ERSI ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Wednesday, 30 April 2025	
Hill AFB & Layton, Utah	
8:15 AM to 8:30 AM	*Executive Committee Arrive, Check-in*
8:30 AM to 10:00 AM	*Executive Committee Discussion*
9:45 AM to 10:15 AM	**Arrive, Check-in**
10:15 AM to 10:30 PM	**Hill AFB Welcome & Overview**
10:30 AM to 12:00 PM	**Hill AFB 809th MXSS Tour**
12:00 PM to 1:30 PM	**Lunch break**
1:30 PM to 2:00 PM	**Welcome | Announcements | Around the room**
2:00 PM to 4:30 PM	**Committee Updates, Session 1**
2:00 PM to 4:30 PM	Analysis & Test
4:30 PM to 5:00 PM	**Regroup & Dismiss**

A huge thanks to our sponsors for this year:

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Thursday, 1 May 2025	
Hill AFB & Layton, Utah	
7:45 AM to 8:00 AM	**Arrive**
8:00 AM to 11:00 AM	**Committee Updates, Session 2**
8:00 AM to 10:00 AM	Residual Stress Characterization
10:00 AM to 10:15 AM	Break
10:15 AM to 11:00 AM	NDE/NDI/QA/Data Management
11:00 AM to 12:00 PM	**Discussion: ERSI Path Forward**
12:00 PM to 1:30 PM	**Lunch break**
1:30 PM to 2:30 PM	**Open Discussion**
2:30 PM to 4:30 PM	**Committee Break-out Meetings** Analysis & Test Residual Stress Characterization NDE/NDI/QA/Data Management
4:30 PM to 5:00 PM	**Regroup & Dismiss**

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2025 ERSI Workshop
Welcome!

30 April 2025

Dallen L. Andrew, PhD

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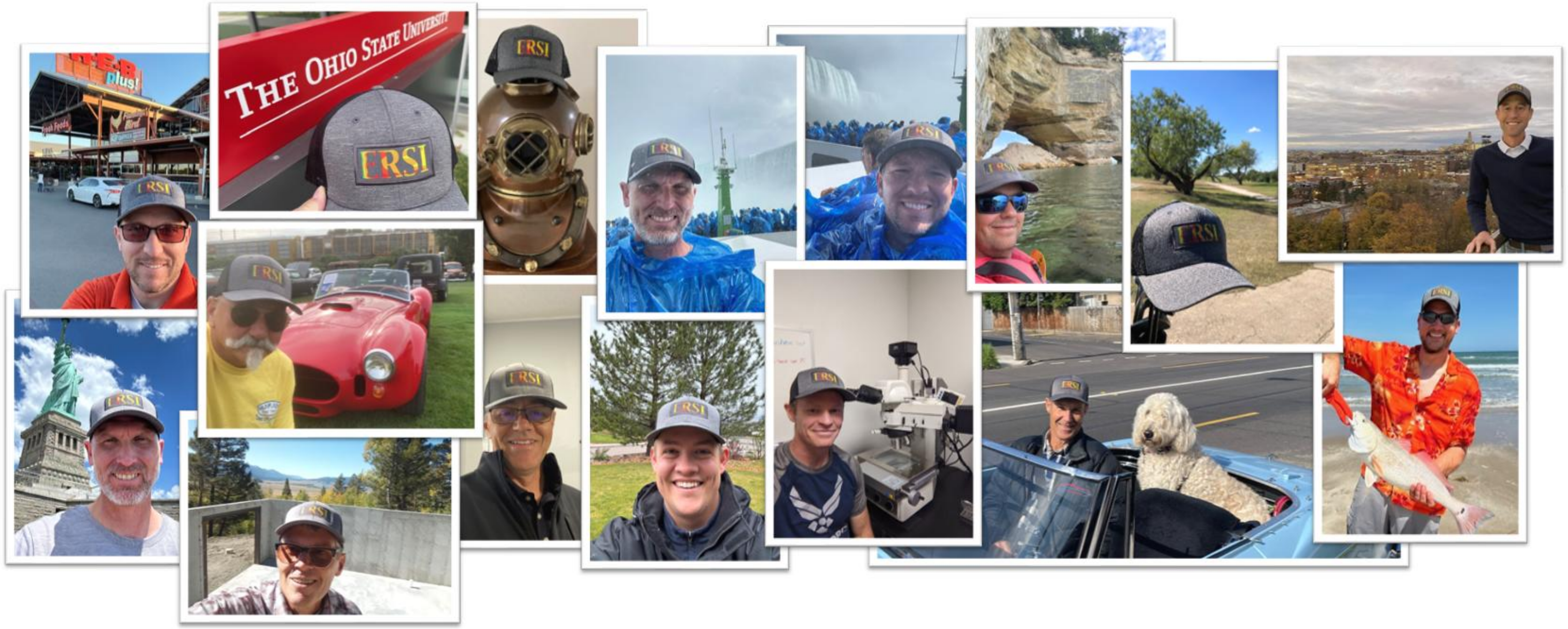
Agenda

- Around the room
- Committee
- Impact slide
- Roadmap
- EZ-SB-17-001 Rev B
- ERSI Interactions
- Discussion & Feedback



Important Stuffs

- Nametags/Poster photos
  - Also I apologize if I missed you or messed up your name
- Coffee/Candy/Cookies/Drinks
- WSU Guest wifi available
- Attendee appreciation gifts

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ERSI purpose:
Where does ERSI add value?

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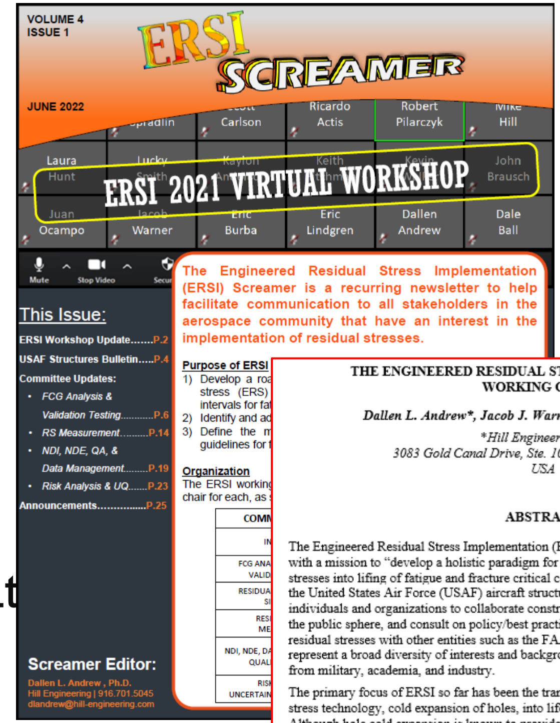
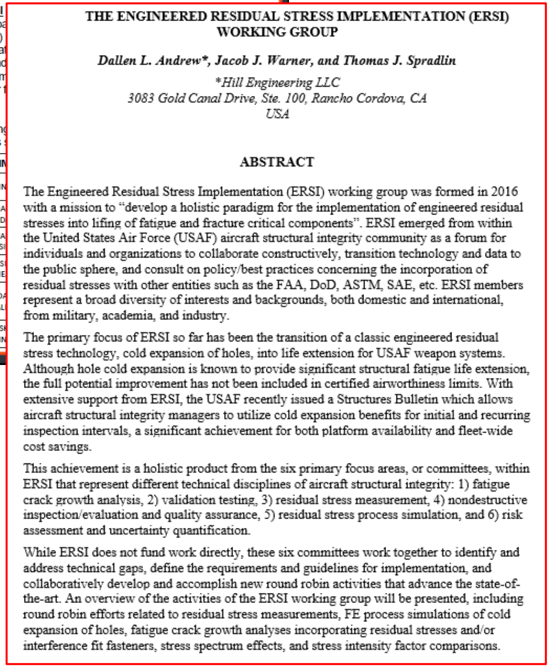
- **EZ-SB-17-001**
- **Analysis and testing**
  - 2016: FCG analysis of Cx holes
  - 2020: Interference fit fasteners
  - 2021: SIF Comparison
  - 2021: Overload challenge
  - 2022: Interference fit fasteners round 2
- **Residual stress characterization**
  - 2017: 2x2 material modeling data
  - 2017: 2x2 Cx Coupons
  - 2017: Contour method inter-laboratory reproducibility uncertaint
  - 2019: 2x2 process simulation analysis
  - 2021: Texture and anisotropy sub-team
  - 2021: Bulk RS measurements in Cx geometrically large holes
  - 2022: Contour method reproducibility experiment A (CMRE-A)
- **NDI / NDE / Data management / Quality assurance**
  - xx: Cx hole blind study [POC: Dallen Andrew, Hill Engineering]





THE ENGINEERED RESIDUAL STRESS IMPLEMENTATION (ERSI) WORKING GROUP

Dallen L. Andrew, Jacob J. Warner, and Thomas J. Spradlin*

**Hill Engineering LLC*
3083 Gold Canal Drive, Ste. 100, Rancho Cordova, CA
USA

ABSTRACT

The Engineered Residual Stress Implementation (ERSI) working group was formed in 2016 with a mission to "develop a holistic paradigm for the implementation of engineered residual stresses into lifing of fatigue and fracture critical components". ERSI emerged from within the United States Air Force (USAF) aircraft structural integrity community as a forum for individuals and organizations to collaborate constructively, transition technology and data to the public sphere, and consult on policy/best practices concerning the incorporation of residual stresses with other entities such as the FAA, DoD, ASTM, SAE, etc. ERSI members represent a broad diversity of interests and backgrounds, both domestic and international, from military, academia, and industry.

The primary focus of ERSI so far has been the transition of a classic engineered residual stress technology, cold expansion of holes, into life extension for USAF weapon systems. Although hole cold expansion is known to provide significant structural fatigue life extension, the full potential improvement has not been included in certified airworthiness limits. With extensive support from ERSI, the USAF recently issued a Structures Bulletin which allows aircraft structural integrity managers to utilize cold expansion benefits for initial and recurring inspection intervals, a significant achievement for both platform availability and fleet-wide cost savings.

This achievement is a holistic product from the six primary focus areas, or committees, within ERSI that represent different technical disciplines of aircraft structural integrity: 1) fatigue crack growth analysis, 2) validation testing, 3) residual stress measurement, 4) nondestructive inspection/evaluation and quality assurance, 5) residual stress process simulation, and 6) risk assessment and uncertainty quantification.

While ERSI does not fund work directly, these six committees work together to identify and address technical gaps, define the requirements and guidelines for implementation, and collaboratively develop and accomplish new round robin activities that advance the state-of-the-art. An overview of the activities of the ERSI working group will be presented, including round robin efforts related to residual stress measurements, FE process simulations of cold expansion of holes, fatigue crack growth analyses incorporating residual stresses and/or interference fit fasteners, stress spectrum effects, and stress intensity factor comparisons.

Around the room

- ~60 seconds
- Name
- Company
- What do you do
- Why are you here

Around the room updates

- Round robin activities
- Opportunity for collaboration (w/in ERSI and outside)
- USAF/DoD/Industry RS related interest, use, needs

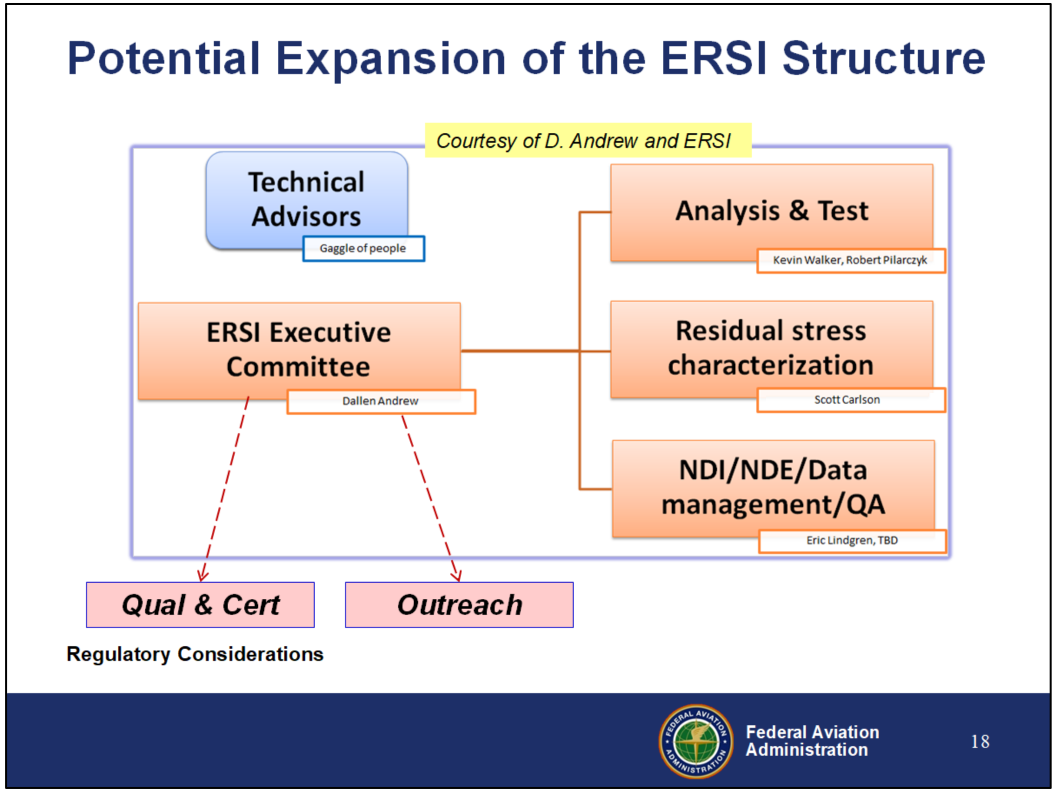
Committees

- Thoughts on committees, leads, and needs
  - Welcome [back] Dr. Carlson

Committees

- Thoughts on committees, leads, and needs
  - How is the committee structure working for you?
    - 8 vs 3 vs 1
    - Time served, replacements
  - Regulatory considerations, Outreach

- Committee: Integrator
- Committee: Fatigue Crack Growth Analysis Methods
- Committee: Validation Testing
- Committee: Residual Stress Process Simulation
- Committee: Residual Stress Measurement
- Committee: Data Management & Quality Assurance
- Committee: Nondestructive Inspection
- Committee: Risk Analysis & Uncertainty Quantification



ERSI Impact

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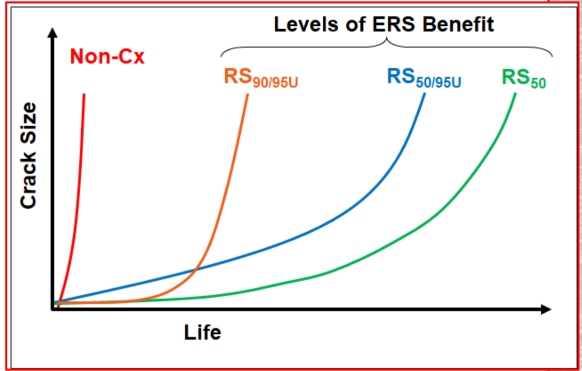
- What would 1 impact slide for ERSI look like?
  - Who's our audience?
    - Technical? Engineering manager? 3 star general?
    - *What would the [your name here]s of the world want to take to "management" to justify a RS-related [IR&D] test program?*
  - Convey issue/scope
    - Impact (recurring intervals?); example; SPO budgets;
  - Key accomplishments



ERSI ENGINEERED RESIDUAL STRESS IMPLEMENTATION

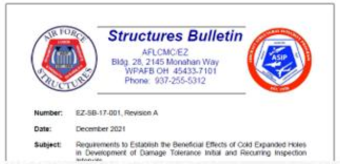
BLUF

- As the USAF inventory continues to age and fleets are operated well beyond their original design goals, sustainment costs continue to escalate.
  - The DoD annual depot maintenance costs are expected to exceed $30B in FY2024
- Engineered residual stresses provide a significant opportunity to extend the life of existing DoD platforms.
- However, it's been shown repeatedly that the ability to properly analyze, apply, and measure engineered residual stresses requires advanced knowledge to ensure appropriate application.
  - Accomplished through an extensive test and analysis program on each individual case with significant cost.
- With the increased number of assets grounded for maintenance, the ability to develop engineered residual stress techniques to extend airframes and lengthen intervals between inspections is essential technology.

Countries Involved: **5**
US Govt Organizations: **4**
USAF ASIP Managers: **10**
National Laboratory: **2**
Universities: **6**
OEMs: **3**
Industry Partners: **34**
ERSI Participants Total: 152

ORIGIN & FOCUS

- The Engineered Residual Stress Implementation (ERSI) working group is a grassroots organization that emerged from within the USAF ASIP community
- Initially formed to identify and address observed technical gaps, define the requirements and guidelines for implementation, and collaboratively develop and accomplish new round robin activities that advance the state-of-the-art concerning the incorporation of residual stresses.
- ERSI consists of three primary focus areas that represent the technical disciplines of aircraft structural integrity that work together: 1) analysis and test, 2) residual stress characterization, and 3) nondestructive inspection/evaluation, quality assurance, data management.



KEY ACCOMPLISHMENTS

- With extensive support from ERSI, the USAF recently issued a Structures Bulletin which allows aircraft structural integrity managers to utilize cold expansion benefits for initial and recurring inspection intervals, a significant achievement for both platform availability and fleet-wide cost savings.
- In addition, ERSI holds an annual workshop and issues a recurring newsletter – the ERSI Screamer - to facilitate communication across the structural integrity community

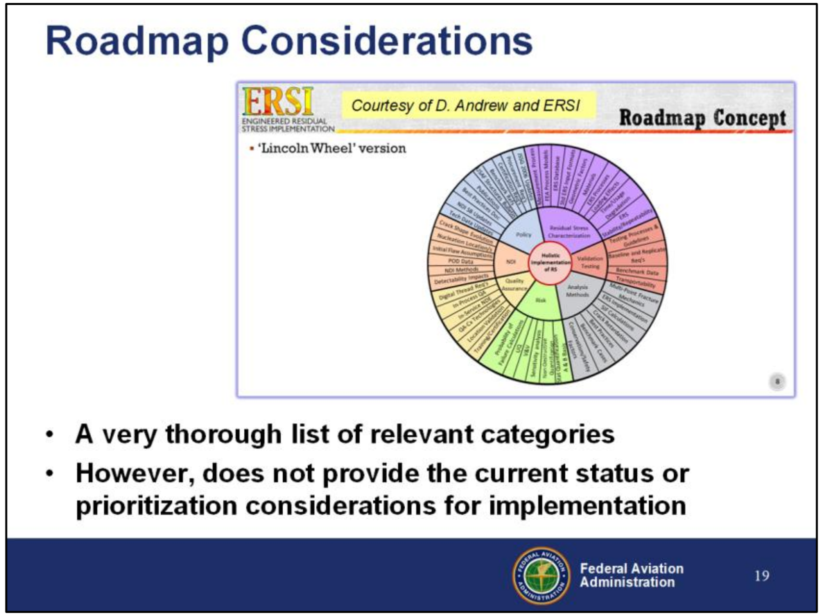
IMPACT

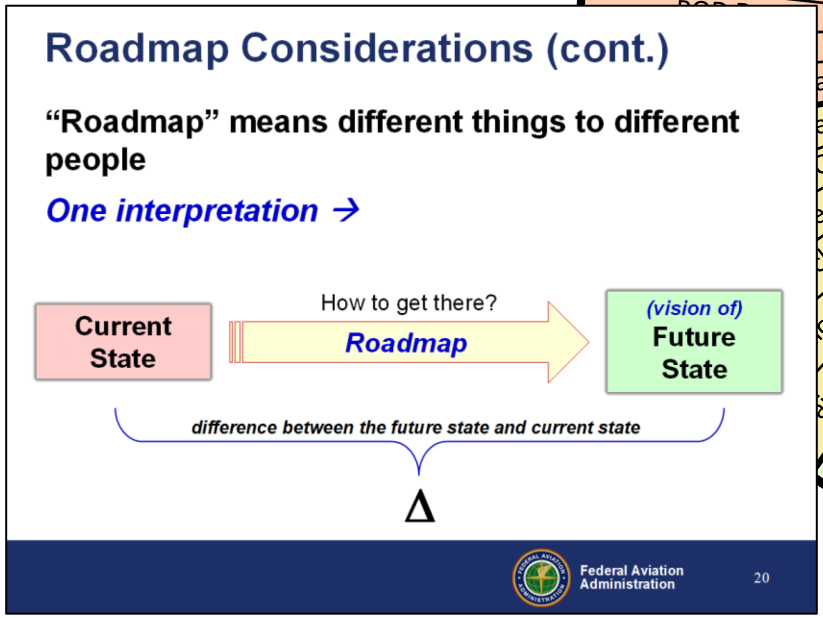
- ERSI represents/captures the stakeholders that are pursuing improved platform availability at less investment per insertion.
- For many USAF aircraft, fastener holes are primary driver for structural inspections, accounting for ~70-90% of fatigue critical locations
  - Cold expansion has been utilized during production and retrofit on approximately 25% to 40% of these critical fastener holes.
- Moving toward a "full credit" approach, where credit for the residual stress from Cx is included to estimate the expected benefit, could have a tremendous impact on reducing maintenance costs for USAF fleets

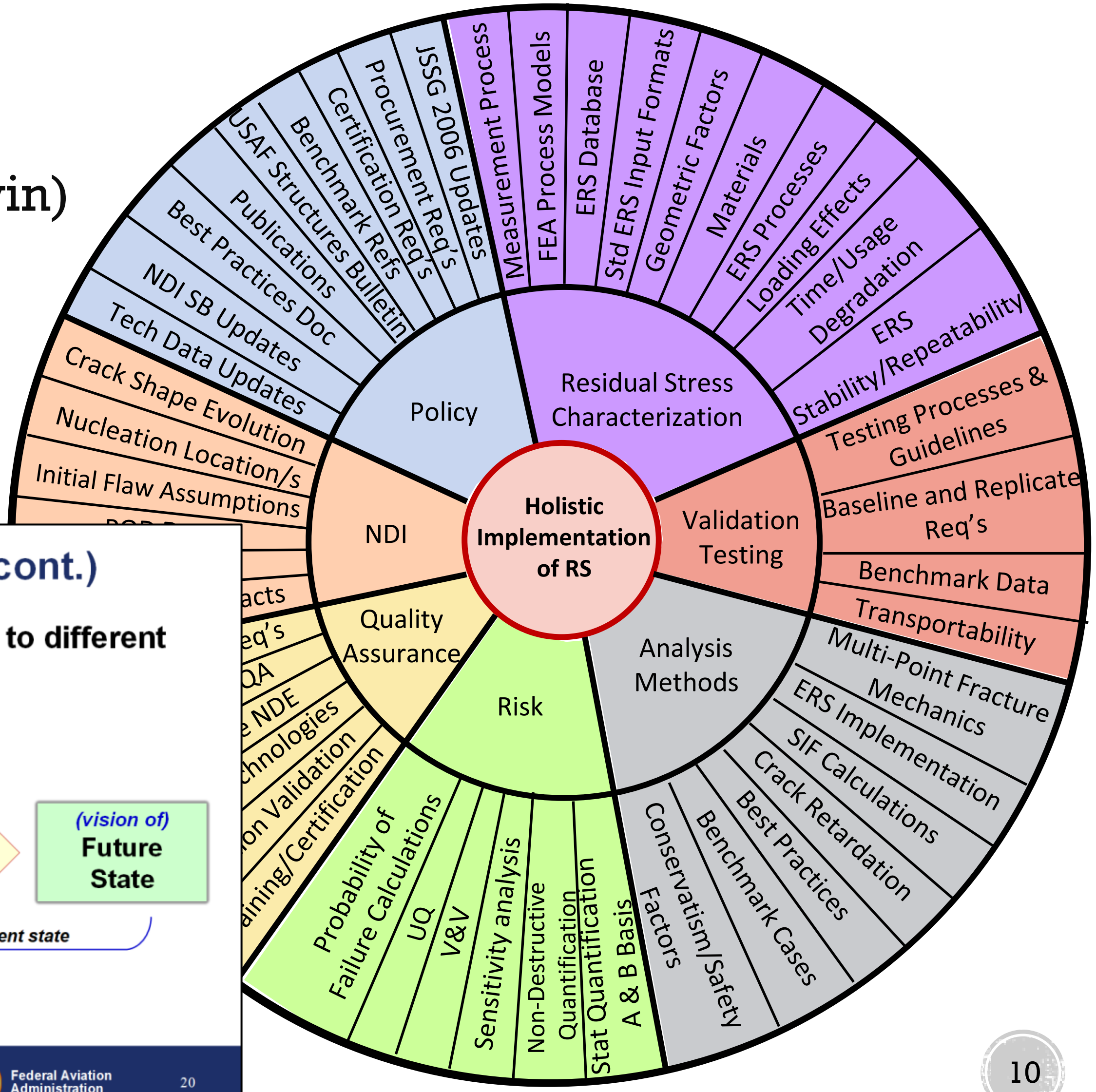
www.residualstress.org

Roadmap Concept

- 'Lincoln Wheel' version
- Need? Usage? Purpose?
  - "Needs of the customer" is not on Lincoln wheel (Kevin)



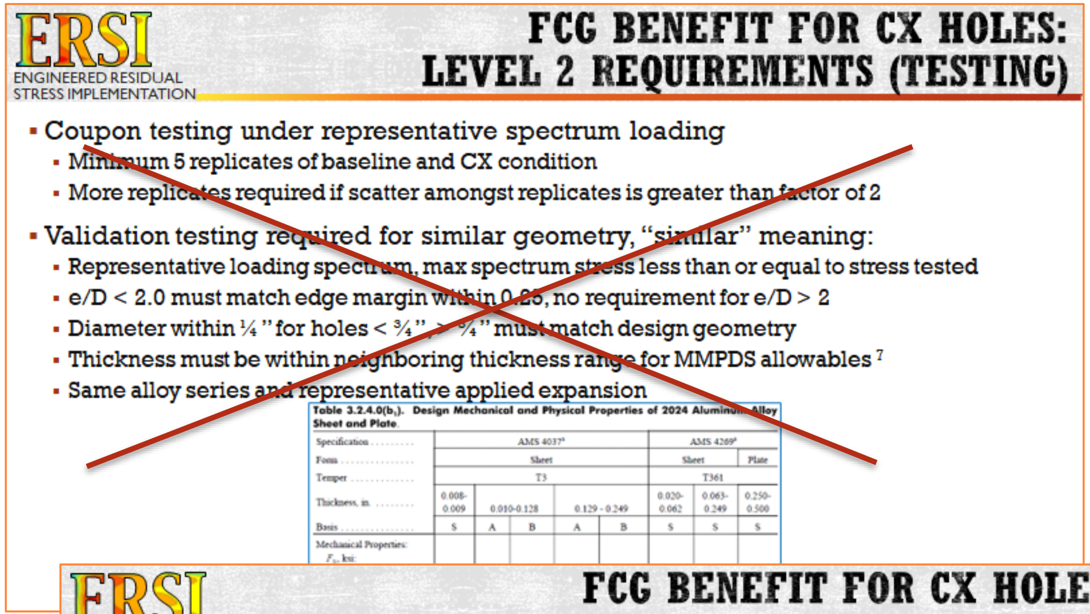


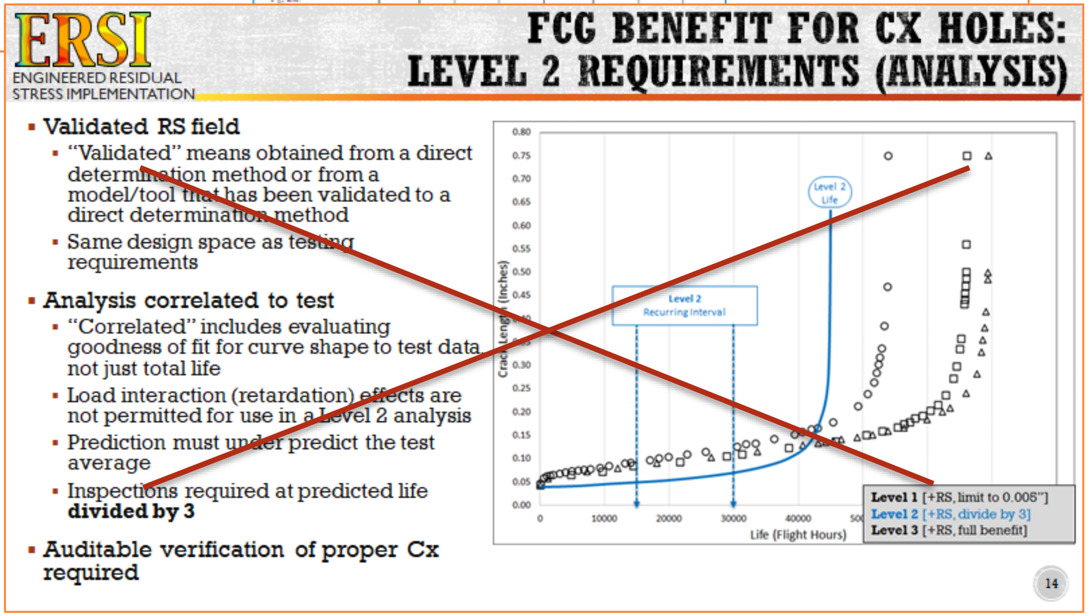


EZ-SB-17-001 Rev B (LAST YEAR)

ERSI ENGINEERED RESIDUAL STRESS IMPLEMENTATION

- Applications to IFF, ForceTec, ForceMate, Taper-Lok, other
- Rev B status
  - Targeting Level 3 benefit
  - Challenges
    - ~~Defining/prescribing the MPFM analysis process & associated details~~
    - ~~Defining/prescribing requirements for RS field~~
    - Verifying Cx was done & was in-spec



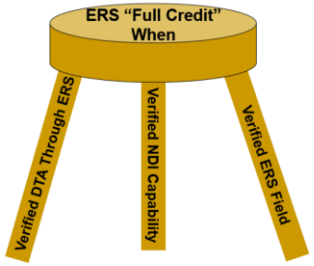


Benefit Levels:

Variations in the amount of benefit needed for the range of aircraft structure applications, their associated complexity, and the cost to substantiate each, has prompted the need to establish different benefit levels as follows:

Level I: Initial inspection interval benefit, using the method described in References 1 and 2 and further defined below, with no recurring inspection interval benefit.

Level II. Level I initial inspection interval benefit and limited recurring inspection interval benefit through explicit incorporation of the non-verified residual stress field in the crack growth analysis.



EZ-SB-17-001 Rev B (DRAFT)

- Requirements to Establish the Beneficial Effects of Cold Expanded Holes and Similar Life Improvement Methods in Development of Damage Tolerance Initial and Recurring Inspection Intervals
- Benefit Levels:
  - Variations in the amount of benefit needed for the range of aircraft structure applications, their associated complexity, and the cost to substantiate each, has prompted the need to establish different benefit levels as follows:
    - Level I: Initial inspection interval benefit, using the method described in References 1 and 2 and further defined below, with no recurring inspection interval benefit.
    - Level II. Level I initial inspection interval benefit and limited recurring inspection interval benefit through explicit incorporation of the residual stress field in the crack growth analysis.
    - Level III. Initial and recurring inspection interval benefits are derived from analysis correlated to the shortest benefit observed in test. **Requires on-aircraft verification of residual stress** and explicit incorporation of the residual stress field in the crack growth analysis.

3 Level III Benefit

3.1 Level III Test Requirements:

The Level III test requirements are identical to those given in Section 1.2.

3.2 Level III Test Data Acceptance Criteria:

The Level III acceptance criteria are identical to those given in Section 1.3.

3.3 Level III Analysis Requirements and Benefit Determination:

For this benefit level, the analyses described in Section 2.4 must be performed. The primary difference between a Level II and Level III is that a Level III benefit is not limited to the predicted life from Analysis 1 in Section 2.4. For Level III the maximum benefit for a recurring inspection interval is limited to the shortest cold expanded damage tolerance coupon test life and requires that all analysis predictions be less than or equal to the average of the cold expanded hole damage tolerance tests (excluding runout tests) in order to utilize any recurring interval benefit.

In addition, the following quality assurance (QA) requirements must be met in order to utilize a Level III benefit:

- Quantified and auditable verification that cold expansion was accomplished is required (e.g. – cold expanded puller load data at time of cold expansion, NDE data at a time post-cold expansion, etc.)
- The level of cold expansion (e.g. – applied or residual expansion) determined from the previous step must correlate directly with the residual stress field that is applied to the DTA and the test coupons from Section 3.1
- Quantified and auditable verification that the proper hole(s) location was cold expansion is required (e.g. – spatial position tracking of cold expansion puller at time of cold expansion, location of NDE tooling at a time post-cold expansion, photographic evidence, etc.)
- The chief engineer or cognizant engineering authority must approve the QA data capture method and recording requirements

ERSI Interactions

- ASIP Manager Update (semi-annual, ASIP and AA&S)
  - Awareness of 'problem areas'/requirements from the SPOs
- Annual briefing to Chuck
  - Part of an ASIP review?
- Plan/Location/Desire for next year
- Coordinate ERSI efforts to present at ASIP
- Outreach
- Screamer


VOLUME 5
ISSUE 1

ERSI SCREAMER

MARCH 2024

This Issue:

The Engineered Residual Stress Implementation (ERSI) Screamer is a recurring newsletter to help facilitate communication to all stakeholders in the aerospace community that have an interest in the implementation of residual stresses.

Purpose of ERSI

1) Develop a roadmap for the implementation of engineered residual stress (ERS) for calculation of initial and recurring inspection intervals for fatigue and fracture critical aerospace components.
2) Identify and address gaps in state-of-the-art.
3) Define the most effective way to document requirements and guidelines for fleet-wide implementation.

Organization

The ERSI working group is broken up into 3 major committees with a chair for each, as shown below.

COMMITTEE NAME	CHAIR(S)
EXECUTIVE COMMITEE Dr. Dallen Andrew (Hill Engineering)	
ANALYSIS & TEST	Robert Pilarczyk (Hill Engineering) Dr. Kevin Walker (QinetiQ)
RESIDUAL STRESS CHARACTERIZATION	Dr. Eric Burba (USAF AFRL) Dr. Adrian DeWald (Hill Engineering)
NDI, NDE, DATA MANAGEMENT, & QUALITY ASSURANCE	Dr. Eric Lindgren (USAF AFRL)

Screamer Editor:
Dallen L. Andrew, Ph.D.
Hill Engineering | 916.701.5045
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Discussion & Feedback

- Need to get regulatory people in the room
  - We're gathering the state-of-the-art but not disseminating it
- Having no load interaction in the SB is an issue
- Interest in DTA ground rules with RS?
  - Need to have 'best practices' that lays out "How ERSI is saying to do it"
  - Need a step-by-step use case of meeting the requirement of the SB
    - An ERSI report, ASM handbook, and/or ASTM STP
- Other
  - Investigating role of the sequence of precracking and Cx
  - For split mandrel process, is there NDI impacts to be considered for updates to the NDI SB?

ERSI 2024 NOTES

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Discussion & Feedback

- What areas/topics do you want to see ERSI focus on in the near future?
- Risk analysis break-out meeting on Thursday (Mark Ryan, LM)
  - Interest, timing

ERSI – *Future* Scope Considerations

- **Military vs. Civil Aviation (?)**
- **Product types – airframe structures / propulsion systems / rotorcrafts / … (?)**
- **Engineered vs. manufacturing-induced (?)**
- **For engineered RS – type of technology (?)**
  - **Cx of holes / shot peening / LPB / LSP / …**
- **Primary use (?)**
  - More accurate life prediction / credits
  - Safety enhancements
  - Part of manufacturing QA
  - *Other..?*

Federal Aviation Administration 21

809 MXSS Science & Engineering Laboratory

OGDEN AIR LOGISTICS COMPLEX

SISTER ALC LABS

809 MXSS Science and Engineering Laboratory
Director – *Eric Billings*

Technical Lead – *Trevor Shoemaker*

NDI PM – *Ward Fong*

Chemistry Flight
- Solution chemistry characterization.
- Gas Chromatography (GC) for organic characterization.
- ICP-OES for metal ion quantification.

Materials Flight
- Optical, scanning electron, NDI, and mass spec. materials characterization.
- Monotonic & cyclic loading materials testing.
- Auto. crack monitoring.
- In-house machine shop.

Adv. Mfg. (RAPID) Flight
- 3D scanners for reverse engineering efforts.
- 20+ Industrial 3D printers.
- Significant polymer and growing metal printing capabilities.

Verification Flight
- Full metrology lab.
- Touch and non-touch CMMs with +/- 0.0002" accuracy.

Metrology & Calibration Flight

Production Support Flight

Applied Research Mission:

To evaluate the suitability of **sustainment-focused** materials processing and lifing techniques for legacy and emerging structural materials.

Fatigue Crack Growth & Testing Committee

2025 ERSI Workshop

Kevin Walker, committee lead
kwalker999@hotmail.com

Robert Pilarczyk, committee co-lead
rtpilarczyk@hill-engineering.com

ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Outline for this 2.5 hour session

- Introduction, summary and overview (Kevin – 20 mins)
- Updates, achievements and plans from Focus Areas
  - Spectrum Loading (Moises/Kevin - 20 mins)
  - IFF and 2025 A-10 Cx Dataset (Bob – 40 mins)
  - Durability and Fatigue Life Testing (Adrian – 20 mins)
- Cx tolerance testing (Evan Ross - 20 mins)
- Building Block Approach (Moises – 20 mins)
- Discussion (All – 10 mins)

Outline of this presentation

- Roster summary
- Vision: Mission and key objectives
- Implementation roadmap
- Focus areas and working groups

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Roster Summary

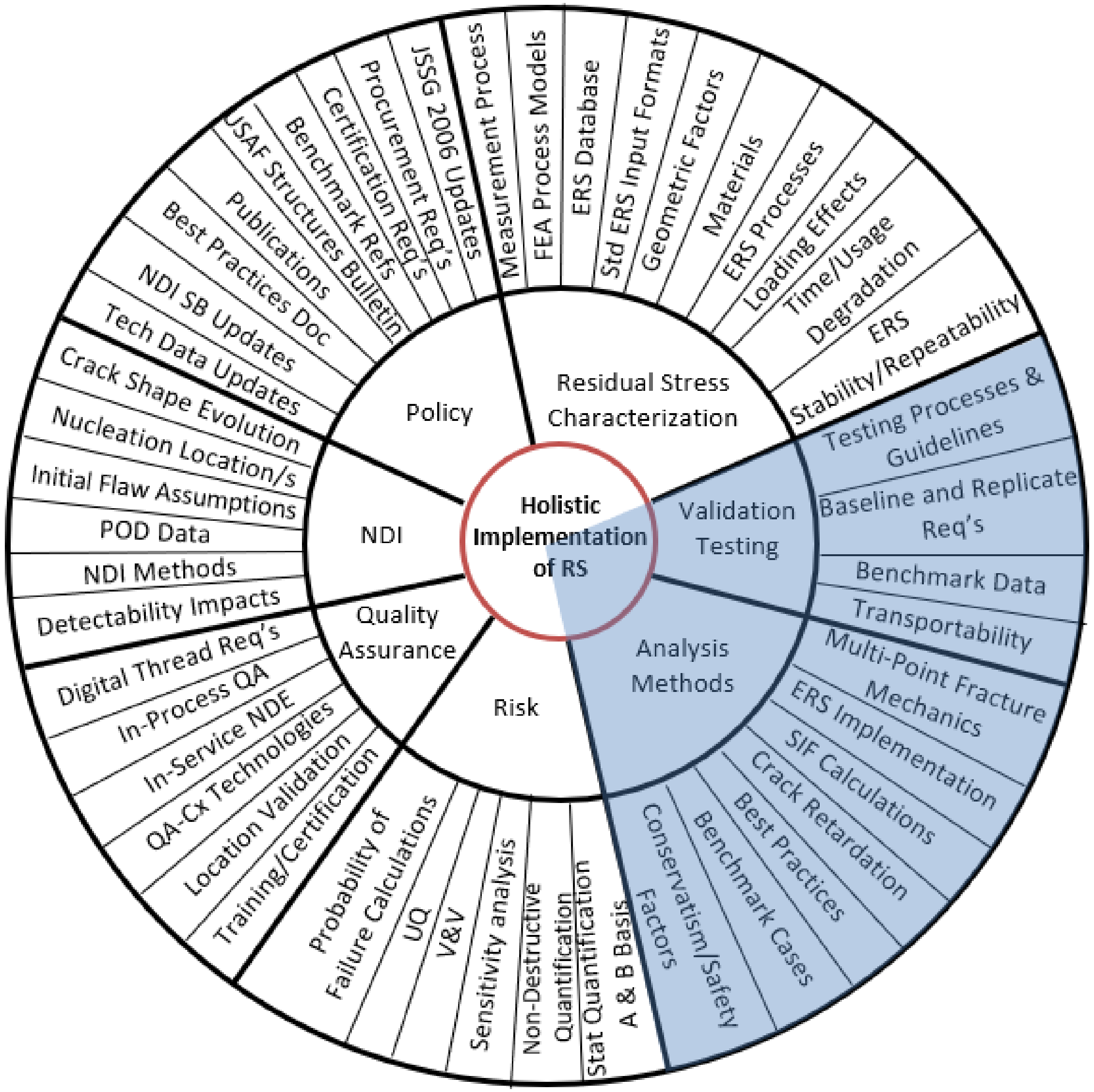
- **Committee members**
  - 75 members (up from 68 last year)
  - Diverse participation from government, OEMs, small businesses, and academia
- **Active participants**
  - ~15 participants in monthly meetings
- **Working groups**
  - Three working groups
    - Spectrum loading
      - Leads – Moises, Walker
      - Participants ~ 7 members
    - Interference fit fasteners
      - Leads – Pilarczyk, Loghin, Ribeiro
      - Participants ~ 19 members
    - Durability and fatigue life benefits
      - Lead – Adrian Loghin
      - Just getting started

Vision

- **Mission statement**
  - Establish **analytical and testing guidelines** to support the implementation of engineered residual stresses
- **Key objectives**
  - Develop and document **best practices** for the integration of engineered residual stresses into fatigue crack growth prediction methodologies
  - Establish **testing requirements** considering the impacts of residual stress on fatigue crack growth
  - Develop **datasets and case studies** to support analysis methods validation
  - Identify, define, and enable the **resolution of gaps** in the analytical methods state-of-the-art
  - Support the development of an **implementation roadmap**

Implementation Roadmap

- **Approach**
  - Leverage ASIP Lincoln Wheel
  - Tailored for ERS
  - Identify key focus areas
  - Highlight focus areas based on criticality and maturity
- **Benefits**
  - Utilize to communicate development needs



Focus Areas

- **Spectrum loading and retardation (active)**
  - Investigate the appropriate methods to characterize crack retardation due to spectrum loading for conditions with residual stress
  - Gather and/or develop test data to support validation of methods
  - Document best practices and lessons learned
- **Interference fit fasteners (IFF) and residual stress (active)**
  - Investigate the relationship between interference fit fasteners and residual stresses from Cx and/or Taper-Lok
  - Identify appropriate methods to incorporate interference fit fastener benefit for conditions with residual stress
  - Document best practices and lessons learned
- **Durability testing and fatigue life benefits (now active)**
  - Review existing test data and develop summary to document Cx life impacts on early crack nucleation and growth
  - Identify any testing needs to further refine understanding

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Spectrum Loading Working Group

- **Participation**
  - ~ 10 members
- **Objectives**
  - Collaborate to understand load interaction effects on crack growth using simple spectrum loading (spike overload) and spectrum loading. Validate and understand limitations of proposed modeling for plastic tip constraint loss.
- **Approach**
  - Perform blind predictions with various analysis tools and retardation approaches
  - Develop validation test data to compare/contrast with analysis predictions
- **Key collaboration areas**
  - Boeing CSM Spectrum Loading Round Robin (Moises)
  - Spike Overload Testing (Boeing & QinetiQ Australia/Mississippi State)
  - Re-visit of Cx RR#1 (Kevin)

Accomplishments – Spectrum Loading

- **Spectrum loading constraint-loss**
  - Publications as follows:

  - Walker, K.F., et al., Simulation of fatigue crack growth in aluminium alloy 7075-T7351 under spike overload and aircraft spectrum loading. International Journal of Fatigue, 2025. 190: p. 108660.
  - Newman, J.C. and K.F. Walker, Fatigue Crack Growth on Several Materials under Single-Spike Overloads and Aircraft Spectra during Constraint-Loss Behavior. Materials Performance and Characterization, 2024. 13(2).
  - Newman , J.C., Jr., and Walker, K.F., Fatigue Crack Growth in 7075-T6 Aluminium Alloy Under Single-Spike Overloads and Aircraft Spectra, in Variable-Amplitude Loading (VAL5). 2024: Dresden, Germany.
  - Newman , J.C., Jr., and Walker, K.F., Fatigue crack growth on several materials under single spike overloads and aircraft spectra, in International Committee on Aeronautical Fatigue. 2023: Delft, The Netherlands.

IFF Working Group

- **Participation**
  - 13 members
- **Objective**
  - Collaborate to establish validated analytical methods for Interference Fit Fasteners (IFF)
    - Review Physics of Interference Fit Fastener
    - Characterize Existing Methods & Data
    - Identify Key Factors and Gaps in Current Methods/Data
- **Approach**
  - Phased approach with increasing complexity
    - Phase I: Baseline stress analysis verification
    - Phase II: Stress intensity factor comparisons
    - Phase III: Crack growth analyses comparisons
  - Validation tests sponsored by A-10 team to accompany analyses
- **Key collaboration areas**
  - IFF Analysis Round Robin (Pilarczyk, Loghin, Ribeiro)
  - A-10 IFF Testing & Analysis Program (Warner, Smith)

Accomplishments IFF

- ERSI IFF Analysis Round Robin
  - Predictions received for baseline stress analysis
  - Eight different participants utilizing five different software packages
- A-10 IFF Testing
  - Testing completed to characterize as-installed + remote load stress states
  - Comparisons with blind predictions in work
- Publications
  - Ribeiro, R.L., et al., Interference Fit Fasteners: A Finite Element Process Modeling Round Robin. Materials Performance and Characterization, 2025. (in coordination for publication)
  - Pilarczyk, R.T., et al., Testing & Analysis of Interference Fit Fasteners: An A-10 ASIP & ERSI Joint Effort. 2024 USAF ASIP Conference Proceedings.

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Durability and Fatigue Life Test Working Group

- **Participation: 1 (Adrian)**
- **Objective:**
  - Extend our understanding and modeling capabilities beyond long crack behavior
- **Approach**
  - It is not clear what would be the best initial approach. It was suggested in a previous Tcon to investigate the 0.005 inch initial crack size usage in different damage tolerance practices. If this is a desired goal of this working group, we could define some approaches that could be accomplished.
  - Any feasible approach would include a collaboration between various expertise domains: modeling, testing, material characterization, NDE.
- **Key collaboration areas (very general)**
  - Short crack behavior, measurement, modeling
  - Microstructural small crack measurement and modeling
  - Microstructure characterization, reconstruction, crystal plasticity, ...

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Future Plans

- **Key focus areas for 2025-2026**
  - **To be discussed at this Workshop**

Summary

- **Diverse, active committee focused on key aspects for accurate analytical predictions with supporting validation data**
- **Topic areas have expanded beyond Cx since the original round robin**
  - Areas are critical for practical application
- **Refocusing on Cx cases is important moving forward**
  - Address differences between predictions and tests
  - Incorporate effects of IFF and spectrum

Spectrum Loading Effects: Progress and Path Forward

Moises Y. Ocasio, committee co-lead
moises.y.ocasio-latorre@boeing.com

Agenda

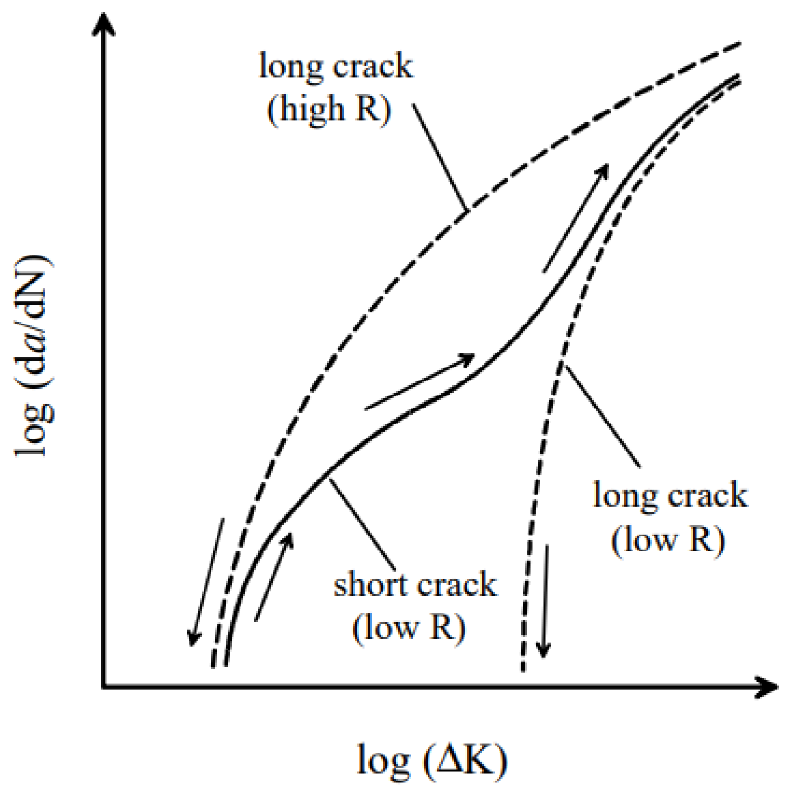
- Goals and Key Lessons Learned
- Spike Overload Testing
- 7075-T7351 Round Robin Effort
- Spectrum Loading Effects on Cracks Growing from Fastener Holes
- Path Forward

Goals and Key Lessons Learned

- Goals
  - Investigate and validate the appropriate methods to characterize crack retardation due to spectrum loading for conditions with residual stress.
  - Gather and/or develop test data to support validation of methods
- Lessons Learned
  - "Understanding and improving our ability to model spike overload cases is considered fundamental to the prediction for spectrum loading" – *2021 Overload Challenge conclusion*
  - Residual crack wake plasticity from pre-cracking leads to artificially high da/dN threshold values. This has been extensively studied by J.C. Newman and others, and the community is becoming increasingly aware of this as methodologies for spectrum loading effects in residual stress conditions are refined.
  - Constraint loss is crucial for predicting retardation, especially in spike overload testing. Newman's model suggests that the transition to complete slant crack growth (plane stress) occurs when ΔK_{eff} reaches a specific percentage of the sheet thickness, providing a reliable estimate of constraint loss behavior.

Lessons Learned

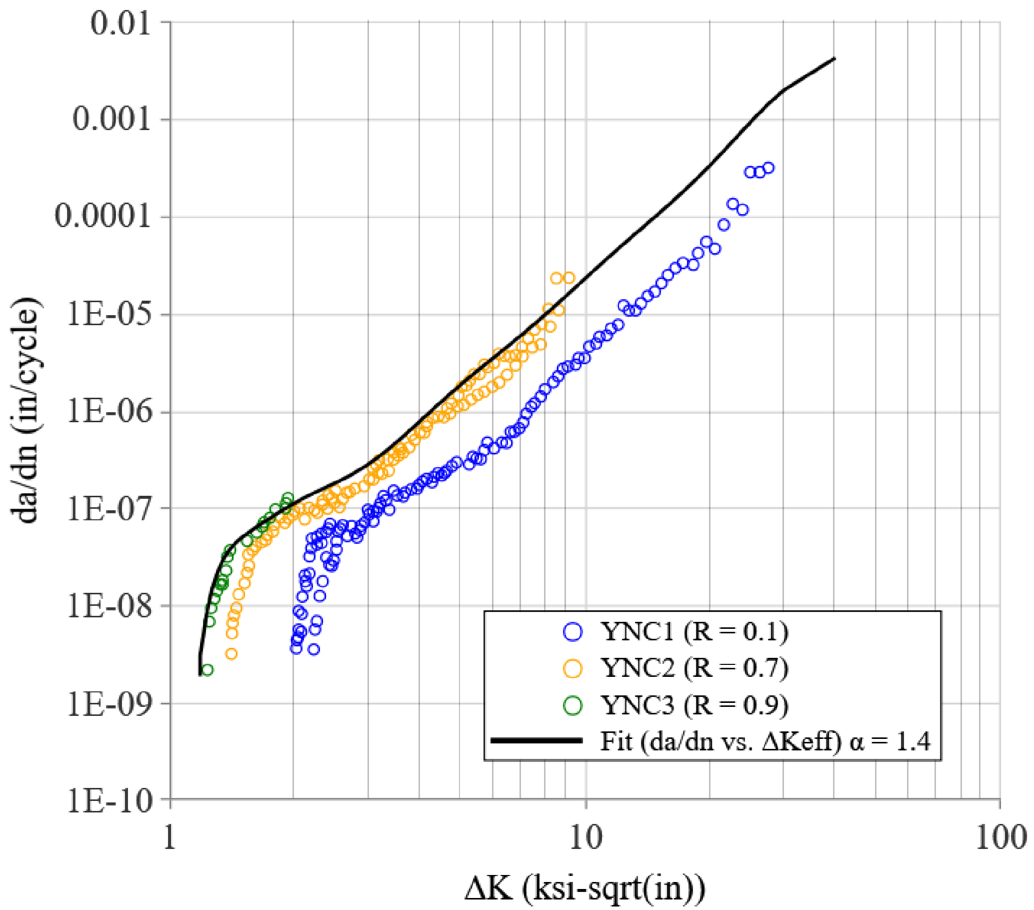
Lesson #1: Region I "Adjustments"



- This effect often refer as "short crack anomaly", but it should be called "long crack anomaly". In other words, the problem is that long cracks – due to residual crack wake plasticity (from pre-cracking) –produce artificially high FCGR threshold values.
- In contrast, short cracks align with high stress ratio long cracks near the threshold because they are essentially 'closure-free.'
- Two solutions are proposed:
  1. CPCA-like pre-cracking.
  2. Adjusting the analysis curve to either short crack data or high stress ratio data near the threshold (this will be illustrated on the next slide)."

K. Tokaji, T. Ogawa, and Y. Kameyama, "The Effects of Stress Ratio on the Growth Behavior of Small Fatigue Cracks in an Aluminum Alloy 7075-T6 (With Special Interest in Stage I Crack Growth)," Fatigue and Fracture of Engineering Materials and Structures, v. 13 (1990), pp. 411-421.

da/dN Fit: 7050-T7451 L-T example

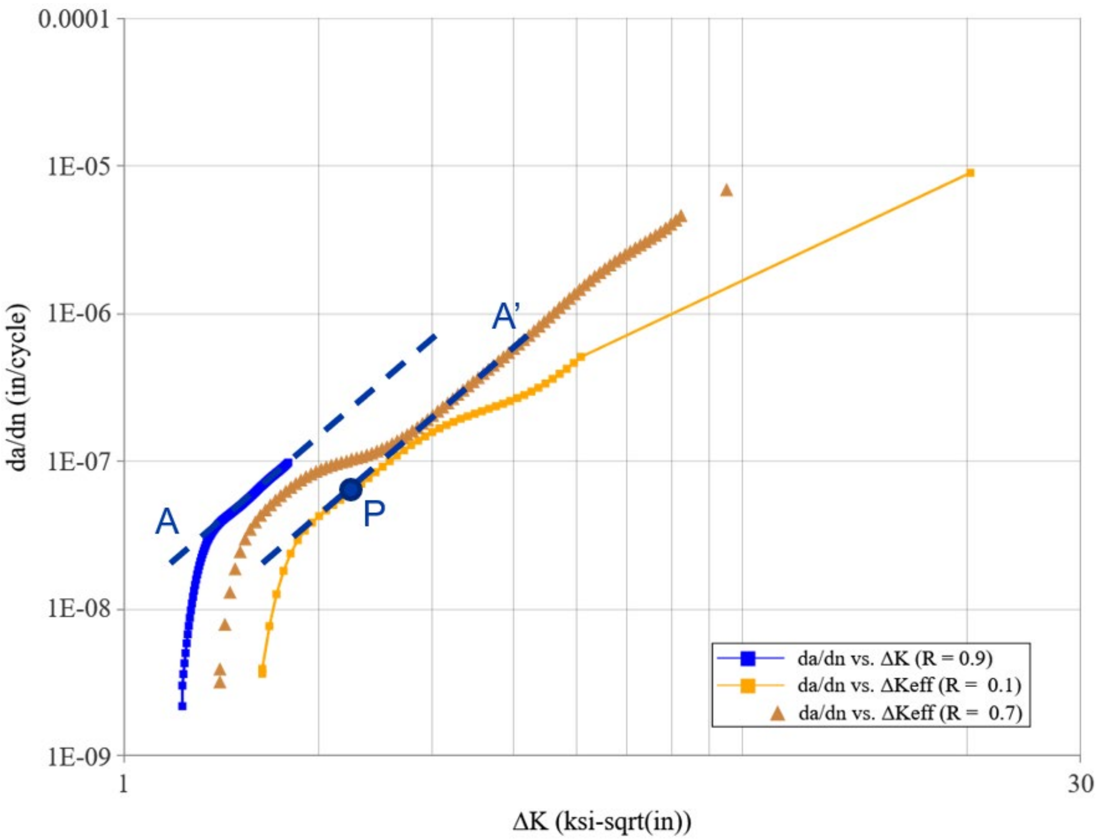


- Maximum Likelihood Estimate (MLE) approach used to fit through 7050-T7451 L-T data from (1).
- Curve fit to R = 0.9 was assumed to be 'closure free'
- α = 1.4 provides the best fit constraint

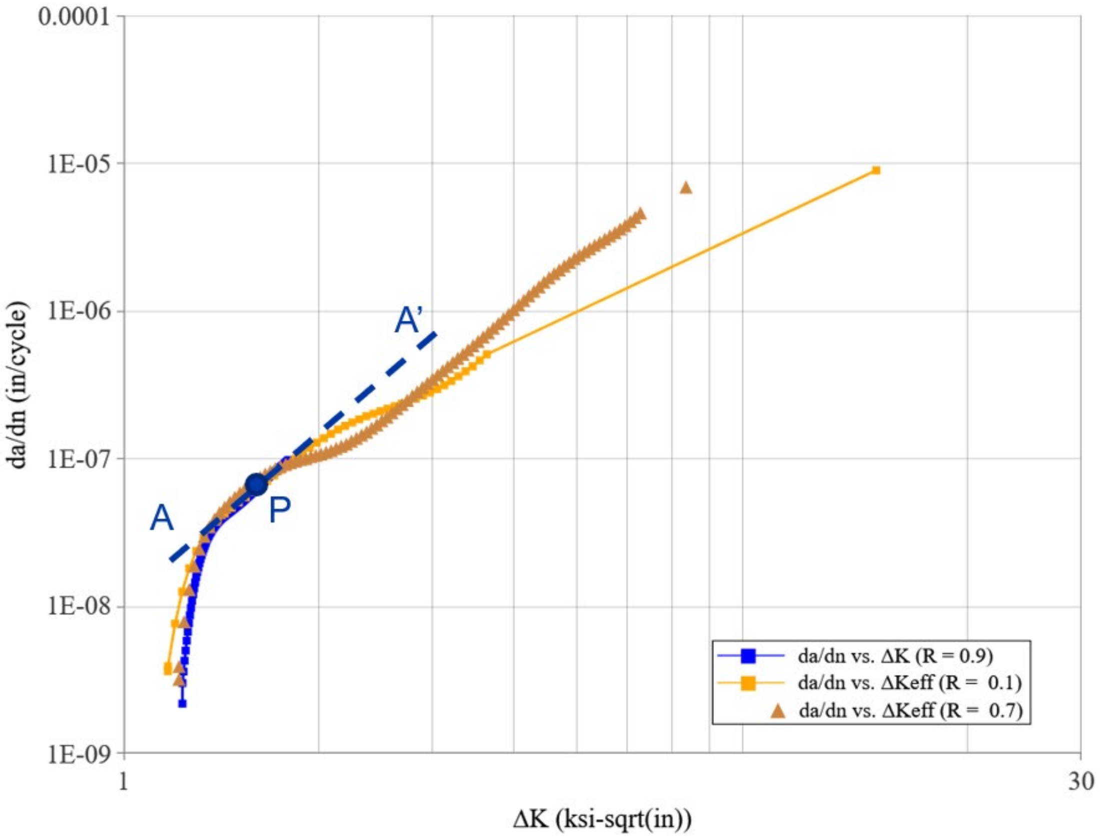
(1) Newman, J. C., Jr., Yamada, Y., and Newman, J. A. (April 1, 2010). "Crack-Closure Behavior of 7050 Aluminum Alloy near Threshold Conditions for Wide Range in Load Ratios and Constant K_{max} Tests."

da/dN Fit: 7050-T7451 L-T example, cont.

α = 3, Plane Strain

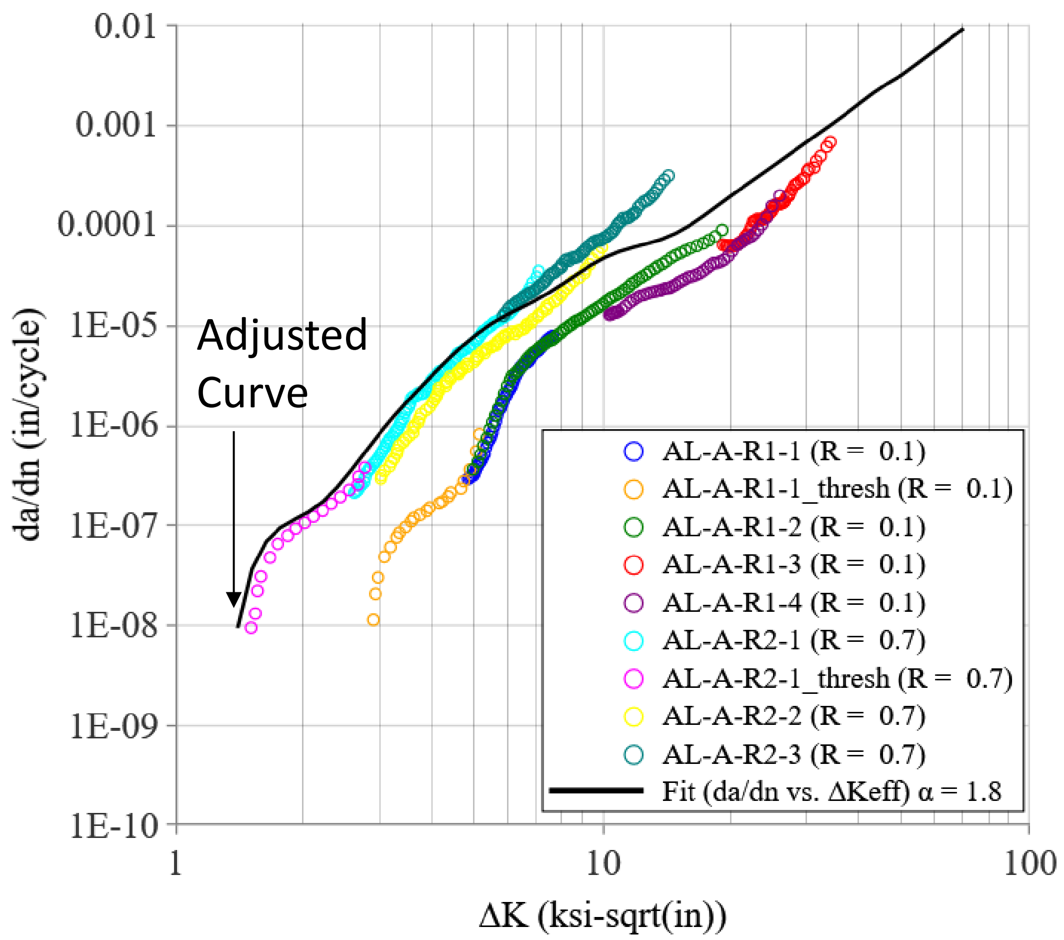


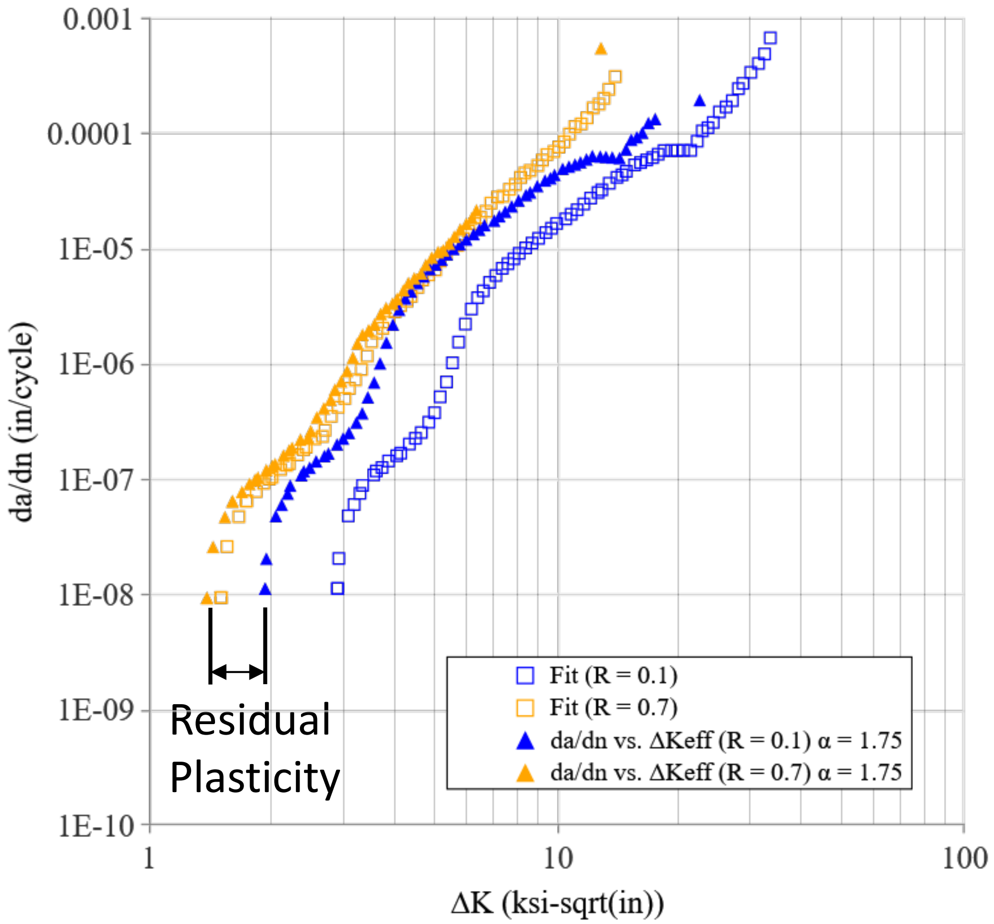
α = 1.3



This is a good example where effective curves collapse is enough to get a good fit without further modification of region I, but … baseline data was CPCA!

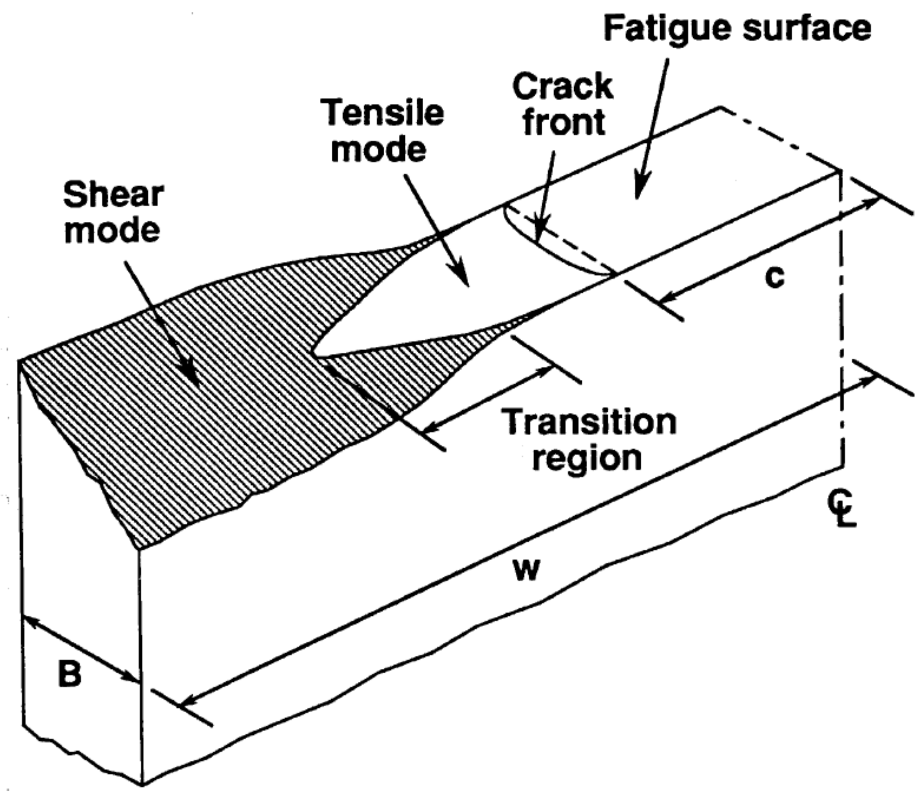
da/dN Fit: 7075-T6 L-T Boeing IRAD





da/dN-ΔKeff curve needs Region I adjustment. Pre-cracking method was ASTM LR.

Lesson #2: Constraint Loss



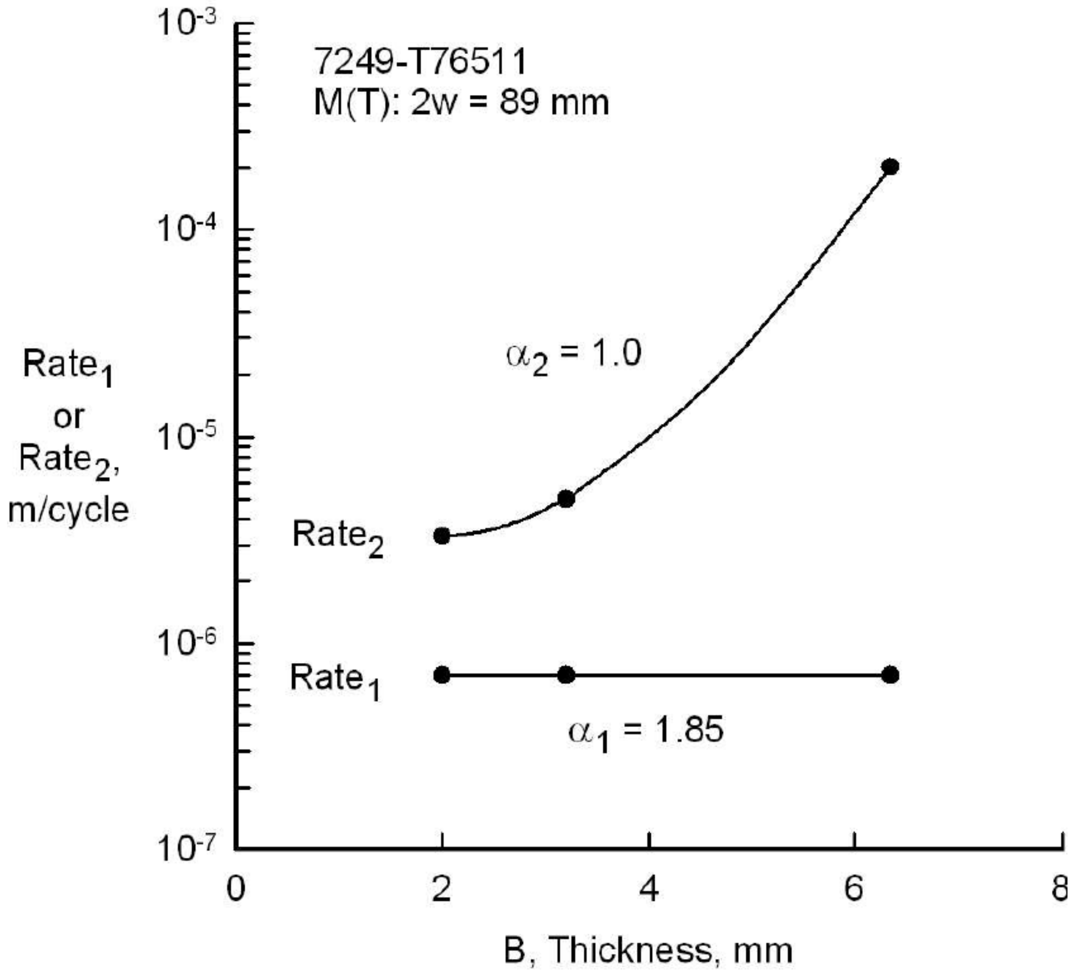
Newman JC Jr, Bigelow CA, Shivakumar KN. *Three-dimensional elastic-plastic finite-element analysis of constraint variations in cracked bodies*. Eng. Frac. Mech 1993

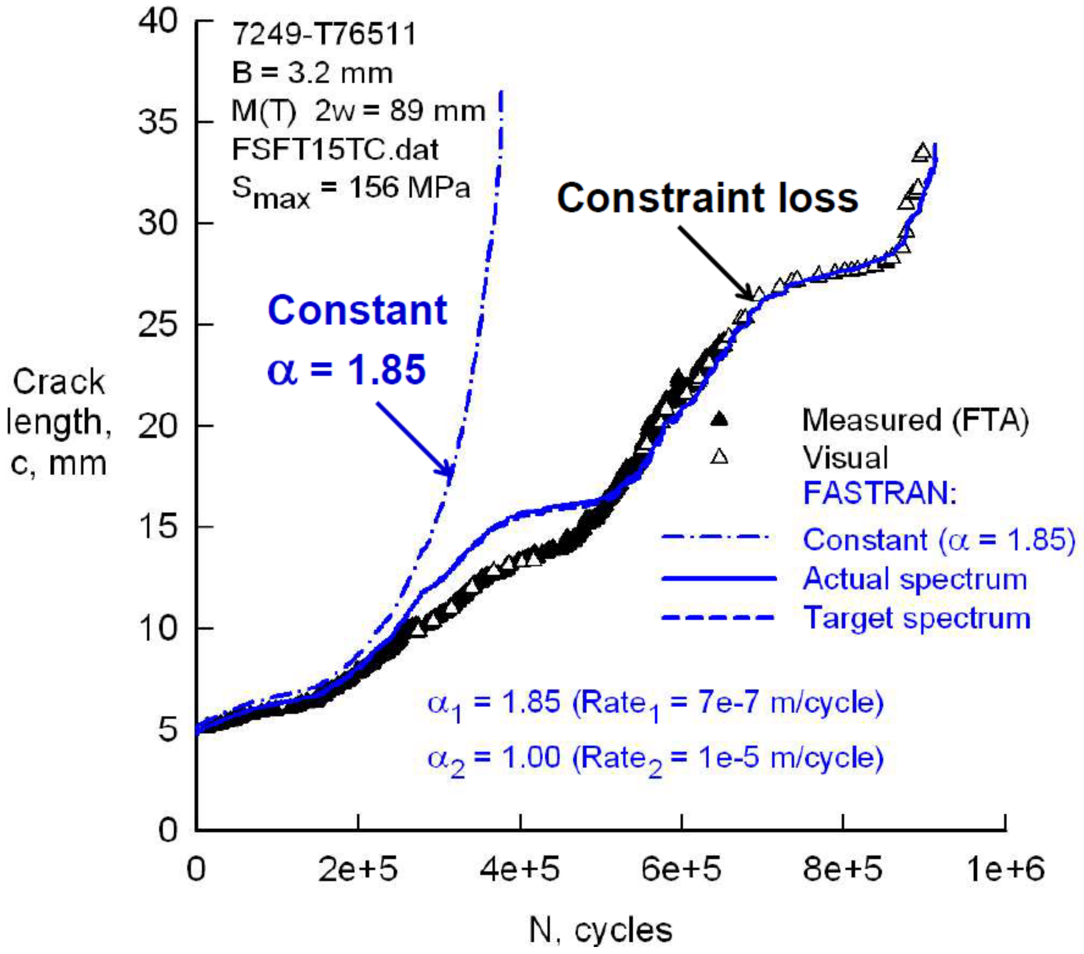
- The global constraint decreases as ΔK increases.
- The development of shear lips is evidence of the transition from a flat to a slant type of crack growth, which is closely associated with the loss of constraint.
- Schijve (1979) proposed ΔK_{eff} should control this transition.
- Newman (1992) proposed that transition happens when the plastic zone reaches a certain percentage of material thickness.

$$\mu = \frac{(\Delta K_{eff})_T}{\sigma_0 \sqrt{B}}$$

$$\mu = 0.5 \pm 0.1 \ (Empirical)$$

Example: 7249-T76511 Spectrum Loading

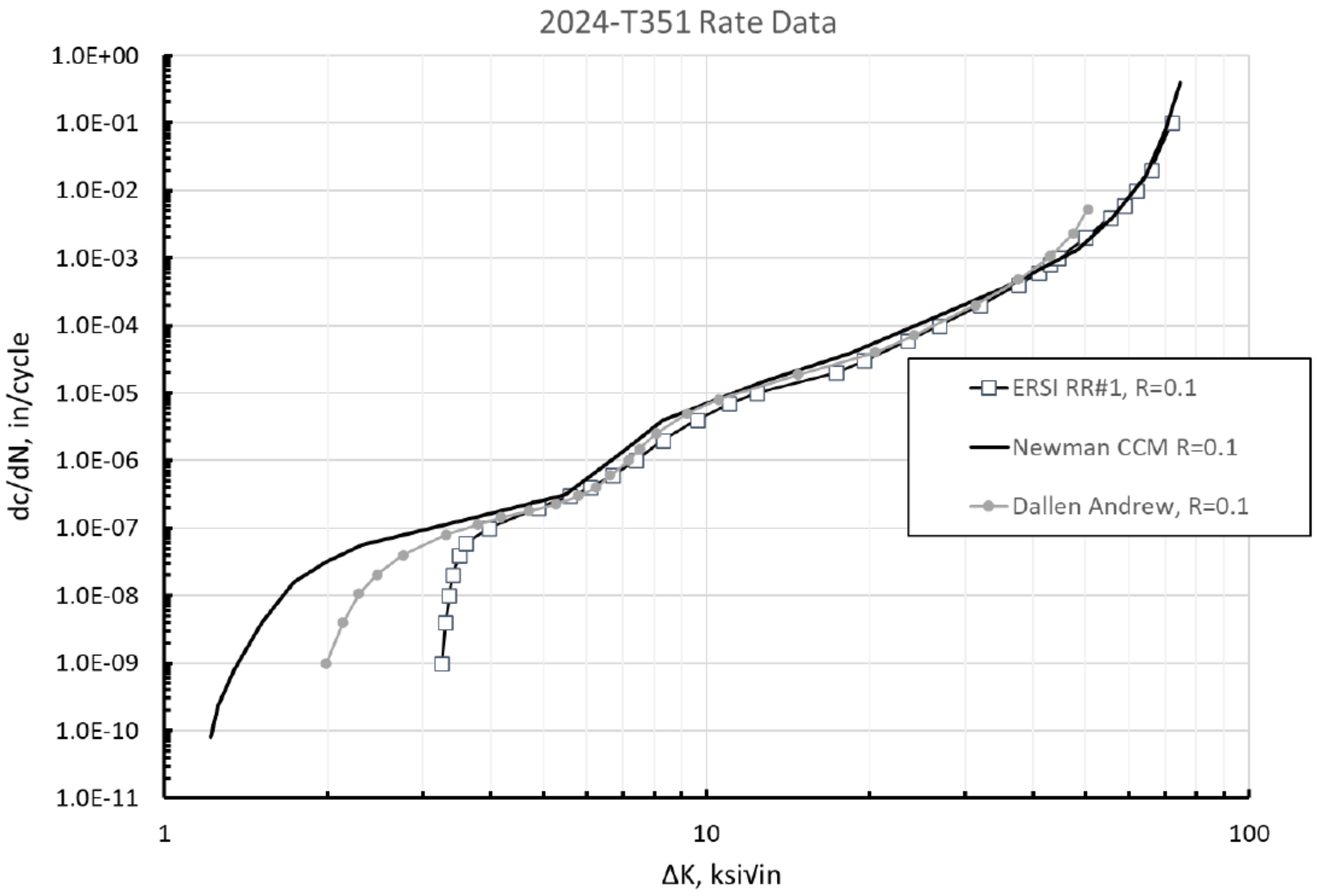


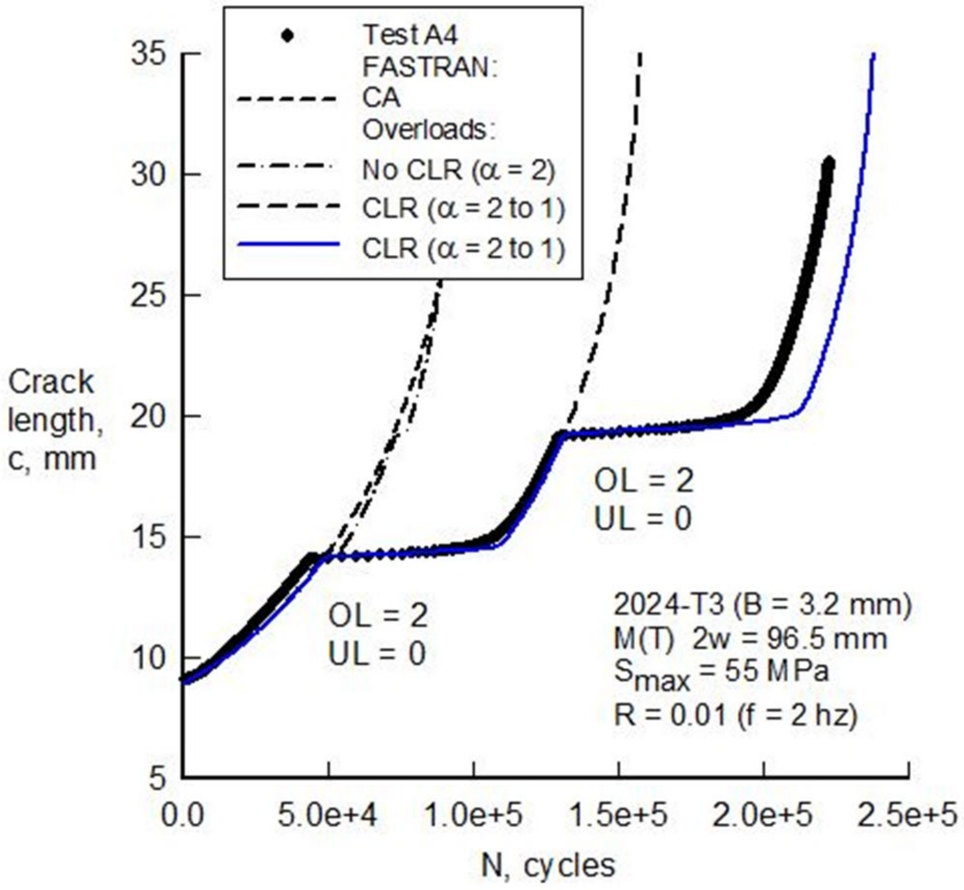


Newman, J.C. and K.F. Walker, *Fatigue Crack Growth Tests and Analyses on 7075 T6 and 7249 T76511 Aluminum Alloy Specimens of Various Thickness under Simulated Aircraft Wing Loading*, in USAF ASIP Conference. 2017: Jacksonville Florida USA.

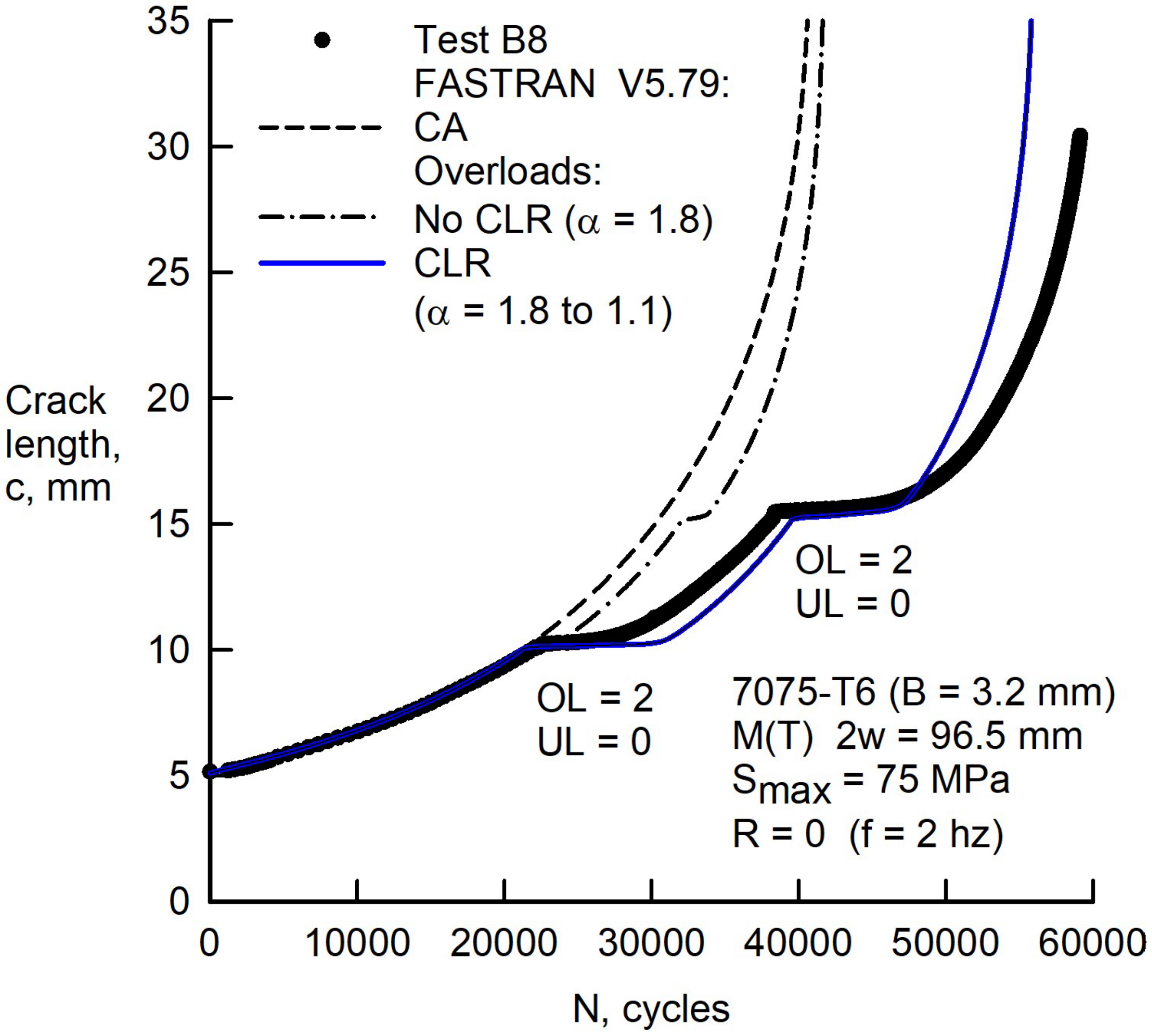
Testing Overview

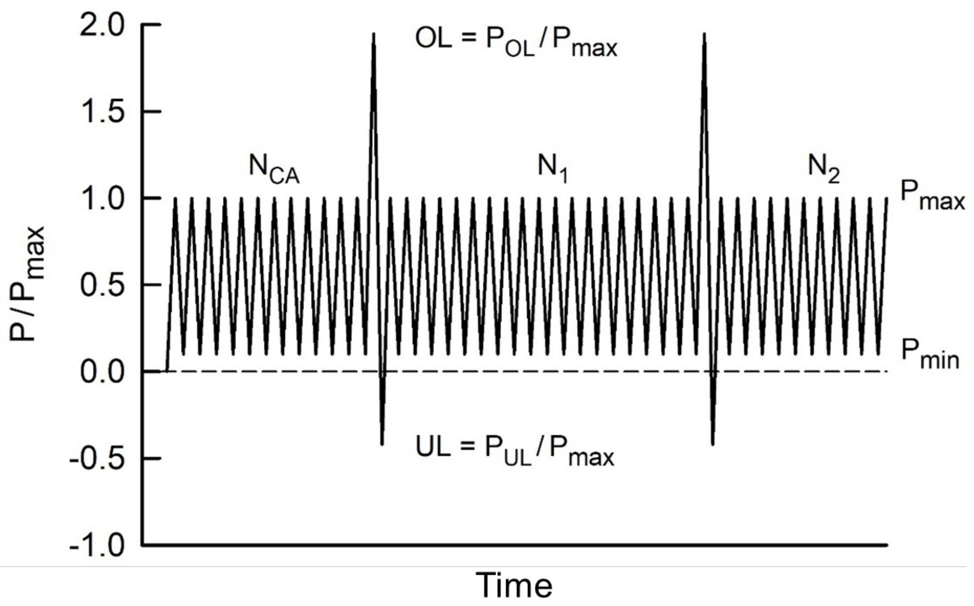
2024-T3 Spike Overload (QinetiQ Australia/MSU)





7075-T6 Spike OL (QinetiQ Australia/MSU), cont.



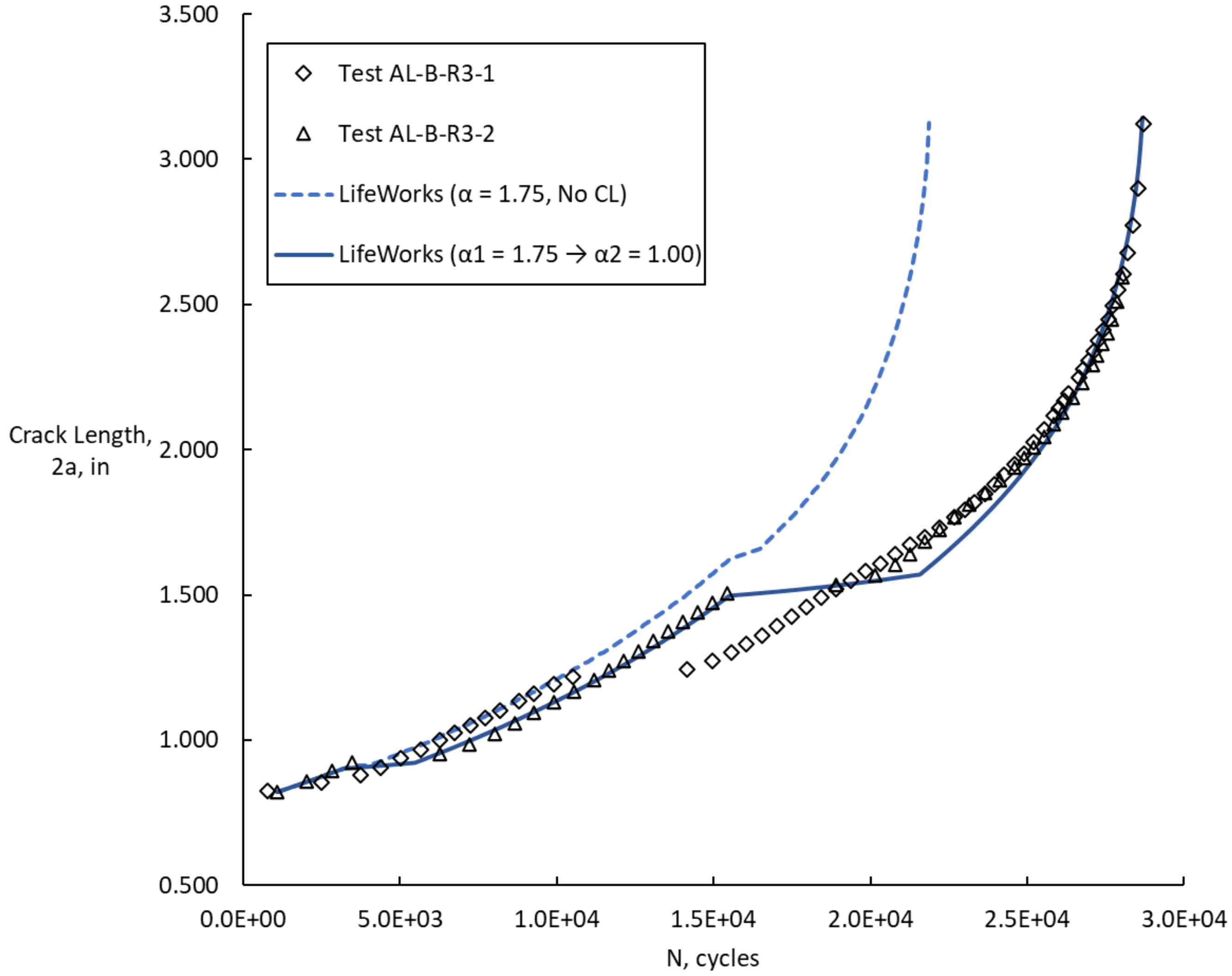


Other QinetiQ Australia IRAD Efforts

- Spike Overload/Underload
  - 2024-T3, 7075-T6, 7075-T7351
  - Stress Ratios: 0, 0.5, 0.7
  - Multiple Stress Levels
- TWIST Spectrum Loading
  - 2024-T3, 7075-T6, 7075-T7351
  - TWIST Levels I and III

- Contact
  - Kevin Walker, PhD
  - Email: KFWalker@QinetiQ.com.au

7075-T6 Spike Overload (Boeing, Task B)



Specimen	M(T)
W	3.95"
B	0.09"
L	17.5"
Notch total length	0.7”
Grain Direction	L-T
Loading Type	Constant Amplitude with OL = 1.8·Pmax
Pmax	3.91 kips
Stress Ratio	0.01

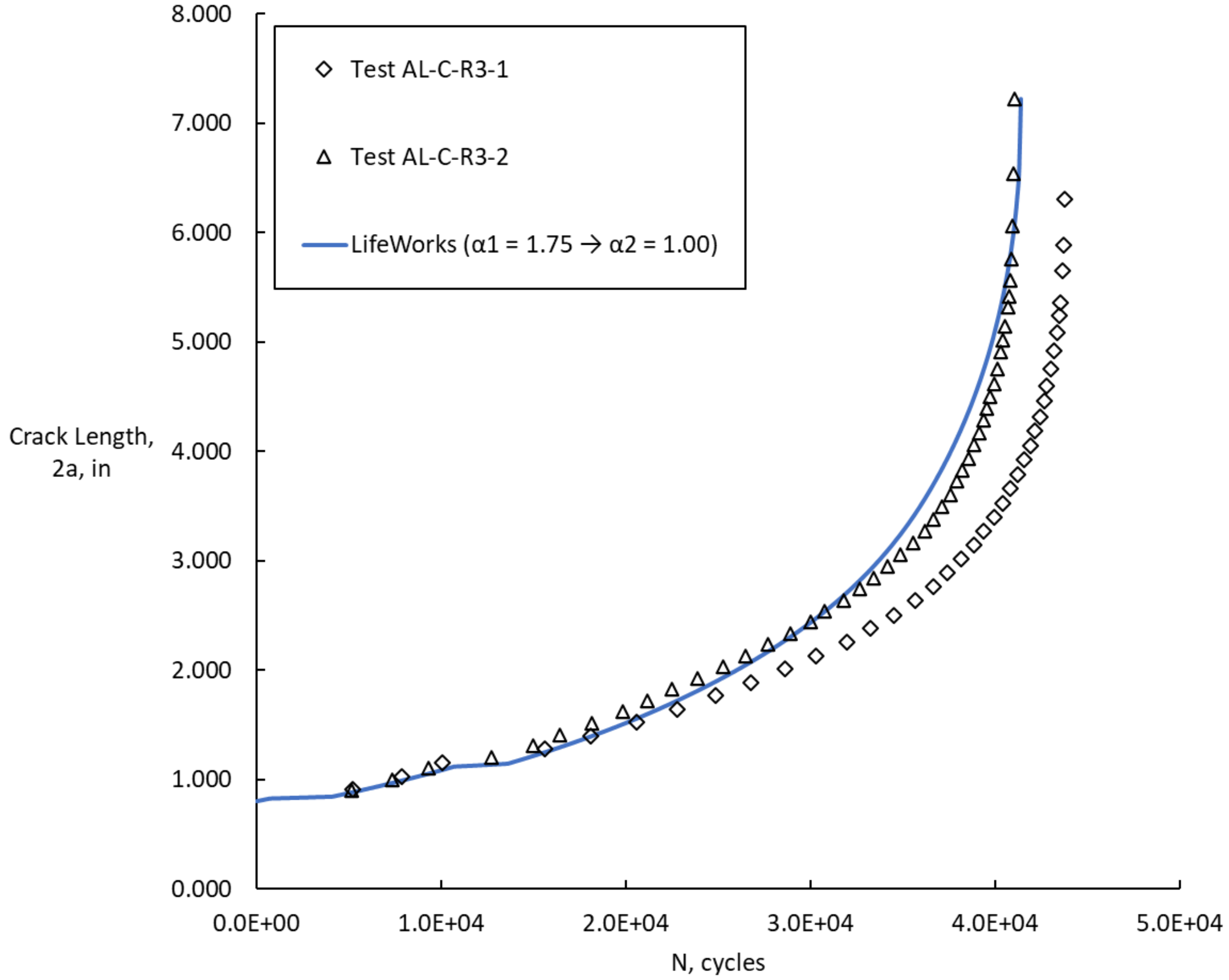
Overloads were applied at two different crack lengths:

$$2a_{OL-1} = 0.84 \text{ inches}$$

$$2a_{OL-2} = 1.2 \text{ inches}$$

ENGINEERED RESIDUAL STRESS IMPLEMENTATION

7075-T6 Spike Overload (Boeing, Task C)



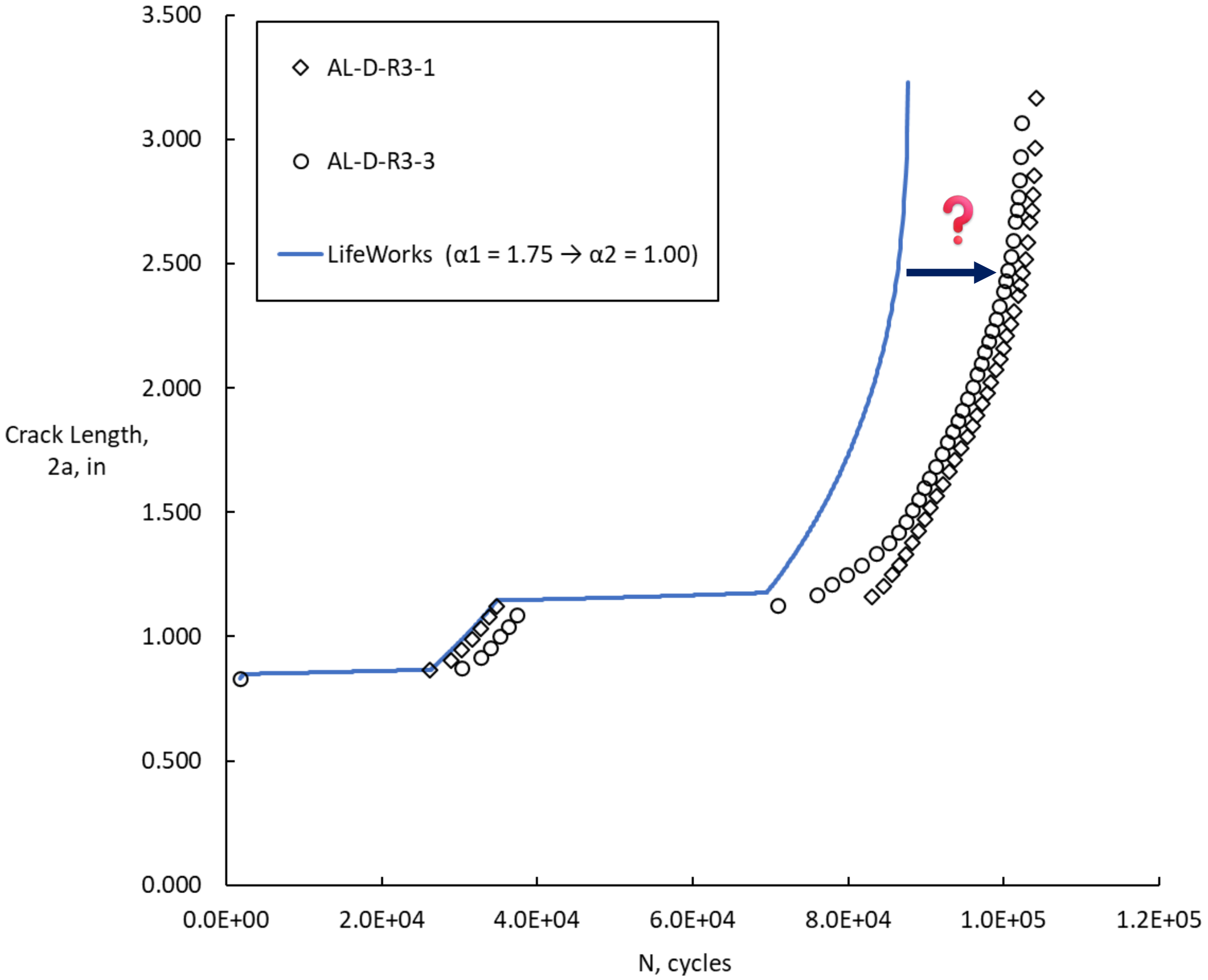
Specimen	M(T)
W	10"
B	0.09"
L	26"
Notch total length	0.7”
Grain Direction	L-T
Loading Type	Constant Amplitude with OL = 1.8·Pmax
Pmax	9.9 kips
Stress Ratio	0.01

Overloads were applied at two different crack lengths:

$$2a_{OL-1} = 0.84 \text{ inches}$$

$$2a_{OL-2} = 1.2 \text{ inches}$$

7075-T6 Spike Overload (Boeing, Task D)



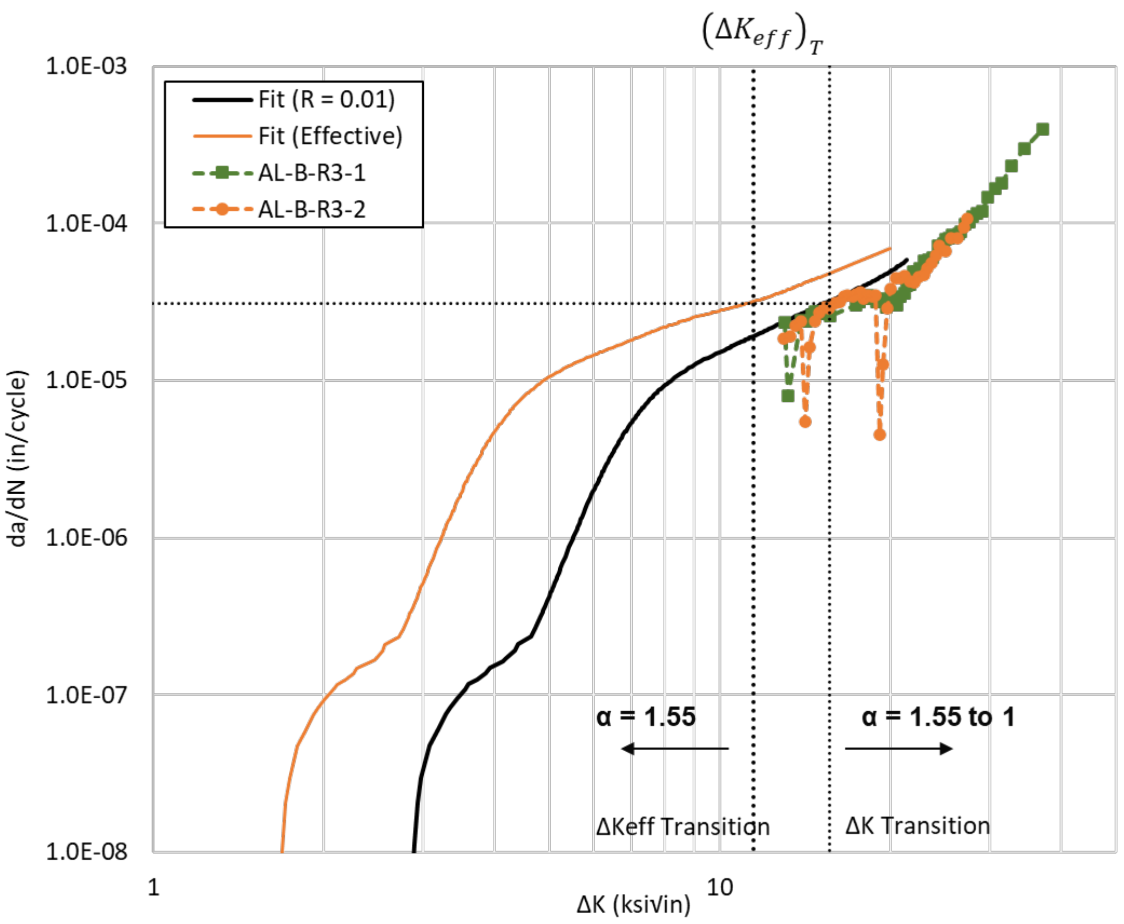
Specimen	M(T)
W	3.95"
B	0.19"
L	17.5"
Notch total length	0.7"
Grain Direction	L-T
Loading Type	Constant Amplitude with OL = 1.8·Pmax
Pmax	6.75 kips
Stress Ratio	0.01

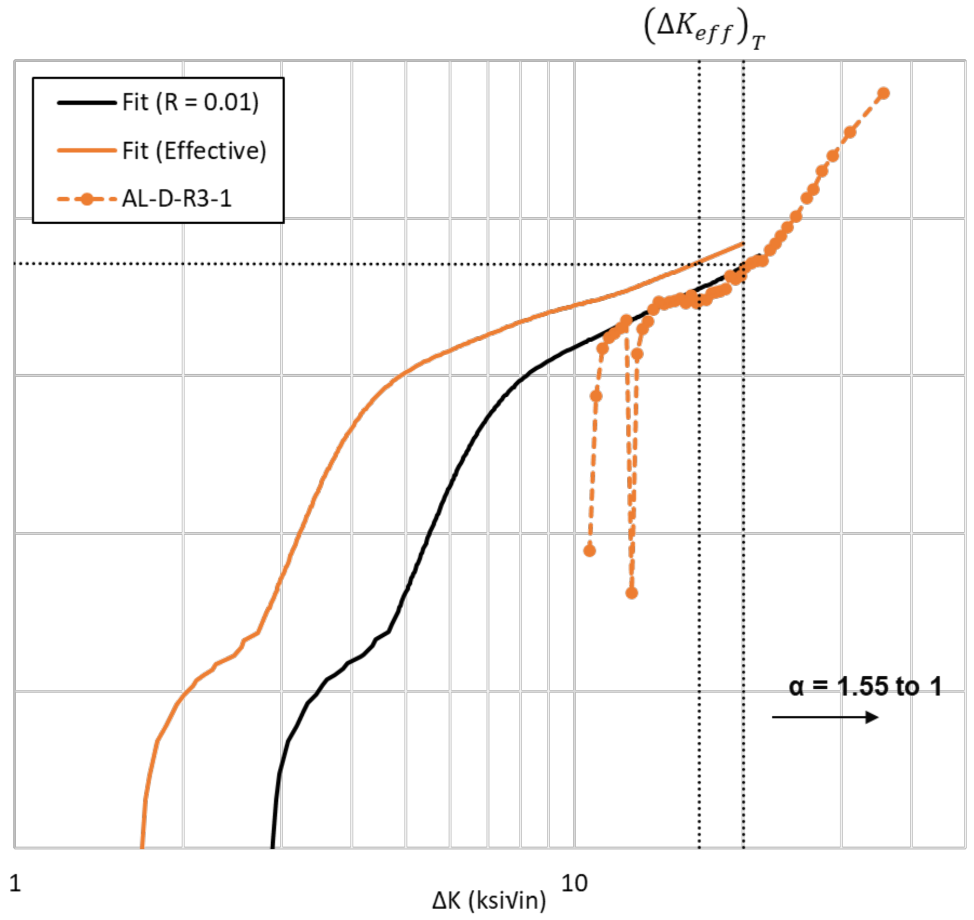
Overloads were applied at two different crack lengths:

$$2a_{OL-1} = 0.84 \text{ inches}$$

$$2a_{OL-2} = 1.2 \text{ inches}$$

Task B vs. Task D

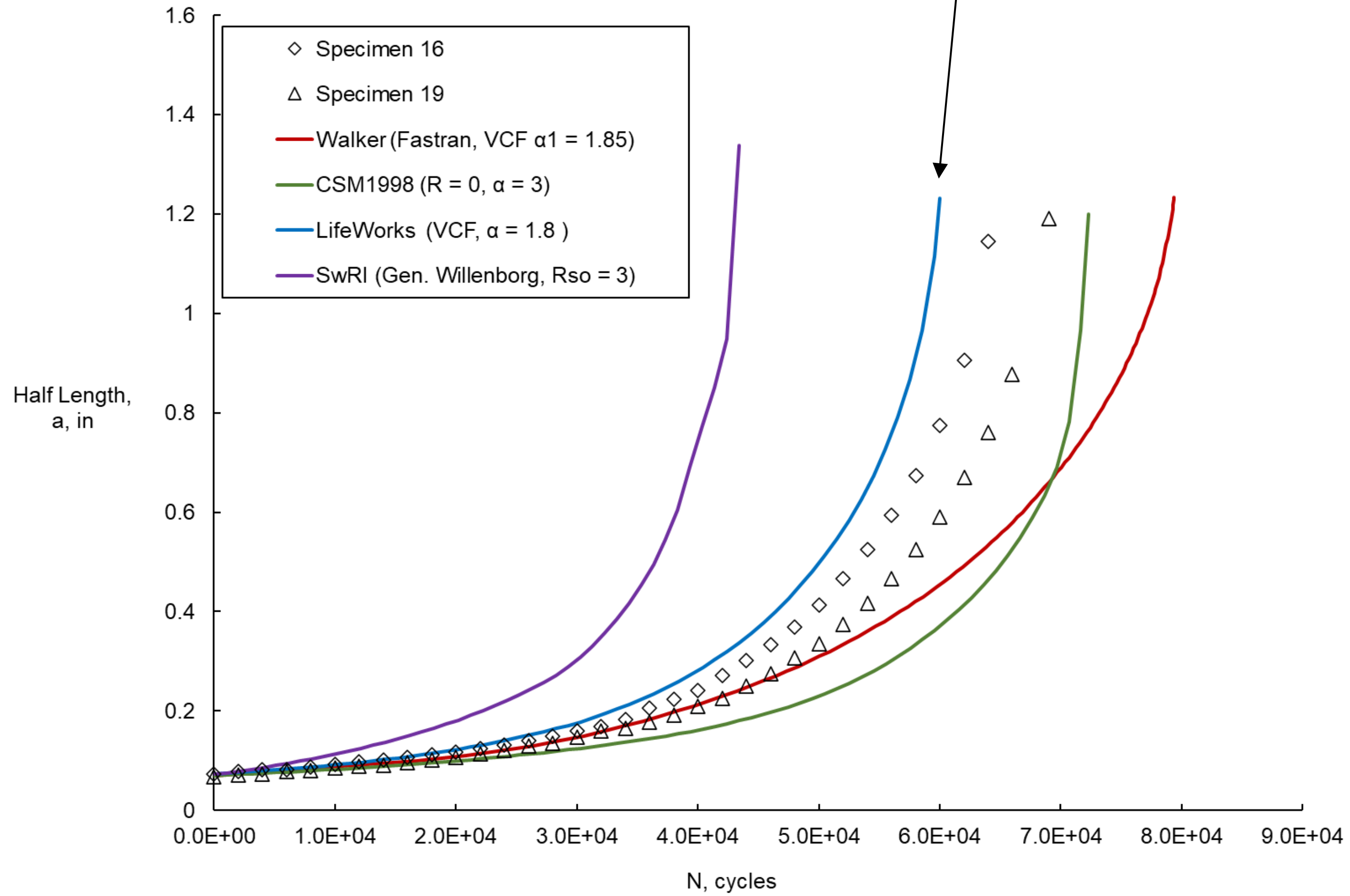




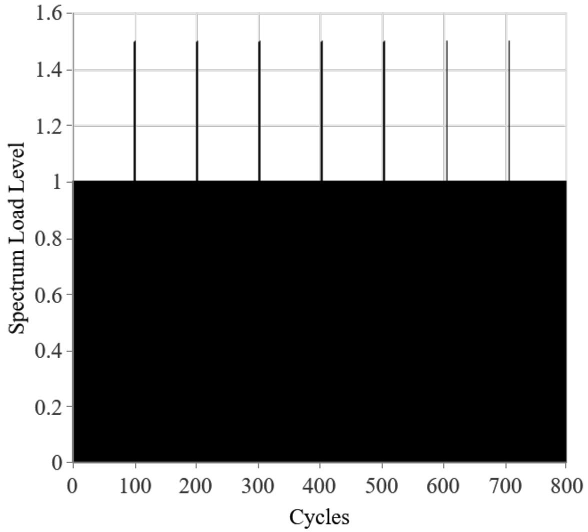
Is $(\Delta K_{eff})_T$ too high? Is plastic zone too small? Is constraint modeling appropriate for this "thicker" geometry?

7075-T651 Boeing RR Effort (Task A)

Corrected to use 7075-**T7351** FCGR Data



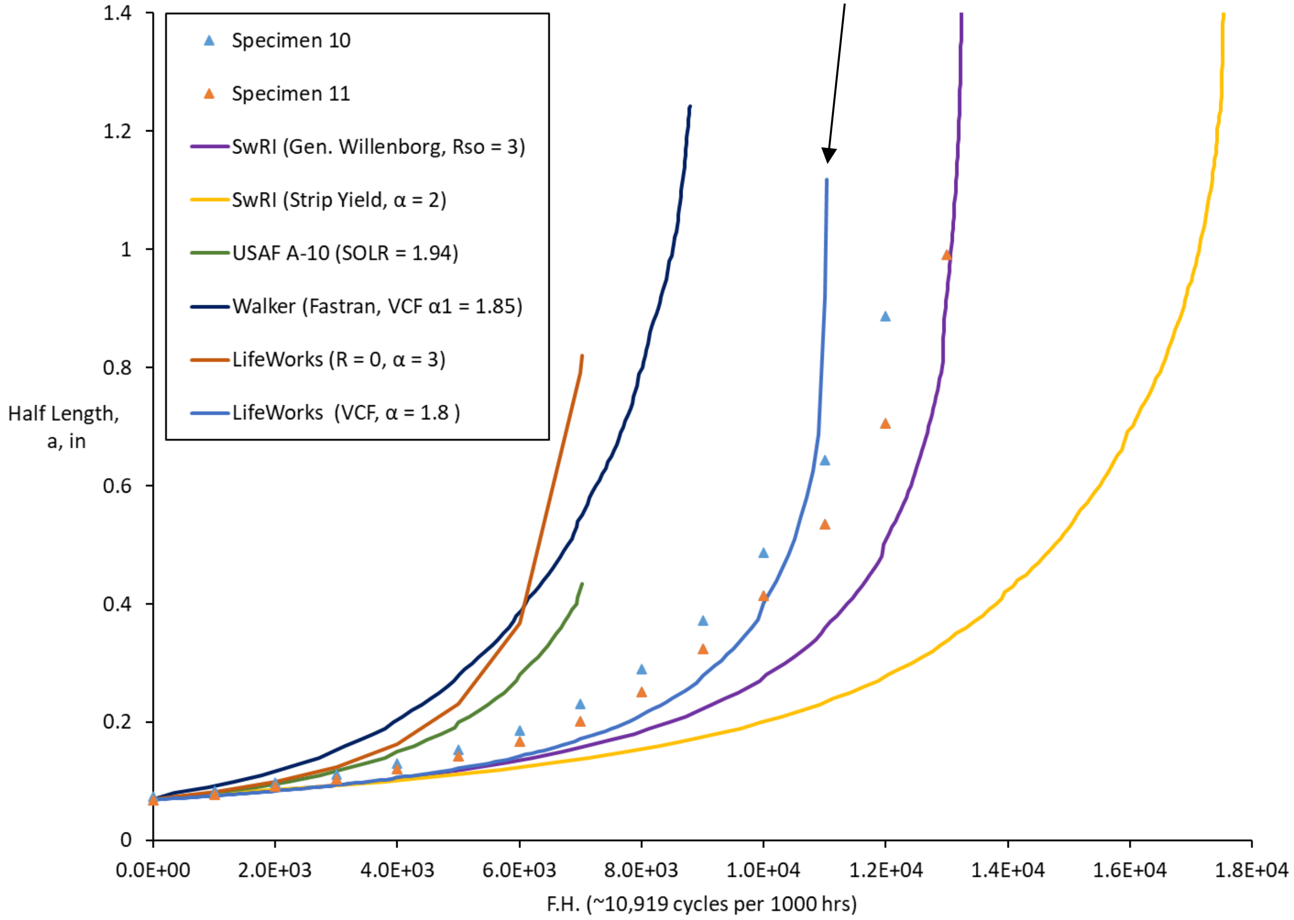
Specimen	M(T)
W	3.95"
B	0.246"
L	16"
Notch total length	0.14”
Grain Direction	L-T
Loading Type	Constant Amplitude with OL = 1.5·Pmax
Pmax	14.7 kips
Stress Ratio	0.01



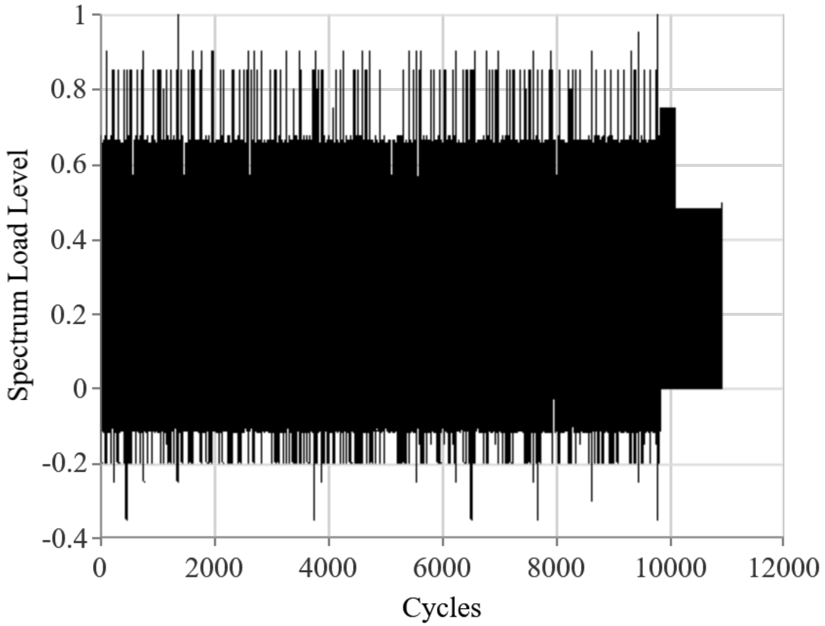
Predictions were misleading because test report incorrectly stated that the material used was 7075-**T7651**

7075-T7351 Boeing RR Effort (Task B)

Corrected to use 7075-**T7351** FCGR Data



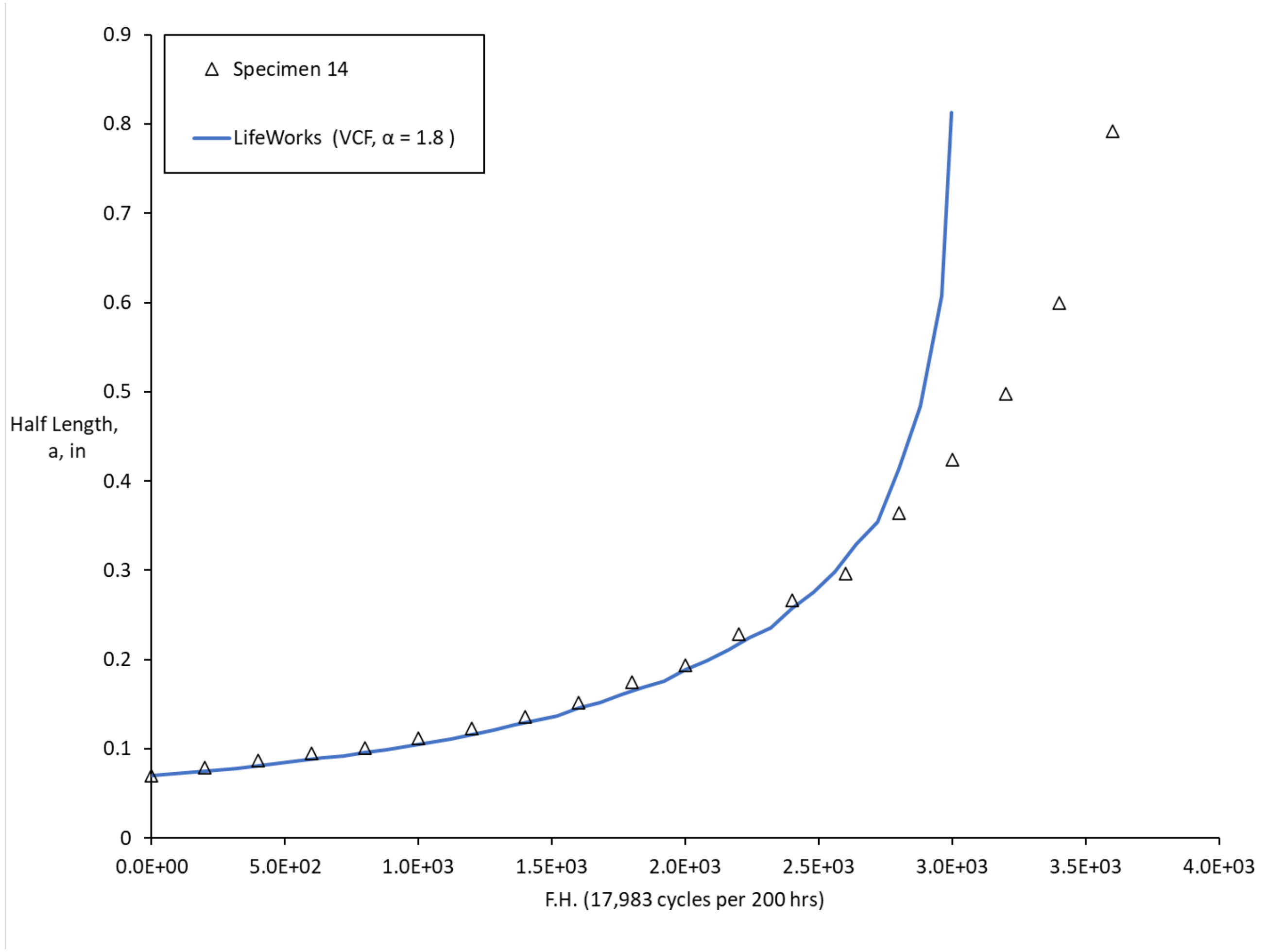
Specimen	Thickness (in)	Width (in)	Stress Level (ksi)	Test Type
M(T)	0.246	3.960	25.0	Lower Wing



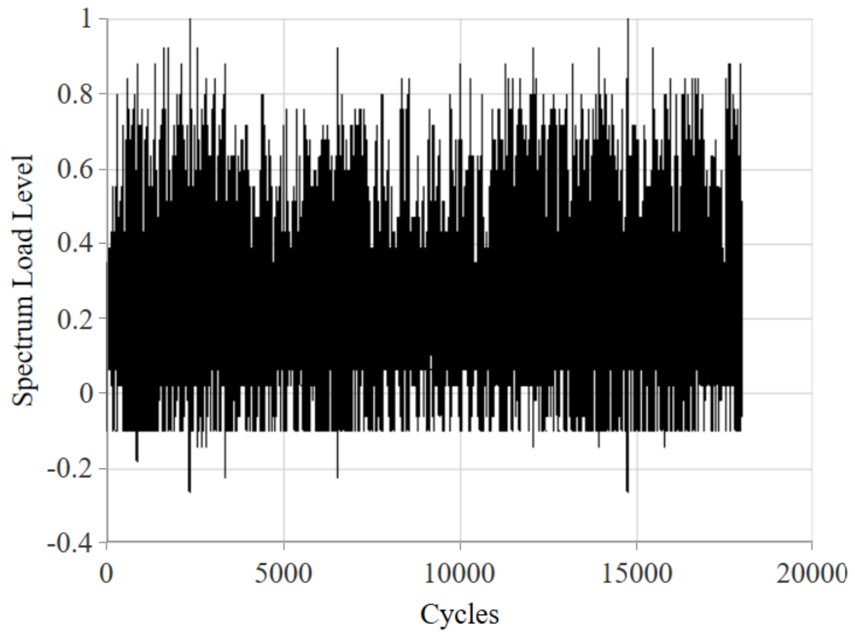
Predictions were misleading because test report incorrectly stated that the material used was 7075-**T7651**

ENGINEERED RESIDUAL STRESS IMPLEMENTATION

7075-T7351 Boeing RR Effort (Task C)

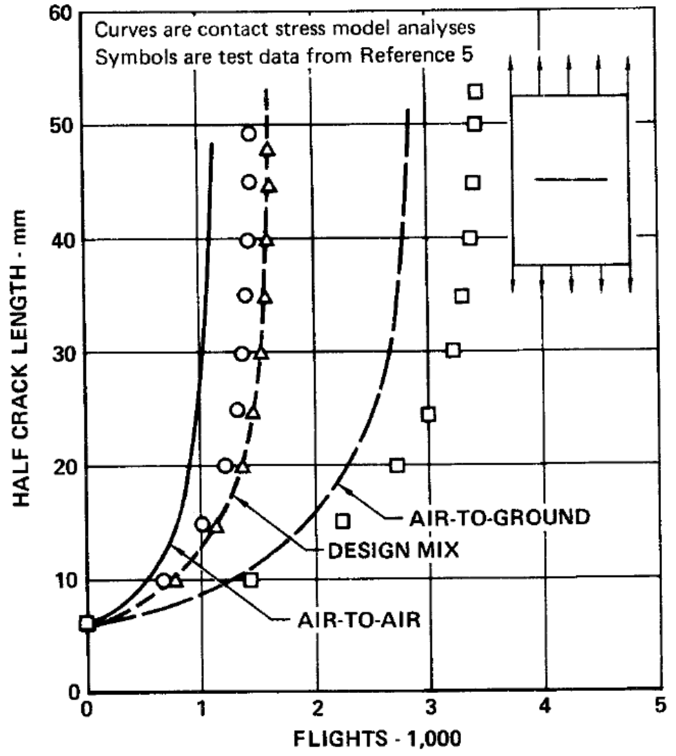


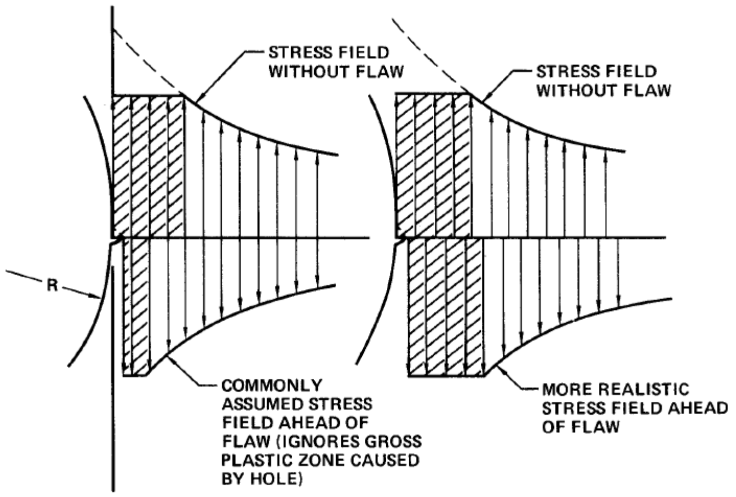
Specimen	Thickness (in)	Width (in)	Stress Level (ksi)	Test Type
M(T)	0.246	3.953	35.0	FALSTAFF



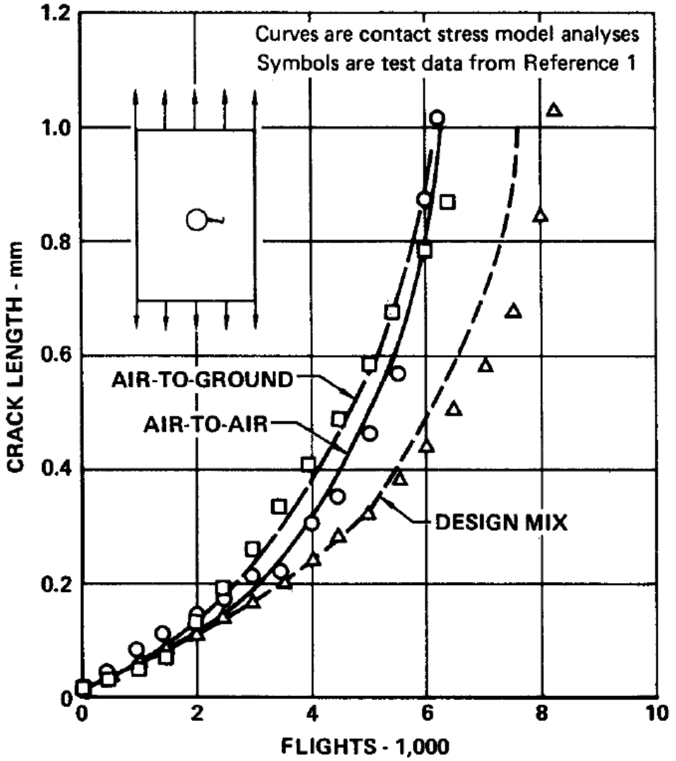
Spectrum Loading Effects on Cracks Growing from Fastener Holes

Historical Efforts





The challenge is to understand the interaction of crack tip plasticity and hole notch plasticity.



Saff, C.R., *Crack Growth Retardation and Acceleration Models*, in ASTM Forum on Damage Tolerance Analysis. 1981: Los Angeles California USA.

Scales of Plasticity

Small Scale

Tensile overloads and compressive underloads can affect (e.g. retard, accelerate, arrest) crack growth rate

Load interaction models try to account for crack growth rate changes due to load sequencing effects.

