ERSI

ENGINEERED RESIDUAL STRESS IMPLEMENTATION (ERSI) WORKSHOP 2017

Date: September 21 – 22, 2017
Location: Weber State University's Center for Continuing Education,
775 University Park Blvd., Clearfield, UT 84015

Thursday September 21 Agenda:

07:30-08:00 Arrive, Breakfast, Welcome and Review
- *Mr. Scott Carlson, Mr. Robert (Bob) Pilarczyk, Mr. Dallen Andrew*

Presentations by Leads Covering Progress:
- Presentation Designed for 30 min Presentation with 15 mins for Questions

08:00-08:45 **Integrator Review – Programmatic Overview and Roadmap**
- *Dr. T.J. Spradlin (USAF – AFRL)*

08:45-09:30 **Analytical Methods for Residual Stress Integration into Fatigue Predictions**
- *Mr. Robert (Bob) Pilarczyk (Hill Engineering, LLC.)*

09:30-09:45 BREAK

09:45-10:30 **Testing and Validation of Analytical Methods**
- *Dr. Tom Mills (Analytical Processes/Engineering Solutions, Inc. (AP/ES))*

10:30-11:15 **Quality Assurance and Data Capture**
- *Dr. Carl Magnuson (Texas Research Institute/Austin, Inc.(TRI-Austin)) & Mr. Hazen Sedgwick (USAF – A-10 ASIP)*

11:15-12:00 **Effects of Residual Stress on NDI Methods**
- *Mr. John Brausch (USAF – AFRL)*

12:00-13:00 LUNCH

13:00-13:45 **Risk Analysis and Uncertainty Quantification**
- *Mr. Lucky Smith, Ms. Laura Domyancic (Southwest Research Institute (SwRI)) and Dr. Juan Ocampo (St. Mary's University)*

13:45-14:30 **Residual Stress Process Simulation**
- *Mr. Keith Hitchman (Fatigue Technologies Incorporated (FTI))*

14:30-15:15 **Residual Stress Measurements**
- *Dr. Mike Hill (Hill Engineering, LLC.)*

15:15-1730 **Break into Groups for Discussion and Planning**
- Proposed Groups – Subcommittee Leads Will Coordinate Discussion
    - Analytical Methods for Residual Stress Integration into Fatigue Predictions
    - Testing and Validation of Analytical Methods
    - Residual Stress Process Simulation
    - NDI & Quality Assurance and Data Management
    - Risk Analysis and Uncertainty Quantification
    - Residual Stress Measurement

Friday September 22 Agenda:

07:30-08:00 **Welcome and Breakfast**

Presentations by Leads Covering Plans for Future Work for 2017 - 2018:

08:00-08:30 **Analytical Methods for Residual Stress Integration**
- *Mr. Robert (Bob) Pilarczyk (Hill Engineering, LLC.)*

08:30-09:00 **Residual Stress Measurements**
- *Dr. Mike Hill (Hill Engineering, LLC.)*

09:00-09:10 BREAK

09:10-09:40 **Effects of Residual Stresses on NDI Methods and Quality Assurance and Data Capture**
- *Mr. John Brausch (USAF – AFRL), Dr. Carl Magnuson (Texas Research Institute/Austin, Inc.(TRI-Austin)) & Mr. Hazen Sedgwick (USAF – A-10 ASIP)*

09:40-10:10 **Testing and Validation of Analytical Methods**
- *Dr. Tom Mills (Analytical Processes/Engineering Solutions, Inc. (AP/ES))*

10:10-10:40 **Residual Stress Process Simulation**
- *Mr. Keith Hitchman (Fatigue Technologies Incorporated (FTI))*

10:40-11:00 BREAK FOR LUNCH

11:00-11:30 **Risk Analysis and Uncertainty Quantification**
- *Mr. Lucky Smith & Ms. Laura Domyancic (Southwest Research Institute (SwRI)) and Dr. Juan Ocampo (St. Mary's University)*

11:30-12:00 **Integrator and Programmatic Review**
- *Dr. T.J. Spradlin (USAF – AFRL)*

12:10-13:00 **Review and Final Discussion of ERSI Efforts**
- *Mr. Scott Carlson, Mr. Robert (Bob) Pilarczyk, & Mr. Dallen Andrew*

1300 **Adjourn and Thank You!**

2017 Engineered Residual Stress Implementation (ERSI) Workshop

Held in Layton Utah

September 21 – 22, 2017

NAVAL AIR SYSTEMS COMMAND

FTI FATIGUE TECHNOLOGY

SwRI

LOCKHEED MARTIN

APES, INC.
analytical processes / engineered solutions

CLARKSON UNIVERSITY

THE UNIVERSITY OF UTAH

AIR FORCE RESEARCH LABORATORY

AIR FORCE LCMC

HILL ENGINEERING
Predict. Test. Perform.

THE UNIVERSITY OF CALIFORNIA UCDAVIS DAVIS

BOEING

AEROSPACE SYSTEMS DIRECTORATE

L3 communications

NRC·CNRC

NORTHROP GRUMMAN

AFGROW.NET

StMU

STRESSCHECK

TRI AUSTIN

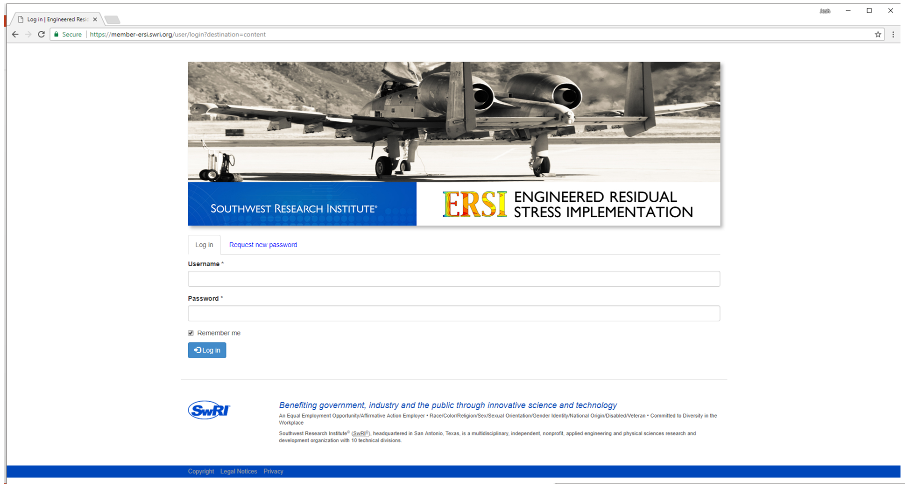
Australian Government
Department of Defence
Science and Technology

ARCONIC

Welcome to the 2017 ERSI Workshop

- Thank you all for coming!
  - Food and Funding
- Restrooms and Break Area are Upstairs
- Internet is Provided for Free as a Guest
- Agenda and Proposed Discussion Format
- Purpose Focused Discussion
  - What are the gaps?
  - What are the documents required?
- ERSI Website

ERSI Website



Username *

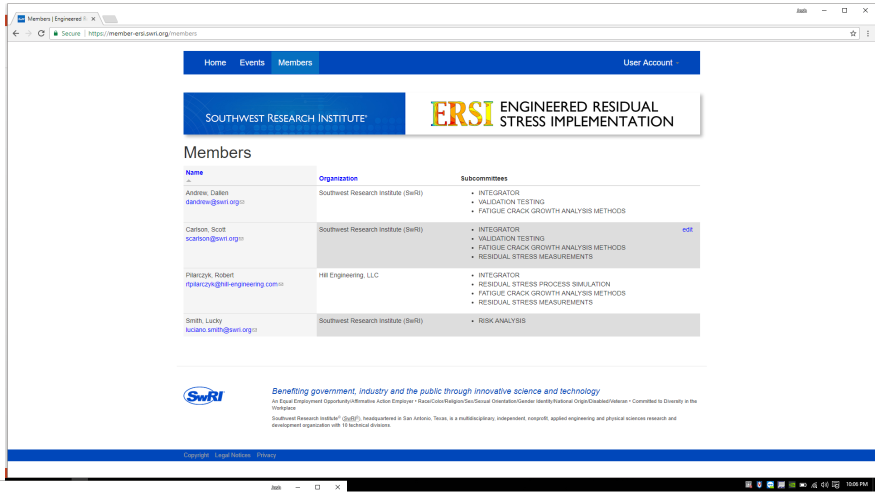
Password *

☑ Remember me

Benefiting government, industry and the public through innovative science and technology

An Equal Employment Opportunity/Affirmative Action Employer • Race/Color/Religion/Sex/Sexual Orientation/Gender Identity/National Origin/Disabled/Veteran • Committed to Diversity in the Workplace

Southwest Research Institute® (SwRI®), headquartered in San Antonio, Texas, is a multidisciplinary, independent, nonprofit, applied engineering and physical sciences research and development organization with 10 technical divisions.



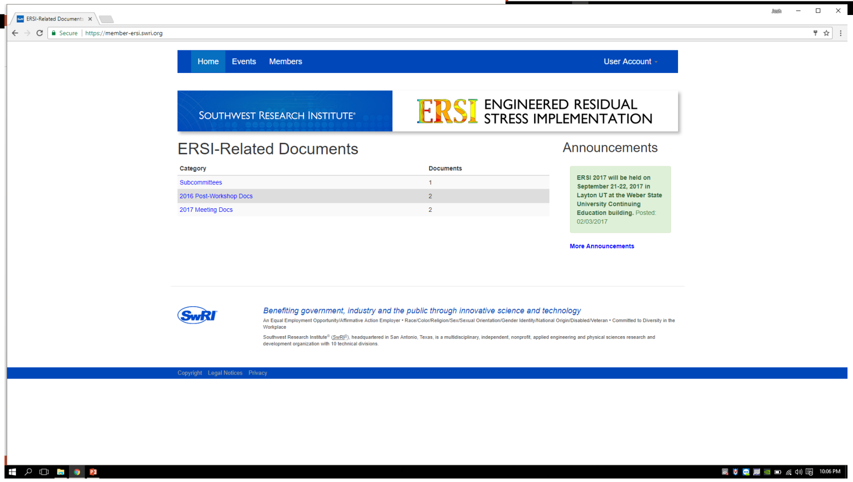
Members

Name	Organization	Subcommittees
Andrew, Dallen dandrew@swri.org	Southwest Research Institute (SwRI)	INTEGRATOR VALIDATION TESTING FATIGUE CRACK GROWTH ANALYSIS METHODS
Carlson, Scott scarlson@swri.org	Southwest Research Institute (SwRI)	INTEGRATOR VALIDATION TESTING FATIGUE CRACK GROWTH ANALYSIS METHODS RESIDUAL STRESS MEASUREMENTS
Pilarczyk, Robert rtpilarczyk@hill-engineering.com	Hill Engineering, LLC	INTEGRATOR RESIDUAL STRESS PROCESS SIMULATION FATIGUE CRACK GROWTH ANALYSIS METHODS RESIDUAL STRESS MEASUREMENTS
Smith, Lucky luciano.smith@swri.org	Southwest Research Institute (SwRI)	RISK ANALYSIS

Benefiting government, industry and the public through innovative science and technology

An Equal Employment Opportunity/Affirmative Action Employer • Race/Color/Religion/Sex/Sexual Orientation/Gender Identity/National Origin/Disabled/Veteran • Committed to Diversity in the Workplace

Southwest Research Institute® (SwRI®), headquartered in San Antonio, Texas, is a multidisciplinary, independent, nonprofit, applied engineering and physical sciences research and development organization with 10 technical divisions.



ERSI-Related Documents

Category	Documents
Subcommittees	1
2016 Post-Workshop Docs	2
2017 Meeting Docs	2

Announcements

ERSI 2017 will be held on September 21-22, 2017 in Layton UT at the Weber State University Continuing Education building. Posted: 02/03/2017

More Announcements

Benefiting government, industry and the public through innovative science and technology

An Equal Employment Opportunity/Affirmative Action Employer • Race/Color/Religion/Sex/Sexual Orientation/Gender Identity/National Origin/Disabled/Veteran • Committed to Diversity in the Workplace

Southwest Research Institute® (SwRI®), headquartered in San Antonio, Texas, is a multidisciplinary, independent, nonprofit, applied engineering and physical sciences research and development organization with 10 technical divisions.

Purpose of ERSI Workshop

1. To identify and **lay out a road map for the implementation of engineered deep residual stress** which can be used in the calculation of initial and recurring inspection intervals for fatigue and fracture critical aerospace components.
2. To **highlight gaps in the stat-of-the-art** and define how those gaps will be filled.
3. Then to define the most **effective way to document requirements and guidelines** for fleet-wide implementation.

Vision of ERSI Working Group

Within 3-7 years have developed a framework for fleet-wide implementation of a more holistic, physics-based approach for taking analytical advantage of the deep residual stresses field, induced through the Cold Expansion process, into the calculations of initial and recurring inspection intervals for fatigue and fracture critical aerospace components. Then move from there to other deep residual stress inducing processes, like Laser Shock Peening , and Low Plasticity Burnishing.

Integrator Review

AFRL HERITAGE | 1917–2017

100 YEARS OF U.S. AIR FORCE SCIENCE & TECHNOLOGY

21 September, 2017

TJ Spradlin, Ph.D.
Structures Technology (RQVS)
Air Force Research Laboratory

Integrity ★ Service ★ Excellence

Outline

- 2017 In-review
- The 3 Pillars of ERSI
- Pursuing Policy Change
- Long Term Organization
- Research Dependency Structure
- Structural Community Awareness

2017 In-review: The Good

- **Technical Progress**
  - Sub-committee activity has been productive
- **Growing Community**
  - 56% increase in active members in one year!
- **ASIP Awareness**
  - Increased ERSI visibility in more program offices
  - Key personnel involved in SB creation

2017 In-review: The Not-So Good

- **Inter-committee Communication**
  - Sub-committee activities not well advertised within the working group
    - Nearly missed opportunities
- **Task Coordination**
  - Many hands make light work*

The 3 Pillars of ERSI

- **Validated DADTA Methods**
  - Physics based approach
  - 0.05” rogue flaw & explicit residual stress field
  - Demonstrate improvement over current approach
- **Quality Assurance (QA)**
  - Determine acceptance criteria
    - Linked to assumed residual stress minimums
- **Non-destructive Inspection (NDI)**
  - Effect of residual stresses on each NDI technique

Pursuing Policy Change: The What

- **Structures Bulletin**
  - Generalized guide to approach a class of problems
  - Concise examples for clarification
  - No requirement of exact software/techniques
- **Best-practices Guide**
  - In-depth technical detail behind why certain approaches are used
  - Substantiating document for a bulletin to reference
  - Enables practitioners
    - List of requirements and technical specifics for completing them

Pursuing Policy Change: The How

- **Structures Bulletin**
  - Drafted by anyone in the defense community
  - Finalized by USAF
  - Living document as requirements evolve
- **Best-practices Guide**
  - Technical community contributes and shapes
  - In-depth technical detail

Distribution A: Approved for Public Release; 19 September 2017; 88ABW-2017-4528

Long Term Organization: Best Practices Guide

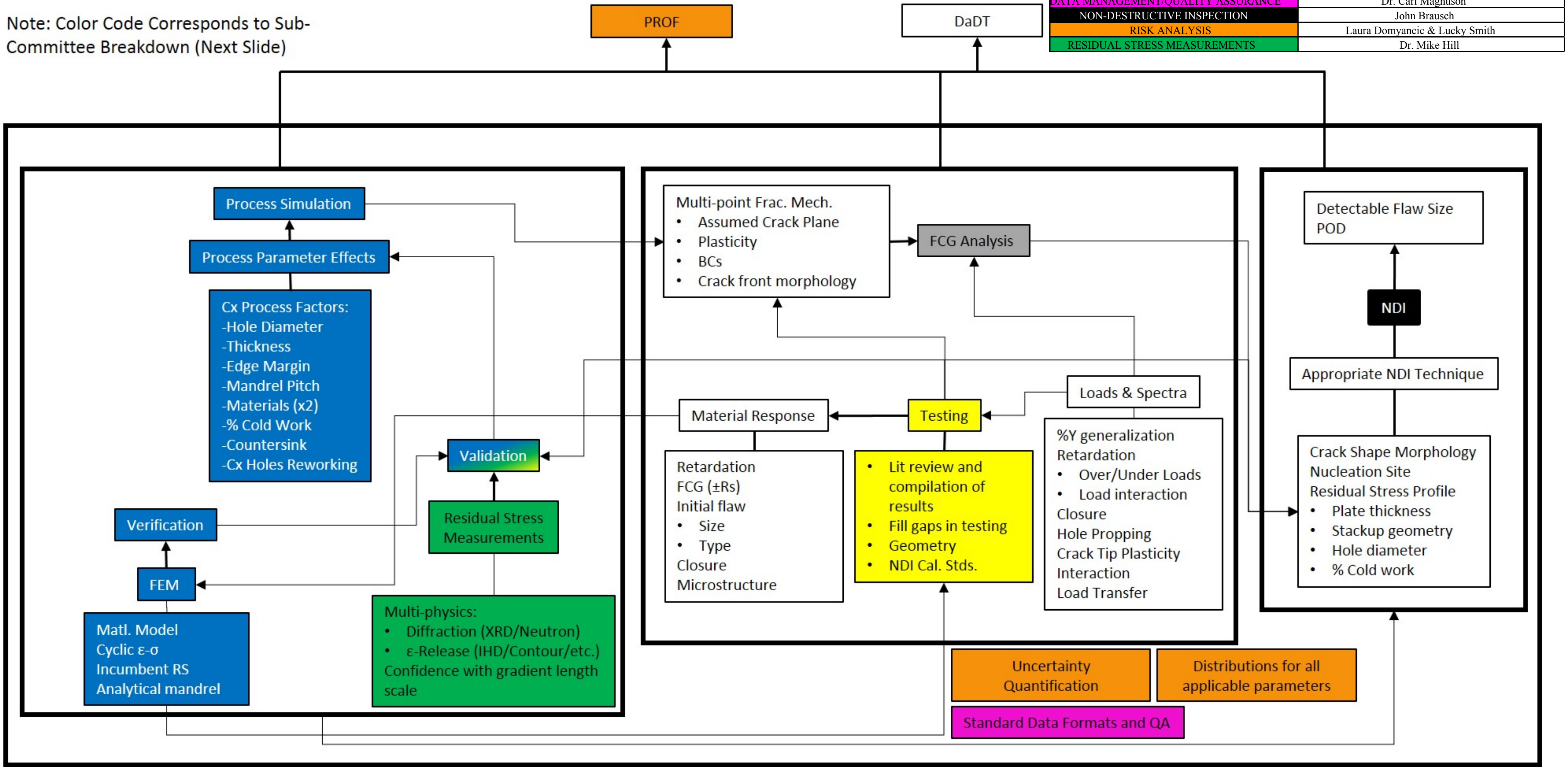
- **ASTM E0804**
  - How
    - Structural Applications Sub-Committee
    - Participate as a task group
  - Why
    - Neutral community
      - Forum of equals
      - Agnostic to funding
    - Long-term stability
    - Internationally welcoming
  - Who
    - Anyone
      - Only ASTM members can vote
    - Broadest base of technical expertise possible

Distribution A: Approved for Public Release; 19 September 2017; 88ABW-2017-4528

Technical Dependencies: Now

Subcommittee	Chair
INTEGRATOR	Dr. Mark Thomsen, Dr. TJ Spradlin, Dr. Dale Ball
VALIDATION TESTING	Dr. Tom Mills
RESIDUAL STRESS PROCESS SIMULATION	Keith Hitchman
FCG ANALYSIS METHODS	Robert Pilarczyk
DATA MANAGEMENT/QUALITY ASSURANCE	Dr. Carl Magnuson
NON-DESTRUCTIVE INSPECTION	John Brausch
RISK ANALYSIS	Laura Domyancic & Lucky Smith
RESIDUAL STRESS MEASUREMENTS	Dr. Mike Hill

Note: Color Code Corresponds to Sub-Committee Breakdown (Next Slide)



PROF

DaDT

Process Simulation

Process Parameter Effects

Cx Process Factors:
-Hole Diameter
-Thickness
-Edge Margin
-Mandrel Pitch
-Materials (x2)
-% Cold Work
-Countersink
-Cx Holes Reworking

Validation

Verification

Residual Stress Measurements

FEM

Matl. Model
Cyclic ε-σ
Incumbent RS
Analytical mandrel

Multi-physics:
- Diffraction (XRD/Neutron)
- ε-Release (IHD/Contour/etc.)

Confidence with gradient length scale

Multi-point Frac. Mech.
- Assumed Crack Plane
- Plasticity
- BCs
- Crack front morphology

FCG Analysis

Loads & Spectra

Material Response

Testing

Retardation
FCG (±Rs)
Initial flaw
- Size
- Type

Closure
Microstructure

- Lit review and compilation of results
- Fill gaps in testing
- Geometry
- NDI Cal. Stds.

%Y generalization
Retardation
- Over/Under Loads
- Load interaction

Closure
Hole Propping
Crack Tip Plasticity
Interaction
Load Transfer

Detectable Flaw Size
POD

NDI

Appropriate NDI Technique

Crack Shape Morphology
Nucleation Site
Residual Stress Profile
- Plate thickness
- Stackup geometry
- Hole diameter
- % Cold work

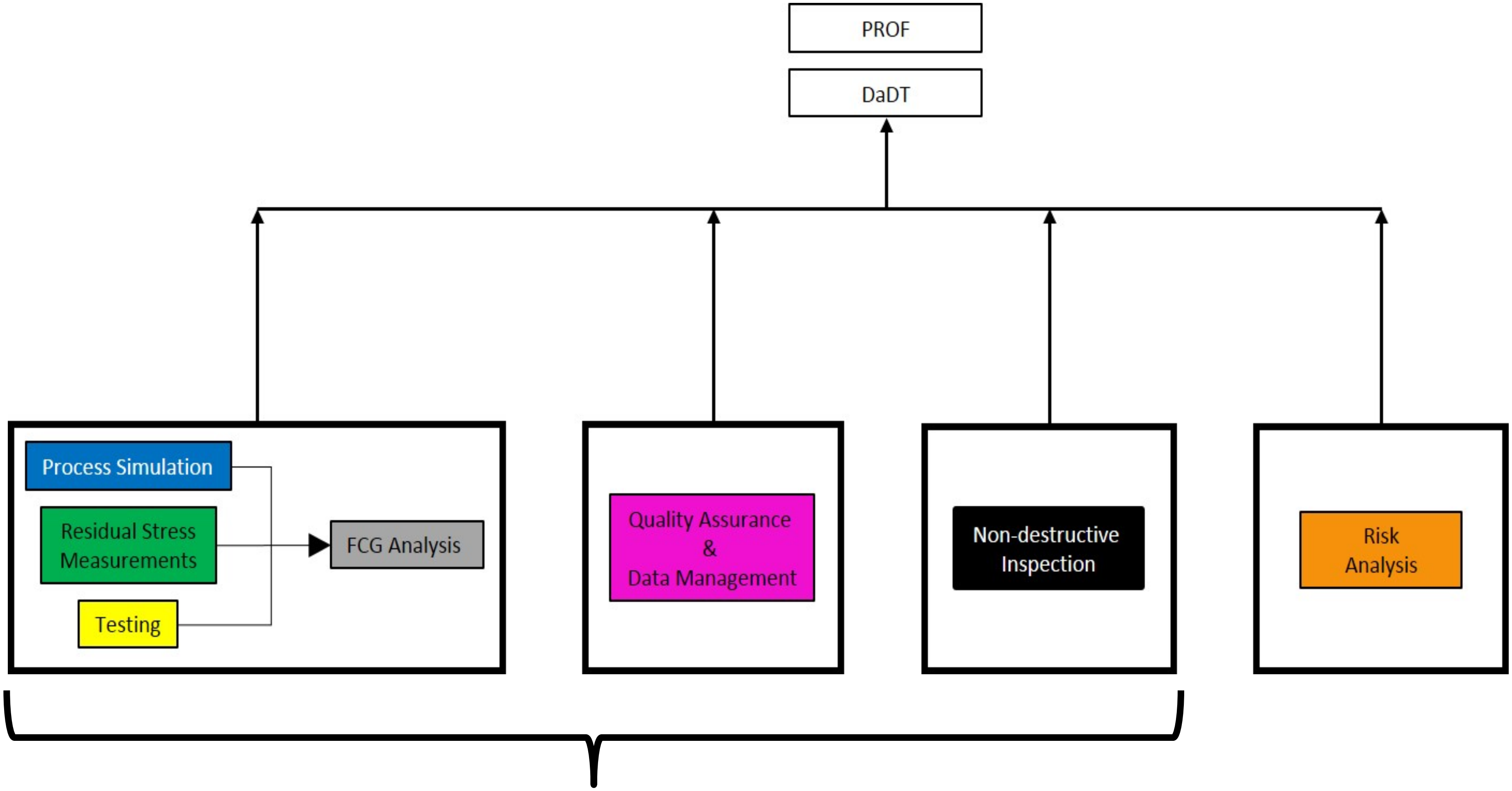
Uncertainty Quantification

Distributions for all applicable parameters

Standard Data Formats and QA

Distribution A: Approved for Public Release; 19 September 2017; 88ABW-2017-4528

Technical Dependencies: Proposed



PROF

DaDT

Process Simulation

Residual Stress Measurements

Testing

FCG Analysis

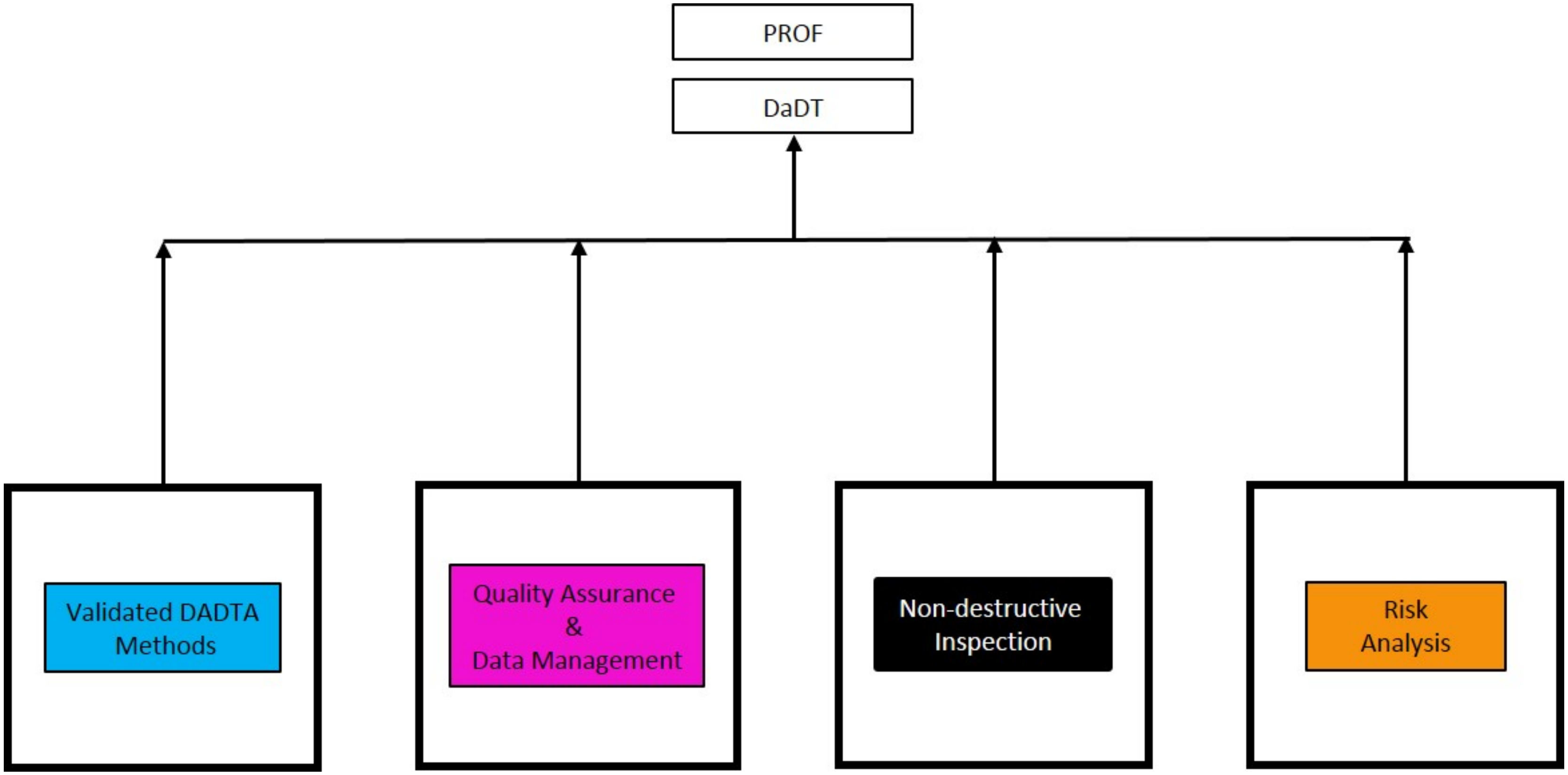
Quality Assurance & Data Management

Non-destructive Inspection

Risk Analysis

Pillar Activities

Technical Dependencies: Proposed



- Pros
  - Increases communication within areas of high dependency
  - Increases visibility of activities
  - Aligns portfolio with targeted research outcome
- Cons
  - One group larger than rest*
  - Loss of resolution by specific technical area

Distribution A: Approved for Public Release; 19 September 2017; 88ABW-2017-4528

Structural Community Awareness: ASIP

- **ASIP 2017**
  - – Why
    - Communication to a broader audience
  - – What
    - 5 Panelist Topics
      - – ASIP Requirements
      - – Validated DADTA
      - – NDI
      - – Quality Assurance
      - – ASIP Manager Perspective
  - – When
    - 29 November, 2017 (Afternoon)

Questions

Analytical Methods Subcommittee: Overview of Recent Efforts

Engineered Residual Stress Implementation Workshop 2017
September 21, 2017

HILL ENGINEERING
Predict. Test. Perform.

ERSI

Robert Pilarczyk
Group Lead – Structural Integrity
Hill Engineering, LLC
rtpilarczyk@hill-engineering.com
Phone: 801-391-2682

Acknowledgements

- A-10 & T-38 Aircraft Structural Integrity Teams
- Air Force Research Lab
- Analysis Methods Subcommittee Participants
- ERSI Working Group

Historical

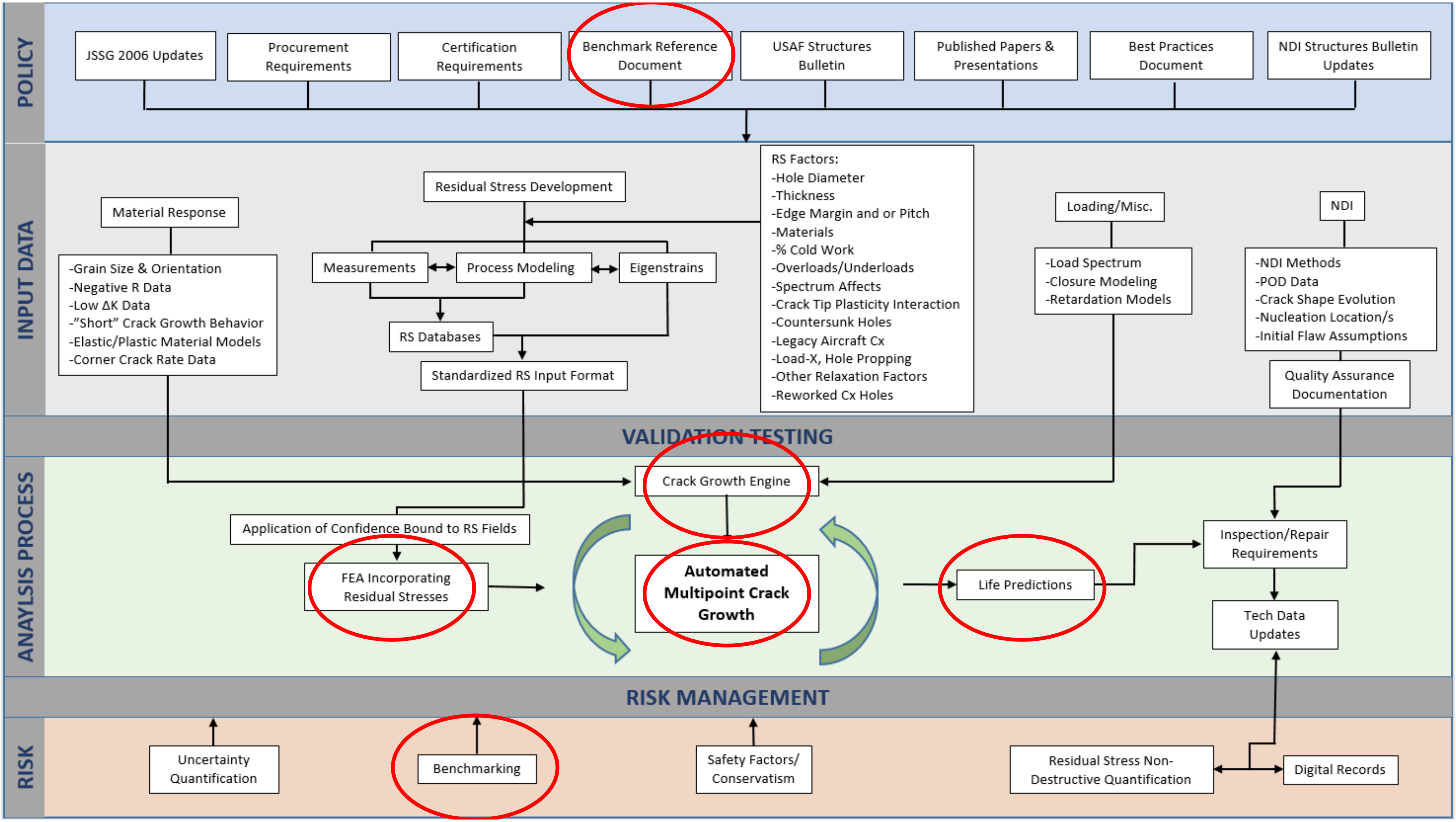
Residual Stress is considered a problem or used as a *band-aid* to address design deficiencies

Emerging

Residual Stress Engineering is a *conventional technology* that assures performance

Agenda

- Round Robin for Cx Holes
- Best Practices Document
- Engineering Implementation of Residual Stress
- Near Surface Residual Stress
- Residual Stress Relaxation
- Overloads/Underloads/Load-X
- Multi-Crack Effects


POLICY
JSSG 2006 Updates
Procurement Requirements
Certification Requirements
Benchmark Reference Document
USAF Structures Bulletin
Published Papers & Presentations
Best Practices Document
NDI Structures Bulletin Updates
INPUT DATA
Material Response
-Grain Size & Orientation
-Negative R Data
-Low ΔK Data
-"Short" Crack Growth Behavior
-Elastic/Plastic Material Models
-Corner Crack Rate Data
Residual Stress Development
Measurements
Process Modeling
Eigenstrains
RS Databases
Standardized RS Input Format
RS Factors:
-Hole Diameter
-Thickness
-Edge Margin and or Pitch
-Materials
-% Cold Work
-Overloads/Underloads
-Spectrum Affects
-Crack Tip Plasticity Interaction
-Countersunk Holes
-Legacy Aircraft Cx
-Load-X, Hole Propping
-Other Relaxation Factors
-Reworked Cx Holes
Loading/Misc.
-Load Spectrum
-Closure Modeling
-Retardation Models
NDI
-NDI Methods
-POD Data
-Crack Shape Evolution
-Nucleation Location/s
-Initial Flaw Assumptions
Quality Assurance Documentation
VALIDATION TESTING
ANAYLSIS PROCESS
Crack Growth Engine
Application of Confidence Bound to RS Fields
FEA Incorporating Residual Stresses
Automated Multipoint Crack Growth
Life Predictions
Inspection/Repair Requirements
Tech Data Updates
RISK MANAGEMENT
RISK
Uncertainty Quantification
Benchmarking
Safety Factors/ Conservatism
Residual Stress Non-Destructive Quantification
Digital Records

Round Robin for Cx Holes

- ❑ **Purpose**
  - ➢ Identify the random and systematic uncertainties associated with DTAs that incorporate residual stresses produced by Cx of fastener holes
  - ➢ Many factors influencing the total uncertainty have been discussed and are currently under investigation by various members of the ERSI team
  - ➢ For the first round-robin exercise, the focus will be on systematic uncertainties, or the uncertainty associated with the system or process used by the analyst (also known as epistemic uncertainties or model-form uncertainties)
  - ➢ Specific input data was provided to each analyst participating in the exercise to minimize the random uncertainties associated with these types of analyses.
  - ➢ The analyst was free to use any means to incorporate the residual stress into the DTA, any software suite, etc., however, it was important that the analyst adhered closely to the guidance provided so that the variability in the predictions will be limited to the aspects left to analyst's discretion.
- ❑ **Main Focus – understand analyst-to-analyst prediction variability given fixed input data**

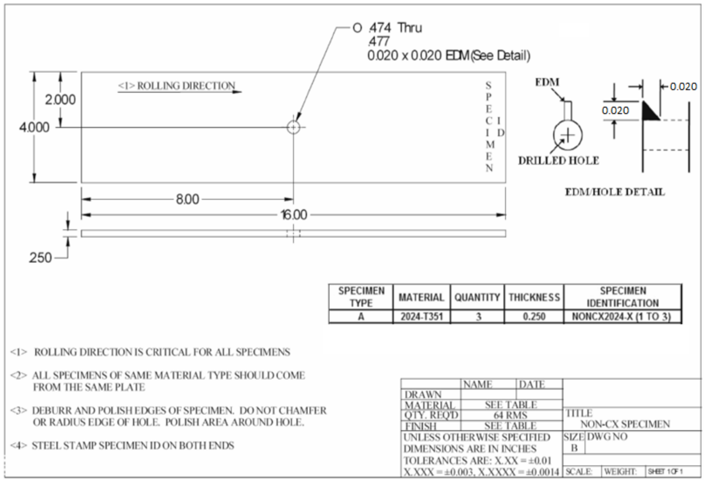
Round Robin for Cx Holes

❑ Conditions

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

❑ Input Data

- ➢ Geometry
- ➢ Initial flaw size, shape, location, and orientation
- ➢ Material properties
- ➢ Loading spectrum
- ➢ Constraints
- ➢ Residual stress (contour results)



SPECIMEN TYPE	MATERIAL	QUANTITY	THICKNESS	SPECIMEN IDENTIFICATION
A	2024-T351	3	0.250	NONCX2024-X (1 TO 3)

<1> ROLLING DIRECTION IS CRITICAL FOR ALL SPECIMENS

<2> ALL SPECIMENS OF SAME MATERIAL TYPE SHOULD COME FROM THE SAME PLATE

<3> DEBURR AND POLISH EDGES OF SPECIMEN. DO NOT CHAMFER OR RADIUS EDGE OF HOLE. POLISH AREA AROUND HOLE.

