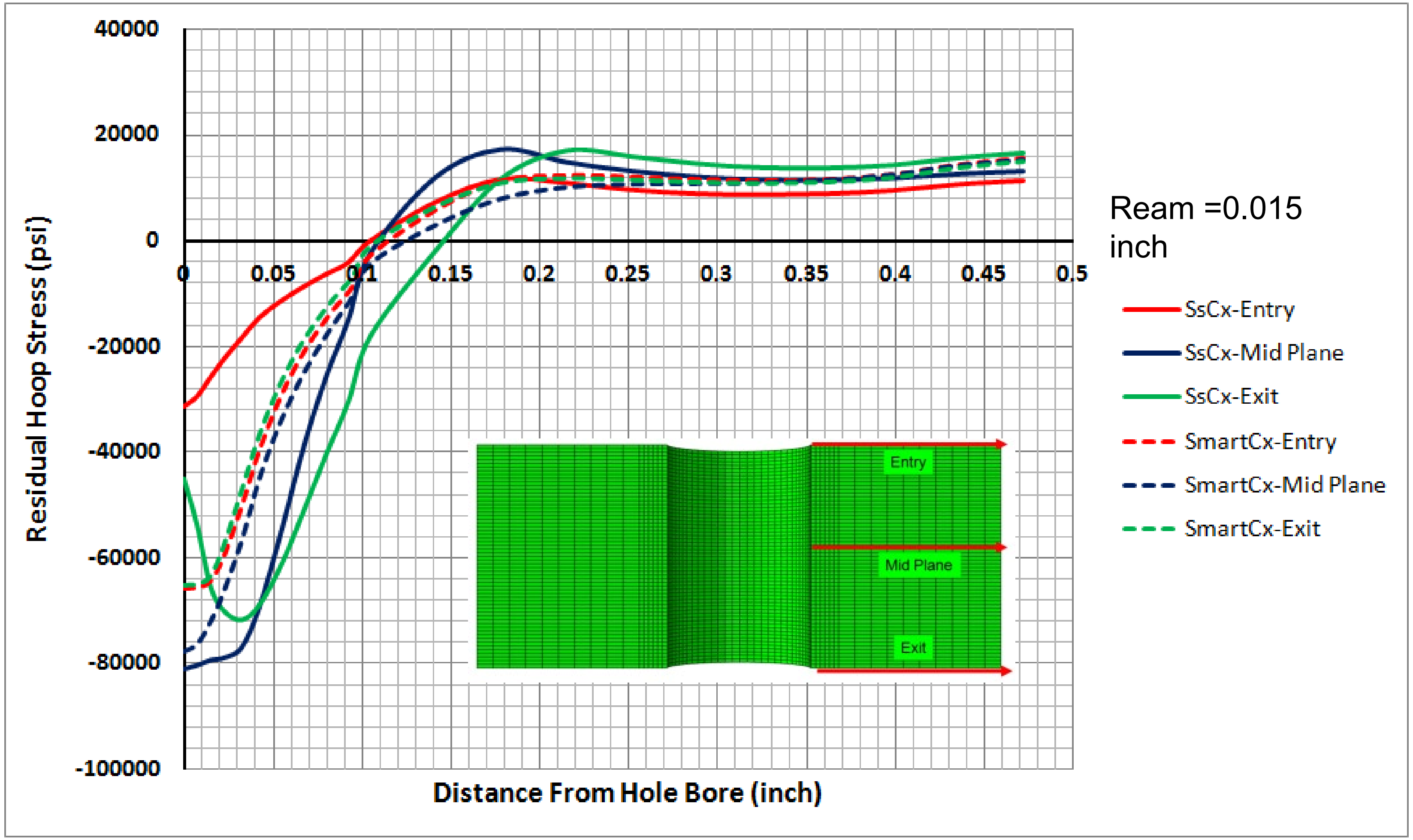
Process Model Comparison

SsCx | SmartCx

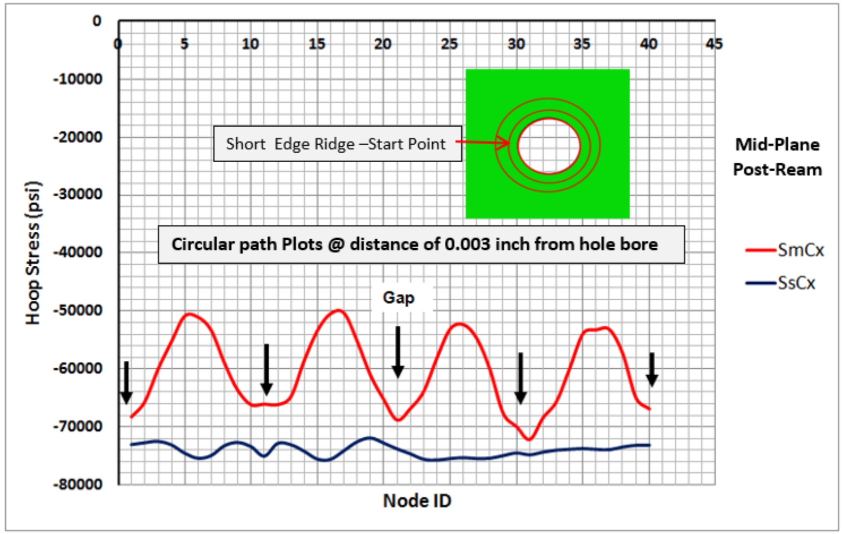


Post-Ream Compressive Hoop Stress (psi) – Contour Plot

Process Model Comparison



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



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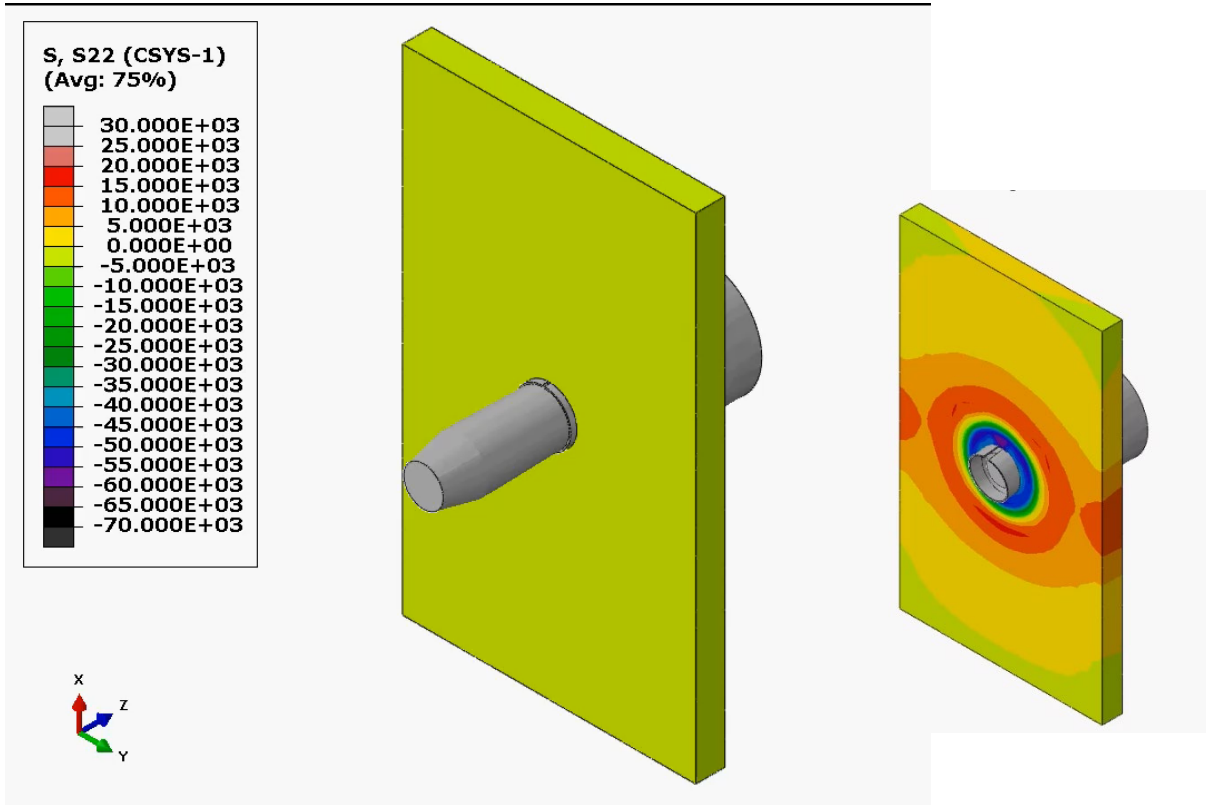
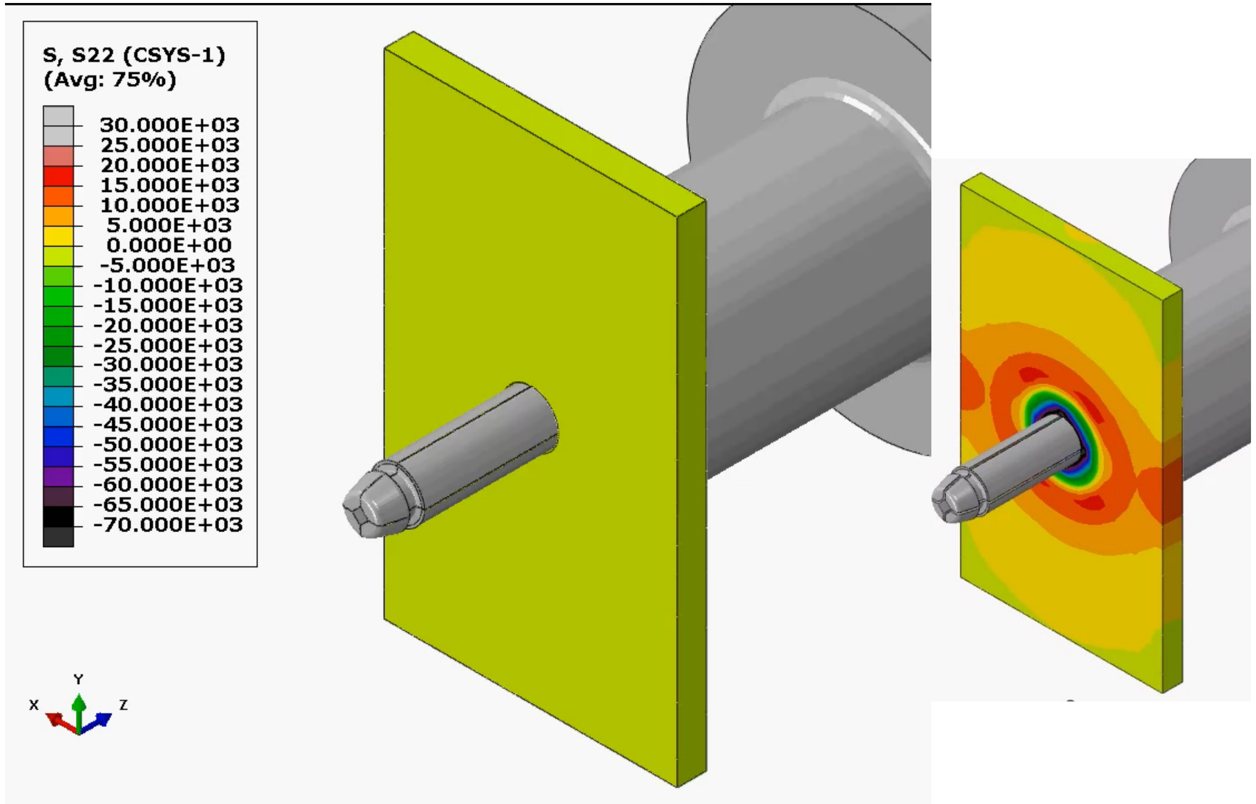
Process Model Animation

SsCx



SmartCx



<u>Parameters</u>
6-3-N tooling (or equivalent)
7010-T7651

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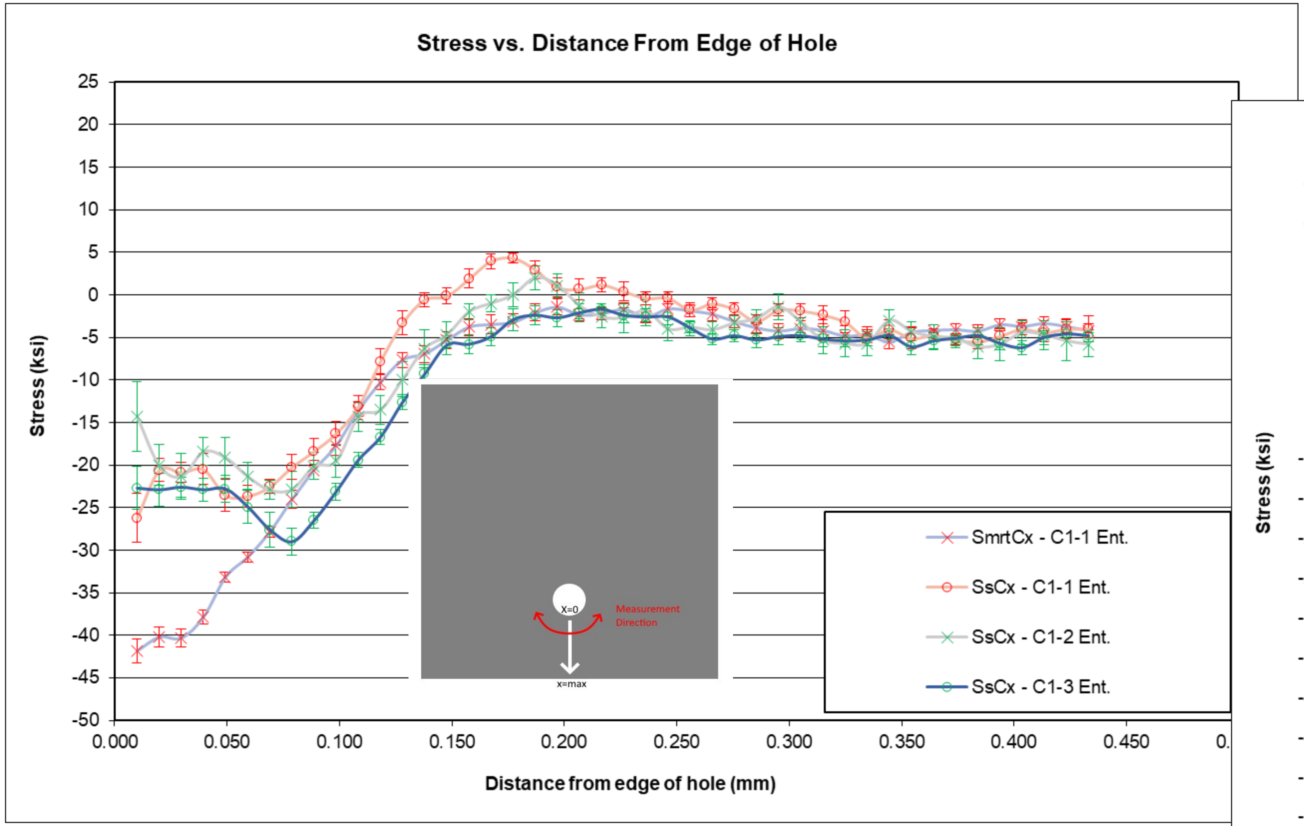
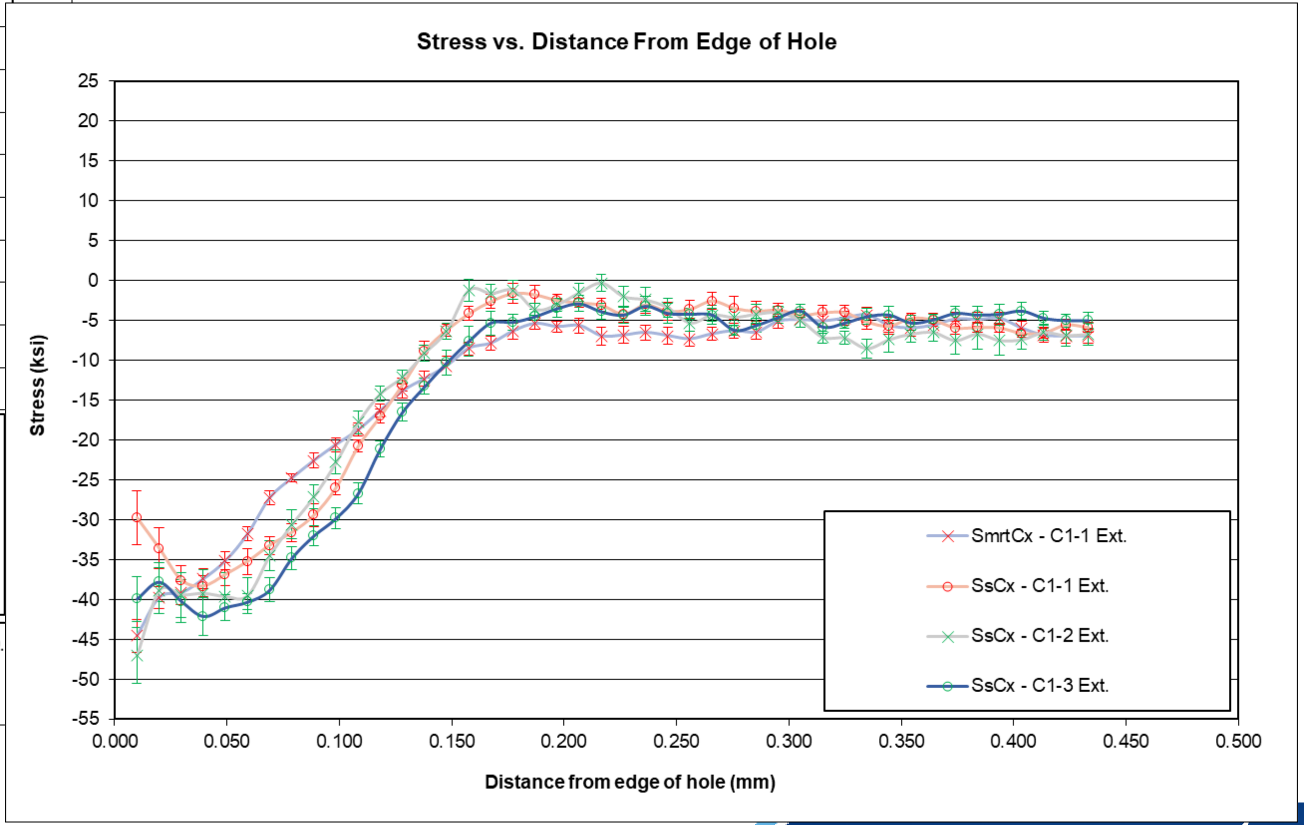
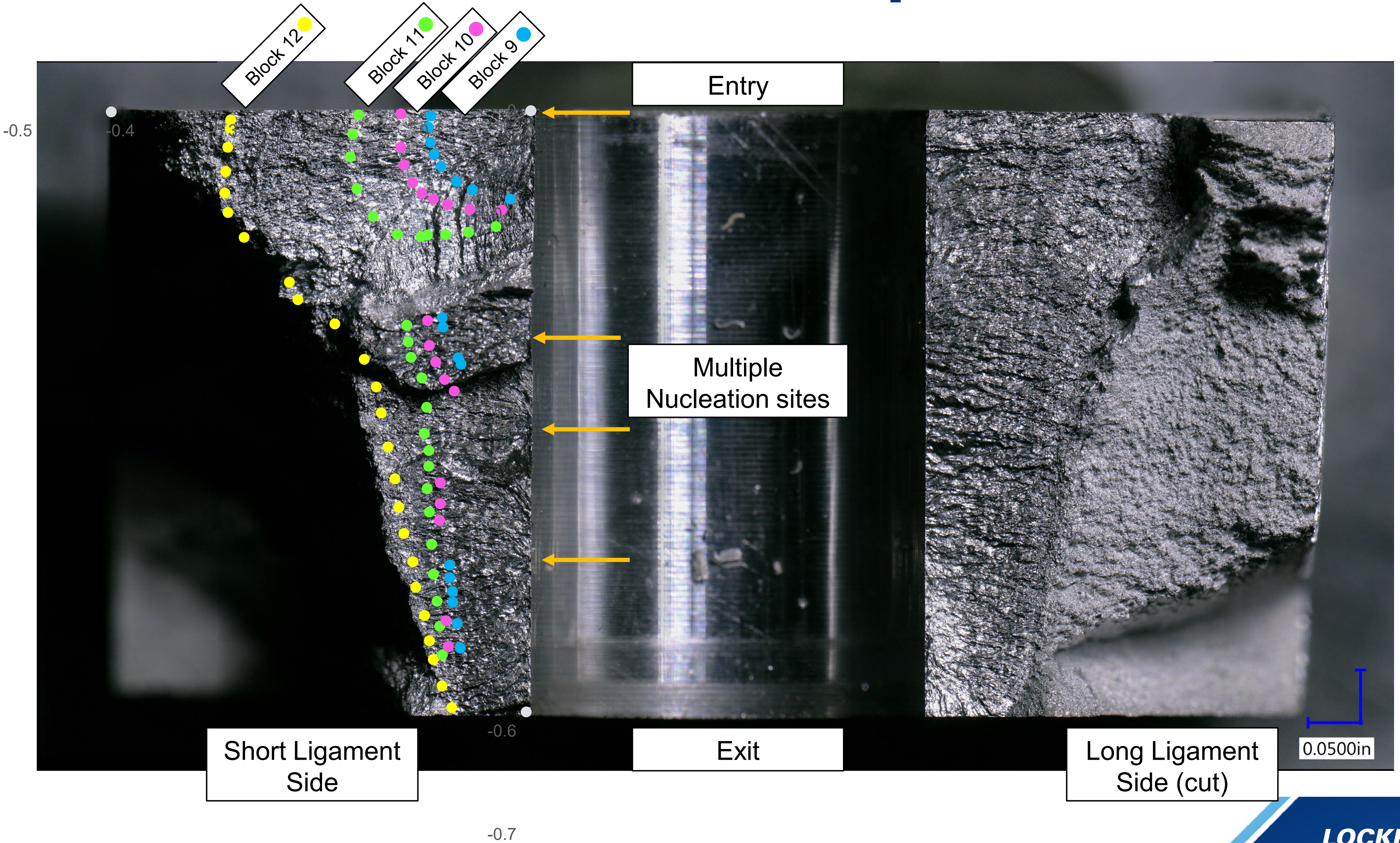
Residual Stress Prediction Comparisons

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





QF of "C" Matrix Test Coupon - SsCx™



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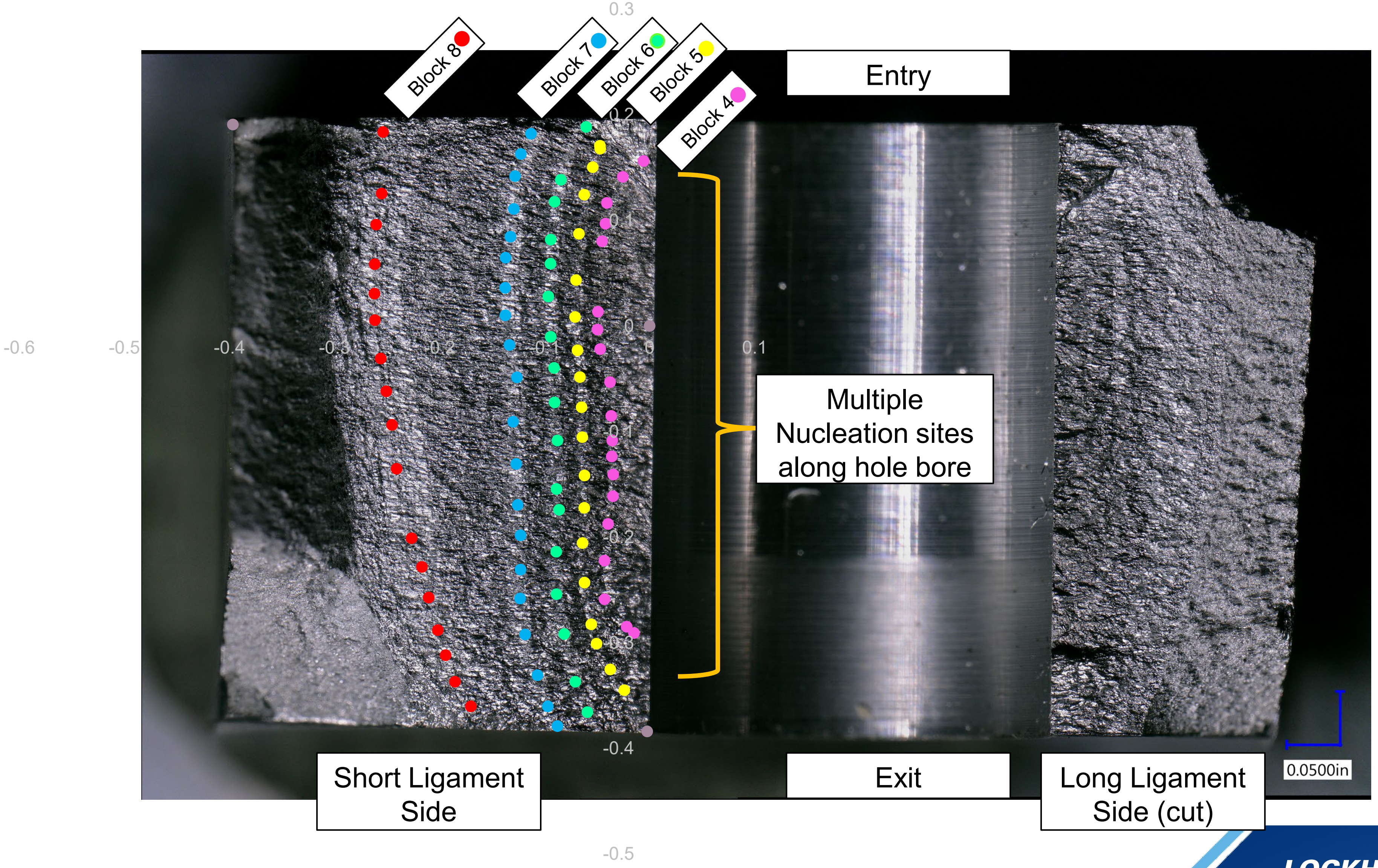
QF of "C" Matrix Test Coupon - SmrtCx™



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Towards a Validated Tool for Improving Fatigue Life Predictions after Cold Expansion

2025 ERSI Workshop – Layton, UT

Presented by: Scott Carlson
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Mr. James Prather (Lockheed Martin)
Dr. Thomas Mills (APES)
Dr. Guillame Renaud (NRC-Canada)

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Overview

1. Purpose of Improving Near-Bore Strain Measurements
2. Overview of Previous 2-inch SsCx DIC results
    1. How close did we get to the bore
    2. What limitations did this provide from a FEA simulation validation point of view
    3. MatchID validation results
3. Experimental Set-up
    1. Overview of DIC setup
    2. Overview of the SsCx process
    3. DIC Data Collection
4. Results
5. Development of Methods for Data Analysis for FEA simulations
6. Conclusion/Path Forward

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

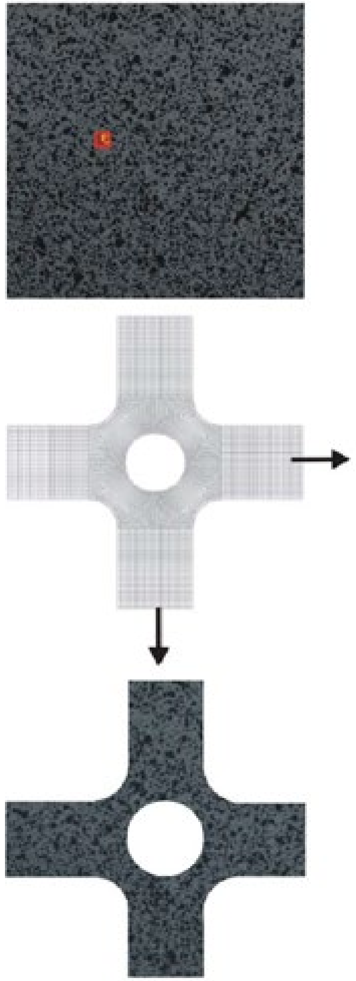

Fig. 1. Distorted reference speckle pattern[1]

[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)*

2inch Cx Coupon
2024-T351 ”Low” Applied Expansion
SsCx Entry Face

FTI Tool Set = 16-0-N
Thickness = 0.25inch
Starting Hole Dia = 0.4770inch

5

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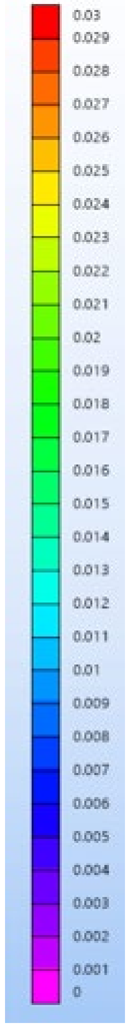
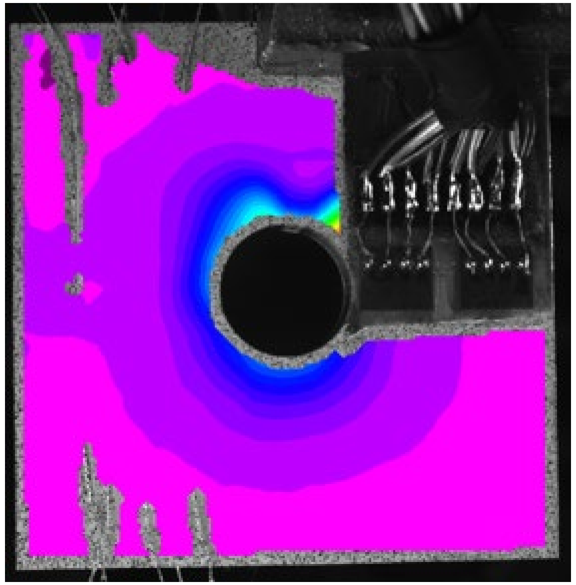
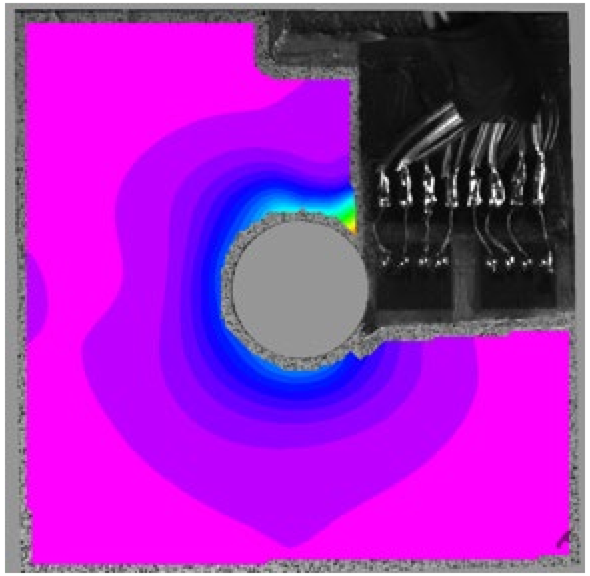
CHAB – Entry (ϵ_1)



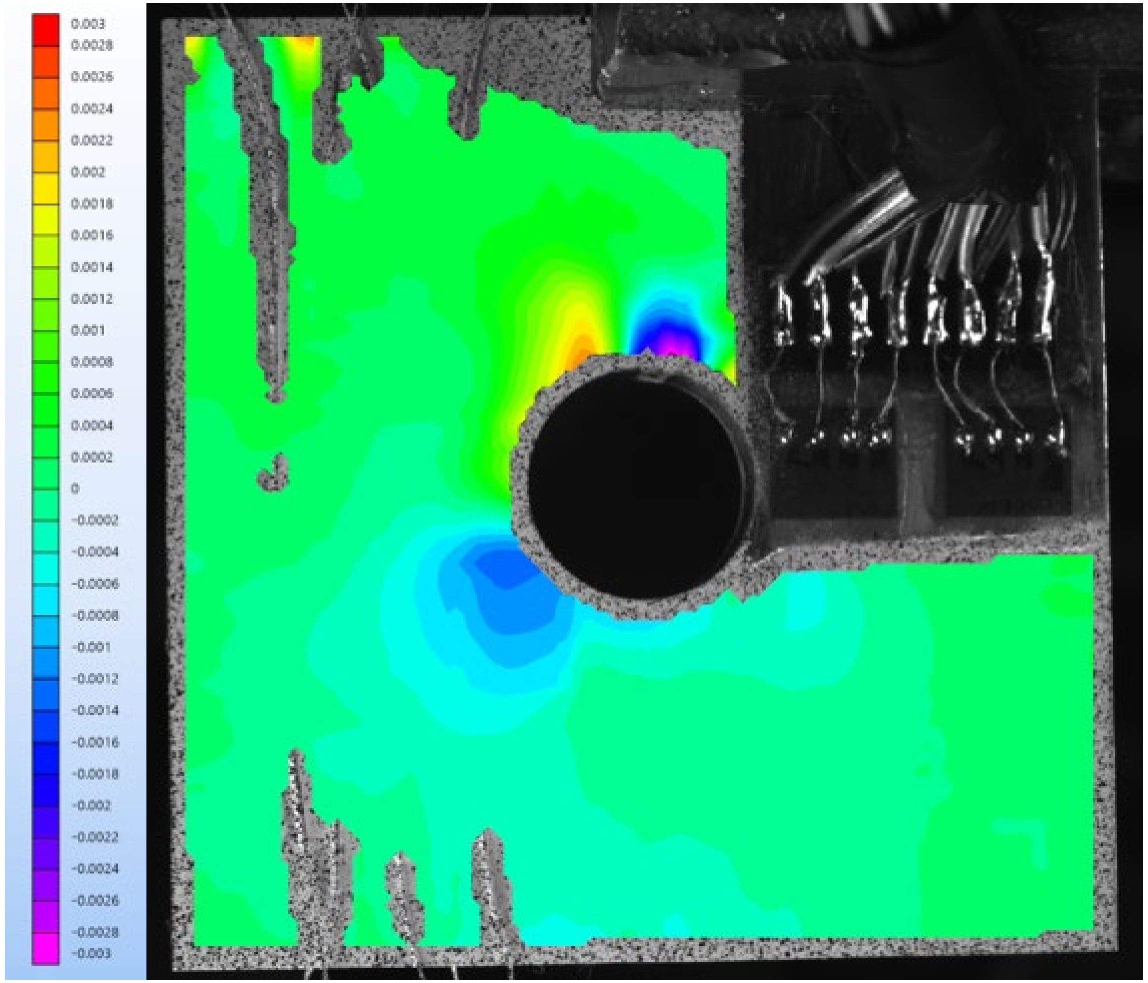
DIC



FEA



Validation (DIC-FEA)



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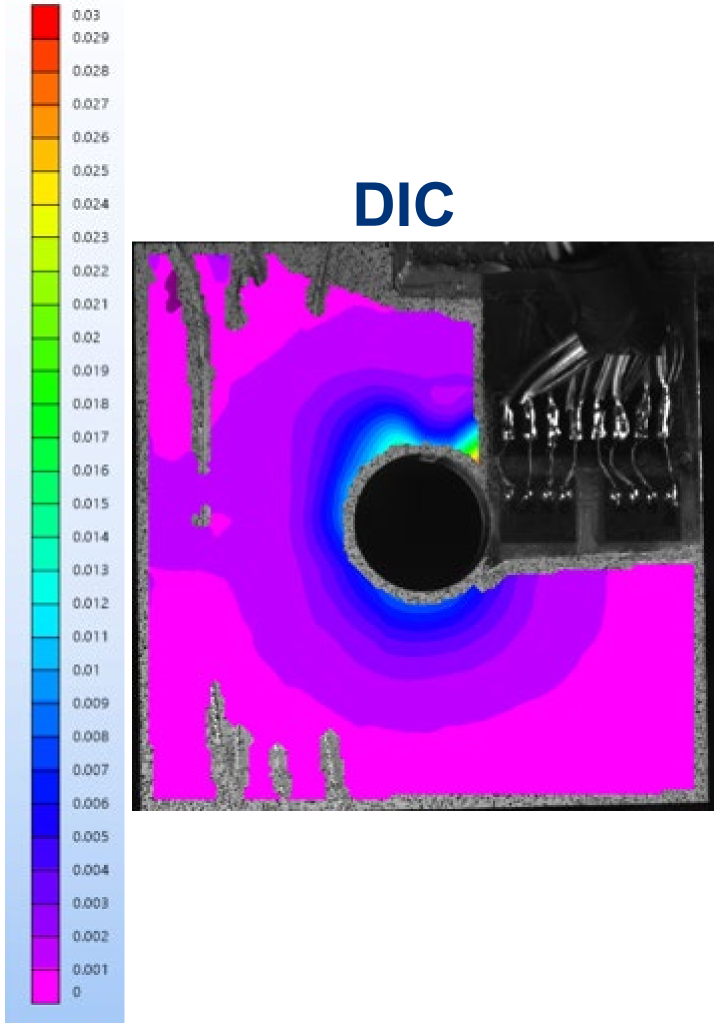
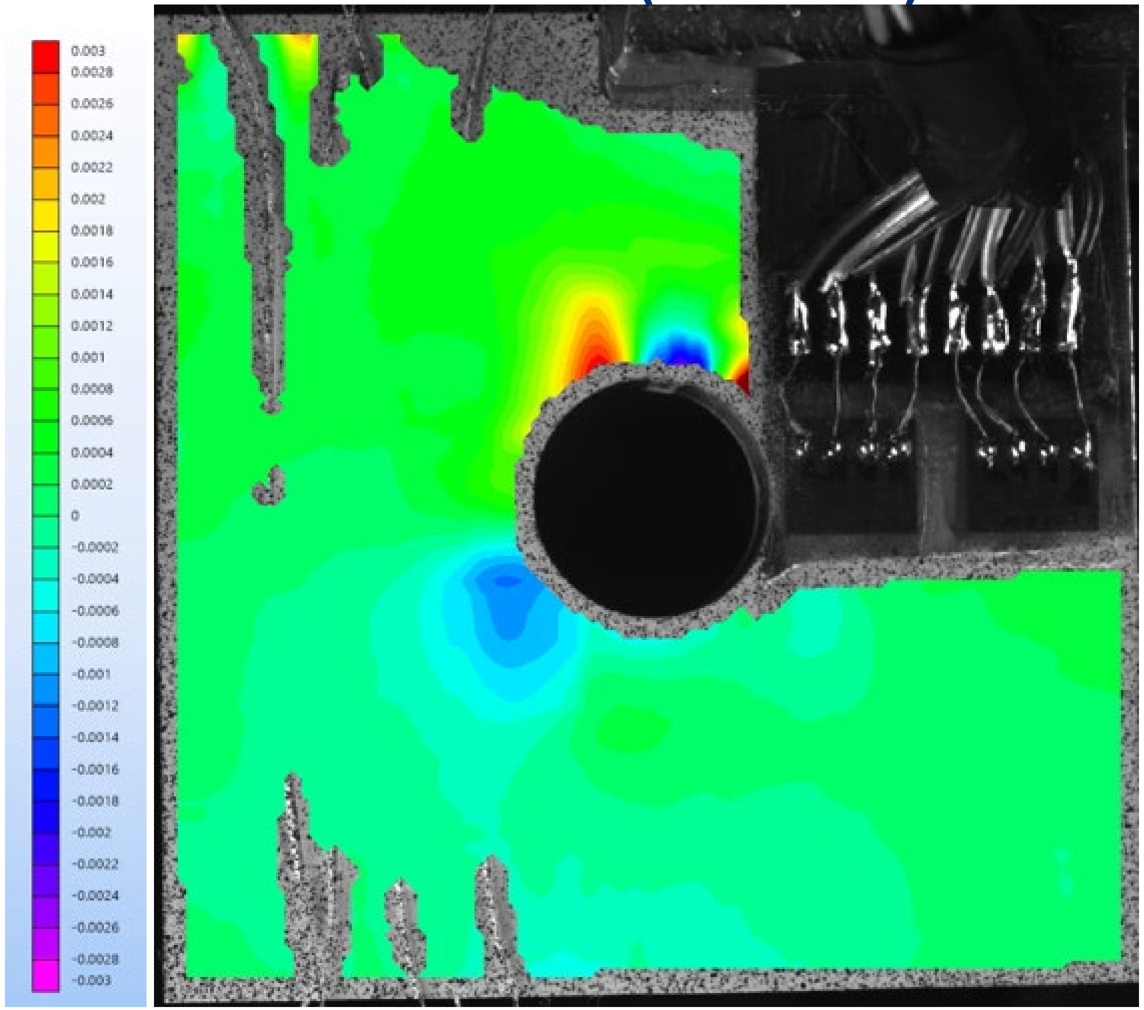
COMB – Entry (ϵ_1)

DIC **FEA**



Validation (DIC-FEA)



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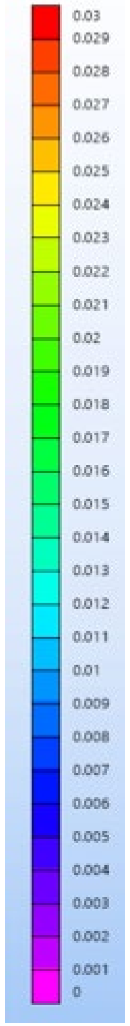
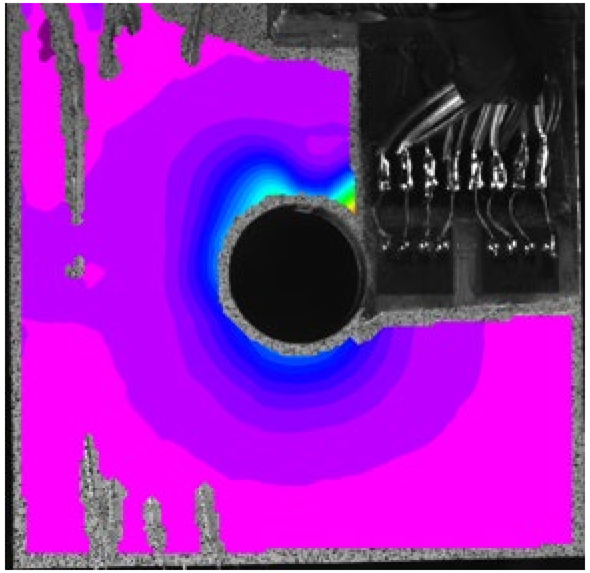
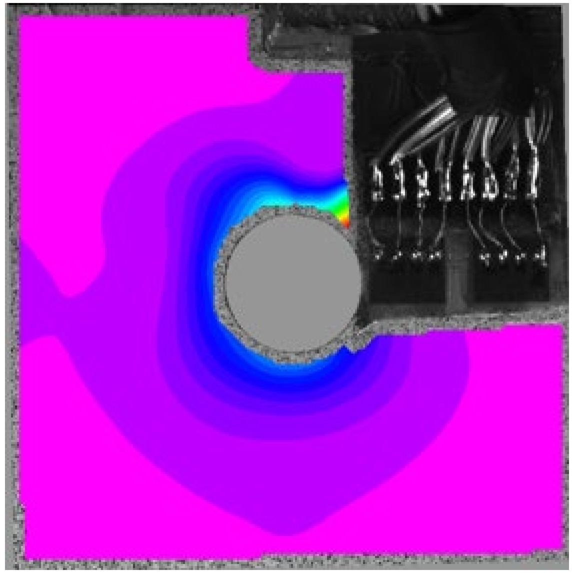
ISO – Entry (ϵ_1)



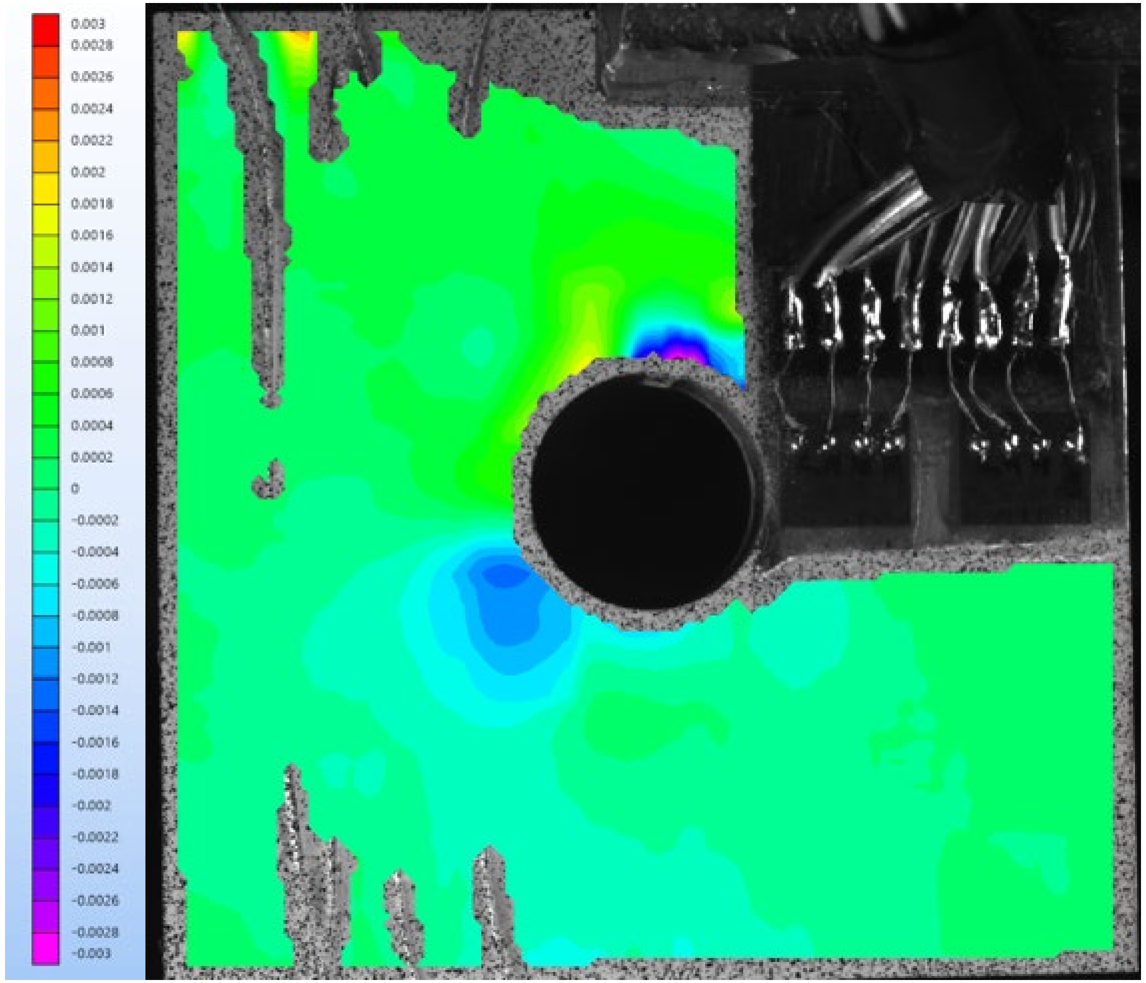
DIC



FEA



Validation (DIC-FEA)



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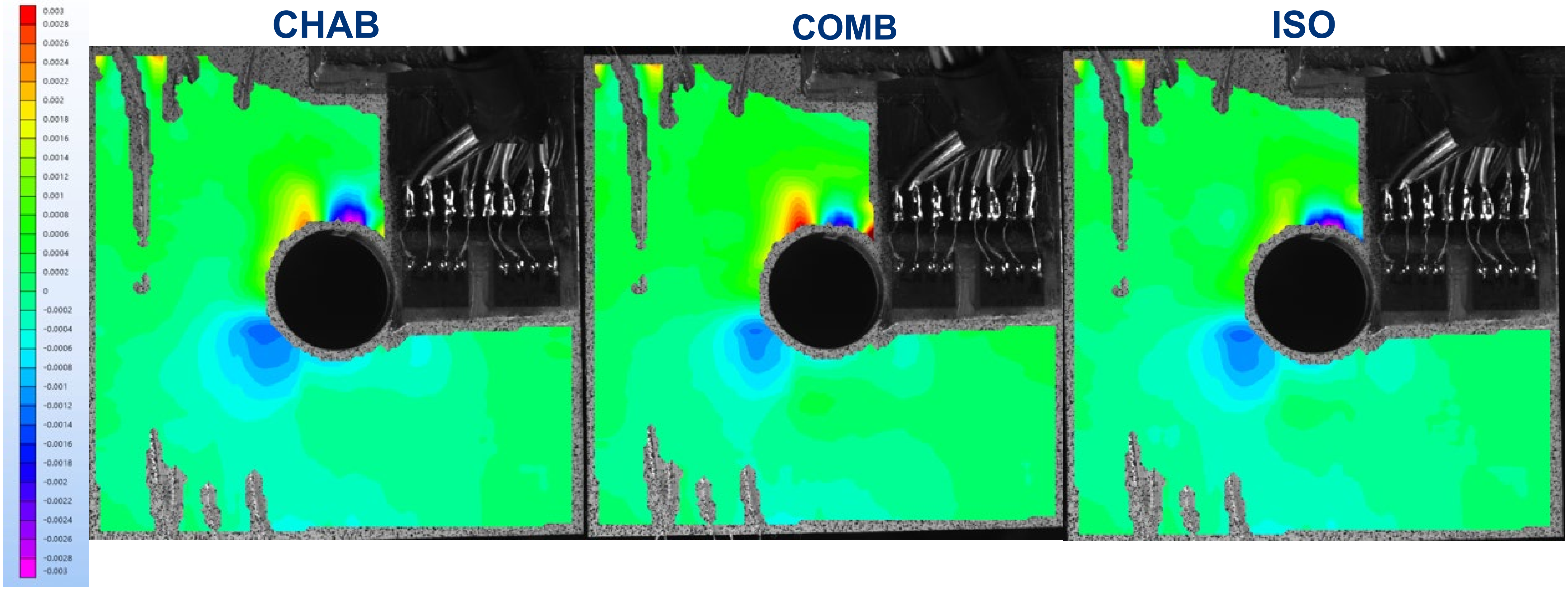
Validation Comparison (ϵ_1)