Large Scale

Extreme loads observed on aircraft components often lead to local yielding at stress concentrations

Cyclic shakedown models try to account for the impact subsequent loads have on stress field

Fatigue Life Prediction

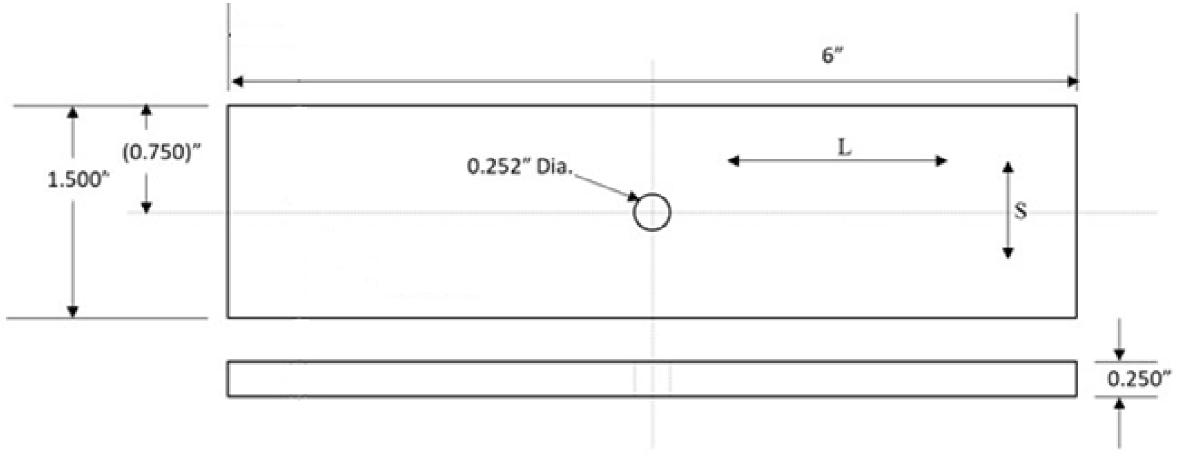
- SIF Calculations and Geometrical Factors
- **Load interaction models**
- **Plastic Constraint Effects in FCG**
- Large Crack Growth
- Small Crack Growth

Fatigue Life Enhancement

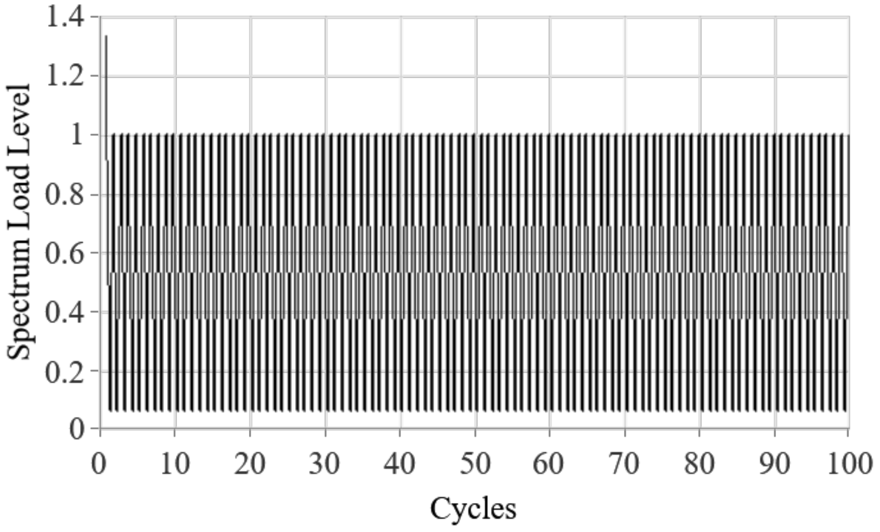
- Direct (e.g.; Cold Work, IFF)
- **Indirect (e.g. Local Plasticity)**

Ti-6Al-4V Boeing IRAD Shakedown Test

- Alloy: Ti-6Al-4V RA Forging
- Grain Direction: L-S
- Yield Strength: 131 ksi
- Max Stress: 28 ksi (L1), 42.1 ksi (L2), 56.1 (L3)
- Constant amplitude loading (R = 0.06) with 1.33 overload at the beginning of the test



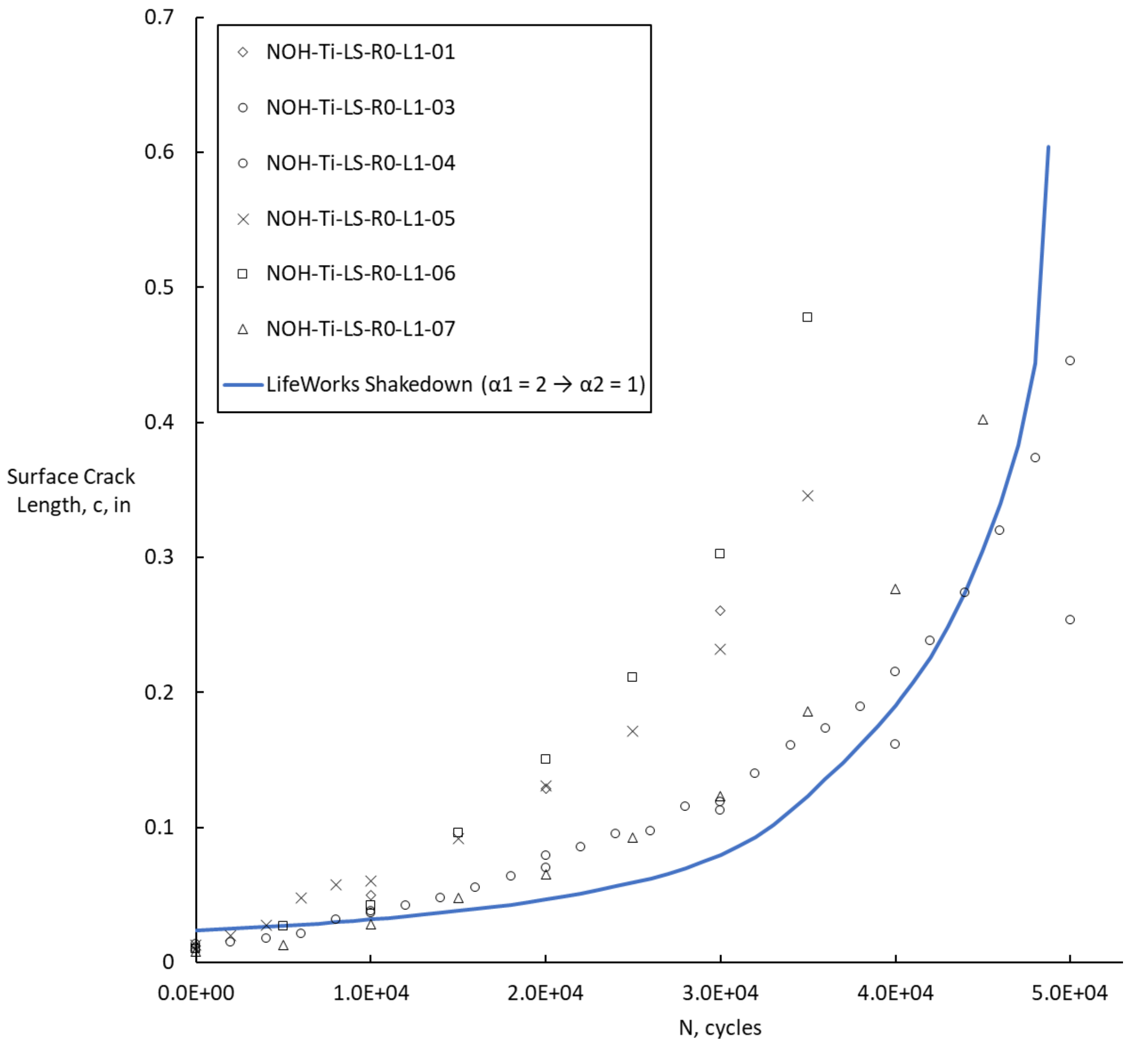
Open Hole Specimen



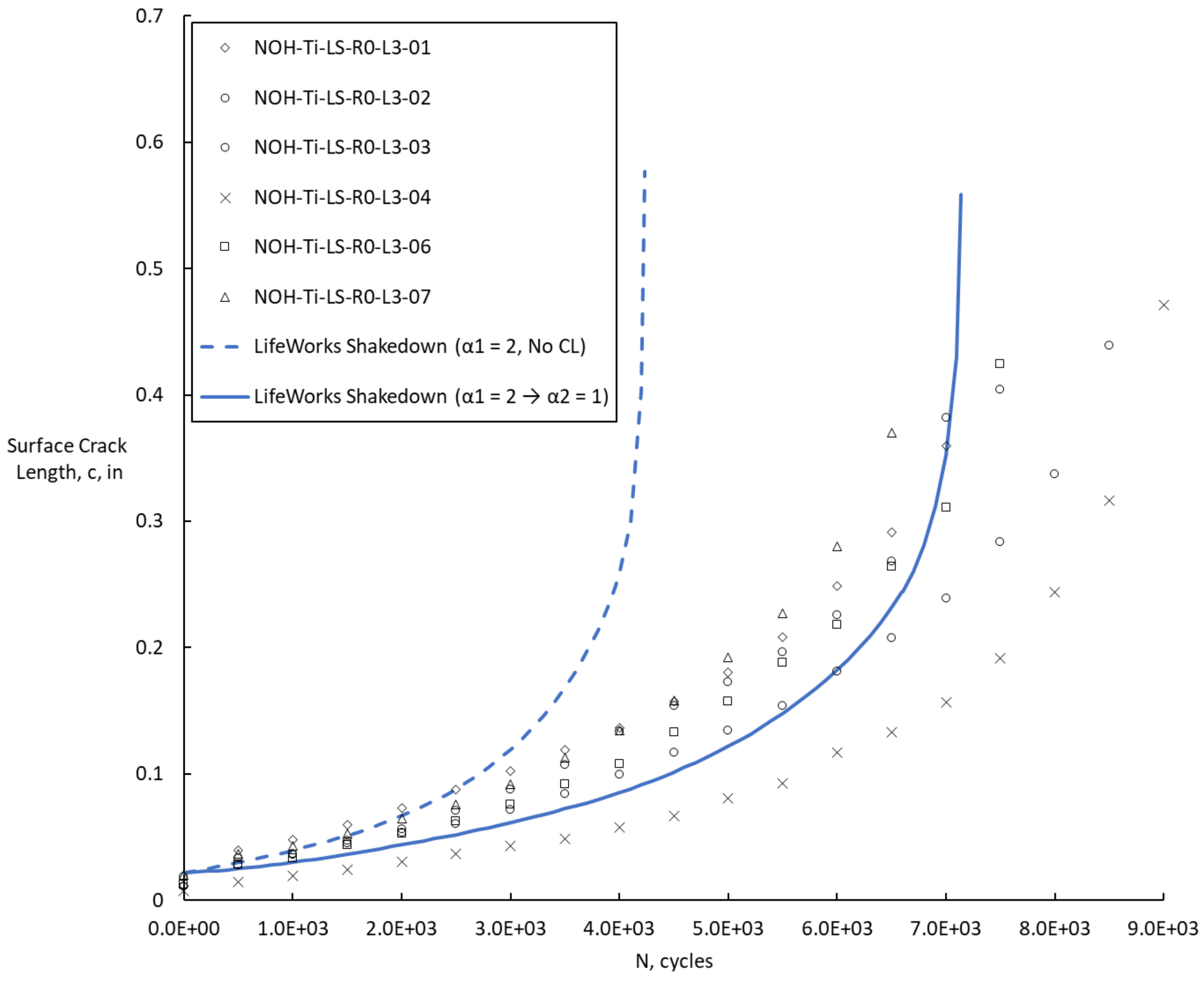
Test Spectrum

Ti-6Al-4V Hole Shakedown Correlation

Max Stress = 28 ksi

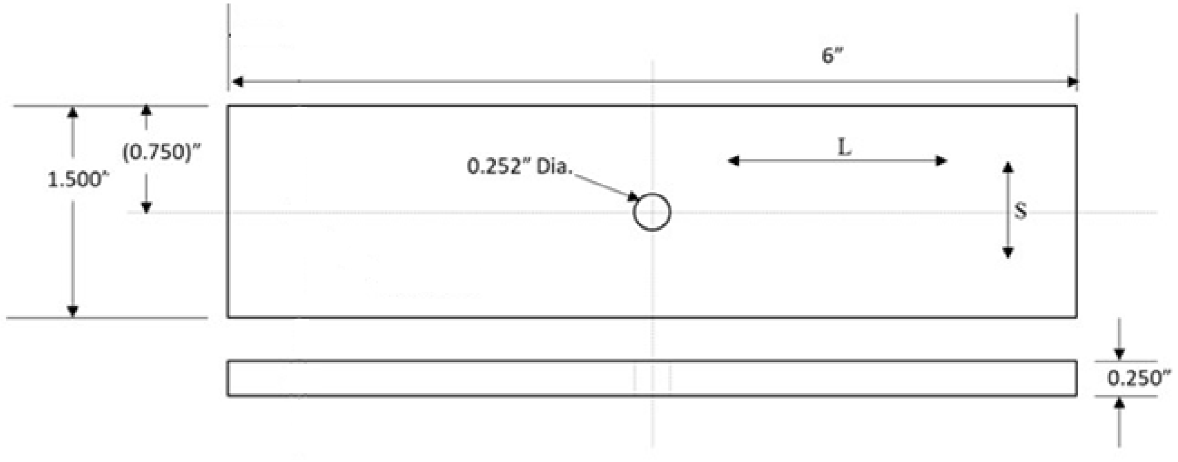


Max Stress = 56.1 ksi

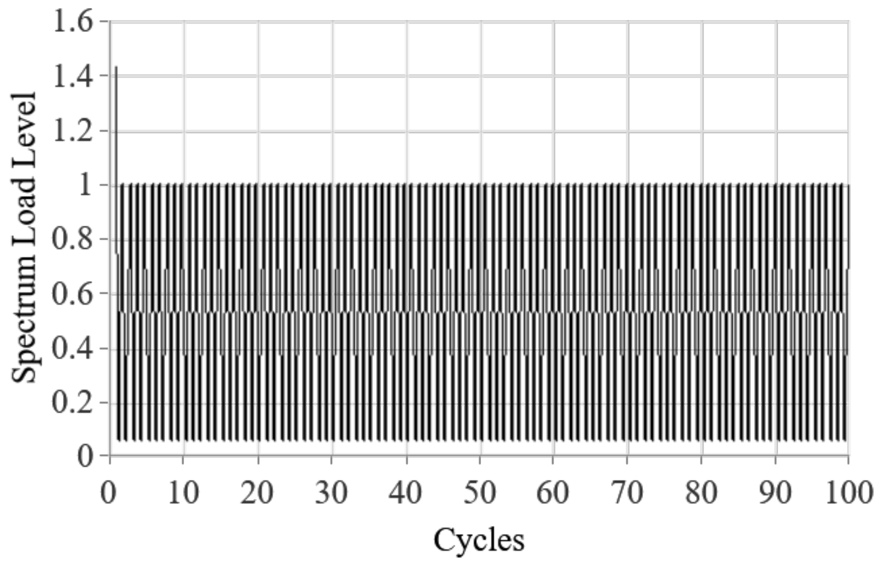


PH13-8Mo Boeing IRAD Shakedown Test

- Alloy / Condition: PH13-8Mo H1000 Bar
- Grain Direction: L-S
- Yield Strength: 229 ksi
- Max Stress: 46.7 ksi (L1), 70.1 ksi (L2), 83.6 (L3)
- Constant amplitude loading (R = 0.06) with 1.43 overload at the beginning of the test



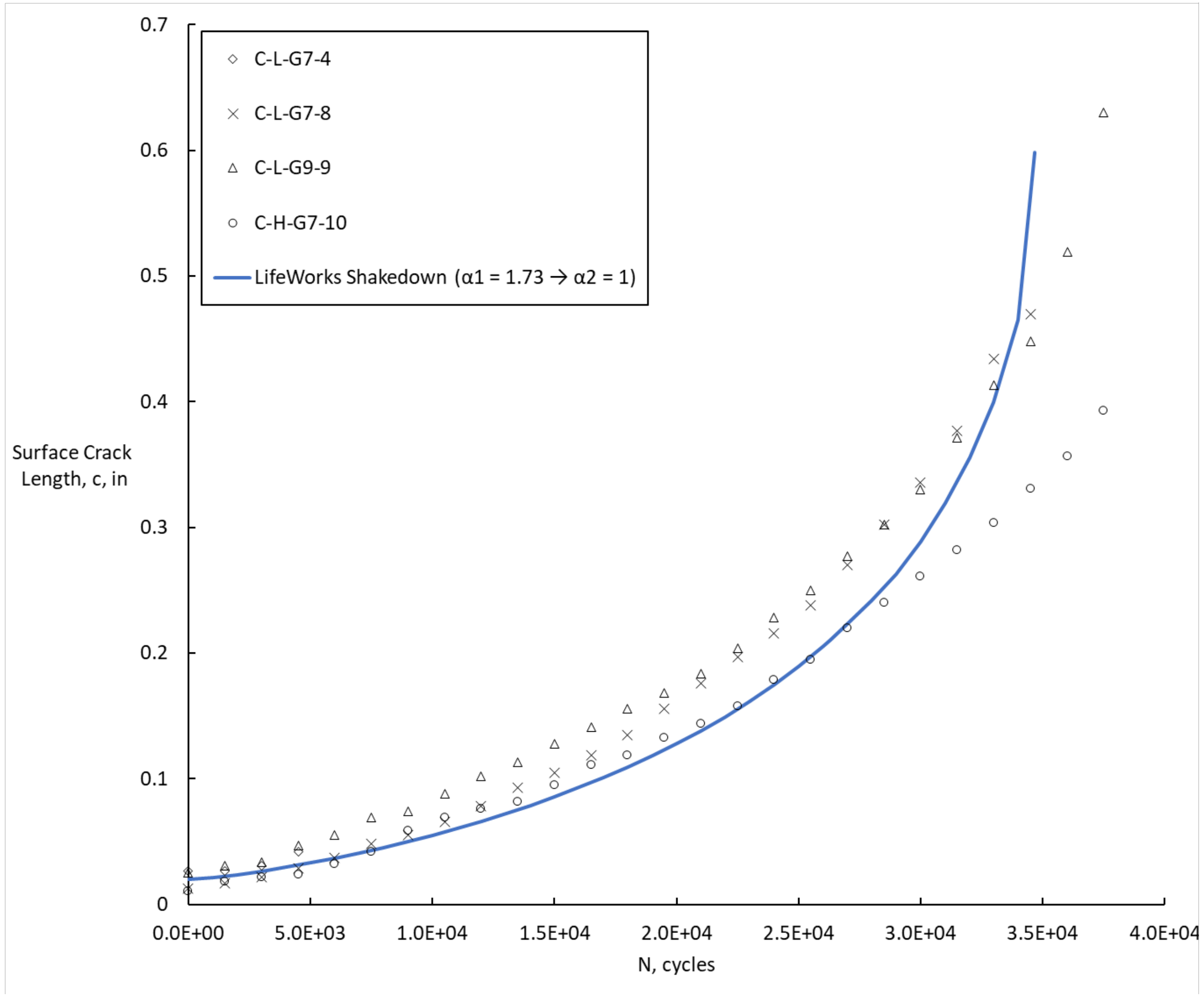
Open Hole Specimen



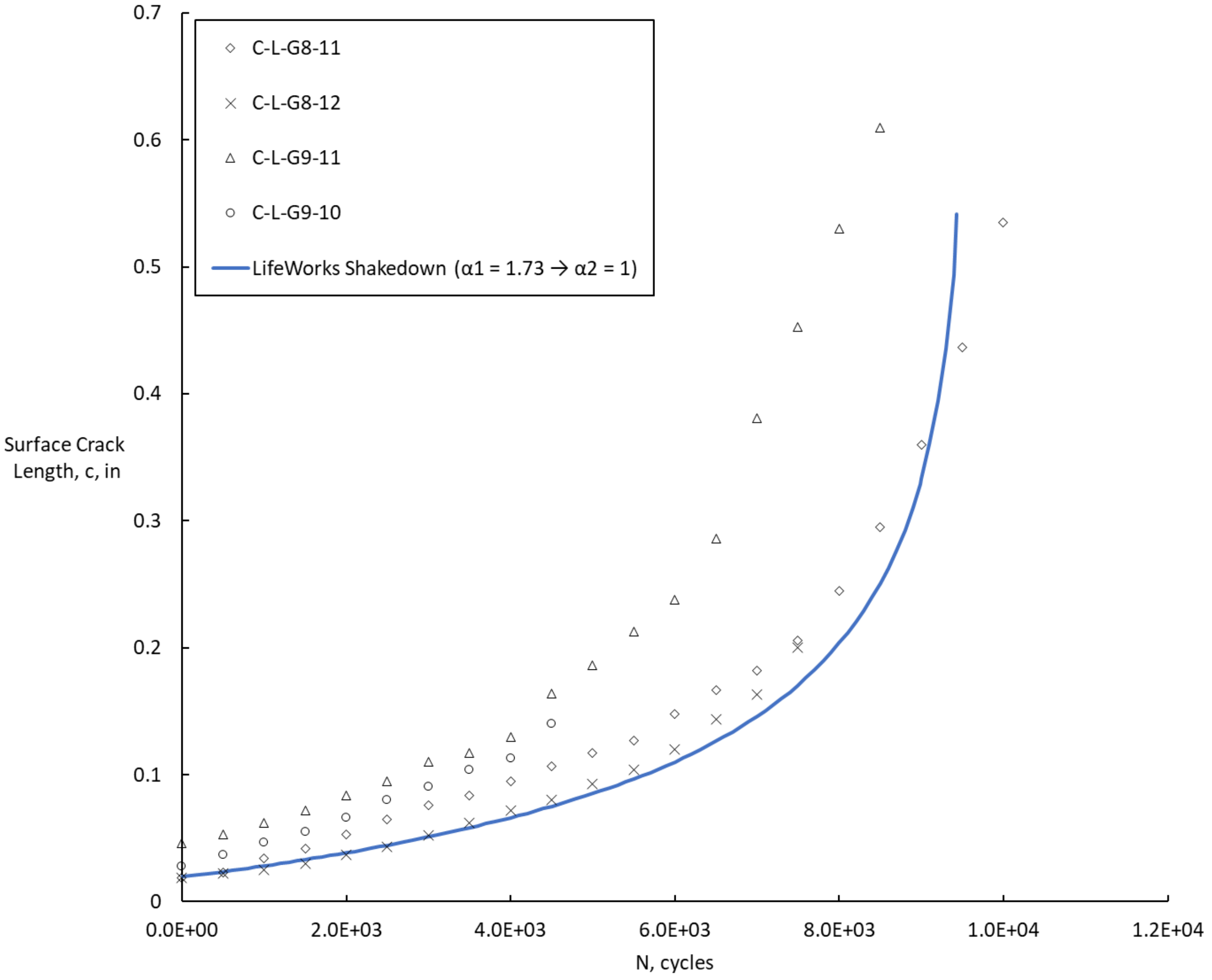
Test Spectrum

PH13-8Mo Hole Shakedown Correlation

Max Stress = 46.7 ksi



Max Stress = 83.6 ksi



Path Forward

Path Forward

- Develop guidelines for considering spectrum loading effects based on lessons learned to date.
- Follow Building Block Approach to link spectrum loading efforts with common ERSI goals.

Geometry	Crack	Spectrum	Residuals	Stress Intensity	Growth Rate	Load Interaction	Plasticity
Middle Tension (MT)	Thru	CA	N/A				
		CA + OL	N/A				
		VA	N/A				
Hole in Plate	Corner	CA	N/A				
		CA + OL	Shakedown				
		VA	Shakedown				
		CA	Cx + Shakedown				
		CA + OL	Cx + Shakedown				
		VA	Cx + Shakedown				
		CA	IFF				
		CA + OL	IFF				
		VA	IFF				

Data Available and Correlation Effort Started

Testing and/or Historical Test Data Evaluation Started

Data Available from other ERSI Related Efforts

Data Not Available or Identified

Testing & Analysis of Interference Fit Fasteners

An A-10 ASIP & ERSI Joint Effort

2025 ERSI Workshop

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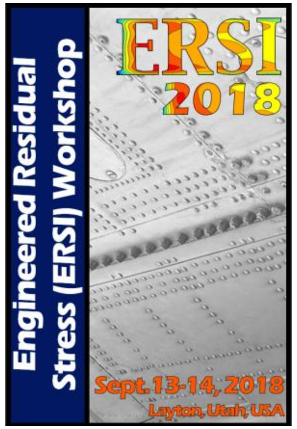
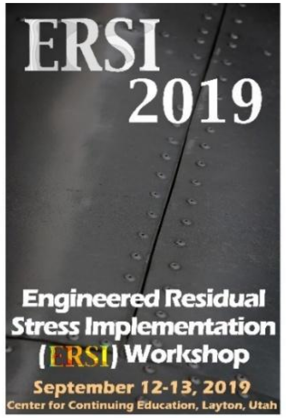
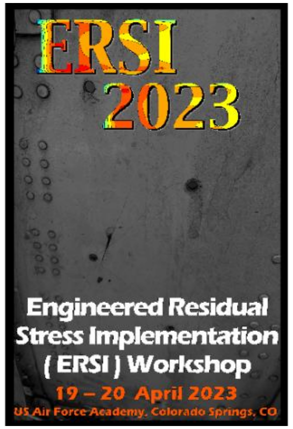
- Thanks for your individual support:
  - A-10 ASIP Team: Jacob Warner, Brian Boeke
  - SwRI: Lucky Smith, Marcus Stanfield, Trenten Wahlen, Michael Worley, Jim Feiger, Paul Clark
  - Hill Engineering: Dallen Andrew

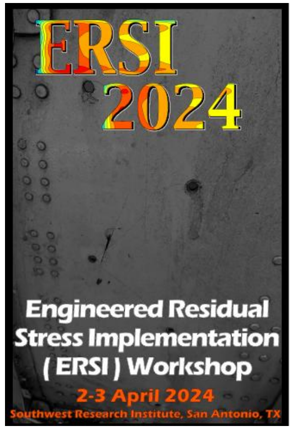
Thanks to the ERSI Working Group for all your hard work!!!

- Round robin participants
  - Renan Ribeiro – Hill Engineering, LLC
  - Yan Bombardier – NRC-Canada
  - Adrian Loghin – Simmetrix Inc
  - Connor Hood – A-10 Program Office
  - Jason Hawks – Boeing
  - Scott Prost-Domasky – APES
  - Zohren Asaee – NRC – Canada
  - David Wieland – SwRI



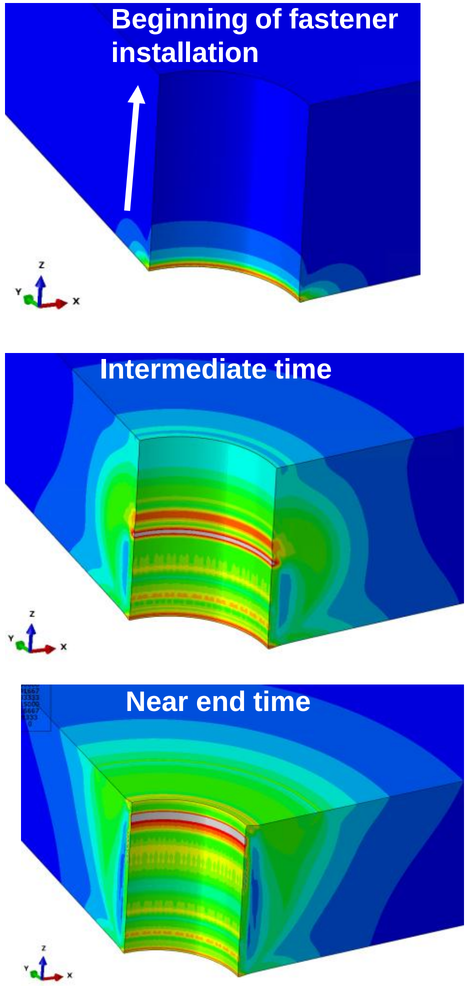






Agenda

- A-10 interference fit fastener testing
- ERSI round robin predictions
  - Objectives and approach
  - Results and comparisons
- A-10 test results
  - Findings and comparisons
- Next steps
- Conclusions



A-10 IFF Testing & Analysis Program

- **Overview**
  - Open literature documents fatigue life benefits due to neat fit and IFF, however, there are no well-established and validated methods to account for the benefits
  - A-10 Damage Tolerance Analyses (DTAs) currently do not include any such benefit
- **Objective**
  - Develop an empirically validated analytical methodology to quantify the damage tolerance impacts of applicable A-10 fastener installations with neat or interference fits
- **Phased Approach**
  - Phase 1: assessment of as-installed state
  - Phase 2: fastener installed + remote loading
  - Phase 3: analytical methodology to account for IFF during crack growth
  - Phase 4: fatigue crack growth testing with IFF

A-10 IFF Testing & Analysis Program

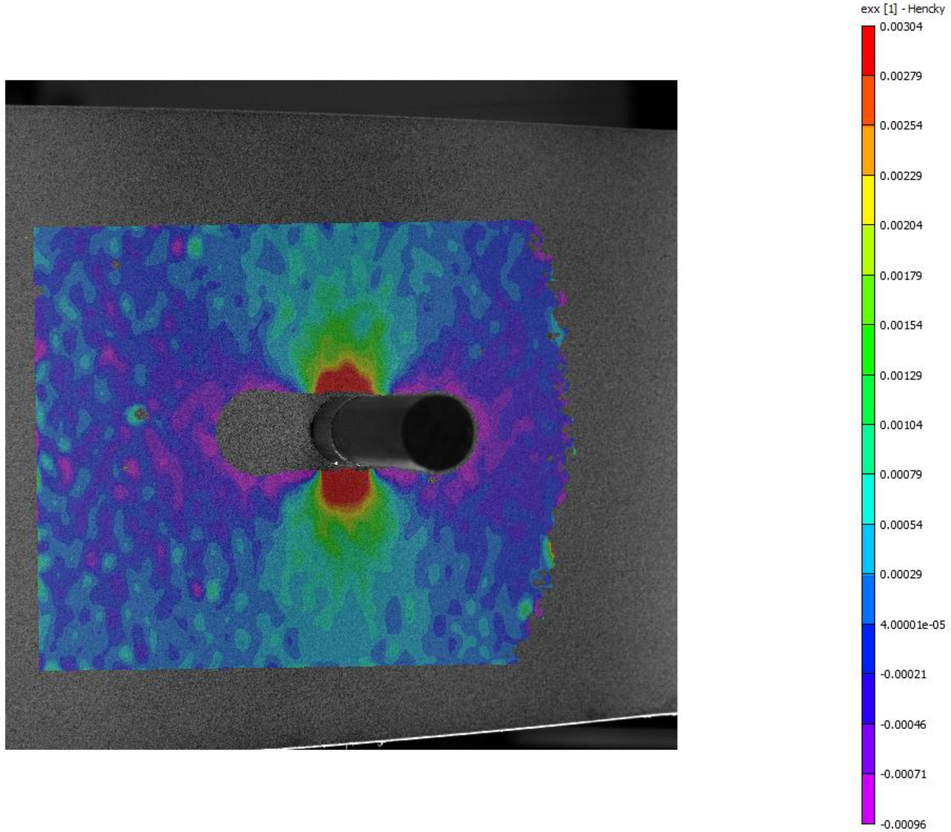
Coupon Details:	Strain Monitoring:
• Coupon Material: 2024-T351 plate • Pin Material: 52100 steel pin • Thickness: 0.25 inch • Hole Diameter: 0.25 inch	• Digital Image Correlation (all specimens) • Strain Gage (initial specimen)
Interference Conditions:	**Fastener Details:**
• Open Hole • Neat Fit • 0.3% Interference • 0.6% Interference • 1.2% Interference	• Precisely Controlled Gauge Pins • Ground Transition Geometry to Represent Hi-Lok • Cetyl Alcohol Lubricant
Stress Levels:	**Data Capture:**

• Static (Phase 2):
  • -30, -10, 0, 10, 20, and 30 ksi
• Fatigue (Phase 4):
  • CA: Smax = TBD, R = TBD
  • VA: TBD
	• Geometric measurements of fastener and hole before/after installation/loading
	  • Capture applied/retained interference
	• Surface strains at fastener install, load, unload, and removal steps
	• Transition point for fastener gapping

Very close attention to small details

A-10 IFF Testing & Analysis Program

- Example DIC setup & results



ERSI IFF Round Robin – Implementation Plan

- **Objective**
  - Collaborate to establish validated analytical methods for IFF applications
  - Utilizing a phased approach, evaluate the influence of IFF on the stress state, stress intensity factors, and crack growth life of critical fastener holes
  - Evaluate differences between working group members' process simulation techniques against carefully planned and executed physical test
  - Improve understanding and validate influence of key factors on IFF performance
- **Phased approach to match A-10 efforts**
  - Phase I: Baseline Stress Analysis Verification
  - Phase II: Stress Intensity Factor Comparisons
  - Phase III: Crack Growth Analyses

ERSI IFF Round Robin Conditions

- Data from A-10 summarized and shared with participant
- Three groups of analyses defined with increasing complexity
  - Group 1: open hole, remote load
  - Group 2: fastener installation, no remote load
  - Group 3: fastener installation + remote load

Table 1. Round-robin analysis conditions, group 1

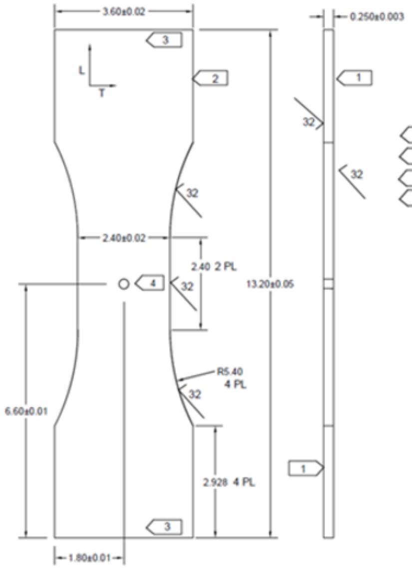
Group	Condition	Sequence Step	Interference Condition	Applied Stress (ksi)
1	1	1 – Apply Remote Stress 2 – Unload	Open Hole	-10, 10, 20, 30

Table 2. Round-robin analysis conditions, group 2

Group	Condition	Sequence Step	Interference Condition	Applied Stress (ksi)
2	1	1 – Installed Fastener 2 – Remove Fastener	0.3% IFF	0
	2		0.6% IFF	
	3		1.2% IFF	

Table 3. Round-robin analysis conditions, group 3

Group	Condition	Sequence Step	Interference Condition	Applied (ksi)
3	1	1 – Installed Fastener 2 – Apply Remote Stress 3- Unload 4 – Remove Fastener	Neat Fit	-10, 10, 20, 30
	2		0.3% IFF	
	3		0.6% IFF	
	4		1.2% IFF	

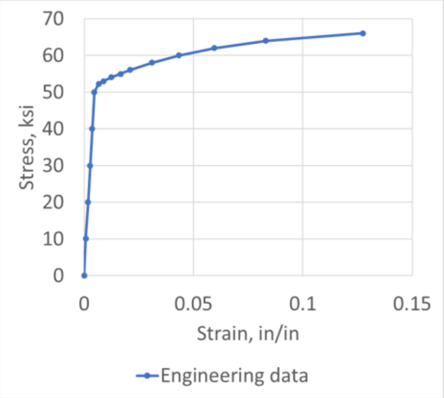


Dimensions in inches unless otherwise noted.

Stock thickness is approximately 0.250 inch. Use as-is.

1. Hand sand with emery cloth in longitudinal direction (each face) to remove mill scale
2. Last 0.020" removal on edges must be done in 0.005" passes.
3. Specimen ID will be engraving in format 7D3-xx-Da-2480, with xx ranging sequentially from 13 to 28
4. Hole preparation (drill & reamer entry face are on Specimen ID side)

Condition	Hole Diameter (in)	Pin Diameter (in)
Open Hole	0.2500	N/A
Neat Fit	0.2500	0.2500
0.3% Interference	0.2500	0.2508
0.6% Interference	0.2500	0.2515
1.2% Interference	0.2500	0.2530

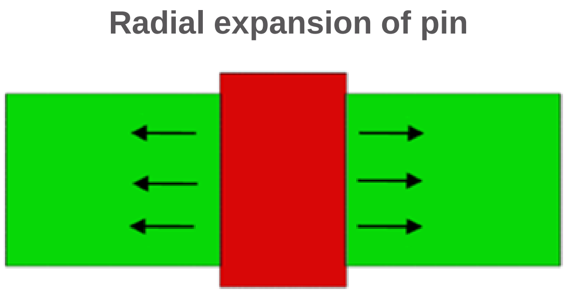
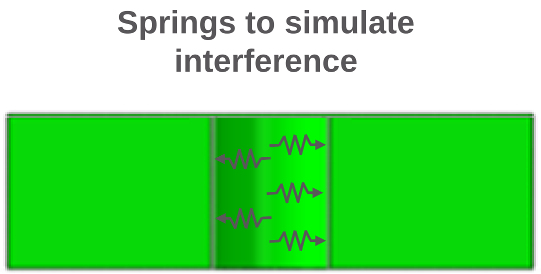
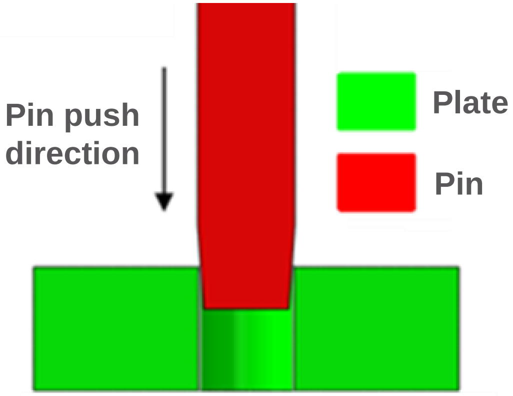


General Material Properties

Property	Coupon	Pin/Plug
Material	2024-T351 plate	4340 Steel
Modulus (ksi)	10,800	29,000
Poisson	0.33	0.29
Ultimate Strength (ksi)	66.7	Model as Elastic
Yield Strength (ksi)	52.2	
Stress-Strain Curve	See note	N/A
Source	A-10 ASIP	N/A

Round Robin Participants

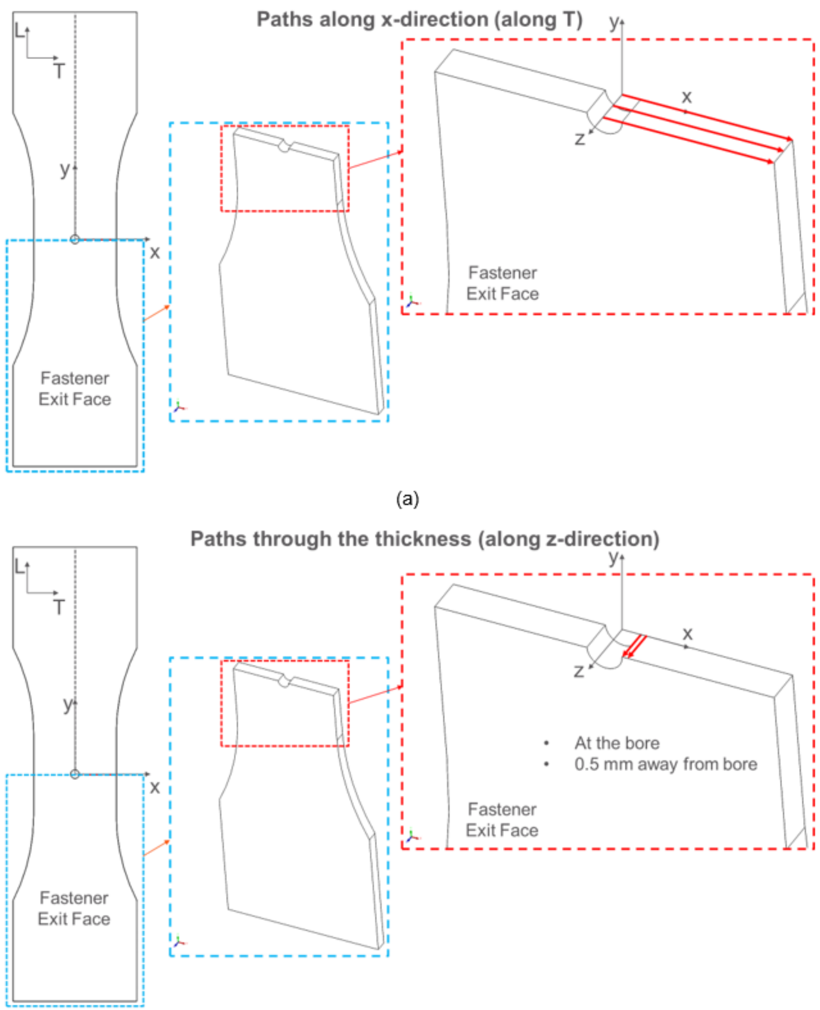
- **Details about participants**
  - From 8 different organizations
  - Five different software packages
    - Abaqus, Ansys, StressCheck, SimCenter 3D, Nx Nastran
  - Several different modeling techniques for fastener installation

Method 1	Method 2	Method 3
Uniform Expansion, then Resolve Interference	Springs to Simulate Interference	Incrementally Push Fastener into Hole, Solve for Equilibrium
3 Submissions	1 Submission	3 Submissions
		

IFF Round Robin - Predictions

- Summary of analysis approaches & data collected

Submission ID	Software	Material behavior (hardening)	IFF modeling	Contact definition
1	Ansys	Isotropic	Uniform expansion	Surface-surface contact Friction (0.3 coeff.)
2	SimCenter 3D	Isotropic	Uniform expansion	Surface-surface frictionless contact
3	StressCheck	Kinematic	None	-
4	Abaqus	Isotropic	Incremental movement of fastener	Surface-surface frictionless contact
5	StressCheck	Kinematic	Normal springs and imposed displacement	No contact (no fastener included)
6	MSC Marc	Combined	Uniform expansion (thermal)	Surface-surface frictionless contact
7	StressCheck	Isotropic	None	-
8	NX Nastran	Isotropic and kinematic	Incremental movement of fastener	Surface-surface Friction (0.459 coeff.)
9	Abaqus	Isotropic	Incremental movement of fastener	Surface-surface frictionless contact

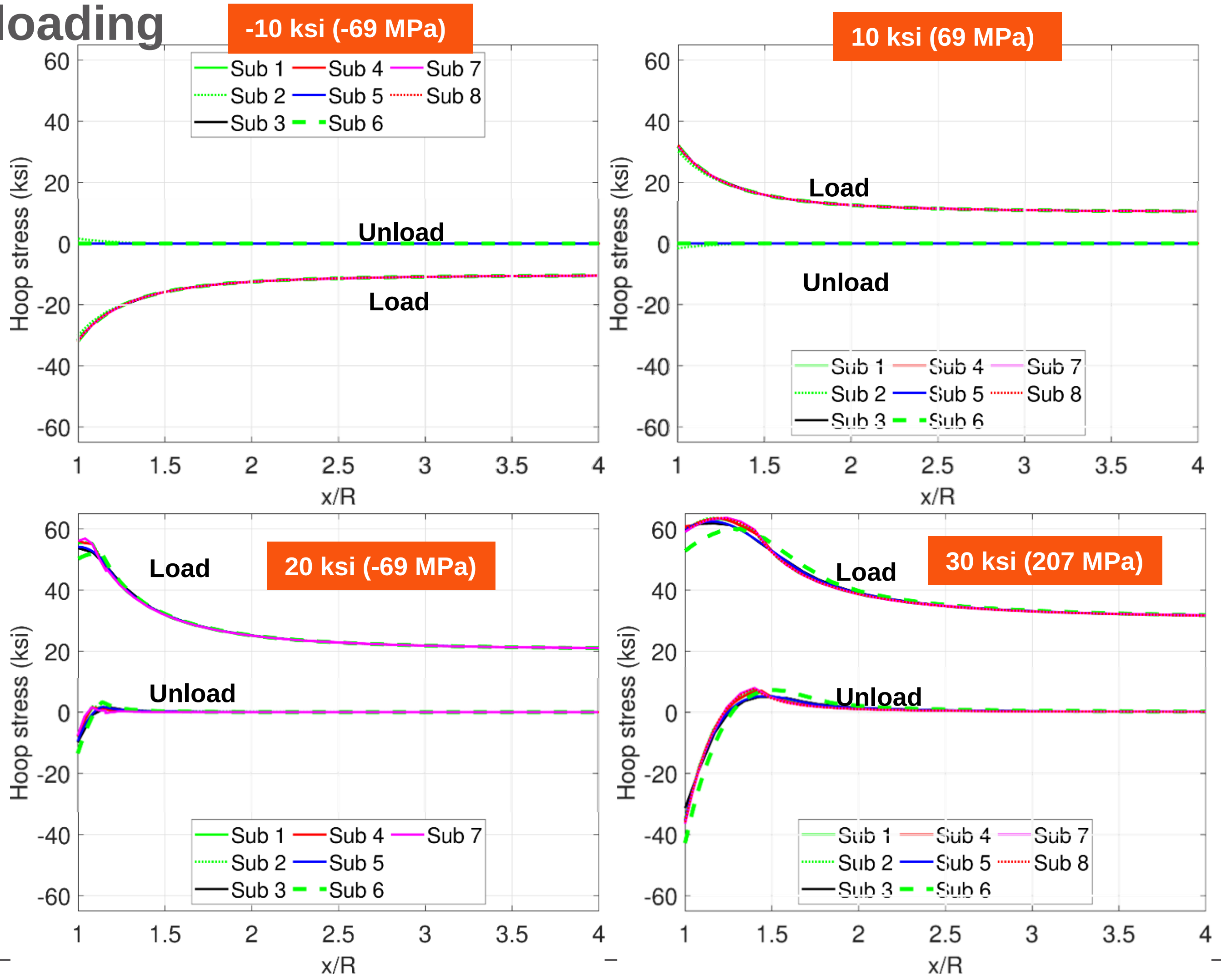


IFF Round Robin - Predictions

- Group 1 – open hole, no fastener, remote loading

Key Takeaways:

- **Consistent predictions across submissions**
  - Plastic onset occurs as expected
    - ~ 33% of Fty
  - Yield zone size
  - ~ 0.25R (20 ksi), 1.00R (30 ksi)



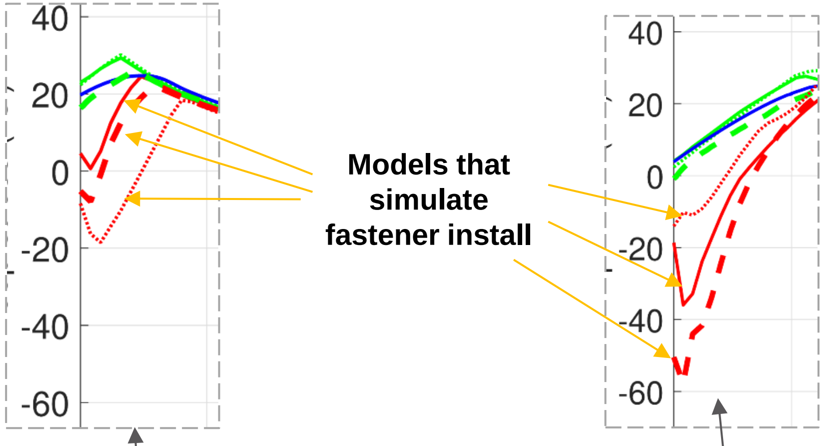
Note: this work has been submitted to the Materials Performance and Characterization journal and approved for publication.

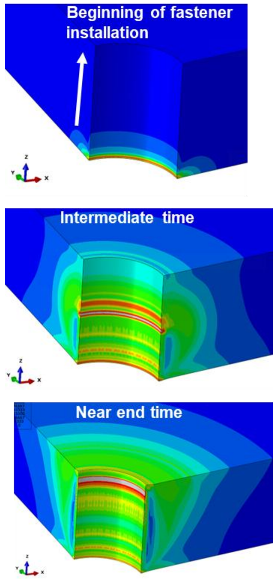
IFF Round Robin - Predictions

- Group 2 – fastener install (no remote loading)

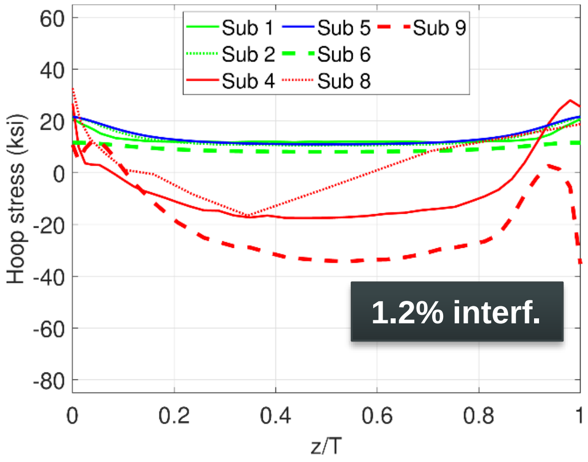
Key Takeaways:

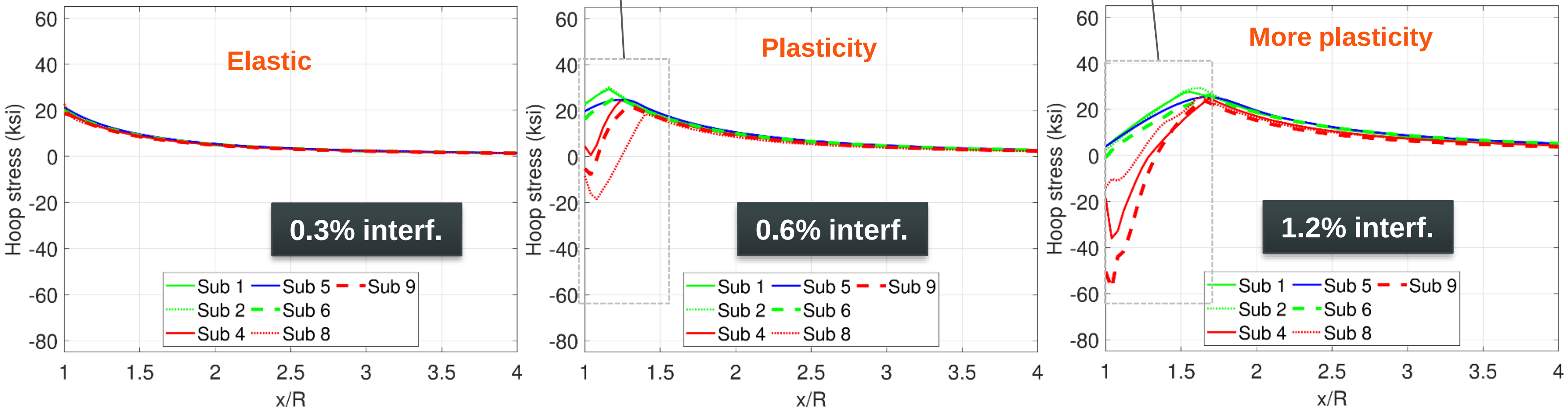
- **Distinct differences based on modeling approaches**
  - Radial expansion and springs give similar results
  - Simulated fastener install results in distinct differences
- **Through thickness behavior differences even more distinct**





Through Thickness at 0.02" from Bore Surface





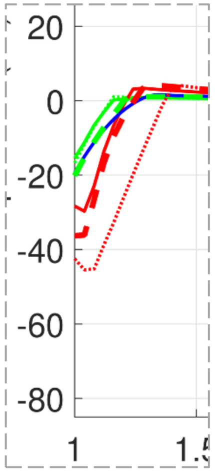
Note: this work has been submitted to the Materials Performance and Characterization journal and approved for publication.

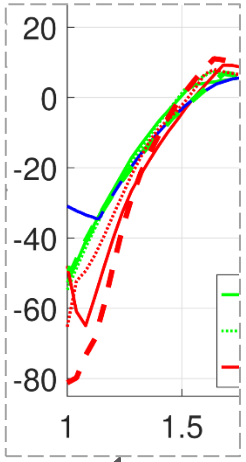
IFF Round Robin - Predictions

- Group 2 – fastener install + uninstall

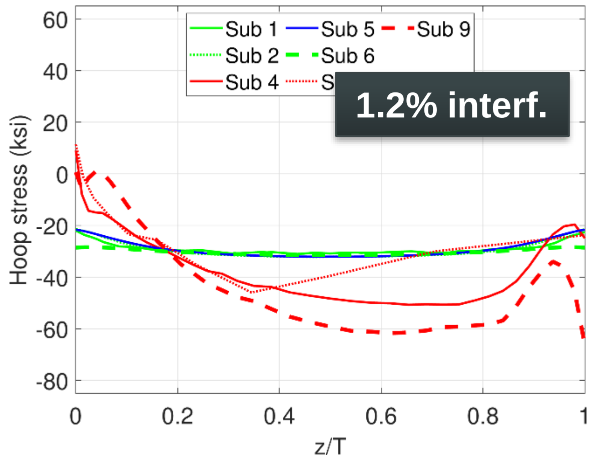
Key Takeaways:

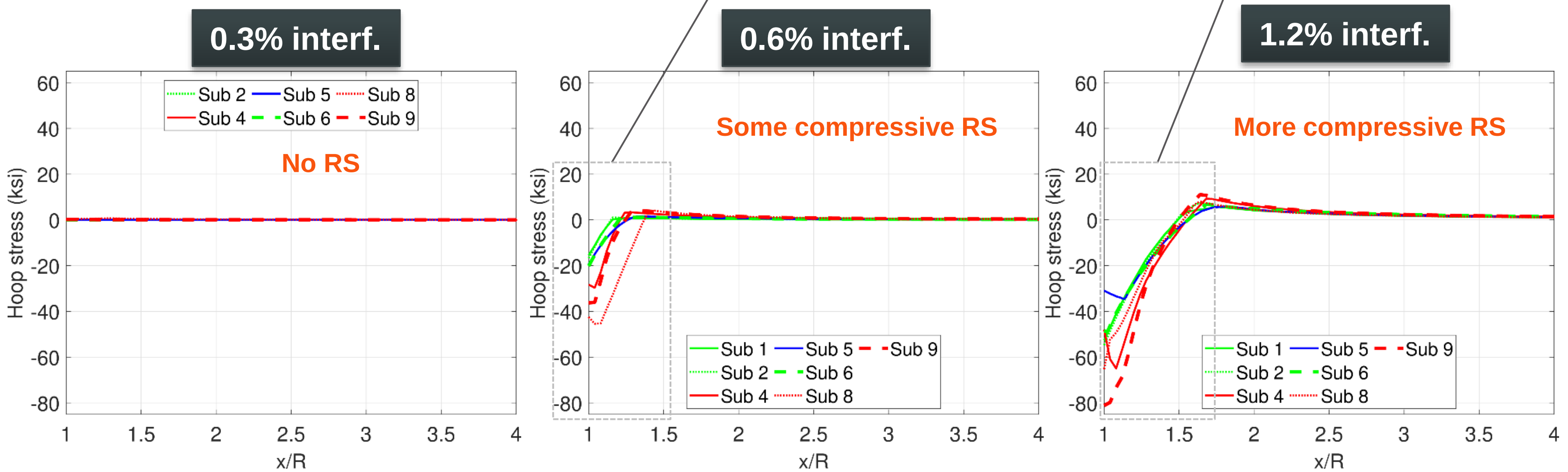
- **Significant residual stress predicted for 0.6% and 1.2% interference**
  - Varying results depending on method





Through Thickness at 0.02" from Bore Surface





ERSI

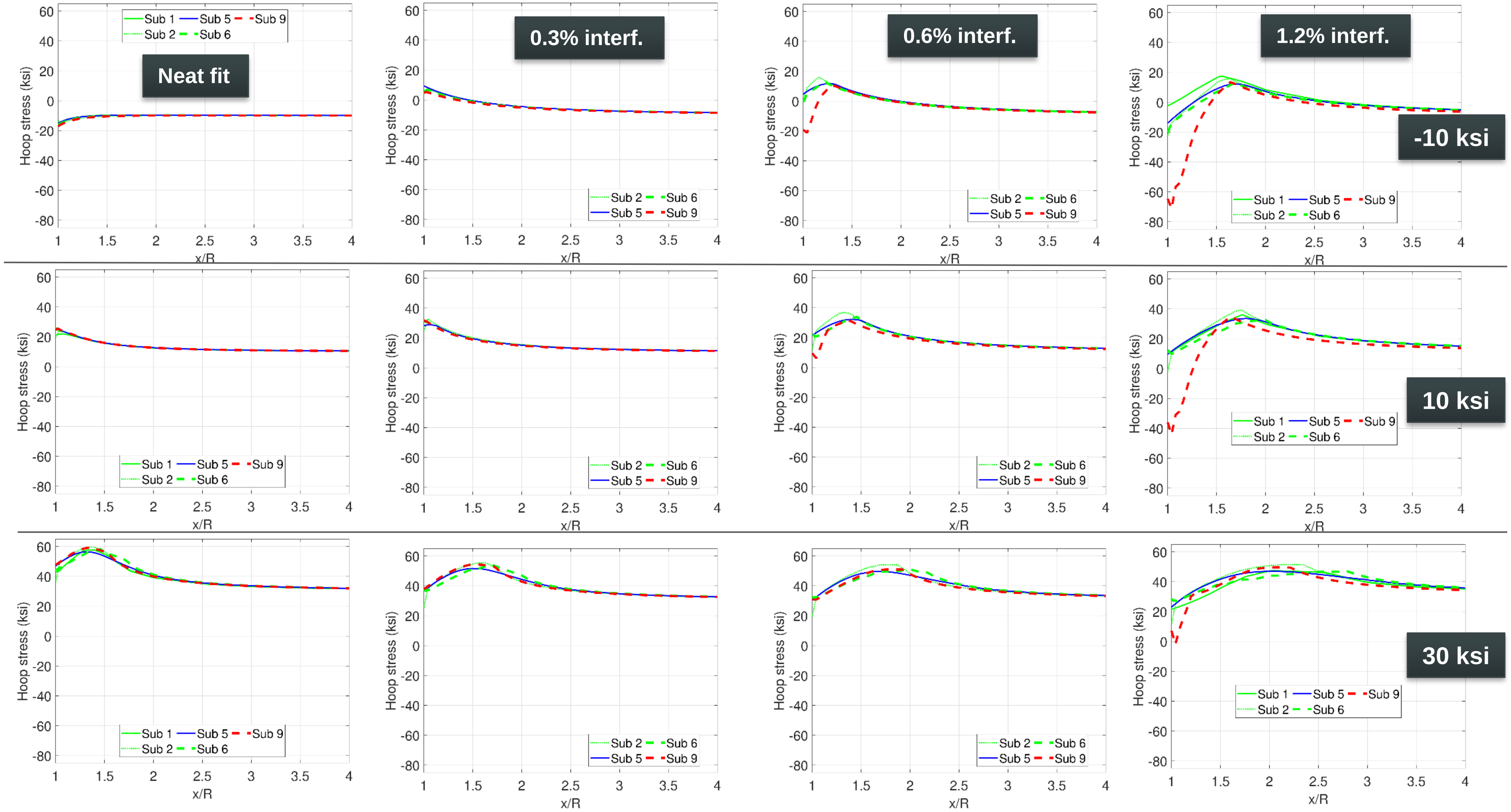
Note: this work has been submitted to the Materials Performance and Characterization journal and approved for publication.

IFF Round Robin - Predictions

- Group 3 – install + load

Key Takeaways:

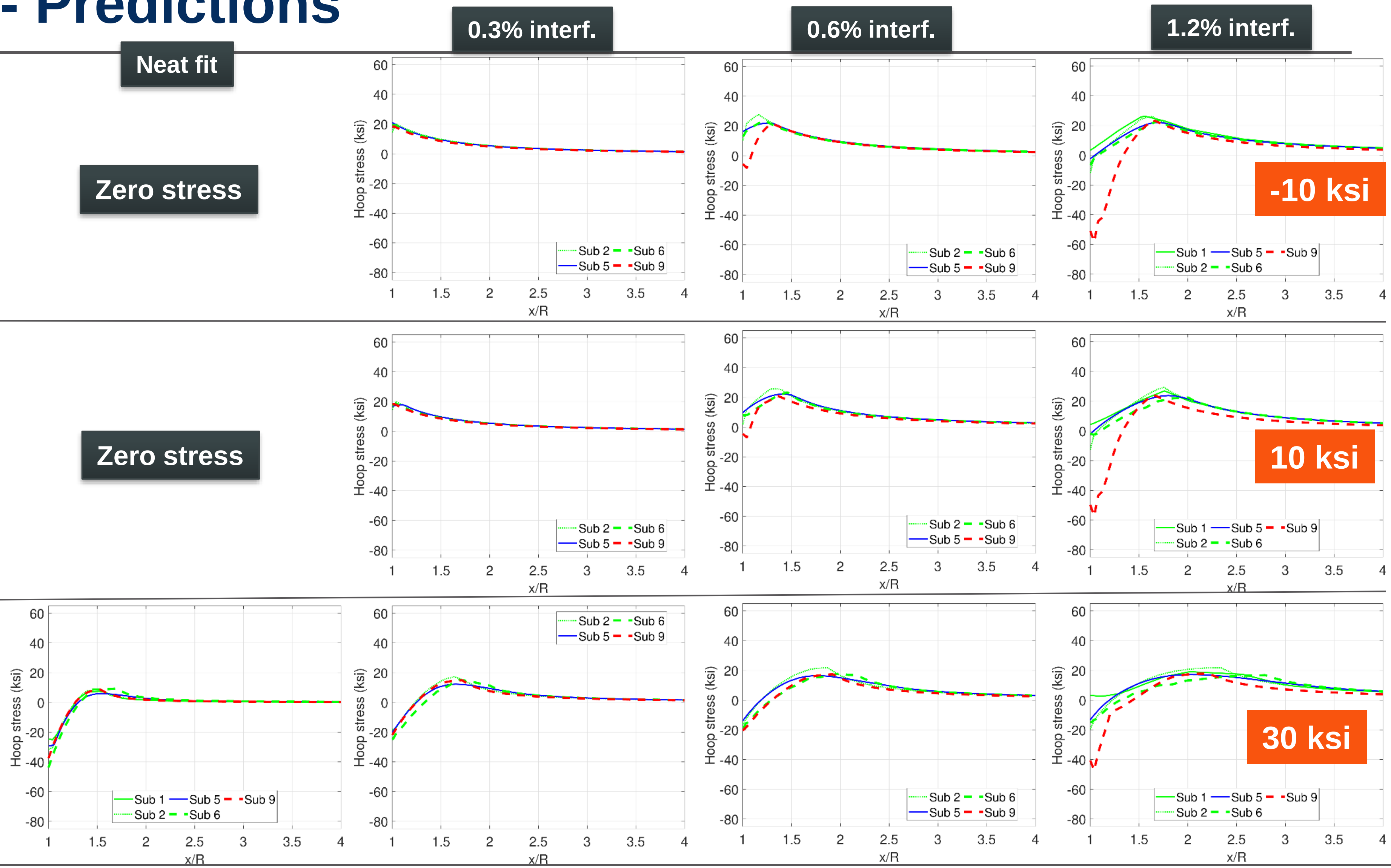
- **Higher applied loads tend to collapse predictions**
- **Consistent differences for model with simulated fastener install**



Note: this work has been submitted to the Materials Performance and Characterization journal and approved for publication.

IFF Round Robin - Predictions

- ❑ **Group 3 – install, load, and unload**



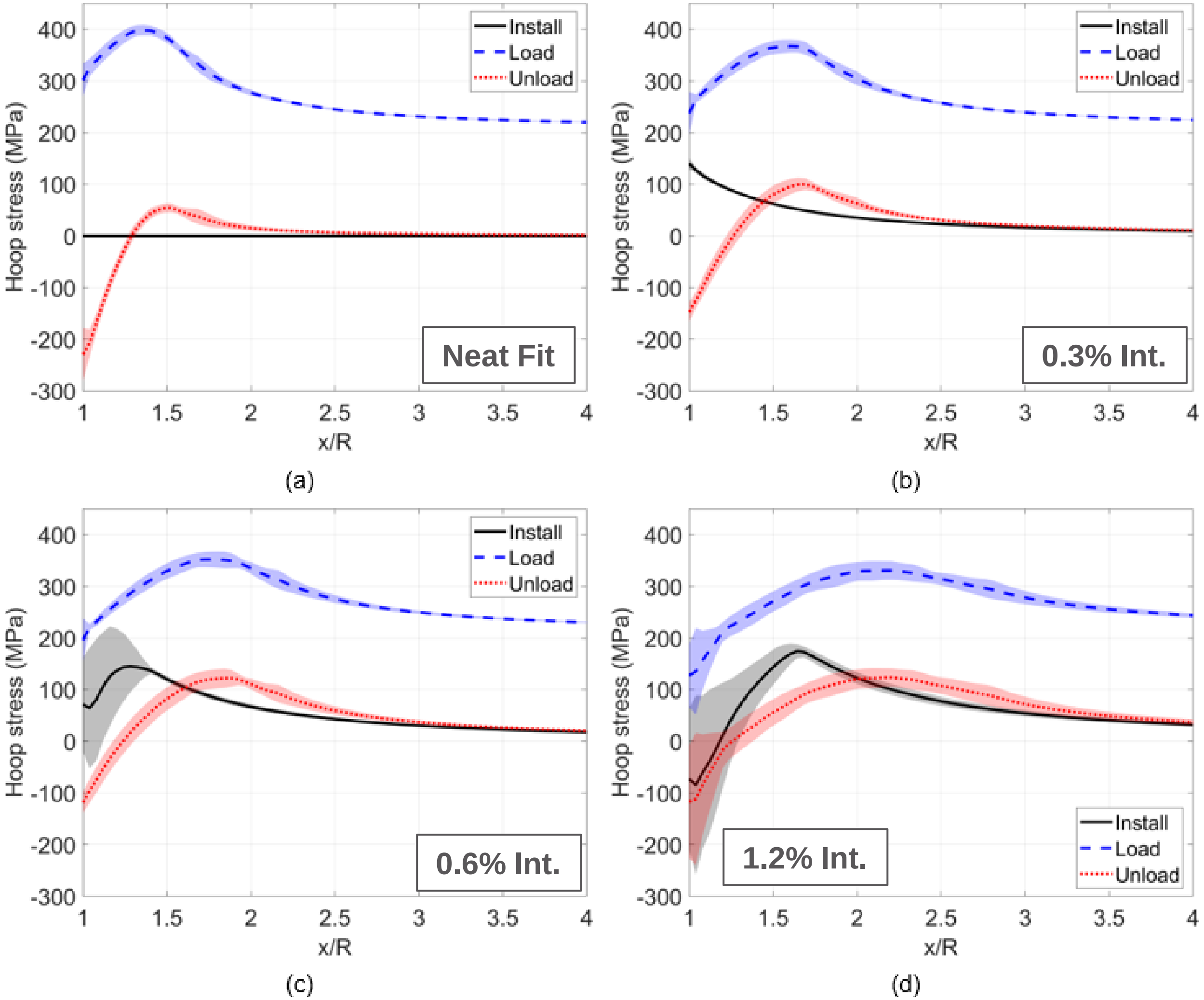
Key Takeaways:

- **Compressive stress near bore, even though fastener is still installed**
  - Stress state is a combination of:
    - Applied stress from interference
    - Residual stress

Note: this work has been submitted to the Materials Performance and Characterization journal and approved for publication.

IFF Round Robin - Predictions

- **Summary of predictions**
  - 30 ksi remote load
  - Combining all predictions with +/- one standard deviation error bars
  - Consistent results for neat fit and 0.3% interference
  - Large variability for 0.6% interference mitigated once load and unload steps are completed
  - Large variability is reduced for 1.2% interference, however, still persists in the load and unload steps



Note: this work has been submitted to the Materials Performance and Characterization journal and approved for publication.

Open Hole: Test Results

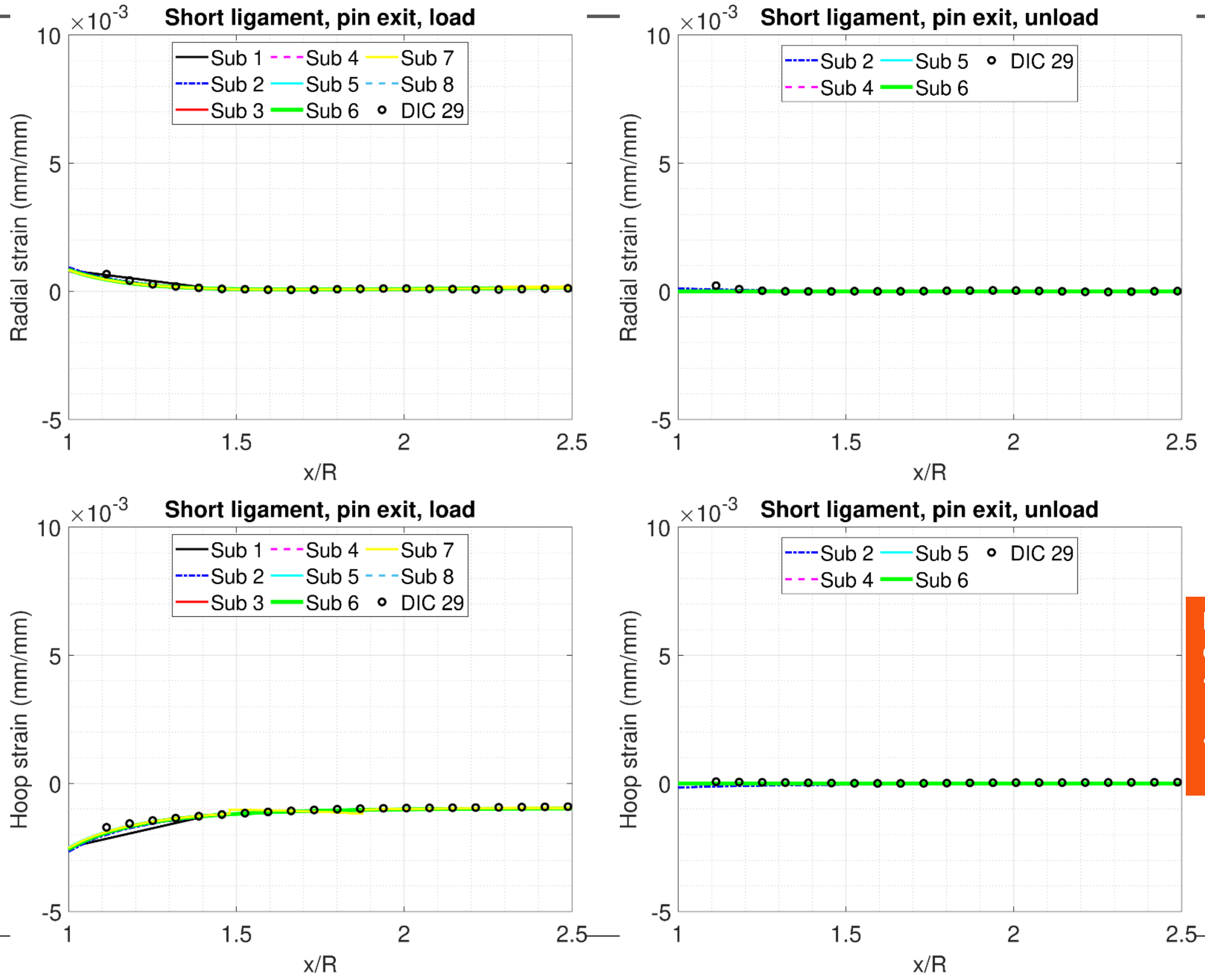
FE round robin (pointwise)

DIC strains (averaged)

Models vs DIC – Open hole, -10 ksi remote stress

Radial strain

Hoop strain



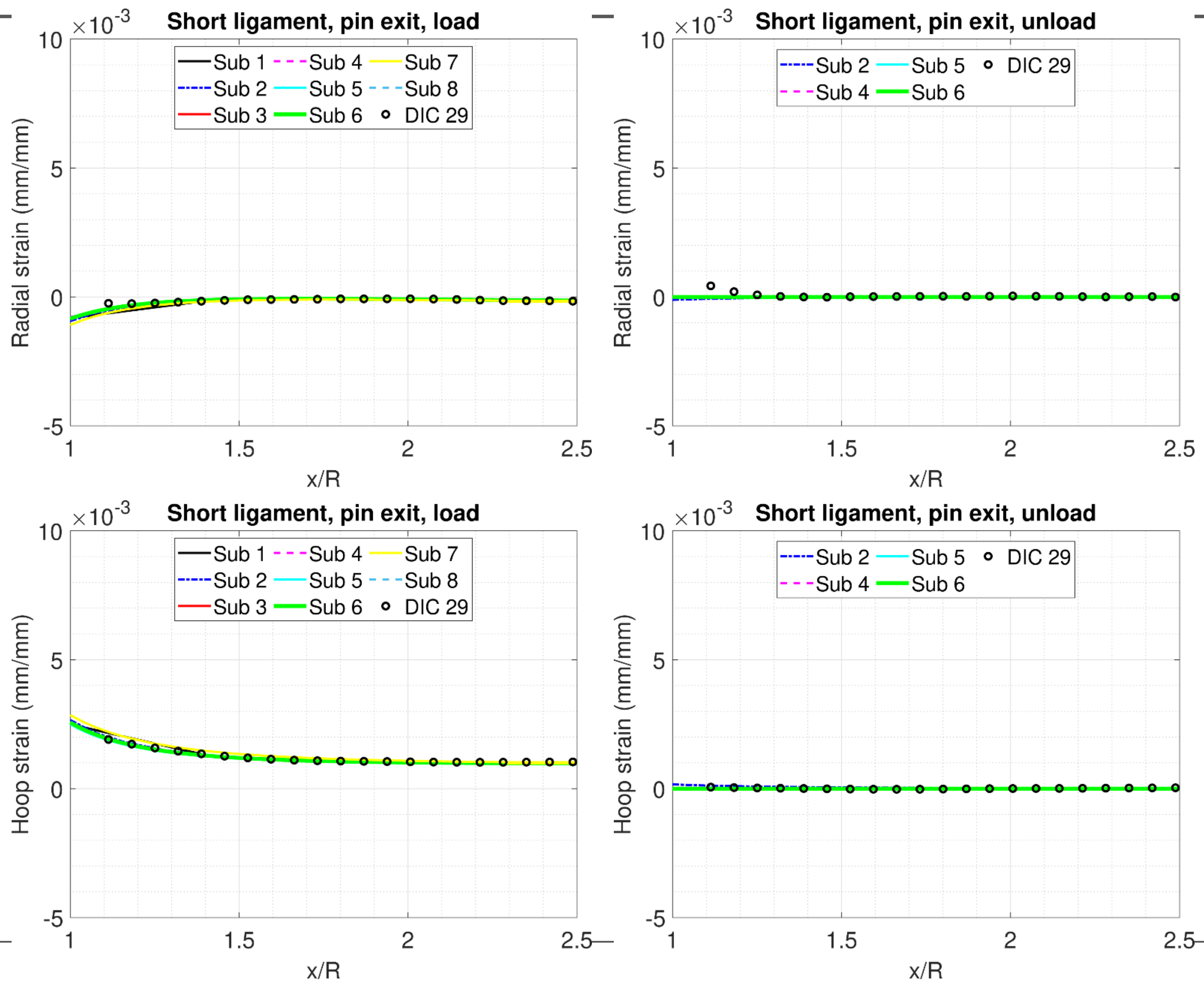
Notes (applies to all results from here on):

- **Results beyond x/R = 2.5 not shown to focus plot near hole only**
- **DIC points were subsampled to plot for easier visualization**

Models vs DIC – Open hole, 10 ksi remote stress

Radial strain

Hoop strain



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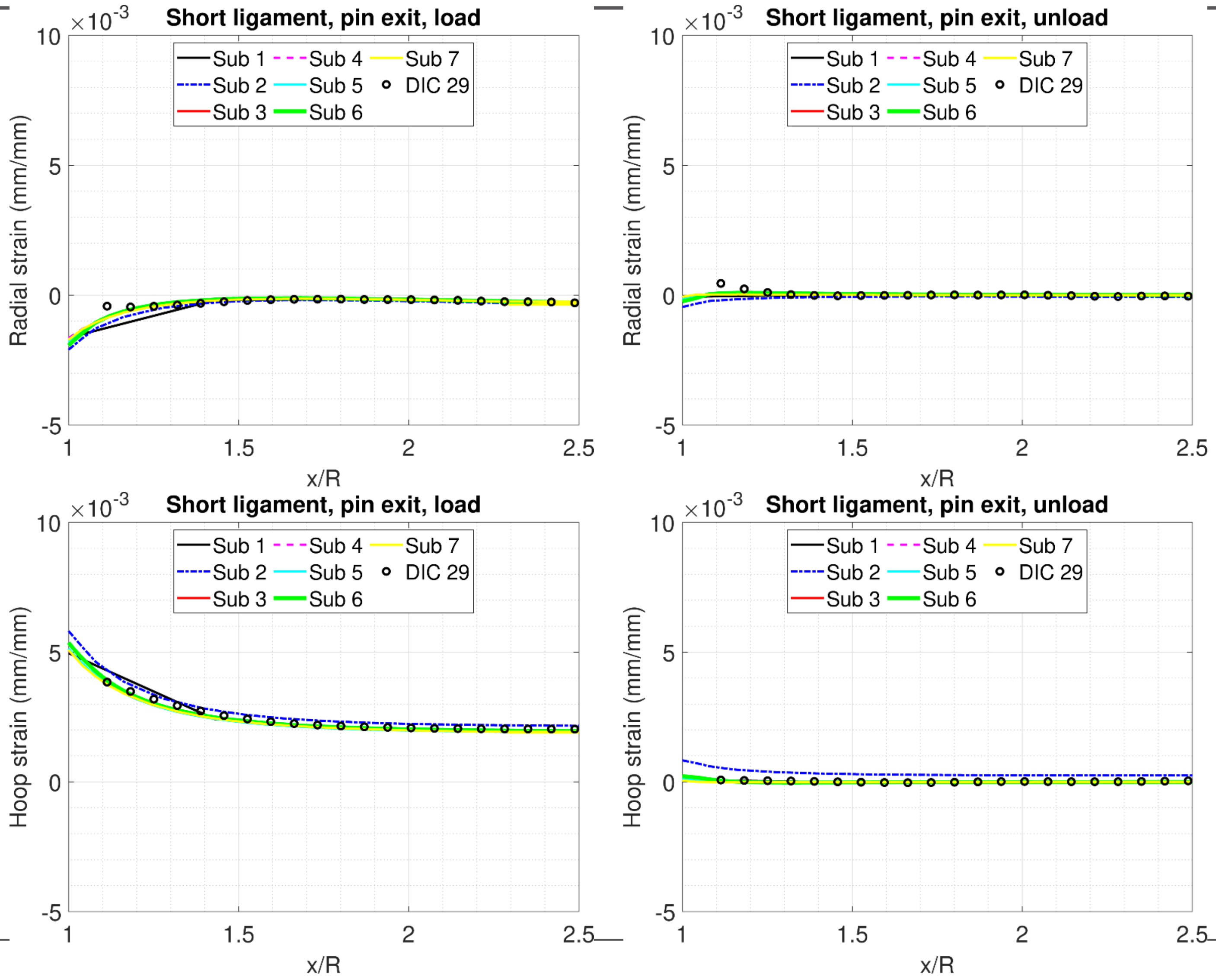
Models vs DIC – Open hole, 20 ksi remote stress

Radial strain

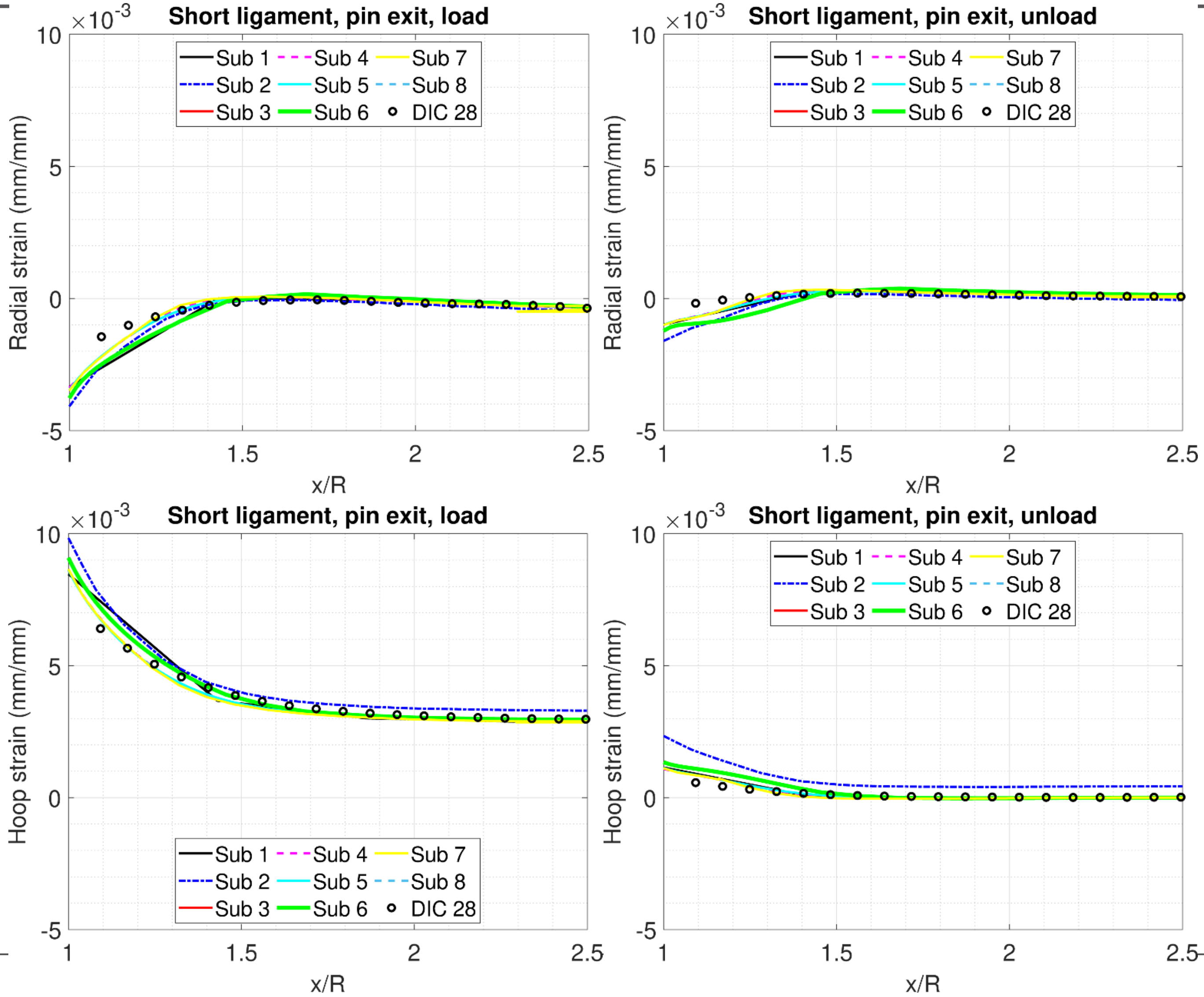
Hoop strain



Models vs DIC – Open hole, 30 ksi remote stress

Radial strain

Hoop strain



Key Takeaways:

- **Overall, models are slightly over-predicting strain relative to test results**

Neat Fit + Remote Load: Test Results

FE round robin (pointwise)

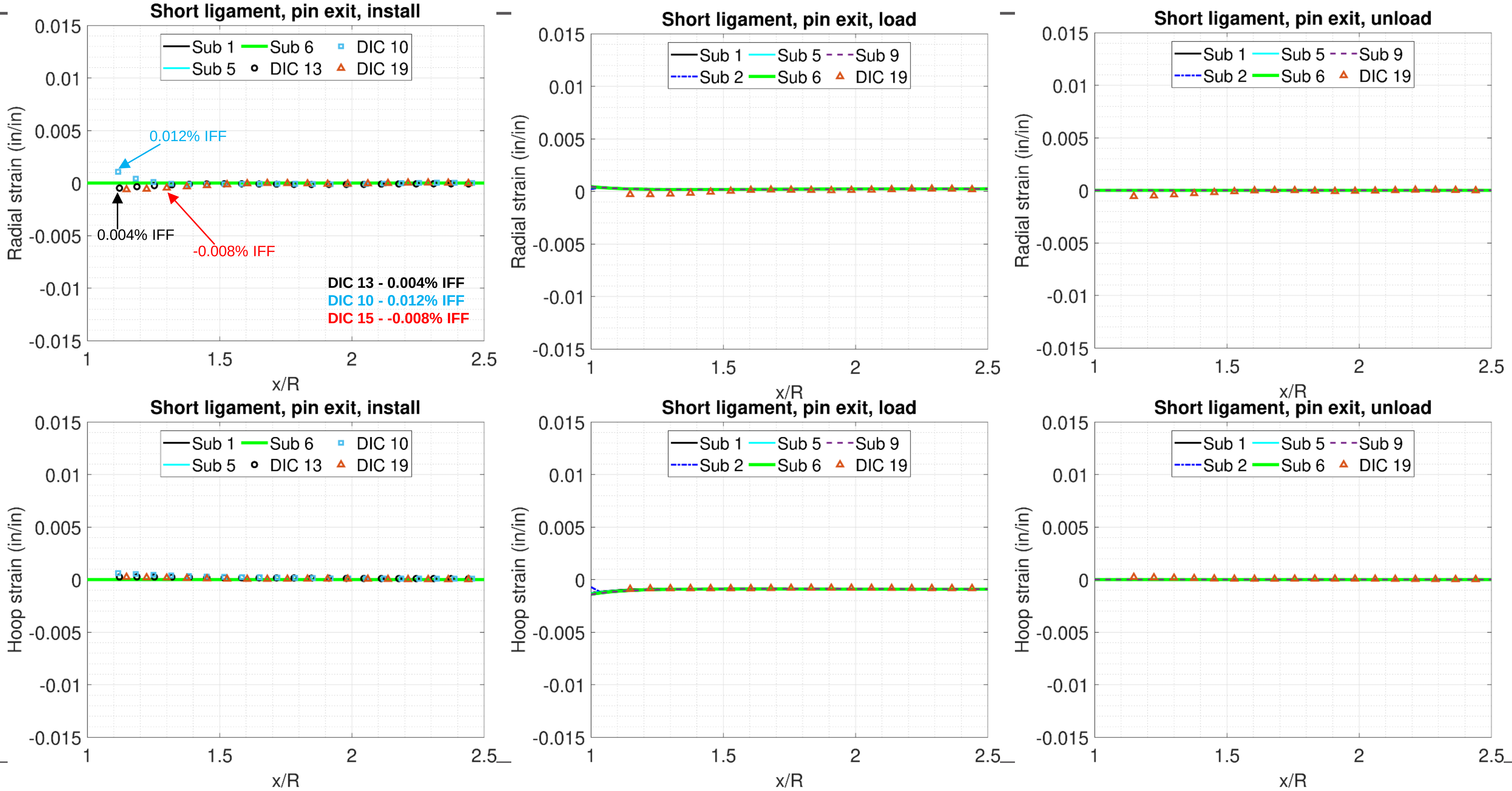
DIC strains (averaged)

Models vs DIC – neat fit, -10 ksi remote stress

DIC coupons
% IFF is based on pin and hole diameter measurements

Radial strain

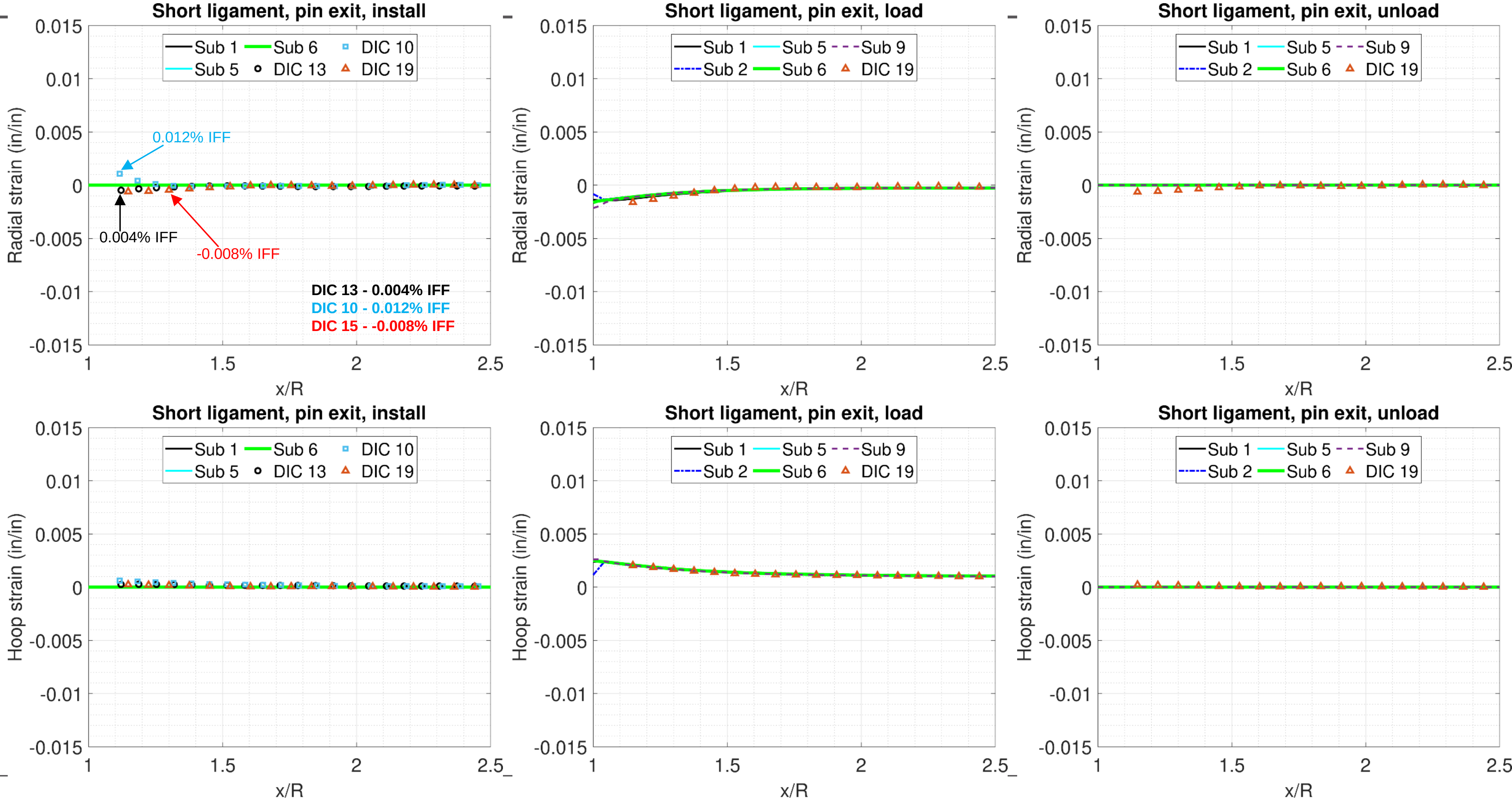
Hoop strain



Models vs DIC – neat fit, 10 ksi remote stress

Radial strain

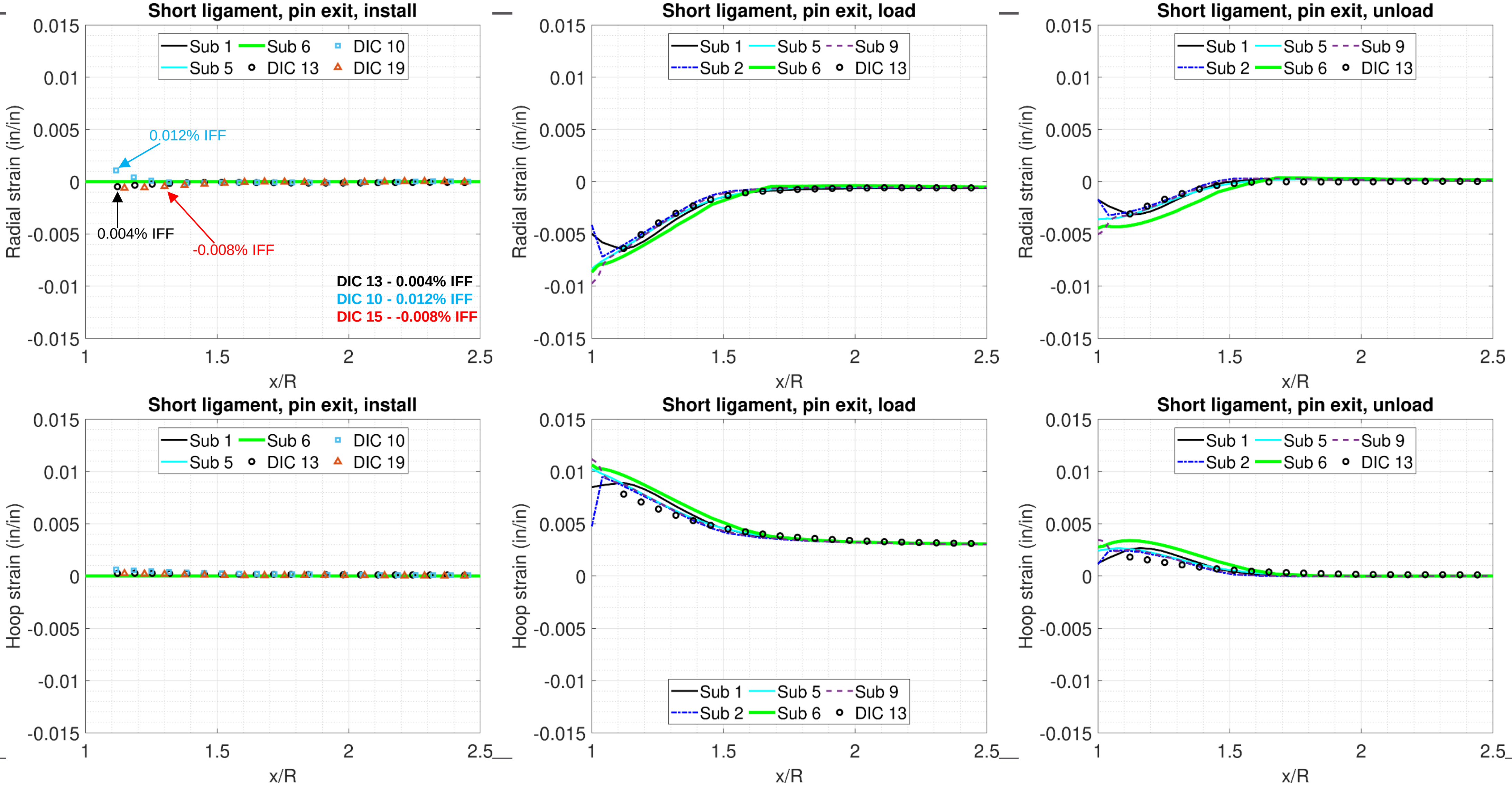
Hoop strain



Models vs DIC – neat fit, 30 ksi remote stress

Radial strain

Hoop strain



0.3% IFF + Remote Load: Test Results

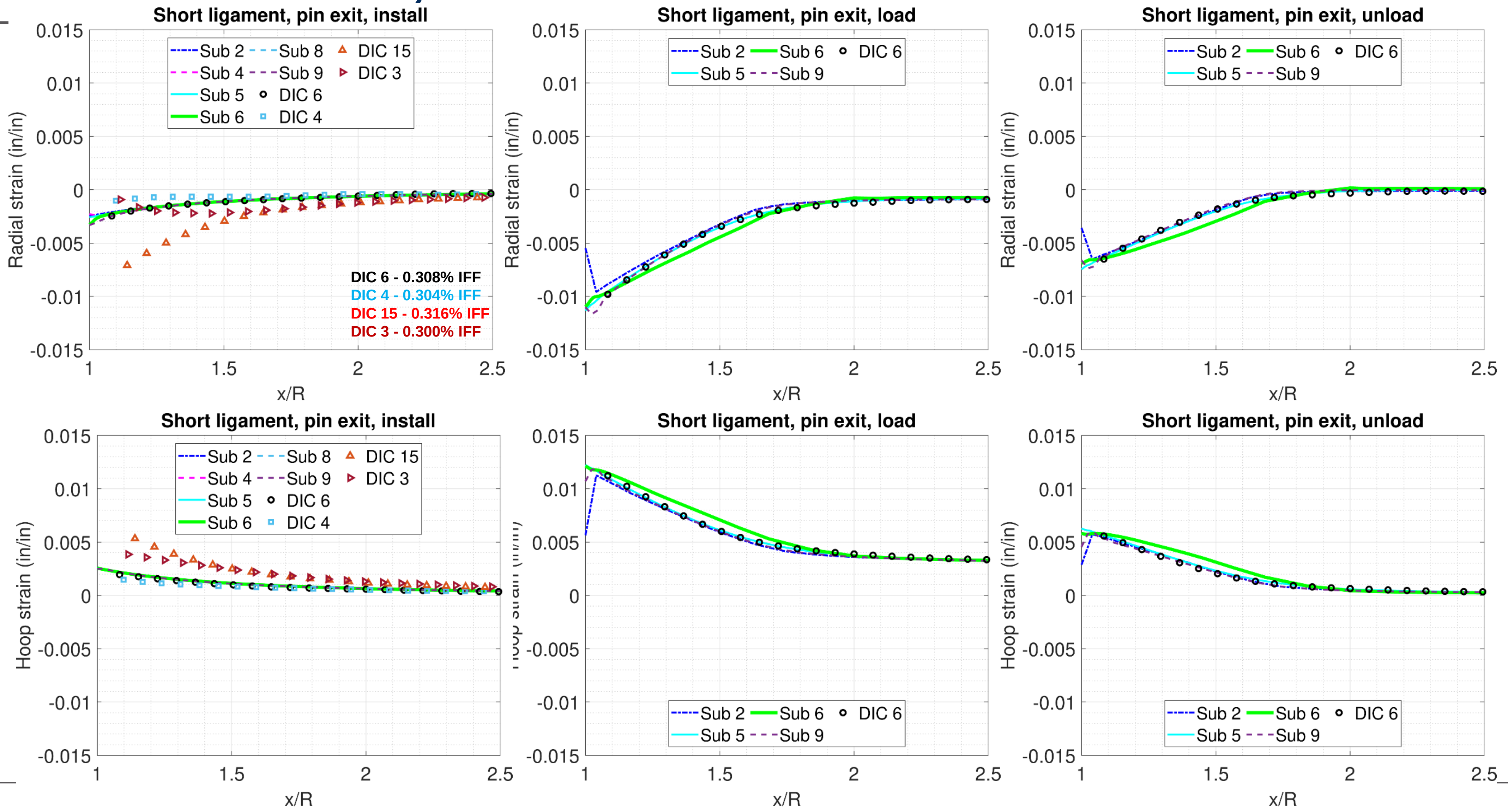
FE round robin (pointwise)

DIC strains (averaged)

Models vs DIC – 0.3% IFF, 30 ksi remote stress

Radial strain

Hoop strain



0.6% IFF + Remote Load: Test Results

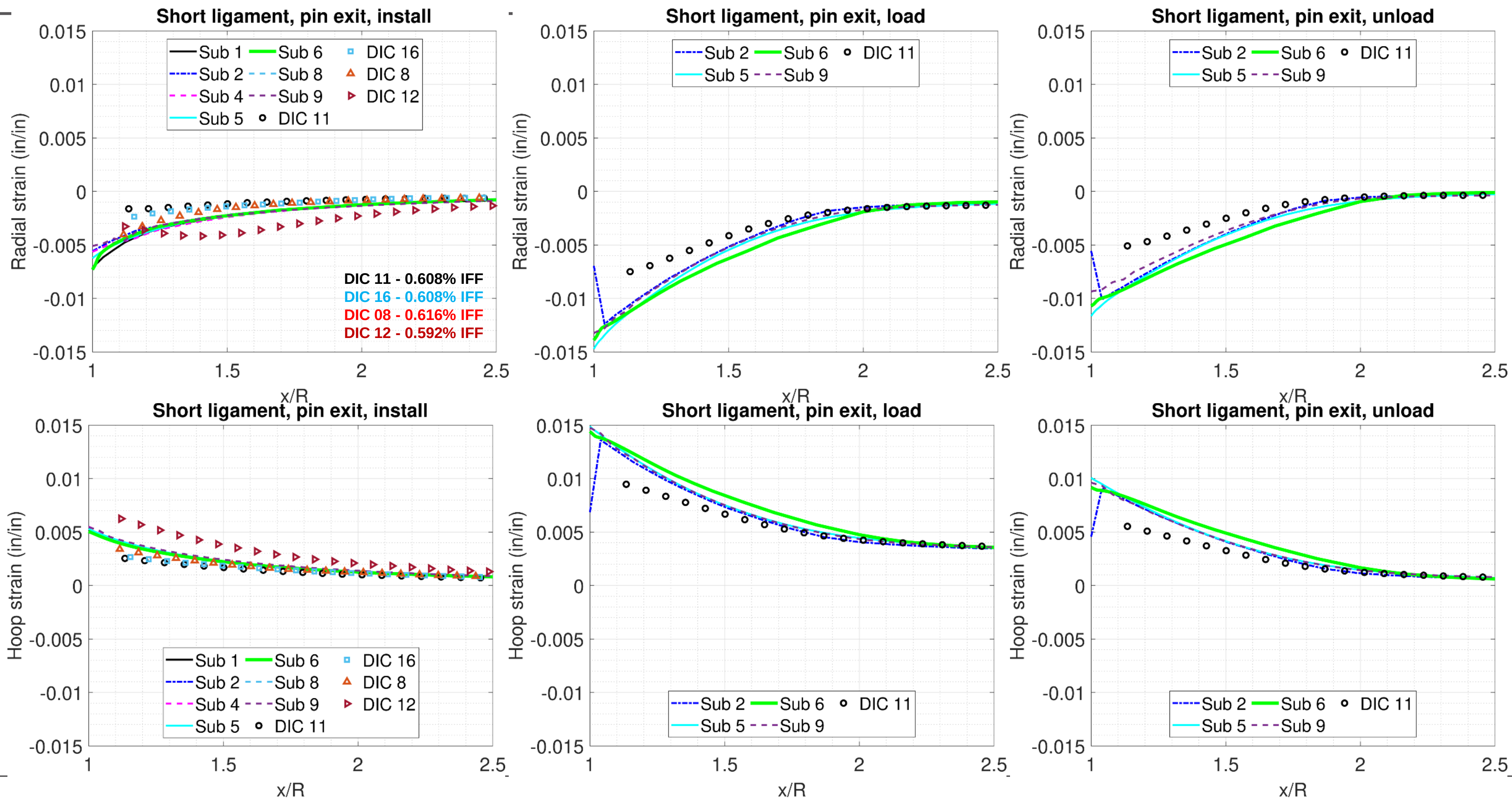
FE round robin (pointwise)

DIC strains (averaged)

Models vs DIC – 0.6% IFF, 30 ksi remote stress

Radial strain

Hoop strain



1.2% IFF + Remote Load: Test Results

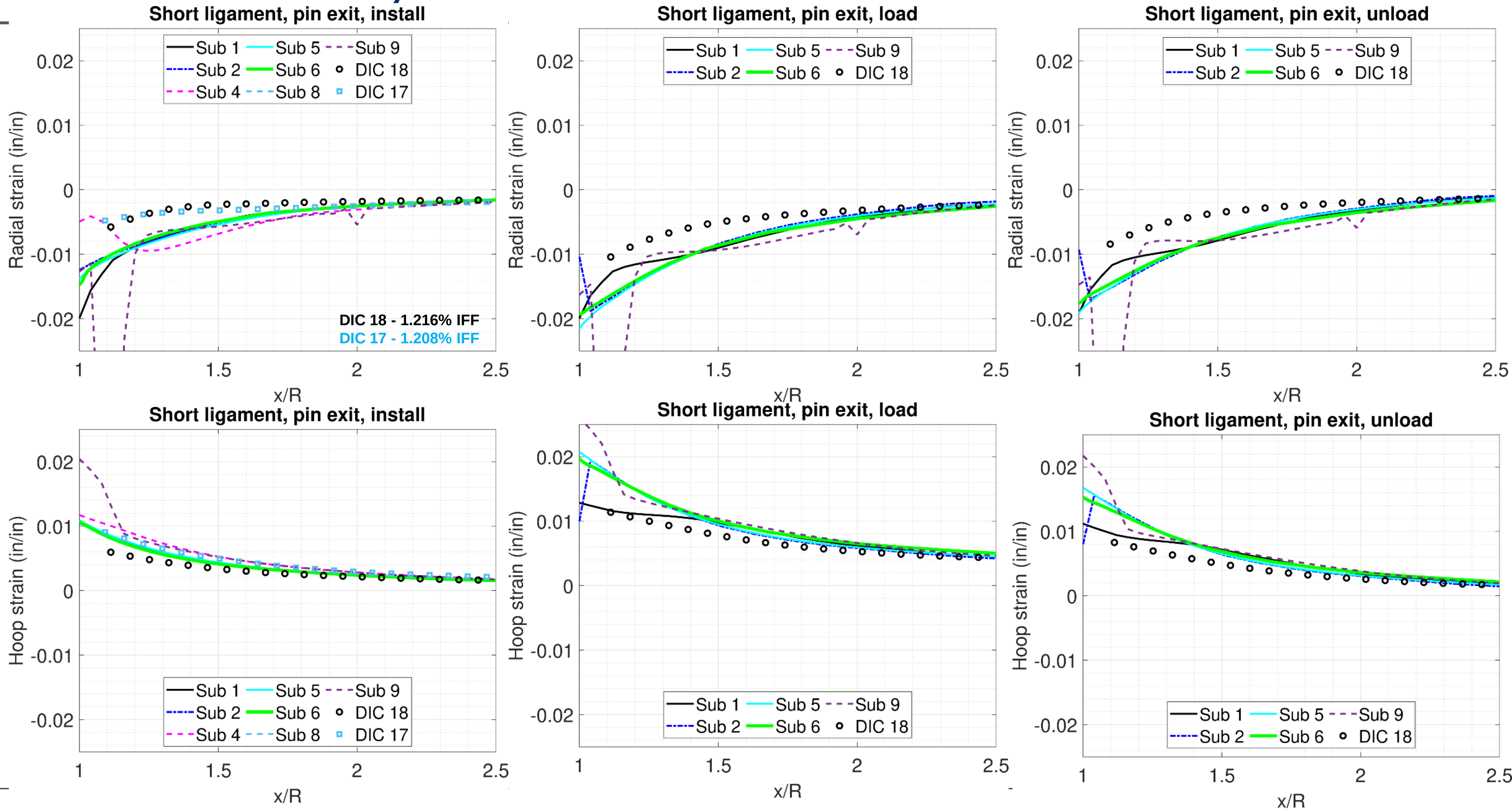
FE round robin (pointwise)

DIC strains (averaged)

Models vs DIC – 1.2% IFF, 30 ksi remote stress

Radial strain

Hoop strain



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Next Steps

- **Continue comparisons between predictions vs test results**
- **Resolve any discrepancies, where possible**
- **Refine analysis approaches, as required**
- **Utilize modeling approaches to:**
  - Complete SIF comparisons
  - Complete FCG predictions
- **Complete A-10 Phase 4 testing (FCG with IFF)**
- **Compare/contrast FCG predictions vs test results**

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Conclusions/Summary

- **Robust IFF dataset being generated by A-10 team**
  - Initial Phase 1 and 2 testing complete
    - Data processing in work
  - FCR testing about to begin
- **Complimentary ERSI round robin effort intended to evaluate performance of differing analysis methods**
  - Initial blind predictions complete
  - Highlights differences in modeling approaches
- **Once complete, a detailed comparison between predictions and test data will be shared with the community**
  - Identify lessons learned and best practices

ERSI

Thanks for your attention

Any questions?

References

1. Sun, Y., Hu, W., Shen, F., Meng, Q., Xu, Y. “Numerical simulations of the fatigue damage evolution at a fastener hole treated by cold expansion or with interference fit pin." International Journal of Mechanical Sciences 107 (2016): 188-200.
2. Chakherlou, T. N., M. Mirzajanzadeh, B. Abazadeh, and Kh Saeedi. "An investigation about interference fit effect on improving fatigue life of a holed single plate in joints." European Journal of Mechanics-A/Solids 29, no. 4 (2010): 675-682.
3. Ribeiro, R. Bombardier, Y., Loghin, A., Hood, C., Hawks, J., Prost-Domasky, S., Asaee, Z., Wieland, D., Pilarczyk, R., Warner, J. “Interference fit fasteners: a finite element process modeling round robin.”, Materials Performance and Characterization, Submitted October 2024.

Backup Slides

A-10 IFF Testing & Analysis Program

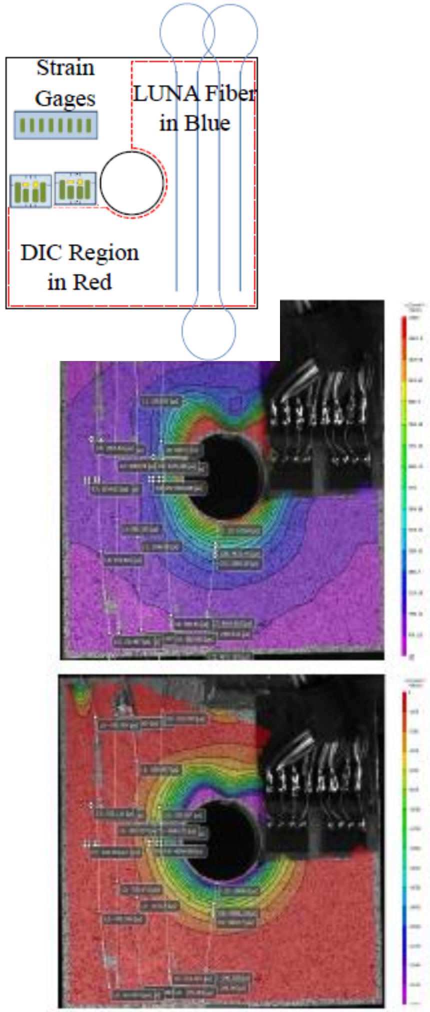
- **Phased approach with increasing complexity**
  - Phase 1: assessment of as-installed state
    - Simulate and empirically quantify the strain and stress state near a hole in the presence of an interference fit fastener
      - 3 levels of interference
      - 3D nonlinear FE process modeling; DIC and strain gages for surface strain measurements
  - Phase 2: fastener installed + remote loading
    - Repeat Phase 1 but with the addition of remote loading and unloading (multiple load levels and interference levels)
  - Phase 3: analytical methodology to account for interference fit fasteners during crack growth
    - Perform multi-point fatigue crack growth analyses including interference fit fastener conditions
    - Blind predictions prior to fatigue testing to be performed in Phase 4
  - Phase 4: fatigue crack growth testing with interference fit fasteners
    - Perform fatigue crack growth testing of neat fit and interference fit conditions
    - Use fatigue test data for validation and refinement of analytical methodology

Parameter	Levels
Coupon material	2024-T351 plate
Pin material	52100 steel pin
Coupon thickness	0.25 inch
Nominal hole size	0.25 inch
Interference conditions	Open hole
	Neat fit
	0.3% interference
	0.6% interference
	1.2% interference
Strain monitoring	DIC (all specimens)
	Strain gage (initial specimen)
Static stress levels (Phase 2)	-30 ksi
	-10 ksi
	0
	10 ksi
	20 ksi
	30 ksi
Fatigue crack growth testing (Phase 4)	Constant amplitude loading Smax = xxx ksi, R = xxx
	Spectrum?

A-10 IFF Testing & Analysis Program

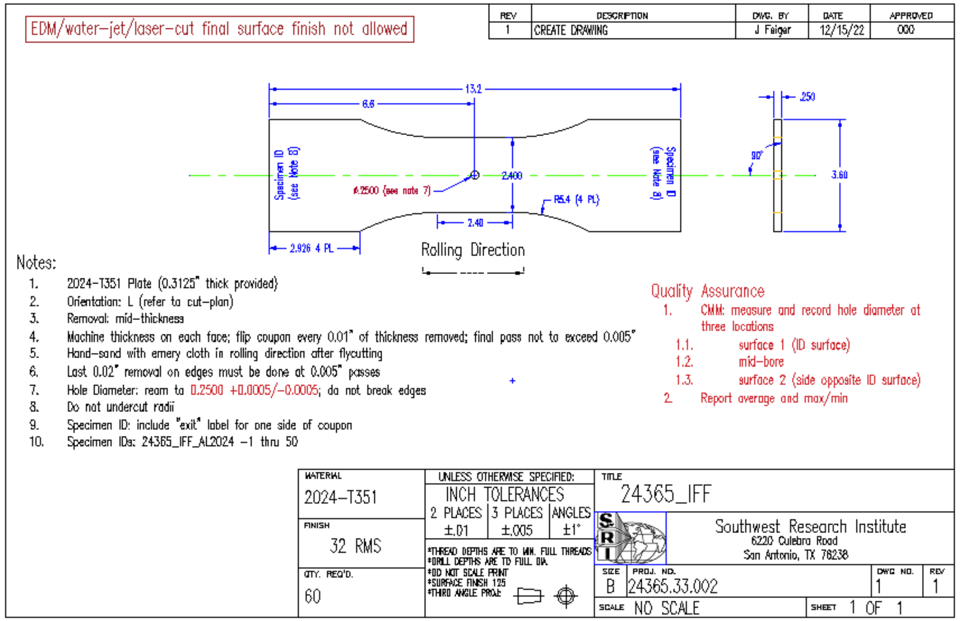
❑ Verification Tests

- ➢ Design conditions
  - Fasteners – gauge pins with ground transition geometry
- ➢ Data capture
  - 3D geometric measurements of fastener and hole
    - Calculate applied interference along bore
  - Surface strains (primarily DIC)
    - Leverage lessons learned from ERSI Cx 2x2 Residual Stress Validation Effort
    - Conditions
      - After fastener install
      - At each applied load
      - After each unload
      - After fastener removal
  - Transition point for fastener gapping
  - 3D geometric measurements after loading and fastener removal
    - Calculate retained interference along bore and characterize any plasticity



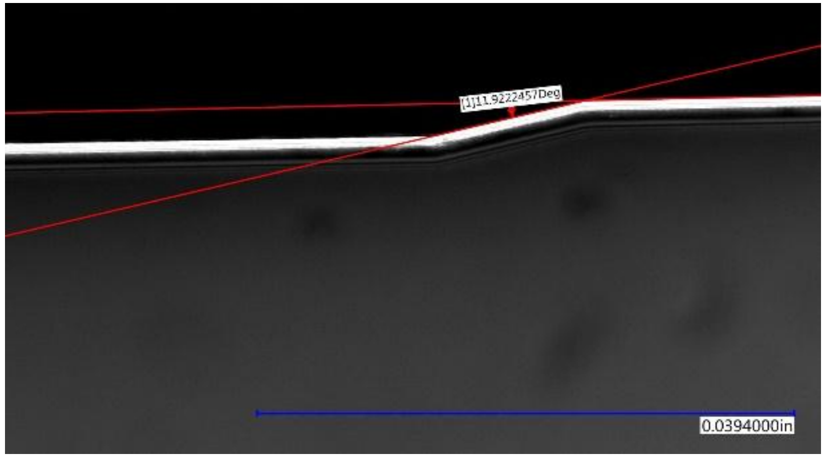
A-10 IFF Testing & Analysis Program

- **Coupon design**
  - “Dog-bone” with geometric center located 0.25” diameter hole
  - Same geometry used in prior ERS studies
  - Extracted in the L direction at mid-thickness
- **Material**
  - 2024-T351 plate (0.3125” thick)
  - Material Testing
    - Tensile (5 coupons)
      - ASTM E8
    - FCGR (multiple R values)
      - ASTM E647
      - M(T) geometry



A-10 IFF Testing & Analysis Program

- **Coupon manufacturing**
  - 50 coupons have been fabricated
  - Holes measured via CMM
  - Gage pins were custom ordered to match the interference fit required per specimen
    - 0.3%, 0.6%, and 1.2% interference
  - Gage pins were machined to match the chamfer of a Hi-Lok
    - One pin from each interference level was measured using an optical comparator to ensure the appropriate chamfer angle was achieved during machining. A sample measurement is provided below.



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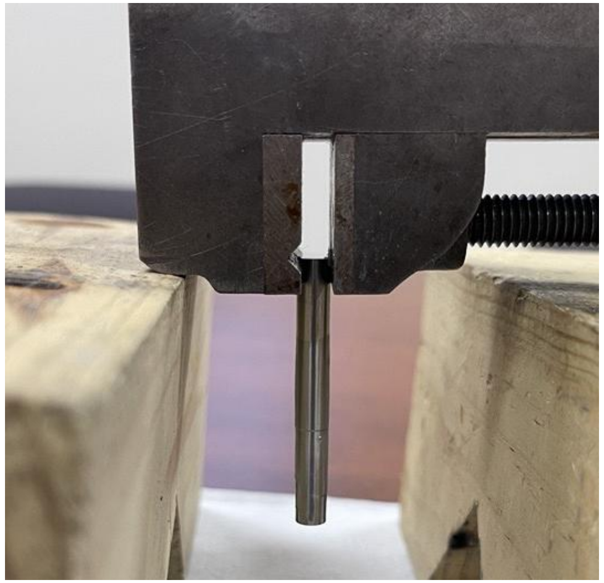
A-10 IFF Testing & Analysis Program

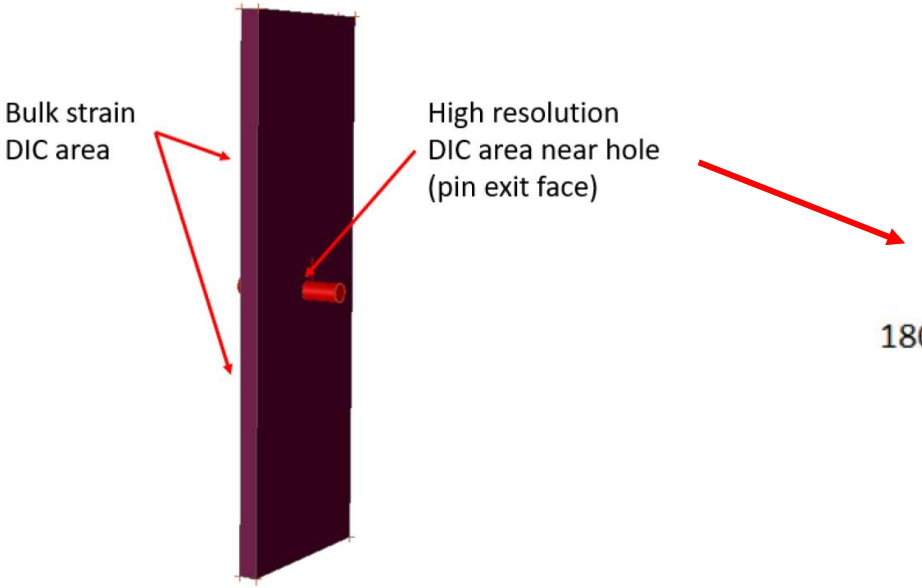
❑ Fastener Preparation

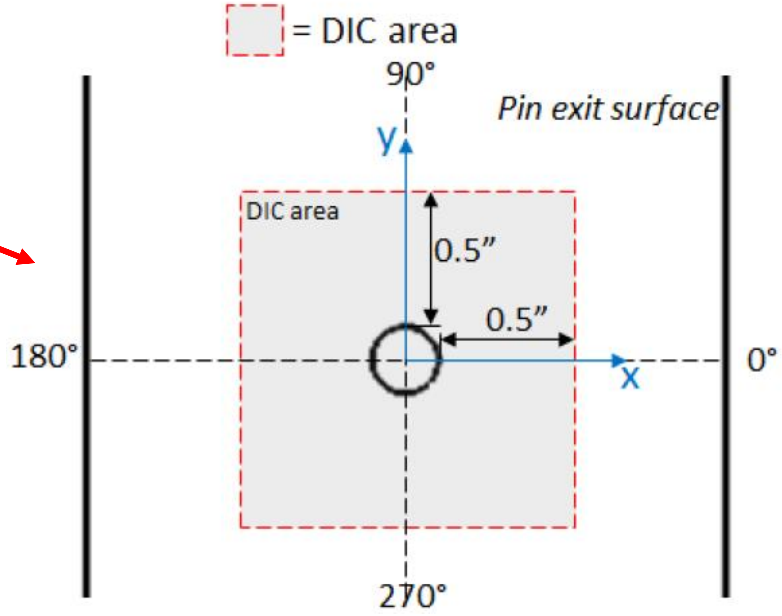
- To mimic the Hi-Lok installation, cetyl alcohol lubricant, Perma-Slik 1460W, will be used to coat the pins prior to installation.
  - Per the lubricant's instructions, the pins will be degreased with trichlorethylene. Then, the pins will be dipped in the lubricant and dried in a slow moving, heated air oven.
  - A coated pin is shown on the left and the degreasing process on the right.



A-10 IFF Testing & Analysis Program

- **DIC setup**
  - Collect digital image correlation (DIC) data globally on the pin entrance side and locally on the pin exit side
    - Global Side: 6” x 2.5” FOV
    - Local Side: 1” X 1” FOV

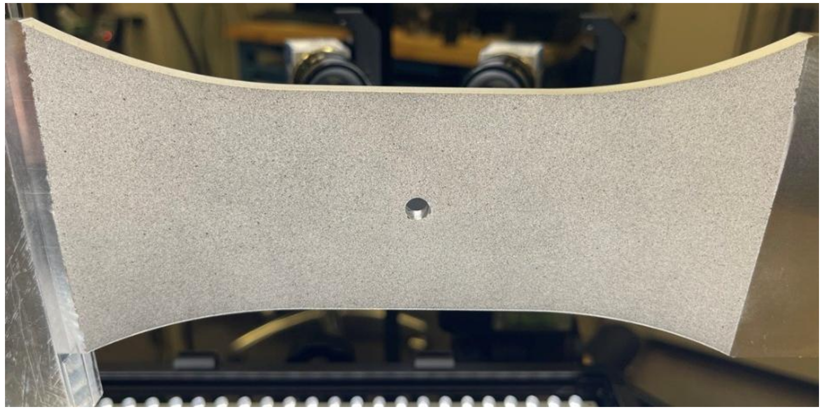




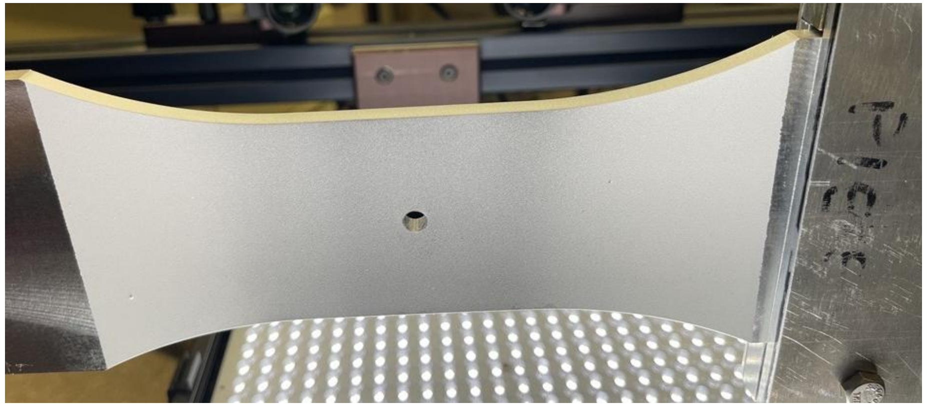
A-10 IFF Testing & Analysis Program

- **Coupon prep for DIC**

Global Side: speckled with black spray paint/stamp



Local Side: airbrushed with a fine, black ink mist



A-10 IFF Testing & Analysis Program

- **DIC Setup**
  - Correlated Solutions software and hardware
  - 3D setup
  - Global side: 5 MP cameras with 25mm lens
  - Local side: 8 MP cameras with 17 mm lens

A-10 IFF Testing & Analysis Program

- **Pin installation setup**
  - Servo-mechanic test frame at constant rate of displacement
  - Gage section supported
  - Relief hole at 3x diameter the fastener hole
  - Record load and displacement during installation
  - Preserve speckle pattern with Teflon and silicone layer

A-10 IFF Testing & Analysis Program

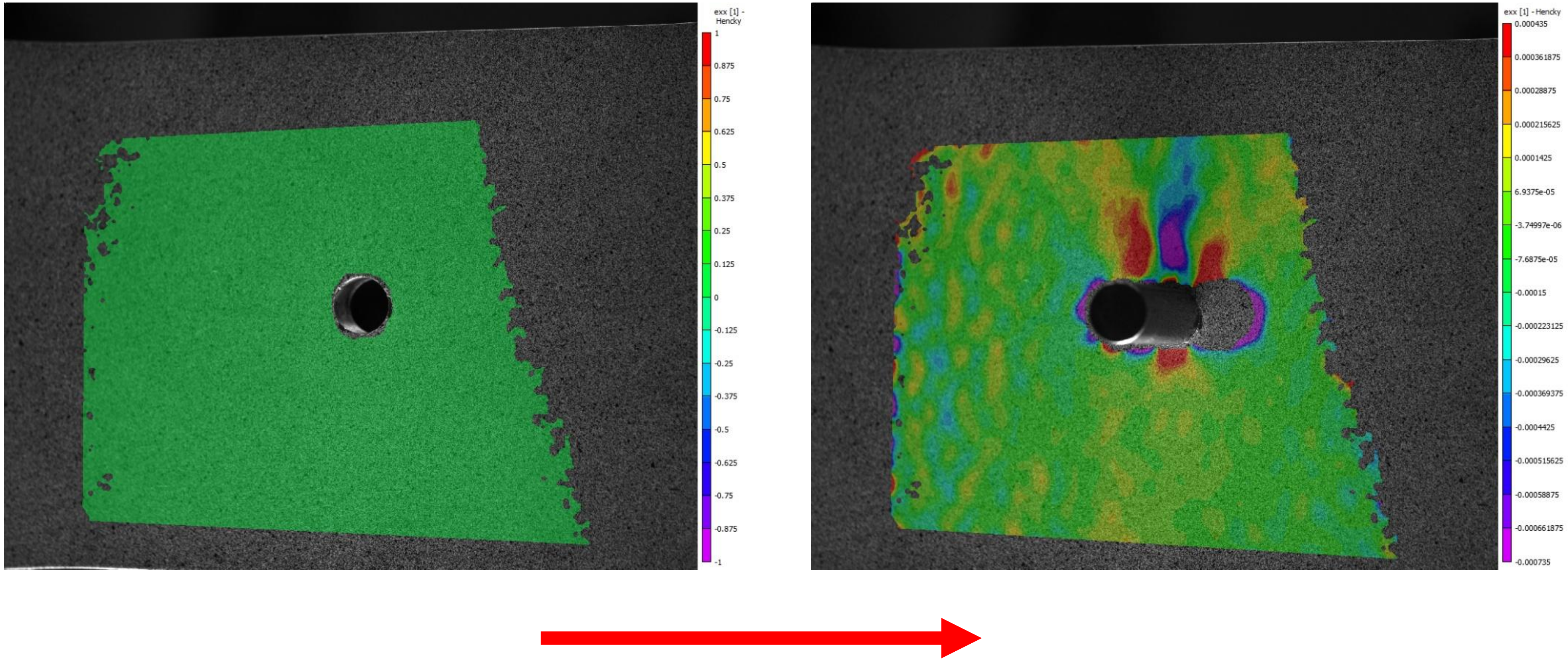
- DIC prior to pin installation

A-10 IFF Testing & Analysis Program

- DIC after to pin installation

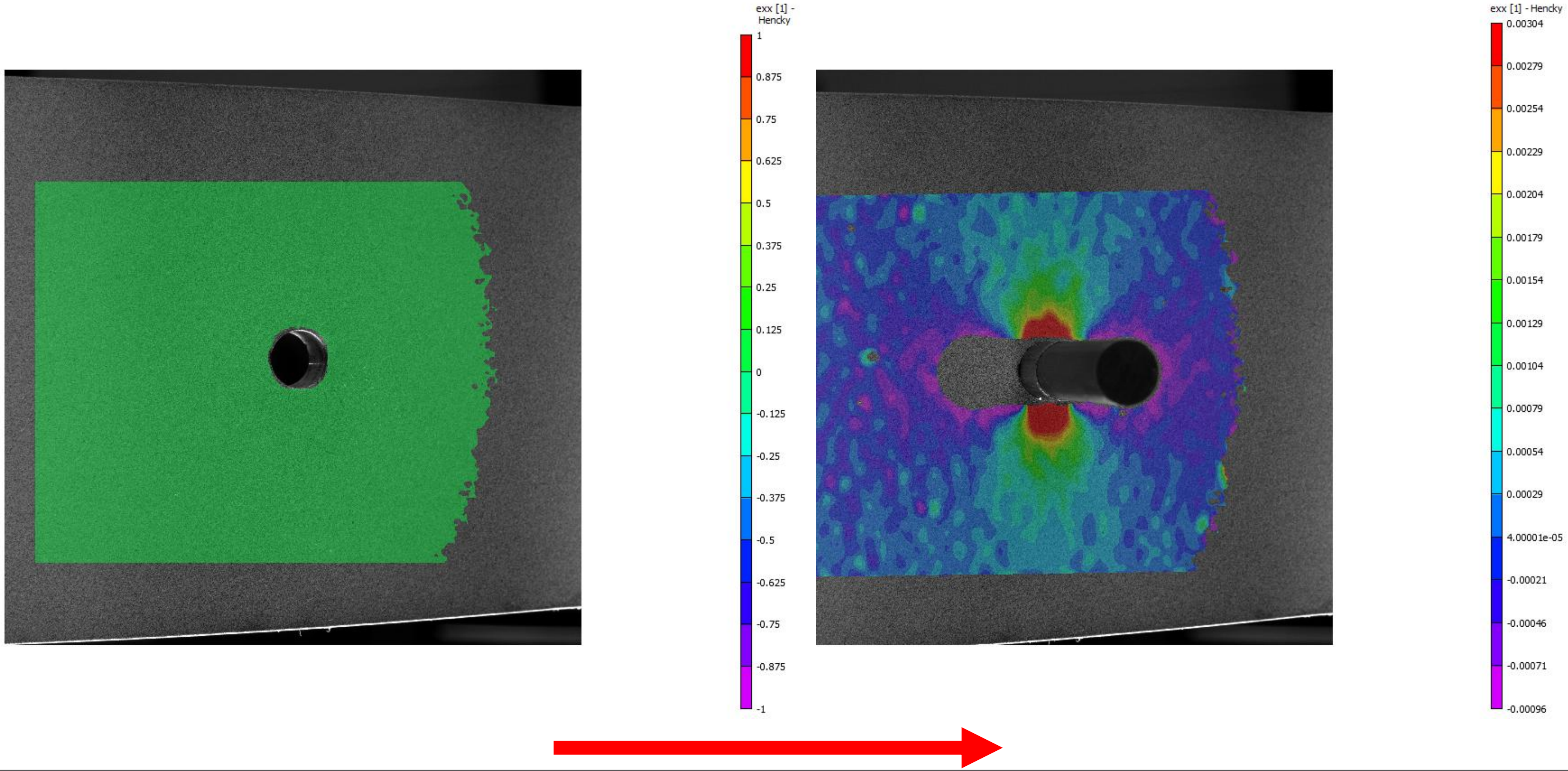
A-10 IFF Testing & Analysis Program

- Global results



A-10 IFF Testing & Analysis Program

- Local results



A-10 Cx Dataset: ERSI Blind Predictions

Robert Pilarczyk
Group Lead – Structural Integrity
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Phone: 801-391-2682

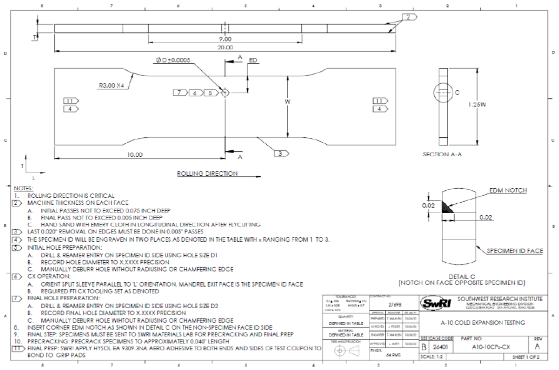
New A-10 Cx Testing

- Purpose
  - The A-10 program is transitioning toward using residual stresses from cold expansion directly in damage tolerance analyses. A test program was developed to target and isolate the load history and residual stress effects for Cx holes. Fatigue tests include baseline non-Cx and Cx holes, constant amplitude and spectrum loading, and are complimented with residual stress measurements for each condition
- Test Data
  - Testing and fractography completed by SwRI and APES

New A-10 Cx Testing, Constant Amplitude Tests

- Input Data
  - Geometry
    - Various (see table)
  - Material
    - Various (see table)
  - Starting flaw
    - Notched, pre-cracked, and final reamed
  - Cx conditions
    - Baseline non-Cx and Cx holes
  - Loading
    - Constant amplitude w/ markerbands
    - Max stresses = 23 and 25 ksi
    - Stress ratio = 0.1, 0.15

Material
7075-T76511 extrusion
2024-T351 plate
2024-T3511 extrusion
7075-T651 plate

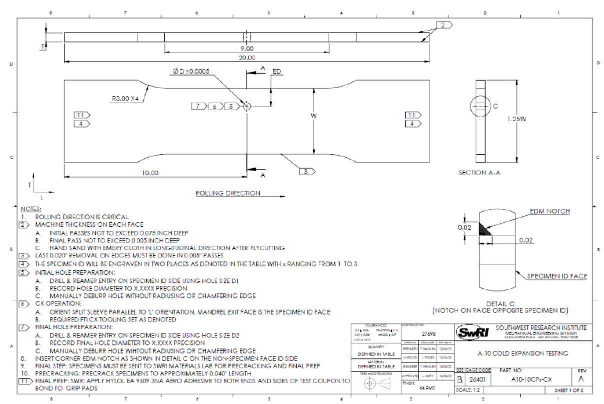


Location	Thickness, in.	Hole Diameter, in.	Hole Offset, in.	Test Type	Replicates
	0.125	0.249	0.500	Baseline	3
				Cx	3
	0.410	0.501	1.690	Baseline	3
				Cx	3
	0.394	0.501	1.040	Baseline	3
				Cx	3
FALSTAFF	0.250	0.250	2.000	Baseline	3
				Cx	3

New A-10 Cx Testing, Variable Amplitude Tests

- Input Data
  - Geometry
    - Various (see table)
  - Material
    - Various (see table)
  - Starting flaw
    - Notched, pre-cracked, and final reamed
  - Cx conditions
    - Baseline non-Cx and Cx holes
  - Loading
    - Variable amplitude

Material	Location	Thickness, in.	Hole Diameter, in.	Hole Offset, in.	Test Type	Test Replicates	RS Replicates
7075-T76511 extrusion		0.125	0.249	0.500	Baseline	3	2
					Cx	3	
7075-T76 sheet		0.190	0.438	1.000	Baseline	3	2
					Cx	3	
AMS 6526		0.190	0.438	0.830	Baseline	3	2
					Cx	3	
2024-T351 plate		0.200	0.197	0.500	Baseline	3	2
					Cx	3	
2024-T351 plate		0.208	0.202	0.470	Baseline	3	NA
					Cx	3	
2024-T3511 extrusion		0.260	0.187	0.680	Baseline	3	2
					Cx	3	
2024-T351 plate		0.410	0.501	1.690	Baseline	3	NA
					Cx	3	
2024-T3511 extrusion		0.394	0.501	1.040	Baseline	3	NA
					Cx	3	
7075-T351 plate		0.245	0.438	1.050	Baseline	3	2
					Cx	3	
AMS 6526		0.250	0.438	0.760	Baseline	3	2
					Cx	3	
7075-T651 plate	FALSTAFF	0.250	0.250	2.0	Baseline	3	NA
					Cx	3	
7075-T651 plate	TWIST/ miniTWIST	0.250	0.250	2.0	Baseline	3	NA
					Cx	3	



ERSI - A-10 Round Robin

- Goals
  - As a collective working group, complete blind predictions based on our best practices
  - Compare/contrast predictions vs test results
  - Utilize findings to refine analysis approach and best practices
- Approach
  - Down select dataset to define analysis conditions
  - Establish initial data and analysis approach/approaches
  - As a team, complete blind predictions

ERSI - A-10 Round Robin

- Down-Selection of Conditions

ERSI Analysis Priority	Location	Spectrum	Max Stress ksi	Stress Ratio R	Material	Thickness in.	Hole Diameter in.	Hole Offset in.	Test Type	Test Replicates
1	A-10 CP 7T	Constant Amplitude	23.00	0.10	2024-T351 plate	0.410	0.501	1.690	Baseline	3
3									Cx	3
2		Constant Amplitude	25.00	0.15	7075-T651 plate	0.250	0.250	2.000	Baseline	3
4									Cx	3
		A-10 Spectrum		N/A	7075-T76511 extrusion	0.125	0.249	0.500	Baseline	3
									Cx	3
		A-10 Spectrum		N/A	7075-T76 sheet	0.190	0.438	1.000	Baseline	3
									Cx	3
		A-10 Spectrum		N/A	AMS 6526	0.190	0.438	0.830	Baseline	3
									Cx	3
		A-10 Spectrum		N/A	2024-T351 plate	0.200	0.197	0.500	Baseline	3
									Cx	3
		A-10 Spectrum		N/A	2024-T351 plate	0.208	0.202	0.470	Baseline	3
									Cx	3
		A-10 Spectrum		N/A	2024-T3511 extrusion	0.260	0.187	0.680	Baseline	3
									Cx	3
5		A-10 Spectrum		N/A	2024-T351 plate	0.410	0.501	1.690	Baseline	3
8									Cx	3
		A-10 Spectrum		N/A	2024-T3511 extrusion	0.394	0.501	1.040	Baseline	3
									Cx	3
		A-10 Spectrum		N/A	7075-T351 plate	0.245	0.438	1.050	Baseline	3
									Cx	3
		A-10 Spectrum		N/A	AMS 6526	0.250	0.438	0.760	Baseline	3
									Cx	3
6		FALSTAFF		N/A	7075-T651 plate	0.250	0.250	2.000	Baseline	3
9									Cx	3
7		TWIST/miniTWIST		N/A	7075-T651 plate	0.250	0.250	2.000	Baseline	3
10									Cx	3

ERSI - A-10 Round Robin

- Conditions
  - Materials
    - 2024-T351 and 7075-T651
  - Spectrum
    - Constant and variable amplitude
    - A-10 wing spectrum, FALSTAFF, and miniTWIST
  - Residual stress
    - Baseline and Cx conditions
    - Gathering applicable RS data
  - Test replicates
    - Typically (3) each condition
  - Additional information
    - Post-test fractography for each coupon

ERSI - A-10 Round Robin

- Approach
  - Phase I: Baseline non-cx conditions, CA loading (in work)
    - Complete predictions & compare/contrast relative to test data
    - Update any analysis inputs, as required
  - Phase II: Cx conditions, CA loading
    - Complete predictions & compare/contrast relative to test data
    - Evaluate life and crack shape evolution
    - Revisit residual stresses and implementation approach, as necessary
  - Phase III: Baseline non-cx conditions, VA loading
    - Complete predictions & compare/contrast relative to test data
    - Review crack retardation and define approach for Cx conditions
  - Phase IIII: Cx conditions, VA loading
    - Complete predictions & compare/contrast relative to test data
  - Document comparisons and associated lessons learned / best practices for all phases

ERSI - A-10 Round Robin

▪ Phase I

- Baseline non-cx conditions, CA loading
  - Follow similar analysis approach & inputs as Cx conditions
  - Complete predictions & compare/contrast relative to test data
  - Update any analysis inputs, as required

ERSI Analysis Priority	Location	Spectrum	Max Stress ksi	Stress Ratio R	Material	Thickness in.	Hole Diameter in.	Hole Offset in.	Test Type	Test Replicates
1	A-10 CP 7T	Constant Amplitude	23.00	0.10	2024-T351 plate	0.410	0.501	1.690	Baseline	3
3									Cx	3
2		Constant Amplitude	25.00	0.15	7075-T651 plate	0.250	0.250	2.000	Baseline	3
4									Cx	3

ERSI - A-10 Round Robin

- Phase I Summary
  - Analysis inputs provided to participants
  - Submissions received from 5 participants
  - Results summarized and up for review in meeting tomorrow
- Phase II Planning
  - Need to finalize approach for residual stress input
  - Asking for inputs from RS characterization committee

Backup Slides

ERSI - A-10 Round Robin

7075-T651 Rate Data

Property	Value
Material	7075-T651 plate
Modulus (ksi)	10400
Poisson	0.33
Ultimate Strength (ksi)	83
Yield Strength (ksi)	73
Plane Stress Fracture Toughness (ksi-root(inch))	58
Plane Strain Fracture Toughness (ksi-root(inch))	27
Rlo	-0.15
Rhi	0.85

da/dN	Stress Ratios (R)					
	K_{max}	ΔK				
	-0.15	0.02	0.1	0.4	0.7	0.85
1.00E-11	1.957	2.15	2.01	1.36	1.15	0.972
1.00E-10	1.995	2.175	2.045	1.39	1.22	1.071
3.00E-10	2.015	2.193	2.065	1.408	1.255	1.119
1.00E-09	2.062	2.237	2.111	1.442	1.3	1.172
2.00E-09	2.103	2.278	2.152	1.473	1.33	1.201
1.00E-08	2.233	2.4	2.28	1.562	1.4	1.255
2.00E-08	2.336	2.492	2.38	1.634	1.44	1.269
4.00E-08	2.529	2.675	2.57	1.765	1.53	1.326
6.00E-08	2.744	2.897	2.787	1.919	1.645	1.41
1.00E-07	3.302	3.485	3.354	2.322	1.965	1.663
2.00E-07	4.052	4.275	4.115	2.89	2.4	1.993
4.00E-07	4.878	5.15	4.955	3.65	2.975	2.425
6.00E-07	5.191	5.49	5.275	3.95	3.175	2.552
1.00E-06	5.477	5.825	5.575	4.225	3.36	2.672
2.00E-06	6.064	6.55	6.2	4.75	3.765	2.984
4.00E-06	7.026	7.65	7.2	5.55	4.4	3.488
6.00E-06	7.895	8.63	8.1	6.26	4.95	3.914
1.00E-05	9.419	10.339	9.675	7.51	5.875	4.596
2.00E-05	11.885	13.11	12.225	9.53	7.25	5.515
4.00E-05	15.605	17.3	16.075	12.6	8.85	6.216
1.00E-04	22.061	24.55	22.75	17.925	11.1	6.874
2.00E-04	26.617	29.7	27.47	21.725	12.5	7.192
4.00E-04	30.493	34.1	31.49	24.885	13.65	7.487
6.00E-04	32.597	36.5	33.675	26.55	14.2	7.595
8.00E-04	34.115	38.225	35.25	27.69	14.625	7.724
1.00E-03	35.231	39.5	36.41	28.5	14.9	7.79
2.00E-03	38.526	43.25	39.83	30.5	15.6	7.979
4.00E-03	42.037	47.25	43.475	31.87	16.13	8.164
1.00E-02	45.77	51.5	47.35	33	16.65	8.401
2.00E-02	47.313	53.25	48.95	33.5	16.875	8.5
1.00E-01	49.287	55.5	51	34.1	17.1	8.575

ERSI - A-10 Round Robin

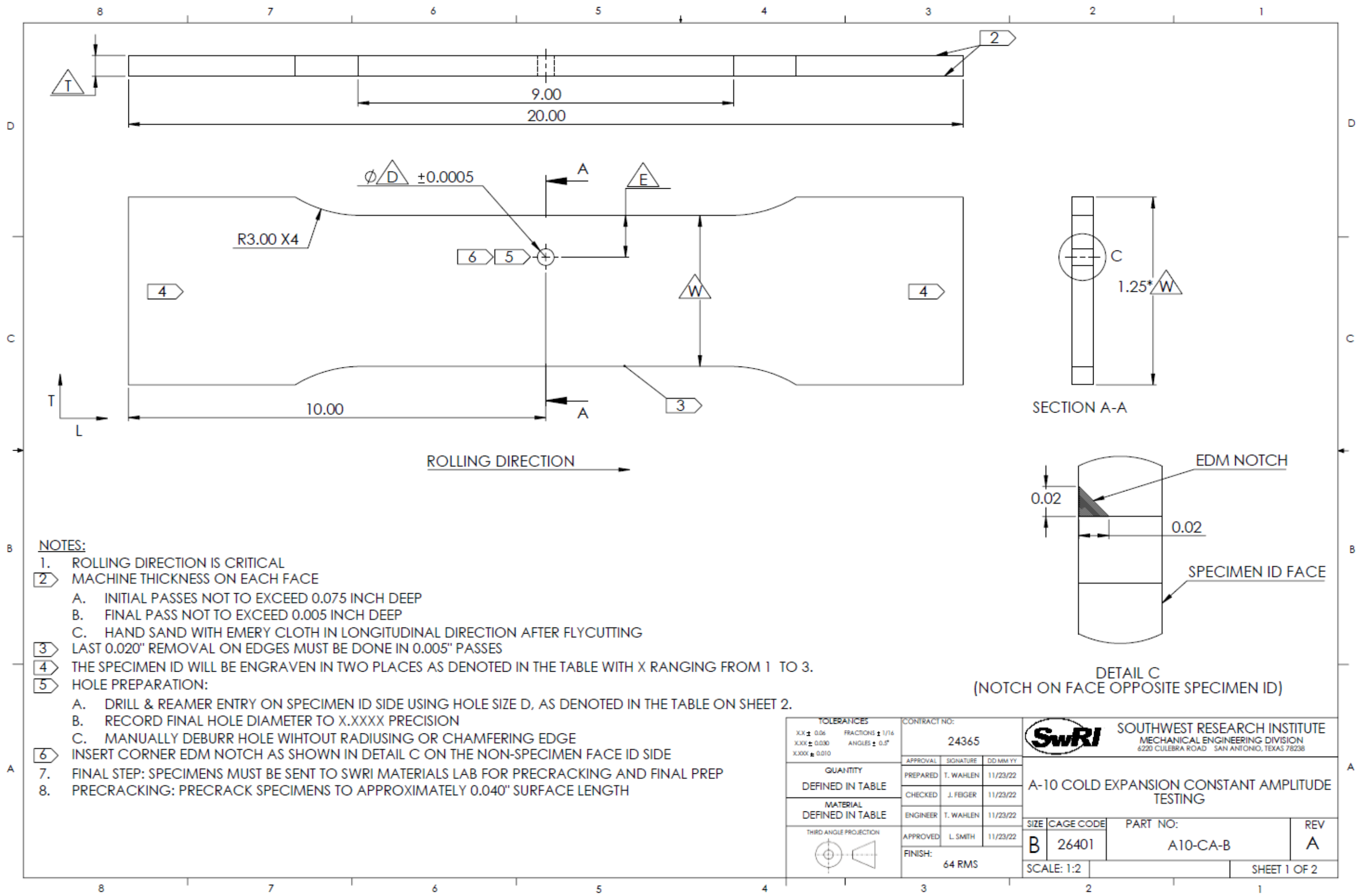
2024-T351 Rate Data

Property	Value
Material	2024-T351 Plate
Modulus (ksi)	10700
Poisson	0.33
Ultimate Strength (ksi)	66
Yield Strength (ksi)	50
Plane Stress Fracture Toughness (ksi-root(inch))	80
Plane Strain Fracture Toughness (ksi-root(inch))	32
Rlo	-0.5
Rhi	0.85

da/dN	Stress Ratios (R)					
	K_{max}		ΔK			
	-0.5	-0.25	0	0.1	0.5	0.8
7.87E-11	1.275	1.300	1.326	1.218	0.959	0.864
2.36E-10	1.318	1.344	1.370	1.259	0.991	0.893
7.87E-10	1.410	1.438	1.466	1.346	1.060	0.955
3.94E-09	1.586	1.617	1.649	1.514	1.192	1.074
1.57E-08	1.815	1.850	1.887	1.733	1.364	1.229
3.15E-08	2.083	2.122	2.165	1.988	1.565	1.409
5.51E-08	2.419	2.466	2.514	2.310	1.817	1.634
1.34E-07	3.757	3.829	3.905	3.586	2.820	2.516
3.15E-07	5.757	5.868	5.983	5.496	4.500	4.100
1.28E-06	7.247	7.383	8.200	8.000	5.800	4.838
3.94E-06	8.713	8.880	10.200	9.200	7.000	6.400
1.46E-05	13.307	13.560	16.000	14.800	10.200	8.225
3.94E-05	19.300	19.704	22.000	21.000	14.000	9.200
1.34E-04	27.553	28.224	32.000	29.000	19.000	10.500
3.94E-04	37.533	38.536	41.000	36.220	23.500	12.000
1.34E-03	49.900	51.360	52.880	48.340	28.000	13.200
3.94E-03	58.507	59.976	61.480	56.060	33.000	14.500
1.65E-02	68.933	70.088	71.210	64.610	37.000	15.600
7.87E-02	76.133	76.696	78.000	70.010	40.000	16.000
3.94E-01	80.800	81.120	82.510	74.800	41.000	16.100

ERSI - A-10 Round Robin

Coupon Drawings



ERSI - A-10 Round Robin

Coupon Drawings

DESIGN INPUTS FOR BASELINE COUPONS							
LOCATION	MATERIAL	WIDTH (W)	THICKNESS (T)	EDGE DISTANCE (E)	HOLE DIAMETER (D)	SPECIMEN ID	QUANTITY
CP 47	7075-T76/ 7075-T76511	3.84	0.125	0.500	0.249	CP47-B-X	3
CP 7T	2024-T351	4.00	0.410	1.690	0.5005	CP7T-B-X	3
CP 5T	2024-T3511	4.00	0.394	1.040	0.5005	CP5T-B-X	3
FALSTAFF	7075-T651	4.00	0.250	2.000	0.250	FALSTAFF-B-X	3

SwRI SOUTHWEST RESEARCH INSTITUTE
MECHANICAL ENGINEERING DIVISION
6220 CULEBRA ROAD SAN ANTONIO, TEXAS 78238

A-10 COLD EXPANSION CONSTANT AMPLITUDE TESTING

SIZE	CAGE CODE	PART NO:	REV
B	26401	A10-CA-B	A
		TABLE OF DIMENSIONS	SHEET 2 OF 2

ERSI - A-10 Round Robin

- Priority #1 (Baseline non-Cx, CA loading)
  - Coupons CP7T-B-01 through -03
  - Geometry
    - Thickness: 0.410”
    - Width (test section): 4.00”
    - Width (grips): 5.00”
    - Hole Diameter: 0.501”
    - Hole Offset: 1.690”
    - EDM notch and crack on short ligament side
  - Material: 2024-T351plate
    - Source: Kevin Walker’s recently updated tabular lookup

ERSI - A-10 Round Robin

- Priority #1 (Baseline Non-Cx, CA loading)
  - Loading: CA, R=0.1, max stress: 23 ksi
    - Stress represents gross cross-section (no hole) of the gauge section

Block file name:	*CP7T-Baseline-27APR*			
Max Normalized	**Min Normalized**	**Cycles**	**Component**	**Component Cycles**
1.00	0.10	1325	CA Block	1325
1.00	0.70	170	Marker	375
1.00	0.10	35		
1.00	0.70	170		
		1700	**TOTAL CYCLES**	**1700**

- Starting crack sizes:

Coupon CP7T-B-02

EDM	
Surface	**Bore**
0.00000	0.03209
0.02415	0.00000

Crack Front Points

Markerband	
Surface	**Bore**
0.02932	0.00000
0.03217	0.00641
0.03332	0.01698
0.02210	0.03368
0.00528	0.04093
0.00000	0.03965

Coupon CP7T-B-03

EDM	
Surface	**Bore**
0.00000	0.02363
0.02735	0.00000

Crack Front Points

Markerband	
Surface	**Bore**
0.04407	0.00000
0.04502	0.00343
0.04601	0.00575
0.04461	0.02467
0.04079	0.03723
0.02101	0.05583
0.01464	0.05998
0.00149	0.06248

ERSI - A-10 Round Robin

- Priority #2 (Baseline Non-Cx, CA loading)
  - Coupons FALSTAFF-B-01 through -03
    - Note: coupon IDs are for consistency with later FALSTAFF spectrum tests, however, these tests are subject to constant amplitude loading
  - Geometry
    - Thickness: 0.250”
    - Width (test section): 4.00”
    - Width (grips): 5.00”
    - Hole Diameter: 0.250”
    - Hole Offset: 2.000”
  - Material: 7075-T651plate
    - Source: Jake Warner’s IFF Round Robin

ERSI - A-10 Round Robin

- Priority #2 (Baseline Non-Cx, CA loading)
  - Loading: CA, R=0.15, max stress: 25 ksi
    - Stress represents gross cross-section (no hole) of the gauge section

Block file name:	*FALSTAFF-MarchOne (BASELINE)*			
Max Normalized	Min Normalized	Cycles by Line	Component	Component Cycles
1.00	0.15	1025	Primary Block	1025
1.00	0.70	125	Marker Band	275
1.00	0.15	25		
1.00	0.70	125		
		1300	TOTAL CYCLES	1300

  - Starting crack sizes:

X = surface
Y = bore

FALSTAFF-B-02

Band	EDM Notch
X	Y
0.00000	0.02499
0.01096	0.01315
0.02342	0.00000

Crack Front Points

X	Y
0.03231	0.00000
0.03411	0.00928
0.03342	0.01631
0.02594	0.03083
0.01257	0.04043
0.00620	0.04016
0.00000	0.03781

FALSTAFF-B-03

Band	EDM Notch
X	Y
0.00000	0.02260
0.00983	0.01159
0.02206	0.00000

Crack Front Points

X	Y
0.03329	0.00000
0.03449	0.00718
0.03405	0.01014
0.03501	0.01666
0.03054	0.02520
0.02502	0.03257
0.01639	0.04052
0.00534	0.04499
0.00000	0.04417

ERSI
Fatigue Crack Growth & Testing Committee
Durability Activity

Prepared by Adrian Loghin, Simmetrix Inc.