<4> STEEL STAMP SPECIMEN ID ON BOTH ENDS

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ARE: X.XX = ±0.01 X.XXX = ±0.003, X.XXXX = ±0.0014

Round Robin for Cx Holes

- ☐ How do we measure “success”?
- ☐ Recall, we are focused on the systematic, not random uncertainties
- ☐ The goal is to understand the consistency, strengths and weaknesses of different analysis methods to focus our efforts moving forward
- ☐ Analysis comparisons:
  - a vs. N, c vs. N
  - da/dN vs. a, dc/dN vs. c
  - a/c vs. a/t
  - Goodness of fit
  - Thru thickness transition
  - Critical crack length
  - Slope transition point

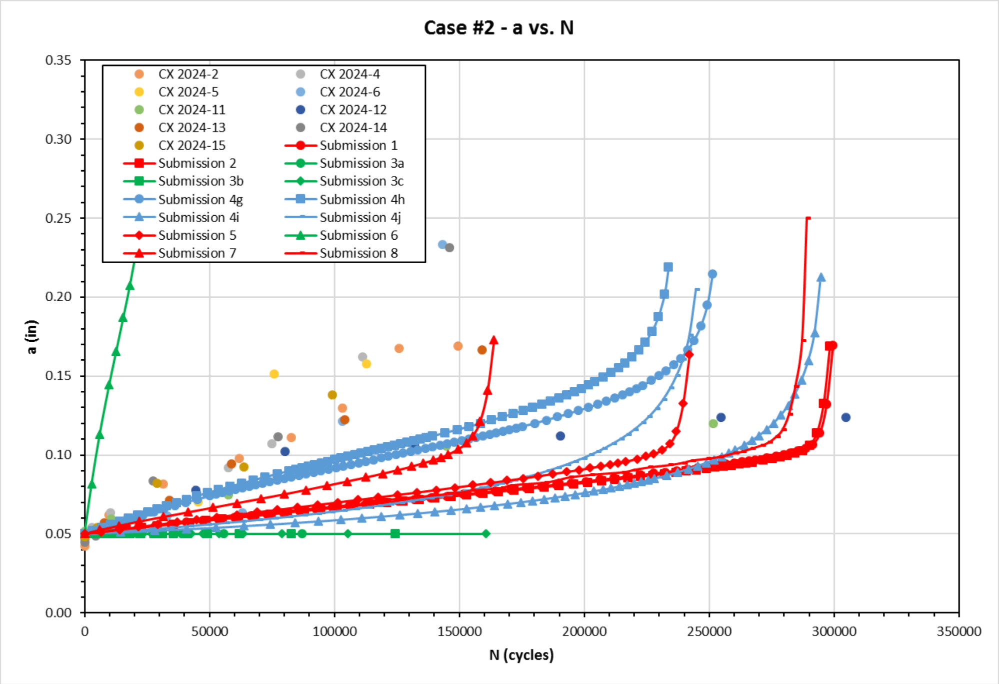
Legend:

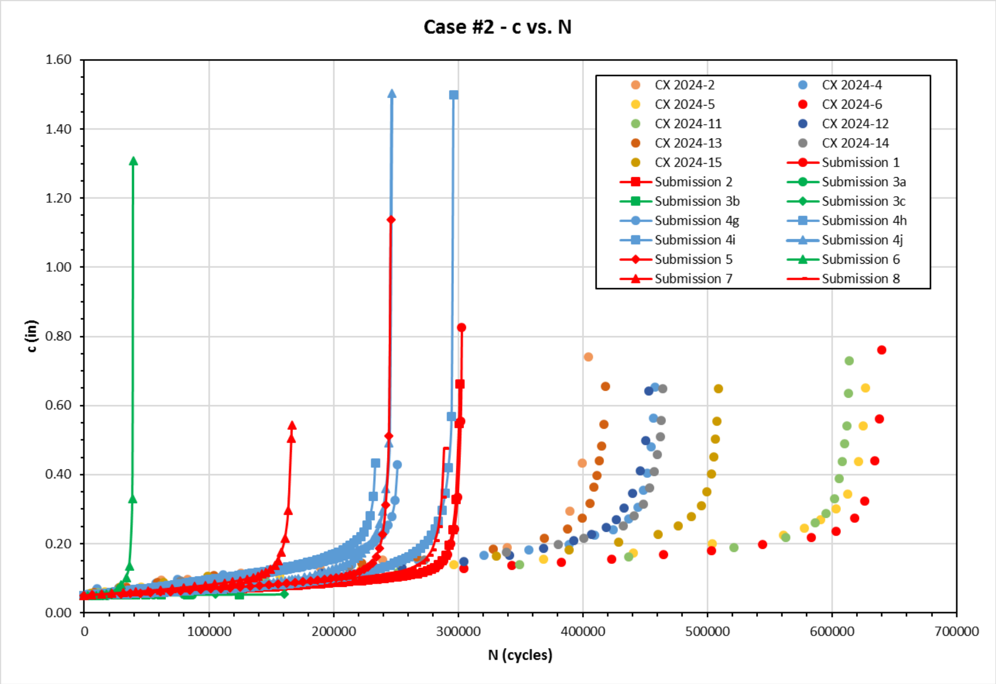
🔴 Coupled FEA-Crack Growth
🟢 AFGROW Standard Solutions
🔵 NASGRO Standard Solutions

Key modeling factors summary sheets available for each case

Round Robin for Cx Holes - Case #2

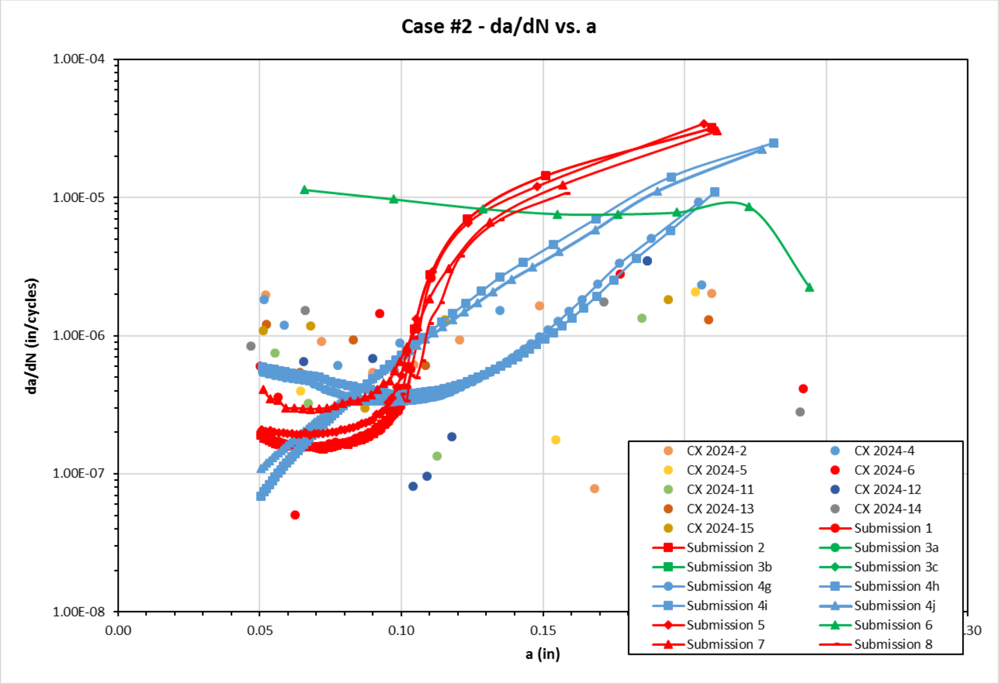
- ☐ Cx Centered Hole

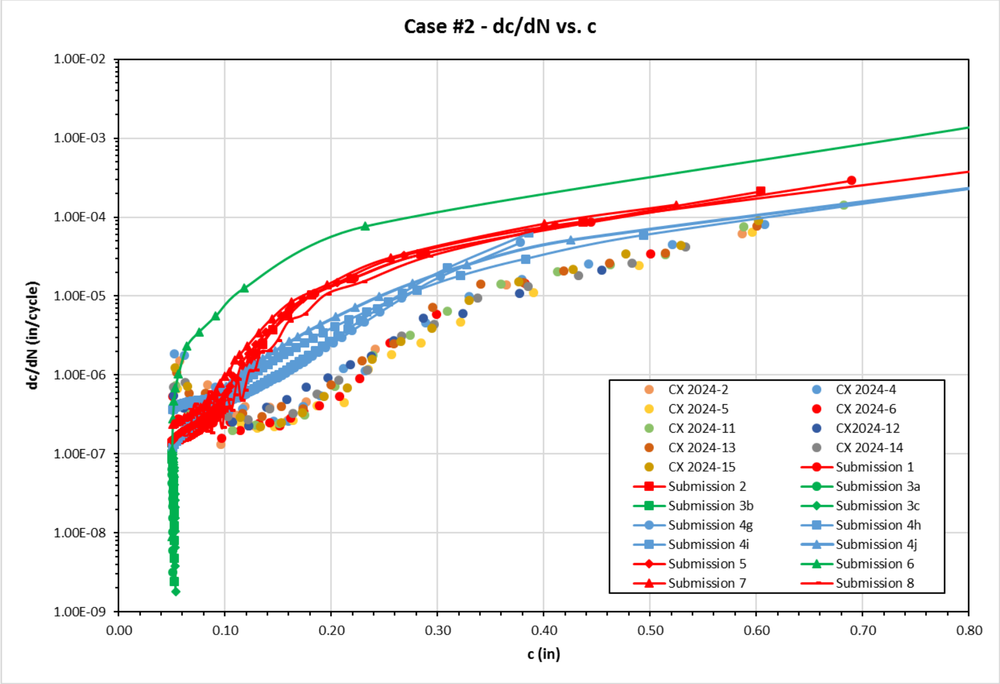




Round Robin for Cx Holes – Case #2

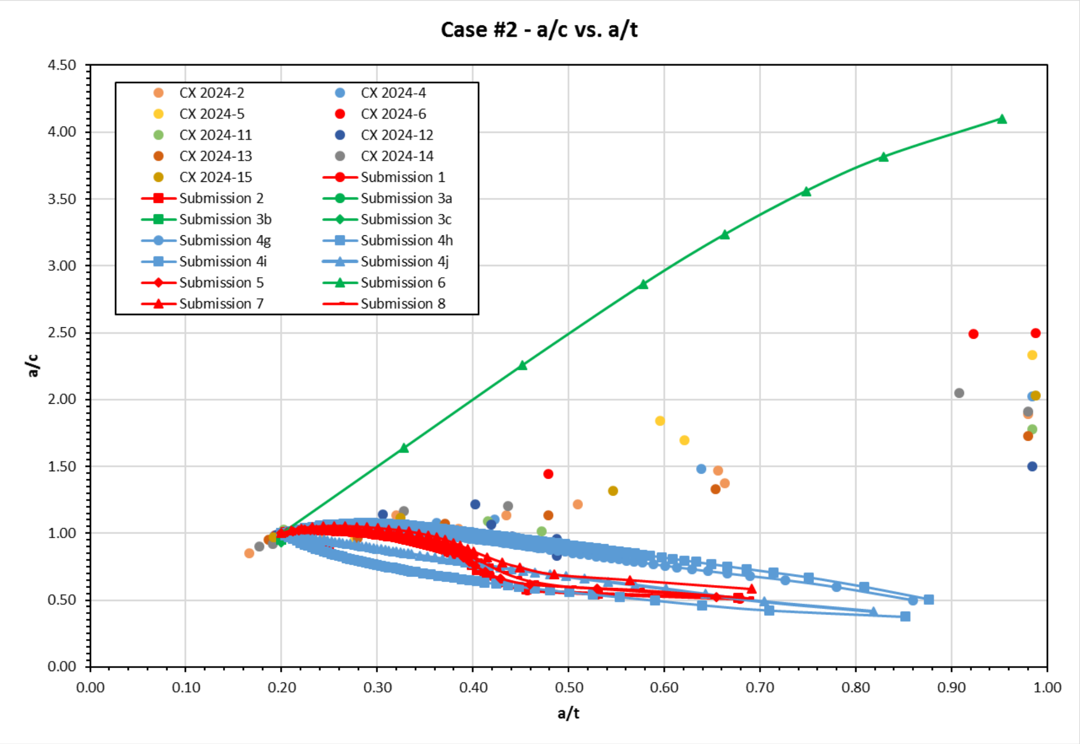
- ☐ Cx Centered Hole





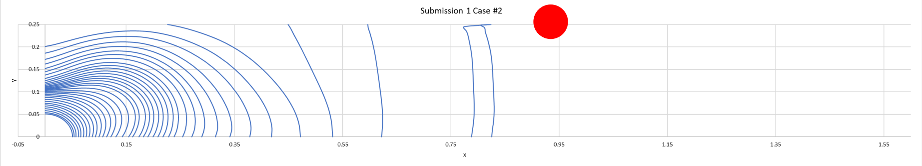
Round Robin for Cx Holes – Case #2

- ☐ Cx Centered Hole

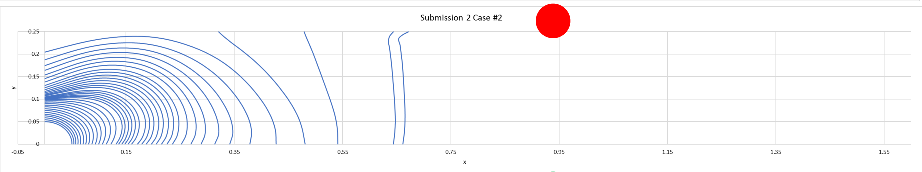


Round Robin for Cx Holes - Case #2

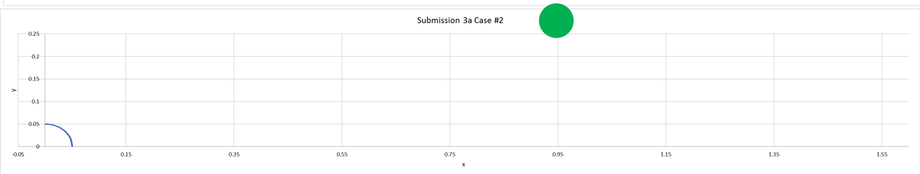
CX2024-8 Case #2



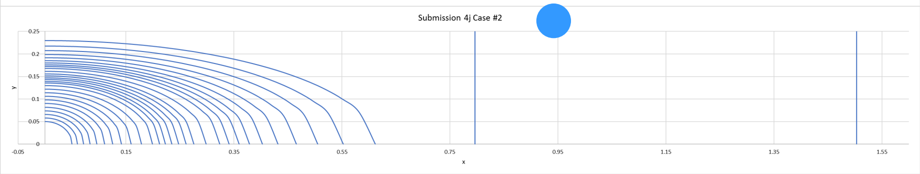
Submission 1 Case #2



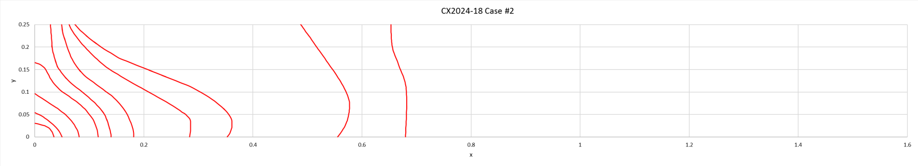
Submission 2 Case #2



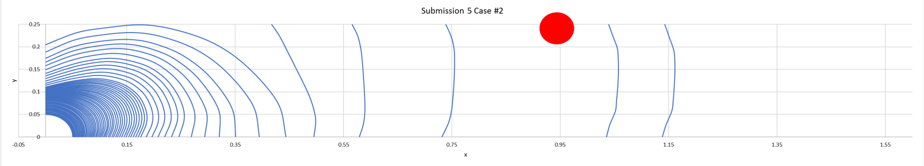
Submission 3a Case #2



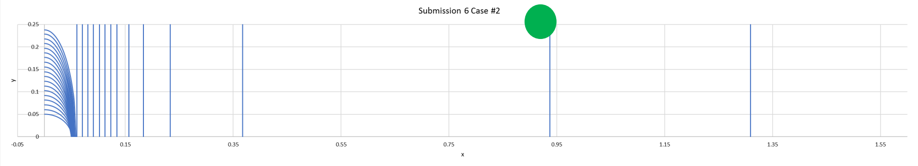
Submission 4j Case #2



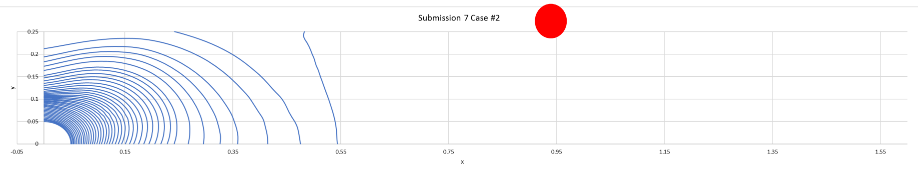
CX2024-18 Case #2



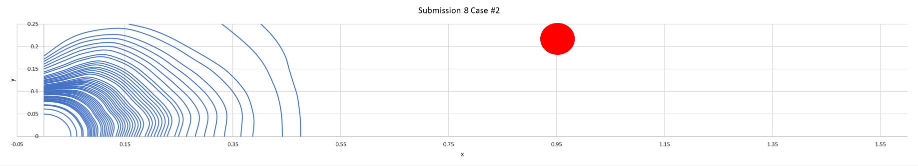
Submission 5 Case #2



Submission 6 Case #2



Submission 7 Case #2



Submission 8 Case #2

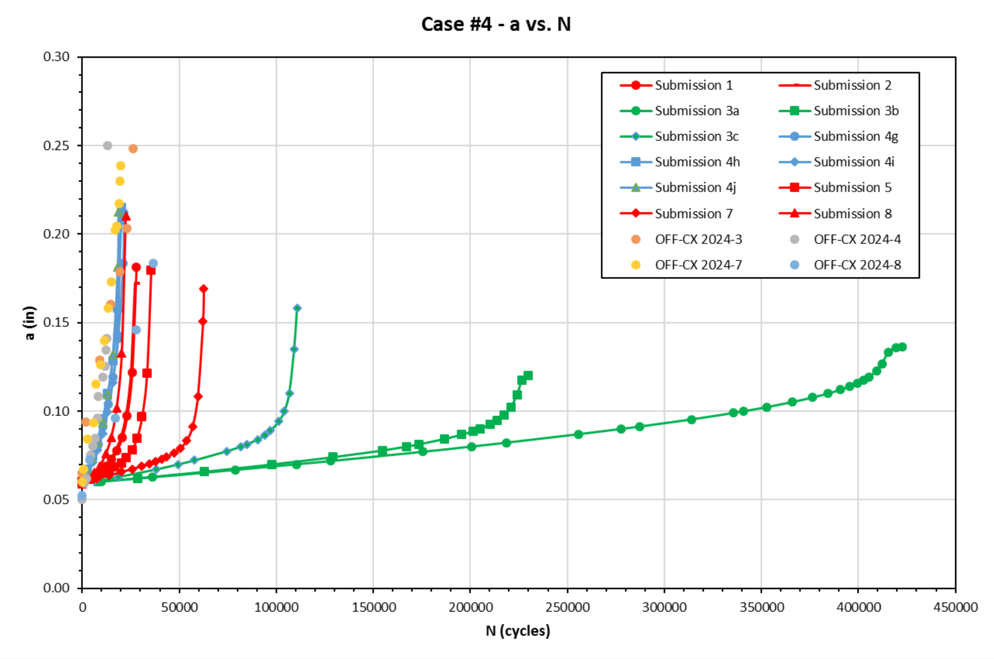
Round Robin for Cx Holes – Case #2

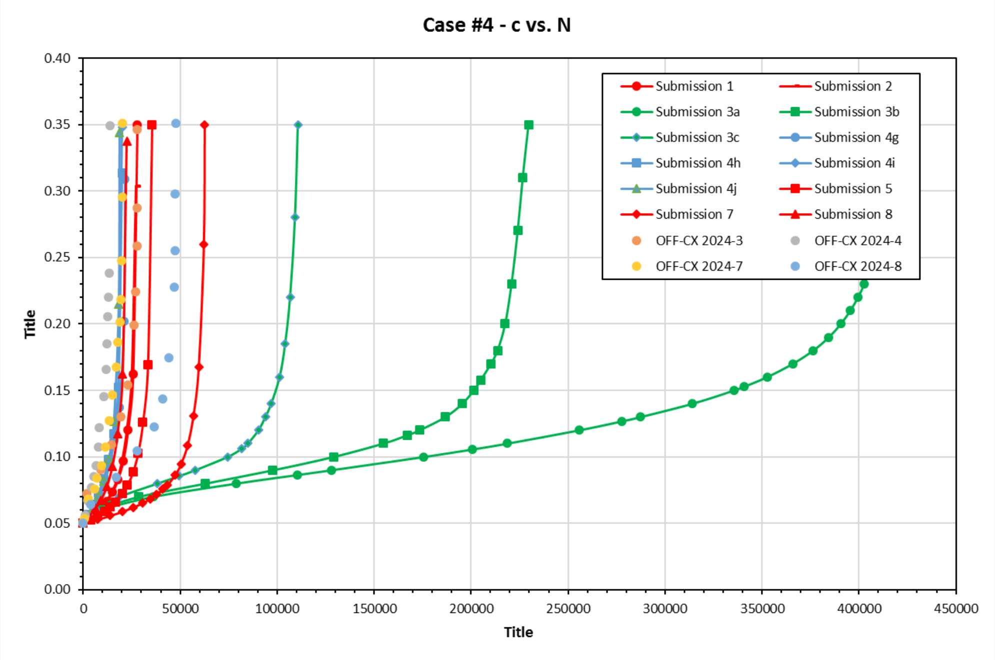
❑ Cx Centered Hole Summary

- ➢ Fatigue life
  - Gaussian integration – AFGROW – No growth for several cases
  - Consistency between similar analytical approaches
  - Under-predict test lives
- ➢ Growth rates
  - Initial – under-predict
  - >0.10” – over-predict
- ➢ Crack aspect ratio
  - Predictions ≠ test behavior

Round Robin for Cx Holes – Case #4

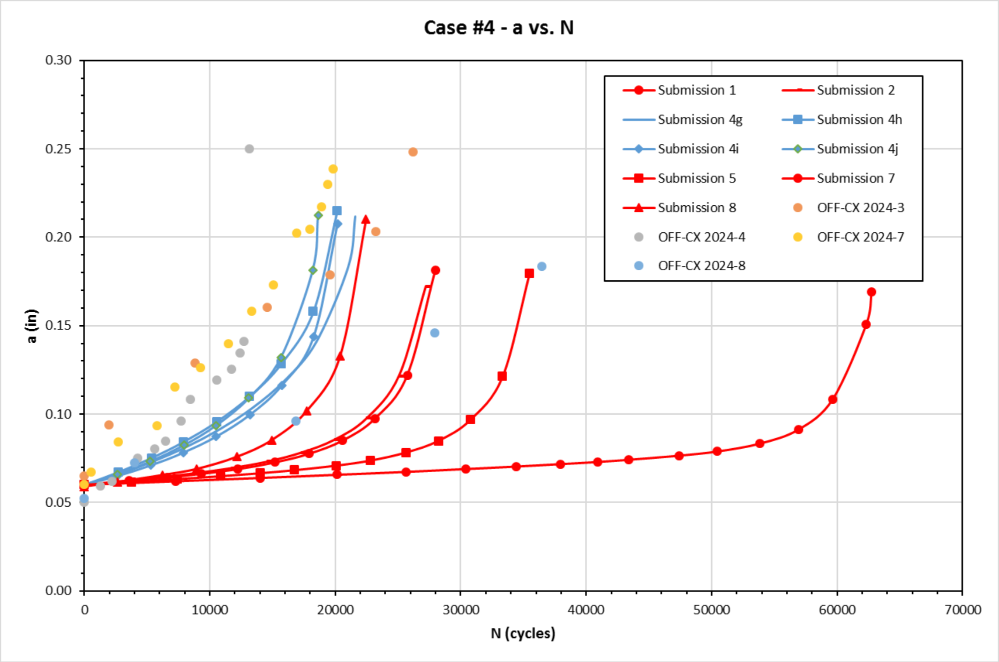
❑ Cx Offset Hole

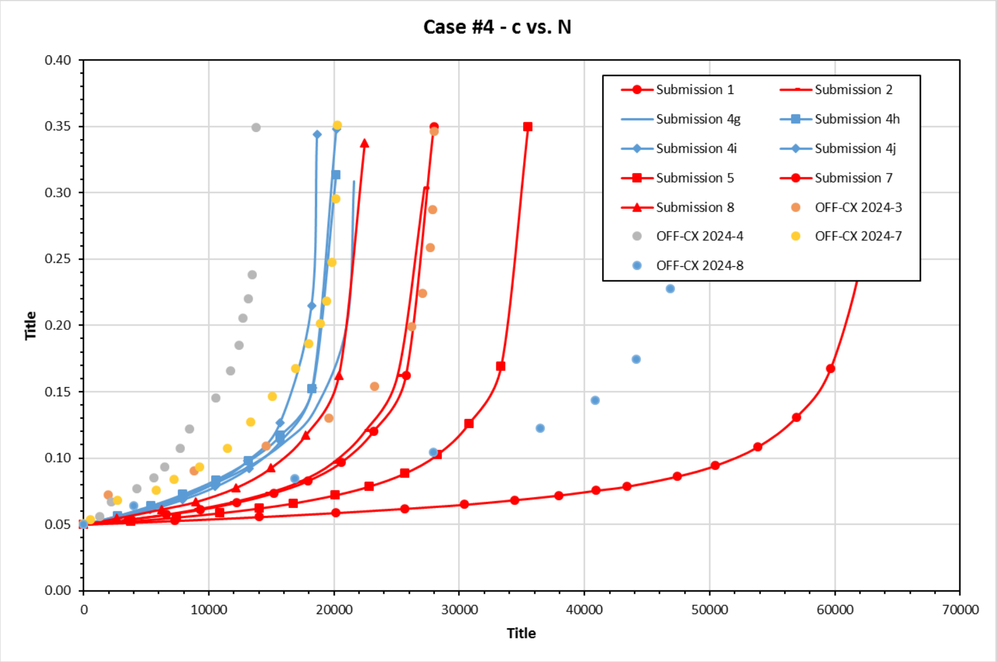




Round Robin for Cx Holes – Case #4

- Cx Offset Hole



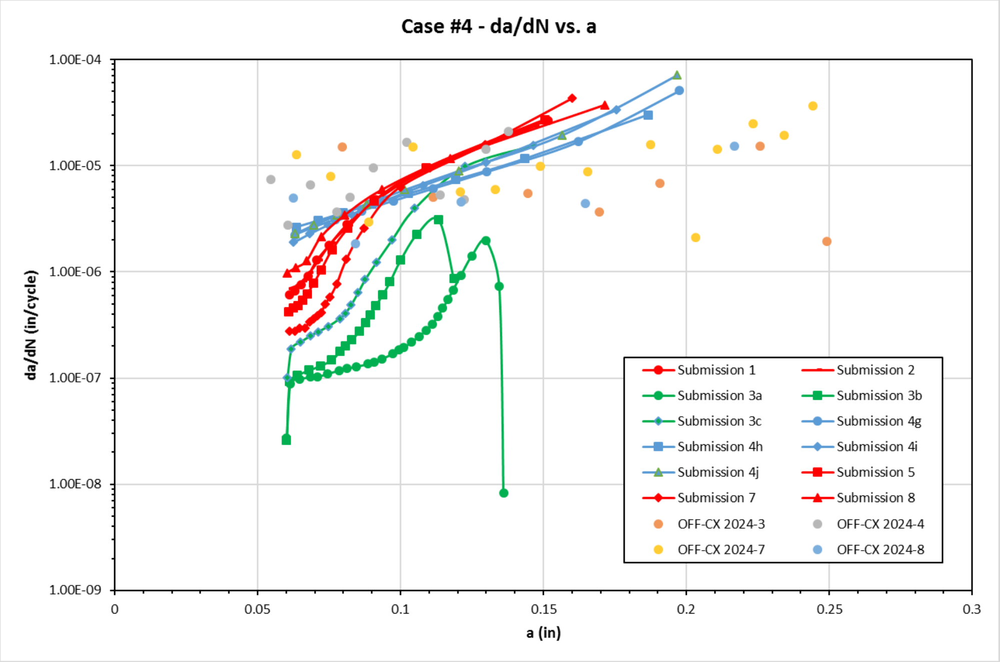


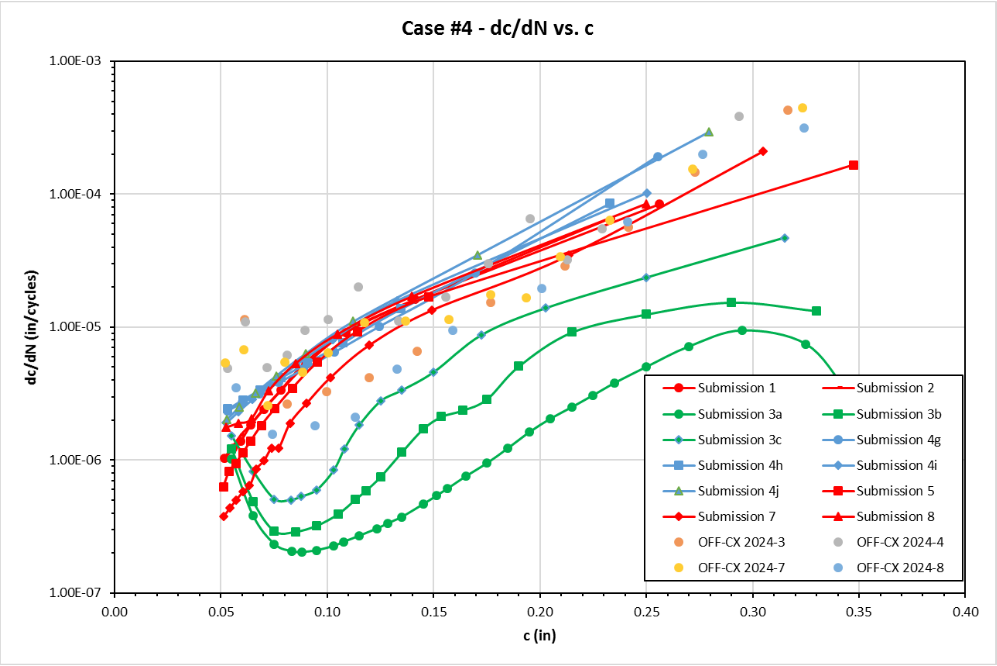
HILL ENGINEERING
Predict. Test. Perform.