Validation Statistics (ϵ_1)

Model	Average ($\mu\varepsilon$)	Standard Deviation ($\mu\varepsilon$)
CHAB	264	311
COMB	286	344
ISO	235	270

Validation Statistics (ϵ_1)

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6. Conclusion/Path Forward

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Overview of Test Fixturing

2D HIGH Mag:

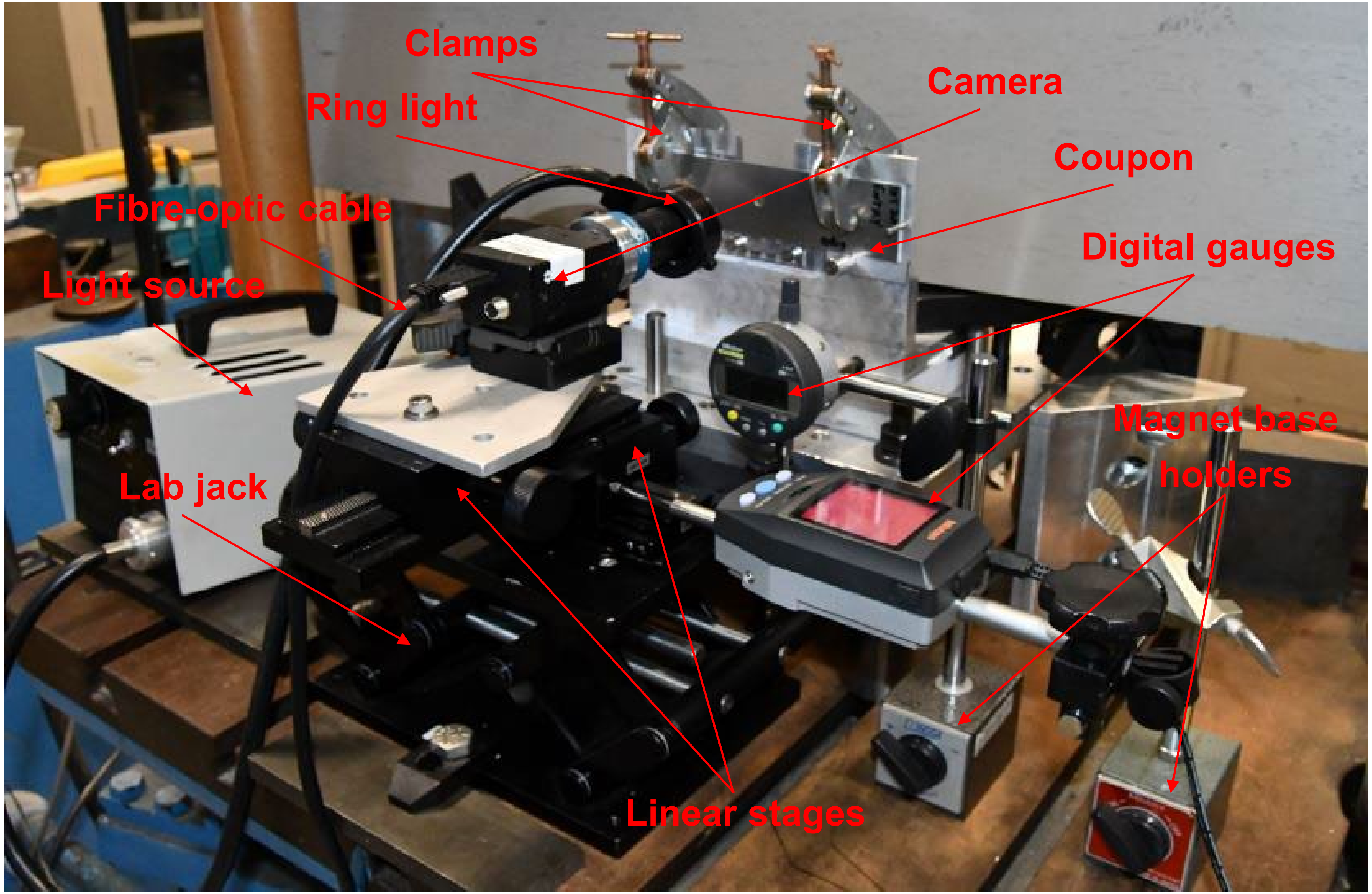
- Scale: 383 pixel/mm

2D LOW Mag:

- Scale: 101 pixel/mm

3D DIC:

- Scale: 37 pixel/mm



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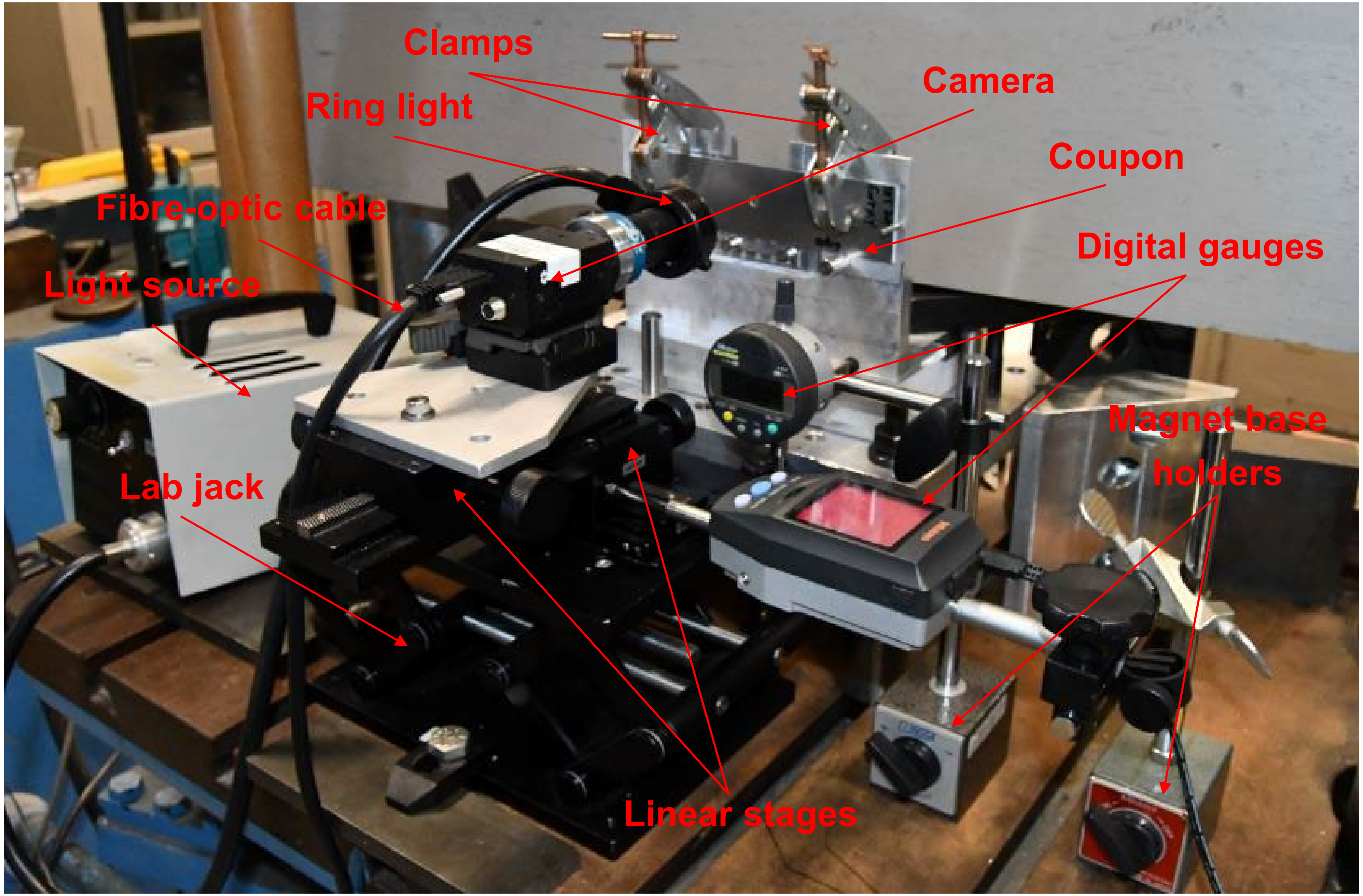
2D DIC [High Mag] Test Setup



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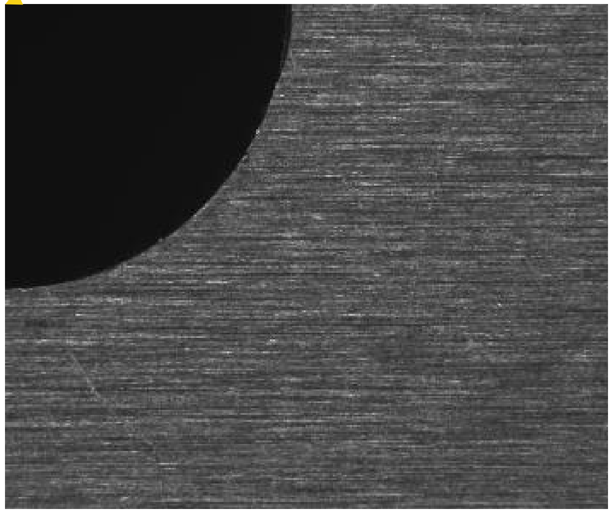
3D DIC Test Setup

- *Avg Mag: 37 pixel/mm*
- *Standoff distance: 170 mm*
- *Baseline: 83.8 mm*
  Alpha: $0.15°$
  Beta: $33.01°$
  Gamma: $-0.35°$

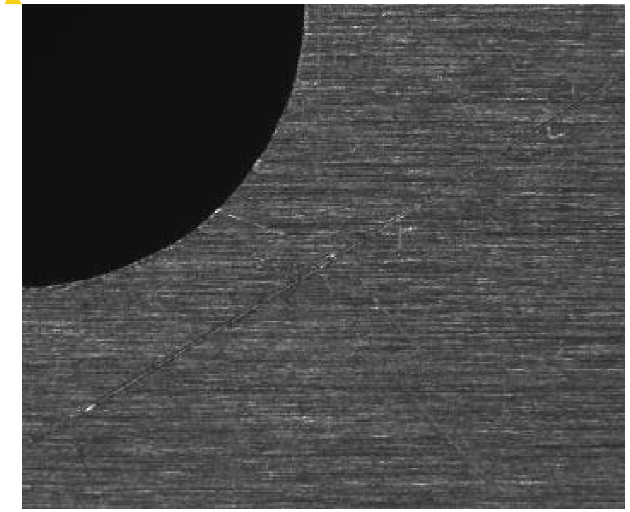
Modified 2D High Magnification setup

- High precision camera adjustment
- Image tracking using FIJI
- Precision adjustment based on imaging results
- Final center position [+/- 26 microns]
- Allows for precise determination of distance to edge of hole from DIC correlation

Center
(+/- 10 pix)



Entry



Exit

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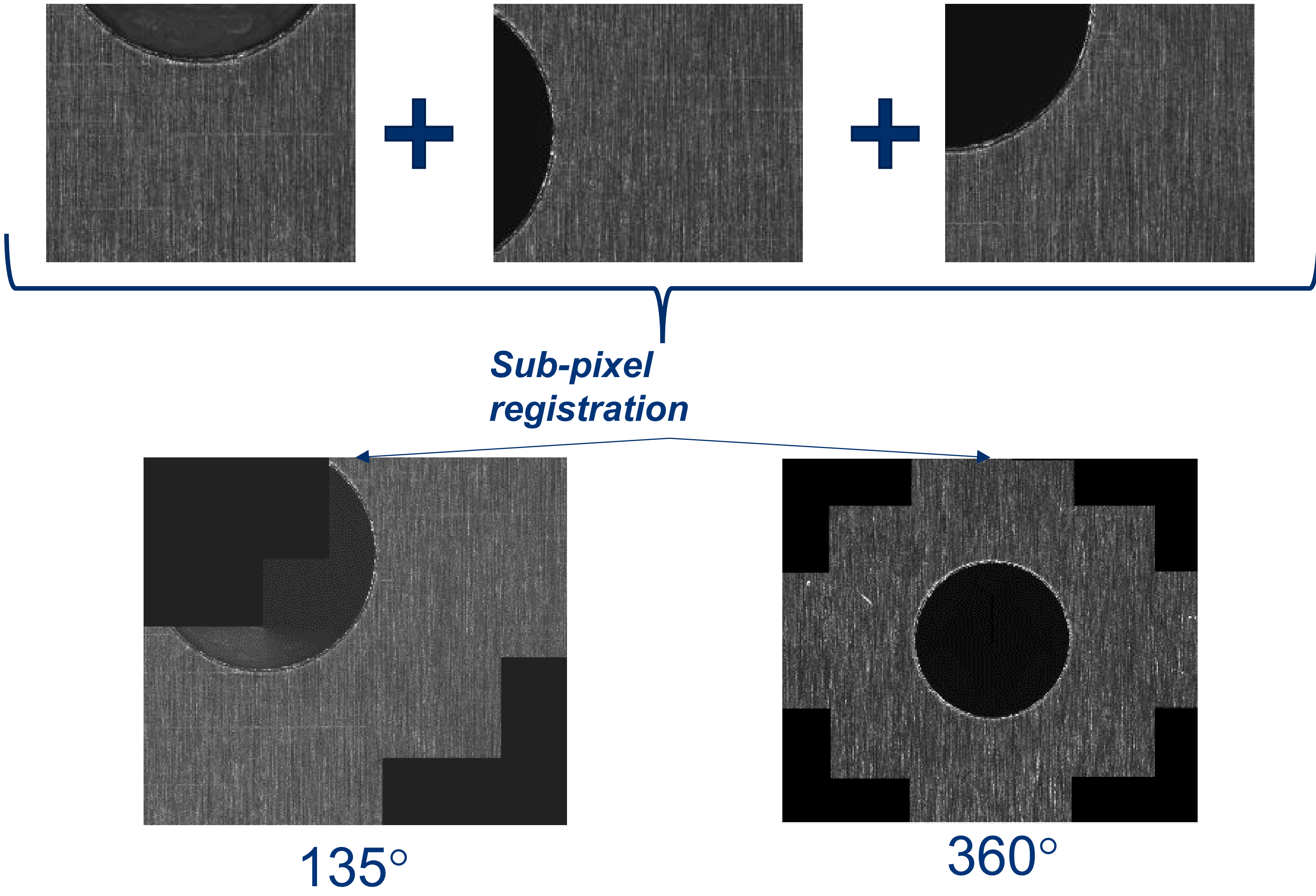
Super-Resolution DIC (SR-DIC)

- Multiple 6.4mm x 5.4 mm AOIs captured
- Images stitched together via sub-pixel registration algorithm
- DIC performed using composite reference and deformed images
- Enables full-field, high resolution strain characterization



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Validation Testing

- Difficult to validate strain accuracy…easier to focus on displacement
- Method would ideally incorporate speckle pattern & lens from test
- Concept: Use gauge shims to displace coupon & measured disp. w/DIC
- Gauge shims measured with calibrated micrometer
- Calculate Difference: DIC Measured Displacement – Actual Displacement
- Plot difference versus S.D $\boldsymbol{\sigma} = \pm[\boldsymbol{MAX}(\boldsymbol{\sigma_{DIC}}) + \boldsymbol{MAX}(\boldsymbol{\sigma_{micrometer}})]$

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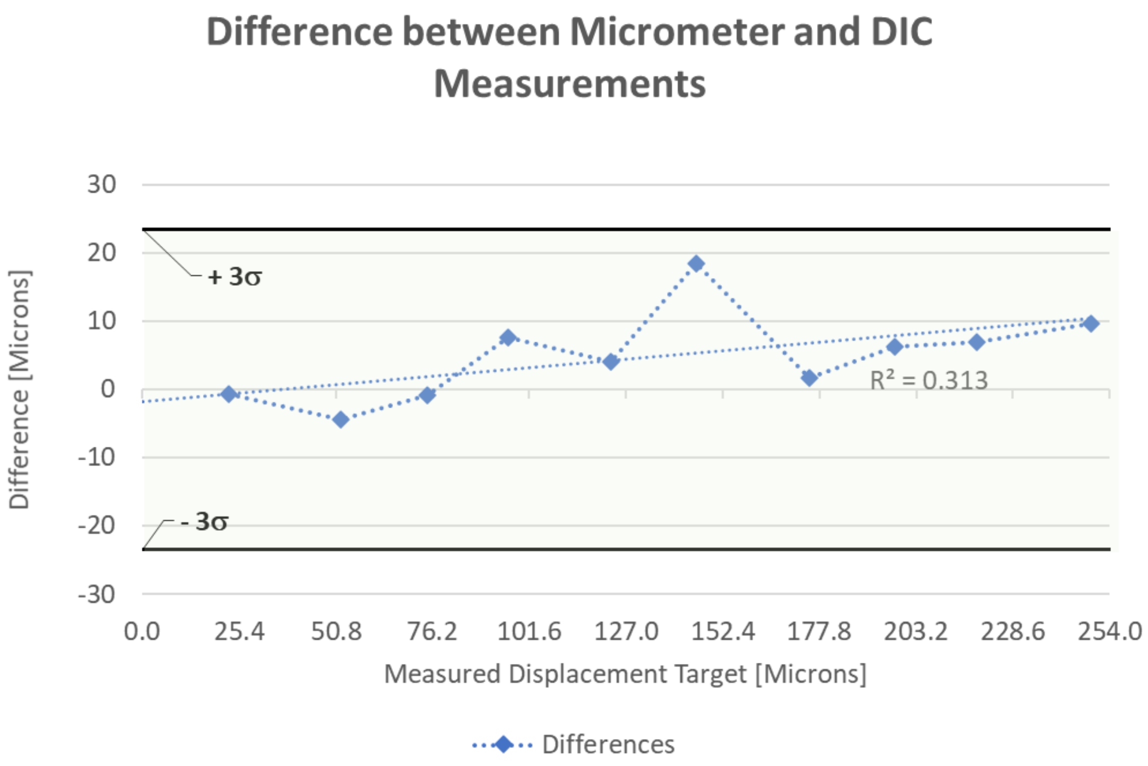
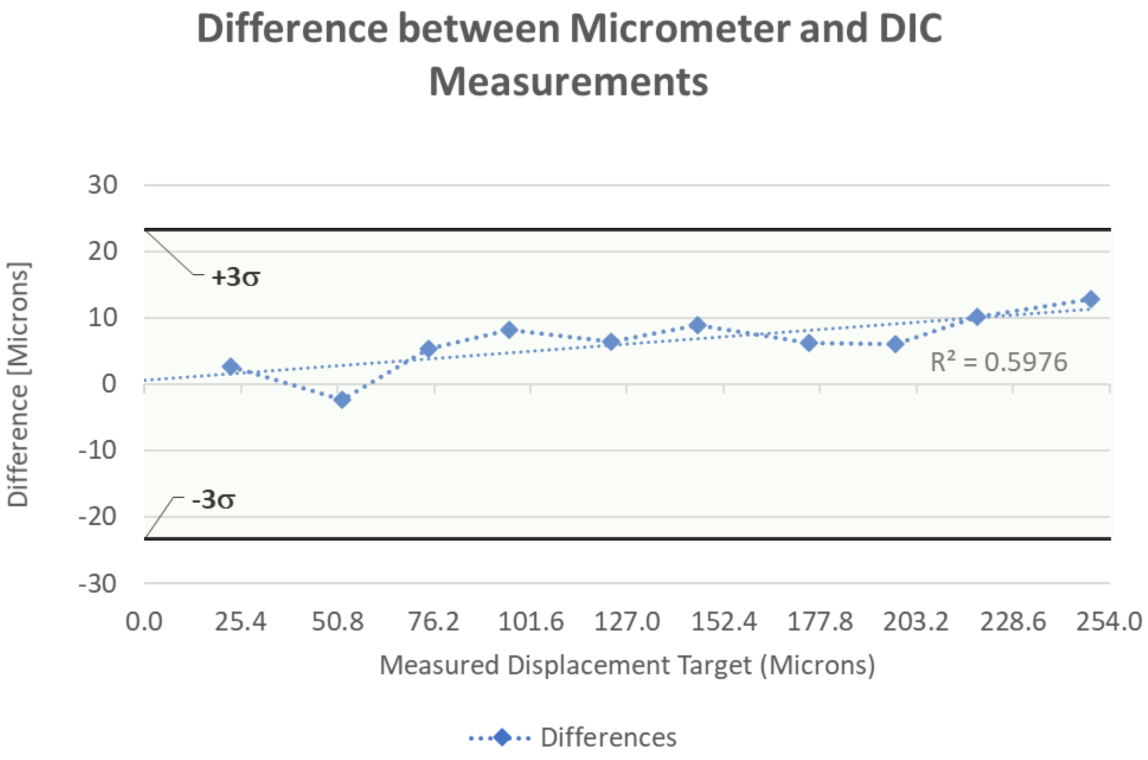
Rigid Body Displacement Testing - Setup

2D High Mag DIC Validation Results

ENTRY FACE



EXIT FACE



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Overview

1. **Purpose of Improving Near-Bore Strain Measurements**
2. **Overview of Previous 2-inch SsCx DIC results**
3. **Experimental Set-up**
4. **Results**
    1. 2024 Coupons
        1. 2D Low
        2. 2D High
        3. 3D High
        4. 2D SR (135°)
        5. 2D SR (360°)
    2. 7050 Coupons
5. **Development of Methods for Data Analysis for FEA simulations**
6. **Conclusion/Path Forward**

BT12 – 2D DIC LOW Mag

2024-T3

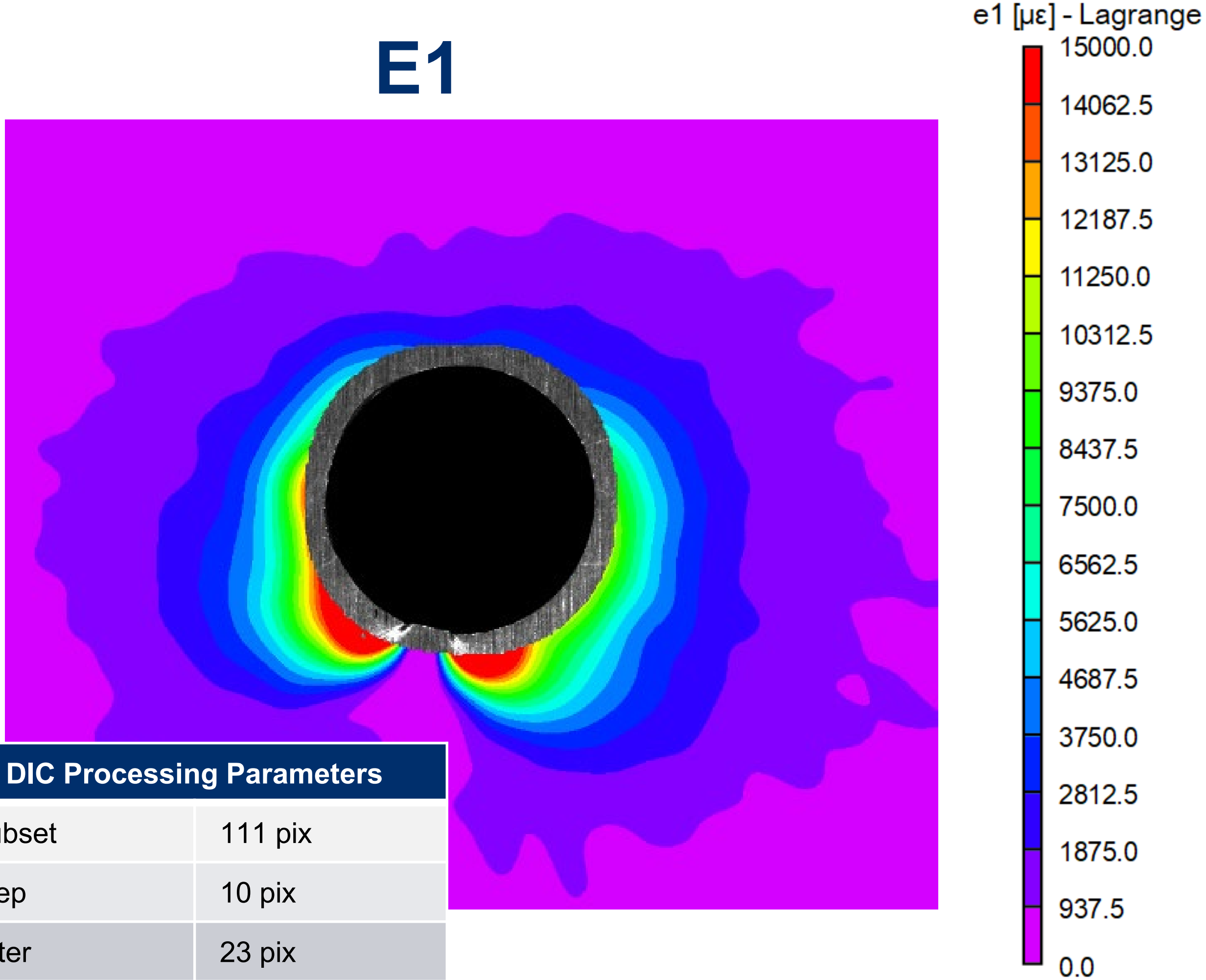
Thickness = 0.063inch

Starting Hole Diameter = 0.2377inch

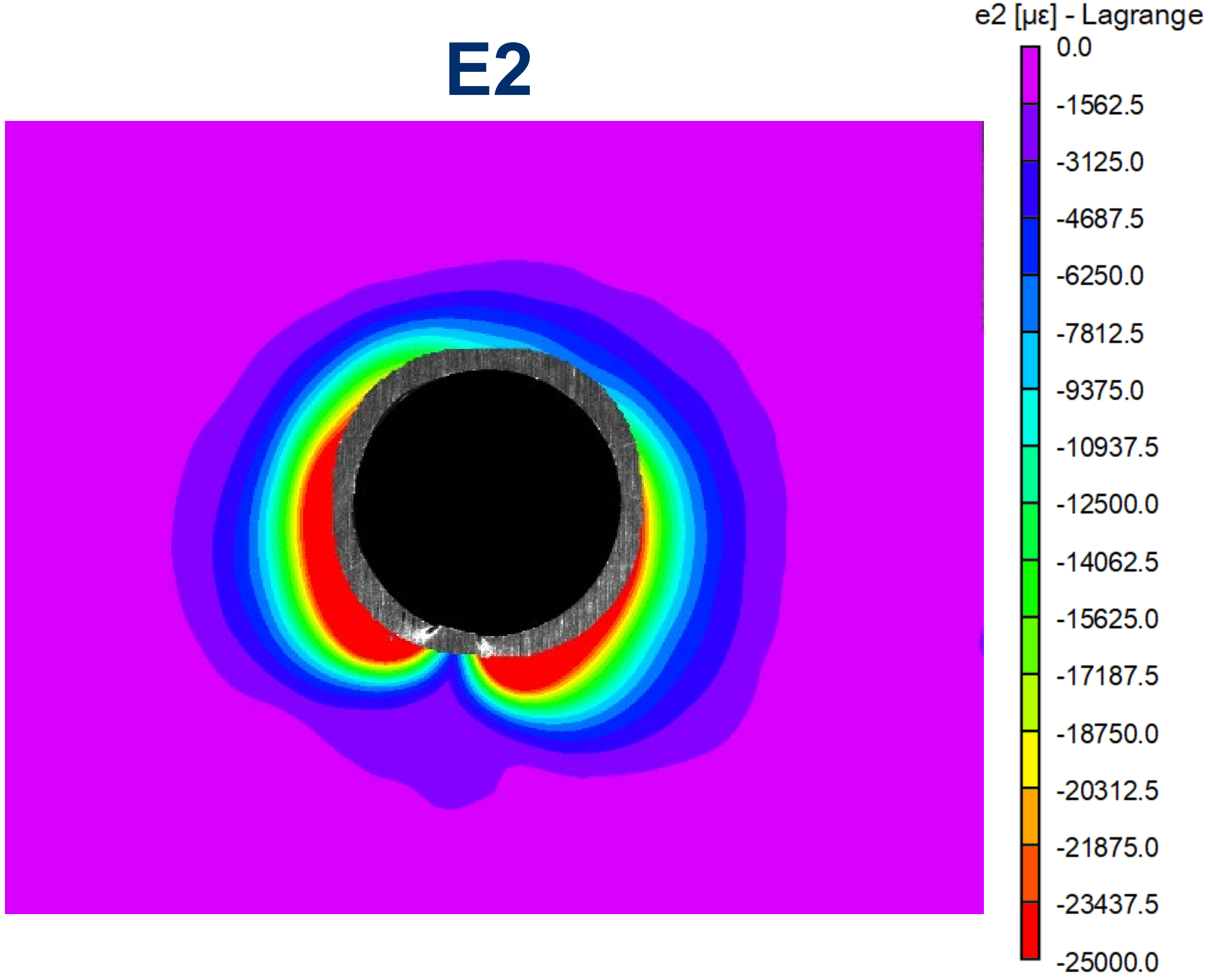
FTI Toolset:

BT12 – Entry Post Cx

E1



E2



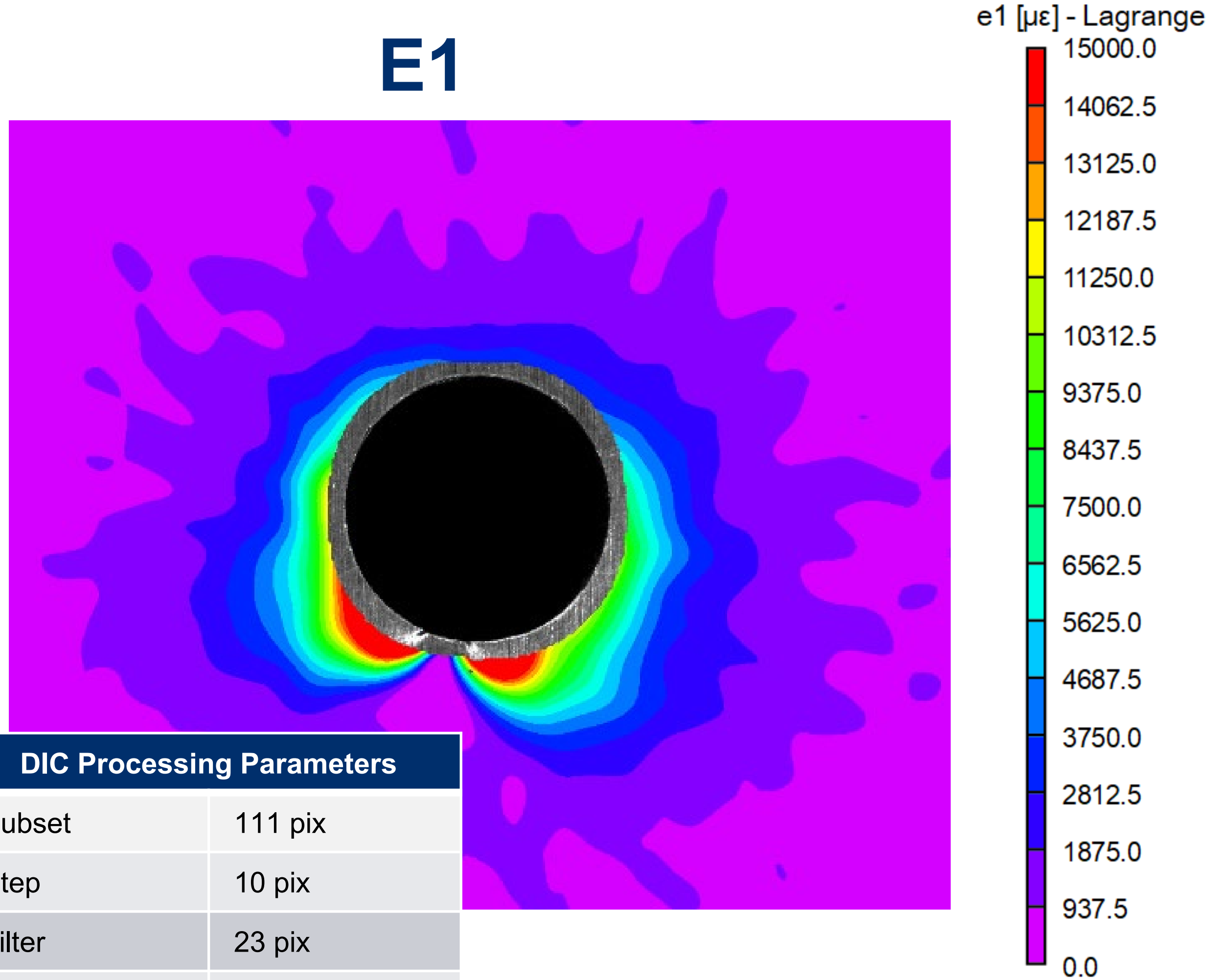
DIC Processing Parameters	
Subset	111 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (2.3 mm)**

Split rotated 12.5° from 6 o'clock orientation

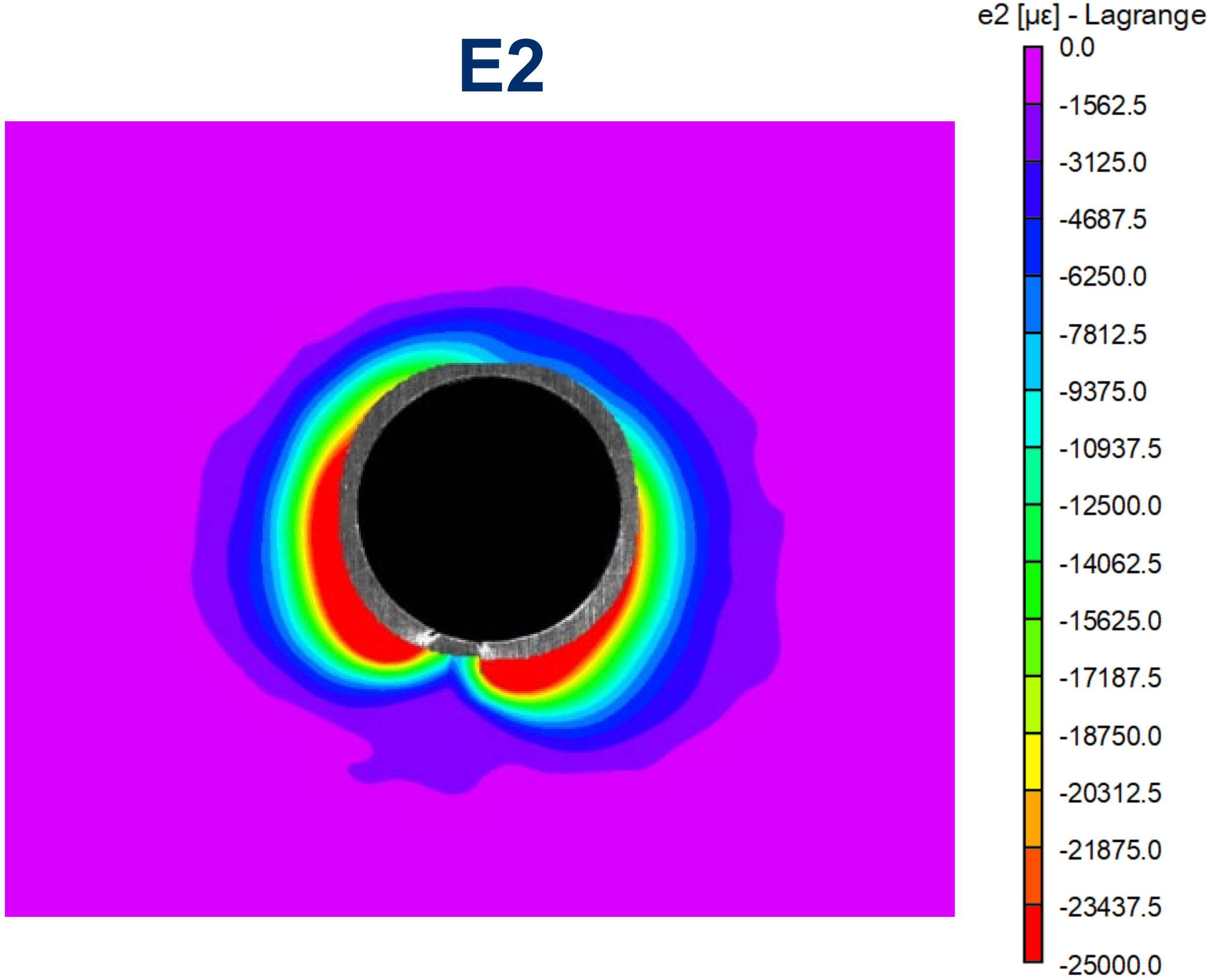
LOCKHEED MARTIN

BT12 – Entry Post Ream

E1



E2

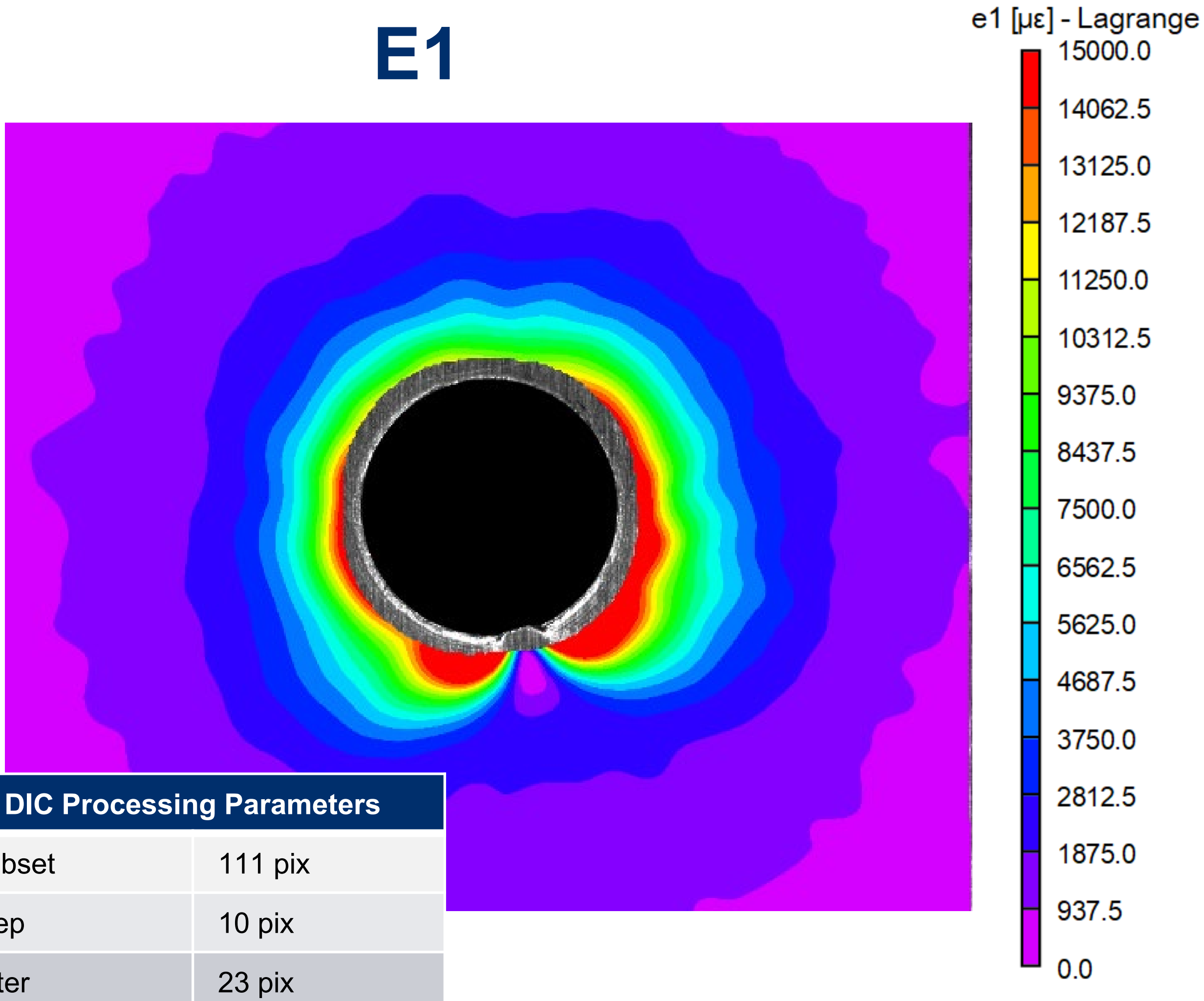


DIC Processing Parameters	
Subset	111 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (2.3 mm)**

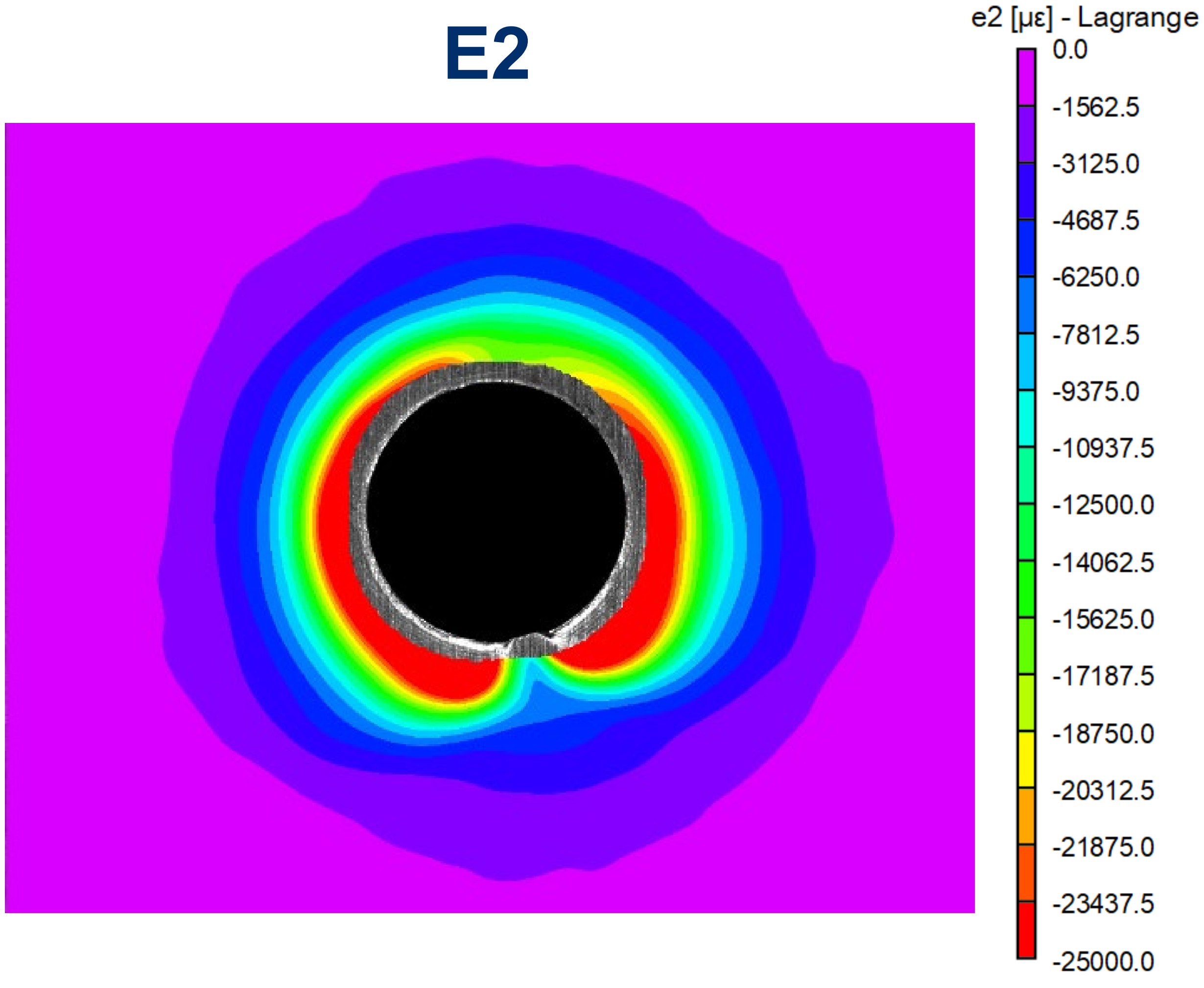
Split rotated 12.5° from 6 o'clock orientation

BT12 – Exit Post Cx

E1



E2

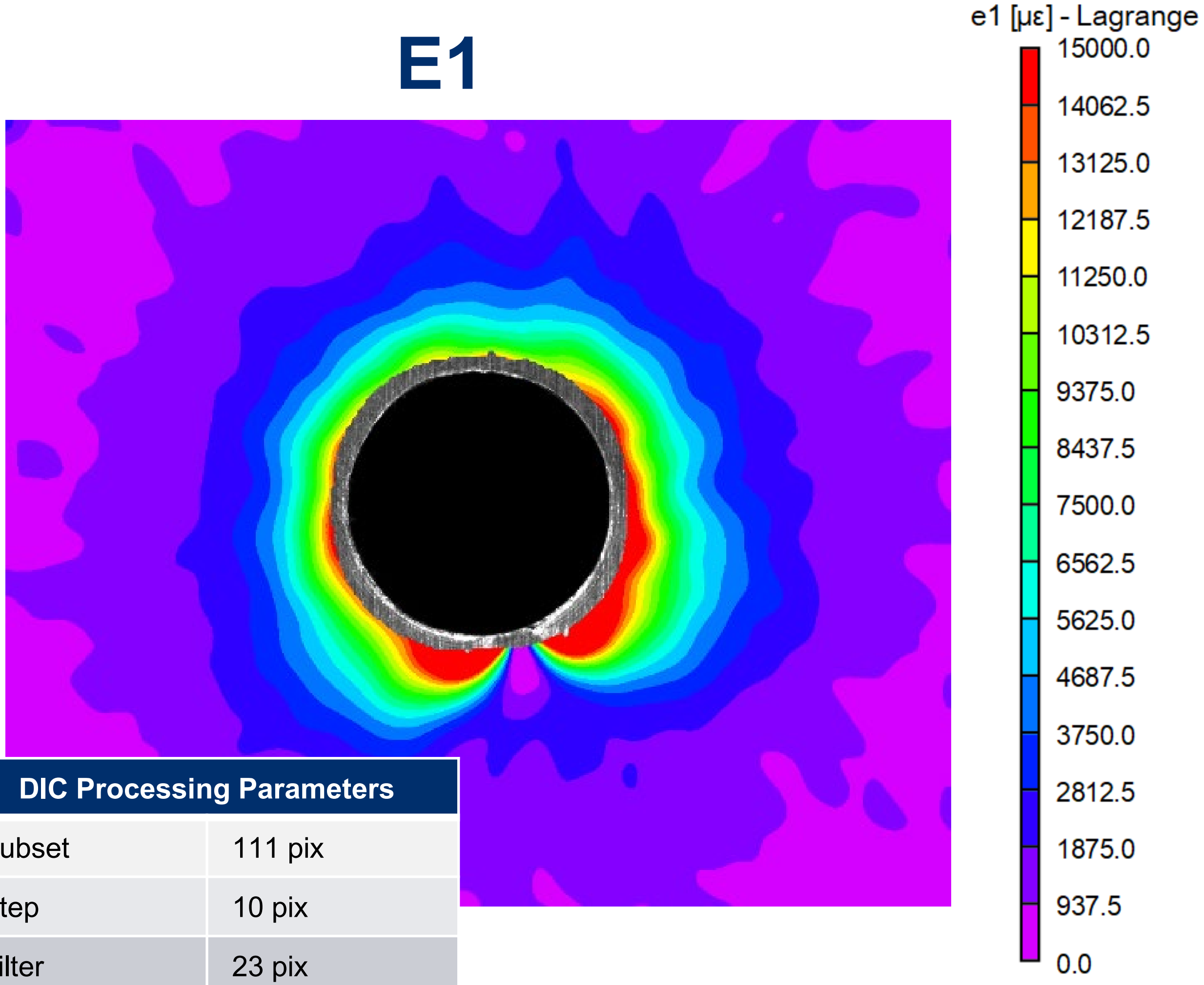


DIC Processing Parameters	
Subset	111 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (2.3 mm)**

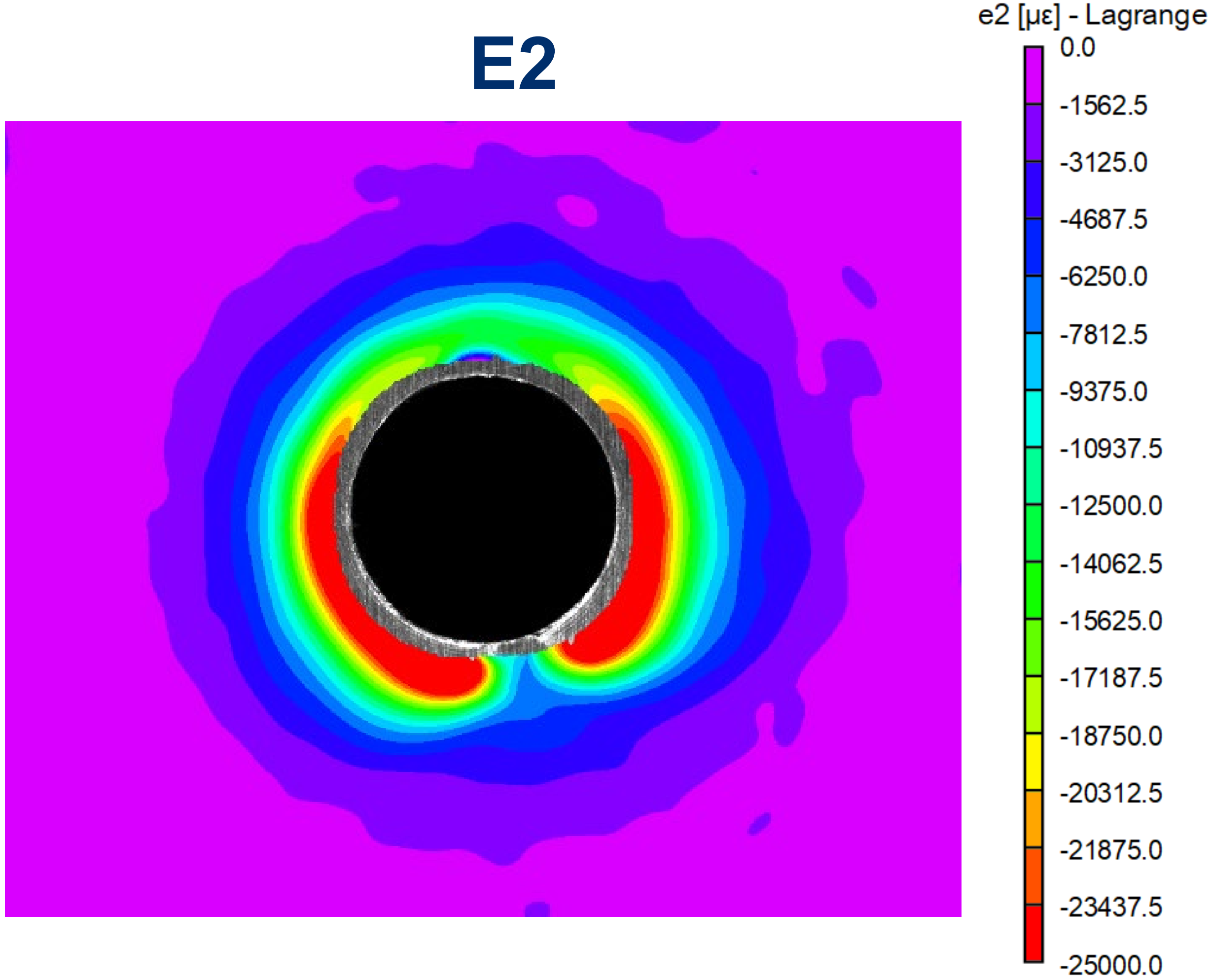
Split rotated 12.5° from 6 o'clock orientation