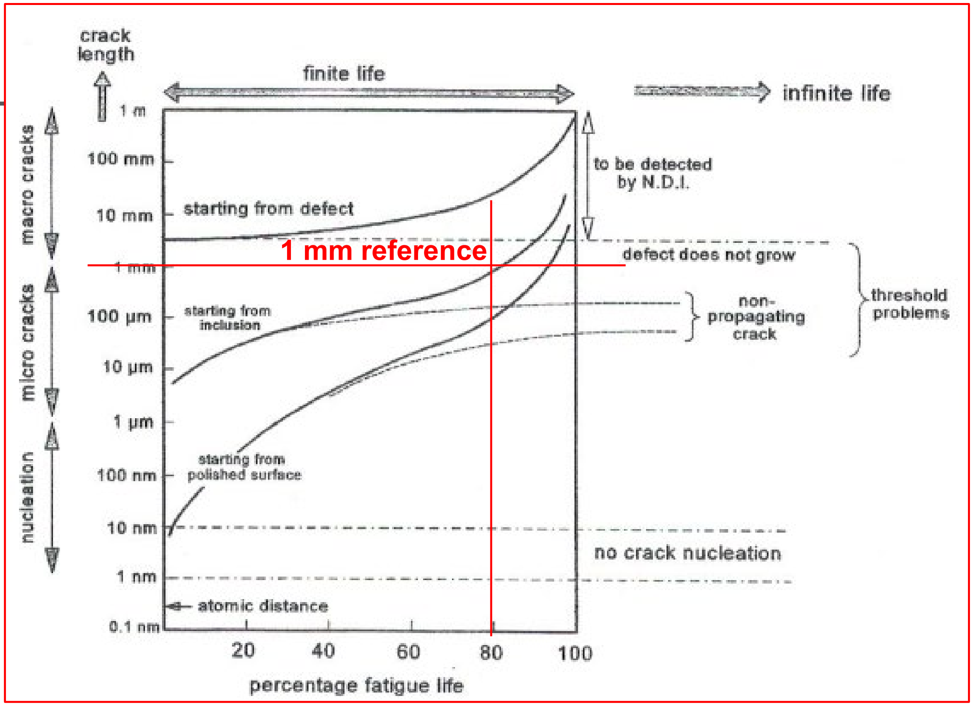
Importance

- Depending on material choice, component application, current fracture-critical methodology for metallic structural components (long crack behavior) might address ~20% of the total life.

- Durability methodology targets damage progression throughout the entire life of the material, from incubation and at different scales relative to the grain size (the common reference)

  - Much more difficult to address and implement due to technology readiness (measurement, modeling), cost, uncertainties that must be accounted for.

  - If such methodology would pass validation requirements, it could have a tremendous value in material assessment and component lifing. Even extending current damage tolerance (validation included) and NDE methodology to crack sizes lower than current detection limit will have a positive impact in industry.



Jaap Schijve, Fatigue of Structures and Materials, Springer, 2009.

TABLE 1

Classes of small fatigue cracks

Type of small crack	*Dimension*	*Responsible mechanism*	*Potential solution*
Mechanically small	$a \lesssim r_y$ [a]	Excessive (active) plasticity	Use of ΔJ, ΔS or crack-tip-opening displacement
Microstructurally small	$a \lesssim d_g$ [b] $2c \lesssim (5\text{–}10)\, d_g$	Crack tip shielding, enhanced $\Delta\epsilon_p$ Crack shape	Probabilistic approach
Physically small	$a \lesssim 1$ mm	Crack tip shielding (crack closure)	Use of ΔK_{eff}
Chemically small	Up to about 10 mm [c]	Local crack tip environment	

[a] r_y is the plastic zone size or plastic field of notch.
[b] d_g is the critical microstructural dimension, *e.g.* grain size, a is the crack depth and $2c$ the surface length.
[c] Critical size is a function of frequency and reaction kinetics.

Ritchie R.O., Lankford J., Overview of the small crack problem, 1986.

From Grains to Properties: Challenges (some …)

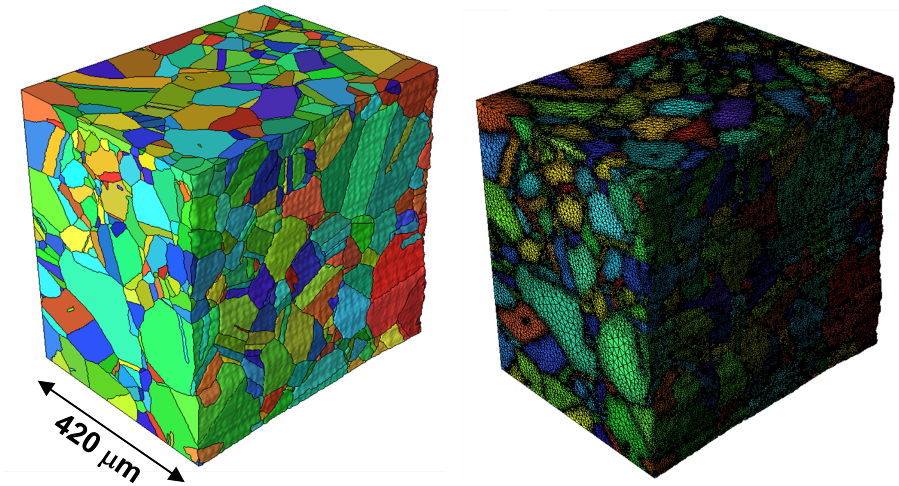
- Technology gaps to perform efficient and accurate 3D grain measurements prior to and during deformation process, capture crack nucleation and growth at various stages (microstructurally small, mechanically short)
- Statistical metrics to identify grain characteristics: size, shape, number of neighbors, orientation
- Validated crystal plasticity models for various material systems
- Similitude principle not applicable, local anisotropy
- Increased model complexity to capture relevant physics
- **Verification&Validation (V&V) and Uncertainty Quantification (UQ) across scale levels**

"Detailed observations over many years has shown that, under cyclic loading, all materials can go through four phases to failure: crack nucleation, stable growth of short cracks, stable growth of long cracks, final unstable failure.", Jeal R.H., Rolls-Royce, 1989.

Higher level of uncertainty for microstructural small and short crack lengths in comparison to long crack behavior

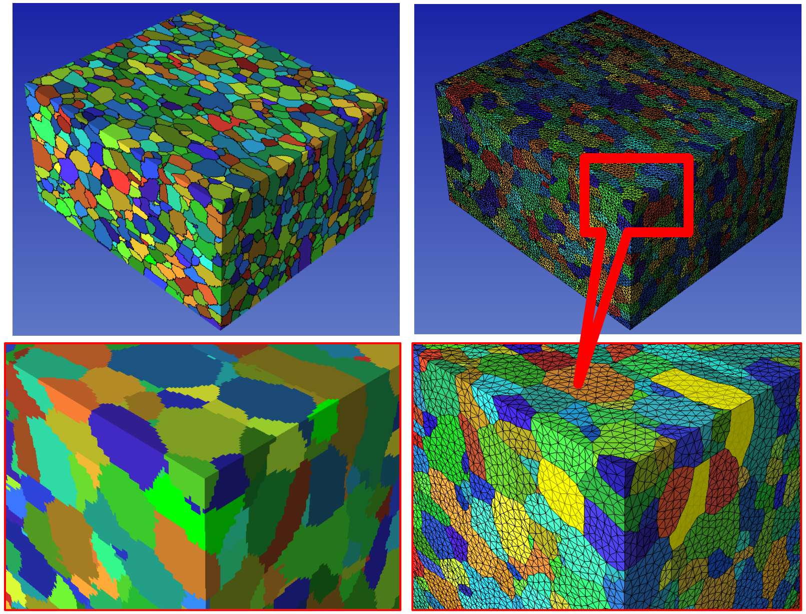
Examples of RVE digital reconstructions suitable for FEA

In718 RVE courtesy of UCSB



Reference: J. C. Stinville et. al., Multi-modal Dataset of a Polycrystalline Metallic Material: 3D Microstructure and Deformation Fields, https://www.nature.com/articles/s41597-022-01525-w, 2022.

Ti64 RVE courtesy of UCSB

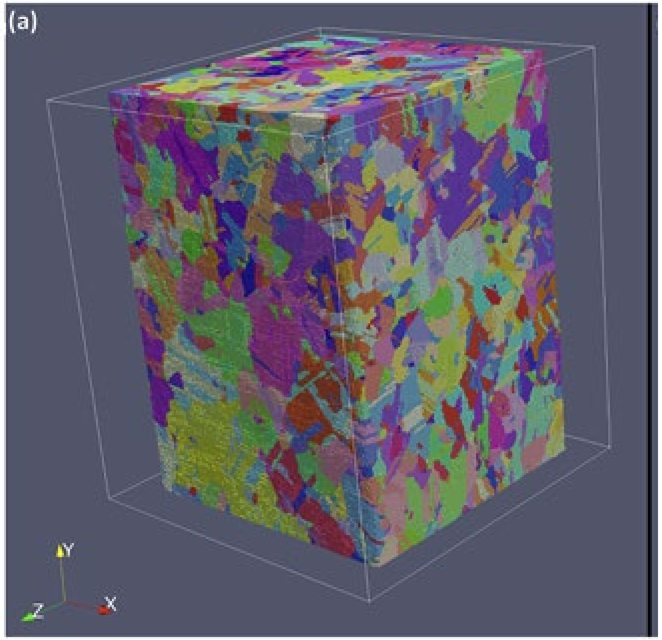


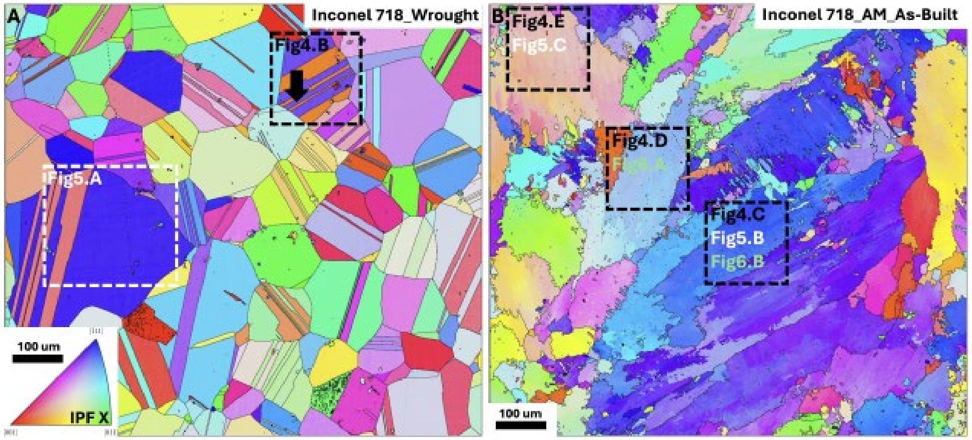
Reference: Klass O., Beall M., Loghin A., Enabling 3D FEA solvers perform mesoscale simulations, NAFEMS20 UK Conference, 2020.

Very limited data on crack nucleation, growth at microstructural scale

Other microstructure measurements

IN625, RVE, from an AFRL challenge





Reference: Chapman M. et al, **AFRL** Additive Manufacturing Modeling Series: Challenge 4, 3D Reconstruction of an IN625 High-Energy Diffraction Microscopy Sample Using Multi-modal Serial Sectioning, 2021.

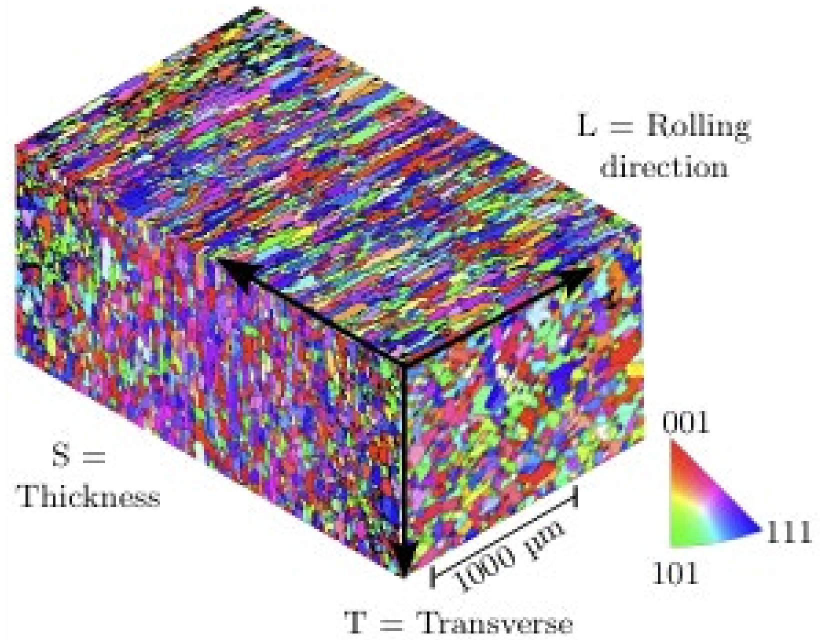
Reference: Calvat M. et al, Learning Metal Microstructural Heterogeity through Spatial mapping of Diffraction Latent Space Features, 2025.

Increased microstructural complexity in AM alloys

Other microstructure measurements

- It is important to note that an initial crack size of 0.005 inches (0.127 mm) that could be considered in crack propagation life assessment is equivalent to about half length of the grain along the rolling direction

AA2024-T351, EBSD performed along the three planes, ST, LT, SL (not a volumetric RVE)

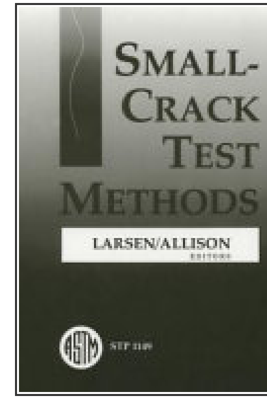


Reference: Kalina M., Schone V. et al, Fatigue crack growth in anisotropic aluminum sheets – phase-field modelling and experimental validation, 2023.

Since we are trying to identify some feasible objective under this task, should we consider investigating usage of initial crack sizes under 0.04″ in fatigue crack growth assessment?

AFRL related work / mostly high temp. applications

- Larsen J., et. al., Reducing uncertainty in fatigue life limits of turbine engine alloys, 2013.
- Small-crack test methods, ASTM STP 1149, 1992
- Caton M., et. al., Developing the capability to monitor small fatigue crack growth under elevated temperature, ultra-high conditions, 2011
- Rosenberg A., et. al., The variability of fatigue in notched bars of IN100, 2012.
- Larsen J., et. al., Prognosis of Turbine Engine Materials, ASIP 2007.
- Manning S.D., et. al., Durability methods development, AFFDL-TR-79-3118, 1979.



Is there anything that we can use from prior work in this ERSI activity?

More Literature (just some...)

Selection of some review publications

- Jaap Schive, Fatigue of Structures and materials, Springer, 2009.
- Anton Hohenwarter, Thomas Leitner and Reinhard Pippan, Fatigue Crack Propagation Across the Multiple Length Scales of Technically Relevant Metallic Materials, Annual Review of Materials Research, 2024.
- P. Chowdhury, H. Sehitoglu, Mechanisms of fatigue crack growth – a critical digest of theoretical developments, 2016.
- Stinville J.C., et. al., Competing Modes for Crack Initiation from Non-metallic Inclusions and Intrinsic Microstructural Features During Fatigue in a Polycrystalline Nickel Based Superalloy, Metallurgical and materials Transactions A, 2018.
- Sangid M., The physics of fatigue crack propagation, International Journal of Fatigue, 2025.
- Davidson D., et. al., Small Fatigue Cracks, SwRI, 2007.
- Suresh S. and Ritchie R.O., Propagation of short fatigue cracks, International Metals Reviews, 1984.
- Ritchie R.O., Lankford J., Overview of the small crack problem, 1986.

TMS White Papers related to durability, V&V, opportunities in material behavior modeling

- The Minerals, Metals & Materials Society (TMS), Accelerating the Broad Implementation of V&V in Computational Models of the Mechanics of Materials and Structures, 2020, www.tms.org/VVaccelerator
- The Minerals, Metals & Materials Society (TMS), Modeling Across Scales: A Roadmapping Study for Connecting Materials Models and Simulations Across Length and Time Scales, 2015, www.tms.org/multiscalestudy
- The Minerals, Metals & Materials Society (TMS), Advanced Computation and Data in Materials and Manufacturing: Core Knowledge Gaps and Opportunities, 2018, www.tms.org/coreknowledge

Short term goals

- It could be beneficial if we understand what was achieved at AFRL in the last decade regarding short crack behavior on high temperature material applications. It would be nice if we could have somebody from AFRL provide a review of the public work related to short crack behavior.
- Should we consider usage of initial crack sizes < 0.04 inch in fatigue crack growth assessments as a potential task under this activity?
  - This was proposed by an attendee (cannot remember who) in a regular ERSI Tcon.
  - The goal makes sense because it could impact current practices

The purpose of keeping this activity alive

- There will be difficulties holding this activity alive within this committee since there are no durability activities or technology developments reported by the group members, round-robin challenges where members can participate.

- There are efforts outside this group (I would say mostly academic research) that focus on durability modeling. Acknowledging the advancement, failures or challenges coming from these activities can be beneficial for this group.

- There are and there will be technological advancements related to imaging, DIC, test procedures, microscopy, modeling procedures that aim at quantification of mechanical behavior of materials used in aerospace industry. It could be very beneficial for this group to discuss these advancements because we can learn and improve our own technology.

Ogden Air Logistics Complex

U.S. AIR FORCE

Cold Expanded Hole Tolerance Effects: Testing

Evan Ross[1], Jacob Warner[1], Trevor Shoemaker[1]

2025 ERSI Workshop
Layton, UT
April 30 – May 1, 2025

[1] United States Air Force

Motivation

- Questions ERSI has heard often:
  - How do we know that each hole was CX'd within tolerance?
  - Can the fatigue life be accurately (or conservatively) predicted?
- What does "in-tolerance" CX look like for A-10 drain holes?
  - What I_a levels could arise?
  - What RS fields are induced?
  - How does I_a impact fatigue performance?
  - Can we accurately predict the fatigue performance?

SHD (in)	t (in)	D (in)	Ia (%)	Notes
0.3560	0.0104	0.3542	5.34	Max tol - 0.003" SHD
0.3580	0.0104	0.3542	4.75	Max tol - 0.001" SHD
0.3590	0.0104	0.3542	4.46	Max in-tol
0.3605	0.0100	0.3540	3.74	Nominal
0.3620	0.0098	0.3530	2.93	Min in-tol
0.3630	0.0098	0.3530	2.64	Min tol + 0.001" SHD
0.3650	0.0098	0.3530	2.08	Min tol + 0.003" SHD

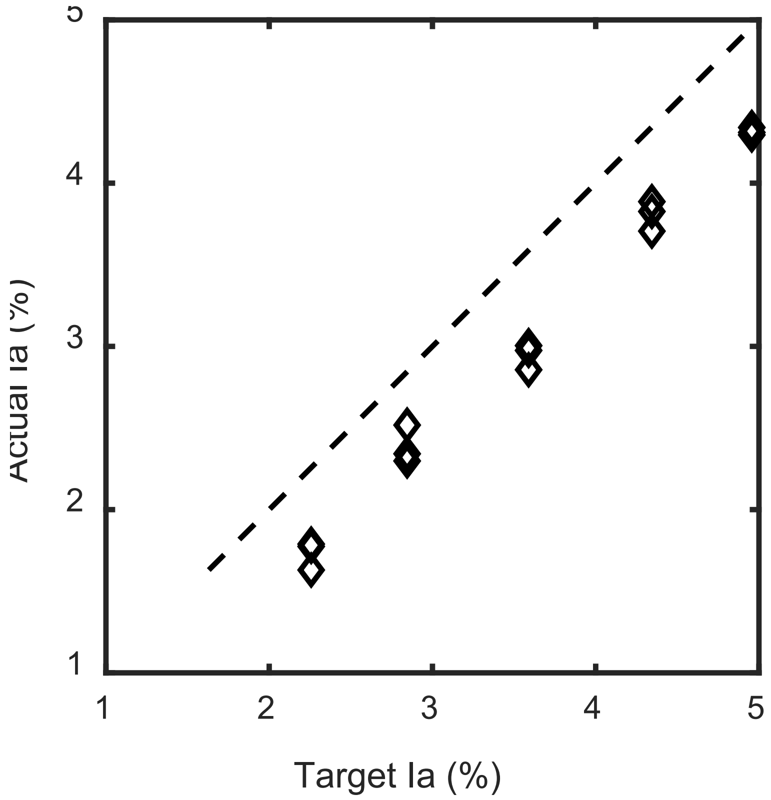
$$I_a = \frac{(D + 2t - SHD)}{SHD} \times 100\%$$

Where:

D = *Major Mandrel Diameter*
t = *Sleeve Thickness*
SHD = *Starting Hole Diameter*

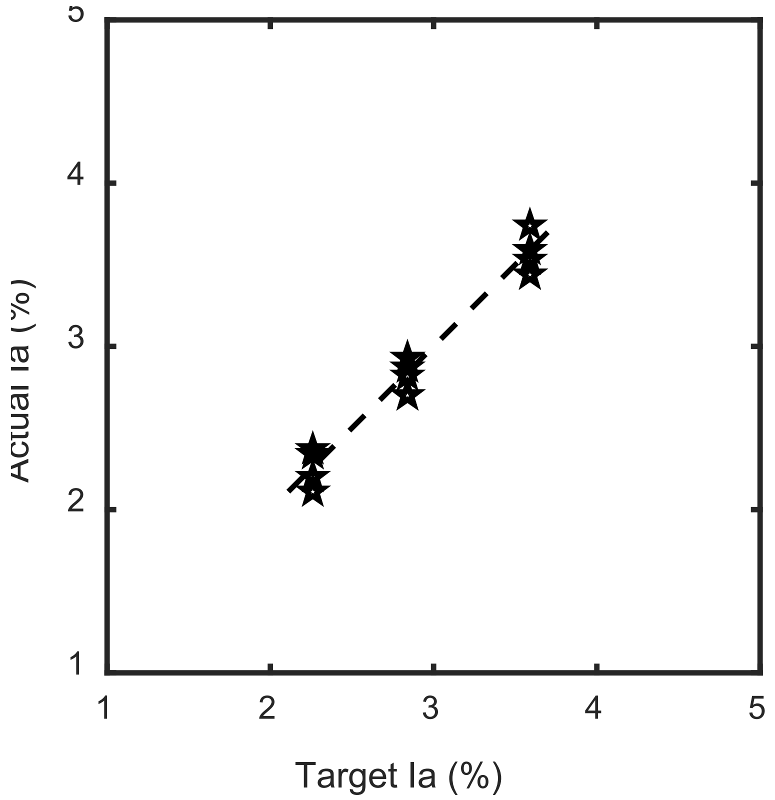
RS Field Characterization

Loc1



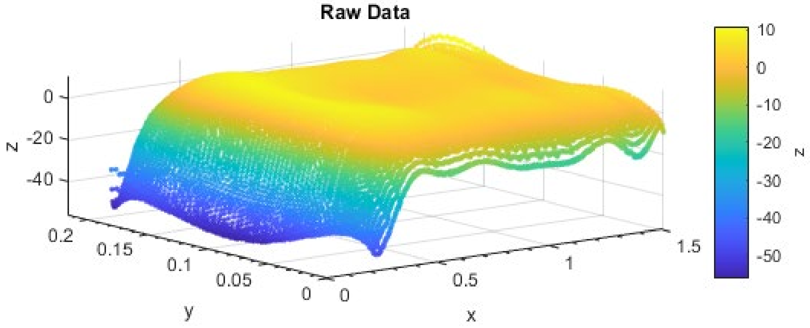
- 2 sets of 15 contour specimens
- I_a varied <0.3% among replicates

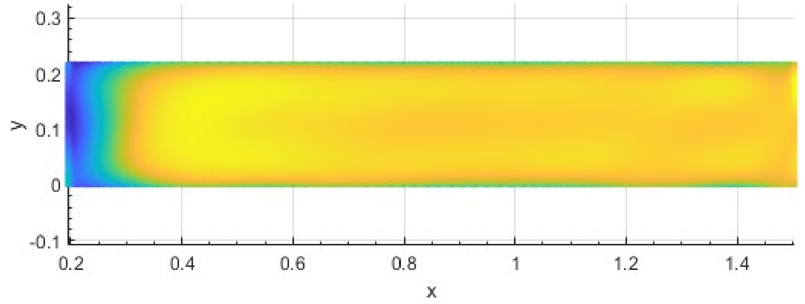
103N



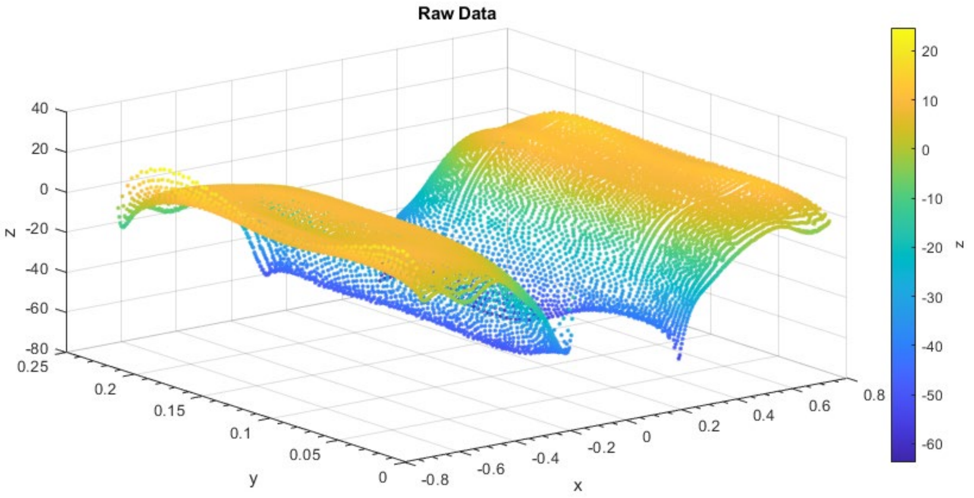
RS Field Characterization

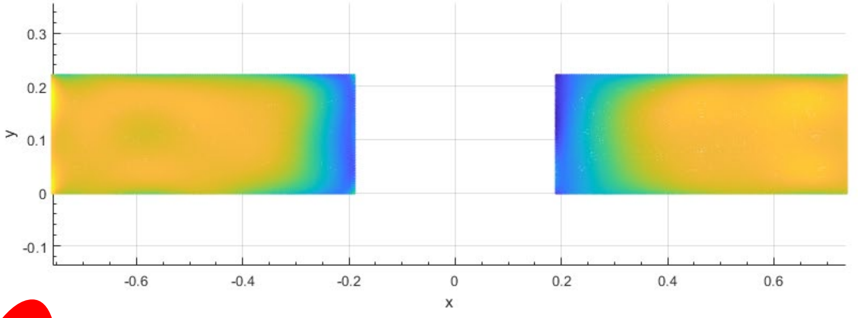
Loc1





103N





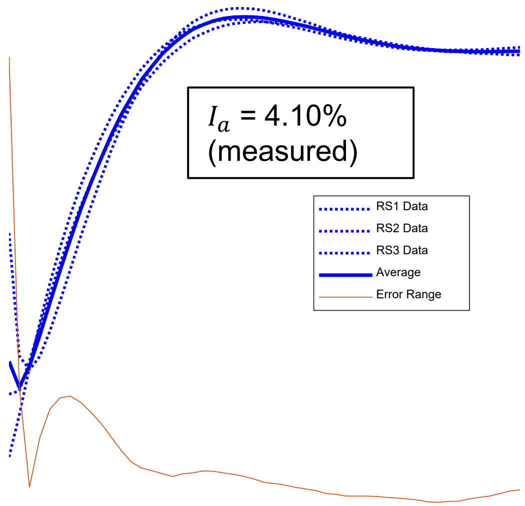
- **2 sets of 15 contour specimens**
- **I_a varied <0.3% among replicates**
- **Loc1: Single-sided**
- **103N: Double-sided; RT, LT, Avg fields**

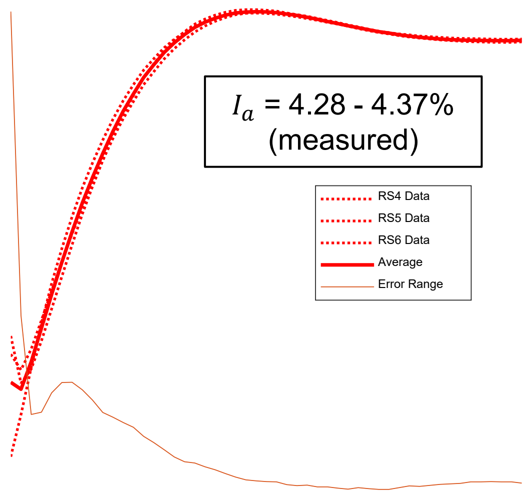
✓ **Lengthwise split (stress-relief cut) before contour measurement** ✗

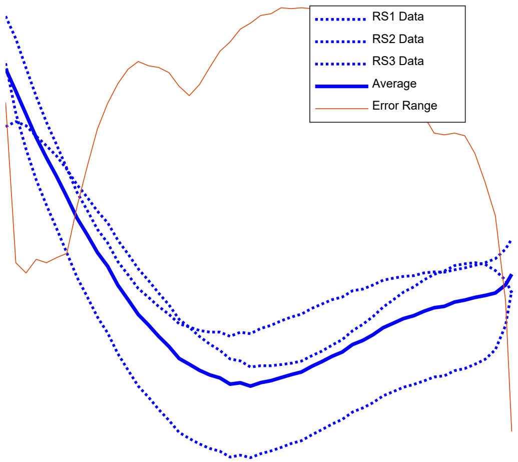
RS Field Characterization (Loc1)

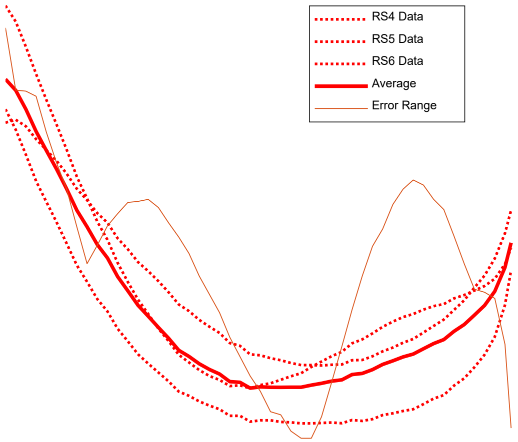
OGDEN AIR LOGISTICS COMPLEX

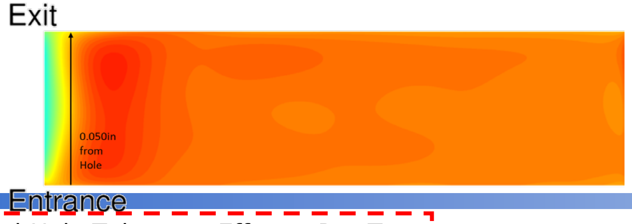
- **Data from 6 specimens shown (groups of 3 replicates)**
- **At mid-thickness, fields varied by 18-35 ksi at the hole bore**
- **At 0.05” from hole bore, fields varied >5 ksi**
- **Is this specimen-to-specimen variation?**







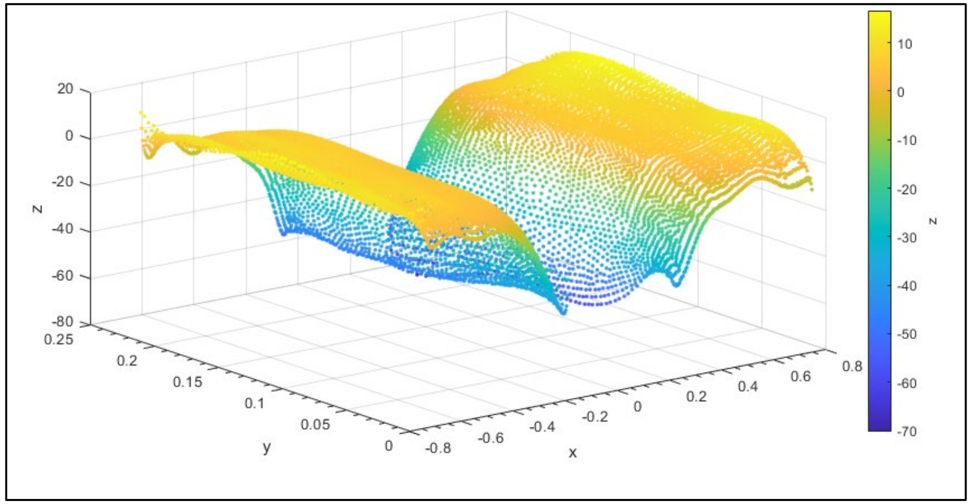


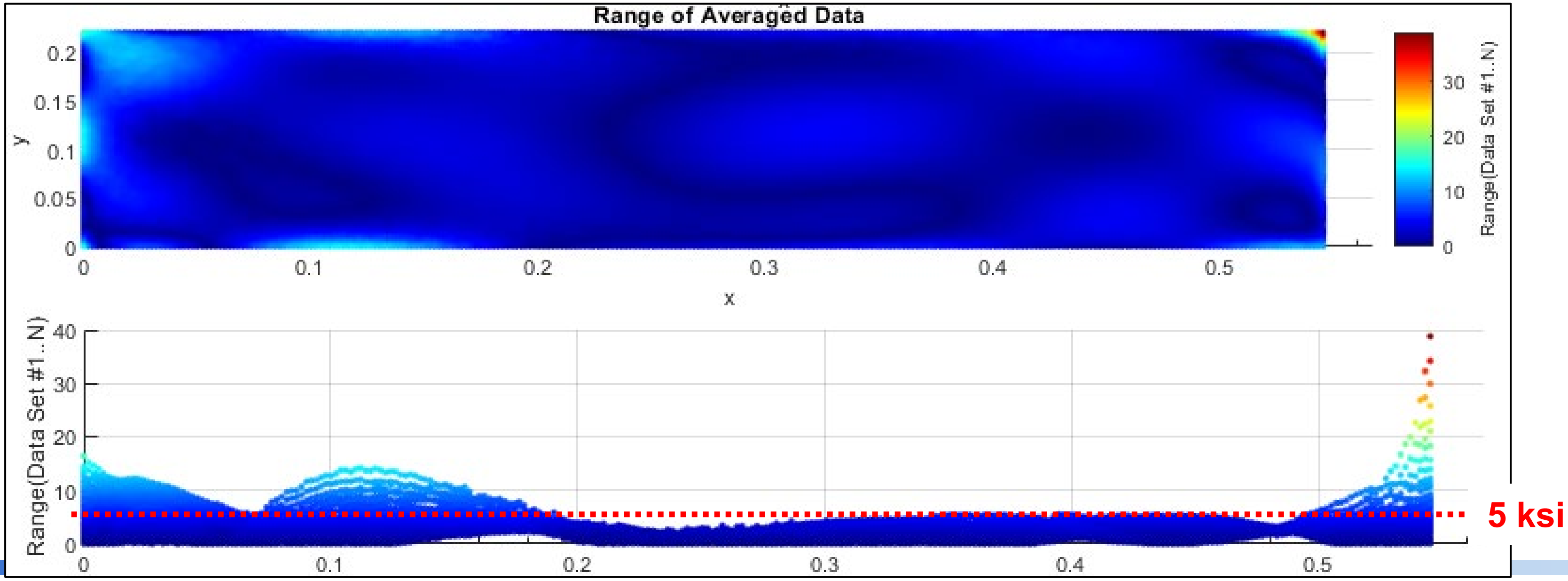


Shoemaker, T. K. Cold-Expanded Hole Tolerance Effects: Pre-Test Predictions (AFGROW Workshop 2023)

RS Field Characterization (103N)

- Double-sided fields should be true replicates
- Fields were compared point-by-point
- >5 ksi difference, typical across 15 specimens
- Remember: No stress-relief cut was performed on the 103N samples prior to contour measurement.
- How does this translate to fatigue life?

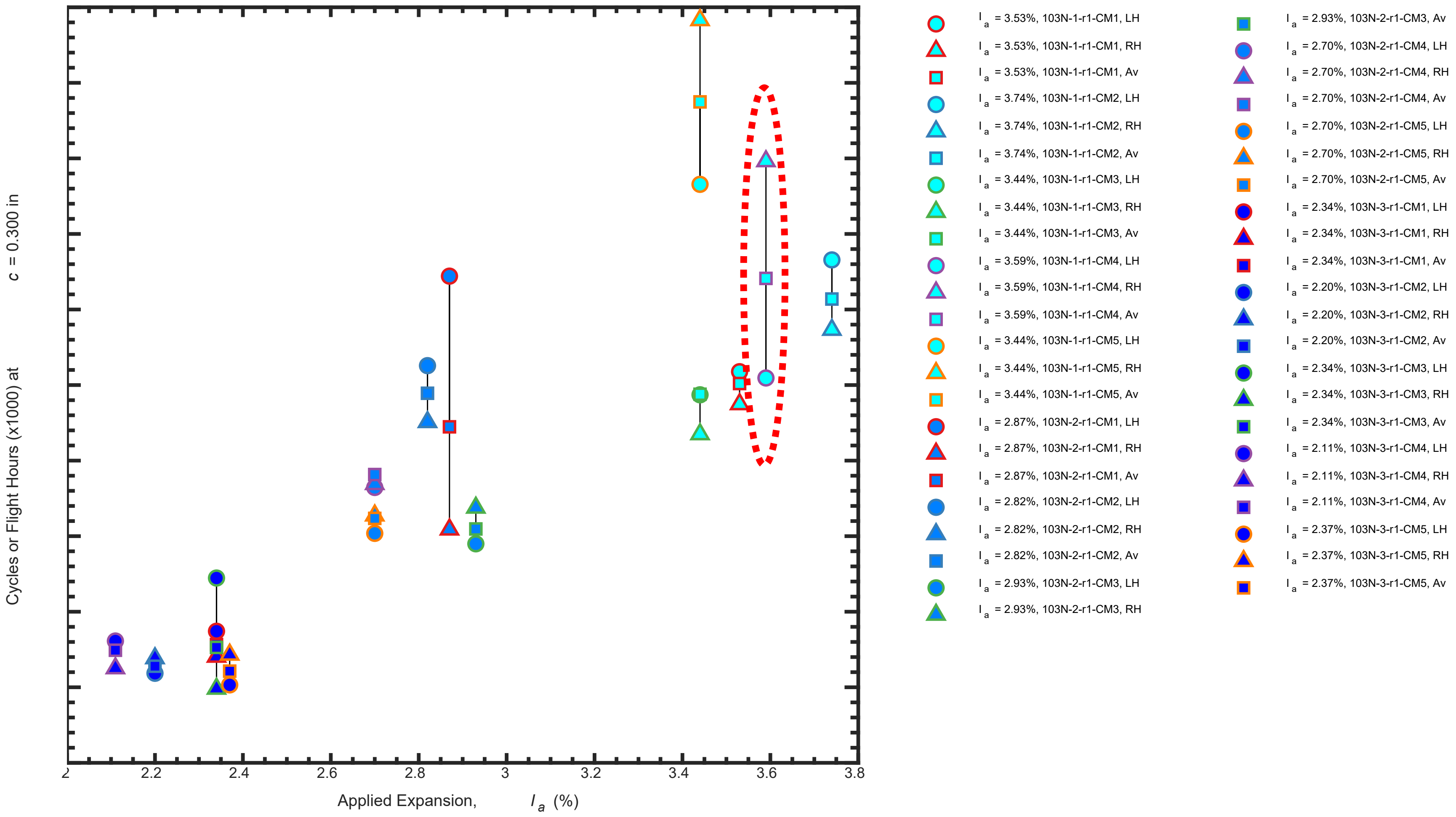




Shoemaker, T. K. Cold-Expanded Hole Tolerance Effects: Pre-Test Predictions (AFGROW Workshop 2023)

RS Field Characterization (103N)

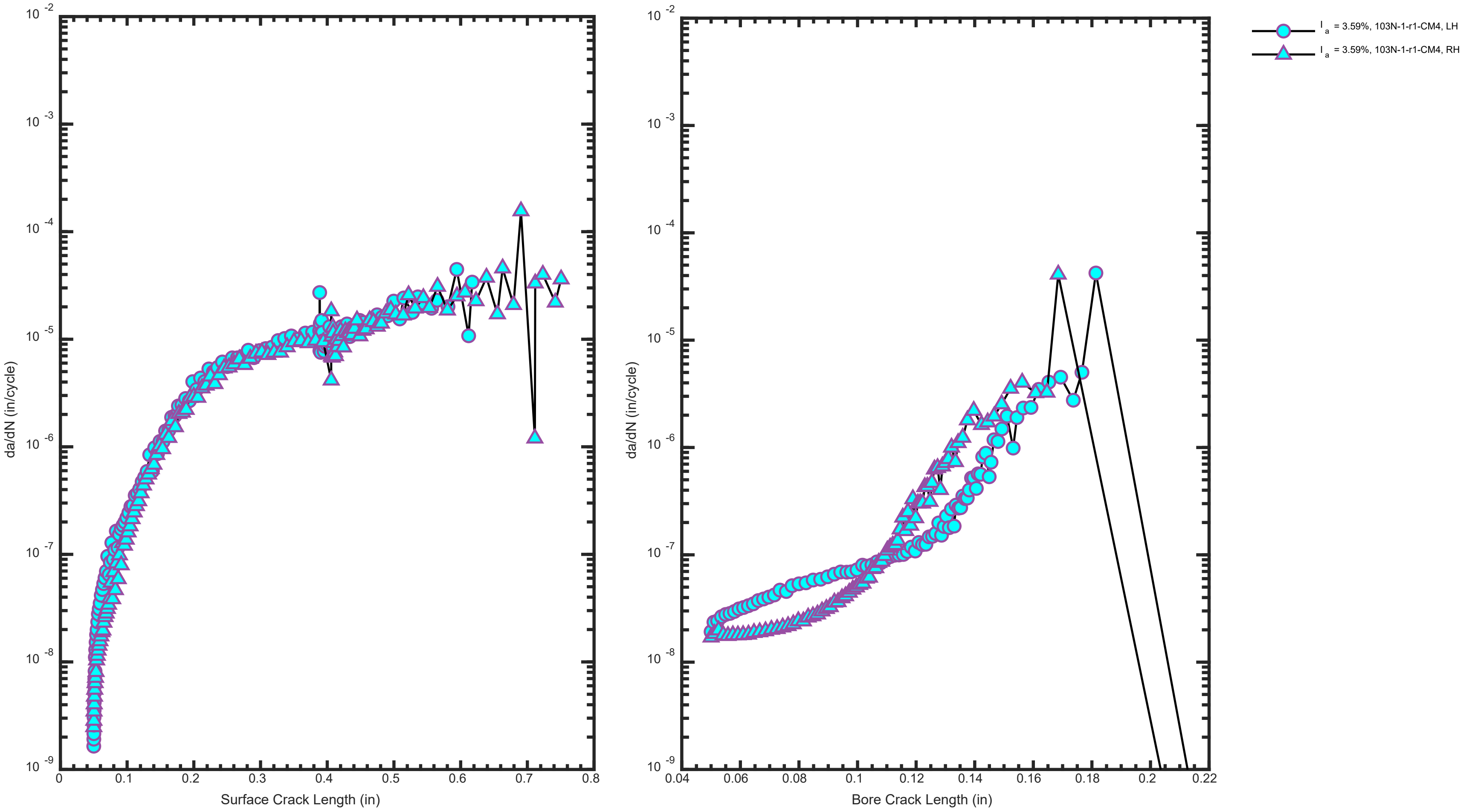
- **BAMpF predictions varied widely between RH-LH sides of this hole**
- **Other predictions with seemingly comparable RS fields were more repeatable**
- **What part of growth is impacted most?**



Shoemaker, T. K. Cold-Expanded Hole Tolerance Effects: Pre-Test Predictions (AFGROW Workshop 2023)

RS Field Characterization (103N)

- **Surface crack growth rates were comparable**
- **Differences showed primarily in the bore crack growth rate**
- **Intuitive based on RS uncertainty at the hole bore**
- **Does testing show similar variation?**

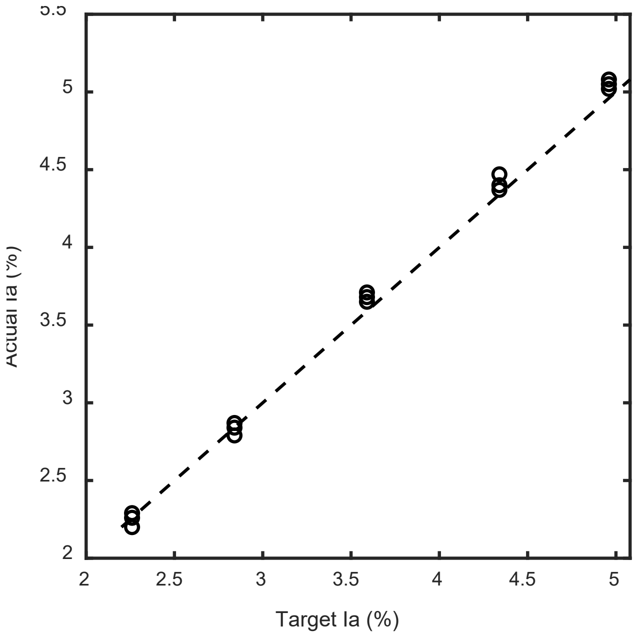


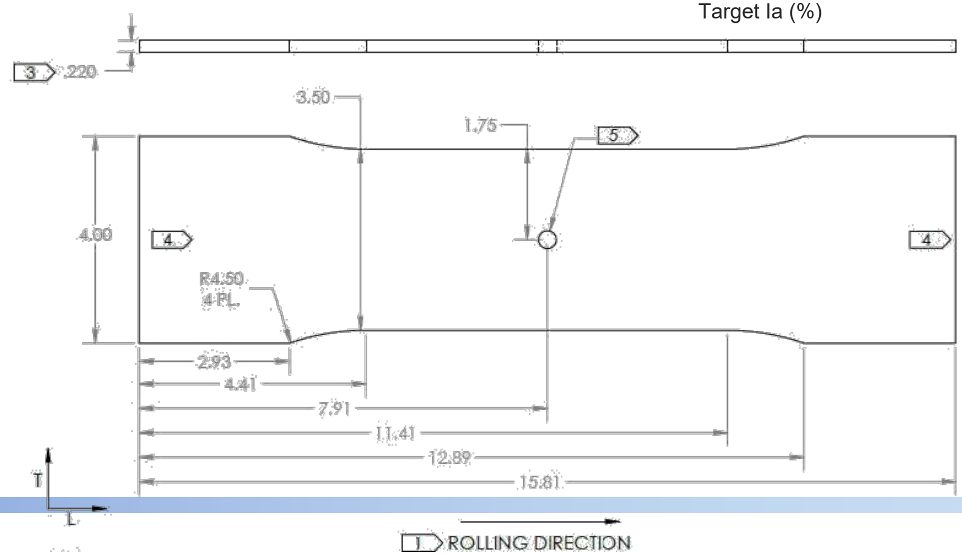
Shoemaker, T. K. Cold-Expanded Hole Tolerance Effects: Pre-Test Predictions (AFGROW Workshop 2023)

Test Conditions

- 15 total fatigue specimens
  - 5 I_a levels, 3 replicates each
  - All within 0.1% of target I_a
- 2024-T351 plate
  - 0.22" thick, 3.5" wide, ~16" long
- EDM corner notch (entrance face)
- Precracked to ~ 0.020"
- Flight spectrum applied at 31.7 ksi to failure
- Surface and bore crack length measurements
- Marker bands for fractographic analysis

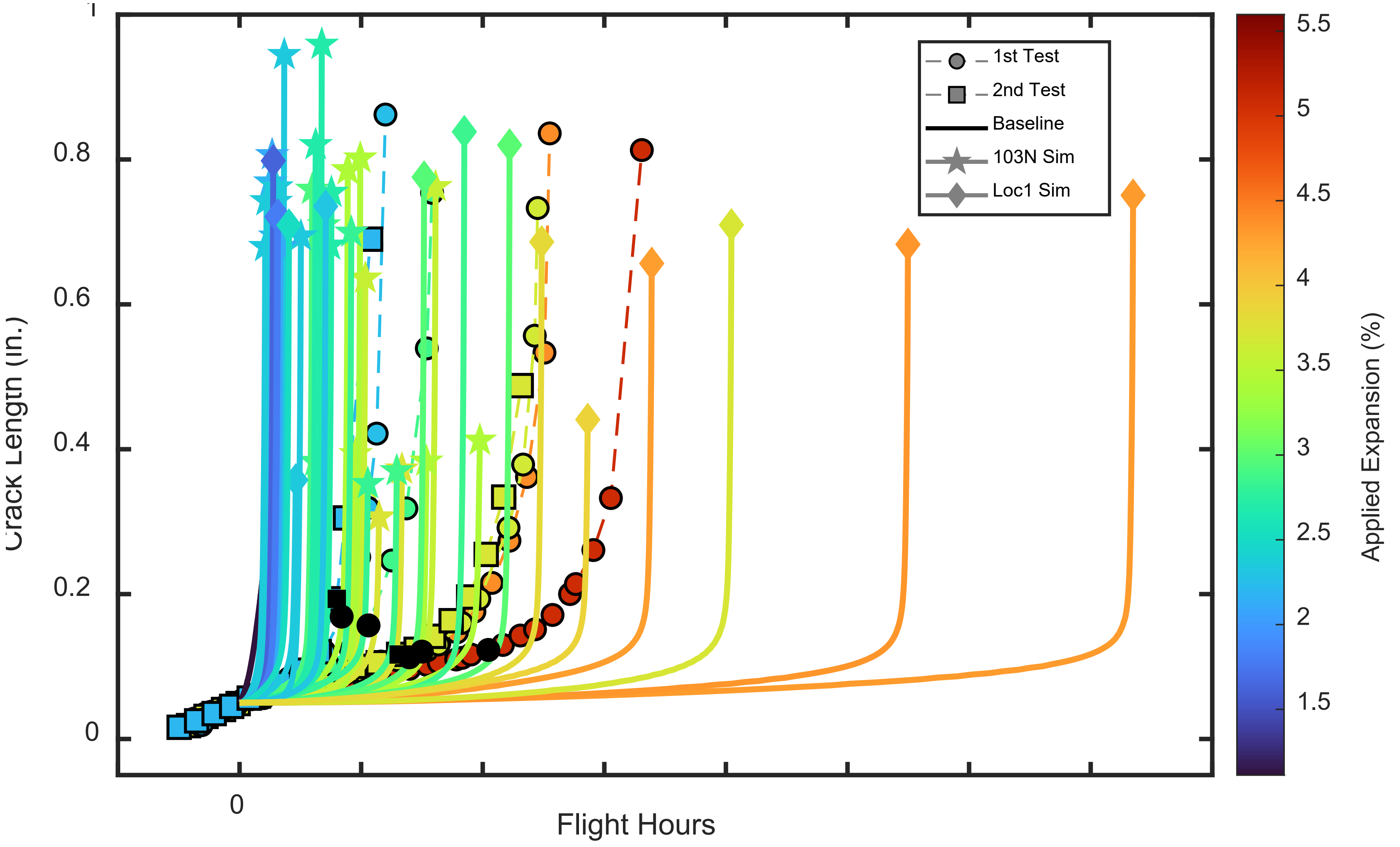
Qty.	Ia (%)
3	4.96
3	4.34
3	3.59
3	2.84
3	2.26





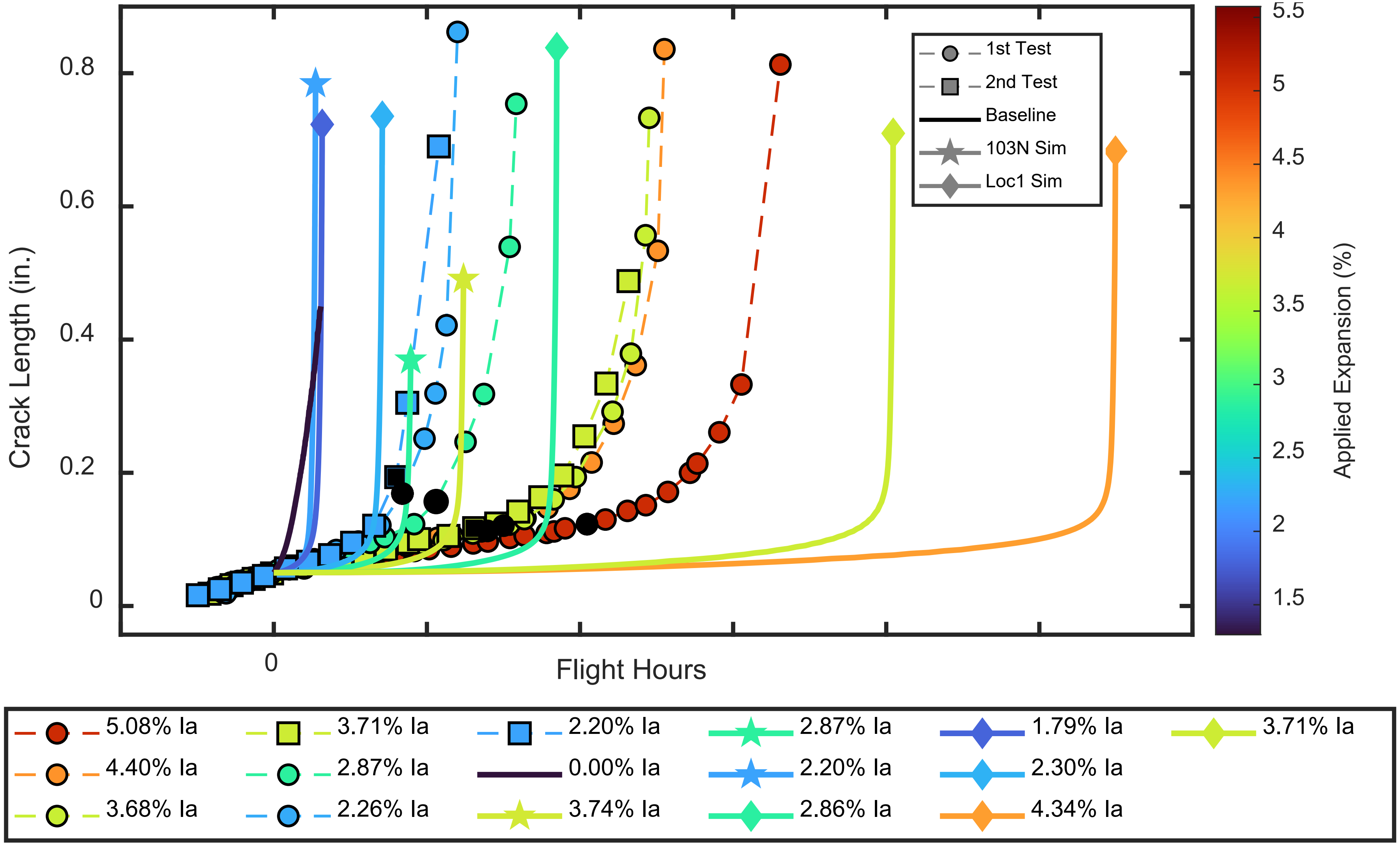
Test Results

- **Test data with all 45 simulations (15 from Loc1 and 15 RH/LH pairs from 103N)**
- **Notice color scale: Longest test has higher I_a than any simulation**



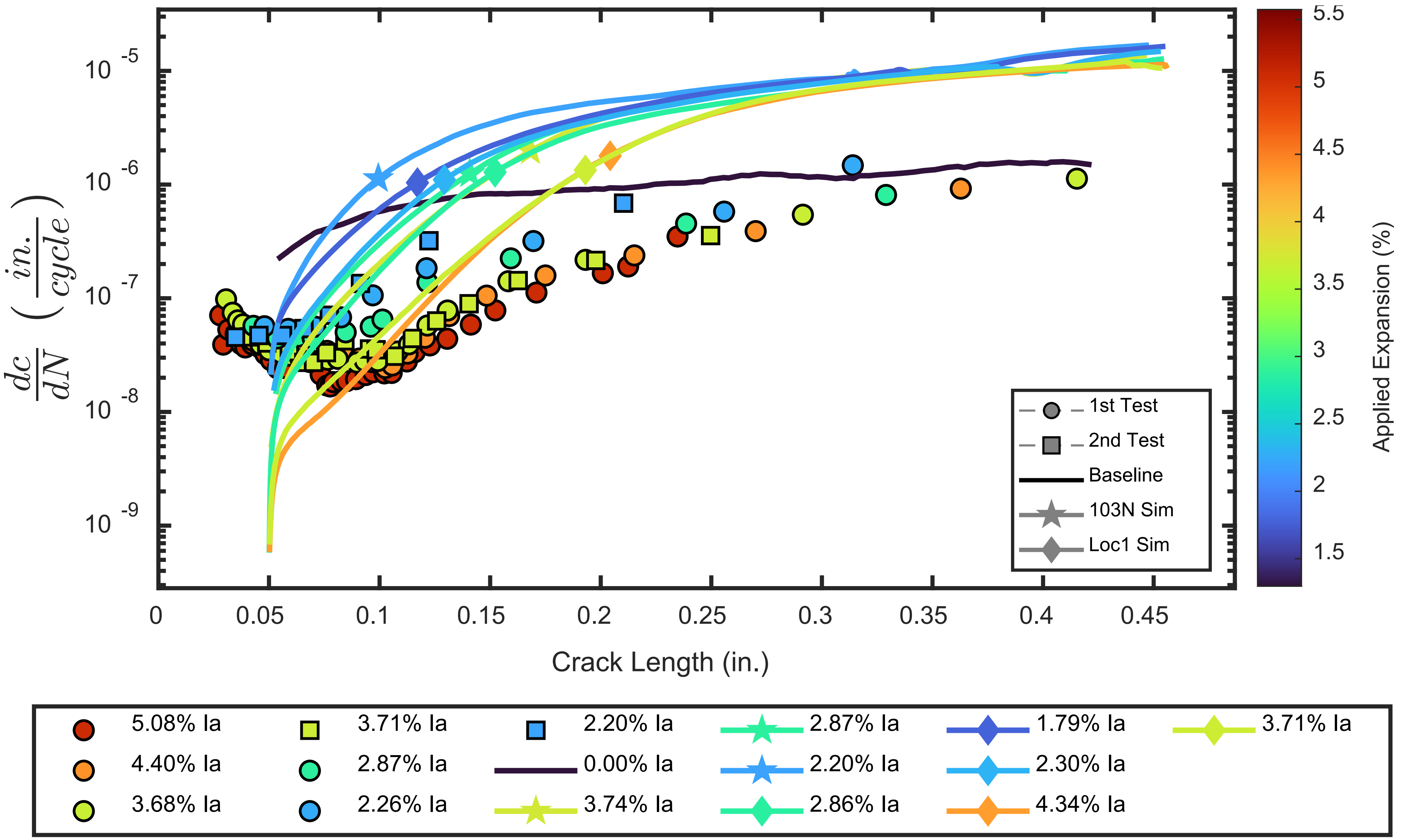
Test Results

- 9 simulations: 1 per target I_a level, plus a no-RS baseline
- Test data pinned at 0.05"
- Life correlates with I_a
- Lives are all similar orders of magnitude, but test vs simulation curve shapes differ



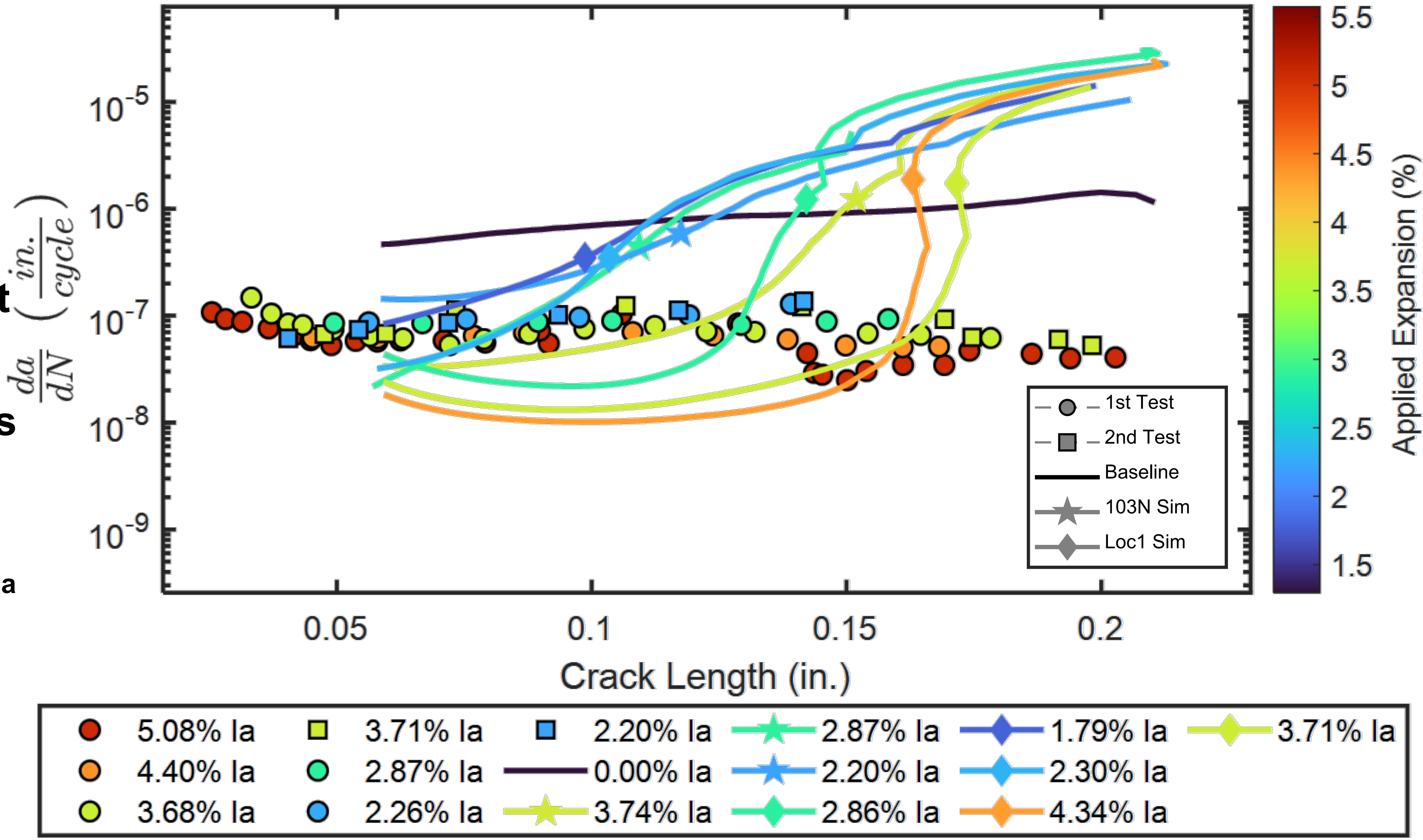
Test Results

- **Surface crack growth rates correlate with I_a**
- **Shape mismatch, especially near-bore**
- **Tests seem to approach baseline simulation at longer c**
- **Contour fields maintain ~3ksi but specimens may be reaching ~0 RS**
- **We have not done baseline (I_a = 0) tests**



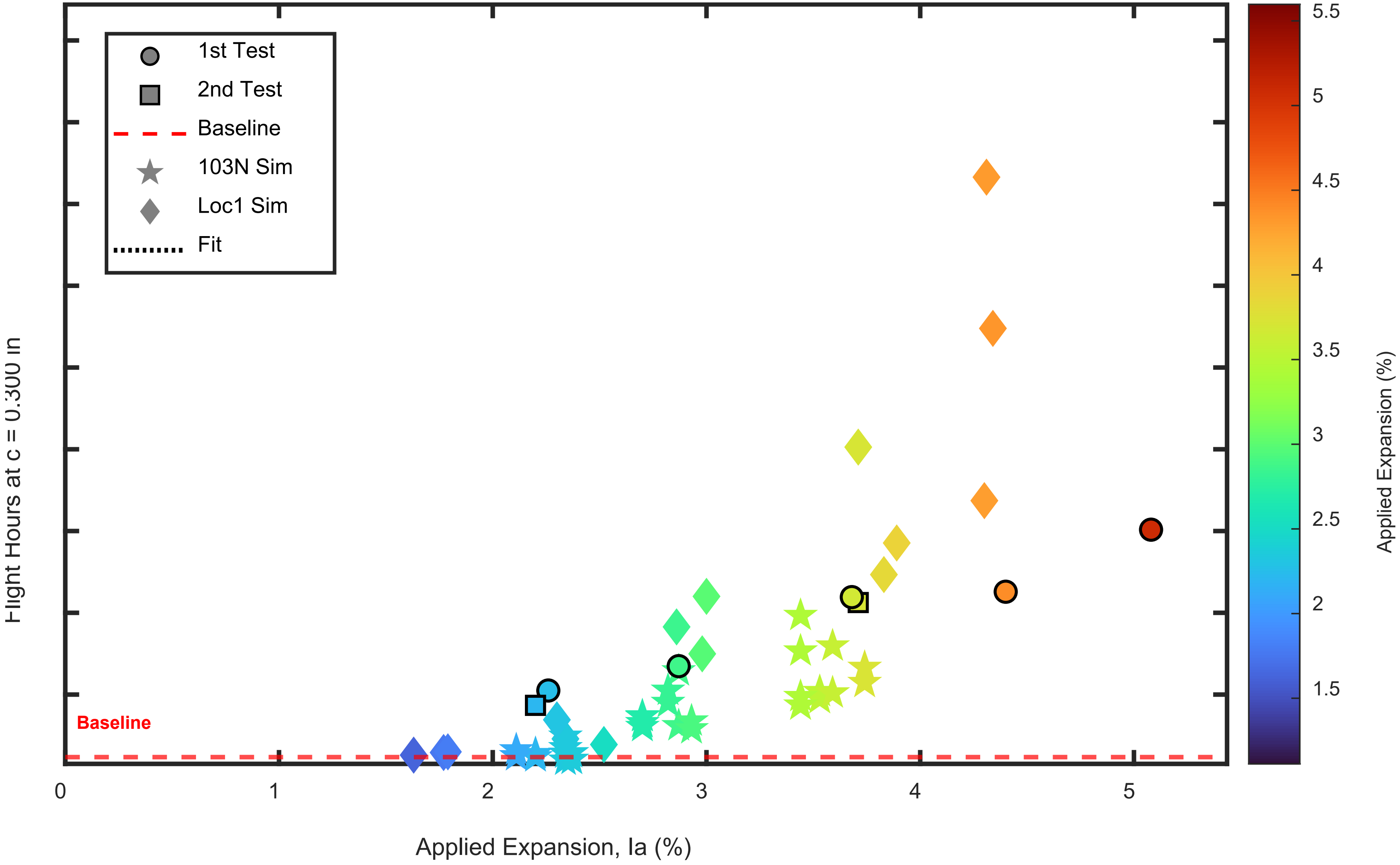
Test Results

- Bore crack growth rates are less distinguishable by I_a
- Monotonically decreasing with slight inflection <0.05”
- Test results show less variation across all I_a than predictions showed for matched I_a
- Would this trend hold at different test stresses?



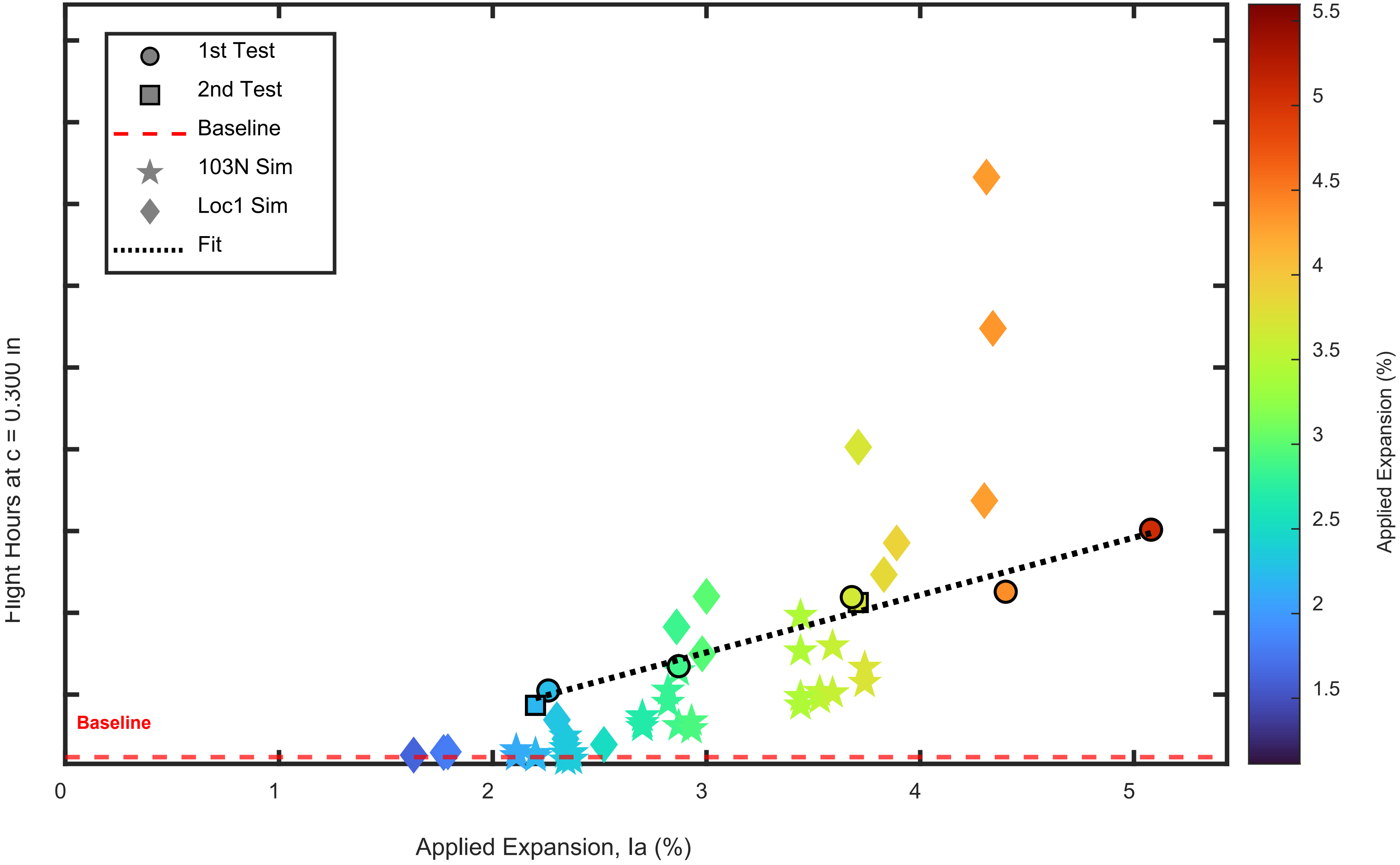
Test Results

- **Excellent test repeatability compared to simulation**



Test Results

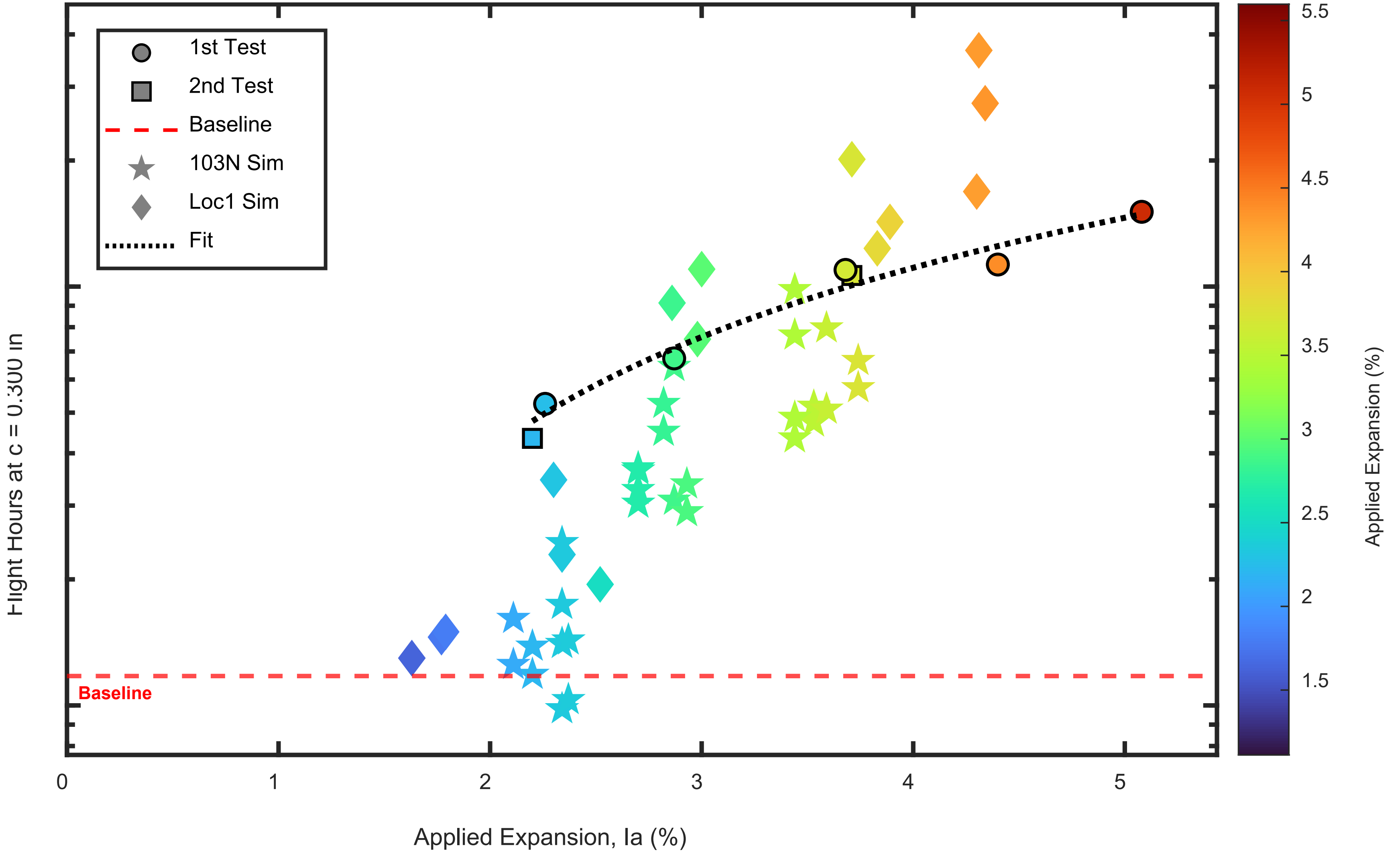
- **Excellent test repeatability compared to simulation**
- **Test life seems to have a linear relationship with I_a**
- **Simulations aren't as clear**



Test Results

OGDEN AIR LOGISTICS COMPLEX

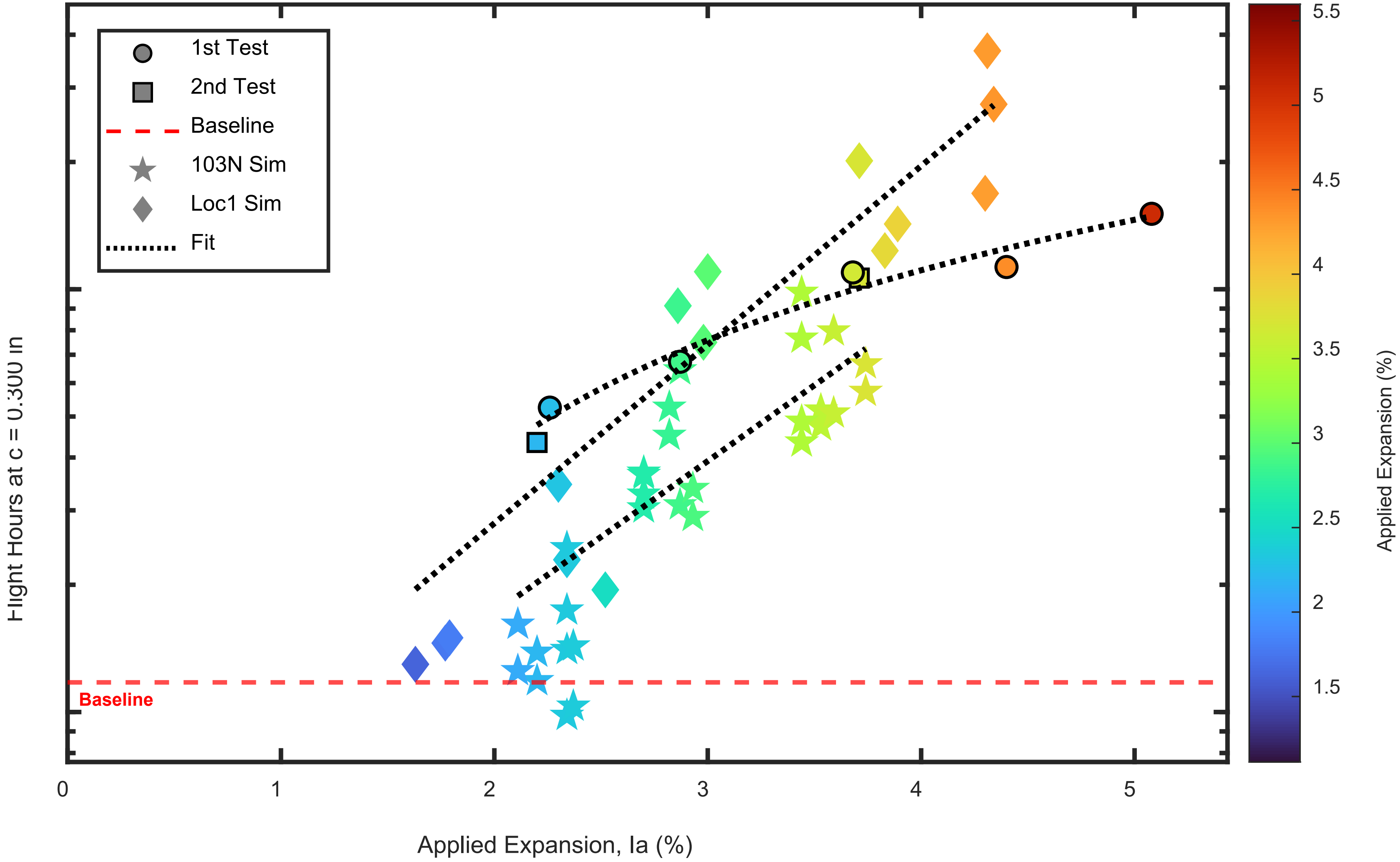
- **Logarithmic Y-axis shows simulations more clearly**
- **Possible overall log-linear trend**
- **Loc1 simulations have consistently longer life than 103N**



Test Results

OGDEN AIR LOGISTICS COMPLEX

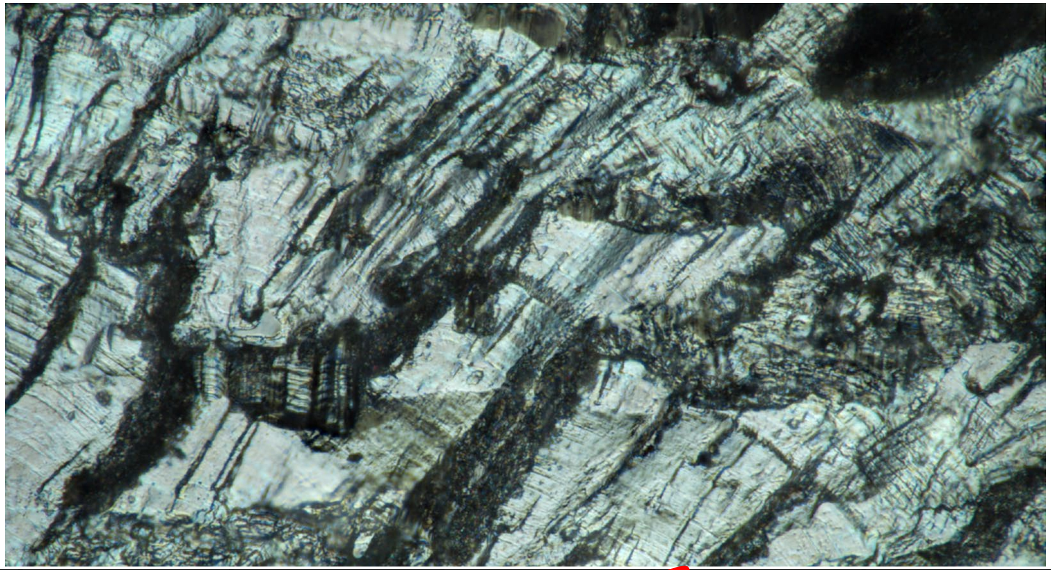
- Logarithmic Y-axis shows simulations more clearly
- Possible overall log-linear trend
- Loc1 simulations have consistently longer life than 103N
- Treated separately, simulations aren't as (log) linear
- Are we seeing the impact of the contour stress-relief cut?

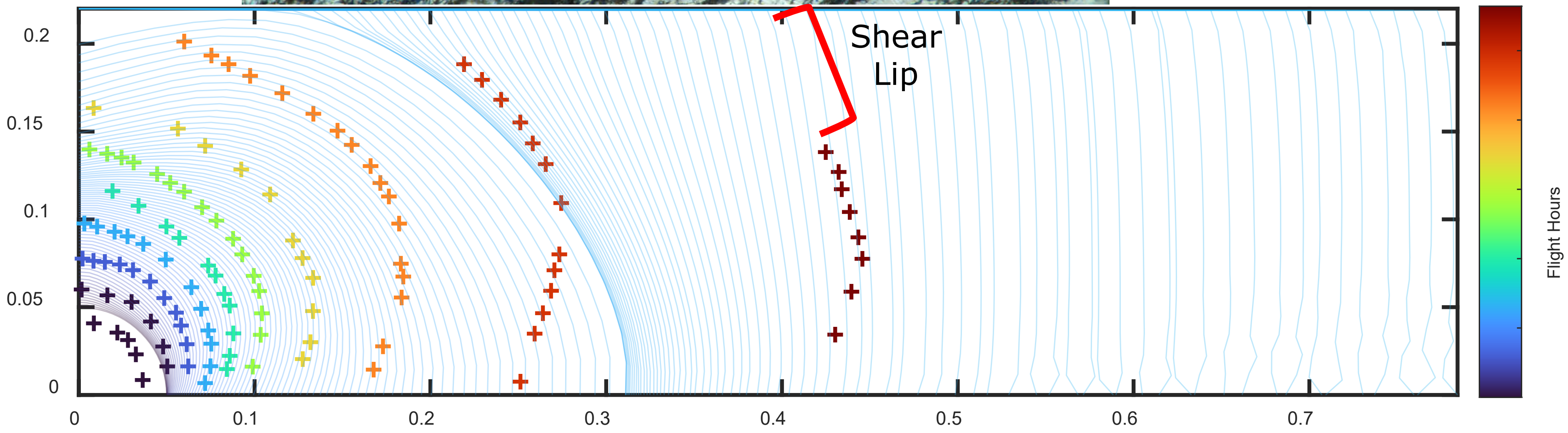


Marker Bands

OGDEN AIR LOGISTICS COMPLEX

- Optical microscope was used to map bands
- Surface marked well, and most were identifiable
- Later bands are shortened due to shear lip formation
- Aiming to use these maps to back-calculate RS fields with StressCheck





Conclusions

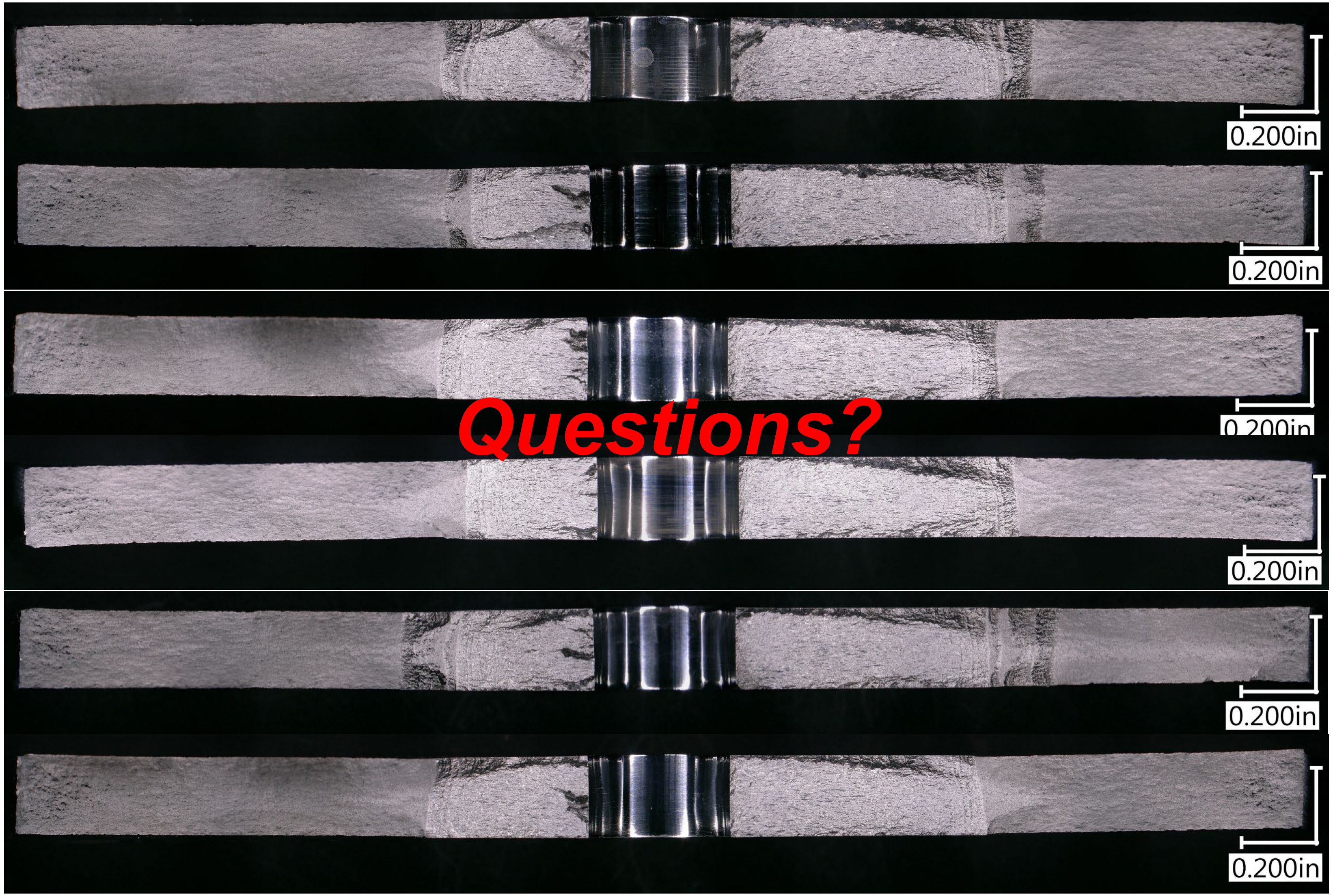
- I_a variation, even within tolerance, greatly impacts fatigue life
- With well-controlled I_a, CX fatigue tests can be very repeatable
- Tight control of I_a should be the standard
- Less scatter in test than simulation highlights measurement uncertainty

Acknowledgements

- Jake Warner
- Hill AFB Materials Lab
  - Trevor Shoemaker
  - Mikki Keller
  - Carl Grimaud
  - Chad Stamey

Discussion

- We are building a high-quality dataset
- Have we achieved our goal to understand the impact of I_a on fatigue life?
- Are there other ways to use replicates with tightly-controlled I_a?
- Considering options:
  - Continue with tests to build confidence
  - Vary loading to examine other facets of the problem
    - Lower stress to see if bore crack growth rates separate
    - Raise stress to see the limit of CX benefit
    - Change spectrum (or constant amplitude) to see different load interactions
- What would make this dataset most useful?



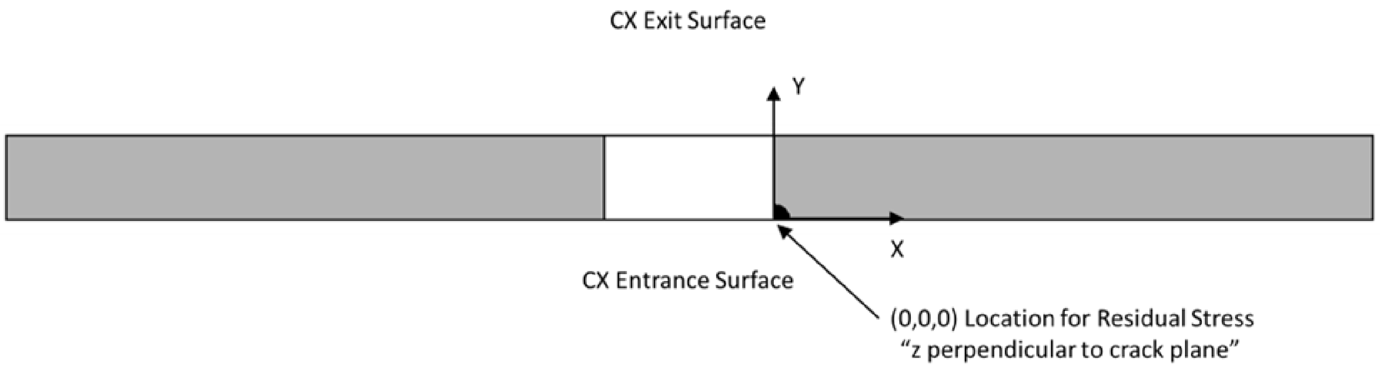
Questions?

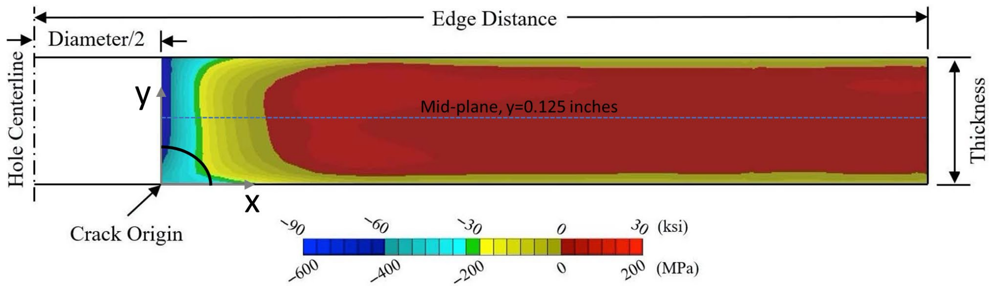
Analysis and Test
RR#1 Cx Holes Revisit

Kevin Walker
Initial version: 1 August 2024
Rev1 : OCT/NOV 2024
Rev2 : MAR 2025

Re-cap on RR#1

Benchmark Condition #	Material	Specimen Type	Thickness (in)	Width (in)	Hole Diameter (in)	Hole Edge Margin	Loading	Max Stress (ksi)
1	2024-T351	Non-CX Baseline	0.25	4.00	0.50	4.0	CA (R=0.1)	10
2		CX						25
3		Non-CX Baseline				1.2		10
4		CX						25





ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Issues considered in review

- Used AFGROW 2 point analysis
- SIF Solution – Advanced Model
- Updated/improved Finite Width Correction (Harter)
- Rate Data (threshold and low-rate regime)
- Surface crack closure correction (βR)
- Offset distance for Residual Stress Profile
- Discovered an issue with the RS database where it adds a final line in the data which needs to be removed!! With this corrected, the results look much better!!

ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Issue with RS database

- RS file with 100 lines ends like this:

1.69697	-0.86	0
1.714646	-0.86	0
1.732323	-0.86	0
1.75	-41.2	0

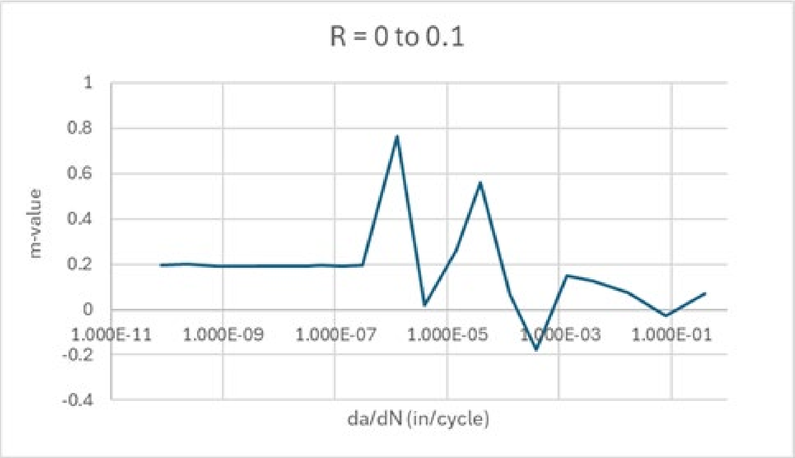
- But the last line is incorrect!! Should be deleted

Rate Data

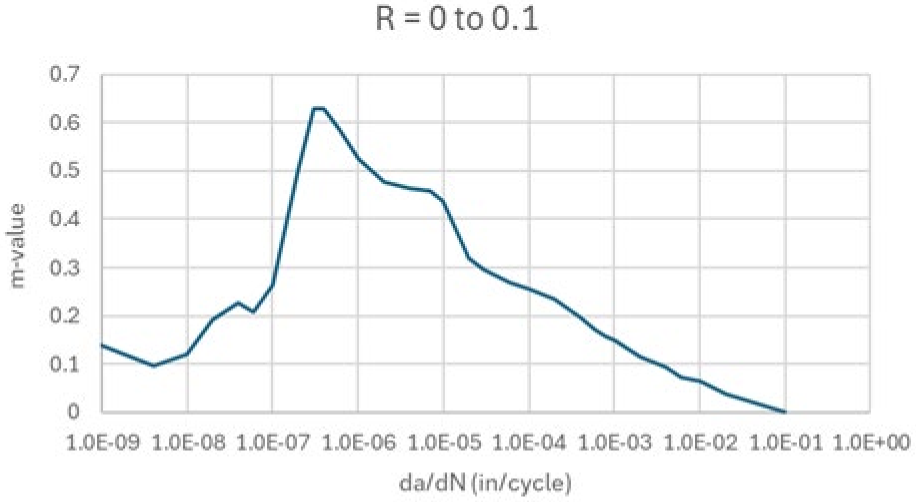
- Rate data has been through several revisions
- Newman analysis and modelling has shown that the threshold is lower than earlier fits
- Jim Harter showed that the "m-curve" fits for the updated rate data were not "smooth" as preferred for the Harter-T method, so some very minor changes were made to correct that, but it had very little impact on the analysis results

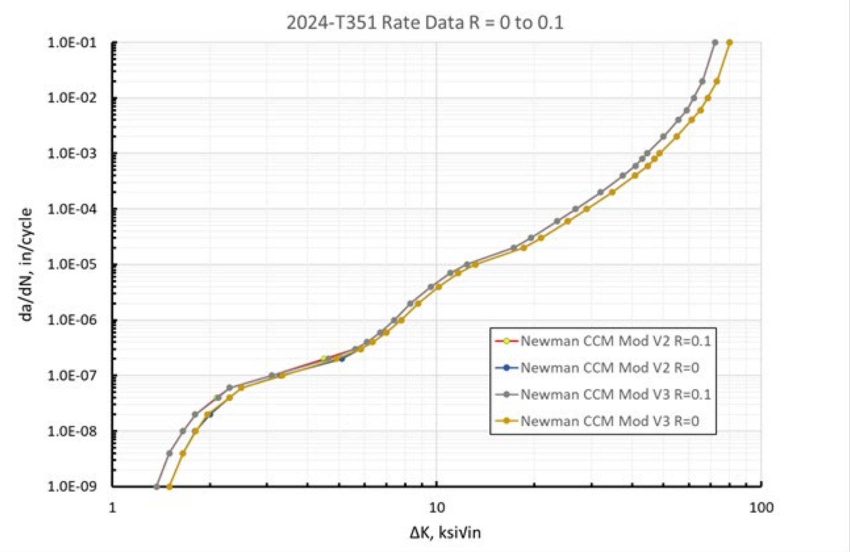
m-curve correction

V2



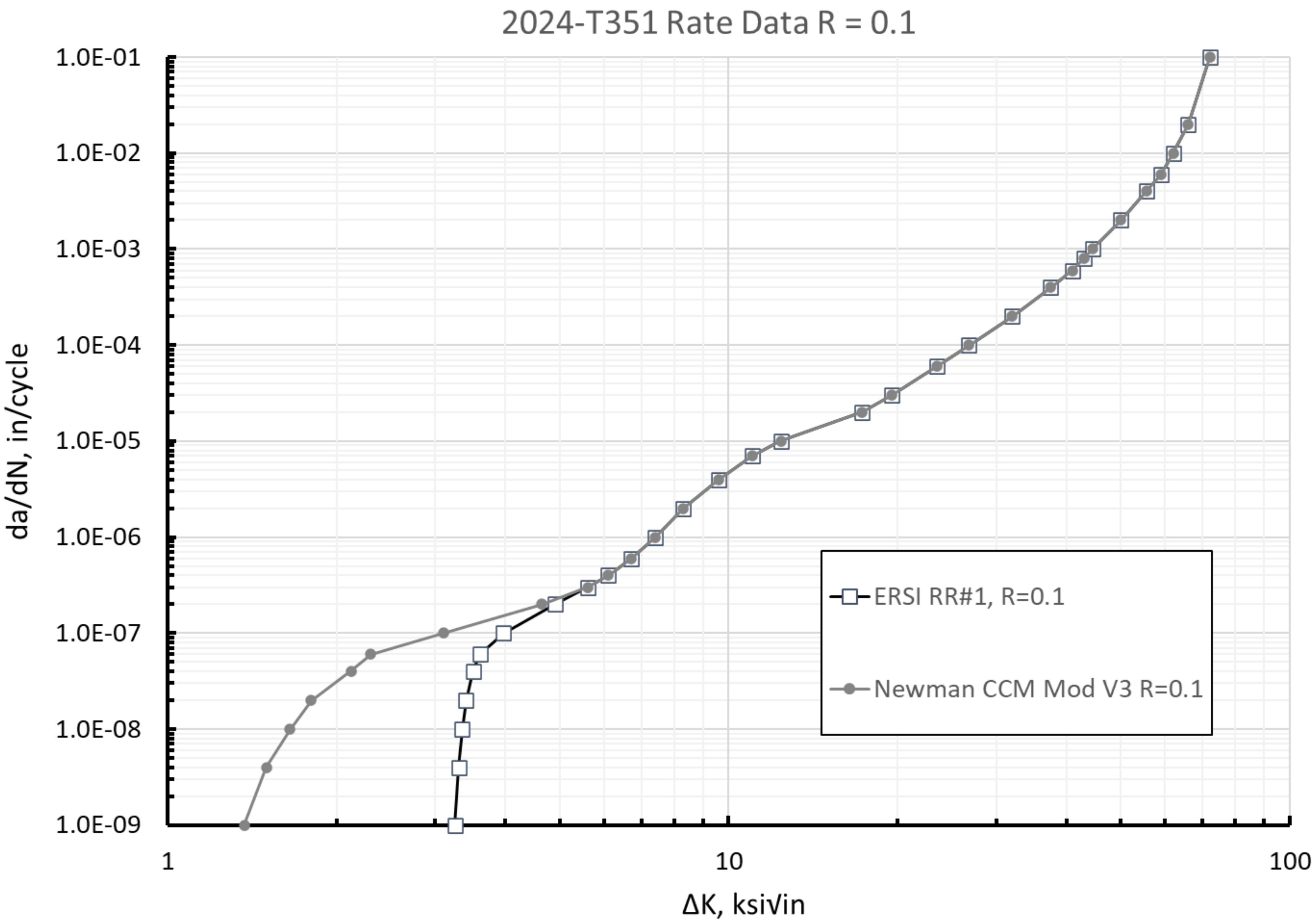
V3



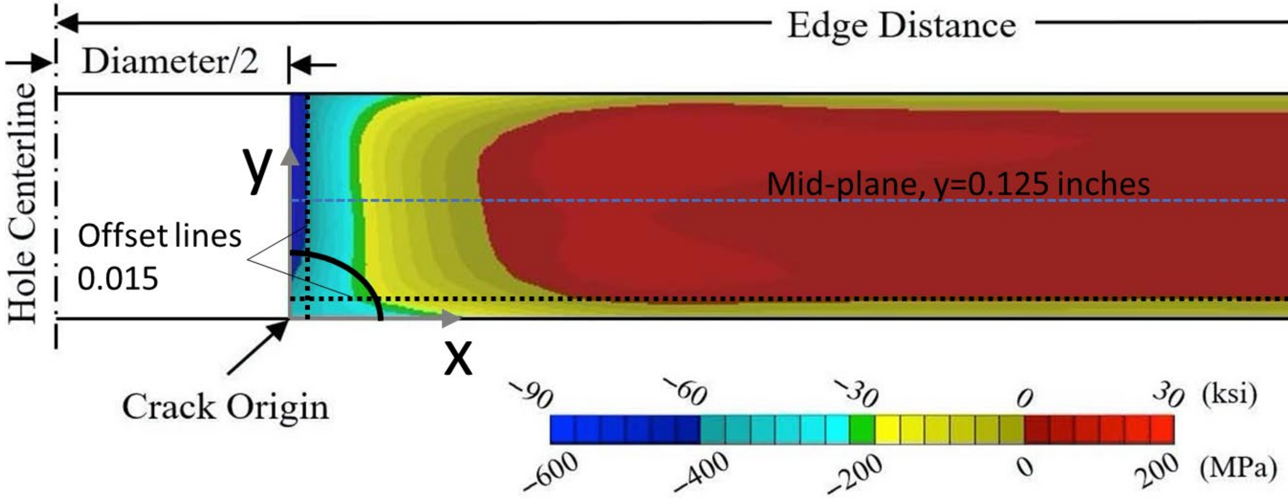


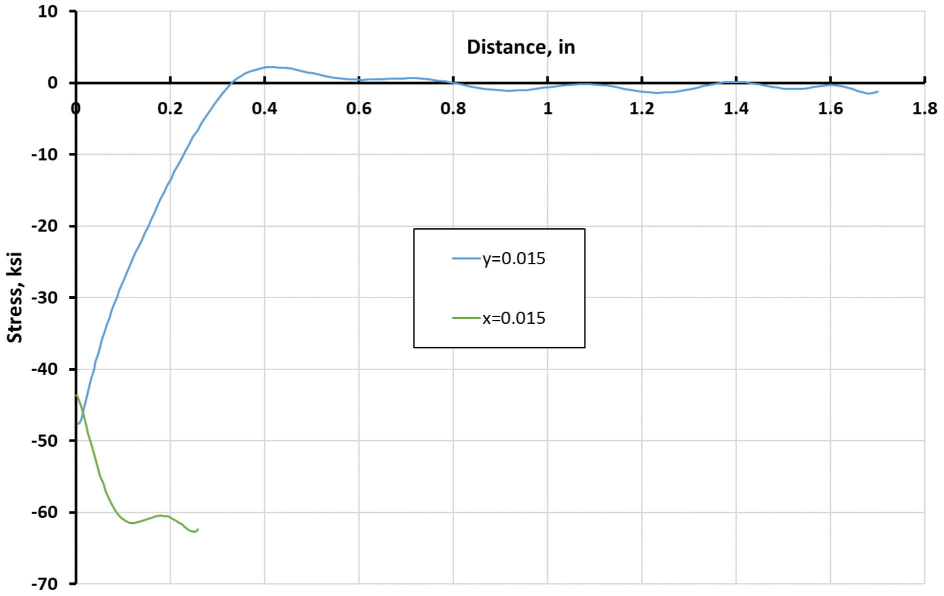
ERSI
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Rate Data



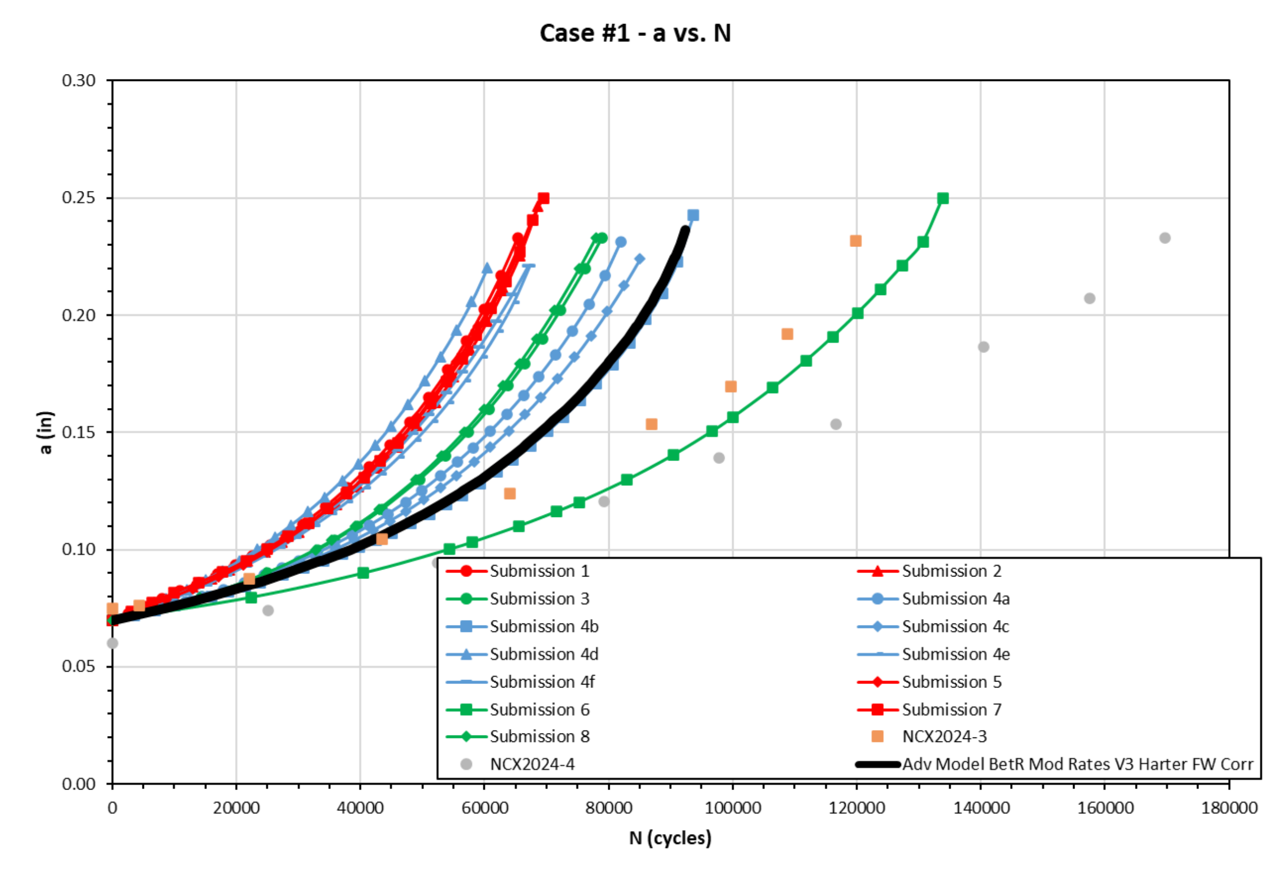
Offset distance – found 0.015 worked best

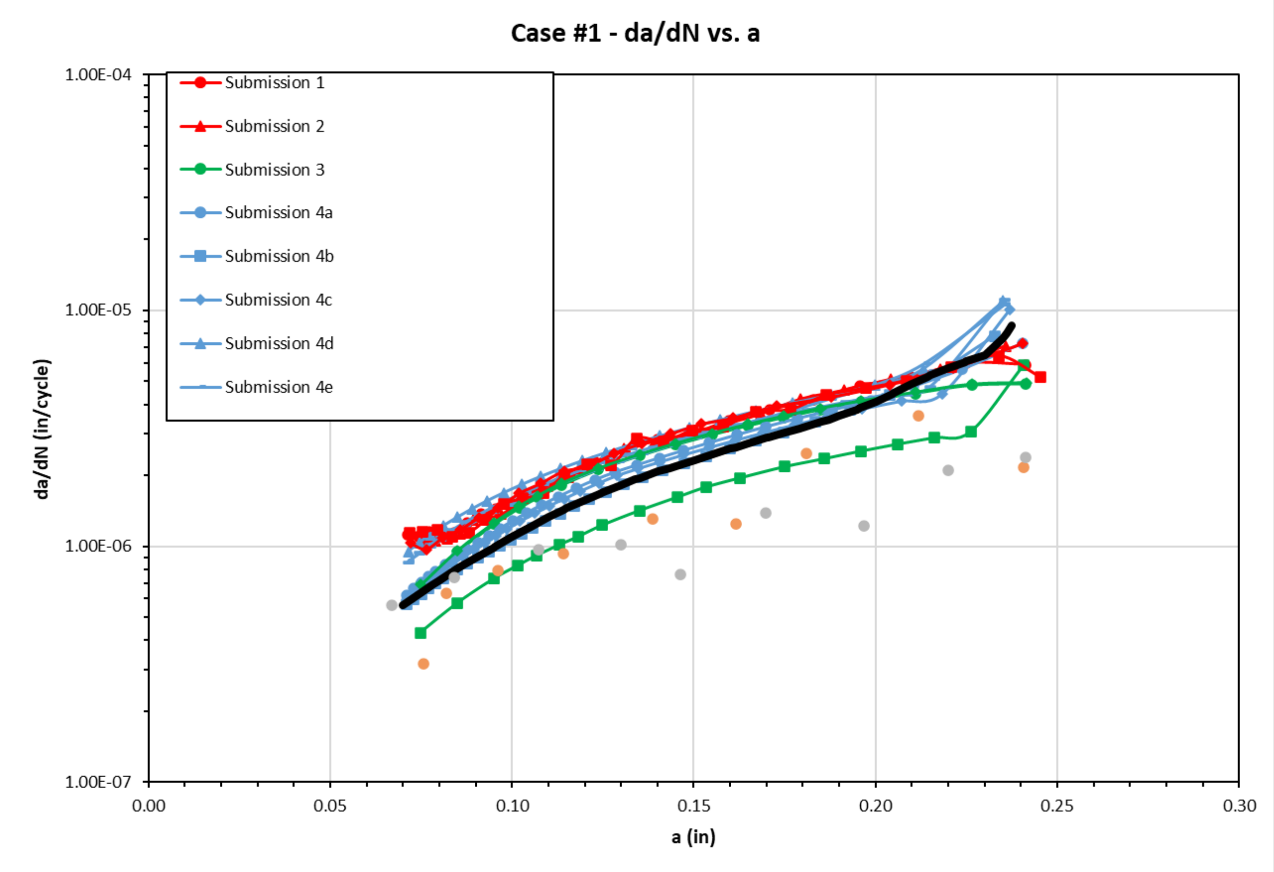




ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Results – Case 1 no Cx CA R=0.1 10 ksi





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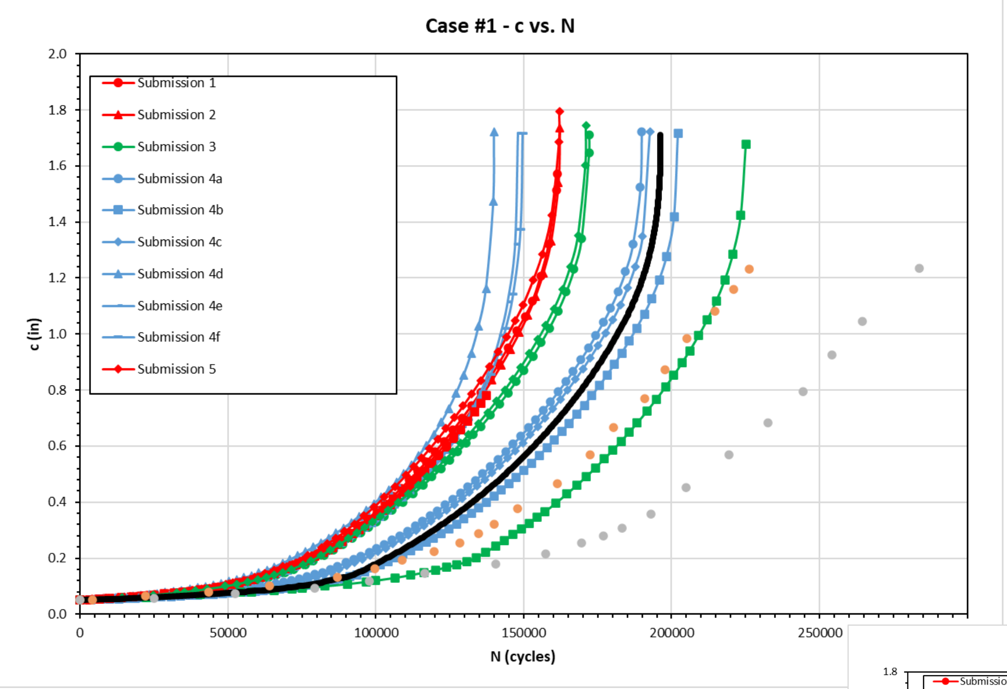
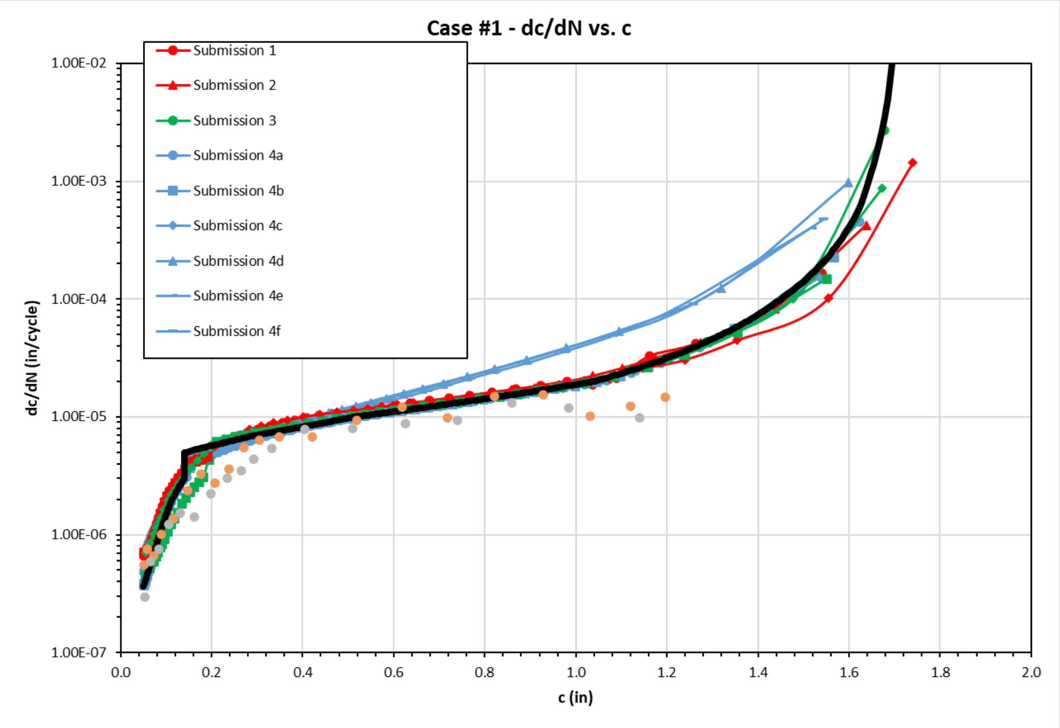
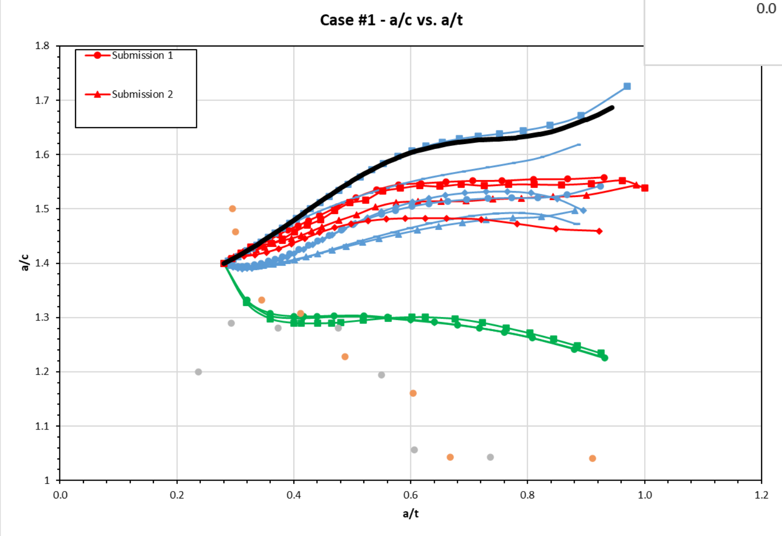
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Results – Case 1 no Cx CA R=0.1 10 ksi

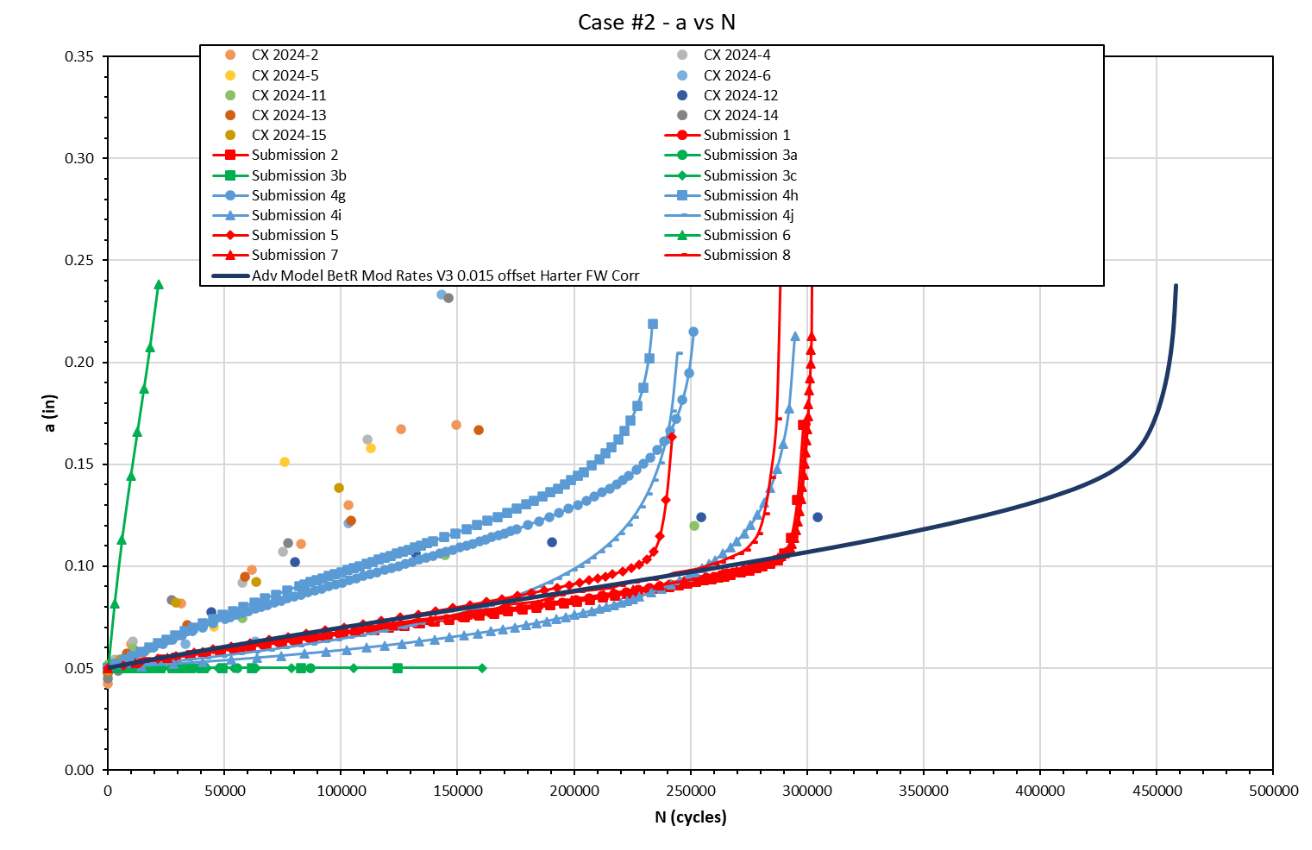


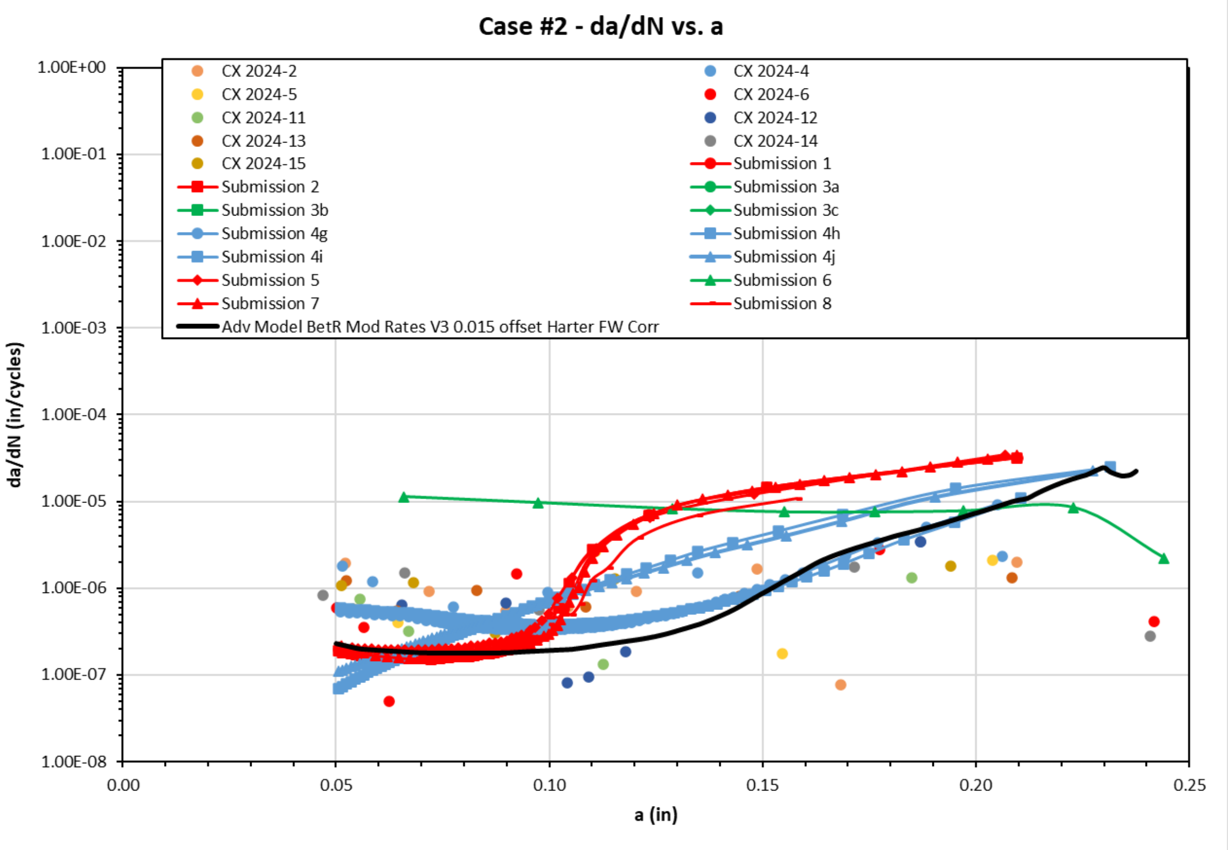




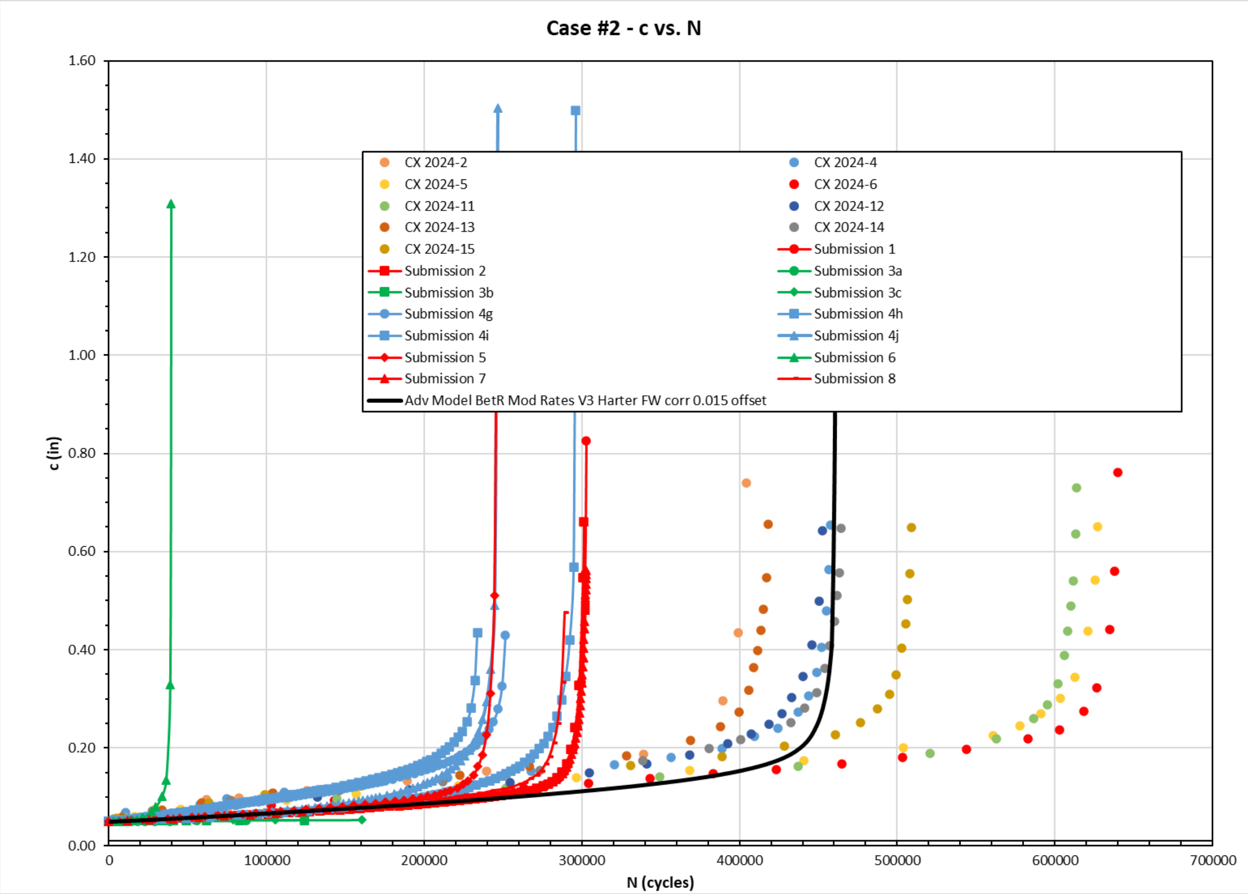
ERSI
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