ERSI

Round Robin for Cx Holes – Case #4

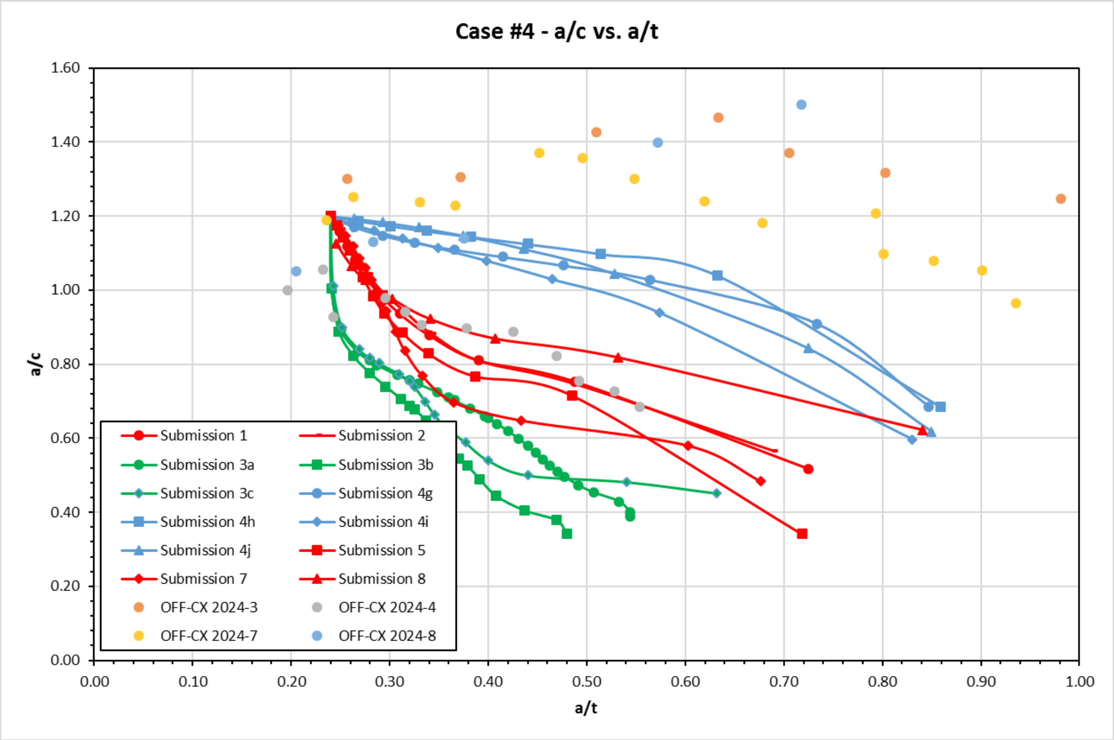
- ☐ Cx Offset Hole



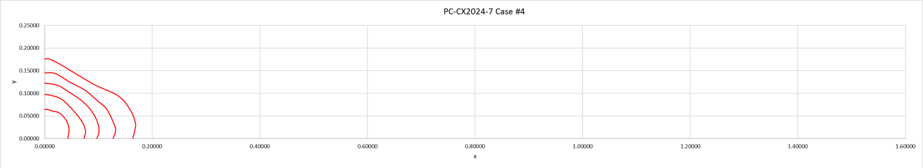


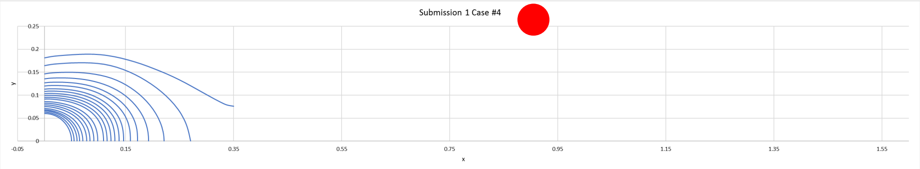
Round Robin for Cx Holes – Case #4

- ❑ Cx Offset Hole

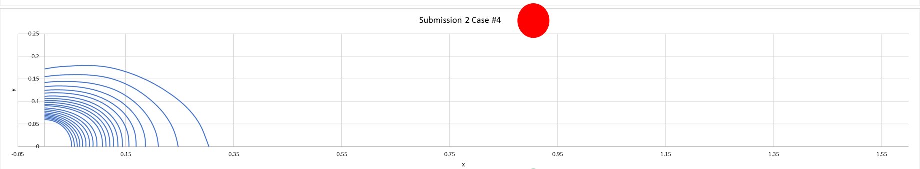


Round Robin for Cx Holes - Case #4

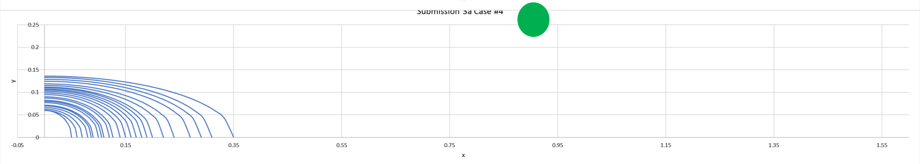




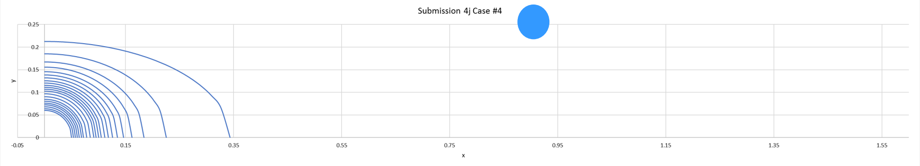
●



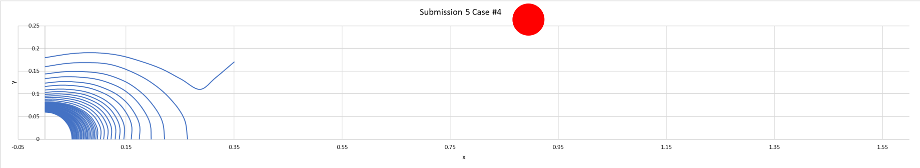
●



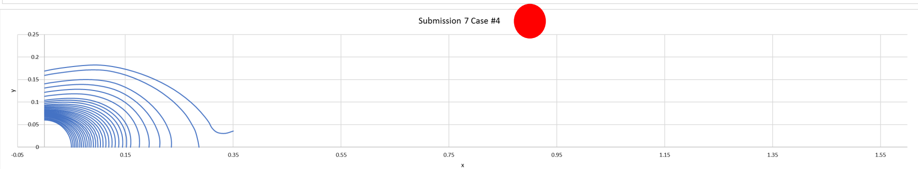
●



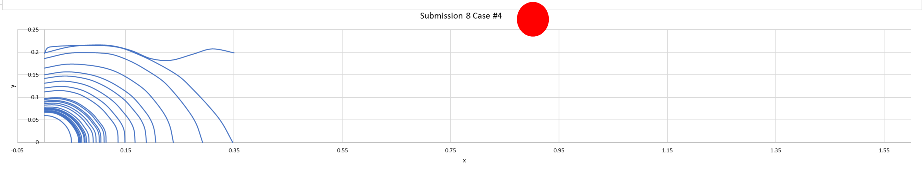
●



●



●



●

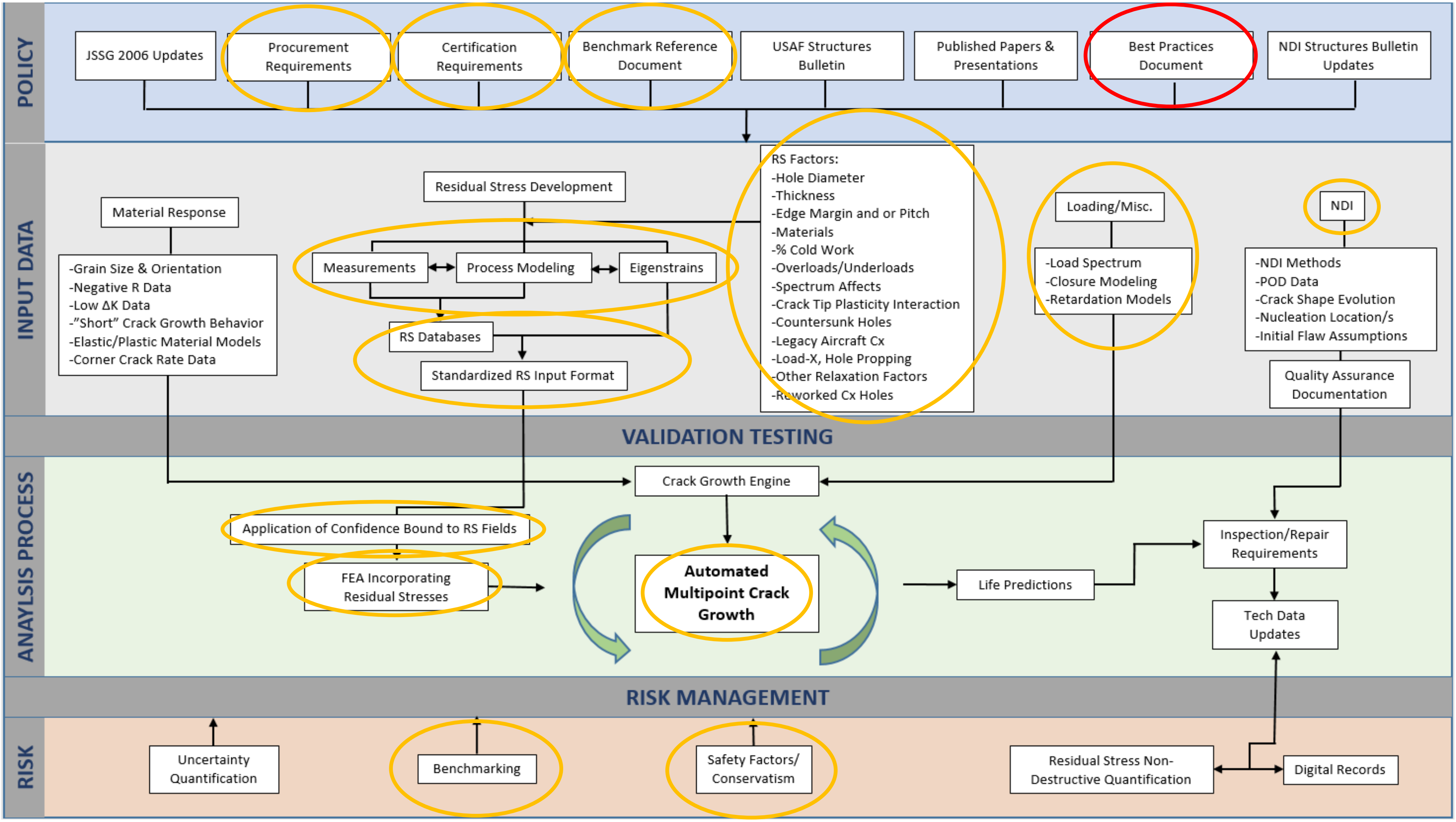
Round Robin for Cx Holes – Case #4

☐ **Cx Offset Hole Summary**

- Fatigue life
  - Gaussian integration – AFGROW – significant over-prediction of life
  - Consistency between similar analytical approaches
  - Reasonable predictions
- Growth rates
  - Initial – under-predict – coupled FEA-crack growth
- Crack aspect ratio
  - Variation between test coupons

Round Robin for Cx Holes - Summary

- ❑ **Collectively Review Results in Analysis Methods Subcommittee**
  - ➢ Additional approaches to compare/contrast results
- ❑ **Identify:**
  - ➢ Analysis best practices
  - ➢ Focus areas for additional investigation
- ❑ **Publish Journal Article**
- ❑ **Identify Follow-On Round Robin Details**



POLICY

JSSG 2006 Updates

Procurement Requirements

Certification Requirements

Benchmark Reference Document

USAF Structures Bulletin

Published Papers & Presentations

Best Practices Document

NDI Structures Bulletin Updates

INPUT DATA

Material Response

-Grain Size & Orientation
-Negative R Data
-Low ΔK Data
-"Short" Crack Growth Behavior
-Elastic/Plastic Material Models
-Corner Crack Rate Data

Residual Stress Development

Measurements

Process Modeling

Eigenstrains

RS Databases

Standardized RS Input Format

RS Factors:
-Hole Diameter
-Thickness
-Edge Margin and or Pitch
-Materials
-% Cold Work
-Overloads/Underloads
-Spectrum Affects
-Crack Tip Plasticity Interaction
-Countersunk Holes
-Legacy Aircraft Cx
-Load-X, Hole Propping
-Other Relaxation Factors
-Reworked Cx Holes

Loading/Misc.

-Load Spectrum
-Closure Modeling
-Retardation Models

NDI

-NDI Methods
-POD Data
-Crack Shape Evolution
-Nucleation Location/s
-Initial Flaw Assumptions

Quality Assurance Documentation

VALIDATION TESTING

ANAYLSIS PROCESS

Crack Growth Engine

Application of Confidence Bound to RS Fields

FEA Incorporating Residual Stresses

Automated Multipoint Crack Growth

Life Predictions

Inspection/Repair Requirements

Tech Data Updates

RISK MANAGEMENT

RISK

Uncertainty Quantification

Benchmarking

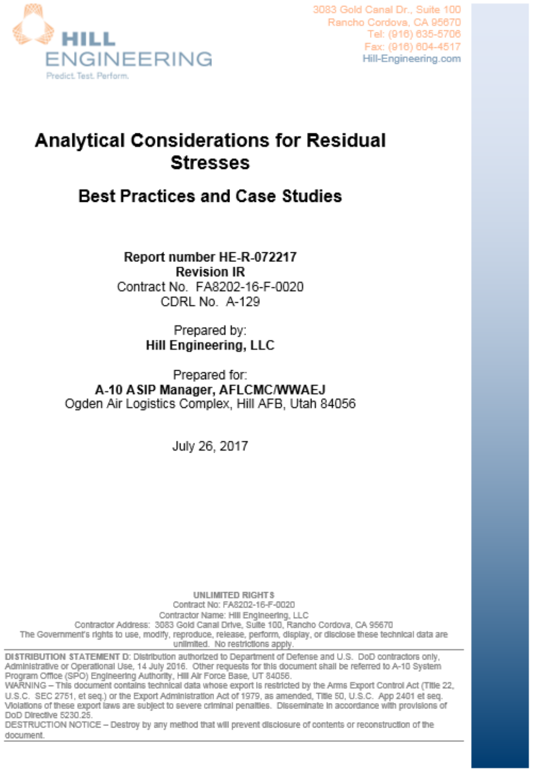
Safety Factors/ Conservatism

Residual Stress Non-Destructive Quantification

Digital Records

Best Practices Document

- ❑ **Purpose**
  - ➢ Share best practices, lessons learned, and analysis methods with community
  - ➢ Document benchmarks and case studies
  - ➢ Compliment other policy documents
- ❑ **Goal - Open Source Document**
- ❑ **Organizational Structure**
  - ➢ Organized similar to AGARD documents
    - Background information
    - Best practices and lessons learned
    - Benchmark problems
    - Case studies



HILL ENGINEERING
Predict. Test. Perform.

3083 Gold Canal Dr., Suite 100
Rancho Cordova, CA 95670
Tel: (916) 635-5706
Fax: (916) 604-4517
Hill-Engineering.com

Analytical Considerations for Residual Stresses

Best Practices and Case Studies

Report number HE-R-072217
Revision IR
Contract No. FA8202-16-F-0020
CDRL No. A-129

Prepared by:
Hill Engineering, LLC

Prepared for:
A-10 ASIP Manager, AFLCMC/WWAEJ
Ogden Air Logistics Complex, Hill AFB, Utah 84056

July 26, 2017

UNLIMITED RIGHTS
Contract No: FA8202-16-F-0020
Contractor Name: Hill Engineering, LLC
Contractor Address: 3083 Gold Canal Drive, Suite 100, Rancho Cordova, CA 95670
The Government's rights to use, modify, reproduce, release, perform, display, or disclose these technical data are unlimited. No restrictions apply.

DISTRIBUTION STATEMENT D: Distribution authorized to Department of Defense and U.S. DoD contractors only, Administrative or Operational Use, 14 July 2016. Other requests for this document shall be referred to A-10 System Program Office (SPO) Engineering Authority, Hill Air Force Base, UT 84056.
WARNING – This document contains technical data whose export is restricted by the Arms Export Control Act (Title 22, U.S.C. SEC 2751, et seq.) or the Export Administration Act of 1979, as amended, Title 50, U.S.C. App 2401 et seq. Violations of these export laws are subject to severe criminal penalties. Disseminate in accordance with provisions of DoD Directive 5230.25.
DESTRUCTION NOTICE – Destroy by any method that will prevent disclosure of contents or reconstruction of the document.

Best Practices Document

❑ Chapter I - Introduction

- Introduction to fatigue, damage tolerance, and residual stress
- Residual stress inducing processes and associated key characteristics
- Residual stress measurement techniques and associated key characteristics
- Considerations for modeling approaches
- Current guiding policy
- Historical modeling approaches

Mechanical Methods – Key Characteristics

Mechanical Method	Typical Applications	Typical Depth of Residual Stress	Durability Benefit	Damage Tolerance Benefit
Shot Peening	Widespread – Surface of Parts	~ 0.002-0.008	Yes	Minimal
Surface Rolling	Rolled Threads, Gear Teeth, Fillets	~ 0.04"	Yes	Yes
Low Plasticity Burnishing	Fan Blades, Radii	~ 0.04"	Yes	Yes
CX Holes	Critical Fastener Holes	~ 1 radius	Yes	Yes
Laser Shock Peening	Critical Geometric Features	~ 0.04"	Yes	Yes
Forming		Surface to Full Field	Yes	Yes

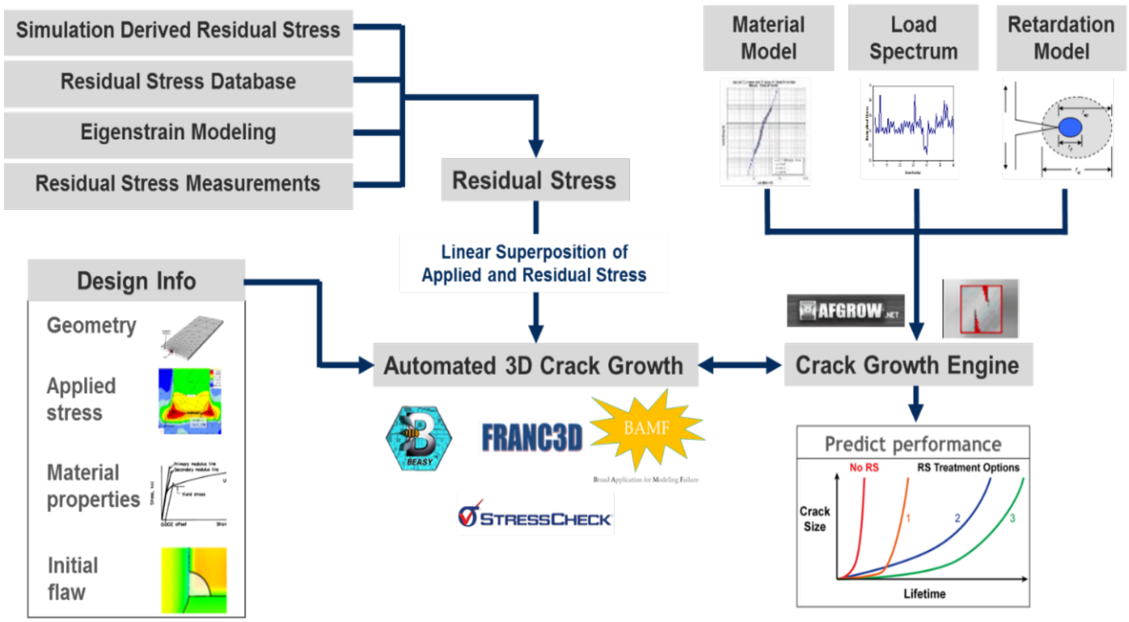
Strengths & Weaknesses of Various Residual Stress Measurement Techniques

Measurement Technique	Strengths	Weaknesses
XRD with layer removal	Portable equipment	Significantly affected by microstructure variations Less repeatable than other techniques
Neutron Diffraction	2D mapping of multiple components Bulk residual stress	Difficult to obtain (limited facilities) Significantly affected by microstructure variations
Hole Drilling	Portable equipment ASTM standard Near-surface measurement Multiple stress components	Less repeatable than other techniques
Ring Core	Portable equipment Near-surface measurement Multiple stress components	Large averaging volume
Contour	2D mapping of residual stress Bulk residual stress	Difficult to resolve sharp stress gradients
Slitting	Excellent measurement repeatability	Limited to extruded cross-sections

Best Practices Document

☐ Chapter II – Analytical Processes

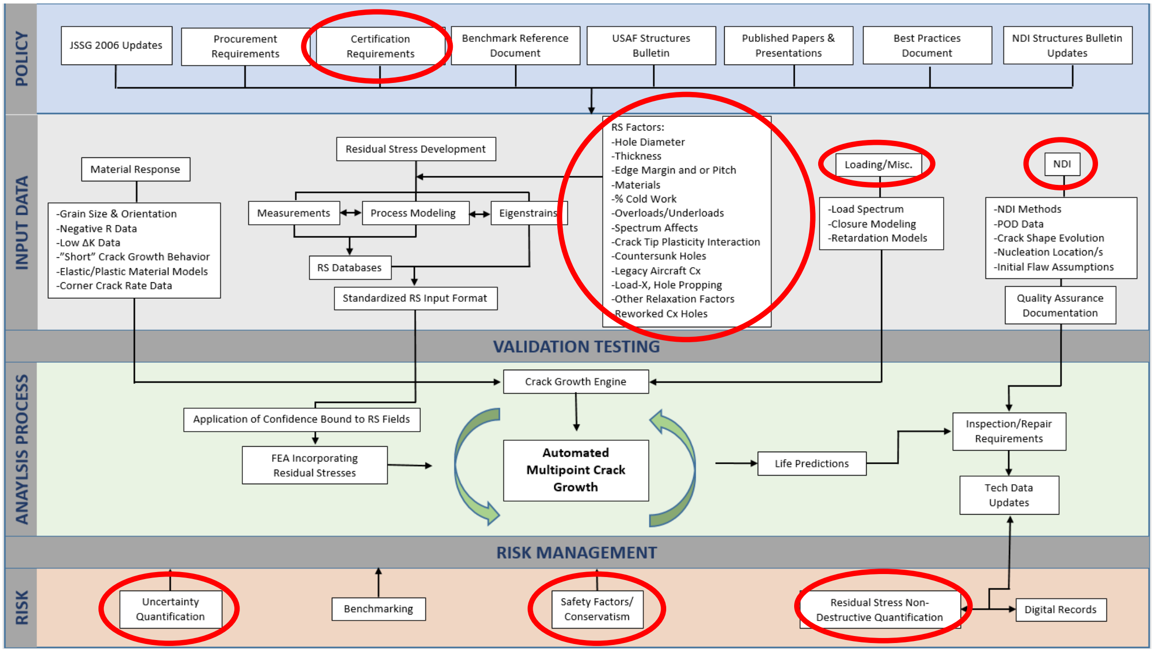
- Overview of analytical processes
- Key input data
    - Design info
    - Material models
    - Loading spectrum & retardation
    - Residual stress
- Analysis processes
    - Multi-point fracture mechanics
    - Coupled FEA
    - Other analytical approaches
- Way forward & recommendations



Best Practices Document

❑ Chapter III – Other Considerations

- ➢ Factors influencing residual stress and the associated uncertainty
  - Key factors influencing residual stress
  - Variability in residual stress data
- ➢ Validation testing
- ➢ Non-destructive inspections
- ➢ Quality assurance
- ➢ Risk management
- ➢ Certification considerations
- ➢ Way forward & recommendations



POLICY

JSSG 2006 Updates

Procurement Requirements

Certification Requirements

Benchmark Reference Document

USAF Structures Bulletin

Published Papers & Presentations

Best Practices Document

NDI Structures Bulletin Updates

INPUT DATA

Material Response

-Grain Size & Orientation
-Negative R Data
-Low ΔK Data
-"Short" Crack Growth Behavior
-Elastic/Plastic Material Models
-Corner Crack Rate Data

Residual Stress Development

Measurements

Process Modeling

Eigenstrains

RS Databases

Standardized RS Input Format

RS Factors:
-Hole Diameter
-Thickness
-Edge Margin and or Pitch
-Materials
-% Cold Work
-Overloads/Underloads
-Spectrum Affects
-Crack Tip Plasticity Interaction
-Countersunk Holes
-Legacy Aircraft Cx
-Load-X, Hole Propping
-Other Relaxation Factors
-Reworked Cx Holes

Loading/Misc.

-Load Spectrum
-Closure Modeling
-Retardation Models

NDI

-NDI Methods
-POD Data
-Crack Shape Evolution
-Nucleation Location/s
-Initial Flaw Assumptions

Quality Assurance Documentation

VALIDATION TESTING

ANAYLSIS PROCESS

Crack Growth Engine

Application of Confidence Bound to RS Fields

FEA Incorporating Residual Stresses

Automated Multipoint Crack Growth

Life Predictions

Inspection/Repair Requirements

Tech Data Updates

RISK MANAGEMENT

RISK

Uncertainty Quantification

Benchmarking

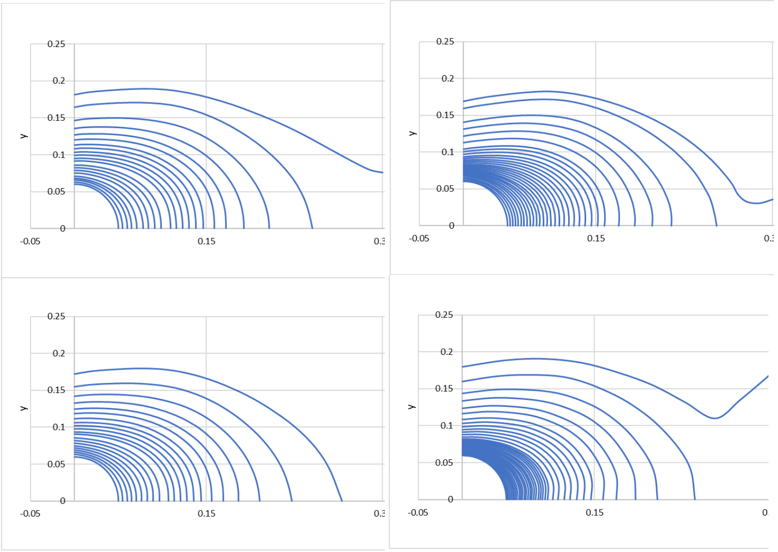
Safety Factors/ Conservatism

Residual Stress Non-Destructive Quantification

Digital Records

Best Practices Document

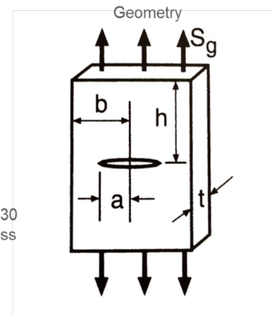
- ☐ **Chapter IV - Benchmark Cases**
  - ➢ Handbook solutions
  - ➢ ERSI round robin results

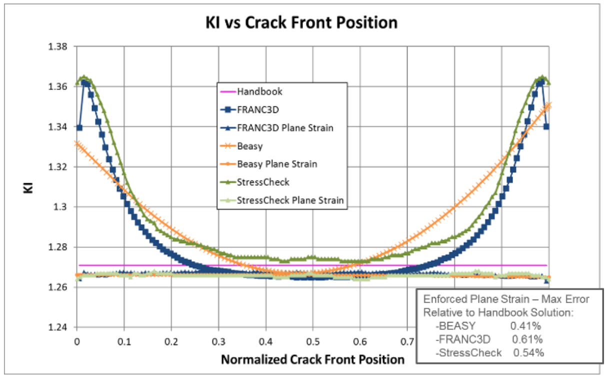


Dimensions (inches)

h = 5
b = 5
a = 0.5
t = 5

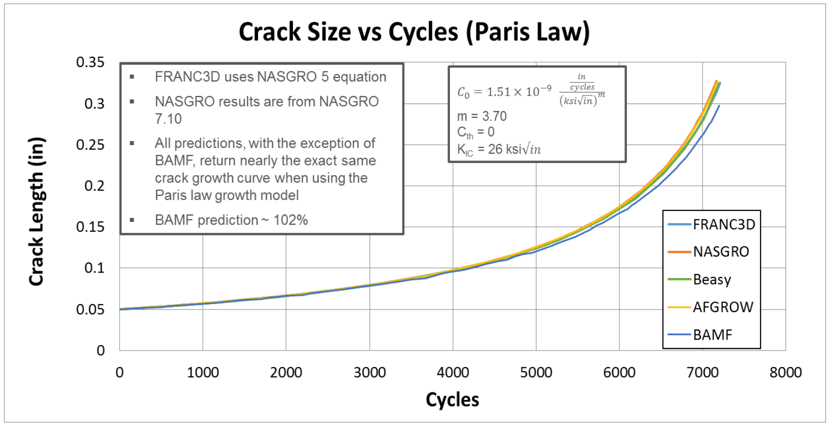
Material: E = 3.0e7, v = 0.30
Loading: Uniform unit stress (1 psi)





Enforced Plane Strain – Max Error Relative to Handbook Solution:

-BEASY	0.41%
-FRANC3D	0.61%
-StressCheck	0.54%

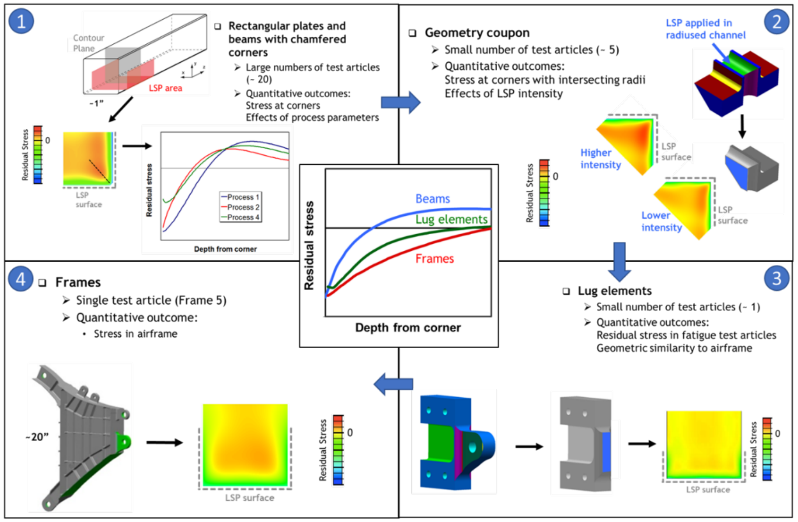


- FRANC3D uses NASGRO 5 equation
- NASGRO results are from NASGRO 7.10
- All predictions, with the exception of BAMF, return nearly the exact same crack growth curve when using the Paris law growth model
- BAMF prediction ~ 102%

$C_0 = 1.51 \times 10^{-9} \frac{\frac{in}{cycles}}{(ksi\sqrt{in})^m}$
m = 3.70
C_{th} = 0
K_{IC} = 26 ksi$\sqrt{in}$

Best Practices Document

- ☐ **Chapter V – Case Studies**
  - Laser shock peening case study
  - Cx hole case study

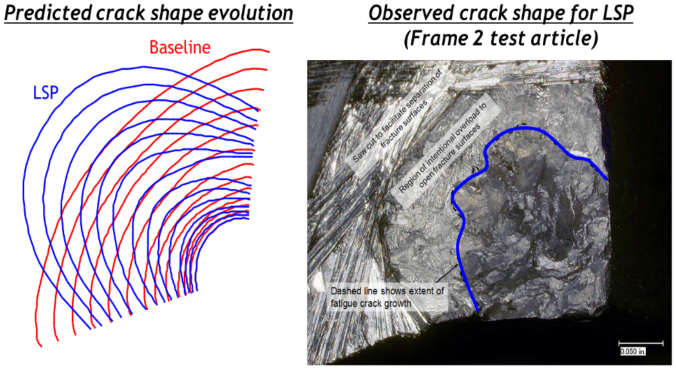


① ☐ **Rectangular plates and beams with chamfered corners**
- Large numbers of test articles (~ 20)
- Quantitative outcomes:
  Stress at corners
  Effects of process parameters

② ☐ **Geometry coupon**
- Small number of test articles (~ 5)
- Quantitative outcomes:
  Stress at corners with intersecting radii
  Effects of LSP intensity

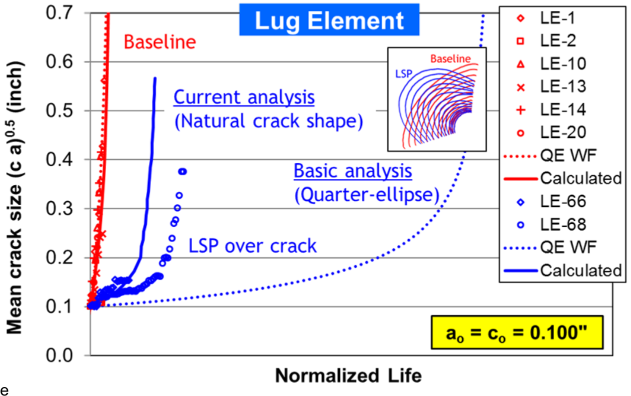
③ ☐ **Lug elements**
- Small number of test articles (~ 1)
- Quantitative outcomes:
  Residual stress in fatigue test articles
  Geometric similarity to airframe

④ ☐ **Frames**
- Single test article (Frame 5)
- Quantitative outcome:
  - Stress in airframe



Predicted crack shape evolution

Observed crack shape for LSP (Frame 2 test article)



References:
Polin, L., Bunch, J., Caruso, P., McClure, J. (2011), F-22 Program Full Scale Component Tests to Validate the Effects of Laser Shock Peening, 2011 ASIP Conference
Hill, M., DeWald, A., VanDalen, J., Bunch, J., Flanagan, S., Langer, K. (2012), Design and analysis of engineered residual stress surface treatments for enhancement of aircraft structure, 2012 ASIP Conference

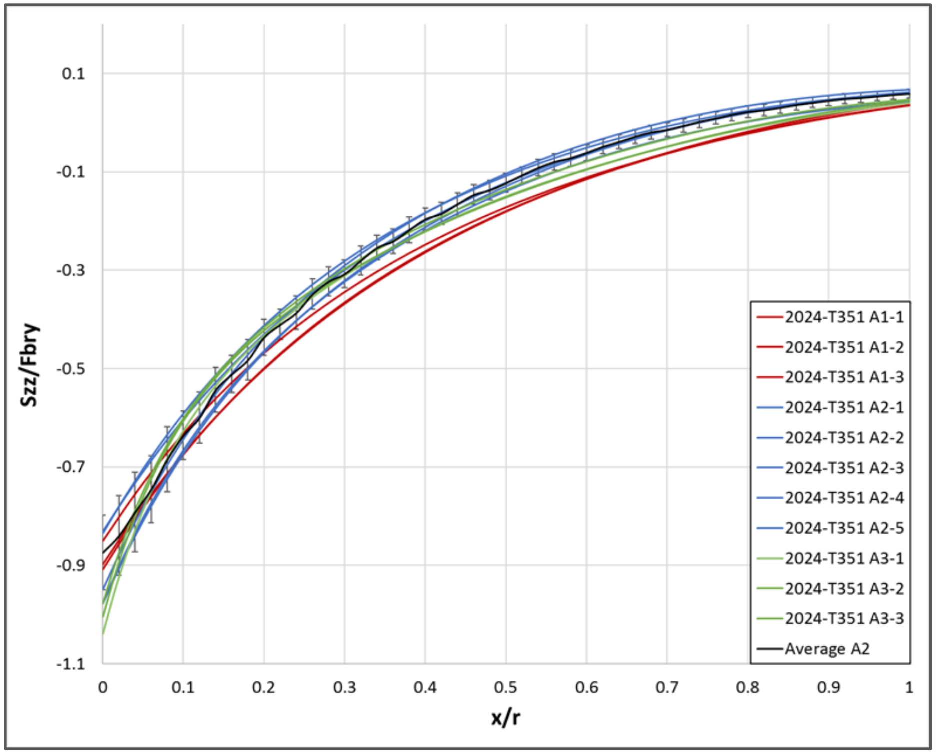
Best Practices Document

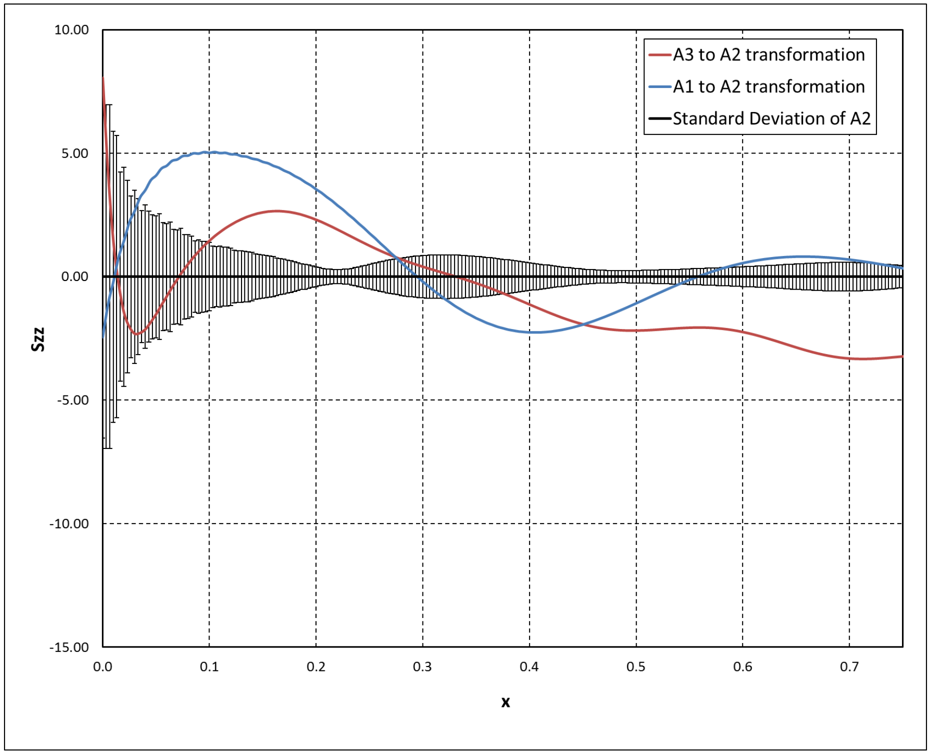
- ☐ **Current Status**
  - Initial draft delivered end of Sep. 2017
  - Review/feedback from USAF
- ☐ **Moving Forward**
  - Document only as good as the inputs provided by community
  - Need inputs related to:
    - Process modeling best practices
    - Other analysis methods
    - Factors that influence residual stress
    - Risk assessment considerations
    - Certification considerations
    - Procurement vs. sustainment considerations
    - Case studies

WE NEED YOU!!