BT12 – Exit Exit Post Ream

E1



E2



DIC Processing Parameters	
Subset	111 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (2.3 mm)**

Split rotated 12.5° from 6 o'clock orientation

LOCKHEED MARTIN

Overview

1. **Purpose of Improving Near-Bore Strain Measurements**
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        1. 2D Low
        2. 2D High
        3. 3D High
        4. 2D SR (135°)
        5. 2D SR (360°)
    2. 7050 Coupons
5. **Development of Methods for Data Analysis for FEA simulations**
6. **Conclusion/Path Forward**

BT15 – 2D DIC HIGH Mag

2024-T3

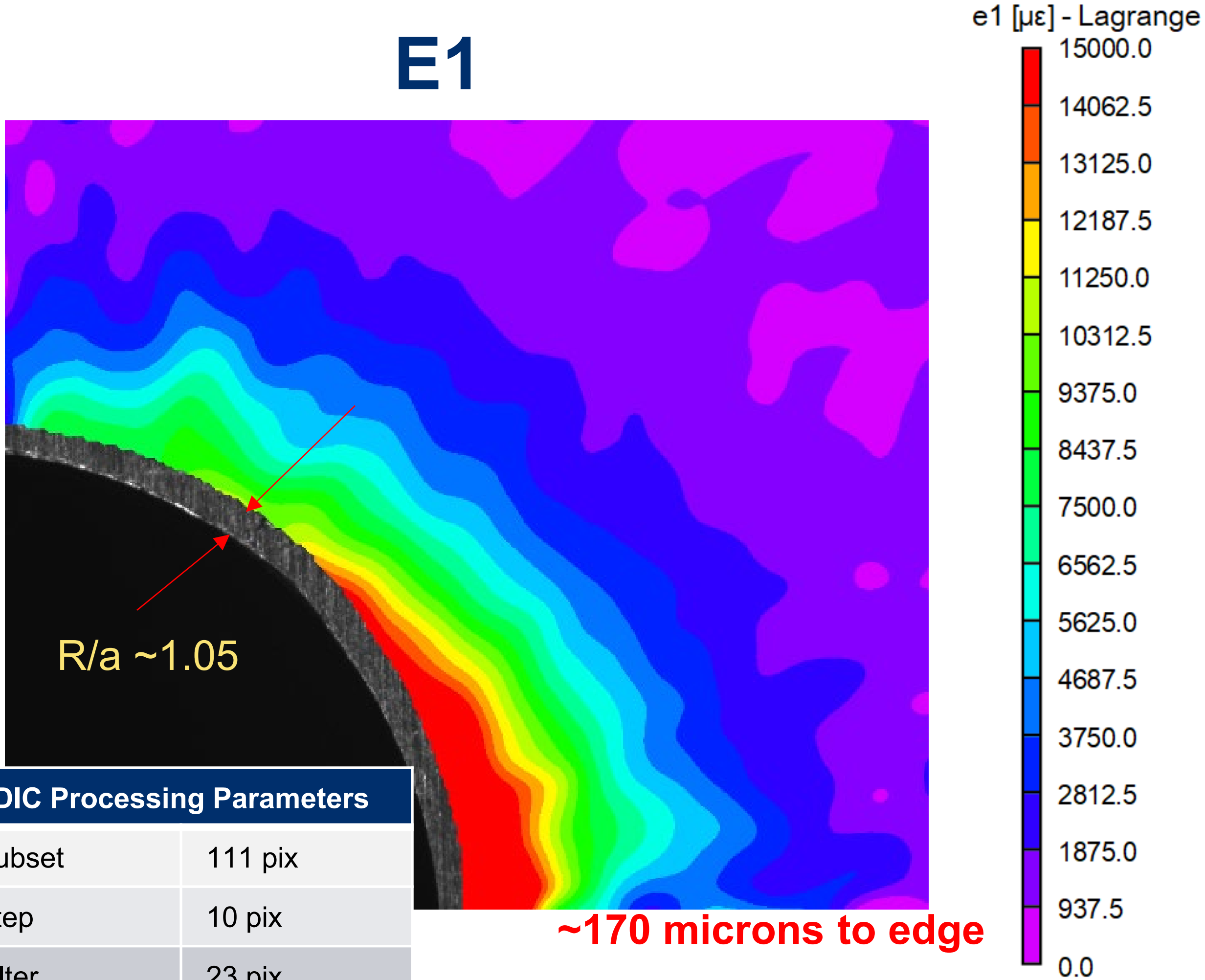
Thickness = 0.063inch

Starting Hole Diameter = 0.2376inch

FTI Toolset:

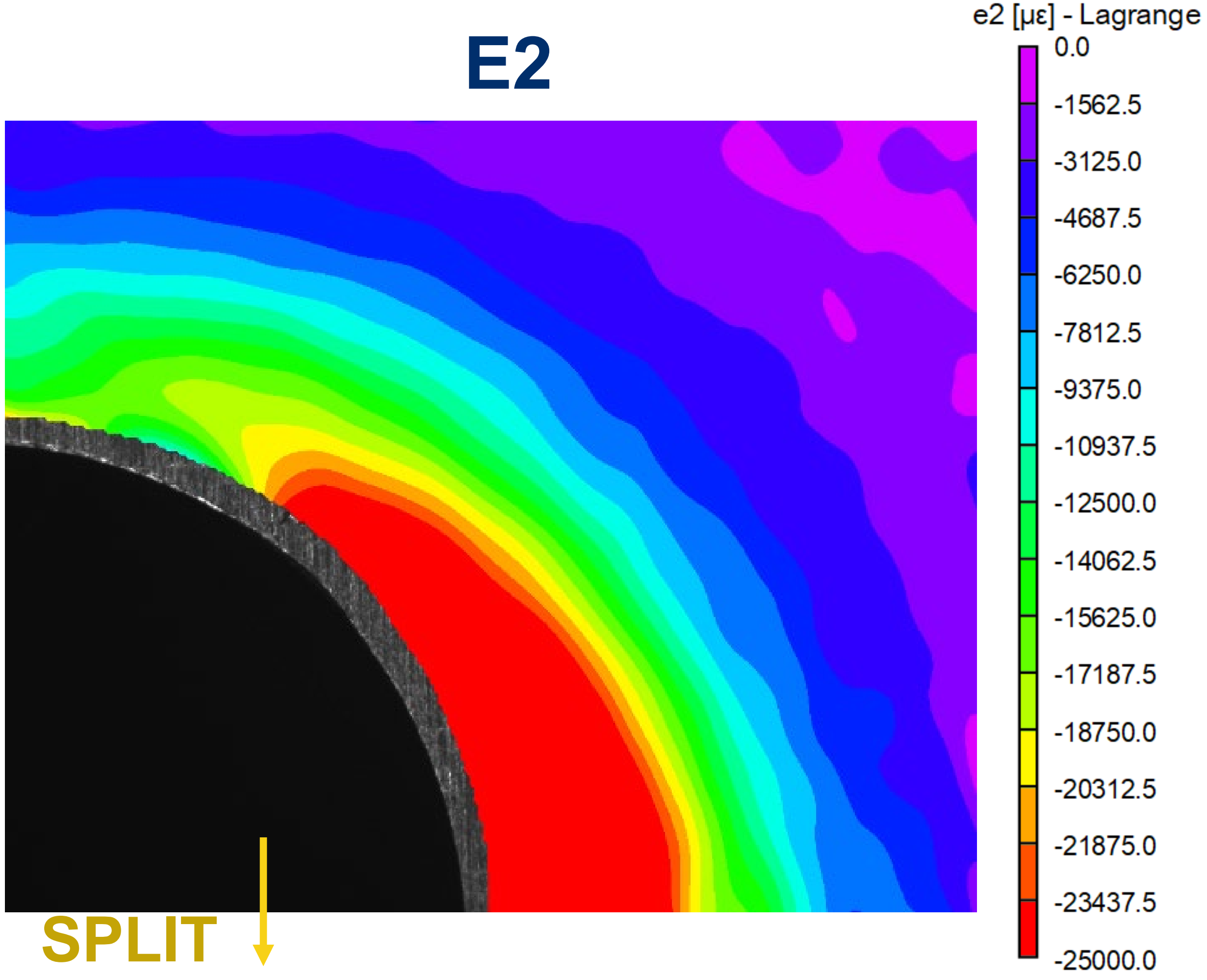
BT15 – Entry Post Cx

E1



DIC Processing Parameters	
Subset	111 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (0.60 mm)**

E2

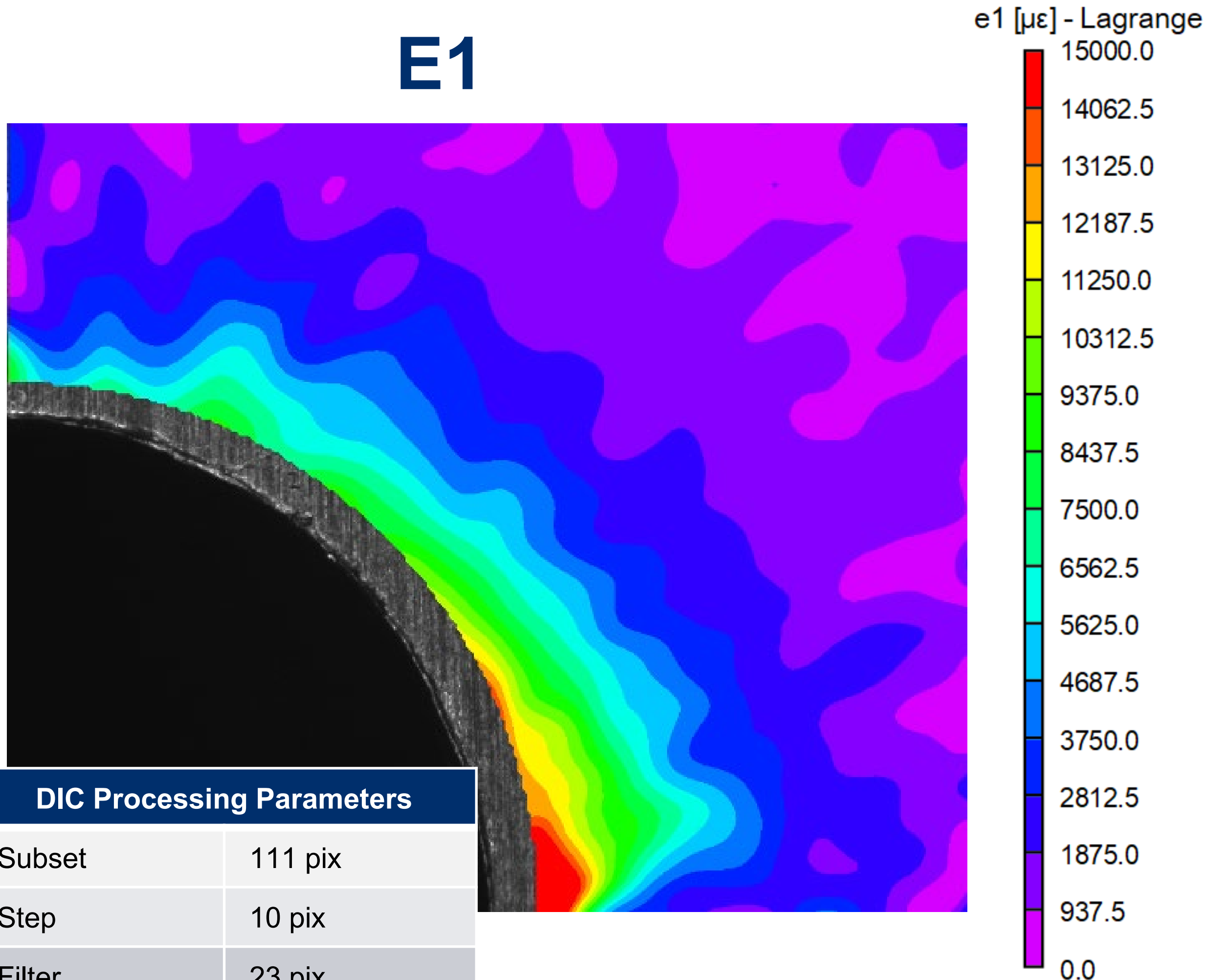


Split rotated 16.7° from 6 o'clock orientation

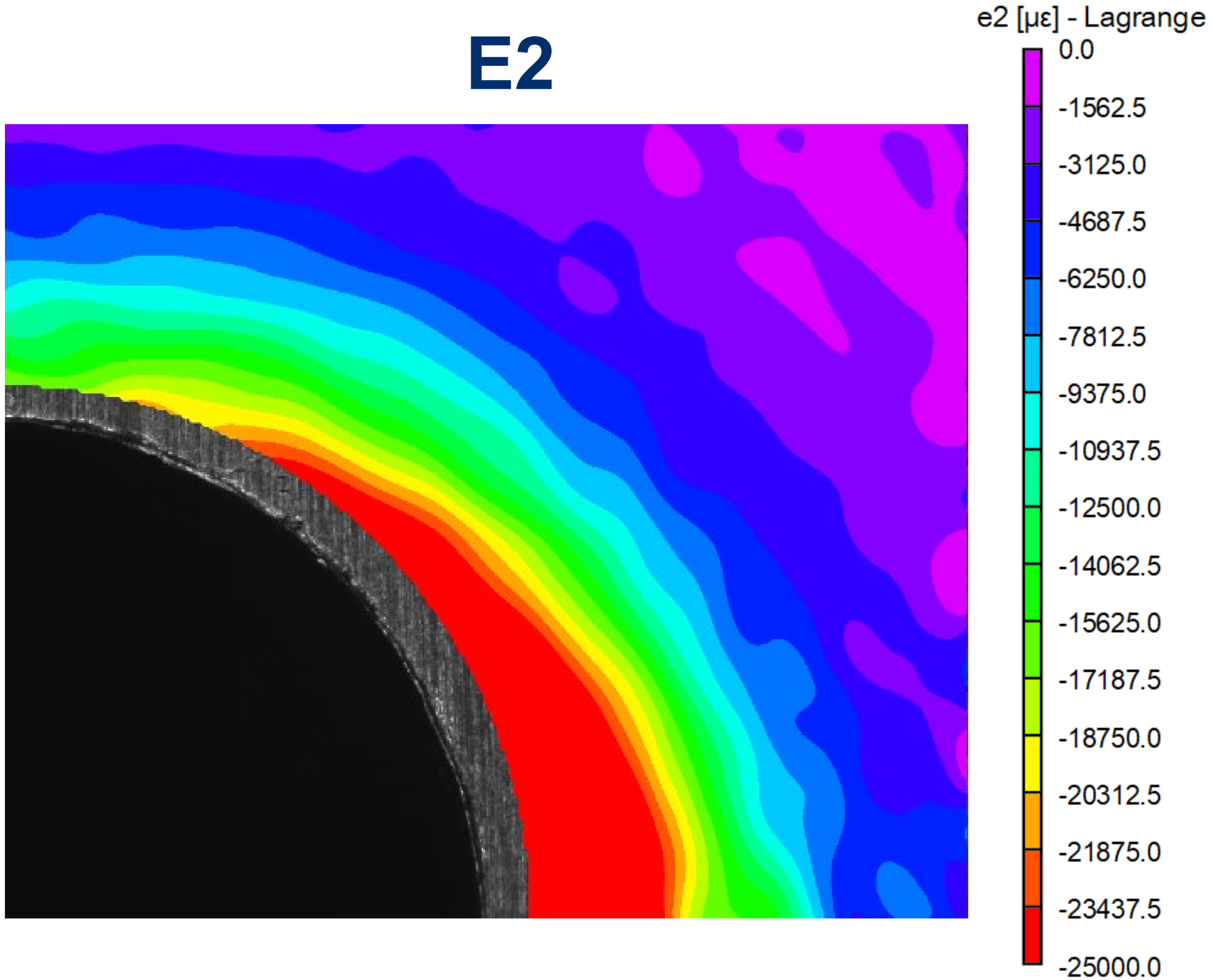
LOCKHEED MARTIN

BT15 – Entry Post Ream

E1

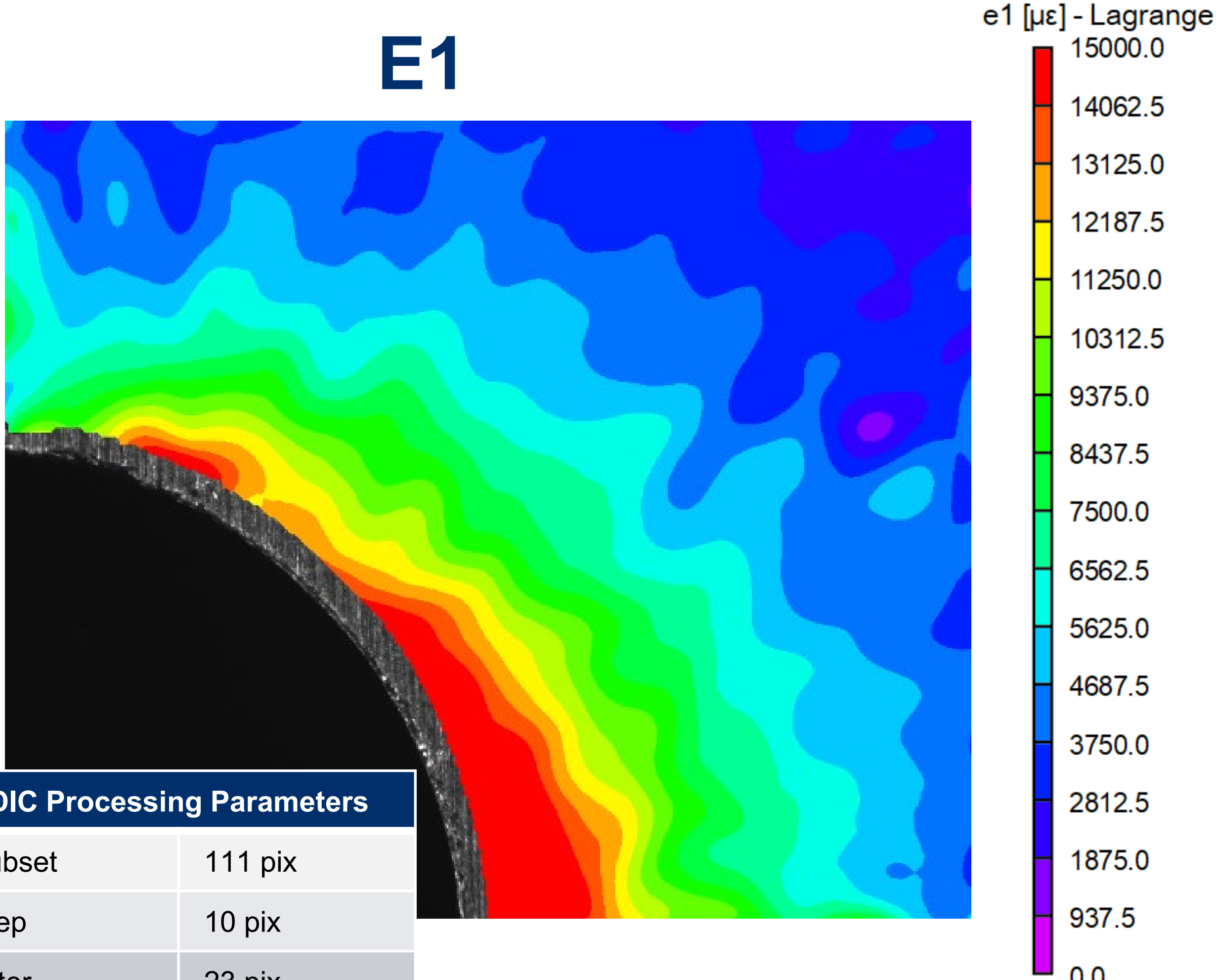


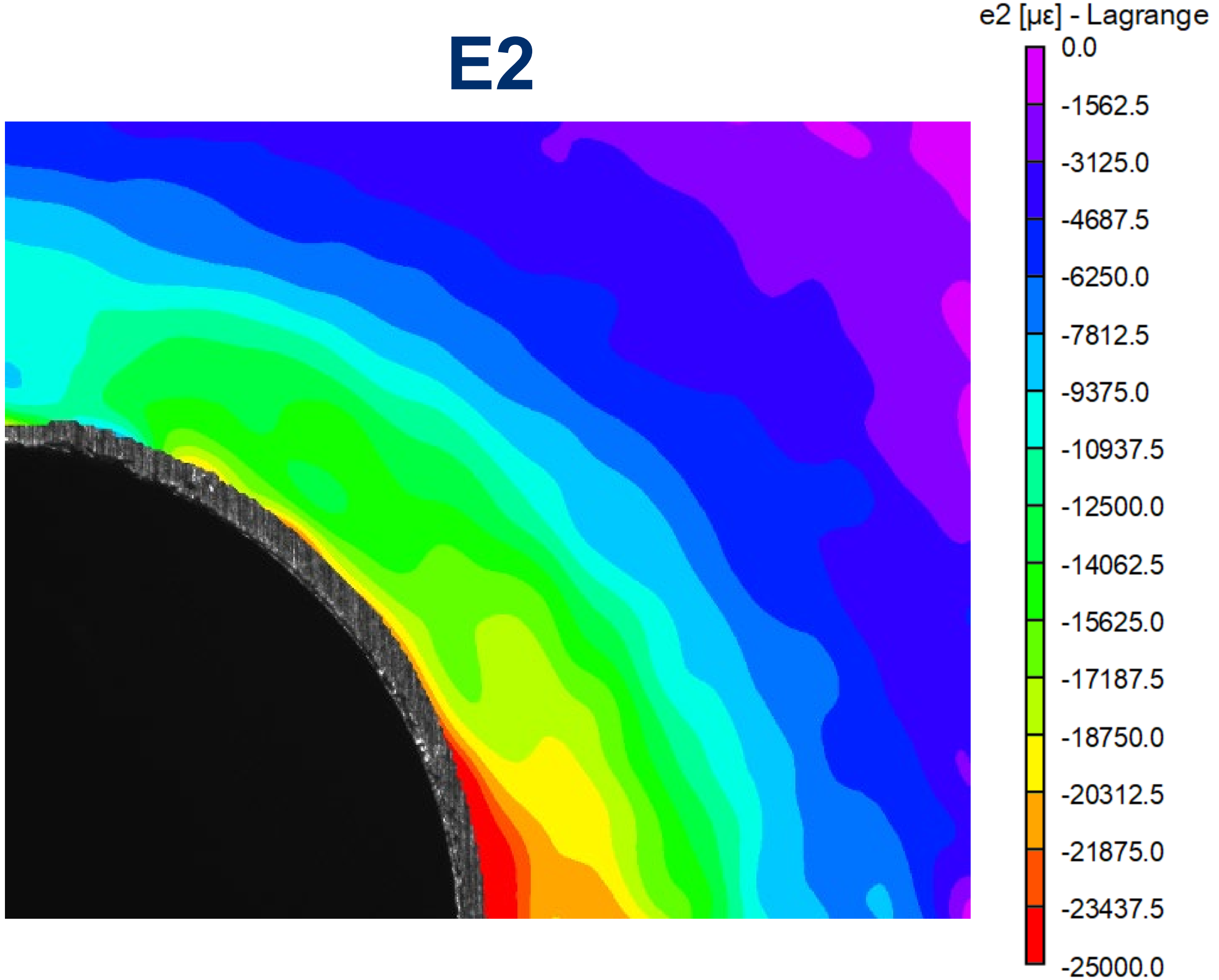
E2



DIC Processing Parameters	
Subset	111 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (0.60 mm)**

BT15 – Exit Post Cx





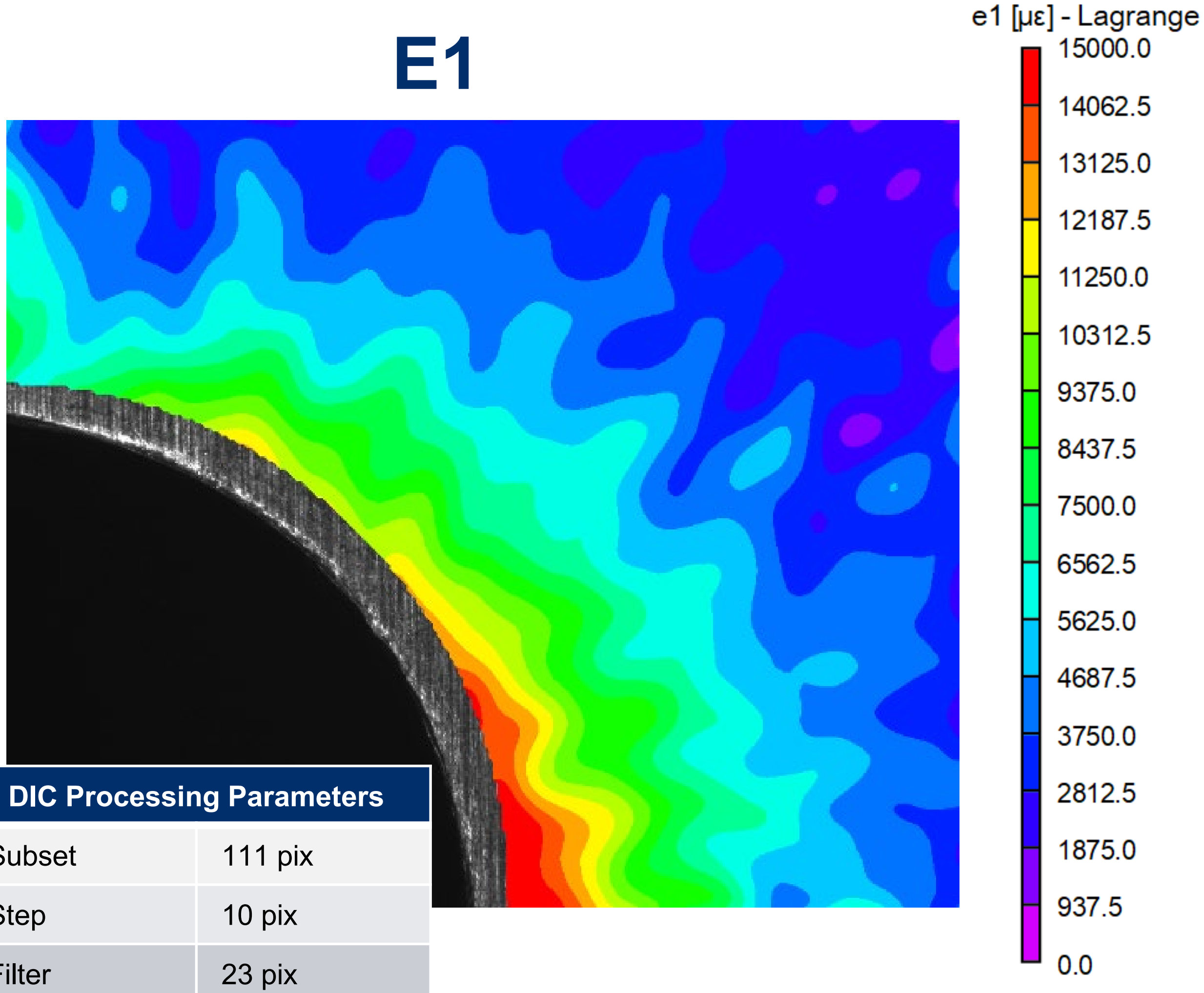
DIC Processing Parameters	
Subset	111 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (0.60 mm)**

Split rotated 16.7° from 6 o'clock orientation

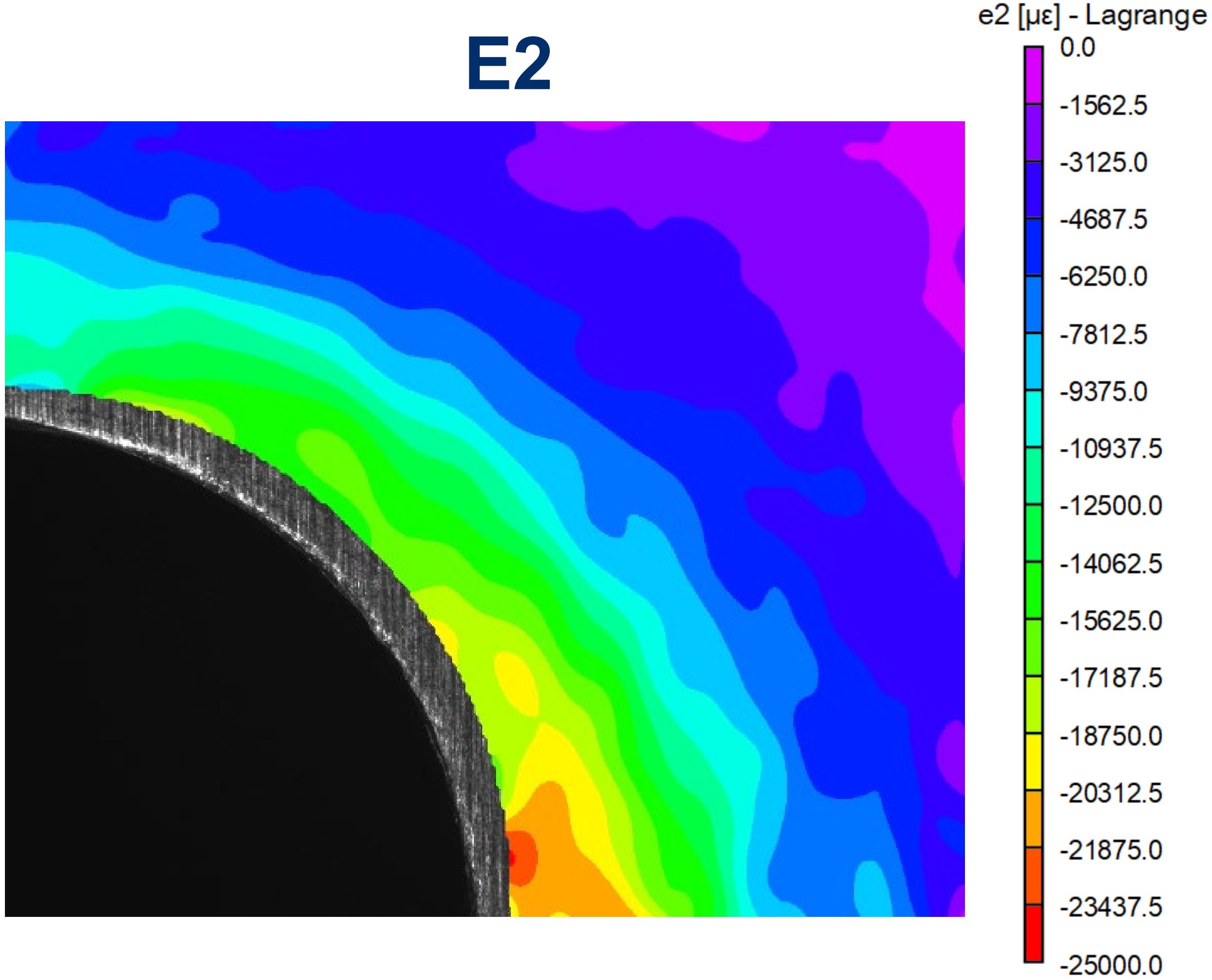
LOCKHEED MARTIN

BT15 – Exit Post Ream

E1



E2



DIC Processing Parameters	
Subset	111 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (0.60 mm)**

Split rotated 16.7° from 6 o'clock orientation

Discussion: Split Orientation

- Early tests indicate that split orientation is difficult to control when oriented away from operator (6 o’clock)
- Angle of misalignment of sleeve from intended direction ~ 16°
- Later testing orients split within operator view (12 o’clock)
  - ***More consistent positioning of split***

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        5. 2D SR (360°)
    2. 7050 Coupons
5. Development of Methods for Data Analysis for FEA simulations
6. Conclusion/Path Forward

BT18 – 3D DIC HIGH Mag

2024-T3

Thickness = 0.063inch

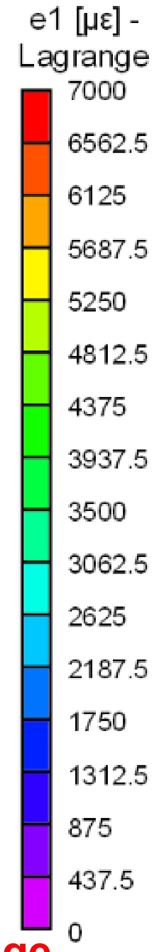
Starting Hole Diameter = 0.2380inch

FTI Toolset:

LOCKHEED MARTIN

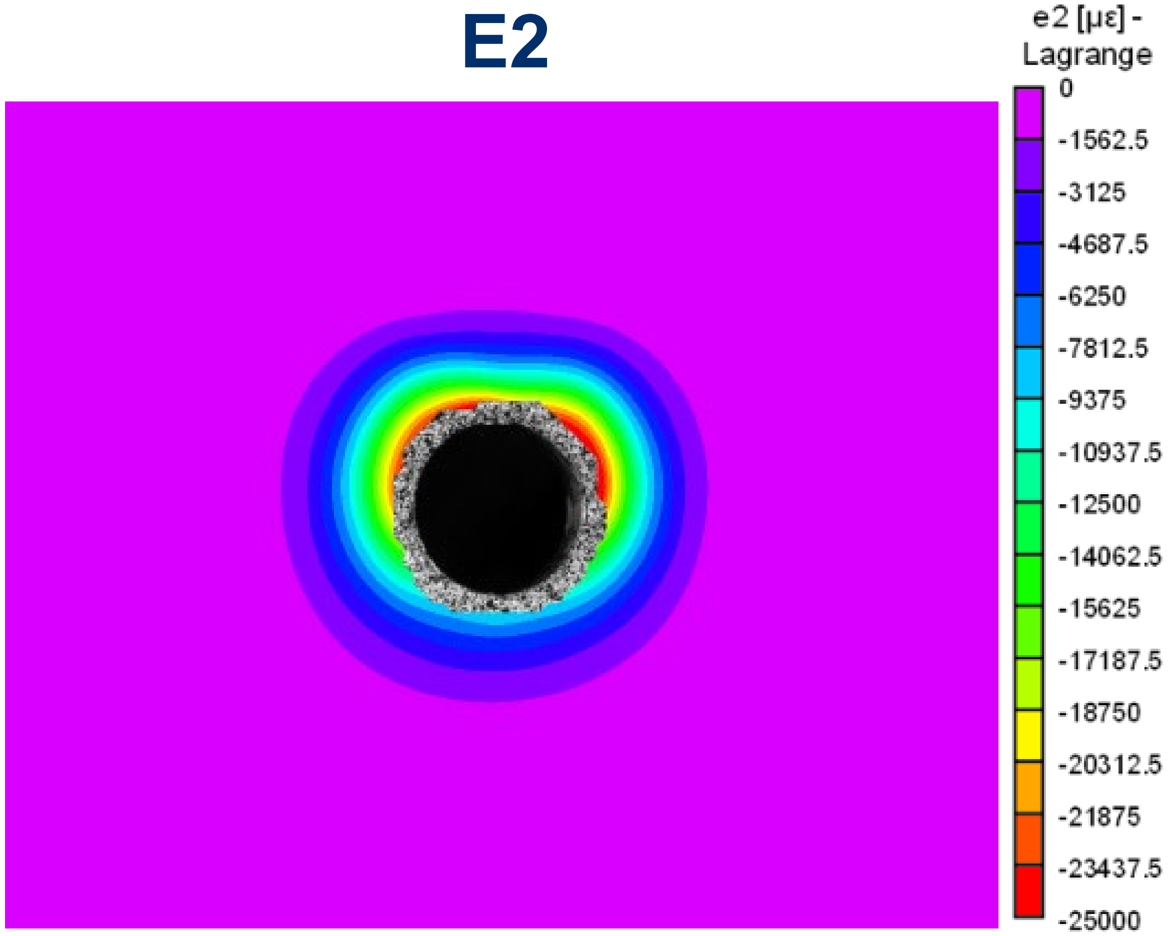
BT18 – Entry Post Cx

E1



~900 microns to edge

E2



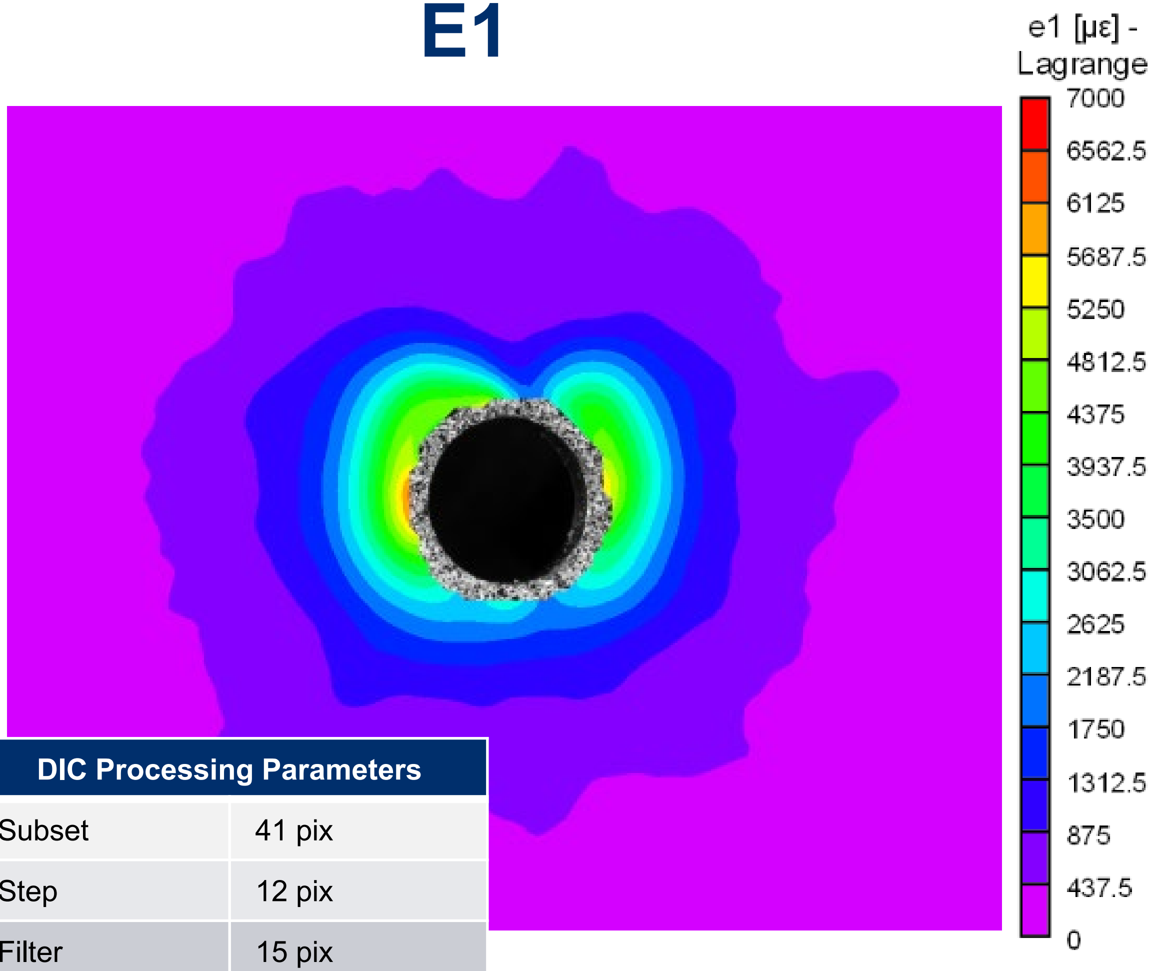
DIC Processing Parameters	
Subset	41 pix
Step	12 pix
Filter	15 pix
VSG	**180 pix (4.86 mm)**

Split at 12 o'clock orientation

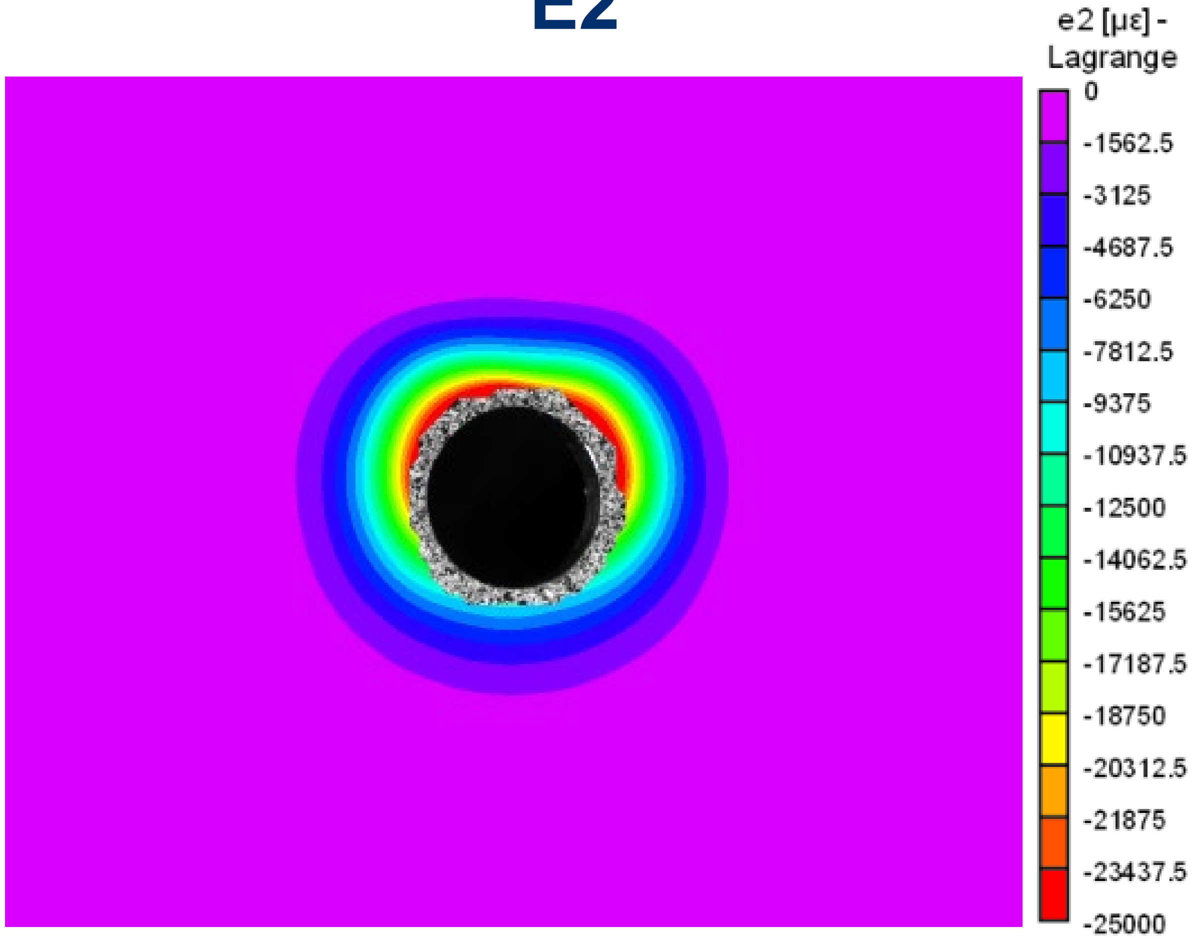
LOCKHEED MARTIN

BT18 – Entry Post Ream

E1



E2

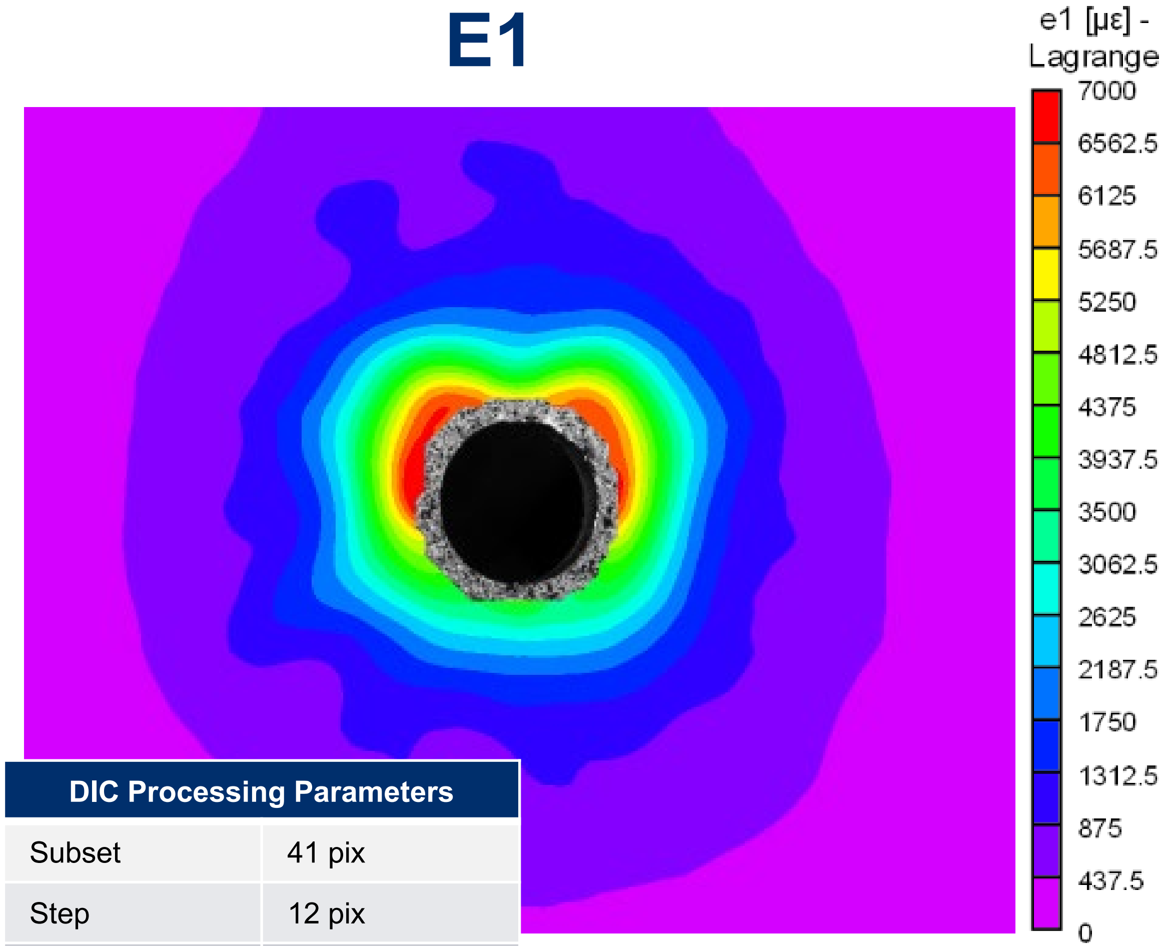


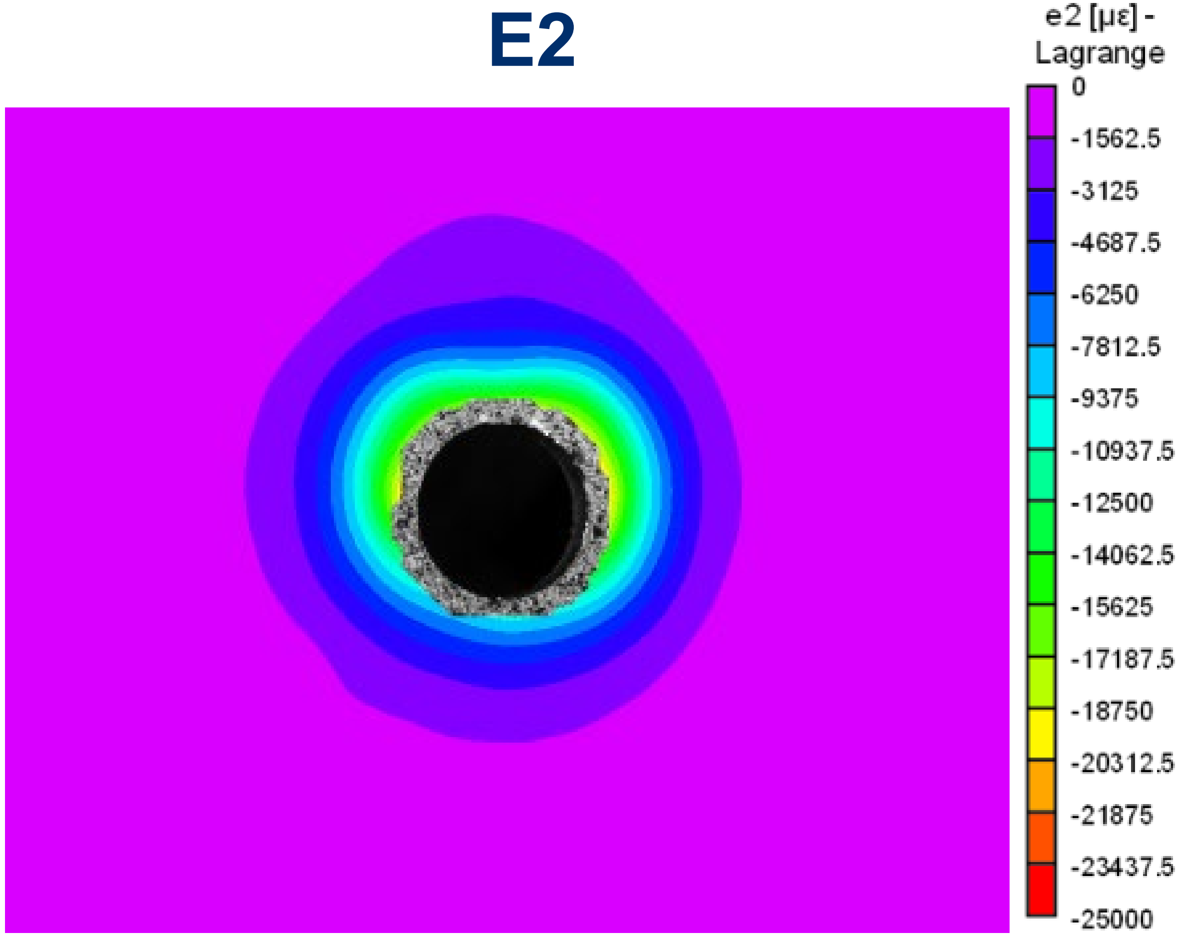
DIC Processing Parameters	
Subset	41 pix
Step	12 pix
Filter	15 pix
VSG	**180 pix (4.86 mm)**