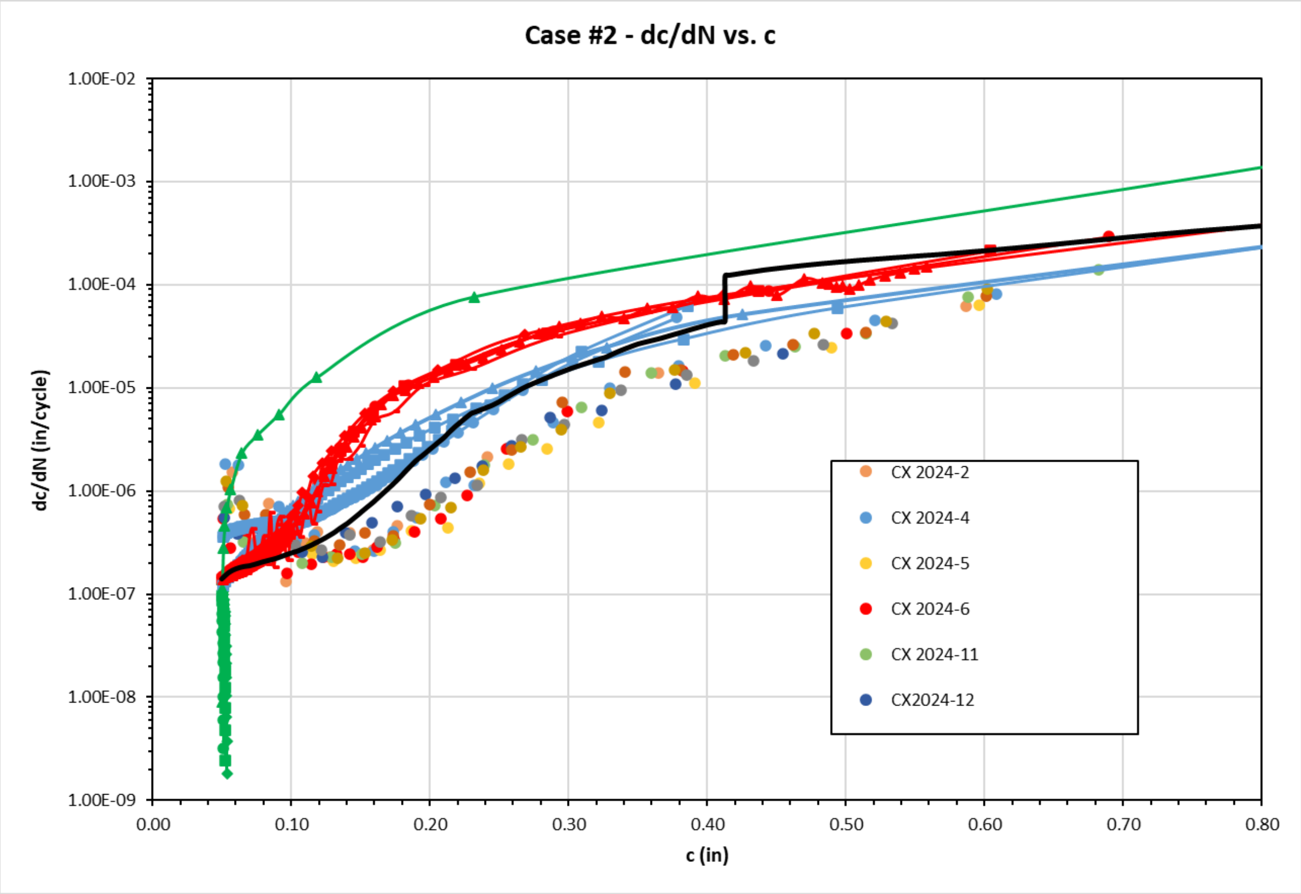
Results – Case 2 Cx CA R=0.1 25 ksi





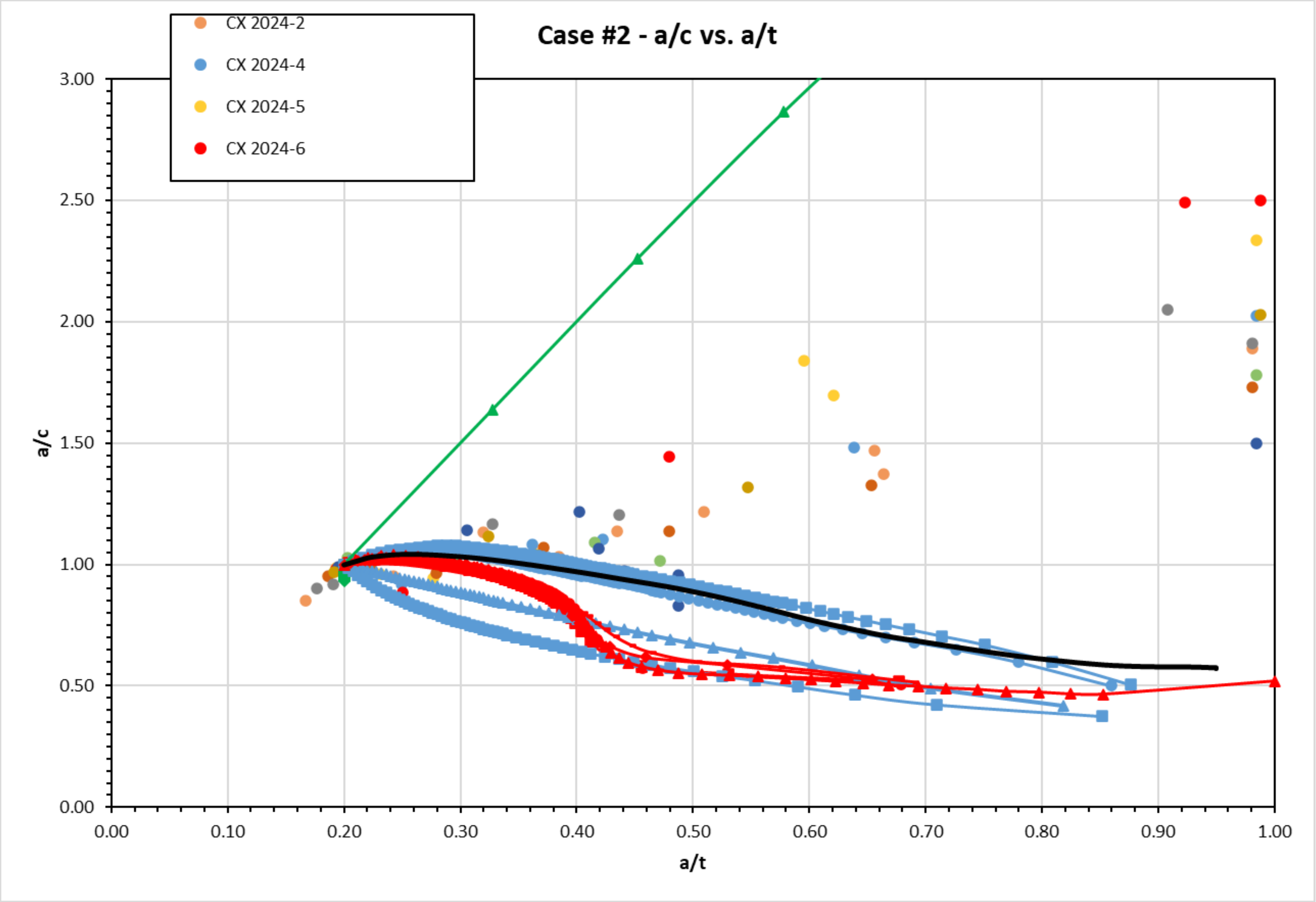
Results – Case 2 Cx CA R=0.1 25 ksi



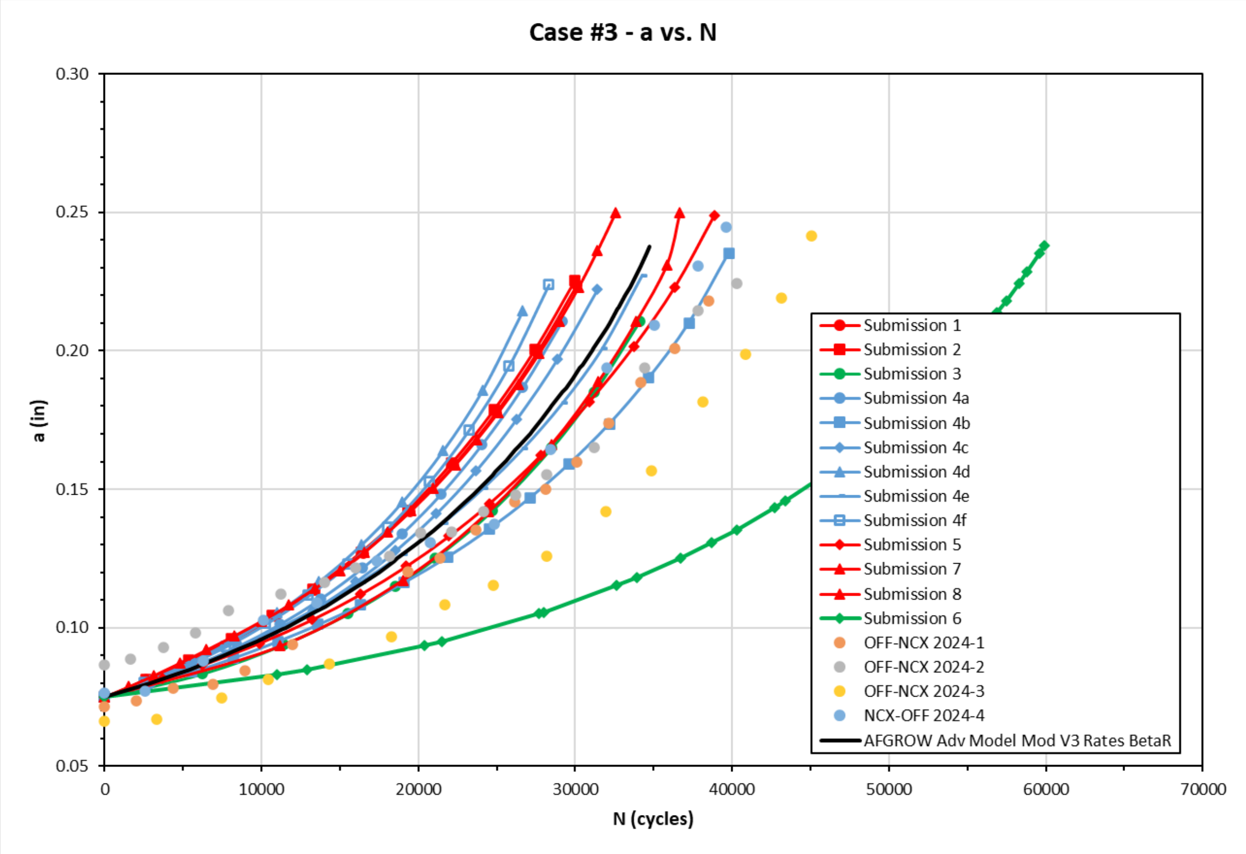


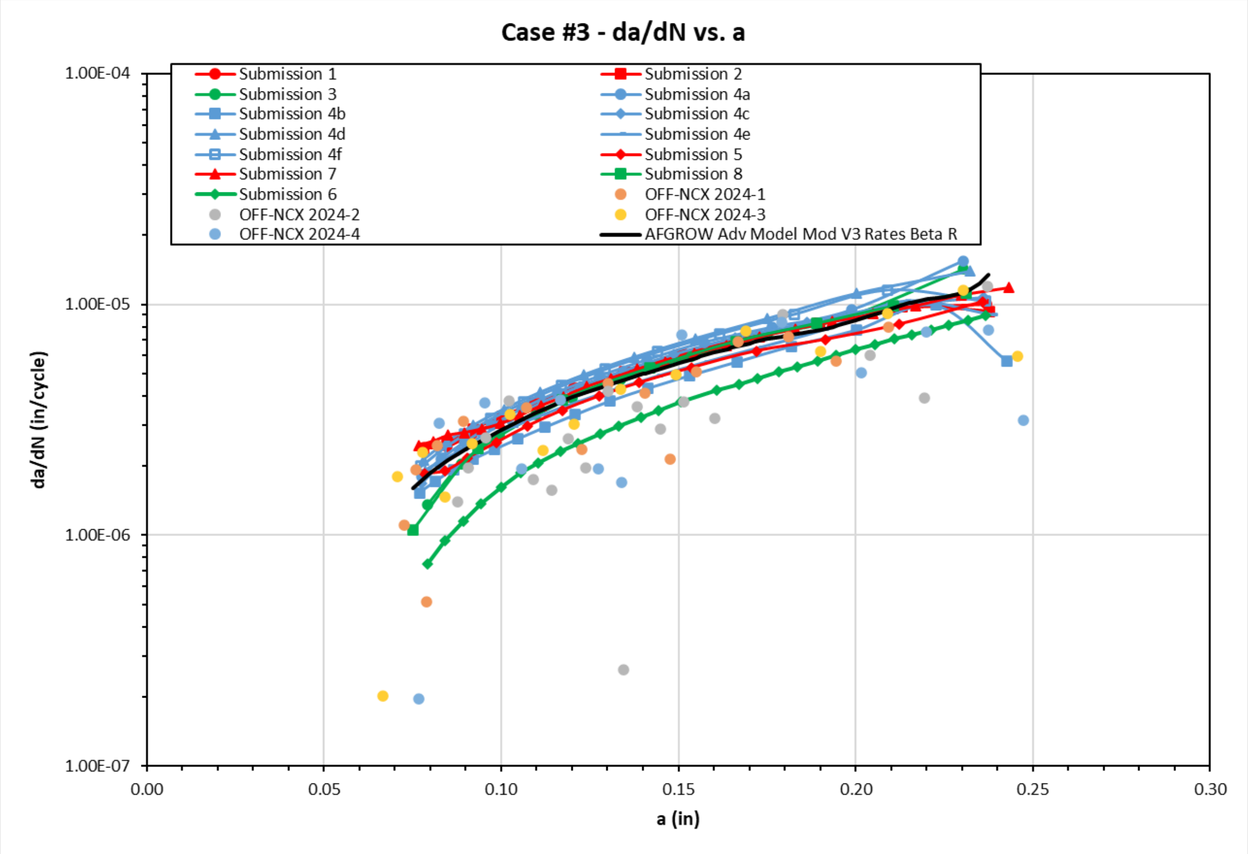
ERSI
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Results – Case 2 Cx CA R=0.1 25 ksi



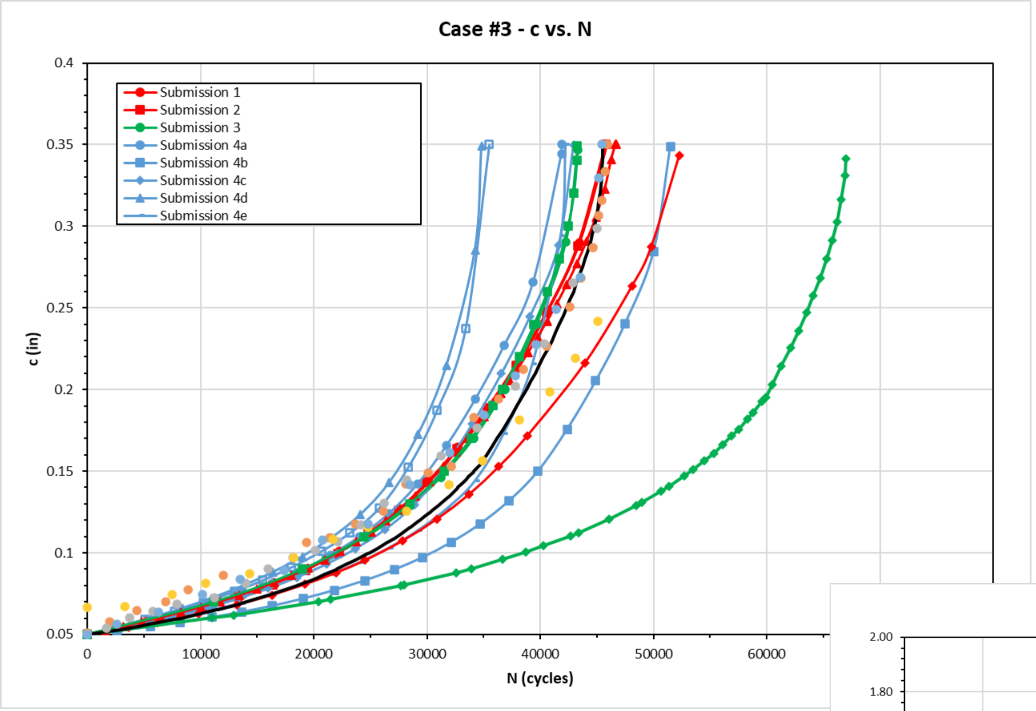
Results – Case 3 no Cx CA R=0.1 10 ksi

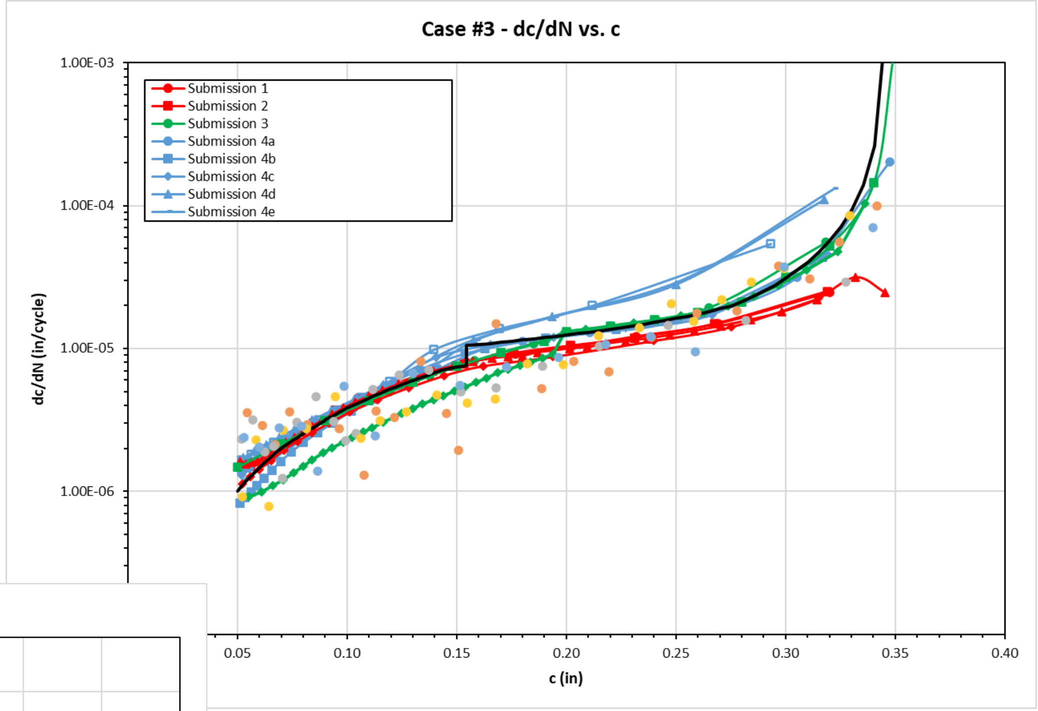


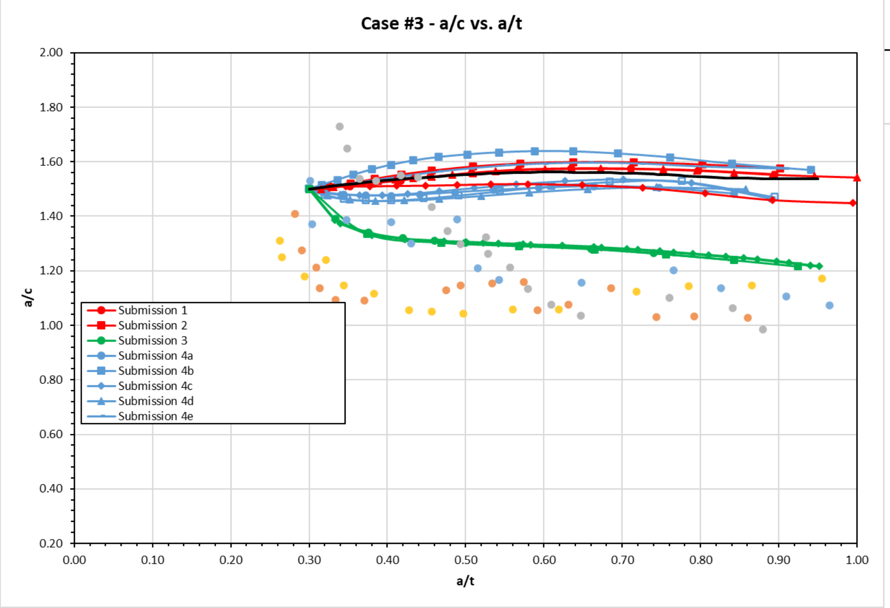


ERSI
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Results – Case 3 no Cx CA R=0.1 10 ksi

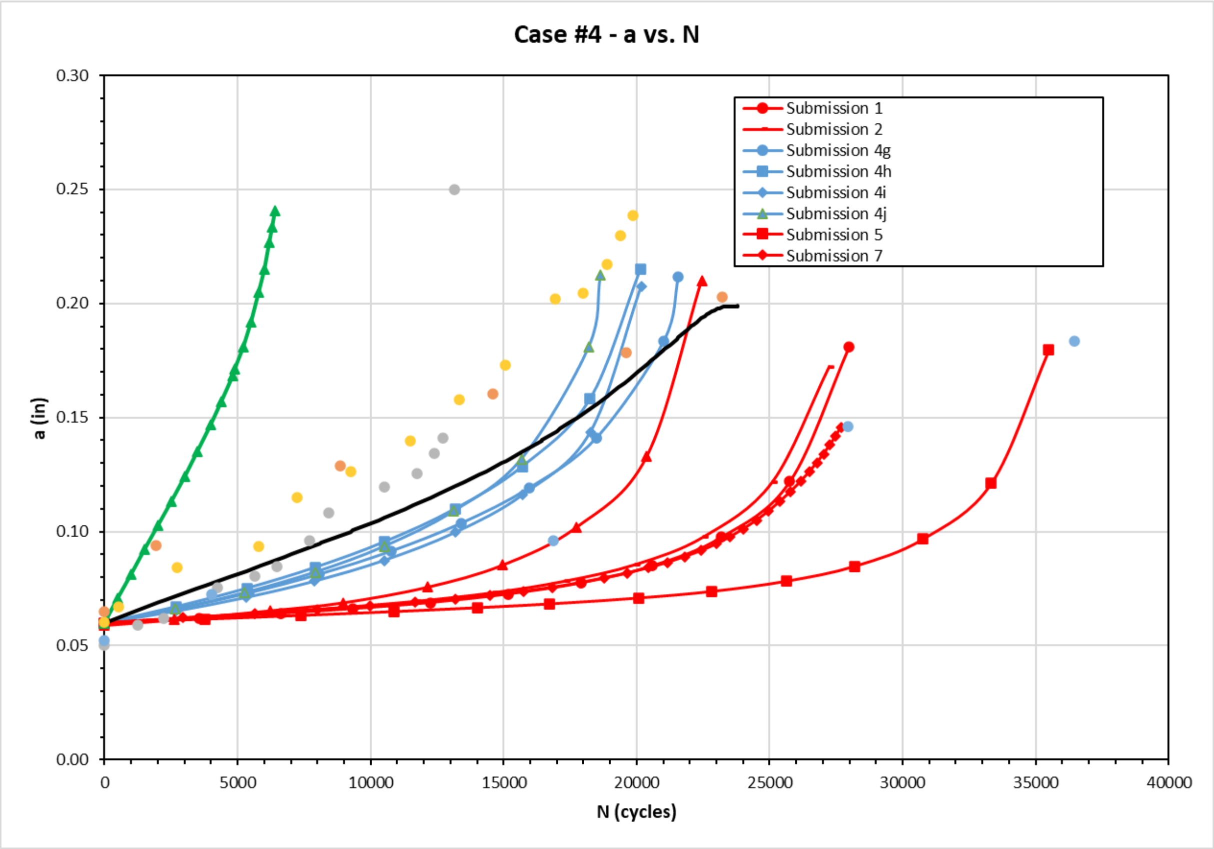


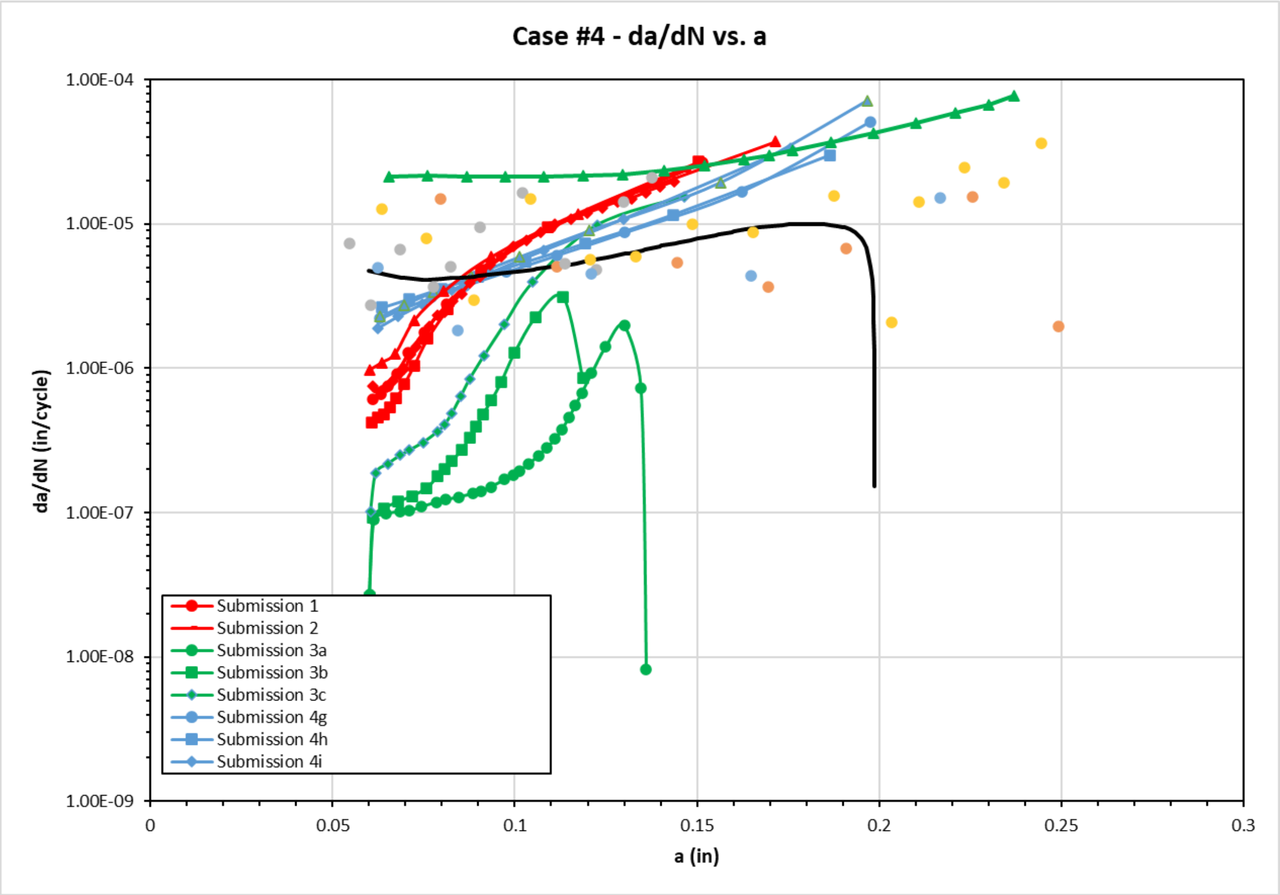




ENGINEERED RESIDUAL STRESS IMPLEMENTATION

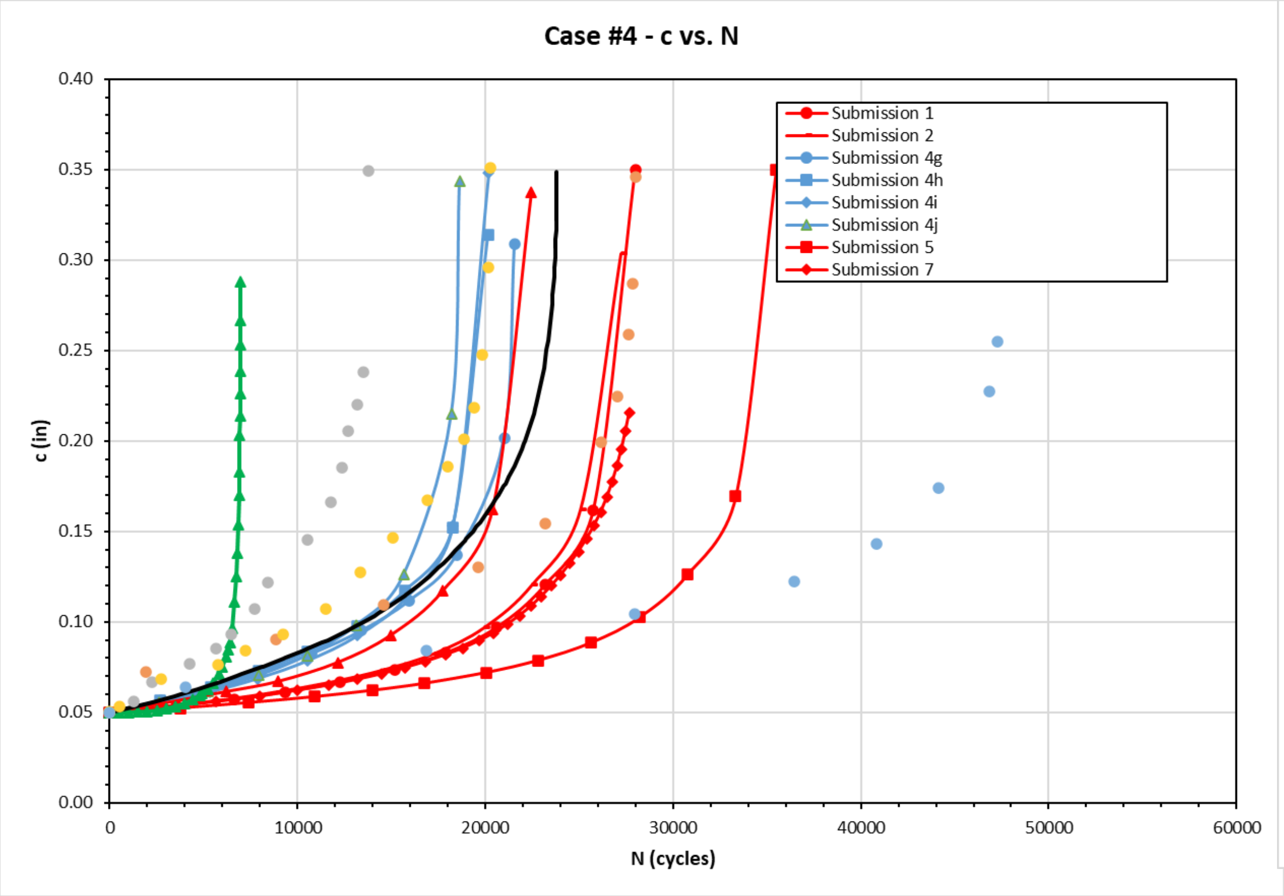
Results – Case 4 Cx CA R=0.1 25 ksi

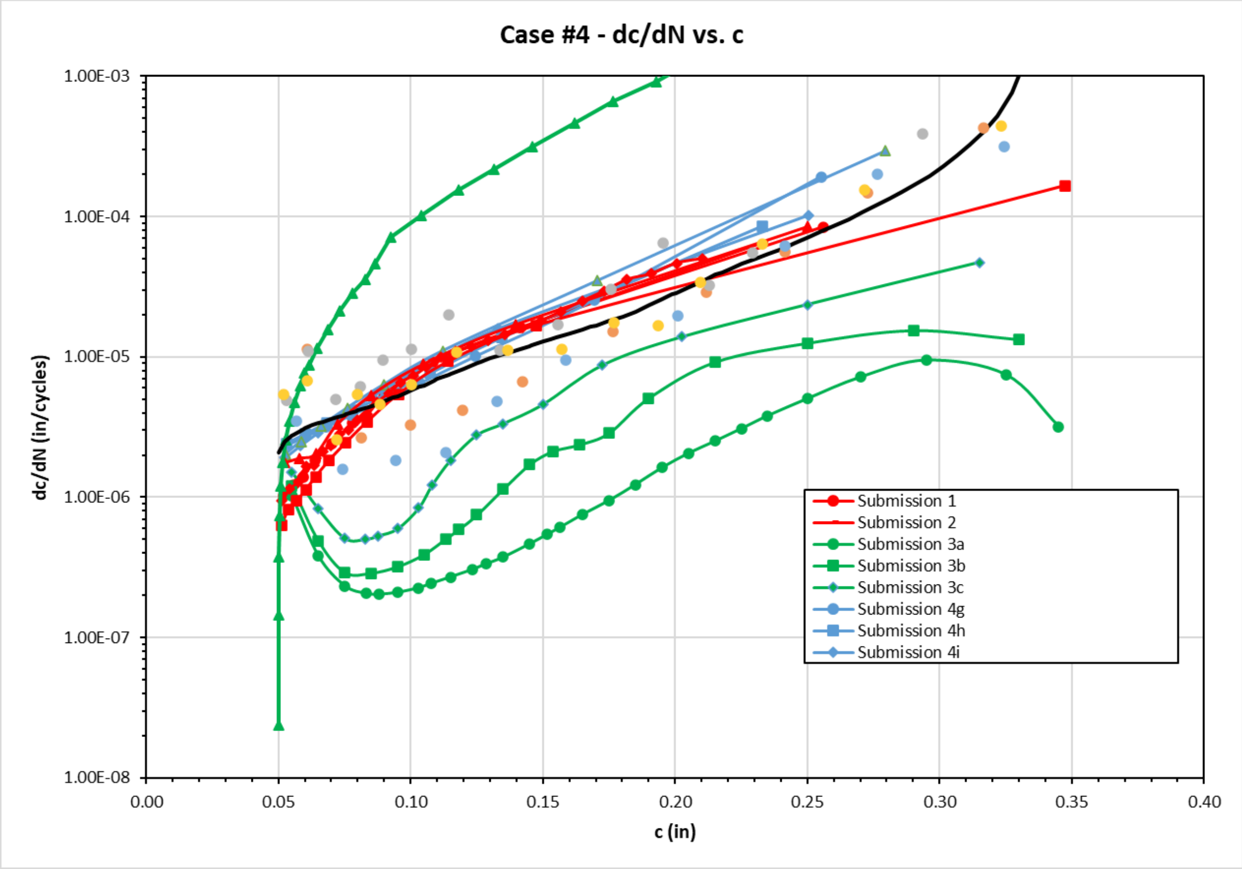




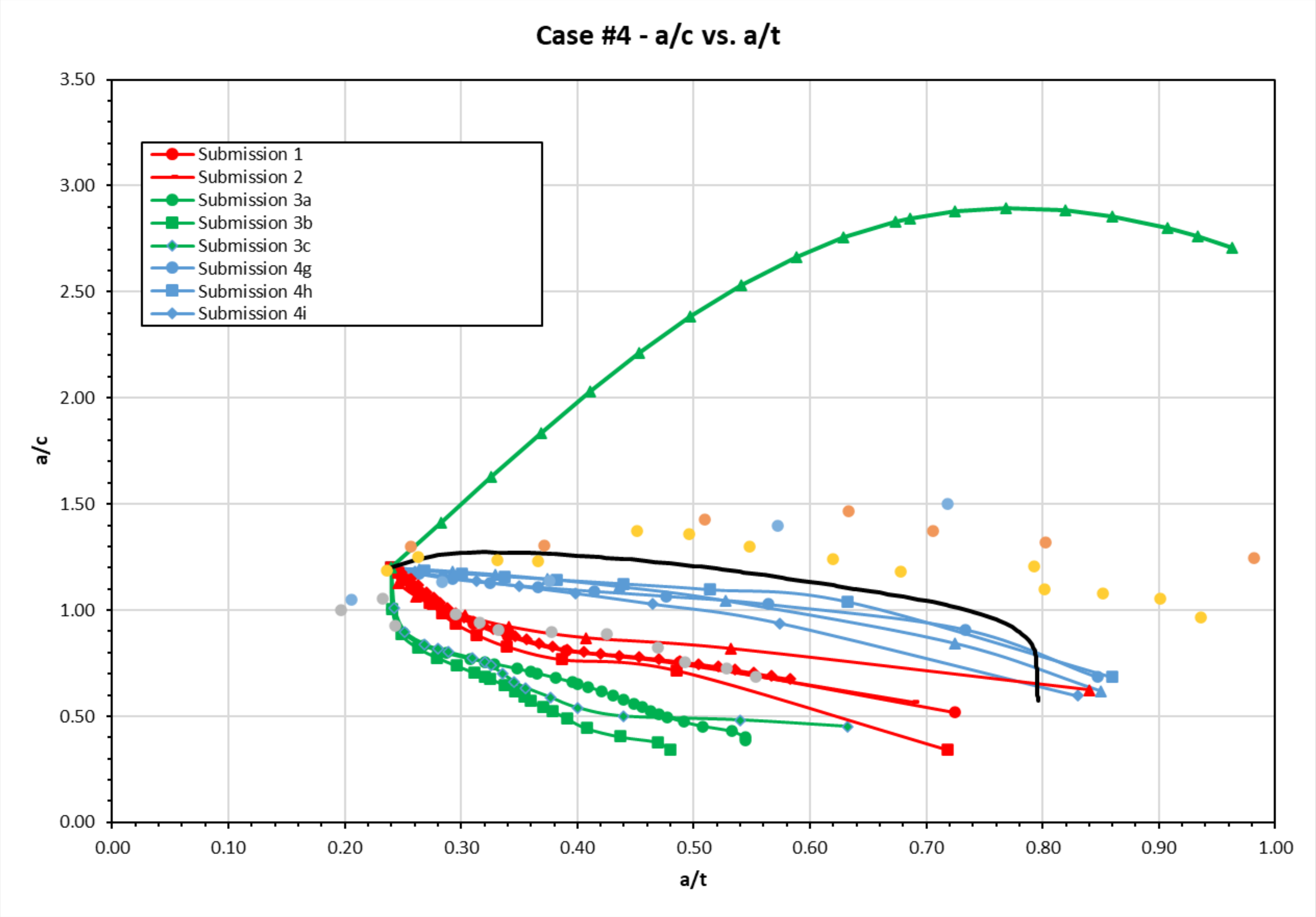
ERSI ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Results – Case 4 Cx CA R=0.1 25 ksi





Results – Case 4 Cx CA R=0.1 25 ksi



Harmonizing Contour and XRD Residual Stress Measurement Data Sets

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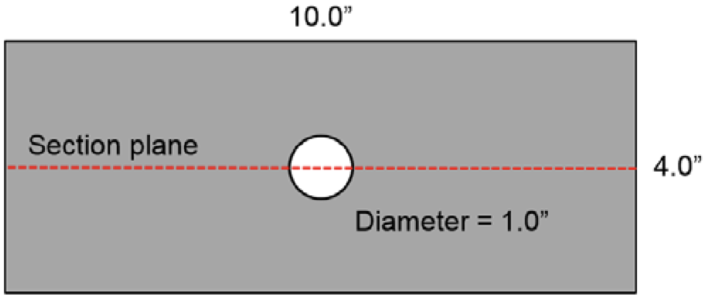
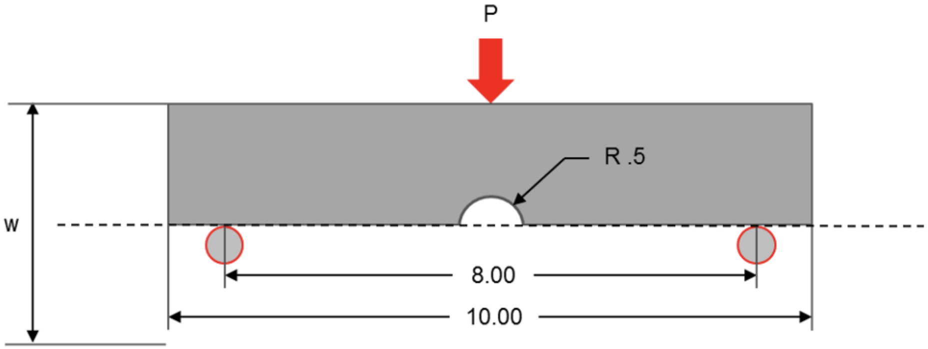
Recap on work done so far

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.





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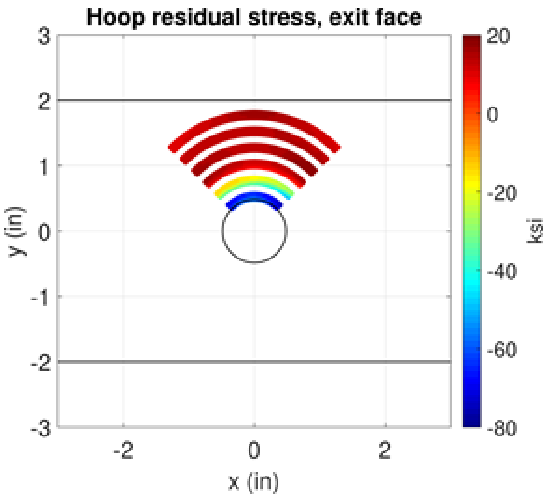
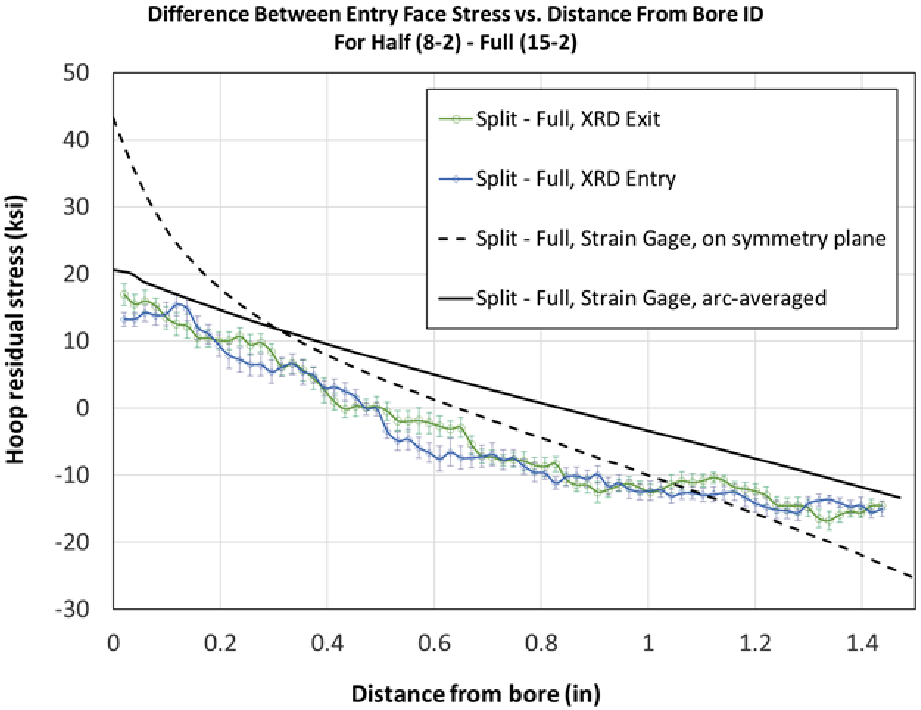
Effect of Split on Face of Geometrically Large Coupon

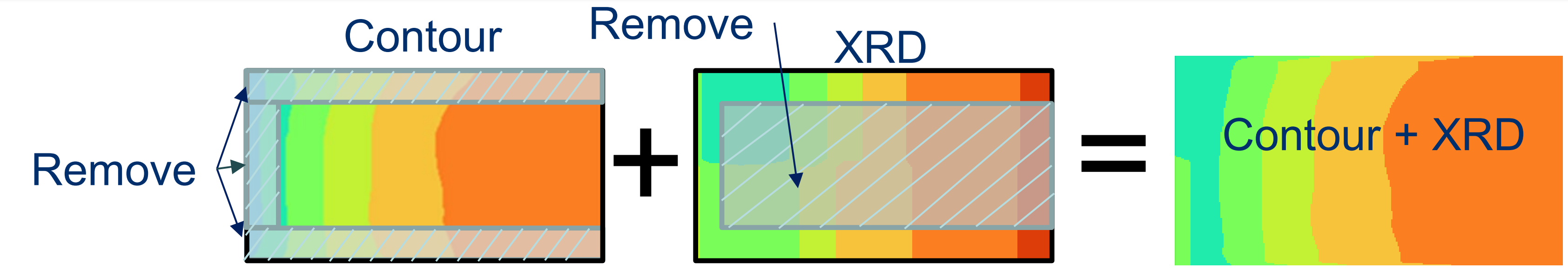
- When corrected for XRD arc averaging, the relaxation as measured by XRD vs. estimated by strain gage & FEM are more closely aligned





Opportunity to Integrate/Harmonize Datasets

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



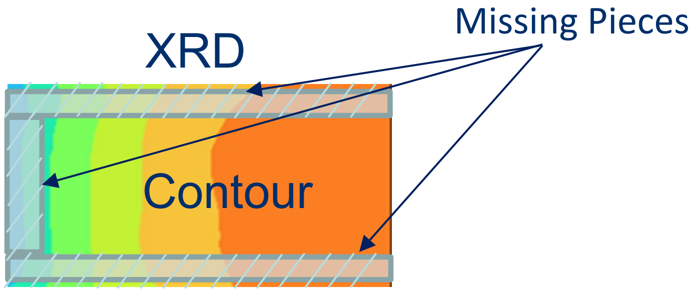
Prather, J., Carlson, S., (2023)., A Novel Approach to Integrating Residual Stress Determination Methods, Proc. 2023 Aircraft Airworthiness & Sustainment Conf., San Antonio, TX, USA.

Questions:

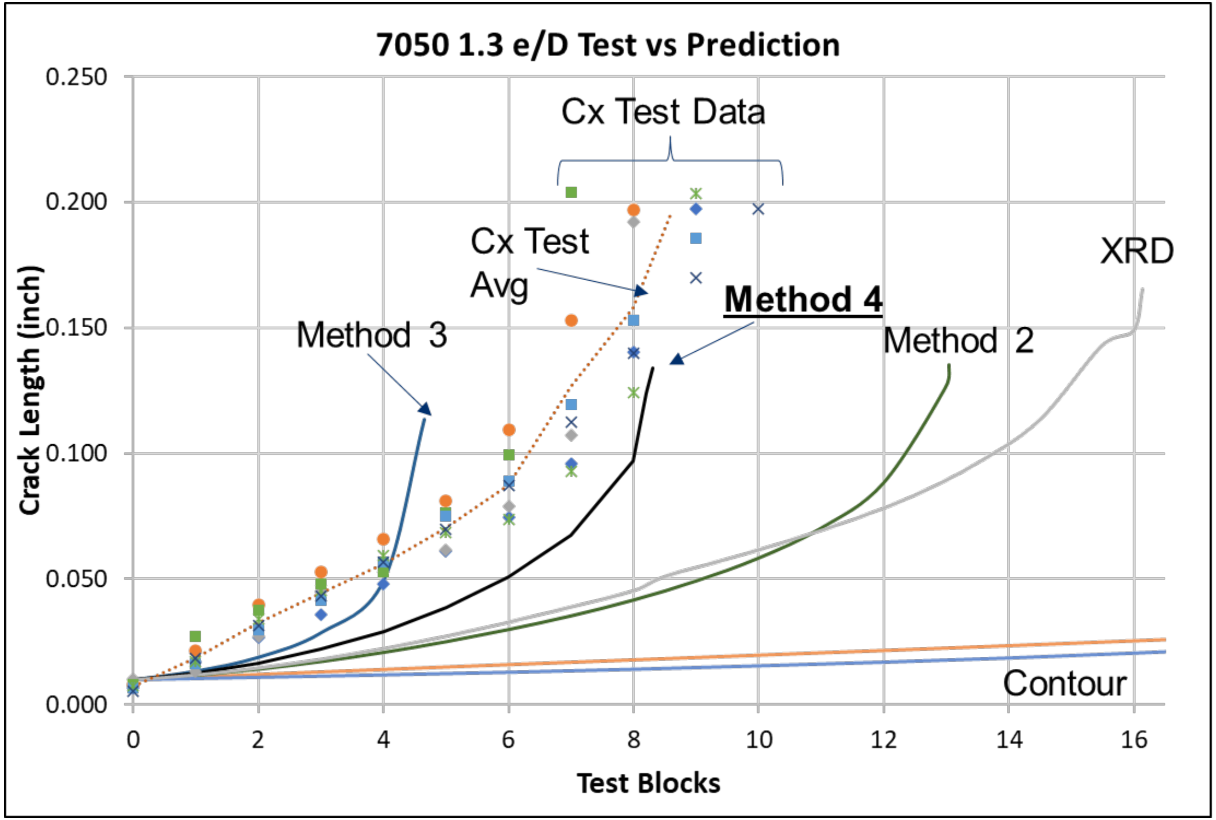
- **Would this approach add value (e.g., improve understanding of fatigue crack growth behavior)?**
- **What methods would be used for measurements?**
- **What methods would be used for stitching?**

Working With Available Data

key pieces of the puzzle were missing



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

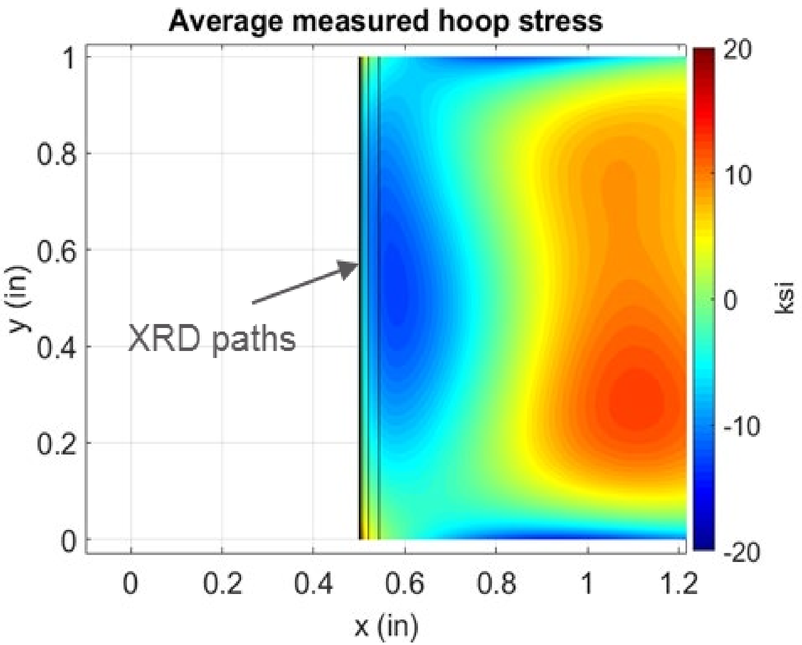


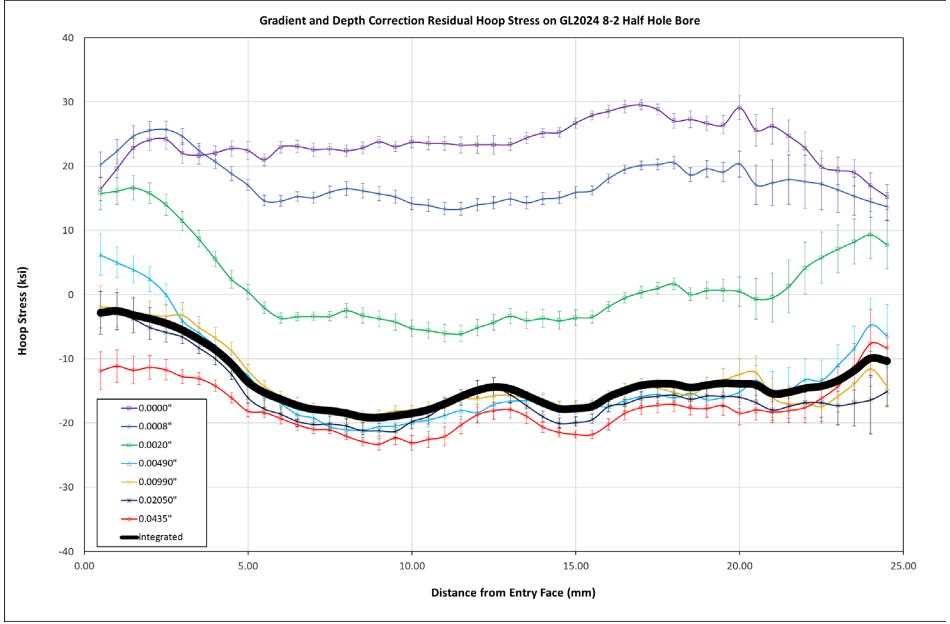
Prather, J., Carlson, S., (2023)., A Novel Approach to Integrating Residual Stress Determination Methods, Proc. 2023 Aircraft Airworthiness & Sustainment Conf., San Antonio, TX, USA

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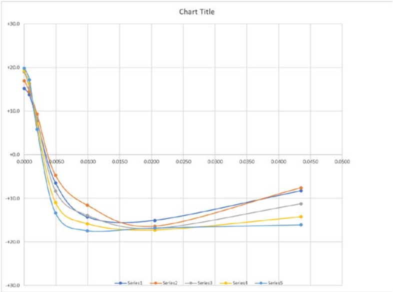
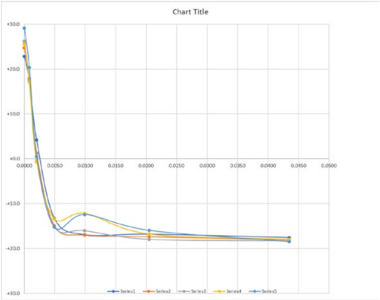
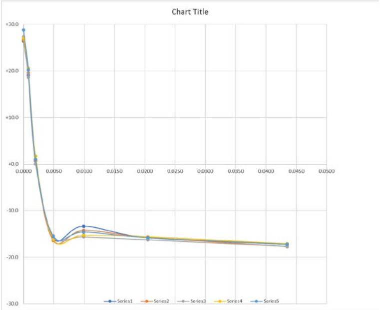
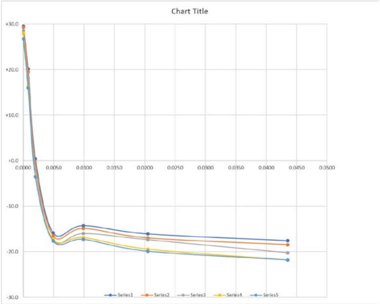
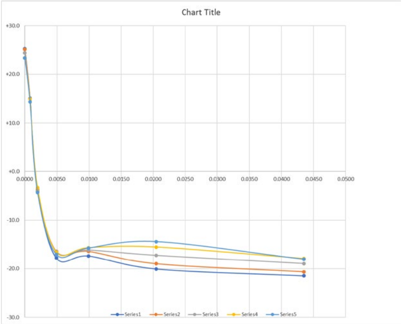
RS in Bore of Cx Hole in Geometrically Large Coupon – Depth profiles at individual points across the bore

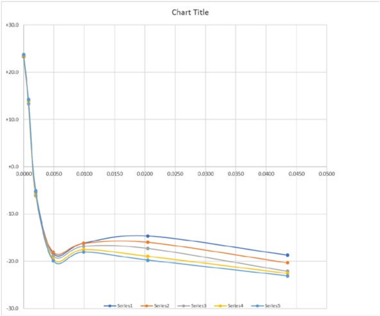


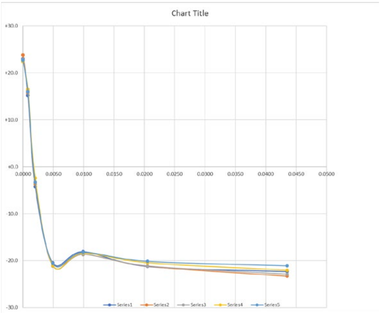


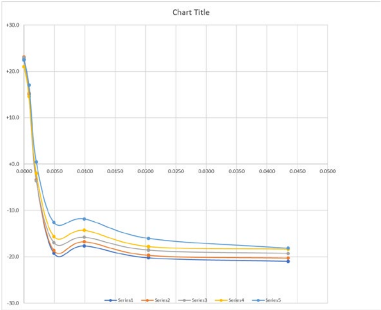












Note: Near surface cold working RS persist to about 0.010” deep

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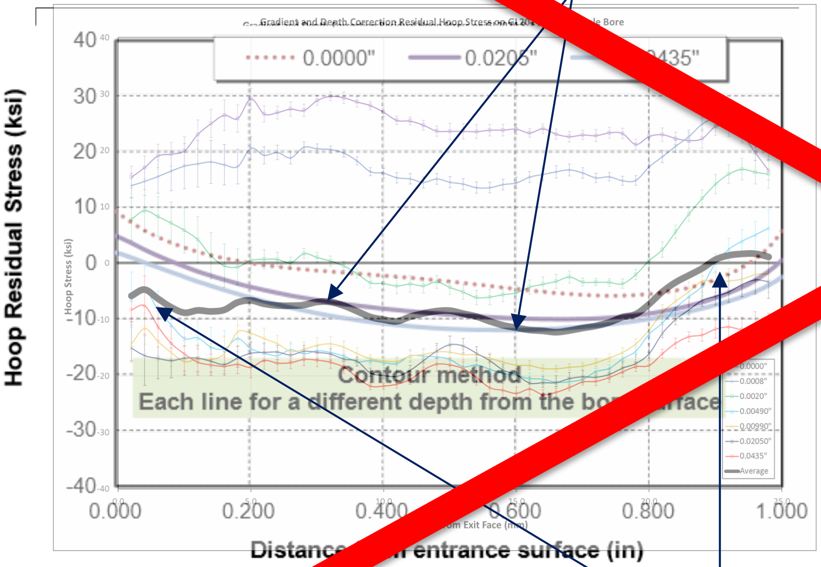
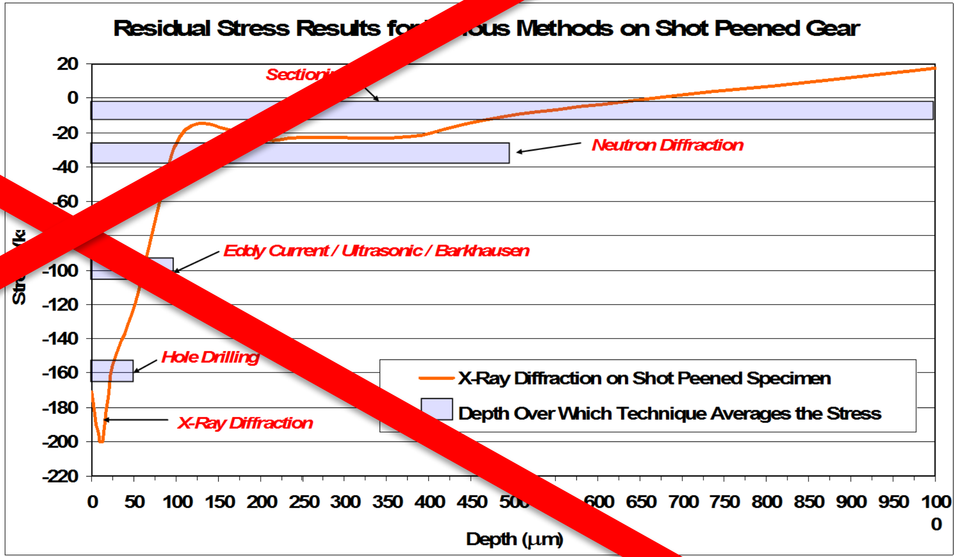
RS in Bore of Cx Hole in Geometrically Large Coupon
Inter-method considerations – yes, the world is round!

"pretty good" agreement in the center

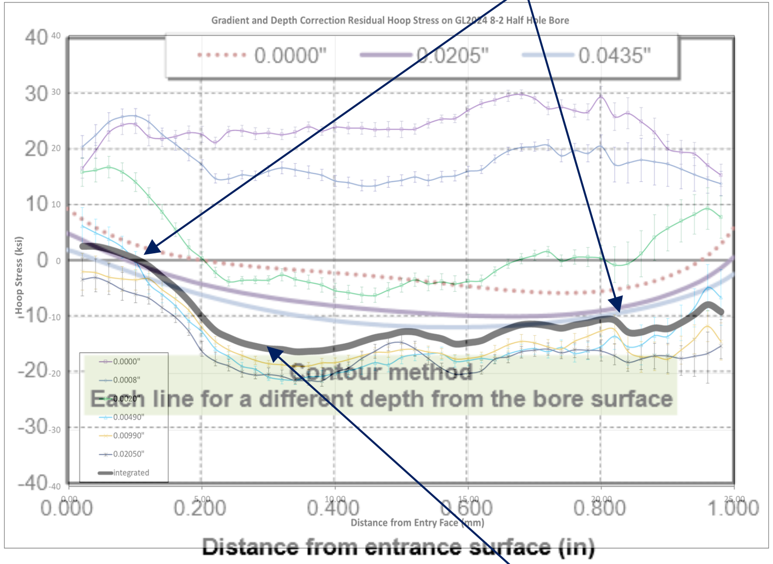


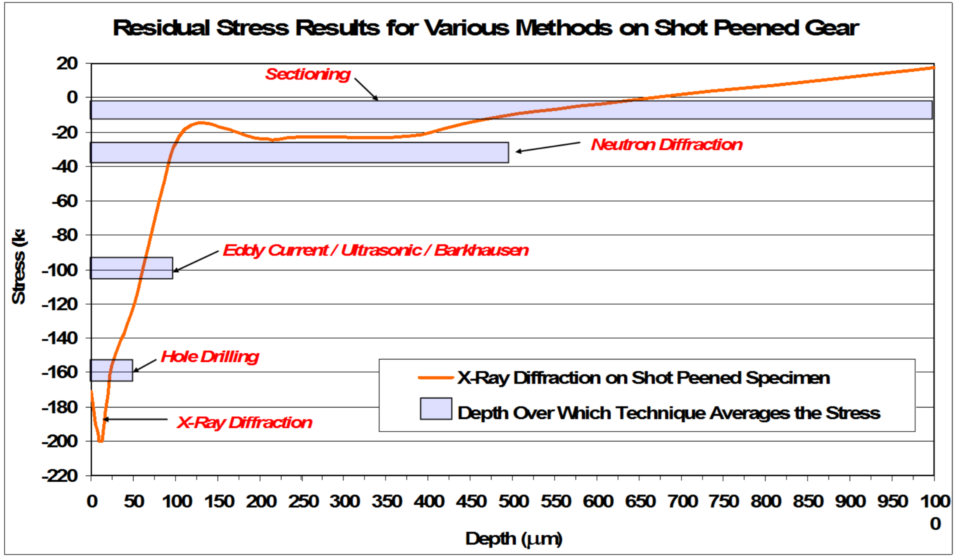


"Ok" agreement near ENT and EXT faces

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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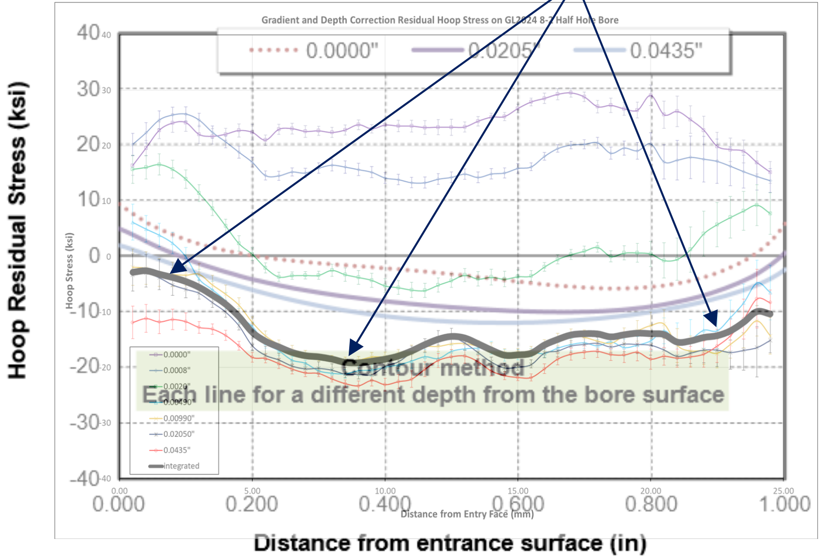
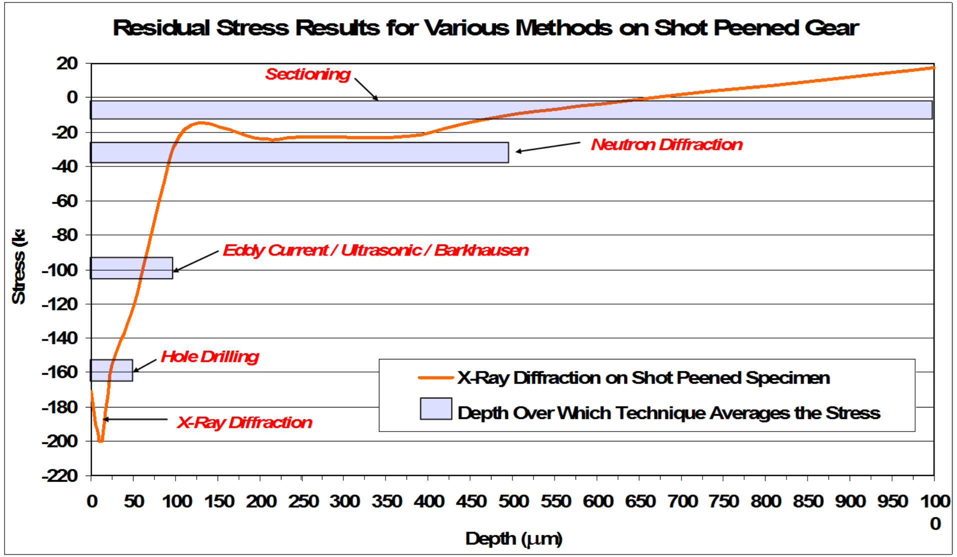
X-RAY DIFFRACTION

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"





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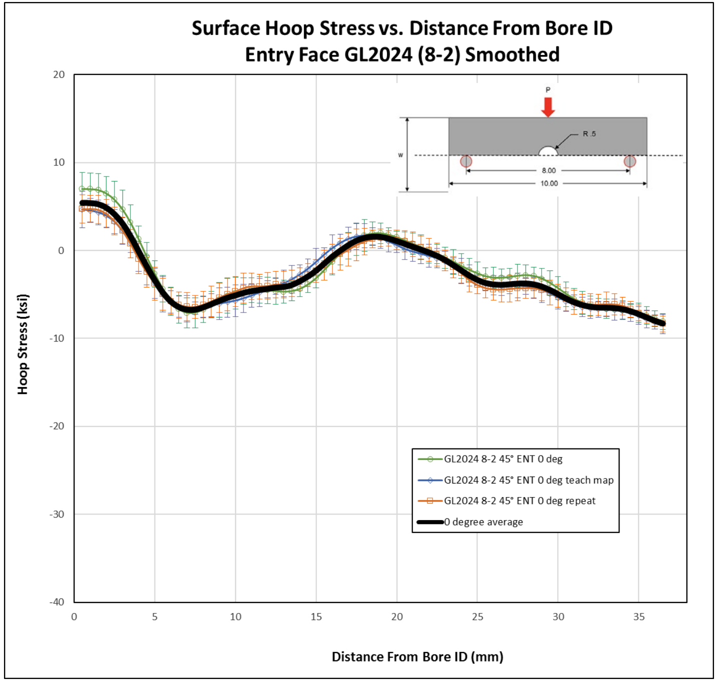
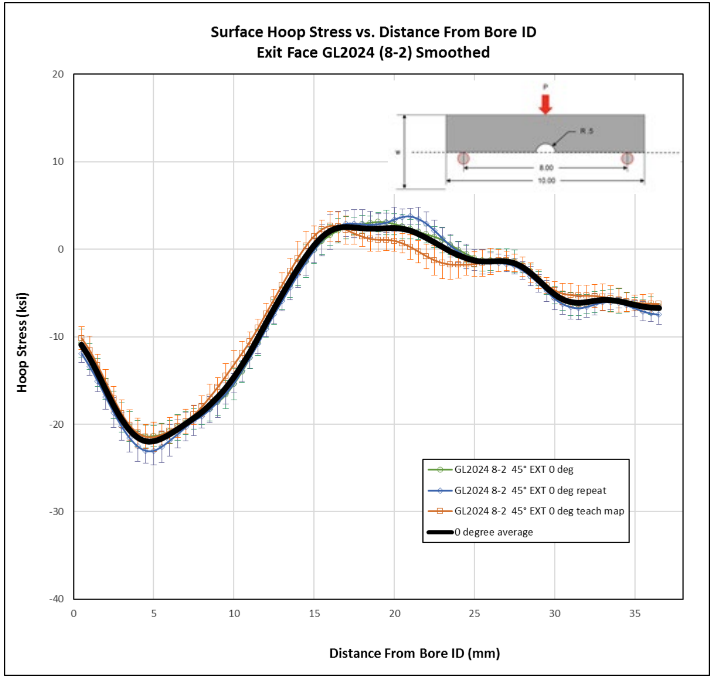
On Entry and Exit Faces at the Surface Only on Split GL

RS on Faces of Geometrically Large Coupon - Split





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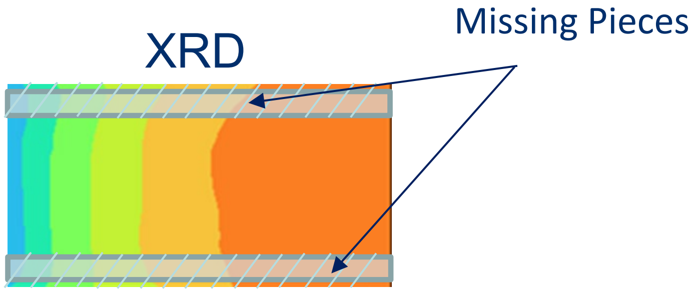
Missing Data for Split GL

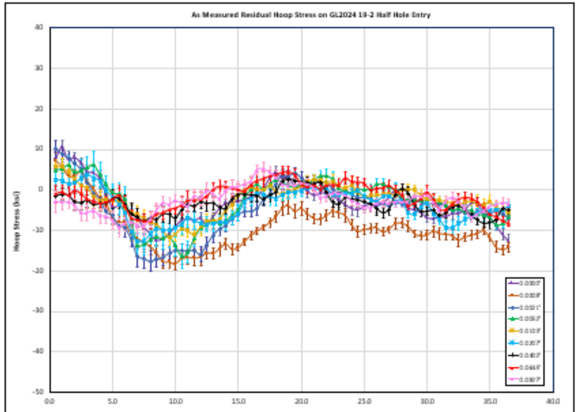


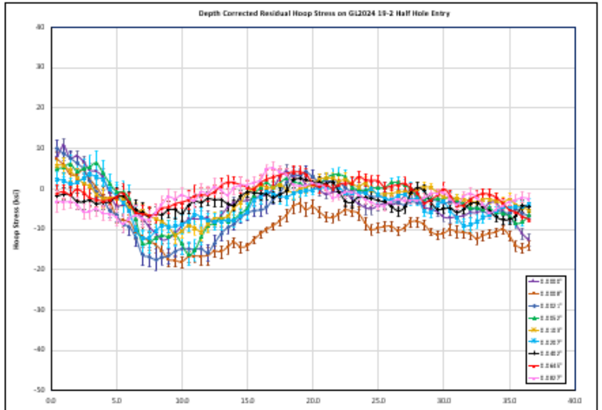
New XRD Data

Entry Face 0.000” to 0.080” deep

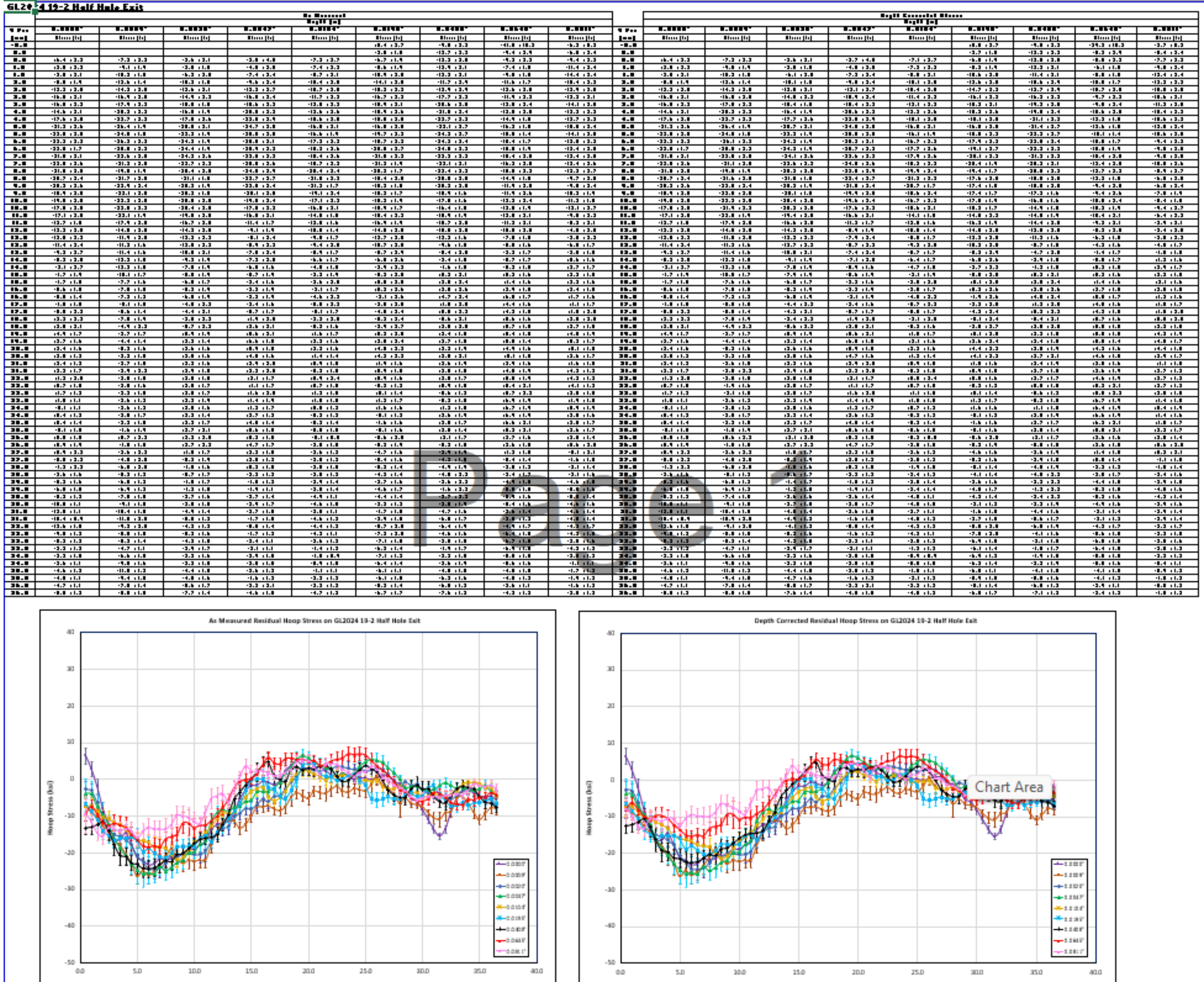
GL2024 19-2 Half Hole Entrance (etchside)

Pos [mm]	As Measured [illegible]									Pos [mm]	Depth Corrected [illegible]								
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]





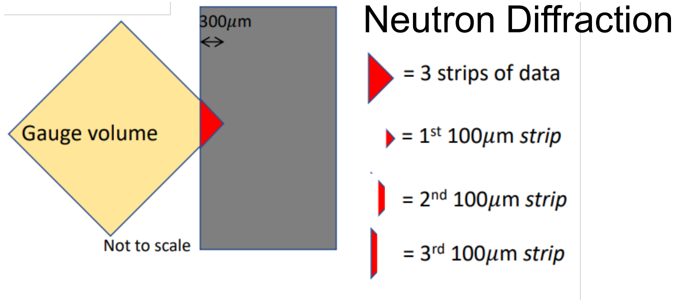
Exit Face
0.000” to 0.080” deep



Dataset improvements using deconvolution 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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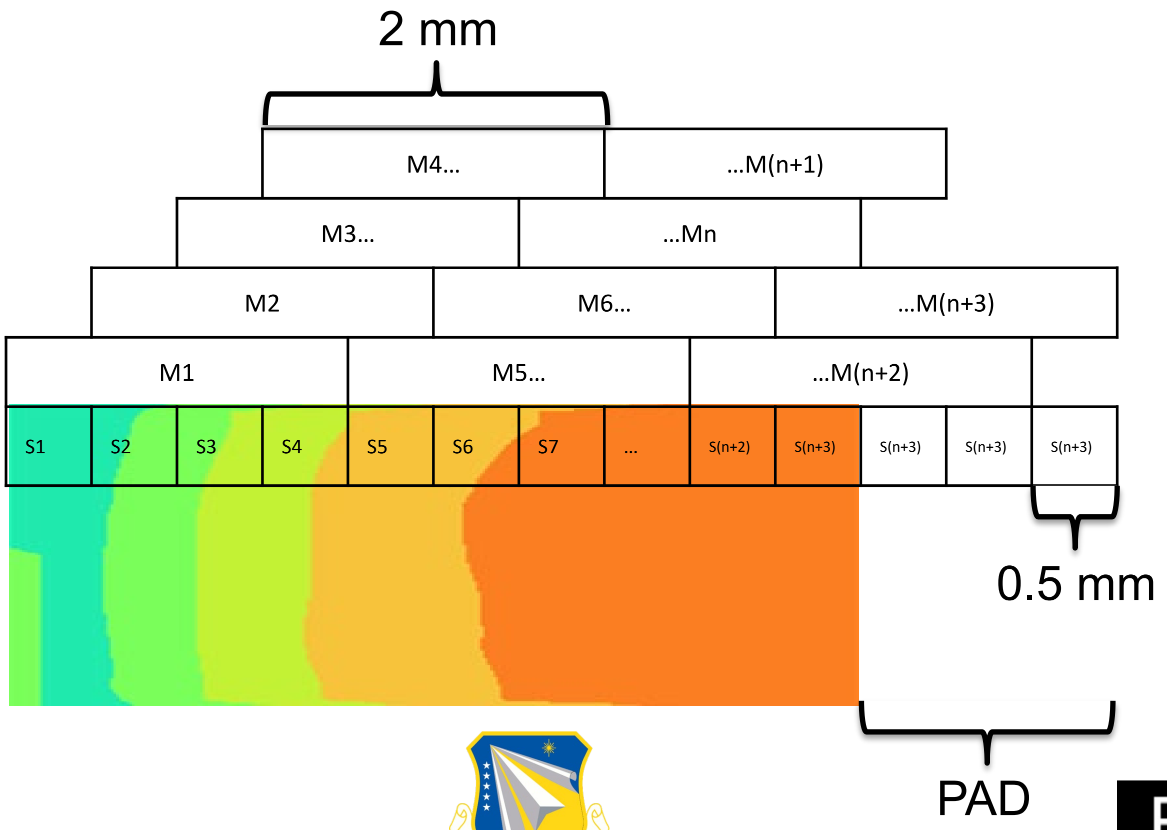
Alternate Approach to Deconvolution of GL Data

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



Alternate Approach to Deconvolution

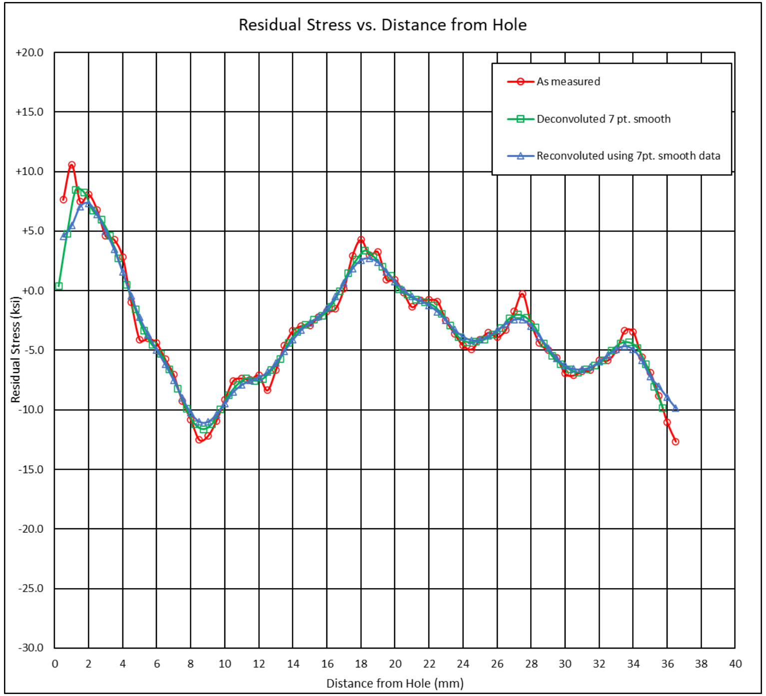
By "padding" the array at the end of the data set where it is approximately linear far from the hole, a sufficient number of equations can be obtained for a direct solution.

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…

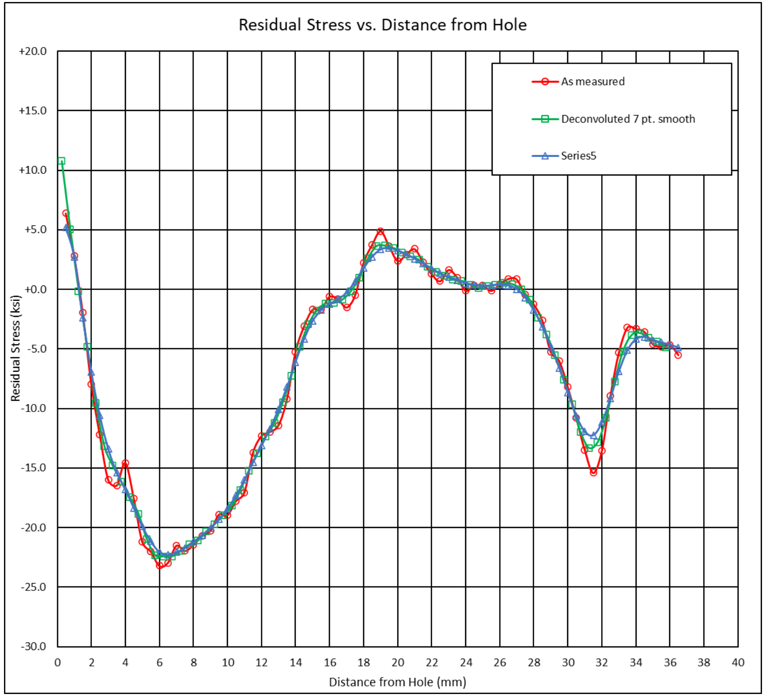
Solve the series of equations to obtain solutions for each Sn value
Other methods are also possible i.e. Moore-Penrose Inverse

Padded Array Approach to Deconvolution

Entry 0.000" deep



Exit 0.000" deep



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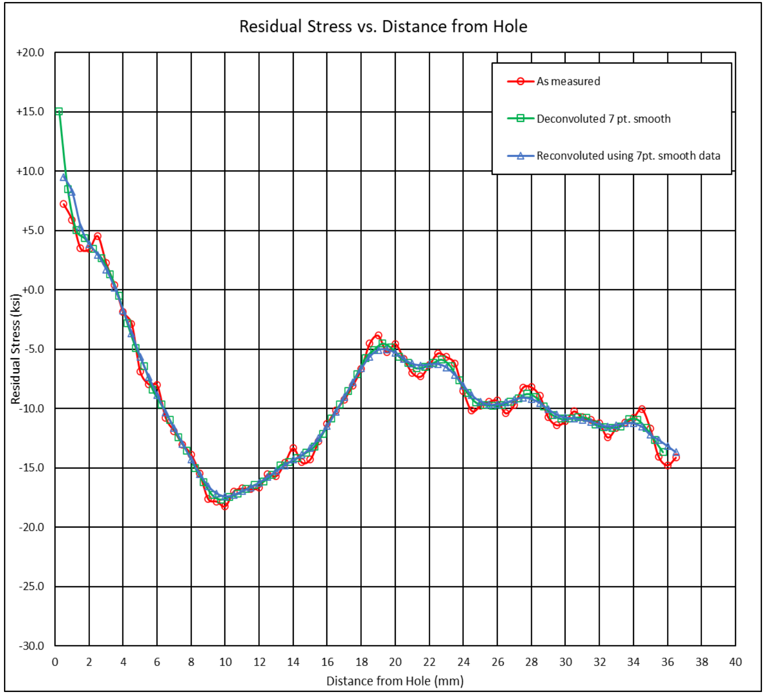
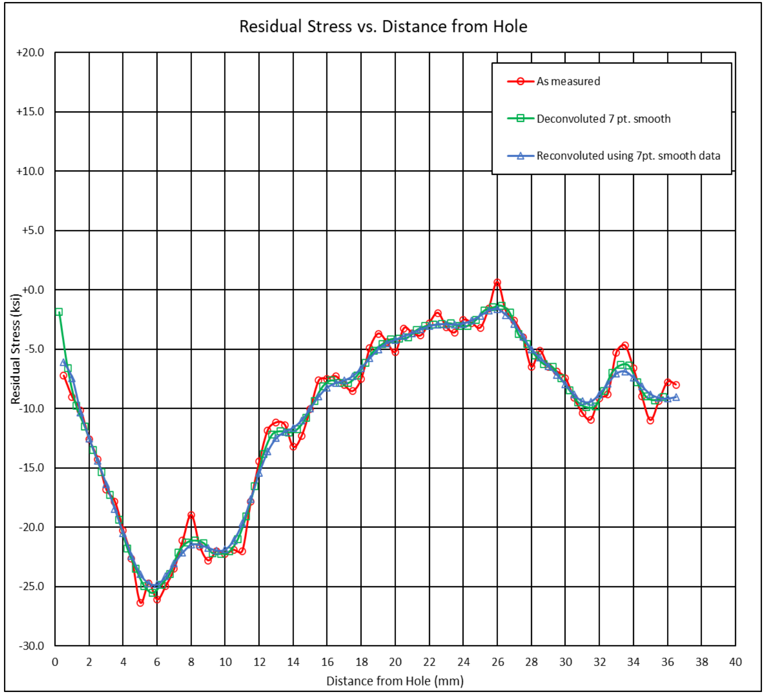
Padded Array Approach to Deconvolution

Entry 0.0008” deep



Exit 0.0009” deep



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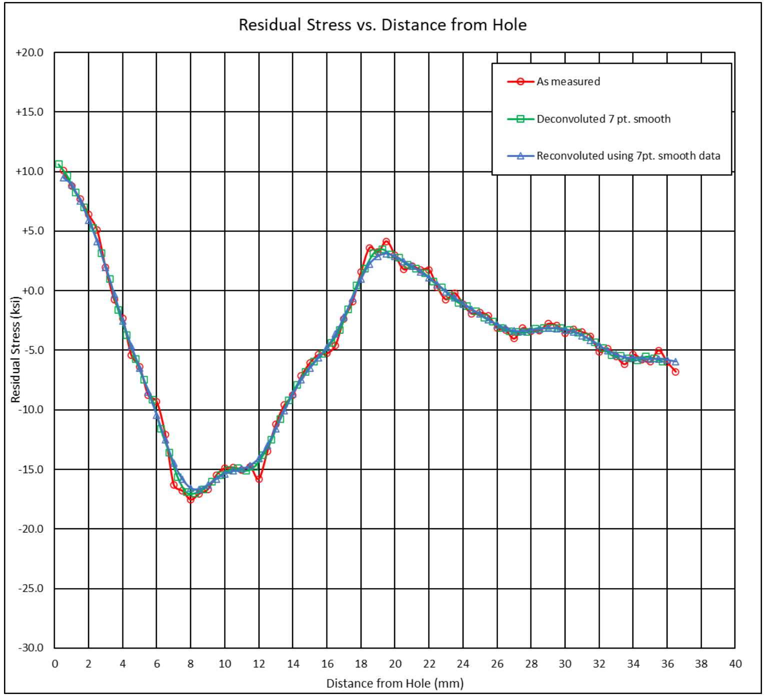
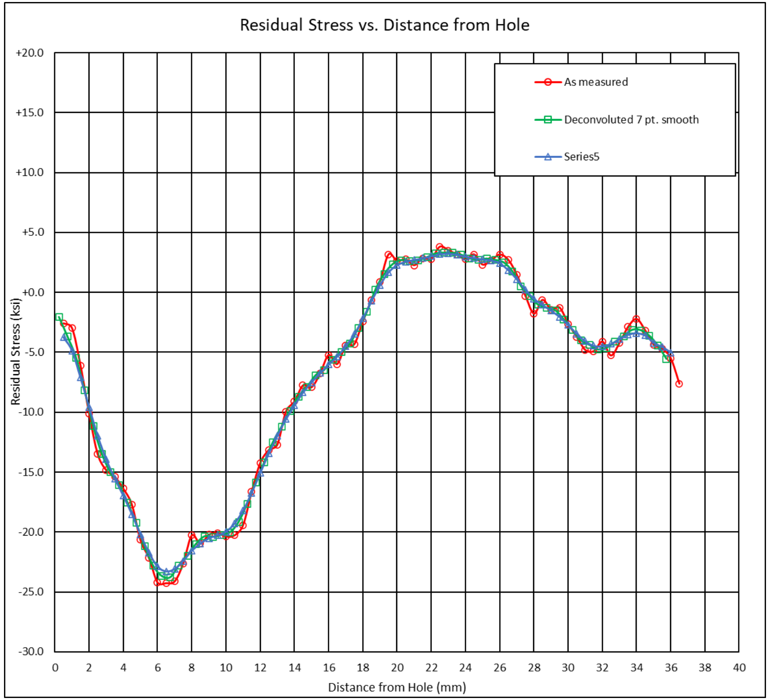
Padded Array Approach to Deconvolution

Entry 0.002” deep



Exit 0.002” deep



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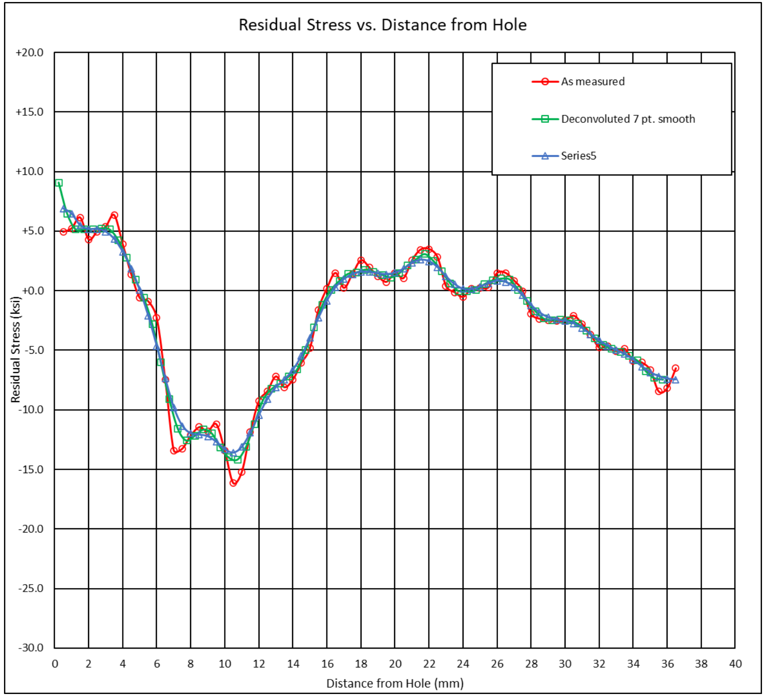
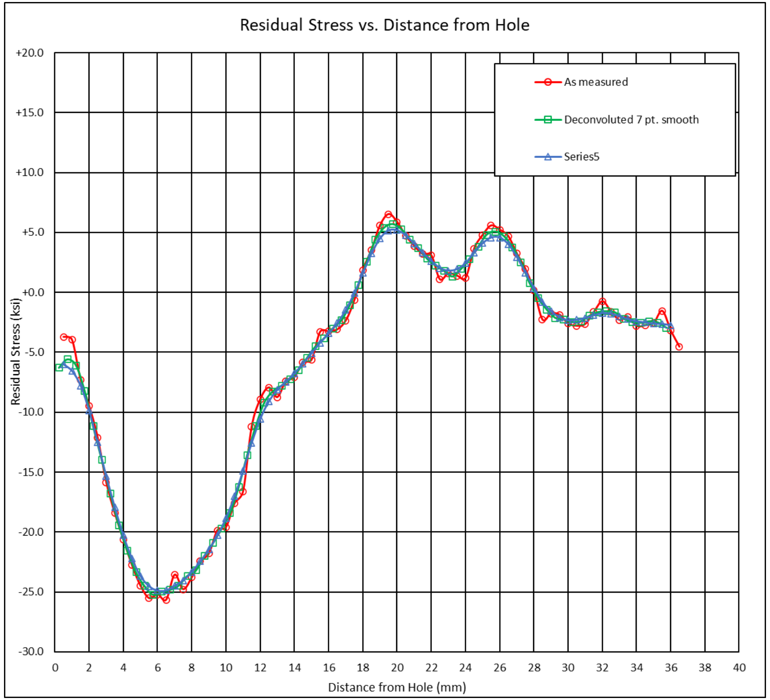
Padded Array Approach to Deconvolution

Entry 0.005" deep



Exit 0.005" deep



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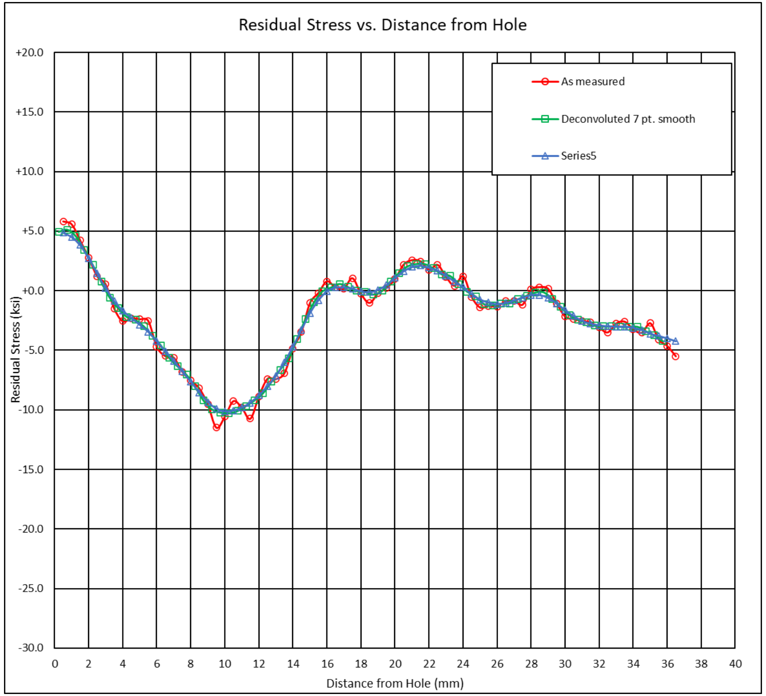
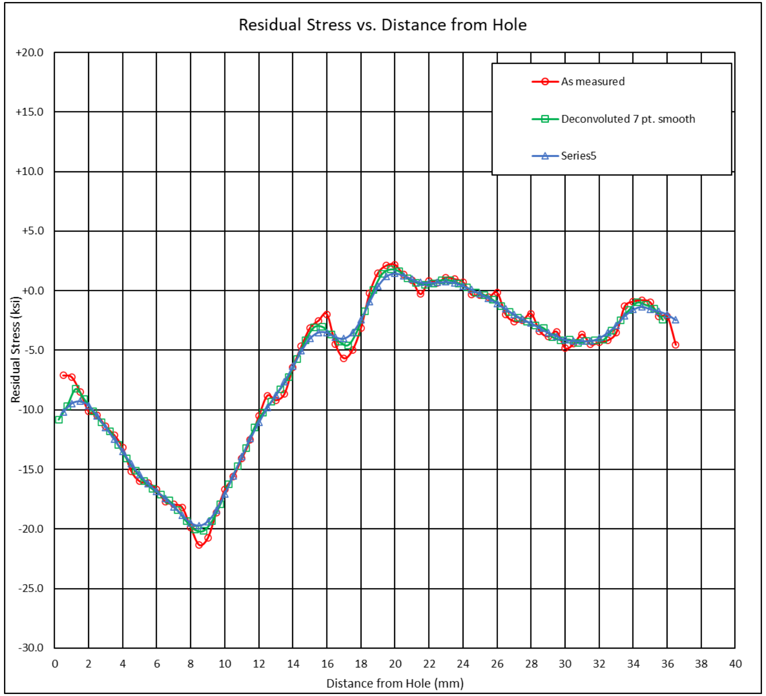
Padded Array Approach to Deconvolution

Entry 0.010" deep



Exit 0.010" deep



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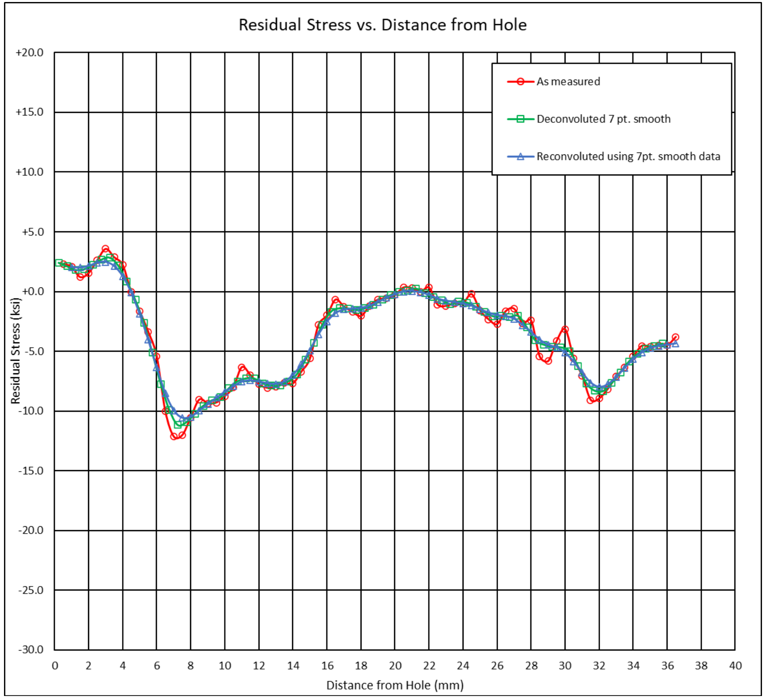
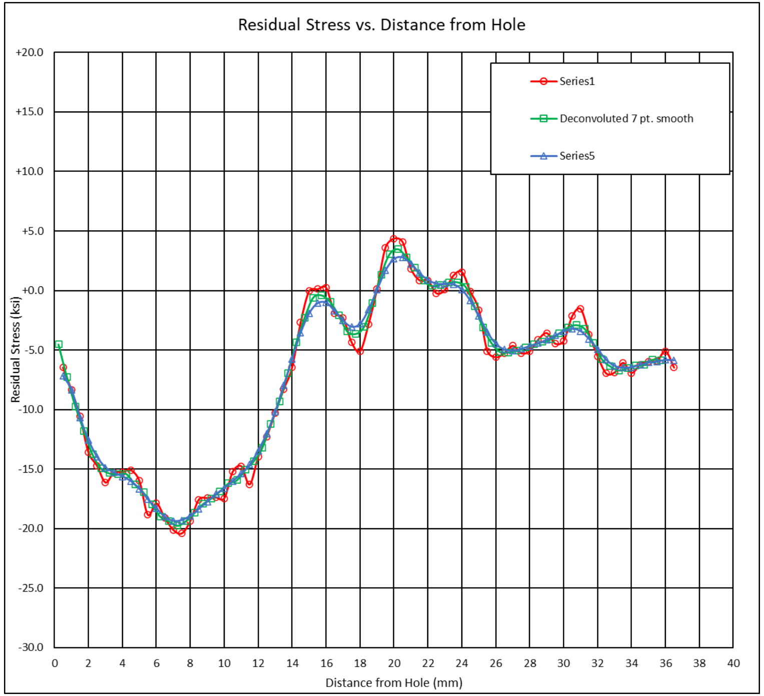
X-RAY DIFFRACTION

Padded Array Approach to Deconvolution

Entry 0.020” deep



Exit 0.020” deep



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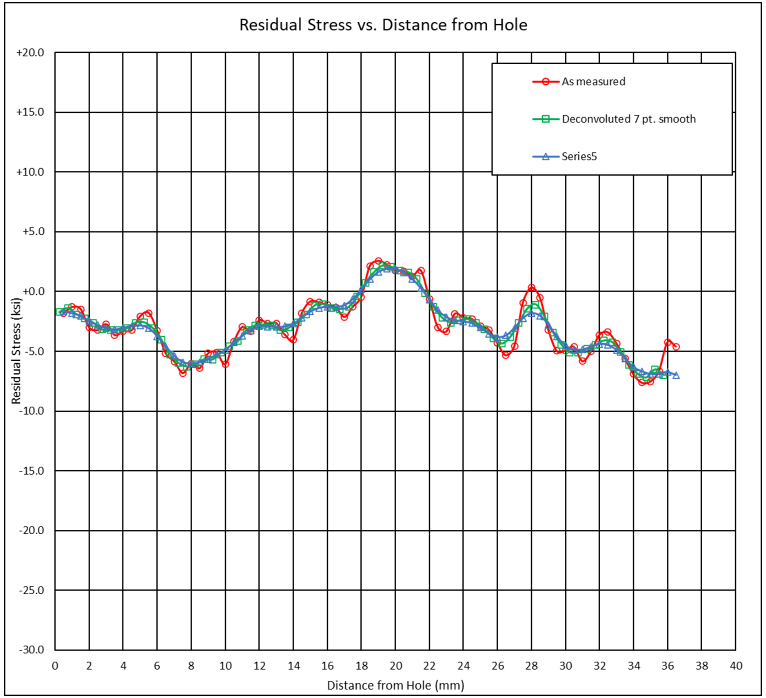
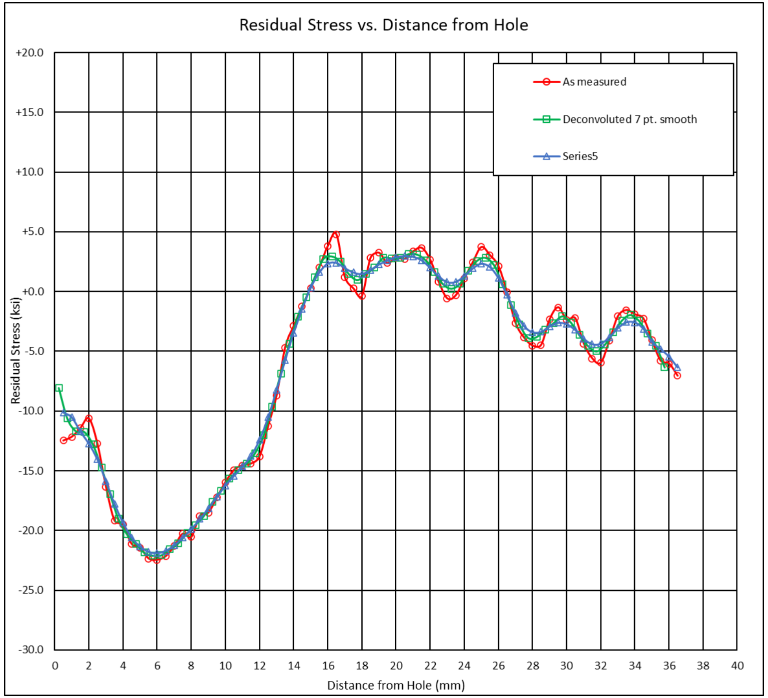
X-RAY DIFFRACTION

Padded Array Approach to Deconvolution

Entry 0.040" deep



Exit 0.040" deep



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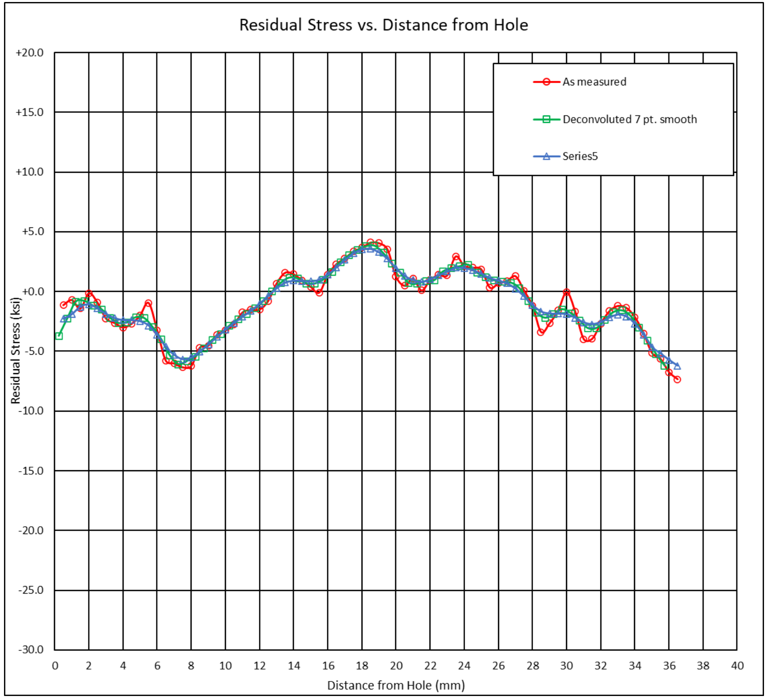
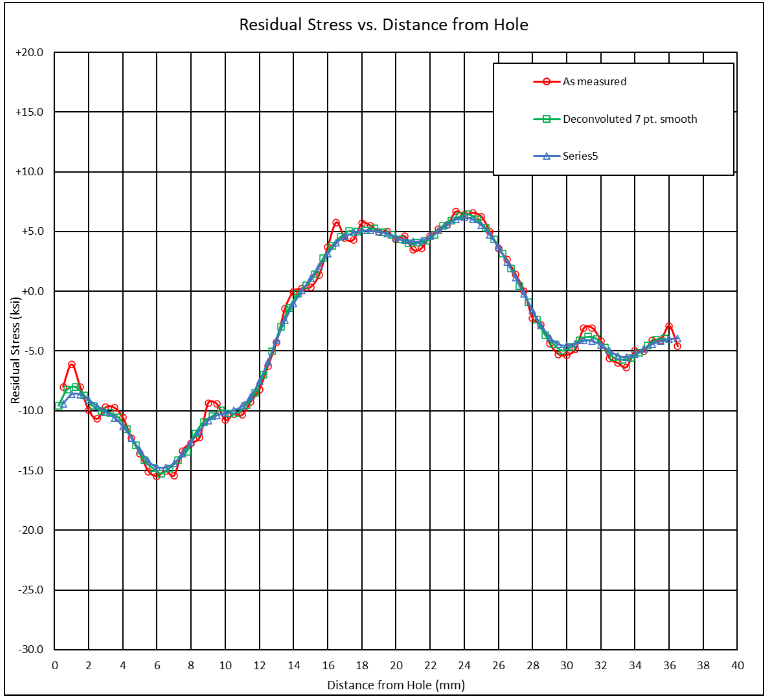
Padded Array Approach to Deconvolution

Entry 0.060” deep



Exit 0.060” deep



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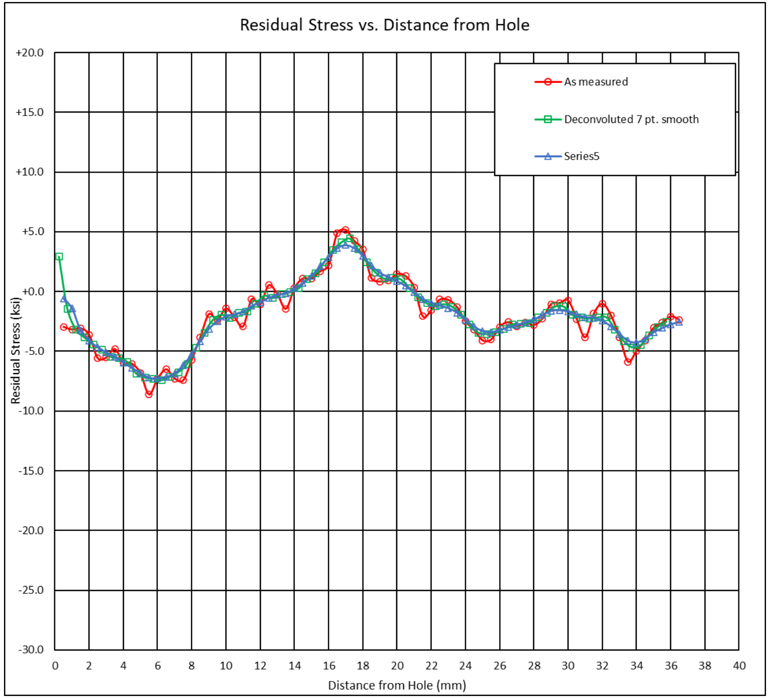
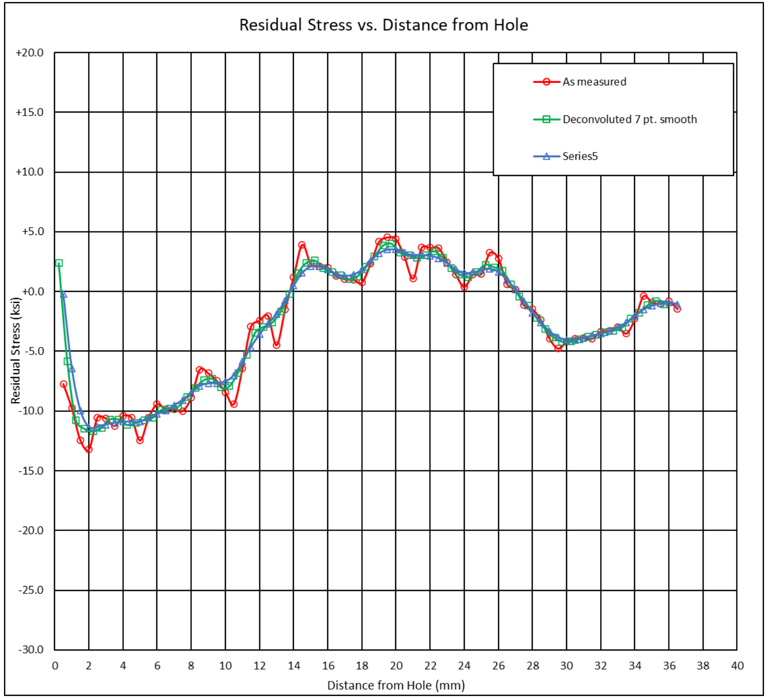
PROTO
X-RAY DIFFRACTION

Padded Array Approach to Deconvolution

Entry 0.080" deep



Exit 0.080" deep



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PROTO
X-RAY DIFFRACTION

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?

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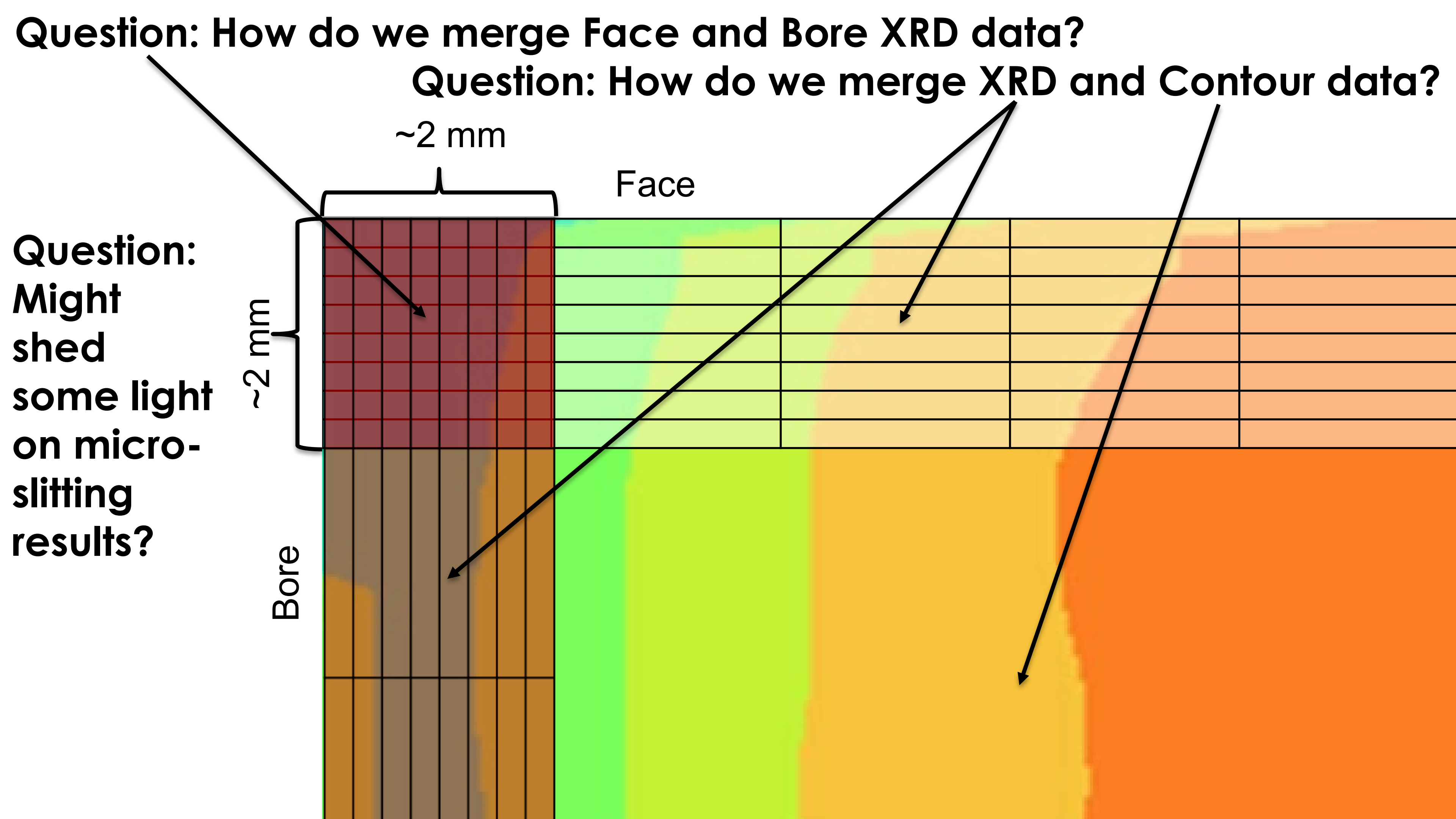
X-RAY DIFFRACTION


Question: How do we merge Face and Bore XRD data?
Question: How do we merge XRD and Contour data?
~2 mm
Face
Question: Might shed some light on micro-slitting results?
~2 mm
Bore

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

Presented by: Scott Carlson
Scott.Carlson@lmco.com
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^{TM}) To[illegible] M[illegible] 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

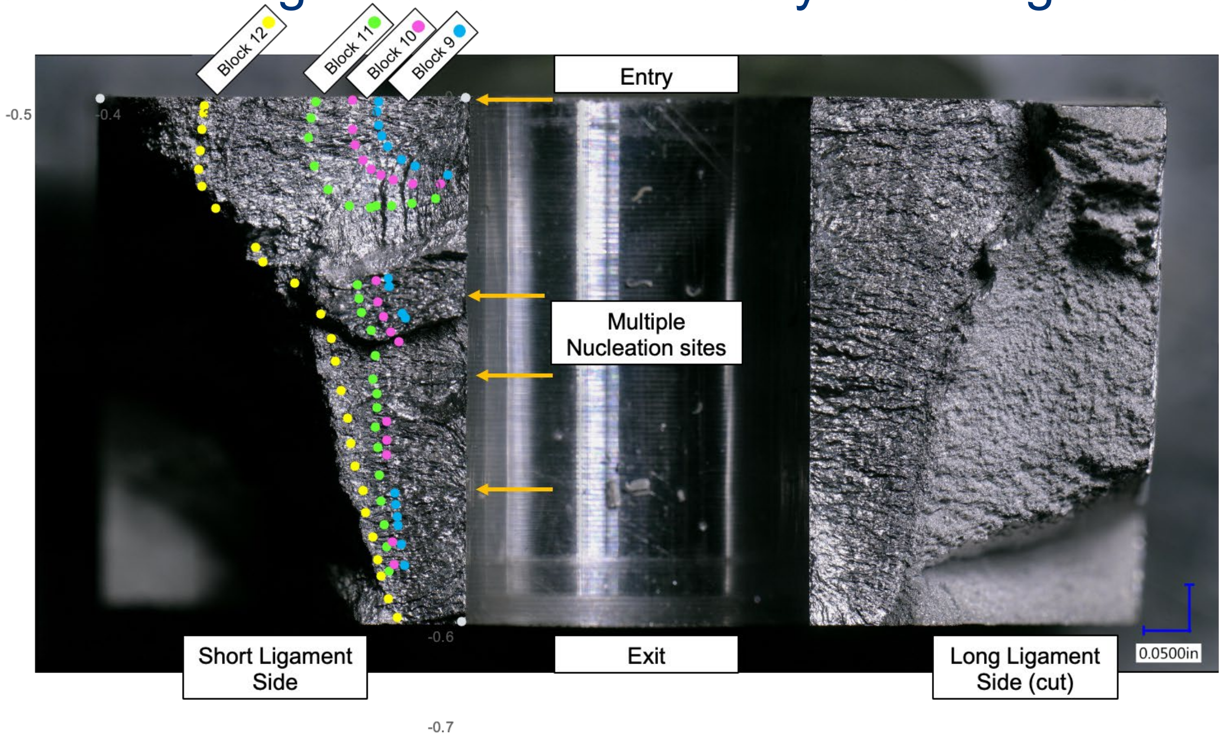
- **No Central Funding Source for all Work**
  - All Work provided at cost to the process/data owning organization – data “owned” by the group that processed the coupons
- 2016 NRC, FTI and SwRI Developed a FEA Round Robin Exercise
  - Goal was to compare state-of-the-art FEA process simulation methods 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

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!



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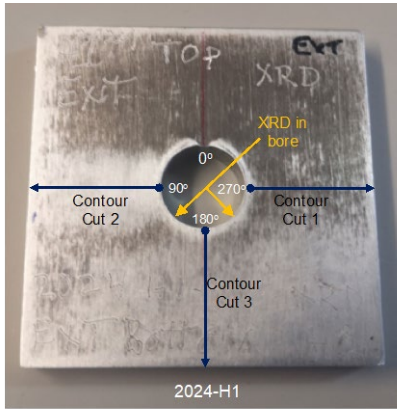
Lessons We're Learning

- 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



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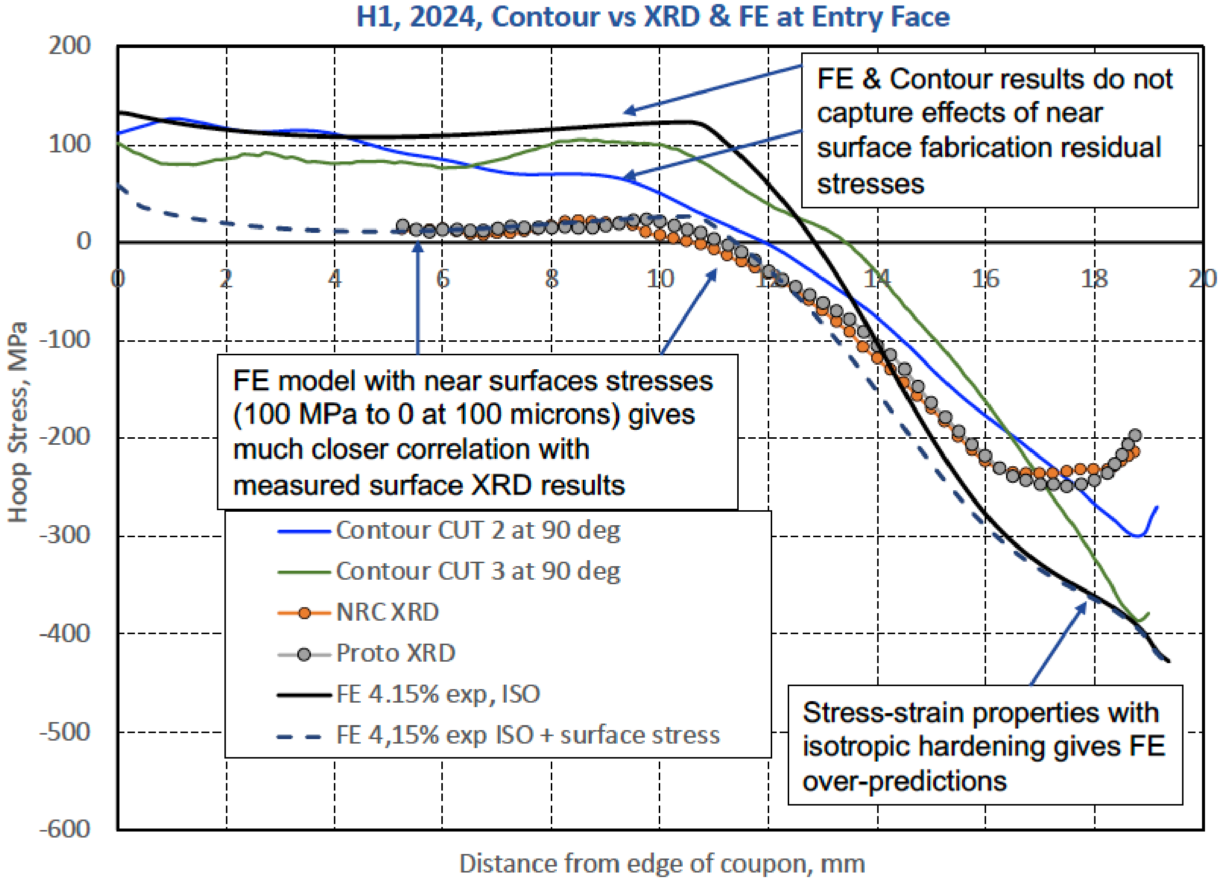
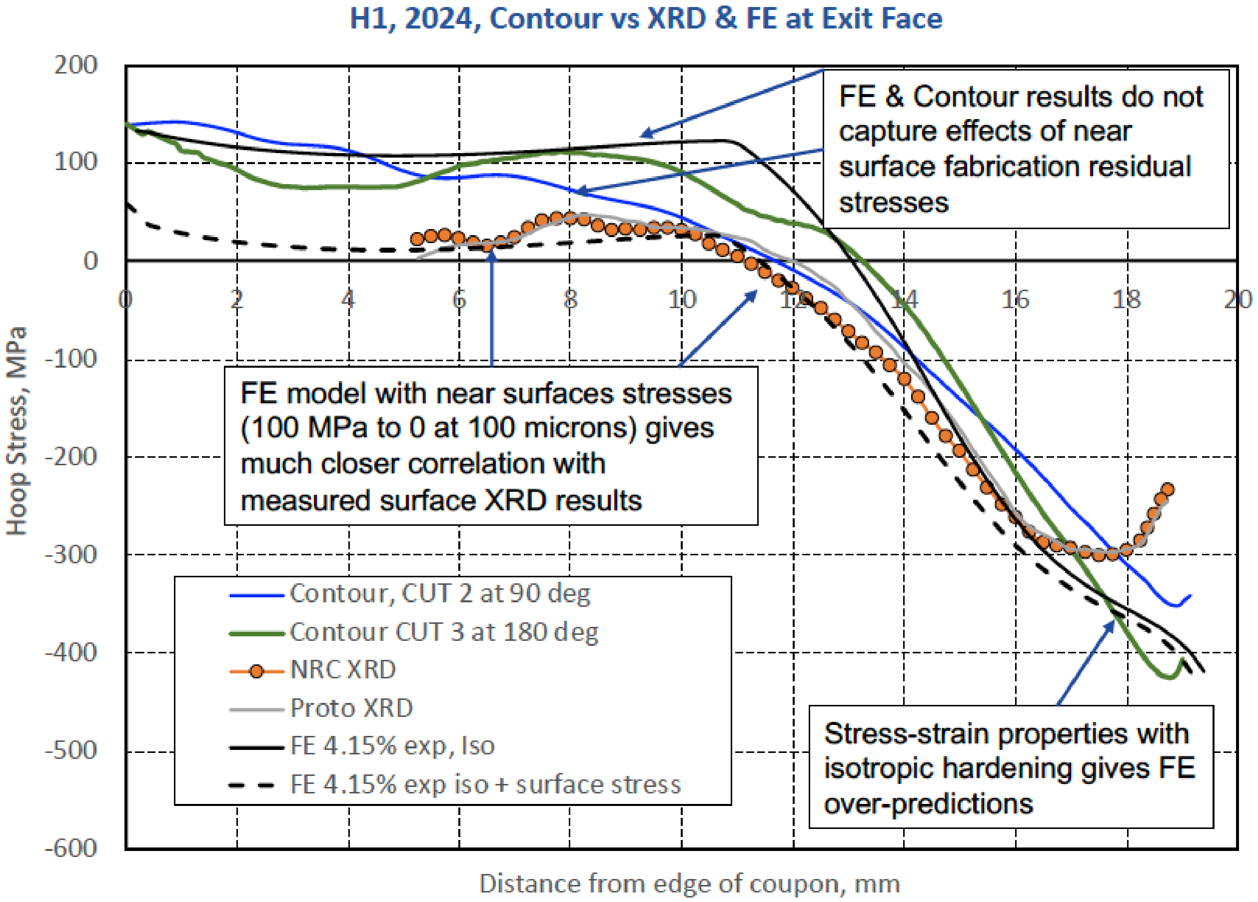
Initial Method for Combining RS Data

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





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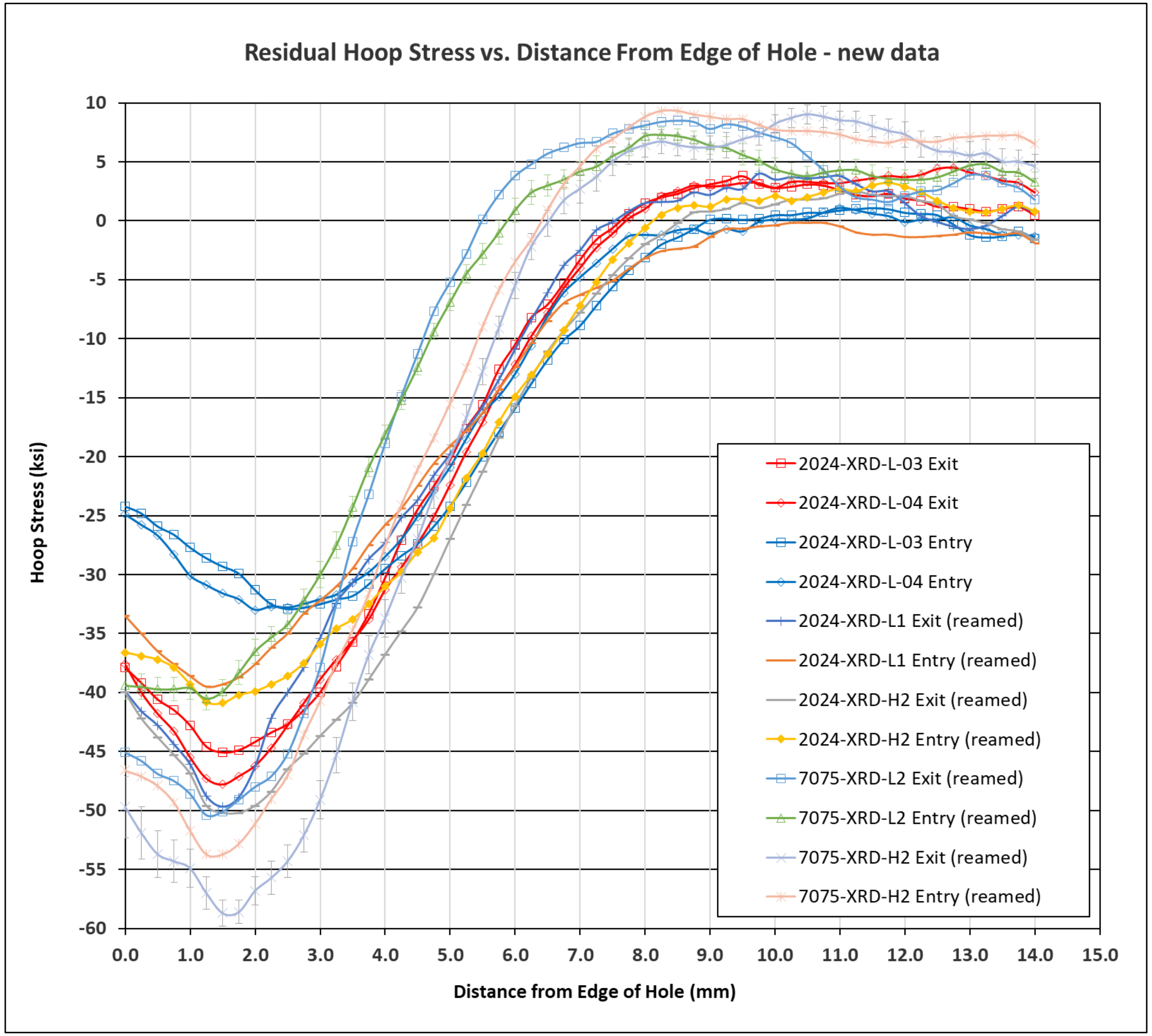
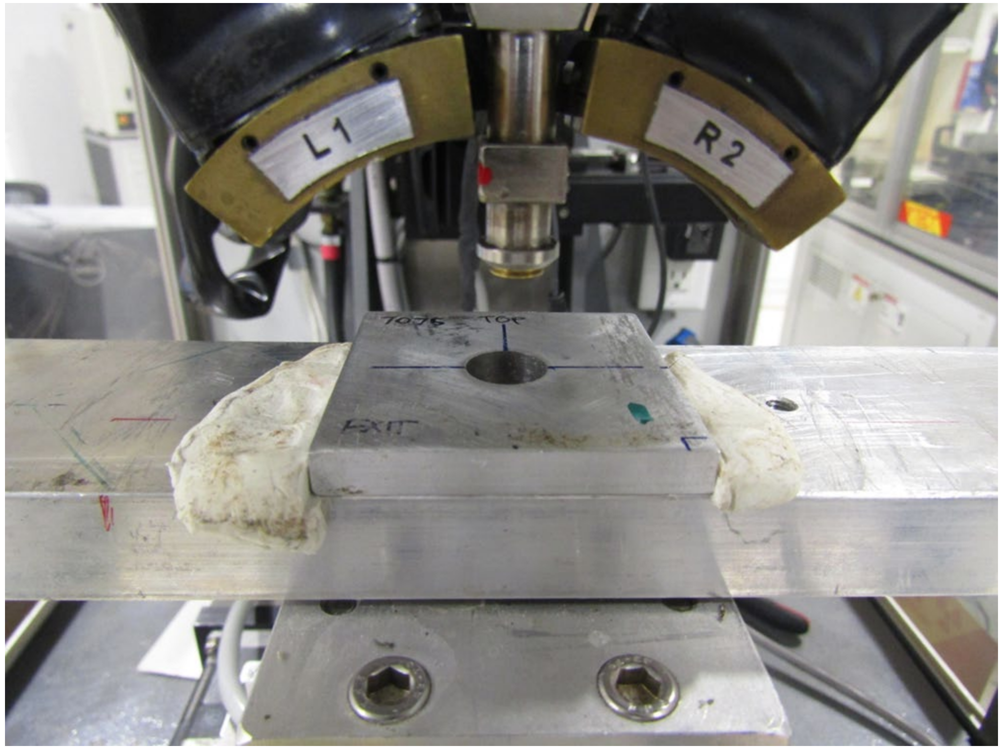
RS on surface faces of 2x2 Coupons new data for 2024-T351 and 7075-T651

PROTO X-RAY DIFFRACTION





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

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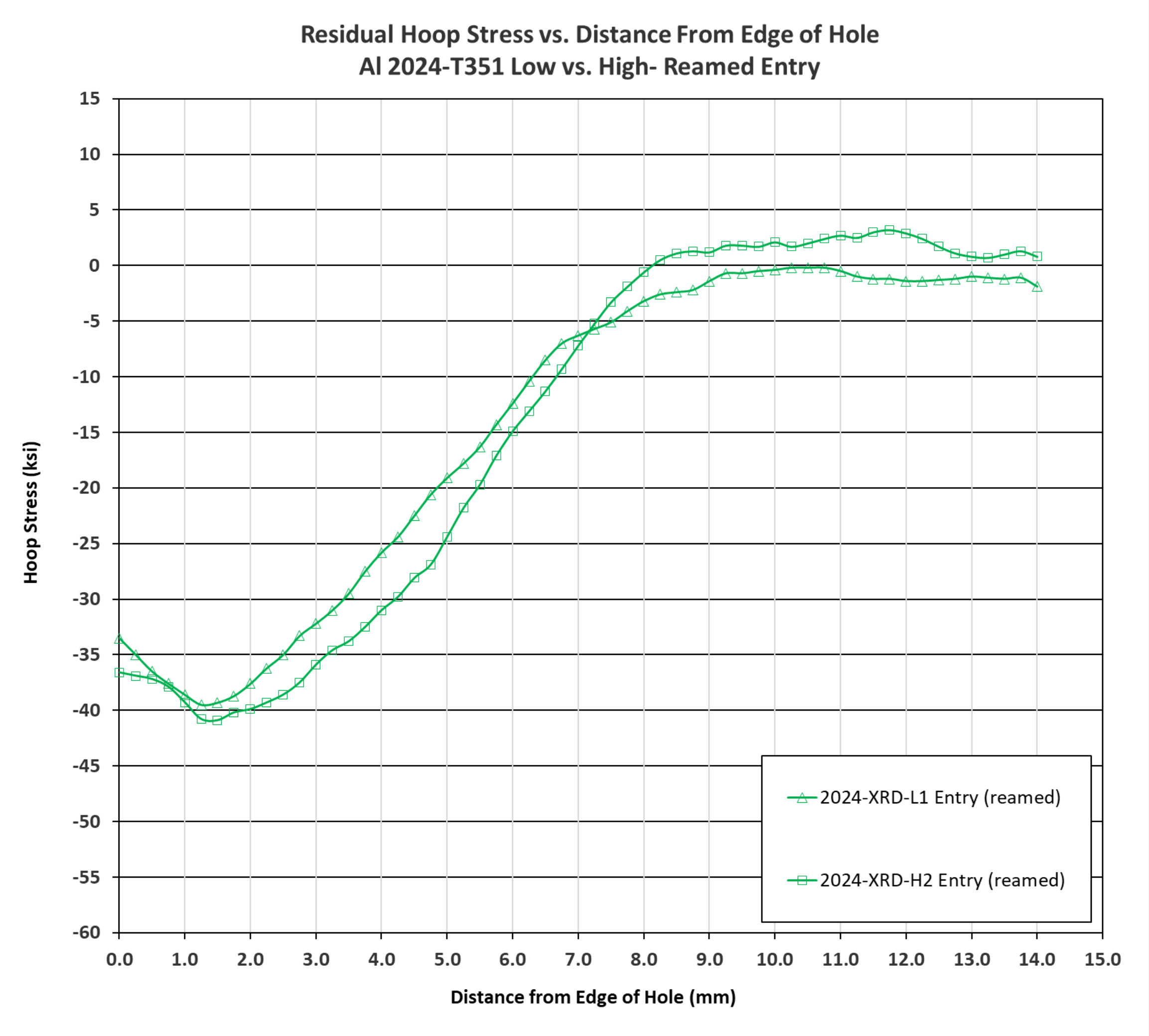
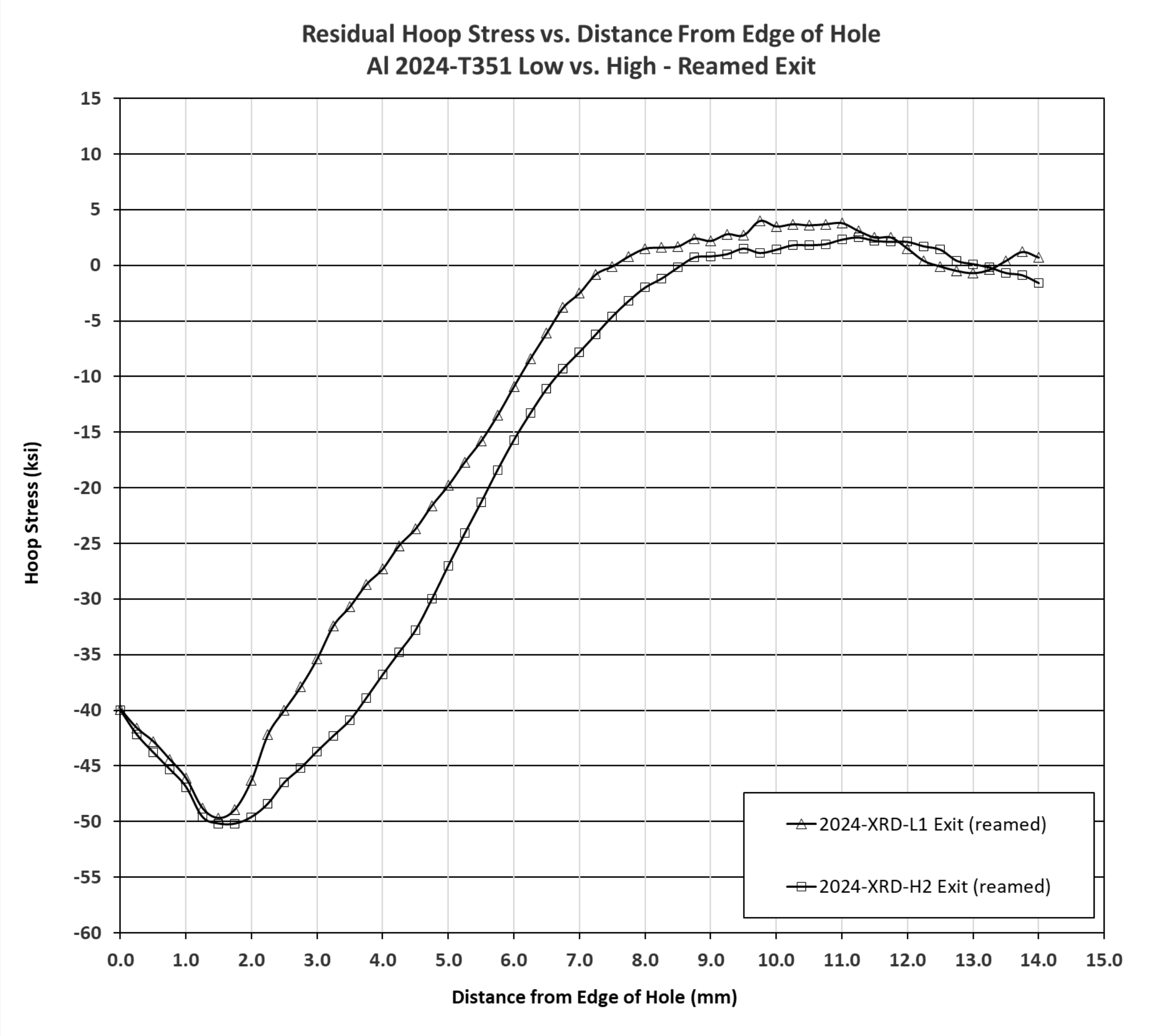
Low Cx vs. High Cx (Reamed Condition)

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





PROTO X-RAY DIFFRACTION

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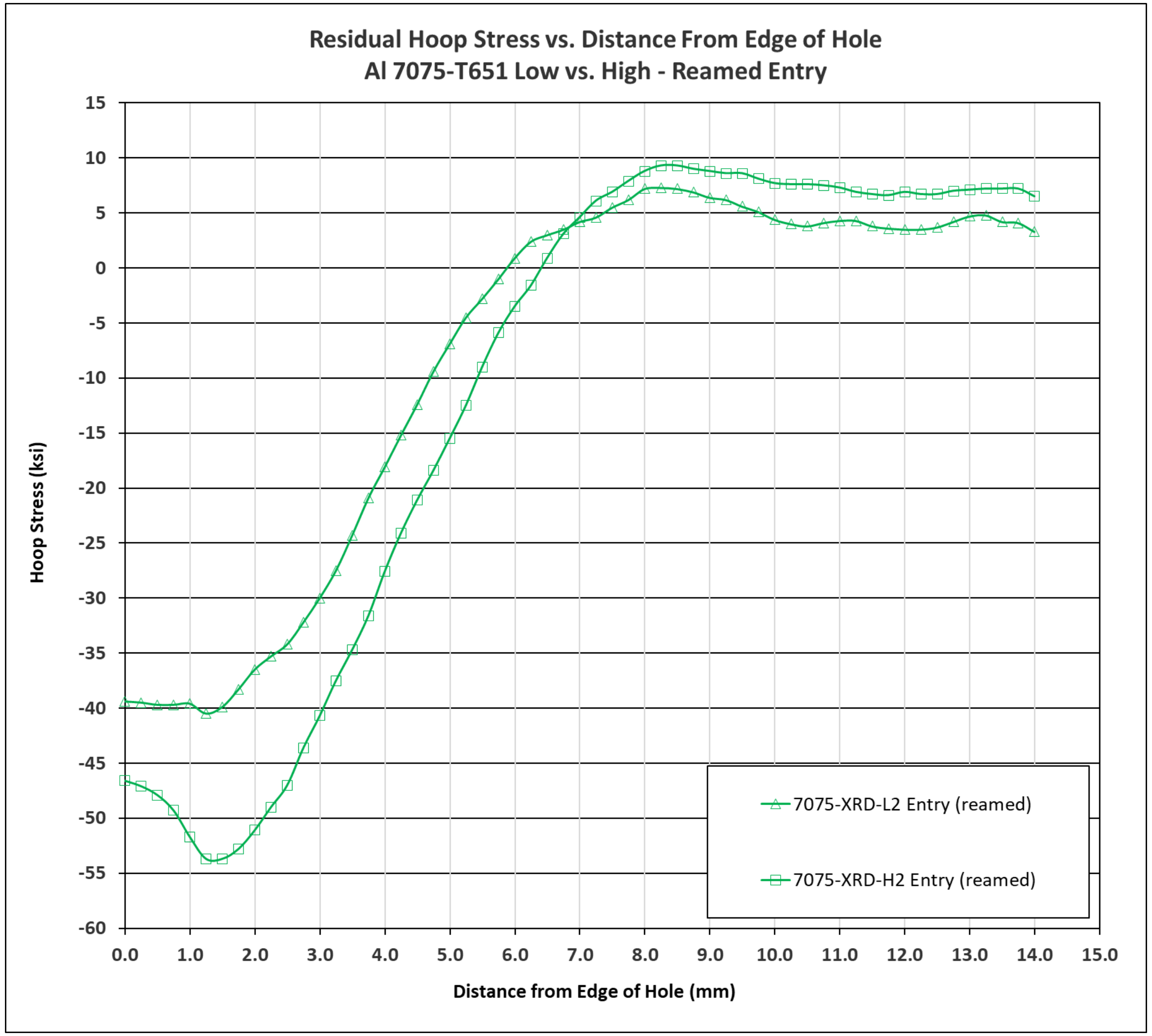
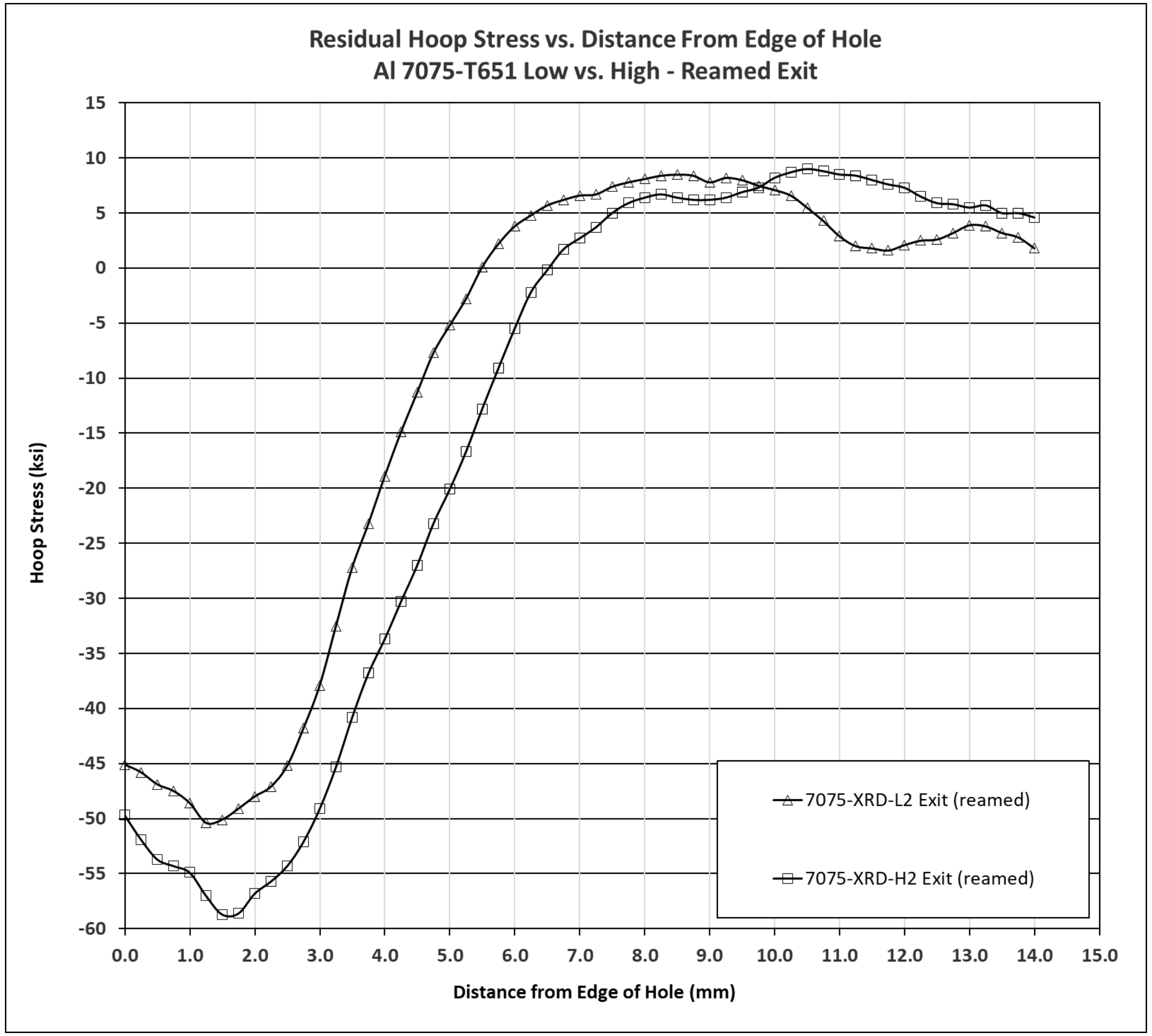
Al 7075-T651 (Reamed) – Low Cx vs. High Cx





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?