Engineering Implementation of Residual Stress

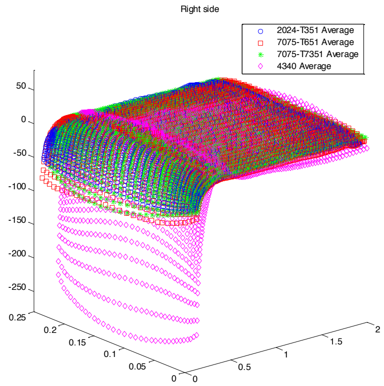
❑ Non-Dimensional Residual Stress – Hole Diameter



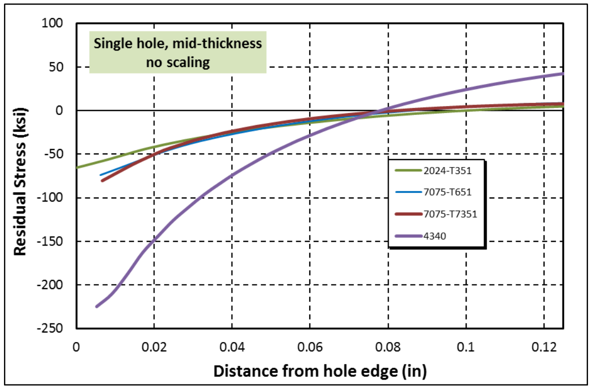


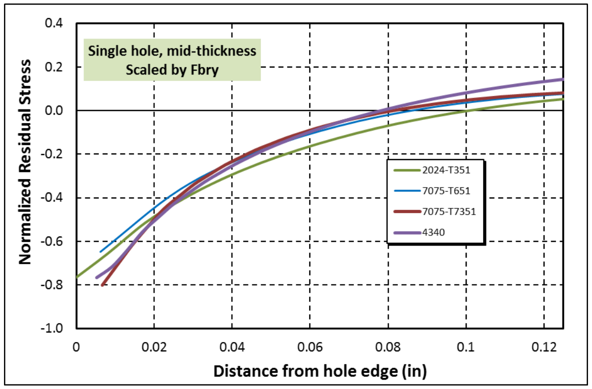
Engineering Implementation of Residual Stress

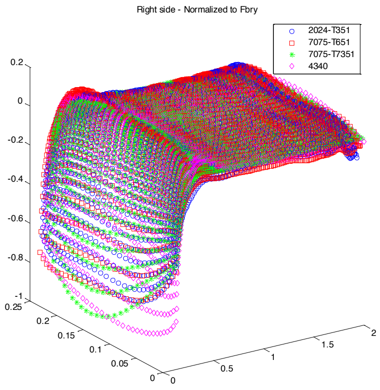
- Non-Dimensional Residual Stress – Material Properties
  - Can we utilize basic material properties (F_{ty}, F_{su}, F_{bru}, F_{bry}, etc.) to understand residual stress variations across different material types?



From MMPDS-04	2024-T351	7075-T651		7075-T7351		4340	
Basis	A	A		A		S	
Ftu (L)	64	77	1.20	67	1.05	220	3.44
Fty (L)	48	69	1.44	55	1.15	185	3.85
Fcy (L)	39	67	1.72	54	1.38	193	4.95
Fsu (L)	38	43	1.13	38	1.00	132	3.47
Fbru (e/D=1.5) (L)	97	117	1.21	105	1.08	297	3.06
Fbru (e/D=2.0) (L)	119	145	1.22	134	1.13	385	3.24
Fbry (e/D=1.5) (L)	72	97	1.35	83	1.15	267	3.71
Fbry (e/D=2.0) (L)	86	114	1.33	100	1.16	294	3.42

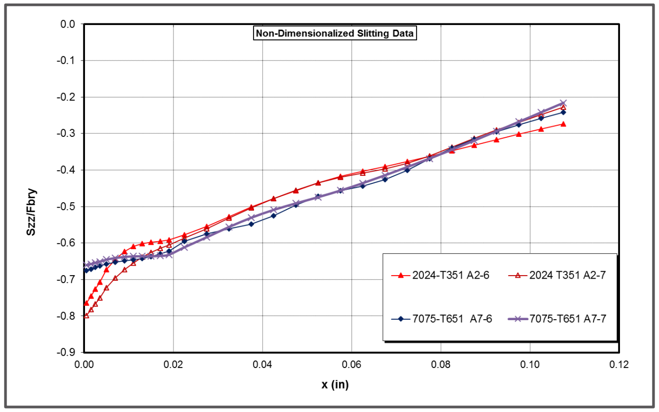


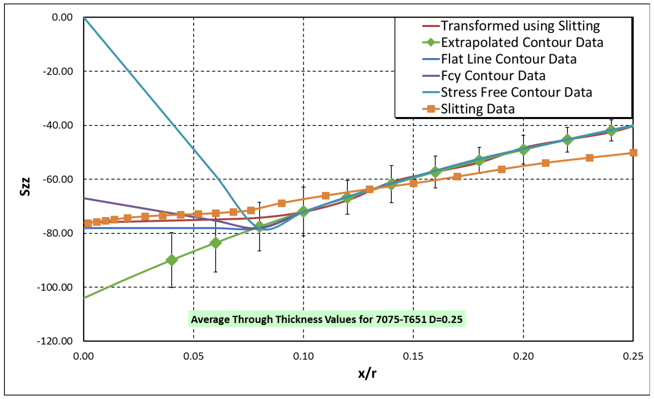




Refine Near Surface Residual Stress Understanding

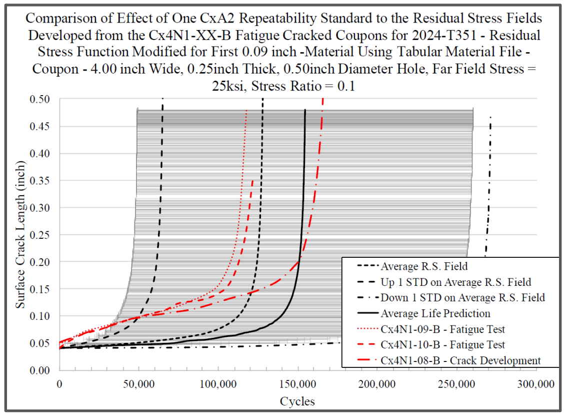
- ☐ **Investigate compliment of different measurement techniques to understand near surface residual stress**
  - ➢ All measurement techniques have strengths/weaknesses
  - ➢ Cx hole process modeling and measurement investigation
  - ➢ Geometrically "large" coupon program
- ☐ **Investigate engineering approaches to near surface residual stress behavior**
  - ➢ Impacts on:
    - Residual stress
    - Residual stress intensity, K_{res}
    - Damage tolerance life

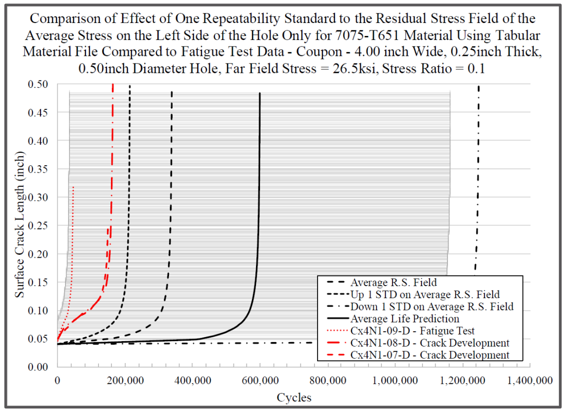




Residual Stress Relaxation

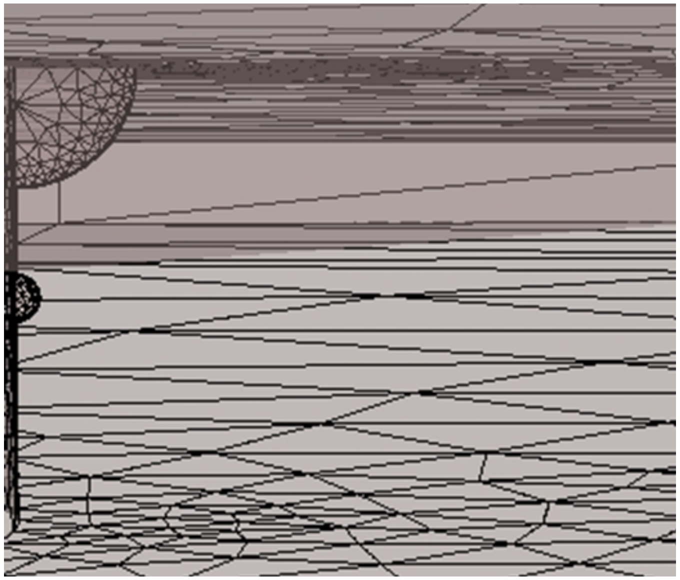
- ❑ **Modeling Residual Stress Relaxation under Cyclic Loading (Jones)**
  - ➢ Short presentation in breakout session
- ❑ **Quantifying the Effect of a Fatigue Crack on the Residual Stress Field (Carlson)**
- ❑ **Effects of Tensile and Compressive Overloads (APES-AA&S)**
  - ➢ Open and filled holes
- ❑ **Effects of Load Transfer (APES-AA&S)**
- ❑ **Legacy vs. New Manufacture Residual Stress Comparisons**
  - ➢ Review during measurement overview presentation





Other Focus Areas

- ☐ **Multi-Crack Effects (APES, HE)**
    - ➢ Compare growth of single crack with same primary crack (mandrel entrance corner) in presence of secondary bore crack.
    - ➢ Compare evolution of SIFs (primary crack) for single vs. multi-crack scenarios.
- ☐ **Crack Closure Effects (APES)**



Conclusions/Summary

- **Significant Collaboration within Analysis Methods Subcommittee**
  - Thanks to those individuals that have provided inputs
- **First Cx Hole Residual Stress Round Robin Successful**
  - (8) submissions – thank you
  - Need to digest results to understand key findings
- **Best Practices Document Established**
  - Need inputs from community
- **Additional Programs Addressing Key Modeling Factors/Questions**

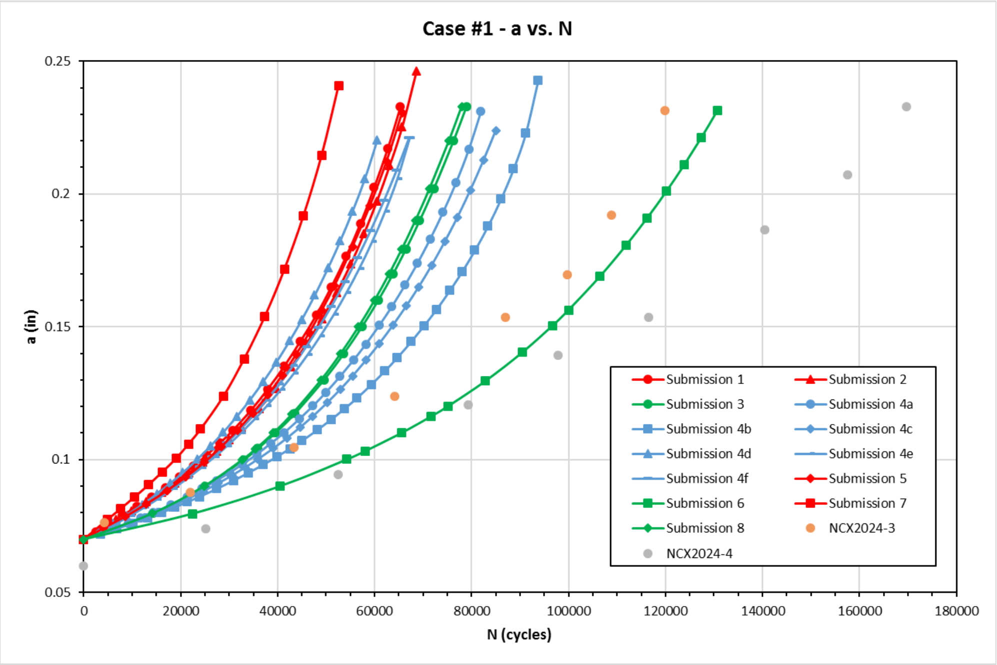
We are Positively Progressing Progressively – Cheers!!

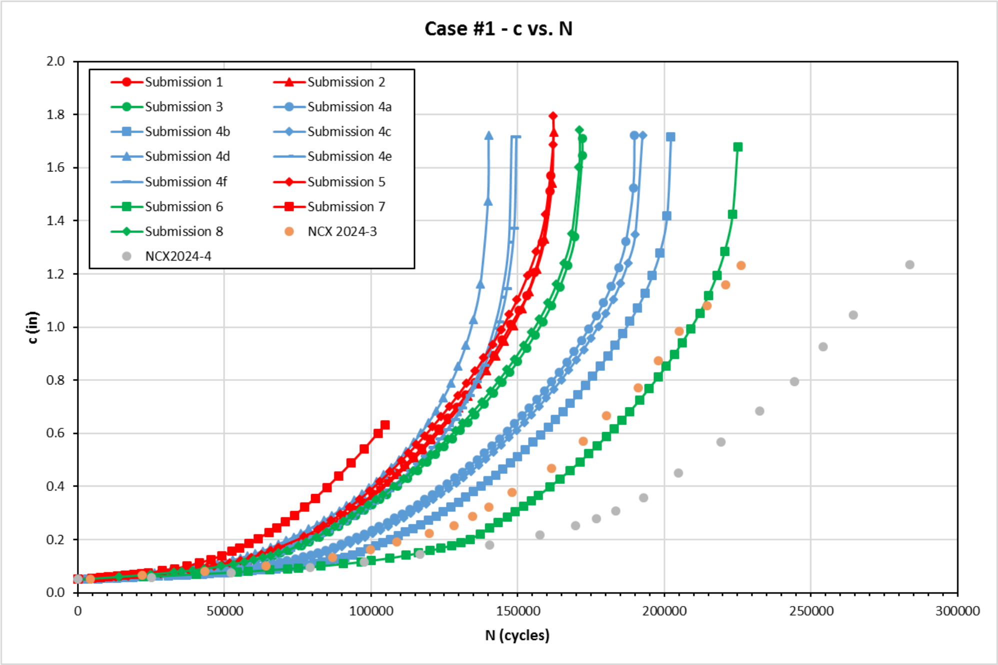
Questions?

Backup Slides

Round Robin for Cx Holes – Case #1

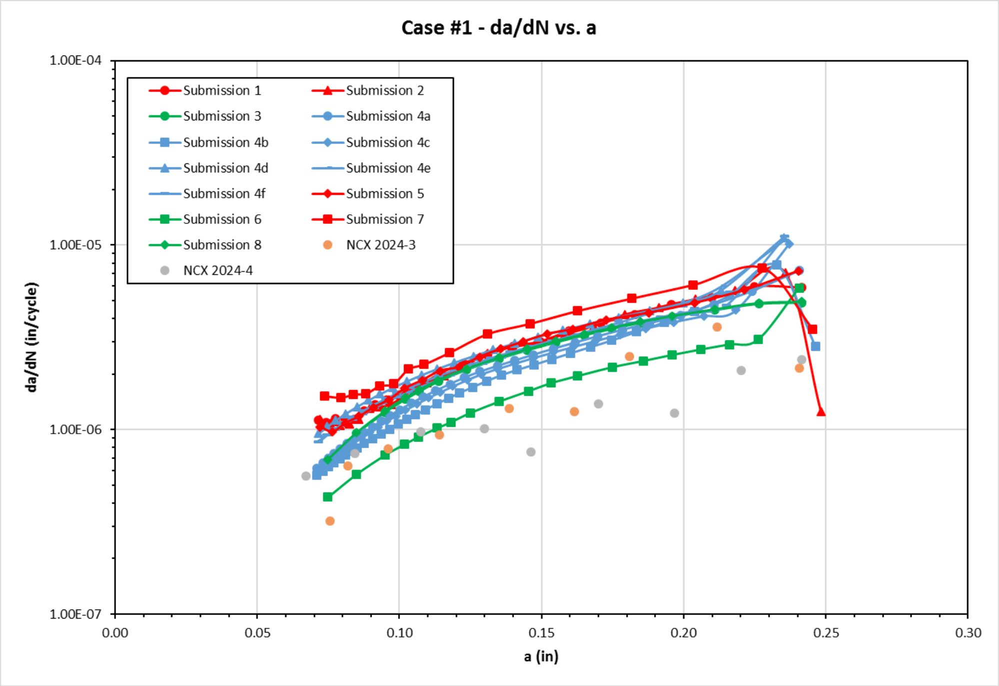
- ☐ Non-Cx Centered Hole

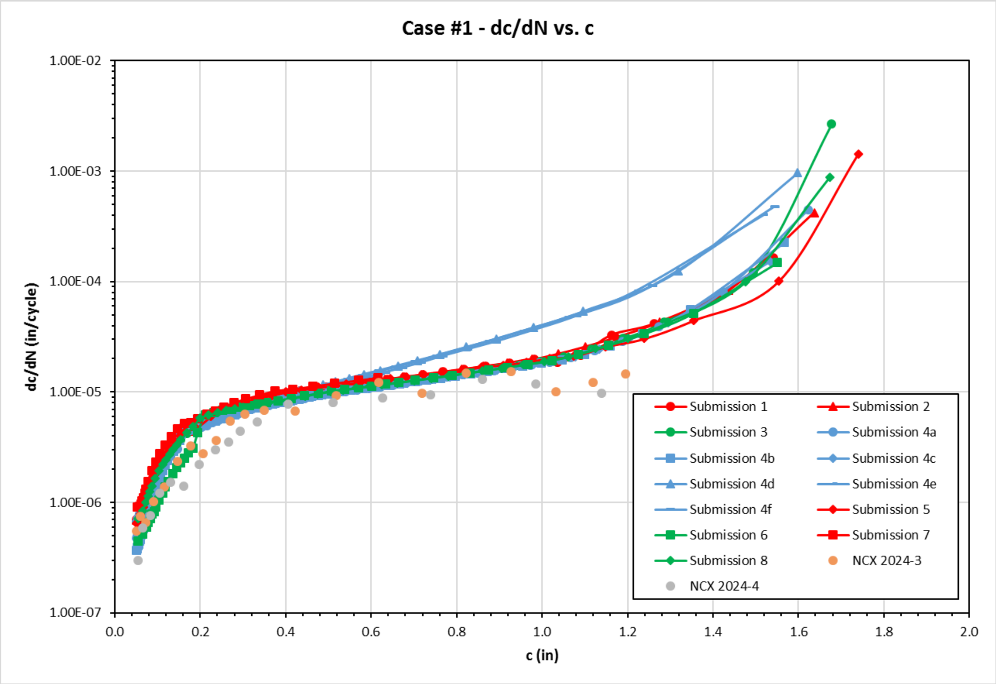




Round Robin for Cx Holes – Case #1

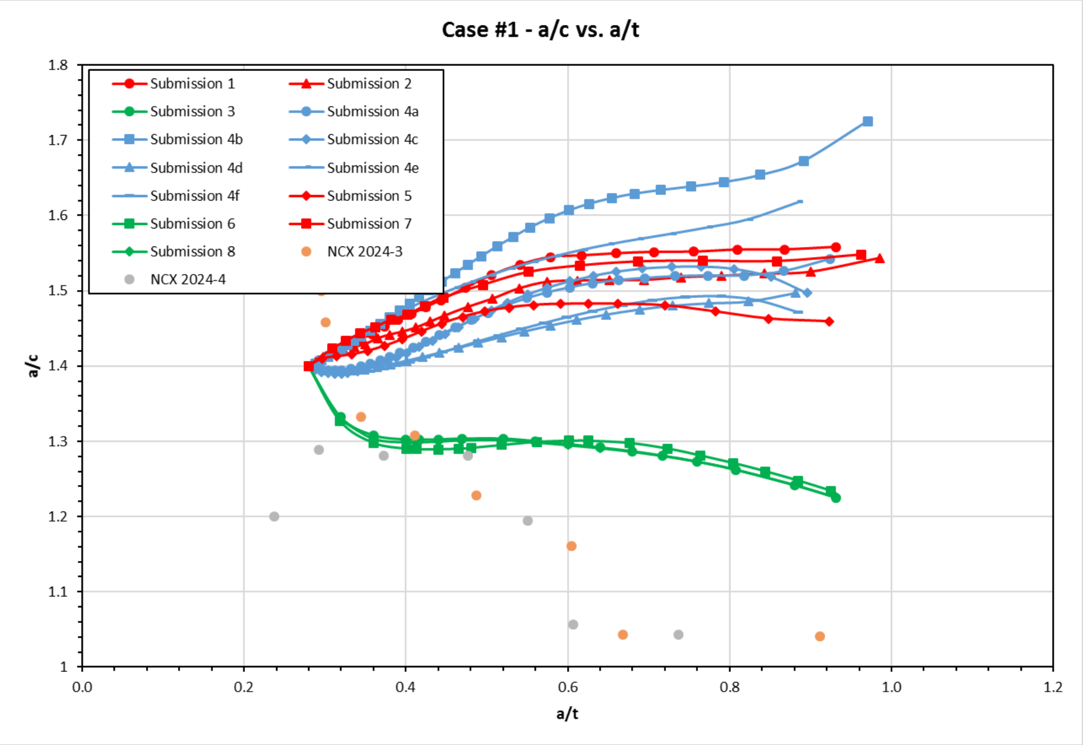
- ☐ Non-Cx Centered Hole



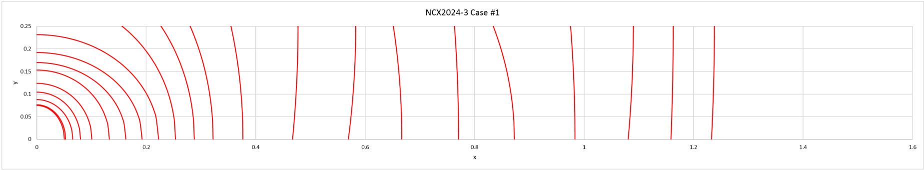


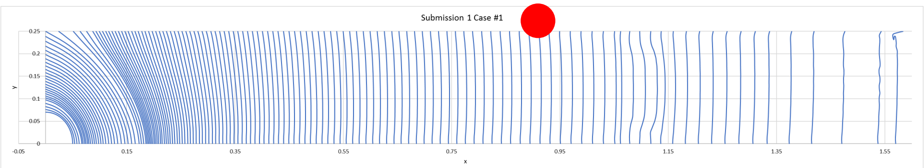
Round Robin for Cx Holes – Case #1

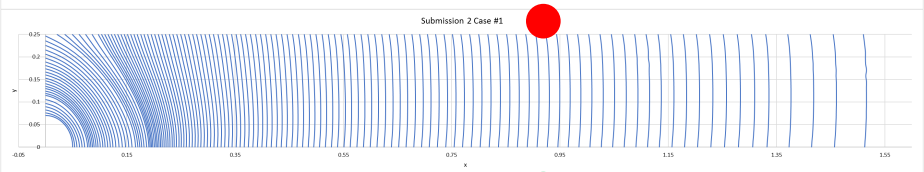
- ☐ Non-Cx Centered Hole

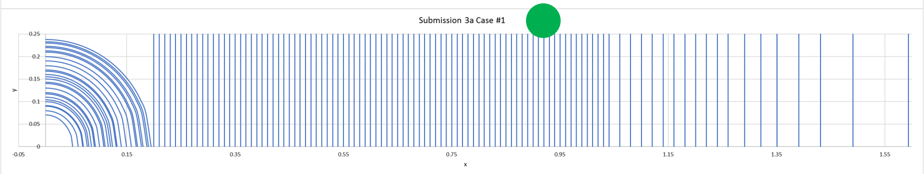


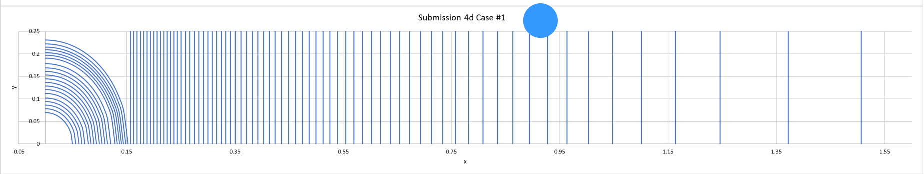
Round Robin for Cx Holes - Case #1

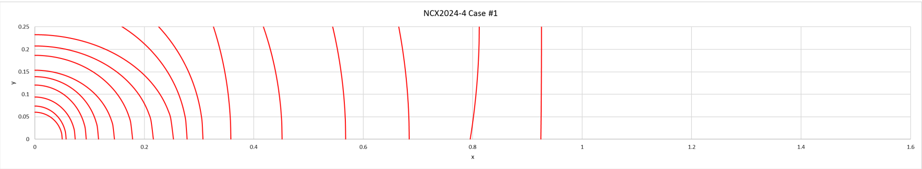


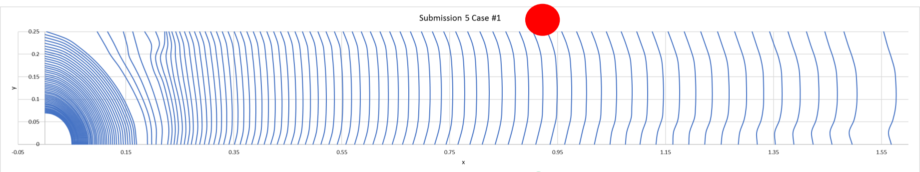


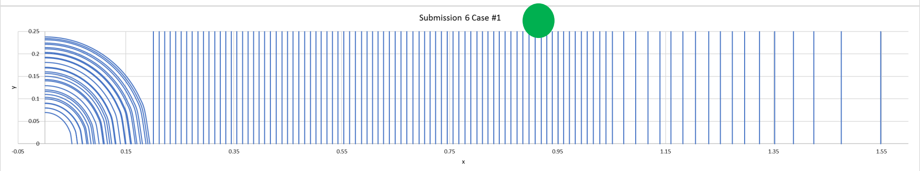


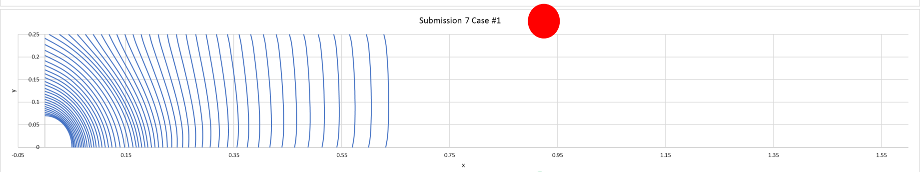


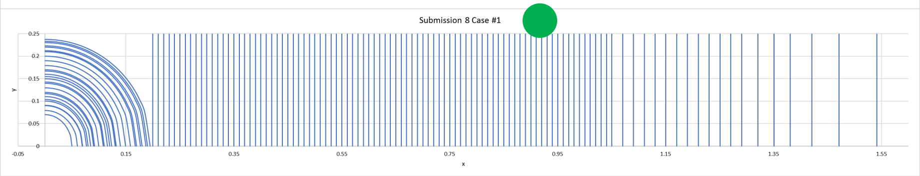












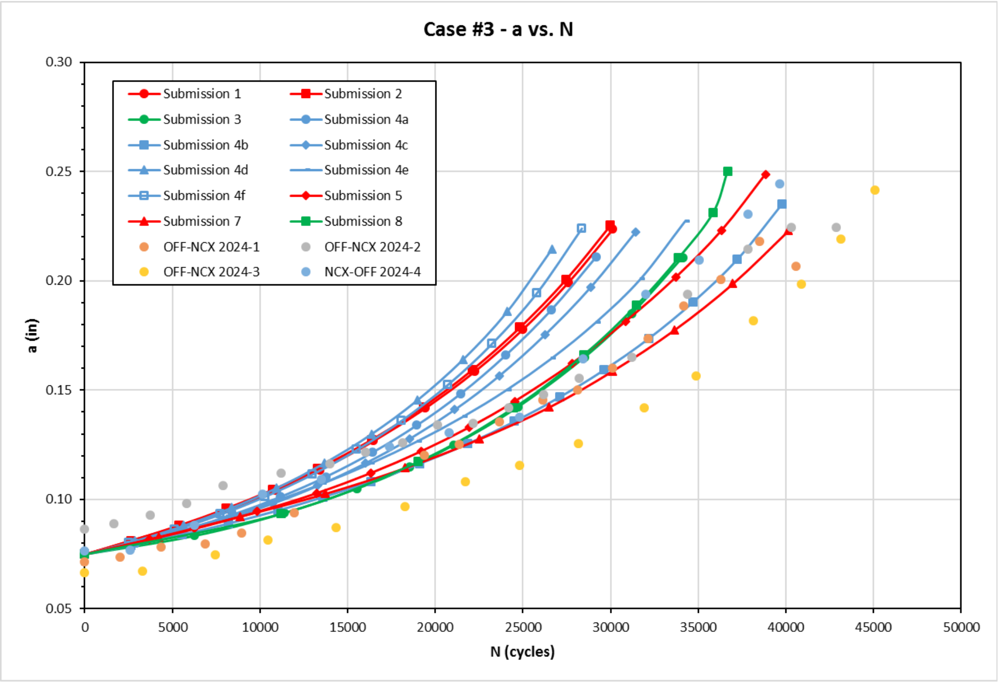
Round Robin for Cx Holes – Case #1

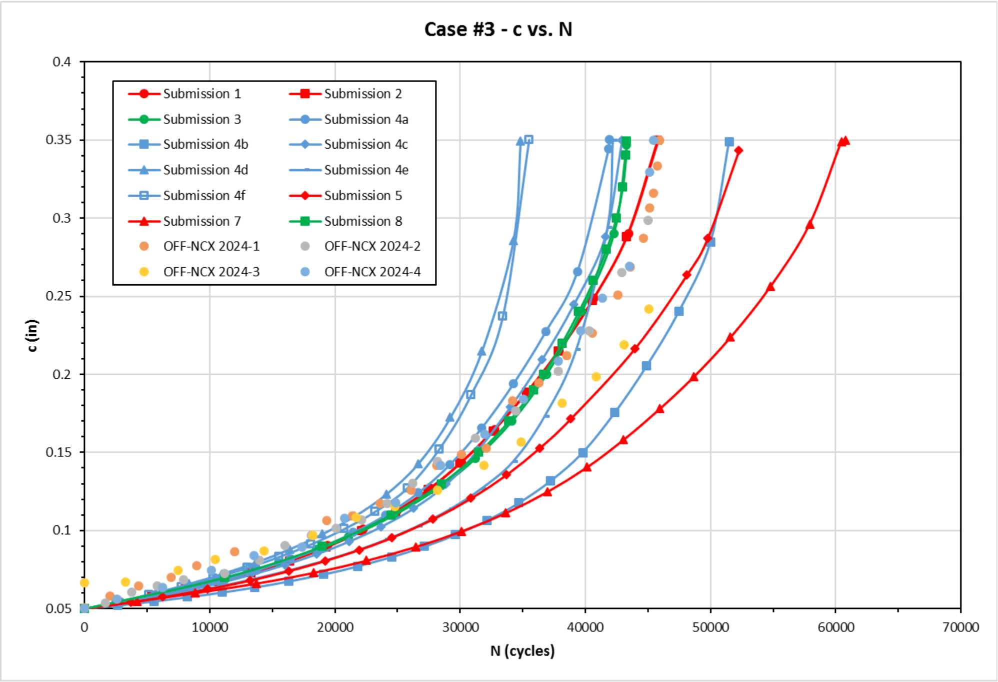
☐ Non-Cx Centered Hole Summary

- ➢ Fatigue life
  - Consistency between similar analytical approaches
  - Over-predict test lives
- ➢ Growth rates
  - Slight over-prediction, but similar slopes/trends
- ➢ Crack aspect ratio
  - AFGROW closest representation of crack aspect ratio
  - Continues to be a struggle

Round Robin for Cx Holes – Case #3

❑ Non-Cx Offset Hole


Case #3 - a vs. N

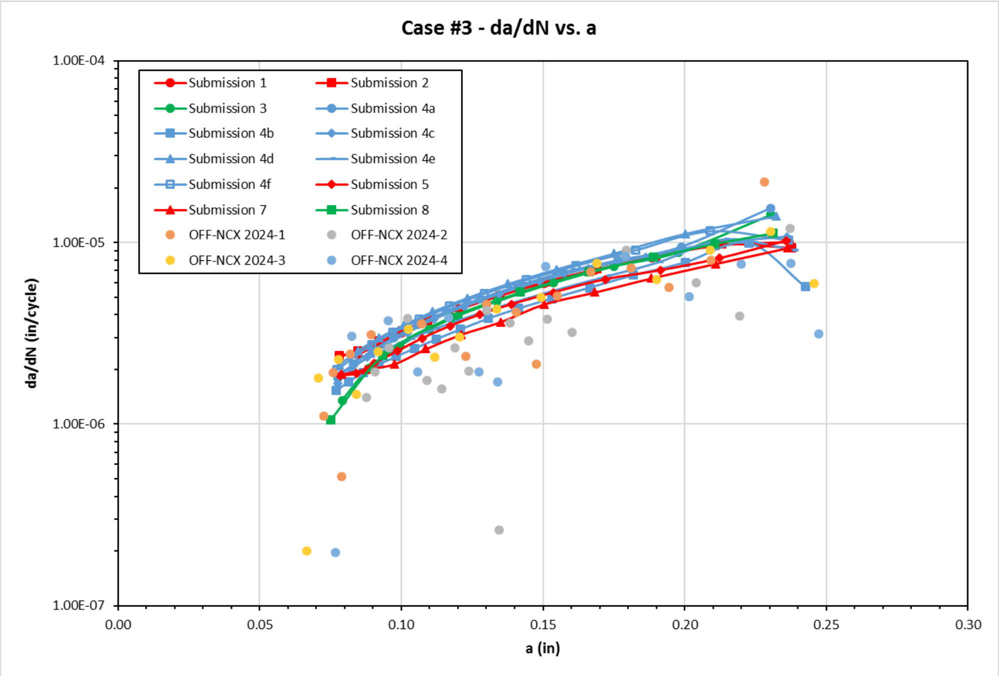

Case #3 - c vs. N

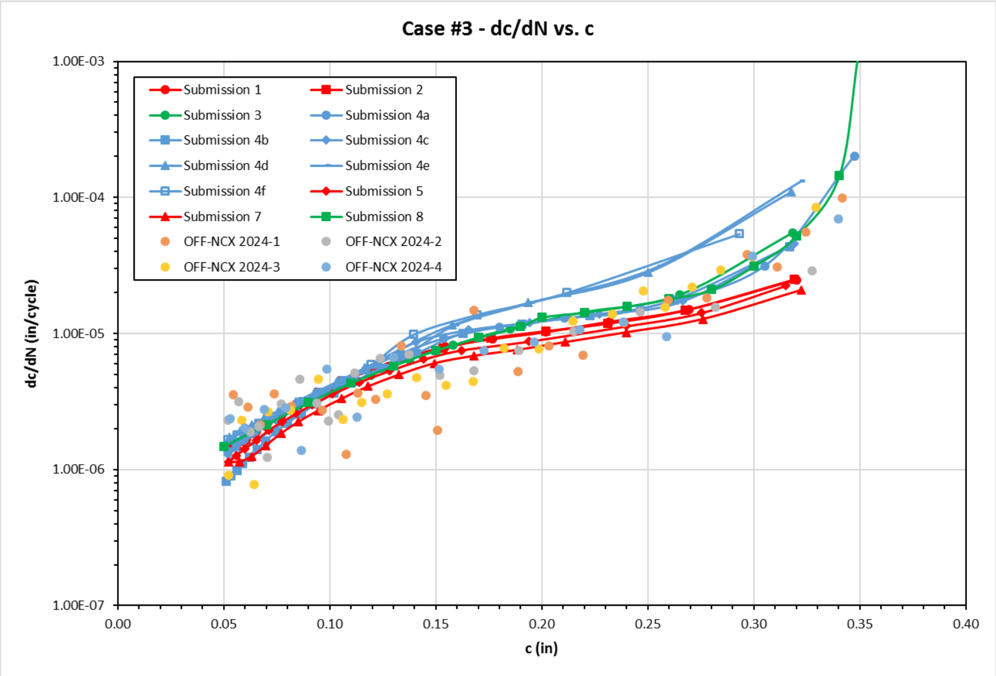
HILL ENGINEERING
Predict. Test. Perform.