Split at 12 o'clock orientation

LOCKHEED MARTIN

BT18 – Exit Post Cx



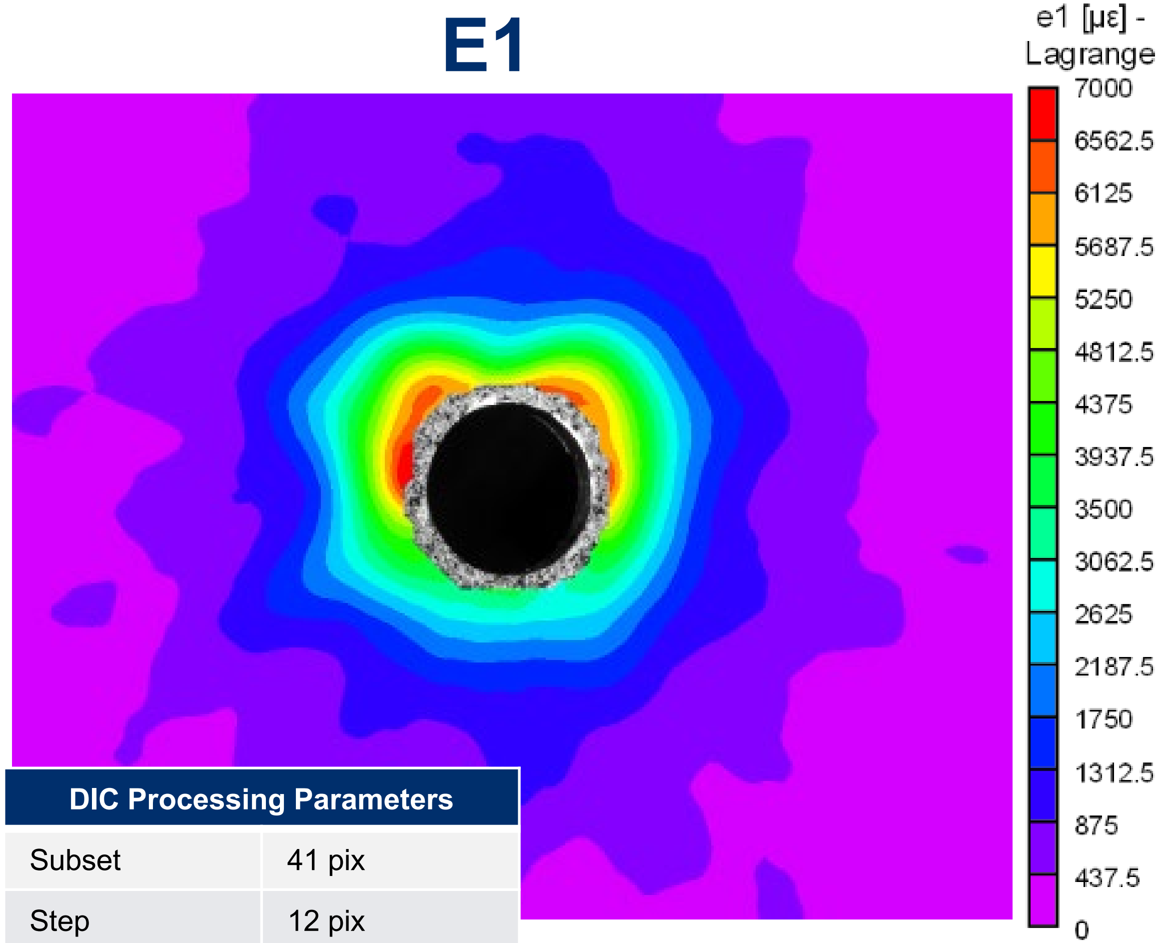


DIC Processing Parameters	
Subset	41 pix
Step	12 pix
Filter	15 pix
VSG	**180 pix (4.86 mm)**

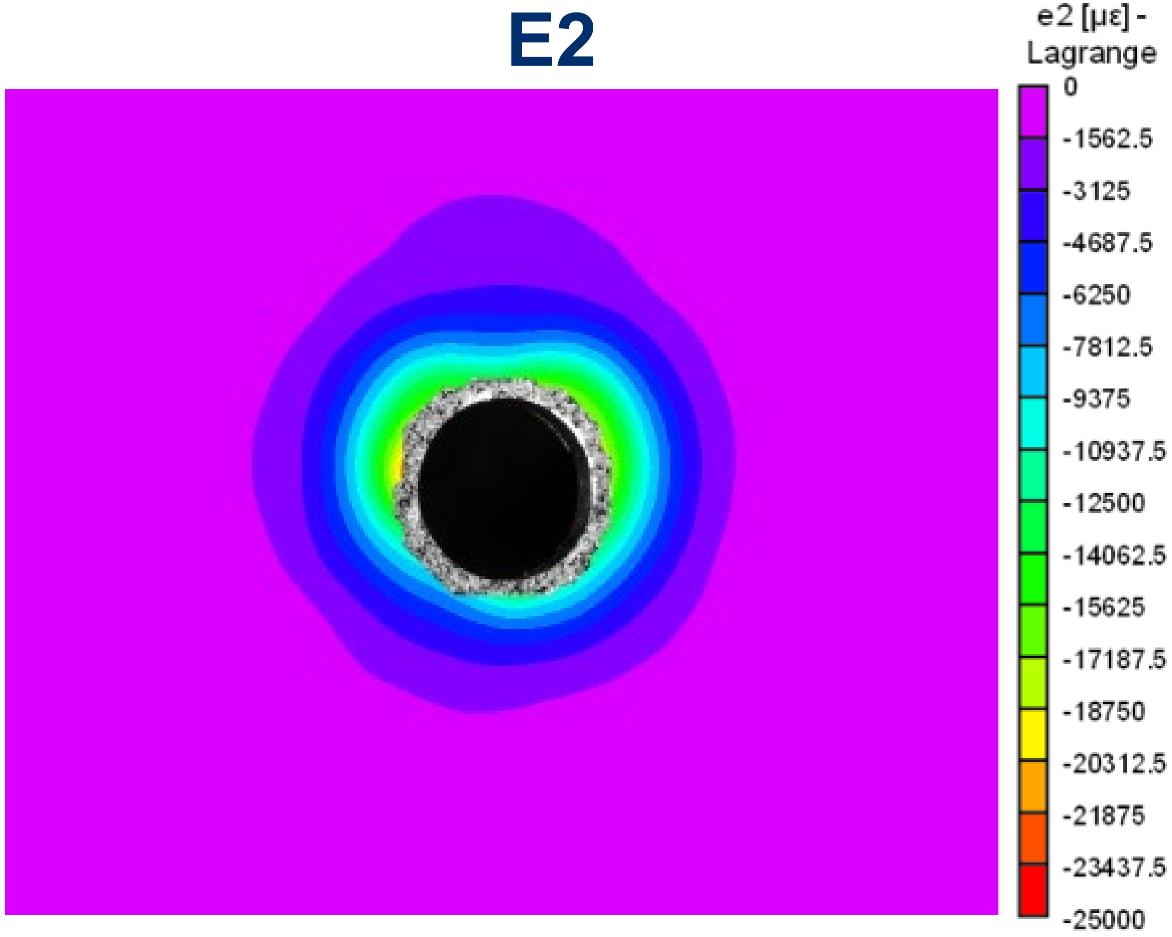
Split at 12 o'clock orientation

BT18 – Exit Post Ream

E1



E2



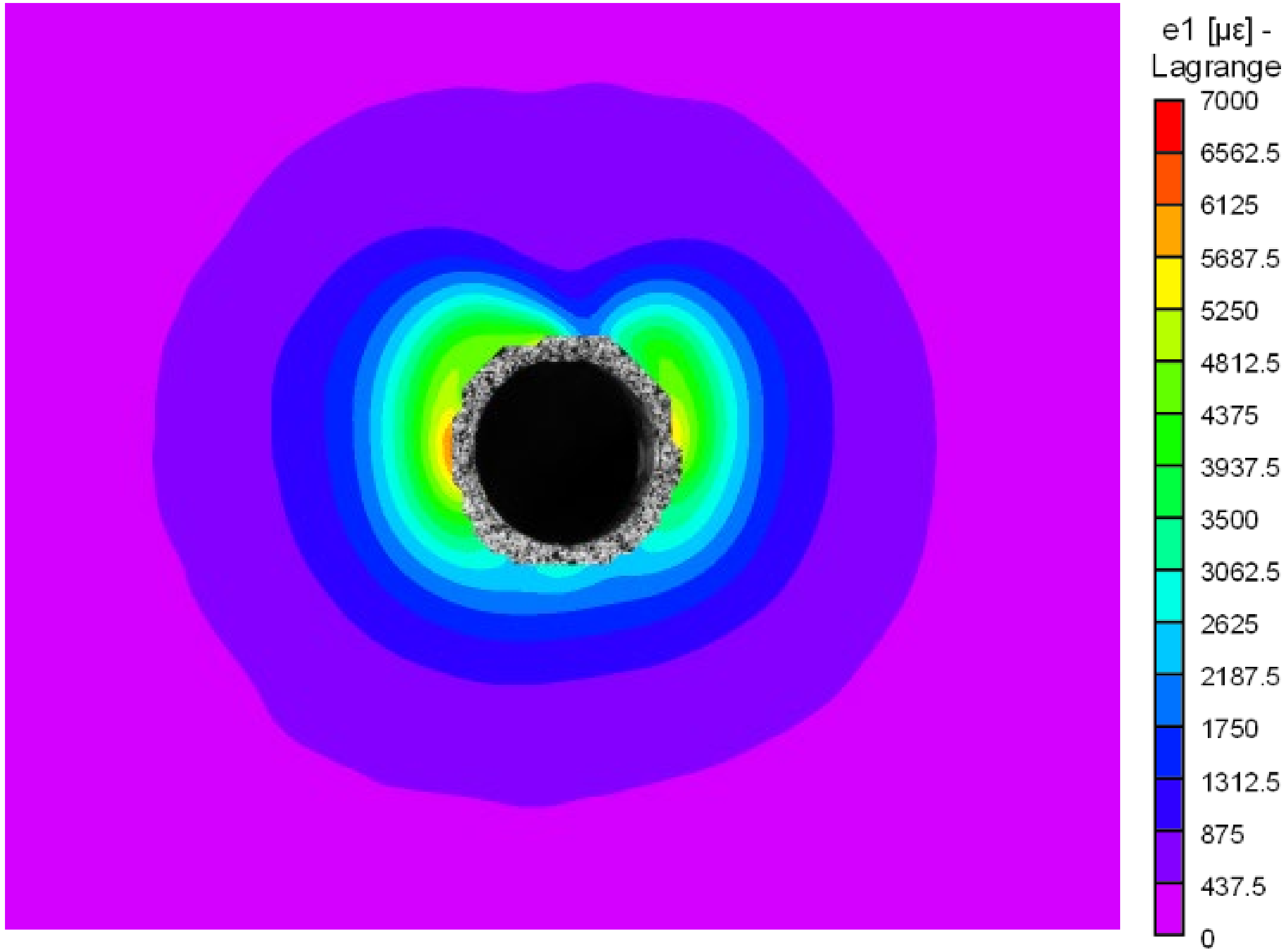
DIC Processing Parameters	
Subset	41 pix
Step	12 pix
Filter	15 pix
VSG	**180 pix (4.86 mm)**

Split at 12 o'clock orientation

LOCKHEED MARTIN

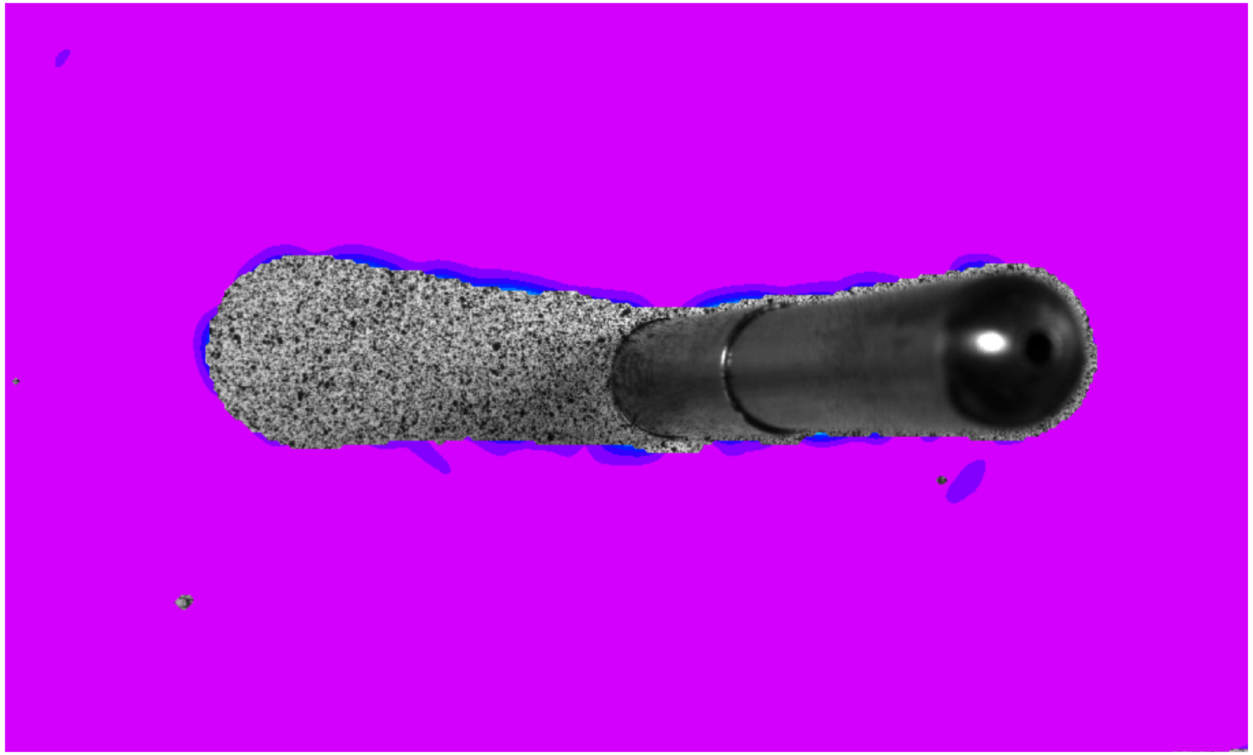
Discussion: DIC Strain Scales: 3D vs 2D

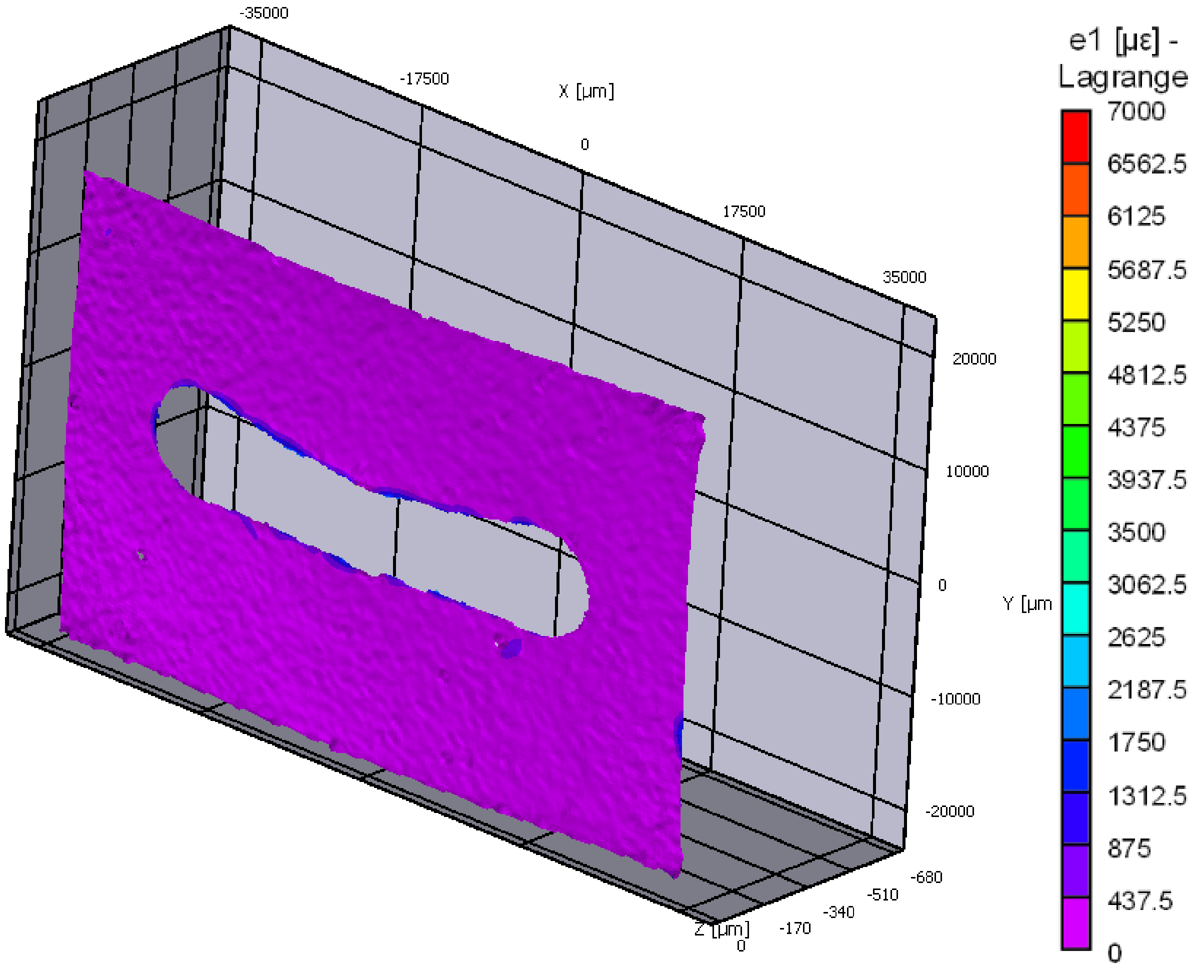
- 2D high mag DIC gets ~3x closer to edge of hole vs 3D
- 2D high mag captures higher strain magnitude/gradient
- To highlight peak strains in 3D dataset, scale reduced to 0 < E1 < 7000 microstrain



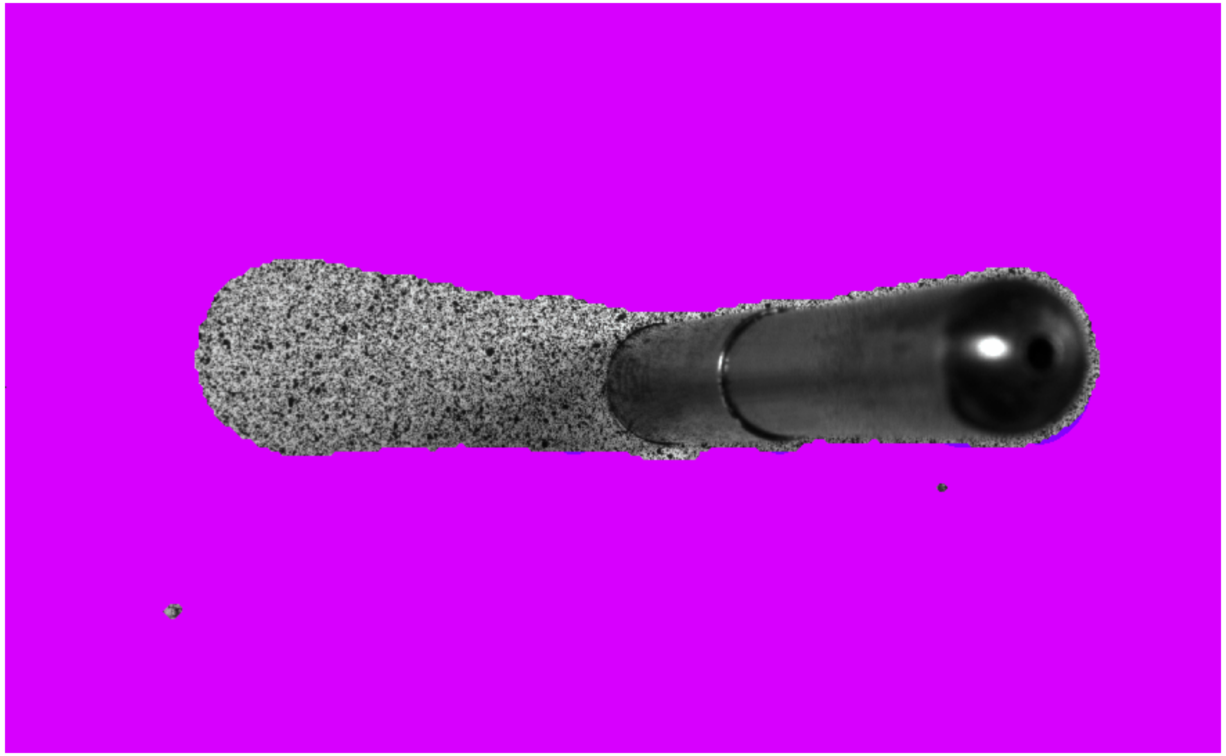
LOCKHEED MARTIN

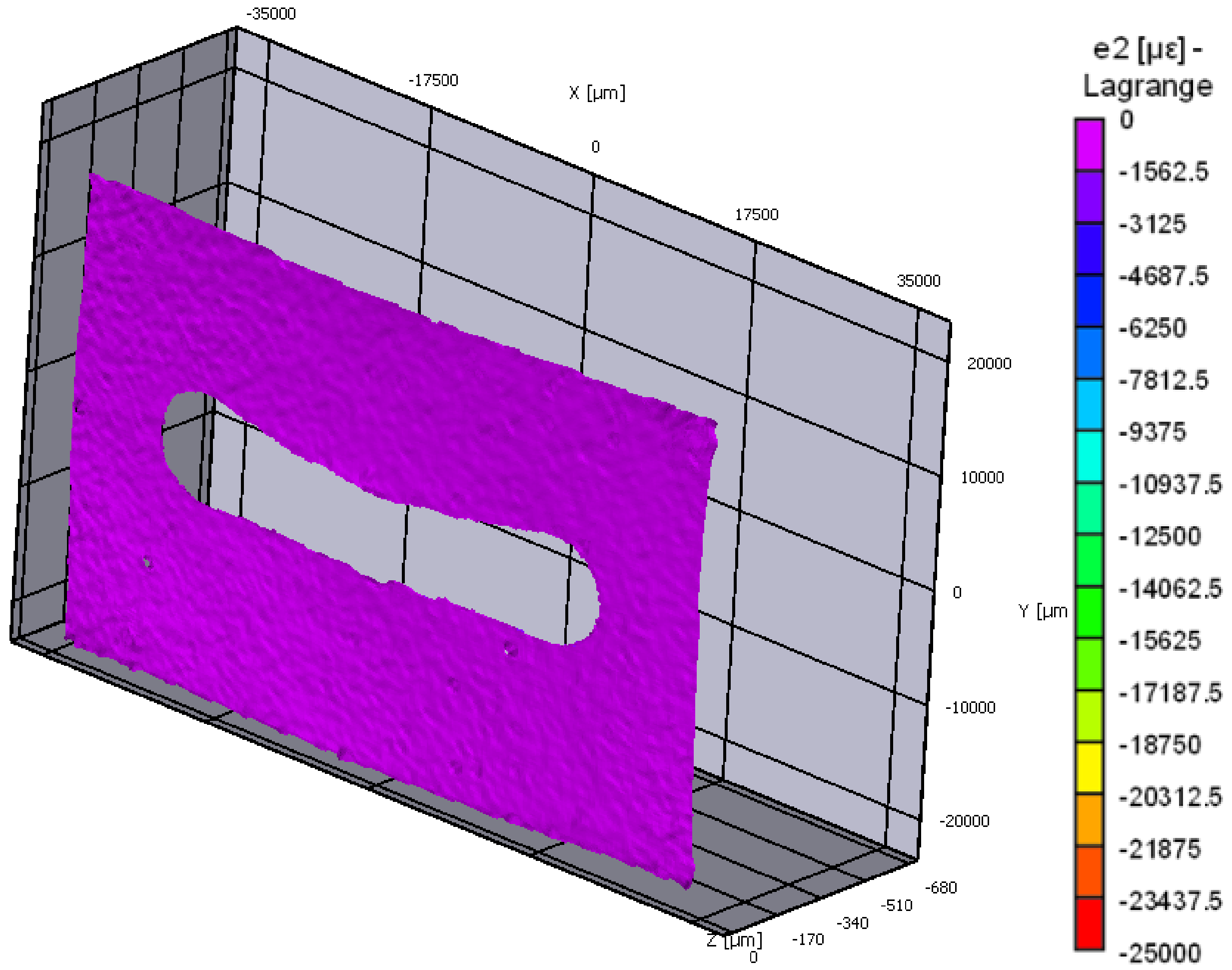
BT18 – In-Situ: Max Principal Strain (2D/3D views)





BT18 – In-Situ: Min Principal Strain (2D/3D views)





LOCKHEED MARTIN

Overview

1. **Purpose of Improving Near-Bore Strain Measurements**
2. **Overview of Previous 2-inch SsCx DIC results**
3. **Experimental Set-up**
4. **Results**
    1. 2024 Coupons
        1. 2D Low
        2. 2D High
        3. 3D High
        4. 2D SR (135°)
        5. 2D SR (360°)
    2. 7050 Coupons
5. **Development of Methods for Data Analysis for FEA simulations**
6. **Conclusion/Path Forward**

LOCKHEED MARTIN

BT13 2D DIC Super-resolution (135°)

2024-T3

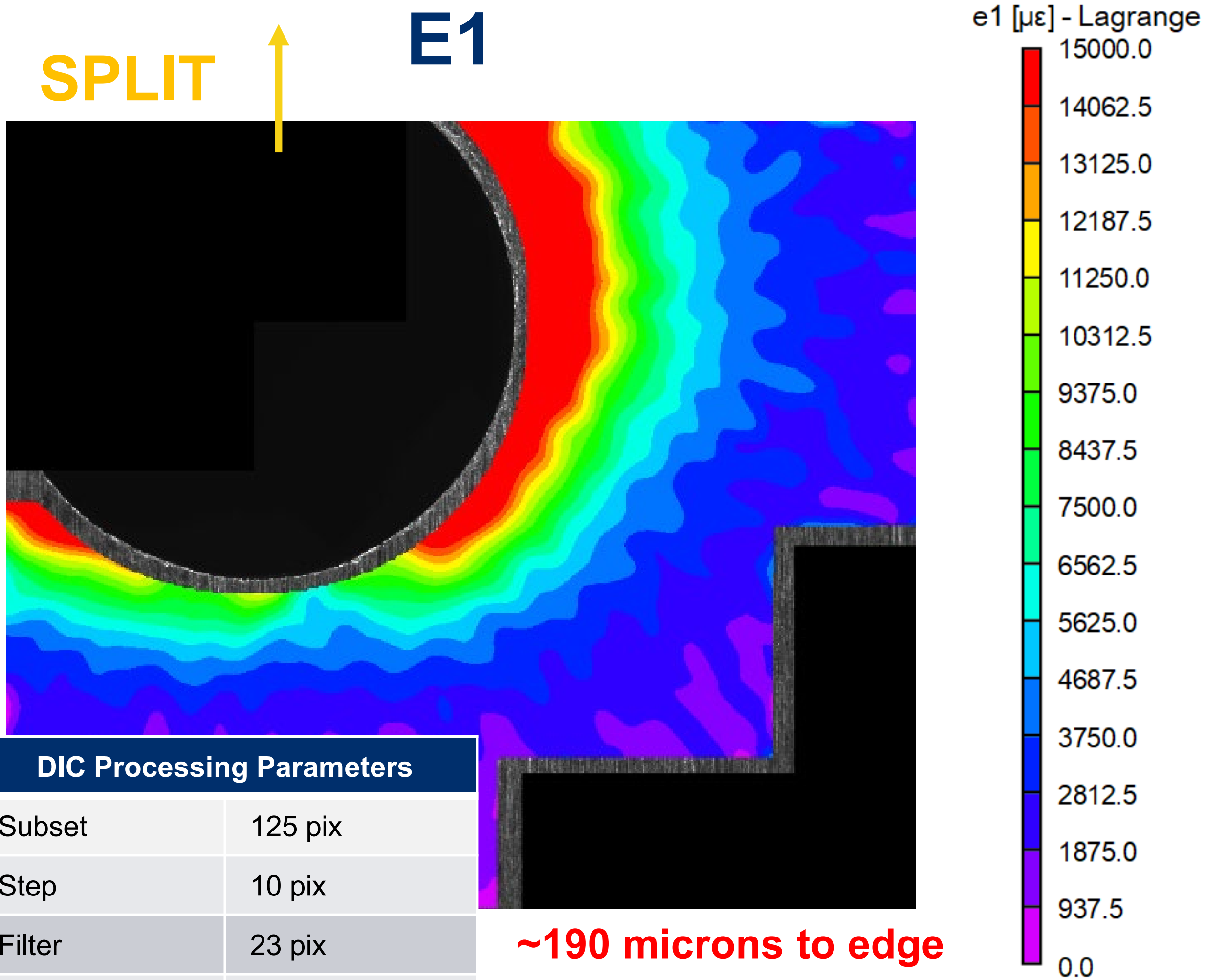
Thickness = 0.063inch

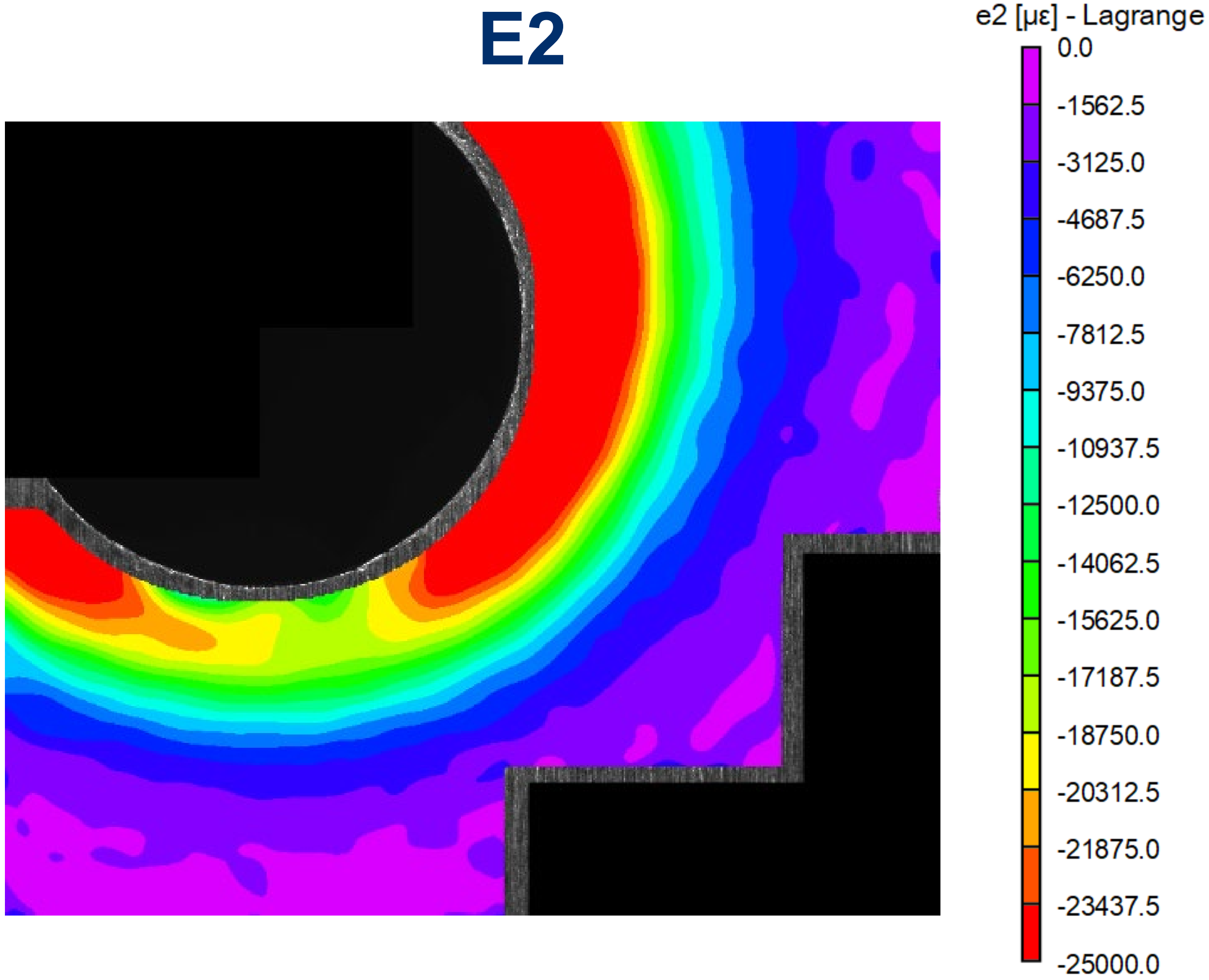
Starting Hole Diameter = 0.2361inch

FTI Toolset:

LOCKHEED MARTIN

BT13 – Entry Post Cx



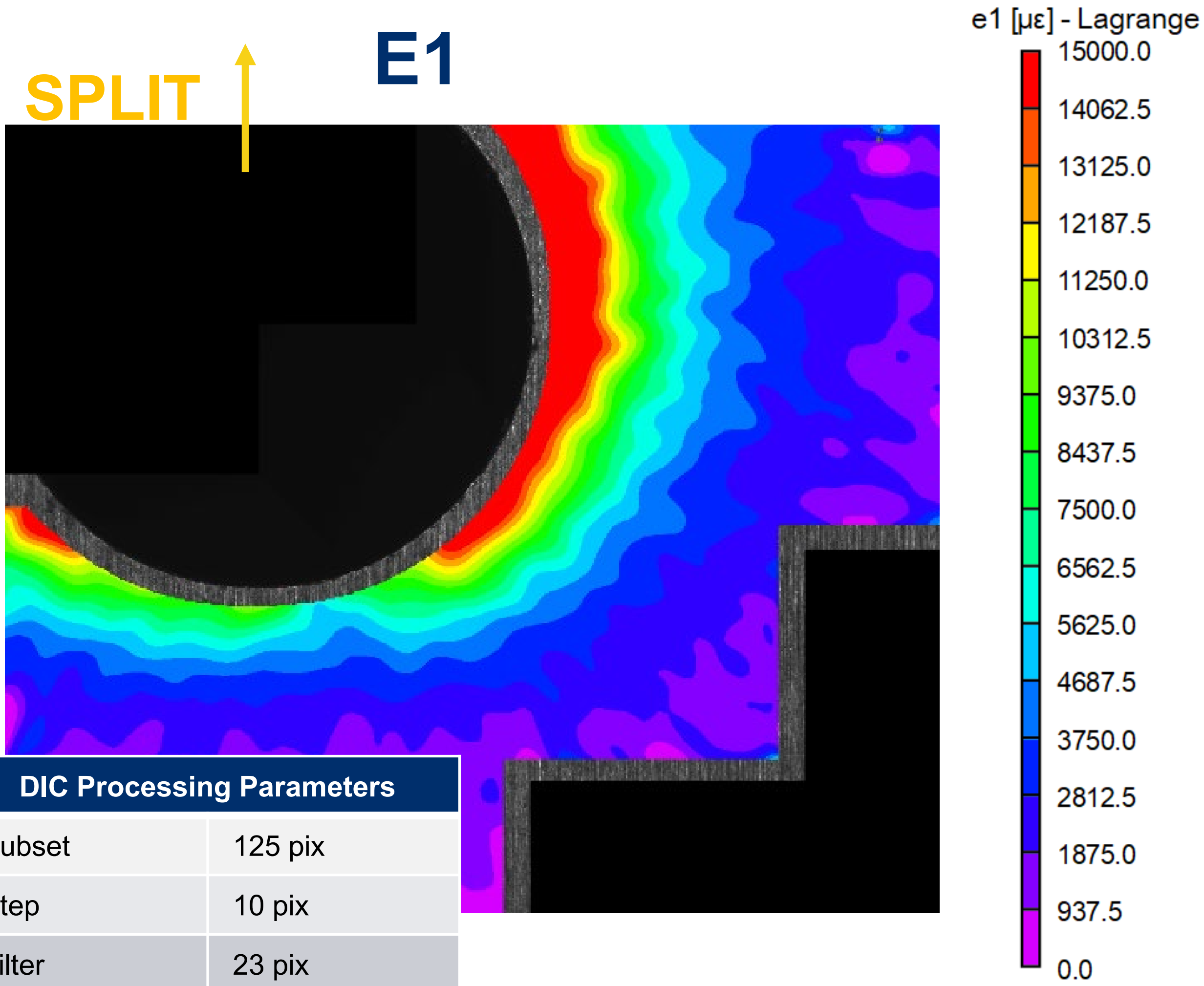


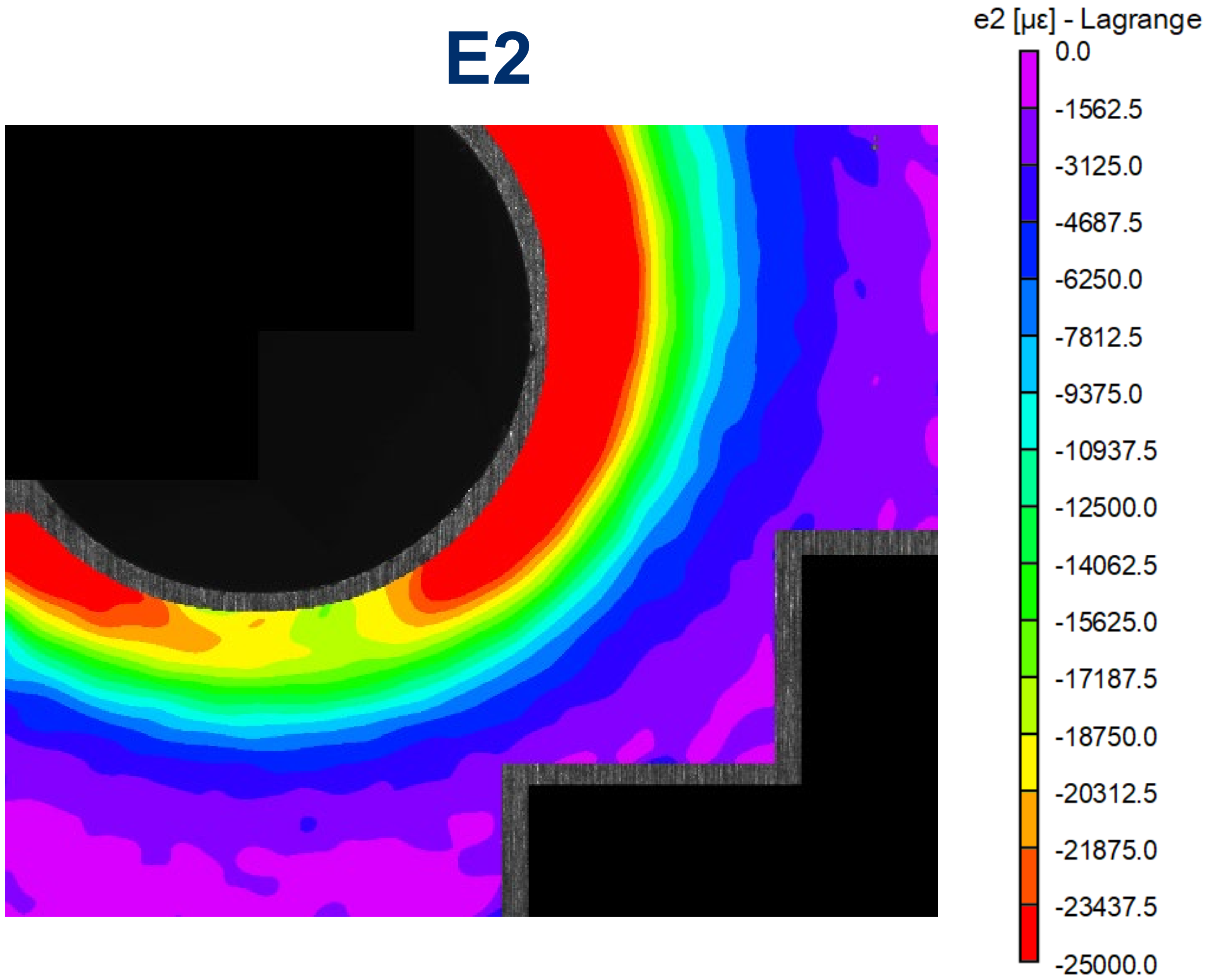
DIC Processing Parameters	
Subset	125 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (0.60 mm)**

Split at 12 o'clock orientation

LOCKHEED MARTIN

BT13 – Entry Post Ream



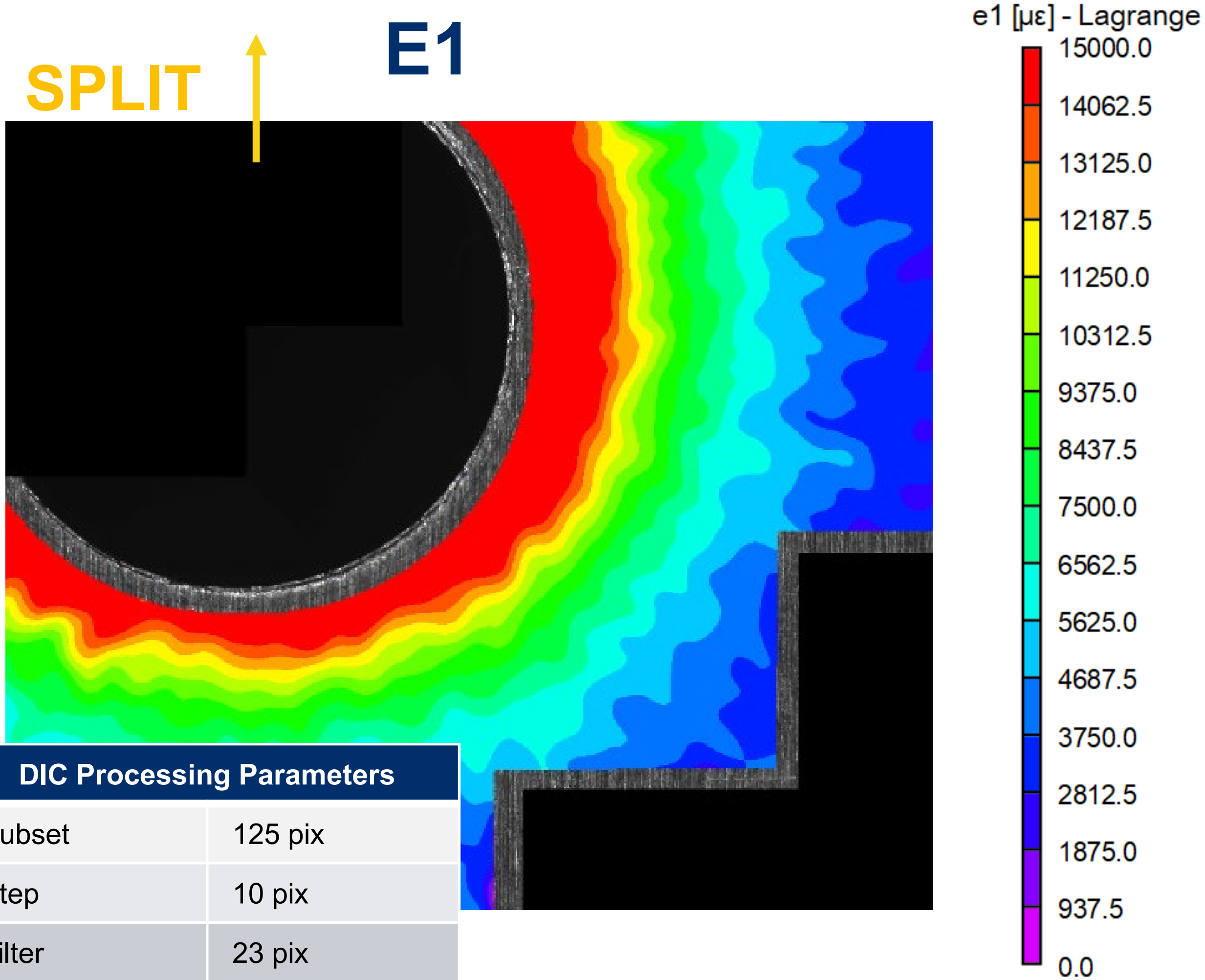


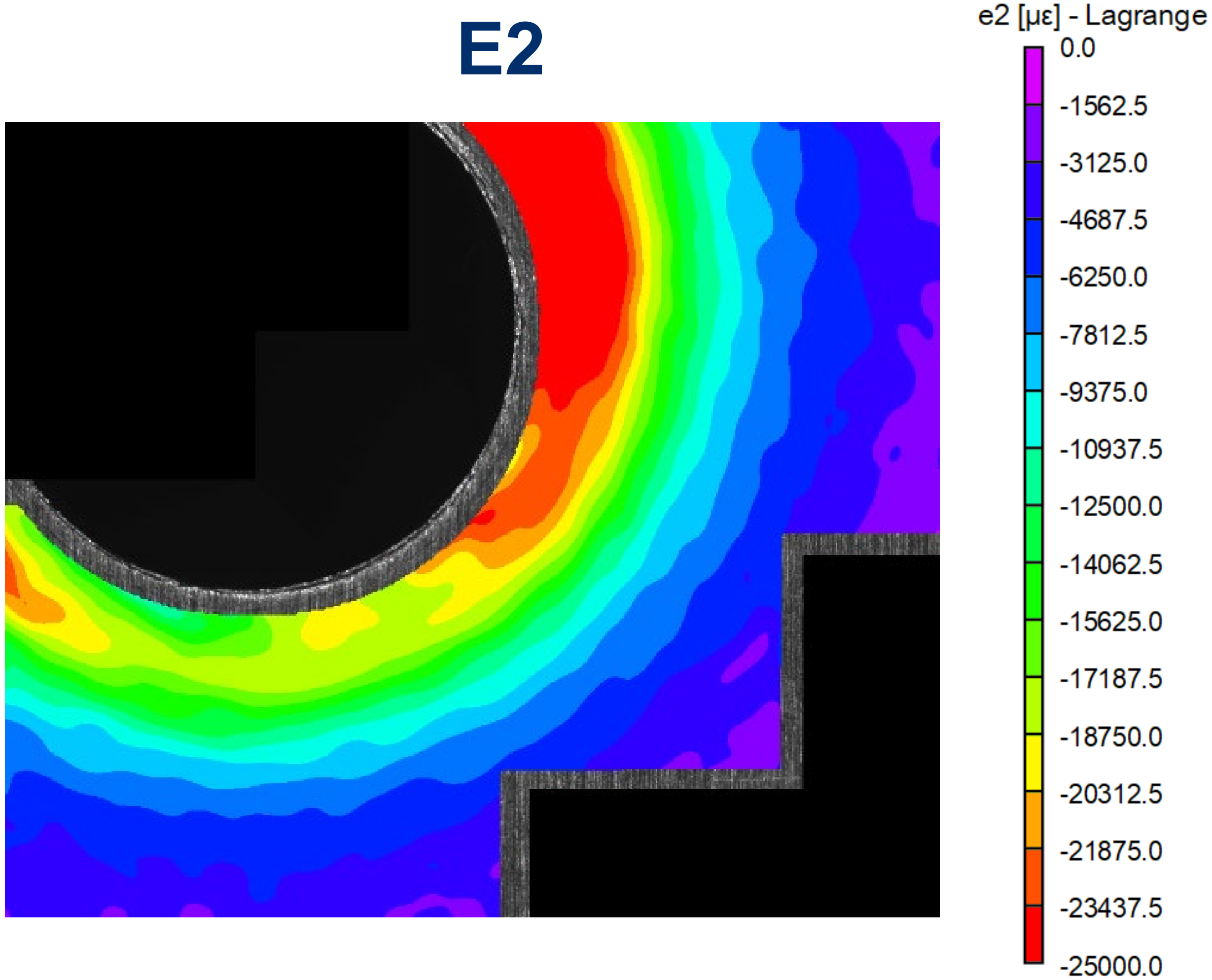
DIC Processing Parameters	
Subset	125 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (0.60 mm)**