PROTO X-RAY DIFFRACTION

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

PROTO X-RAY DIFFRACTION

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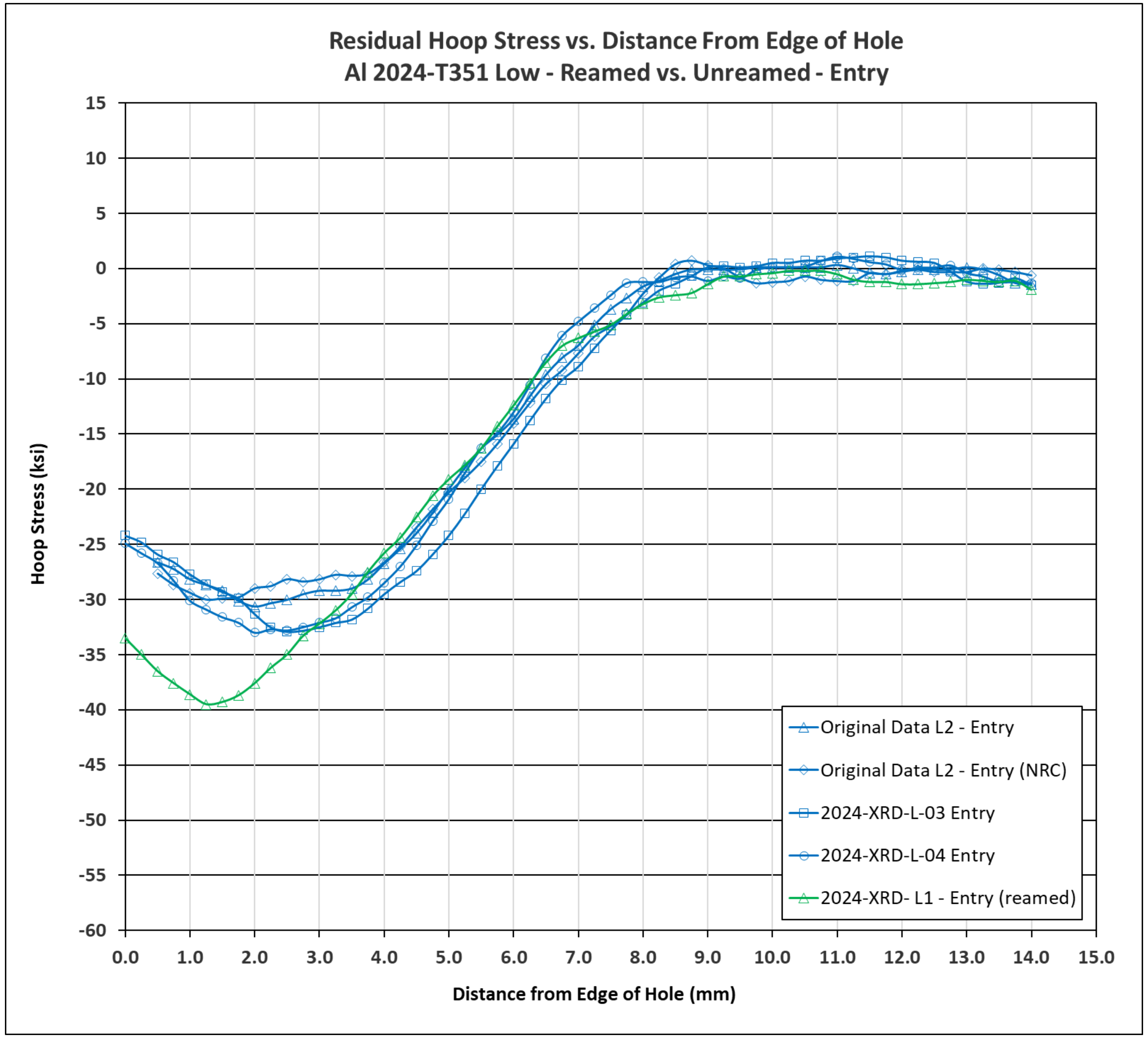
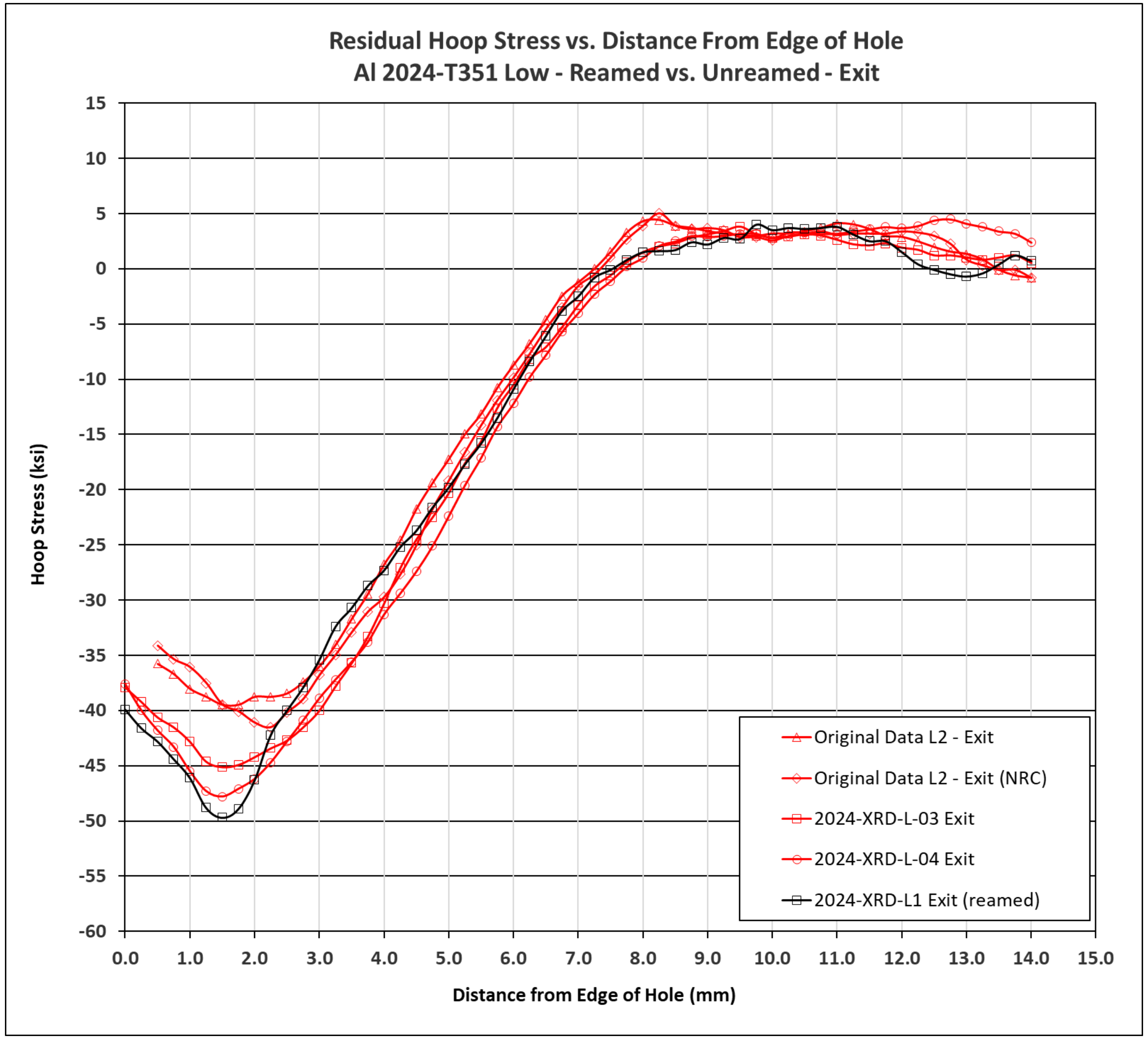
Al 2024-T351 High Cx - Reamed vs. Un-reamed





PROTO X-RAY DIFFRACTION

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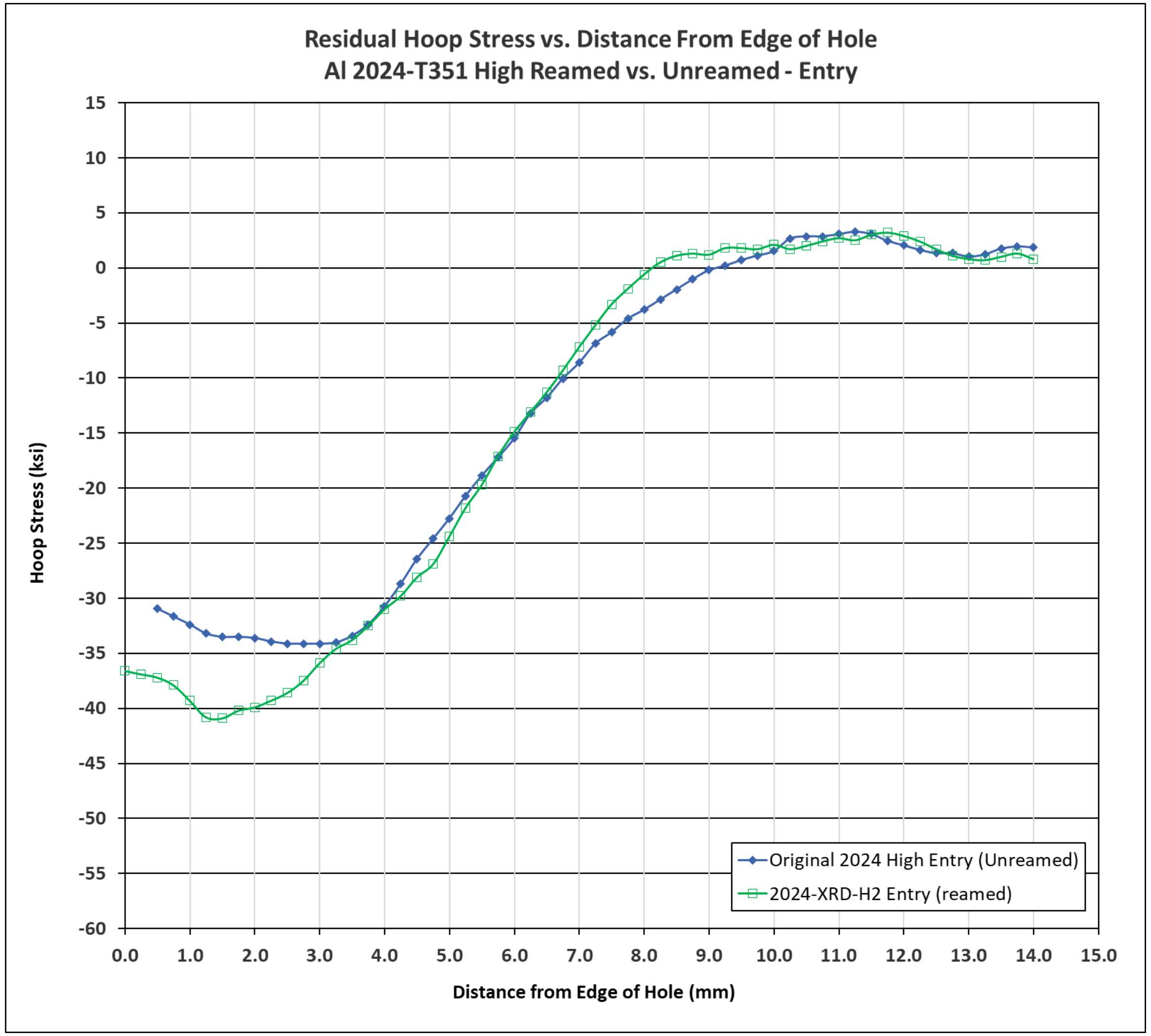
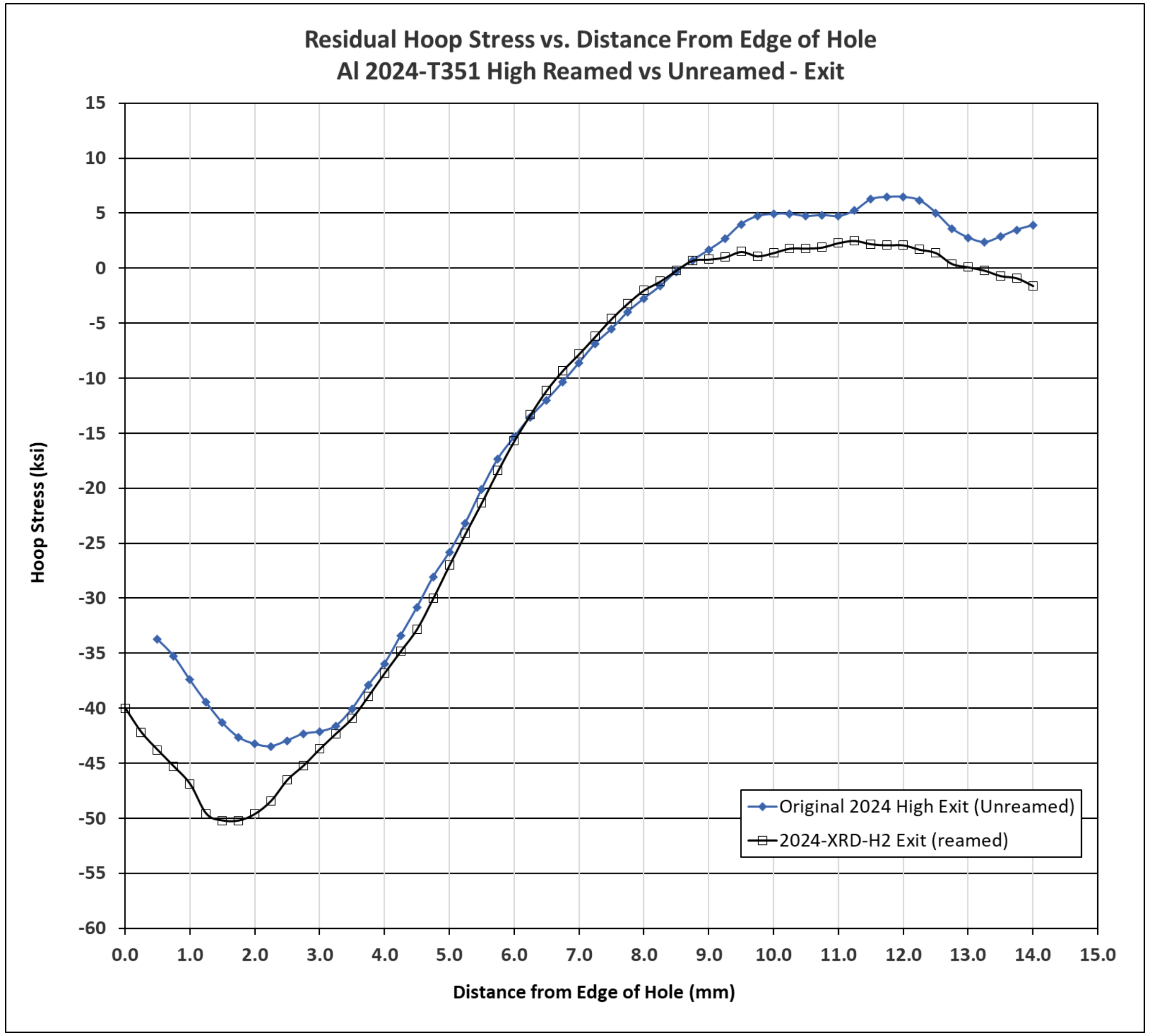
Al 2024-T351 High Cx - Reamed vs. Un-reamed





PROTO X-RAY DIFFRACTION

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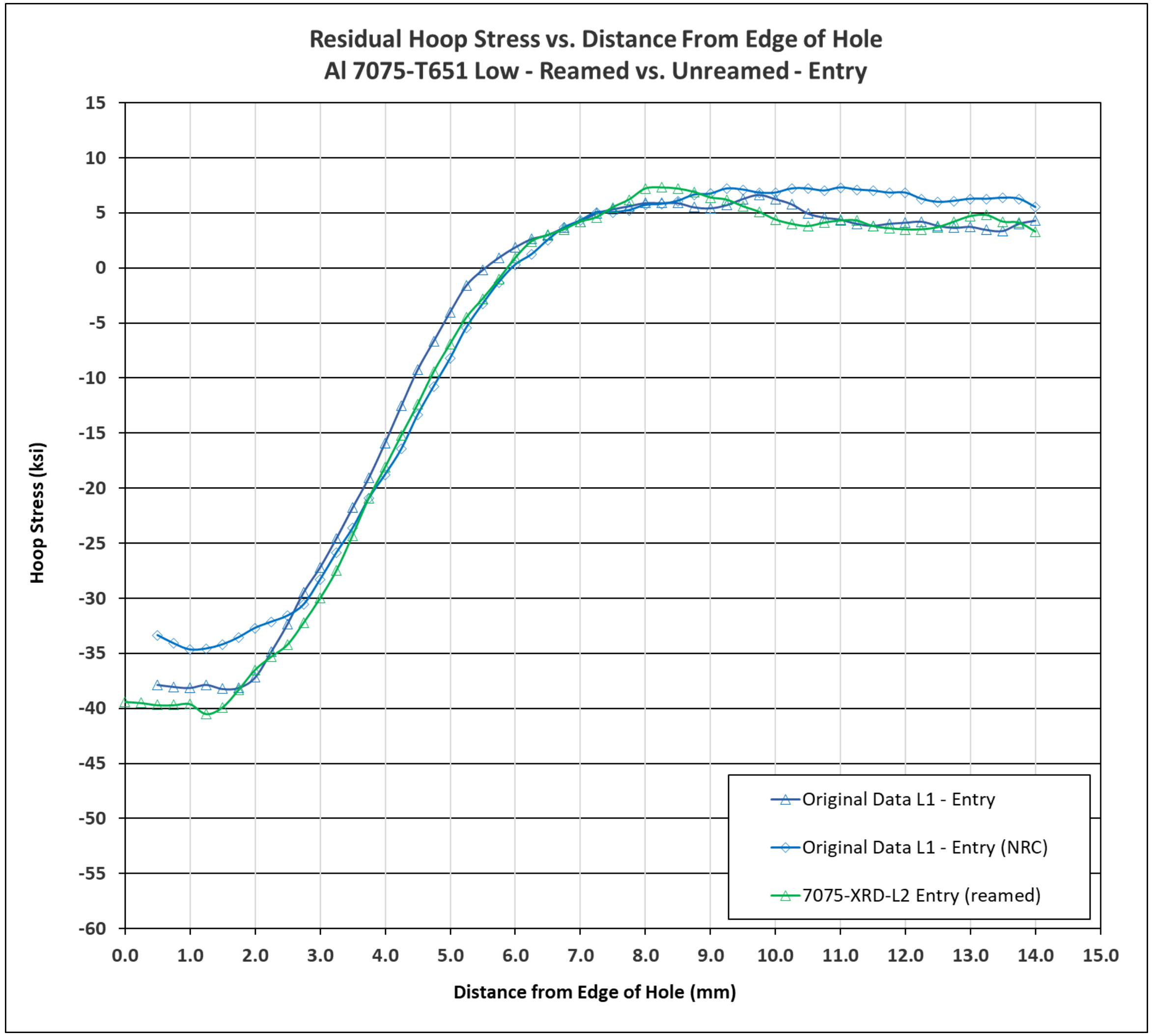
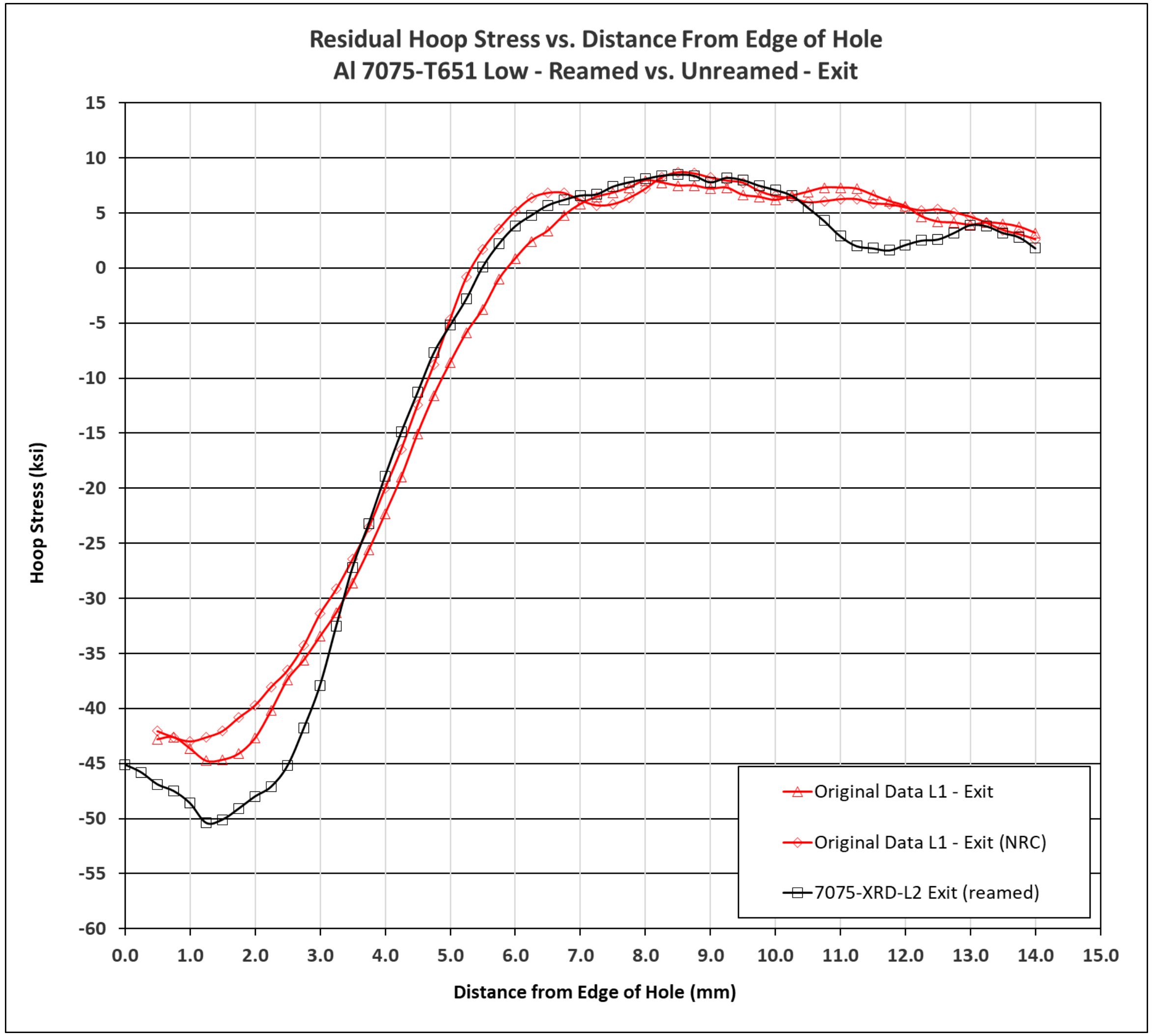
Al 7075-T651 Low Cx- Reamed vs. Un-reamed





PROTO
X-RAY DIFFRACTION

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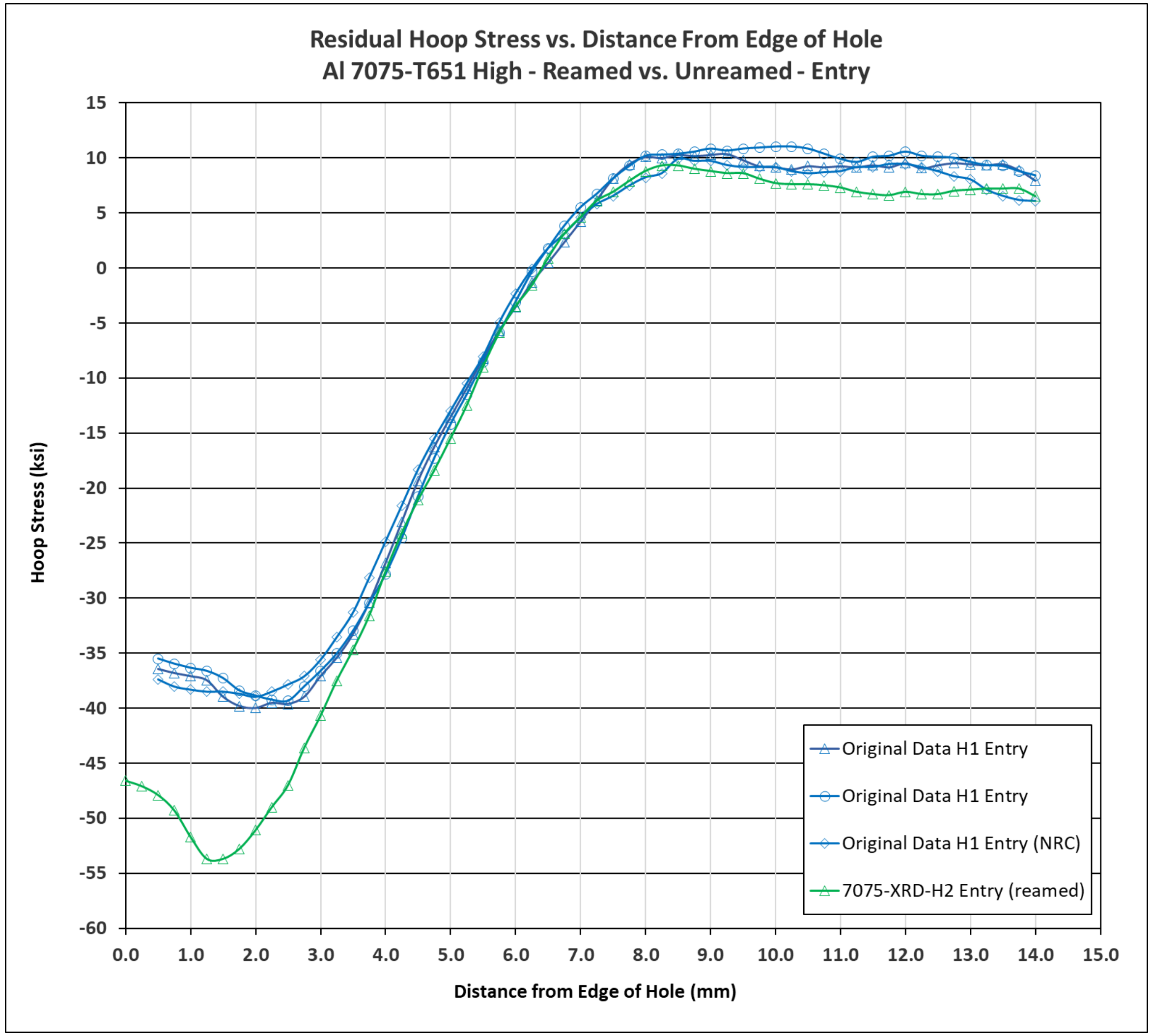
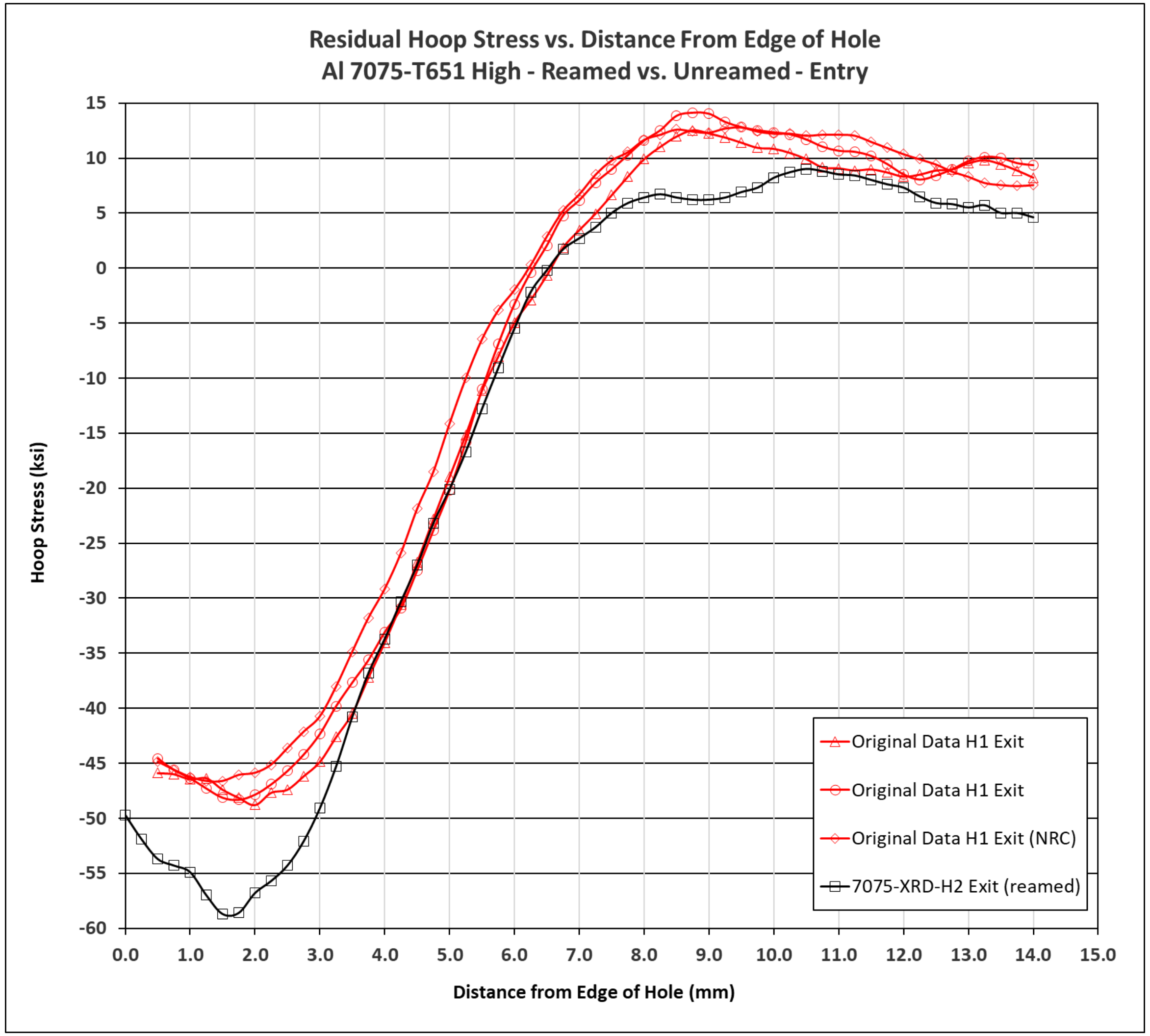
Al 2024-T351 Low & High Cx - Reamed vs. Un-reamed





PROTO X-RAY DIFFRACTION

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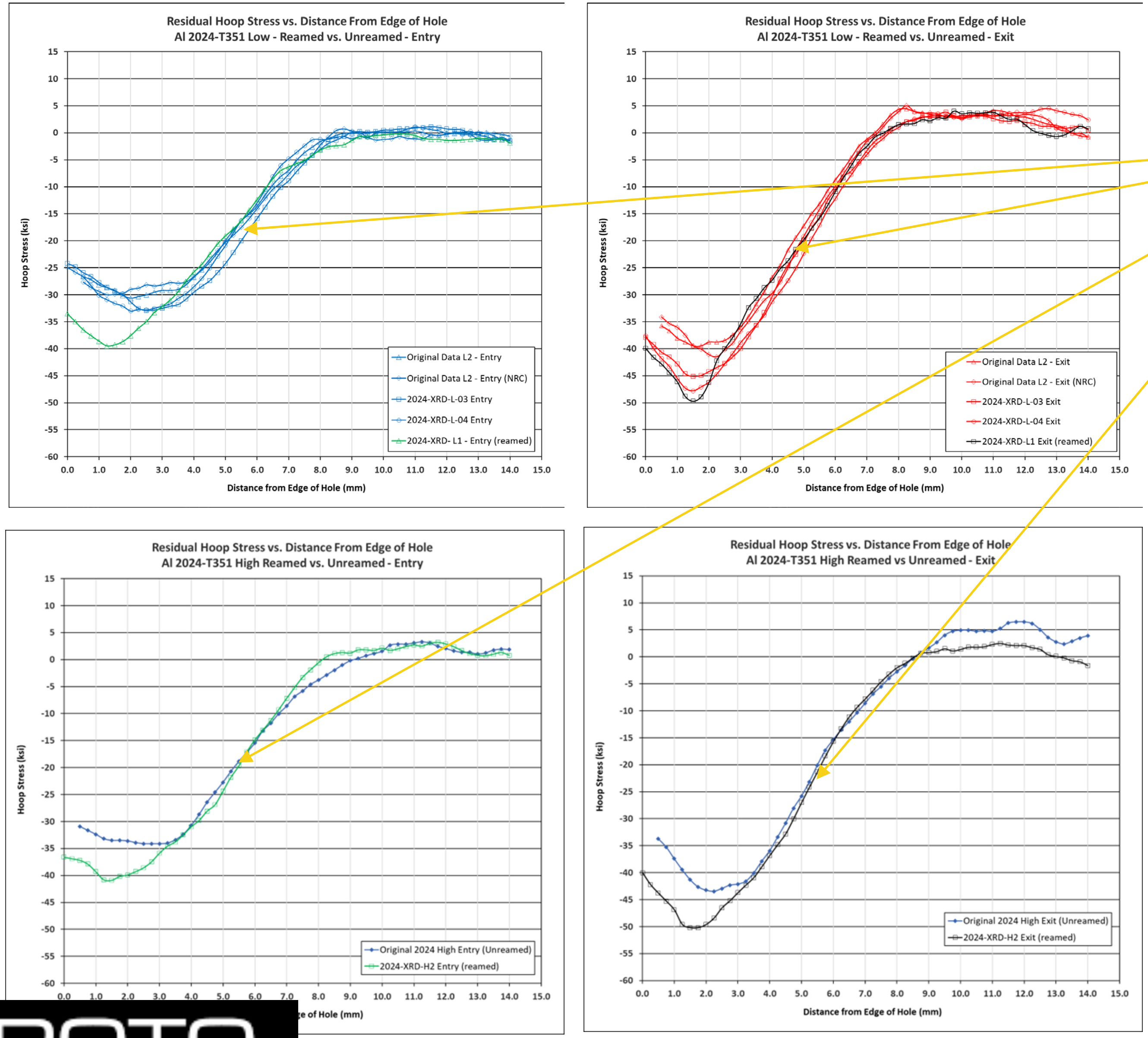
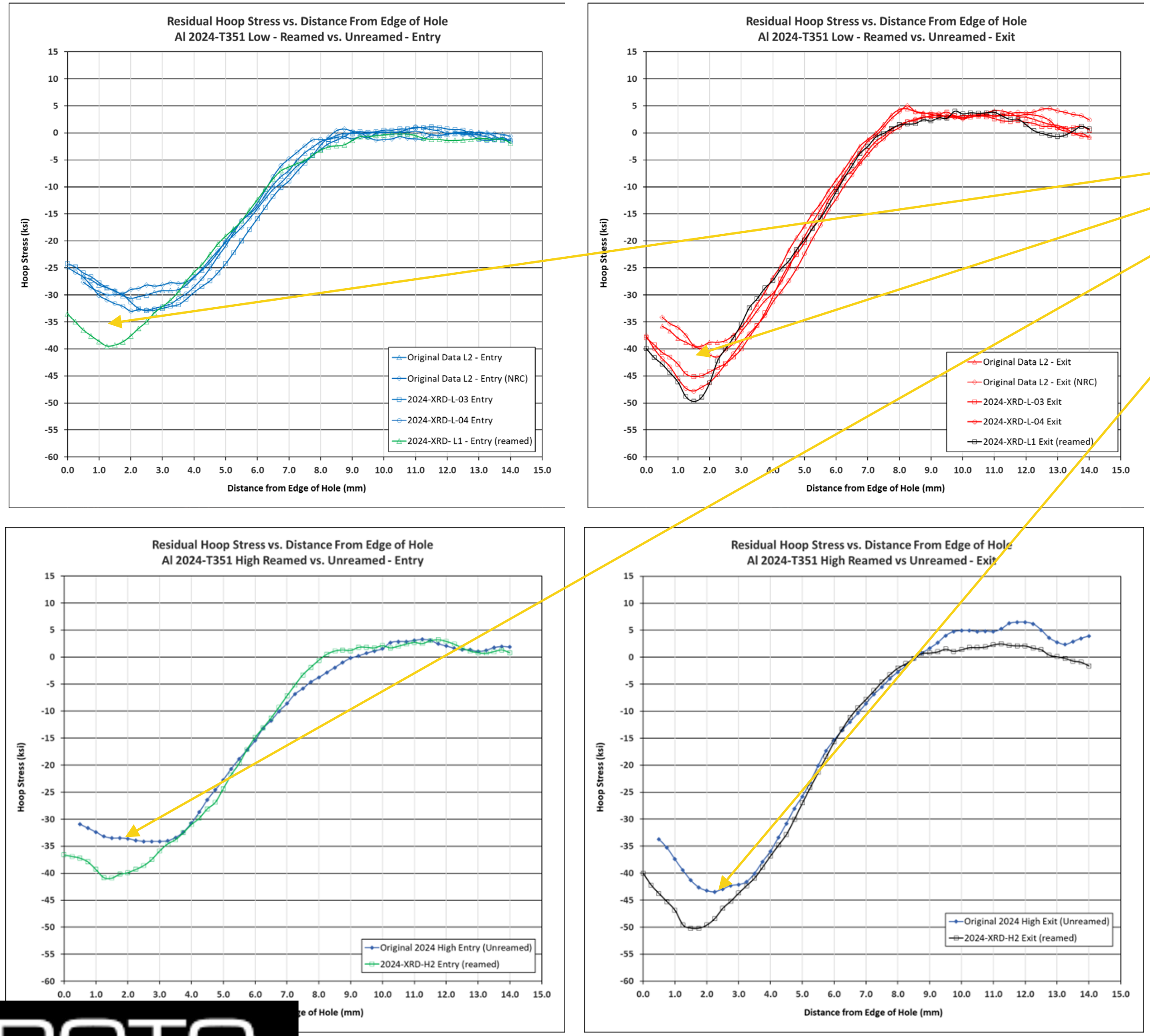
Al 2024-T351 Low & High Cx - Reamed vs. Un-reamed



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

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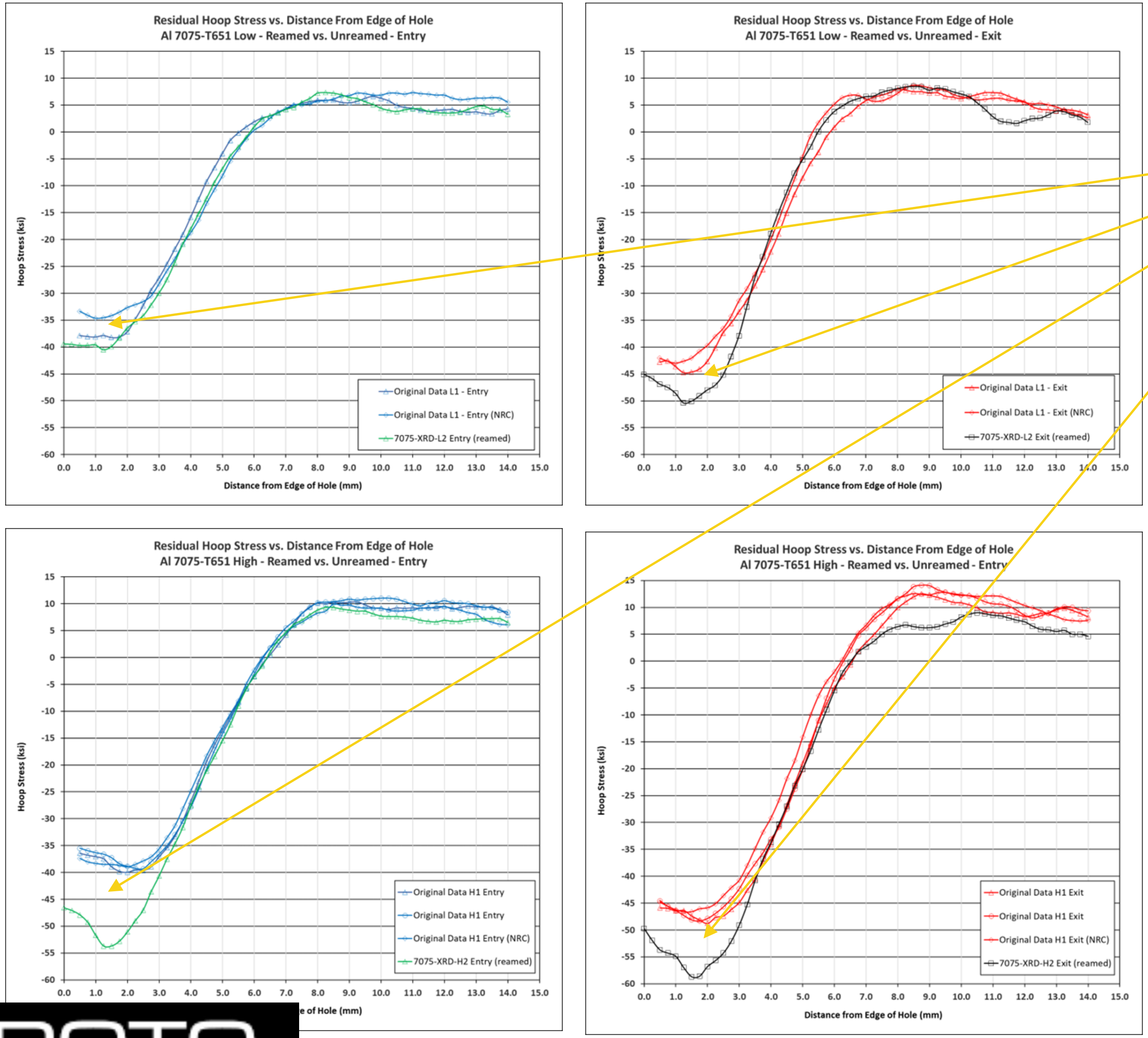
Al 7075-T651 Low & High Cx - Reamed vs. Un-reamed



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

PROTO X-RAY DIFFRACTION

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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.

PROTO X-RAY DIFFRACTION

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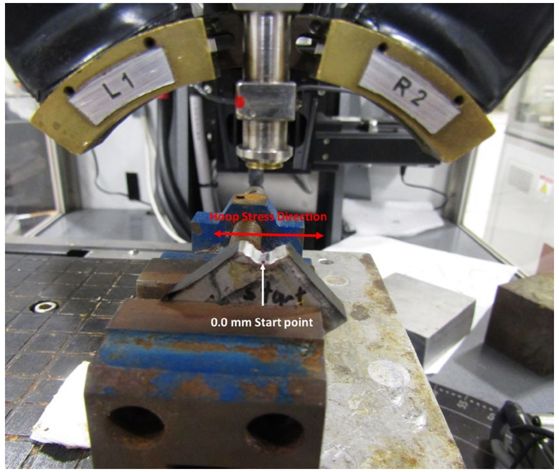
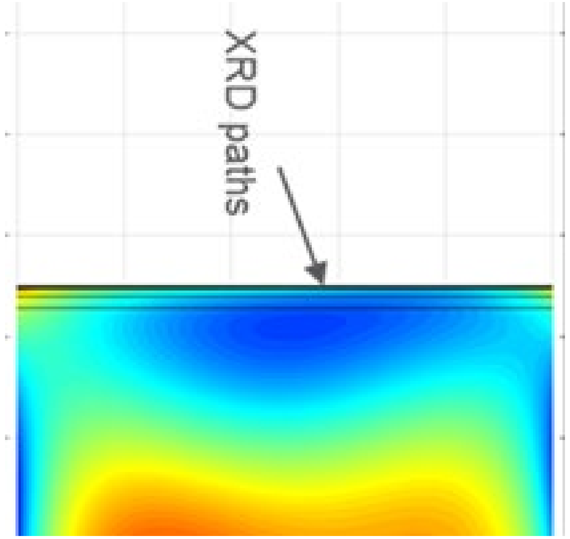
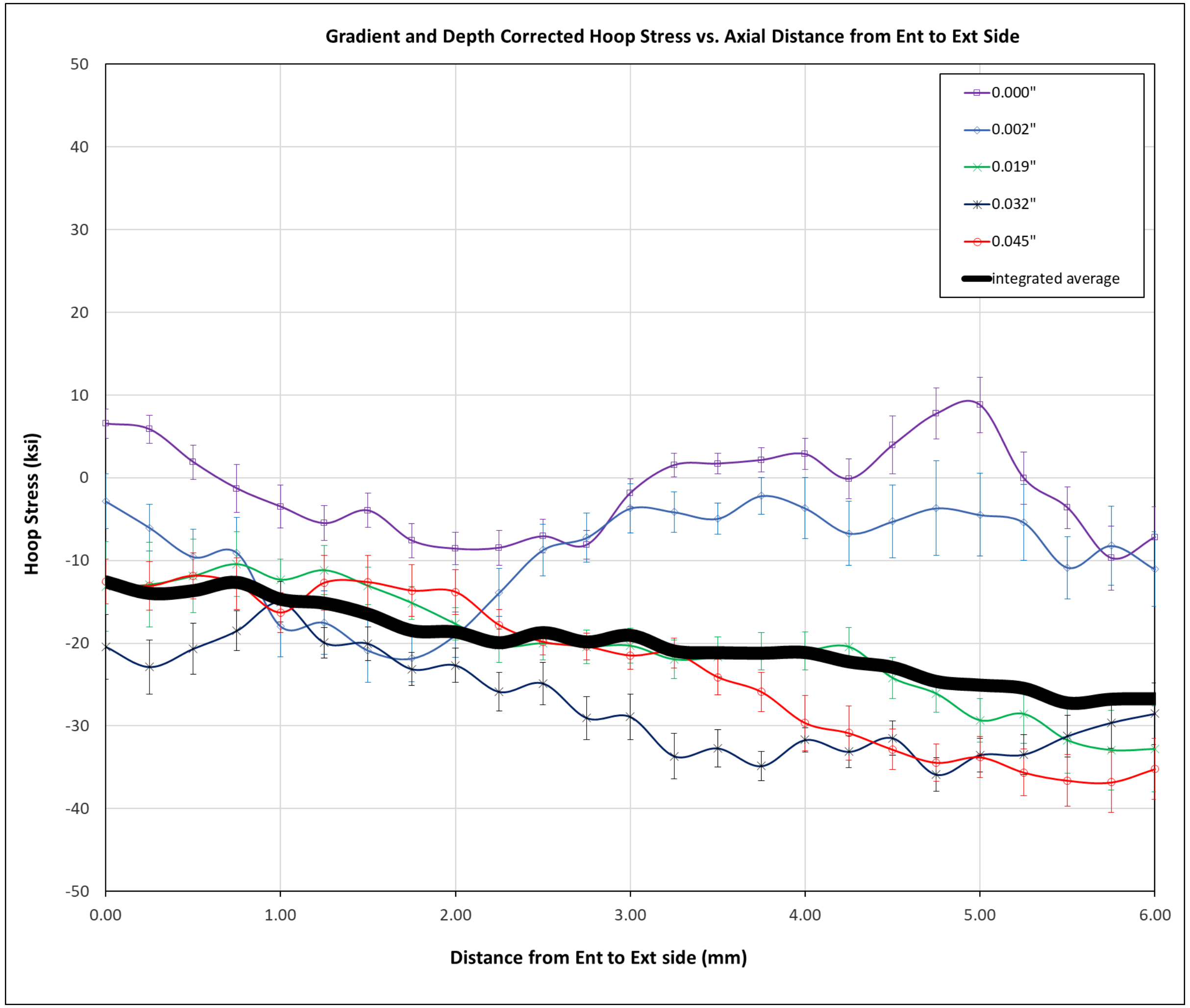
RS in Bore of 2 x 2 Cx Hole – 2024-T351 High (Un-reamed)

- 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







PROTO X-RAY DIFFRACTION

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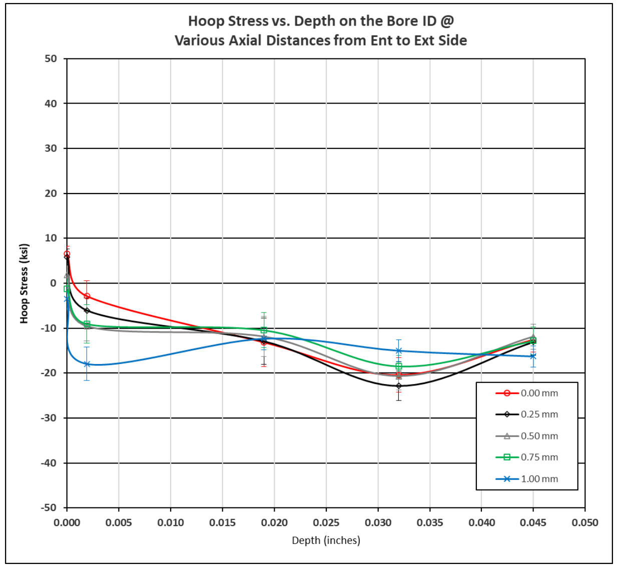
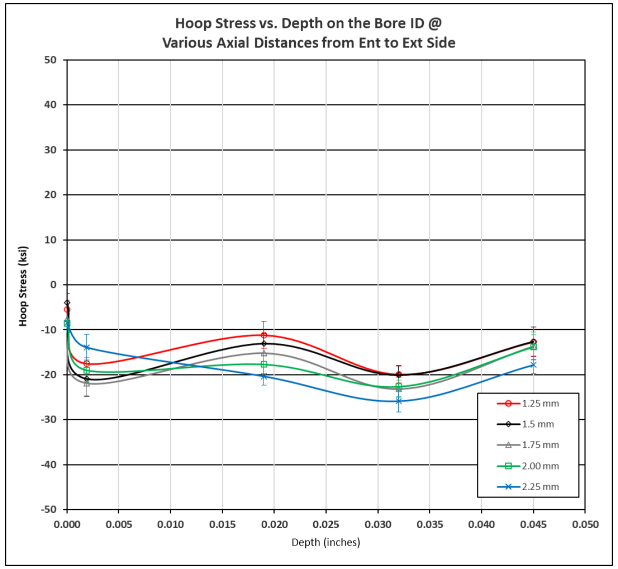
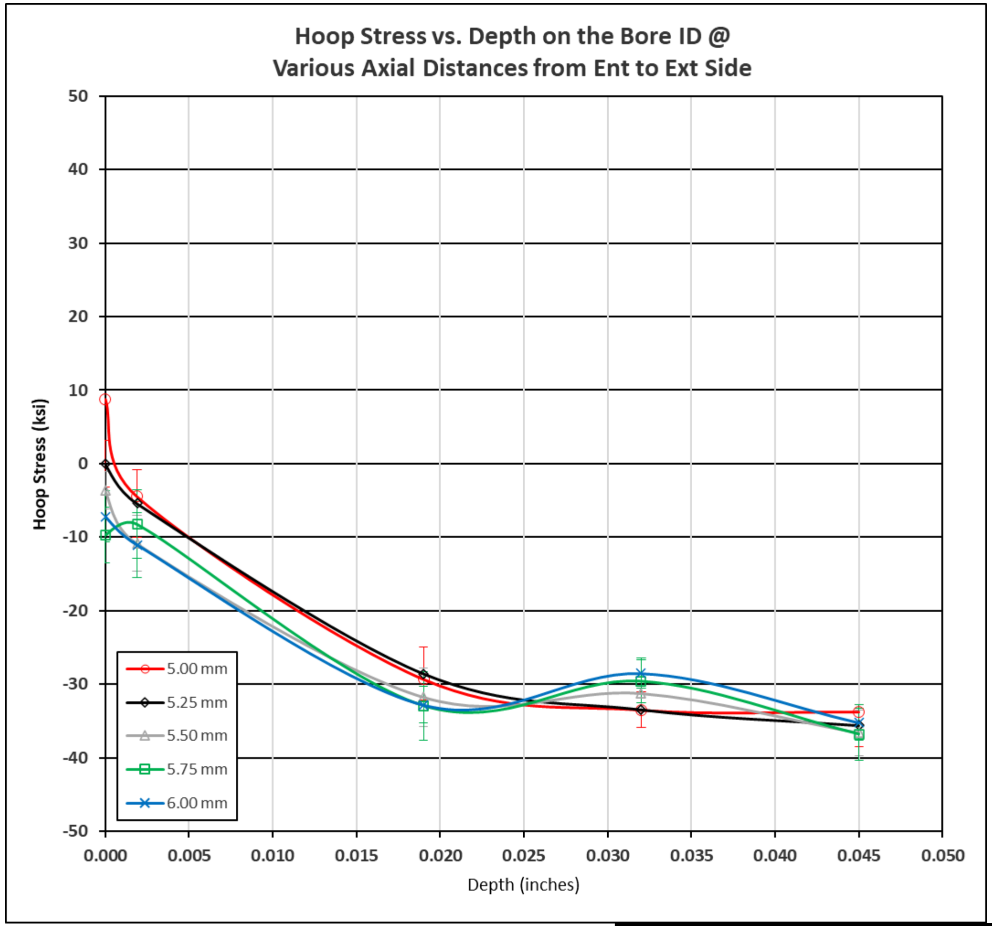
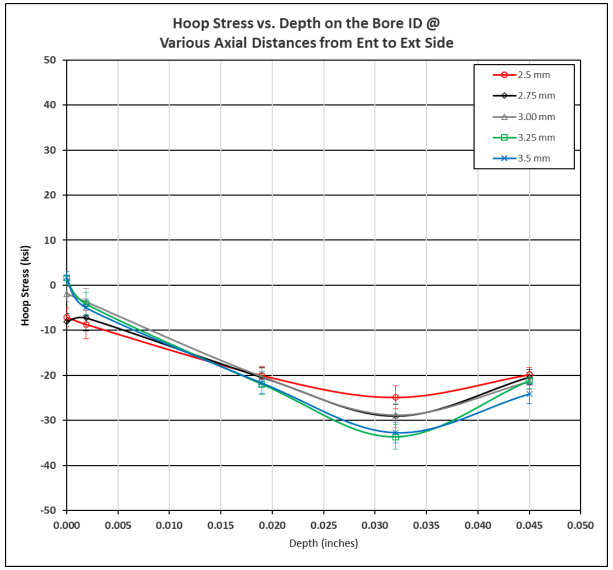
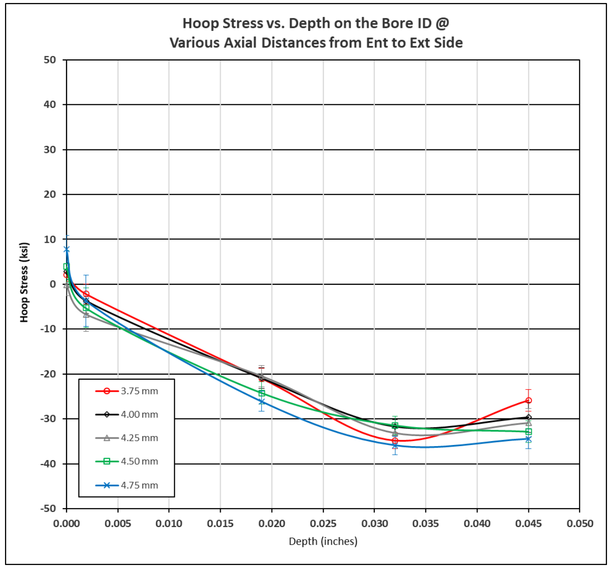
RS depth profiles at individual points across the bore
2 x 2 Cx Hole – 2024-T351 High (Un-reamed)





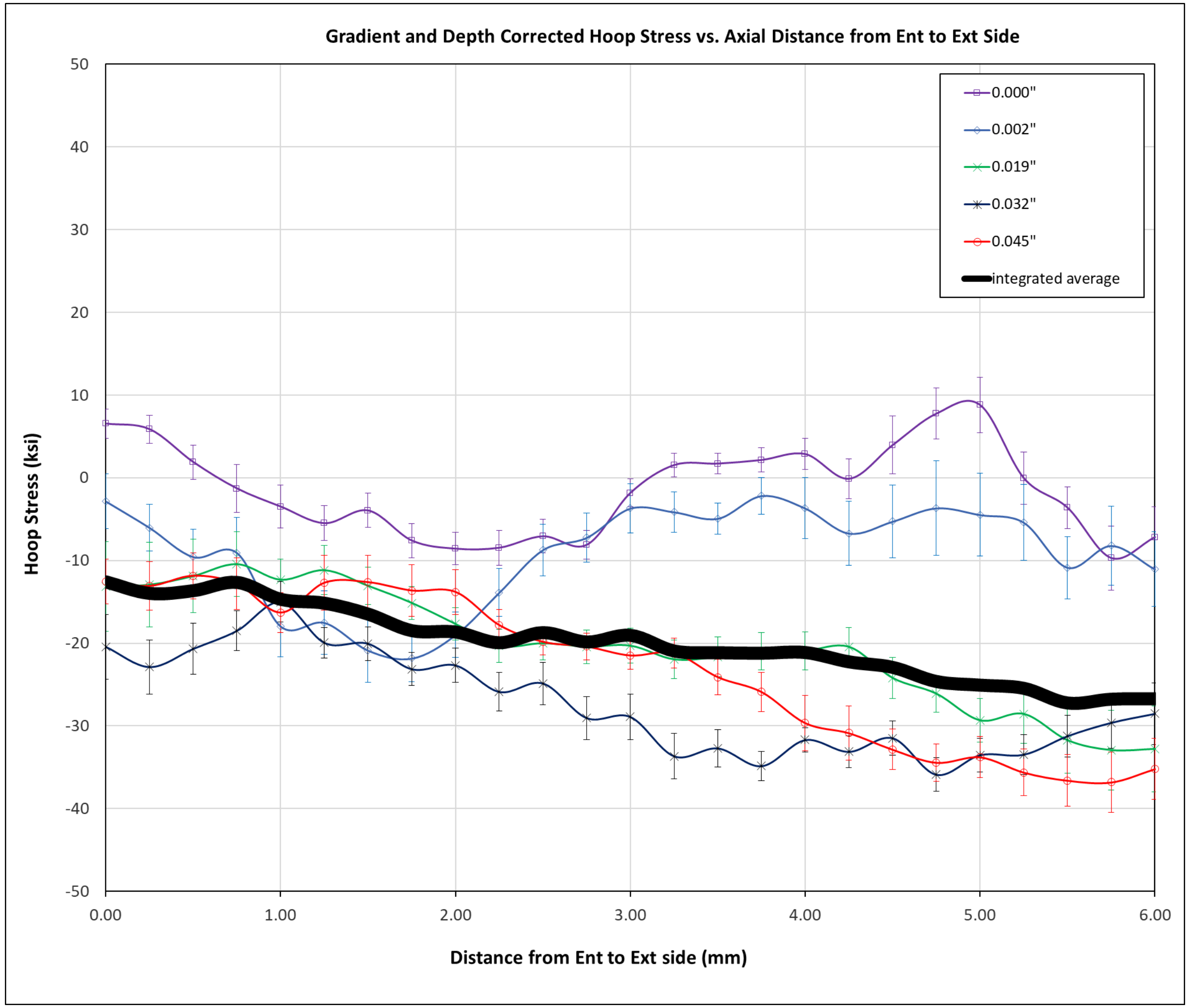


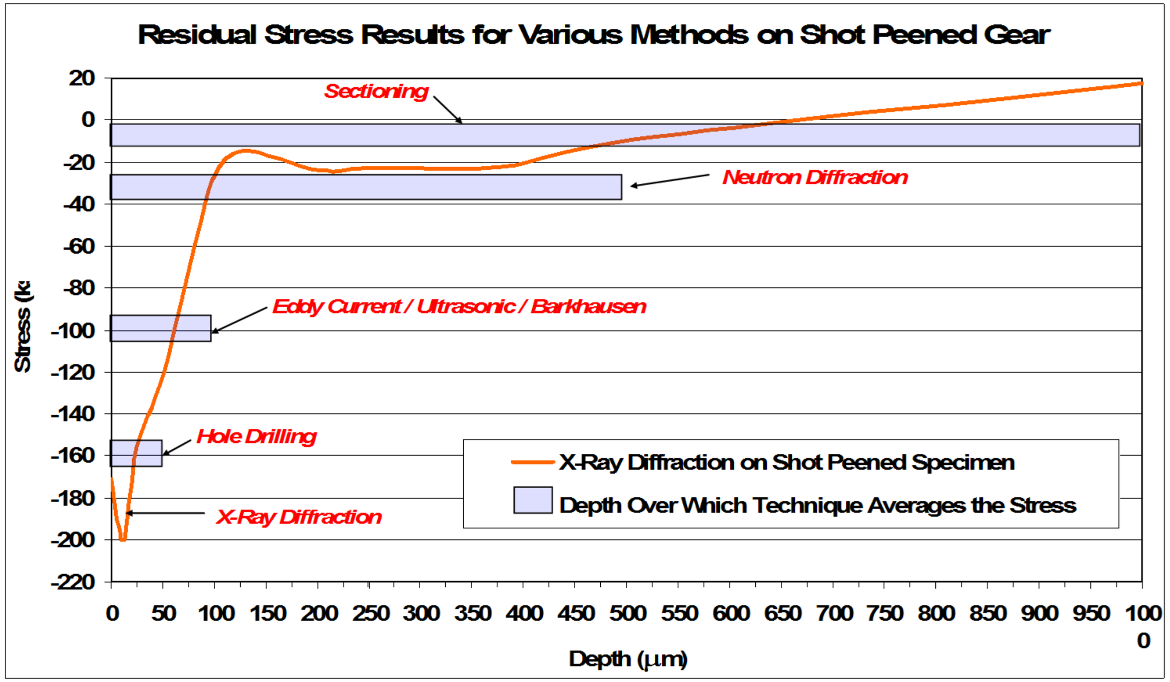




Note: near surface cold working RS persist to ~ 0.025" deep

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

PROTO X-RAY DIFFRACTION

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Conclusions

PROTO X-RAY DIFFRACTION

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.

PROTO X-RAY DIFFRACTION

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Thank You

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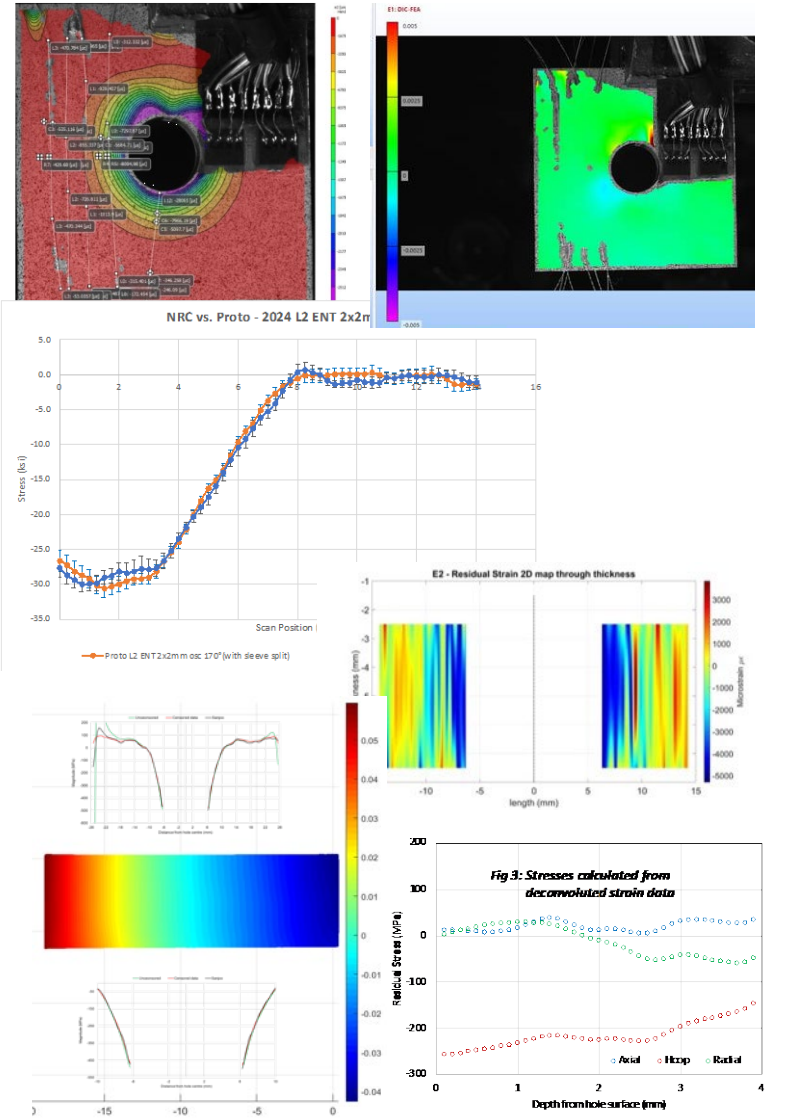
Work Completed

- 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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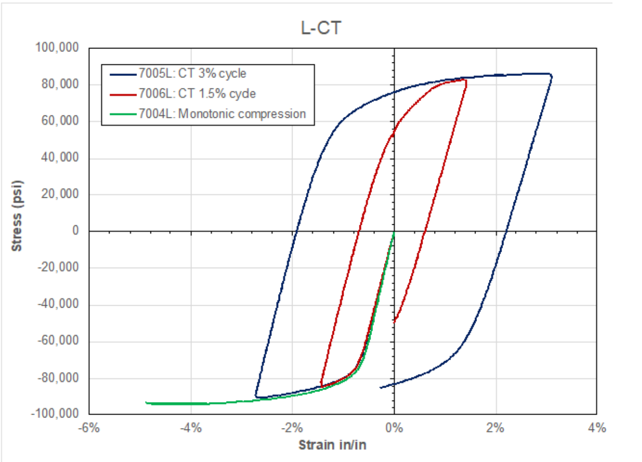
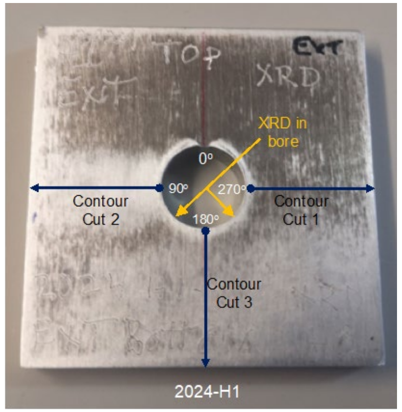
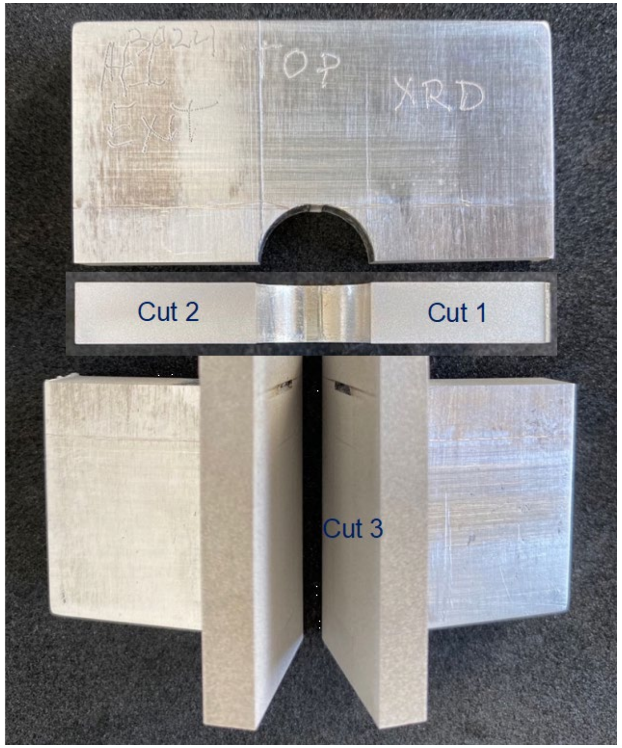
Work In Progress

- 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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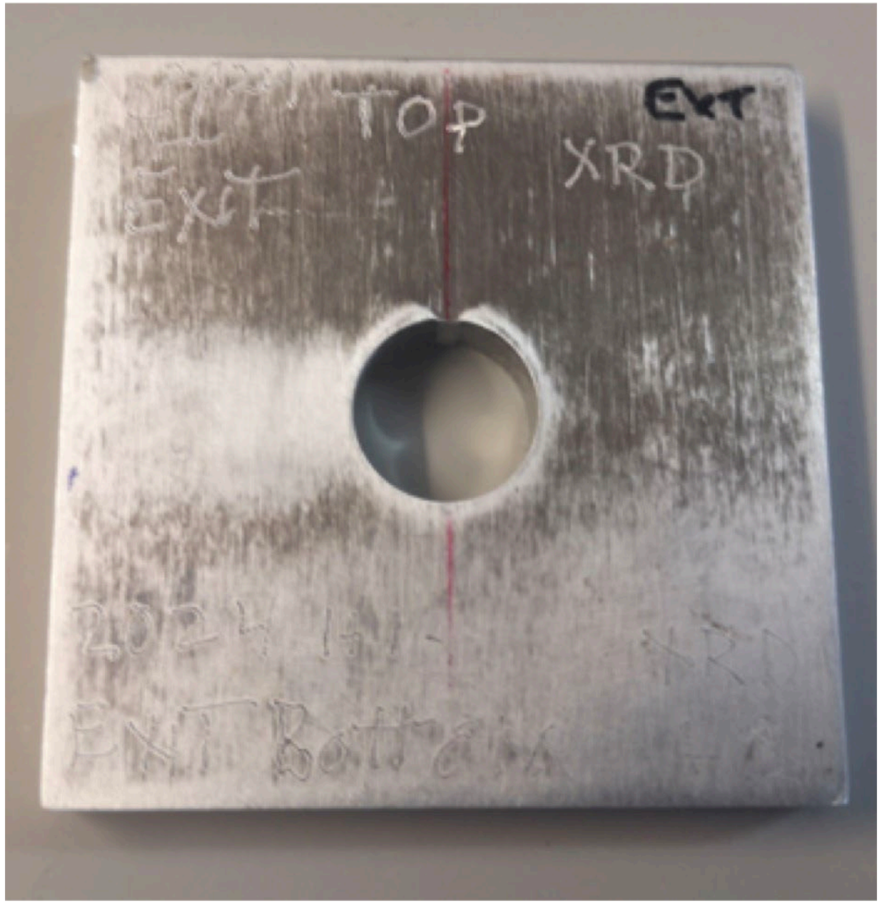
Different Data Sets for Same Case

- 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?

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Cx Processing DIC Data vs. Strain Gauge

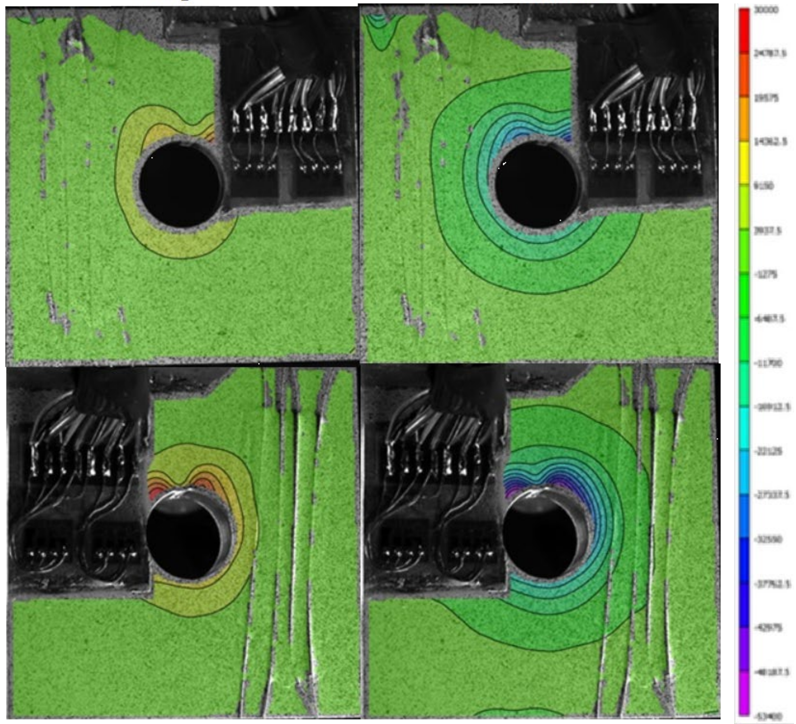
- During Cx Processing Real-Time DIC, LUNA Fiber Optics and Strain Gauges Captured Full-Field Strains
  - Limited ability to capture strains “at the edge of the hole” due to DIC and Cx processing factors
  - Goal was to validate DIC as the “standard” for surface strain results for FEA validation purposes

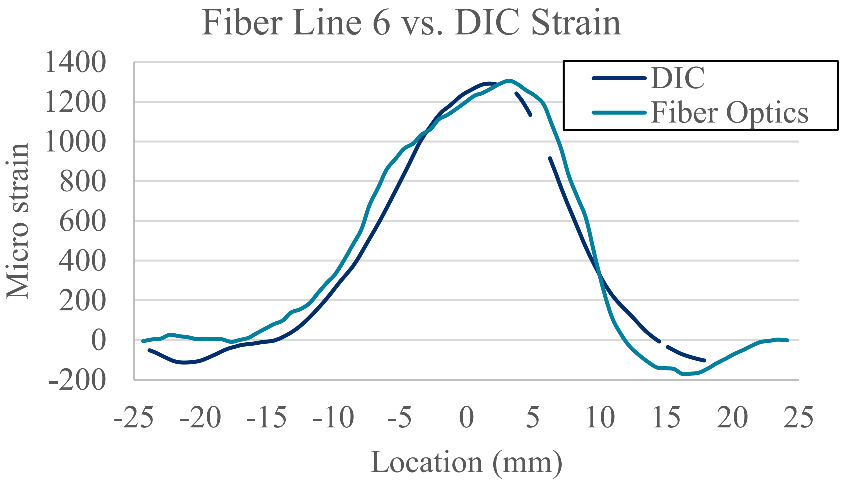
Strain Comparison: Gage vs. DIC			
Location	**Gage**	**DIC**	**%Diff**
1	0.003571	0.003573	0.05%
2*	-0.005699	-0.005684	0.26%
3	0.000984	0.000969	1.54%
4	-0.000459	-0.000430	6.43%
*Adjusted for 13.6 degree split rotation			

Hoop Radial

Entrance

Exit





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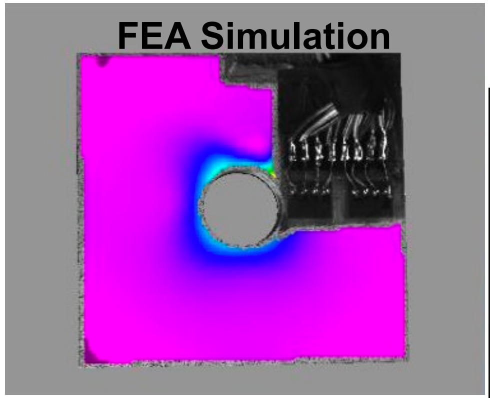
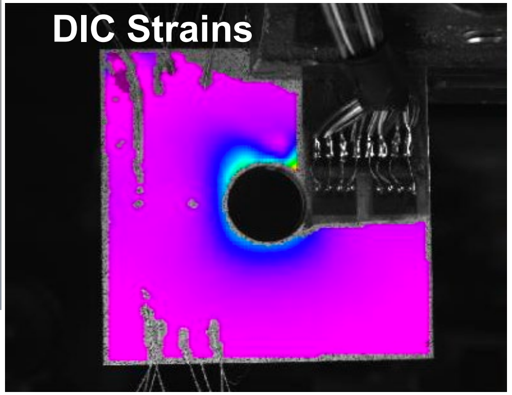
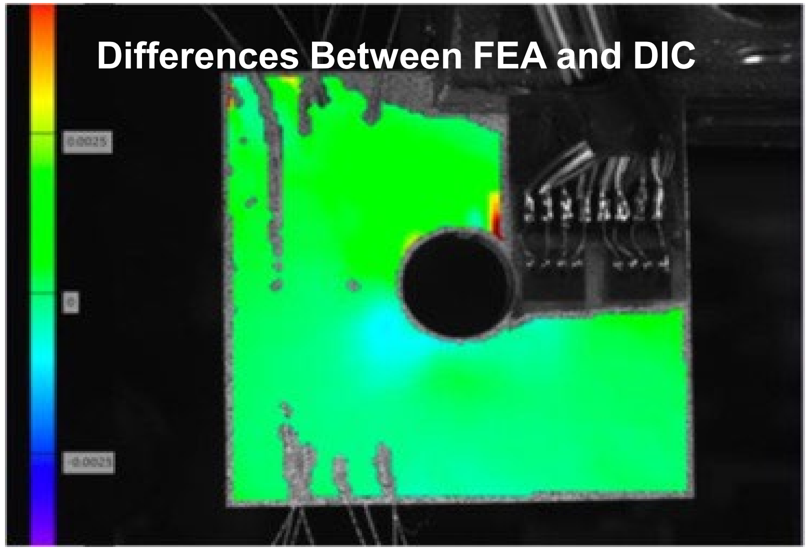
Application of MatchID

- 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







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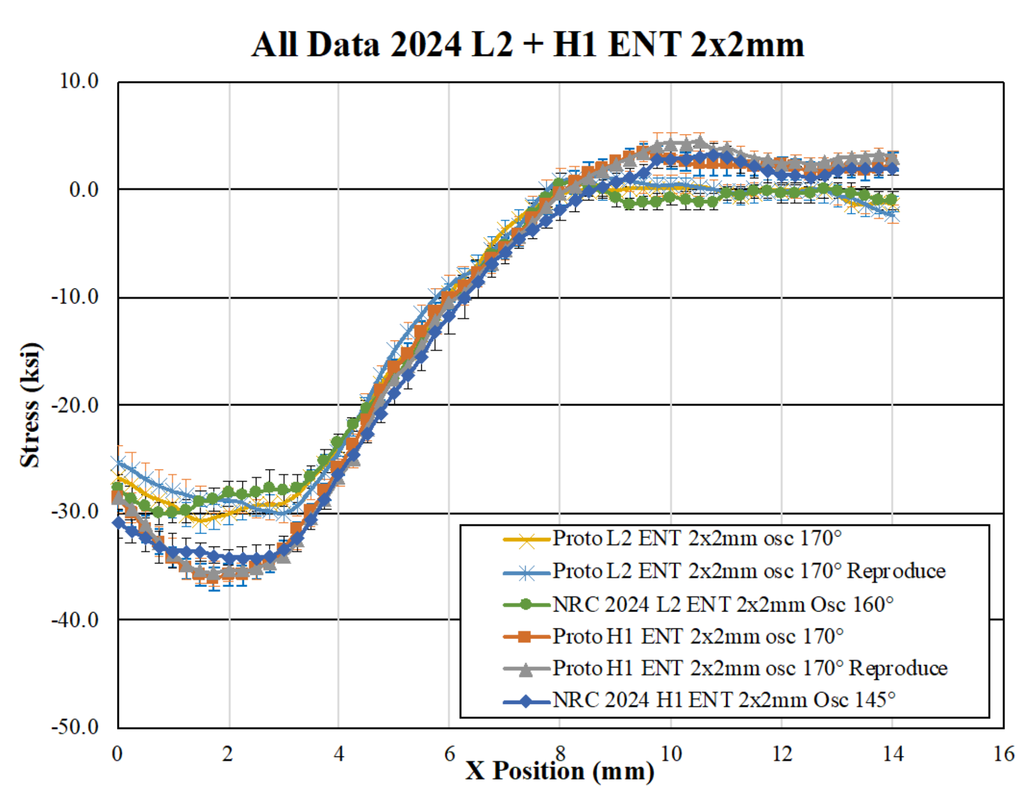
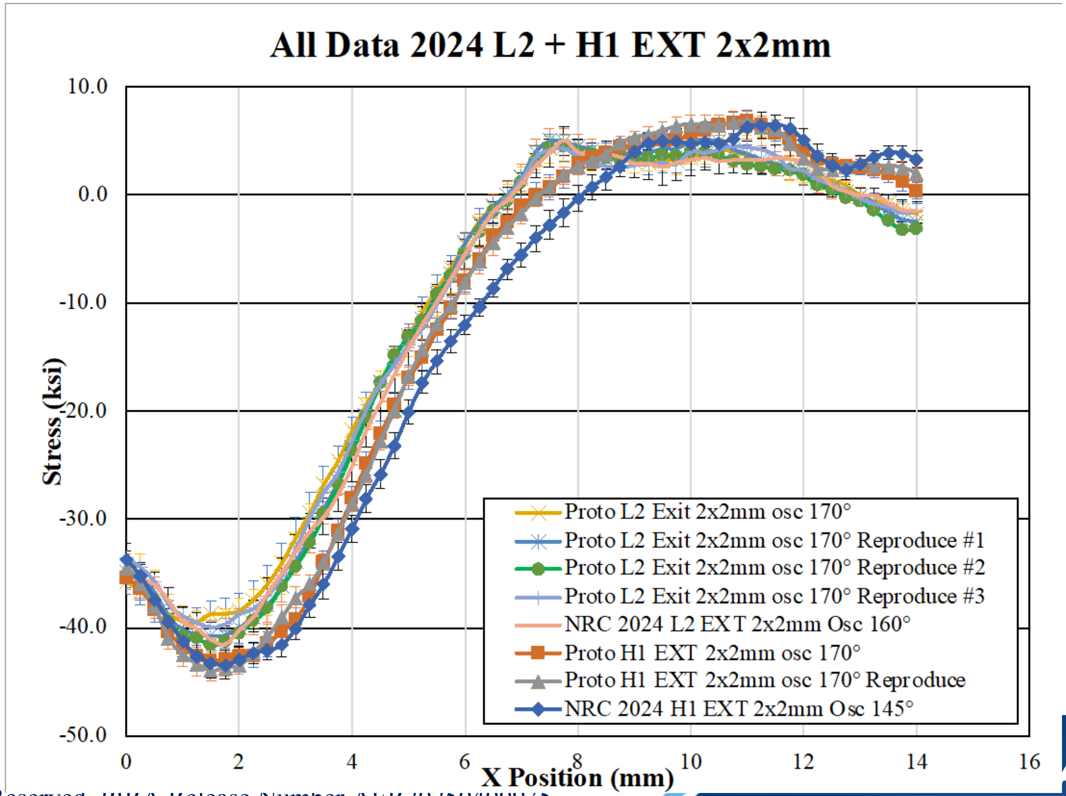
Surface XRD Round Robin Results

- 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

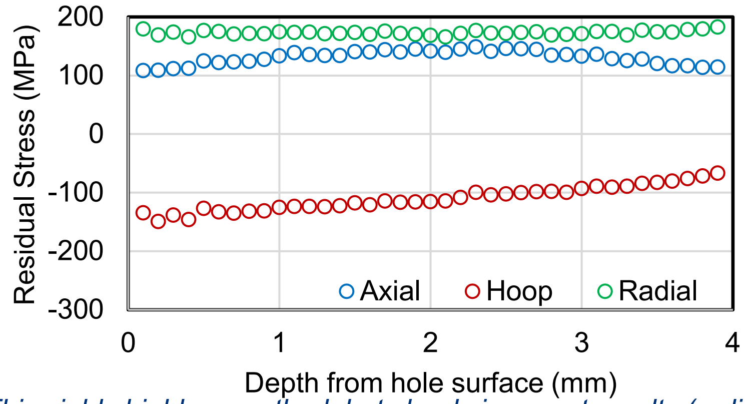
- Dr. Richard Moats Oversaw all Experiments with Deconvolution Data Analysis Approach Being Validated Prior to Application to Cx Data
  - 2024 Coupons at JPARC
  - 7075 Coupons at Oak Ridge NL

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.

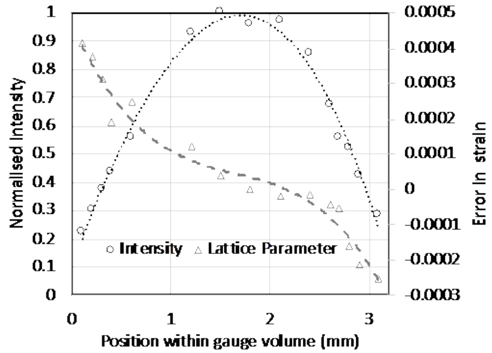
1. Collect lattice strains in 3 orthogonal direction with a step size of 100μm positioned at the centre of the thickness



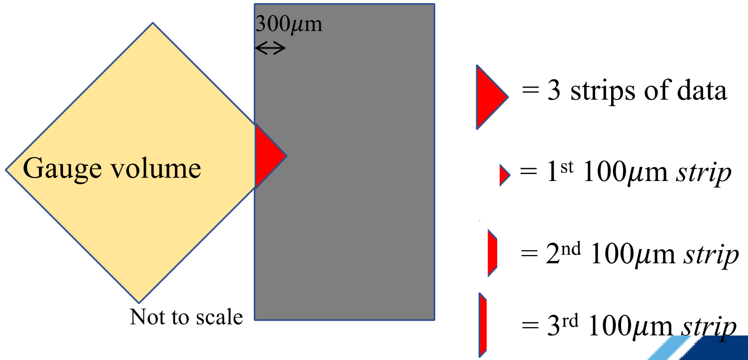
This yields highly smoothed, but clearly incorrect results (radial direction must be close to 0 MPa at the surface)

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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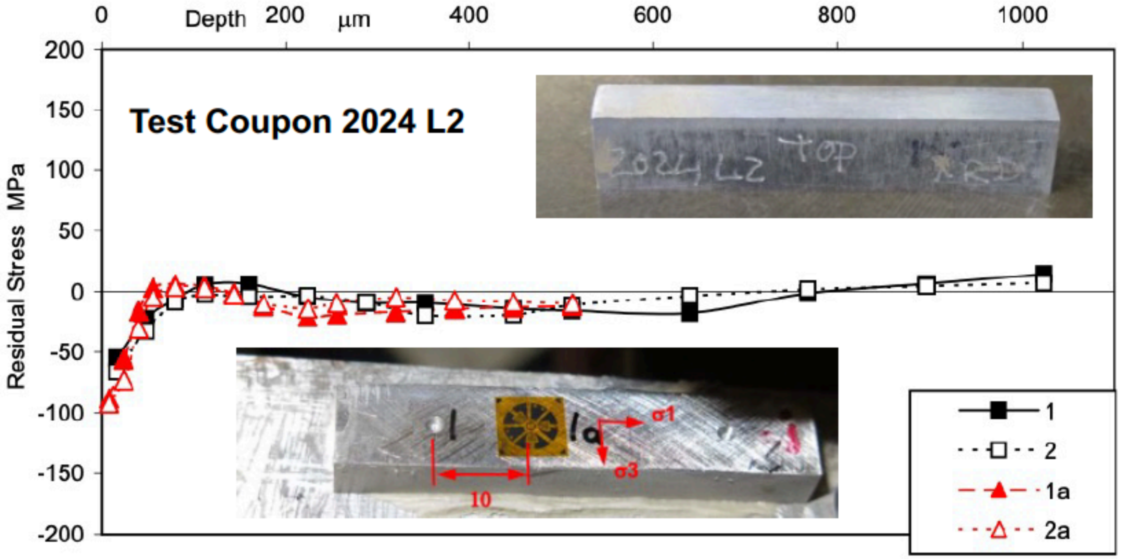
Questions Asked About Rolling Stresses

- 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

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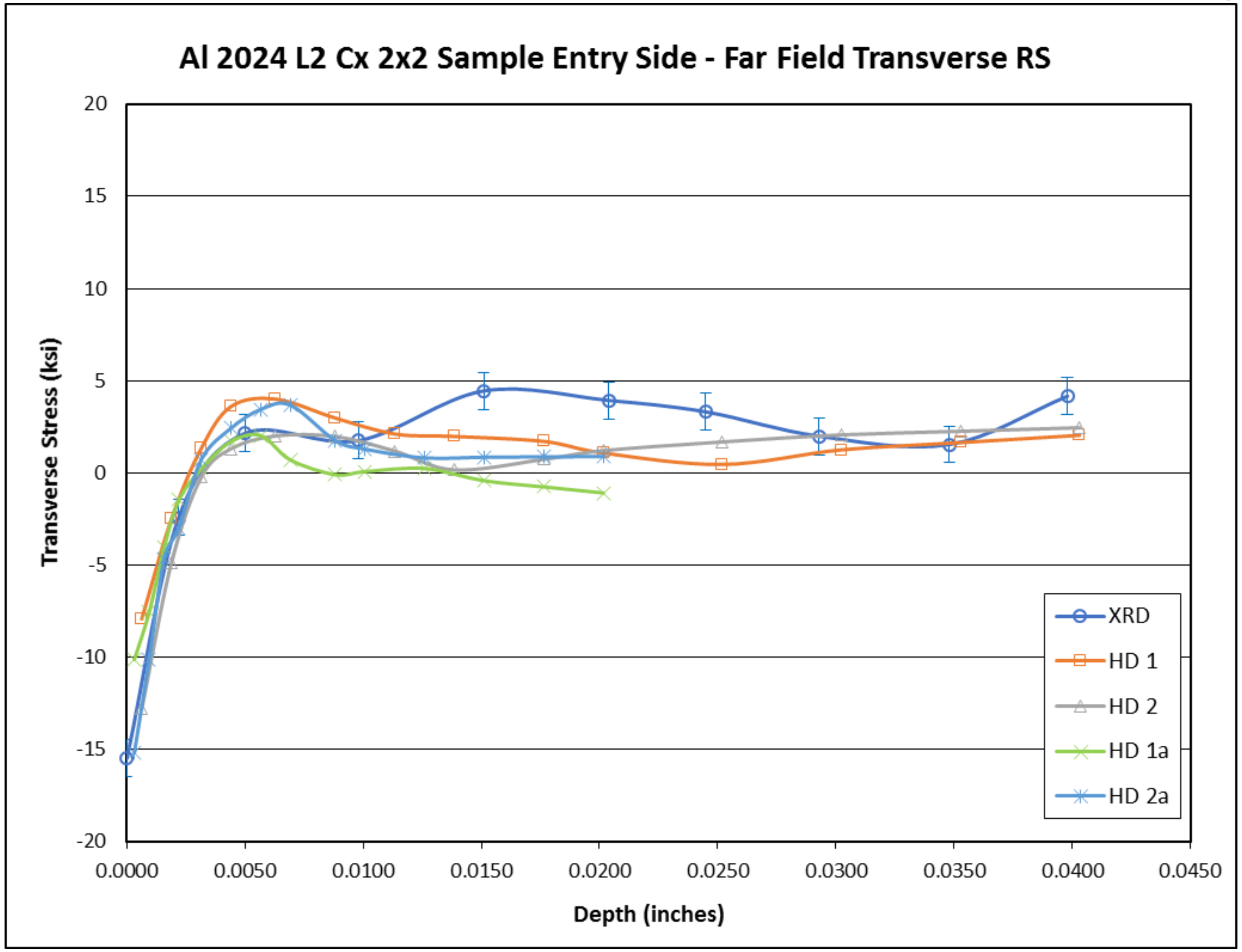
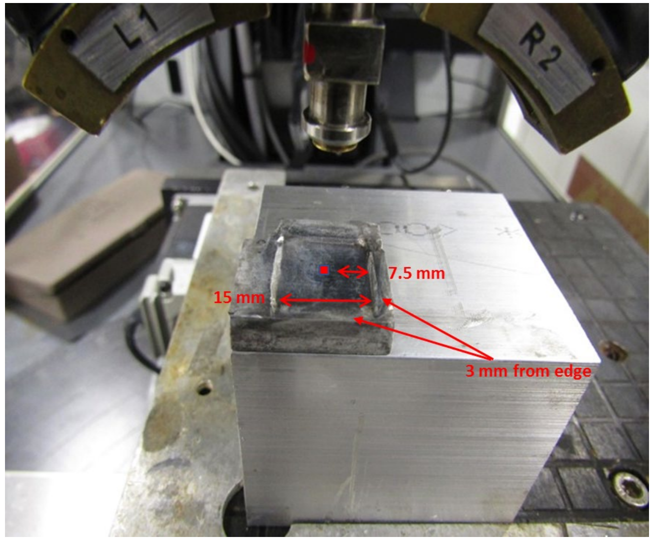
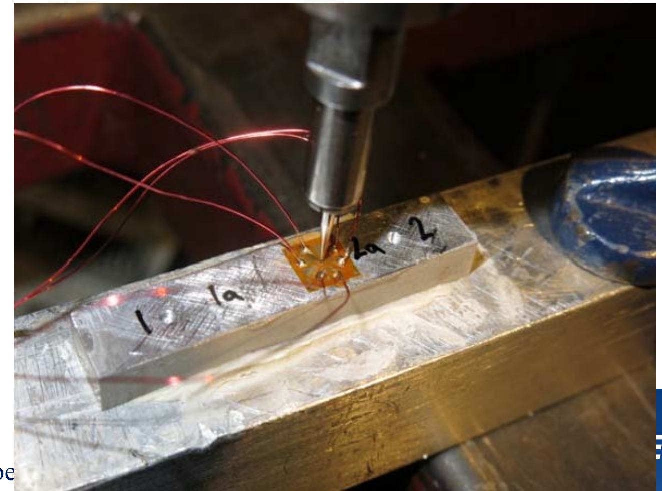
Rolling Stresses Answered

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







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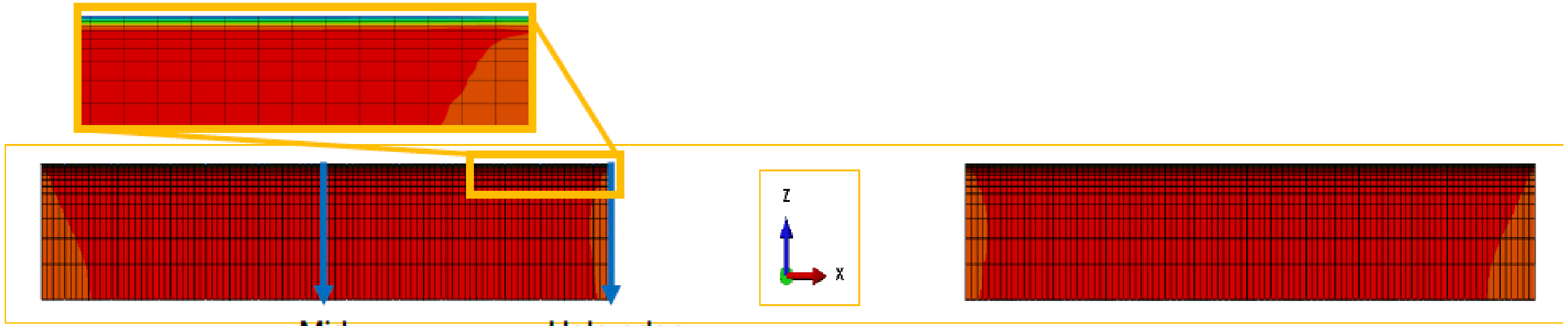
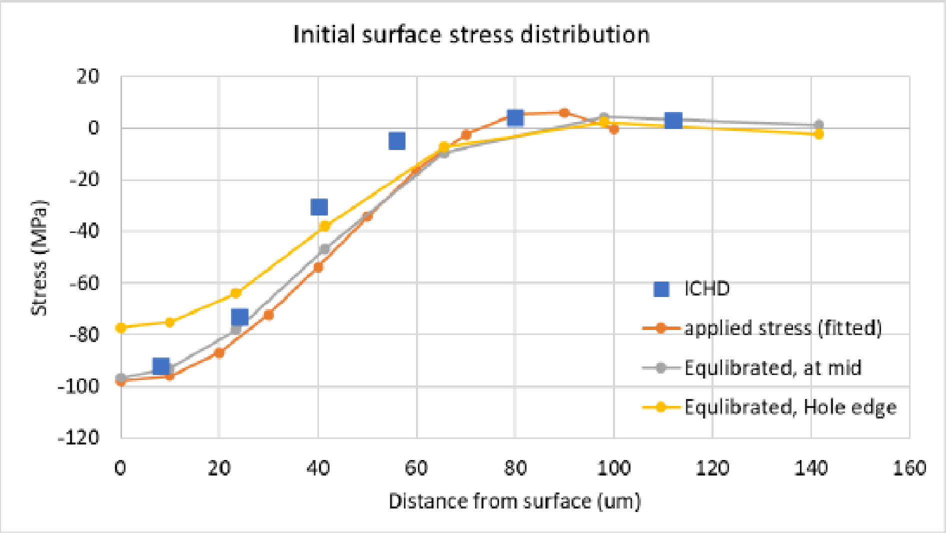
Initial Method for Combining RS Data

- 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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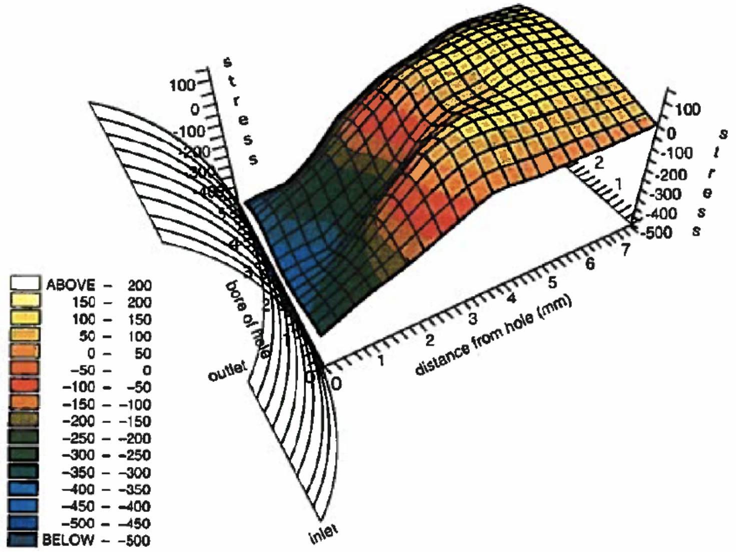
Agenda



- **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*

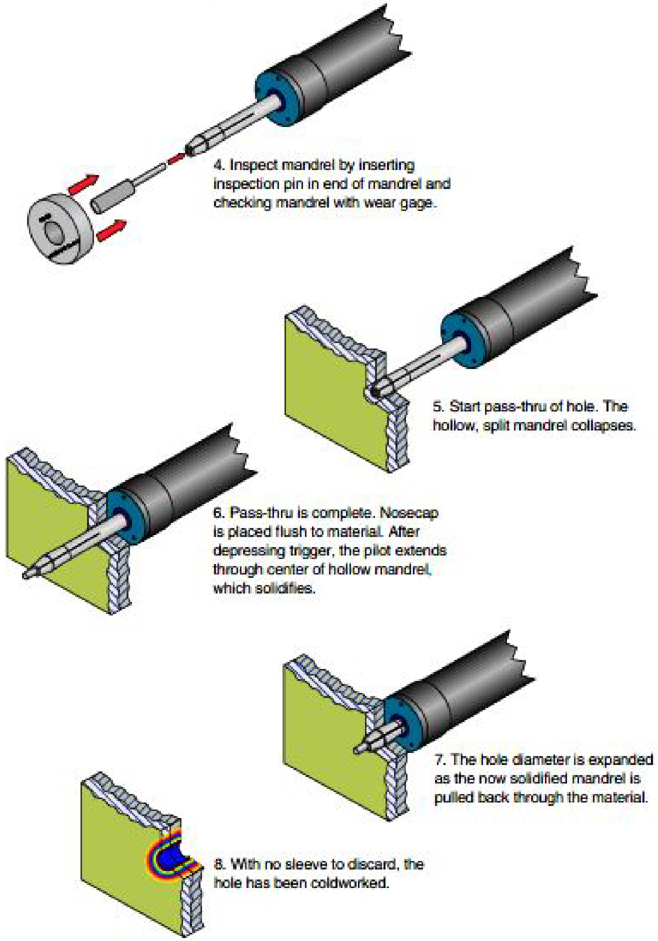
Project Overview

- **Increased Automation and Production Time Reduction Demands**
  - *SsCx^{TM} 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^{TM} 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^{TM} 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 straight pin is pushed thru mandrel*
  - *Lub is forced into mandrel*
  - *Mandrel and pin are pulled back thru hole*

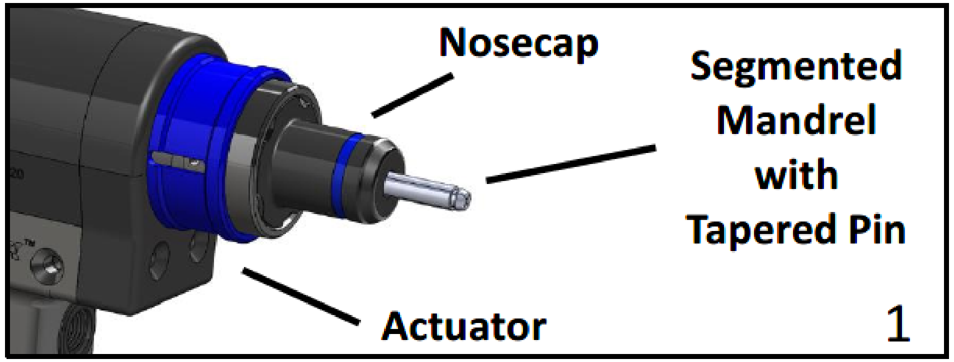
1. Drill start hole with start drill.
2. Ream hole to proper starting size with start hole reamer.
3. Verify start hole with hole gage.

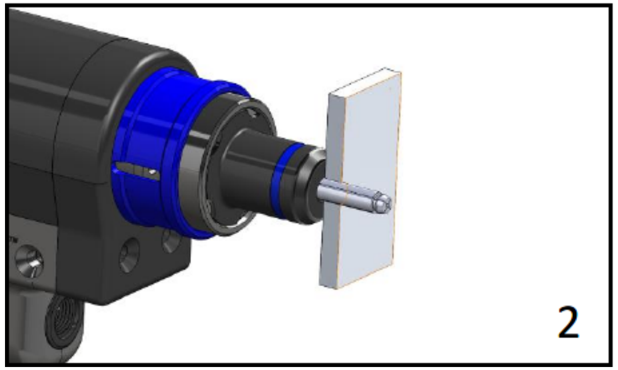


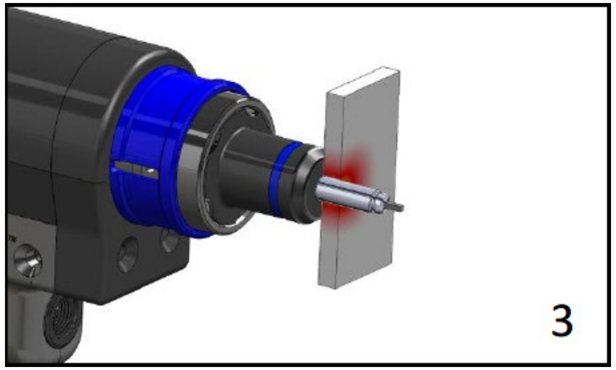
9. Inspect coldworked hole with hole gage.
10. Ream hole to final size with piloted reamer.
11. Inspect final reamed hole with hole gage. Countersink if necessary.

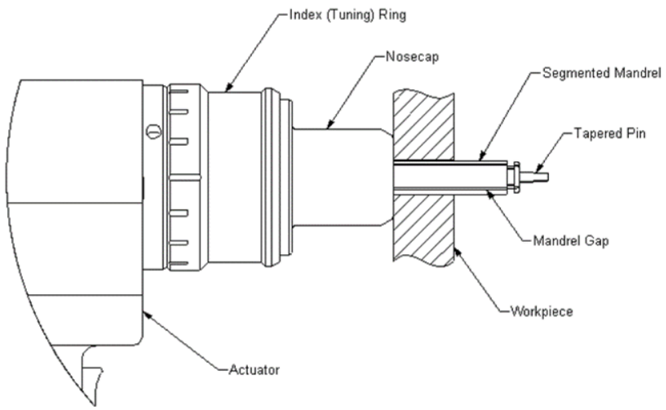
SmartCx™ by FTI

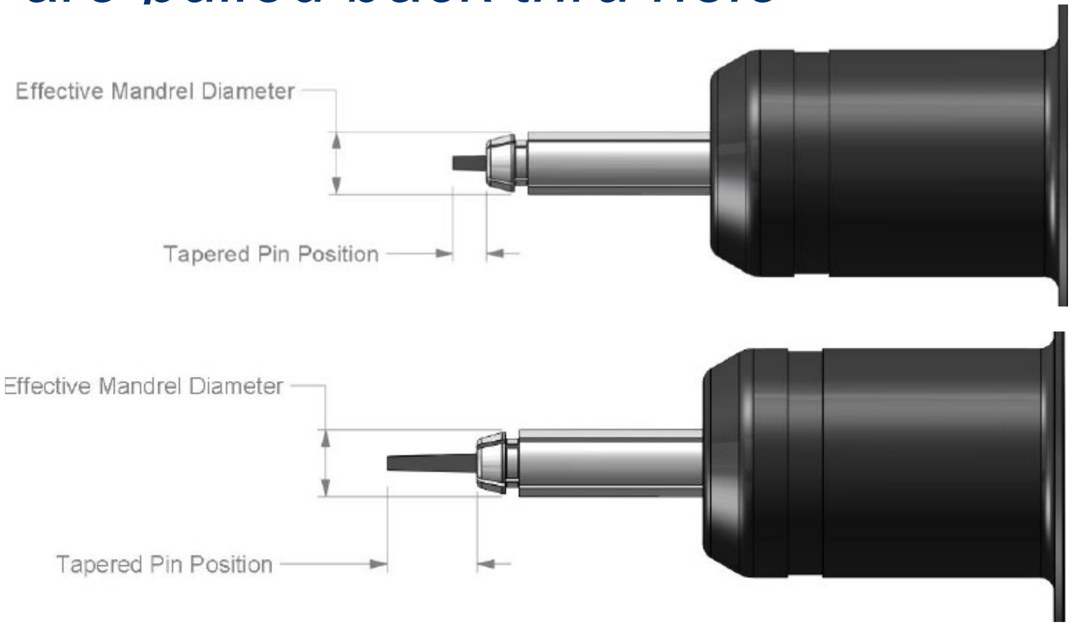
- **SmartCx™ Process and Tooling**
  - *4-split mandrel is inserted into the hole*
  - *Drives a tapered pin thru split mandrel*
    - **Allows for adjustment of applied expansion**
  - *Lub is forced into mandrel*
  - *Mandrel and pin are pulled back thru hole*











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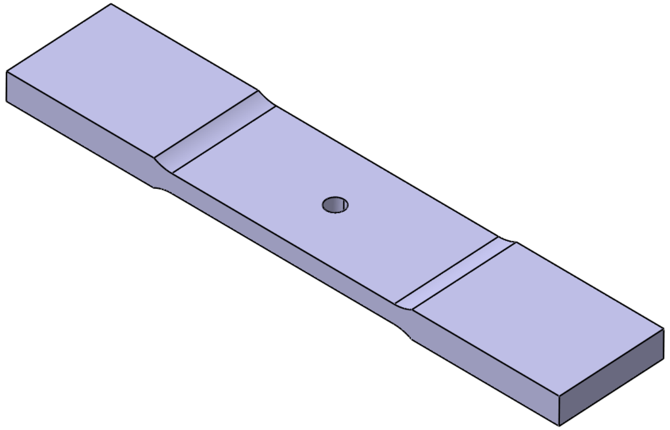
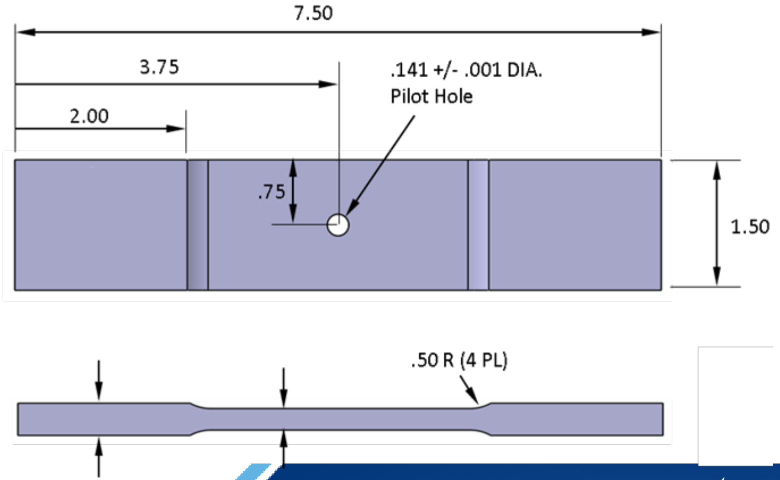
Test Program Overview

- **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™ Performance**
  - *Pre-crack cycles and post-final ream testing considered*

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™ 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%	
7050-Sm-01	7050Cx-24											0.024
7050-Sm-02												
7050-Sm-02	7050-Cx25											0.023
7050-Sm-03												
7050-Sm-03	7050-Cx26											0.021
7050-Sm-04												
7050-Sm-04	7050-Cx27											0.023
7050-Sm-05												
7050-Sm-05	7050-Cx28											0.024
7050-SmrtCx(TunO)-01		SmrtCx-Max		0.2276	0.2273	0.2277	0.2275	0.2304	0.2303	1.44%	1.96%	
7050-SmrtCx(TunO)-01	7050Cx-29											0.019
7050-SmrtCx(TunO)-02												
7050-SmrtCx(TunO)-02	7050-Cx30											0.020
7050-SmrtCx(TunO)-03												
7050-SmrtCx(TunO)-03	7050-Cx31											0.018
7050-SmrtCx(TunO)-04												
7050-SmrtCx(TunO)-04	7050-Cx32											0.018
7050-SmrtCx(TunO)-05												
7050-SmrtCx(TunO)-05	7050-Cx33											0.022

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								

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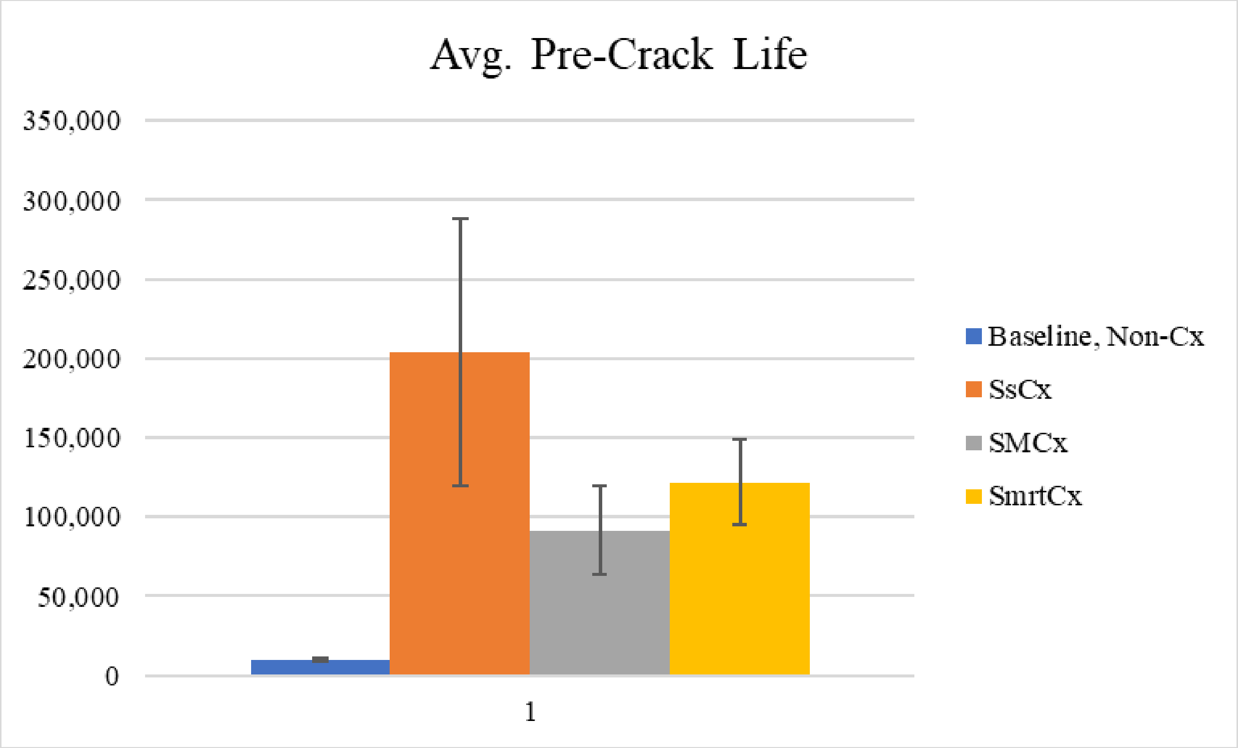
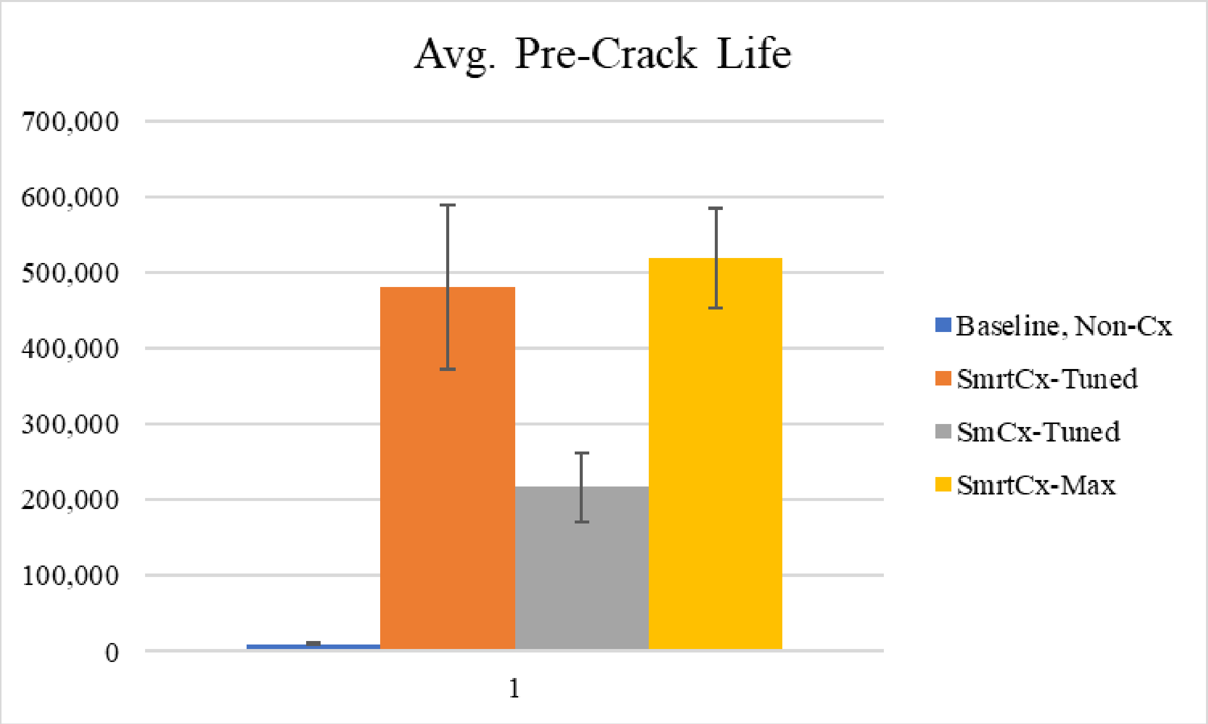
Test Matrix and Pre-Crack & Final Lives

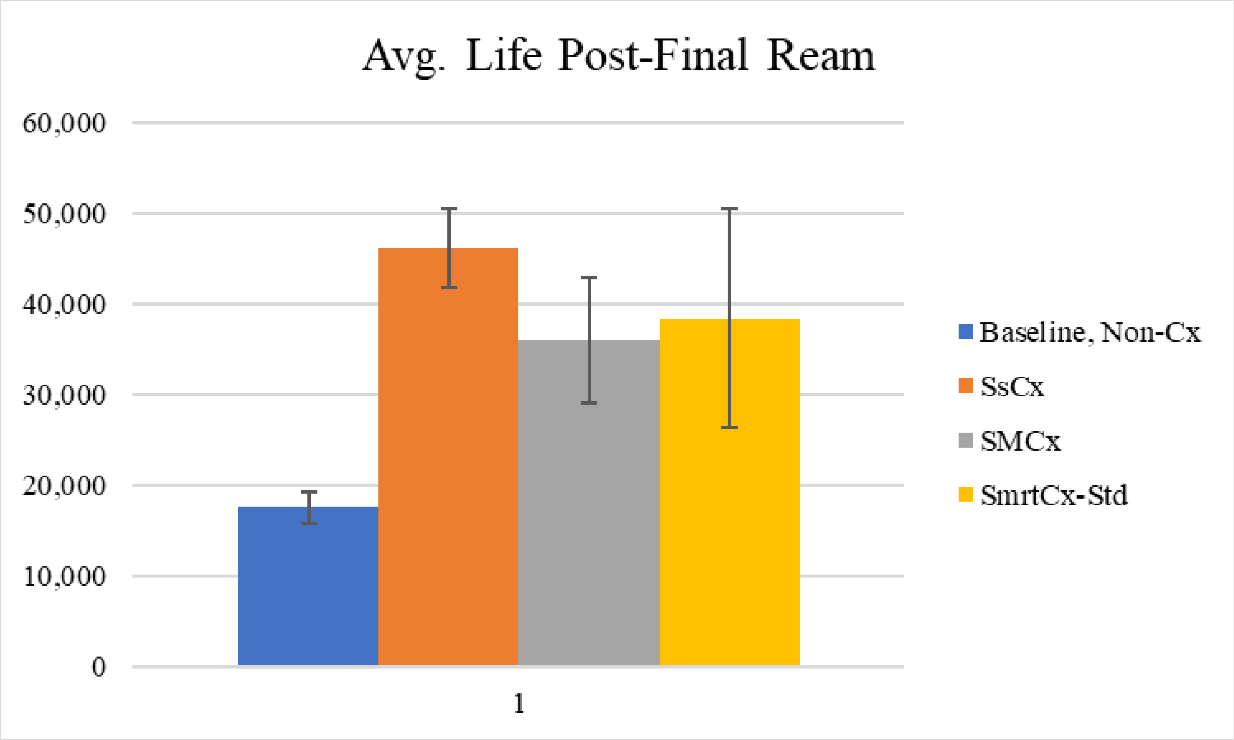
Coupon Name	Manufactured ID	Cx Process	Pre-Crack Surface Length From Notch (inch)	Average Life for Pre-Cracking	Std on Pre-Crack Life	Final Ream Diameter Requirement (inch)	Average Life Post Final Ream	Std on Life Post Final Ream
7050-SMCx-Mx-01		SmrtCx-Tuned		480,634	108,599	0.2650±0.004inch	**39,426**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

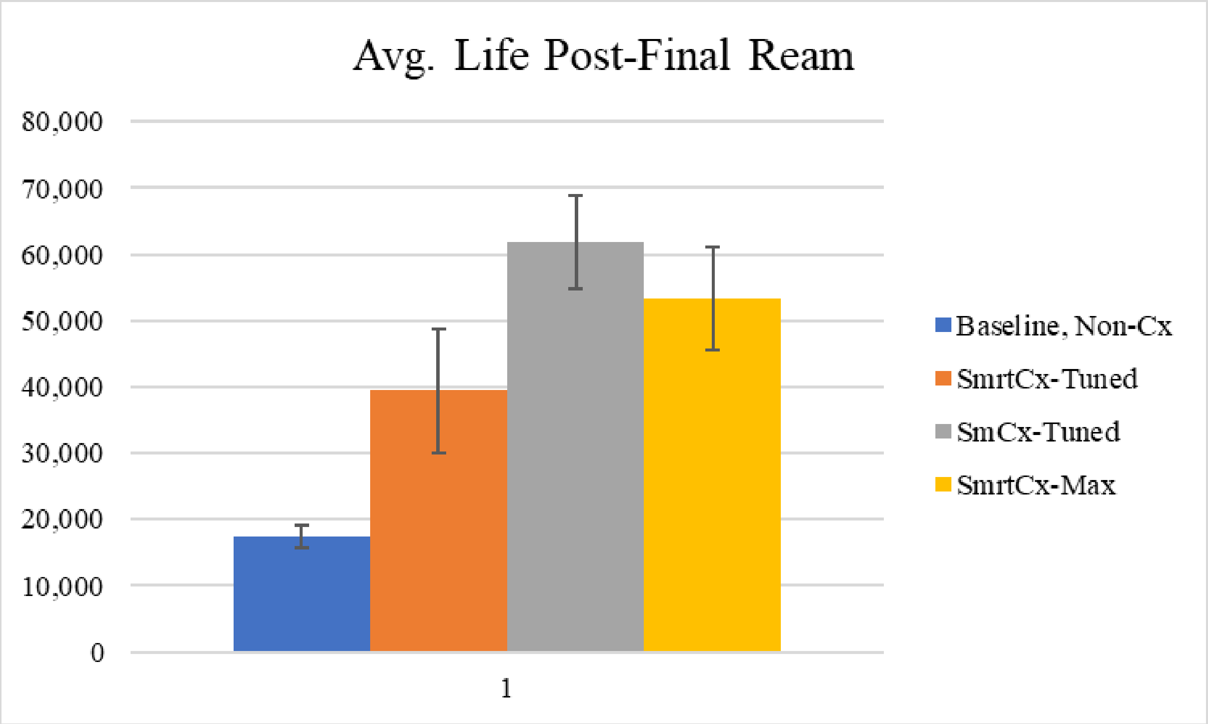
Pre-Crack Lives





Post-Final Ream Lives





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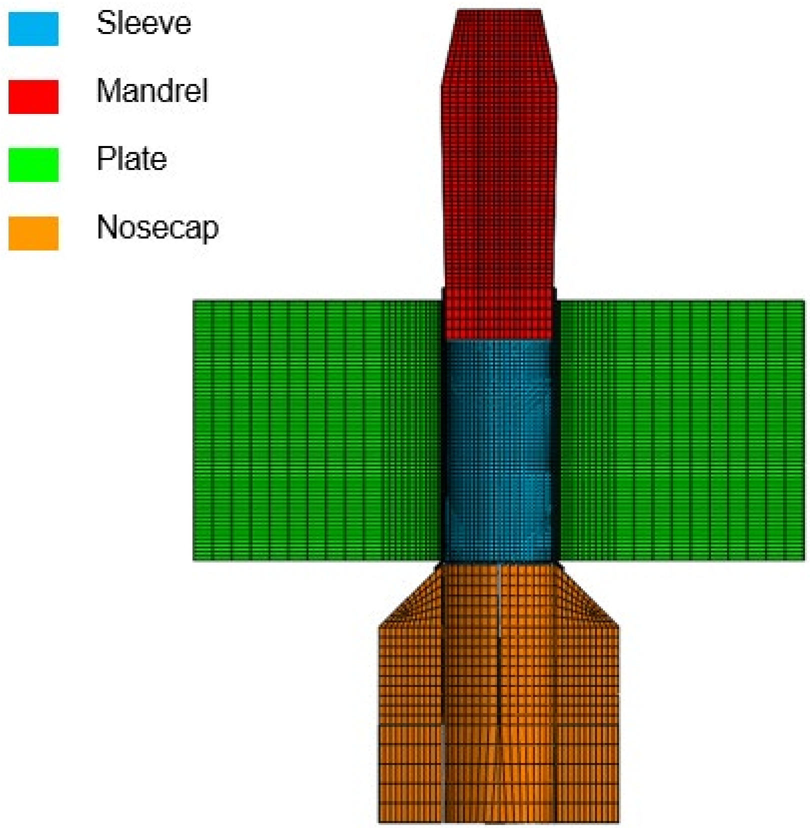
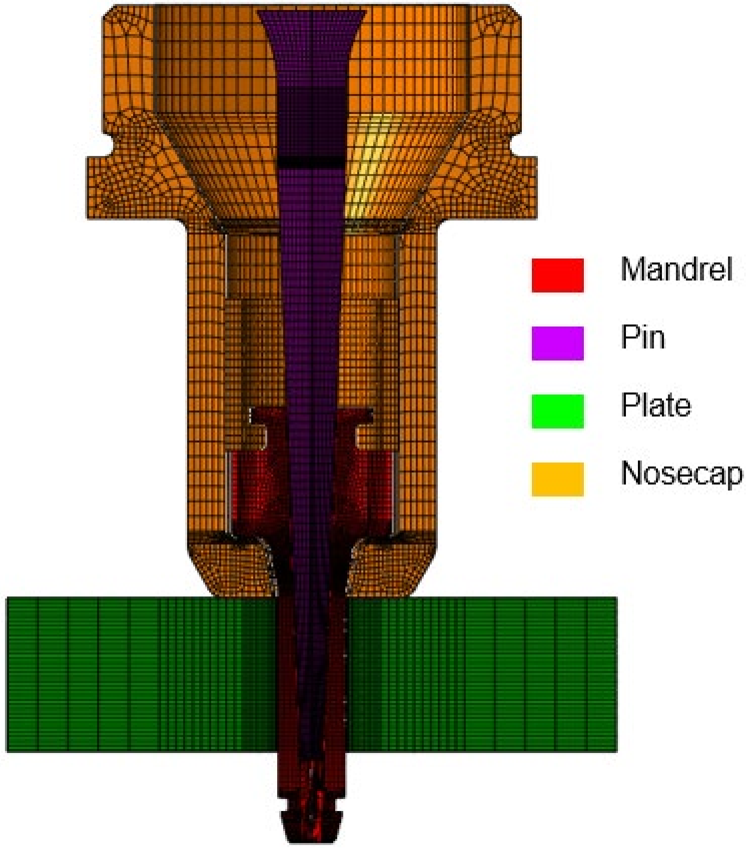
Process Model Comparison

SsCx



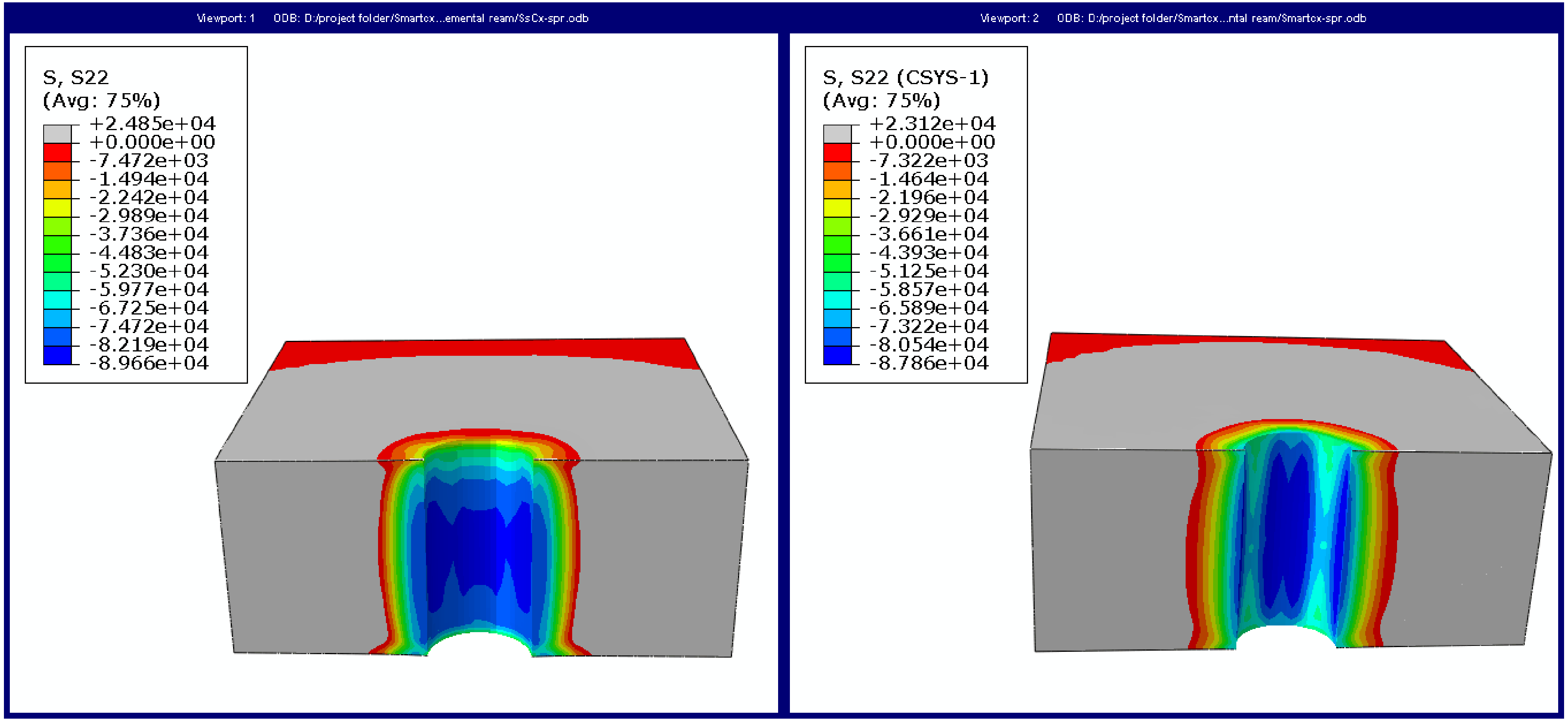
Parameters
6-3-N tooling (or equivalent)
7010-T7651

SmartCx



Process Model Comparison

SsCx   SmartCx



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

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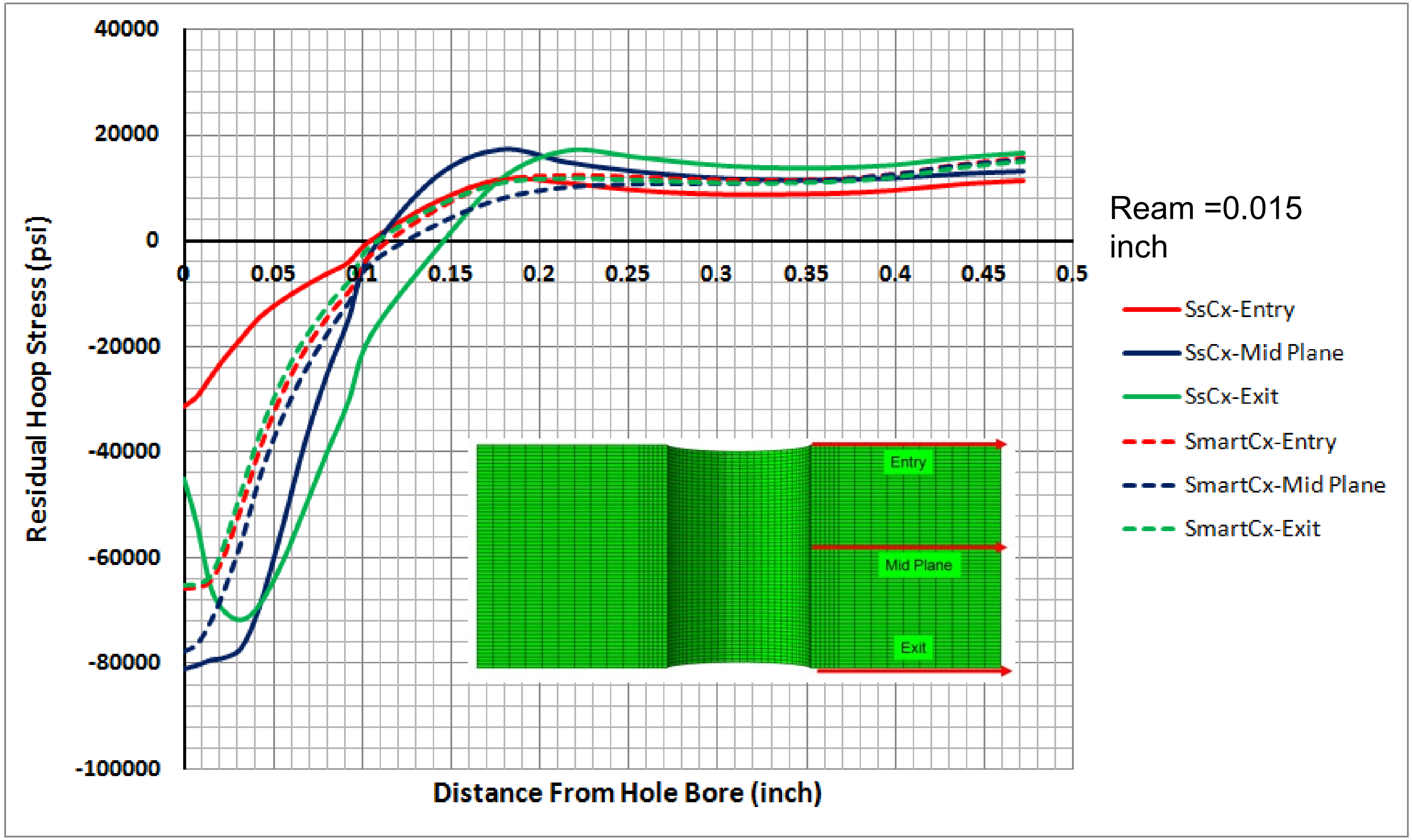
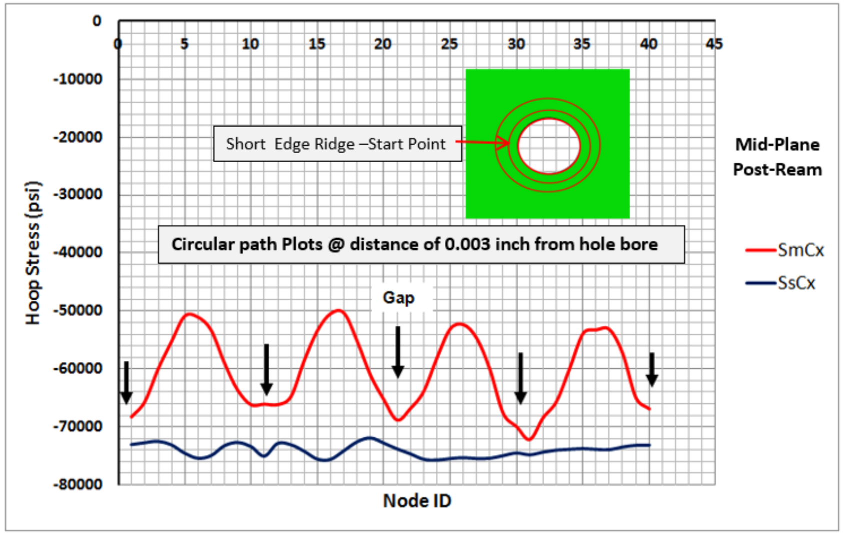
Process Model Comparison