ERSI

Round Robin for Cx Holes – Case #3

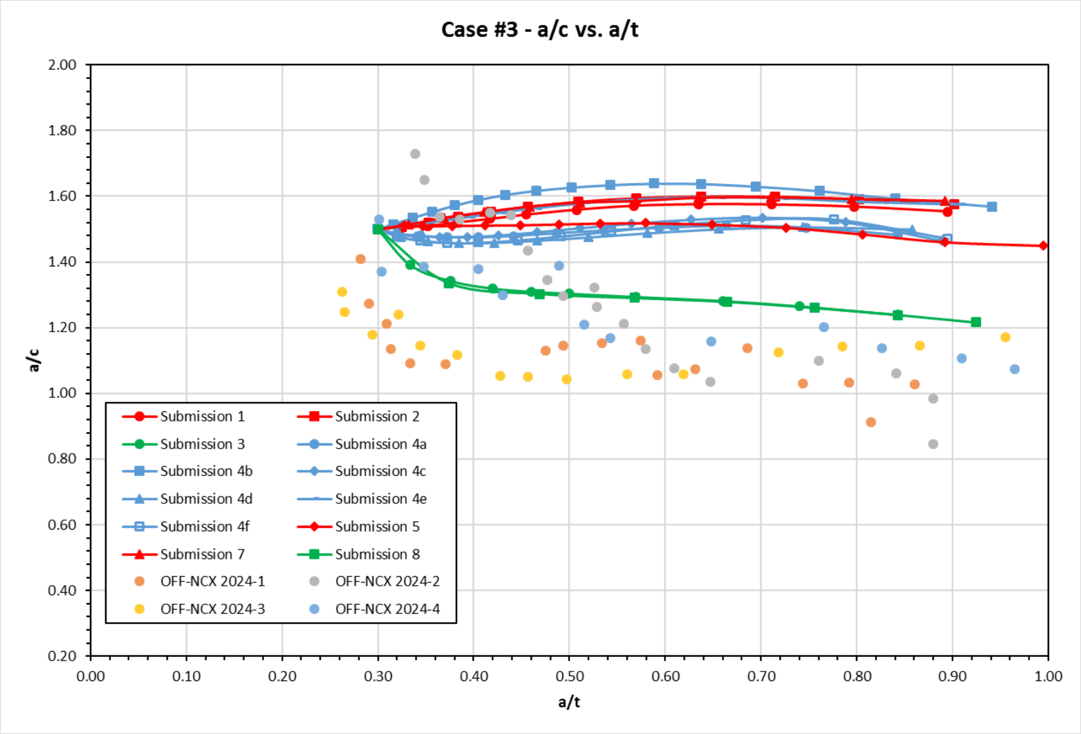
- Non-Cx Offset Hole



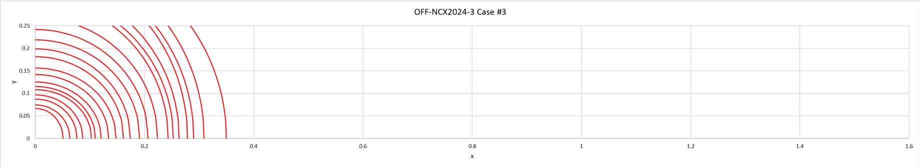


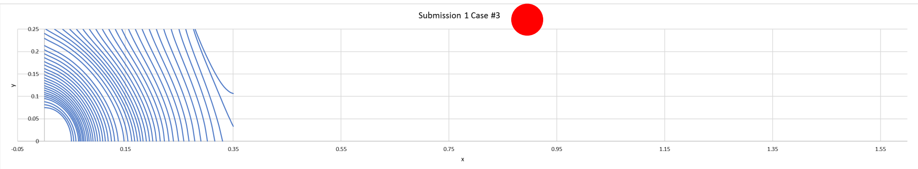
Round Robin for Cx Holes – Case #3

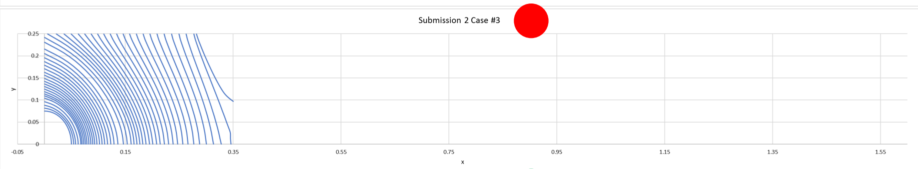
- ☐ Non-Cx Offset Hole

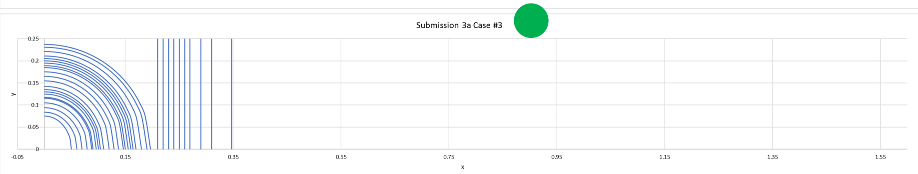


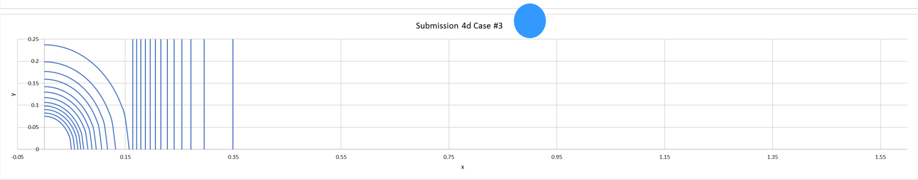
Round Robin for Cx Holes - Case #3

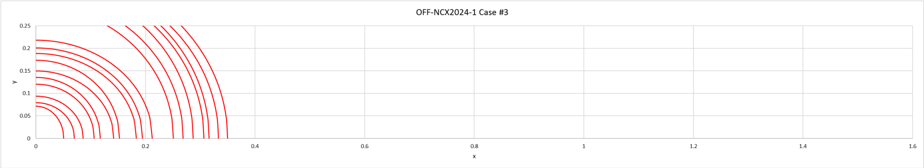

OFF-NCX2024-3 Case #3

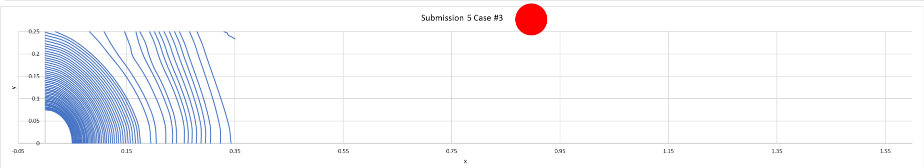

Submission 1 Case #3 ●

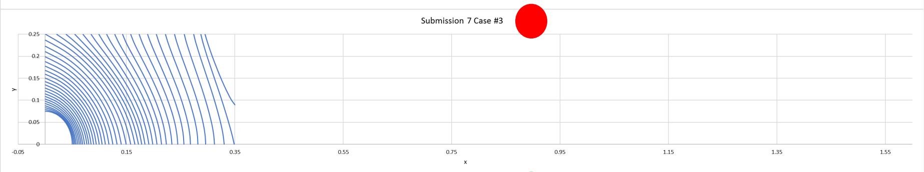

Submission 2 Case #3 ●

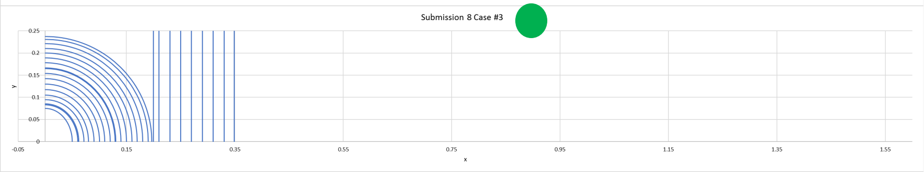

Submission 3a Case #3 ●


Submission 4d Case #3 ●


OFF-NCX2024-1 Case #3


Submission 5 Case #3 ●


Submission 7 Case #3 ●


Submission 8 Case #3 ●

Round Robin for Cx Holes – Case #3

- **Non-Cx Offset Hole Summary**
  - Fatigue life
    - Consistency between similar analytical approaches
    - Over-predict test lives
  - Growth rates
    - Similar slopes/trends
  - Crack aspect ratio
    - AFGROW closest representation of crack aspect ratio
    - Continues to be a struggle

Fatigue Testing and Validation

Fatigue Crack Growth in Engineered Residual Stress Fields

ERSI
Layton, UT

21 Sep 2017

Thomas Mills, Ph.D.
Analytical Processes / Engineered Solutions, Inc.

Acknowledgments

- A-10 & T-38 ASIP
- AFRL
- SwRI
- ERSI Subcommittees

Contents

- Why do we test?
- Analysis data needs
- Peak Valley Load Excursion Effects at CX Holes
- Effect of Applied Stress Ratio on Crack Growth at CX Holes
- Equipment Inventories
- Future validation cases
- Crack Growth Material Data

ERS: Why do we test?

- Certification of a process for production / repair
- Iterate design (w/ desire for computational methods up front)
- Examine variability and interactions in a process
  - Uncover modeling needs
- Provide validation data for models
- Provide “foundation” data (e.g., crack growth rate data)
- Understand failure modes and evolution

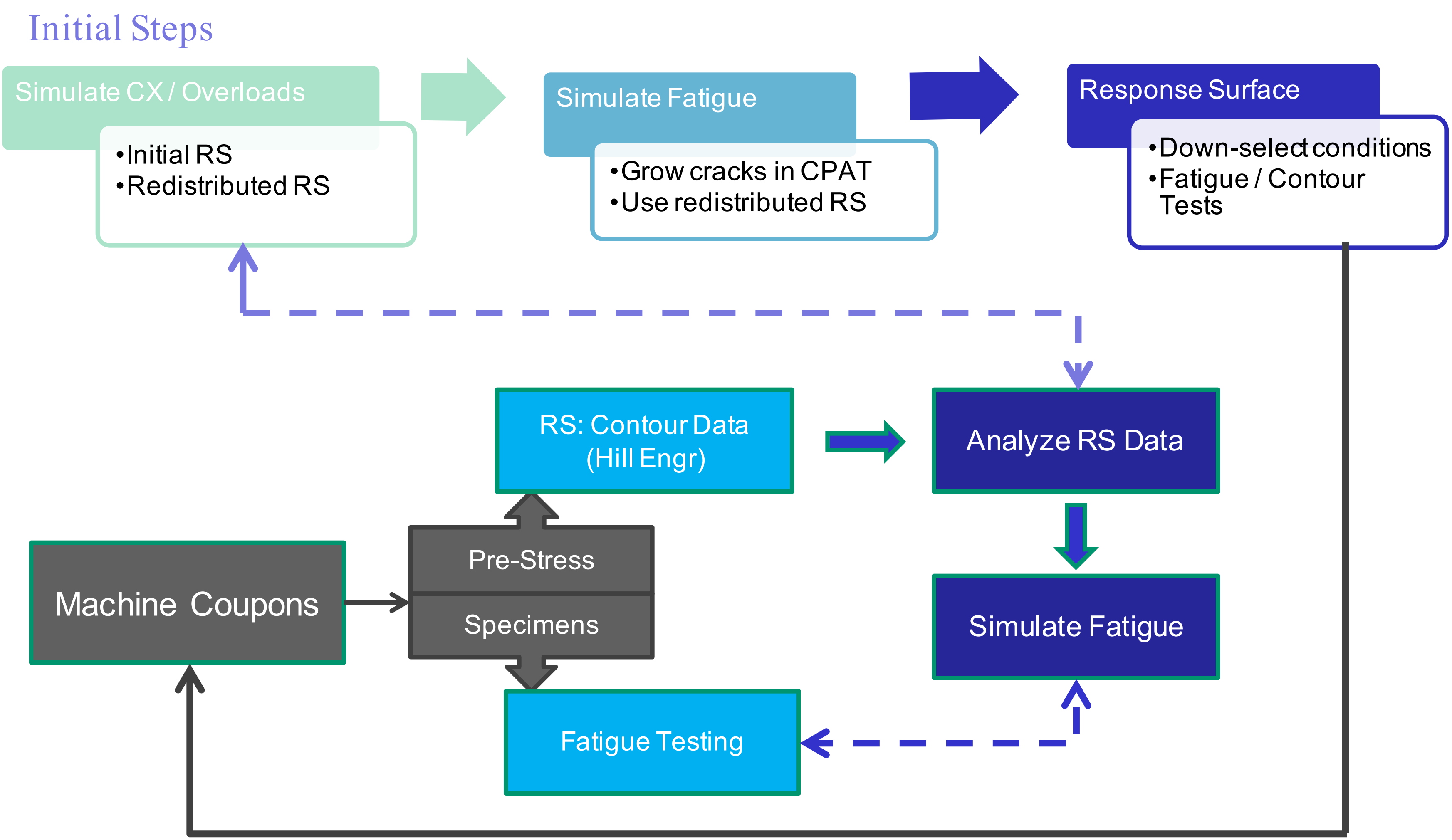
Data to Support ERSI Analysis Group

- What are the big needs?
  - Most sensitive parameters to crack growth in RS fields:
    - Material data (da/dN vs. ΔK)
    - Stress distribution / redistribution
    - Closure phenomena
  - Validation cases
    - Primarily constant amplitude

Residual Stress (RS) Redistribution

Compression / Tension Overloads (OL)

Task Process Flow



Initial Steps

Simulate CX / Overloads
- Initial RS
- Redistributed RS

Simulate Fatigue
- Grow cracks in CPAT
- Use redistributed RS

Response Surface
- Down-select conditions
- Fatigue / Contour Tests

RS: Contour Data (Hill Engr)

Analyze RS Data

Simulate Fatigue

Machine Coupons

Pre-Stress

Specimens

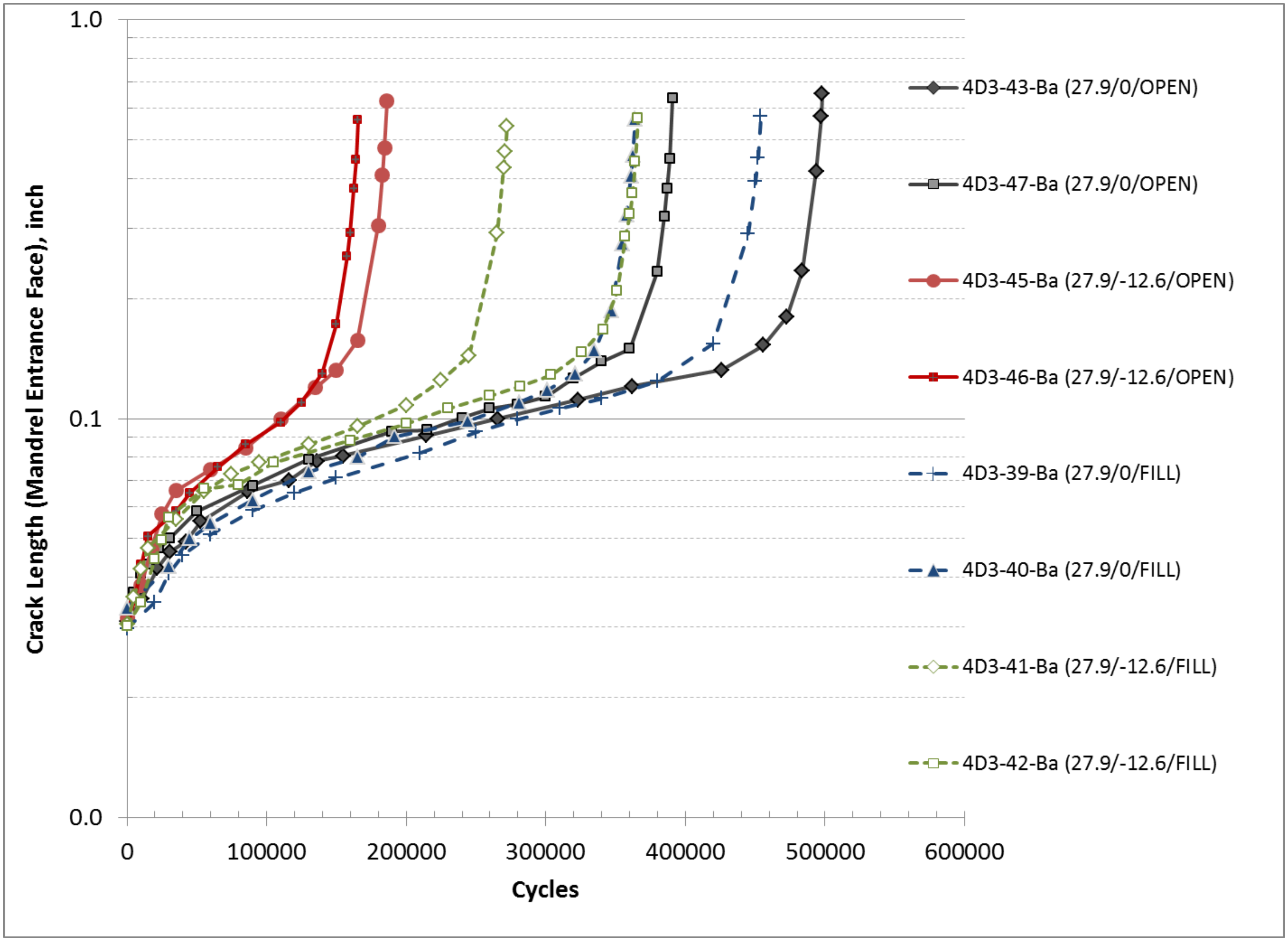
Fatigue Testing

Test Matrix

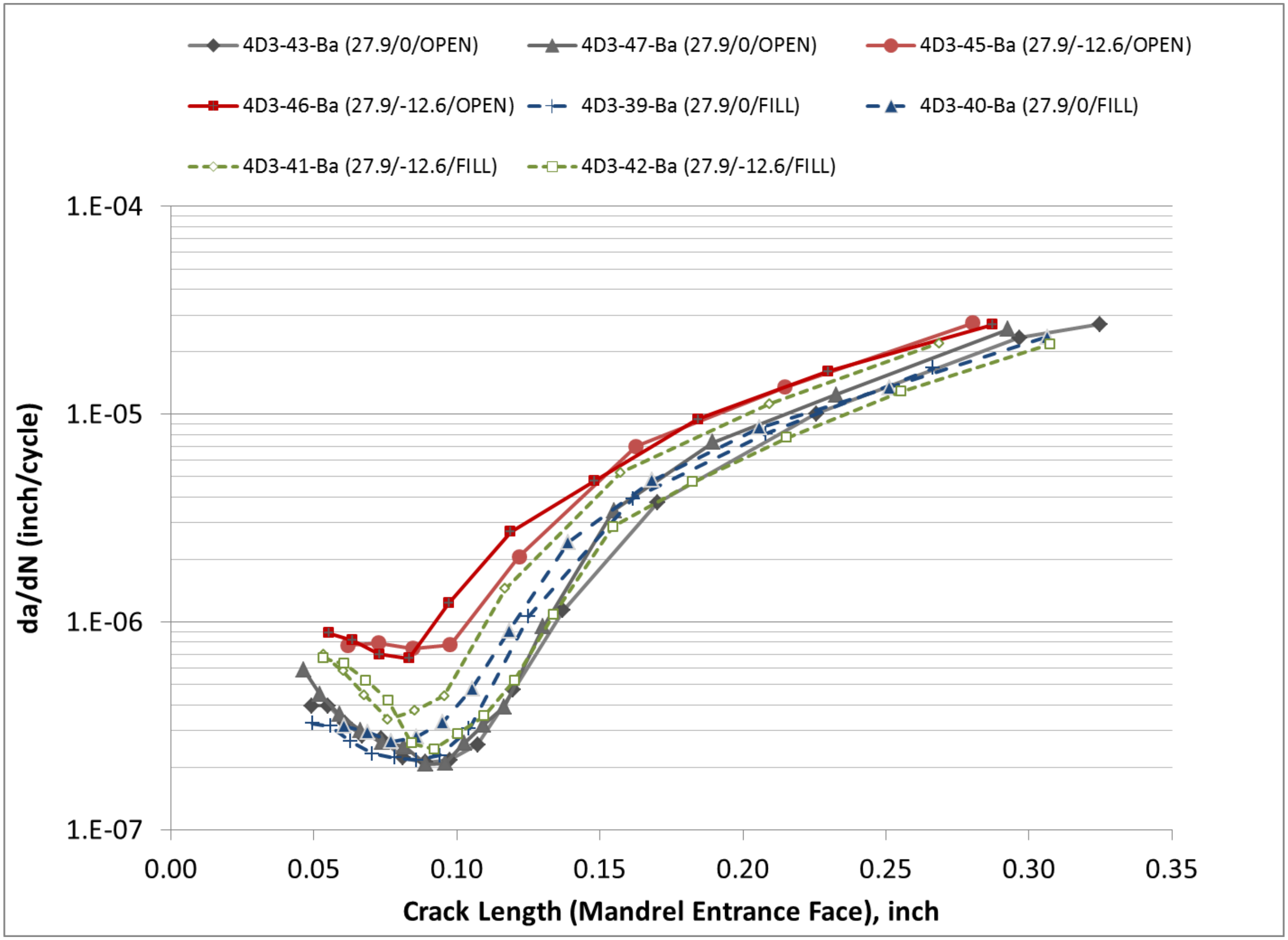
- 2024-T351 & 7075-T651Al
- Evaluate two open-hole and two filled-hole RS specimens using Contour Method
  - +27.9/0
  - +42.1/0
  - +27.9/-12.6
  - +42.1/-12.6
- Evaluate two open-hole and two filled-hole fatigue specimens without high tension OL
  - +27.9/0
  - +27.9/-12.6
- All fatigue tests conducted at 25 ksi, R + 0.1
  - Initial crack size approximately 0.03 inch x 0.045 inch
  - Initial ream diameter produced “max” interference, 4.3%

2024-T351
Fatigue Results

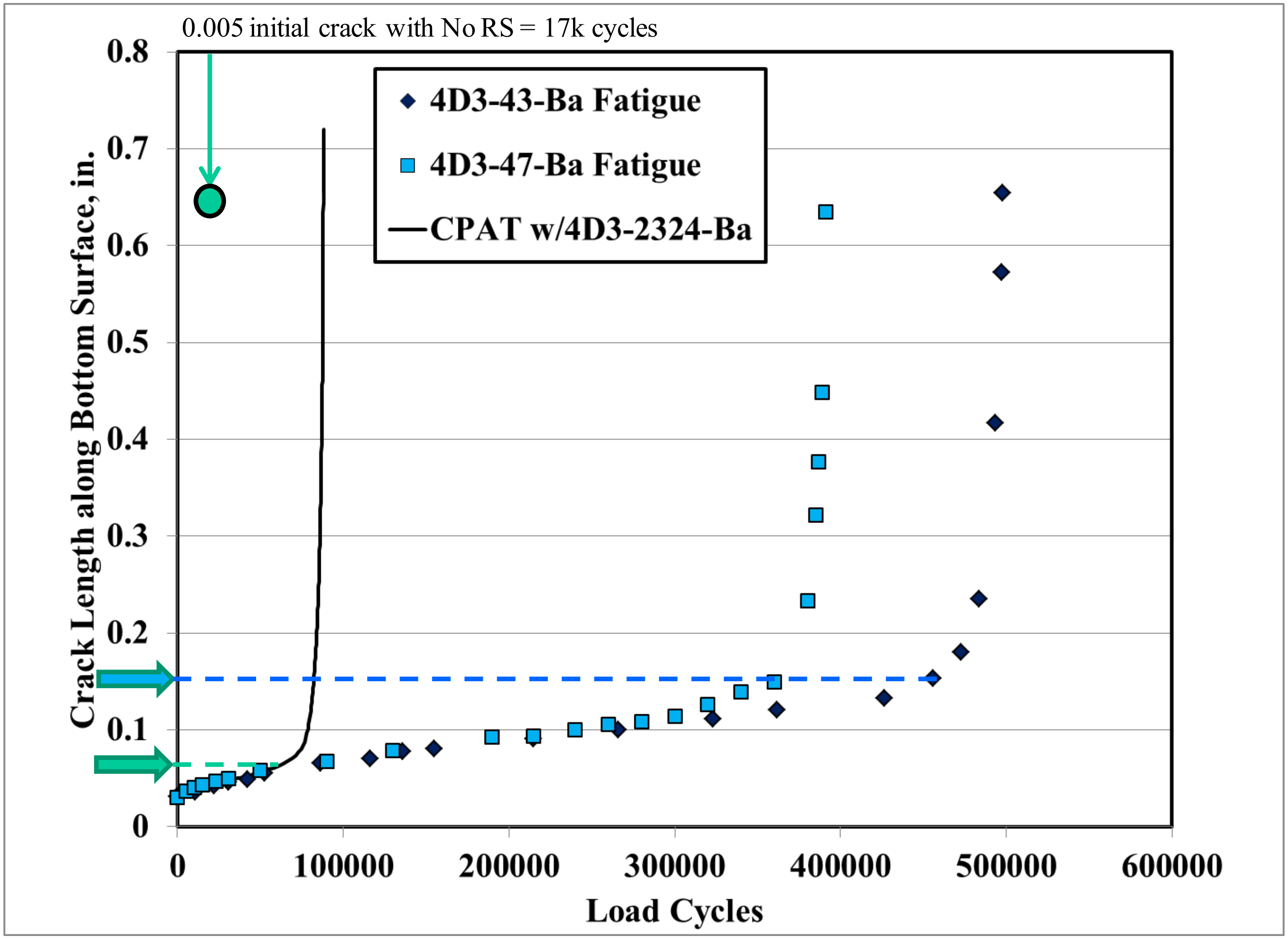
Underloads: a vs. N Data



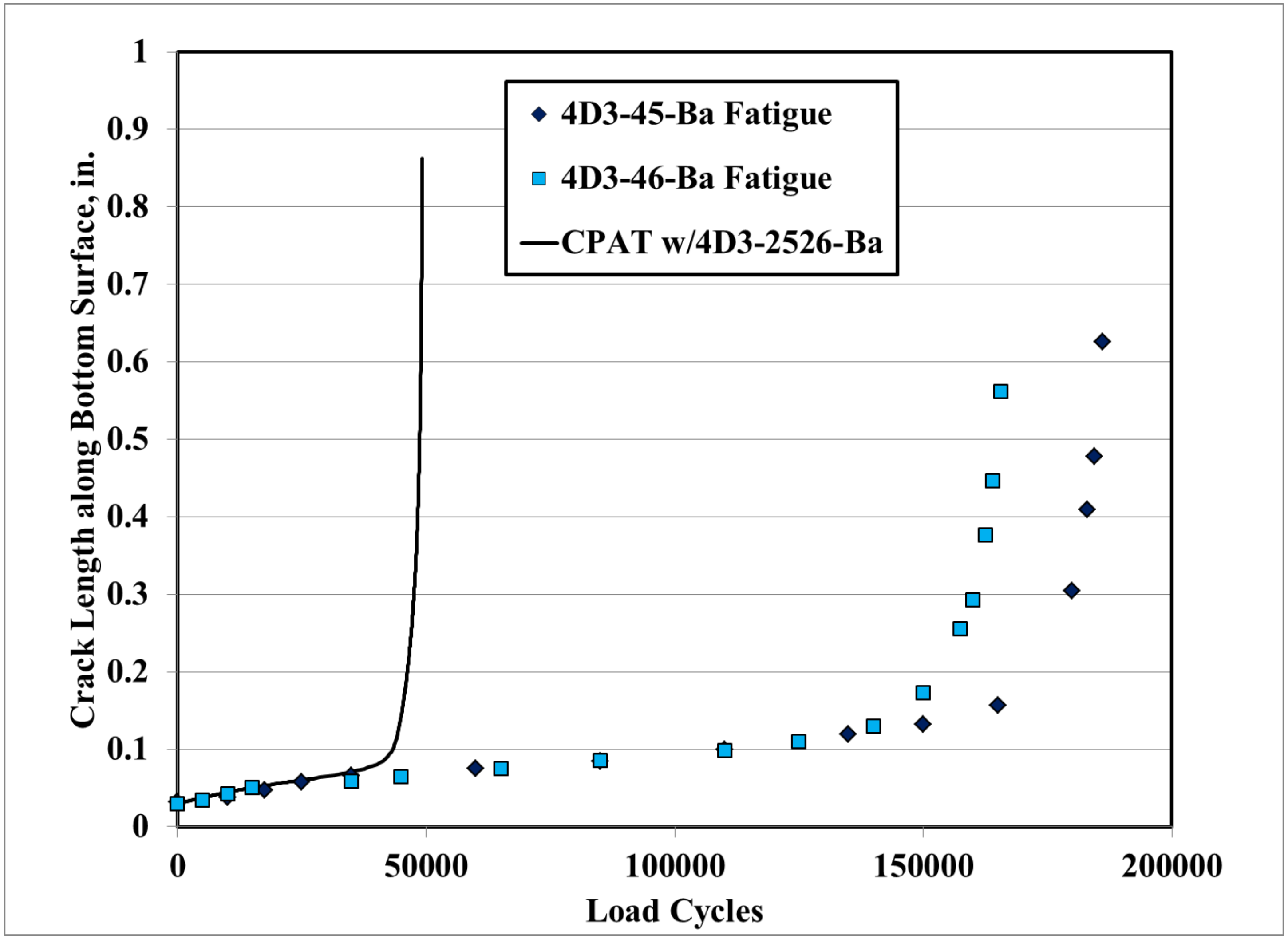
Underloads: da/dN vs. a (7-pt)



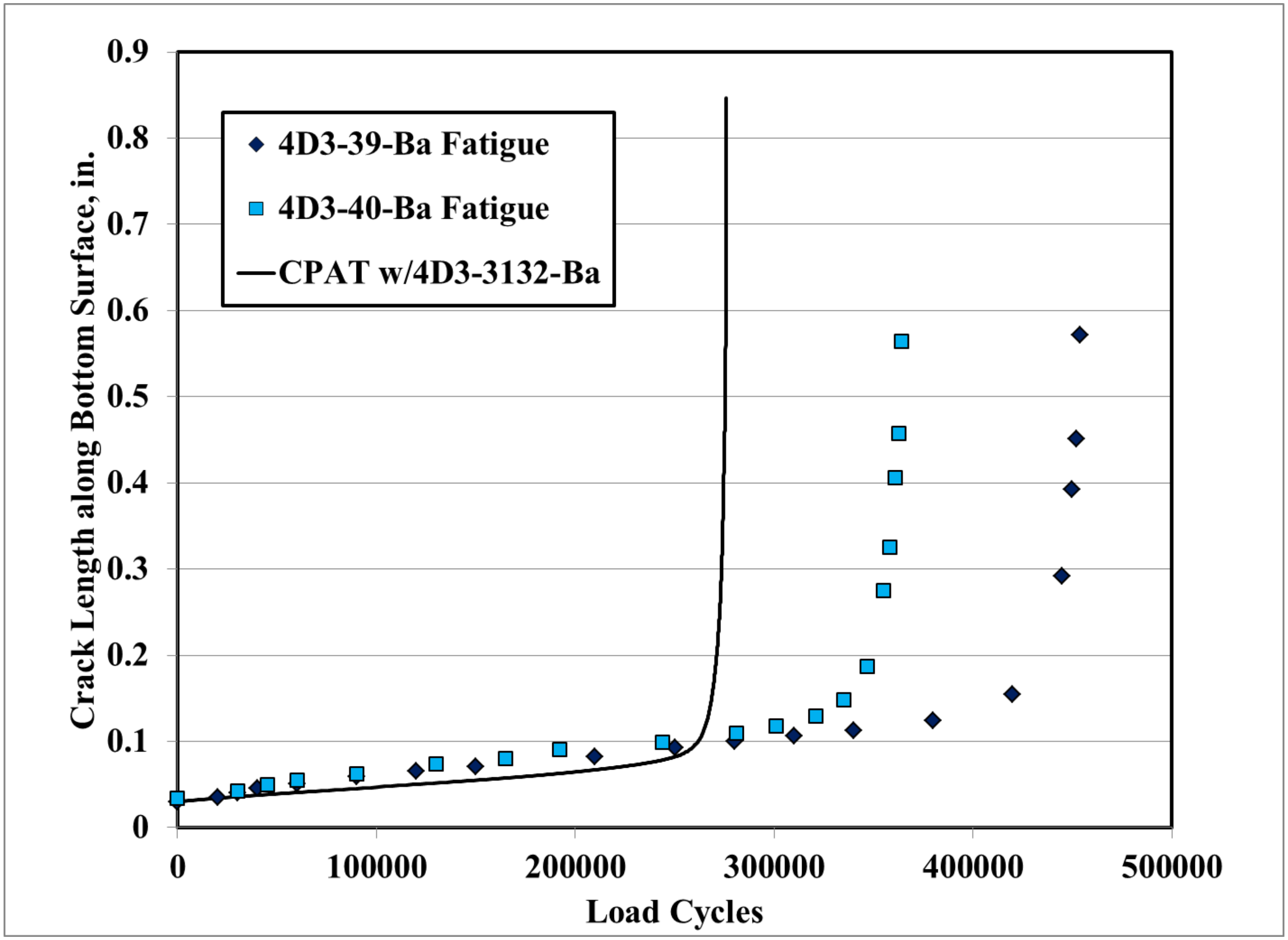
FCG using Contour Data
27.9 / 0 / OPEN



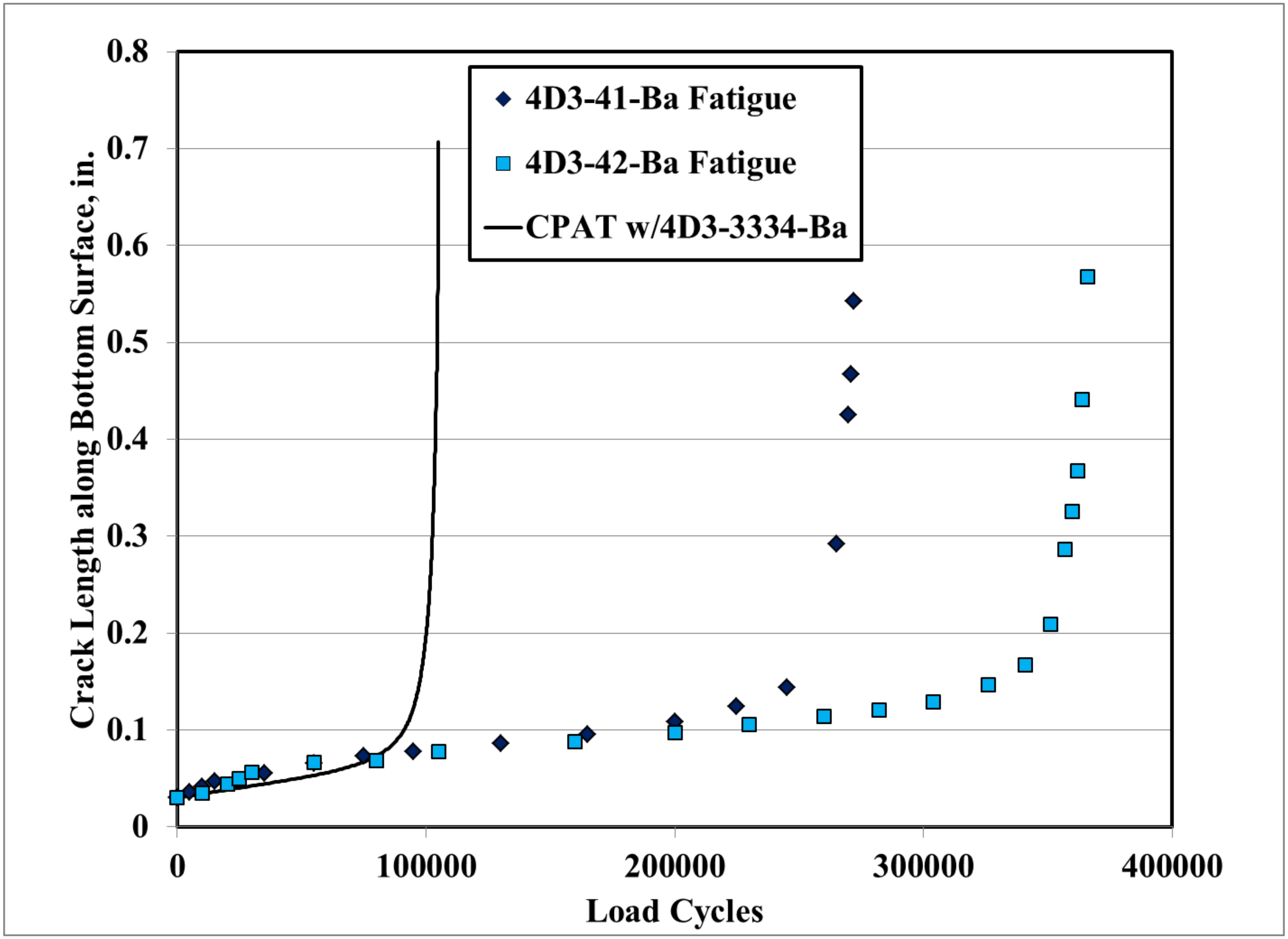
FCG using Contour Data
27.9 / -12.6 / OPEN