Split at 12 o'clock orientation

LOCKHEED MARTIN

BT13 – Exit Post Cx

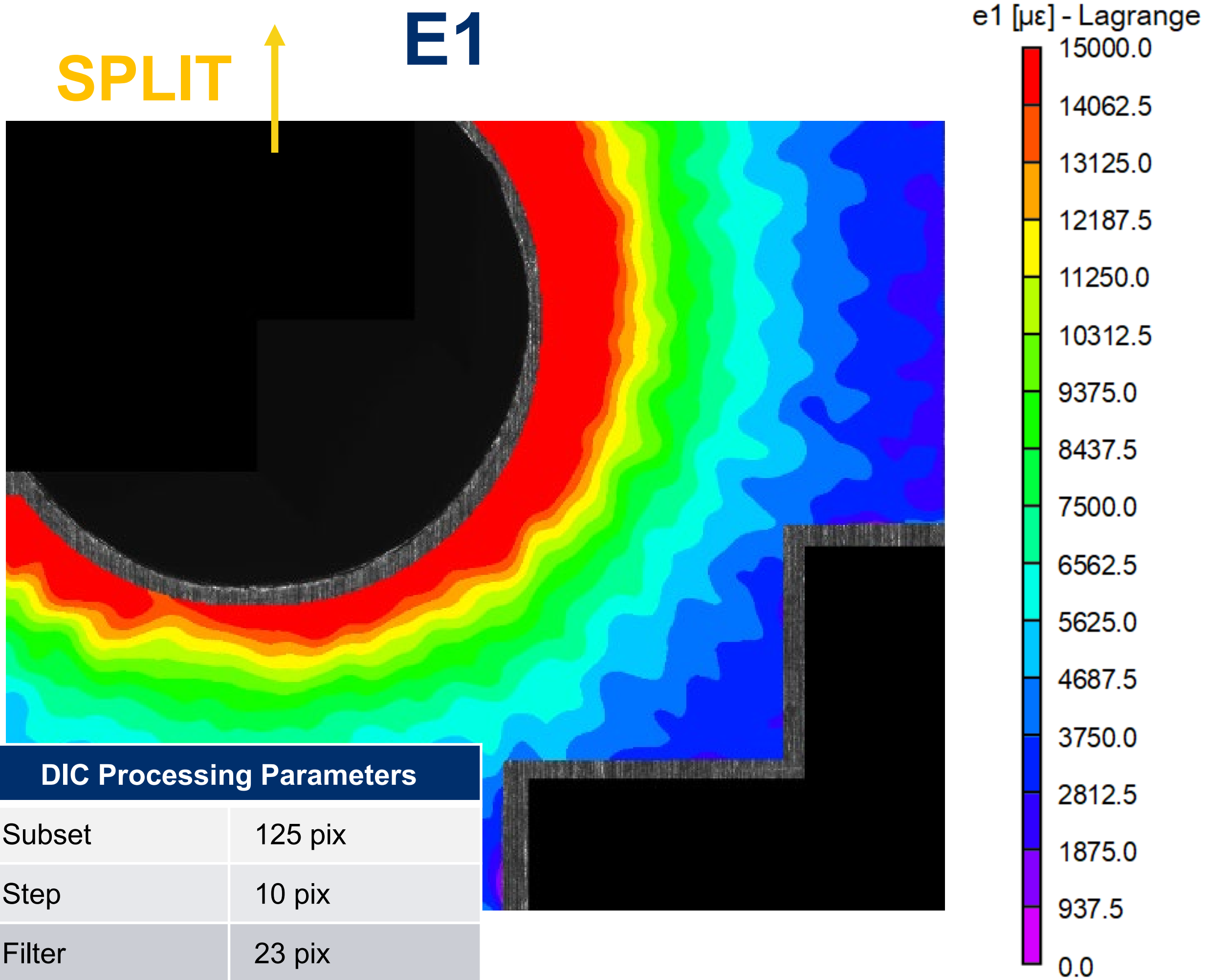


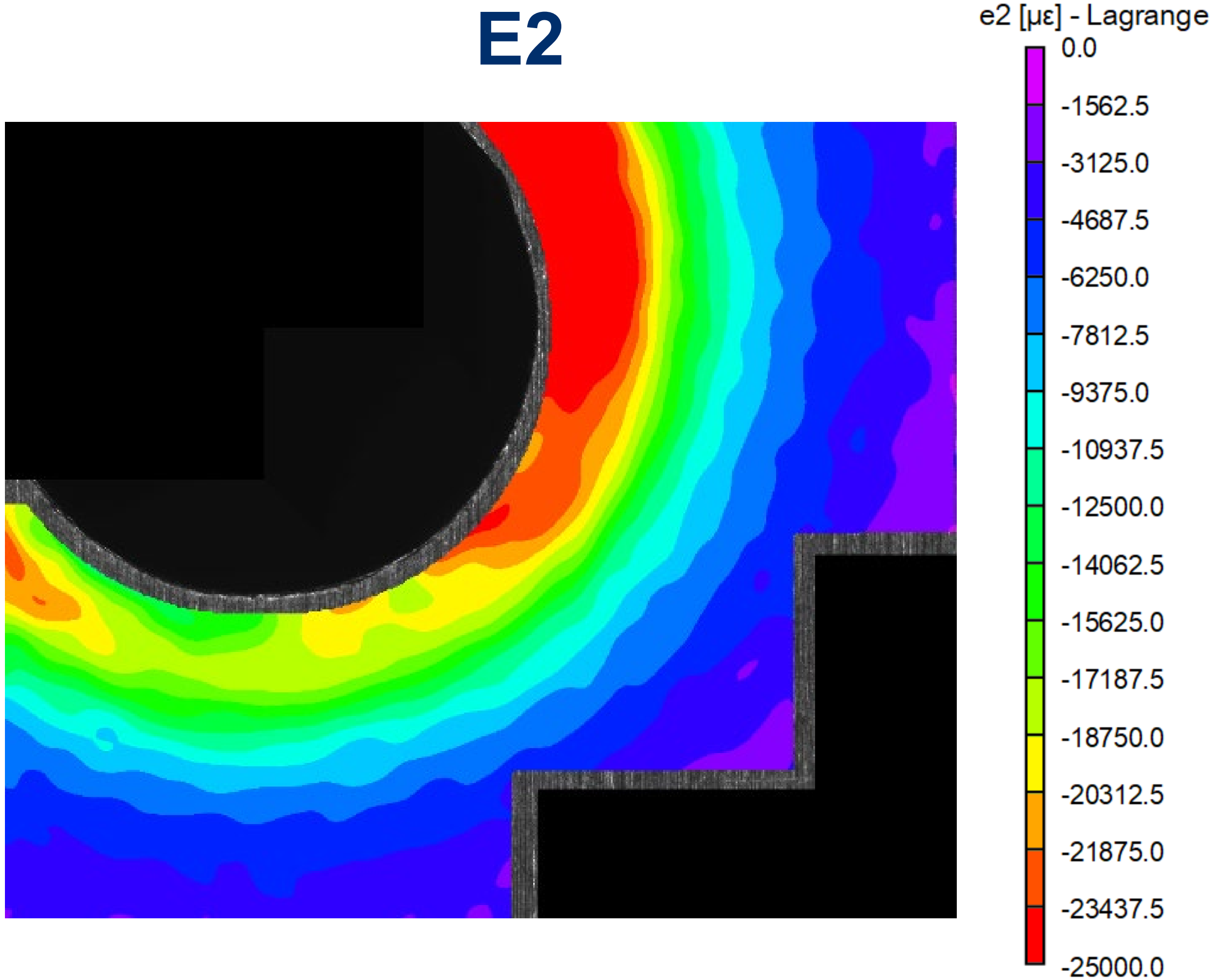


DIC Processing Parameters	
Subset	125 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (0.60 mm)**

Split at 12 o'clock orientation

BT13 – Exit Post Ream





DIC Processing Parameters	
Subset	125 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (0.60 mm)**

Split at 12 o'clock orientation

LOCKHEED MARTIN

Overview

1. Purpose of Improving Near-Bore Strain Measurements
2. Overview of Previous 2-inch SsCx DIC results
3. Experimental Set-up
4. Results
    1. 2024 Coupons
        1. 2D Low
        2. 2D High
        3. 3D High
        4. 2D SR (135°)
        5. 2D SR (360°)
    2. 7050 Coupons
5. Development of Methods for Data Analysis for FEA simulations
6. Conclusion/Path Forward

BT20 2D DIC Super-Resolution (360°)

2024-T3

Thickness = 0.063inch

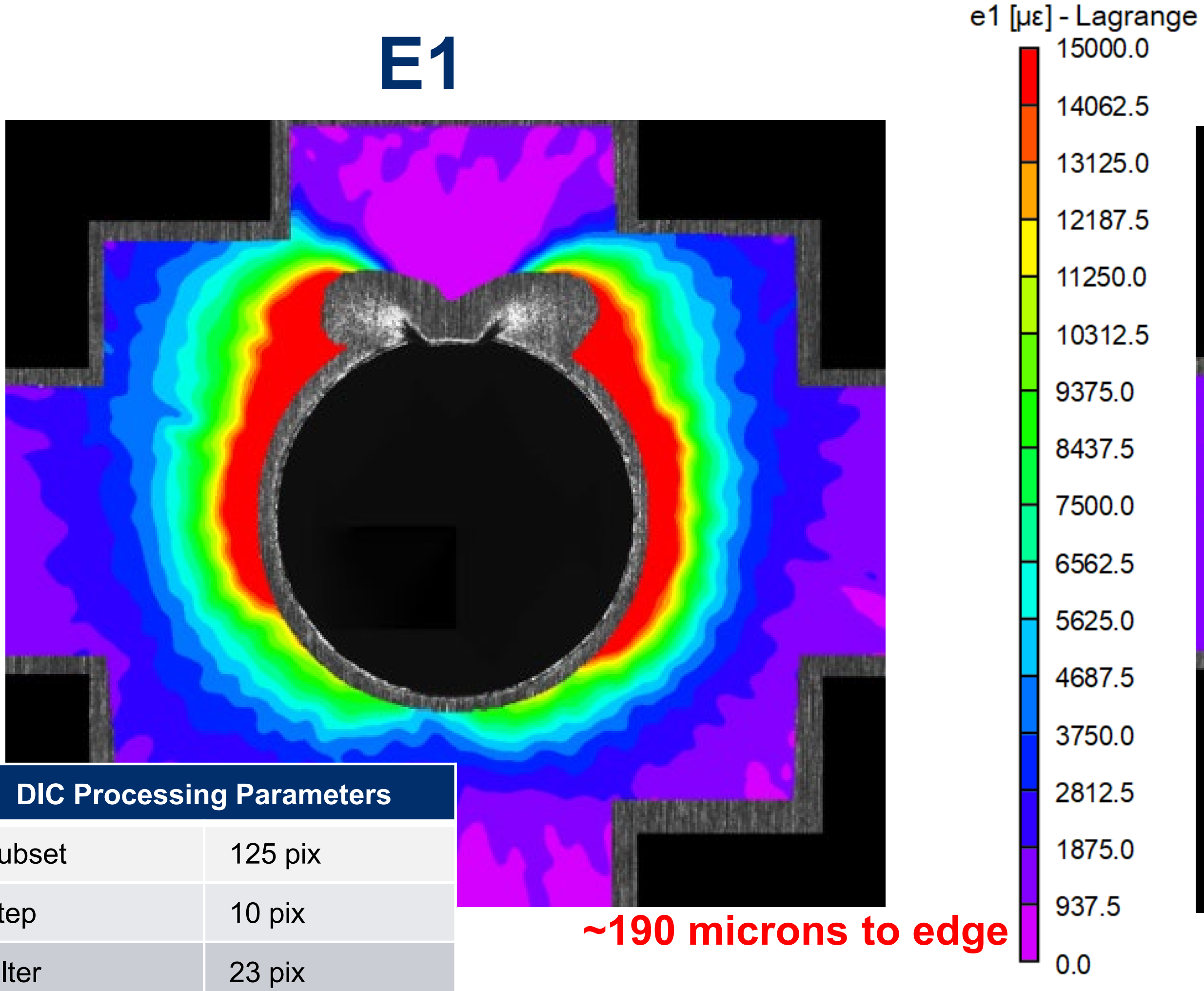
Starting Hole Diameter = 0.2359inch

FTI Toolset:

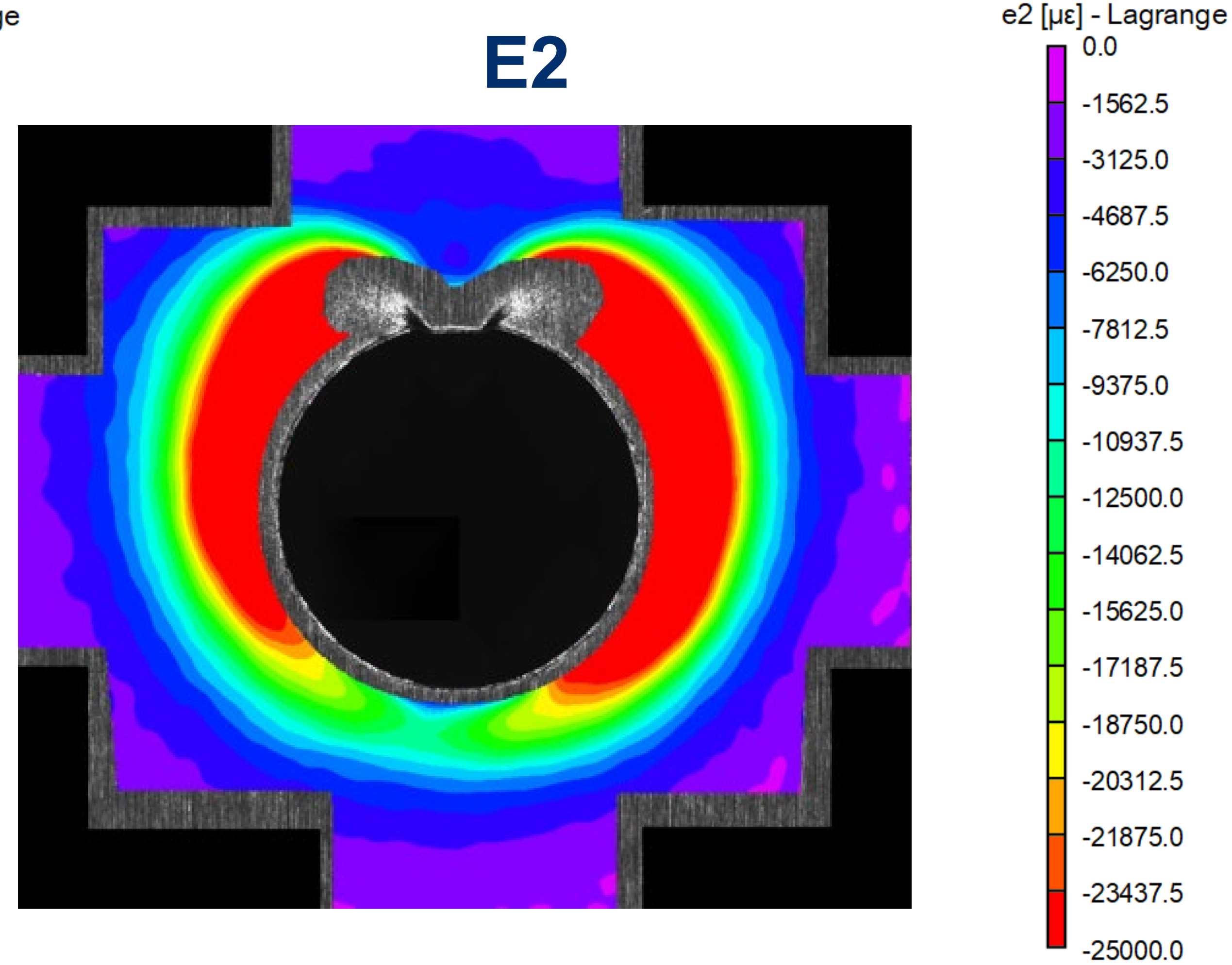
LOCKHEED MARTIN

BT20 – Entry Post Cx

E1



E2

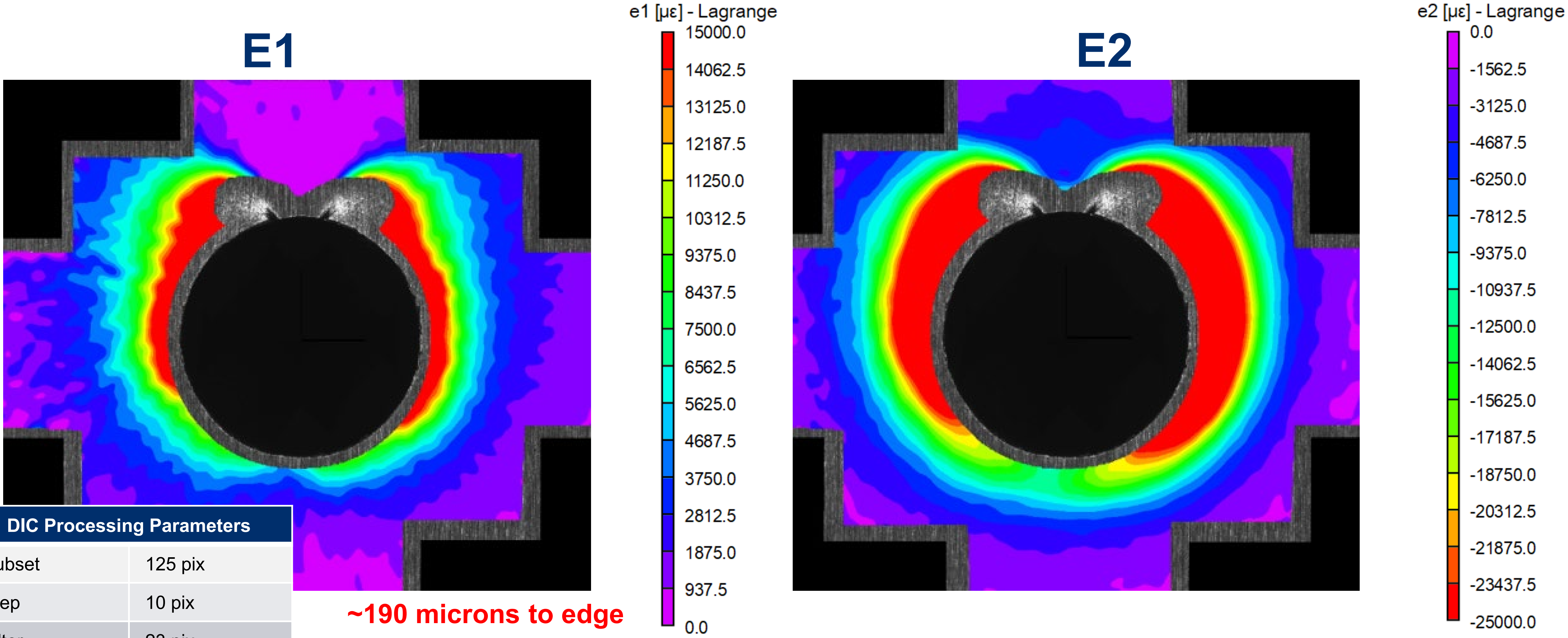


DIC Processing Parameters	
Subset	125 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (0.60 mm)**

Split at 12 o'clock orientation

LOCKHEED MARTIN

BT20 – Entry Post Ream

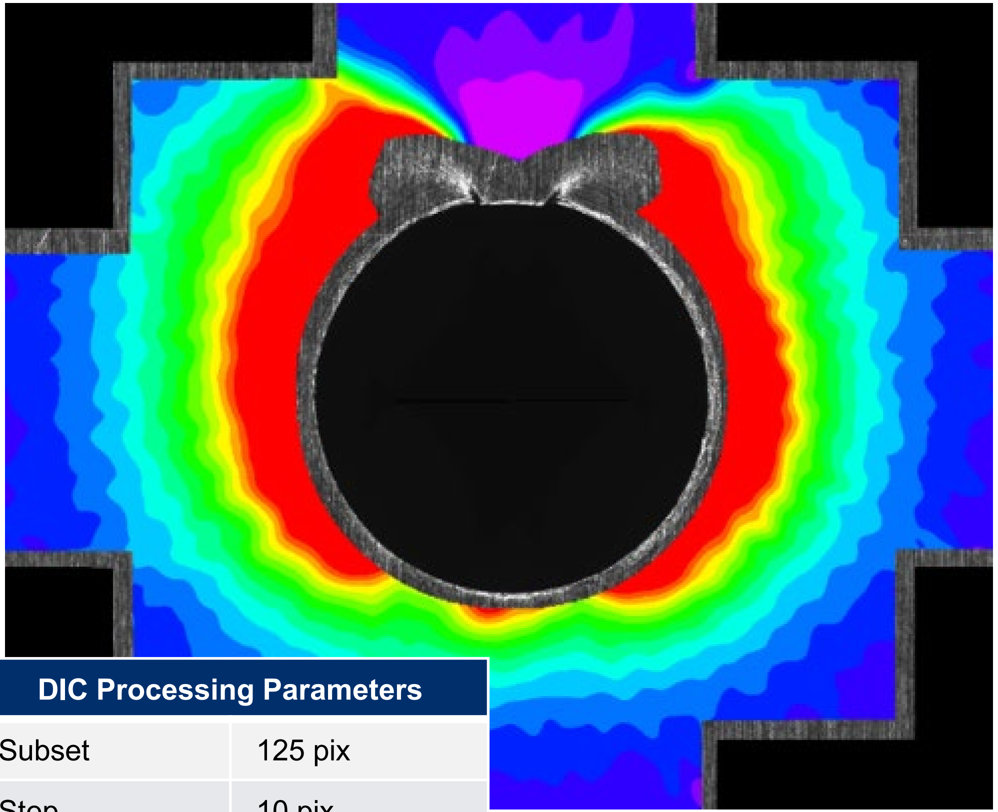


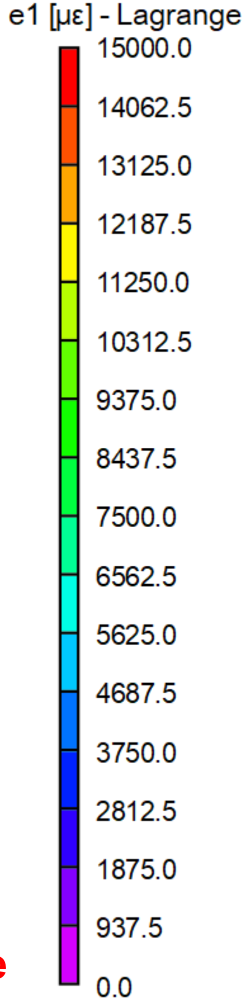
DIC Processing Parameters	
Subset	125 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (0.60 mm)**

Split at 12 o'clock orientation

BT20 – Exit Post Cx

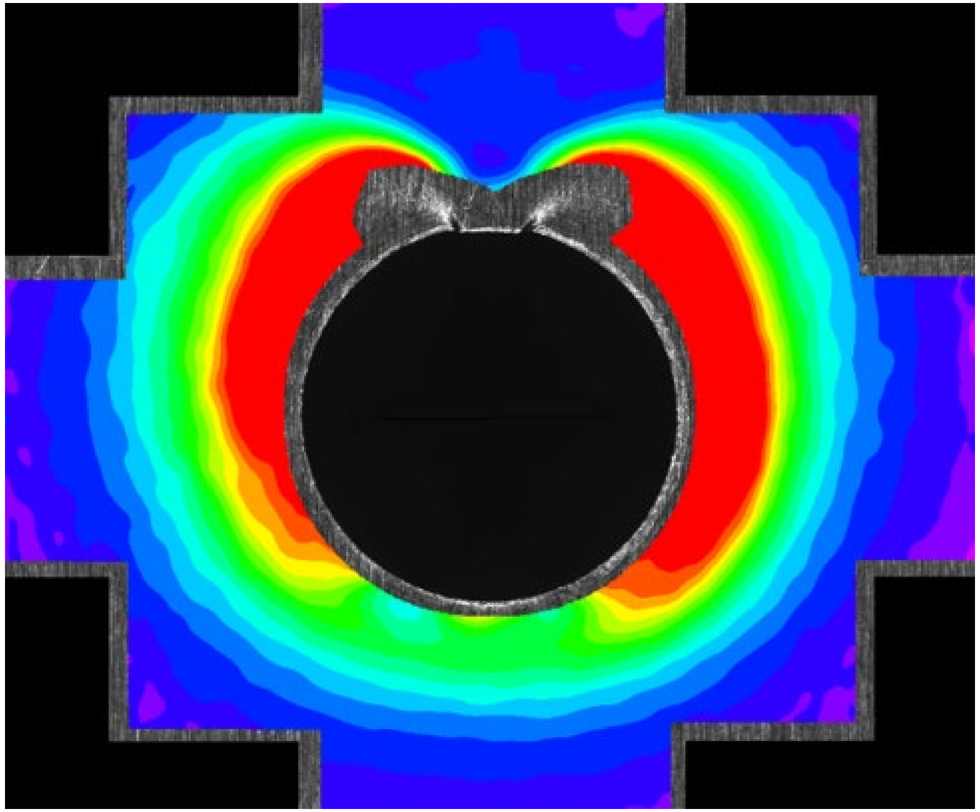
E1

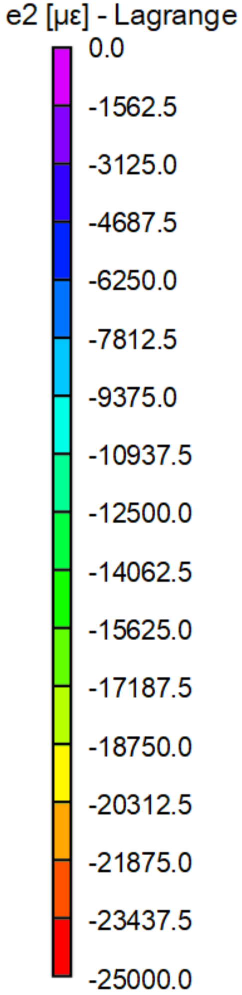




~190 microns to edge

E2



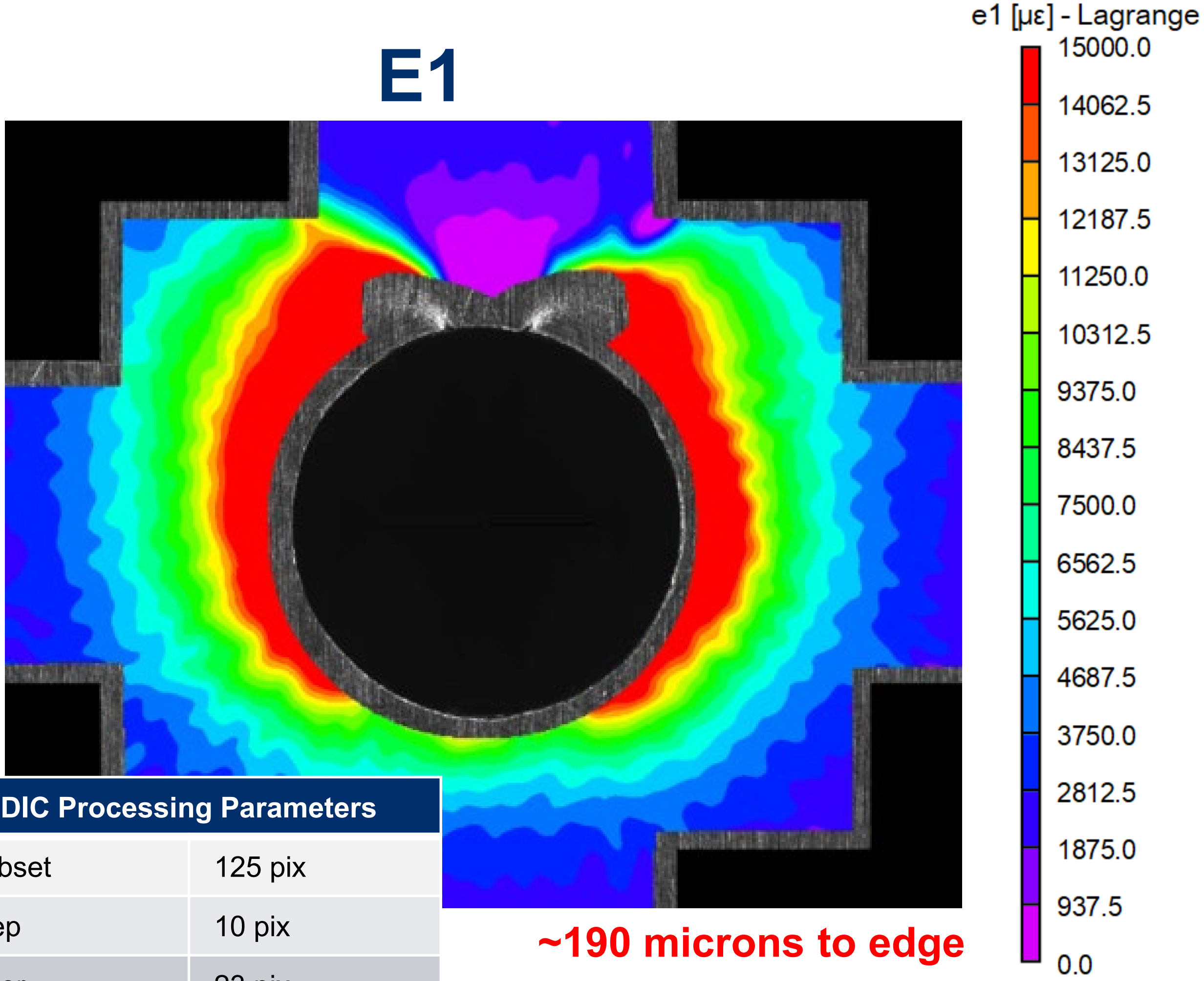


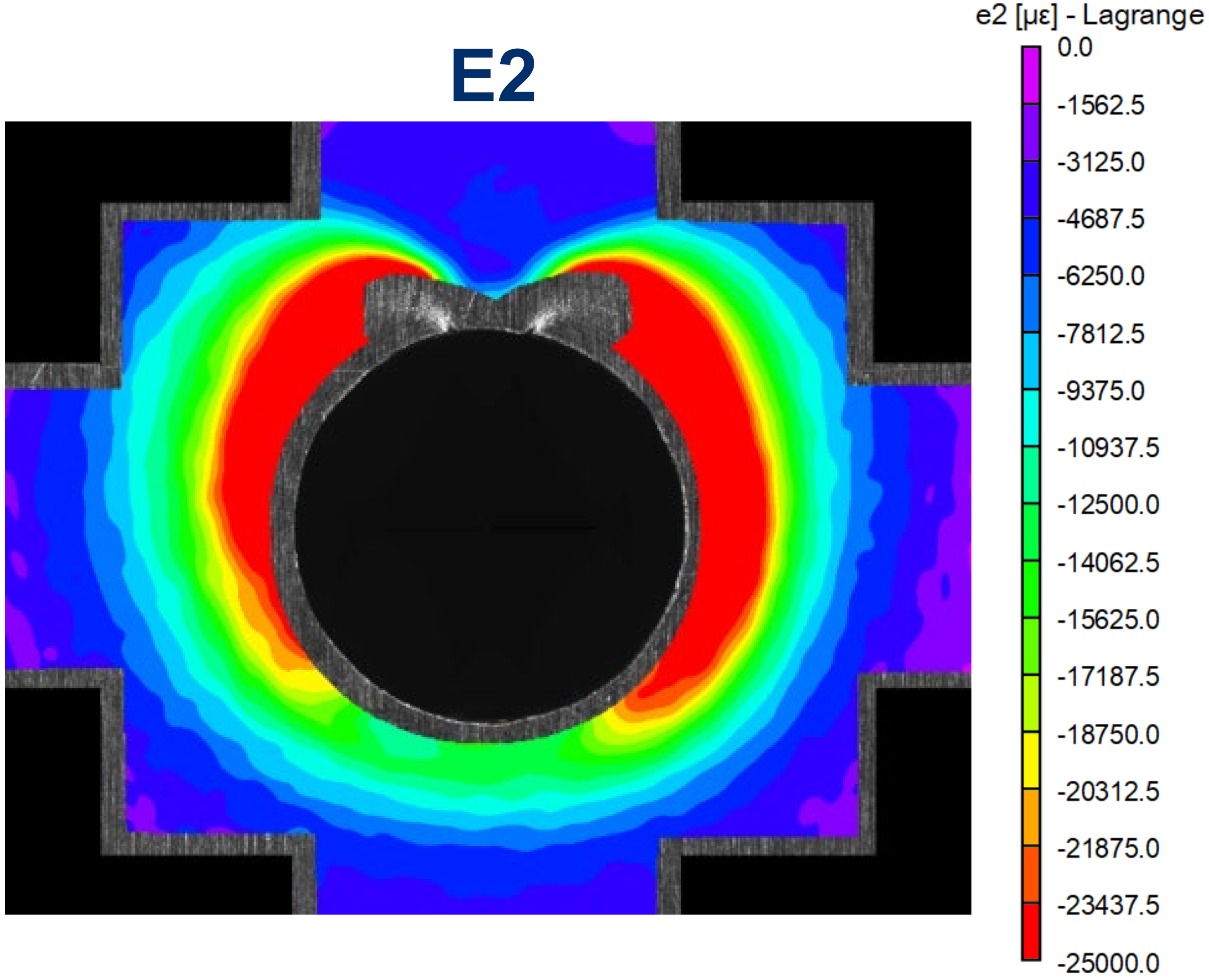
DIC Processing Parameters	
Subset	125 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (0.60 mm)**

Split at 12 o'clock orientation

LOCKHEED MARTIN

BT20 – Exit Post Ream





DIC Processing Parameters	
Subset	125 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (0.60 mm)**

Split at 12 o'clock orientation

LOCKHEED MARTIN

Overview

1. **Purpose of Improving Near-Bore Strain Measurements**
2. **Overview of Previous 2-inch SsCx DIC results**
3. **Experimental Set-up**
4. **Results**
    1. **2024 Coupons**
    2. **7050 Coupons (SuperResolution)**
        1. **Low Expansion – Reamed**
        2. **Low Expansion - Unreamed**
        3. **High Expansion – Reamed**
        4. **High Expansion - Unreamed**
5. **Development of Methods for Data Analysis for FEA simulations**
6. **Conclusion/Path Forward**

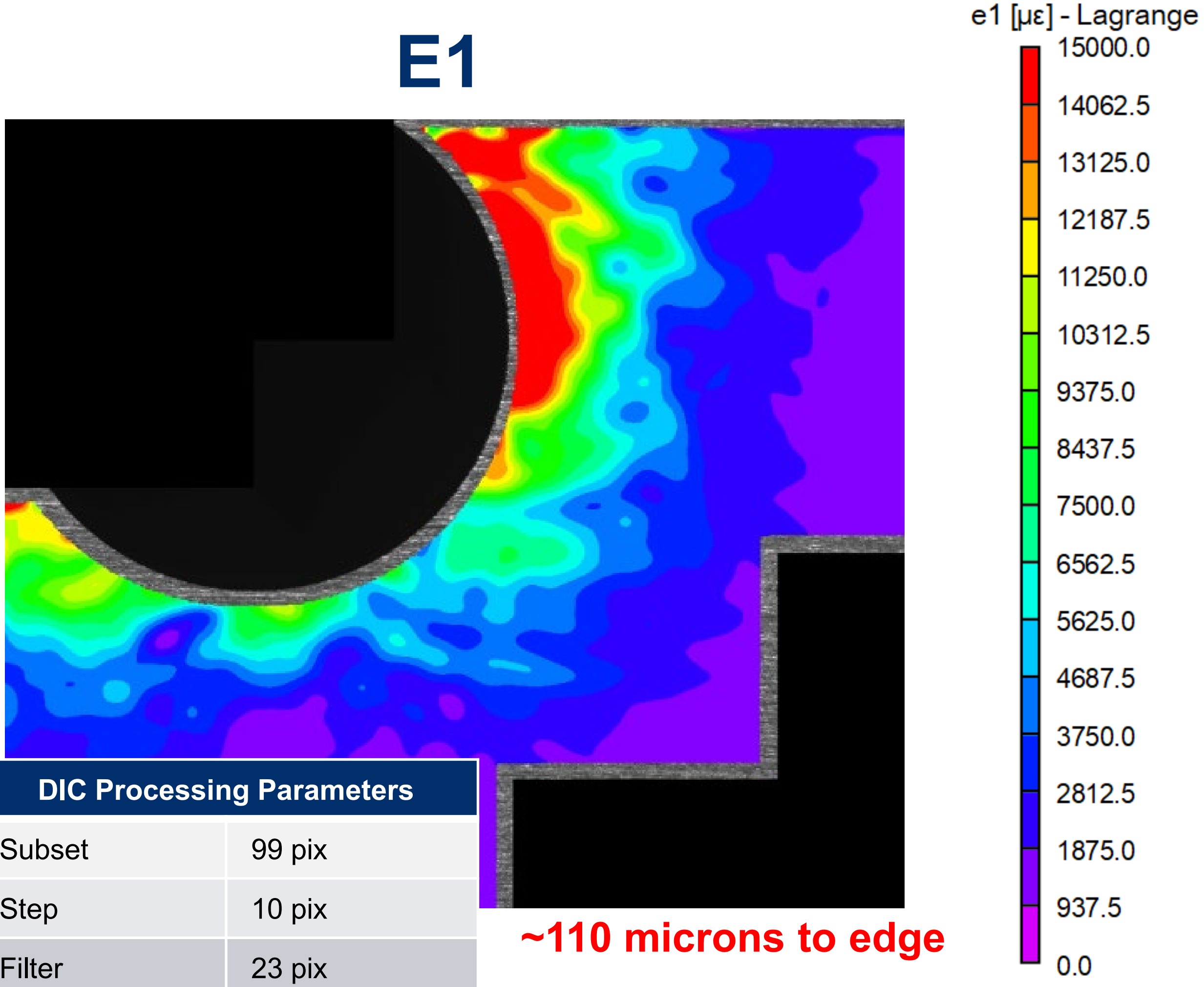
7050-T7451 “Low” Cx + Ream
2D DIC Super-resolution (270°)

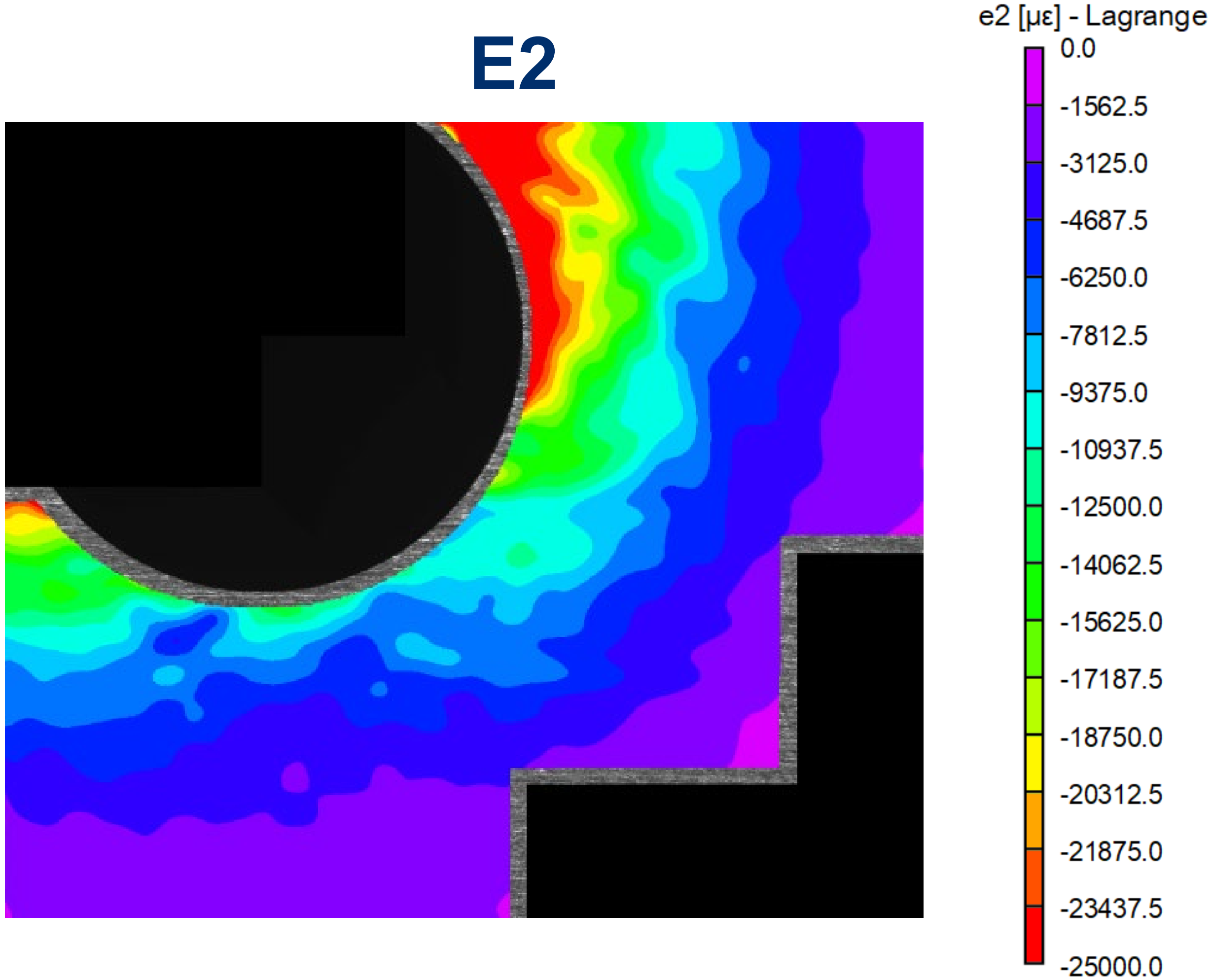
Thickness = 0.25inch

Starting Hole Diameter = 0.2379inch

FTI Toolset:

7050-L-REM-02 – Entry Post Cx



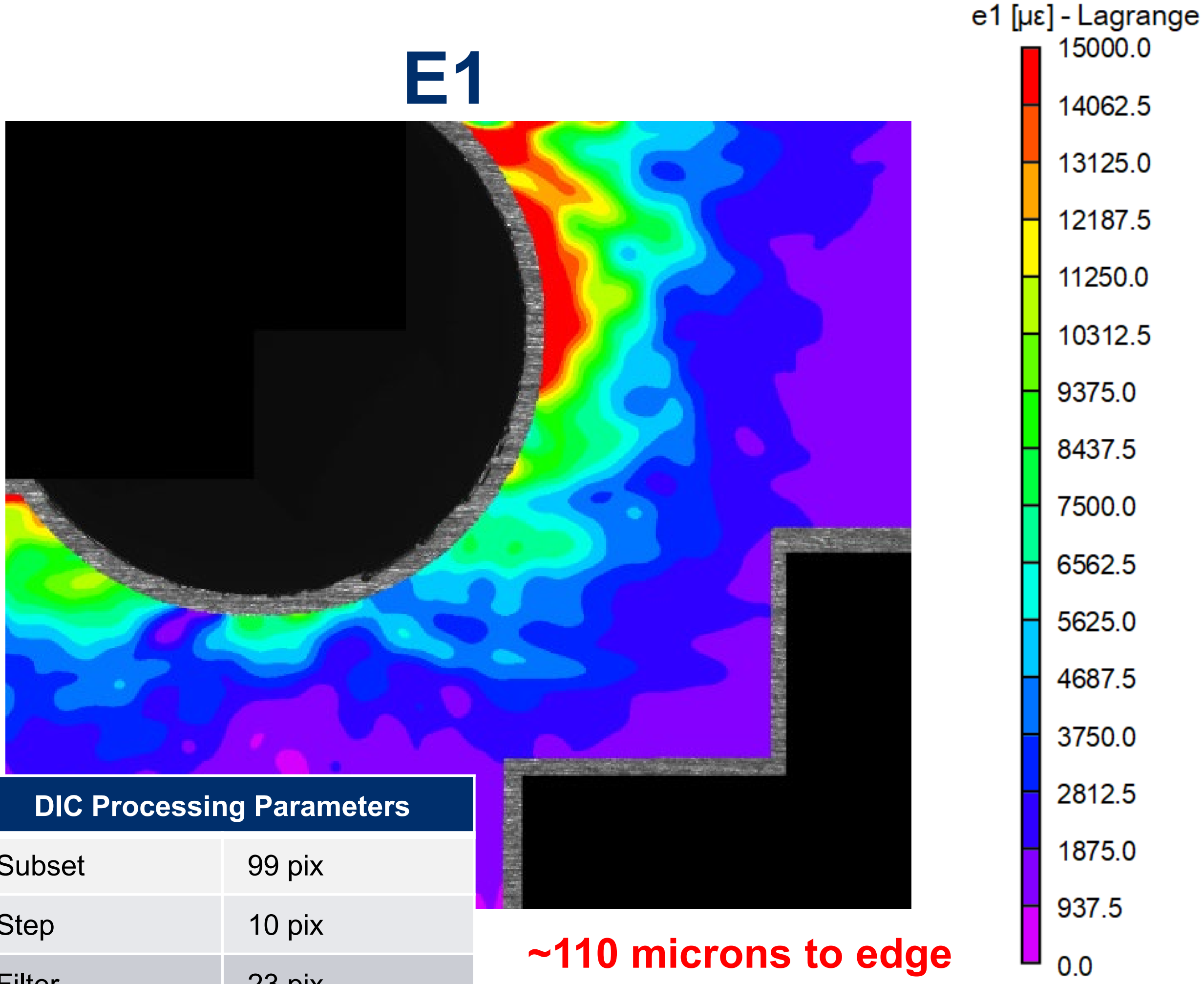


DIC Processing Parameters	
Subset	99 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (0.60 mm)**

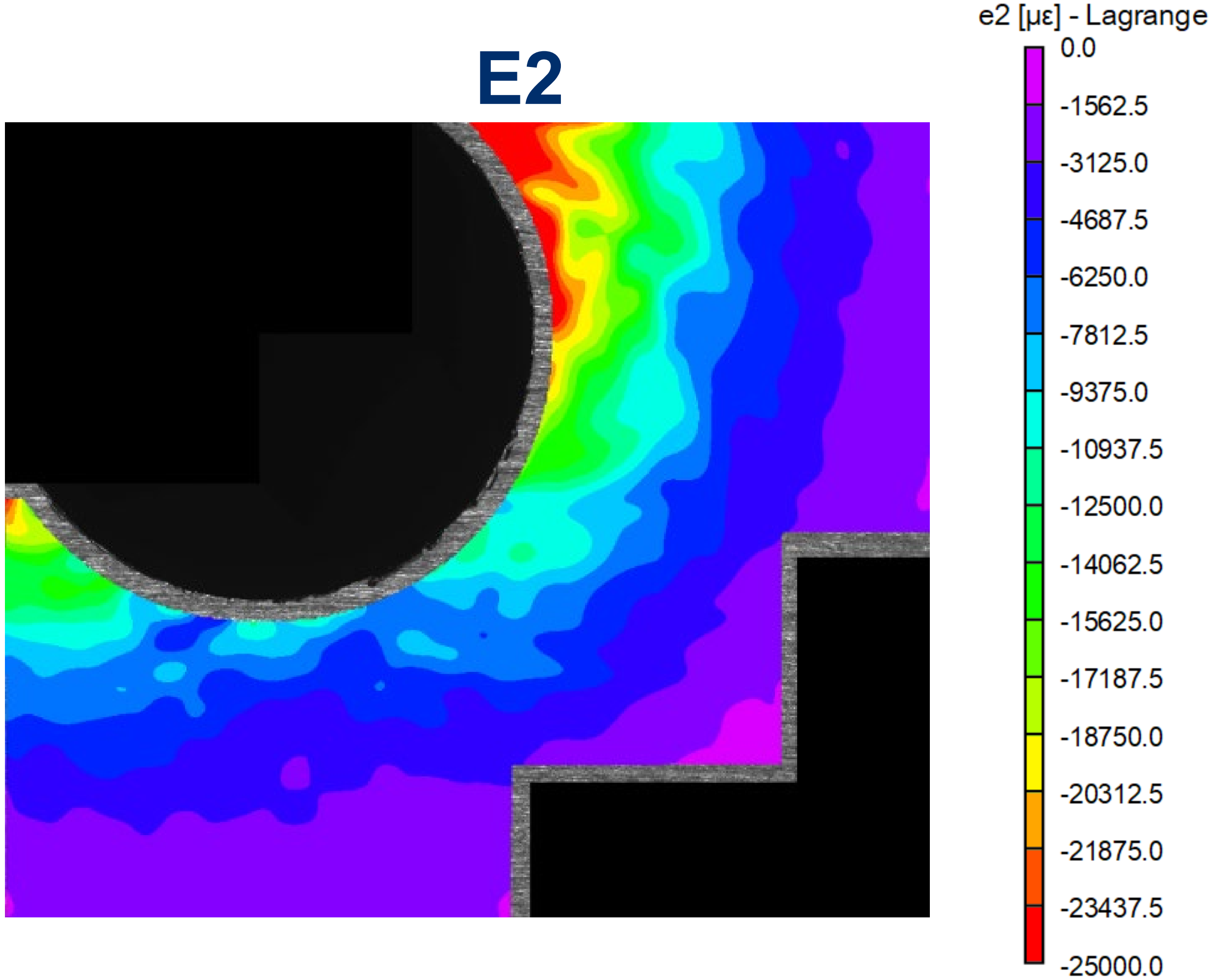
Split at 12 o'clock orientation

7050-L-REM-02 – Entry Post Ream

E1



E2



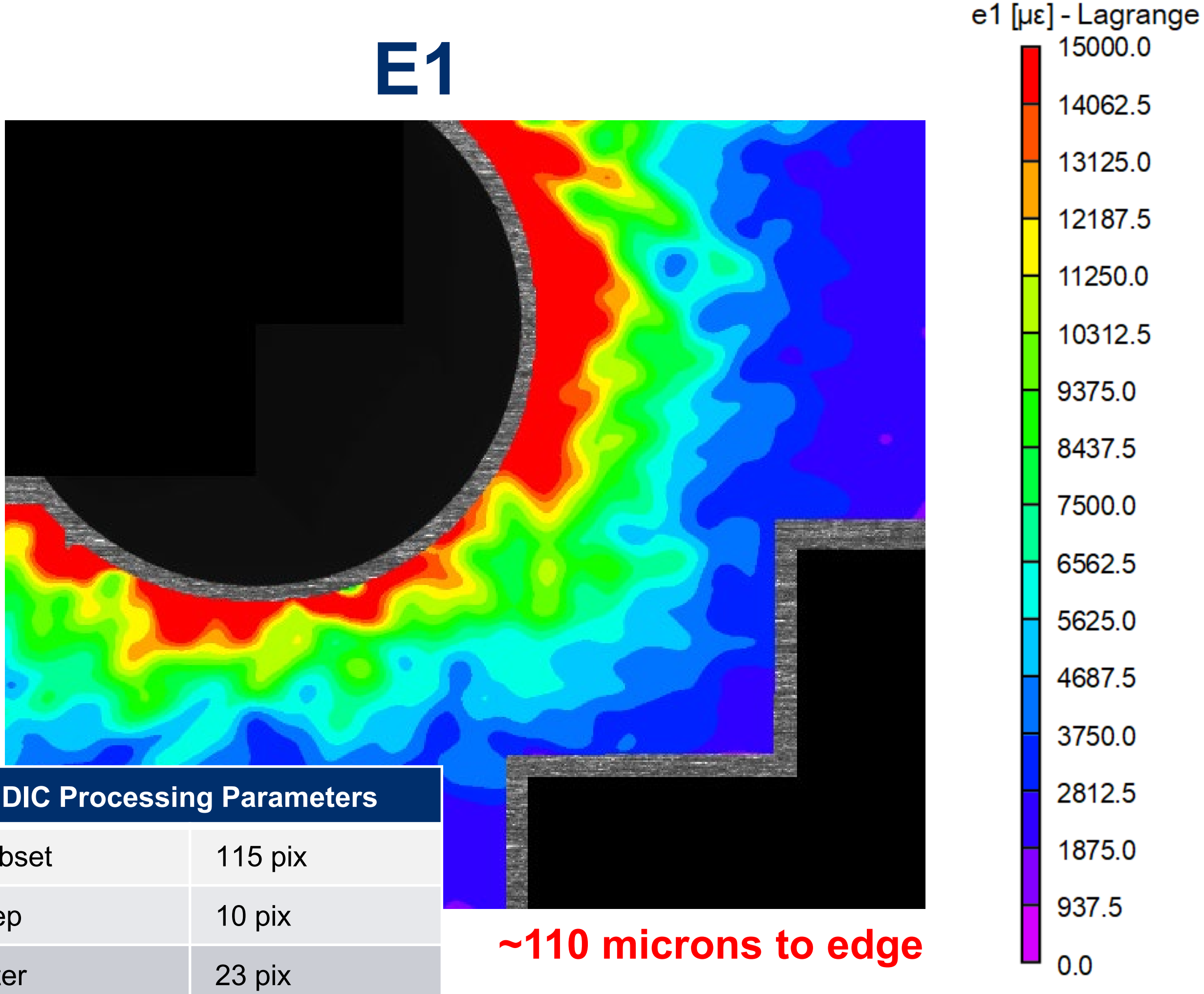
DIC Processing Parameters	
Subset	99 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (0.60 mm)**