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



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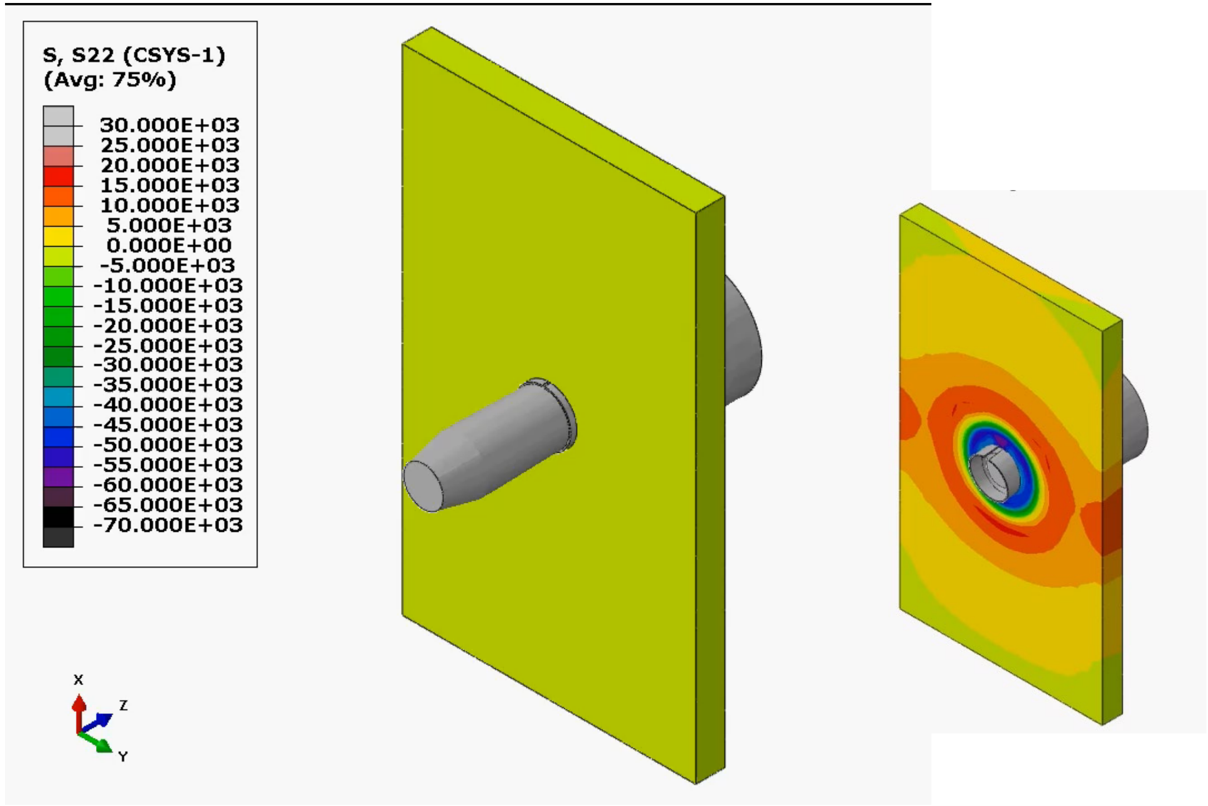
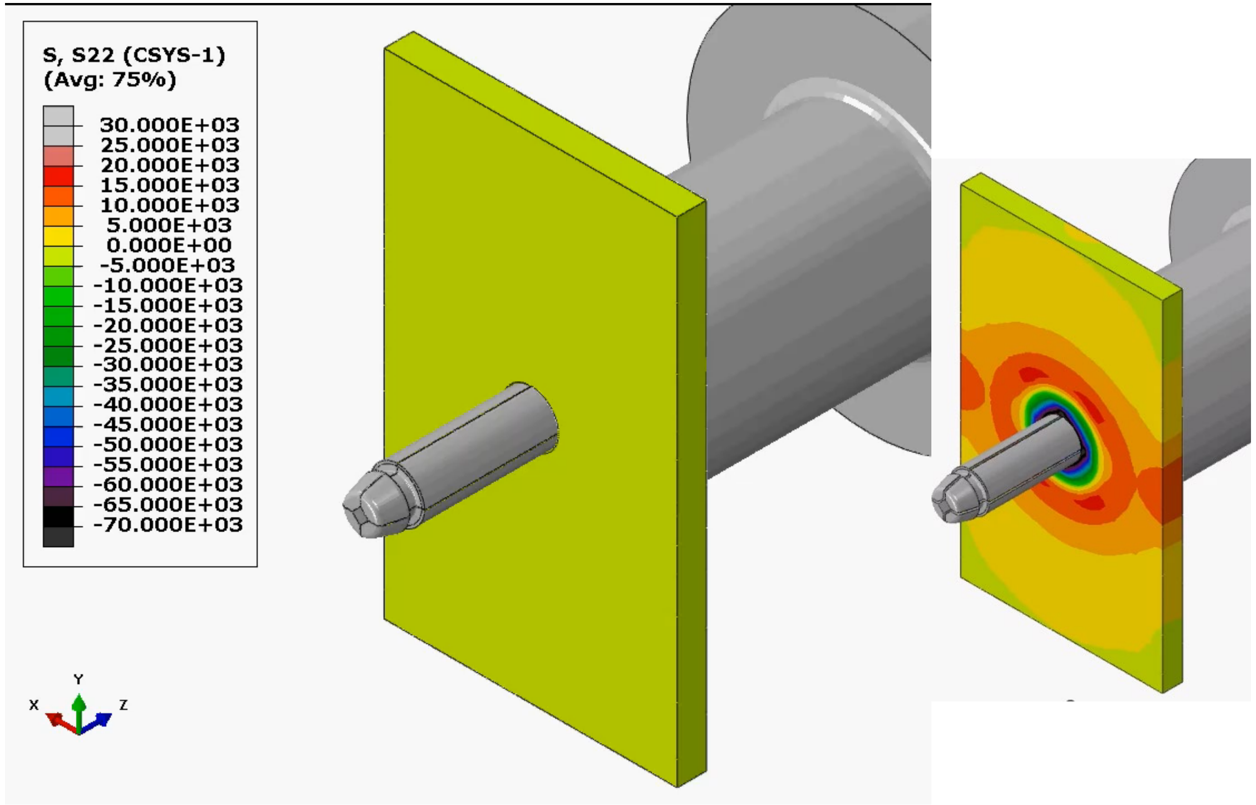
Process Model Animation

SsCx



SmartCx



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

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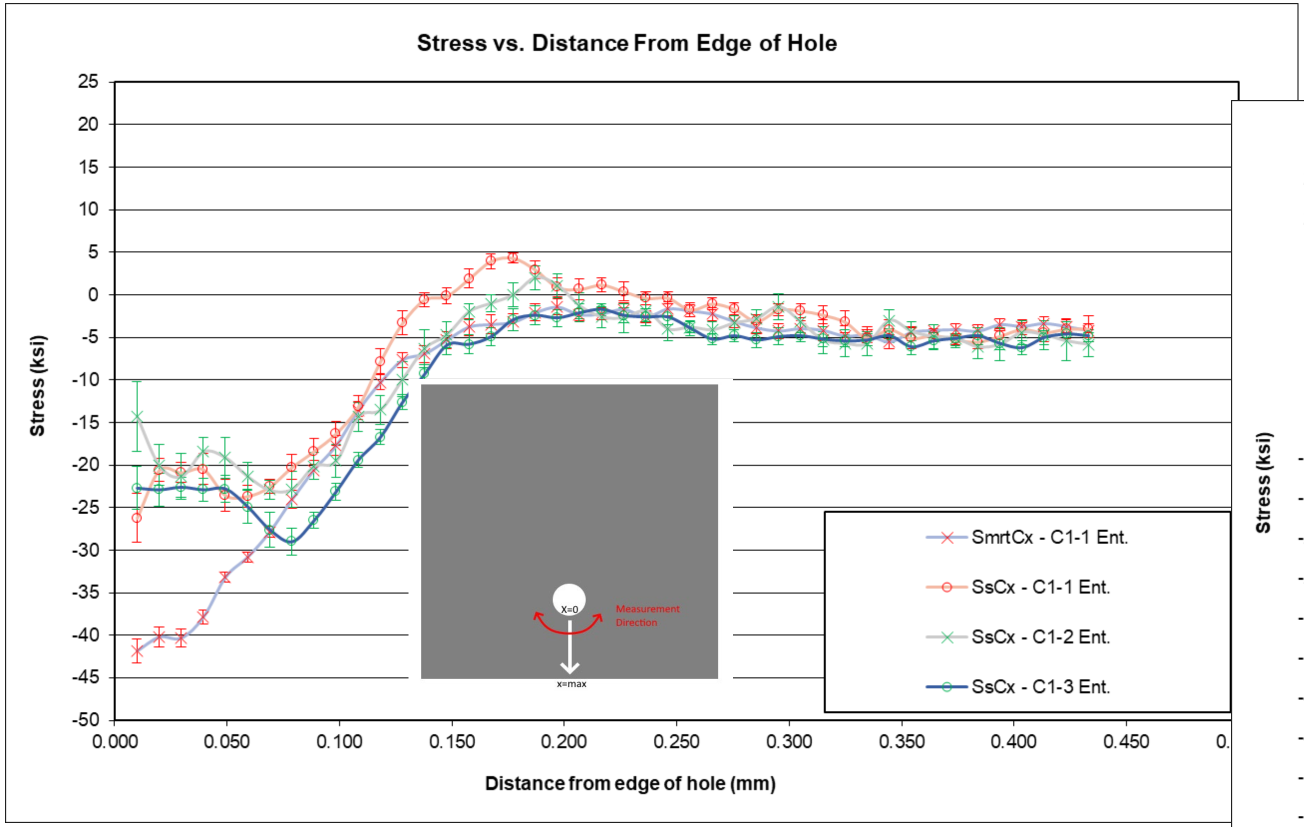
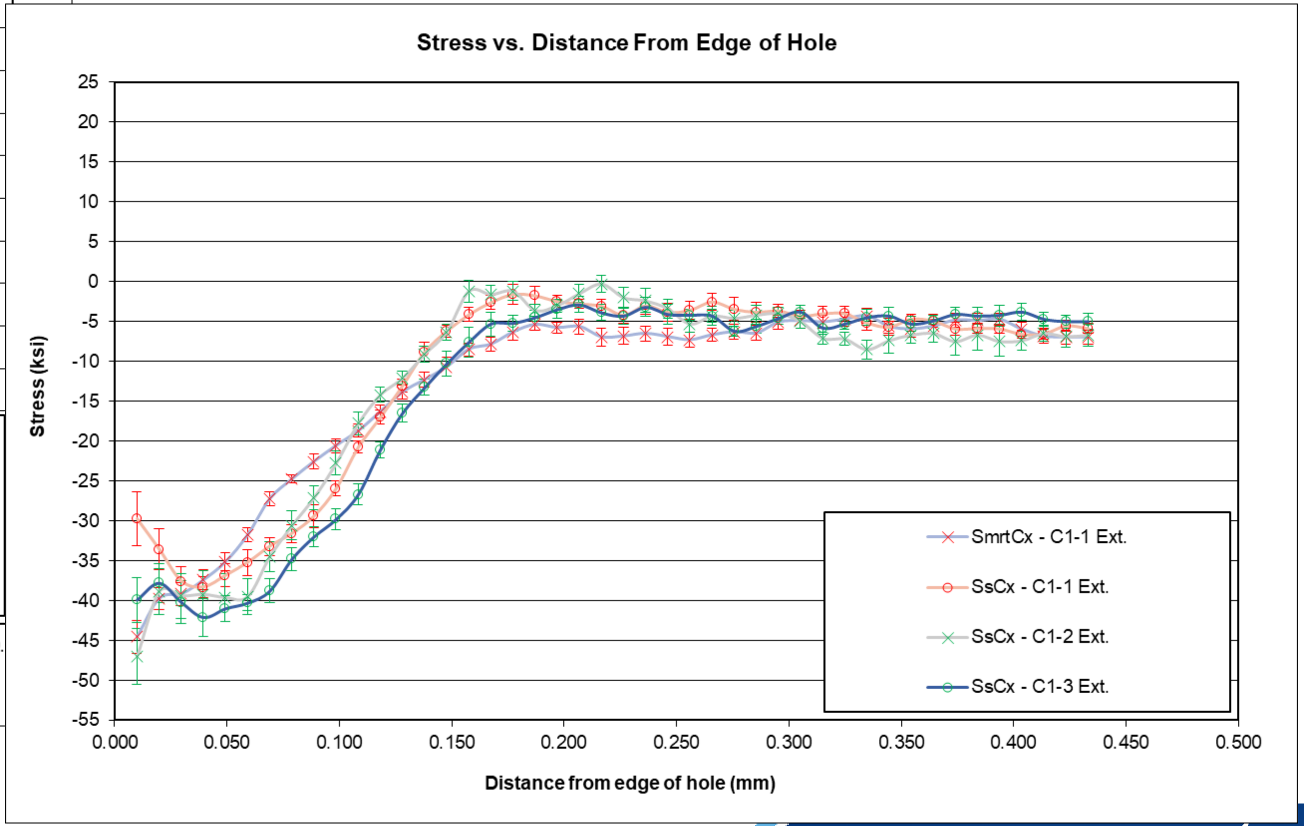
Residual Stress Prediction Comparisons

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





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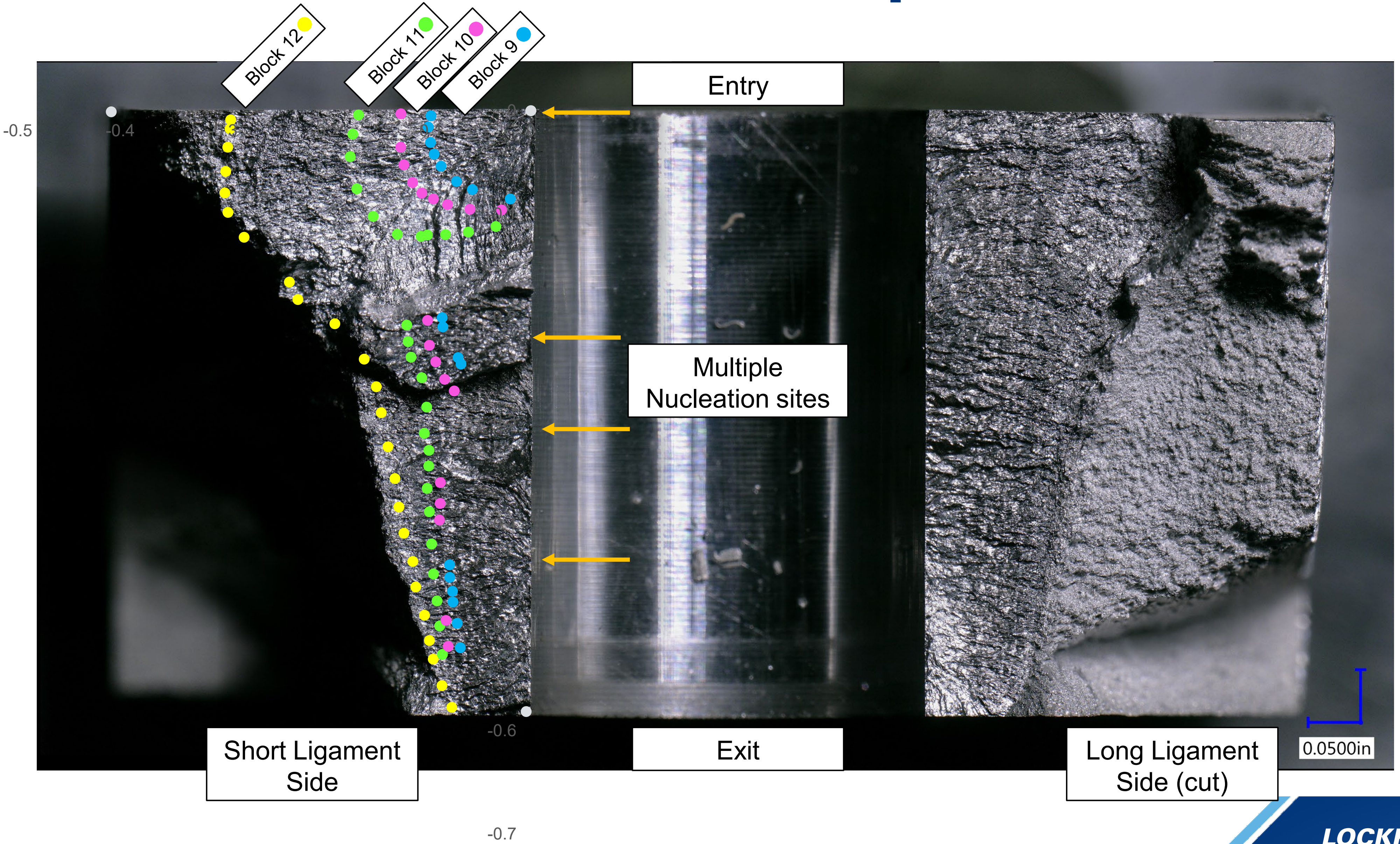
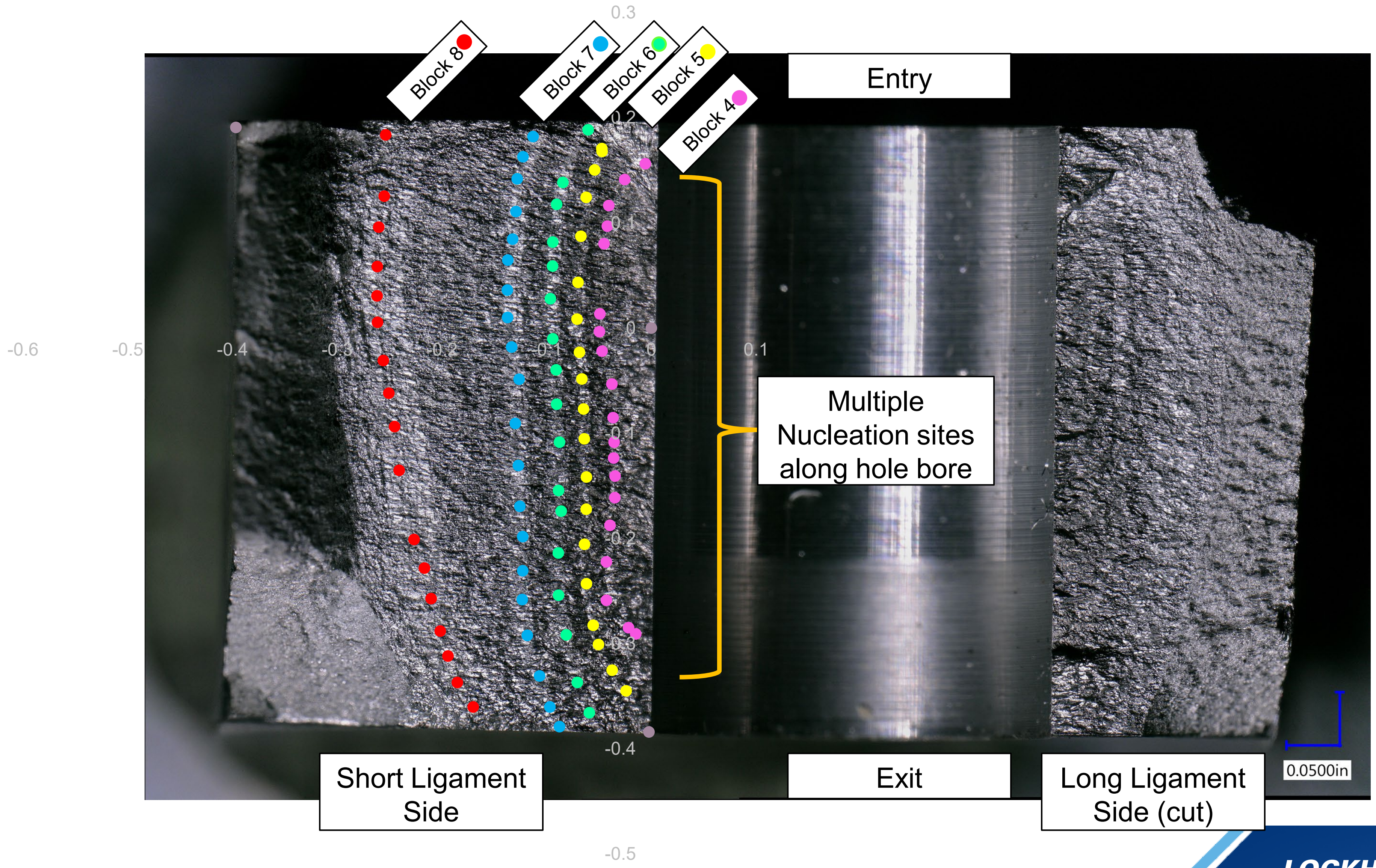
QF of “C” Matrix Test Coupon - SsCx™



LOCKHEED MARTIN

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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Dr. David Backman (NRC-Canada)
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Mr. David Mauldin (Lockheed Martin)
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

LOCKHEED MARTIN

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

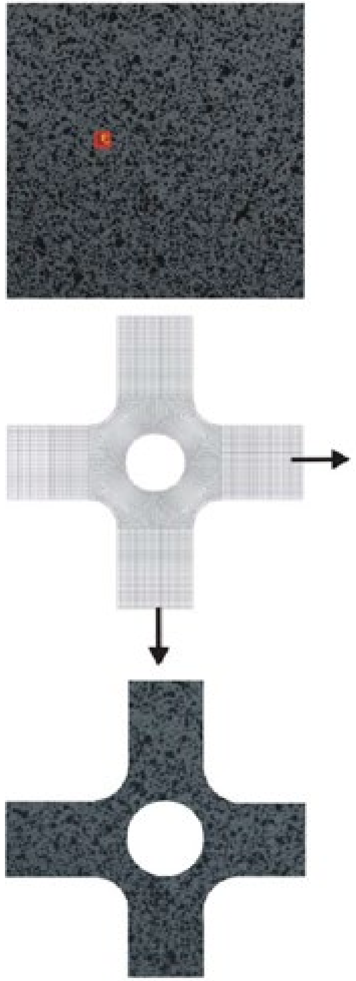


Fig. 1. Distorted reference speckle pattern[1]

[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)*

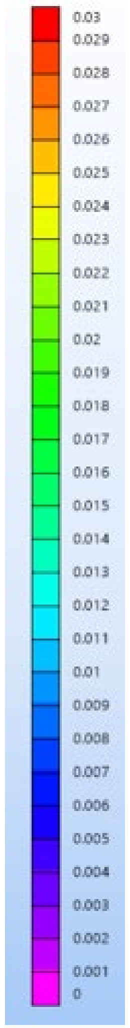
LOCKHEED MARTIN

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

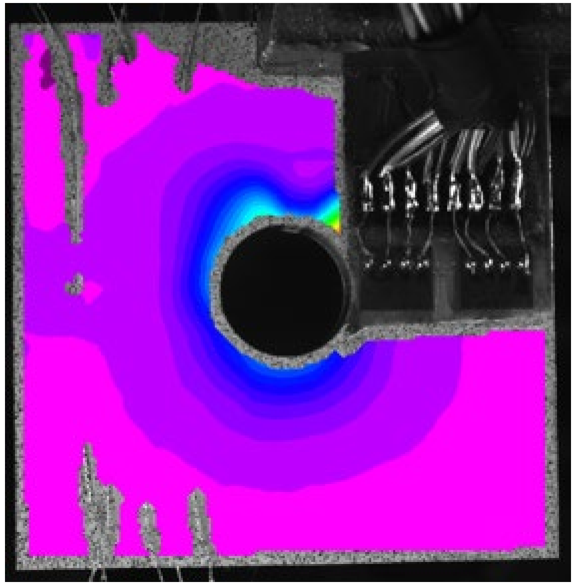
FTI Tool Set = 16-0-N
Thickness = 0.25inch
Starting Hole Dia = 0.4770inch

5

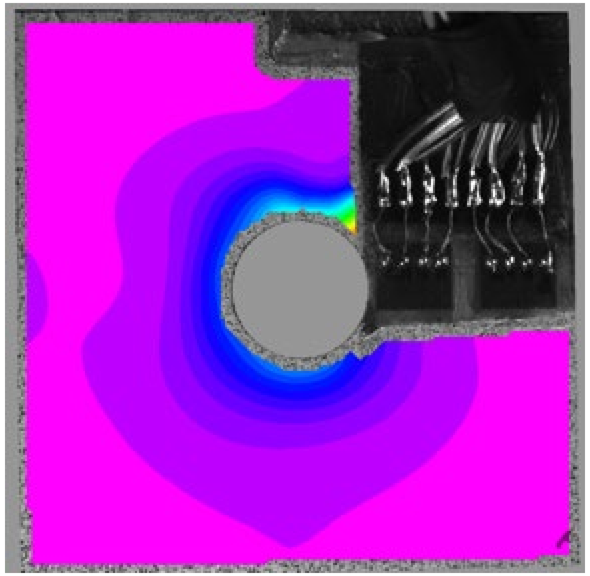
CHAB – Entry (ϵ_1)



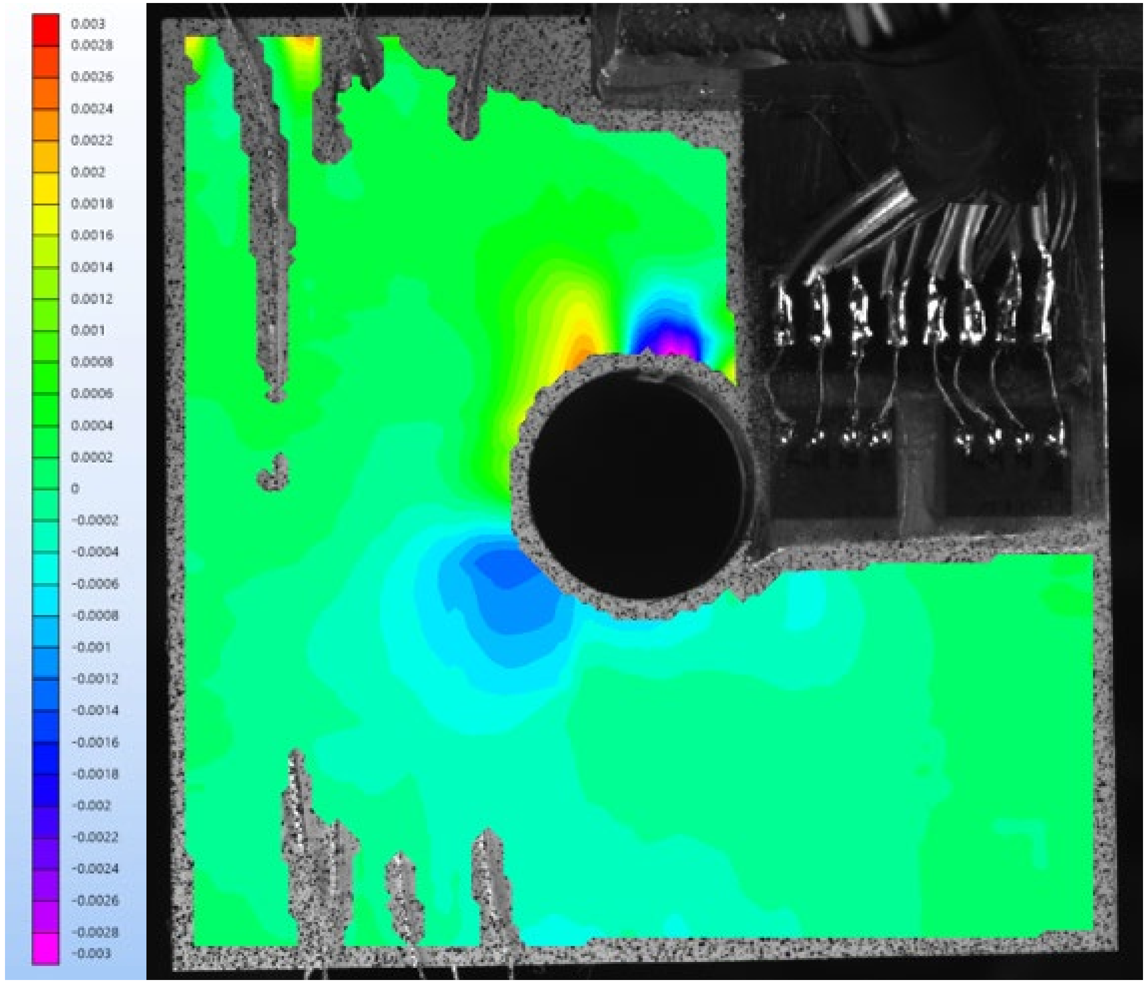
DIC



FEA



Validation (DIC-FEA)



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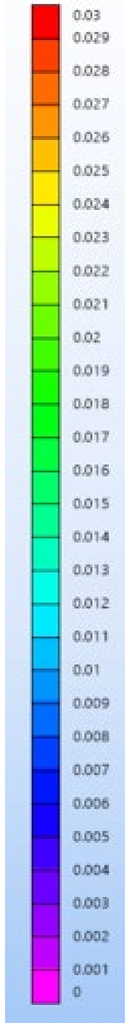
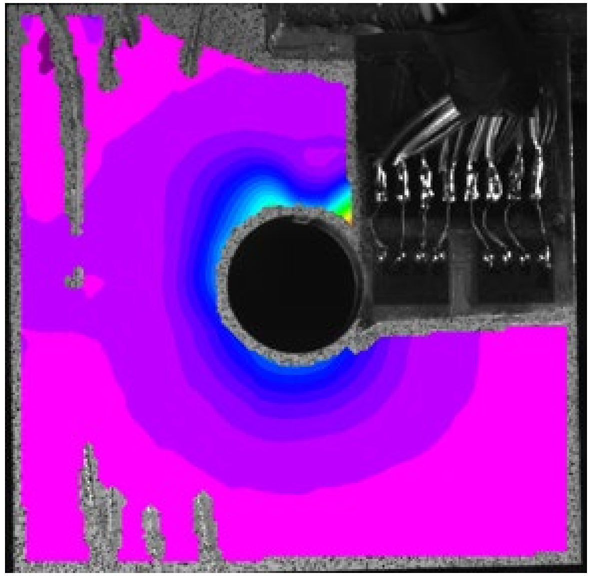
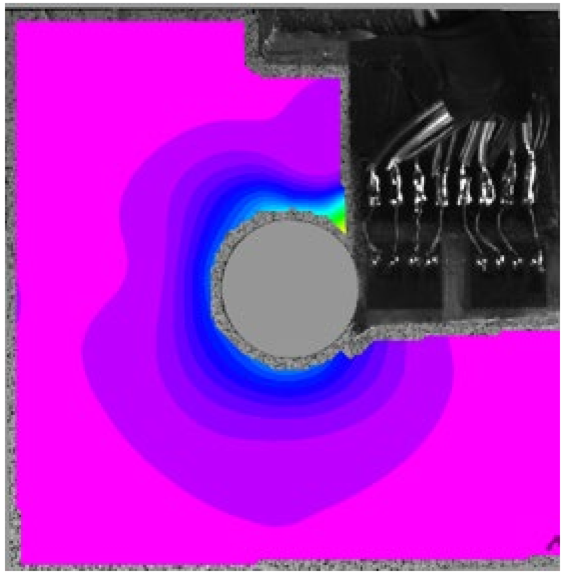
COMB – Entry (ϵ_1)



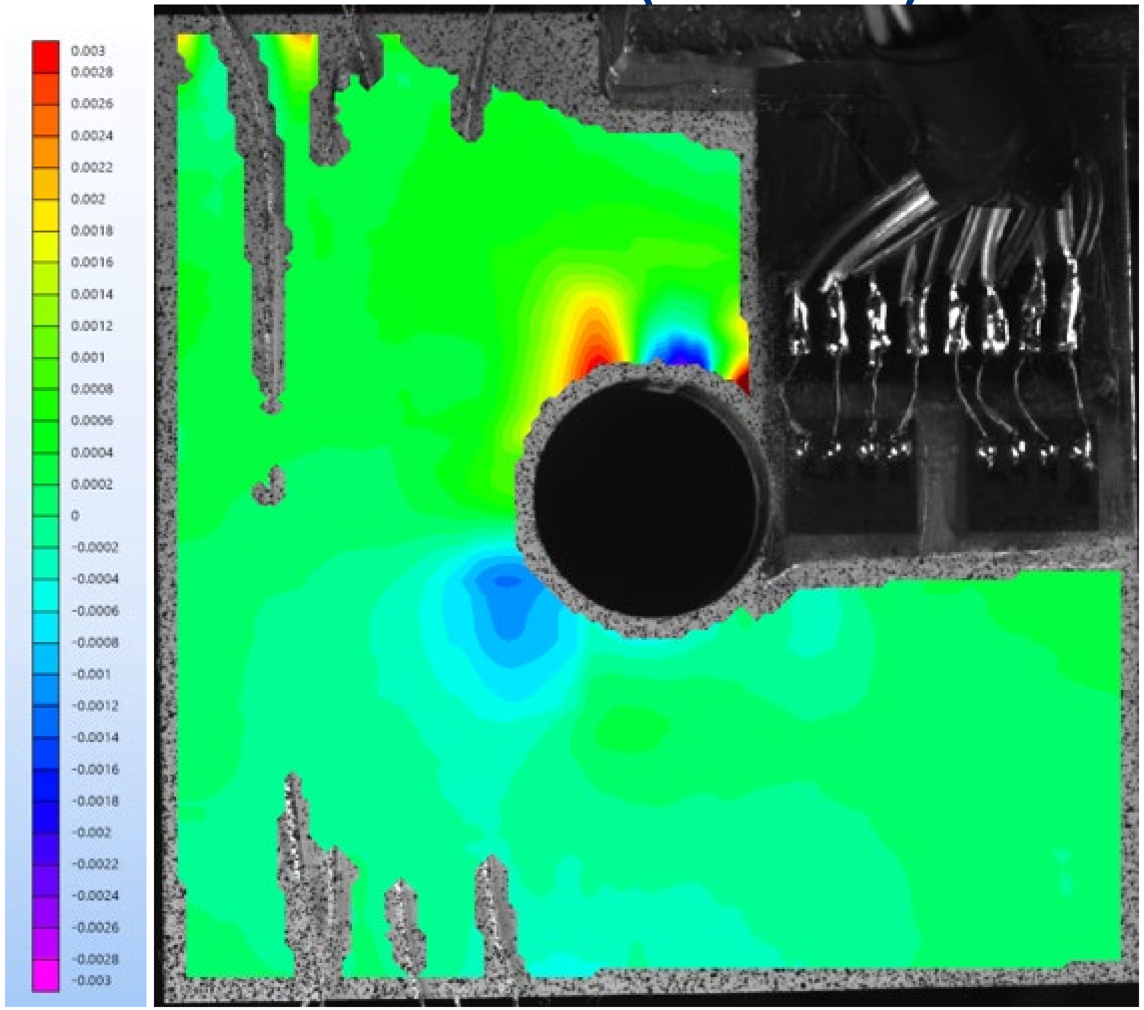
DIC



FEA



Validation (DIC-FEA)



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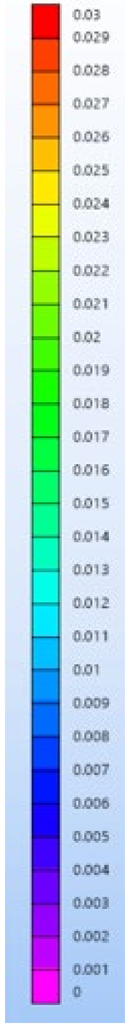
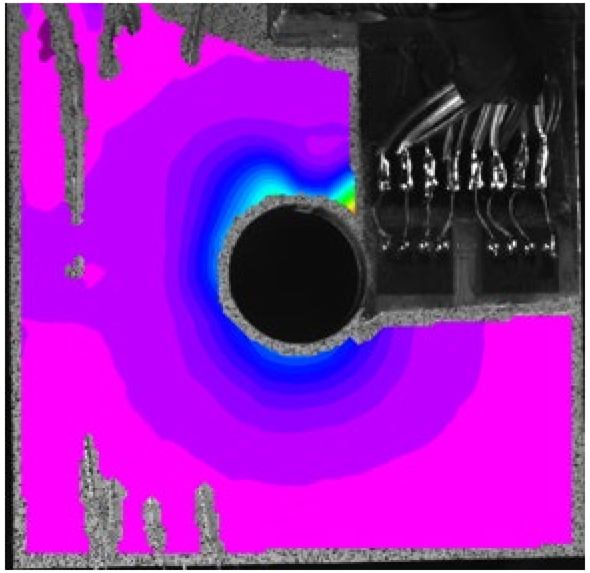
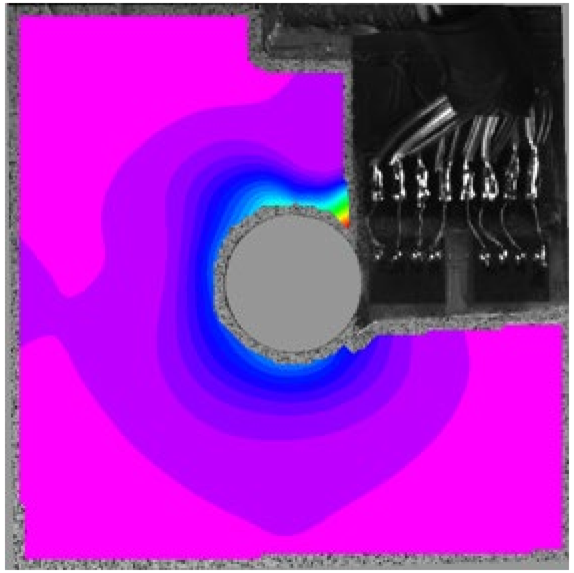
ISO – Entry (ϵ_1)



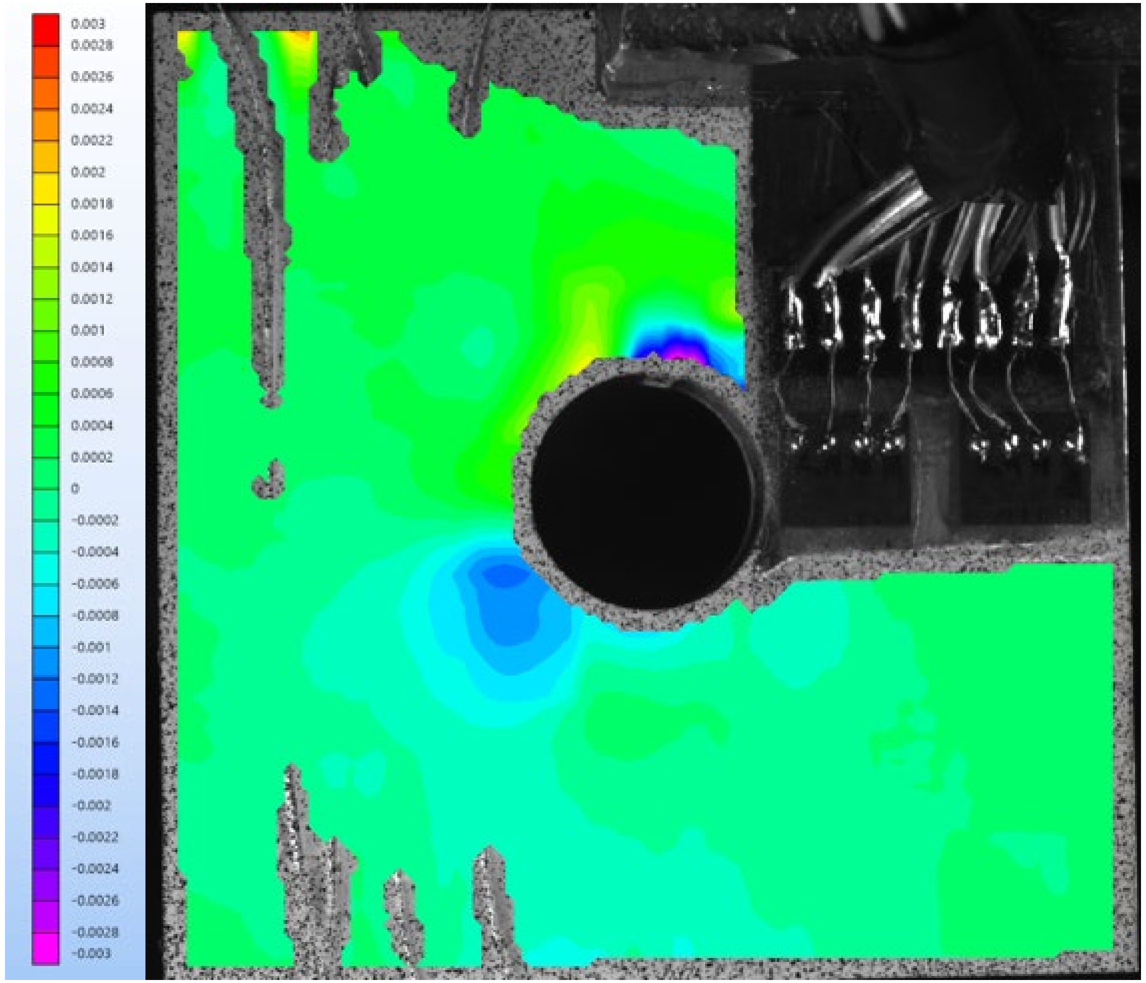
DIC



FEA



Validation (DIC-FEA)



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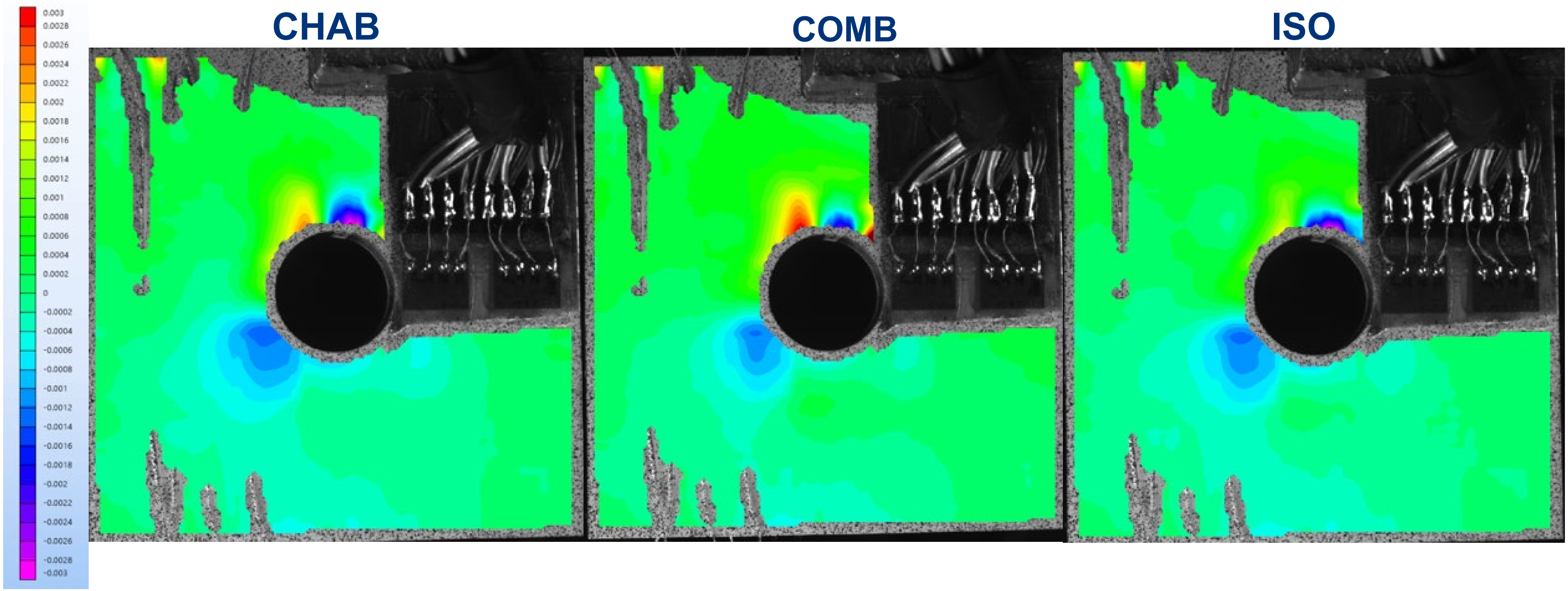
Validation Comparison (ϵ_1)



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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)

Overview

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Overview of Test Fixturing

2D HIGH Mag:

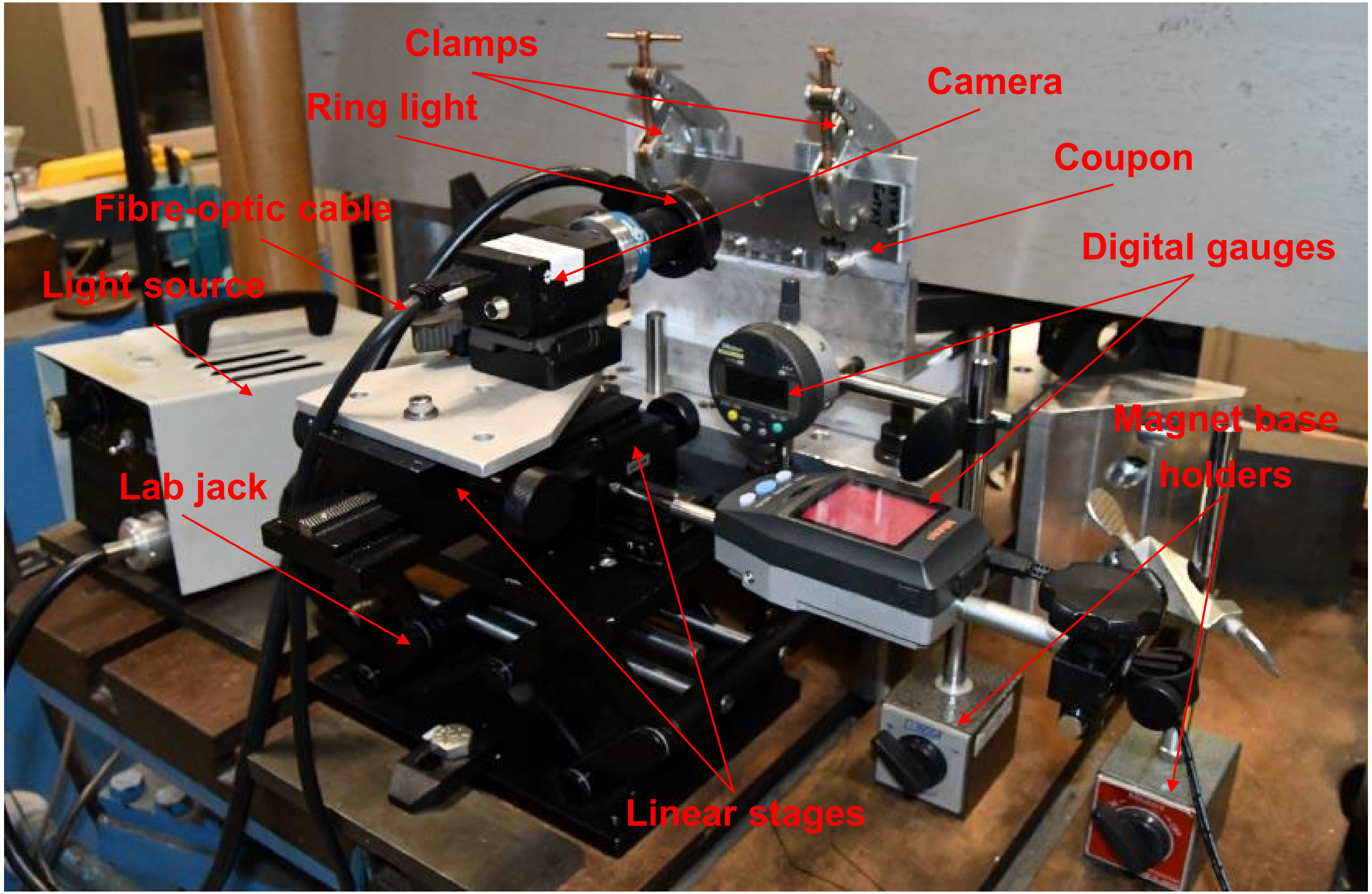
- Scale: 383 pixel/mm

2D LOW Mag:

- Scale: 101 pixel/mm

3D DIC:

- Scale: 37 pixel/mm



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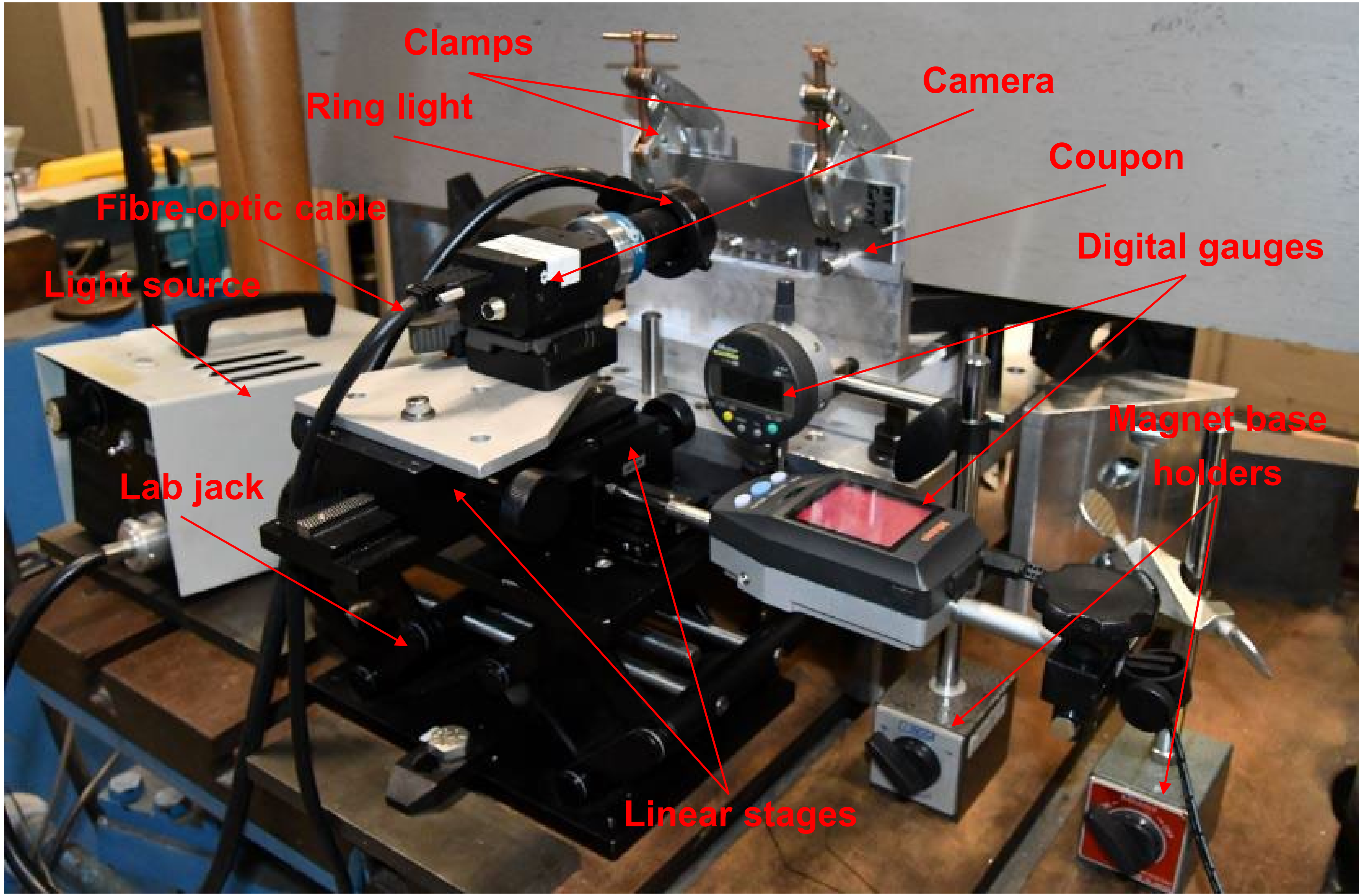
2D DIC [High Mag] Test Setup



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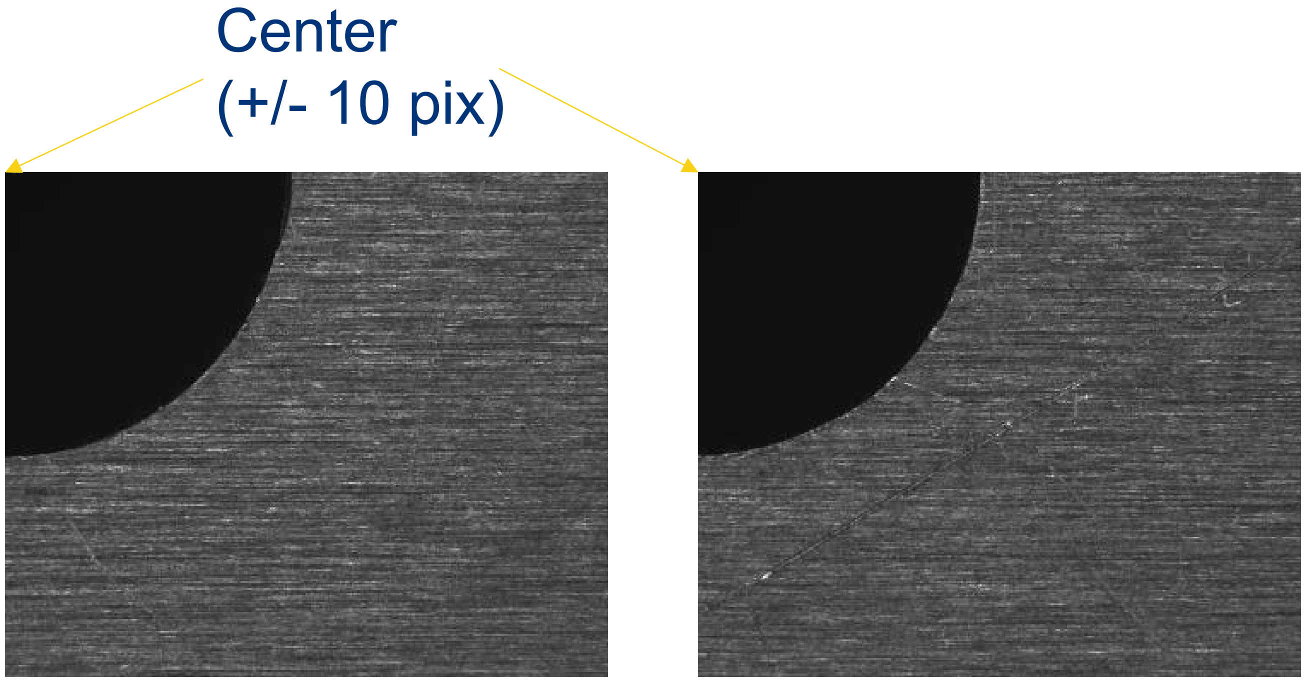
3D DIC Test Setup

- *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

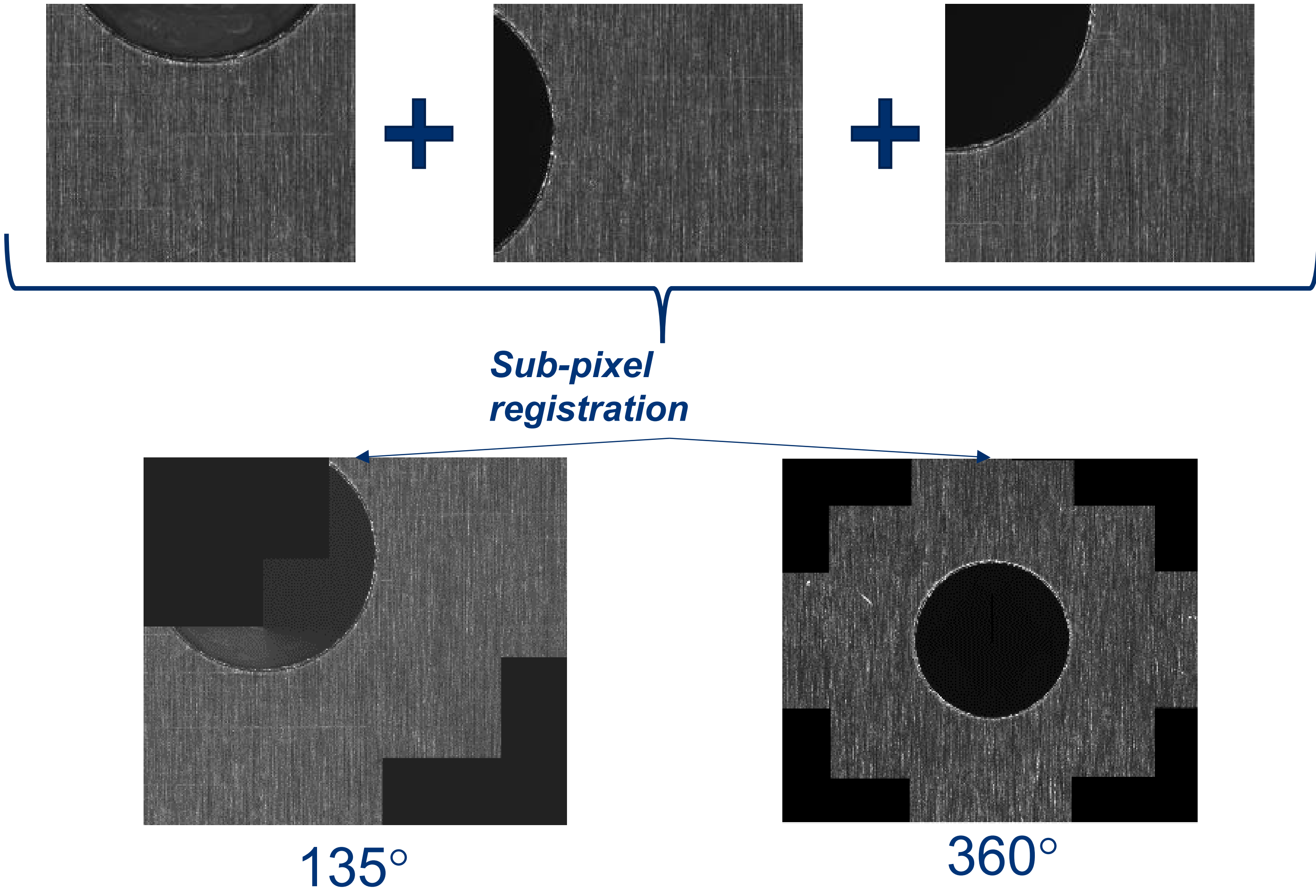
- High precision camera adjustment
- Image tracking using FIJI
- Precision adjustment based on imaging results
- Final center position [+/- 26 microns]
- Allows for precise determination of distance to edge of hole from DIC correlation



Entry ***Exit***

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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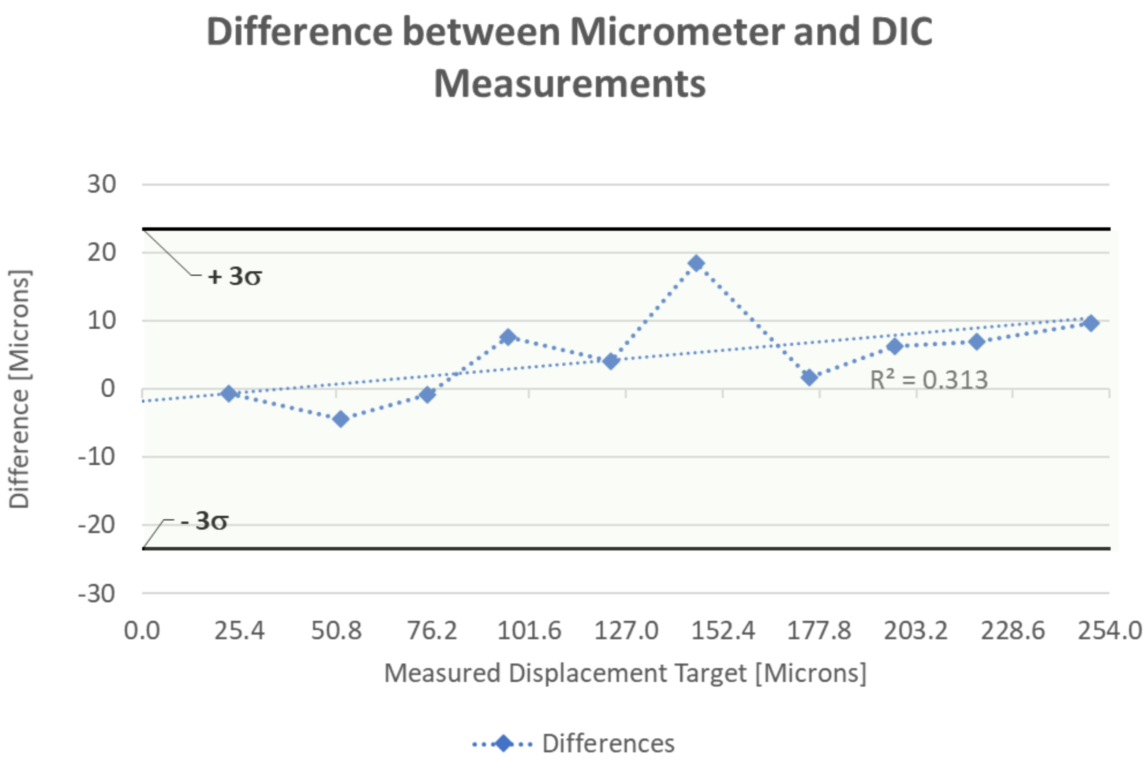
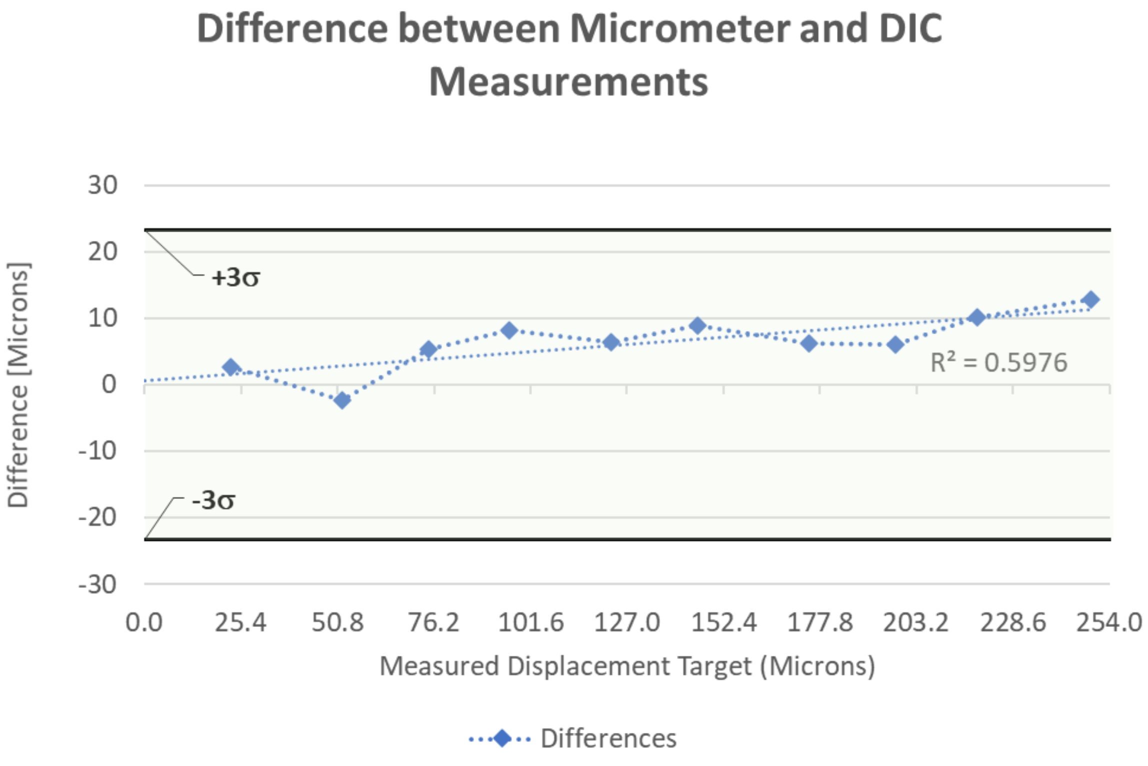
Rigid Body Displacement Testing - Setup

2D High Mag DIC Validation Results

ENTRY FACE



EXIT FACE



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Overview

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    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

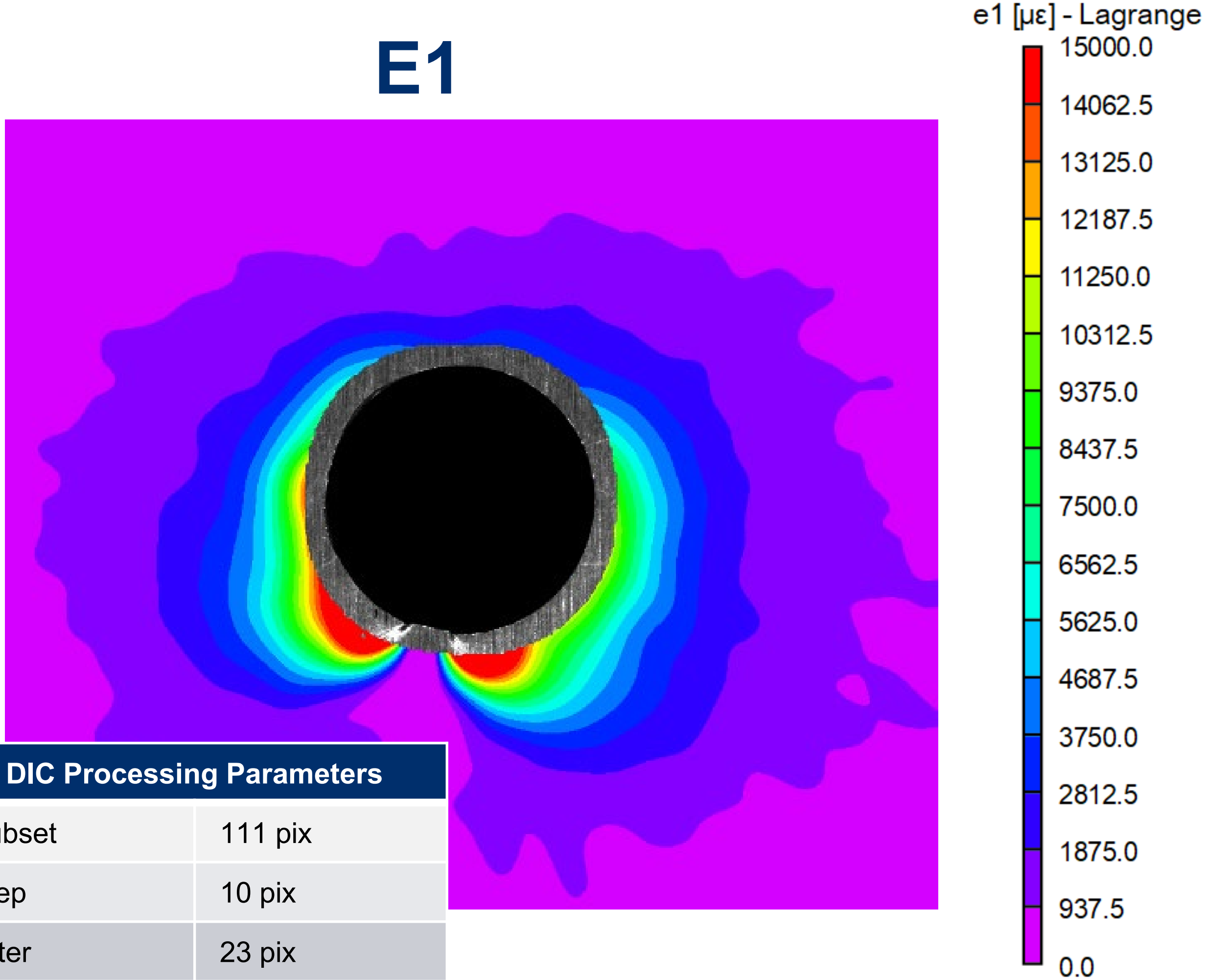
Thickness = 0.063inch

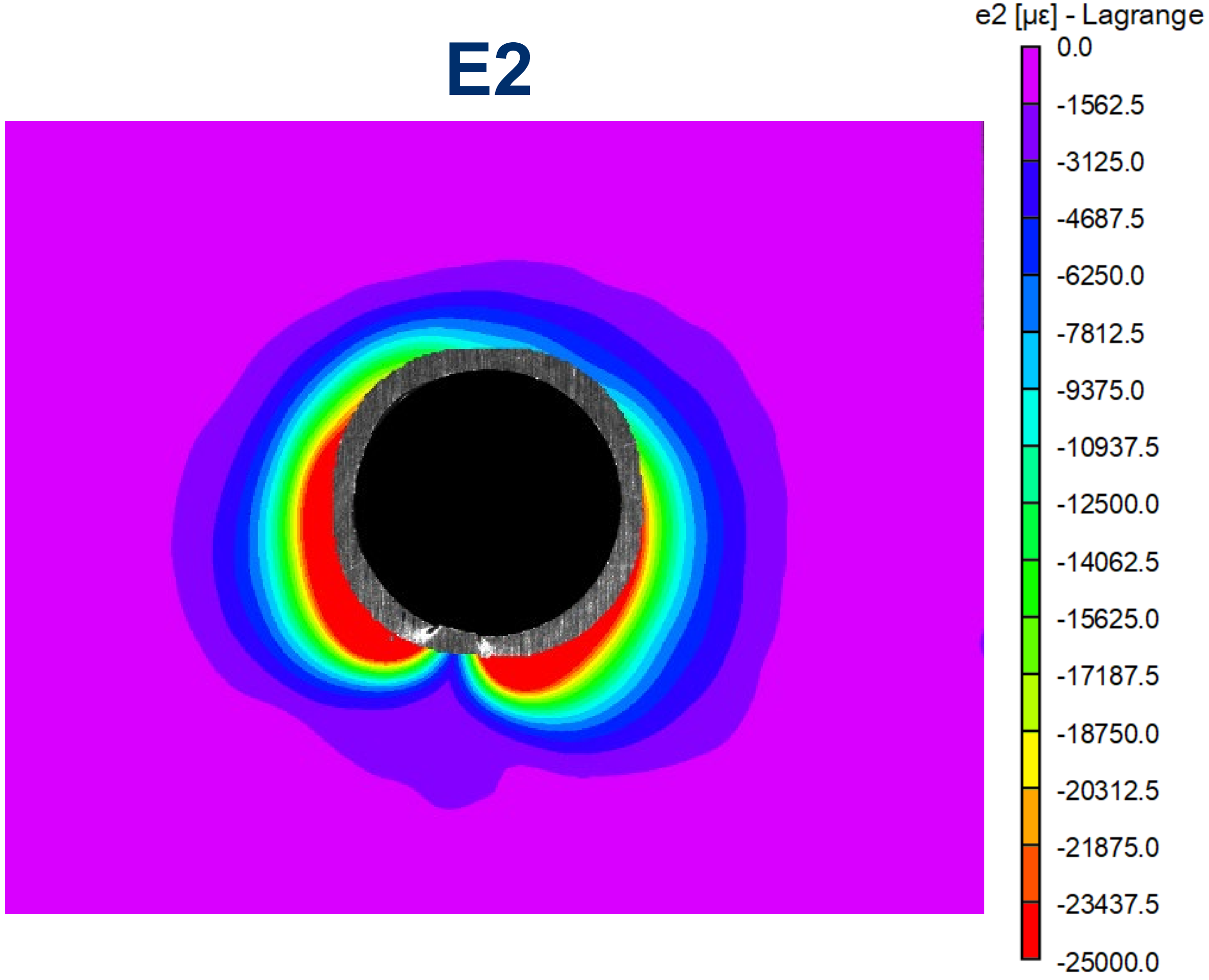
Starting Hole Diameter = 0.2377inch

FTI Toolset:

LOCKHEED MARTIN

BT12 – Entry Post Cx





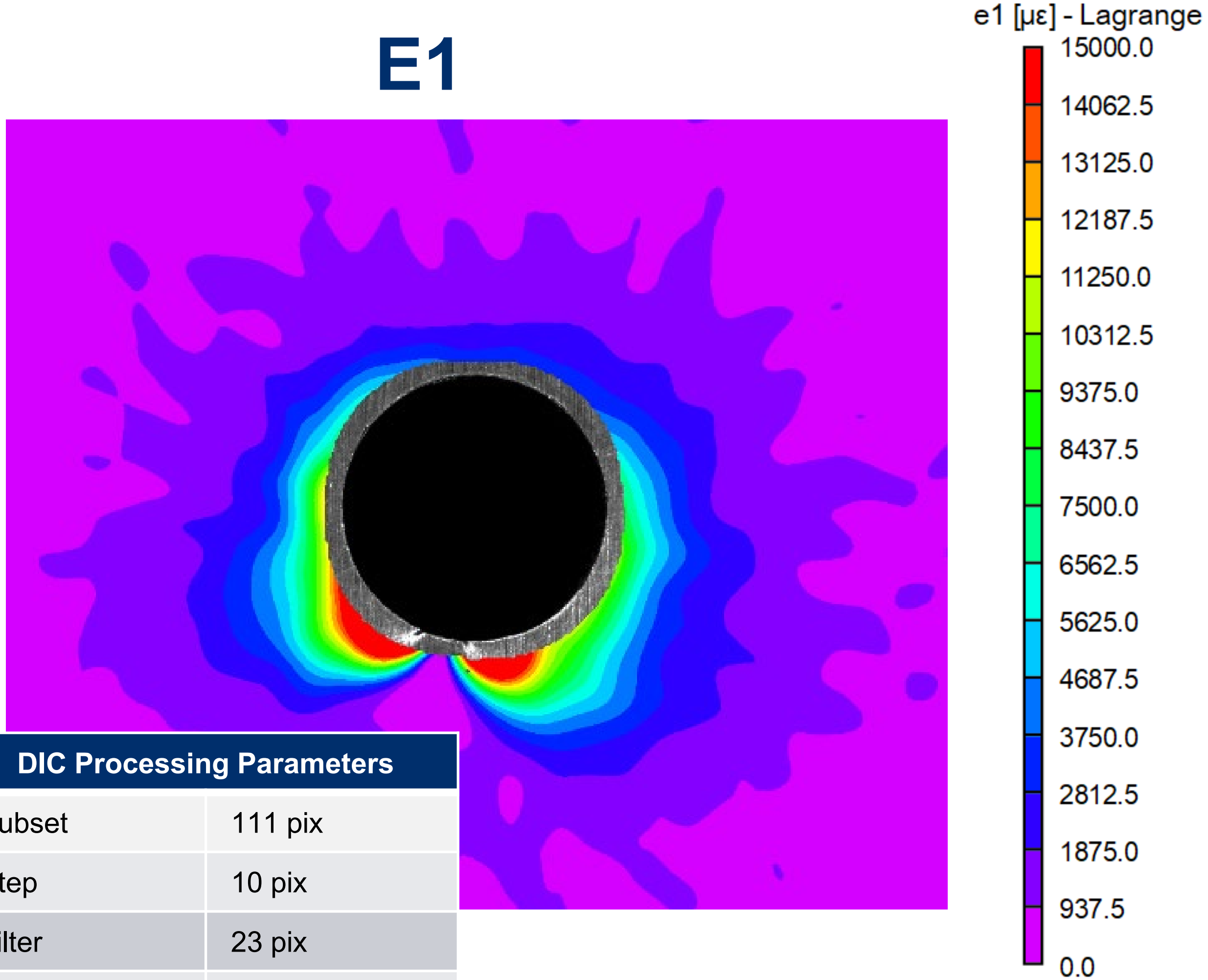
DIC Processing Parameters	
Subset	111 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (2.3 mm)**

Split rotated 12.5° from 6 o'clock orientation

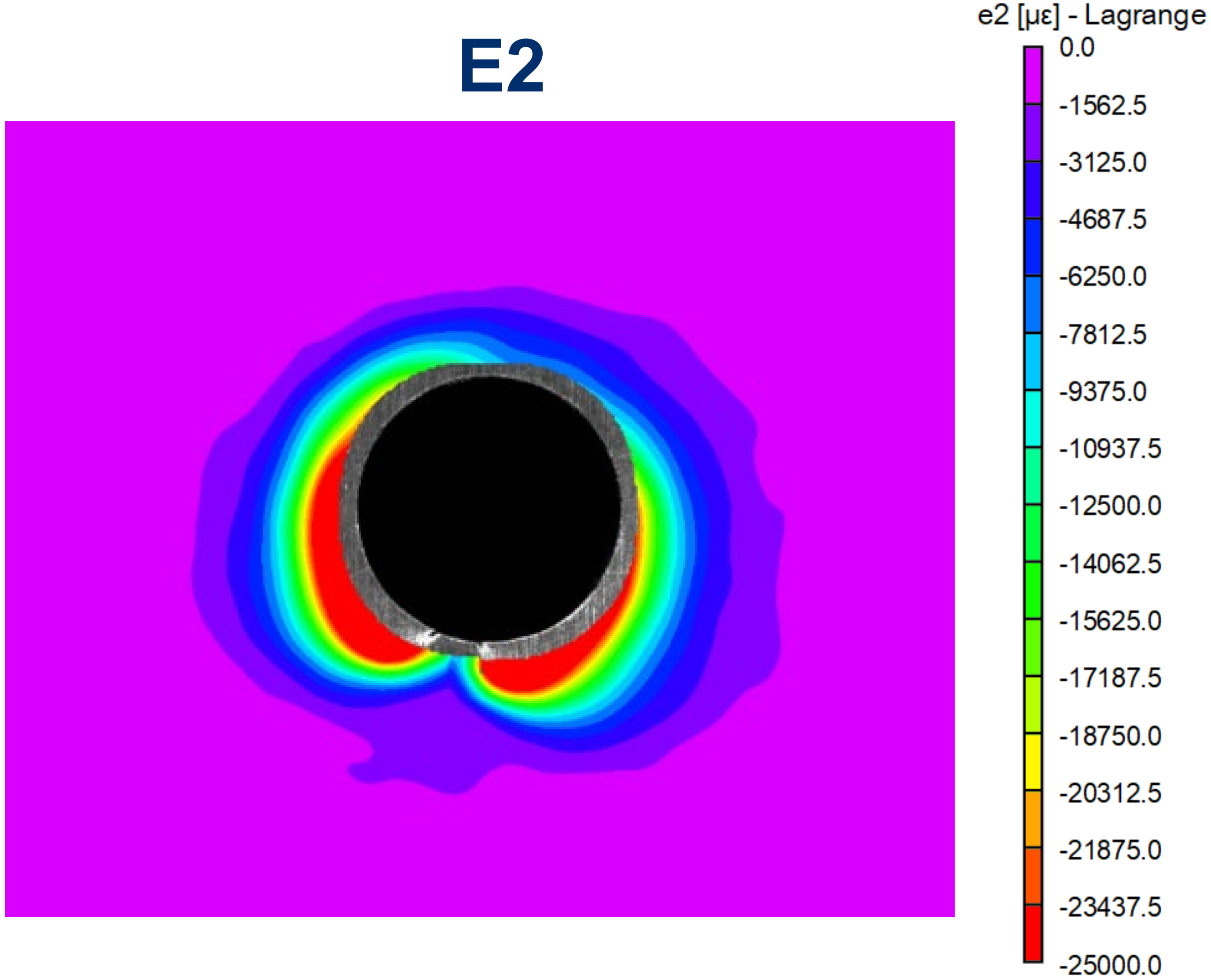
LOCKHEED MARTIN

BT12 – Entry Post Ream

E1



E2

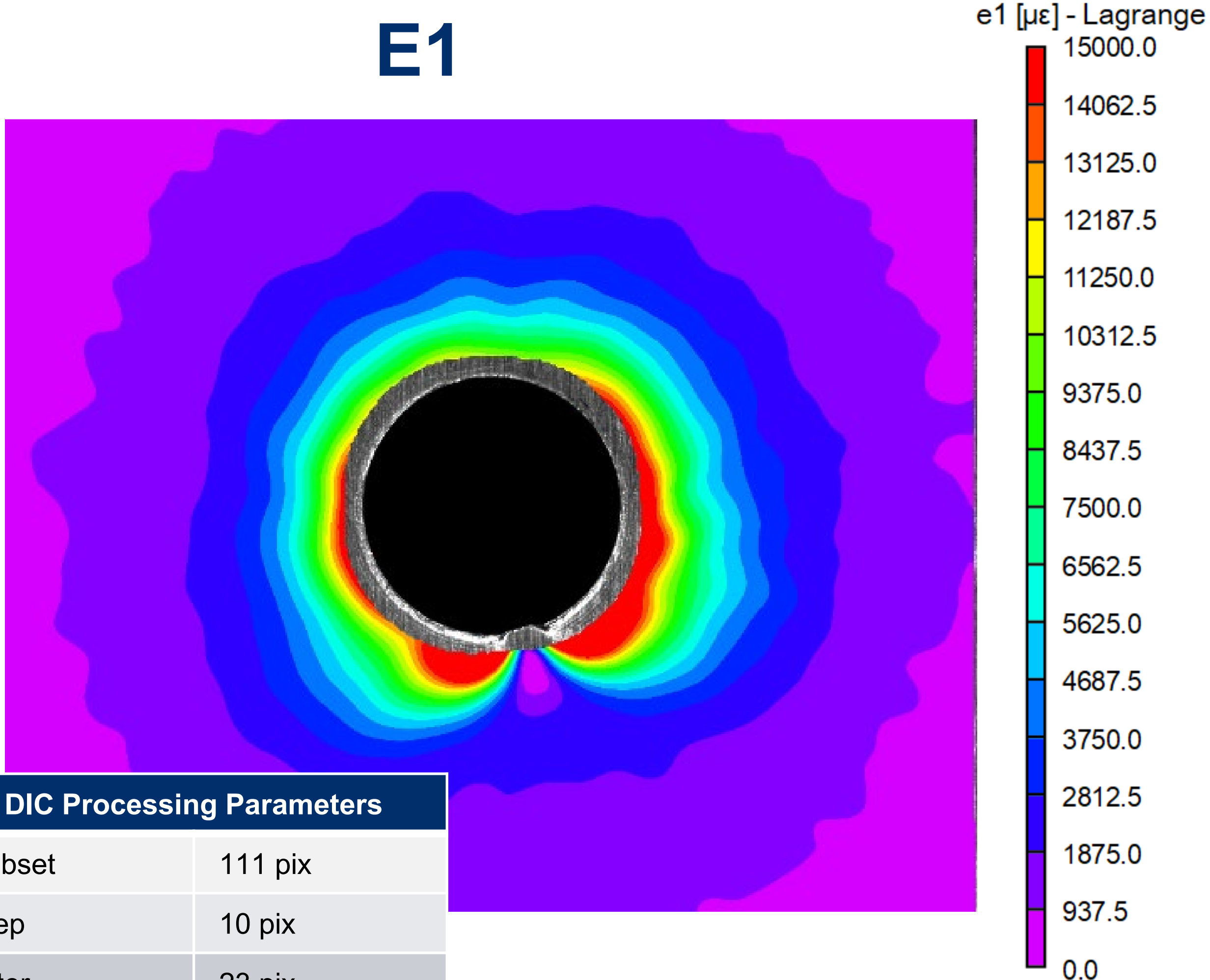


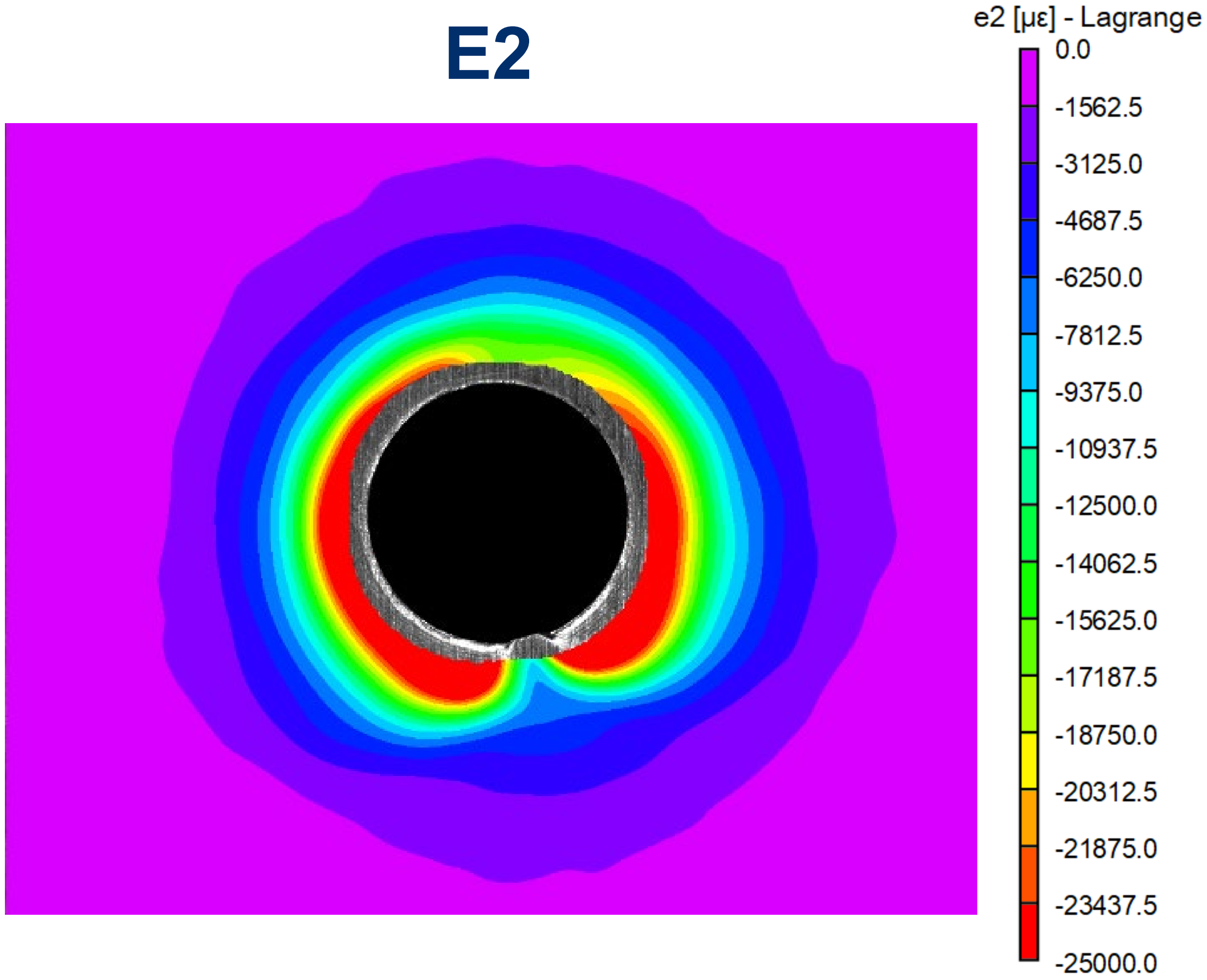
DIC Processing Parameters	
Subset	111 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (2.3 mm)**

Split rotated 12.5° from 6 o'clock orientation

LOCKHEED MARTIN

BT12 – Exit Post Cx



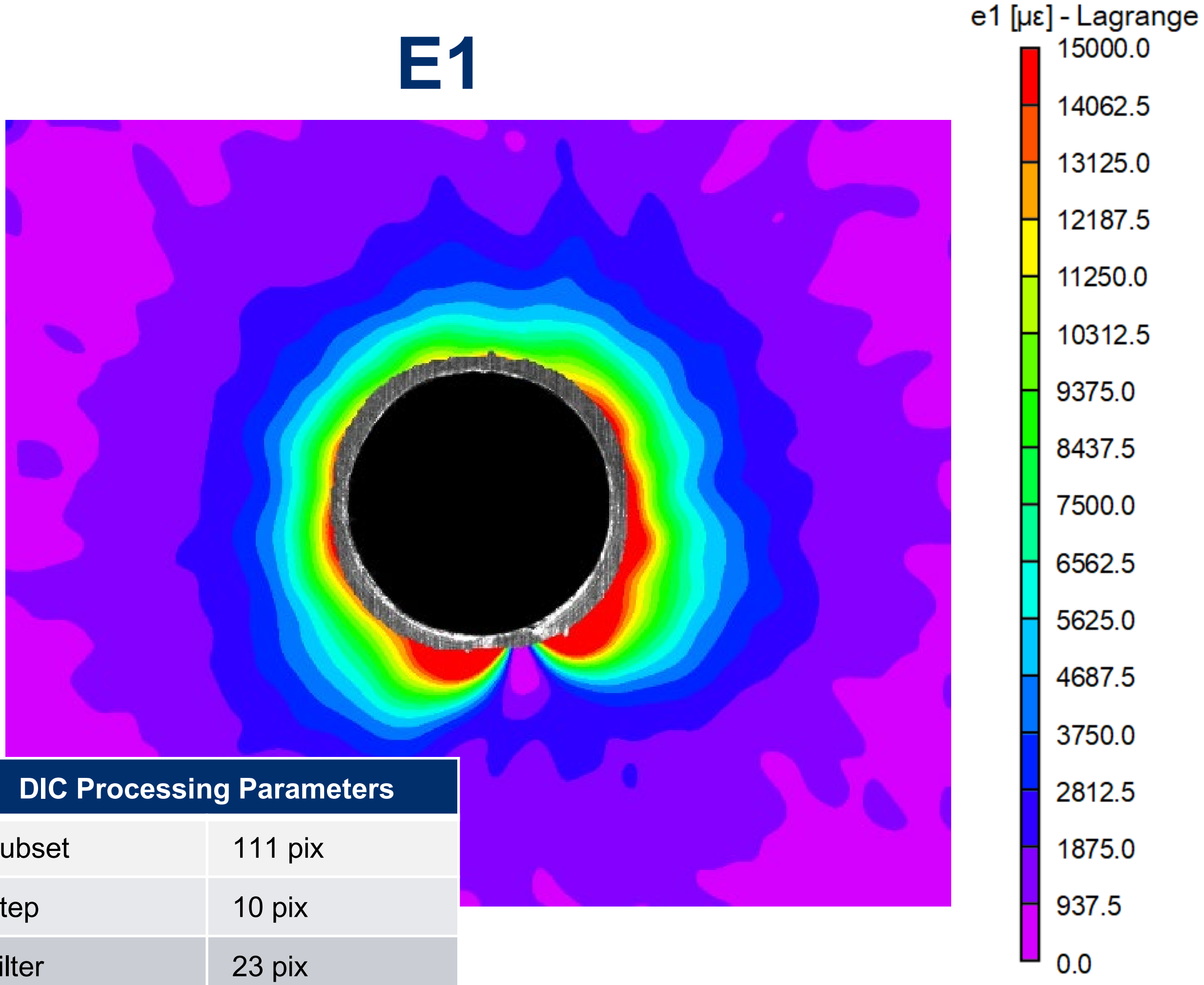


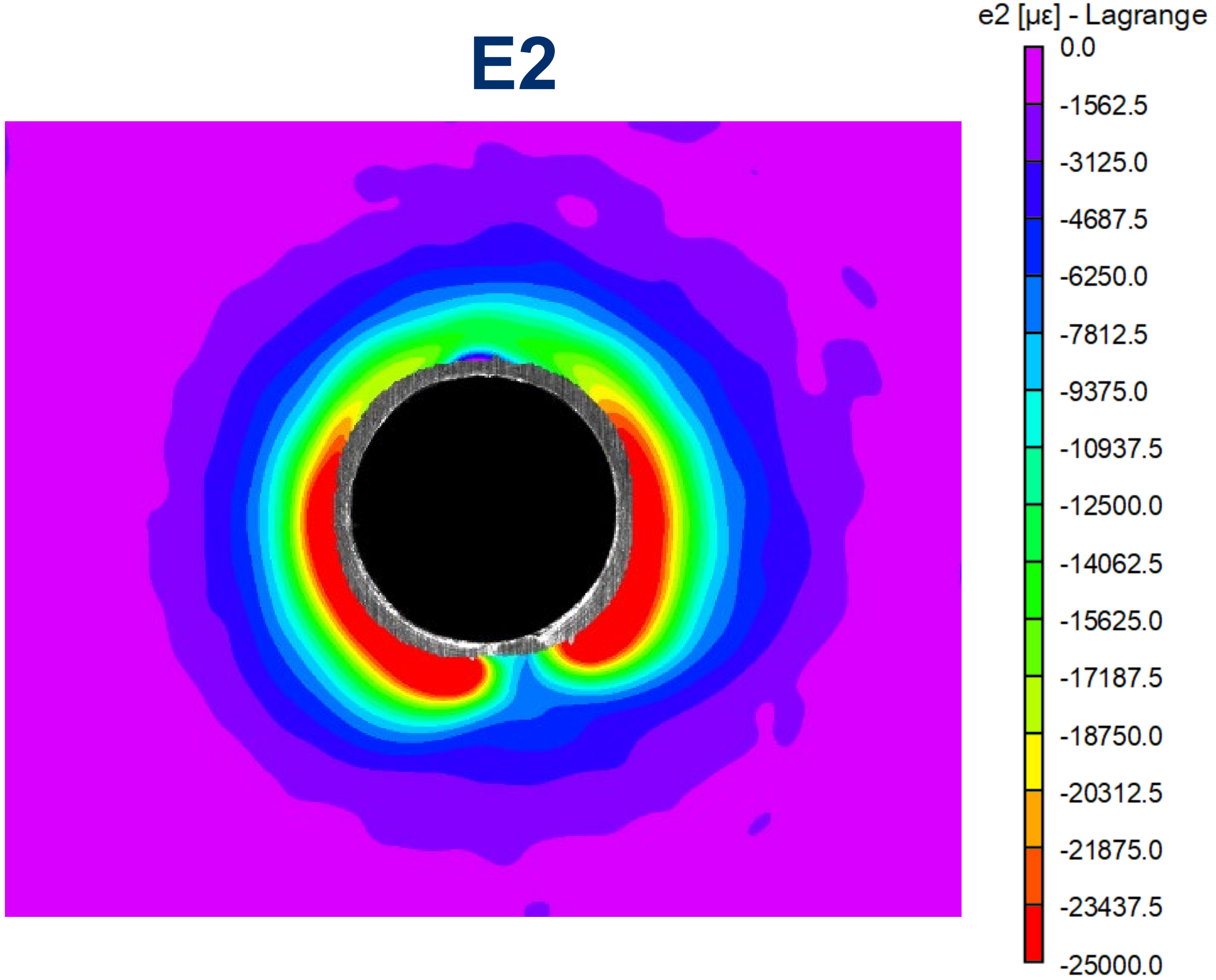
DIC Processing Parameters	
Subset	111 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (2.3 mm)**

Split rotated 12.5° from 6 o'clock orientation

LOCKHEED MARTIN

BT12 – Exit Exit Post Ream





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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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**

BT15 – 2D DIC HIGH Mag

2024-T3

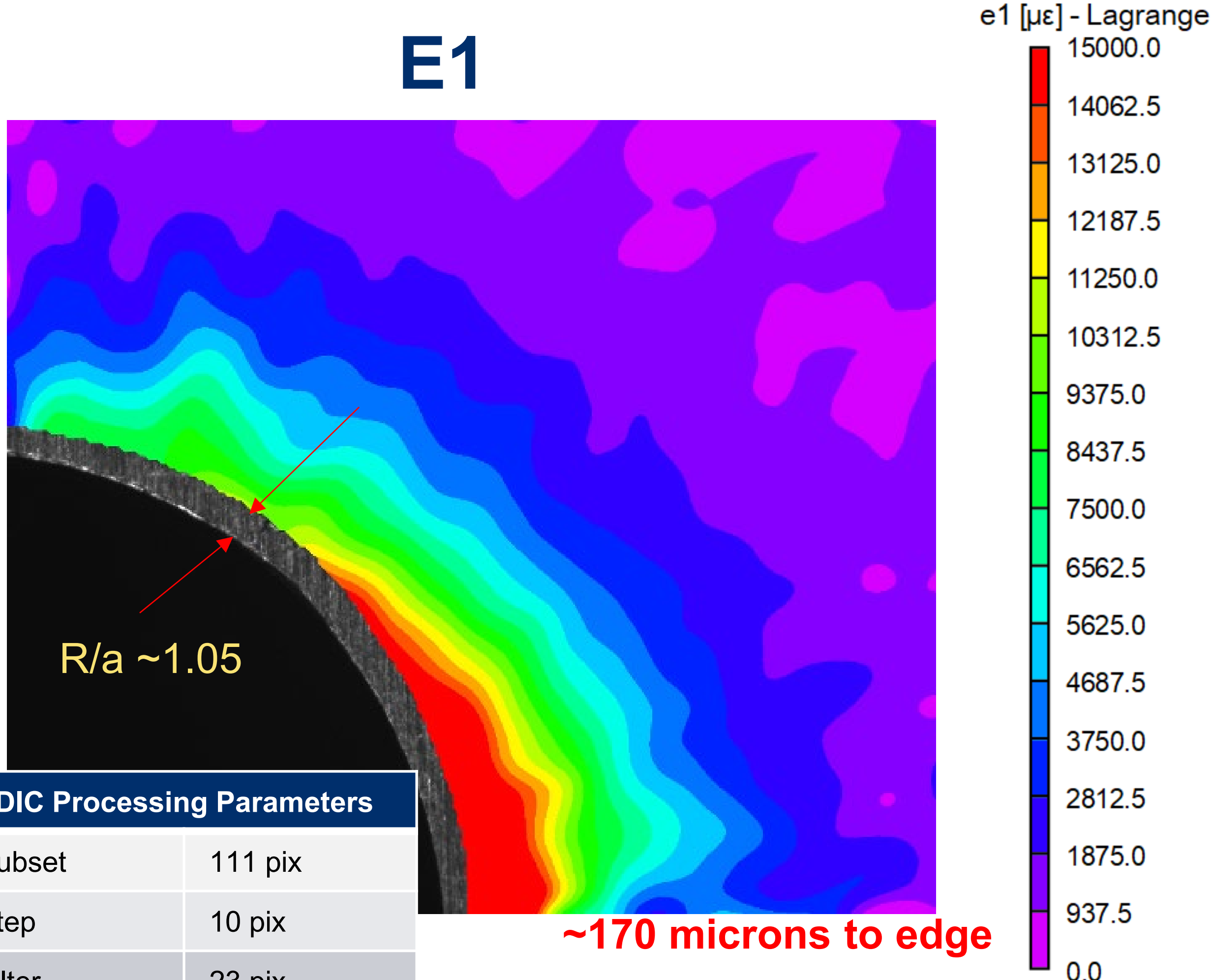
Thickness = 0.063inch

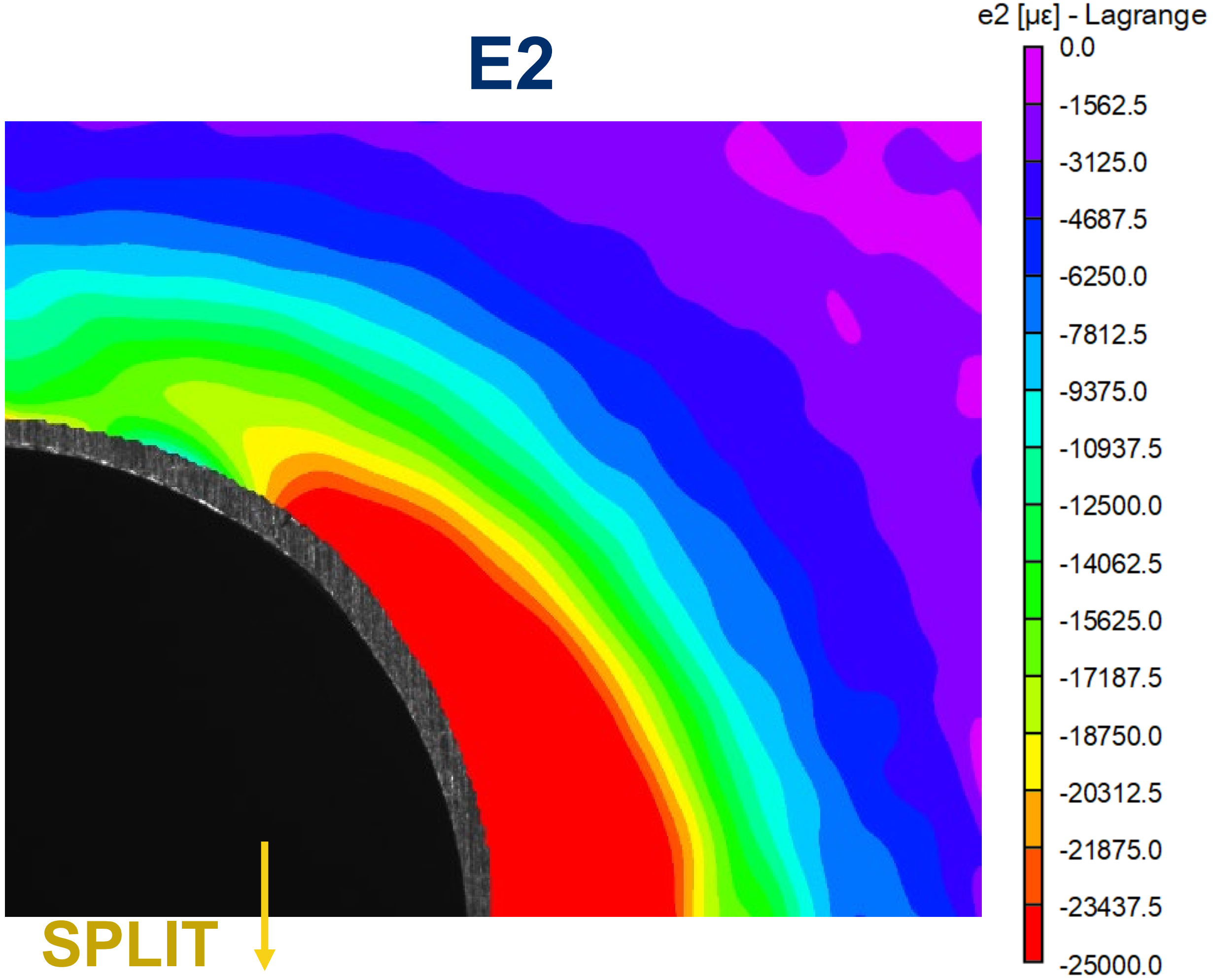
Starting Hole Diameter = 0.2376inch

FTI Toolset:

LOCKHEED MARTIN

BT15 – Entry Post Cx





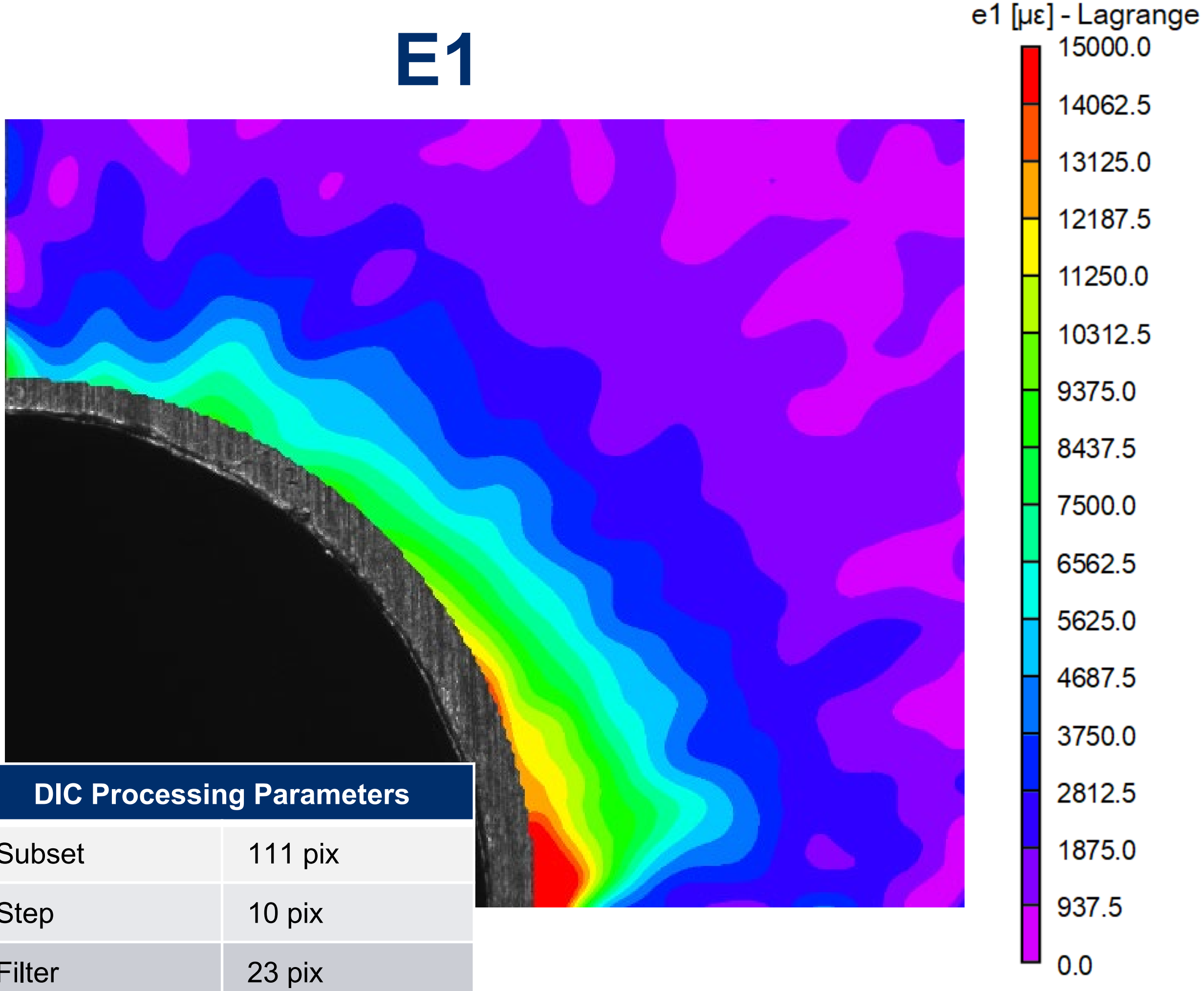
DIC Processing Parameters	
Subset	111 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (0.60 mm)**

Split rotated 16.7° from 6 o'clock orientation

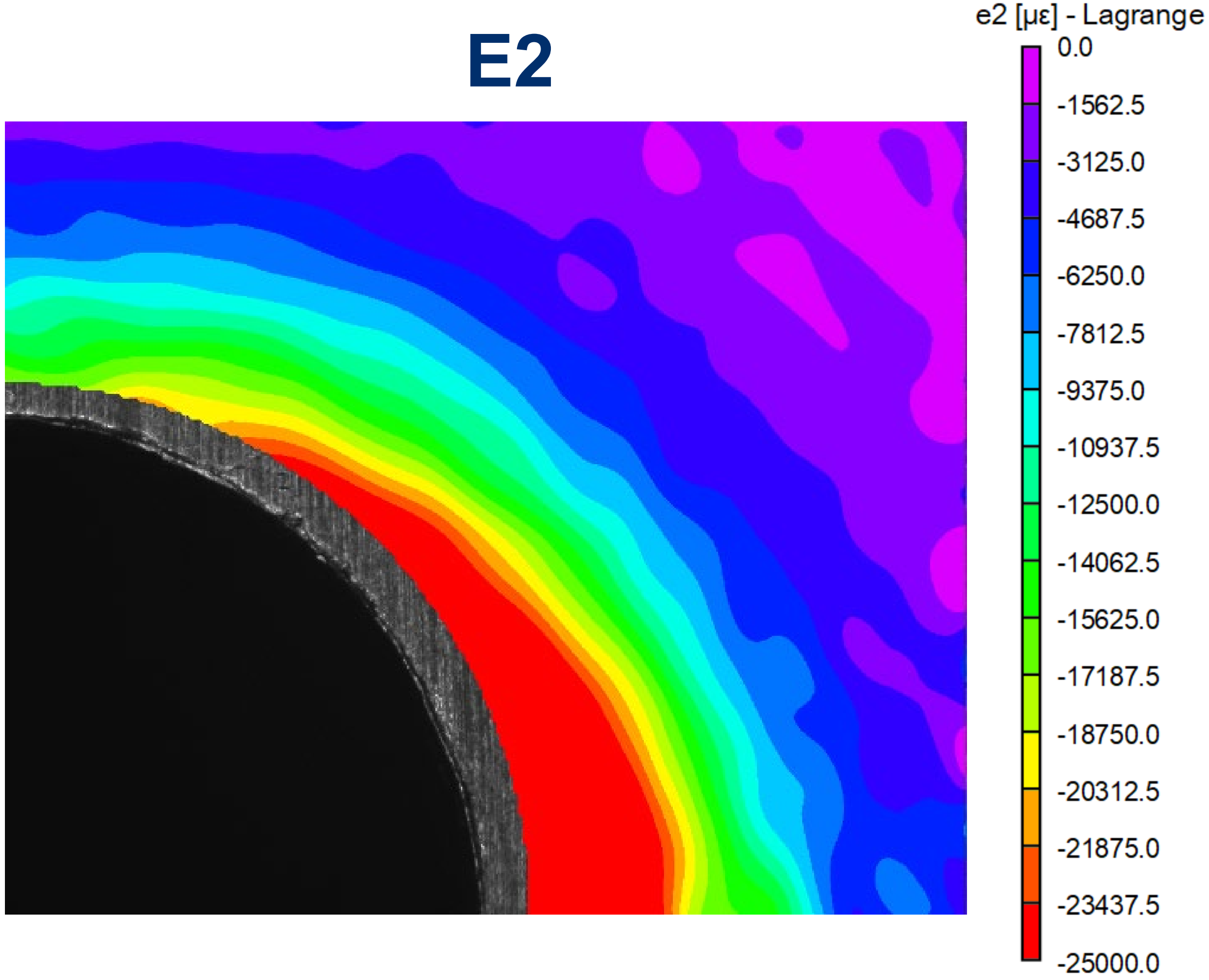
LOCKHEED MARTIN

BT15 – Entry Post Ream

E1



E2

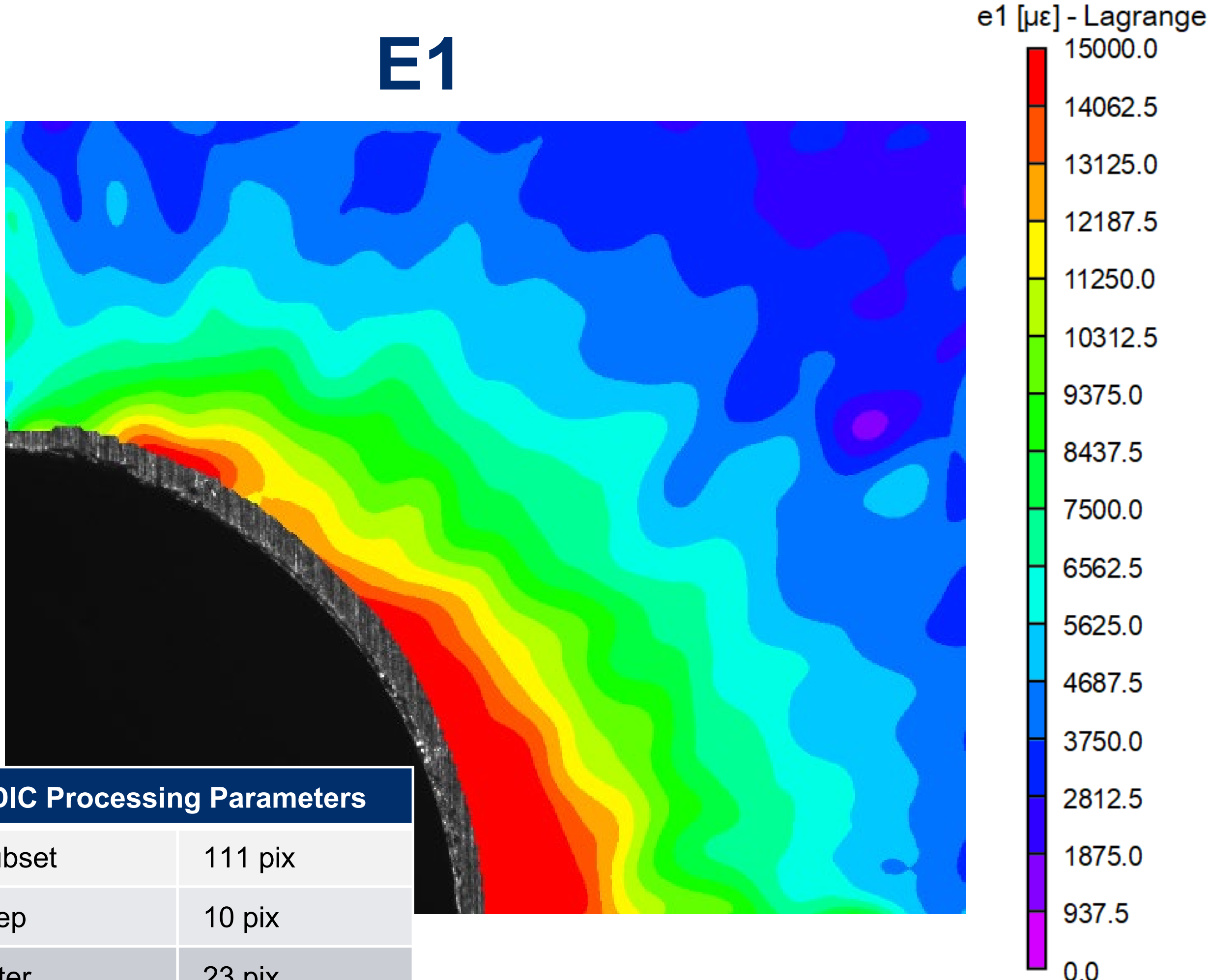


DIC Processing Parameters	
Subset	111 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (0.60 mm)**

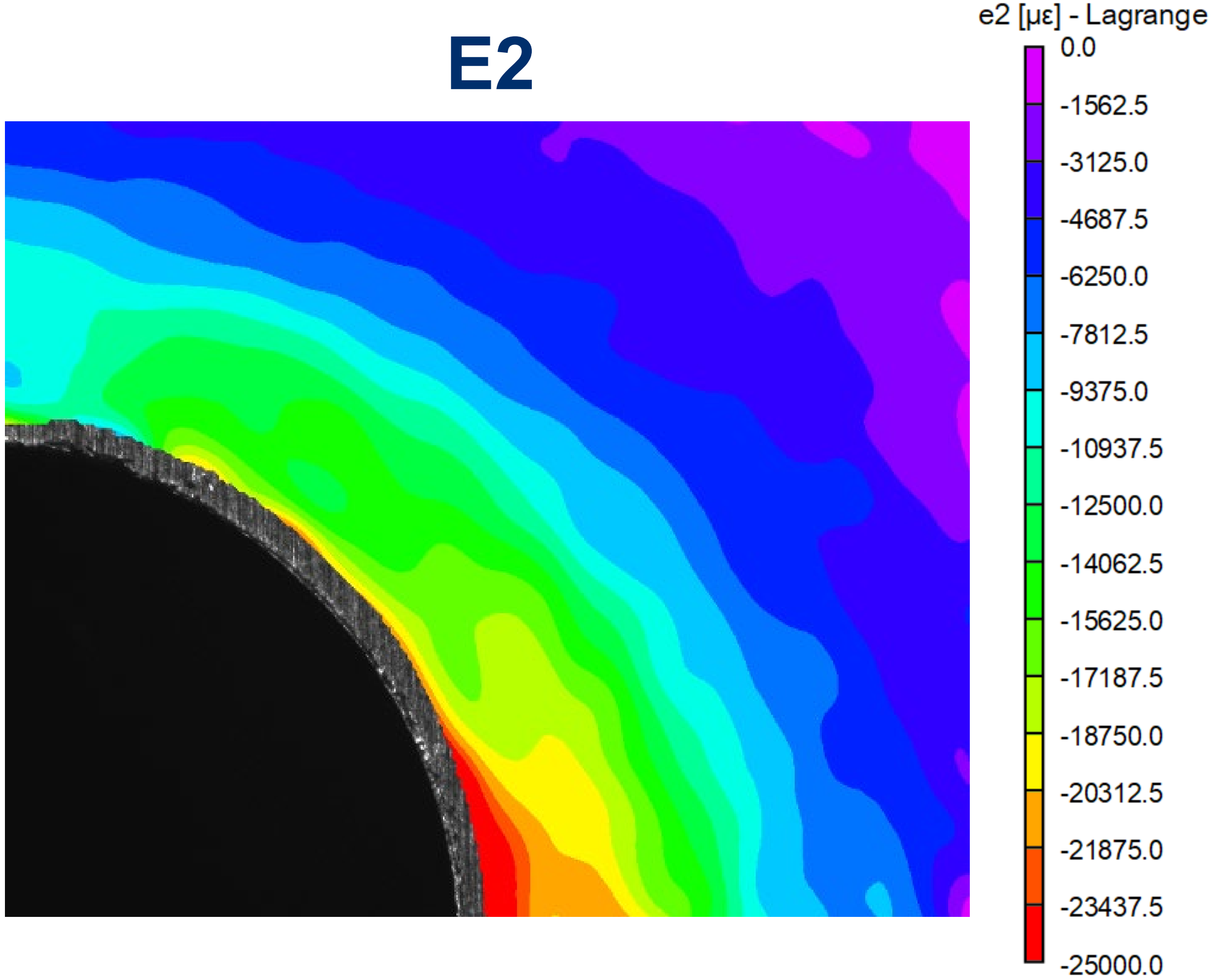
LOCKHEED MARTIN

BT15 – Exit Post Cx

E1



E2



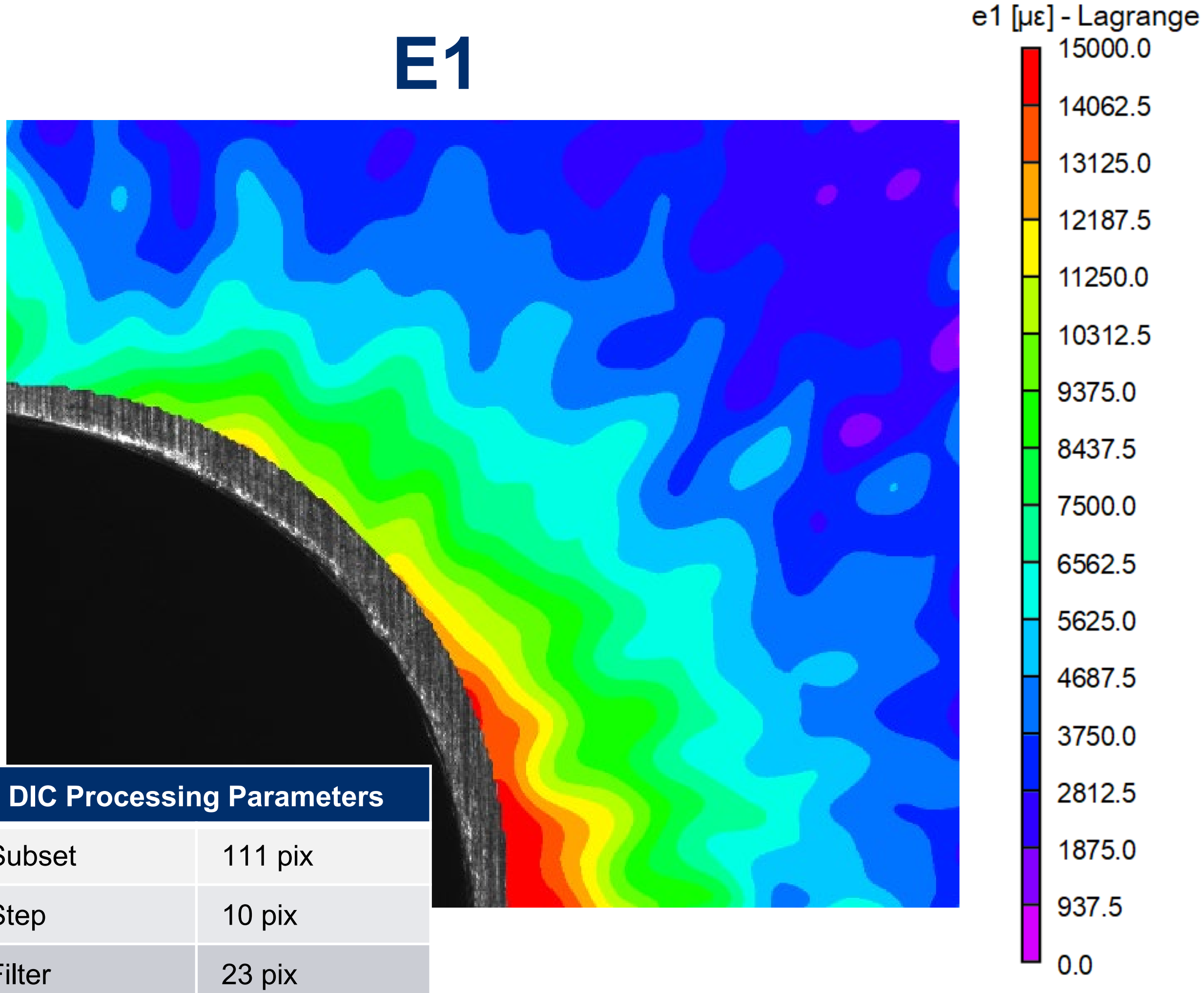
DIC Processing Parameters	
Subset	111 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (0.60 mm)**

Split rotated 16.7° from 6 o'clock orientation

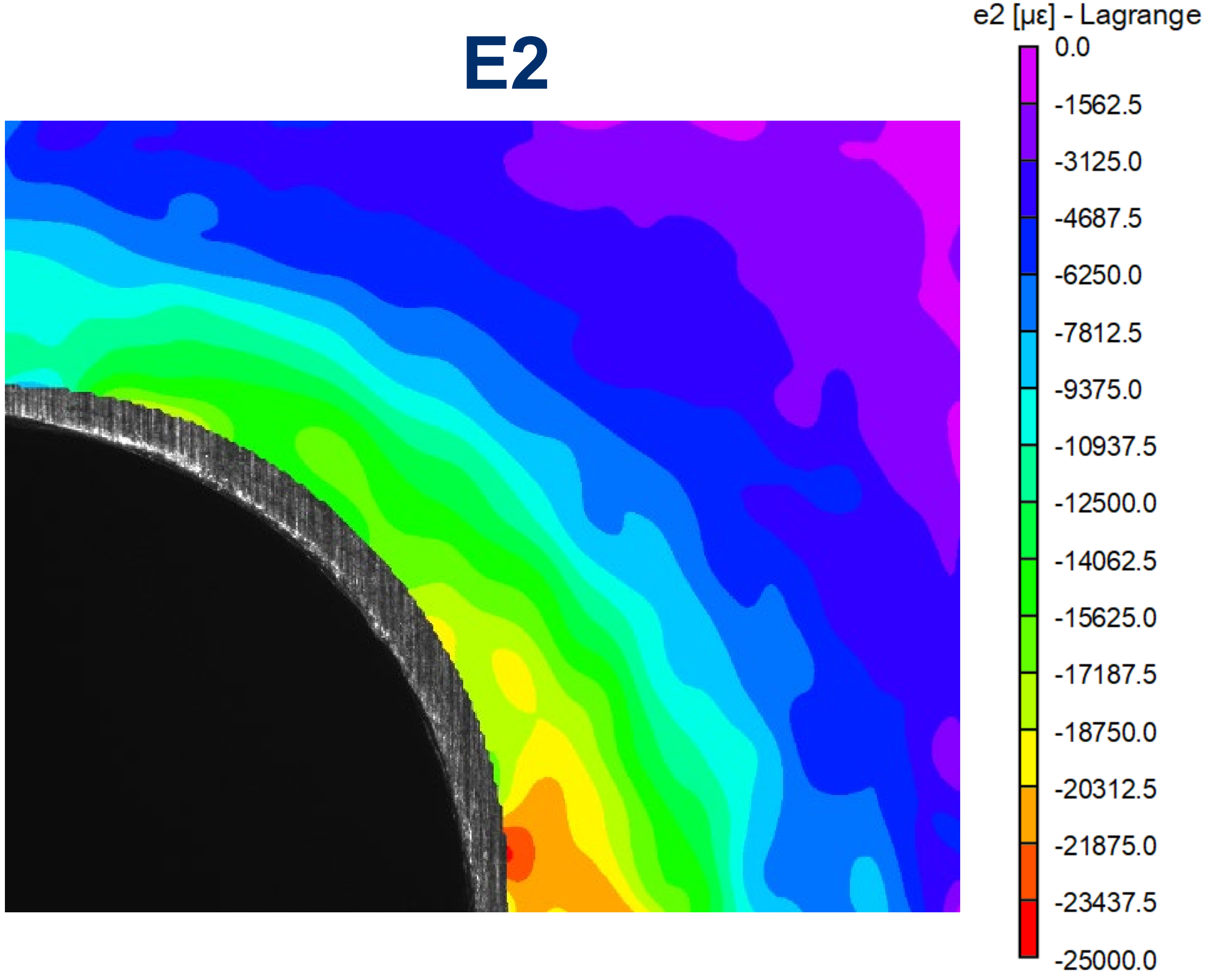
LOCKHEED MARTIN

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

LOCKHEED MARTIN

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***

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**

BT18 – 3D DIC HIGH Mag

2024-T3

Thickness = 0.063inch

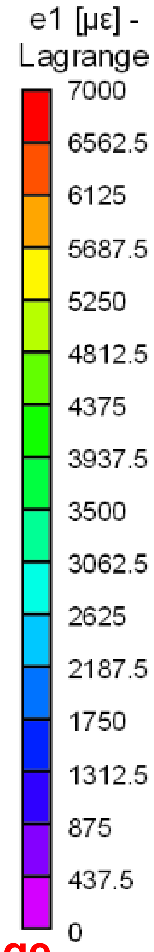
Starting Hole Diameter = 0.2380inch

FTI Toolset:

LOCKHEED MARTIN

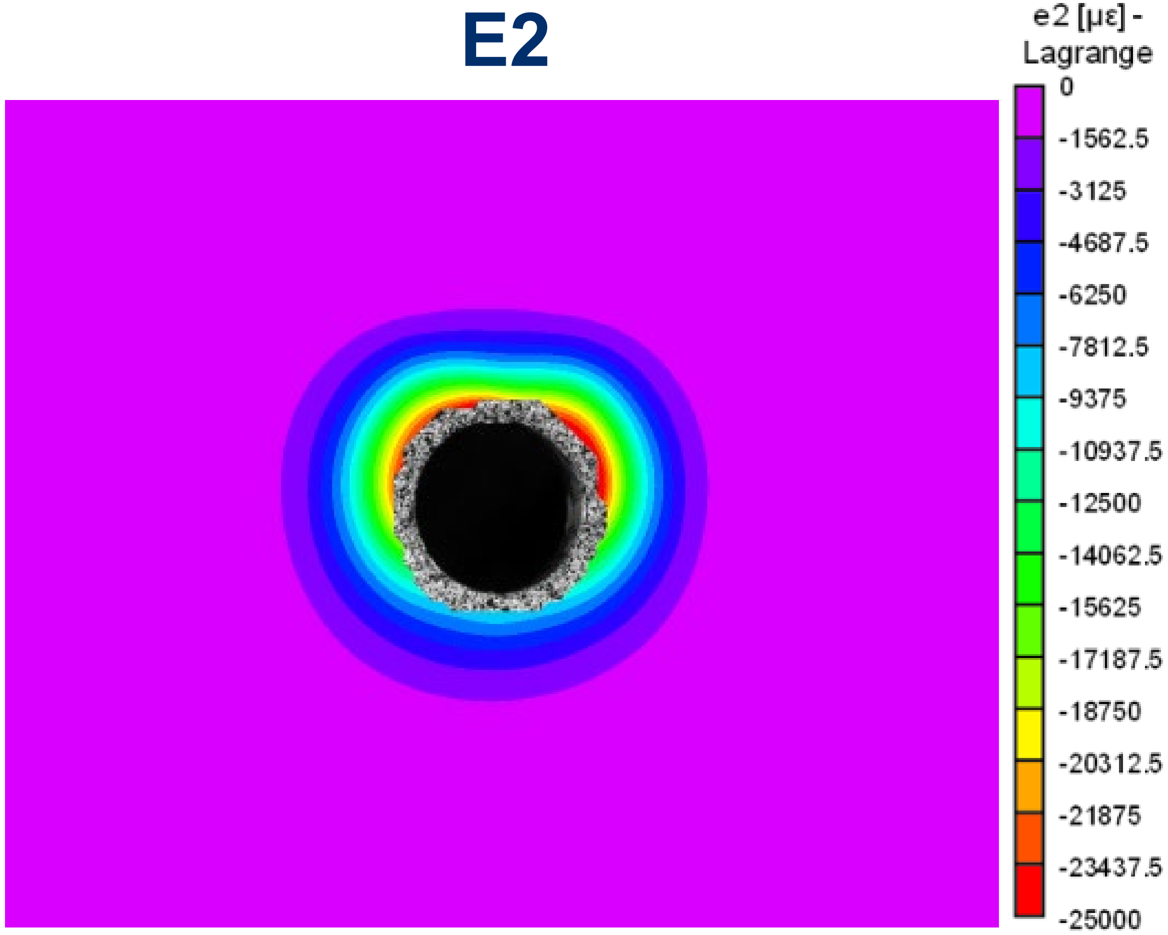
BT18 – Entry Post Cx

E1



~900 microns to edge

E2



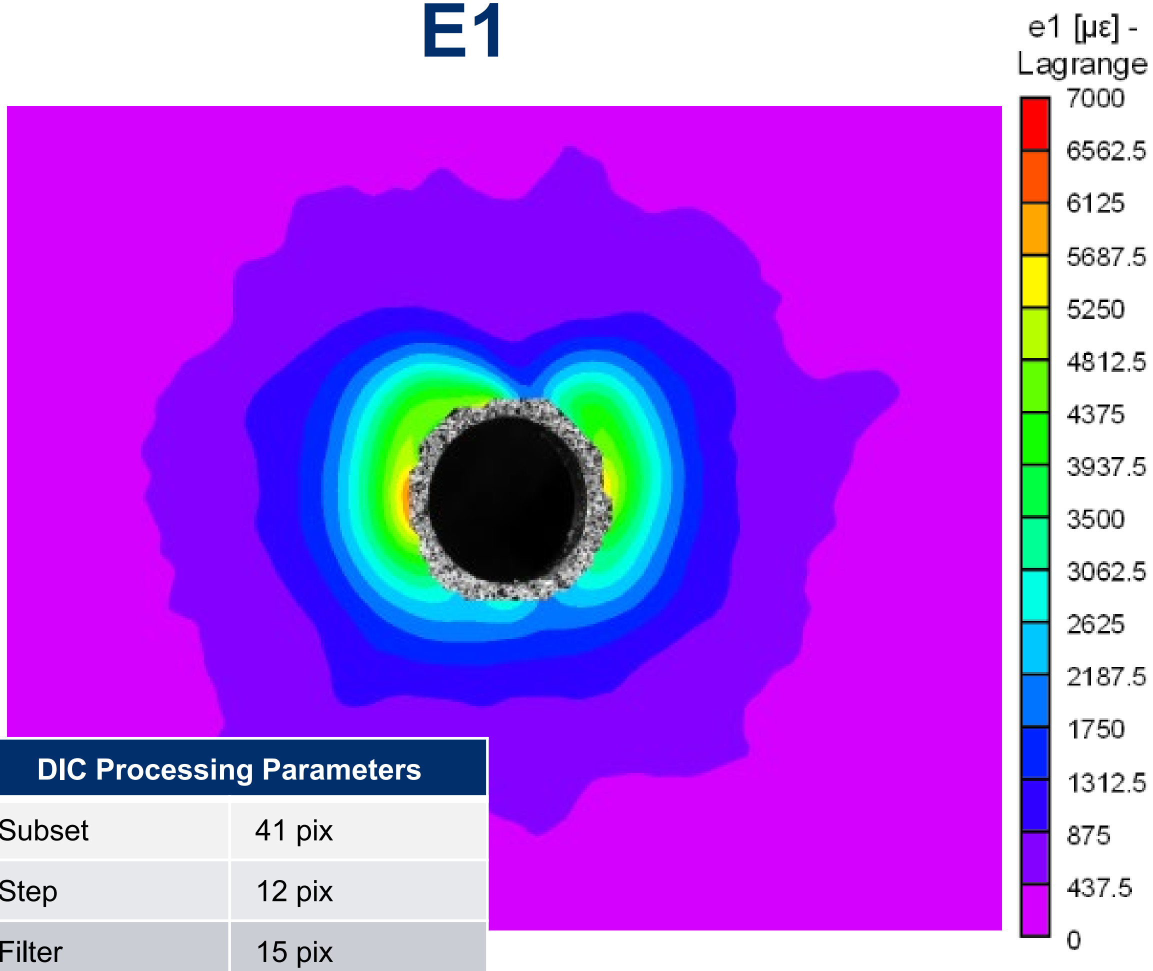
DIC Processing Parameters	
Subset	41 pix
Step	12 pix
Filter	15 pix
VSG	**180 pix (4.86 mm)**

Split at 12 o'clock orientation

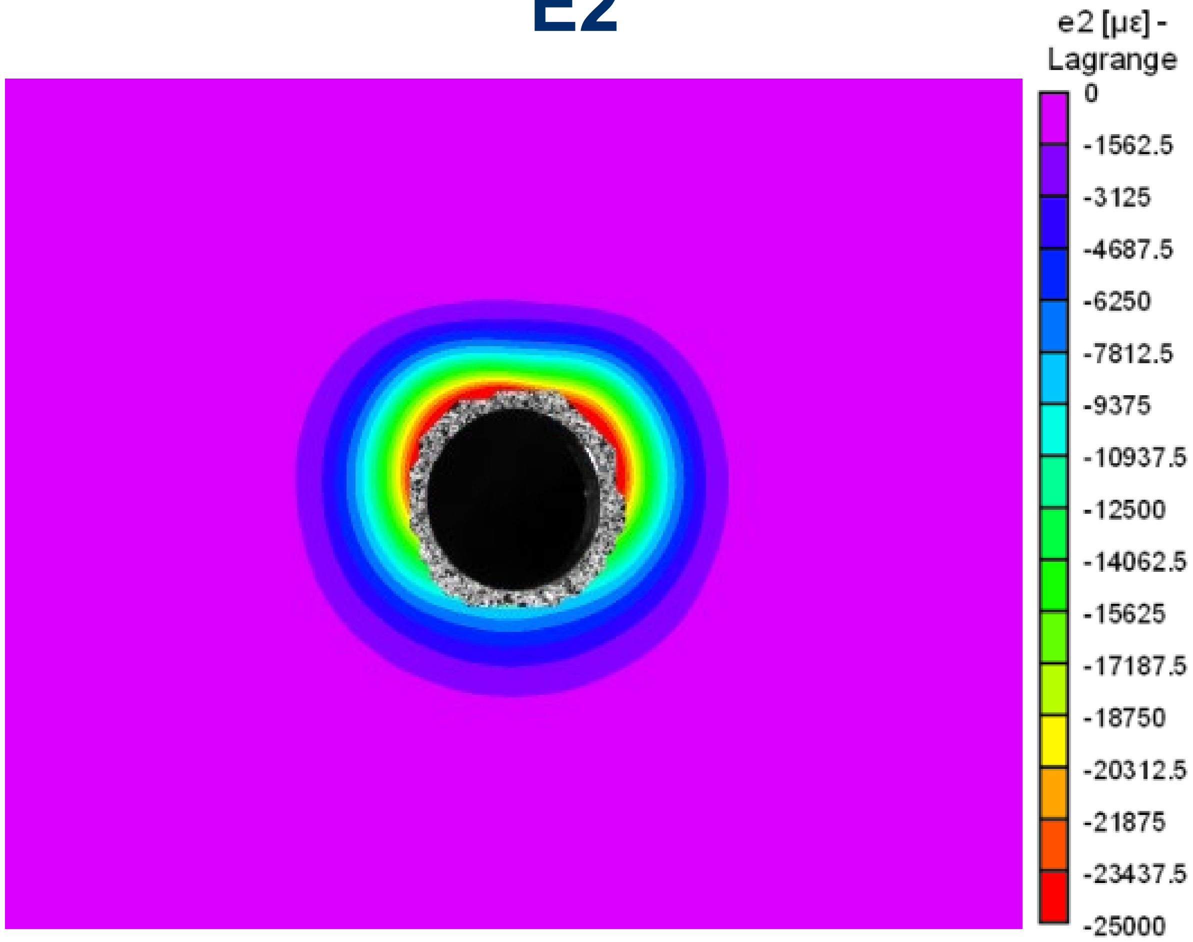
LOCKHEED MARTIN

BT18 – Entry Post Ream

E1



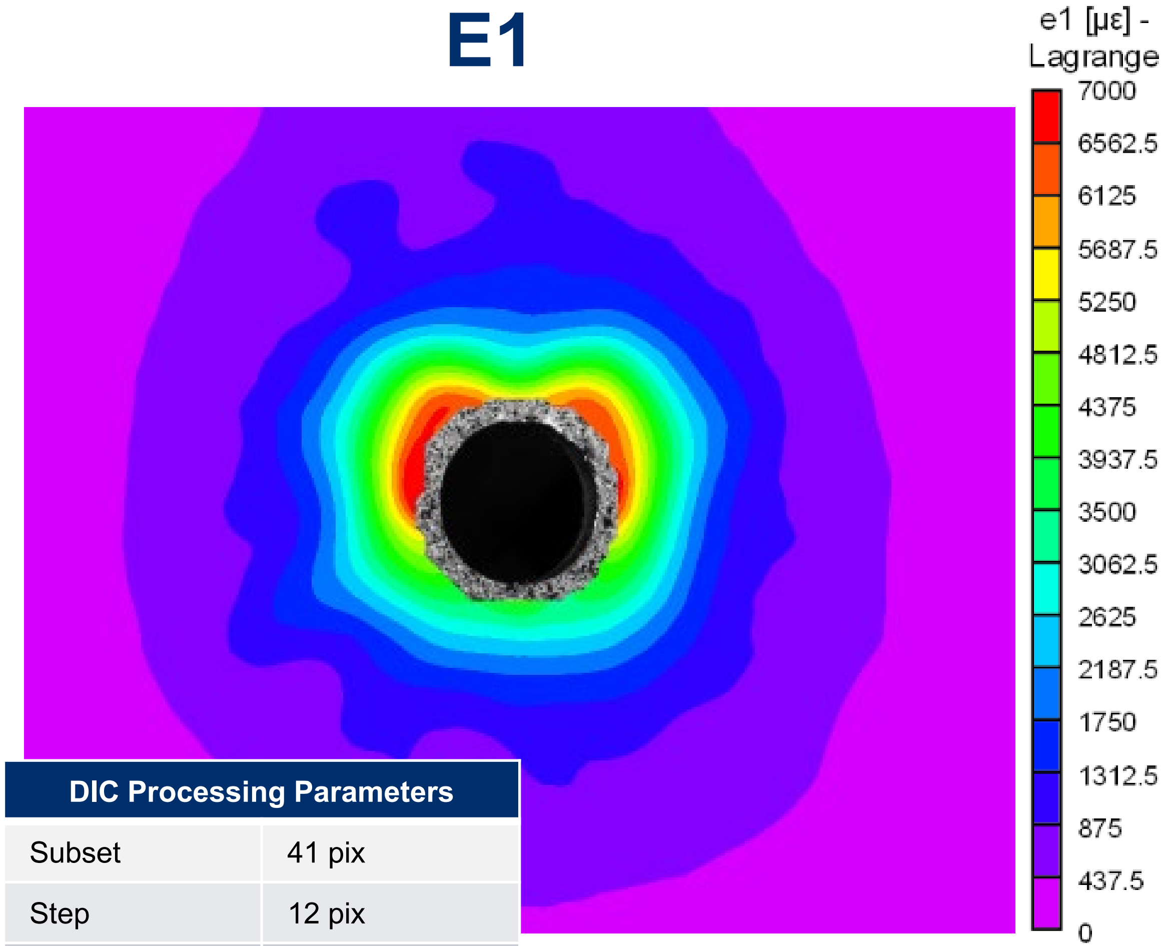
E2

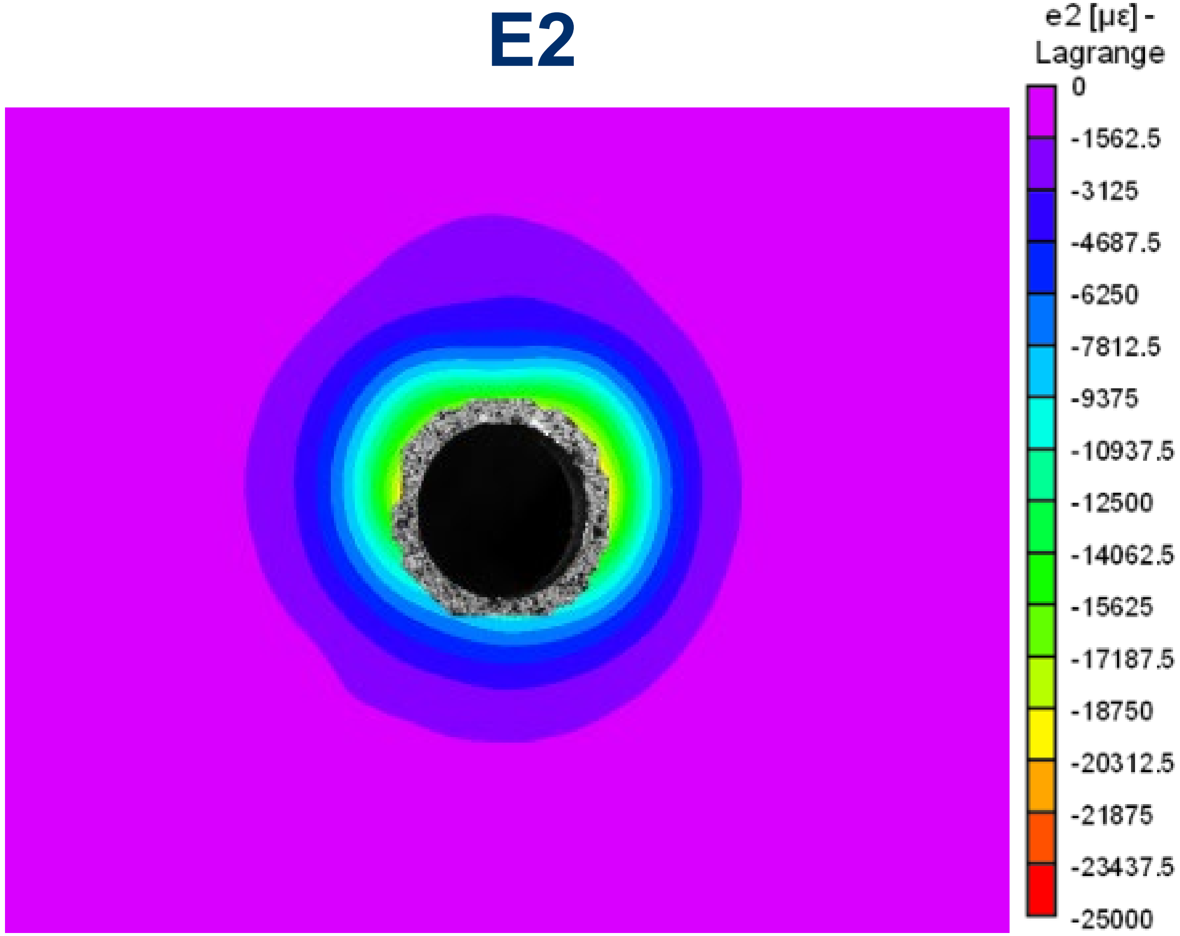


DIC Processing Parameters	
Subset	41 pix
Step	12 pix
Filter	15 pix
VSG	**180 pix (4.86 mm)**