FCG using Contour Data
27.9 / 0 / FILL

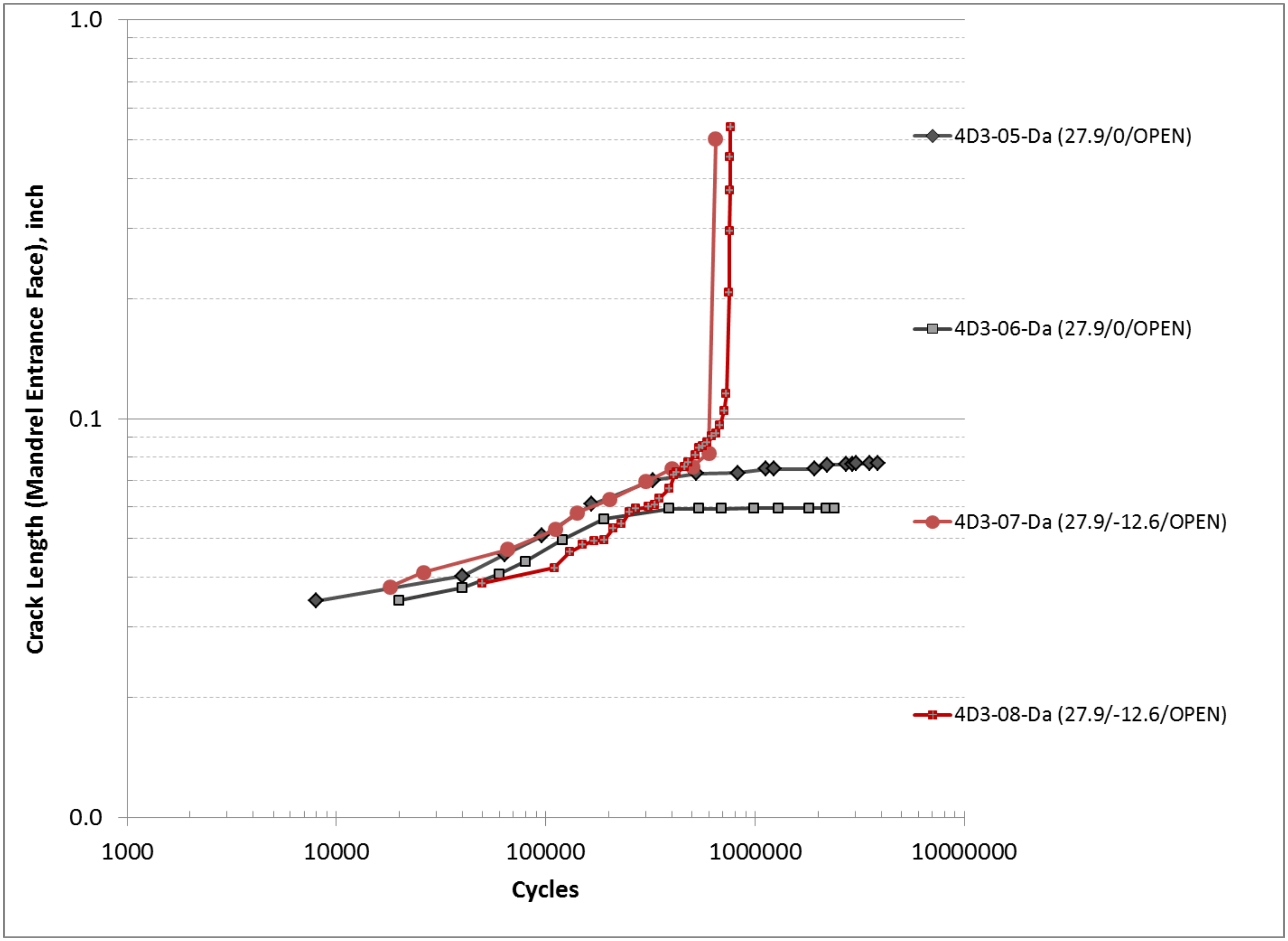


FCG using Contour Data 27.9 / -12.6 / FILL

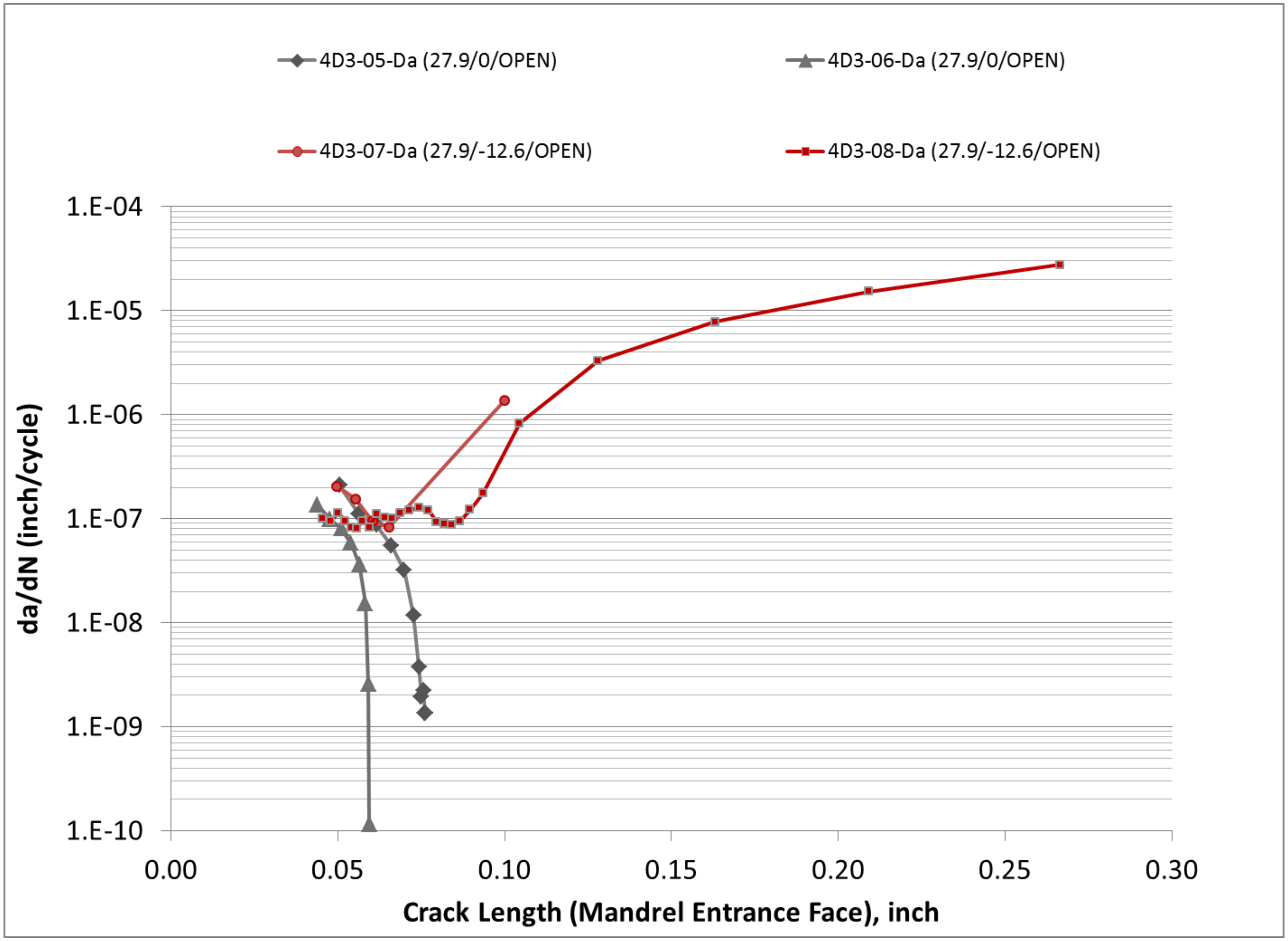


7075-T651
Fatigue Results

Underloads: a vs. N Data



Underloads: da/dN vs. a (7-pt)



Redistribution: Observations

2024-T351 Aluminum

- Test life with compression preload was 37% of that without.
- Simulation life with compression preload was 55% of that without.
- Unfortunately, test lives were to 3x to 5x greater than computed lives.
- Valuable data sets for future simulations:
  - Well characterized residual stress
  - Well behaved crack growth in experiments
  - Tightly controlled processing during CX

7075-T651 Aluminum

- Compression preload allowed cracks to grow to failure.
- Remainder of specimens underwent crack arrest.
- Most models arrested--common problem with 7075.

Applied R Effects

2024-T351 (APES)
7075-T7351 (SwRI)

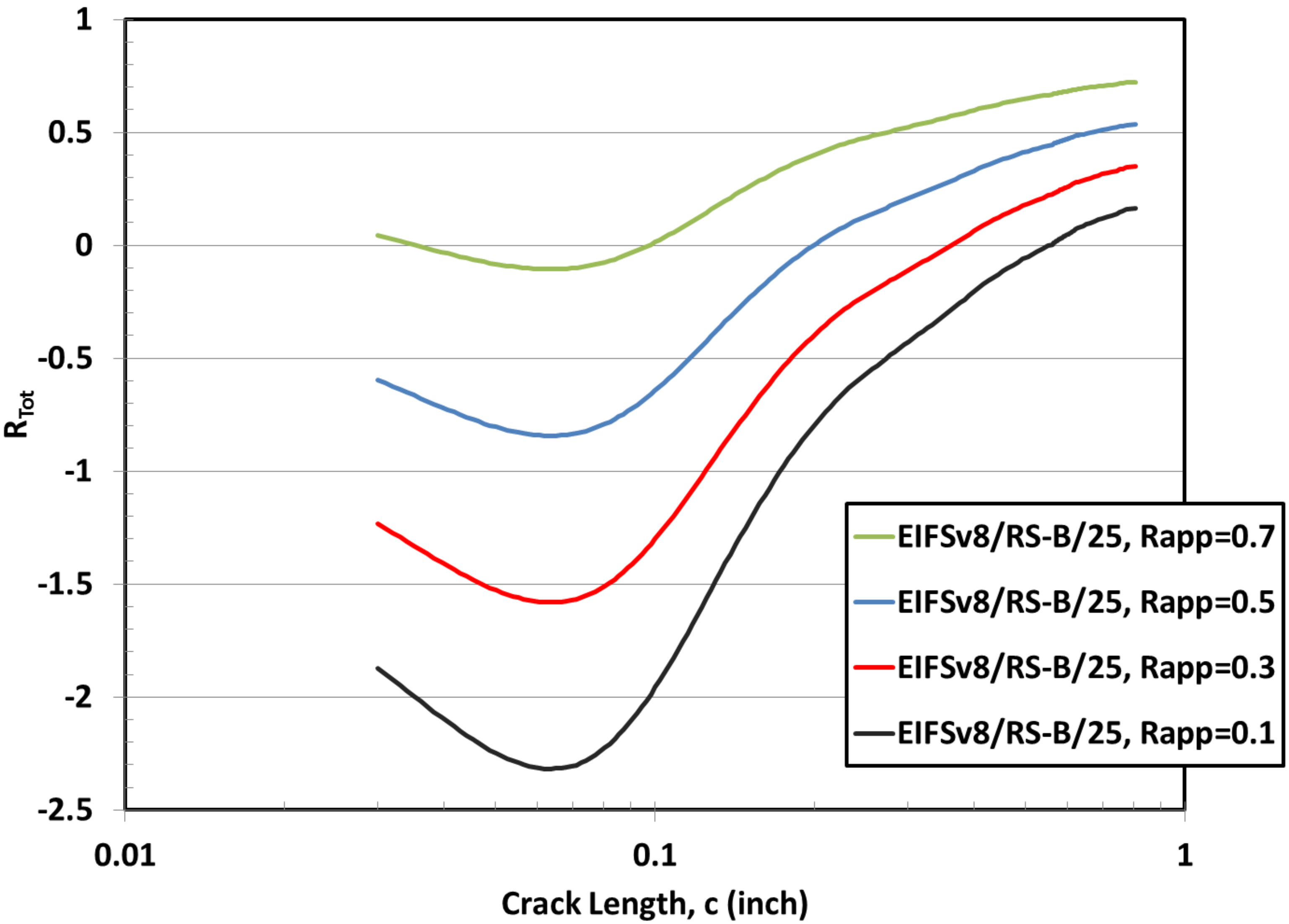
Test Conditions and Goal

- Goal: examine behavior of CX crack growth under various applied R

- APES (2024-T351)
  - Five replicates at
  - R_{app} = 0.1, 0.3, 0.5, 0.7

- SwRI (7075-T7351)
  - Four replicates at
  - R_{app} = 0.02, 0.1, 0.4, 0.6, 0.7, 0.8