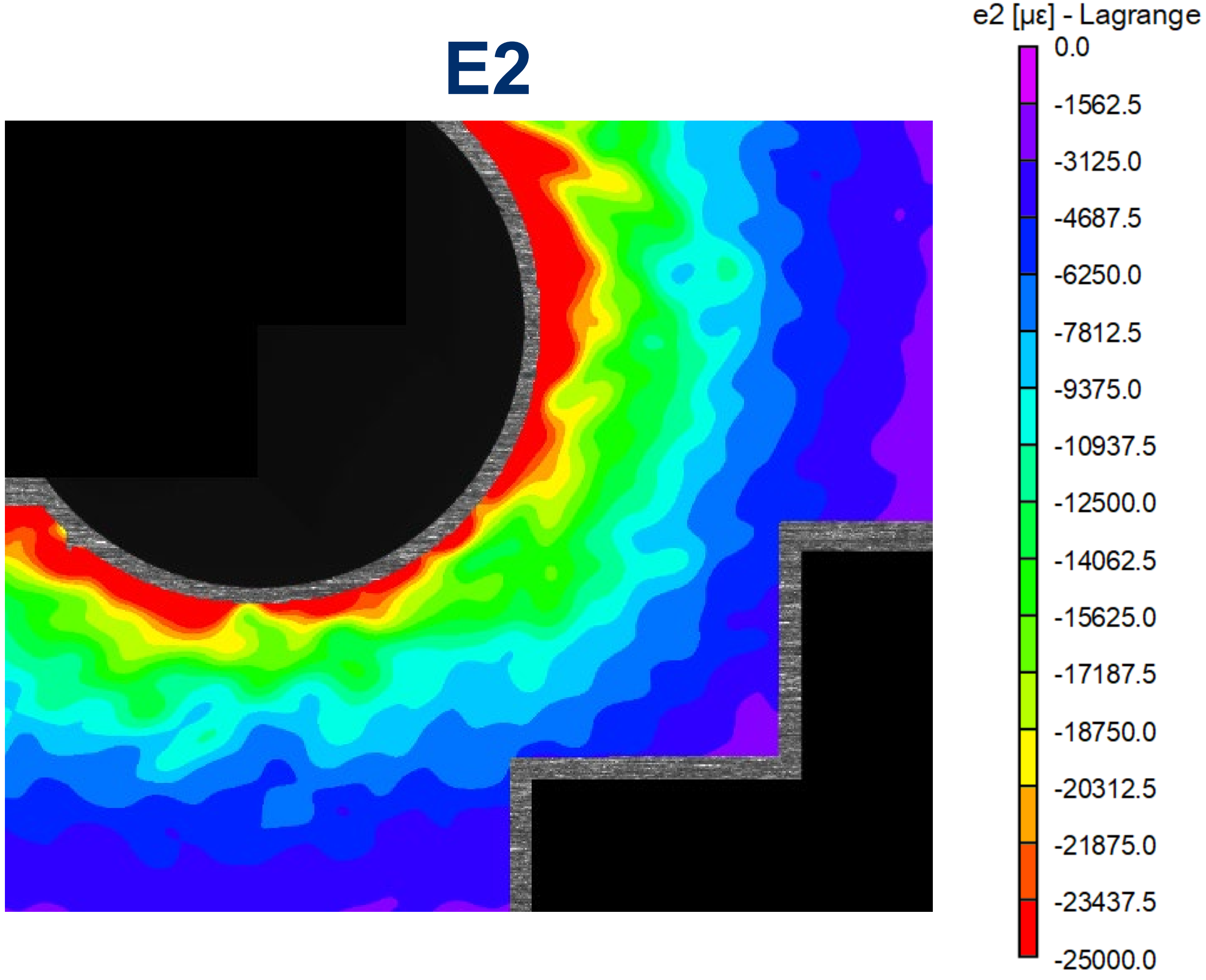
~110 microns to edge

Split at 12 o'clock orientation

LOCKHEED MARTIN

7050-L-REM-02 – Exit Post Cx

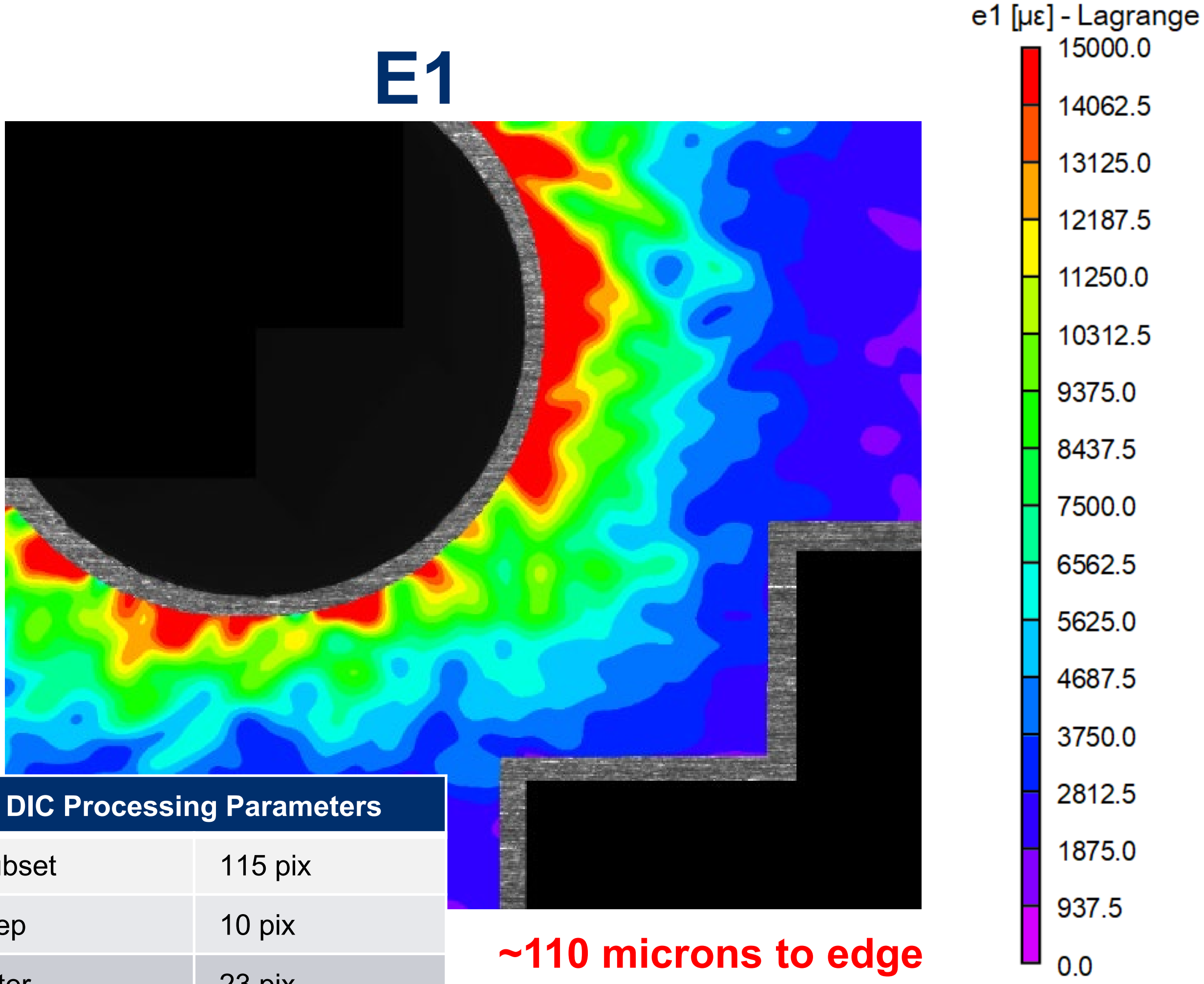


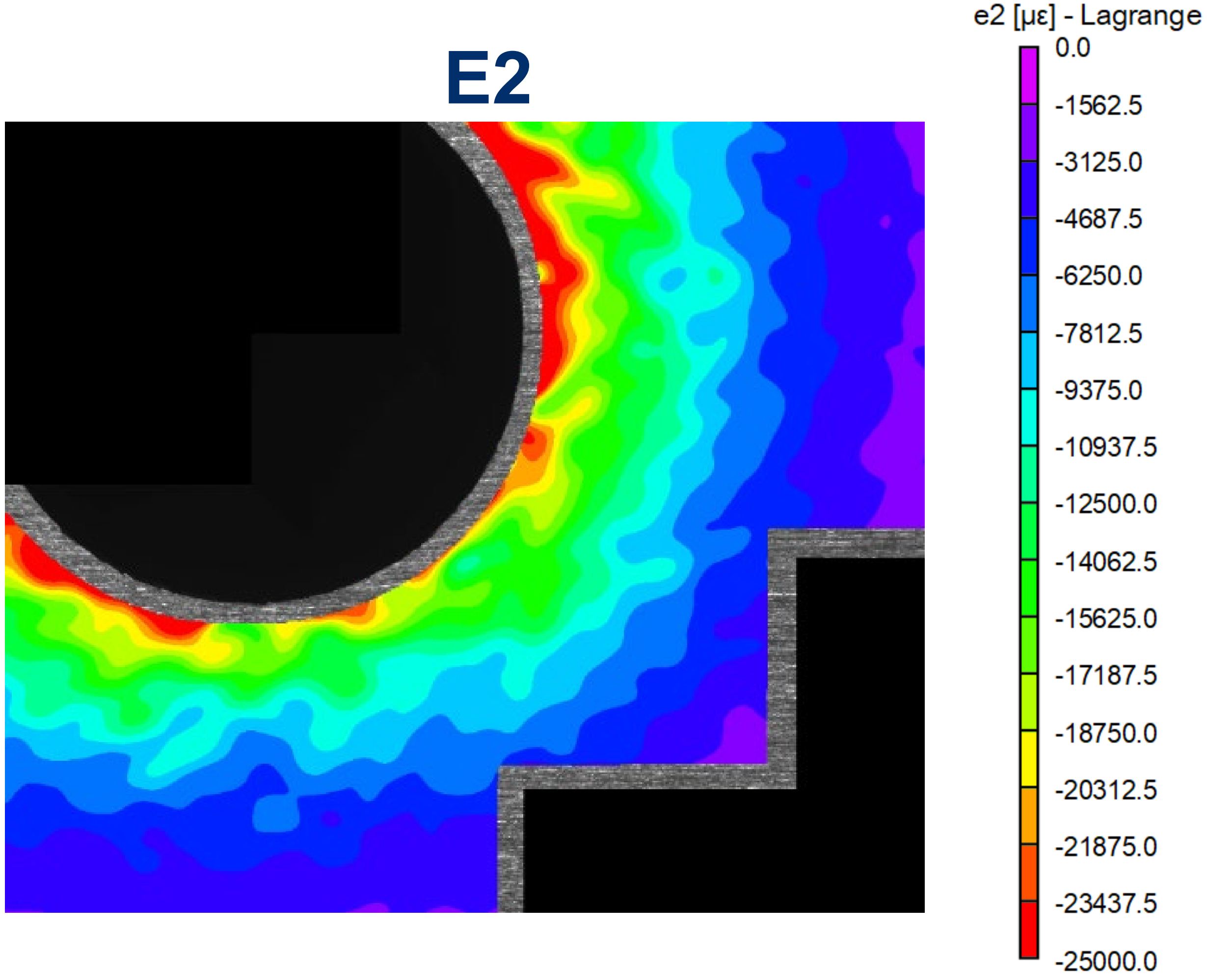


DIC Processing Parameters	
Subset	115 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (0.60 mm)**

Split at 12 o'clock orientation

7050-L-REM-02 – Exit Post Ream





DIC Processing Parameters	
Subset	115 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (0.60 mm)**

Split at 12 o'clock orientation

LOCKHEED MARTIN

7050-T7451 “Low” Cx
2D DIC Super-resolution (270°)

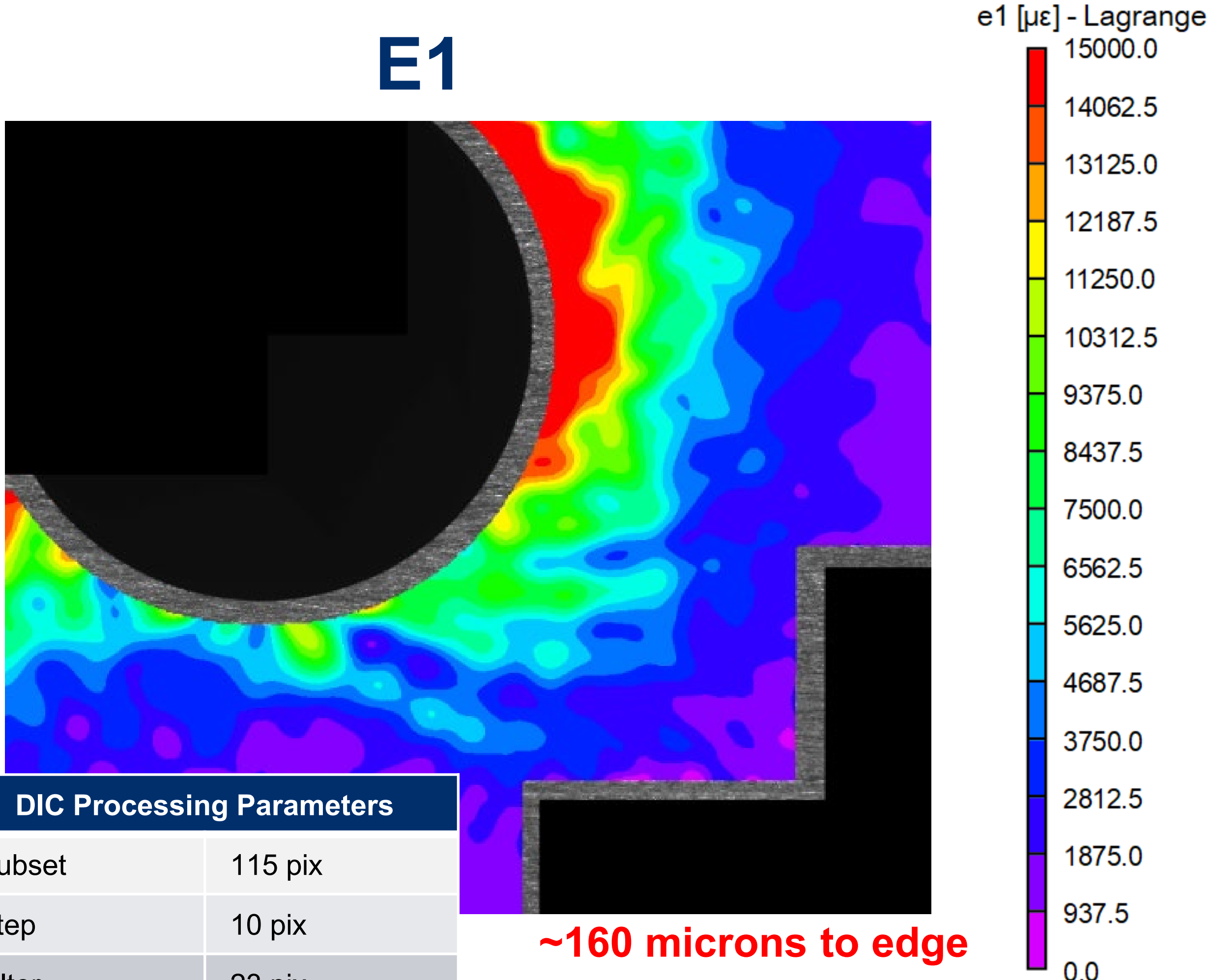
Thickness = 0.25inch

Starting Hole Diameter = 0.2379inch

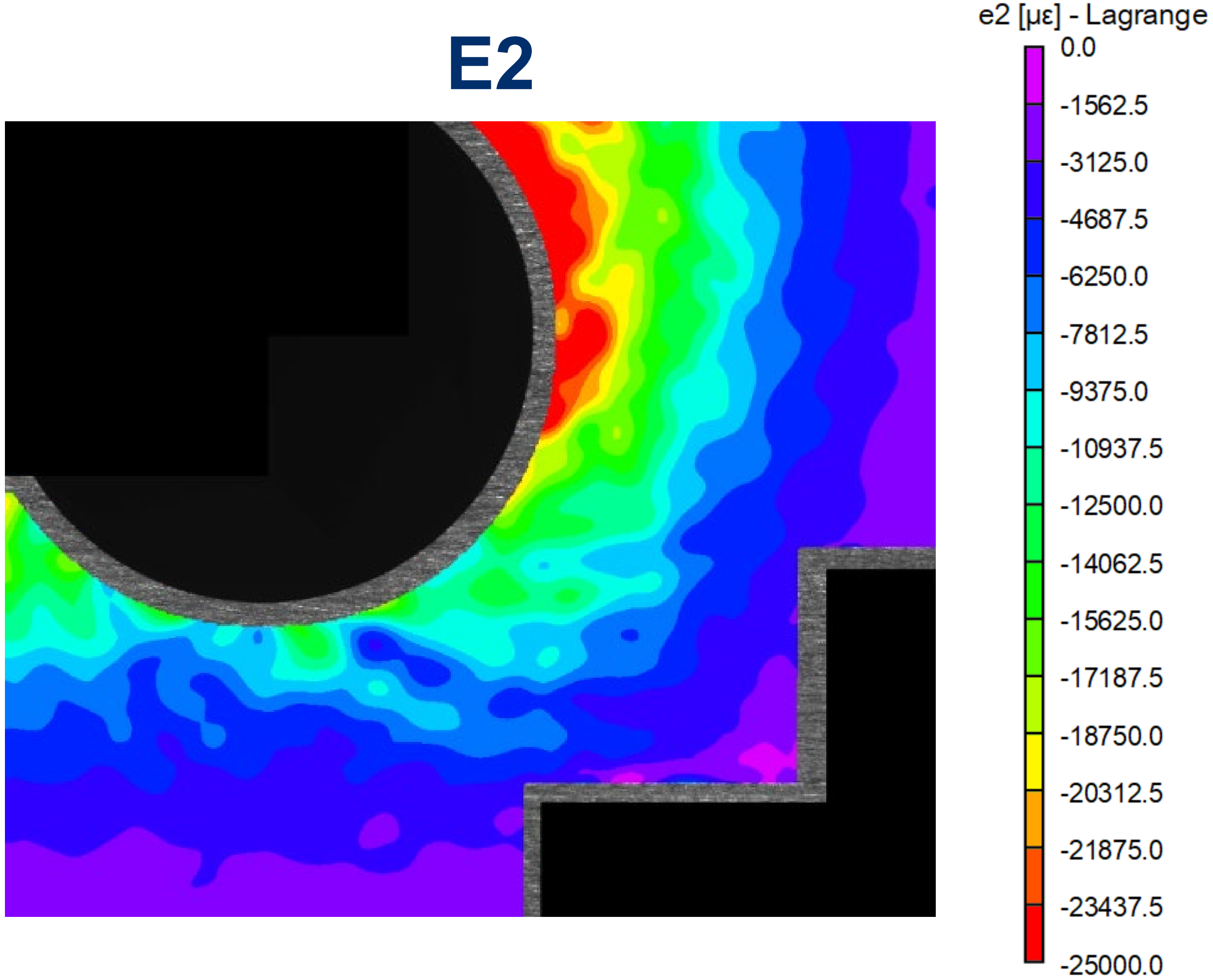
FTI Toolset:

7050-L-U-REM-02 – Entry Post Cx

E1



E2



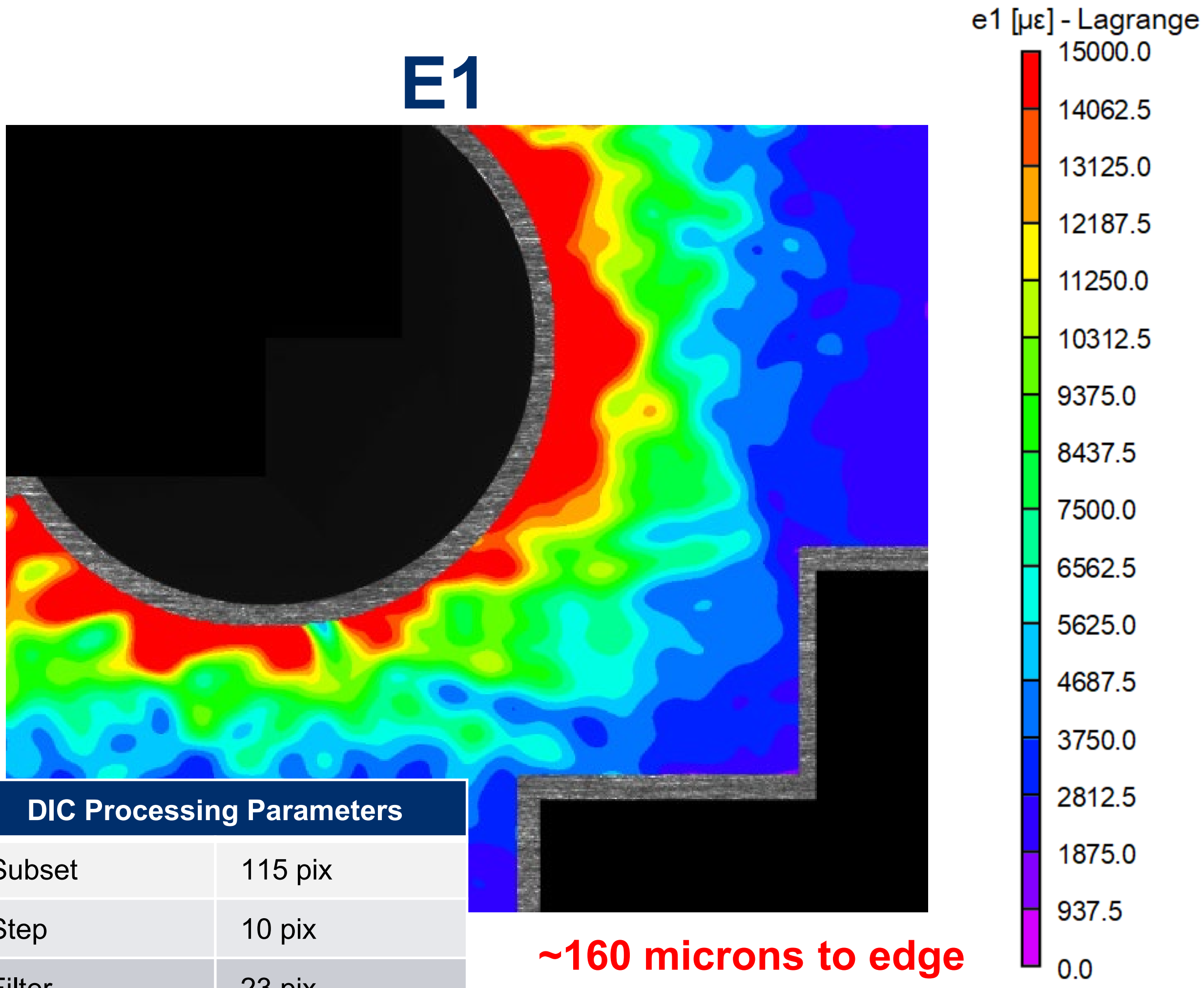
DIC Processing Parameters	
Subset	115 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (0.60 mm)**

Split at 12 o'clock orientation

LOCKHEED MARTIN

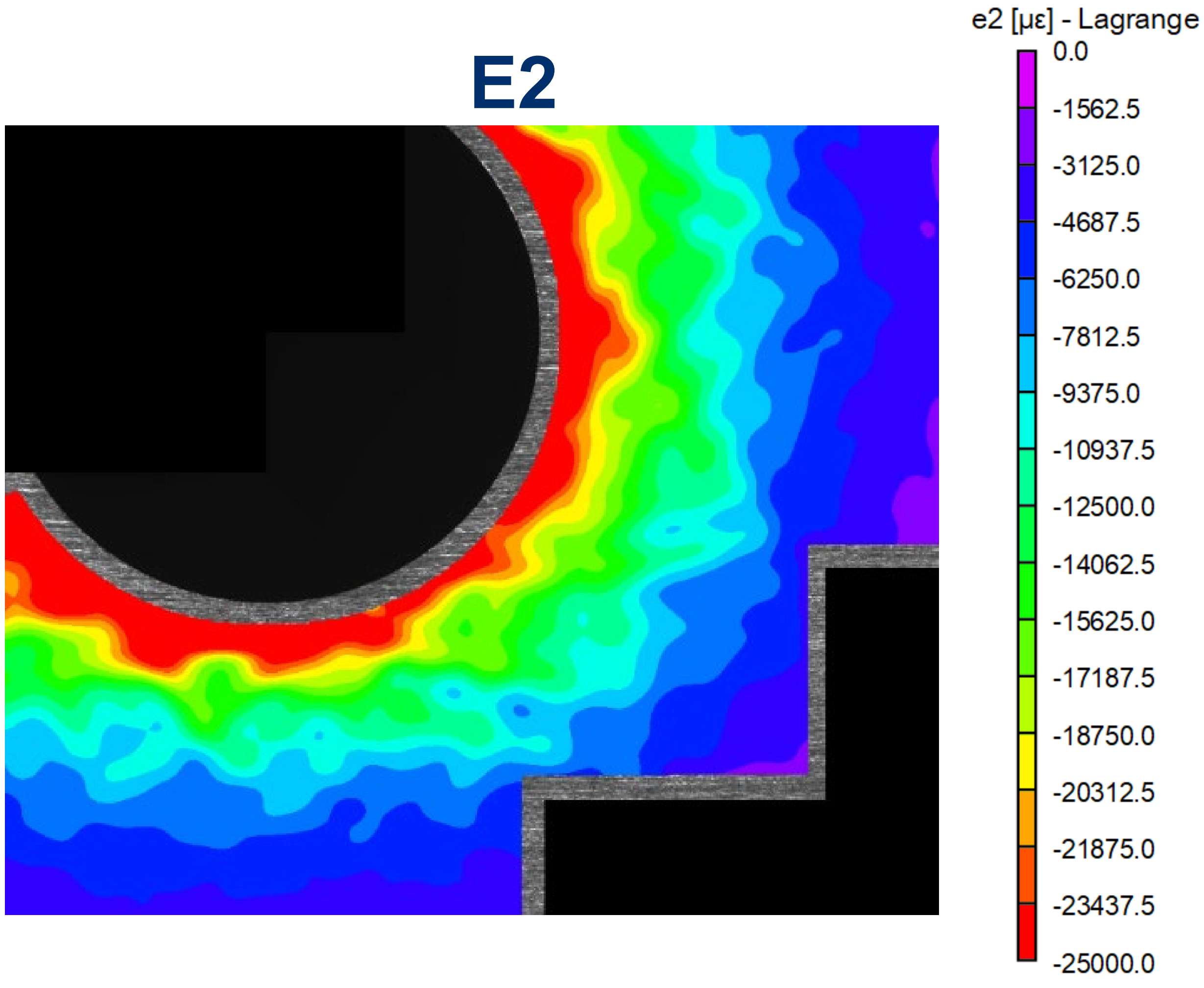
7050-L-U-REM-02 – Exit Post Cx

E1



~160 microns to edge

E2



DIC Processing Parameters	
Subset	115 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (0.60 mm)**

Split at 12 o'clock orientation

LOCKHEED MARTIN

7050-T7451 “High” Cx + Ream 2D DIC Super-resolution (270°)

Thickness = 0.25inch

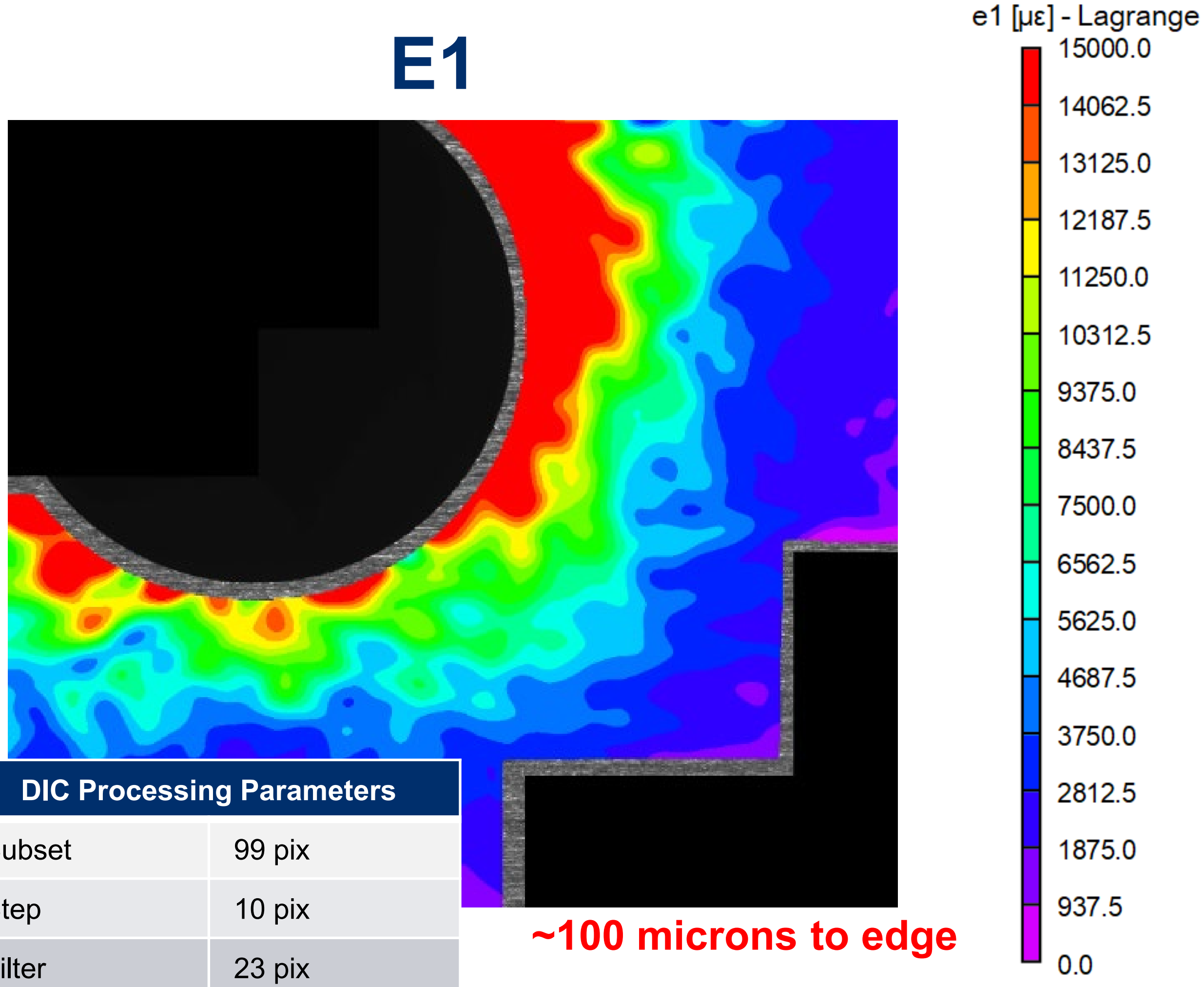
Starting Hole Diameter = 0.2355inch

FTI Toolset:

LOCKHEED MARTIN

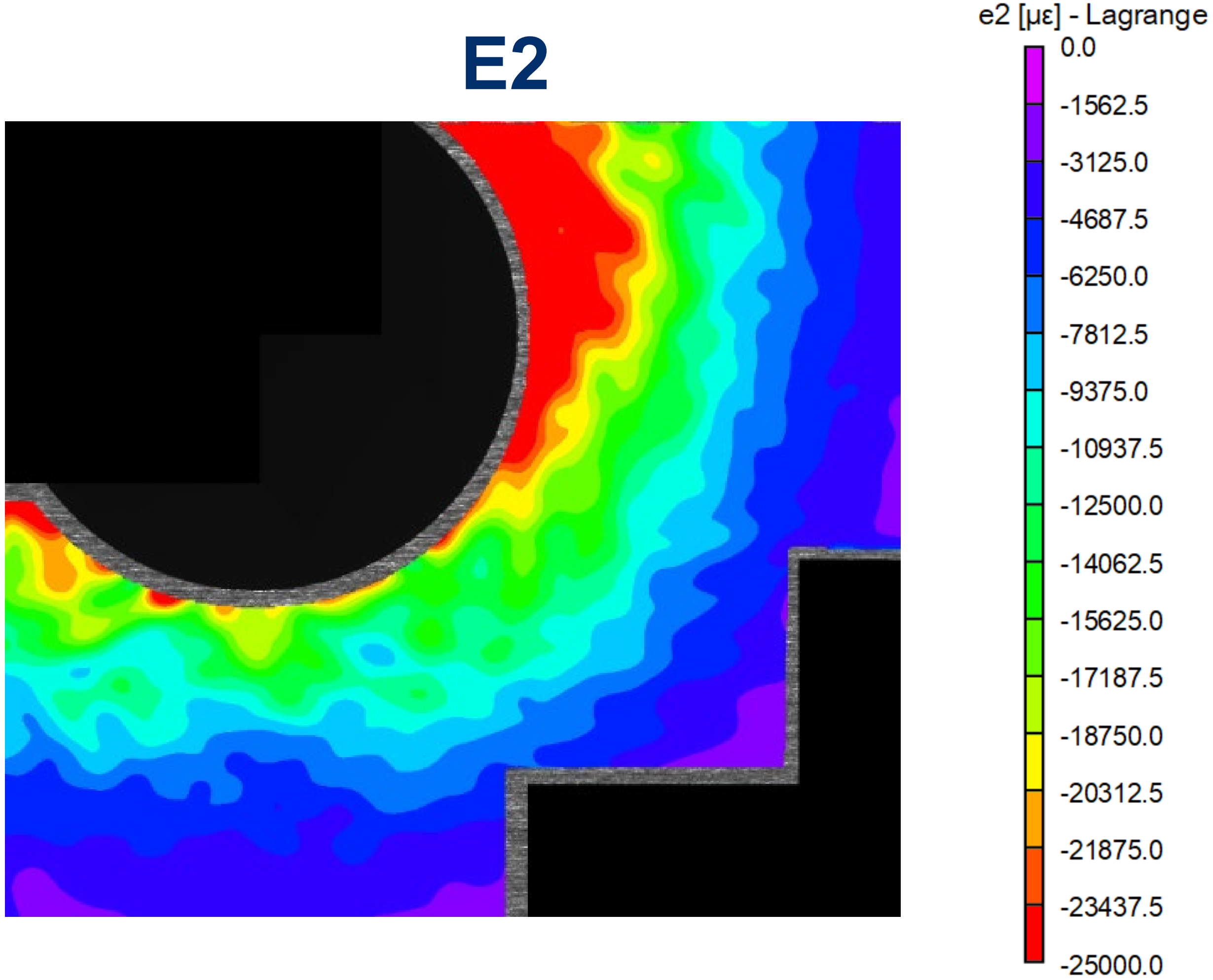
7050-H-REM-02 – Entry Post Cx

E1



~100 microns to edge

E2



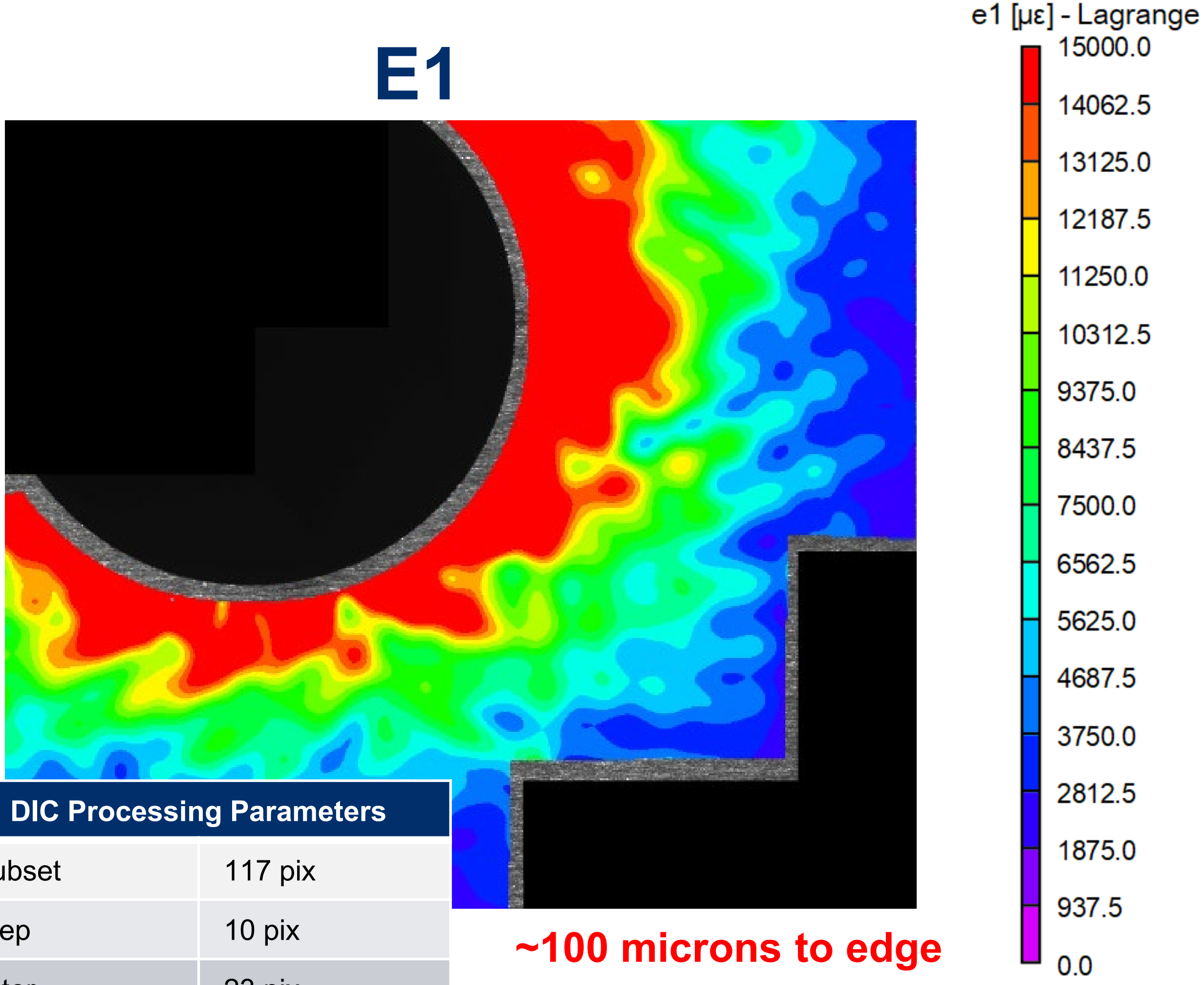
DIC Processing Parameters	
Subset	99 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (0.60 mm)**

Split at 12 o'clock orientation

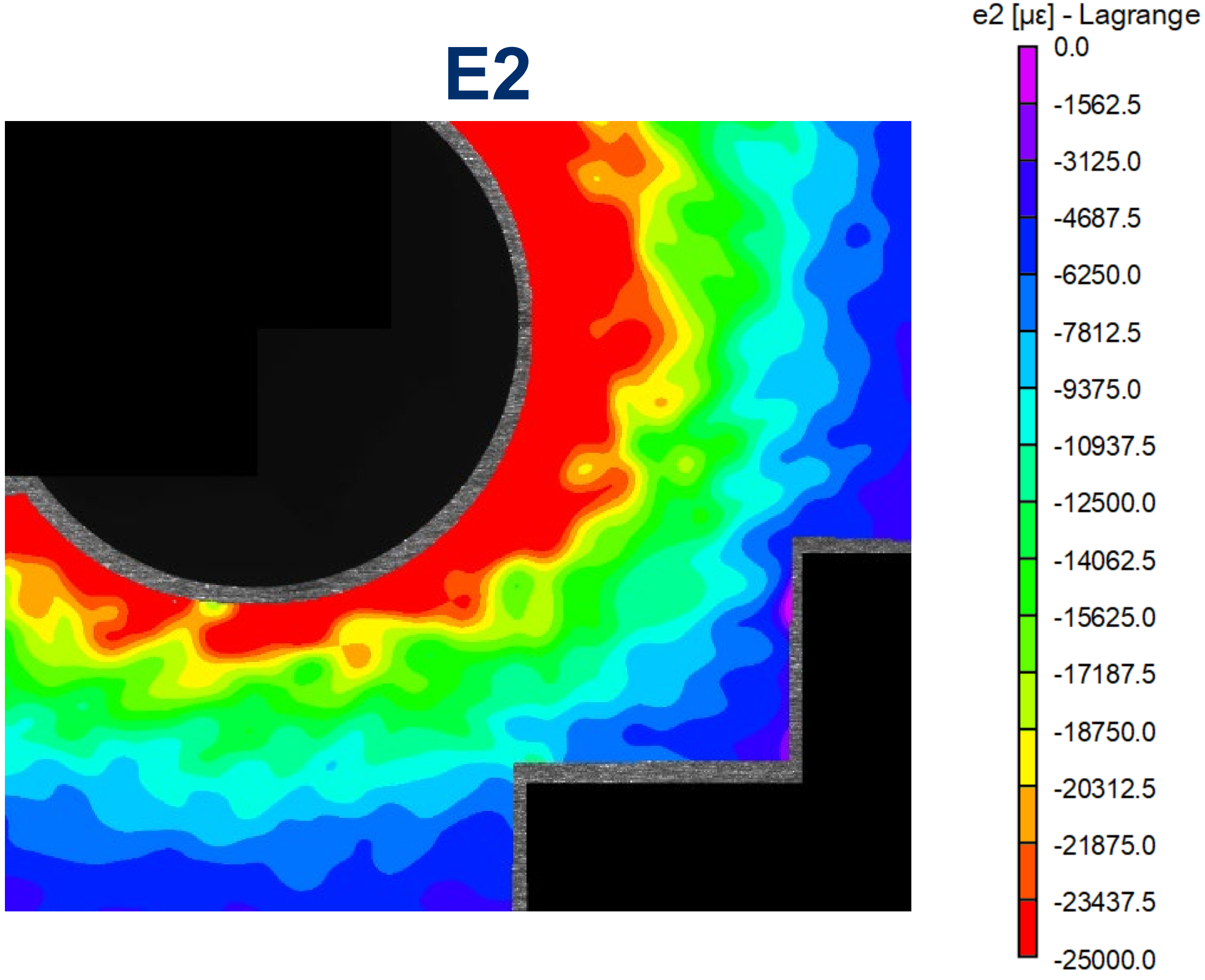
LOCKHEED MARTIN

7050-H-REM-02 – Entry Post Ream

E1



E2



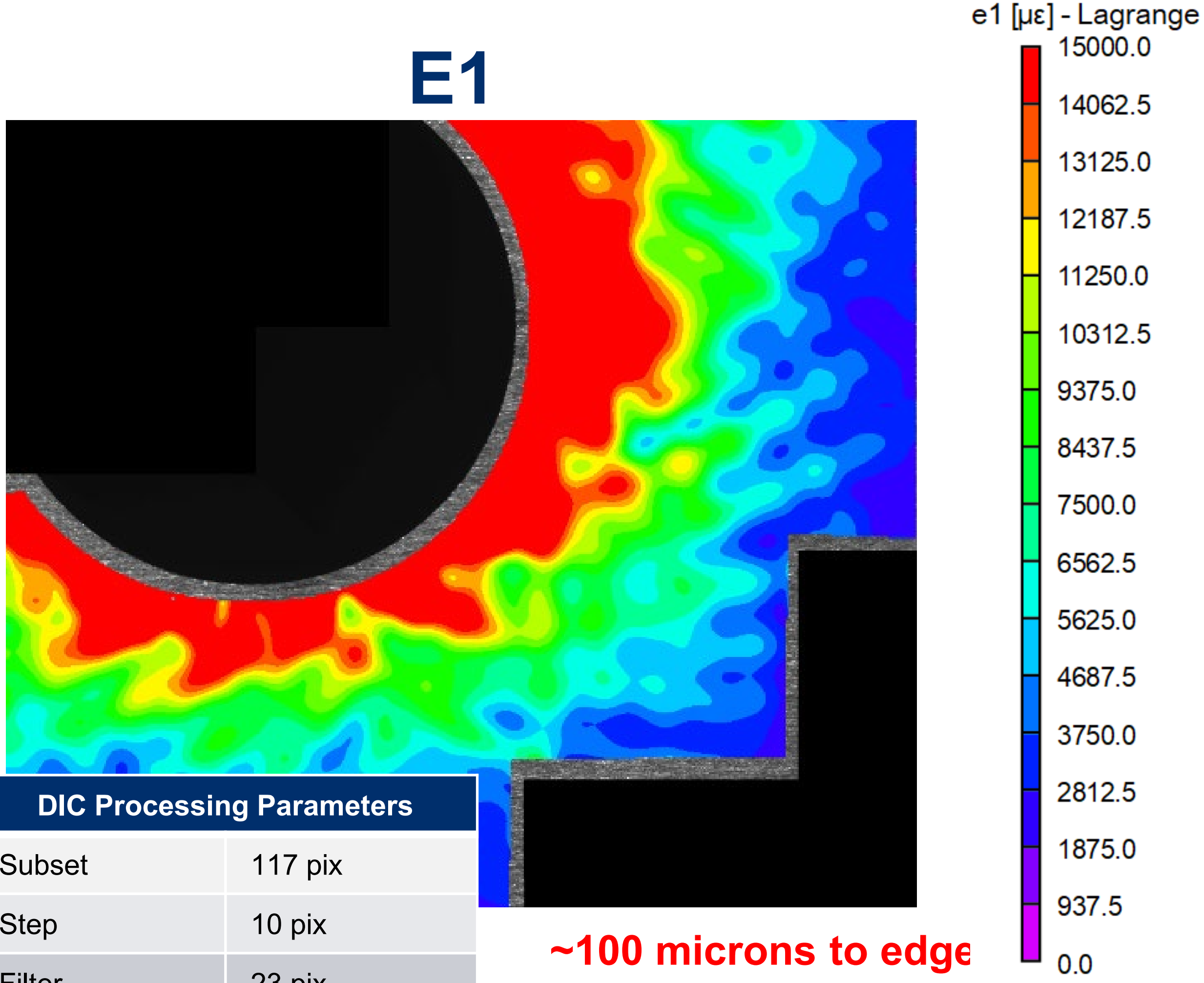
DIC Processing Parameters	
Subset	117 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (0.60 mm)**