Split at 12 o'clock orientation

BT18 – Exit Post Cx



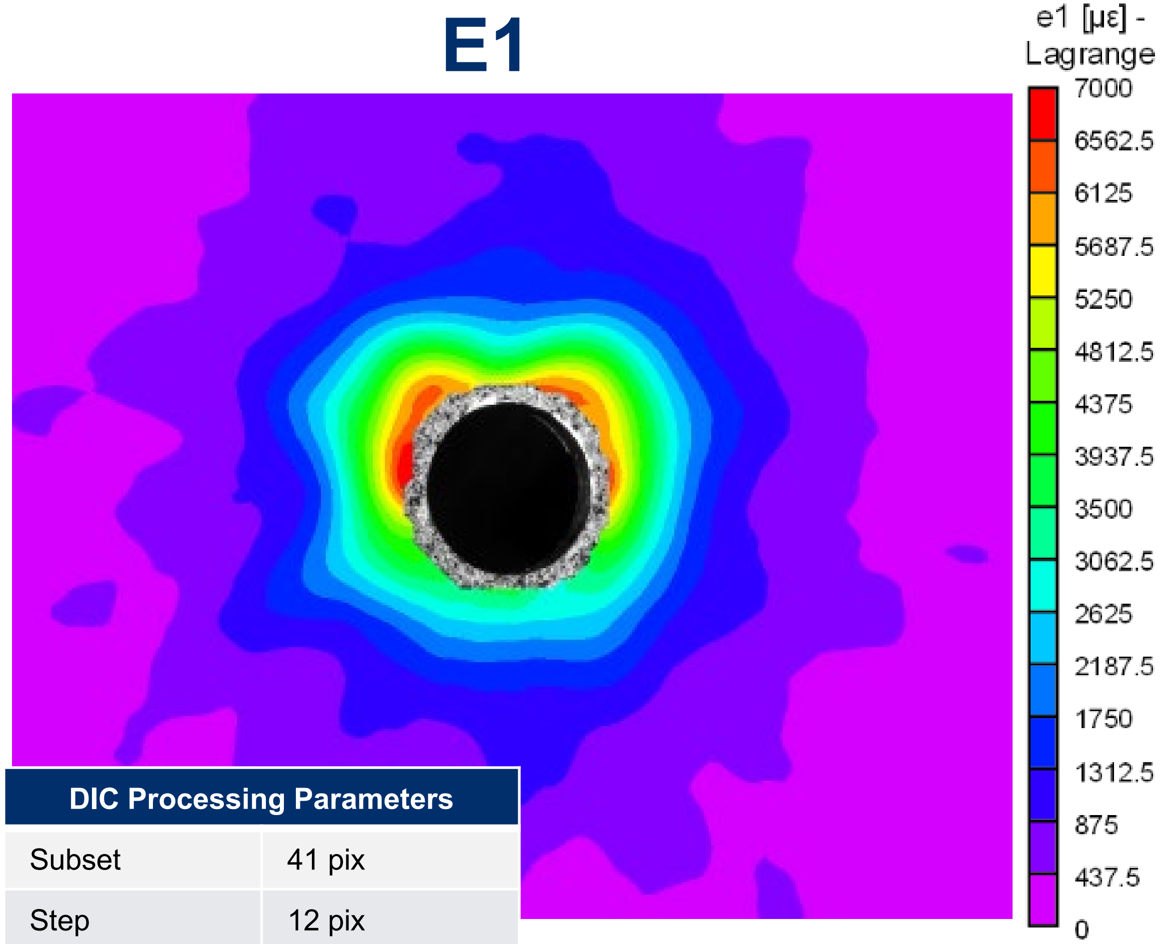


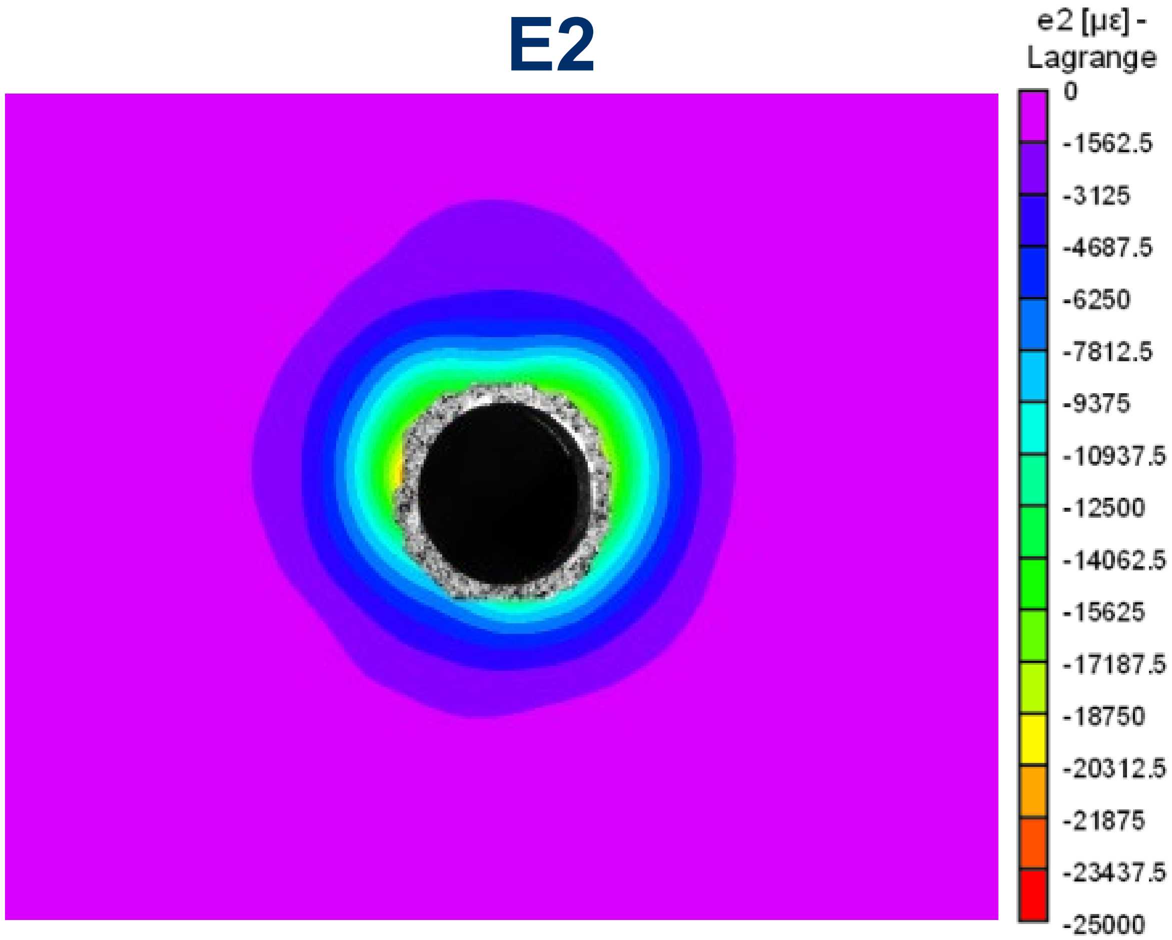
DIC Processing Parameters	
Subset	41 pix
Step	12 pix
Filter	15 pix
VSG	**180 pix (4.86 mm)**

Split at 12 o'clock orientation

LOCKHEED MARTIN

BT18 – Exit Post Ream



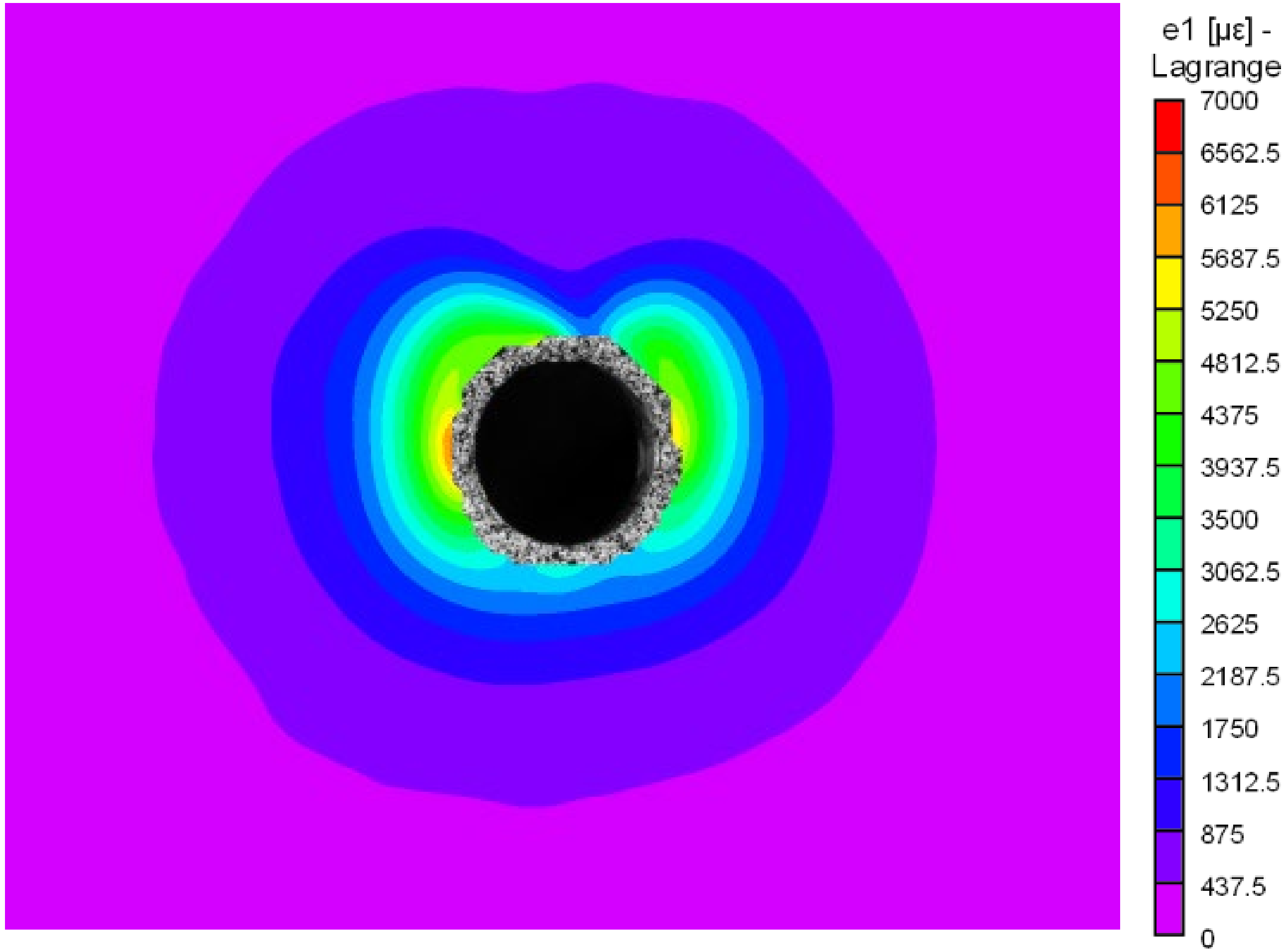


DIC Processing Parameters	
Subset	41 pix
Step	12 pix
Filter	15 pix
VSG	**180 pix (4.86 mm)**

Split at 12 o'clock orientation

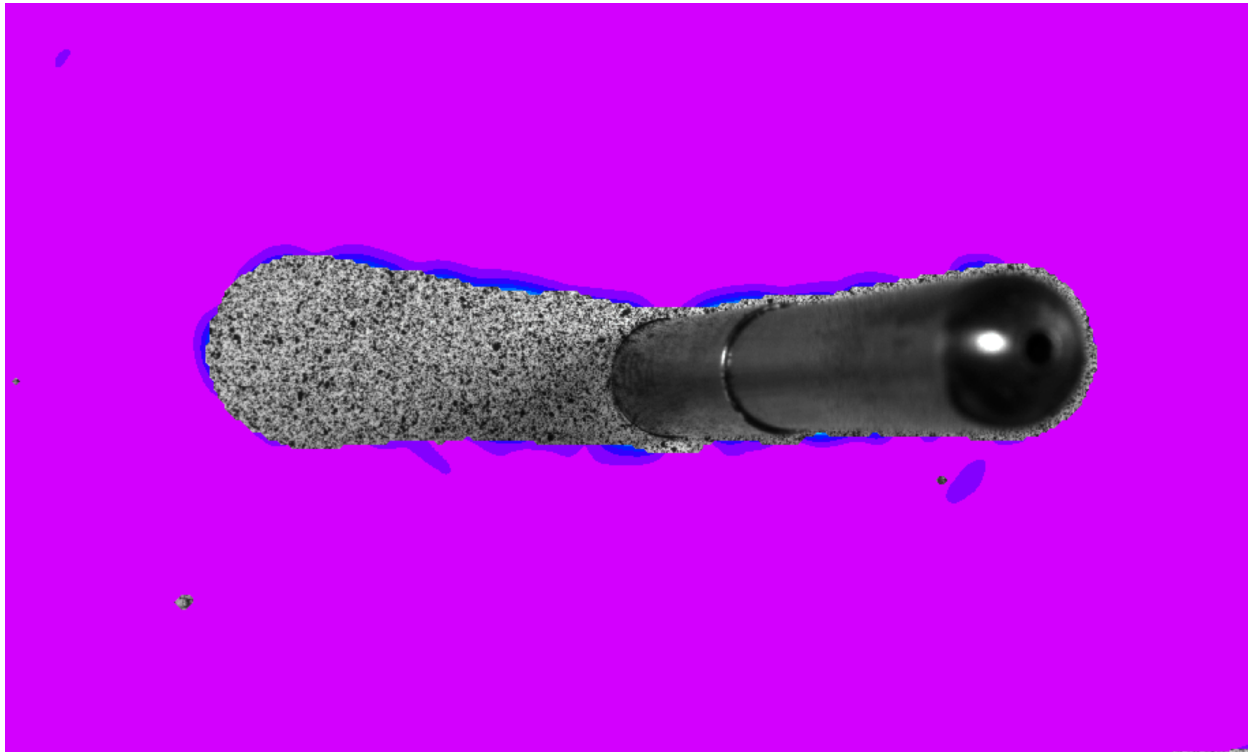
Discussion: DIC Strain Scales: 3D vs 2D

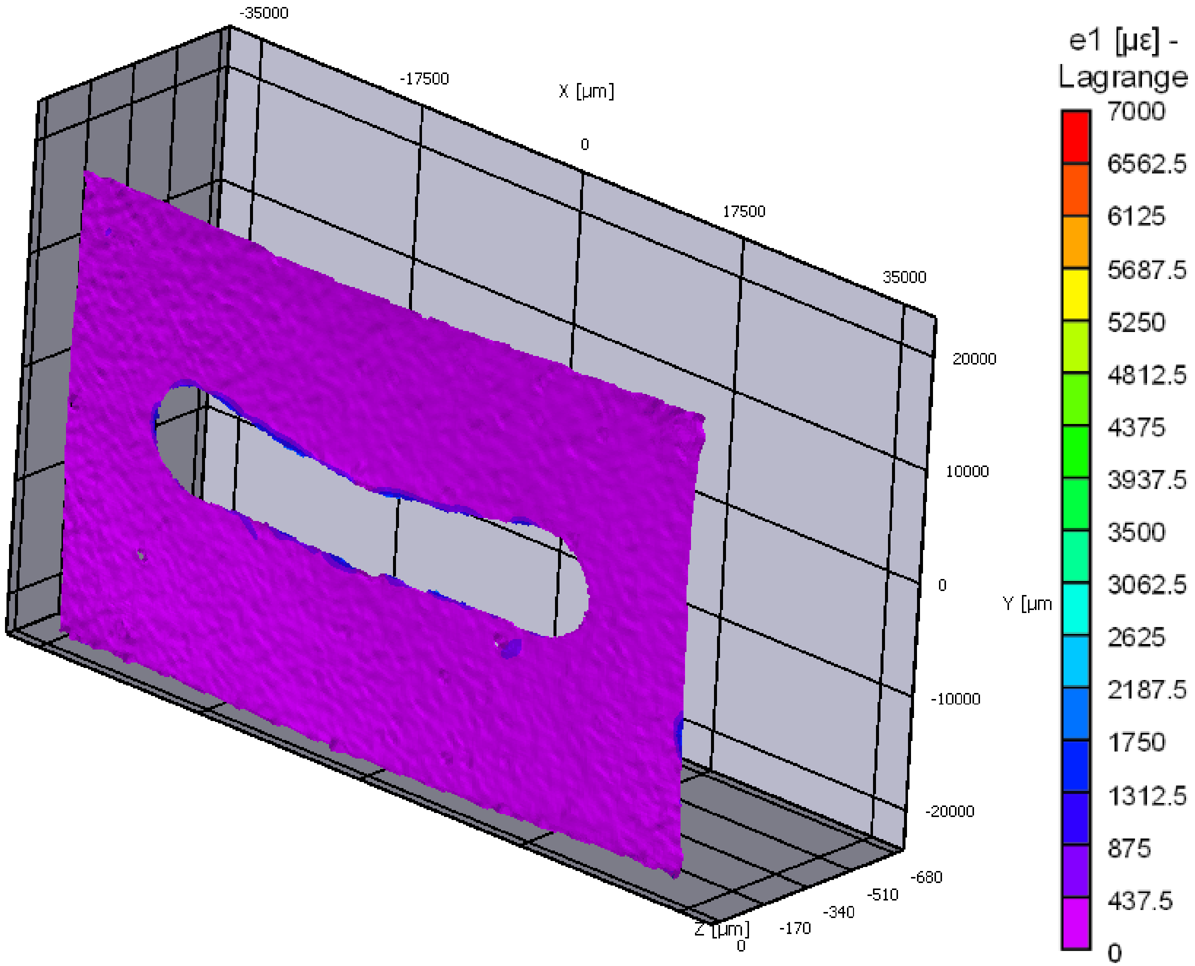
- 2D high mag DIC gets ~3x closer to edge of hole vs 3D
- 2D high mag captures higher strain magnitude/gradient
- To highlight peak strains in 3D dataset, scale reduced to 0 < E1 < 7000 microstrain



LOCKHEED MARTIN

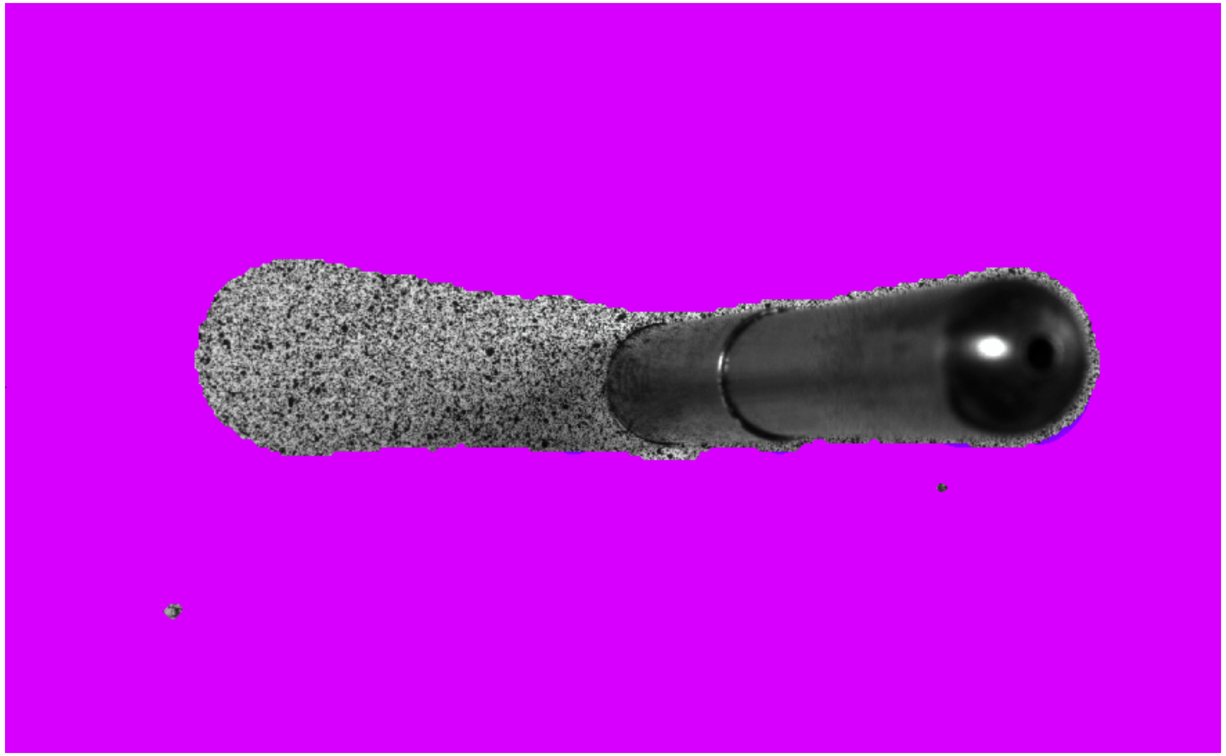
BT18 – In-Situ: Max Principal Strain (2D/3D views)

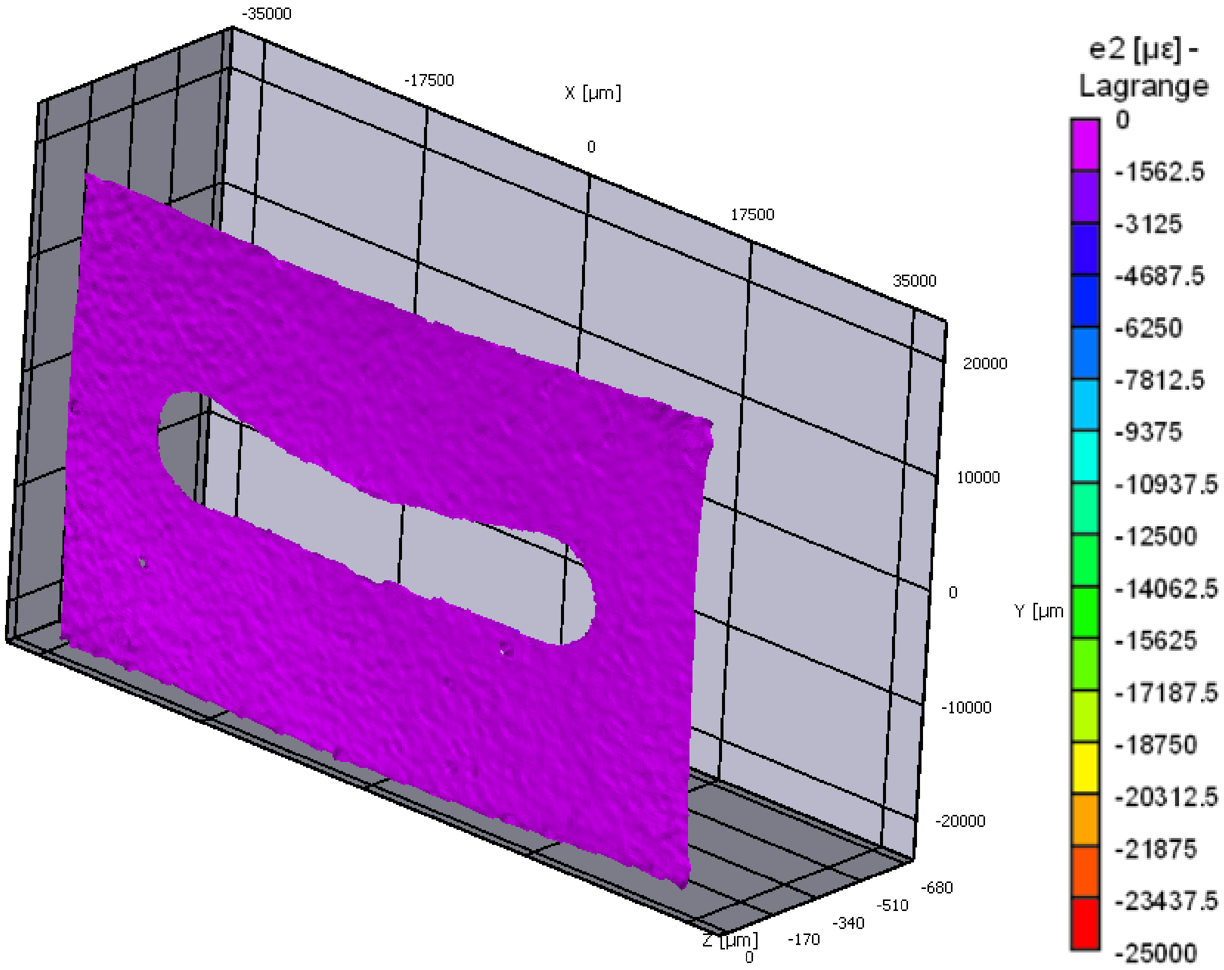




LOCKHEED MARTIN

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

BT13 2D DIC Super-resolution (135°)

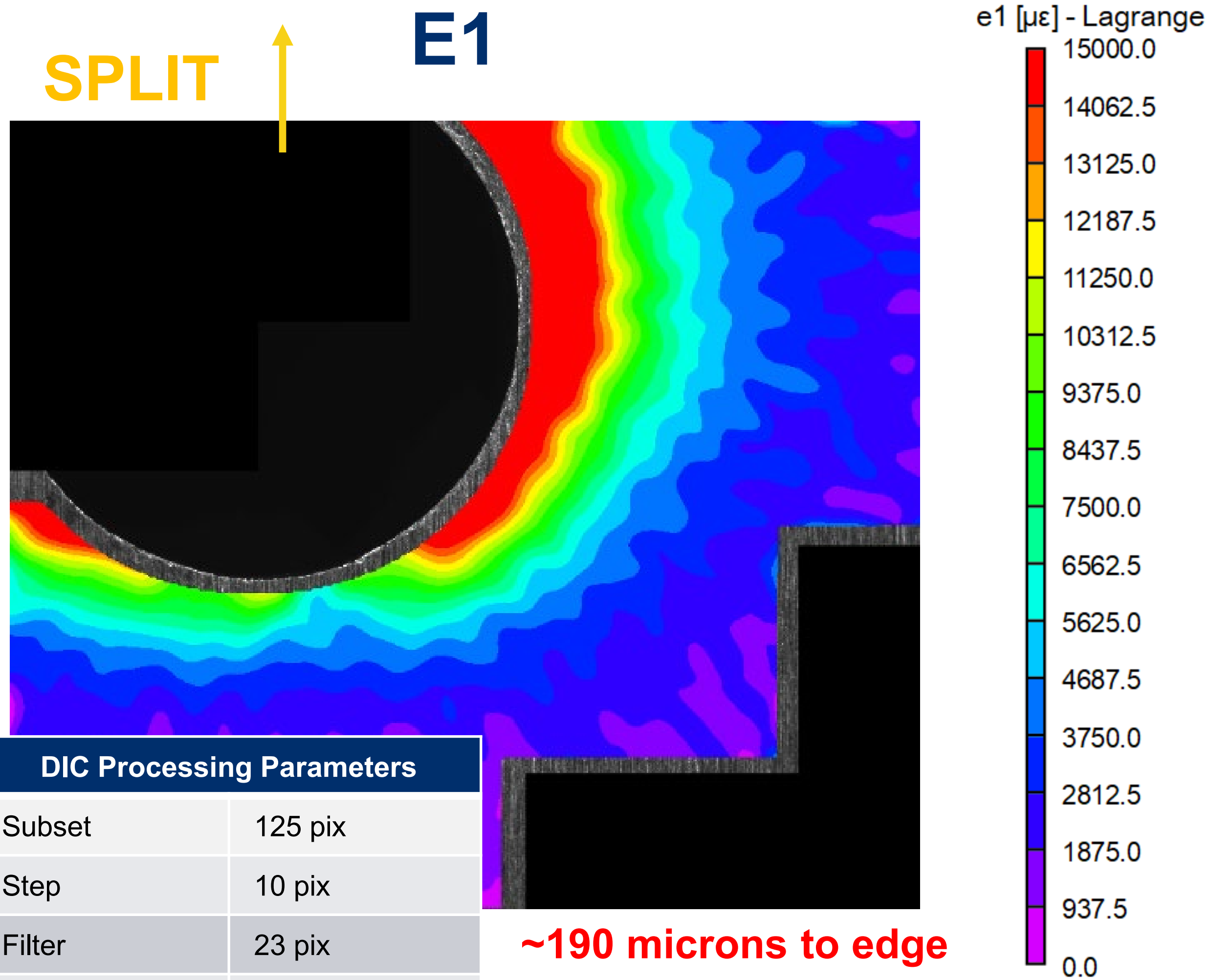
2024-T3

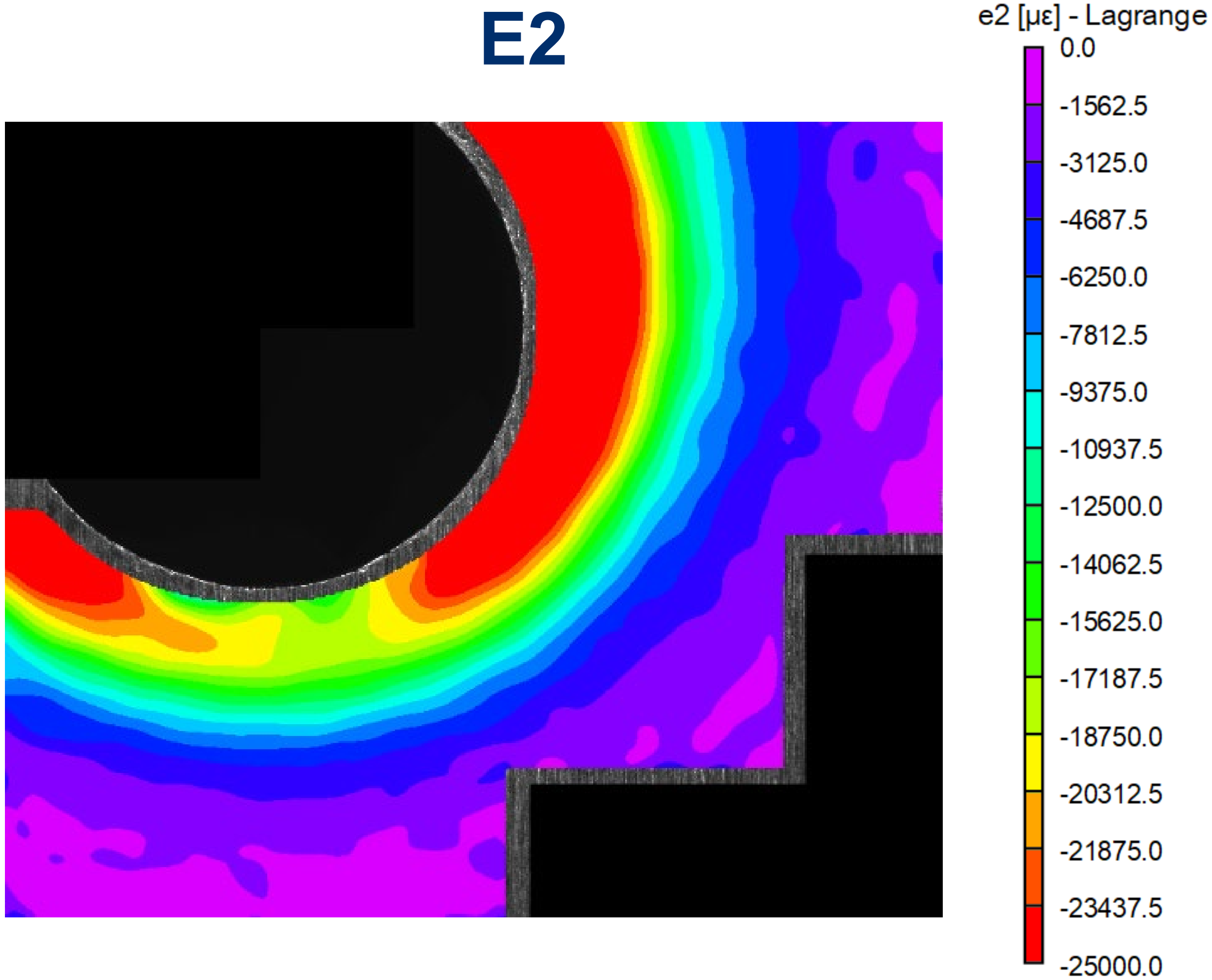
Thickness = 0.063inch

Starting Hole Diameter = 0.2361inch

FTI Toolset:

BT13 – Entry Post Cx

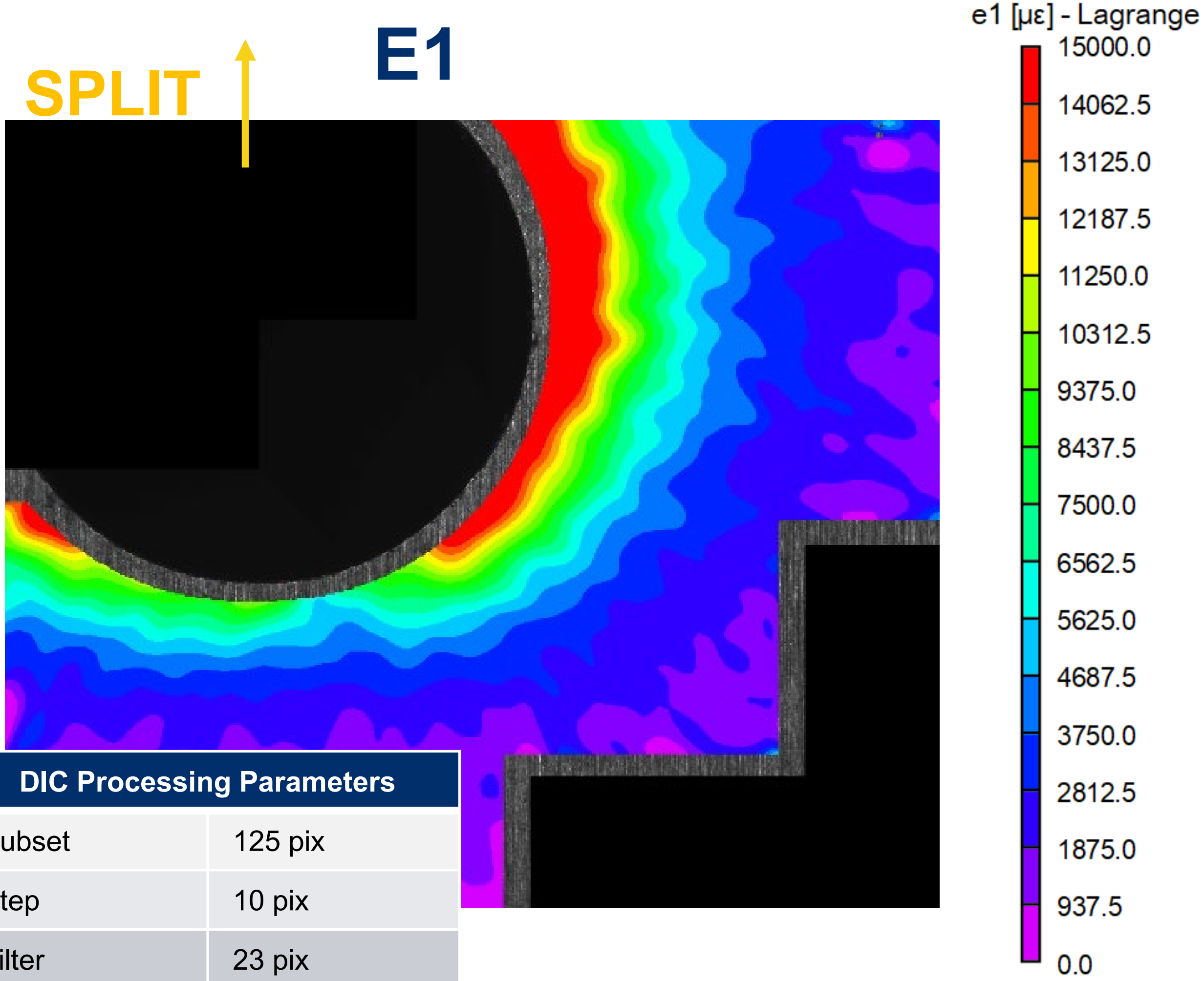


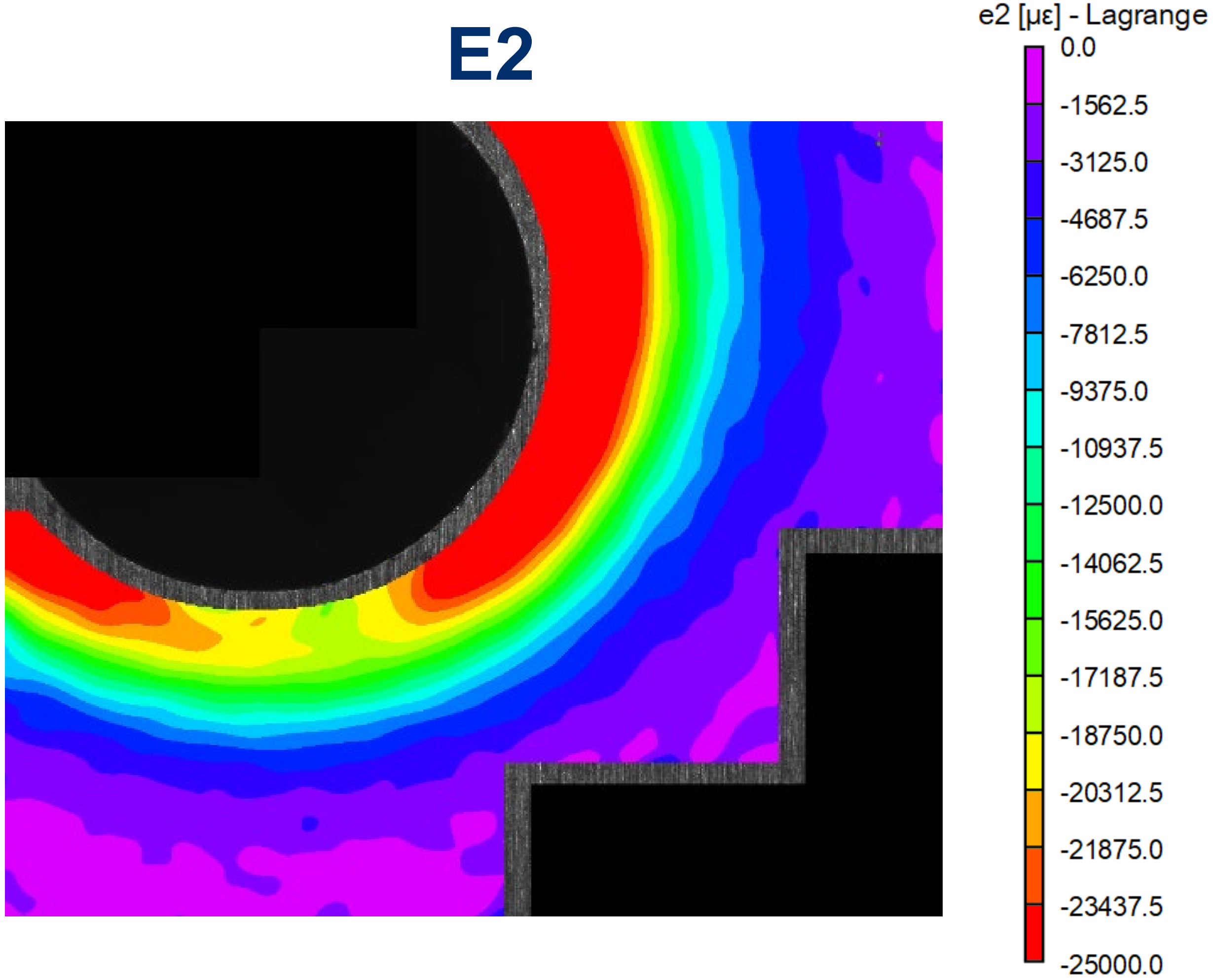


DIC Processing Parameters	
Subset	125 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (0.60 mm)**

Split at 12 o'clock orientation

BT13 – Entry Post Ream



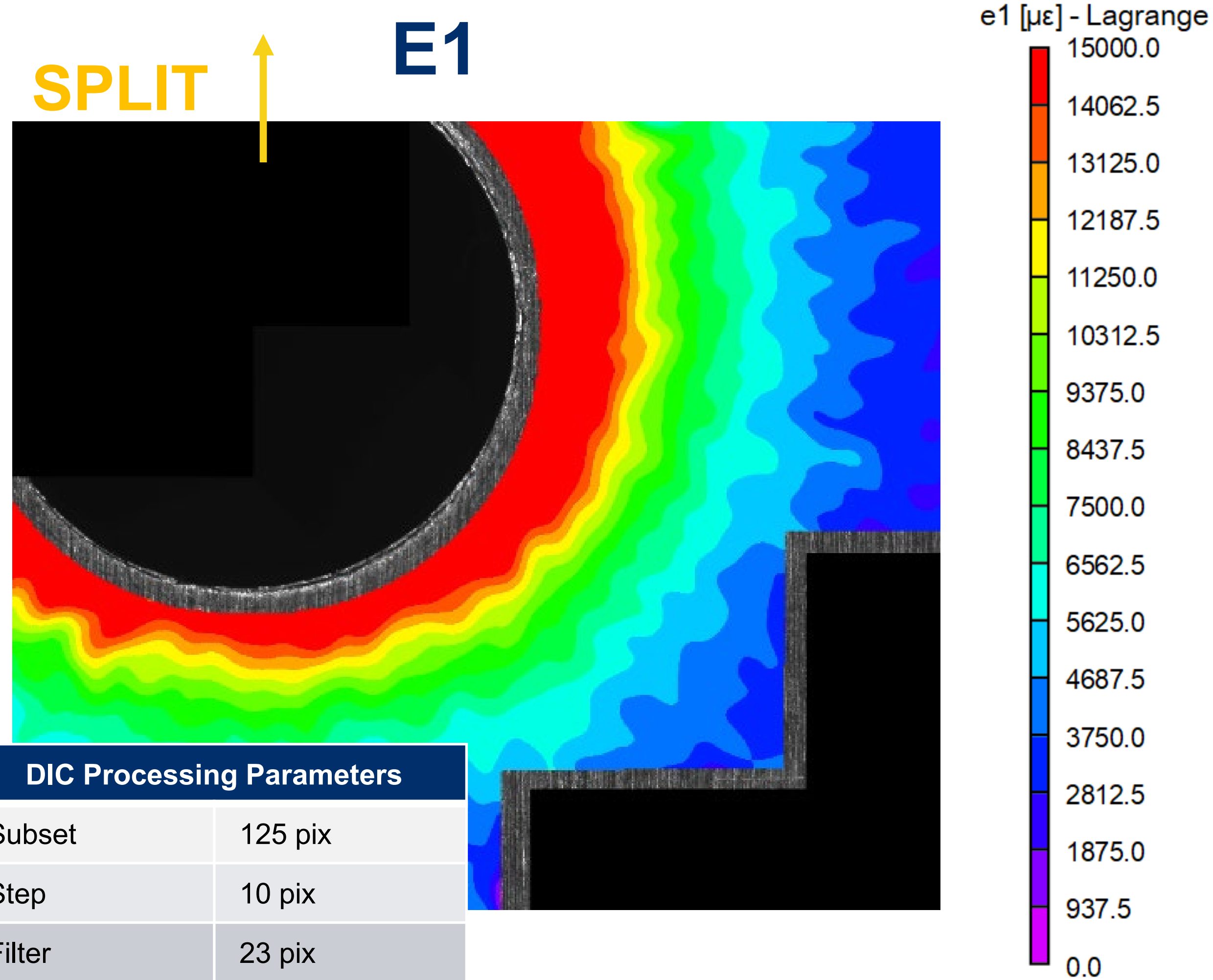


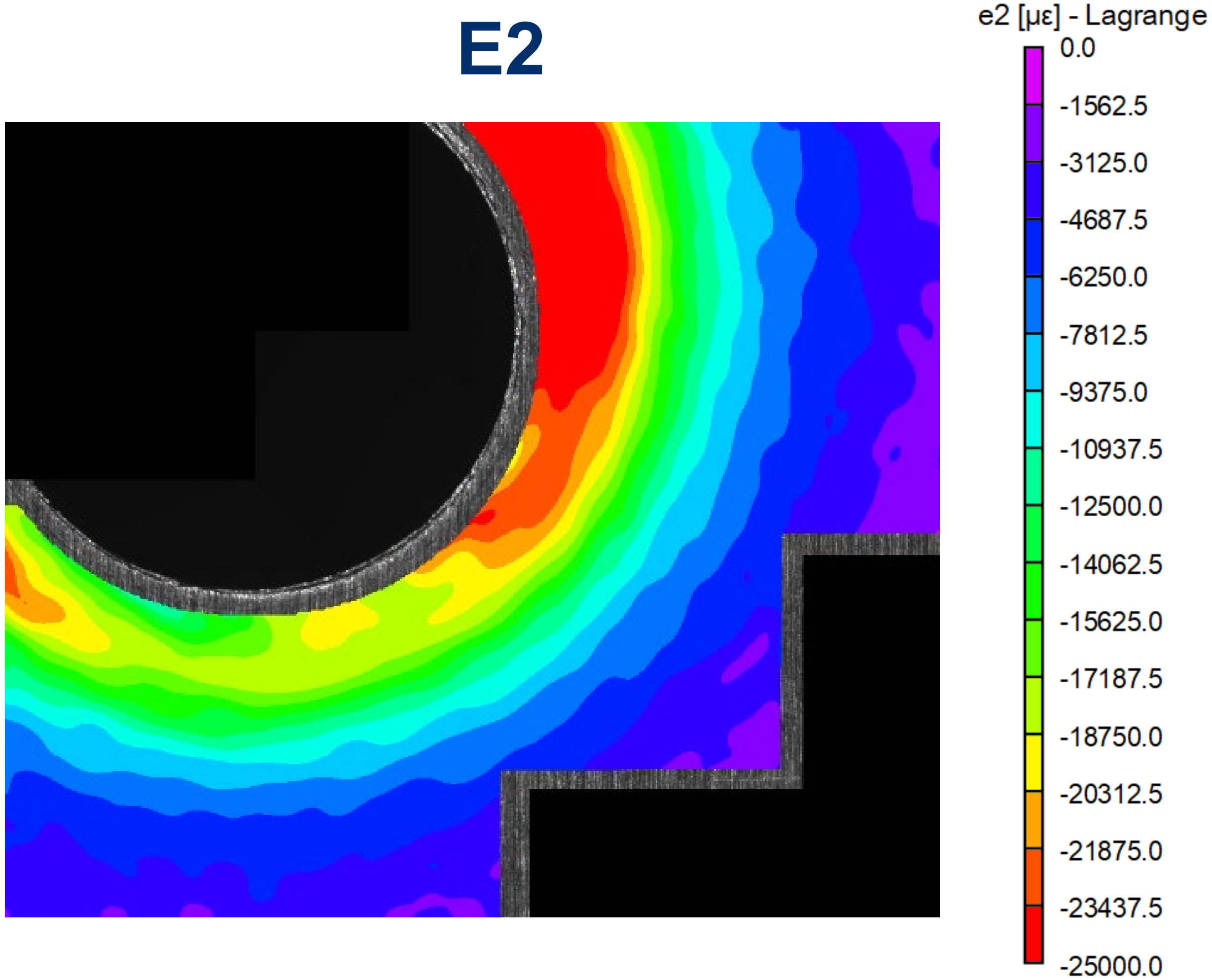
DIC Processing Parameters	
Subset	125 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (0.60 mm)**

Split at 12 o'clock orientation

LOCKHEED MARTIN

BT13 – Exit Post Cx



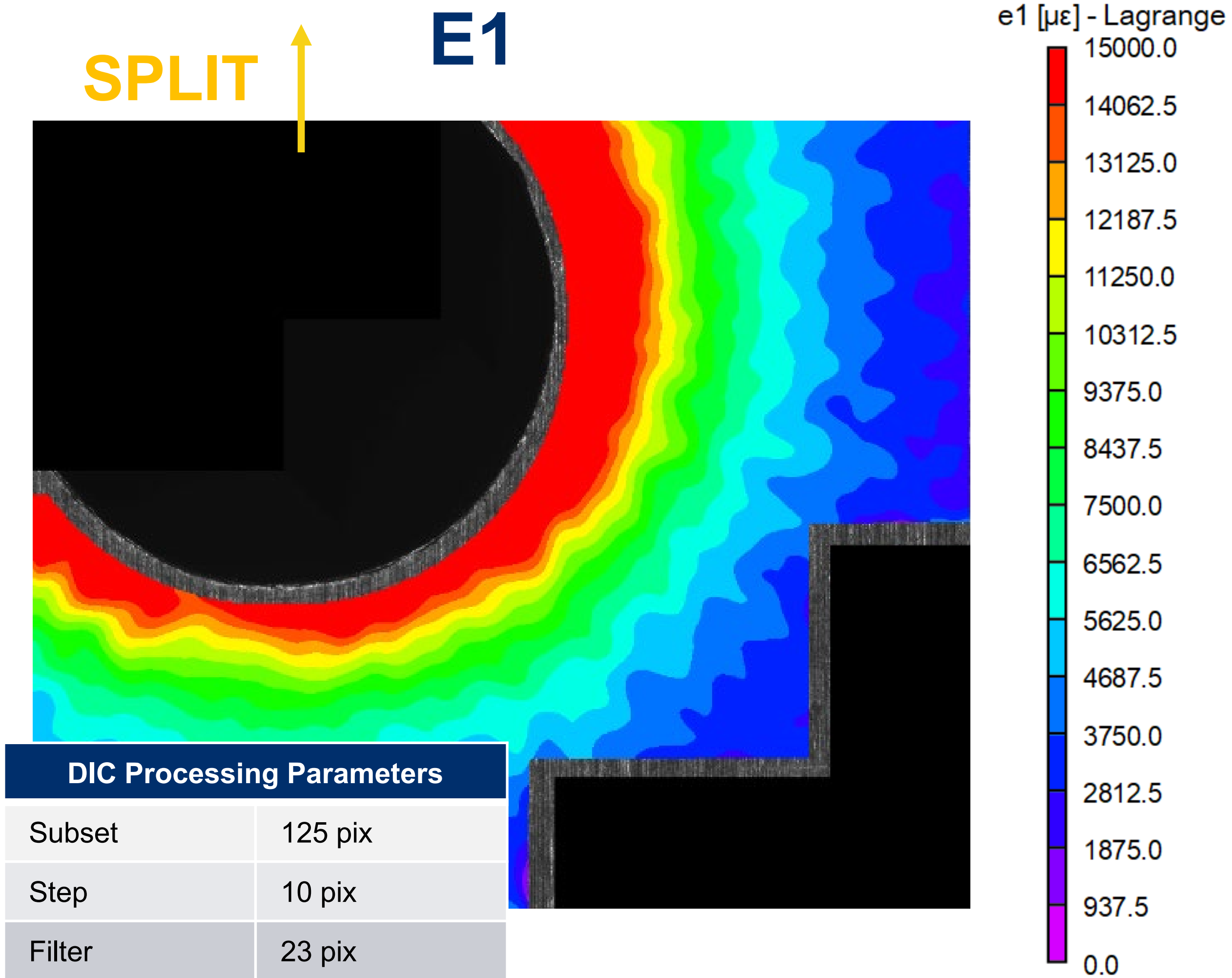


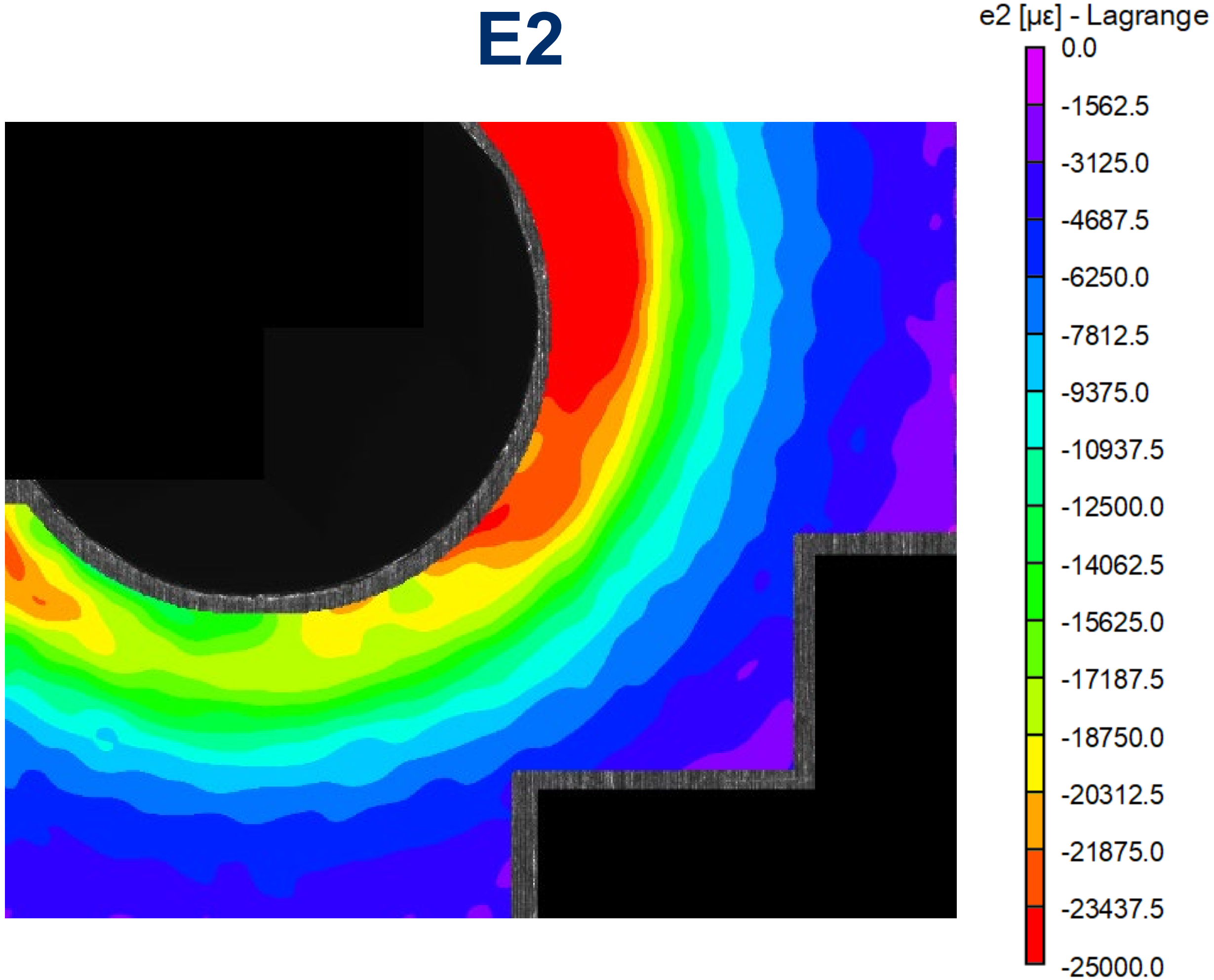
DIC Processing Parameters	
Subset	125 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (0.60 mm)**

Split at 12 o'clock orientation

LOCKHEED MARTIN

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°)

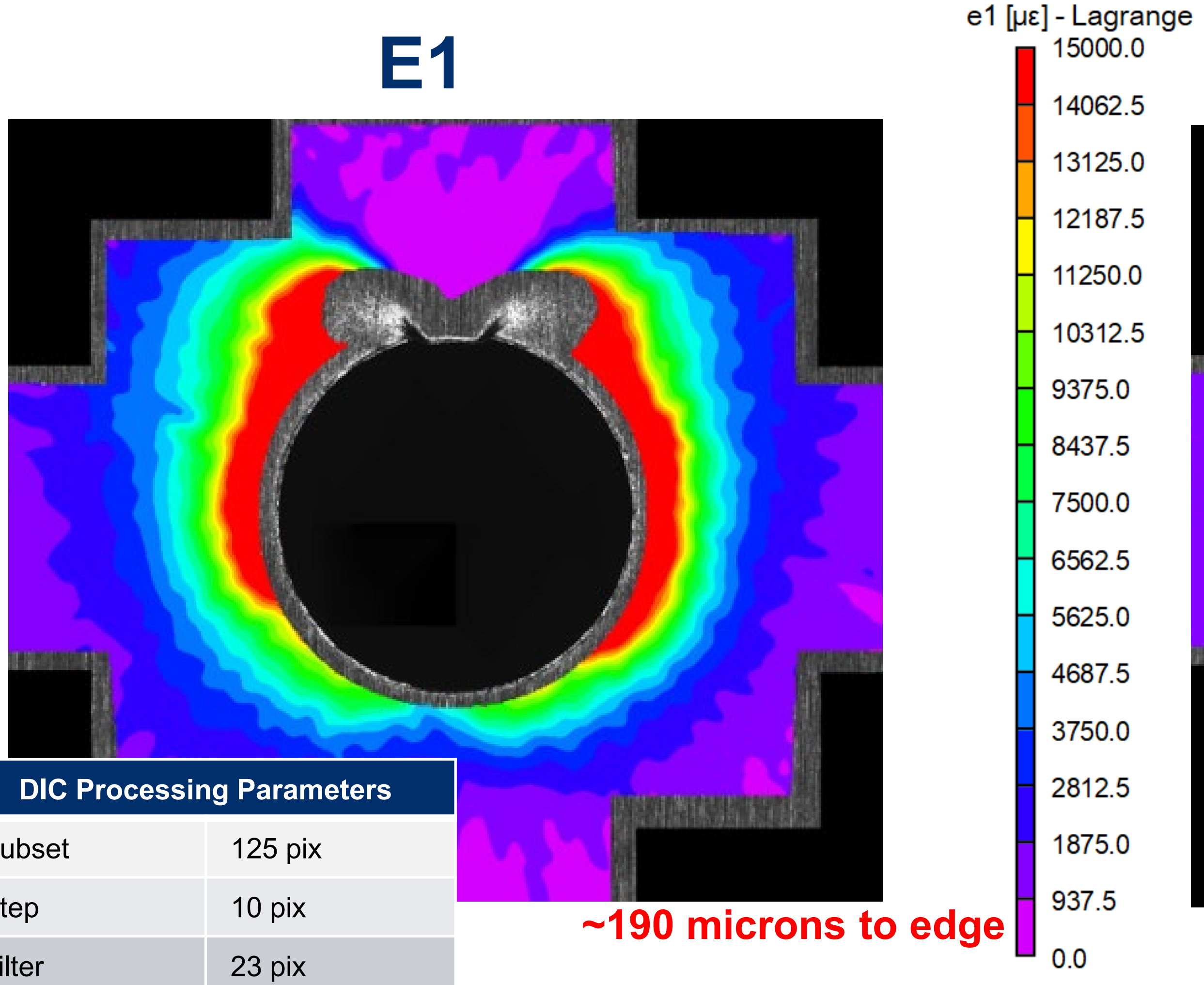
2024-T3

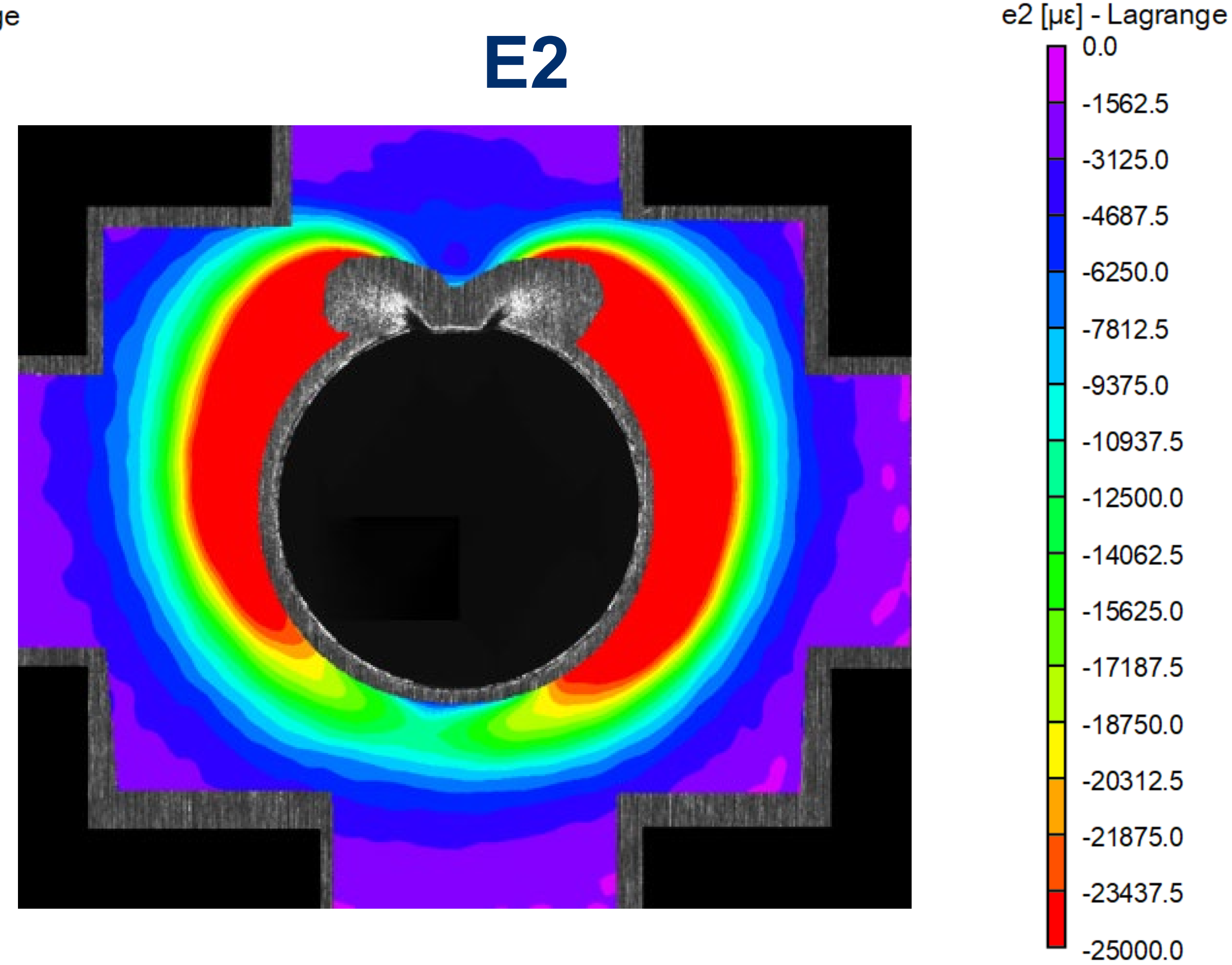
Thickness = 0.063inch

Starting Hole Diameter = 0.2359inch

FTI Toolset:

BT20 – Entry Post Cx

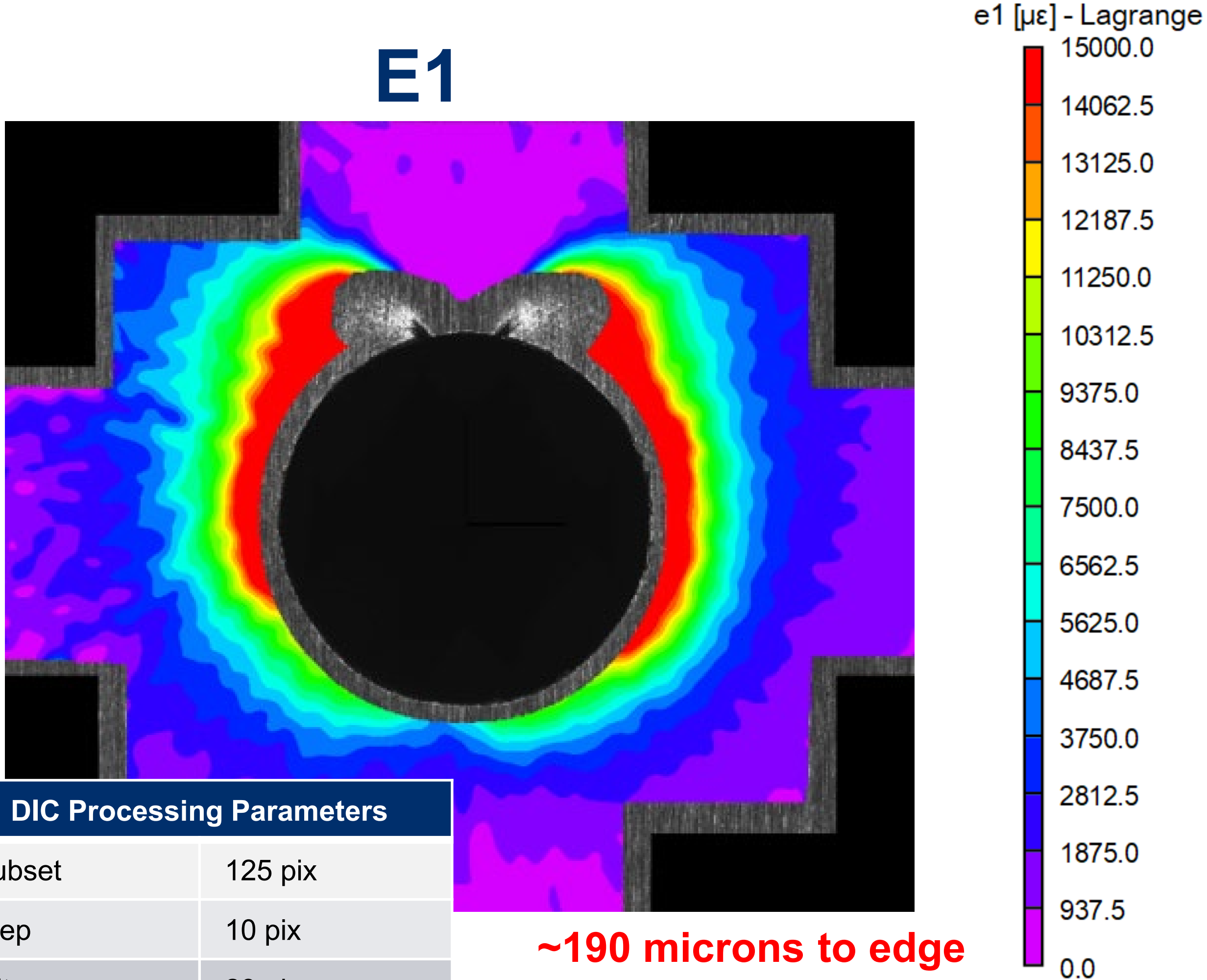


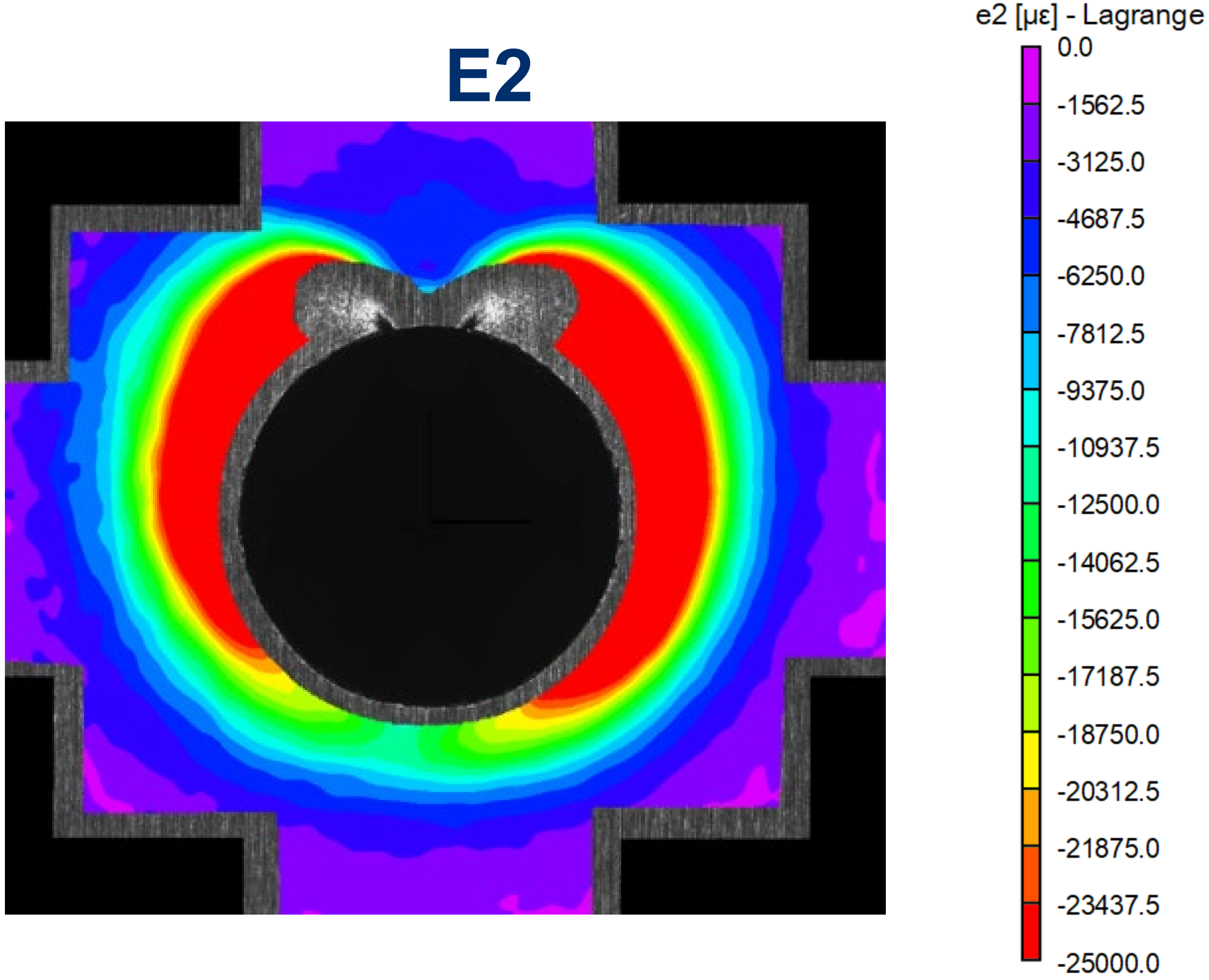


DIC Processing Parameters	
Subset	125 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (0.60 mm)**

Split at 12 o'clock orientation

BT20 – Entry Post Ream



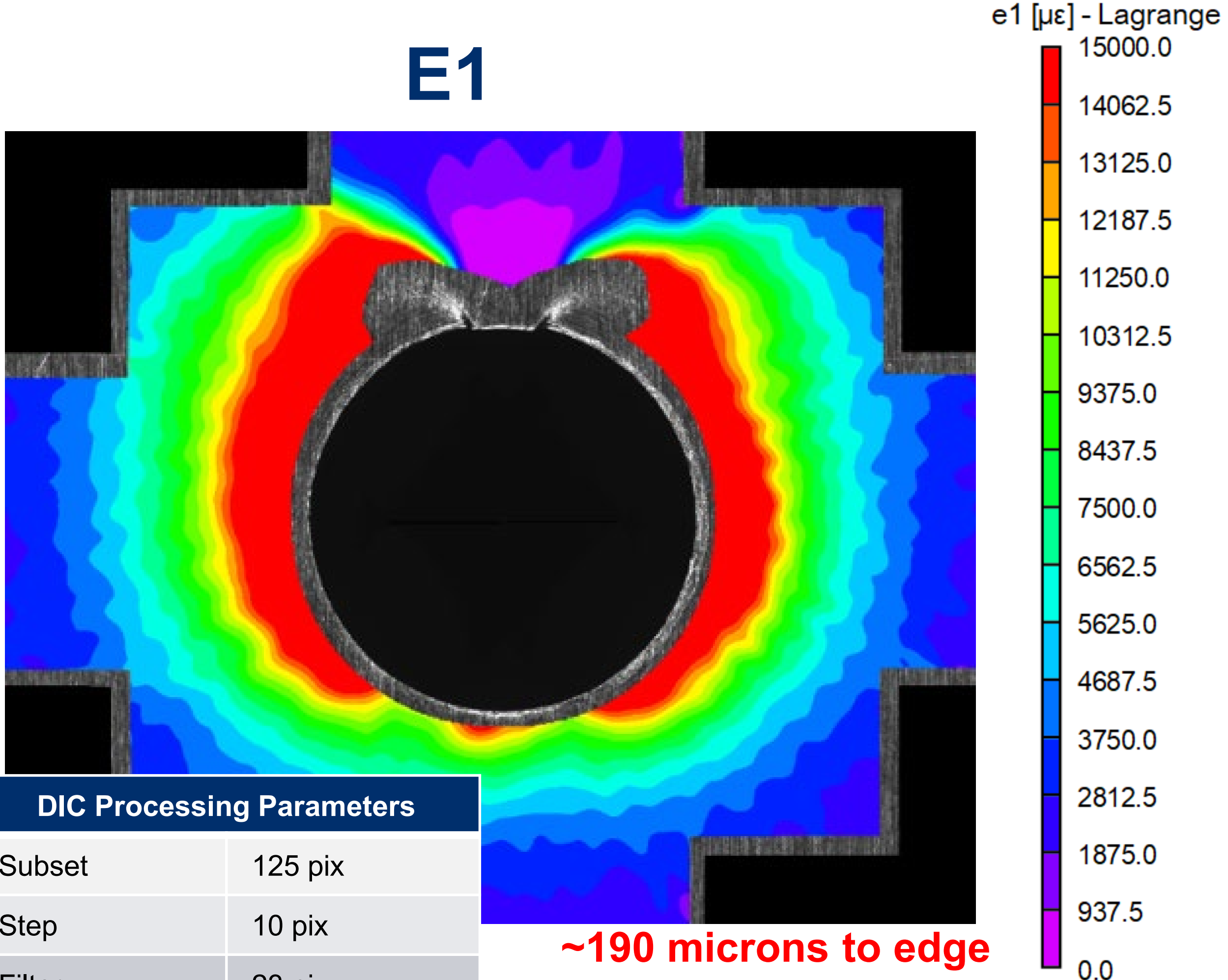


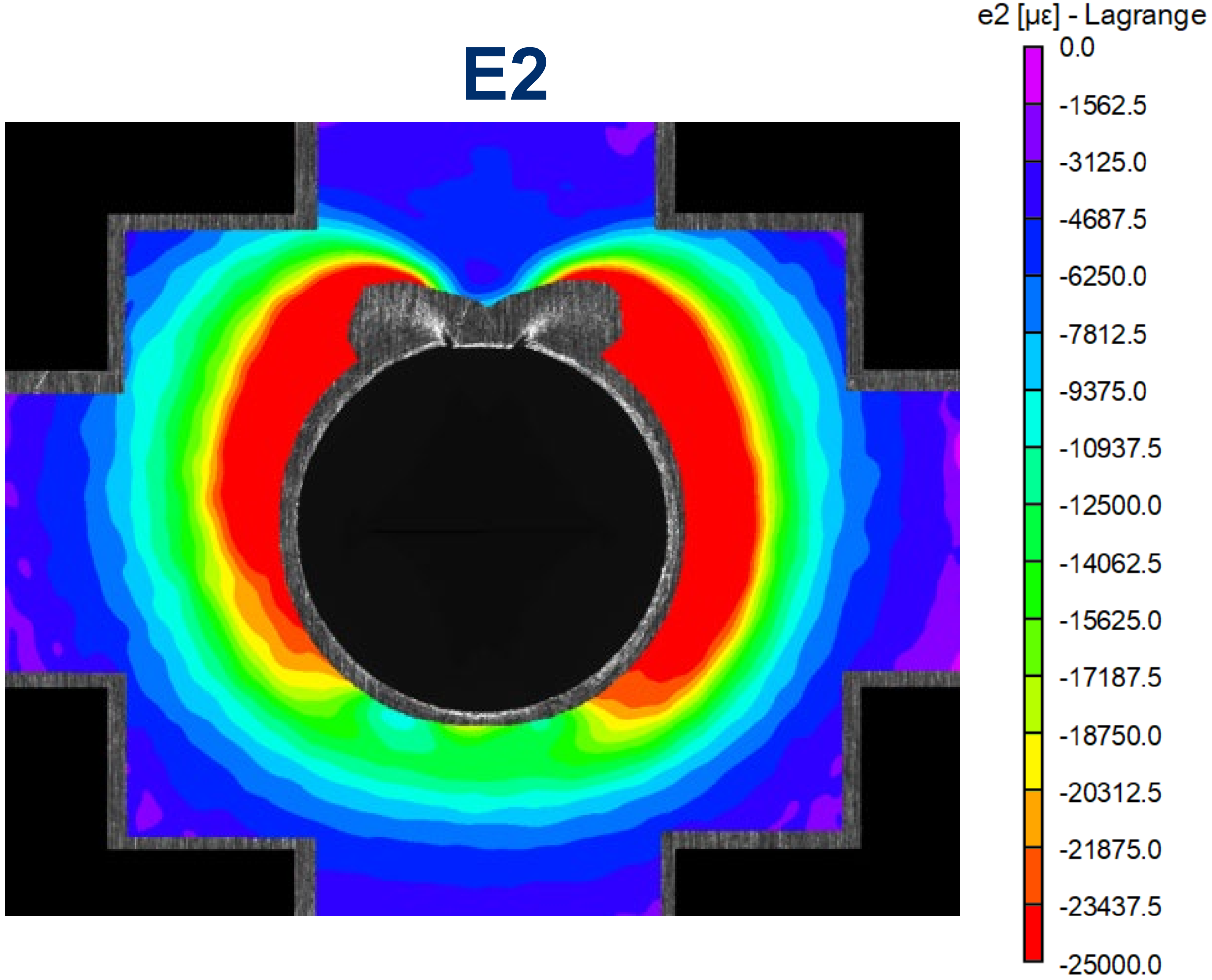
DIC Processing Parameters	
Subset	125 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (0.60 mm)**

Split at 12 o'clock orientation

LOCKHEED MARTIN

BT20 – Exit Post Cx



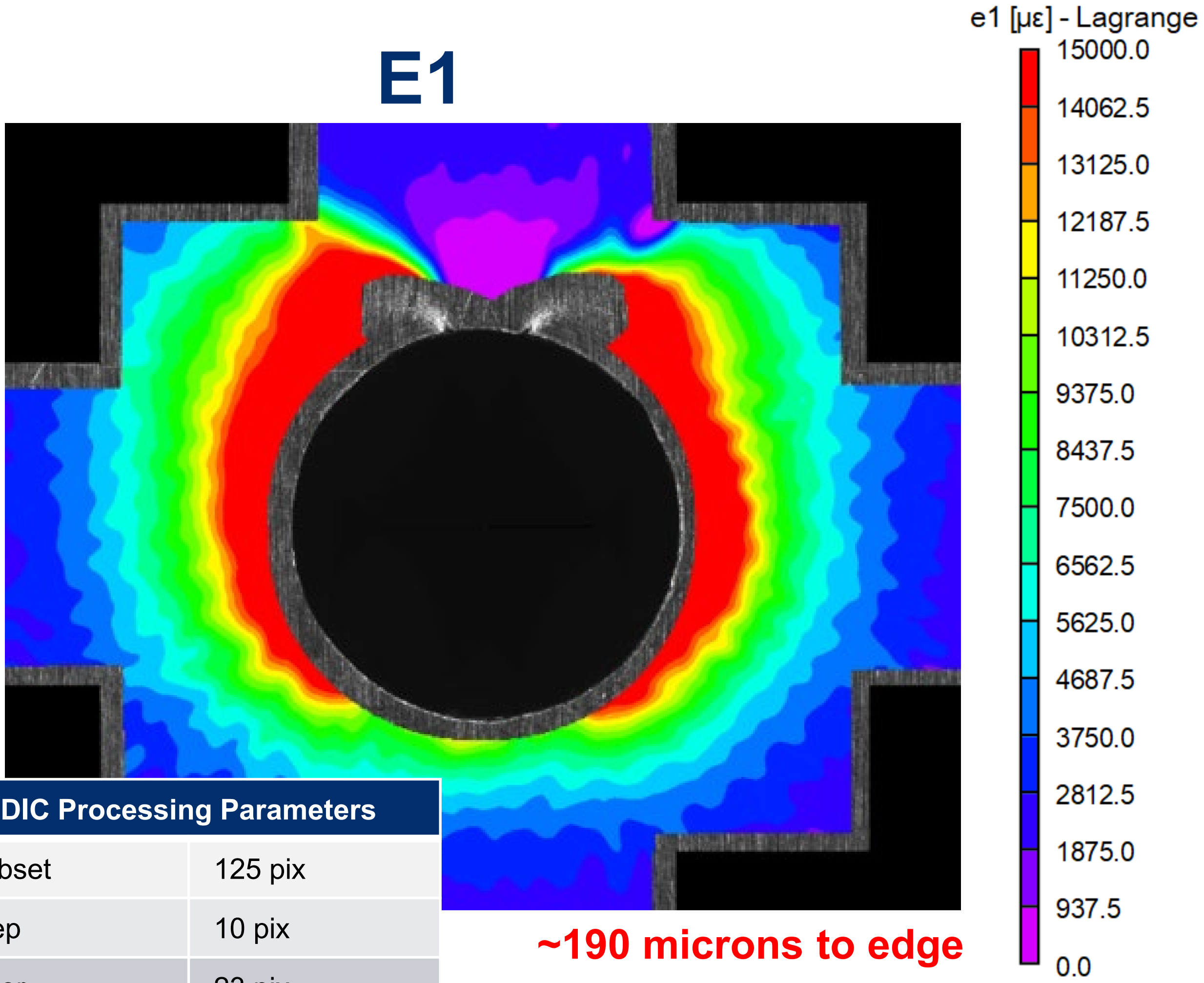


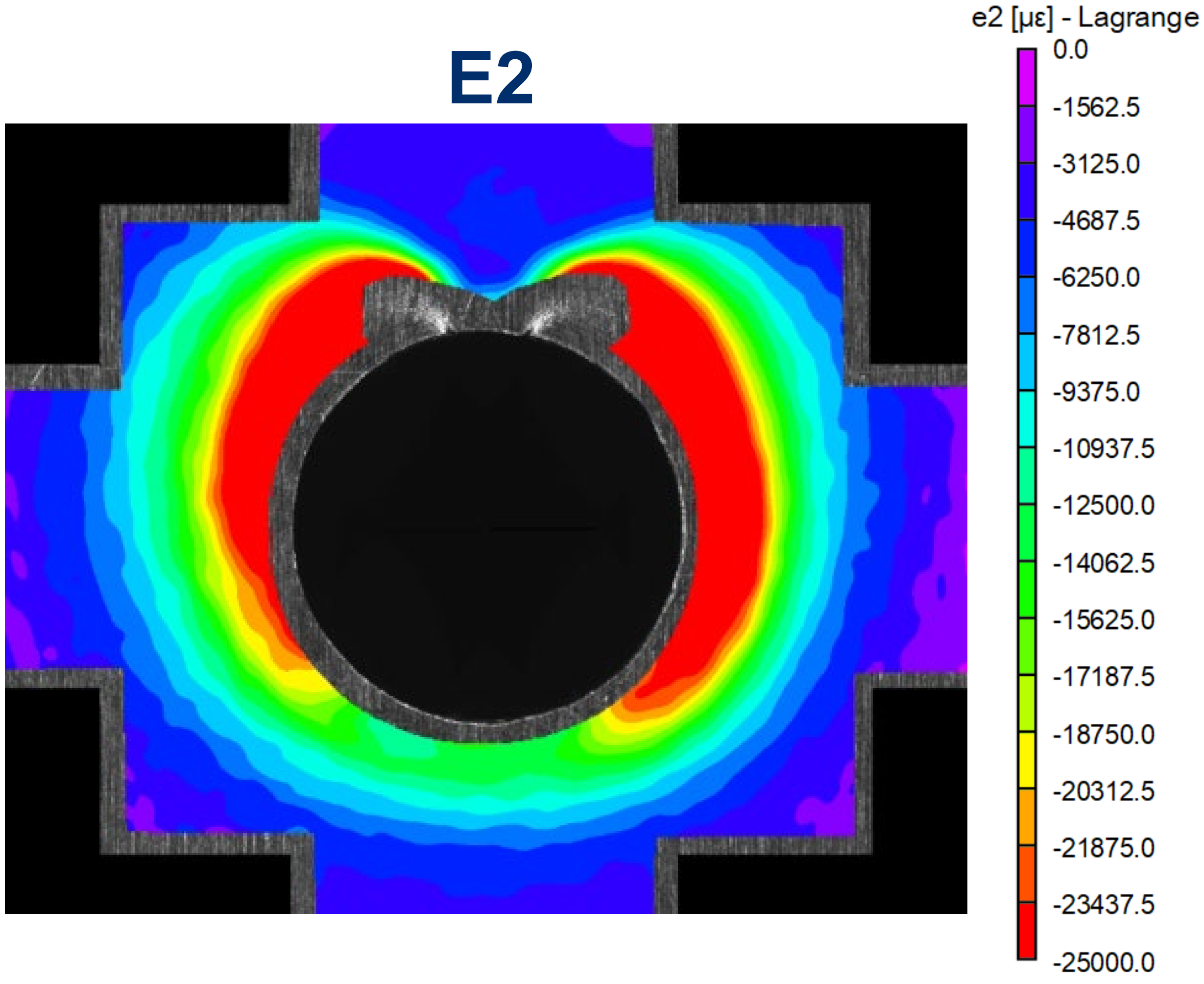
DIC Processing Parameters	
Subset	125 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (0.60 mm)**

Split at 12 o'clock orientation

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

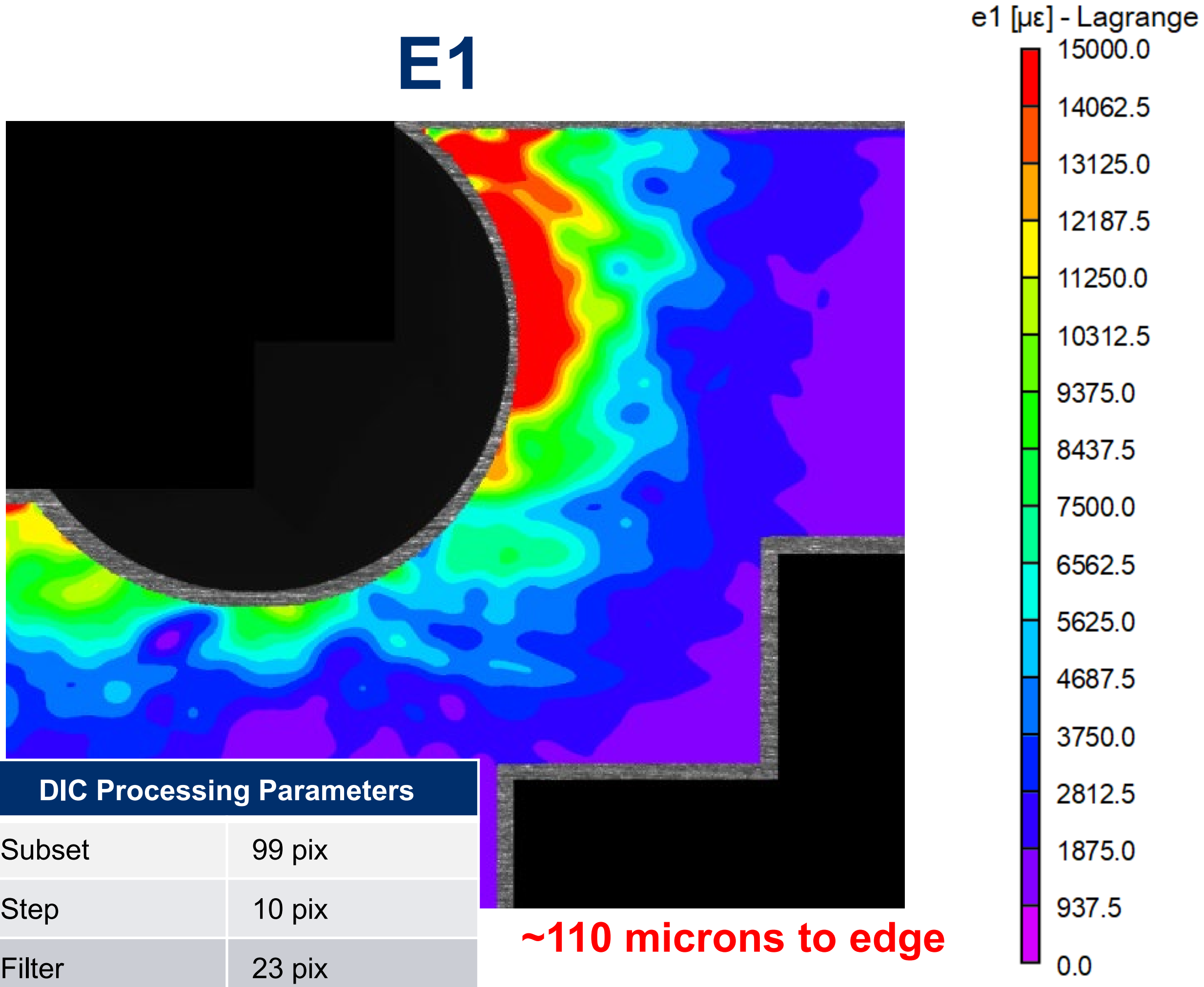
Starting Hole Diameter = 0.2379inch

FTI Toolset:

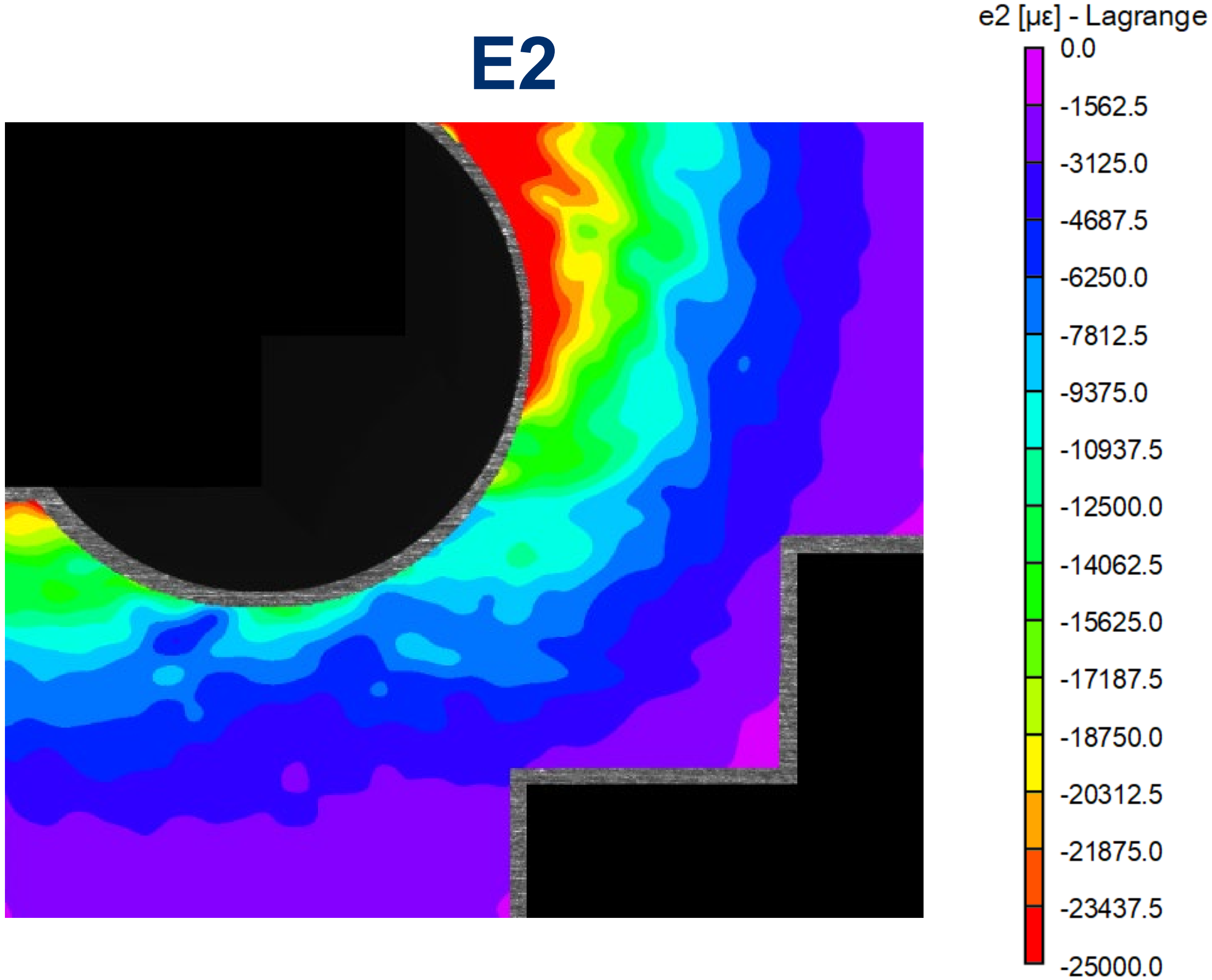
LOCKHEED MARTIN

7050-L-REM-02 – Entry Post Cx

E1



E2

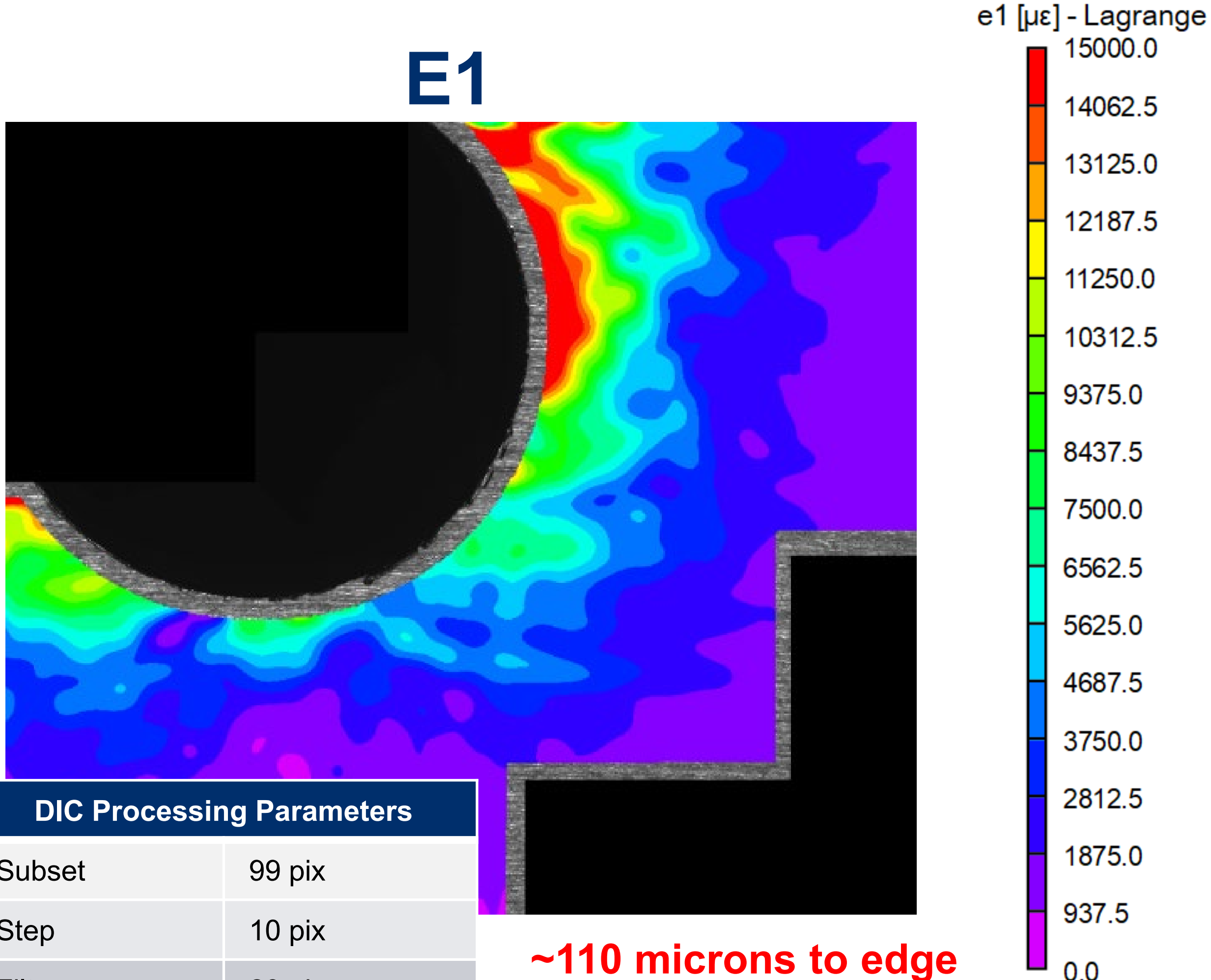


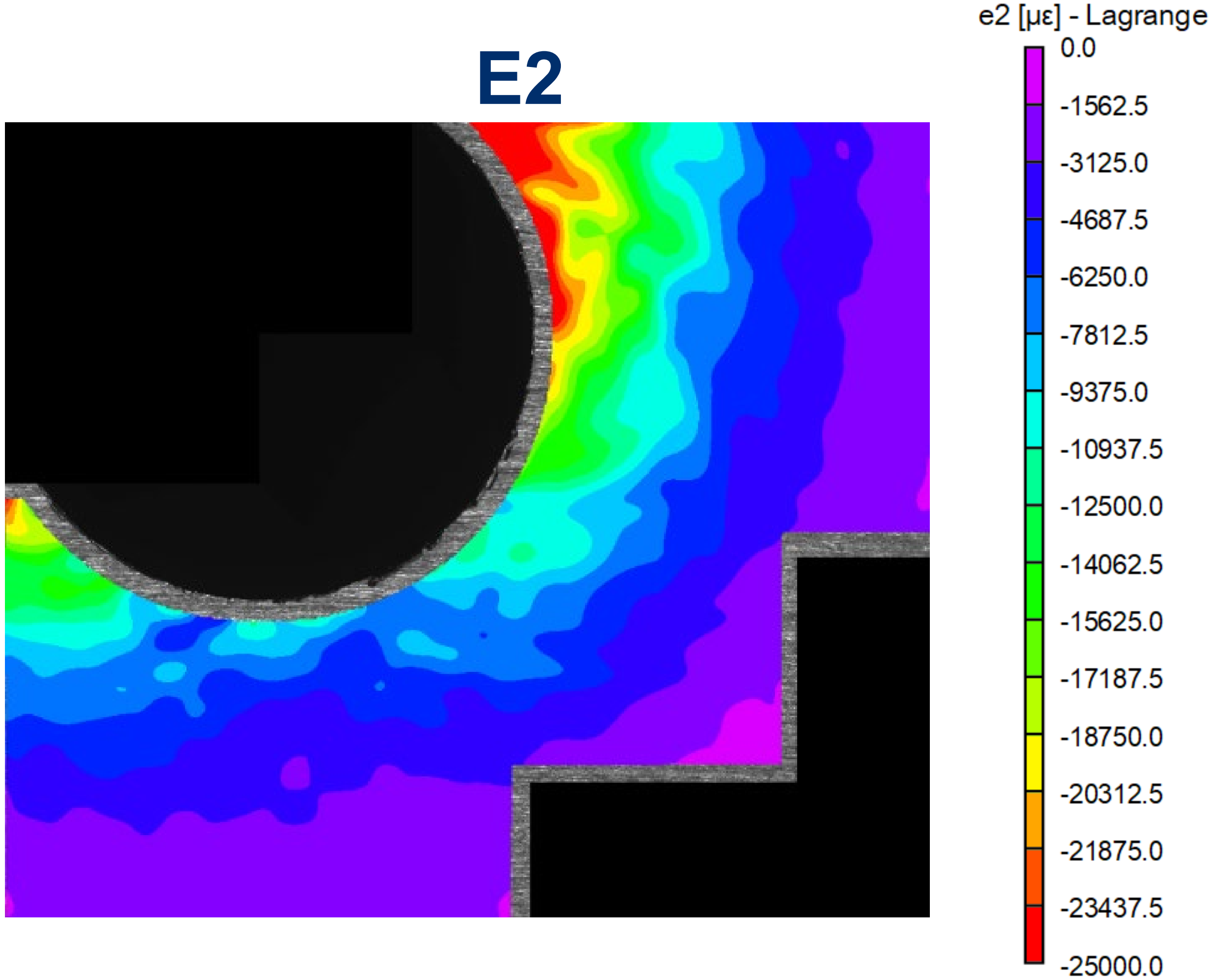
DIC Processing Parameters	
Subset	99 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (0.60 mm)**

Split at 12 o'clock orientation

LOCKHEED MARTIN

7050-L-REM-02 – Entry Post Ream





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

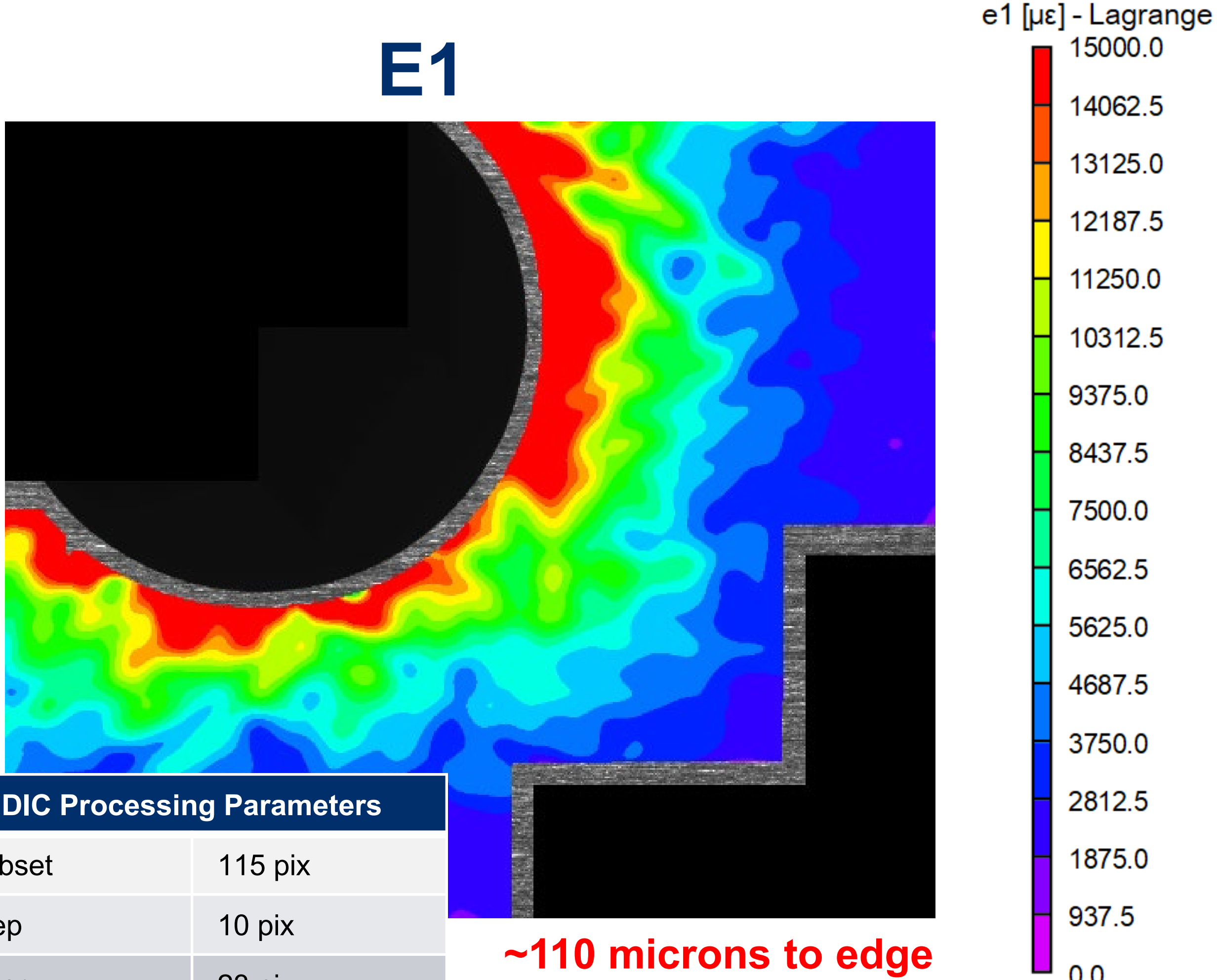
~110 microns to edge

Split at 12 o'clock orientation

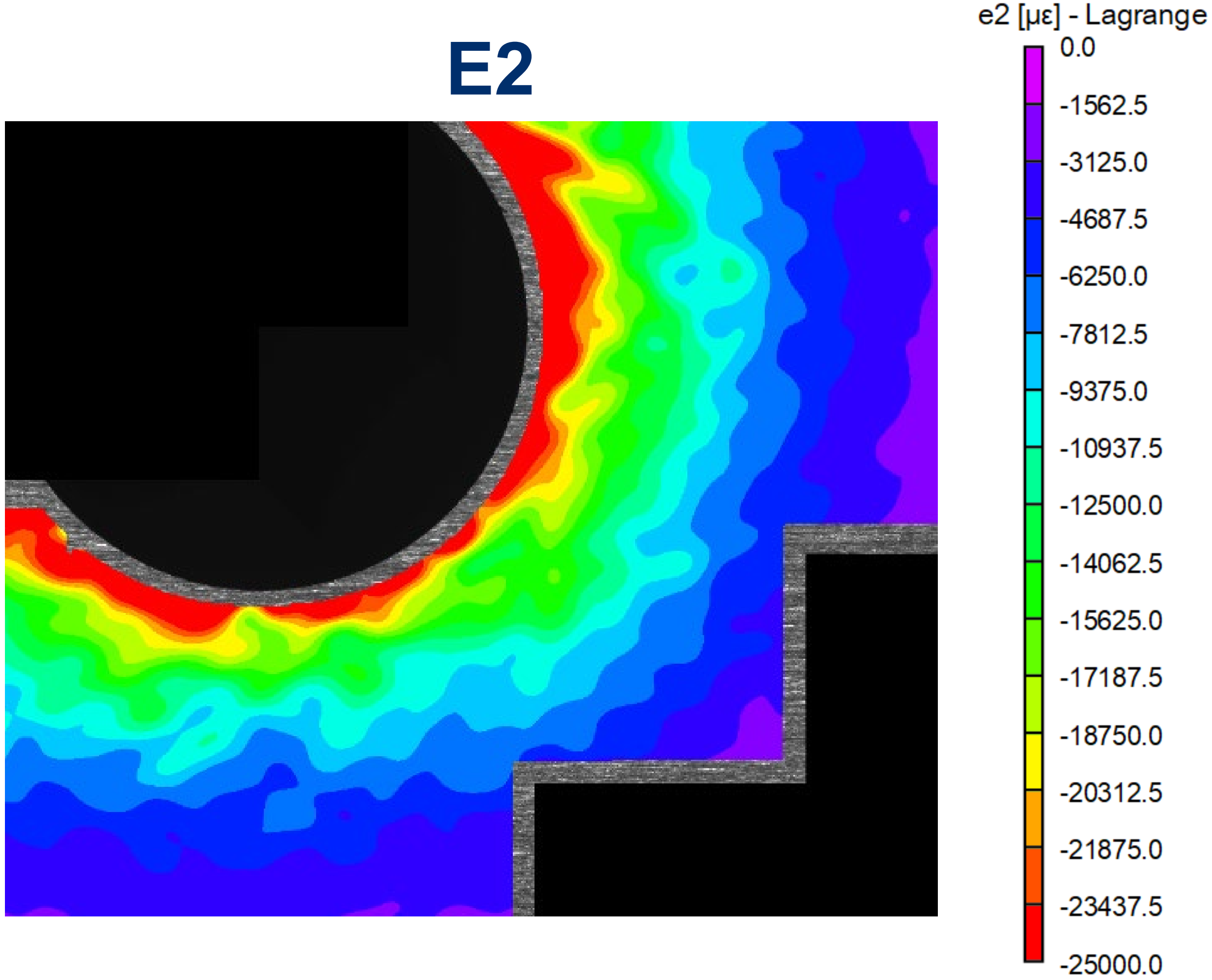
LOCKHEED MARTIN

7050-L-REM-02 – Exit Post Cx

E1



E2



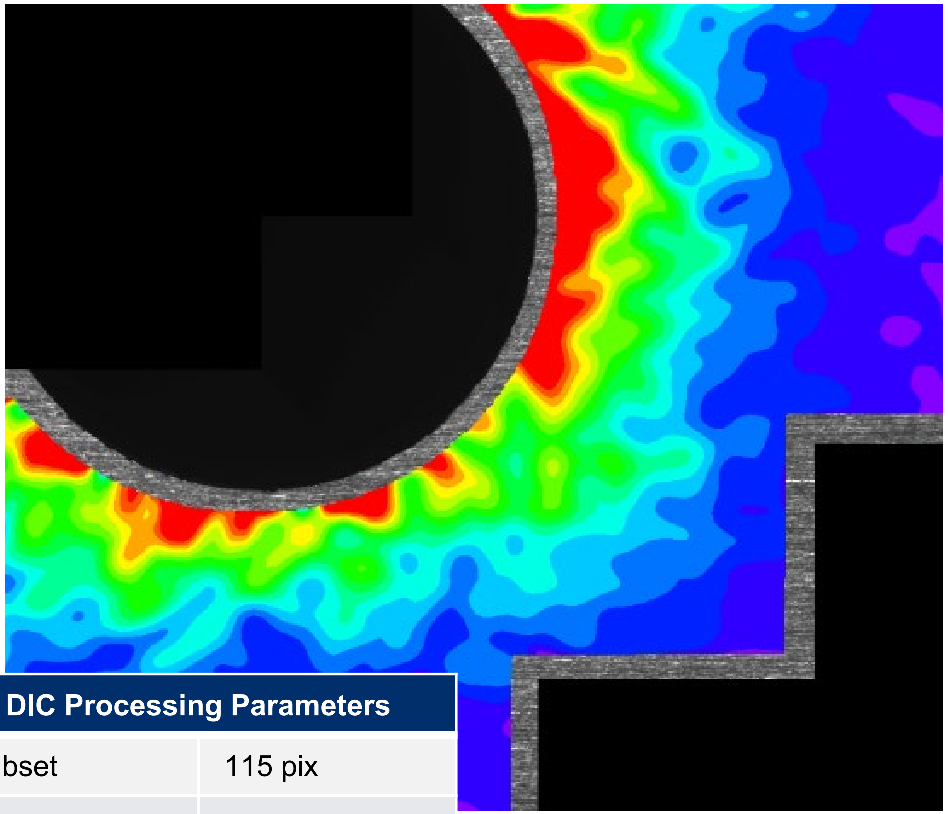
DIC Processing Parameters	
Subset	115 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (0.60 mm)**

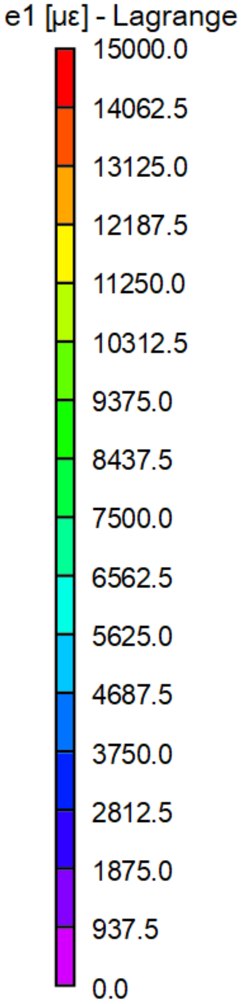
Split at 12 o'clock orientation

LOCKHEED MARTIN

7050-L-REM-02 – Exit Post Ream

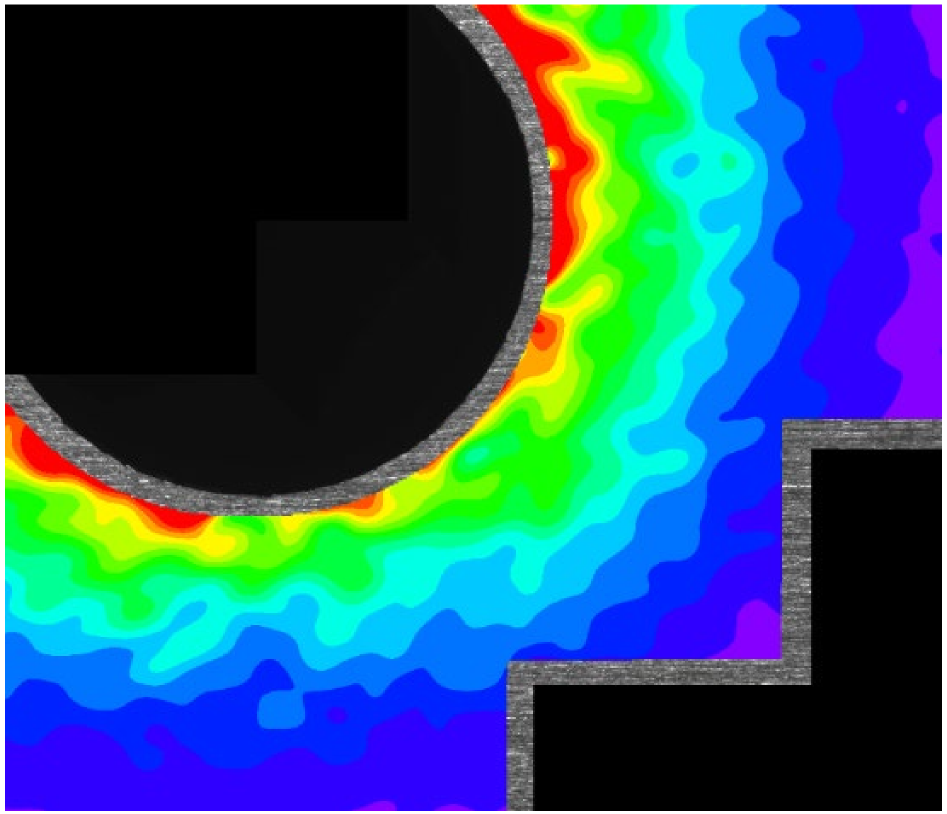
E1

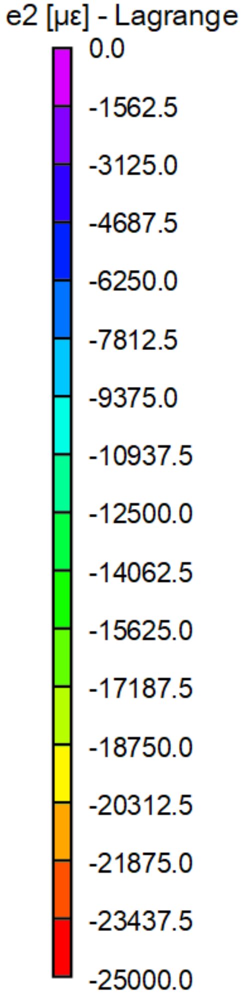




~110 microns to edge

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

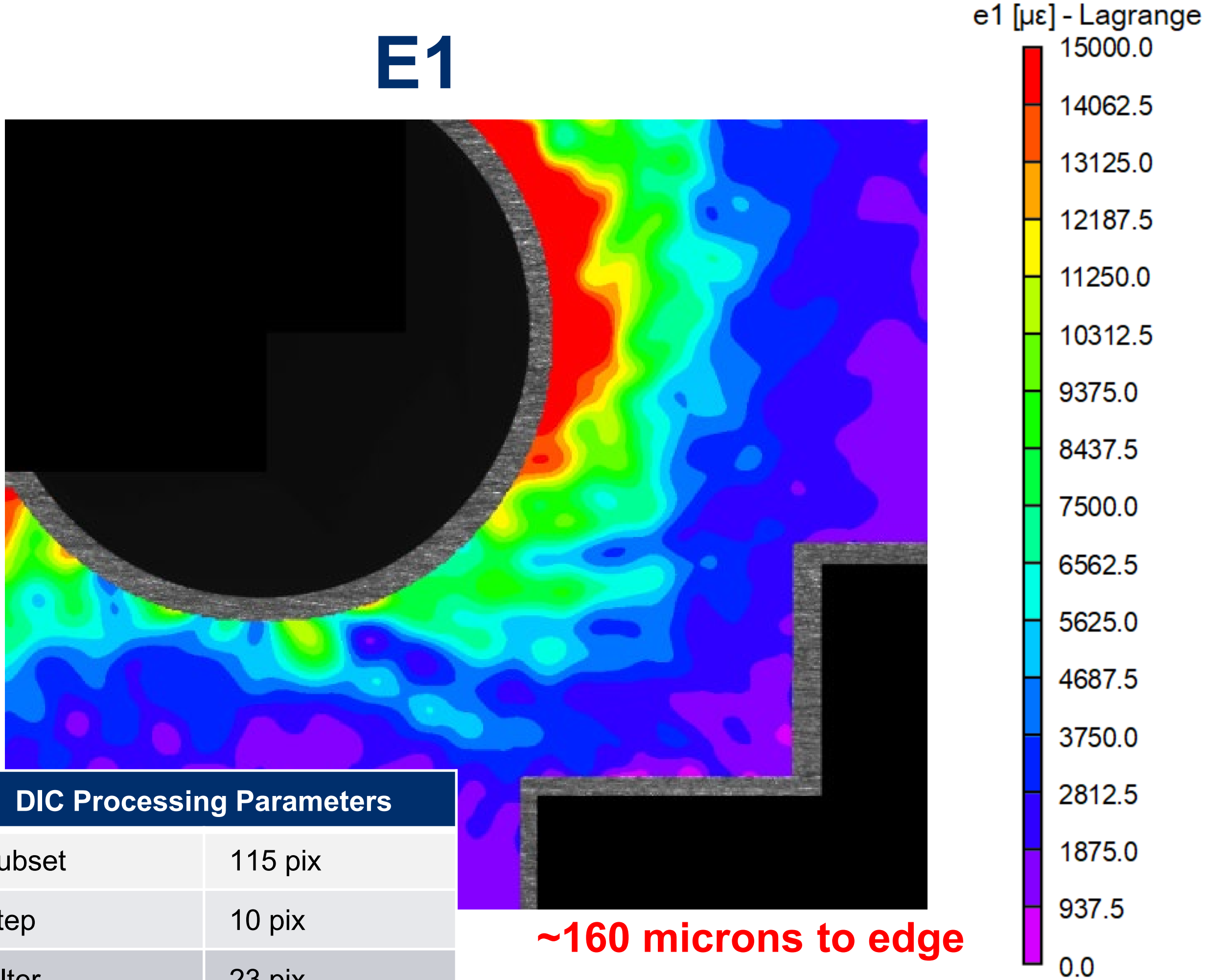
LOCKHEED MARTIN

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

Thickness = 0.25inch
Starting Hole Diameter = 0.2379inch
FTI Toolset:

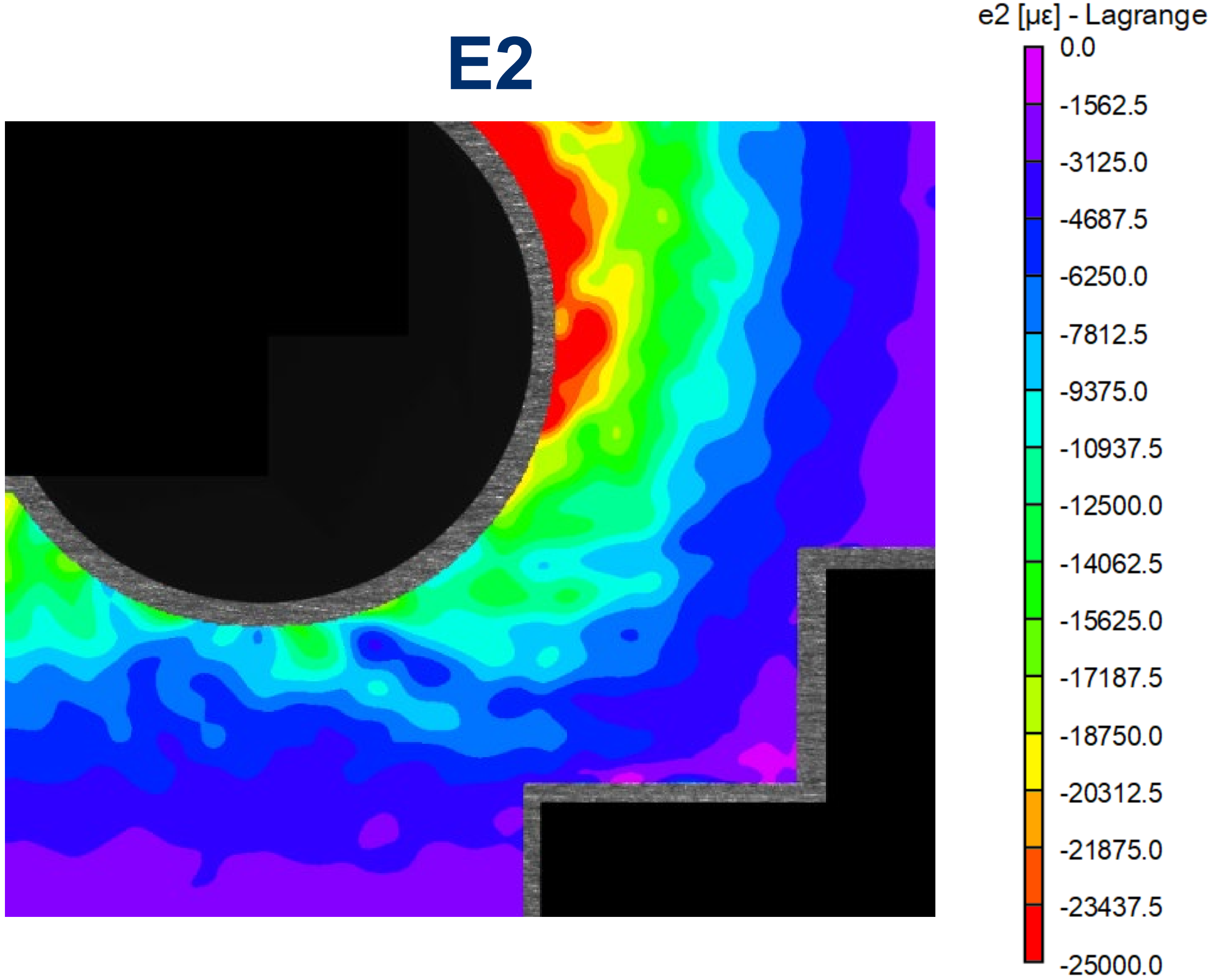
7050-L-U-REM-02 – Entry Post Cx

E1



~160 microns to edge

E2



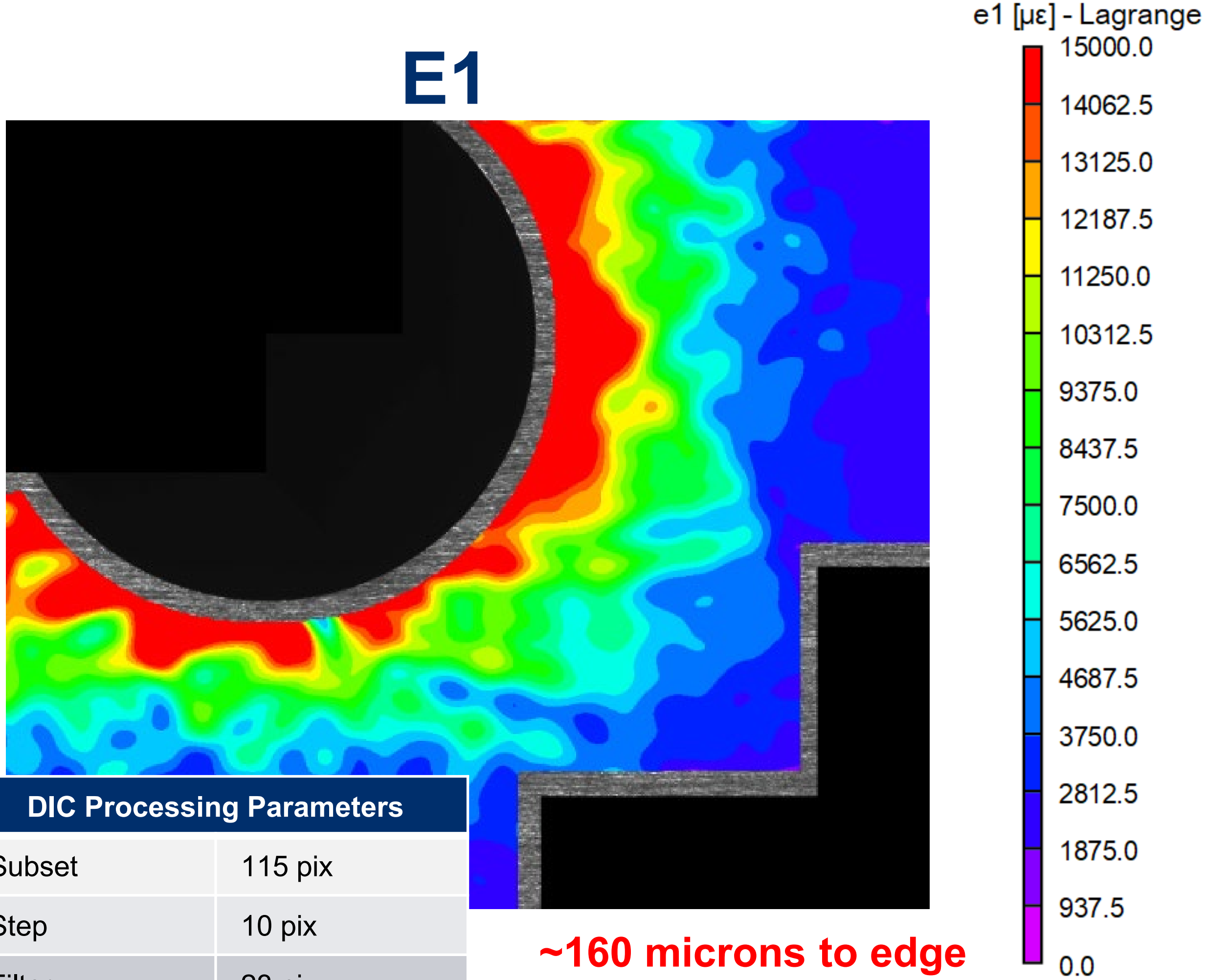
DIC Processing Parameters	
Subset	115 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (0.60 mm)**

Split at 12 o'clock orientation

LOCKHEED MARTIN

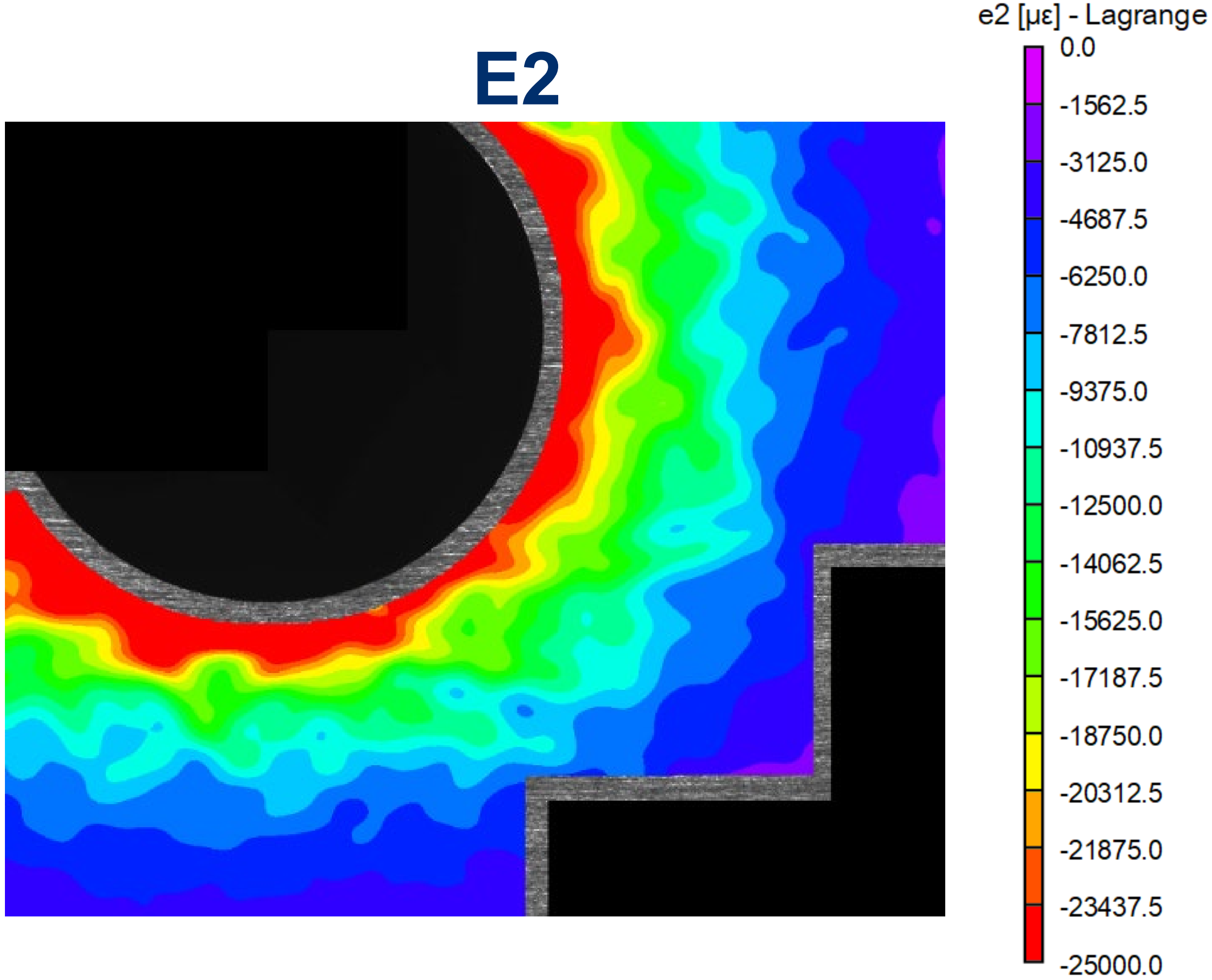
7050-L-U-REM-02 – Exit Post Cx

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°)

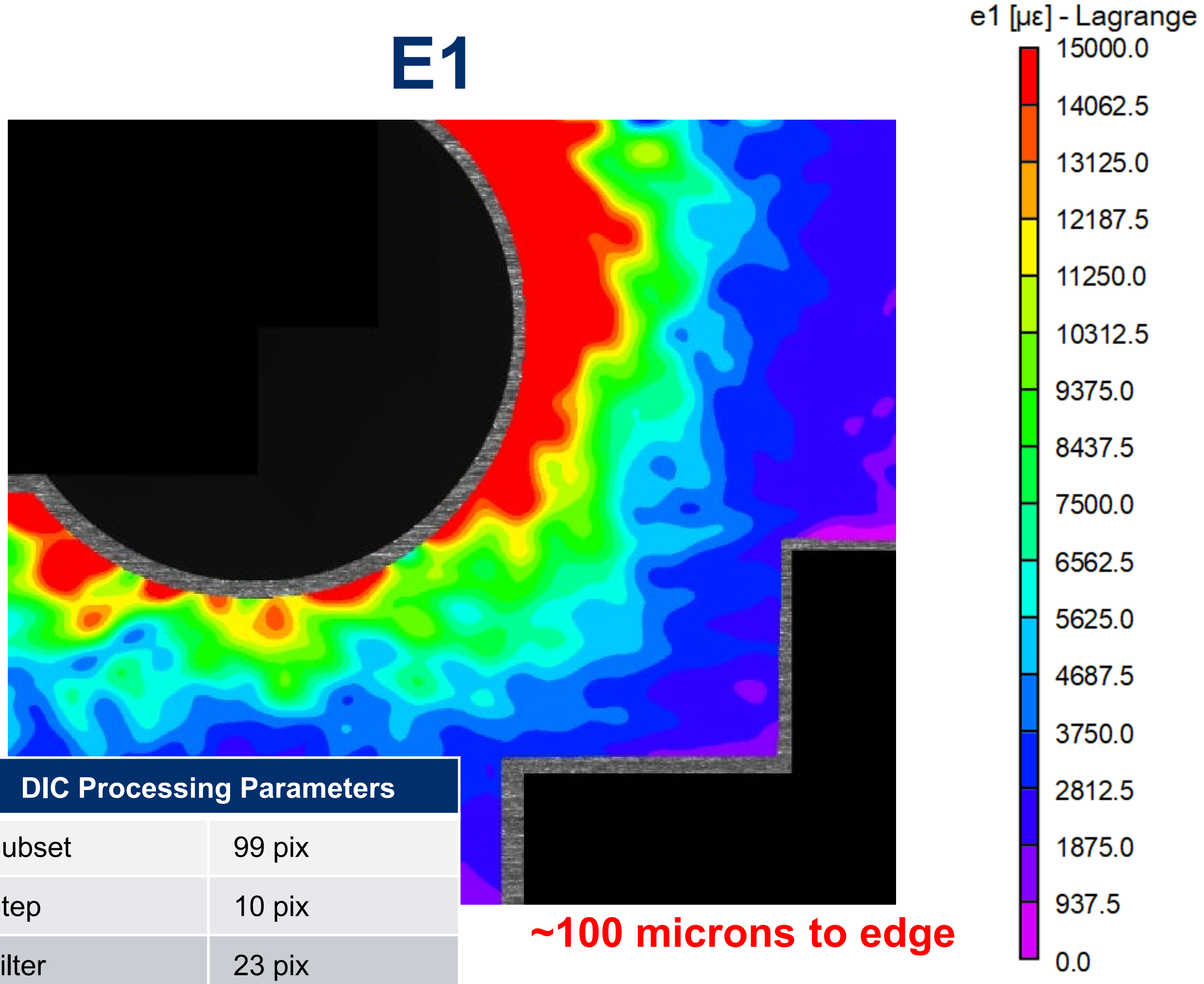
Thickness = 0.25inch

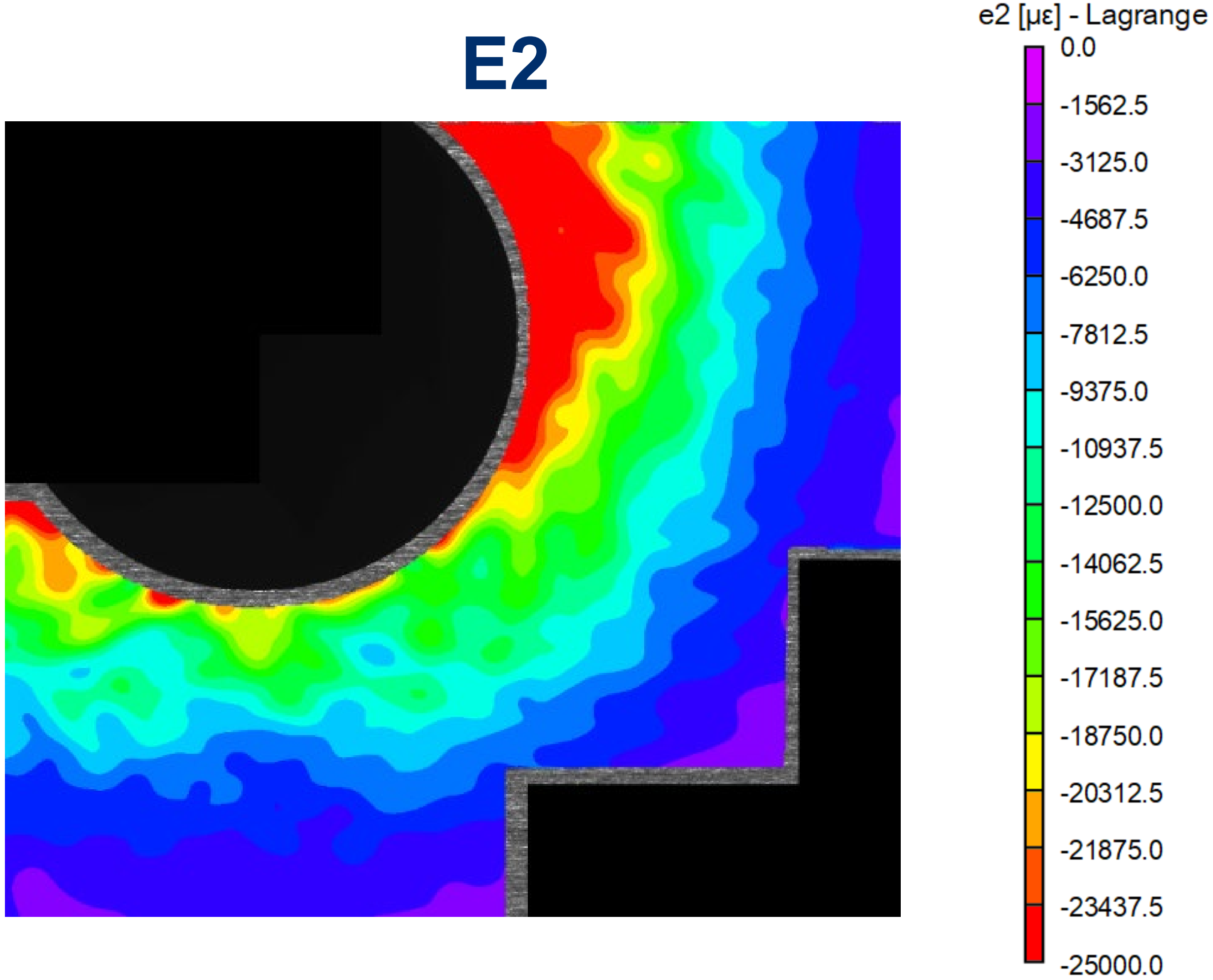
Starting Hole Diameter = 0.2355inch

FTI Toolset:

LOCKHEED MARTIN

7050-H-REM-02 – Entry Post Cx



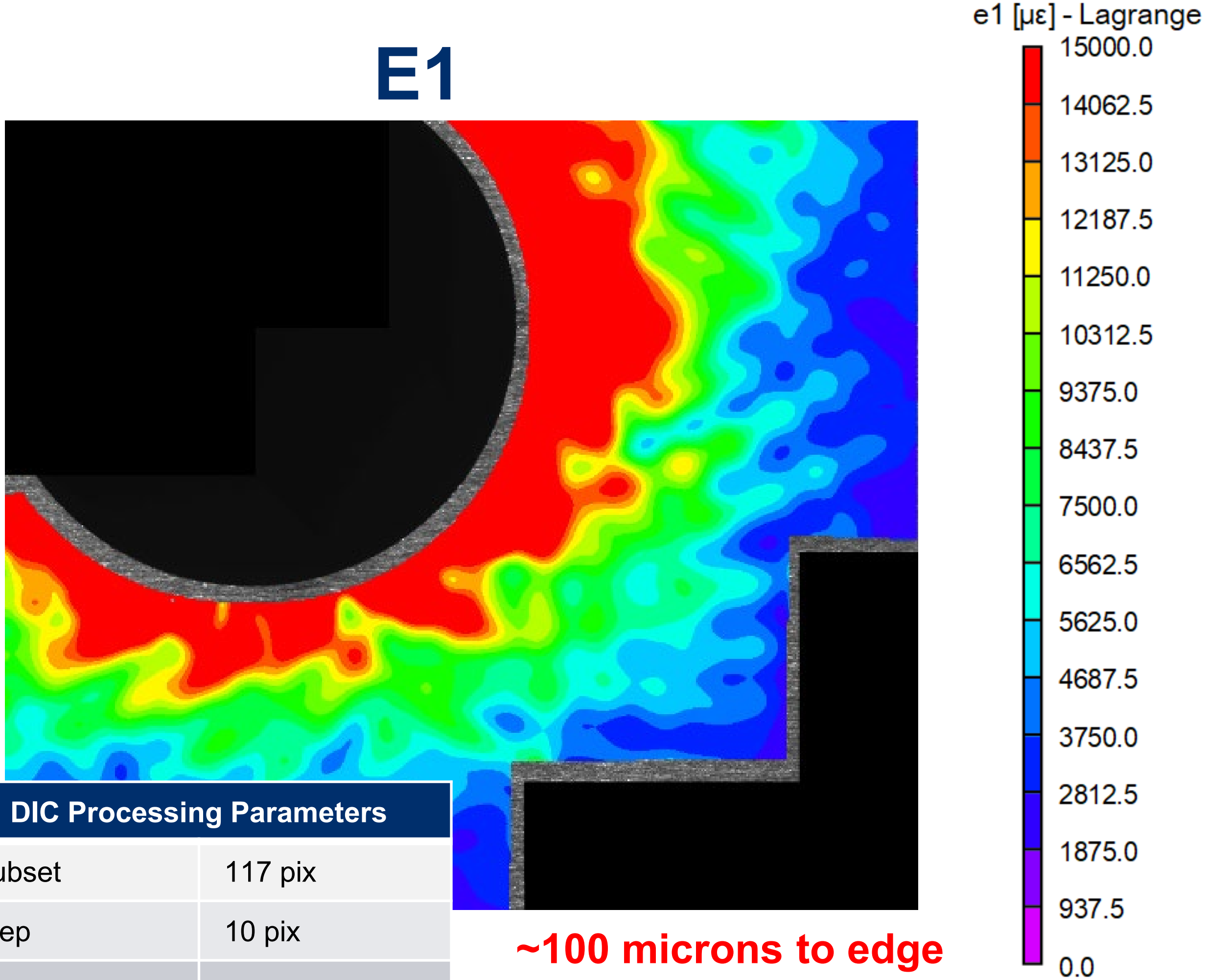


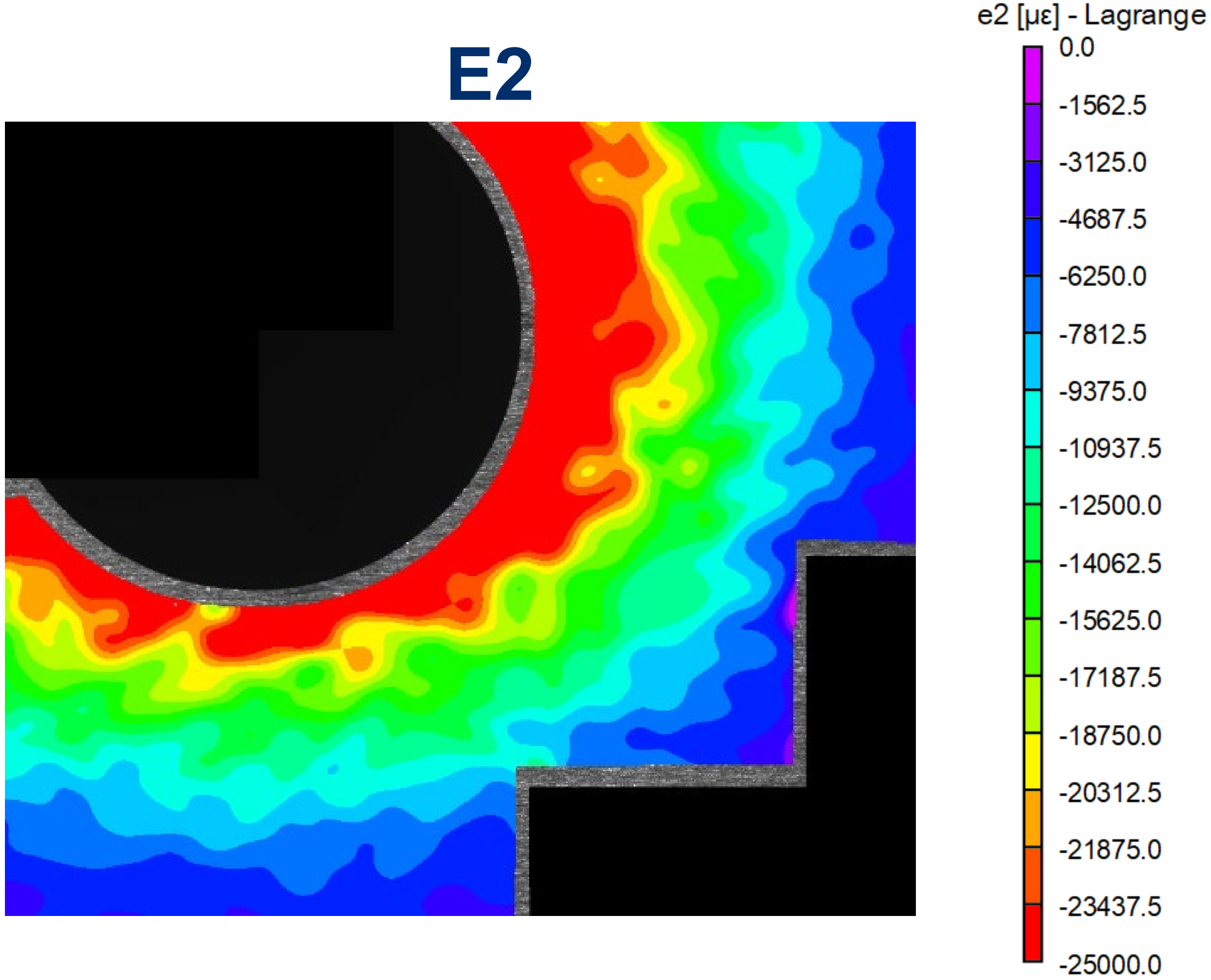
DIC Processing Parameters	
Subset	99 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (0.60 mm)**

Split at 12 o'clock orientation

LOCKHEED MARTIN

7050-H-REM-02 – Entry Post Ream





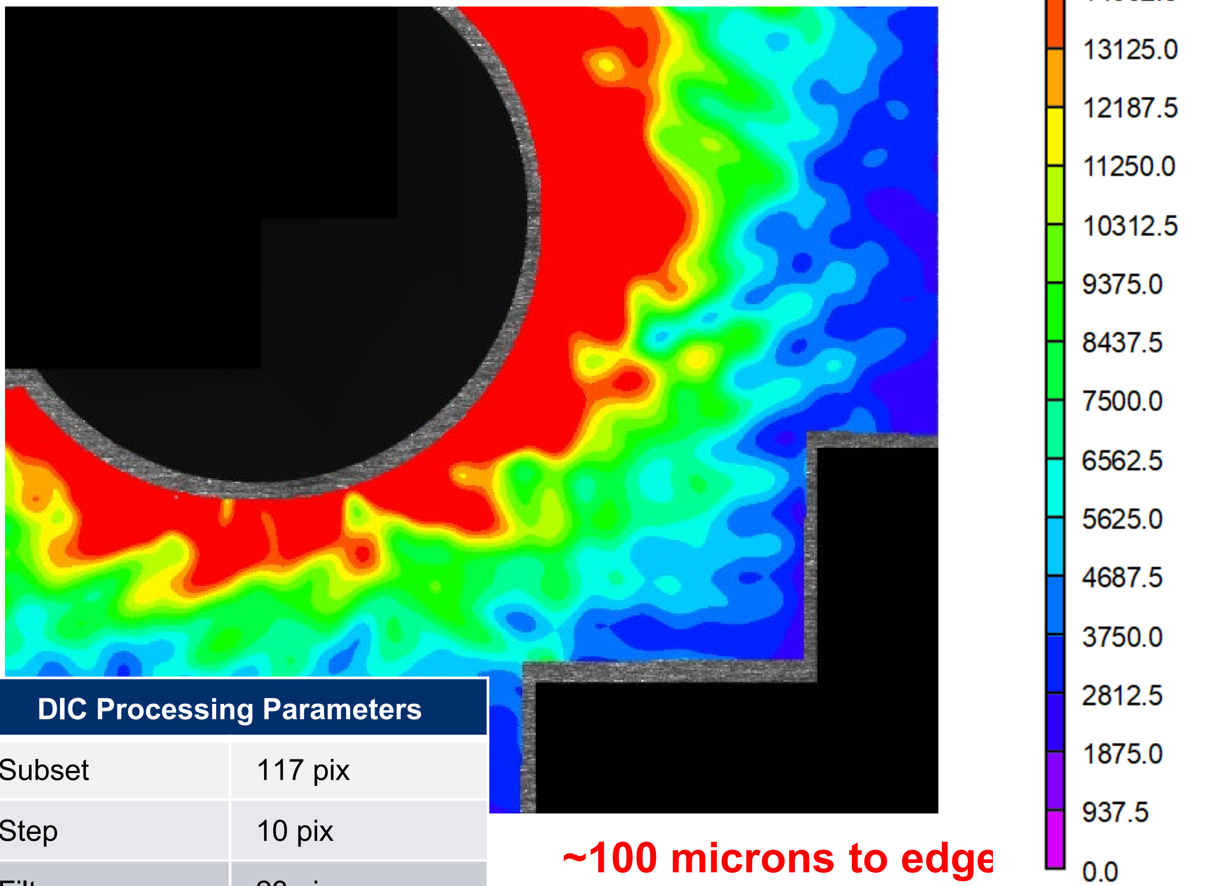
DIC Processing Parameters	
Subset	117 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (0.60 mm)**

Split at 12 o'clock orientation

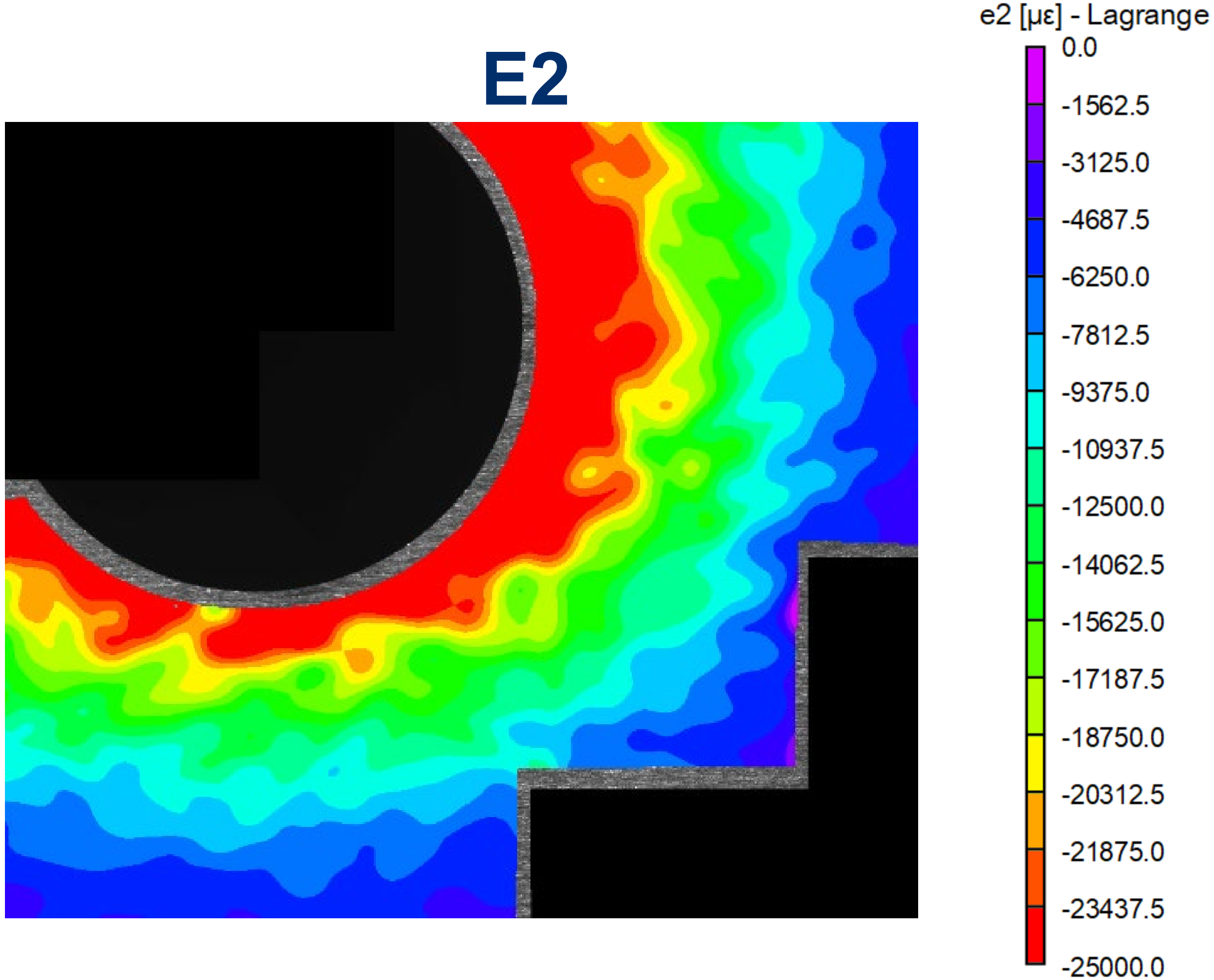
LOCKHEED MARTIN

7050-H-REM-02 – Exit Post 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

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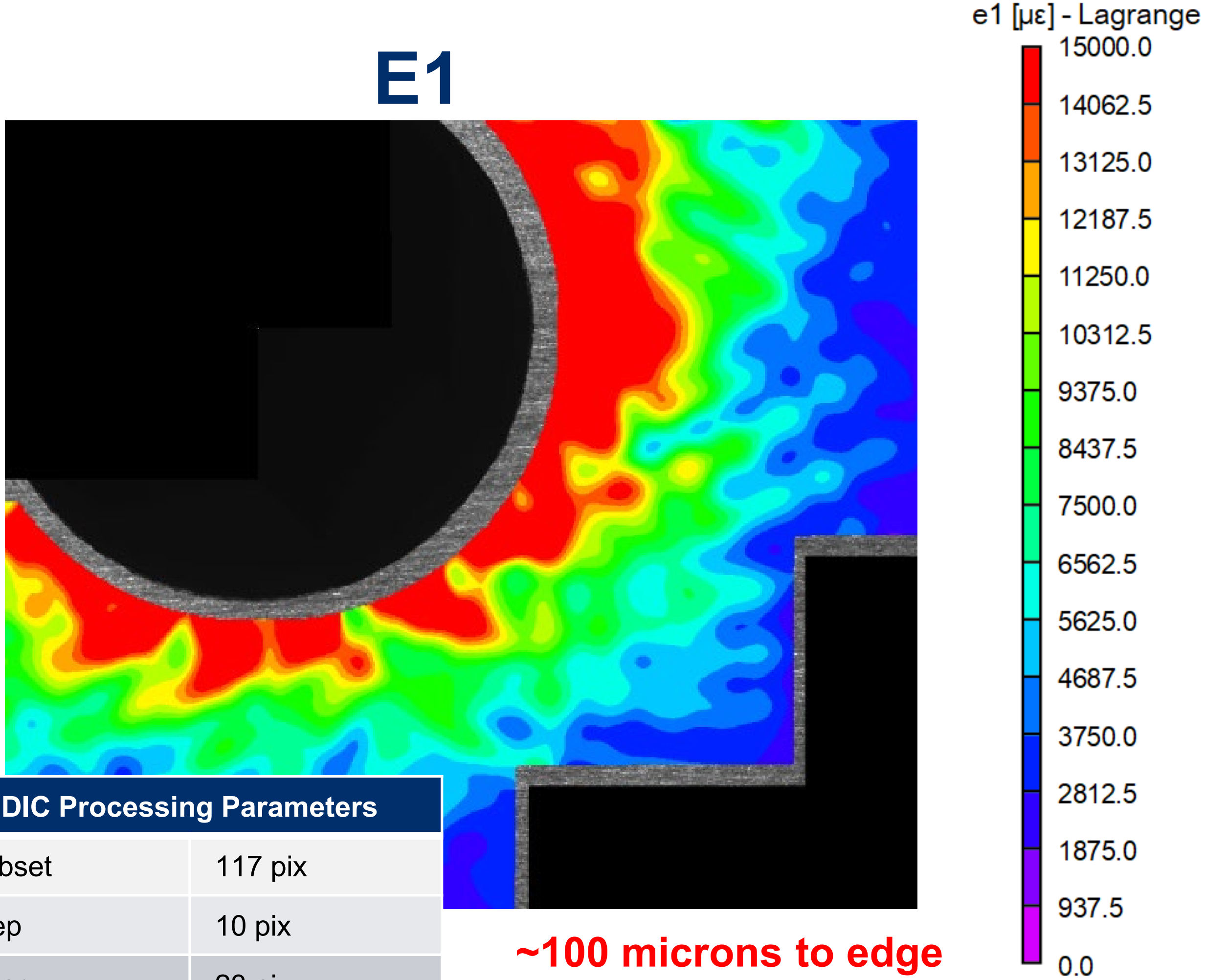
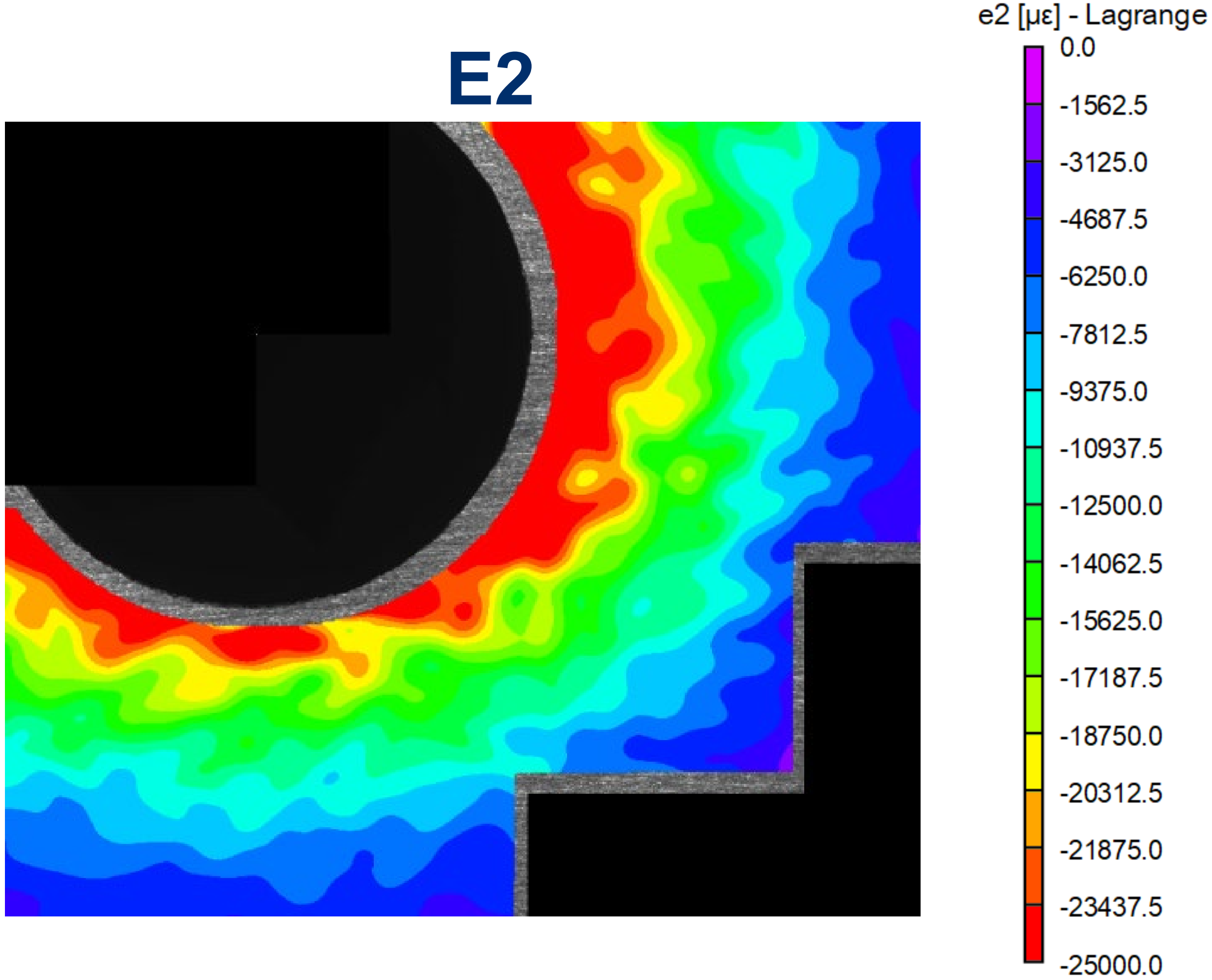
7050-H-REM-02 – Exit Post Ream





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

Split at 12 o'clock orientation

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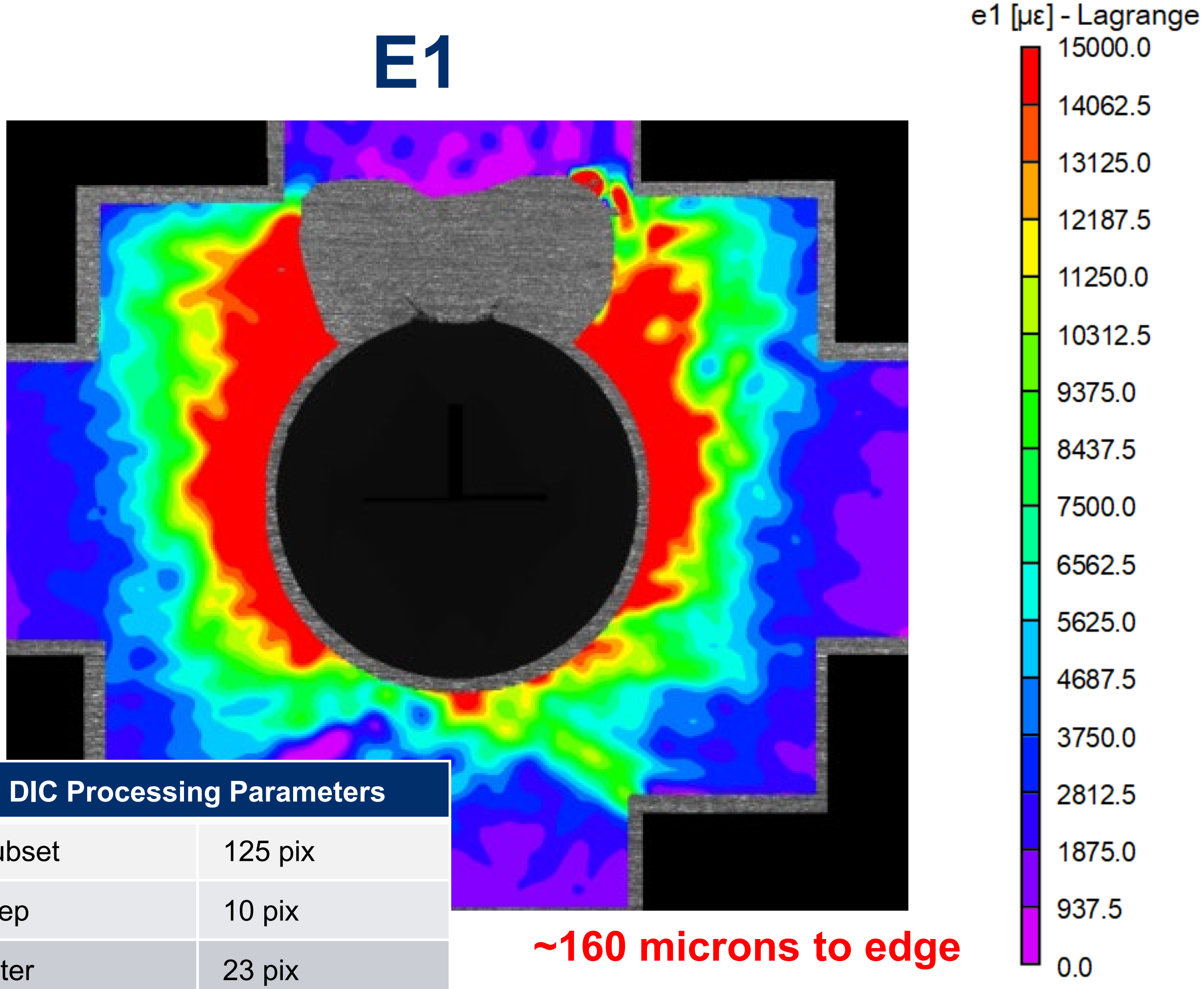
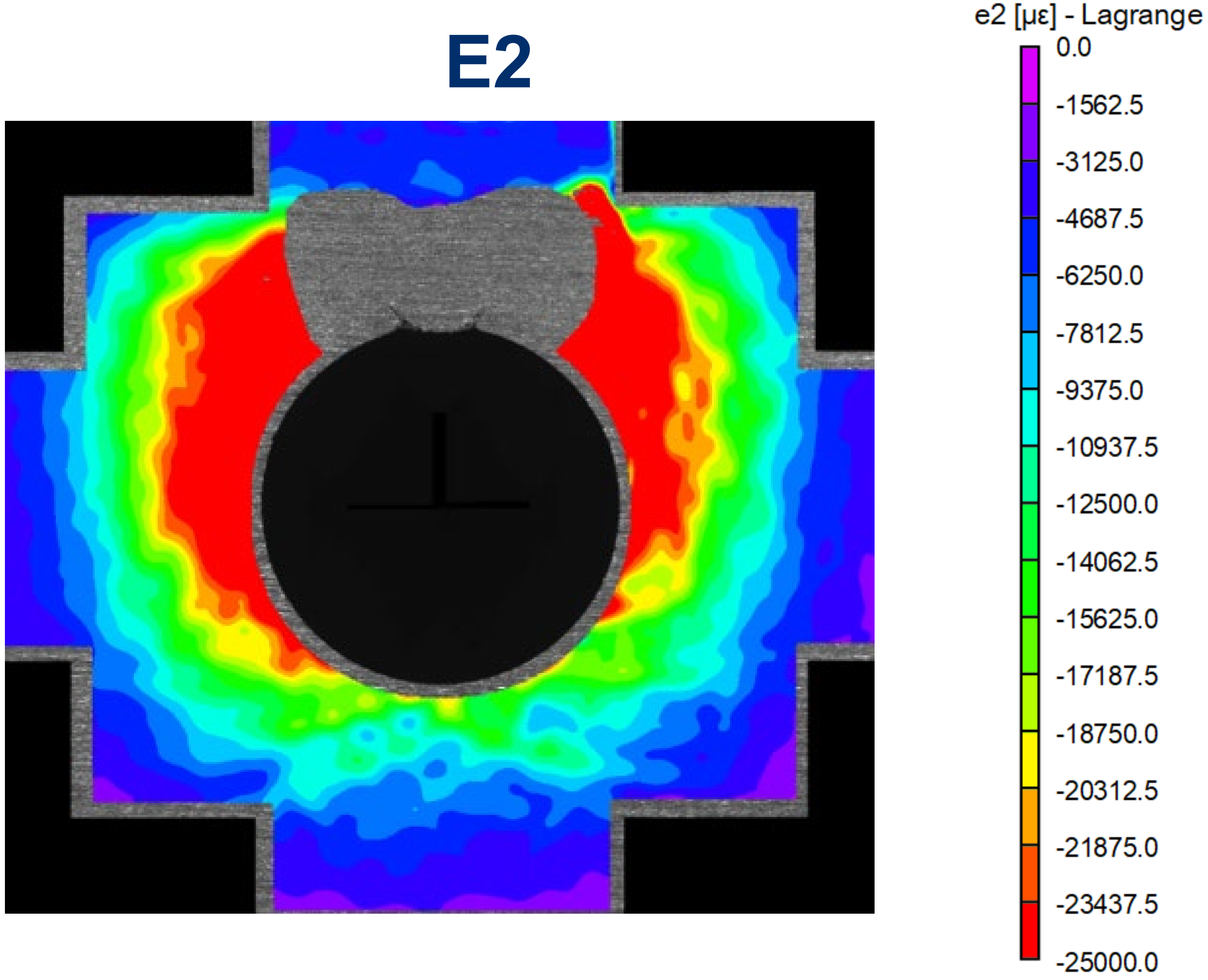
7050-T7451 “High” Cx
2D DIC Super-resolution (360°)

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

7050-L-H-REM-02 – Entry Post Cx





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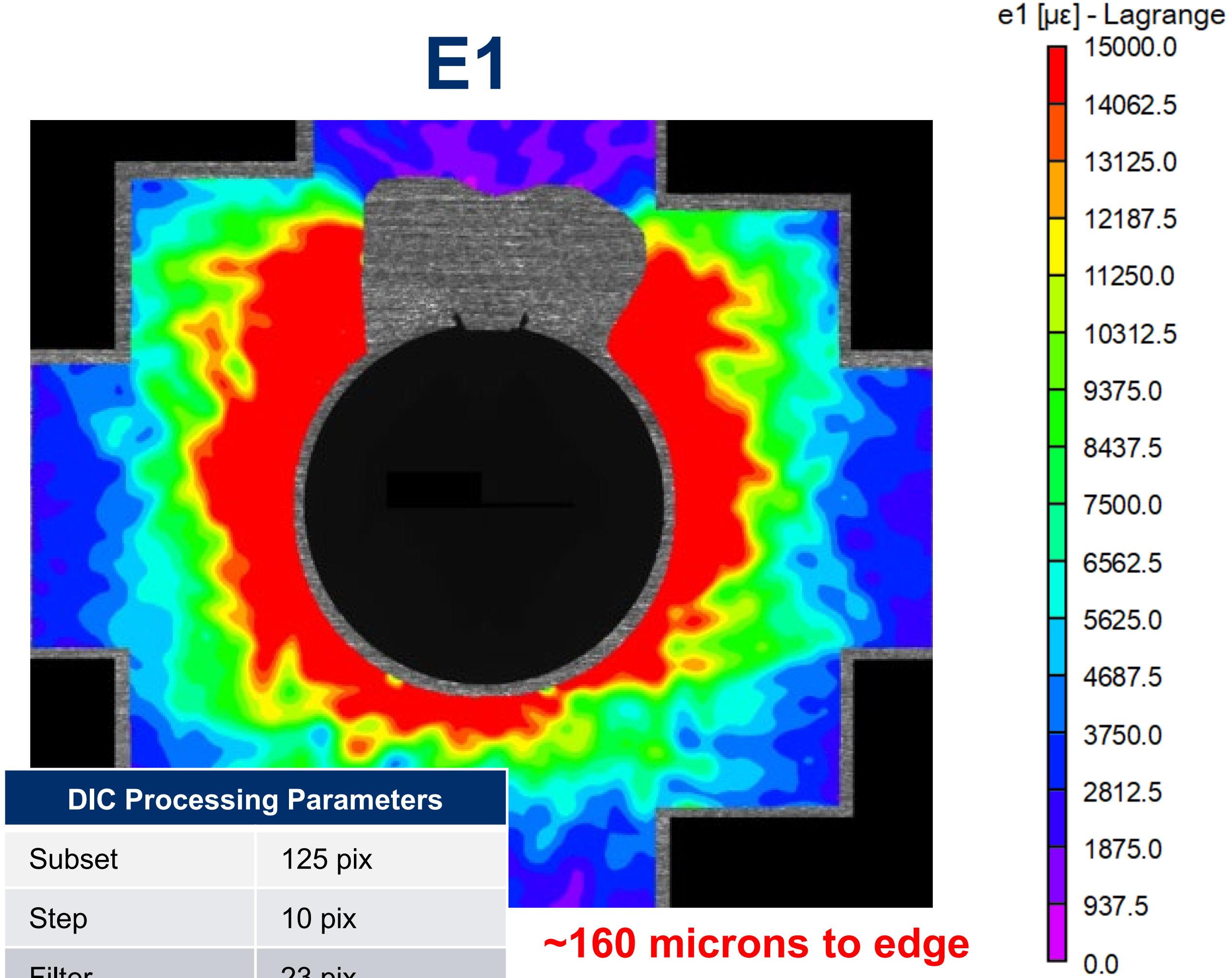
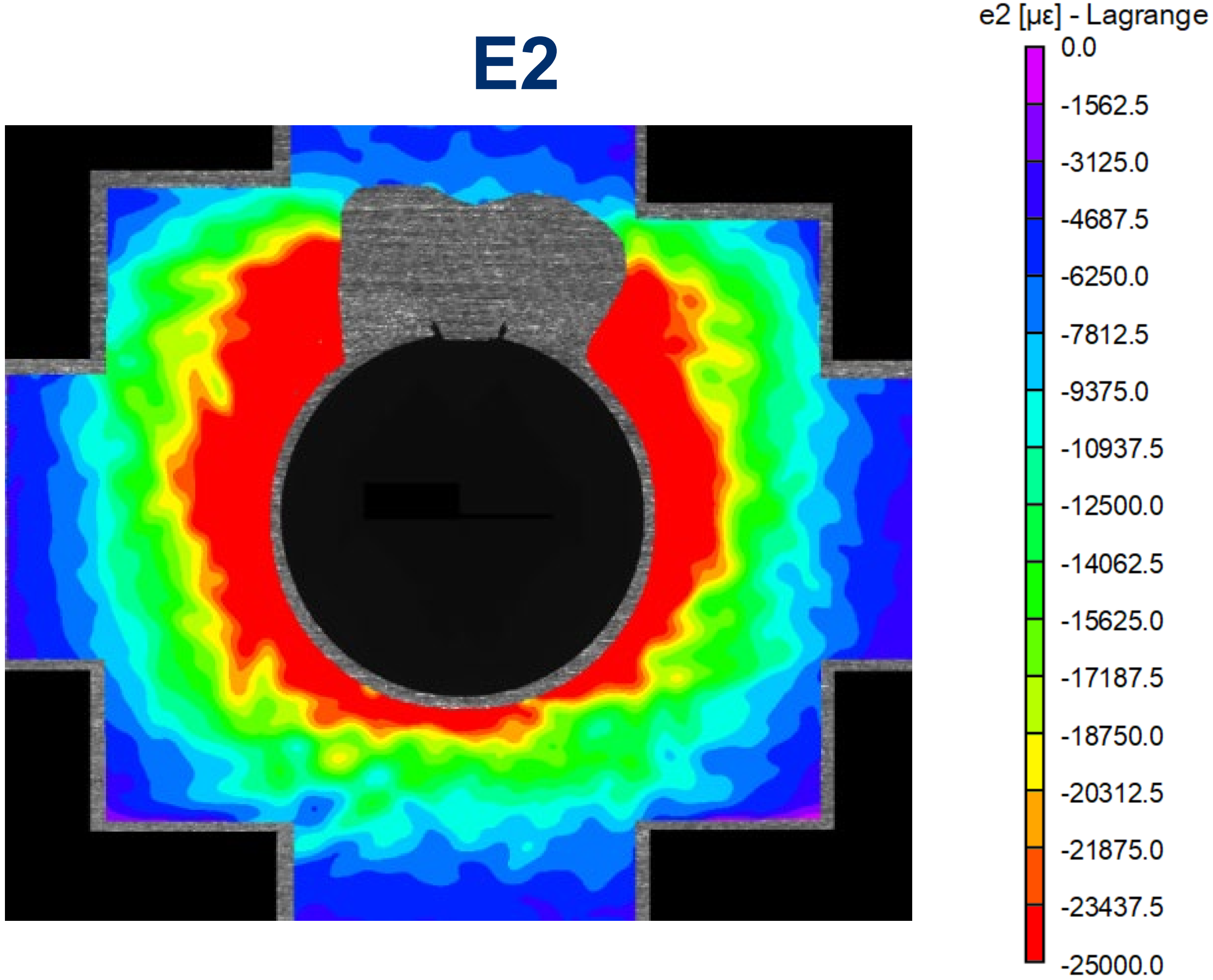
Filter	23 pix
VSG	**230 pix (0.60 mm)**

Split at 12 o'clock orientation

LOCKHEED MARTIN

7050-L-H-REM-02 – Exit Post Cx



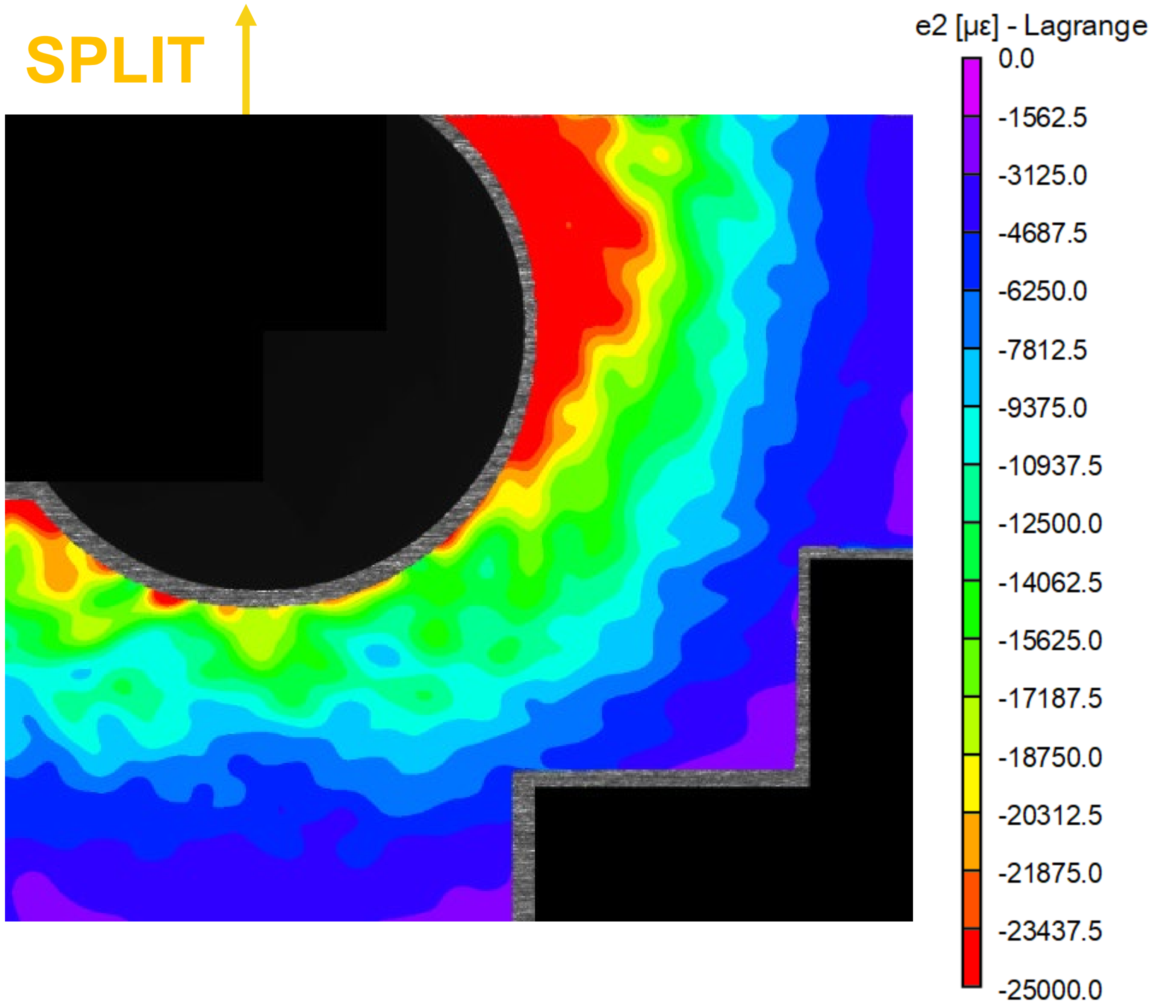


DIC Processing Parameters	
Subset	125 pix
Step	10 pix
Filter	23 pix
VSG	**230 pix (0.60 mm)**

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]



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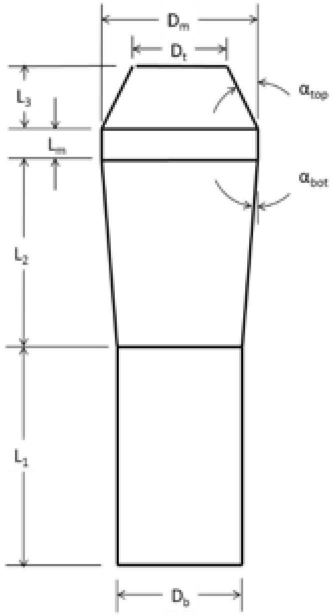
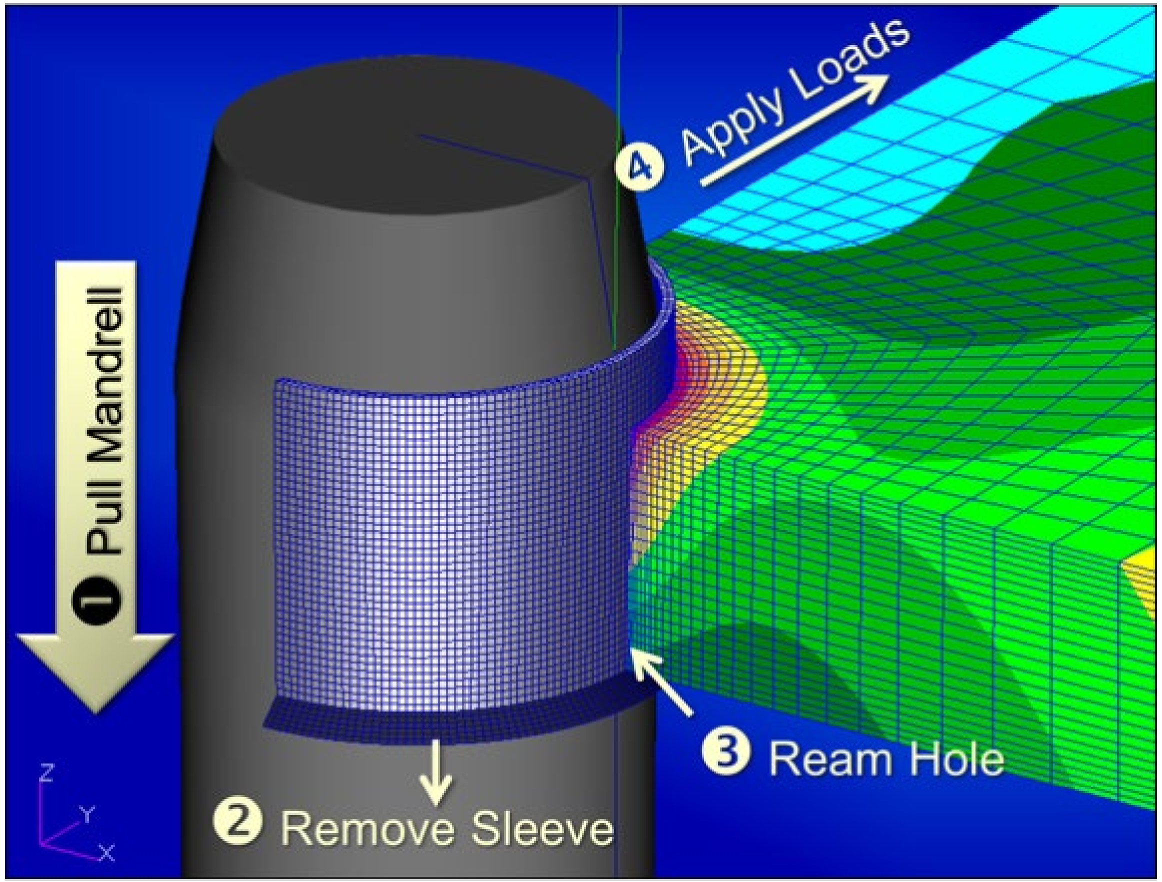
SsCx™ Process Model

- 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)

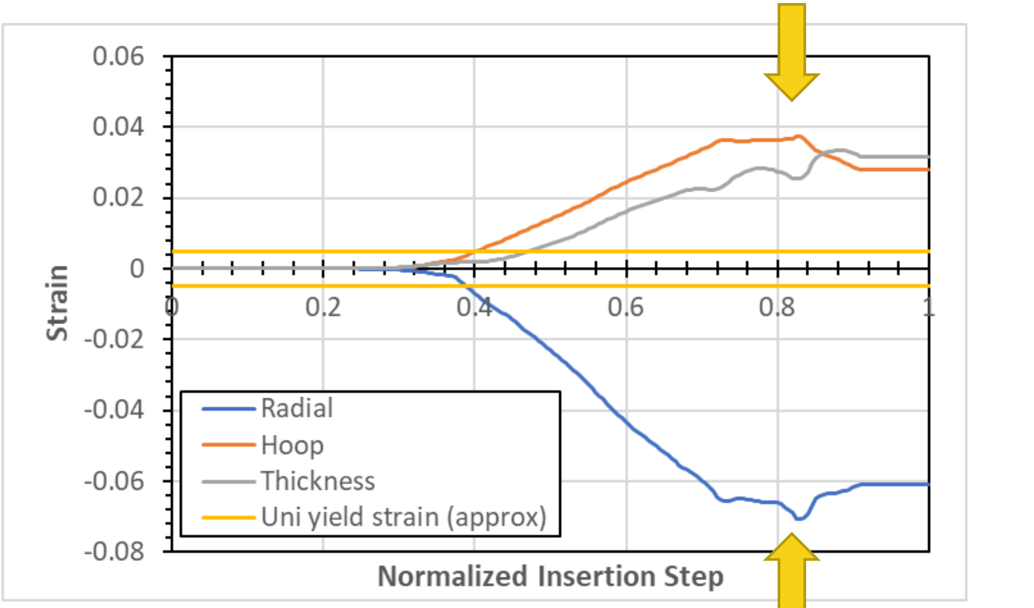




*%Cx Defined by Geometry Parameters

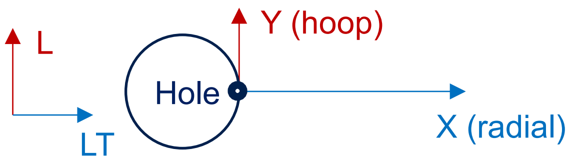
Cx Mechanics Study

- 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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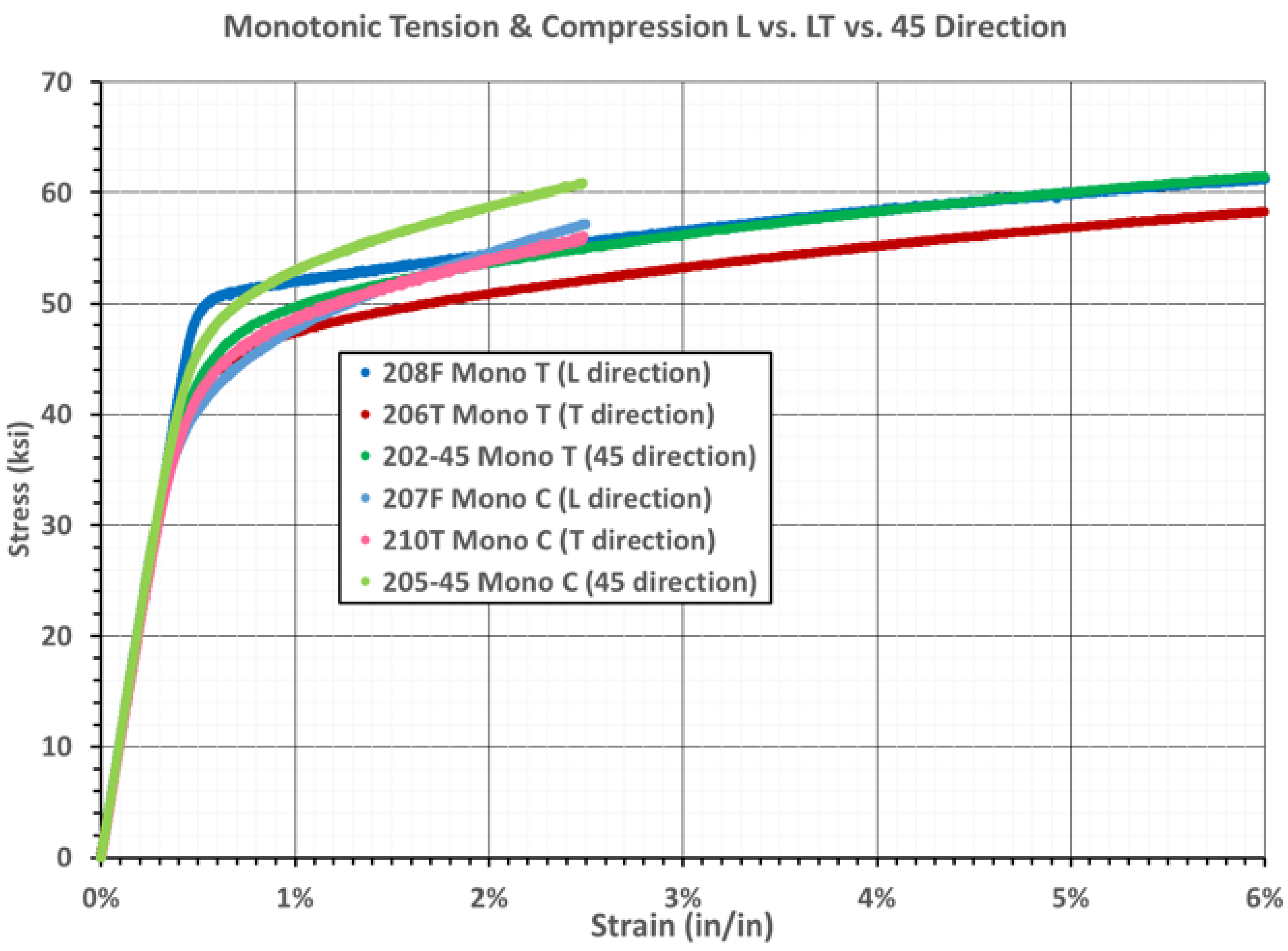
2024-T351 Material Data

- 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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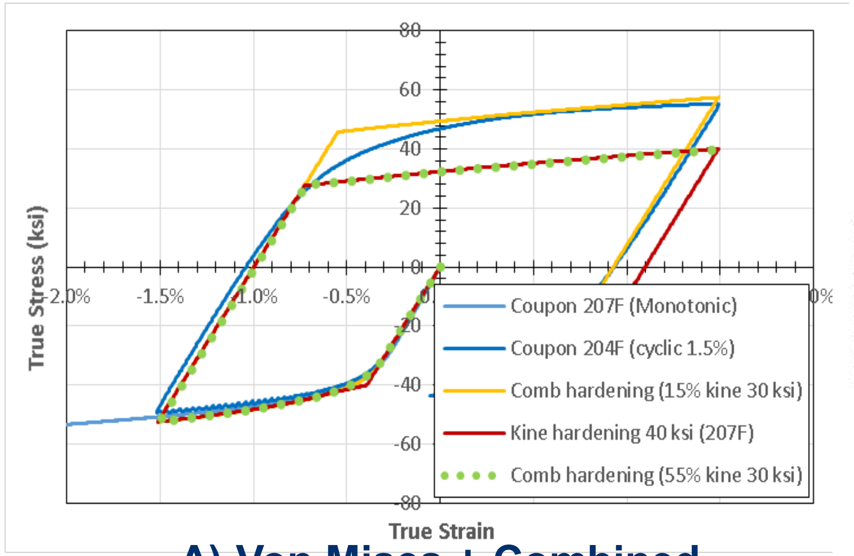
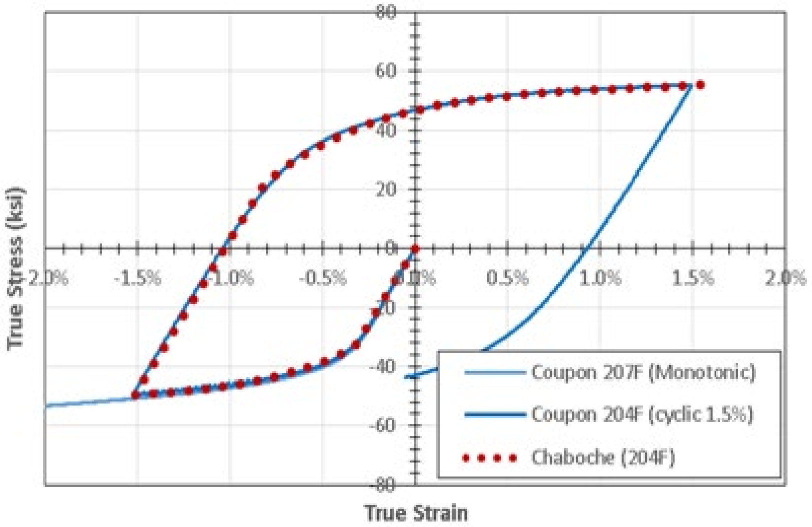
2024-T351 Material Models

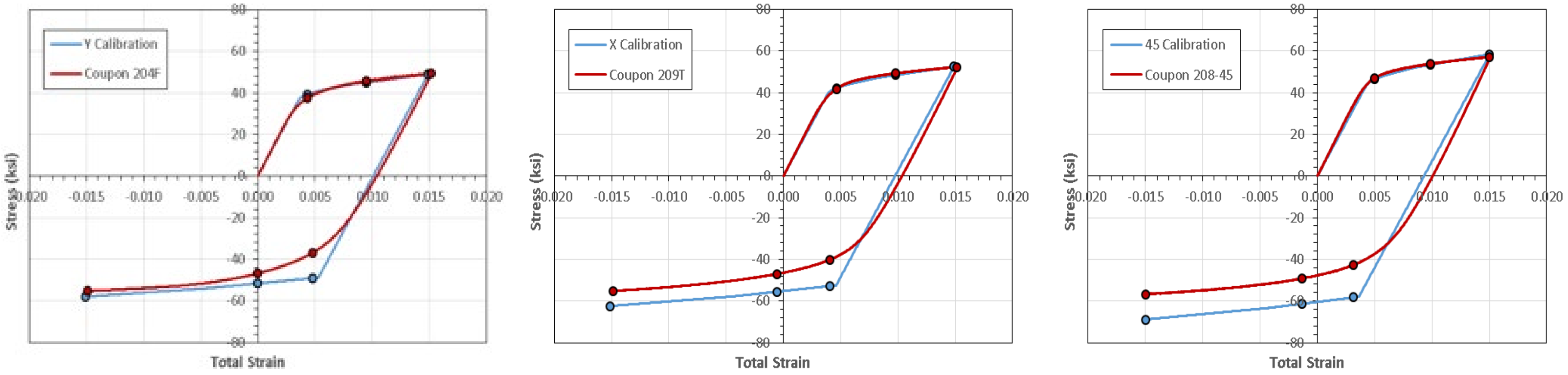
- Calibration using Cyclic Test Data
  - Model A) Linear reversed yielding (does not match reverse yielding shape)
  - Model B) Chaboche: Nonlinear reverse yielding but isotropic plasticity
  - Model C) Anisotripic plasticity but linear reverse yielding
  - No model to deal with difference between tension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



A) Von Mises + Combined Hardening



B) Chaboche

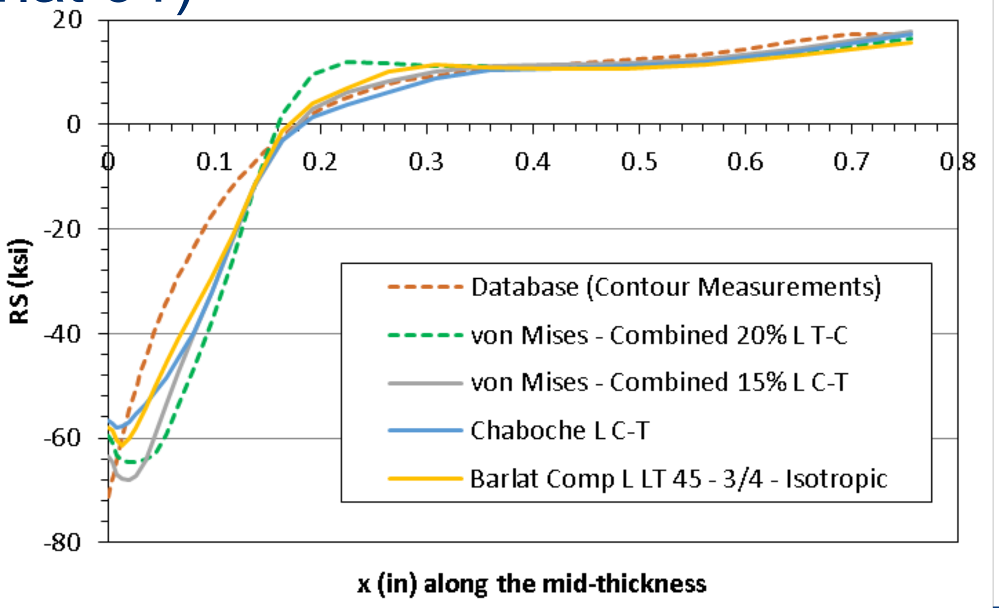


C) Barlat 91

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

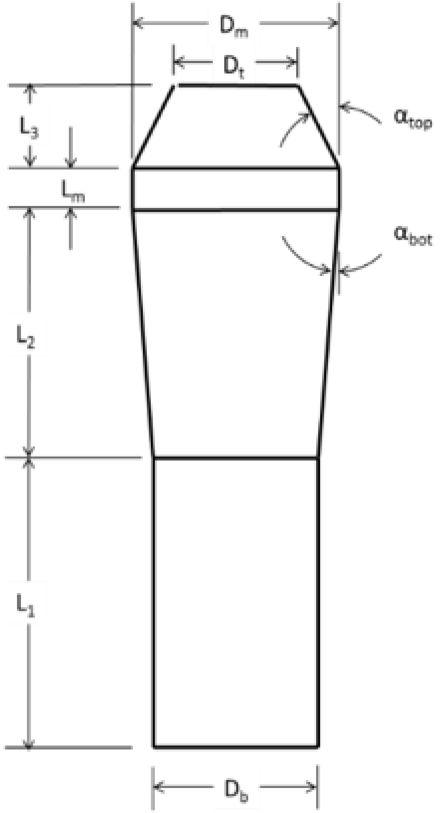
- Plate
  - Hole diameter: 0.2365 in
  - Plate thickness: 0.06 in
  - Plate width: 3 in

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

- Mandrel and Sleeve

Mandrel		CBM-8-0-N-*	
Major Ø	ØD	0.4684 ('L'), 0.2302 ('H')	Starting Hole: Ø0.235 - 0.238"
Minor Ø	ØB	0.2150	Final Reamed Hole: Ø(N/A
Major Ø 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 Ø (while on mandrel B Ø)	f	0.267	
Sleeve Gap (while on mandrel B Ø)	G	0.012, max.	

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



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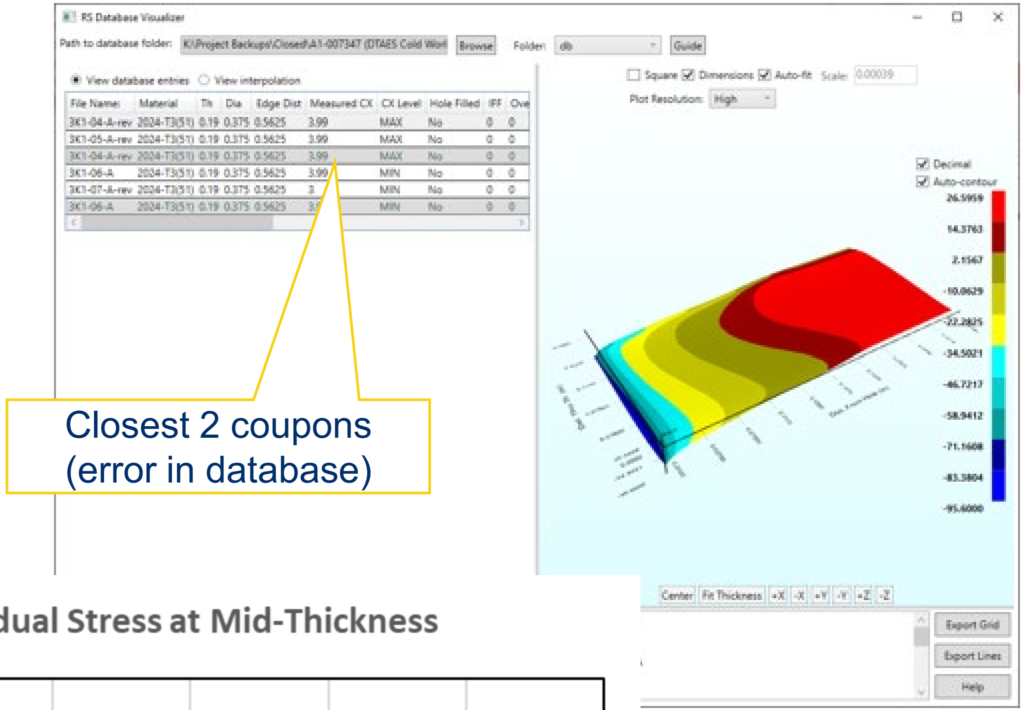
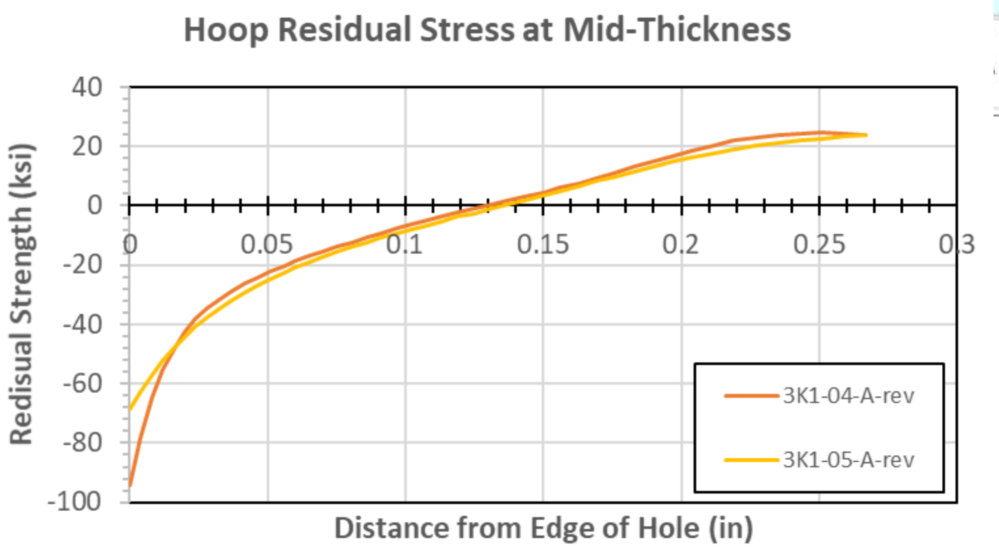
RS Database Entries

- 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

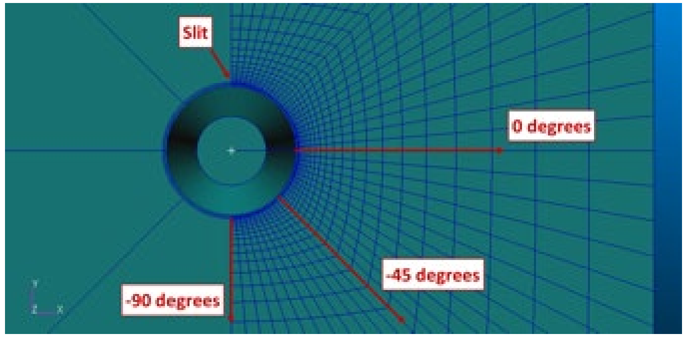
! Database cannot extrapolate to BT15 values

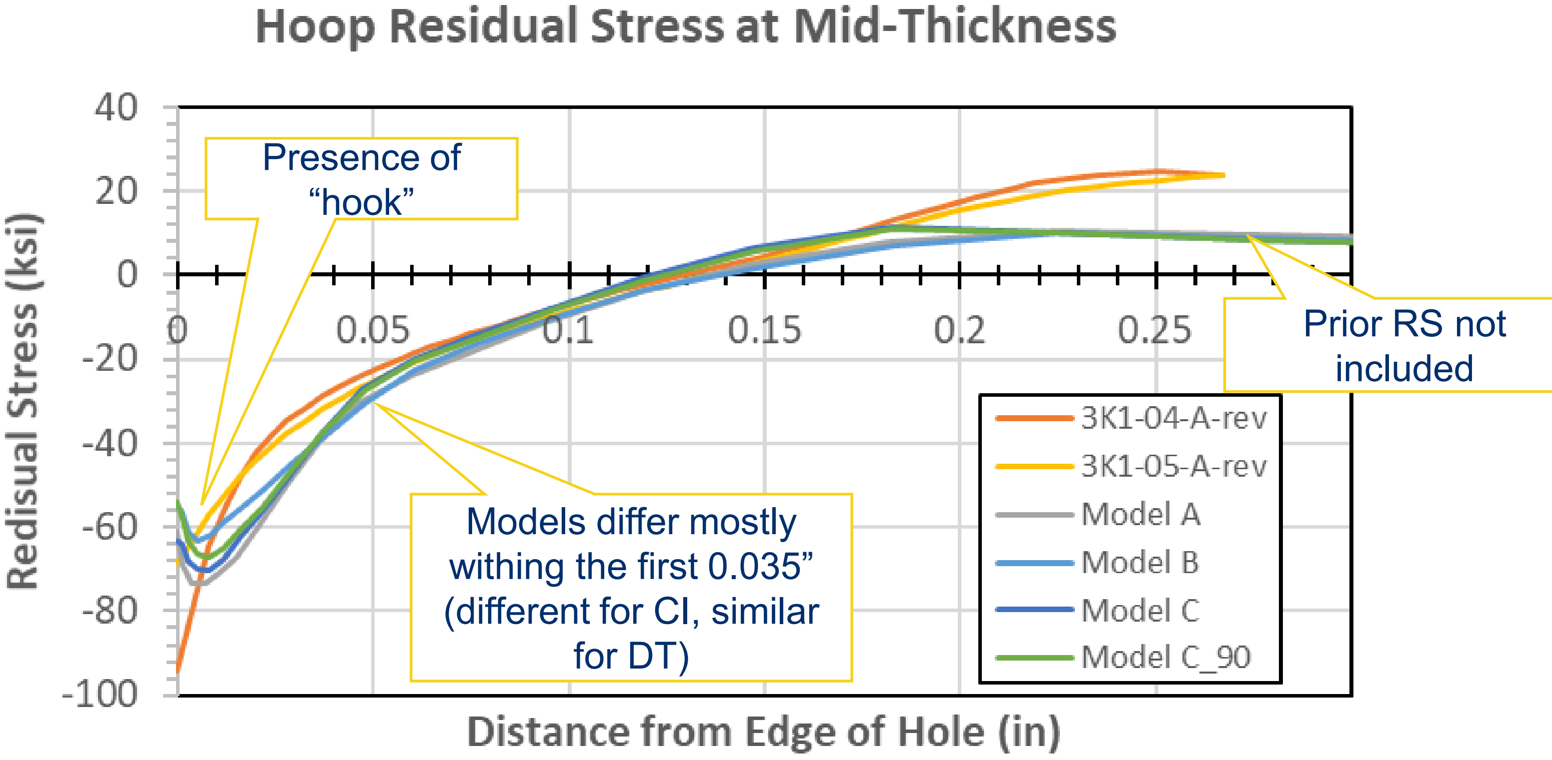




Models A, B, C – Stress Comparison

- 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





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

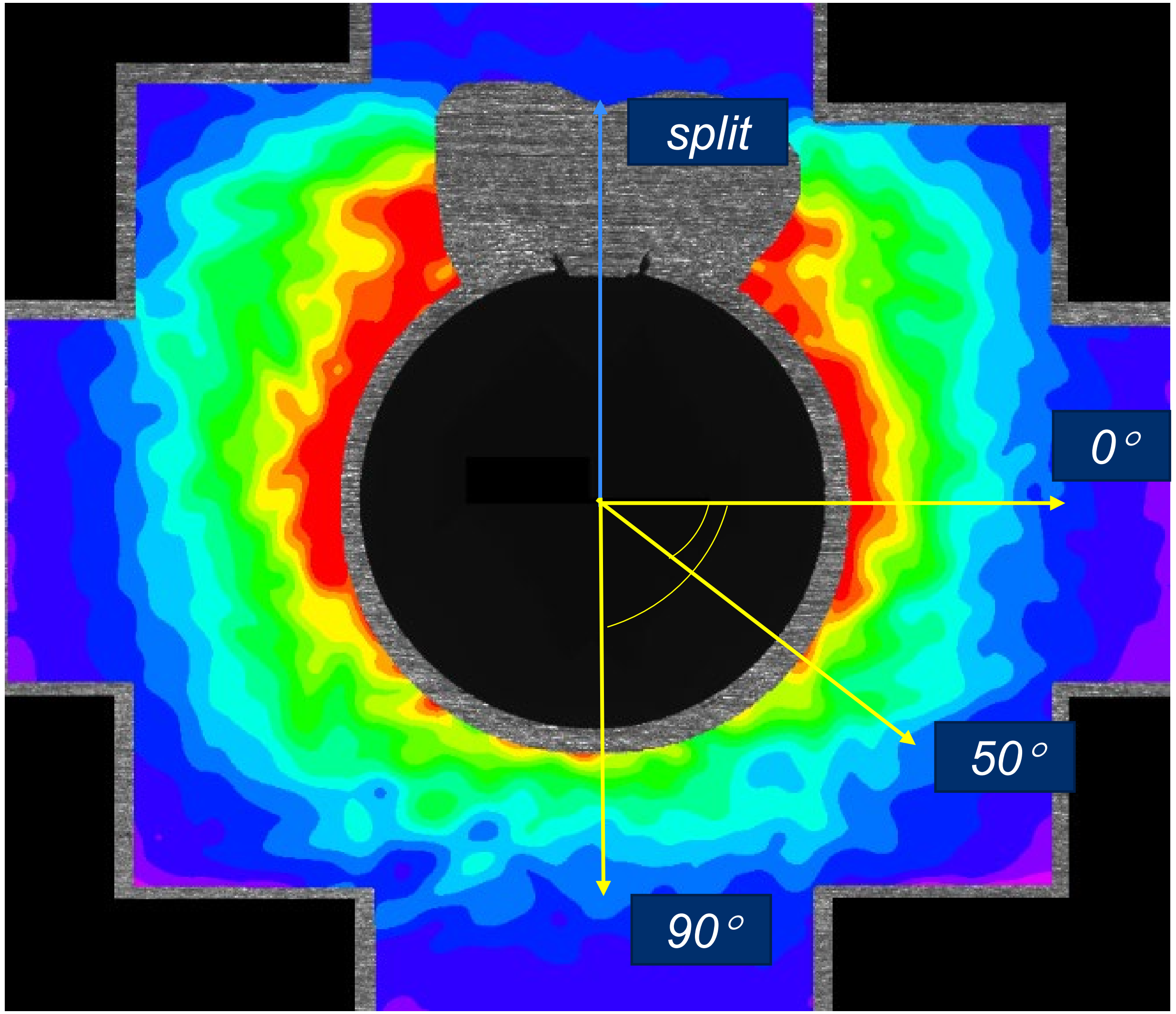
- Efficient Material Calibration Protocol
  - Material model calibration using bi-axial testing considering (proper mixity ratio)
    - Less coupons, more representative of the actual physics
    - Potentially: anisotropic calibration on a single coupon (if 1:1 ratio)

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

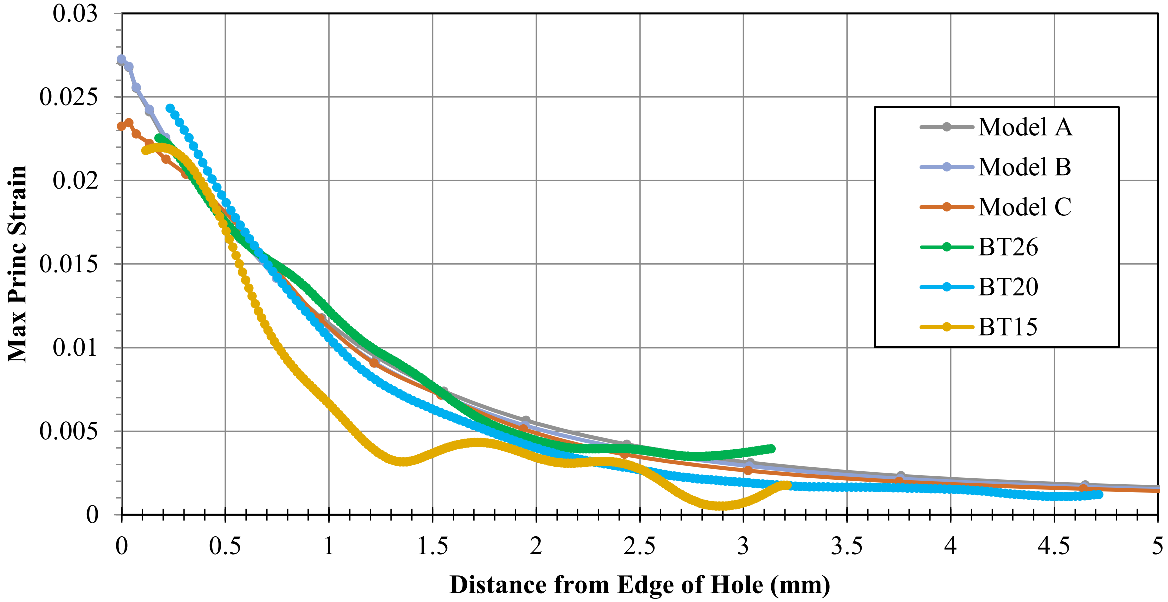
- E1 and E2 strains extracted along radial lines
- To normalize across differing hole sizes, strains plotted against **R/a**
    - **R =** radial distance of strain extraction point
    - **a =** radius of expanded/reamed hole
- Strains plotted for each coupon, then averaged across coupons



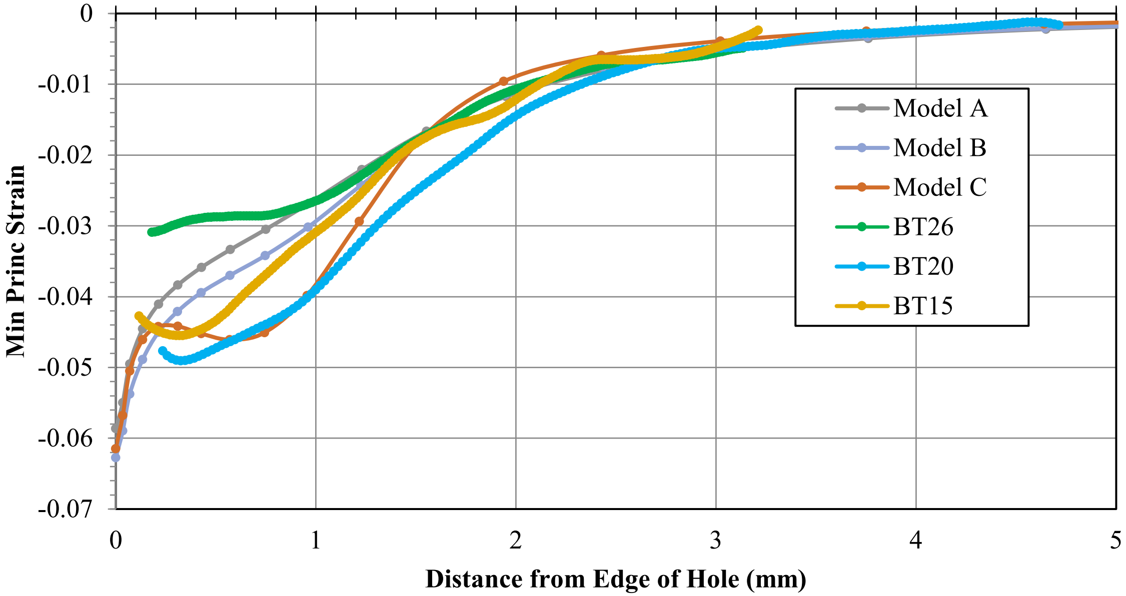
DIC vs FEA: Entry Face Strain Data

Al2024 DIC vs FEA – 0° - *Entry*

Max Princ Strain on Entrance Face 0 degrees



Min Princ Strain on Entrance Face 0 degrees



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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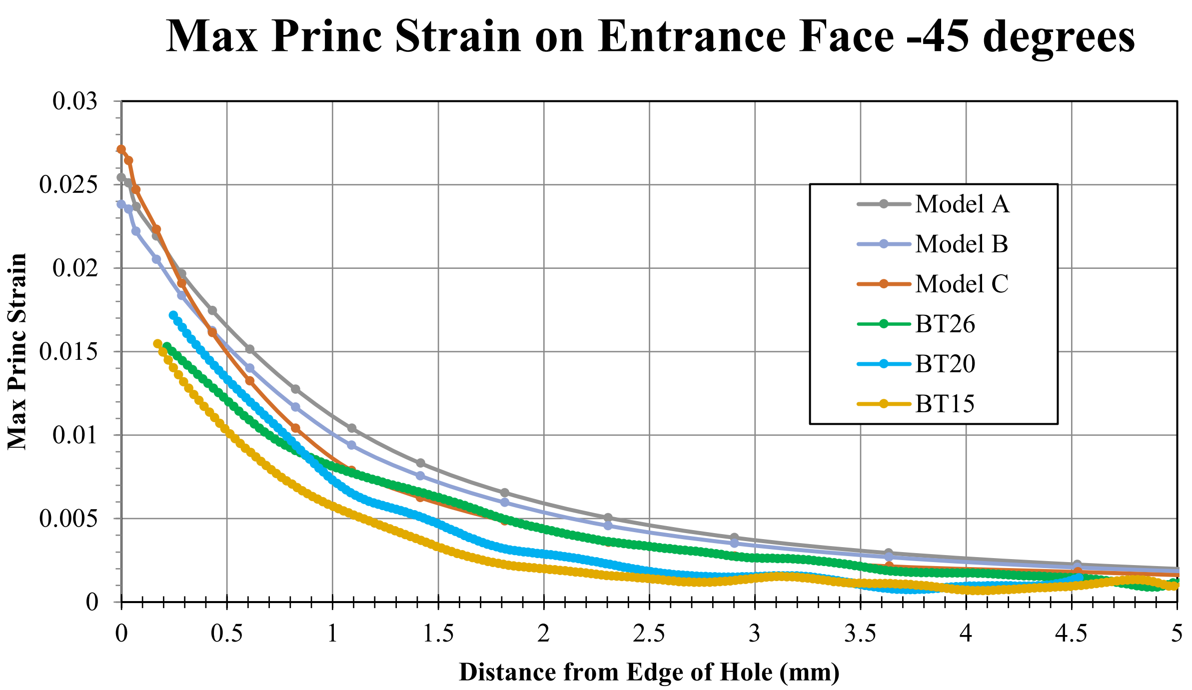
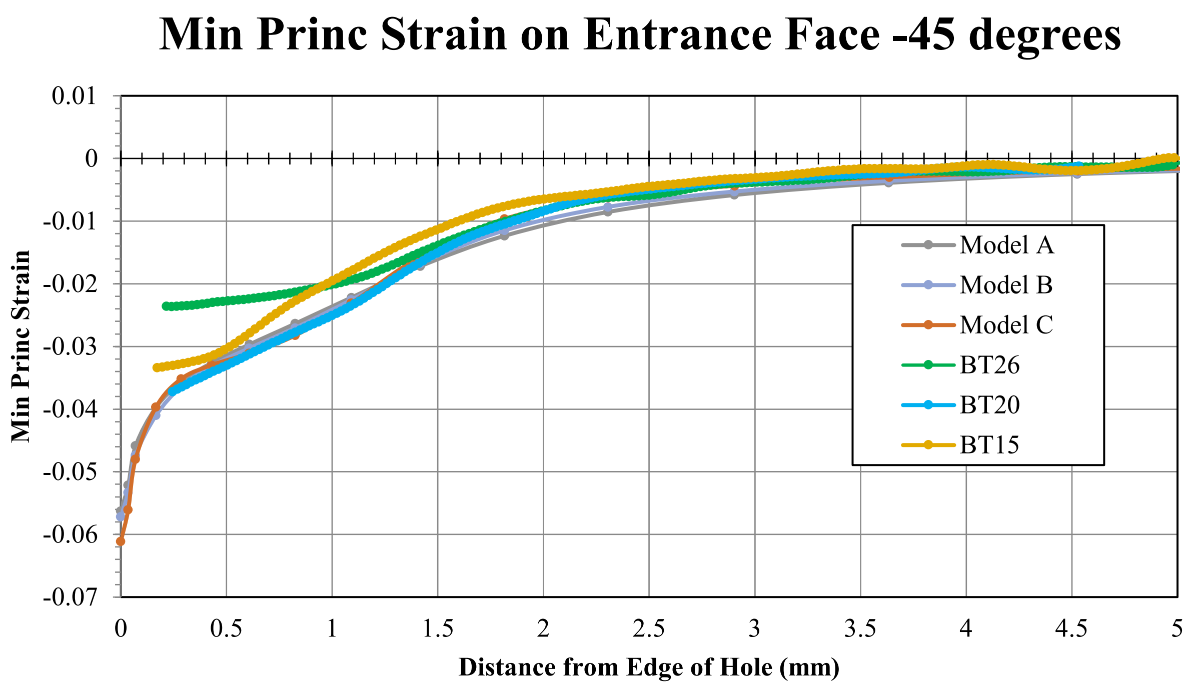
Al2024 DIC vs FEA - 45 ° - *Entry*





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

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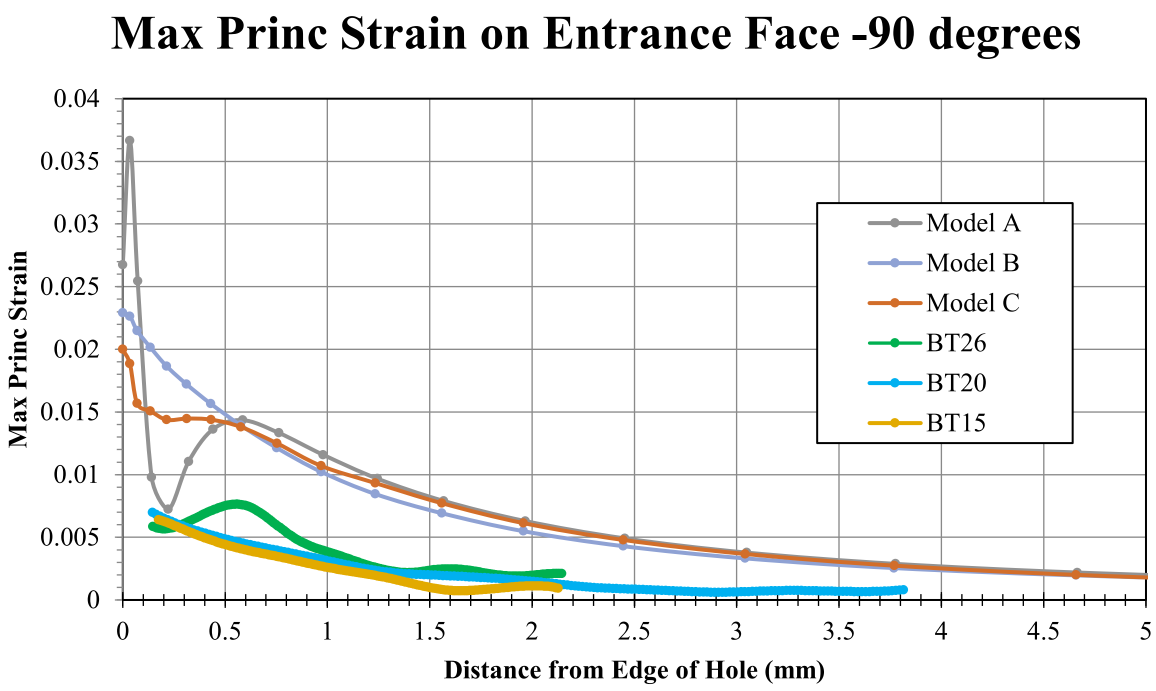
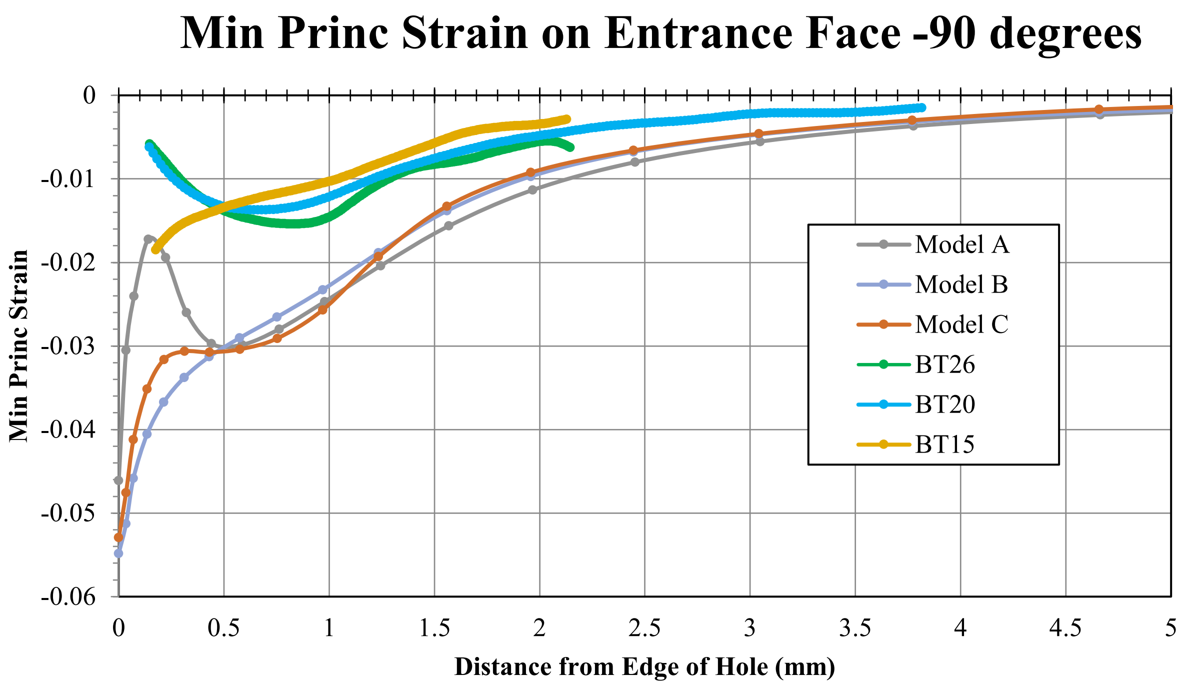
Al2024 DIC vs FEA - 90 ° - *Entry*

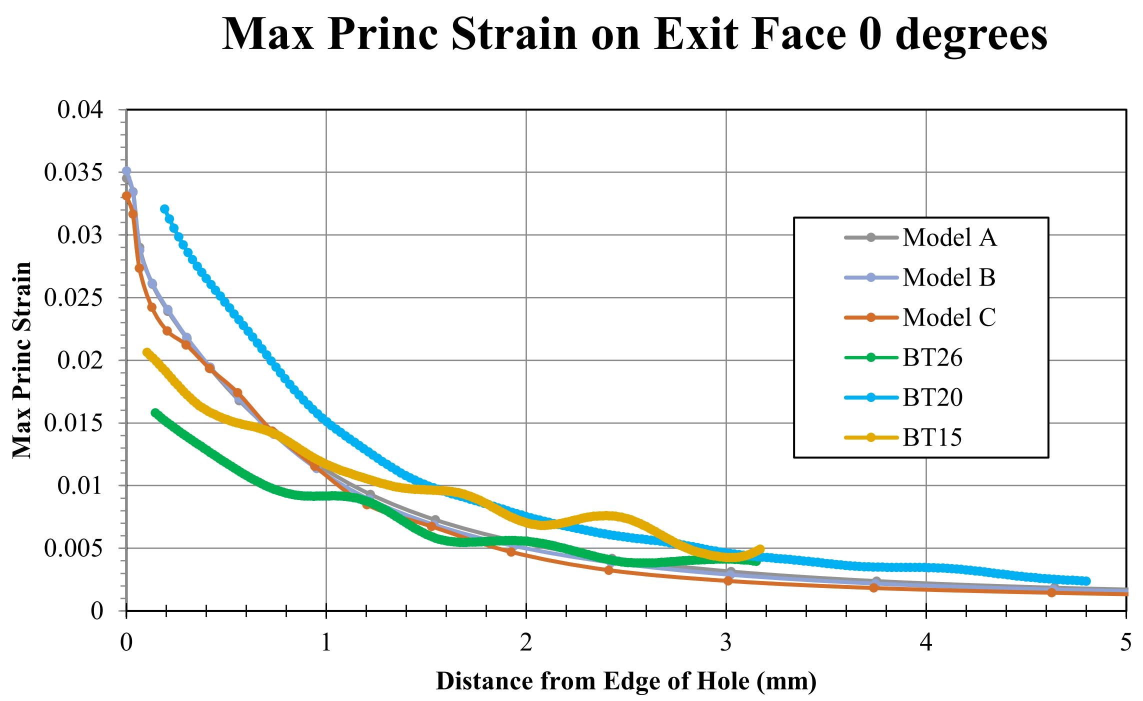


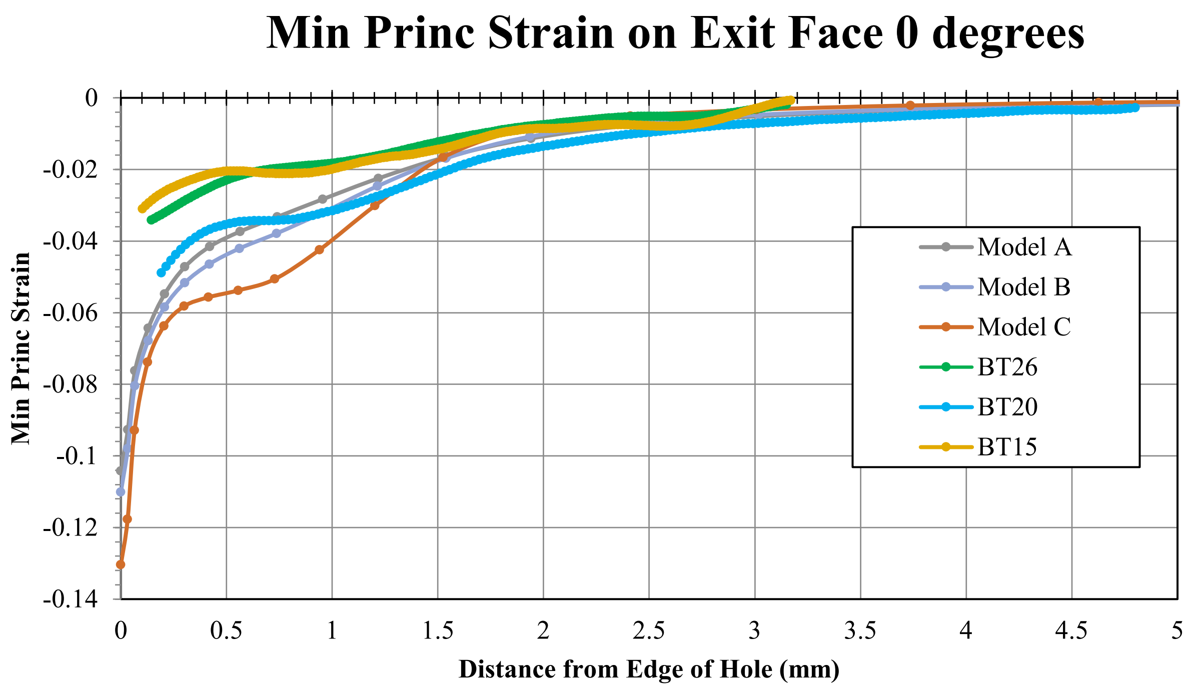


BT26 (starting diam 0.2380 in)
BT15 (starting diam 0.2376 in)
BT20 (starting diam 0.2359 in)

DIC vs FEA: Exit Face Strain Data

Al2024 DIC vs FEA – 0° - *Exit*





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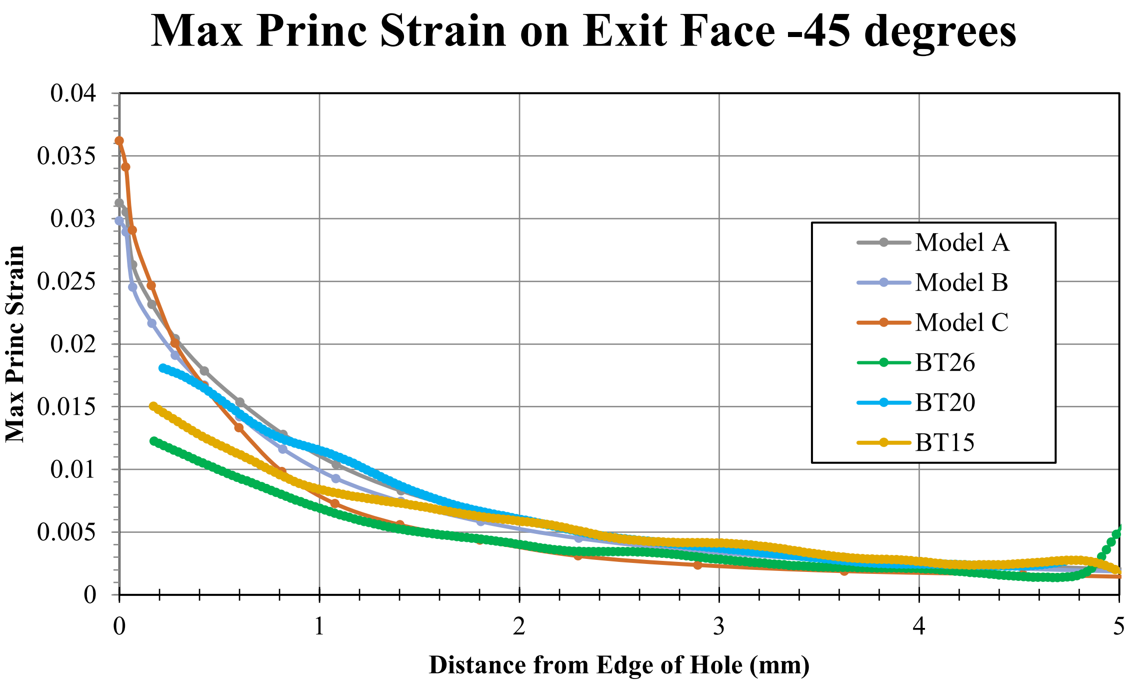
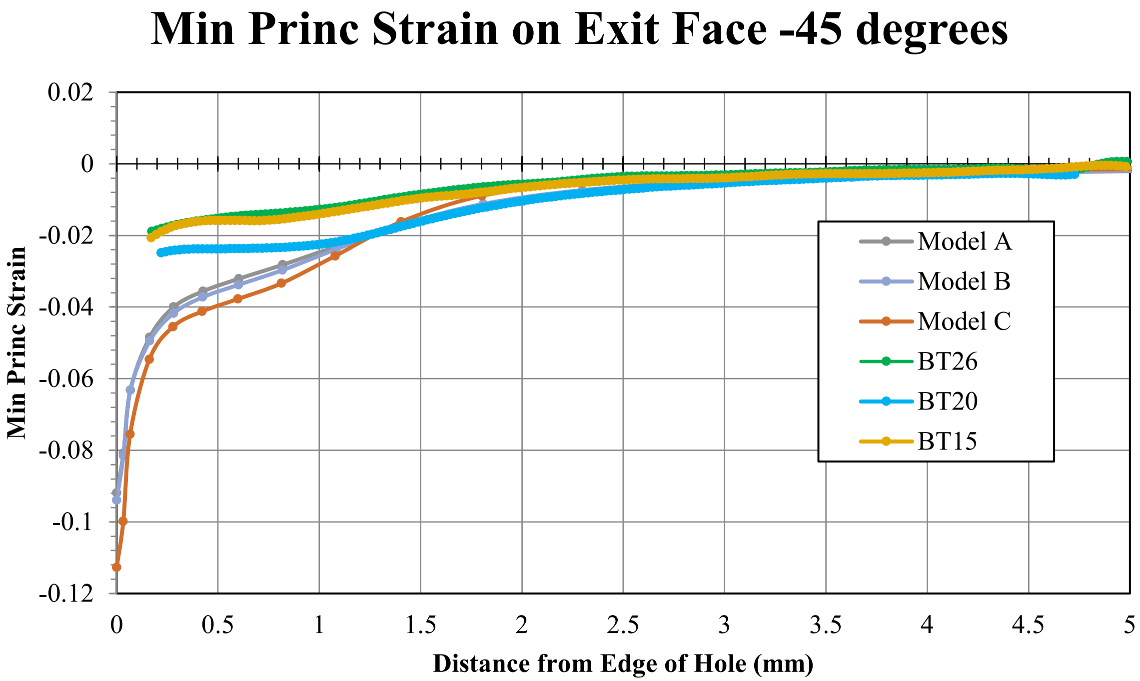
Al2024 DIC vs FEA - 45 ° - *Exit*





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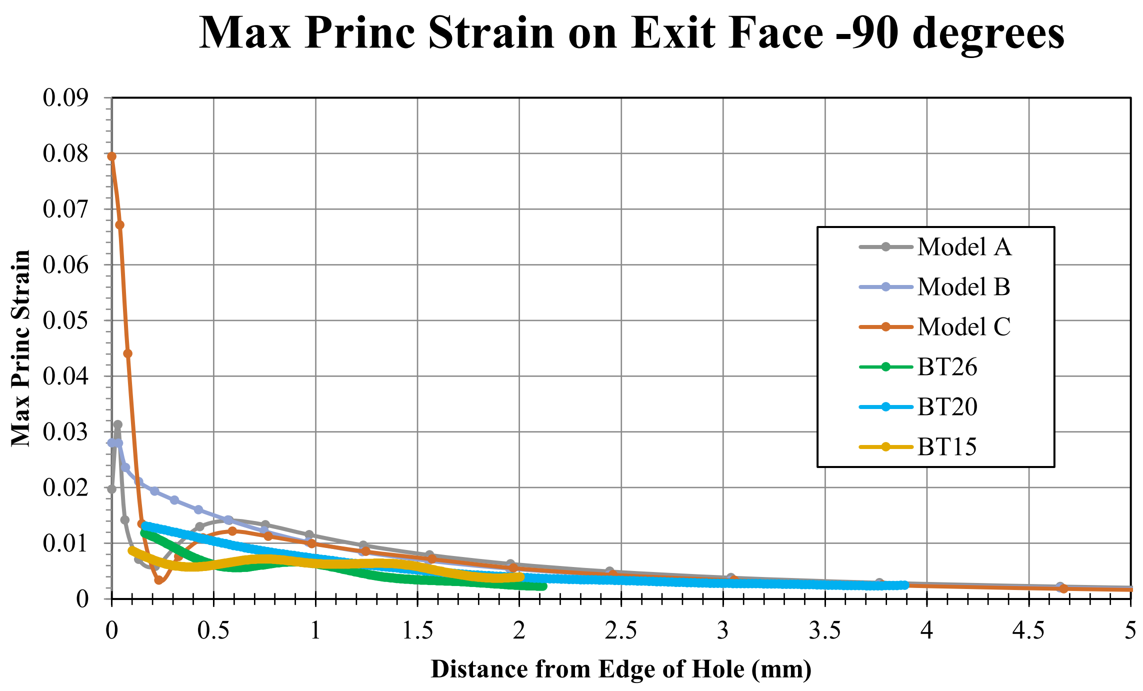
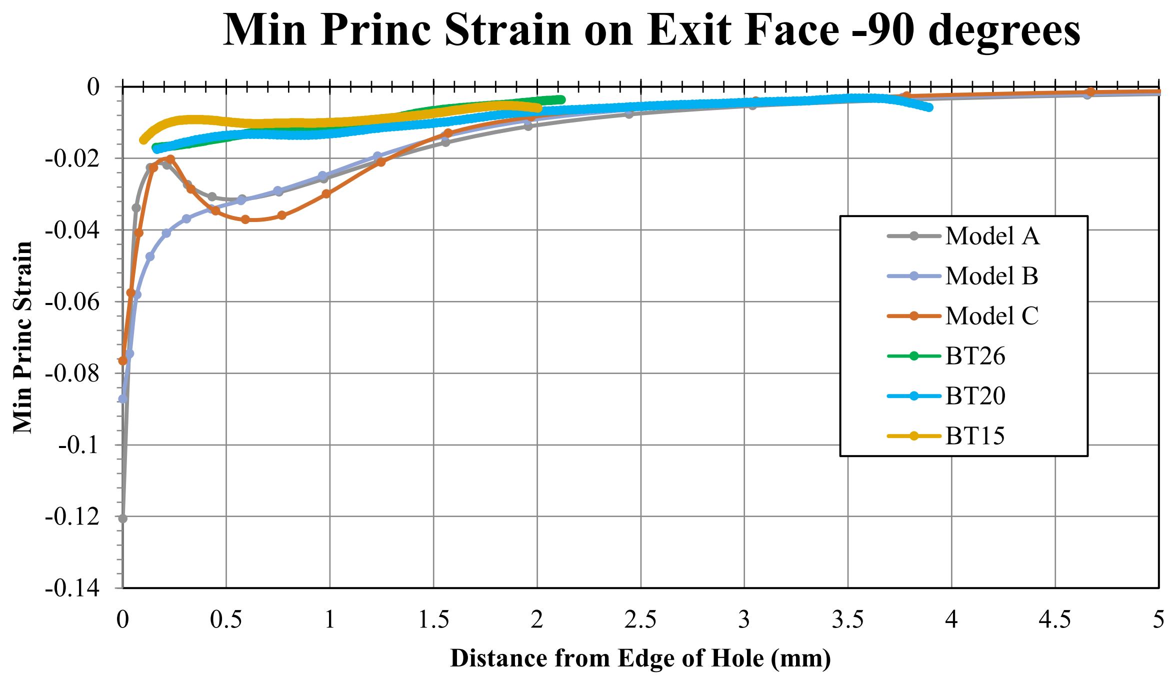
BT20 (starting diam 0.2359 in)

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

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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

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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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Update on NDE for Cold Working Verification and Validation

30 April 2025

Agenda

Background

Program Overview

NDE Methods

- Screening
- Evaluation
- LFEC in-hole

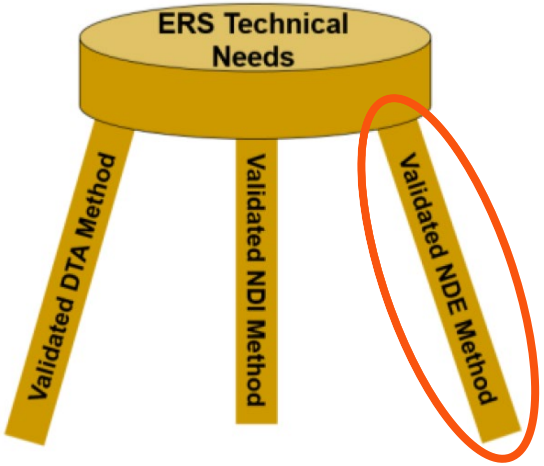
NDE Results

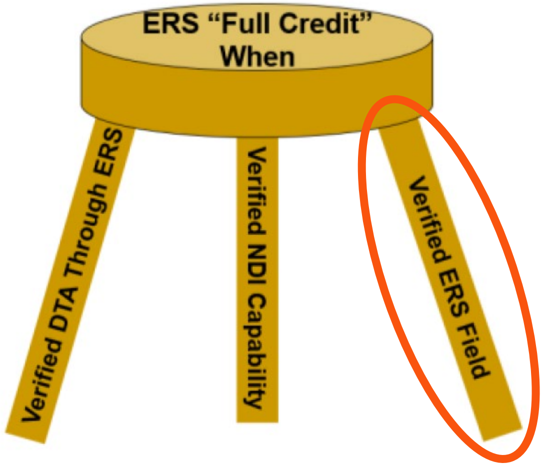
UT Demonstrations

Background

Significance of Problem

- Extensive experience applying hole cold expansion (Cx) to extend fatigue life and inspection intervals
- Critical fastener holes are the primary driver for structural inspections
  - ~70% to 90% of the fatigue critical locations on the airframe, whereas 25% to 40% are Cx'd
- Current "partial credit" benefit is due to perceived risk of missed or incorrectly Cx'd holes
  - Quality assurance tools to ensure the correct processing occurred at the correct locations are necessary to reach "full credit"
- Implementing a "full-credit" approach has a potential for tremendous impact on reducing maintenance costs for most USAF, other military, and commercial platforms as Cx has been applied widely to all types of aircraft (tactical, transport, and surveillance)
- Development of NDE technologies for Cx holes will play a critical role achieving "full credit"

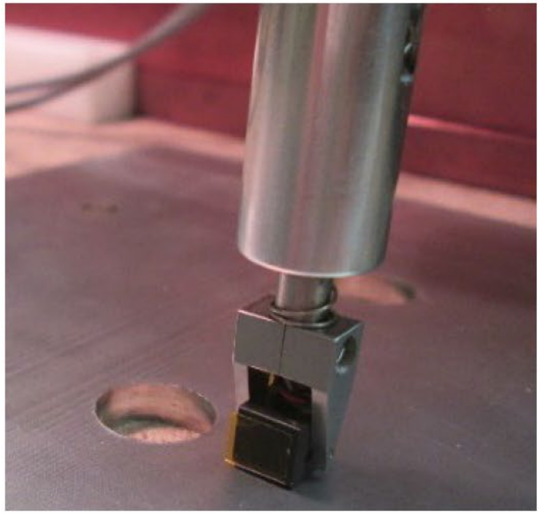


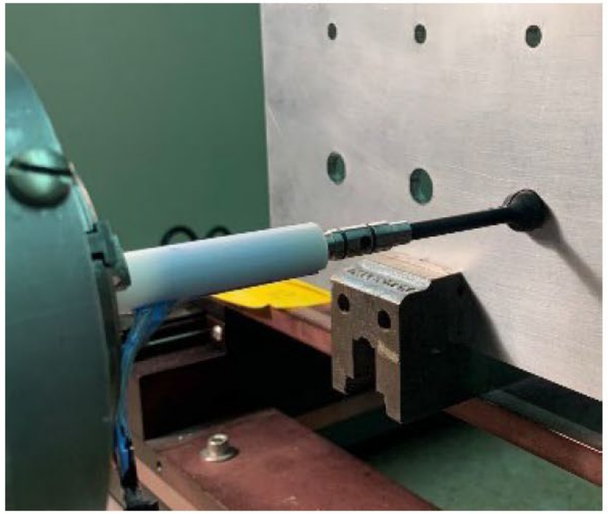


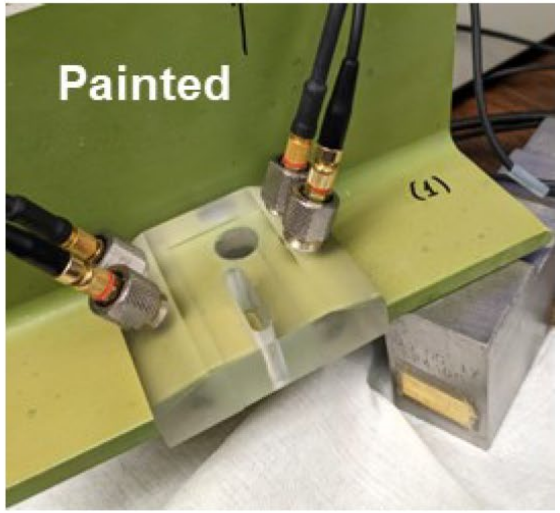
AFRL Core Funded Program

AFRL Core Funded Program

- Developed & optimized prototype NDE techniques for QA of Cx residual stress
- Identified and evaluated key confounding factors
- Focused on straight shank holes, 2024 and 7075 aluminum alloys
- Down-selected to three NDE technologies
  - ET surface scan probe, LFEC in-hole probe, Longitudinal critically refracted (LCR) UT probe
- Program completion March 2023







Current SBIR Program

Leveraging results from the AFRL core funded effort, this program will mature, expand, and implement NDE technologies to meet the quality assurance needs for Cx fastener holes

Key Objectives

- Mature NDE technologies developed on previous program
- Expand NDE technology applications to include countersunk and filled holes
- Optimize NDE technologies based on program testing
- Characterize reliability of NDE technologies
- Refine system components to support fielding of NDE technologies
- Validate and demonstration NDE technologies in relevant environment (TRL = 6)

Program Tasks

✓ Task 1: Program Kickoff
✓ Task 2: NDE Technology Assessment and Requirements Definition
✓ Task 3: NDE Technology Optimization
✓ Task 4: NDE Technology Evaluation
- Task 5: NDE Technology Implementation
- Task 6: NDE Technology Demonstration
- Task 7: Meetings and Reporting

Schedule

Period of Performance

- 3/6/24 – 12/4/25

Description	2024										2025											
	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Task 1																						
Program Kickoff																						
Task 2																						
NDE Technology Assessment and Requirements Development																						
Task 3																						
NDE Technology Optimization																						
Task 4																						
NDE Technology Evaluation																						
Task 5																						
NDE Technology Implementation																						
Task 6																						
NDE Technology Demonstration																						
Task 7																						
Meetings and reporting																						X

Current Date

UT Surface Scan

Utilizes longitudinal critically refracted (LCR) ultrasound wave to measure the amount of hoop stress around a hole

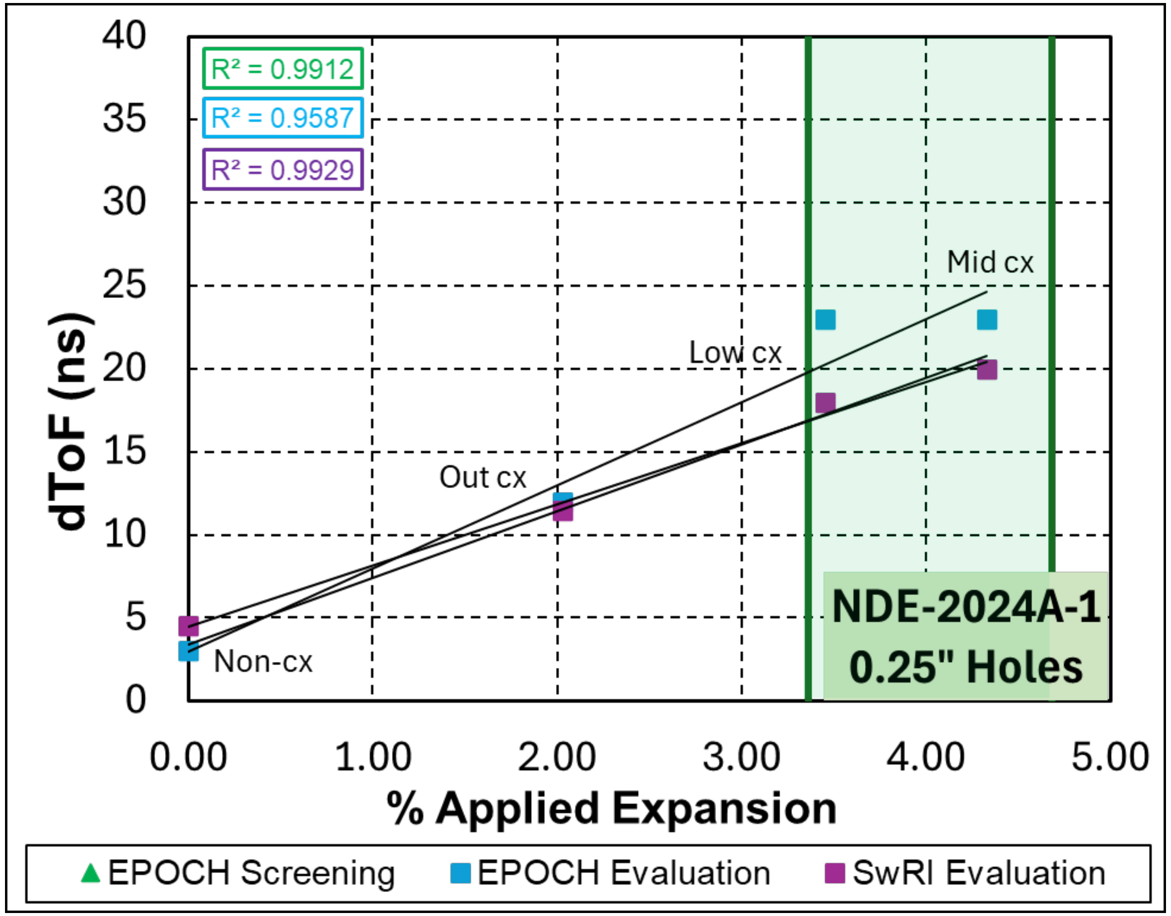
- Cross correlation of LCR waves provide a time-of-flight shift (dToF) when RS is present
- Scanning multiple points moving in radially self-normalizes the measurement
- Screening mode utilizes 2 points (baseline and max stress)
- Evaluation mode collects points along the entire radial path provide more detailed measurement

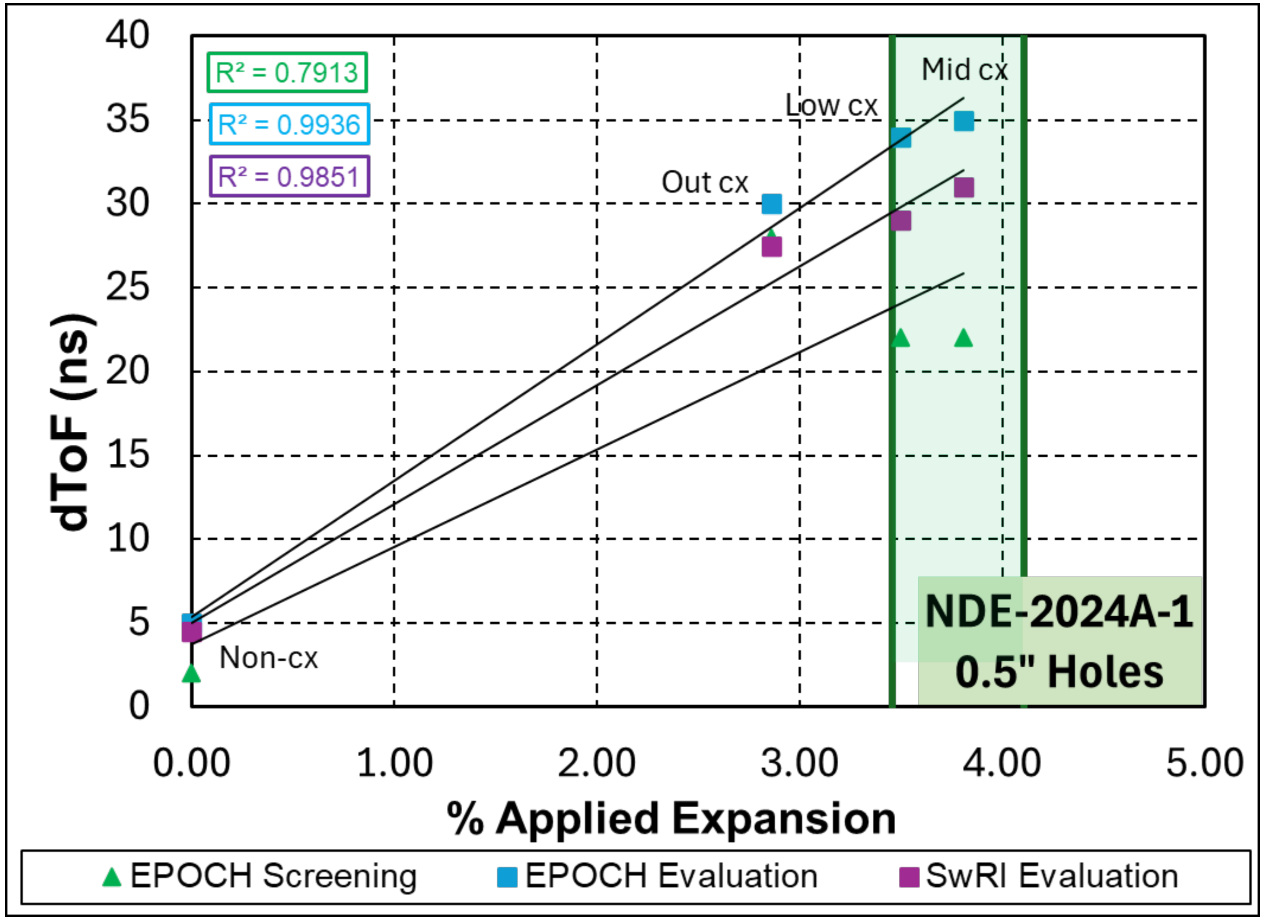
Equipment:

- COTS EPOCH650
- Custom SwRI system for higher fidelity data

UT System Demonstration Video

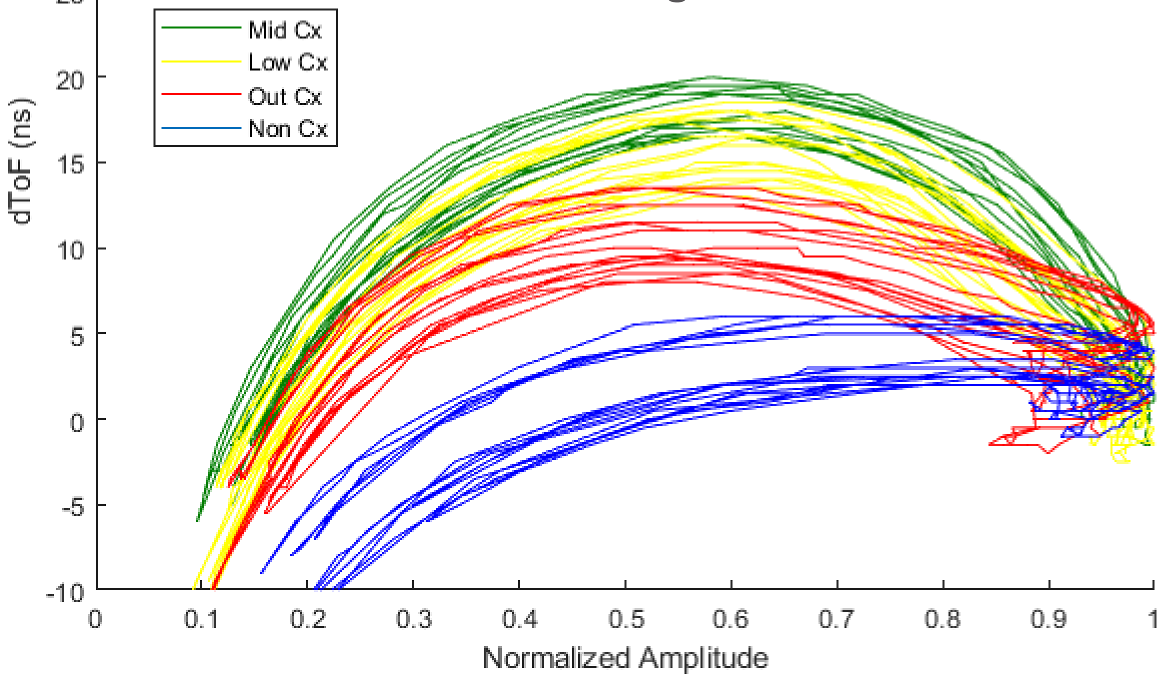
UT Data Results



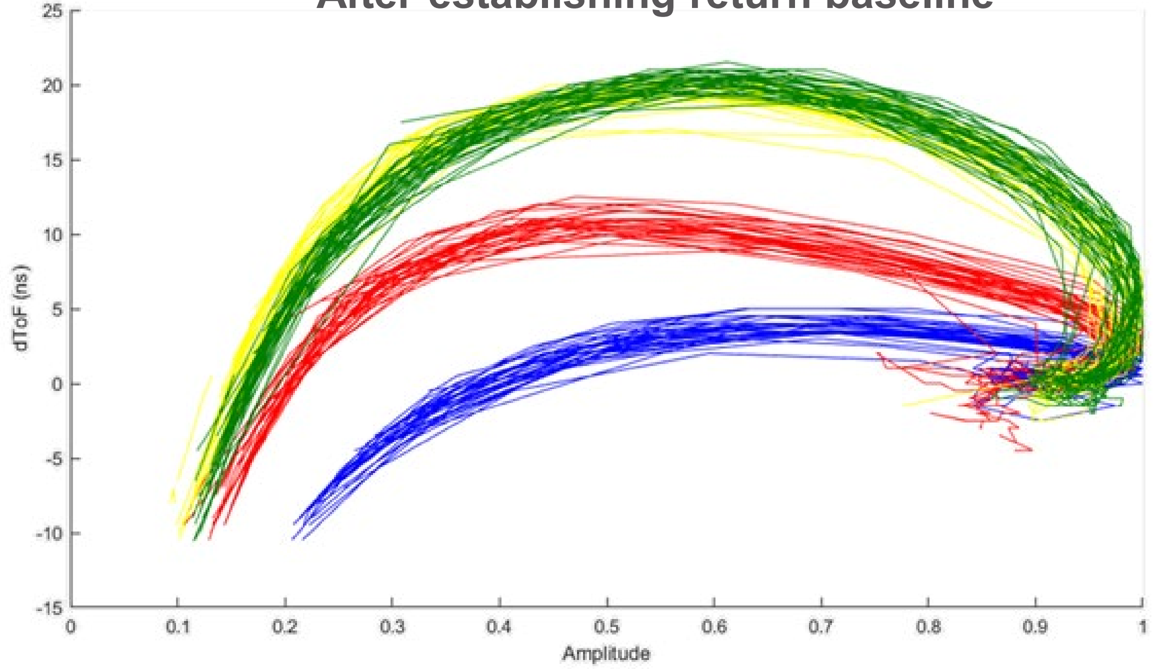


UT Data Results

Prior to establishing return baseline



After establishing return baseline



ET LFEC In-Hole Probe

Full map of conductivity response, similar to the B-Scan captured by the EVi and ECS-5 tools

Post processing tool to view data

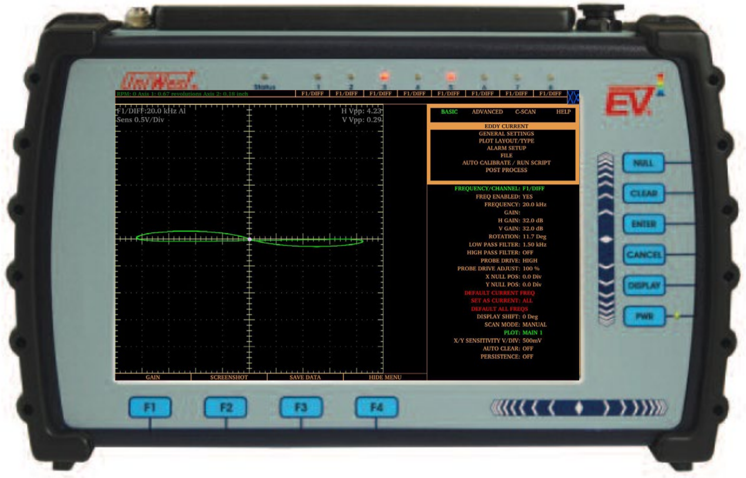
Capability to add post processing to EVi

Hardware components

- Eddy Current Instrument: EVi
- Bolt hole scanner: ECS-5s
- US-2871 and US-2863 LFEC probes

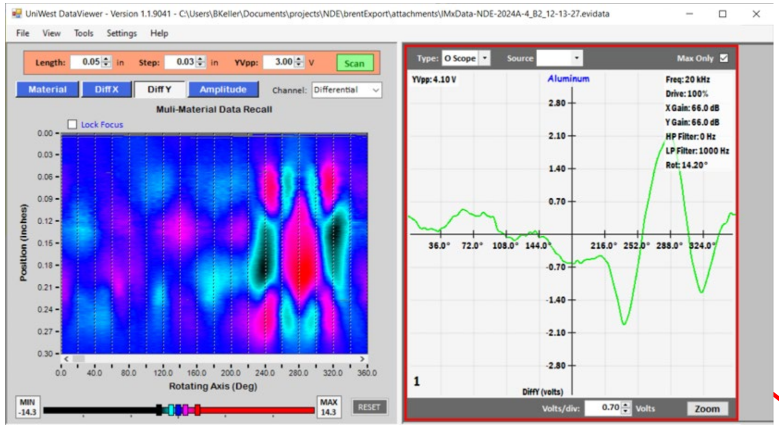
Procedure

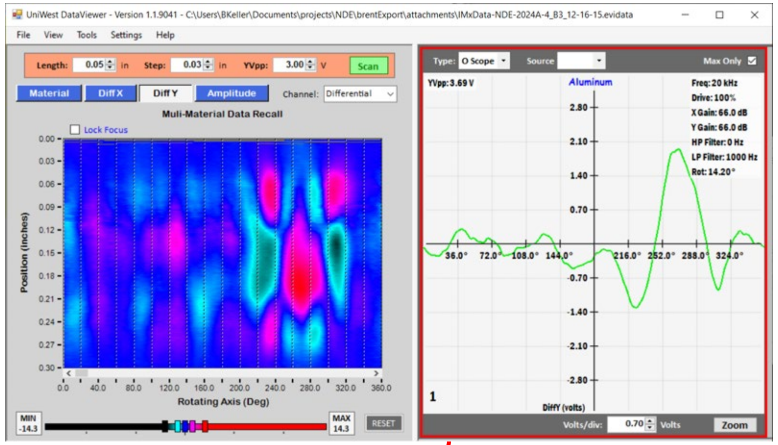
- Set angle based on liftoff
- Set gain horizontal to achieve 80% FSW
- Increase Gain by 24 dB to increase signal amplitude

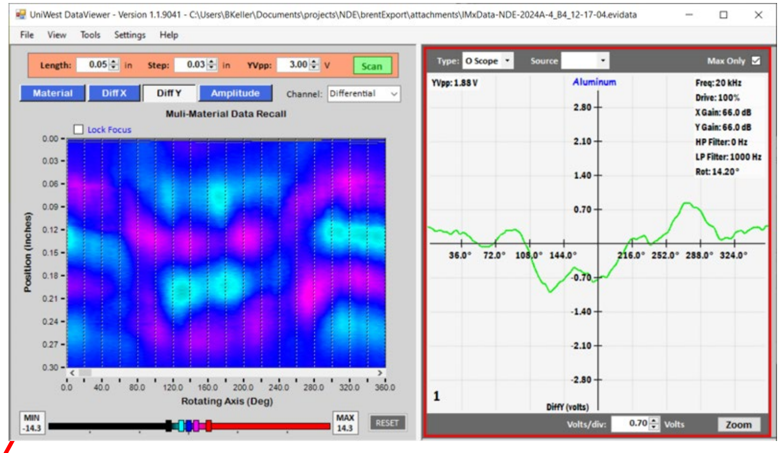


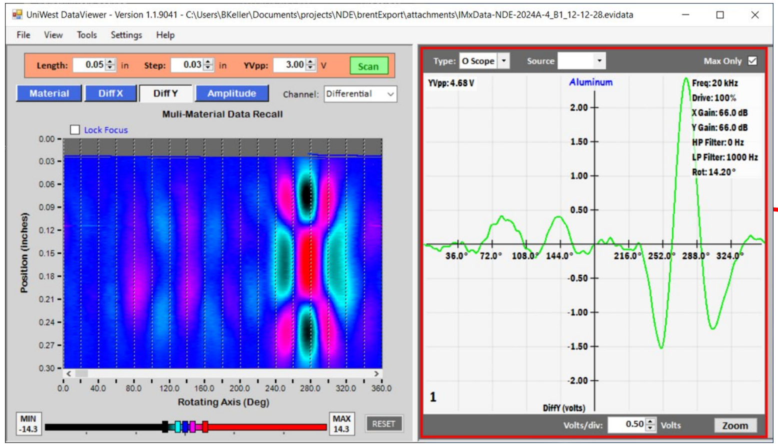
Task 4: NDE Technology Evaluation

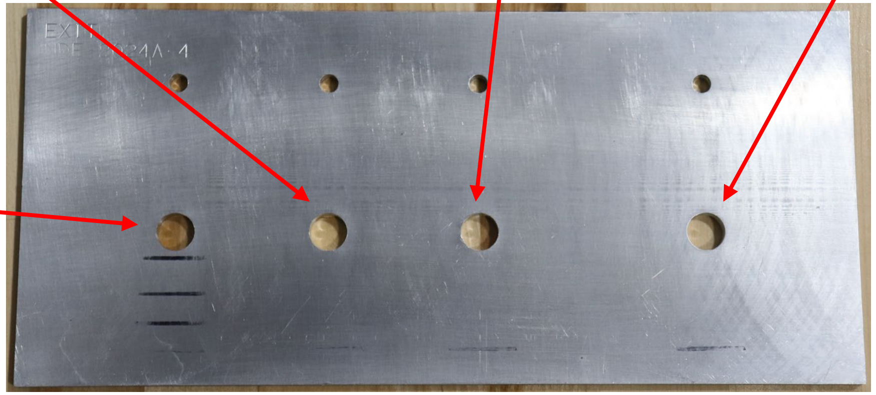
Sample: EXIT NDE2024A-4 Bottom
Thickness: 0.25”
Hole Diameter: 0.50”

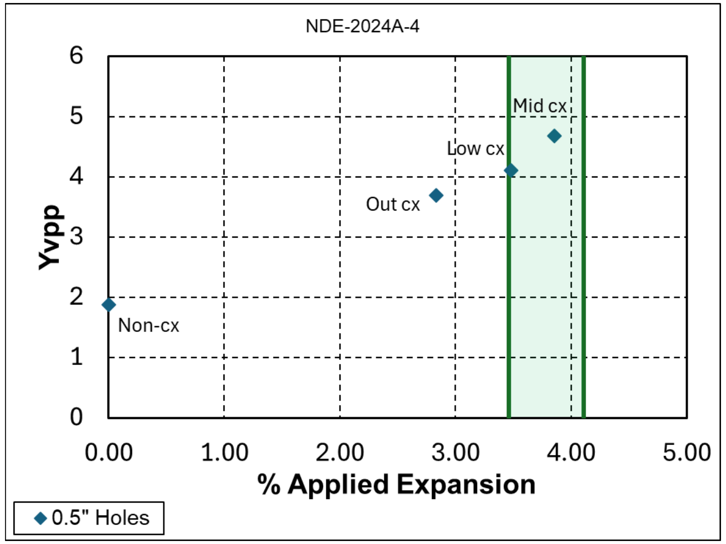












Conclusions

Current tasks remaining on SBIR Program

- Task 5: Technology Implementation-Ongoing refinements, new wedge designs, testing on a/c, etc…
- Task 6: Technology Demonstration

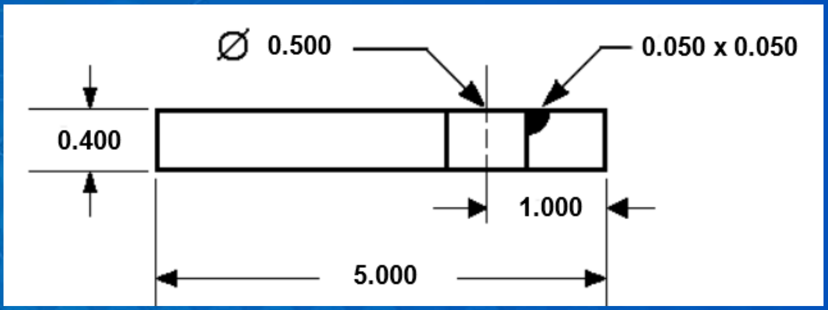
Upcoming program key tasks

- Task 2: NDE Technology Assessment for Titanium and Steel Applications
  - Utilize experience from previous programs to expand to aerospace titanium and steel materials
- Task 3: NDE Tech Assessment for Expanded Geometry Applications
  - Countersunk and filled hole conditions
  - Hole diameters ranging from 0.25 to 1.0 inch
  - Material thicknesses from 0.20 to 1.0 inch
- Task 6: NDE Technology Validation Study
  - Probability of Detection (PoD) Study

QUESTIONS?

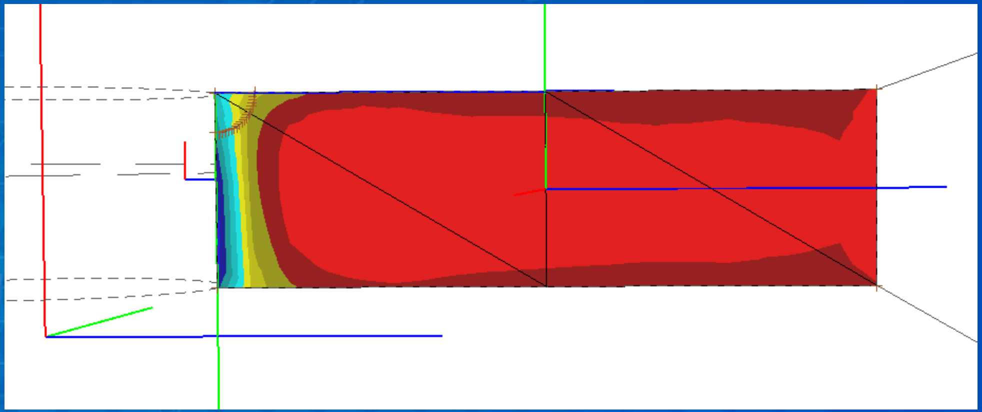
Damage tolerance inputs

- Initial flaw
- Geometric parameters
  - Width
  - Thickness
  - Hole diameter
  - Edge distance
- Material properties
  - Crack growth rates
  - Fracture toughness
- Spectrum loading
- Detectable flaw size



Damage tolerance inputs for Cx hole

- Initial flaw
- Residual stress field
- Geometric parameters
  - Width
  - Thickness
  - Hole diameter
  - Edge distance
- Material properties
  - Crack growth rates
  - Fracture toughness
- Spectrum loading
- Detectable flaw size



DT inputs feeding risk inputs in PROF

- Initial flaw → EIFS (or IDS) distribution
- Geometric parameters
  - Width
  - Thickness
  - Hole diameter
  - Edge distance
- Material properties
  - Crack growth rates

  (Geometric parameters and crack growth rates →) Deterministic crack growth curve
  - Fracture toughness → Toughness distribution
- Spectrum loading → Peak stress/flight distribution
- Detectable flaw size → POD distribution

DT inputs feeding risk inputs in PROF

- Initial flaw → EIFS (or IDS) distribution — DOMINANT
- Geometric parameters
  - Width
  - Thickness
  - Hole diameter
  - Edge distance
- Material properties
  - Crack growth rates

  (Geometric parameters and crack growth rates) → Deterministic crack growth curve
  - Fracture toughness → Toughness distribution
- Spectrum loading → Peak stress/flight distribution
- Detectable flaw size → POD distribution

Cx DT inputs feeding risk inputs

Cx DT inputs		Risk inputs
▪ Initial flaw	→	▪ EIFS (or IDS) distribution
▪ Residual stress field		▪ ??????
▪ Geometric parameters – Width – Thickness – Hole diameter – Edge distance ▪ Material properties – Crack growth rates	→	▪ Deterministic crack growth curve
– Fracture toughness	→	▪ Toughness distribution
▪ Spectrum loading	→	▪ Peak stress/flight distribution
▪ Detectable flaw size	→	▪ POD distribution

How do we incorporate RS into risk?

- Option 1: Incorporate impact of (minimum?) residual stress into EIFS distribution and deterministic crack growth curve
  – Pro: Allows us to use existing PROF framework
  – Con: Ignores the variability in the crack growth evident with different amounts of RS

- Option 2: Incorporate distribution of RS field into analysis, making the crack growth curve probabilistic
  – Pro: Much more realistic given the increased variability in growth with RS
  – Con: Need to understand the sensitivity from expansion to RS field to crack growth (What do we use as our random variable?)

ERSI Risk Analysis Break Out

Risk Analysis with Residual Stresses

Personal Experiences

- Performing risk analyses at structural locations that have accounted for residual stresses does not provide a great benefit if significant inspection data is not available to adjust the durability life
  - Inspections are managed using a durability flaw size
  - Risk cannot assume a smaller flaw size without data

Residual Stresses in Cold-Worked Holes

- Develop a risk procedure that utilizes the cold-worked data (pressure variance, # of holes, possible missed holes) to provide statistical insights into the benefits of the cold work holes
- I believe that the recorded data from engineered residual stress will continue to get better especially if we can show how that data will be used
  - Prove that the data is worth the additional cost of the tools

Futures Risk Analysis Topics and Projects

- What should the risk analysts be doing to help the ERSI team?
- Any ideas and topics that we should think about over the next year?

Risk Analysis Logic Tree Development

BLUF

- Develop an industry wide logic tree for handling various degrees of data at risk analysis locations
- Utilize coupon testing data (Scott Carlson) to create data sets that represents each portion of the logic tree
- Perform studies on the data sets to provide guidelines for defining the inputs
  - MLE vs MOM by median rank
  - Linear vs. non-linear regression
  - Distribution types

Contents

- Risk Scenarios
  - No inspection data
  - Inspection data no findings
    - Less than 10 (or some number)
    - More than 10
    - Multiple inspections
  - Inspection data with less than 3 findings
    - Is it possible to define a failure distribution/EIFSD
  - Inspection data with more than 3 findings
  - Inspection data with findings without details
  - Inspection data with great details
  - **More scenarios that I have not thought about**

Available Data

- 20+ coupons without engineered flaws and fractography
  - Multiple coupons with identical conditions (loading, grain direction, geometry)
- Plan would be to generate multiple datasets using both coupon data and fabricated data to represent each of the risk scenarios and work through the scenarios separately or as a group to develop a generic logic tree for analyst to reference when performing a risk analysis.
- The goal for the logic tree would be to create a best practices document for risk analyst to follow when performing structural risk analyses.