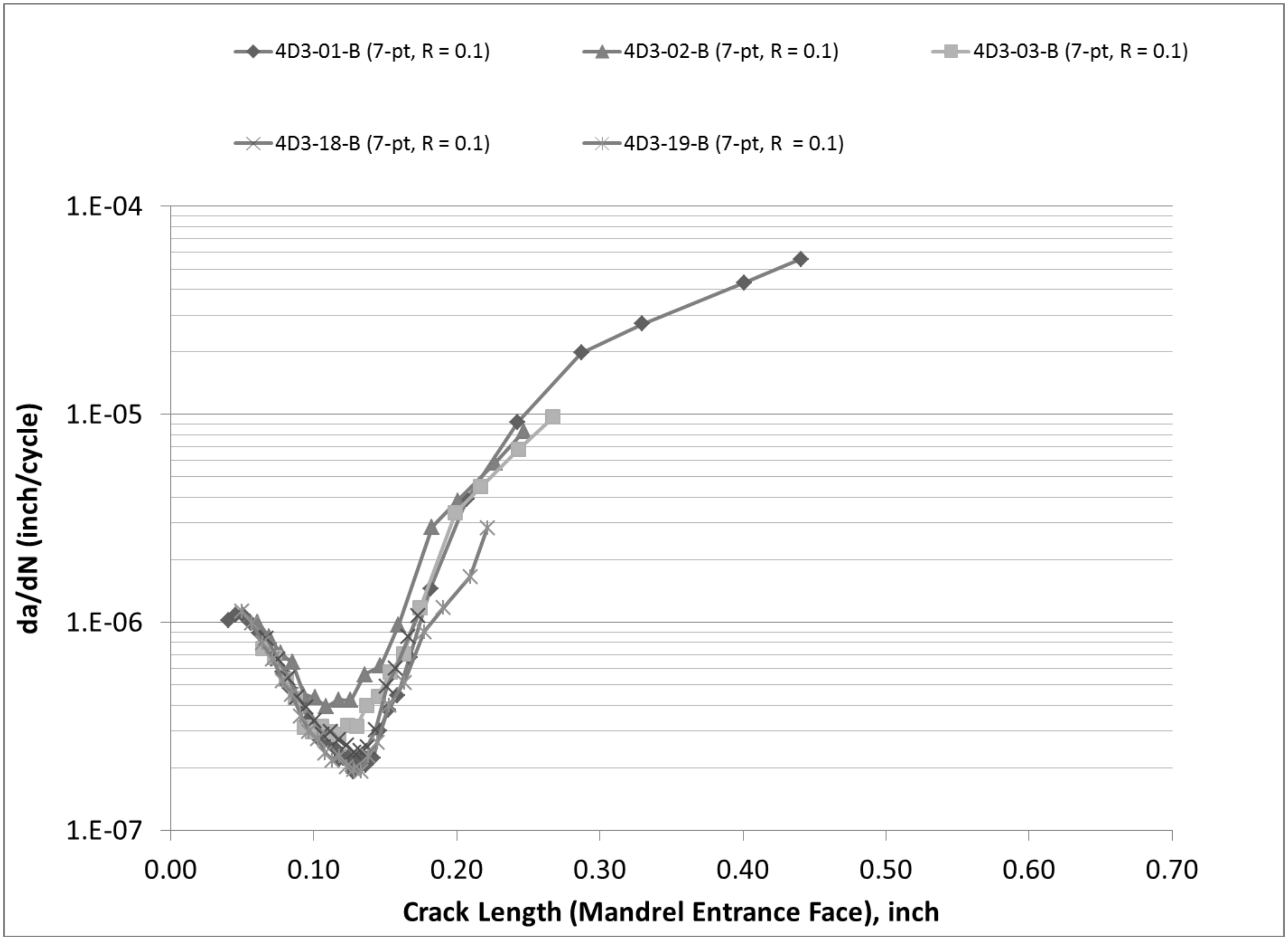
R_{Tot} vs. Crack Length



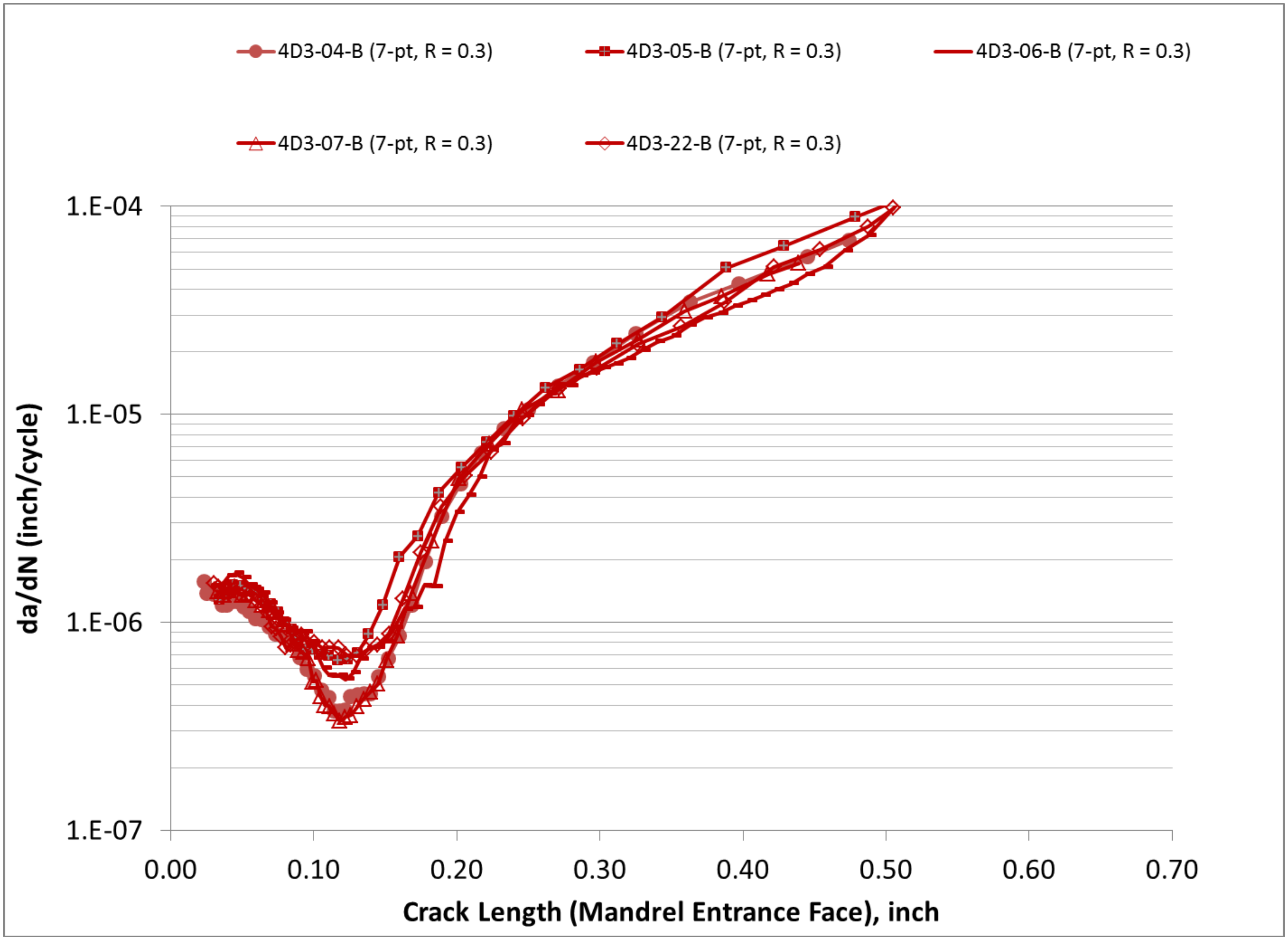
2024-T351

R Effects: Flip Chart

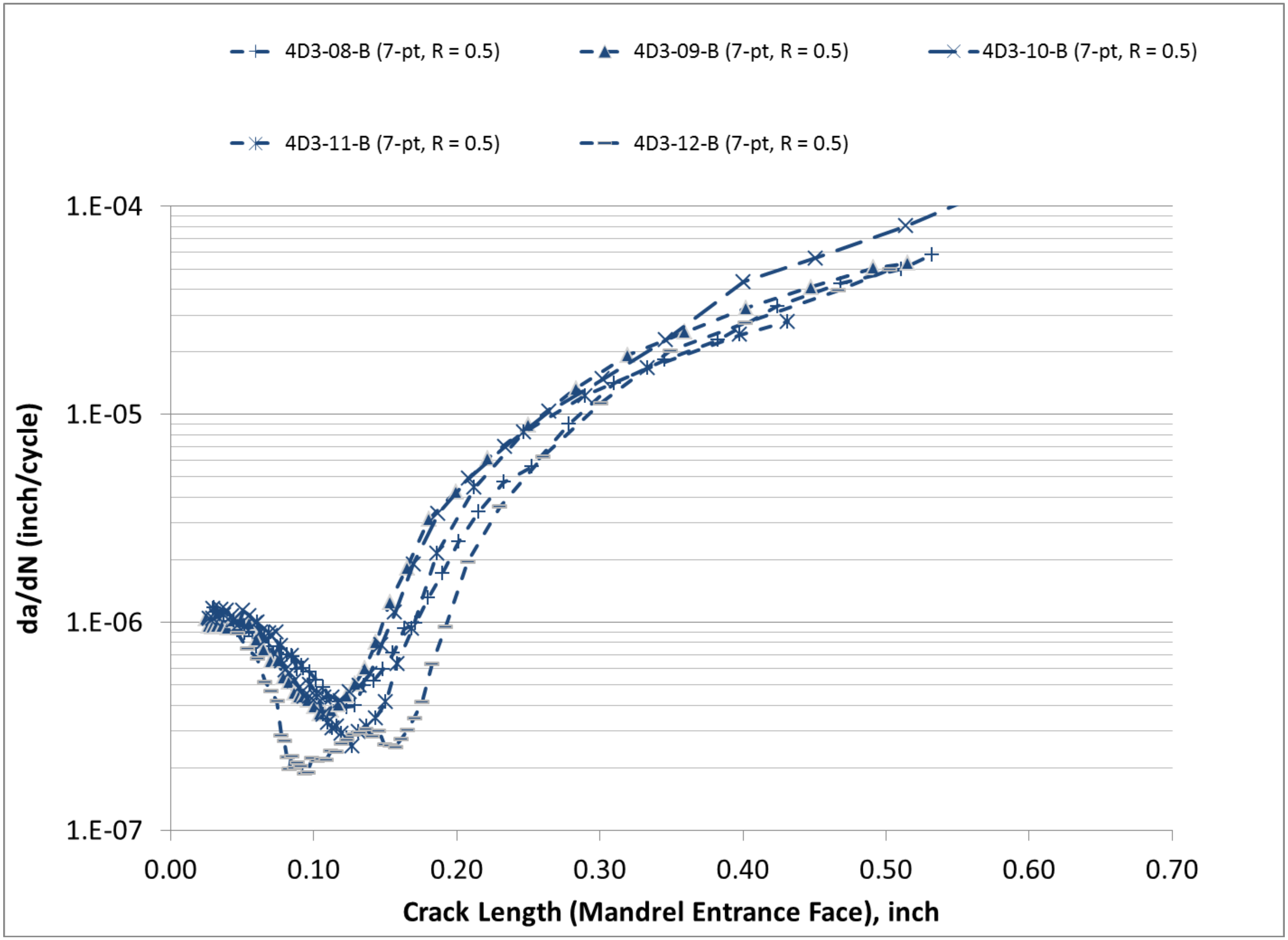
2024-T351: $R_{app} = 0.1$



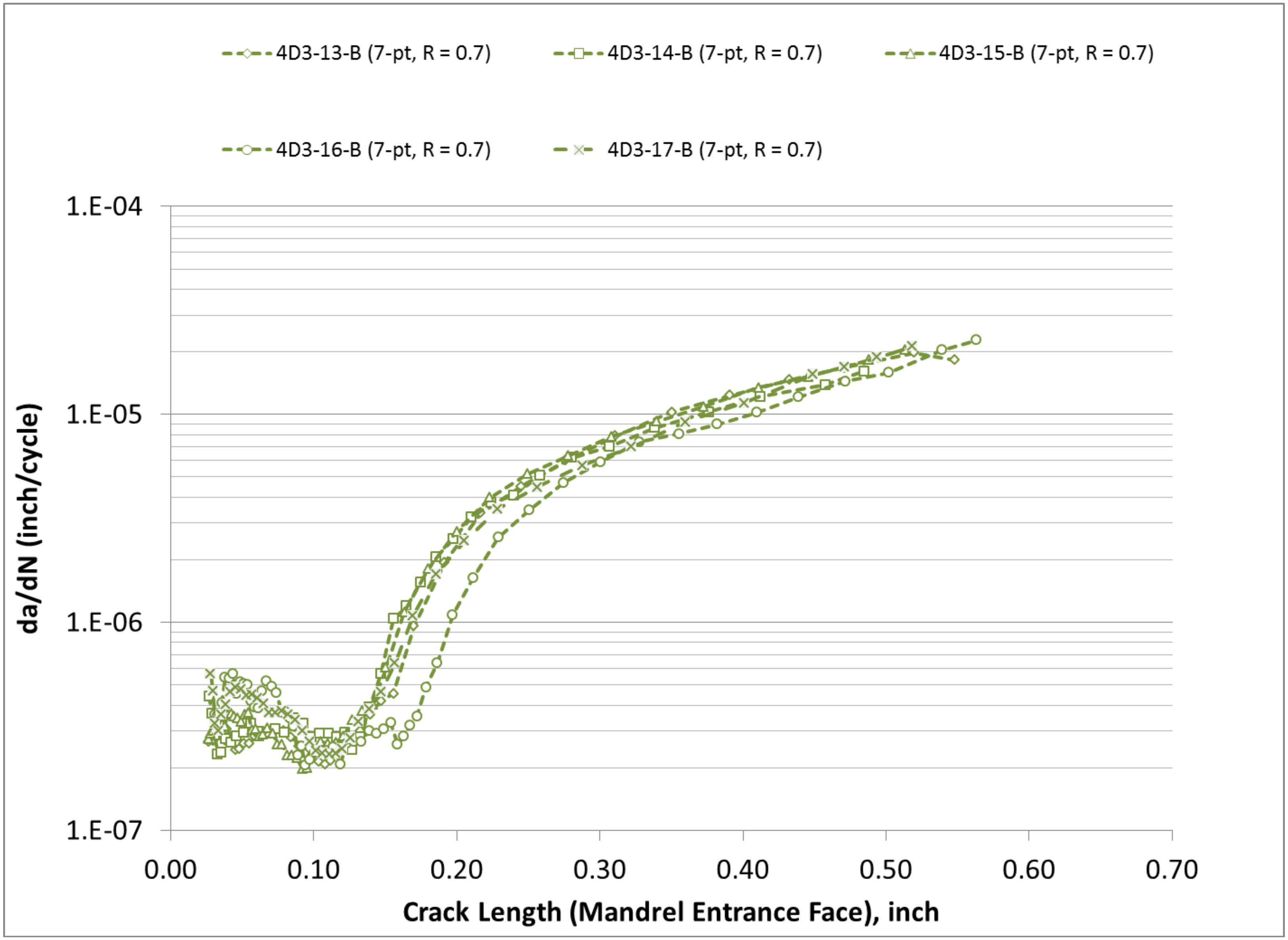
2024-T351: R_{app} = 0.3



2024-T351: $R_{app} = 0.5$



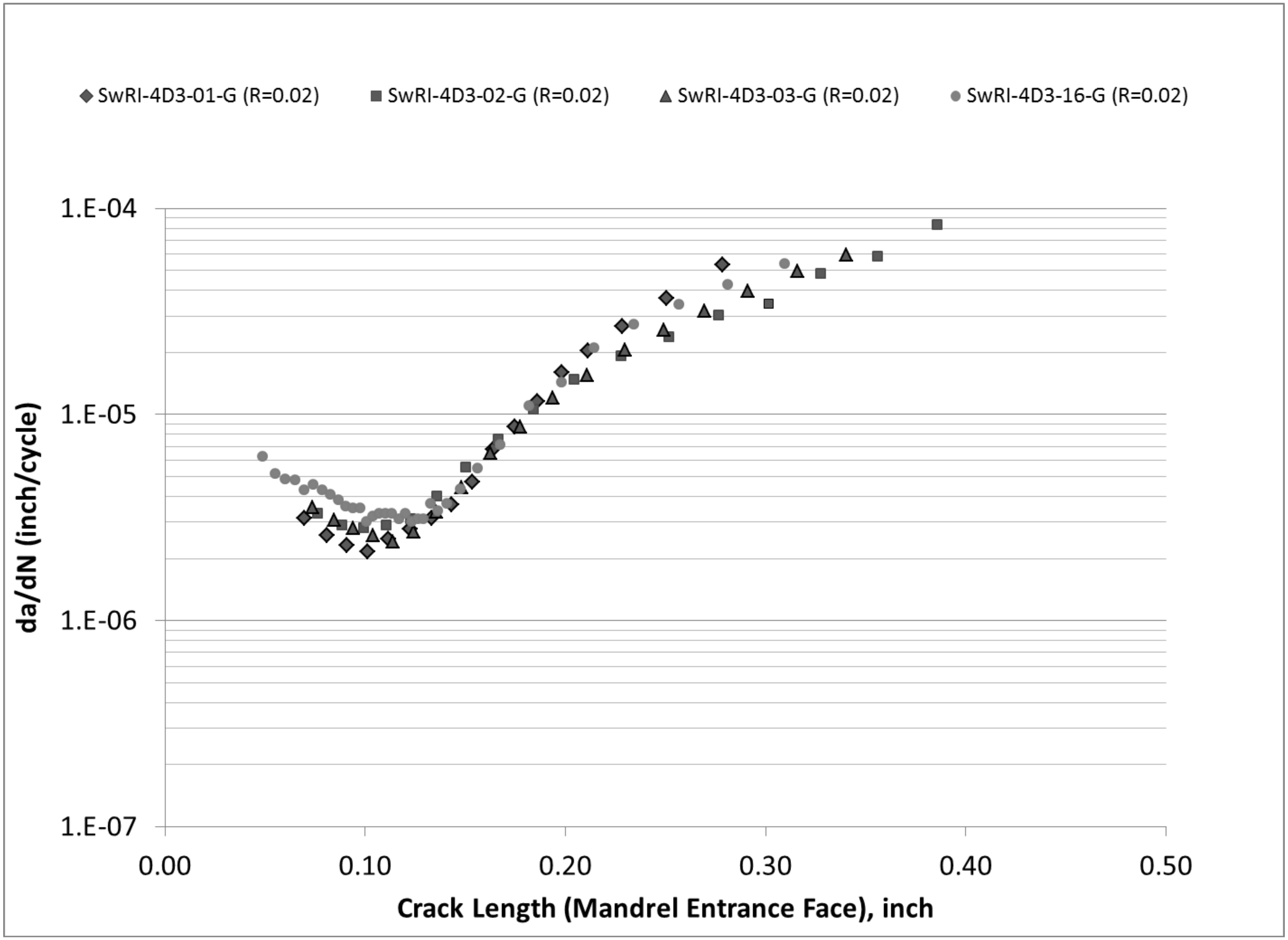
2024-T351: R_{app} = 0.7



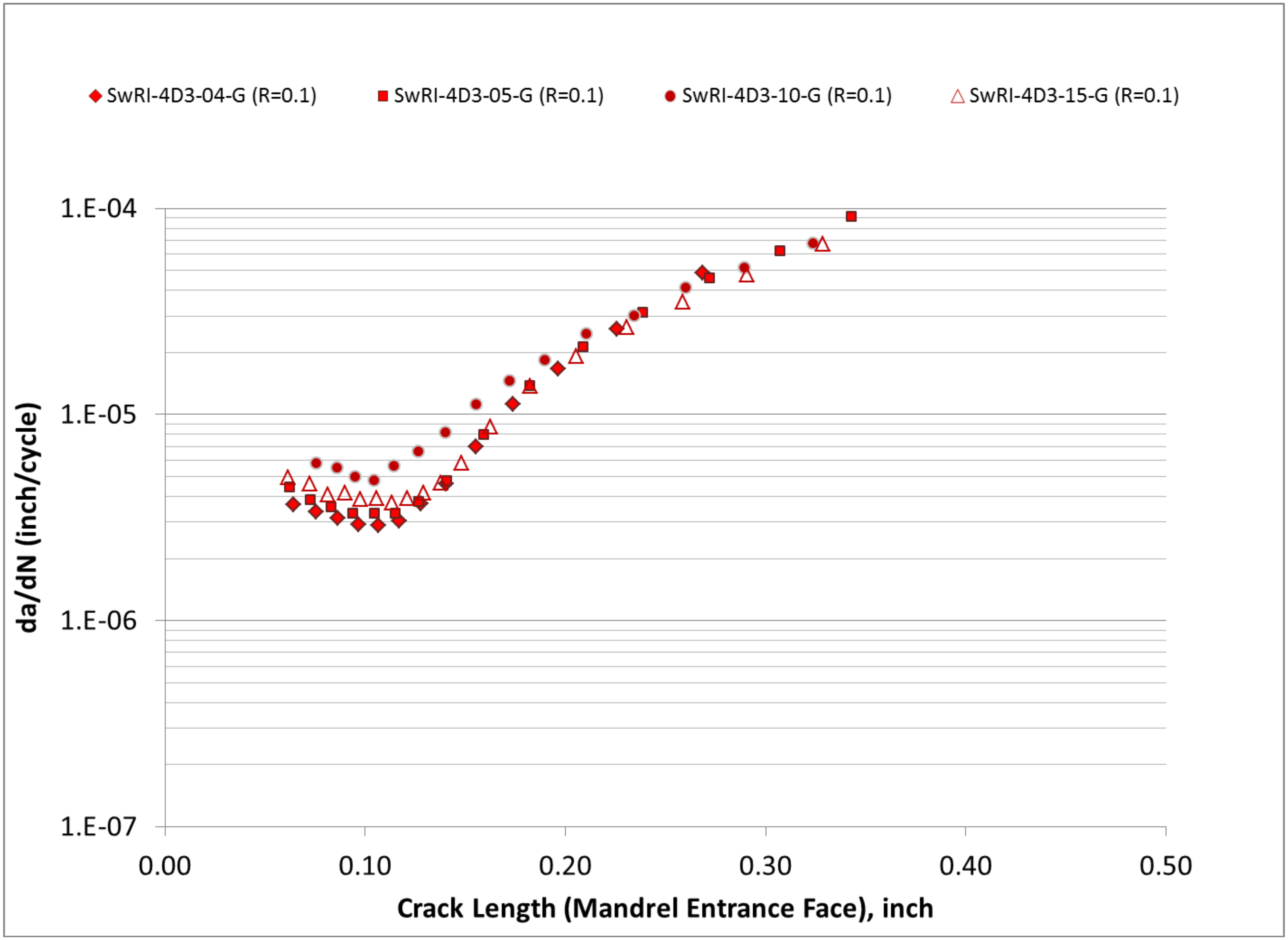
7075-T7351

R Effects: Flip Chart

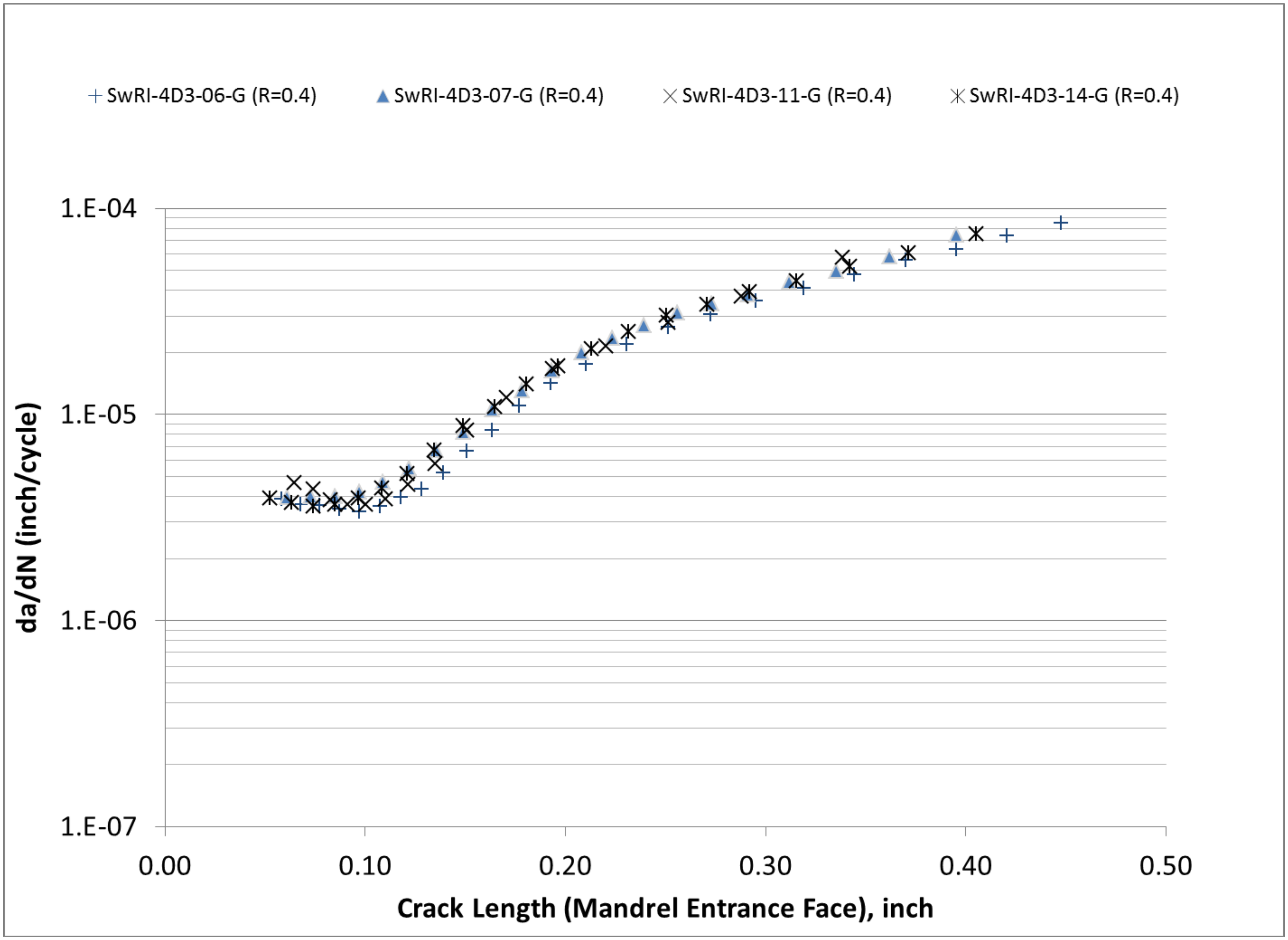
7075-T7351: $R_{app} = 0.02$



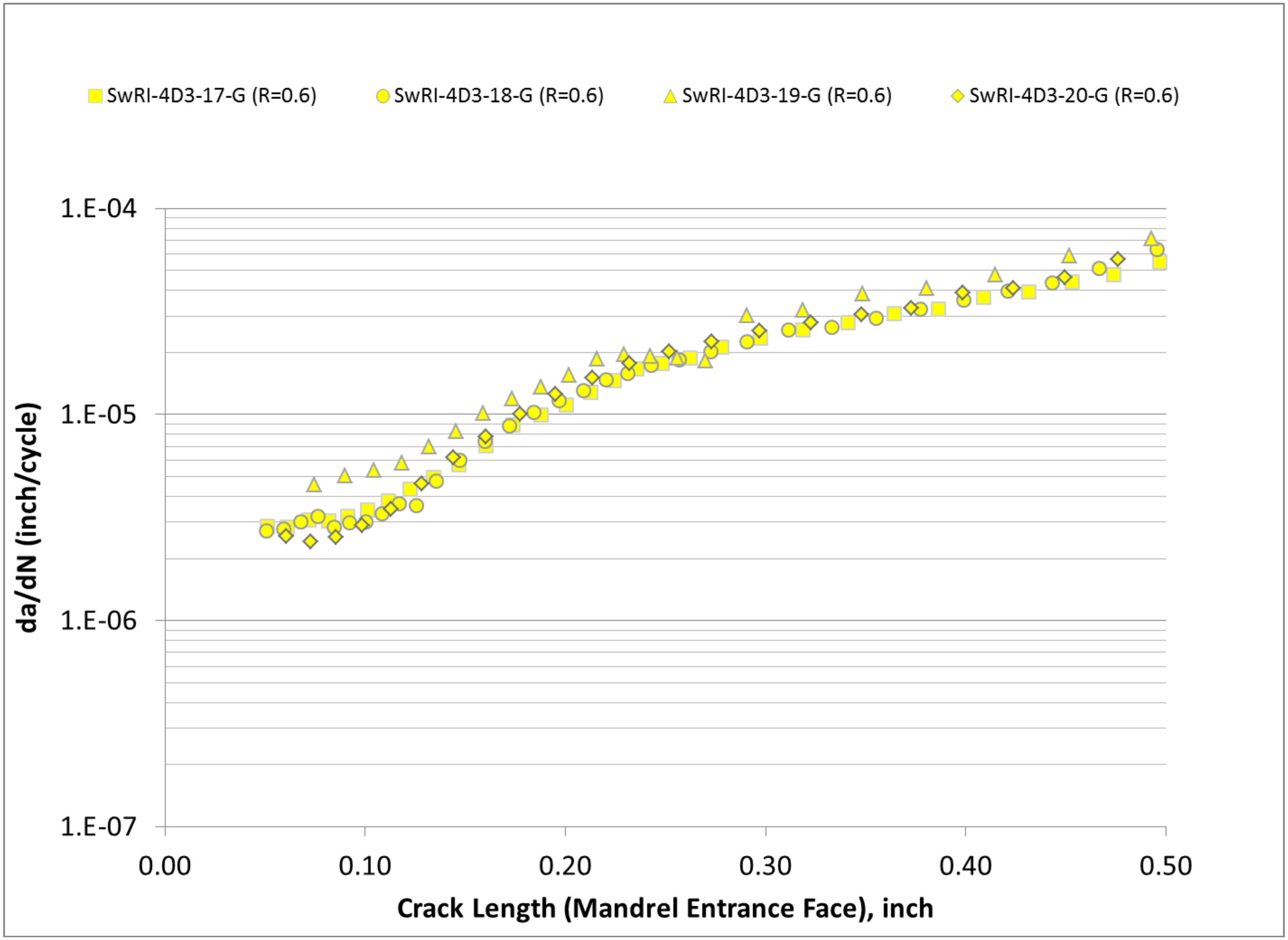
7075-T7351: R_{app} = 0.1



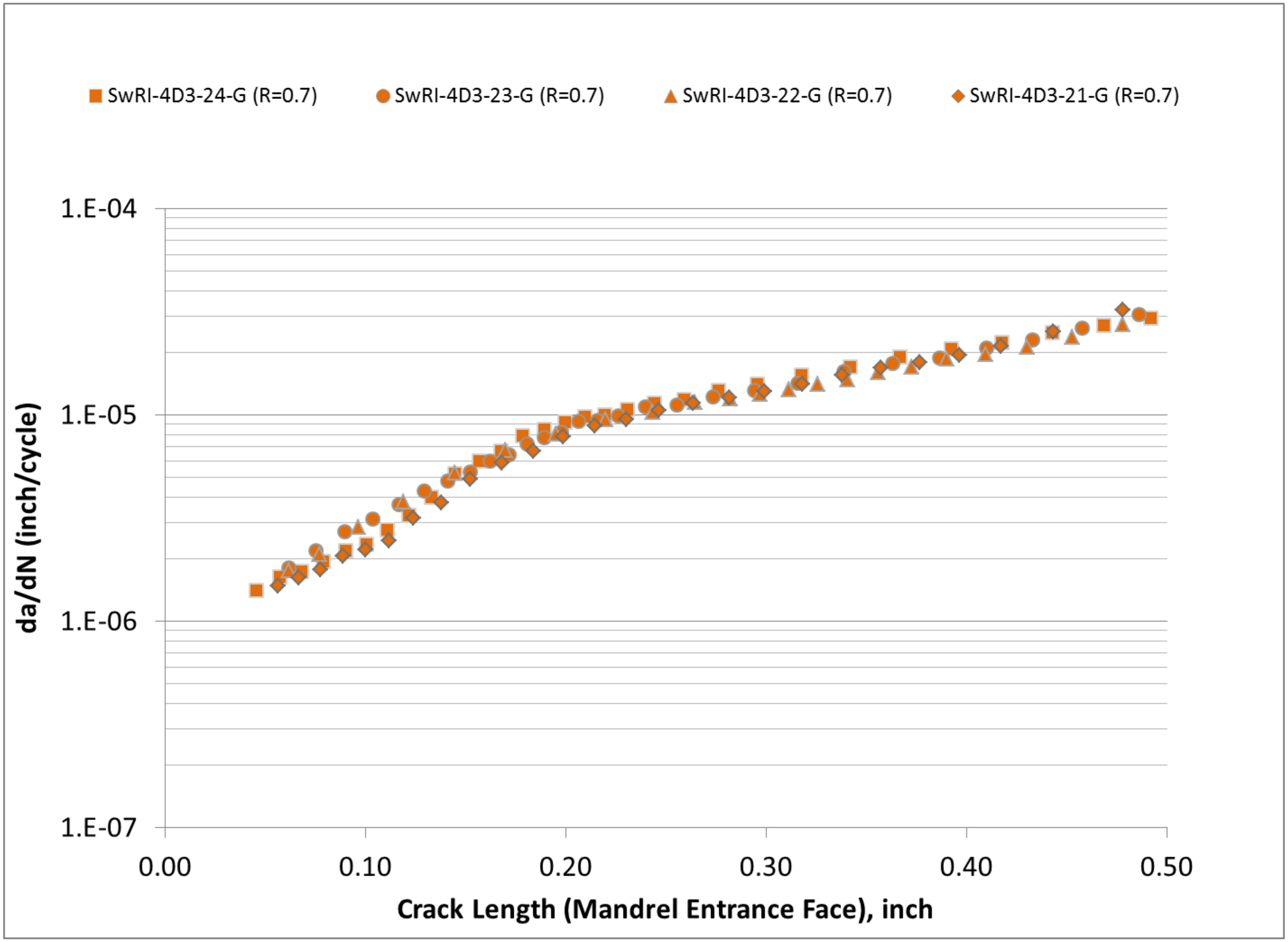
7075-T7351: R_{app} = 0.4



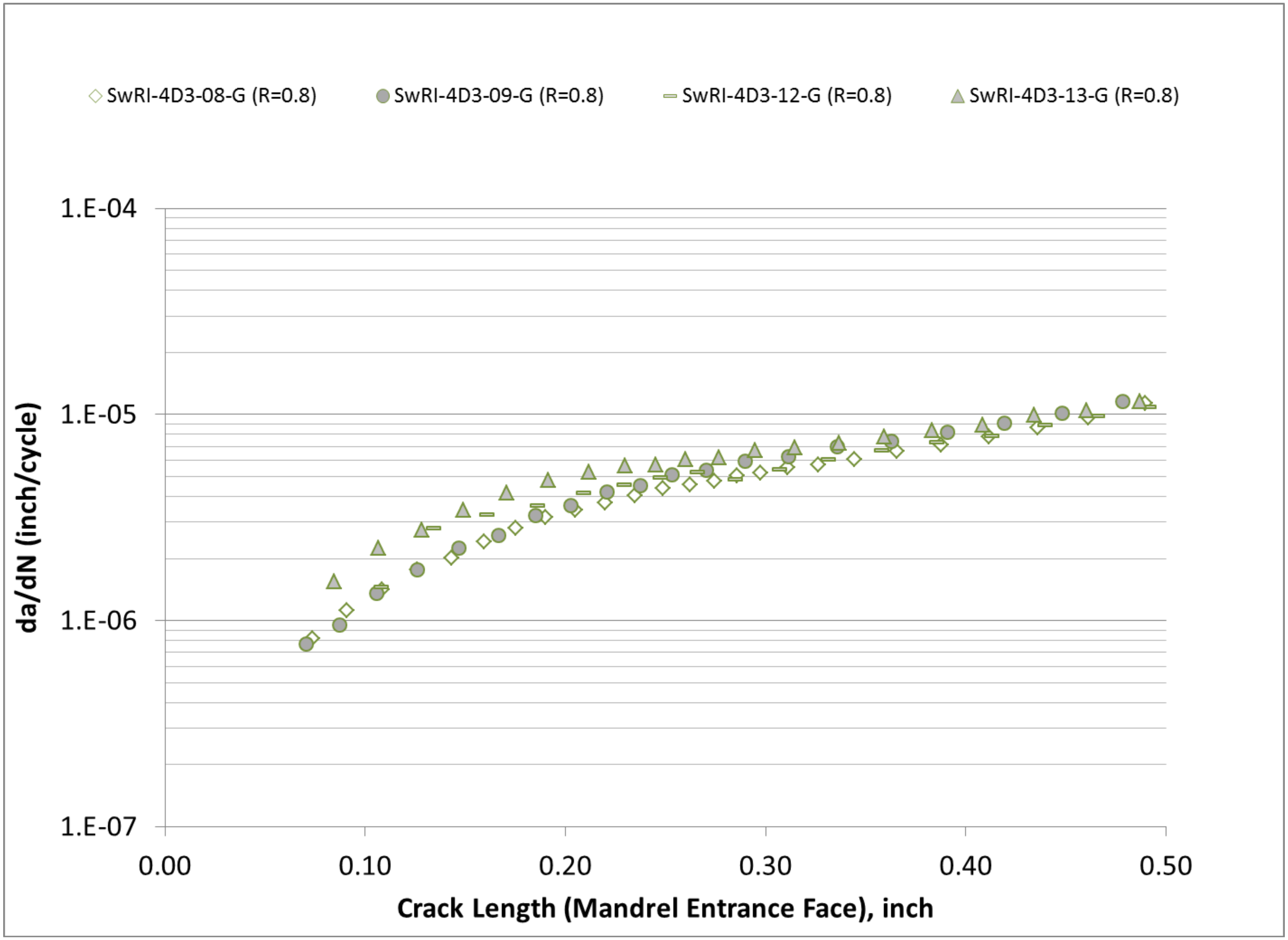
7075-T7351: R_{app} = 0.6



7075-T7351: R_{app} = 0.7

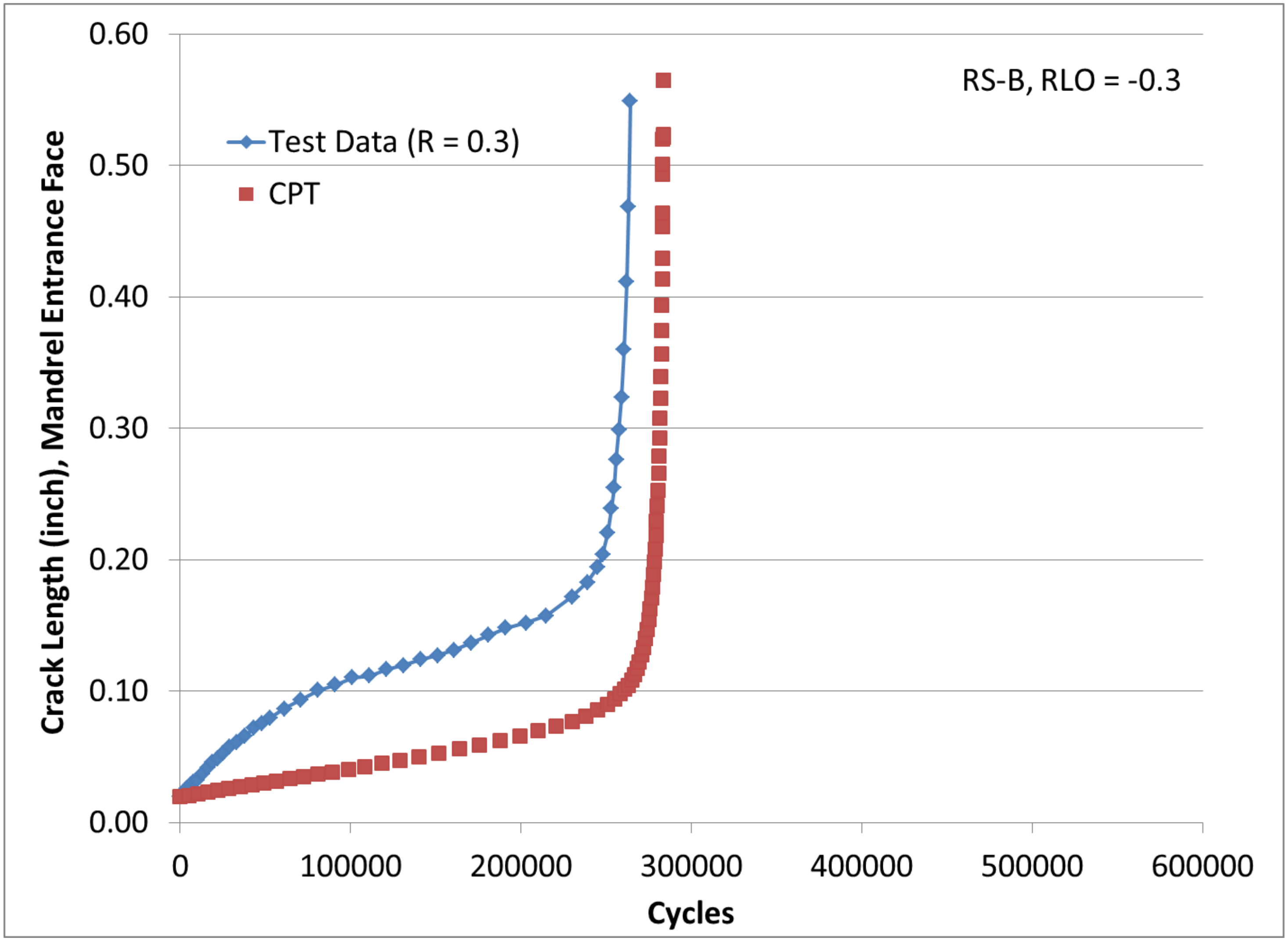


7075-T7351: R_{app} = 0.8

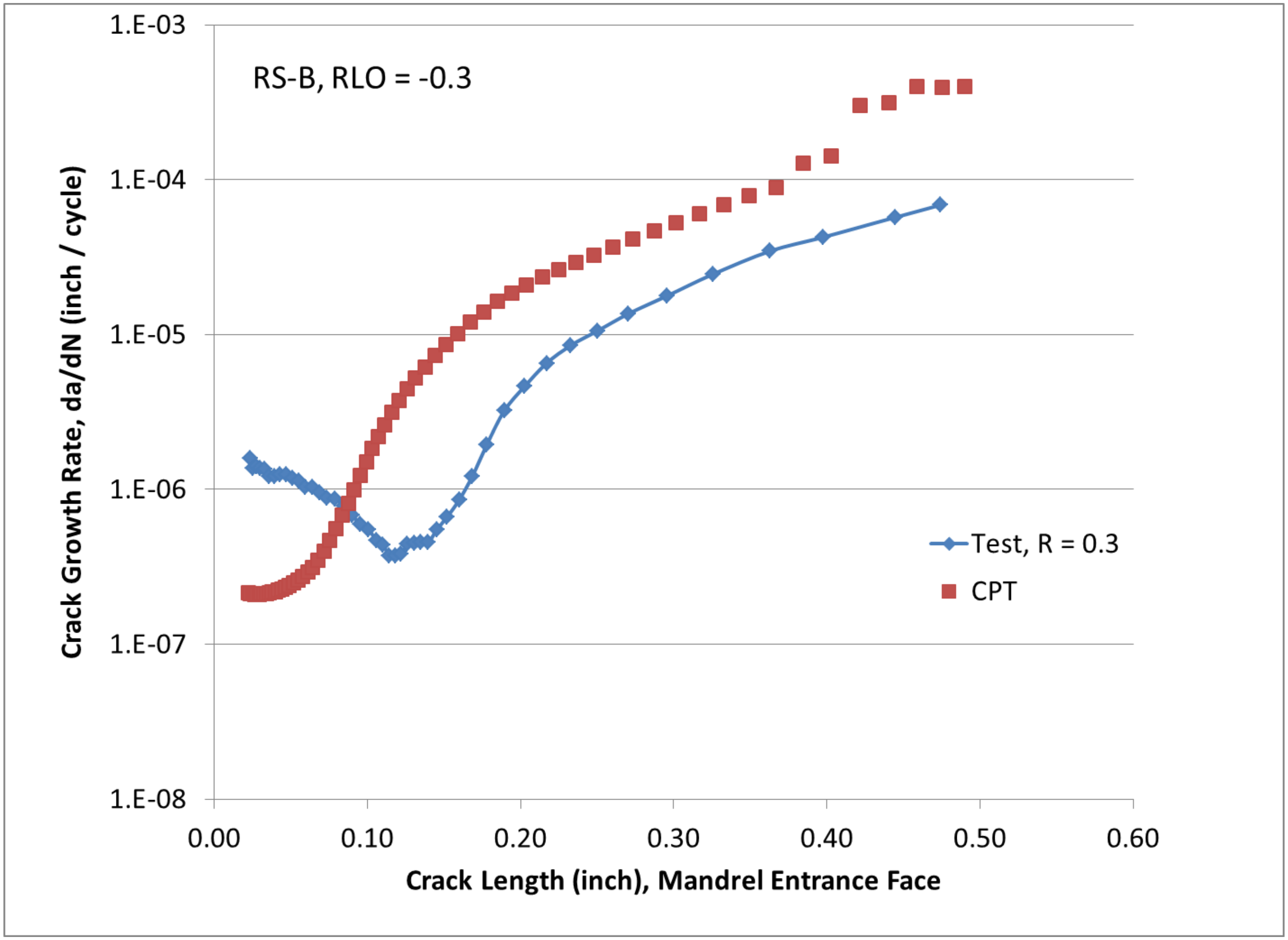


Simulation Results

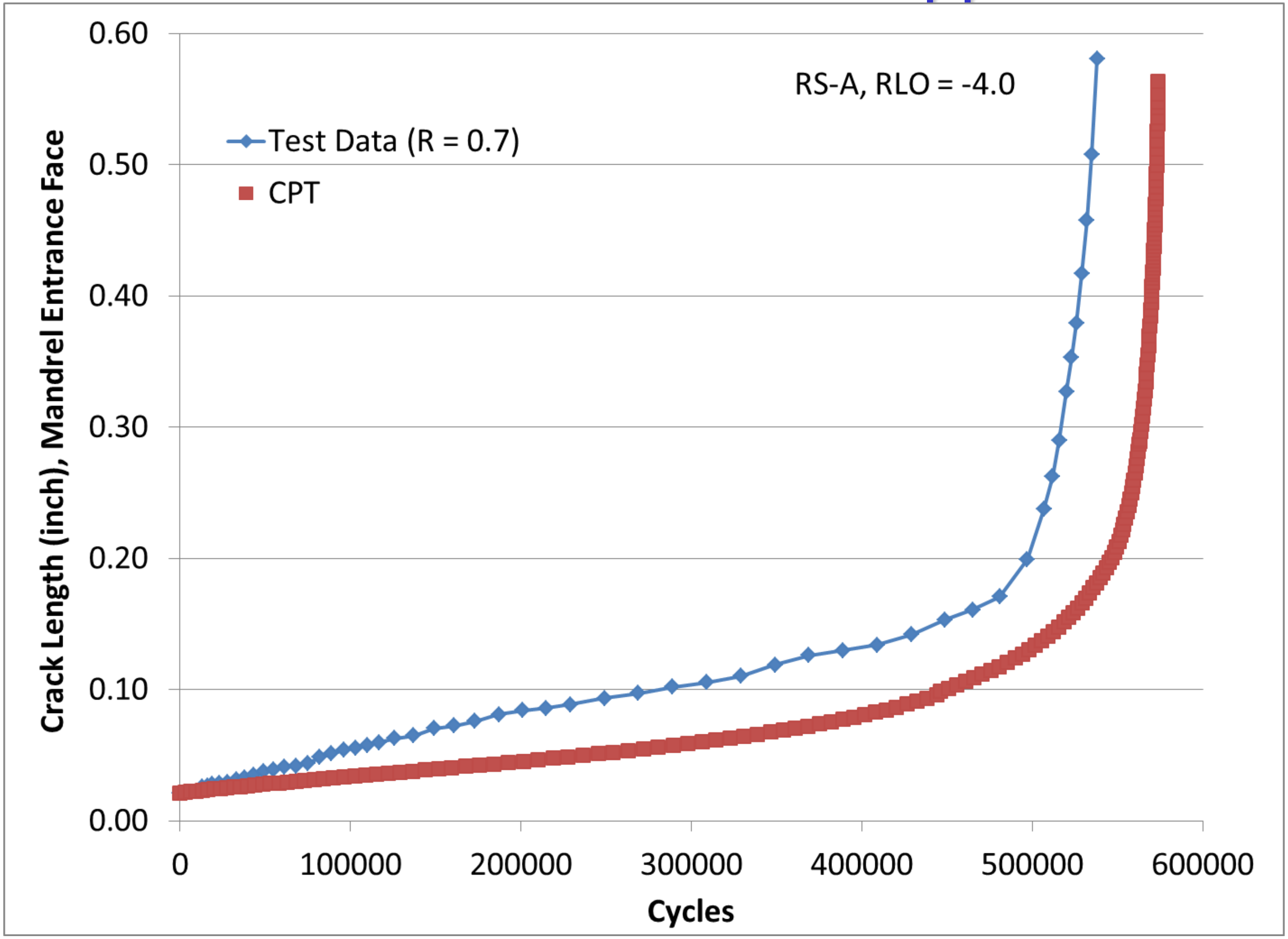
Crack Growth, R_{app} = 0.3



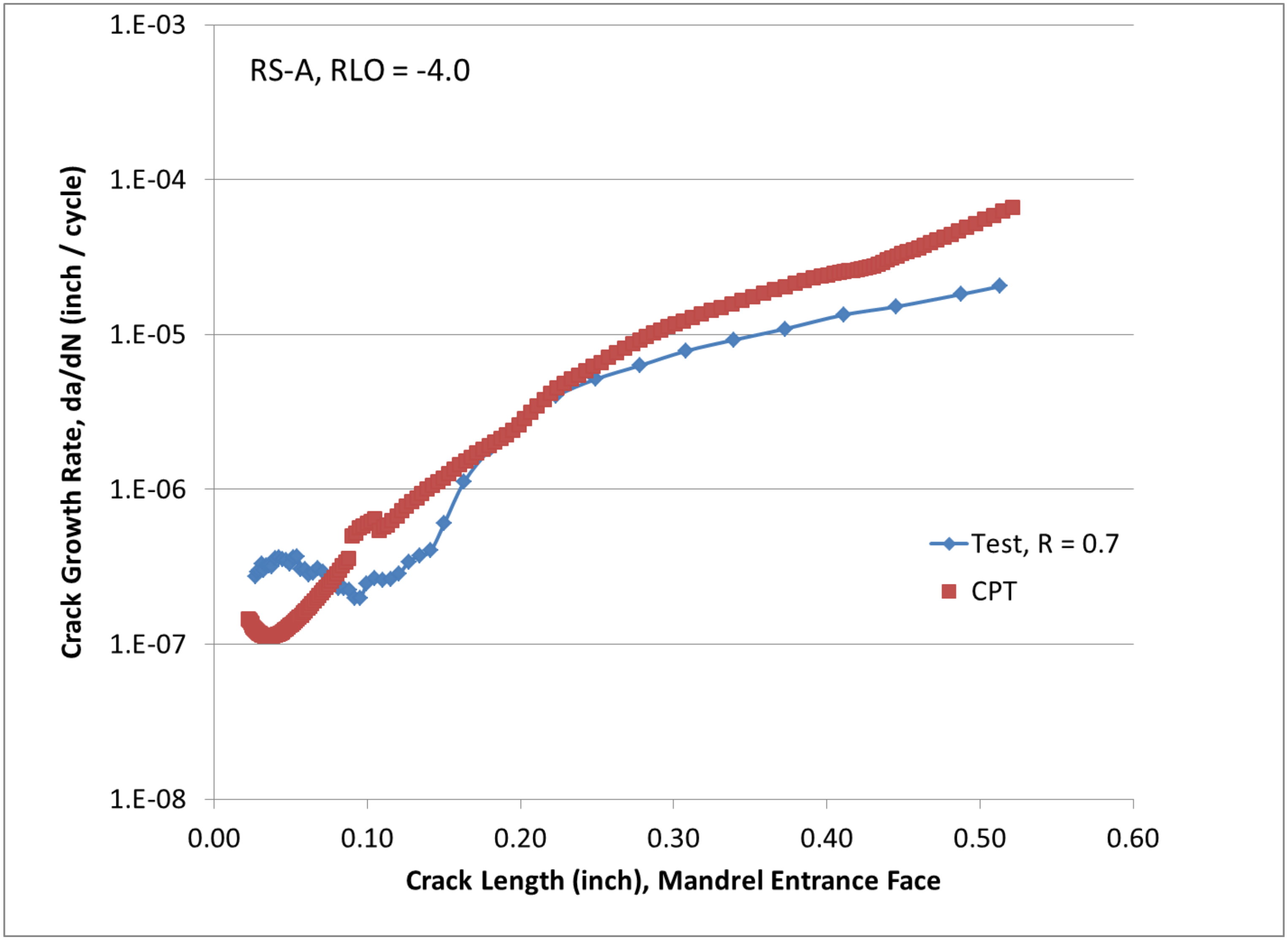
Growth Rate, R_{app} = 0.3



Crack Growth, R_{app} = 0.7



Growth Rate, R_{app} = 0.7



R Effects: Observations

- R Effects
  - Dip in da/dN vs. ‘a’ at lower applied R
  - Dip lessons or disappears at higher applied R depending on alloy
  - Dip more prominent in lower yield strength material: 2024-T351
- CRACK CLOSURE: Quite possibly the single biggest factor in discrepancies between predicted lives and test data
- High priority item for addressing life prediction accuracy
- **Future work** to focus on closure, stress redistribution in front of active crack, and Negative R crack growth data
  - Funded by AFRL and A-10 ASIP

Miscellaneous Items

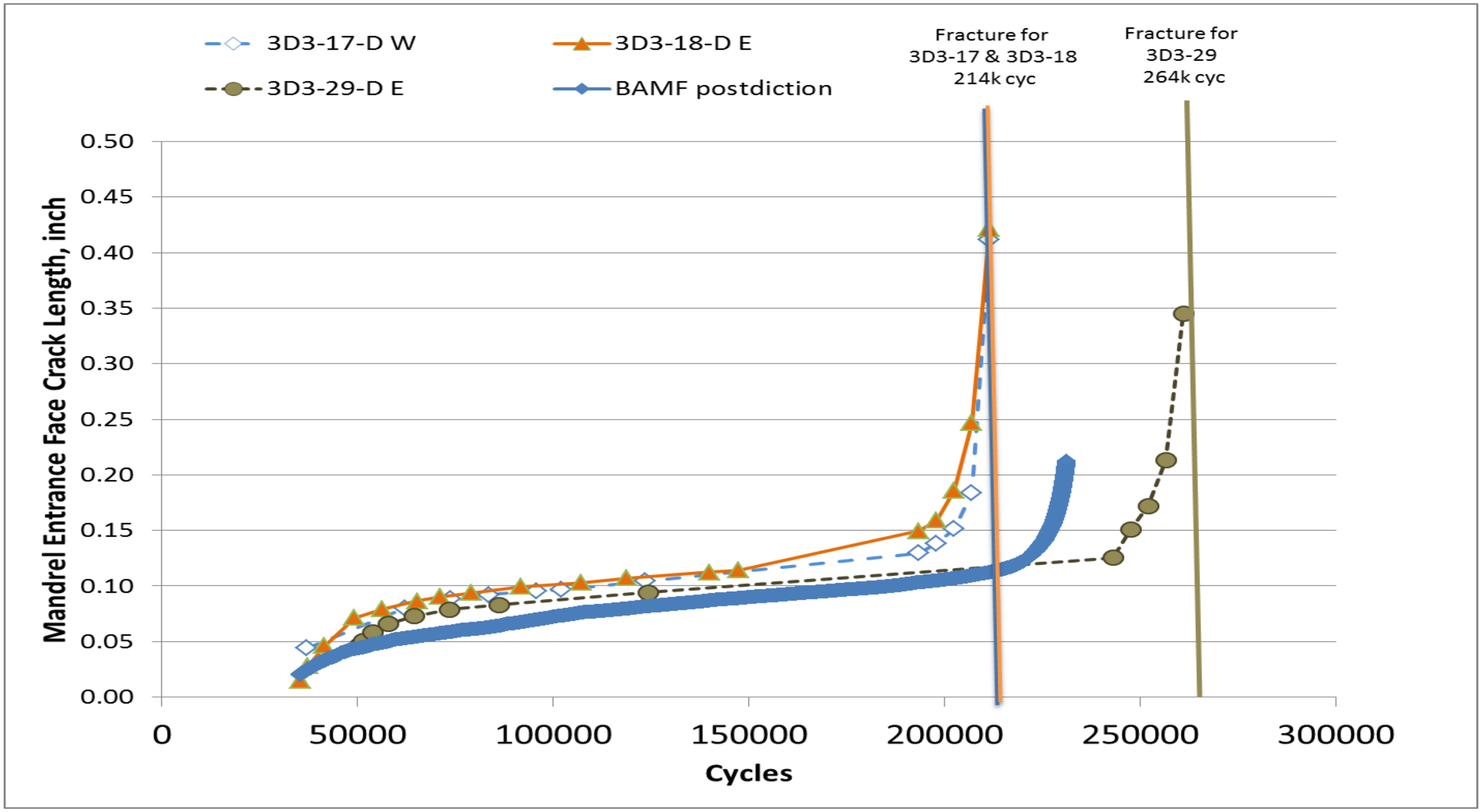
- Test equipment inventory
- CX equipment inventory
- Examining available residual stress data to pick candidates for additional modeling round robin work.
  - Requires corresponding fatigue data
  - Work in conjunction with CAStLE as a possible way to provide new fatigue data sets
  - More on this tomorrow….