~100 microns to edge

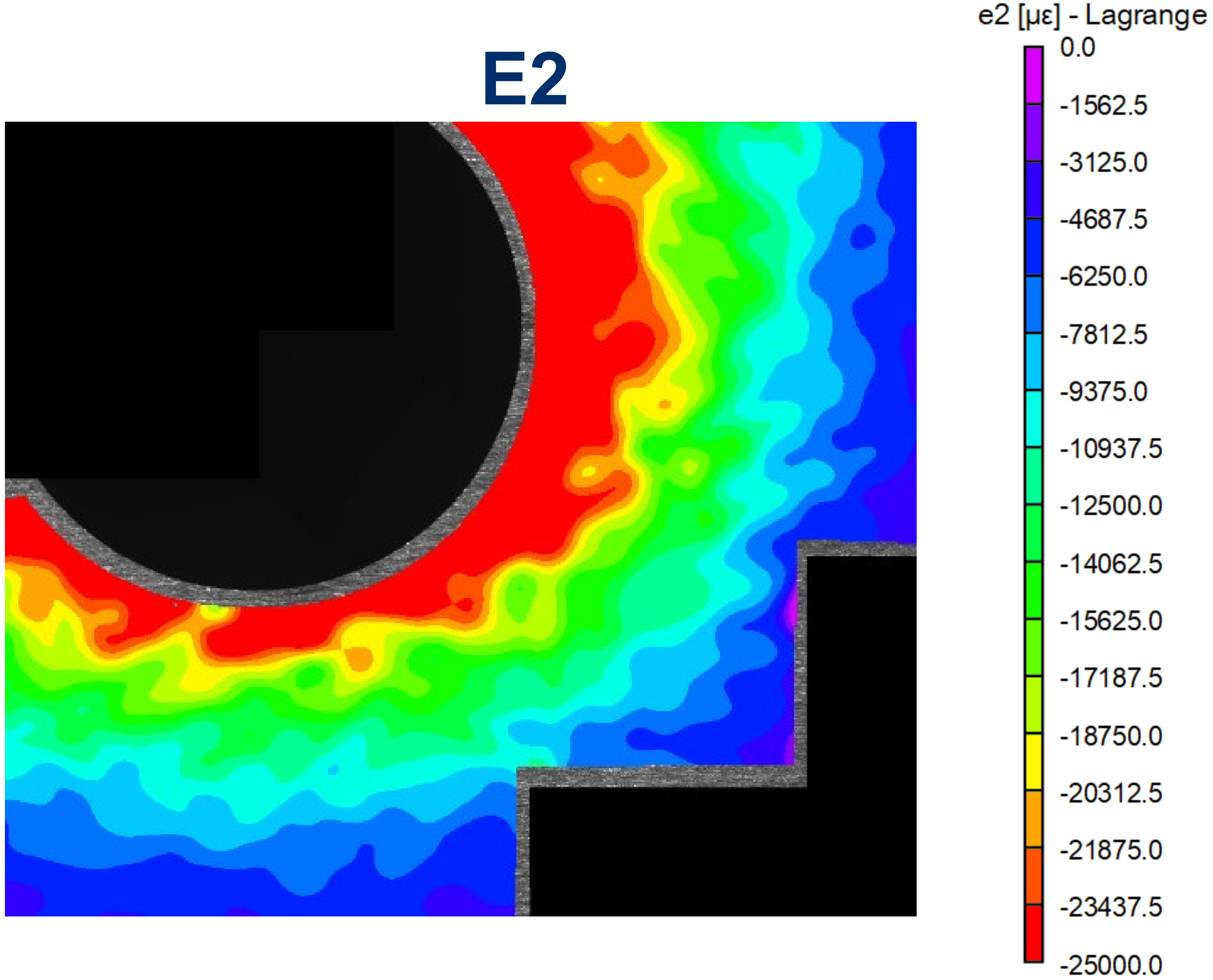
Split at 12 o'clock orientation

7050-H-REM-02 – Exit Post Cx

E1



E2



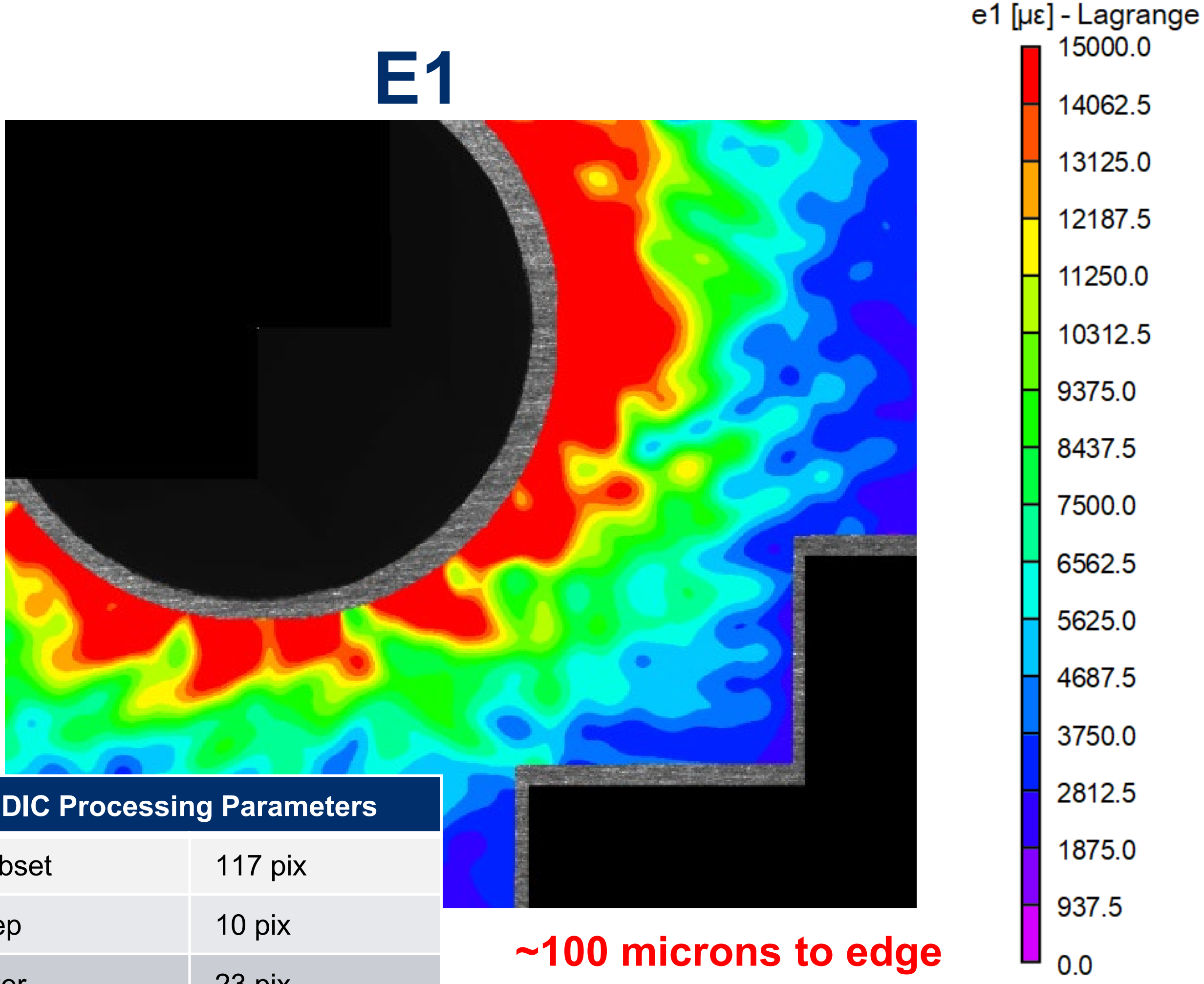
DIC Processing Parameters	
Subset	117 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (0.60 mm)**

Split at 12 o'clock orientation

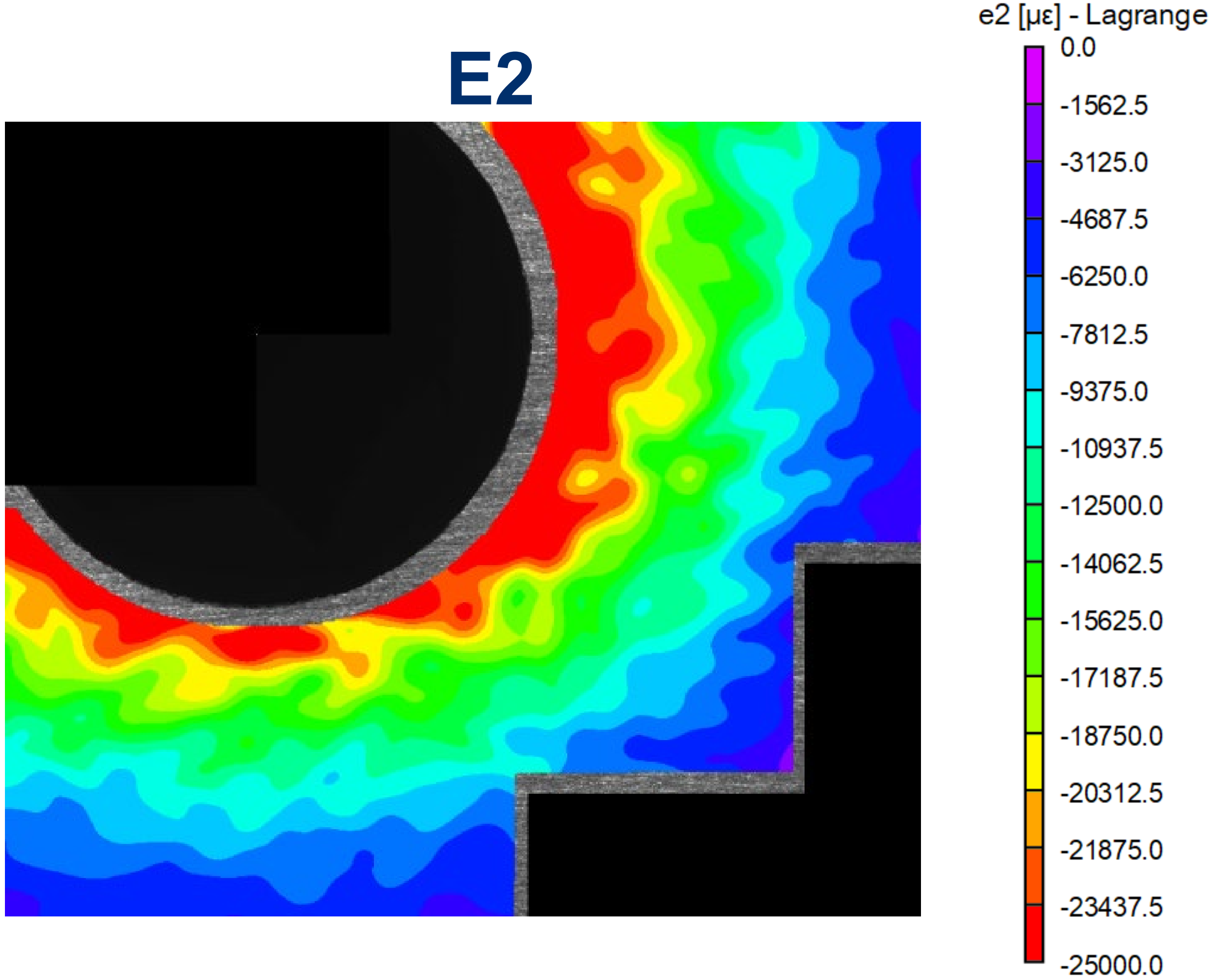
LOCKHEED MARTIN

7050-H-REM-02 – Exit Post Ream

E1



E2



DIC Processing Parameters	
Subset	117 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (0.60 mm)**

Split at 12 o'clock orientation

LOCKHEED MARTIN

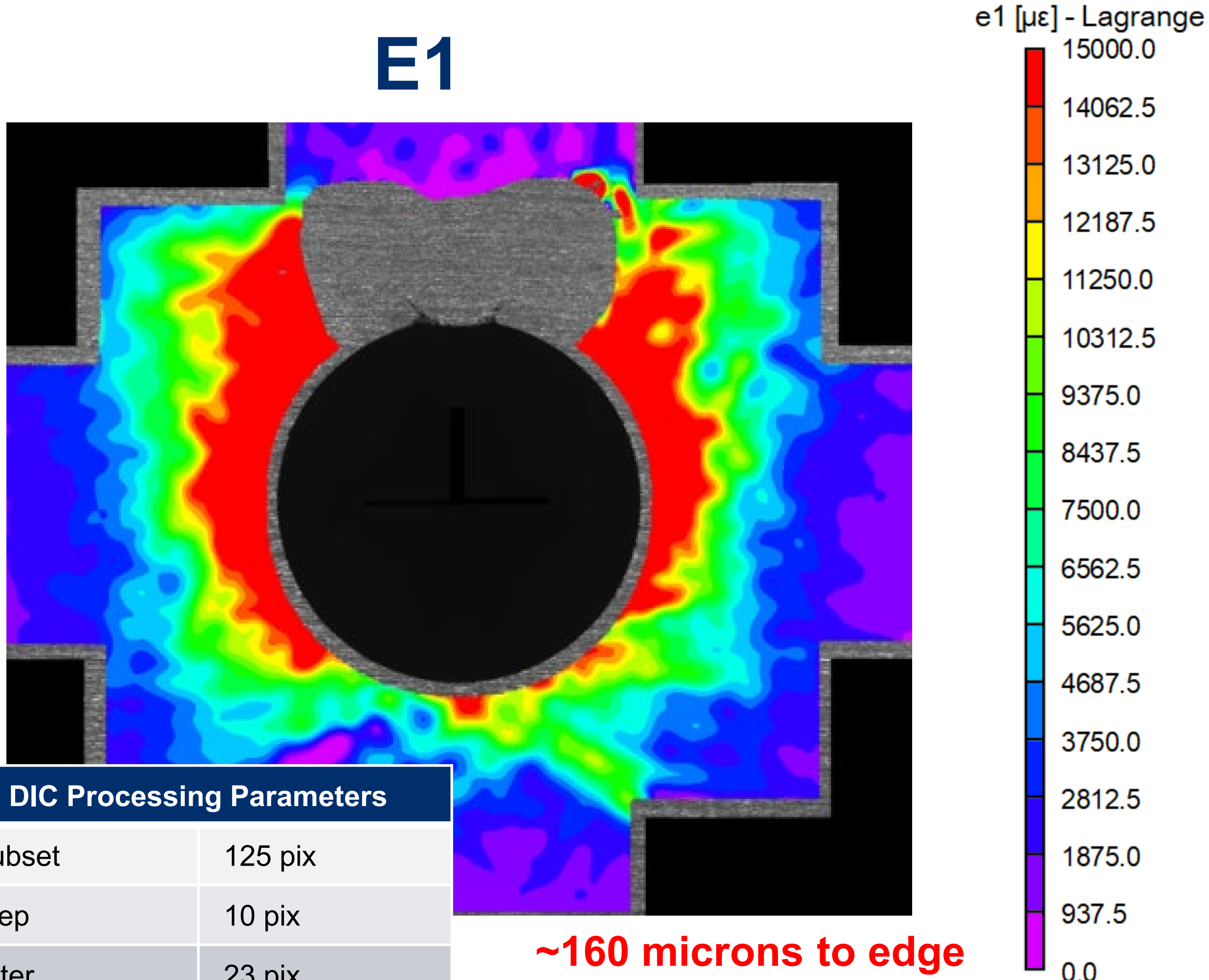
7050-T7451 “High” Cx
2D DIC Super-resolution (360°)

Thickness = 0.25inch
Starting Hole Diameter = 0.2359inch
FTI Toolset:

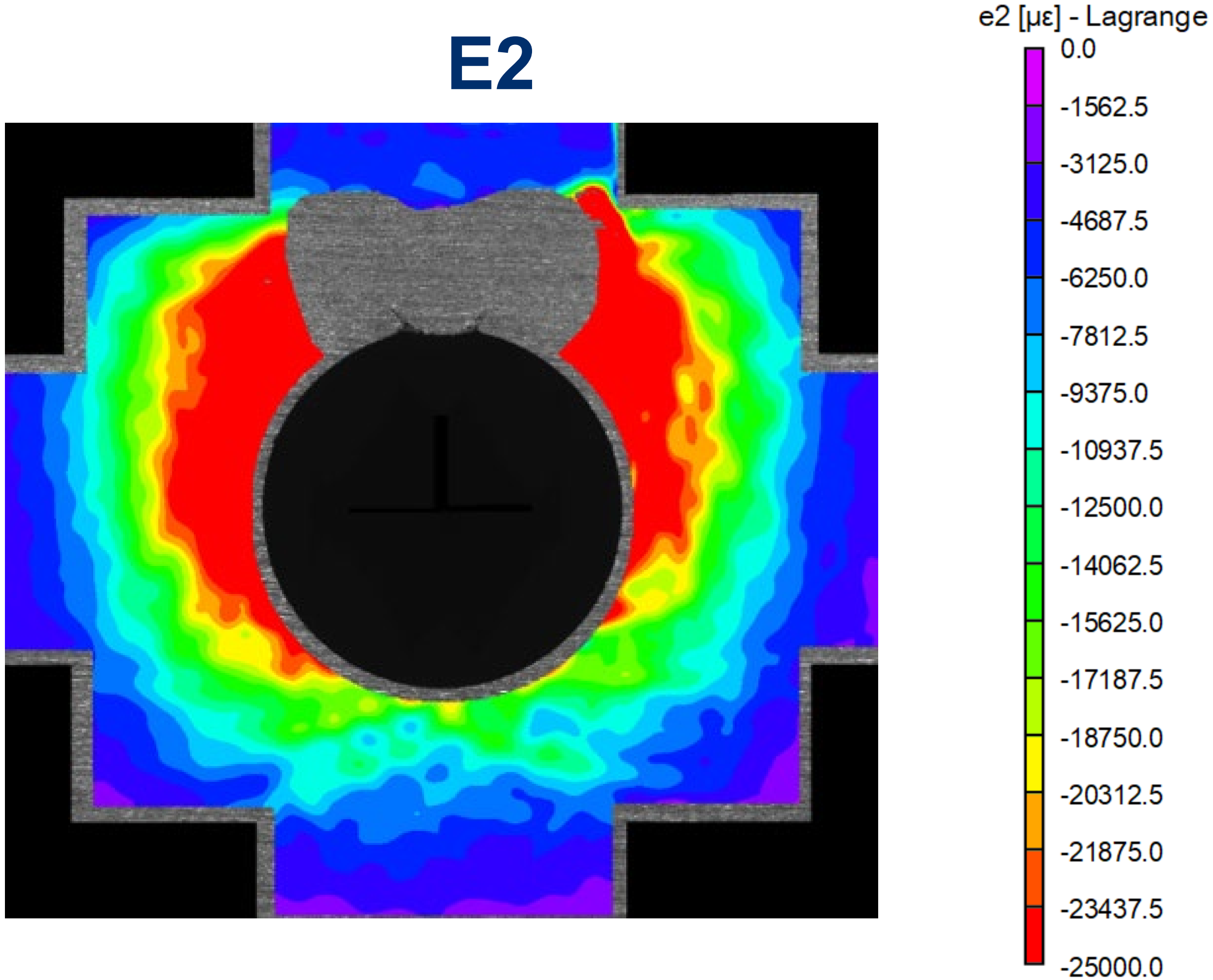
LOCKHEED MARTIN

7050-L-H-REM-02 – Entry Post Cx

E1



E2



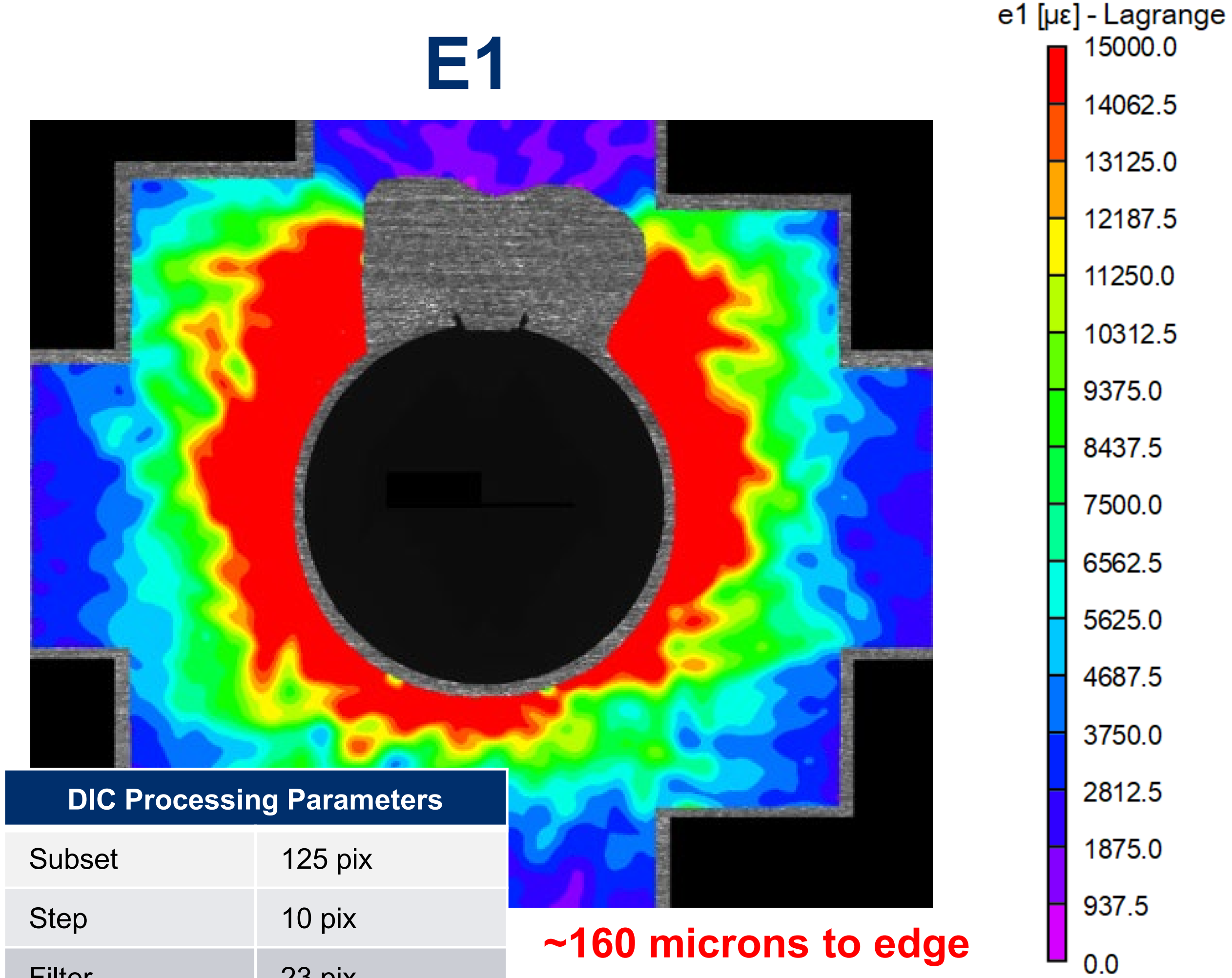
DIC Processing Parameters	
Subset	125 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (0.60 mm)**

Split at 12 o'clock orientation

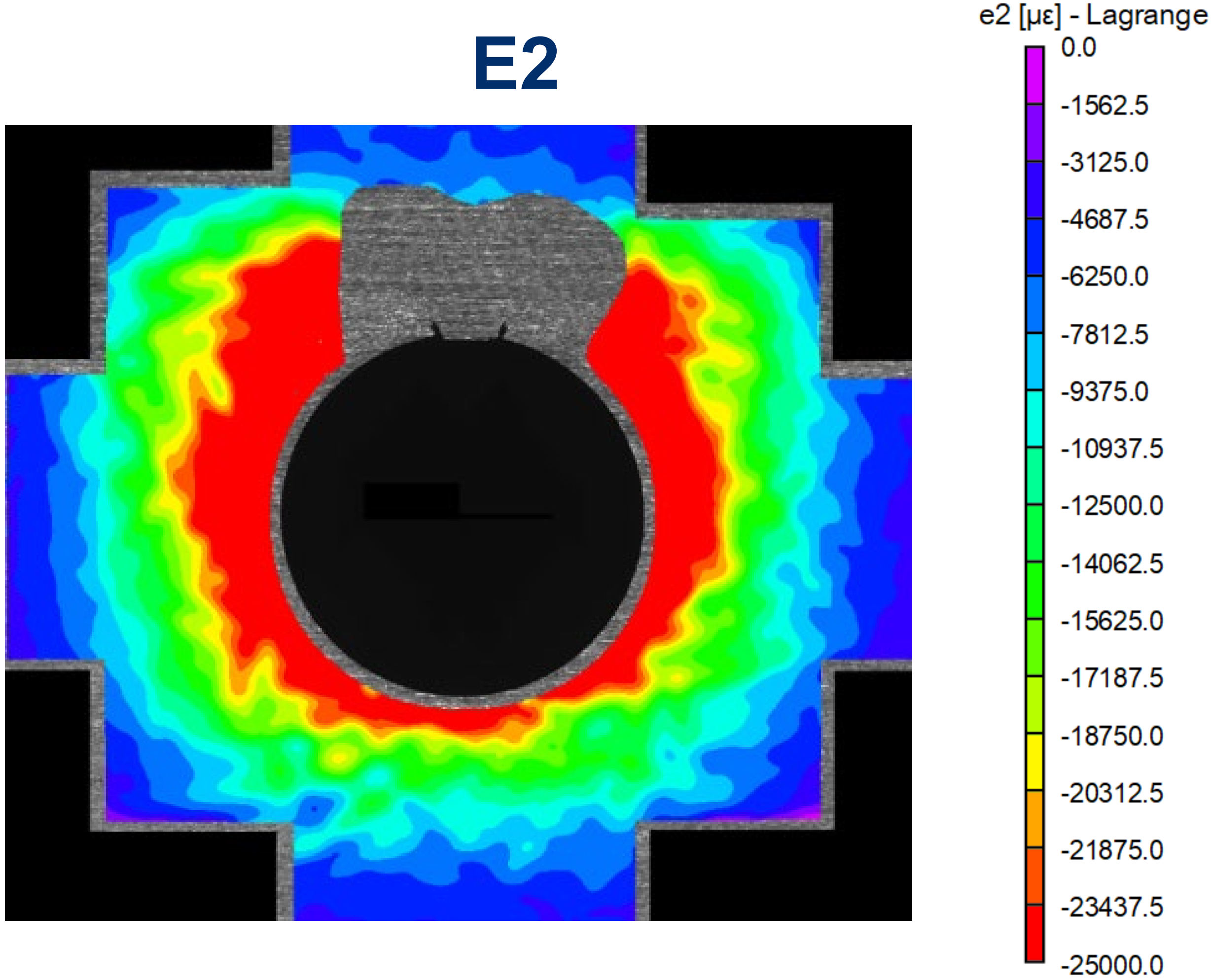
LOCKHEED MARTIN

7050-L-H-REM-02 – Exit Post Cx

E1



E2

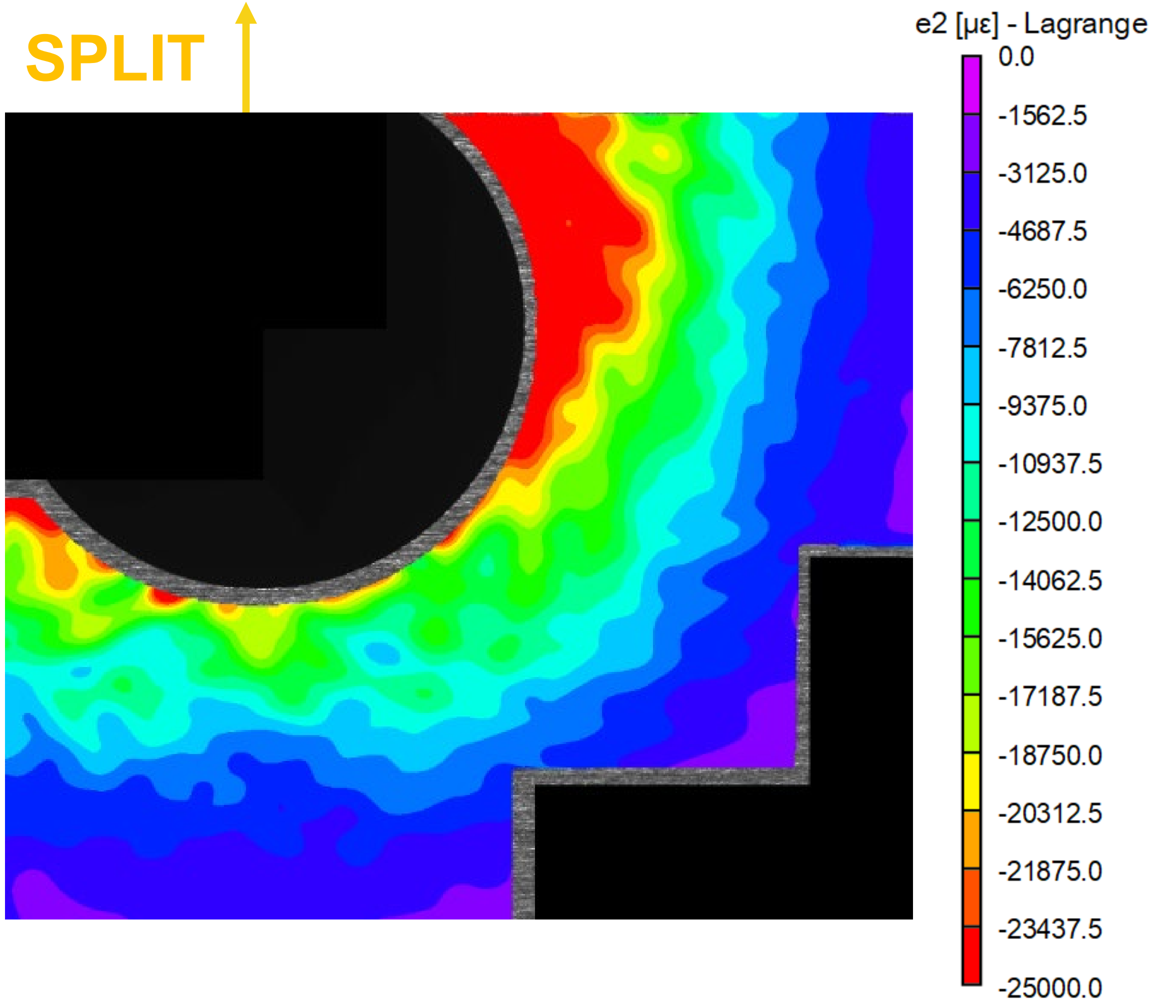


DIC Processing Parameters	
Subset	125 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (0.60 mm)**

Split at 12 o'clock orientation

Discussion: Variability at 90 deg

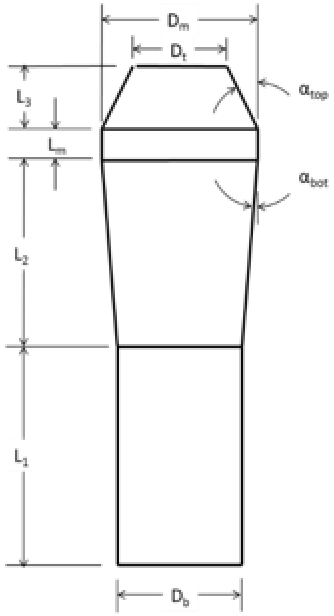
- Al7050 coupon data suggests concentricity in strain field is generally consistent surrounding the hole, except in the 90 deg region (directly across from split)
- For 90 deg region, exit face more concentric than entry face
- Line extraction data shows highest variability between coupons within this region as well
- Difference between low and high expansion coupons [both line extract & full field]

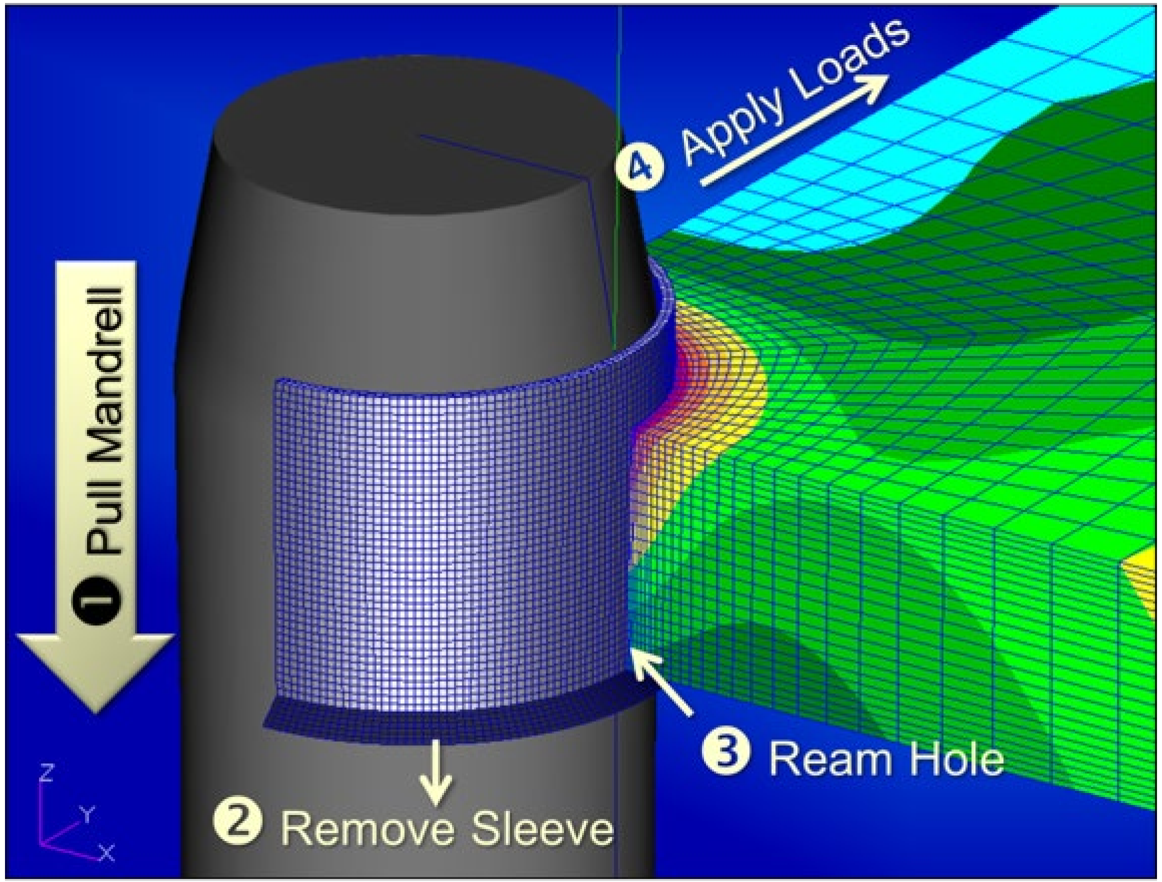


LOCKHEED MARTIN

SsCx™ Process Model

- 3D MSC Marc Finite Element Model
  - PCL: Parameterization, Automation
- Input Parameters for Automated Modeling
  - Geometry*: Plate Length, Width, Thickness; Hole diameter (initial, final), Position, Mandrel Shape, Sleeve Orientation, Thickness, Sleeve Slit Size
  - Material: Stress-strain curves
  - Other: Friction, Mesh, etc.
- Simulation Sequence
  - Step 1: Mandrel insertion
  - Step 2: Sleeve removal
  - Step 3: Hole reaming
  - Step 4: Remote loading (optional)

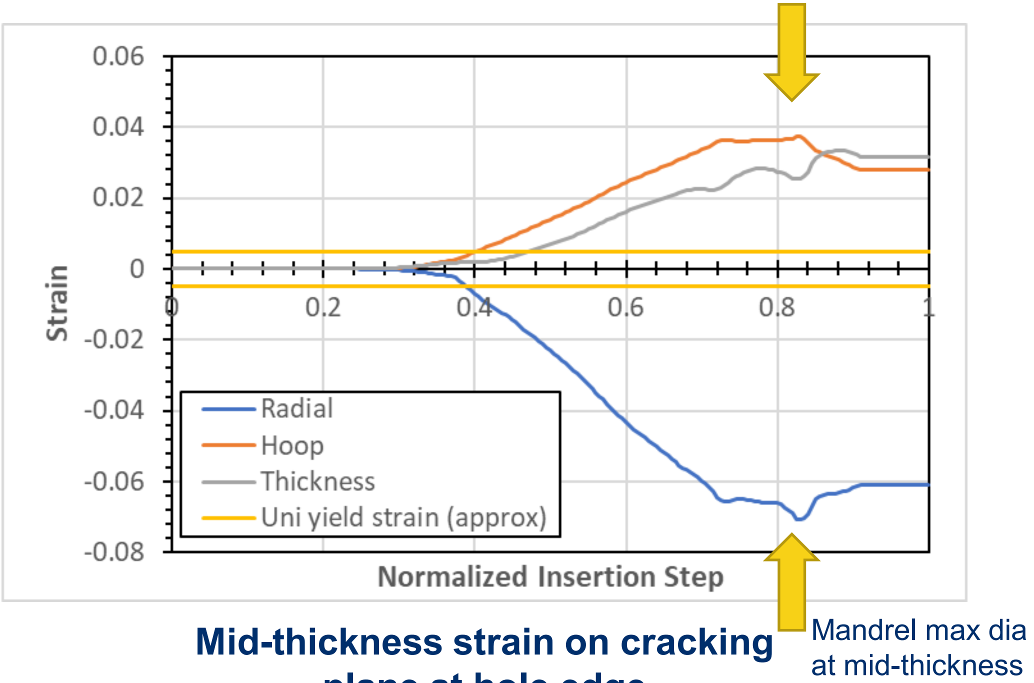




*%Cx Defined by Geometry Parameters

Cx Mechanics Study

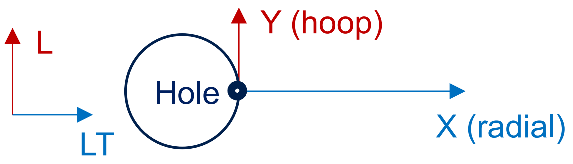
- Simulation Results (Model A)
  - Stress/strain state is multi-axial and changing throughout the Cx process
  - Compressive radial strains can be >2X higher than tensile
    hoop stresses at during mandrel engagement
  - Yielding occurs early in the process
  - Material model must represent the physics, especially in compression
    - Previous simulations used tensile properties in the L direction (typically hoop direction on crack face)



Mid-thickness strain on cracking plane at hole edge

EXAMPLE: Hole Bore Mid-Thickness Location:

Initial yield mainly caused by difference between SX and SY (compressive in radial, tensile in hoop)



- Radial stress (SX) goes into very **high compression**, then releases to zero (free surface) ~ ½ **compression-tension cycle**

- Hoop stress (SY) goes into tension, ends in **residual compression** ~ **¾ tension-compression cycle**

- Thickness stress (SZ) goes through tension, compression, ends in residual tension ~ **1.5 tension-compression cycle**

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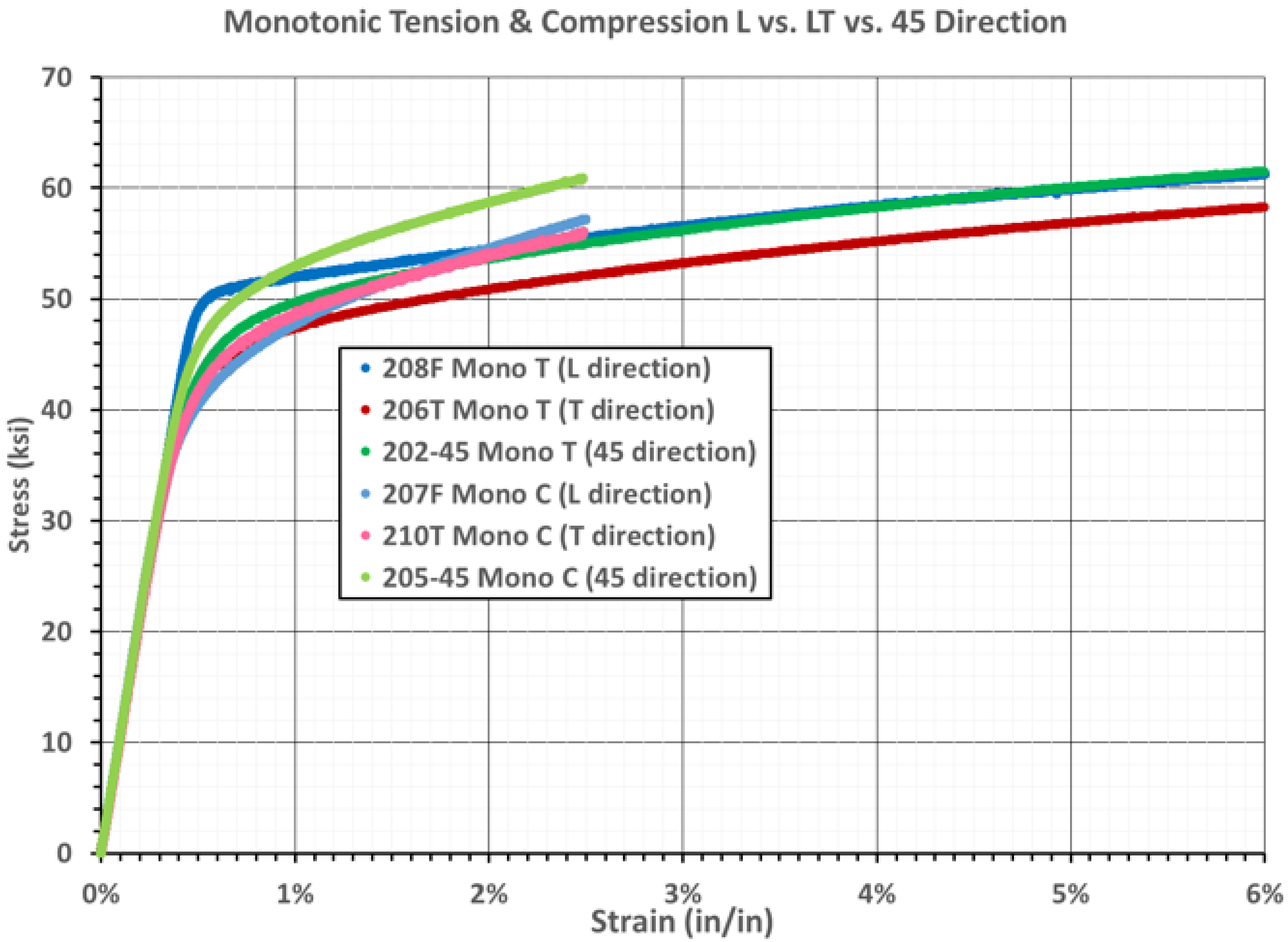
2024-T351 Material Data

- Monotonic Tests
  - Observations:
    - Post-yield properties in L, T and 45° are different
    - Post-yield properties in tension and compression are different
- Challenges:
  - Most material models use a single curve
  - Which one should be used?
  - Compression in radial direction + Tension in hoop direction?
  - Orientation varies with azimuthal position!



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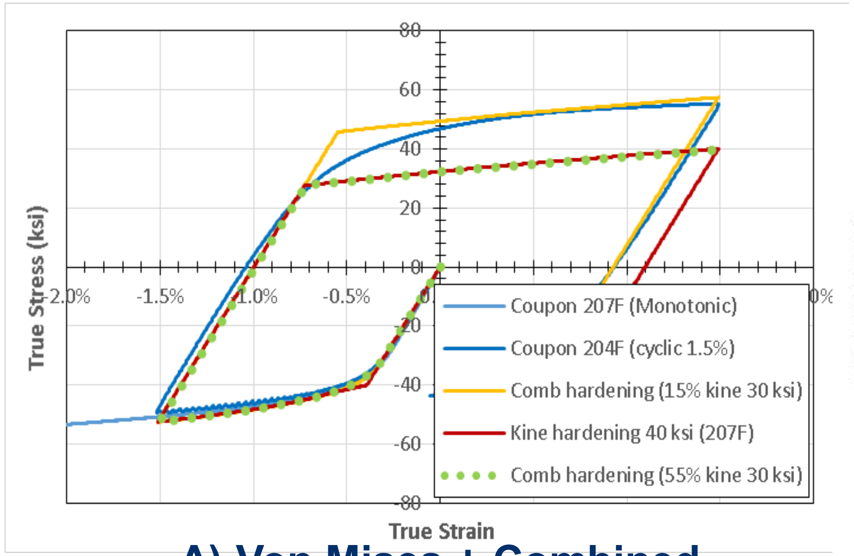
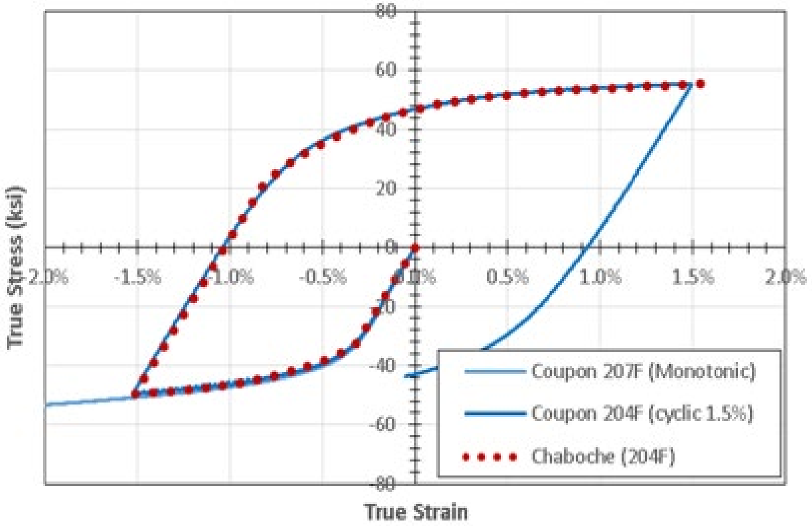
2024-T351 Material Models

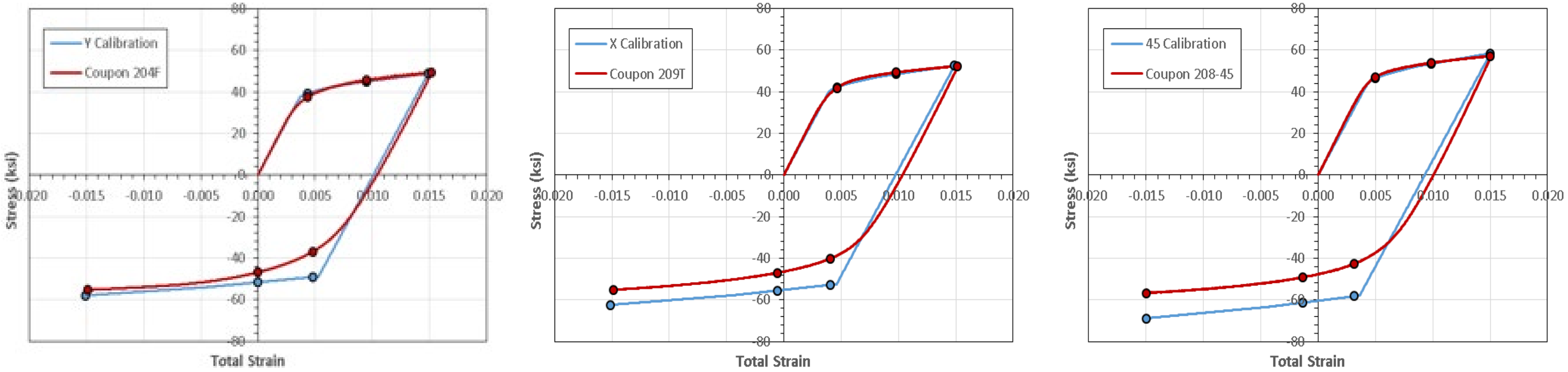
- Calibration using Cyclic Test Data
  - Model A) Linear reversed yielding (does not match reverse yielding shape)
  - Model B) Chaboche: Nonlinear reverse yielding but isotropic plasticity
  - Model C) Anisotripic plasticity but linear reverse yielding
  - No model to deal with difference between tension and compression



A) Von Mises + Combined Hardening



B) Chaboche



C) Barlat 91

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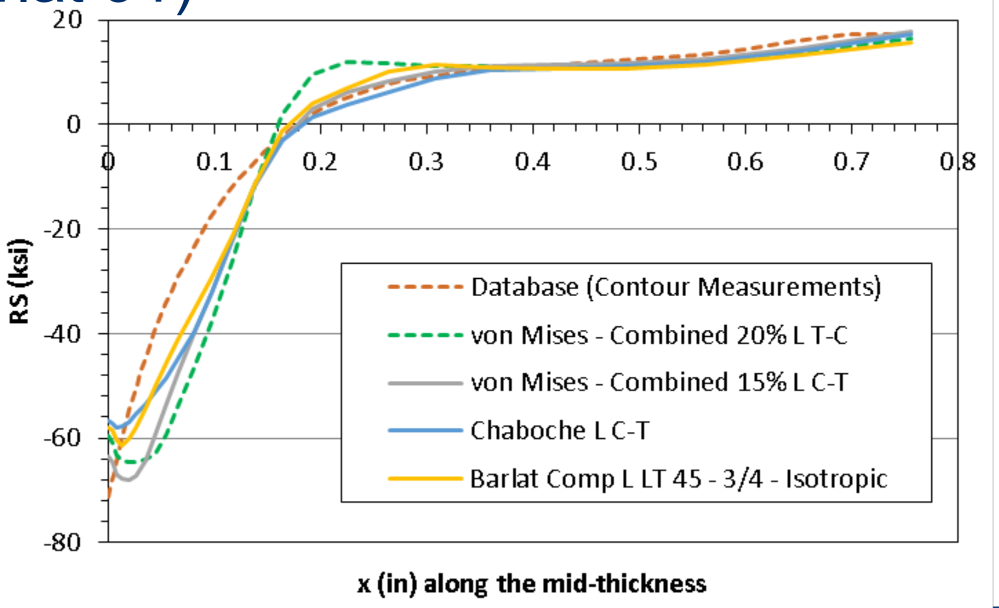
2024-T351 Material Models

- "Best" results from a previous study were obtained using compressive properties
- "Best" isotropic yielding models used L-direction properties
- Chaboche and Barlat models were able to close some of the gap between RS predictions and measurement
- The "best" results were obtained when best-fitting anisotropic yielding properties (fitting accuracy limited with Barlat 91)

Note: Pre-Cx RS is included



- **Selected Models:**
  - **Model A: von Mises – 15% kinematic hardening L C-T**
- Model B: Chaboche L C-T
- Model C: Barlat Comp L LT 45 – ¾ - Isotropic

BT15 Coupon – Key Dimensions

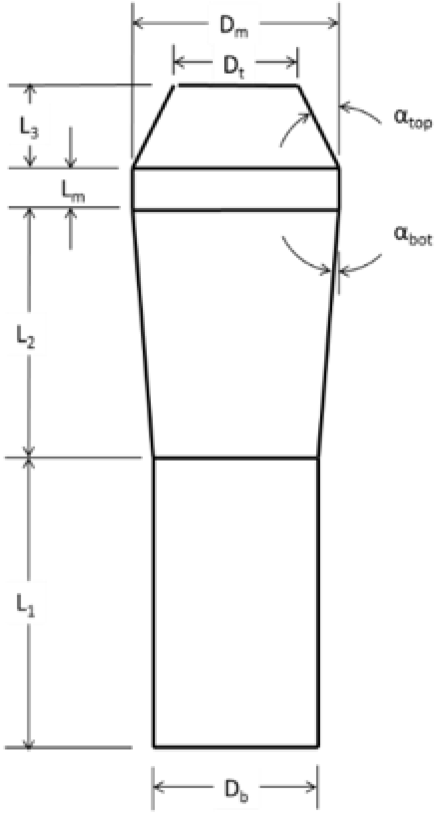
- Plate
  - Hole diameter: 0.2365 in
  - Plate thickness: 0.06 in
  - Plate width: 3 in

$$\%Cx = \frac{0.2302 + 2 * 0.008}{0.2365} - 1 = 4.1\%$$

- Mandrel and Sleeve

Mandrel		CBM-8-0-N-*	
Major ∅	∅D	0.4684 ('L'), 0.2302 ('H')	Starting Hole: ∅0.235 - 0.238"
Minor ∅	∅B	0.2150	Final Reamed Hole: ∅(N/A
Major ∅ Flat Length	---	0.0600	
Taper Length	T	0.3300	
Front Taper Length	F	0.3100	
Front Taper Angle	---	12°	
Sleeve		CBS-8-0-N-*F	
Flare Angle	---	45°	
Sleeve Thickness	t	0.0080	
Sleeve Length	L	1/32" longer than maximum stackup	
Sleeve Flare ∅ (while on mandrel B ∅)	f	0.267	
Sleeve Gap (while on mandrel B ∅)	G	0.012, max.	

NRC measurements: ~0.004 in 0.5° gap in model for efficiency



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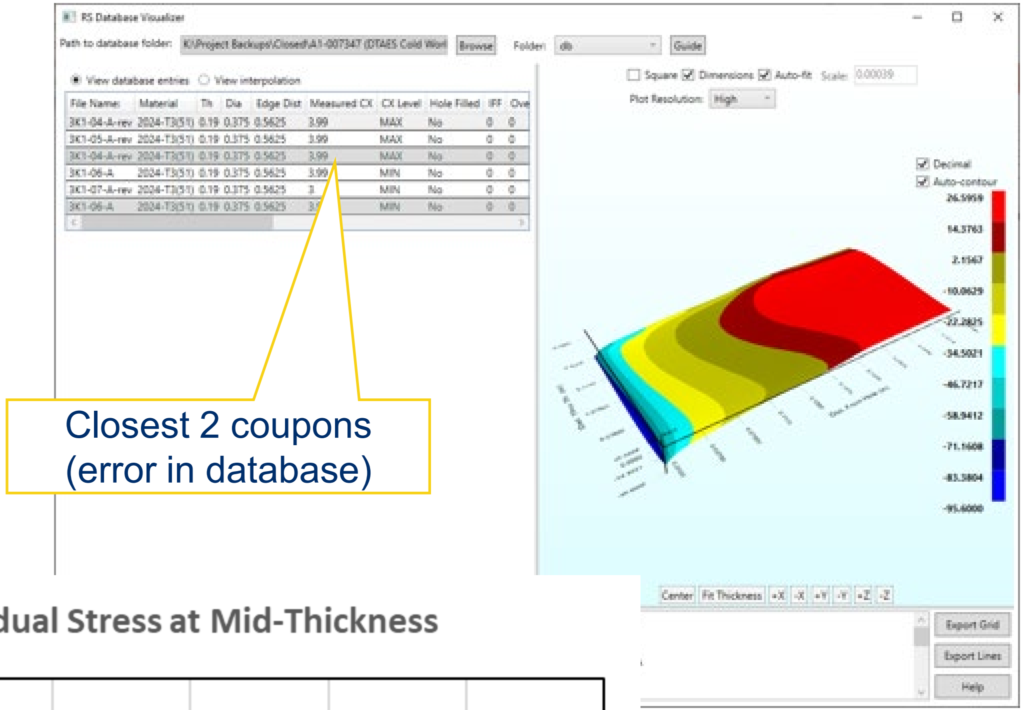
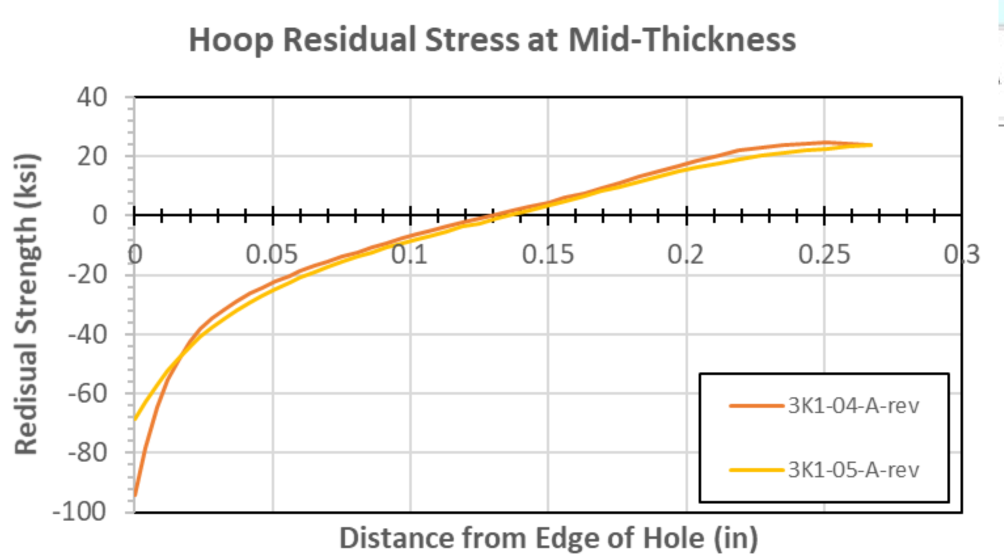
RS Database Entries

- Input Parameters and Key Results

Parameter	BT15 Coupon	Closest DB Value
Material	Al 2024-T3(51)	Al 2024-T3(51)
Hole Diameter	0.2365 in	0.375 in
Plate Thickness	0.06 in	0.19 in
%Cx	4.1%	4% ("high")
Edge Distance	1.5 in	0.5625 in

! Database cannot extrapolate to BT15 values





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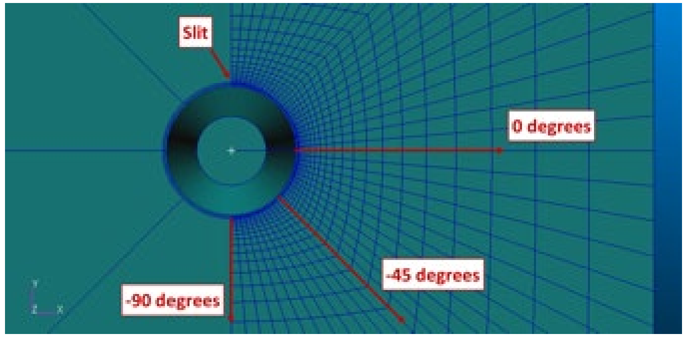
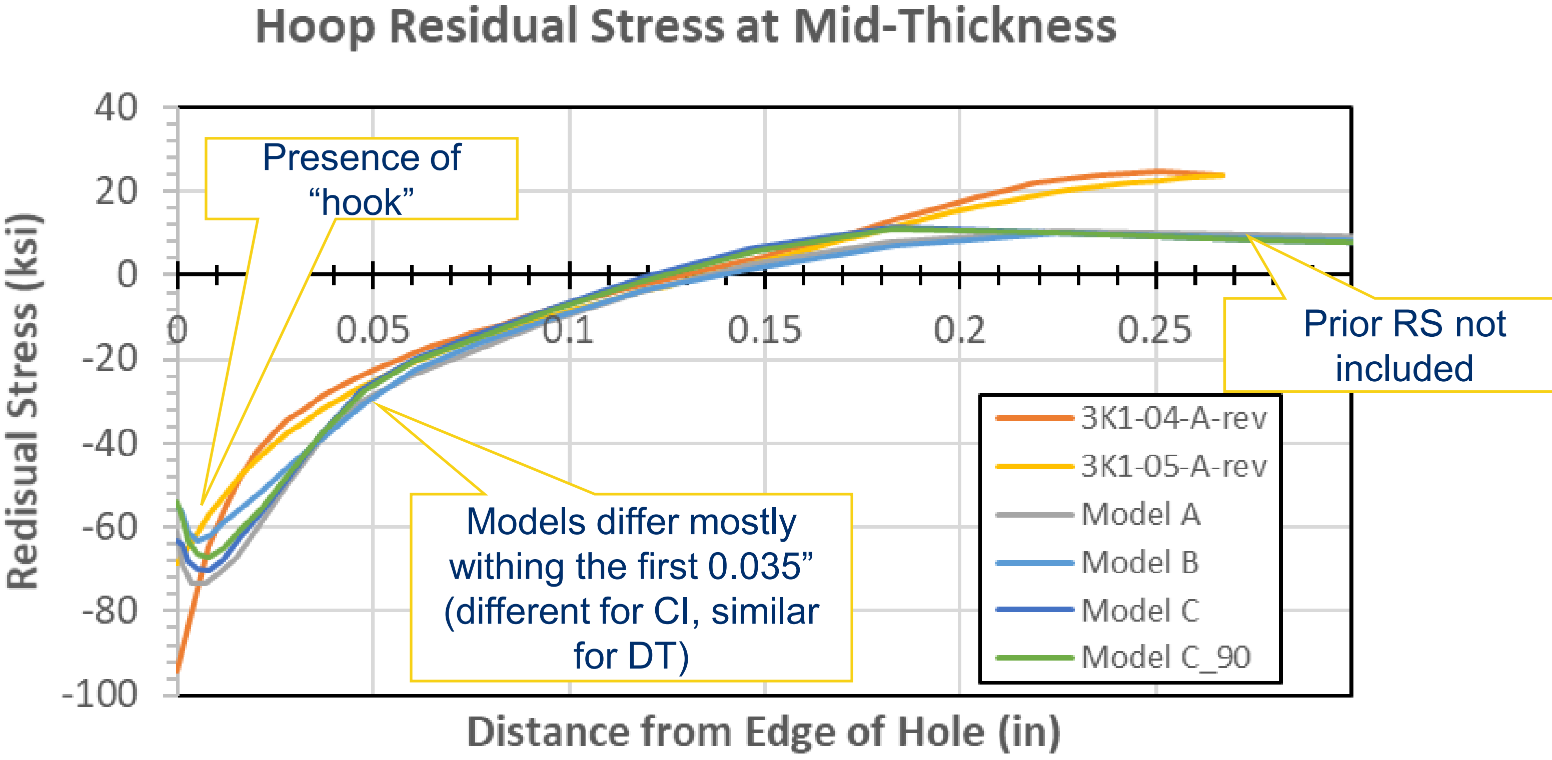
Models A, B, C – Stress Comparison

- Stress Comparison
  - Assumed crack plane on short ligament
  - Hoop stress (crack closing)
  - Mid-thickness results (most consistent contour method results)
  - Slit assumed oriented in the coupon longitudinal direction
- Note
  - Models A, B, C use L-direction properties to prioritise the crack plane
    (L-direction coupon, cracking in T





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Recommended Investigations

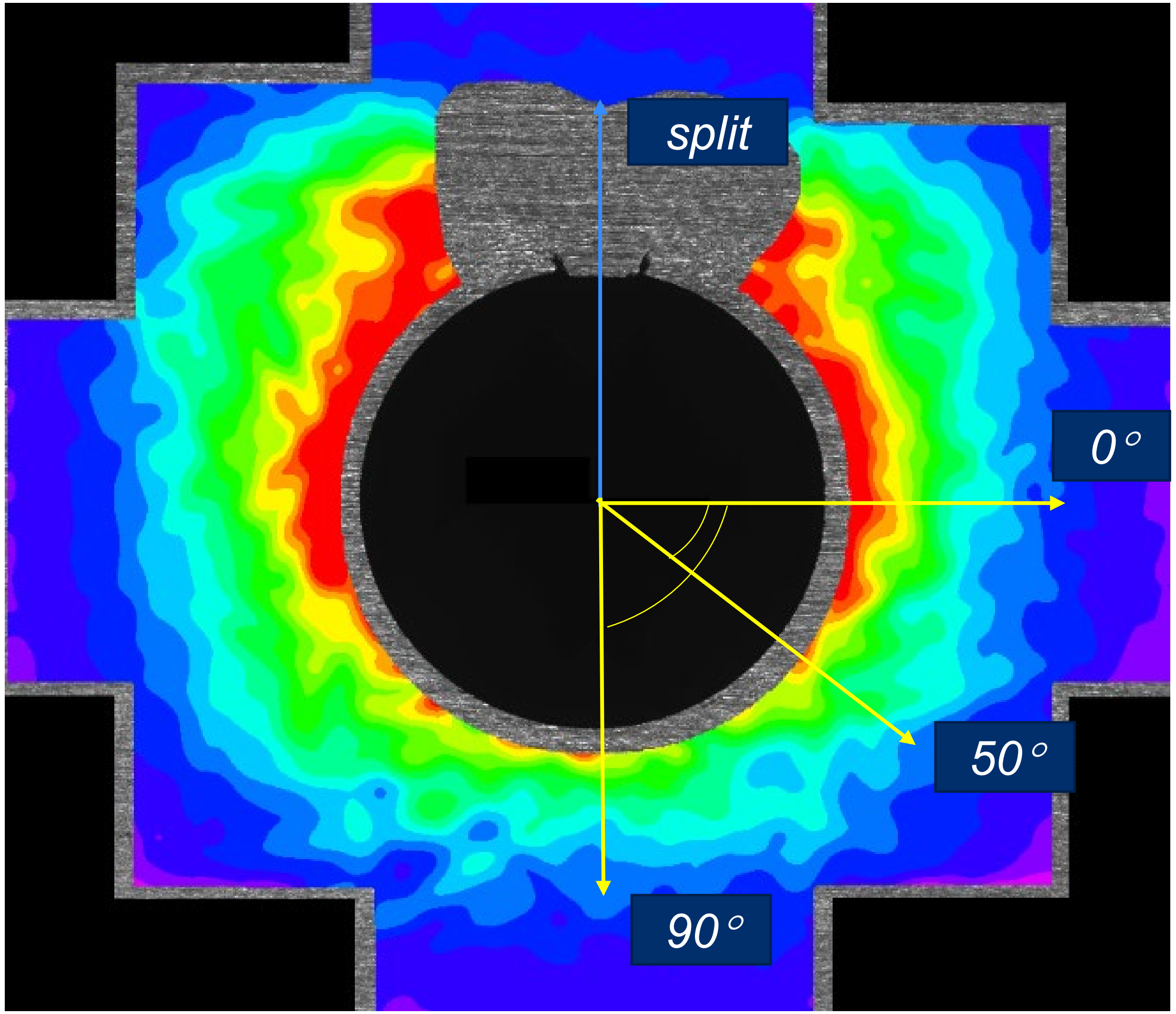
- Material Model Improvement
  - Combination of Barlat and Chaboche
  - Model defined in cylindrical coordinates (material properties interpolated between tension and compression properties depending on azimutal position
- Efficient Material Calibration Protocol
  - Material model calibration using bi-axial testing considering (proper mixity ratio)
    - Less coupons, more representative of the actual physics
    - Potentially: anisotropic calibration on a single coupon (if 1:1 ratio)

Overview

1. Purpose of Improving Near-Bore Strain Measurements
2. Overview of Previous 2-inch SsCx DIC results
3. Experimental Set-up
4. Results
5. Development of Methods for Data Analysis for FEA simulations
    1. Material models used for 2024 FEA vs DIC comparison
    2. Line profile comparisons
    3. Advanced methods
6. Conclusion/Path Forward

Radial Strain Extractions

- E1 and E2 strains extracted along radial lines
- To normalize across differing hole sizes, strains plotted against **R/a**
  - **R =** radial distance of strain extraction point
  - **a =** radius of expanded/reamed hole
- Strains plotted for each coupon, then averaged across coupons



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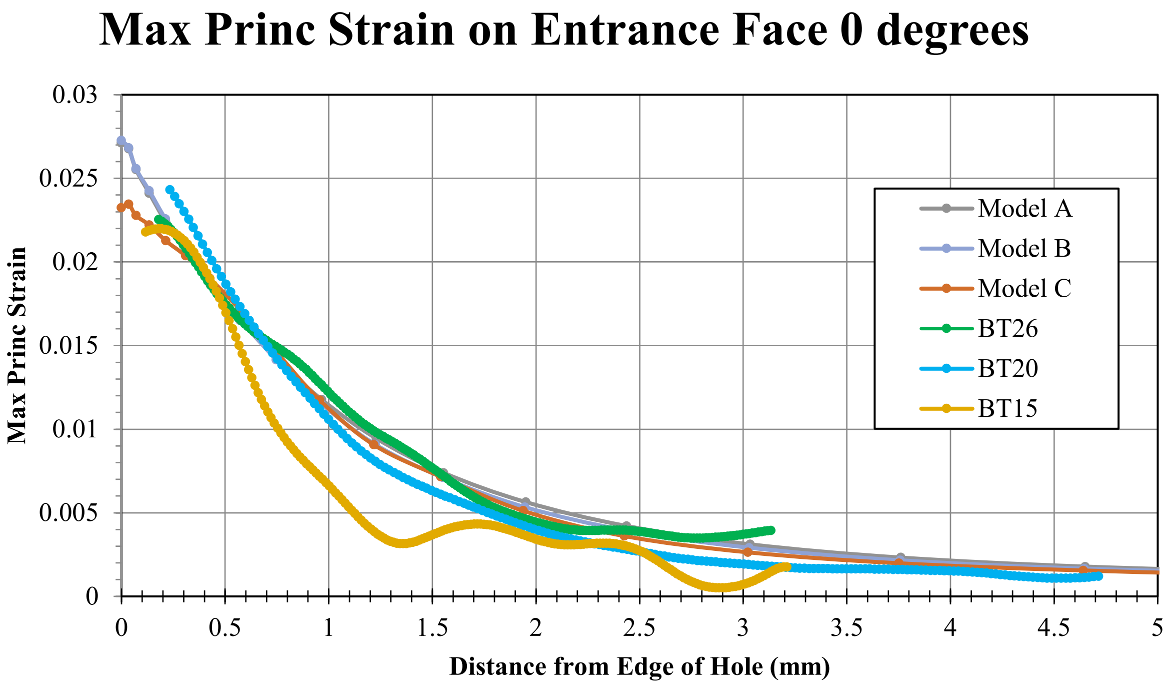
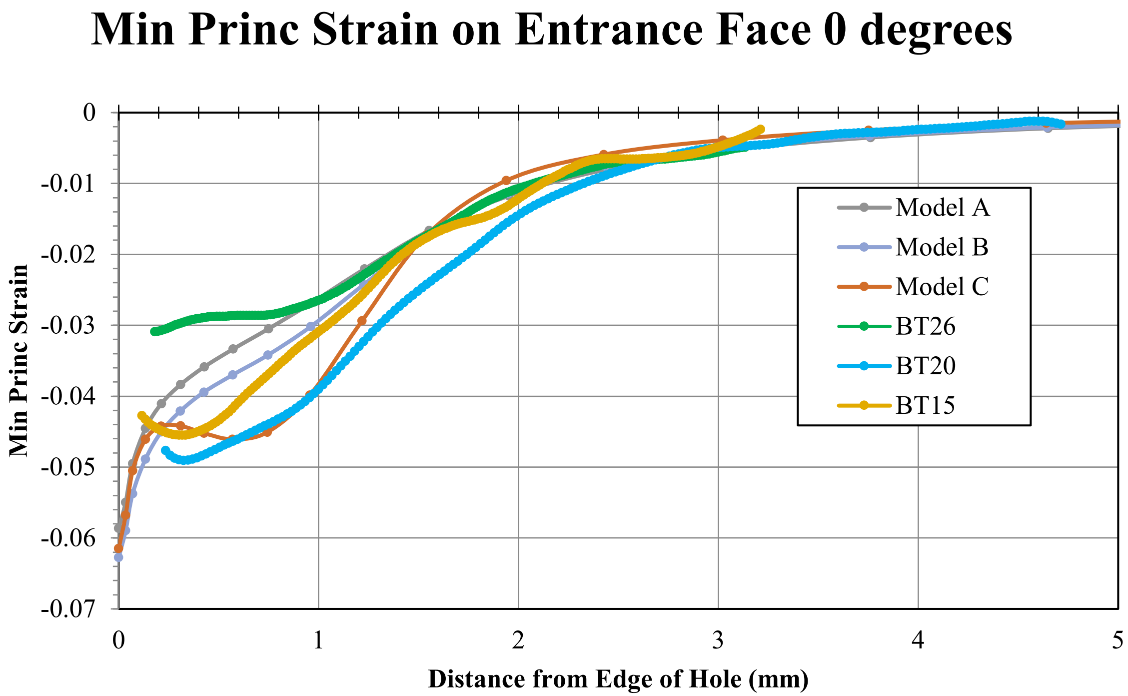
DIC vs FEA: Entry Face Strain Data

Al2024 DIC vs FEA – 0° - *Entry*





BT26 (starting diam 0.2380 in)
BT15 (starting diam 0.2376 in)
BT20 (starting diam 0.2359 in)

Selected Models:

Model A: von Mises – 15% kinematic hardening L C-T
Model B: Chaboche L C-T
Model C: Barlat Comp L LT 45 – ¾ - Isotropic

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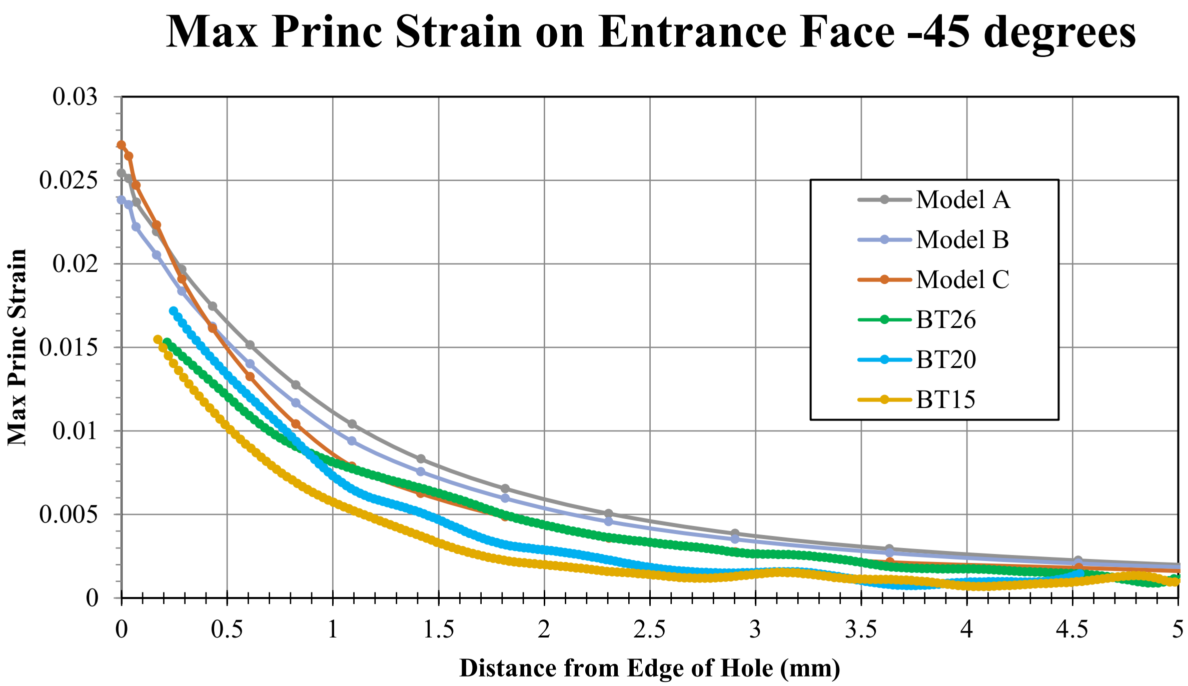
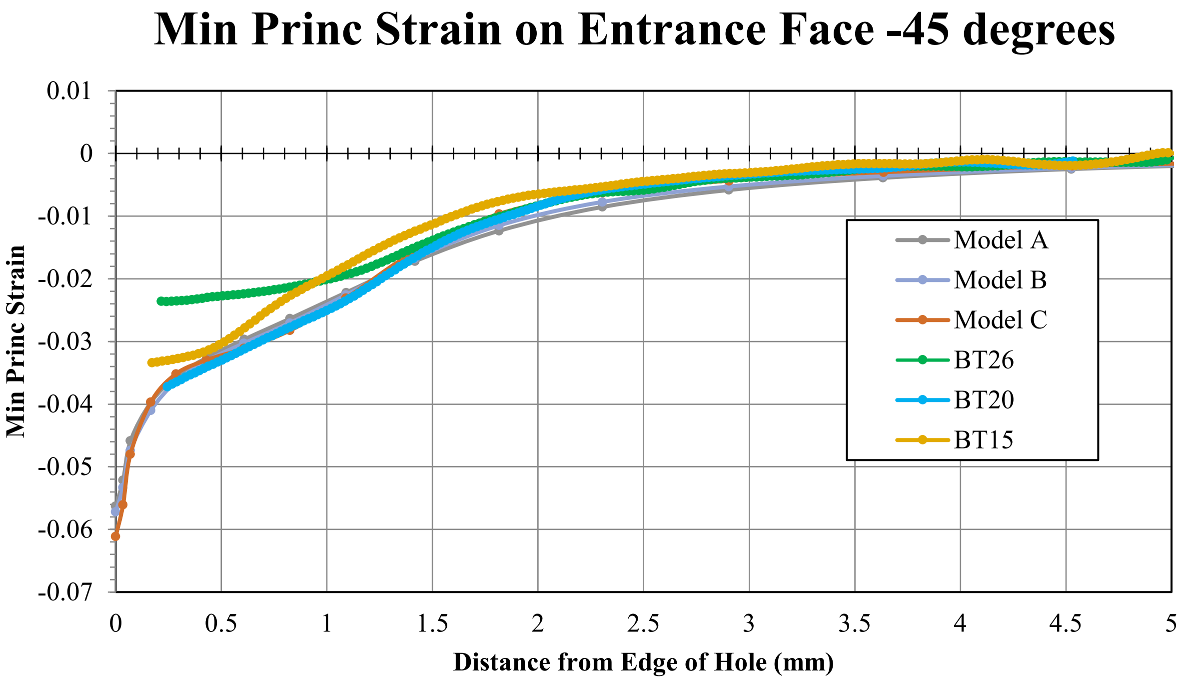
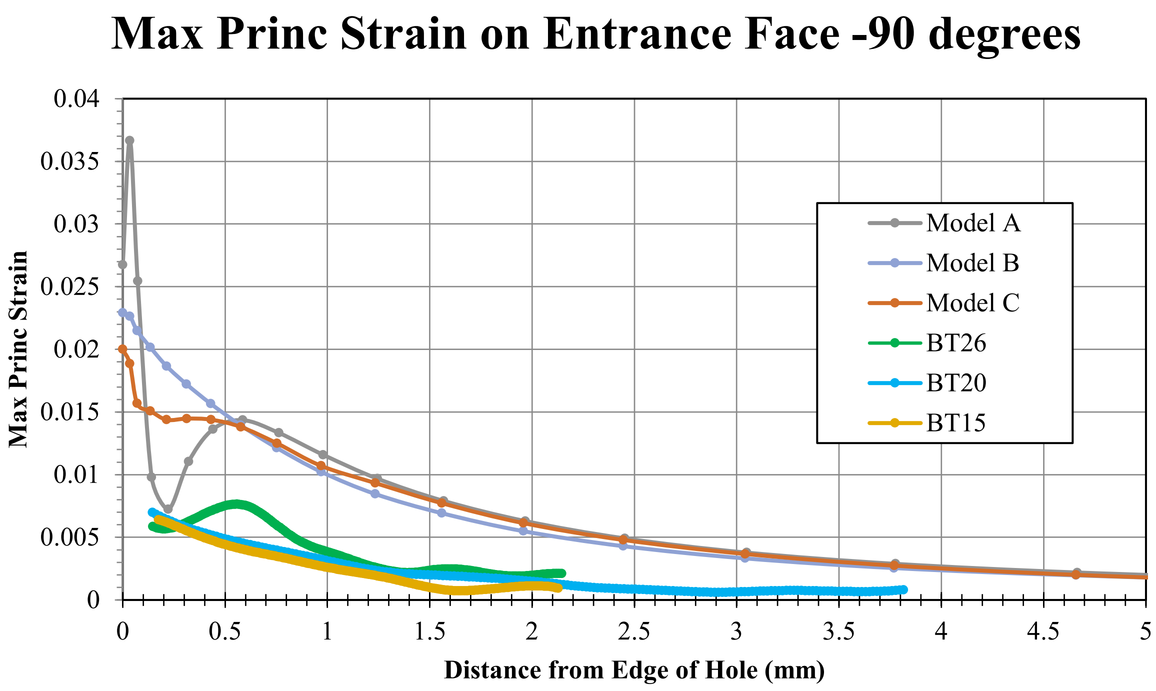
Al2024 DIC vs FEA - 45 ° - *Entry*

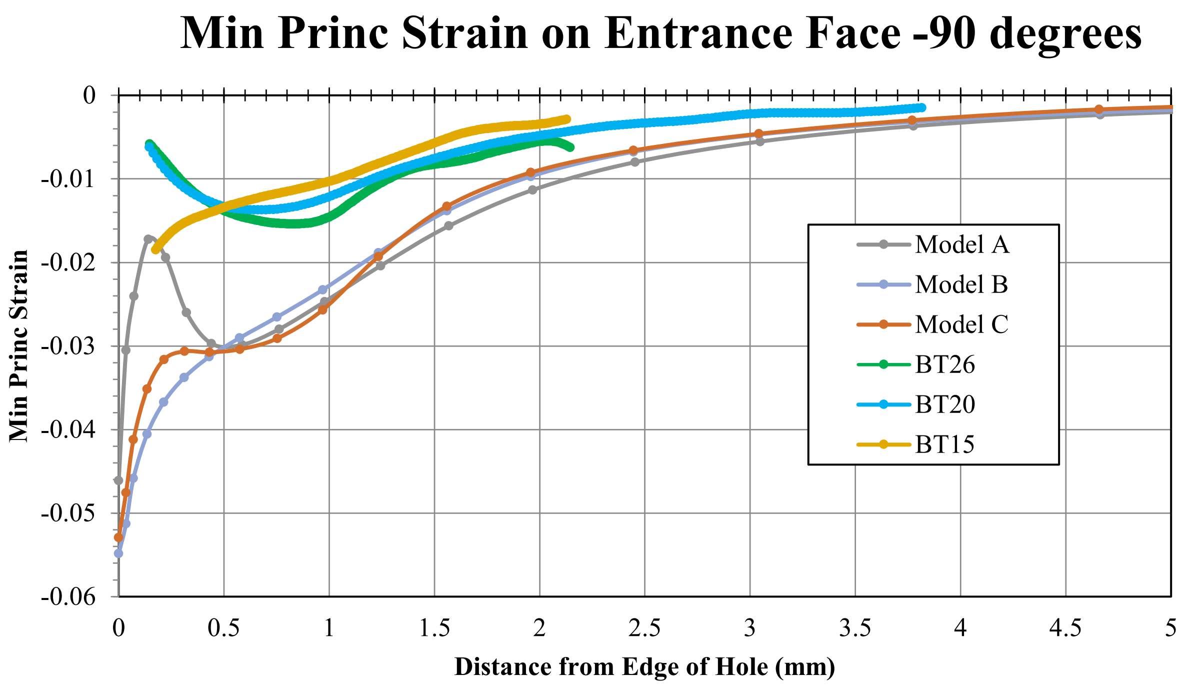




BT26 (starting diam 0.2380 in)
BT15 (starting diam 0.2376 in)
BT20 (starting diam 0.2359 in)

Al2024 DIC vs FEA - 90 ° - *Entry*

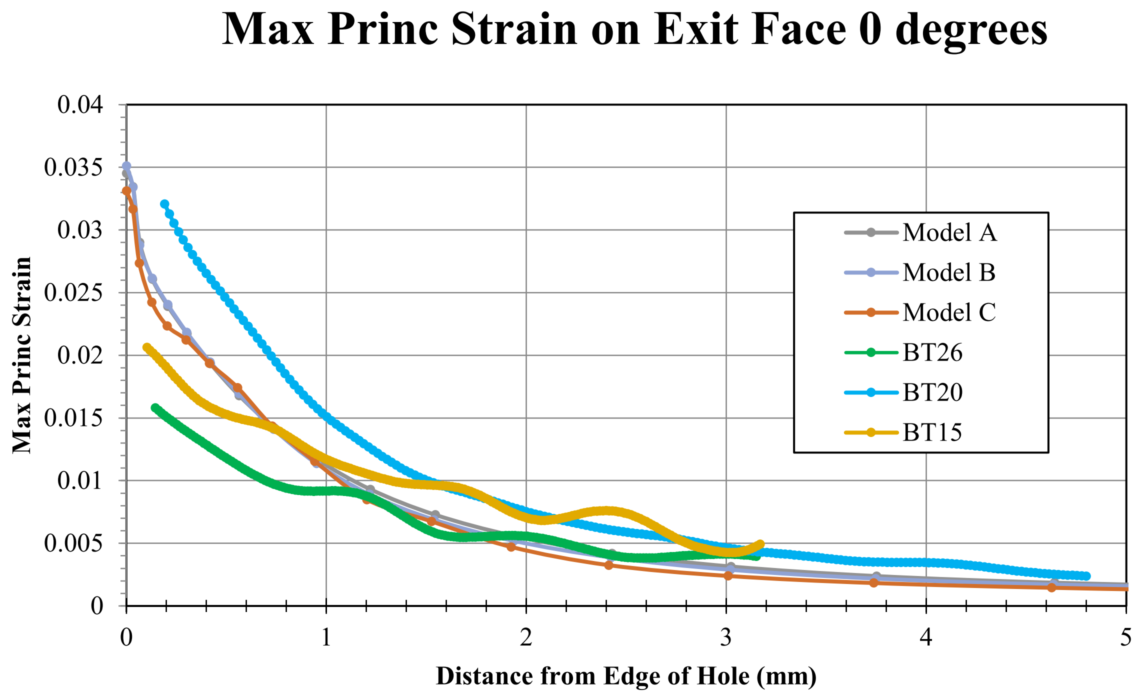


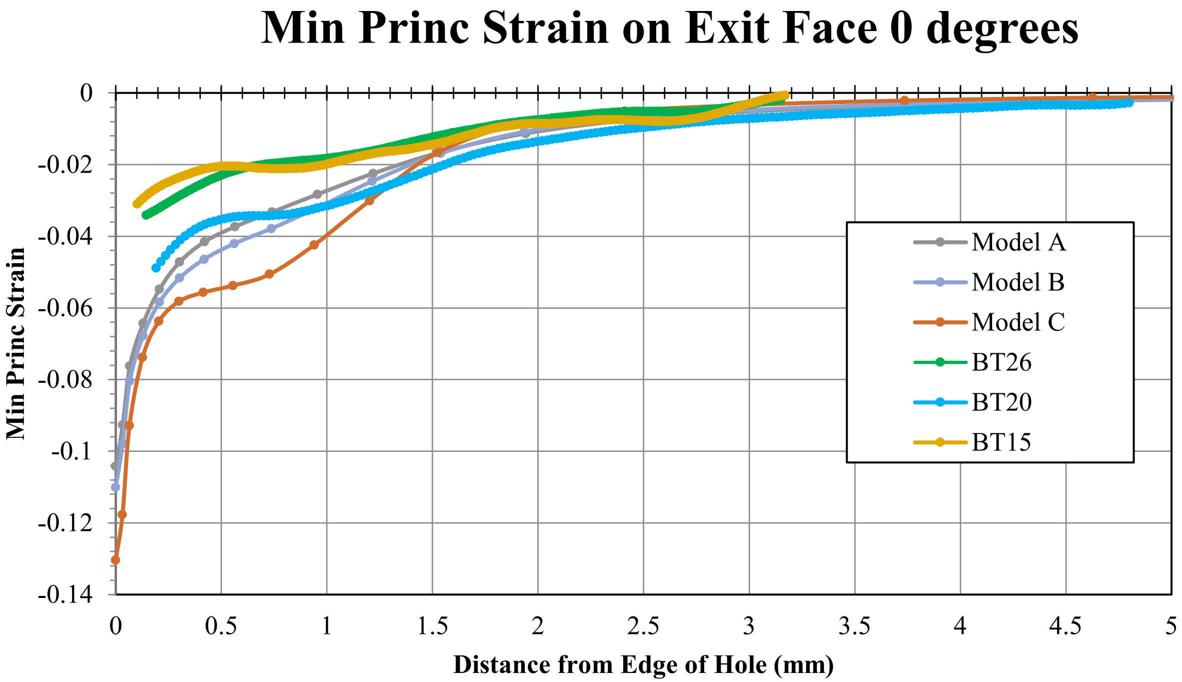


BT26 (starting diam 0.2380 in)
BT15 (starting diam 0.2376 in)
BT20 (starting diam 0.2359 in)

DIC vs FEA: Exit Face Strain Data

Al2024 DIC vs FEA – 0° - *Exit*





BT26 (starting diam 0.2380 in)
BT15 (starting diam 0.2376 in)
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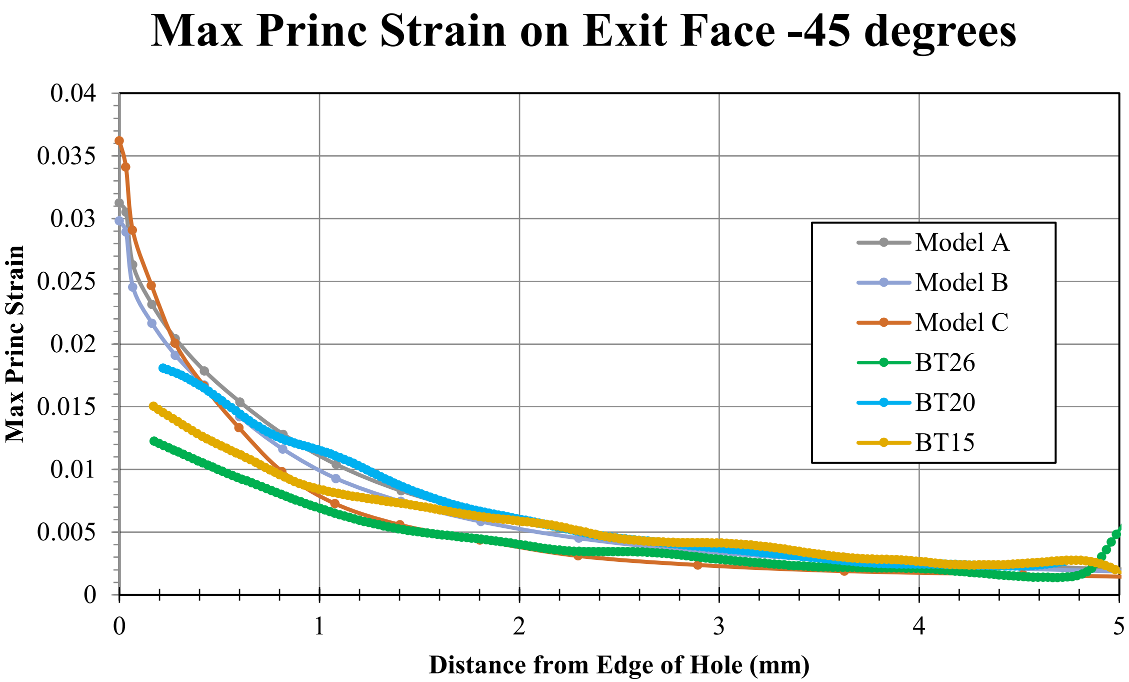
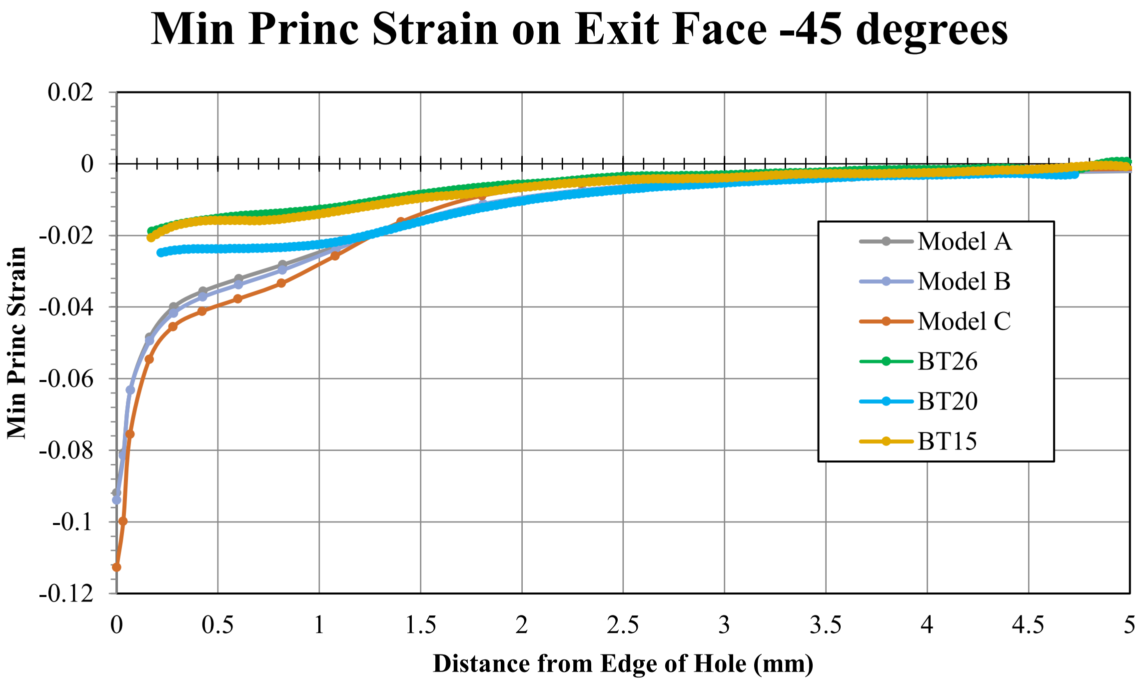
Al2024 DIC vs FEA - 45 ° - *Exit*



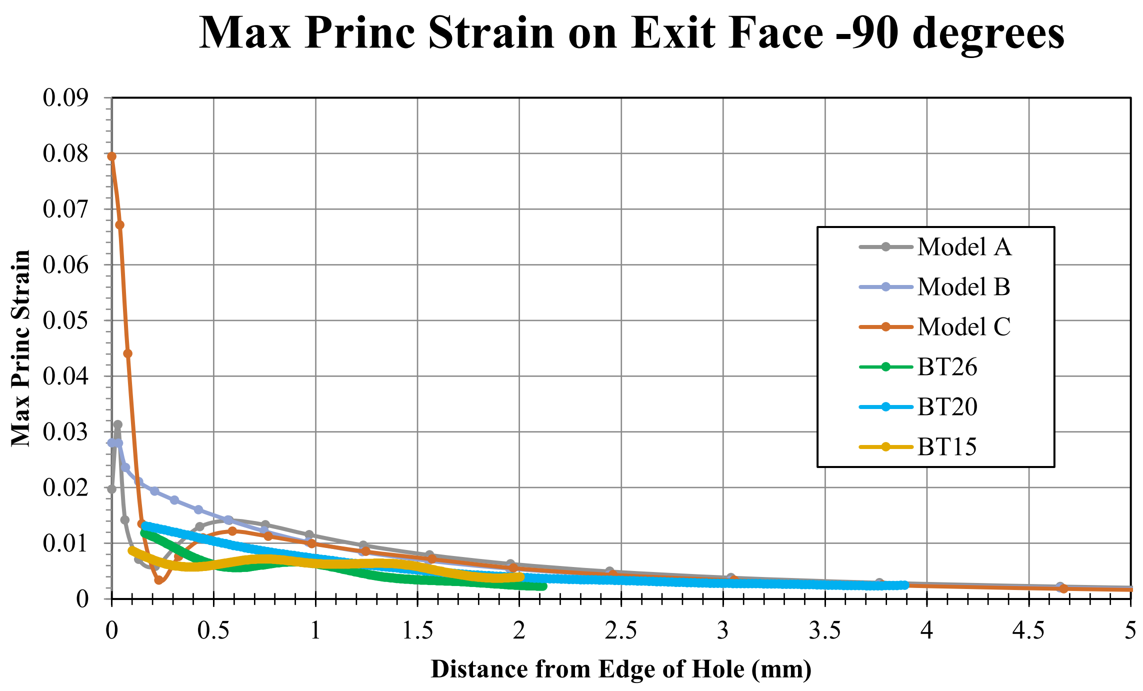


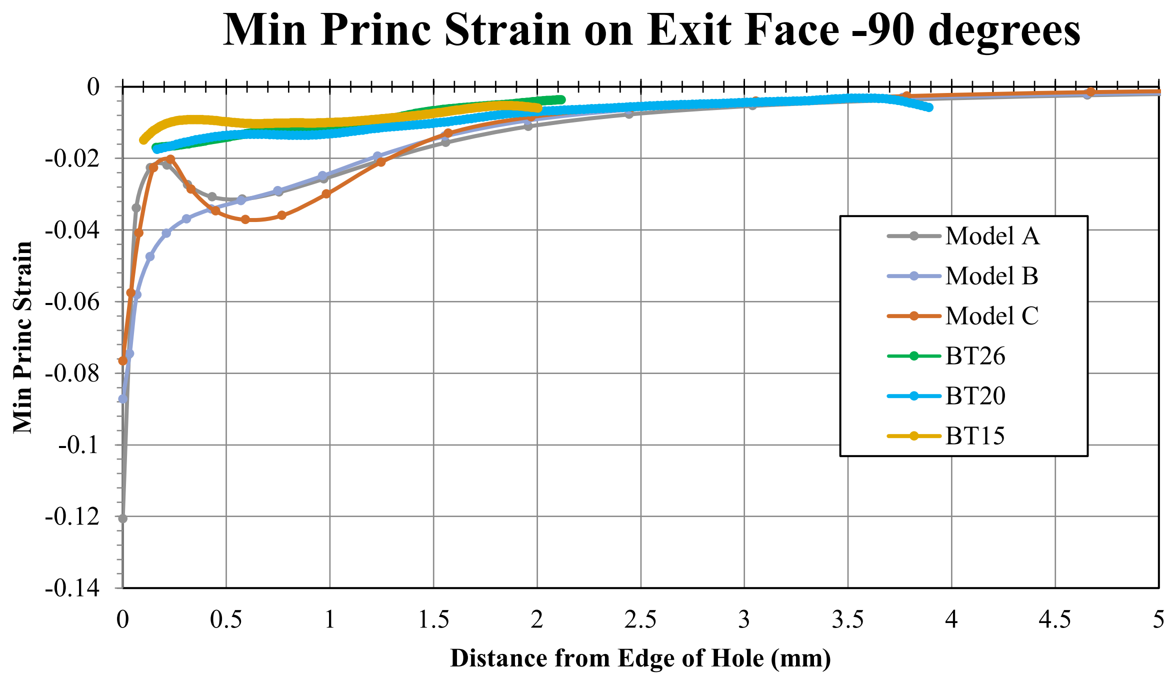
BT26 (starting diam 0.2380 in)

BT15 (starting diam 0.2376 in)

BT20 (starting diam 0.2359 in)

Al2024 DIC vs FEA - 90 ° - *Exit*





BT26 (starting diam 0.2380 in)
BT20 (starting diam 0.2359 in)
BT15 (starting diam 0.2376 in)

Discussion:

- DIC vs FEA Al2024 Process Simulation
  - Difference between FE line profiles relatively modest globally
  - 90 degree entry face shows largest discrepancies between DIC and FEA data
  - Could be potential focus for improved SsCx process simulation models
  - MatchID could be used down the road (once Abaqus model complete)
  - Full field comparison w/MatchID may provide better insight

Overview

1. **Purpose of Improving Near-Bore Strain Measurements**
2. **Overview of Previous 2-inch SsCx DIC results**
3. **Experimental Set-up**
4. **Results**
5. **Development of Methods for Data Analysis for FEA simulations**
6. **Path Forward & Conclusions**

Path Forward

- Implementation of a validated process simulation in Abaqus
- Commissioning of new high mag 3D-DIC system
- Further 2D (and 3D?) SR method development and standardization
- Use of 2D SR and MatchID for FEA process simulation validation
- Development of 7050 material models for future

Conclusions

- Previous low spatial resolution DIC data was not suitable for validating high strain gradients near hole edge
- High magnification 2D-DIC can provide higher spatial & strain resolution over small areas.
- Development of SR-DIC extends high strain & spatial resolution over large areas
- Confirmed region of lower compressive strain opposite split sleeve
- SR-DIC data useful for current and future validation programs

Thank You
Questions/Comments?

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