Material Models

Crack Growth Data

- General consensus that we need to revisit our material models (da/dN vs ΔK)
- Best practices for reducing artificial threshold effects
    - Understanding how data are generated
    - Part-through cracks vs. through cracks
  - Proper understanding of negative R data
    - Cx holes typically have negative R_{tot} except in cases of higher applied ($R_{app} > 0.7$)

Material Model Sensitivity



- BAMF results predicted average behavior of coupon group
- Predicted life here is 70% of that predicted by APES (330k)

Development of Fatigue Crack Growth Rates from Corner Crack Tests

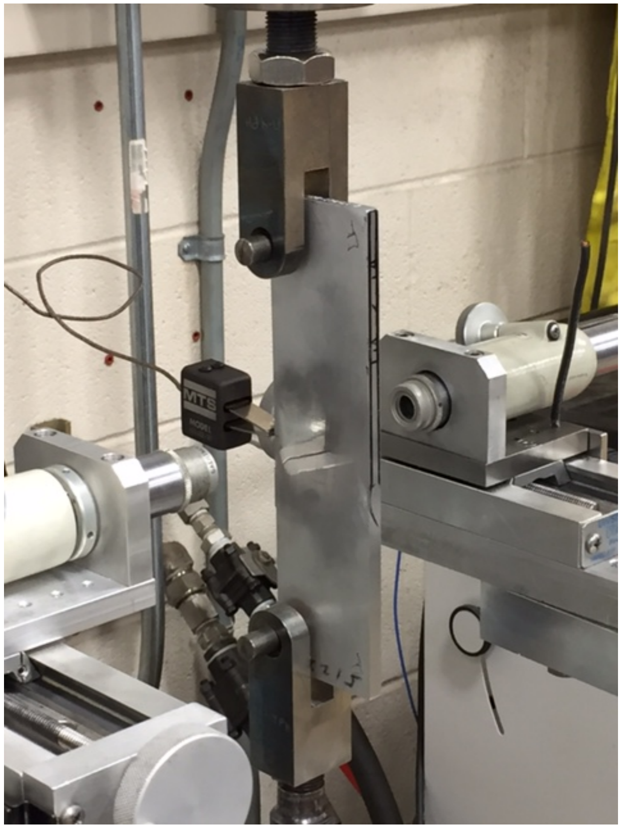
SOUTHWEST RESEARCH INSTITUTE®

Luciano Smith, James Feiger, and Mark Thomsen

ERSI Workshop
September 2017

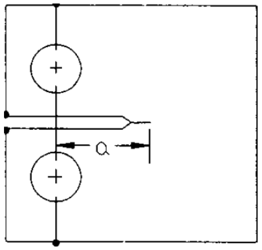
ASTM E647

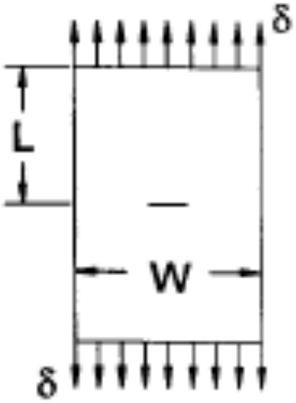
- Standard Test Method for Measurement of Fatigue Crack Growth Rates
  - Specimen configuration
  - Test procedure
  - Calculation of growth rates
  - Reporting requirements

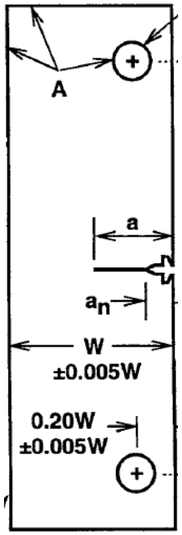


ASTM E647

- Standard Test Method for Measurement of Fatigue Crack Growth Rates
  - – Specimen configuration
    - Three specimens are defined:
      - – Eccentrically-loaded single edge crack tension: ESE(T)
      - – Middle tension: M(T)
      - – Compact: C(T)



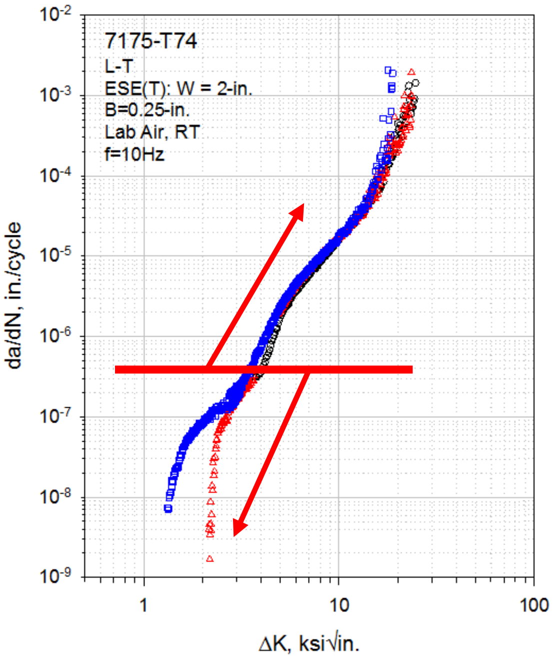




    - Any specimen type is allowed if the K solution is known
      - – "Specimen configurations other than those contained in this method may be used provided that well-established stress-intensity factor calibrations are available"

ASTM E647

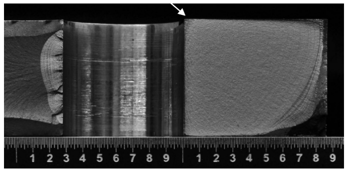
- Standard Test Method for Measurement of Fatigue Crack Growth Rates
  - Specimen configuration
  - Test procedure
    - Number of tests
    - Precracking method
    - Application of load



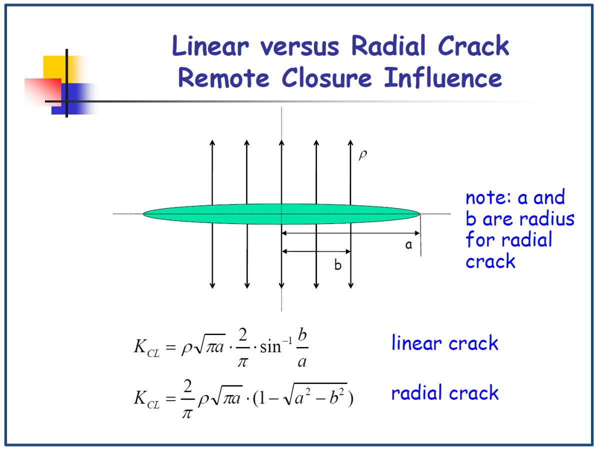
      - Constant force-amplitude or K-control for rates above 10^{-8} m/cycle
      - K-decreasing for rates below 10^{-8} m/cycle (near-threshold)

Motivations for corner crack testing

- Ability to gather L-T and L-S growth rate data in one test
- The standard specimens used for crack growth rate testing are all one-dimensional through cracks
  - The majority of analysis life is as corner crack



- When loading history is properly accounted for (minimizing plasticity induced crack closure), roughness induced closure dominates at low ΔK
  - Closure effect is smaller for radial crack versus linear crack (bulk material constraint)



Linear versus Radial Crack Remote Closure Influence

note: a and b are radius for radial crack

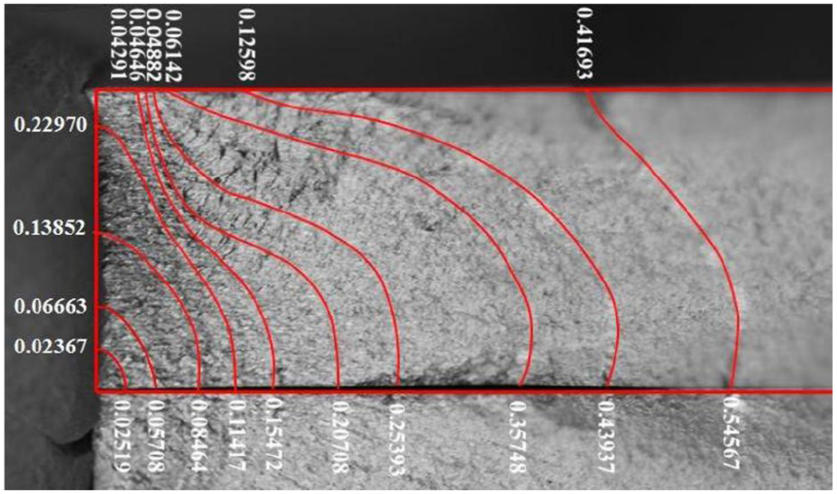
$$K_{CL} = \rho\sqrt{\pi a}\cdot\frac{2}{\pi}\cdot\sin^{-1}\frac{b}{a}$$ linear crack

$$K_{CL} = \frac{2}{\pi}\rho\sqrt{\pi a}\cdot(1-\sqrt{a^2-b^2})$$ radial crack

(Ref: ASTM E08.06.06 meeting minutes, November 15, 2016

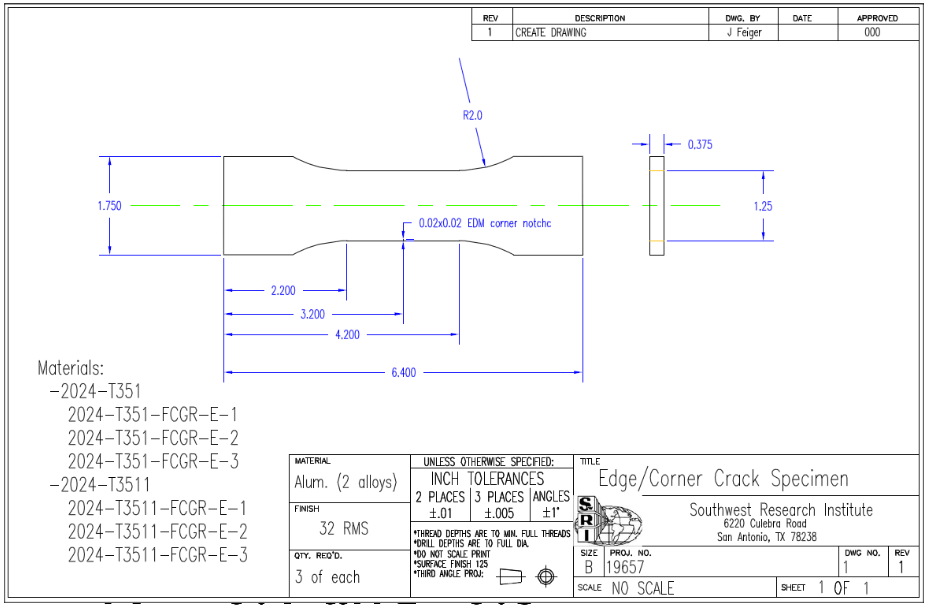
Motivations as related to ERSI

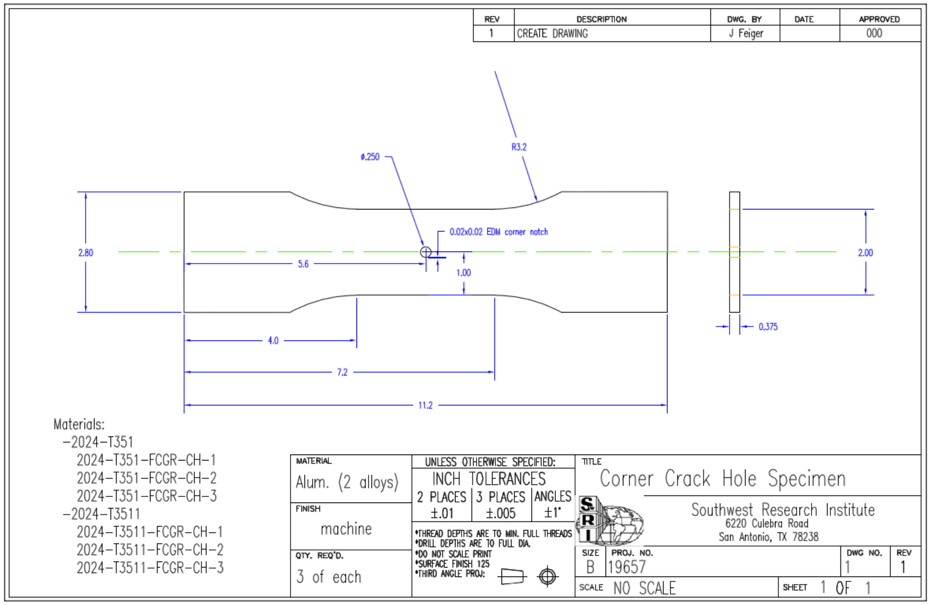
- L-S rates:
  - Through-thickness rates are critical for accurately predicting corner crack aspect ratios
- Corner crack rates:
  - The *vast* majority of coldworked hole life is as corner crack
- Low ΔK rates:
  - Compressive residual stresses shift us onto the lower end of the growth rates curves



Description of corner crack testing

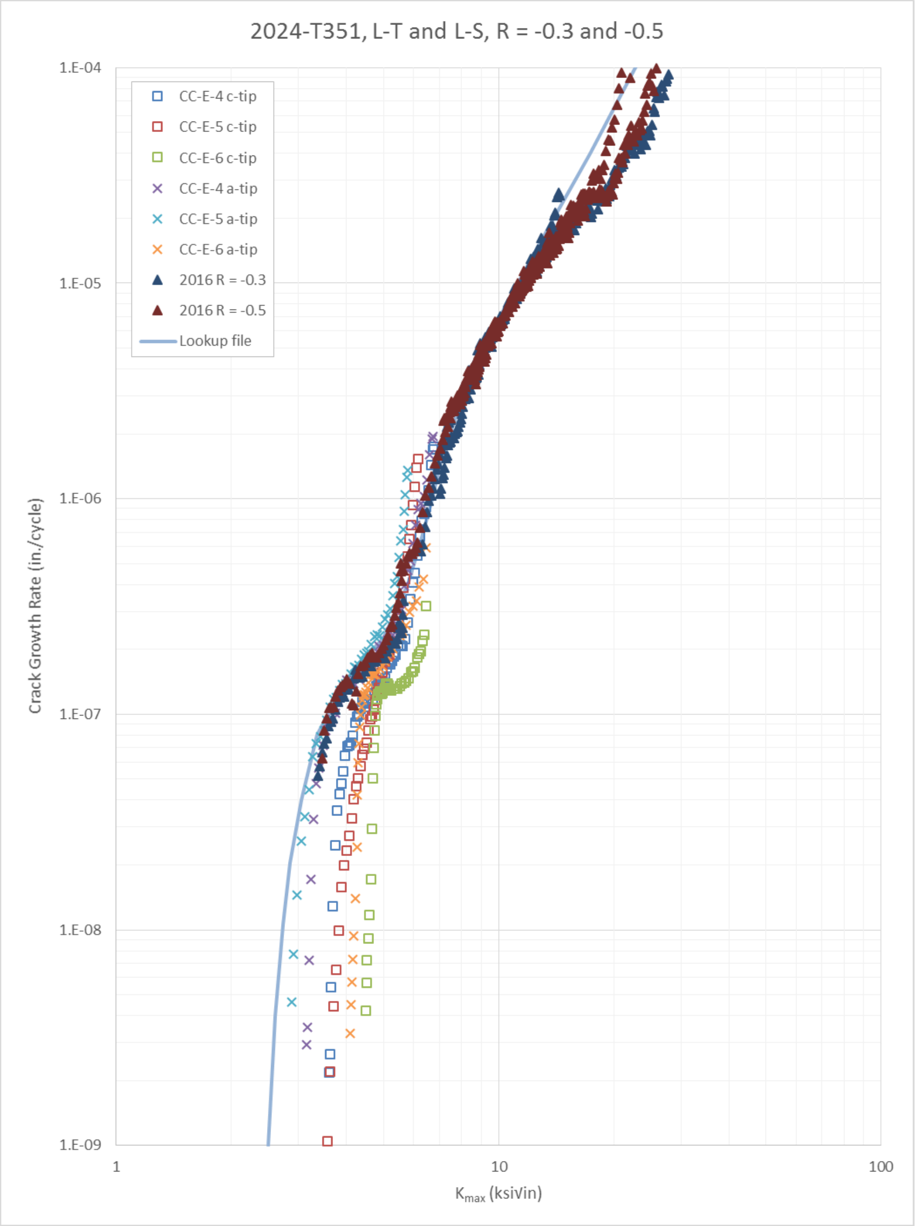
- All procedures follow E647, with two non-standard specimens





- Load shedding controlled by DCPD
  - $C = -4\ \text{in}^{-1}$ $(0.035 < -C\,(K_{max,i} / \sigma_y)^2 < 0.097)$
  - Pre-test assumption of aspect ratios for a-tip K input
  - Post-test correction of applied K for da/dN-ΔK curves

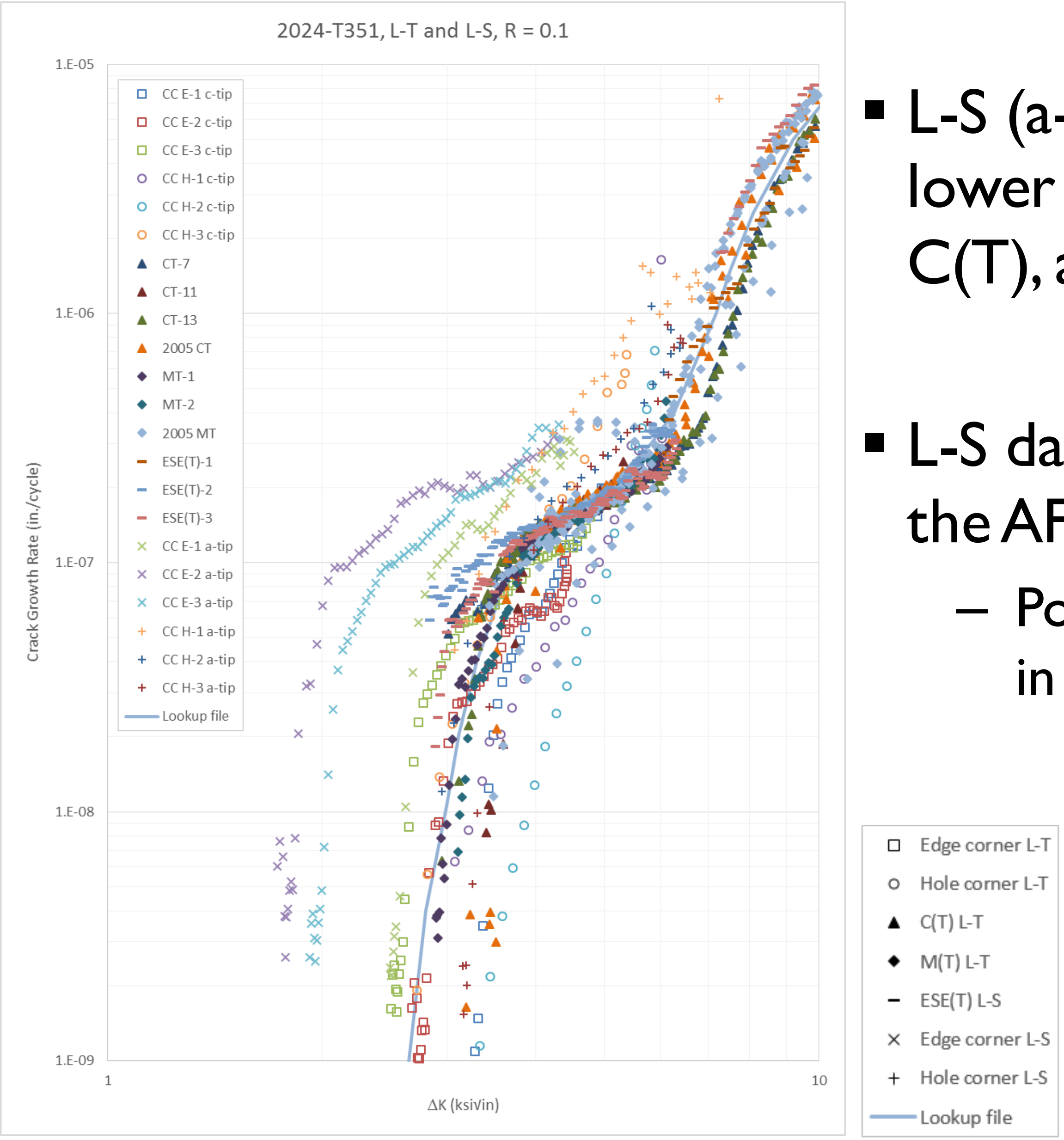
Test results: T351 L-T and L-S, R = -0.3



- Mostly consistent with M(T) data
- L-S (a-tip) data shows lower threshold than L-T (c-tip)
  - Very slightly lower than M(T)

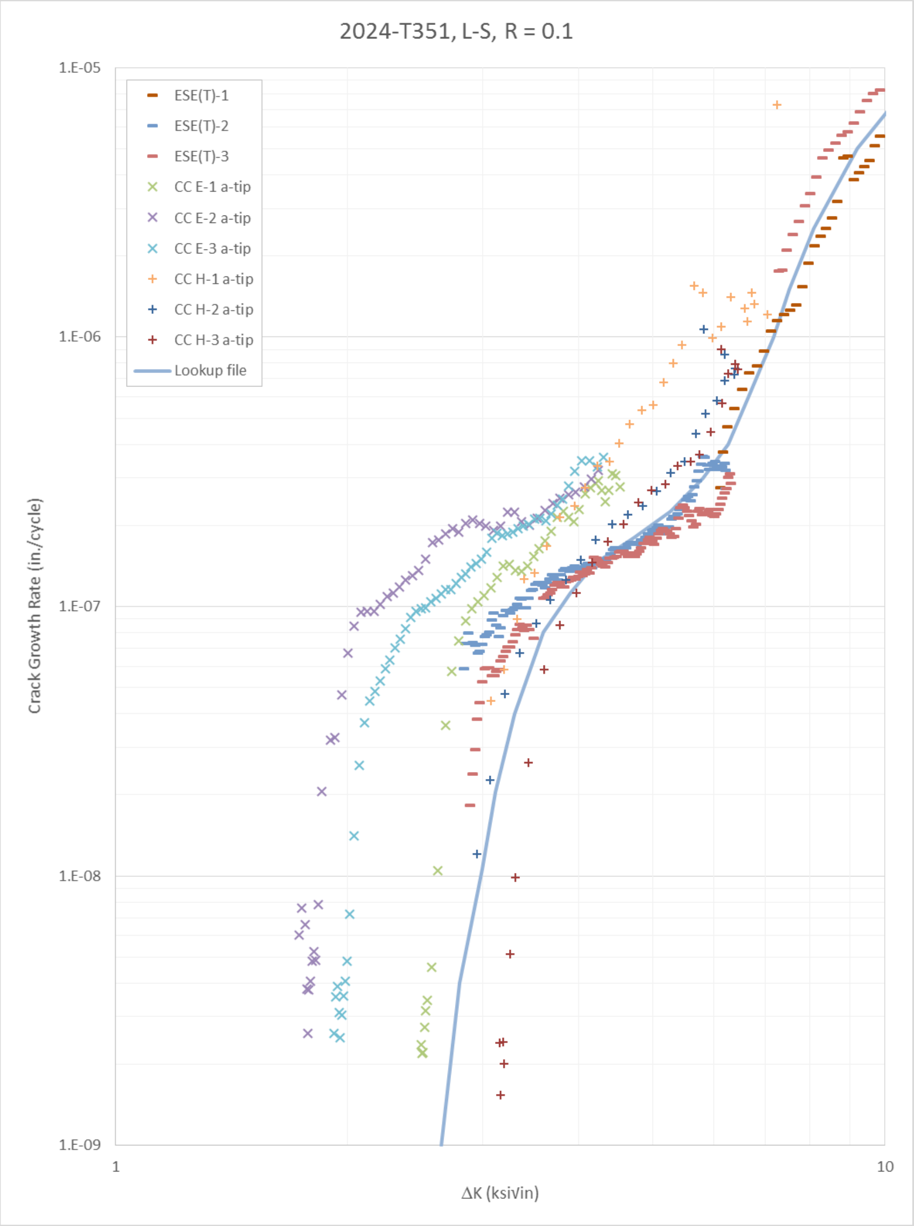
☐ Edge corner L-T
○ Hole corner L-T
▲ C(T) L-T
◆ M(T) L-T
− ESE(T) L-S
× Edge corner L-S
\+ Hole corner L-S
— Lookup file

Test results: T351 L-T and L-S, R = 0.1



- L-S (a-tip and ESE(T)) data shows lower threshold than L-T (c-tip, C(T), and M(T)) data
- L-S data shows faster rates than the AFGROW lookup file
  - Potential for improved accuracy in corner crack aspect ratios

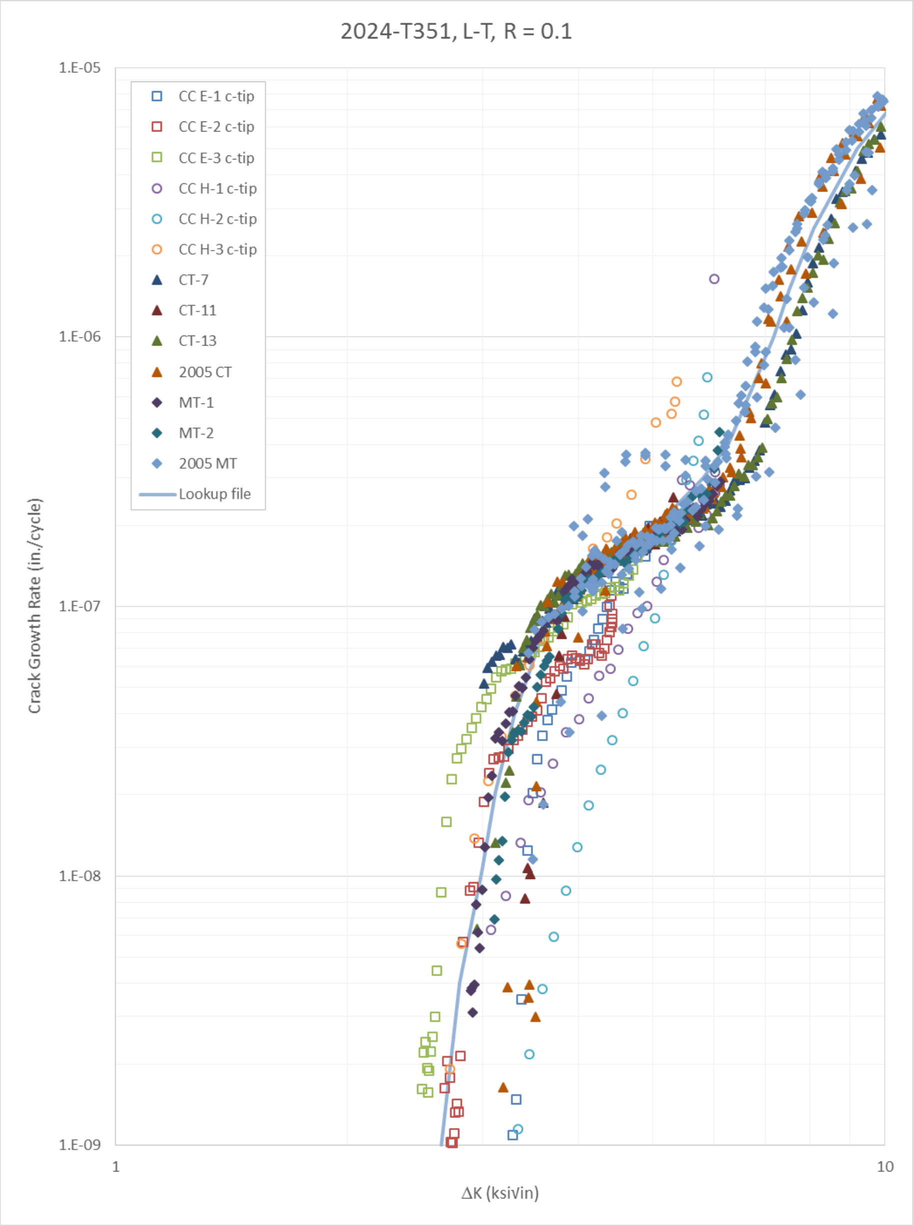
Test results: T351 L-S, R = 0.1



- Edge corner crack data shows lower threshold than both ESE(T) and hole corner crack

☐ Edge corner L-T
○ Hole corner L-T
▲ C(T) L-T
◆ M(T) L-T
− ESE(T) L-S
× Edge corner L-S
\+ Hole corner L-S
— Lookup file

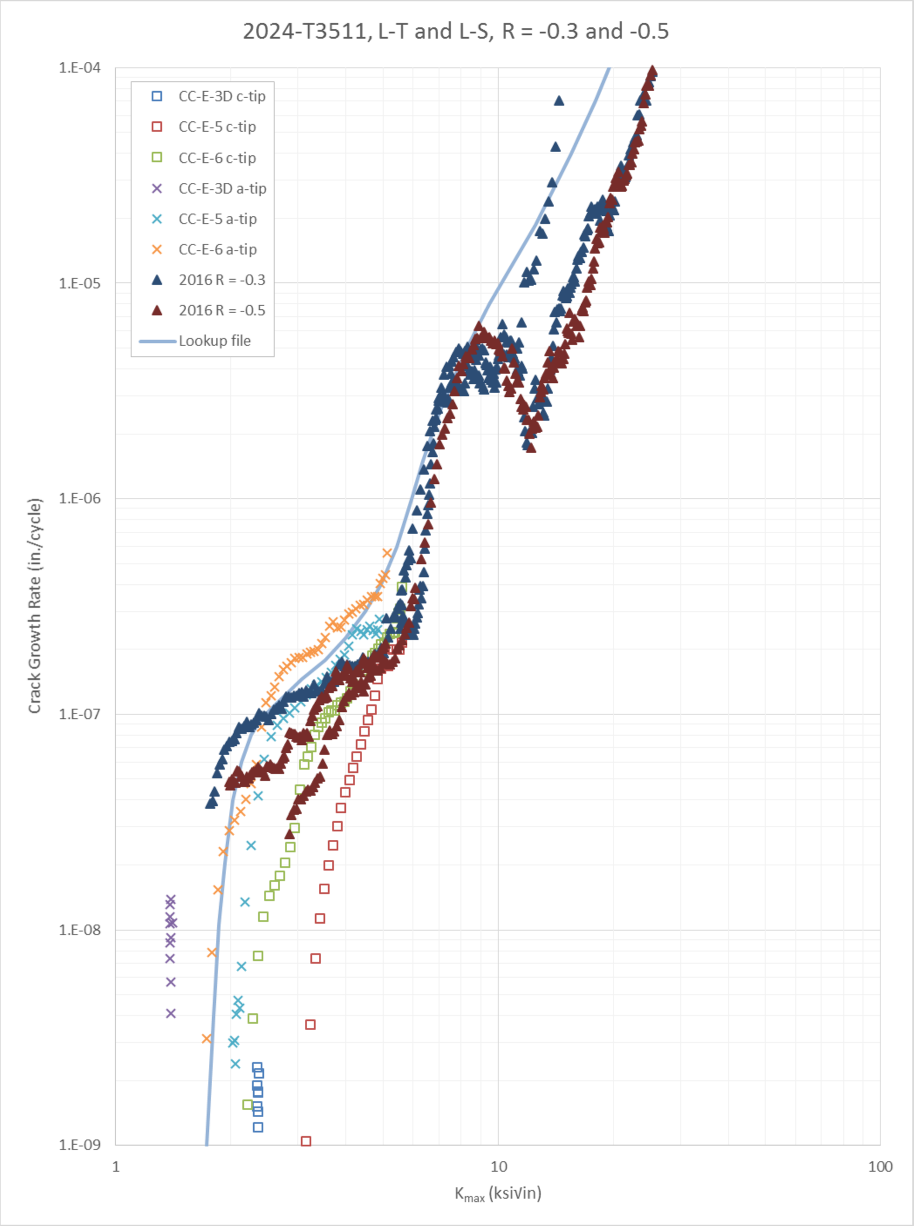
Test results: T351 L-T, R = 0.1



- Corner crack data consistent with C(T) and M(T) data
- Edge corner crack data shows lower threshold than hole corner crack

□ Edge corner L-T
○ Hole corner L-T
▲ C(T) L-T
◆ M(T) L-T
− ESE(T) L-S
× Edge corner L-S
+ Hole corner L-S
— Lookup file

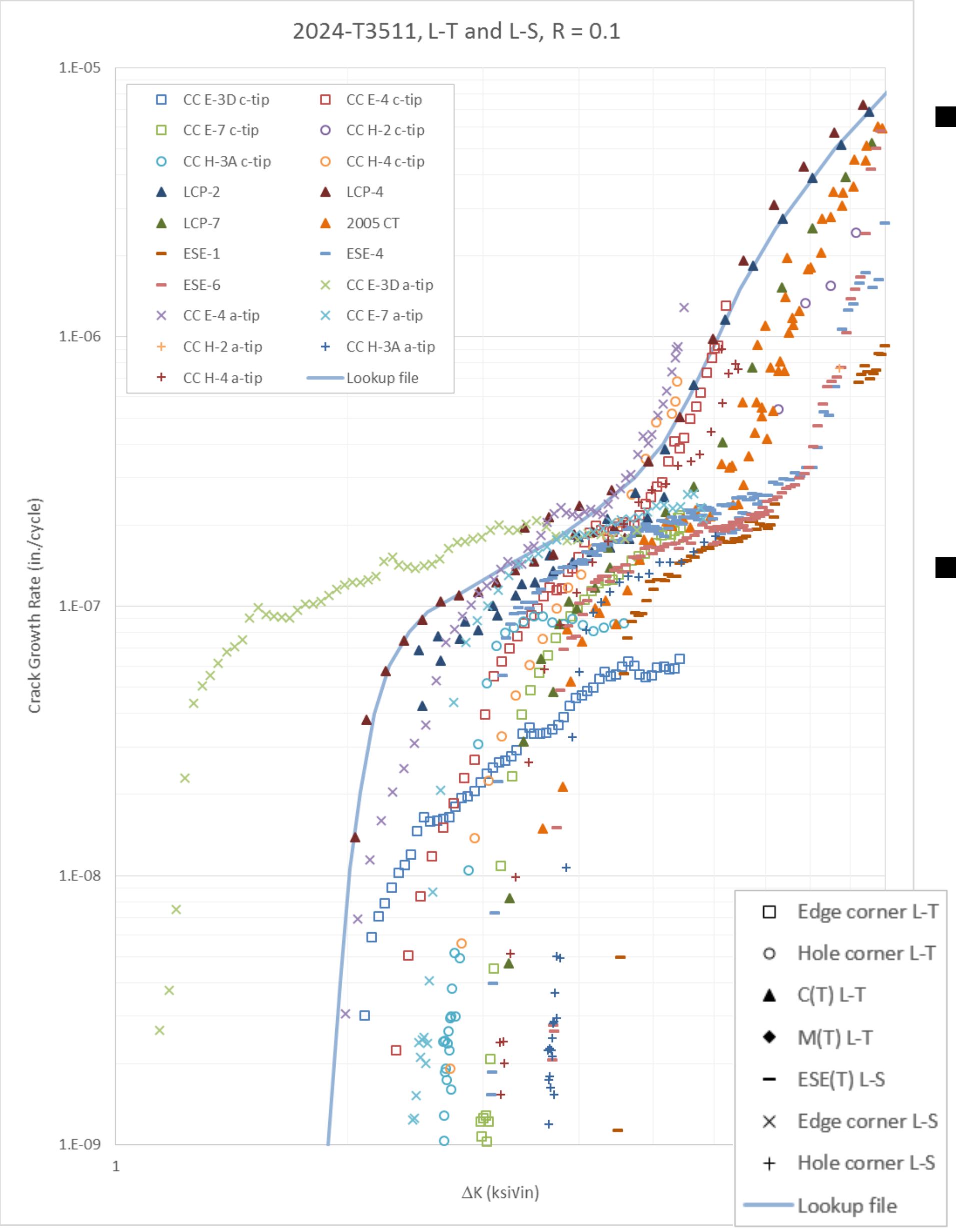
Test results: T3511 L-T and L-S, R = -0.3



- Mostly consistent with M(T) data
- L-S (a-tip) data shows lower threshold than L-T (c-tip)

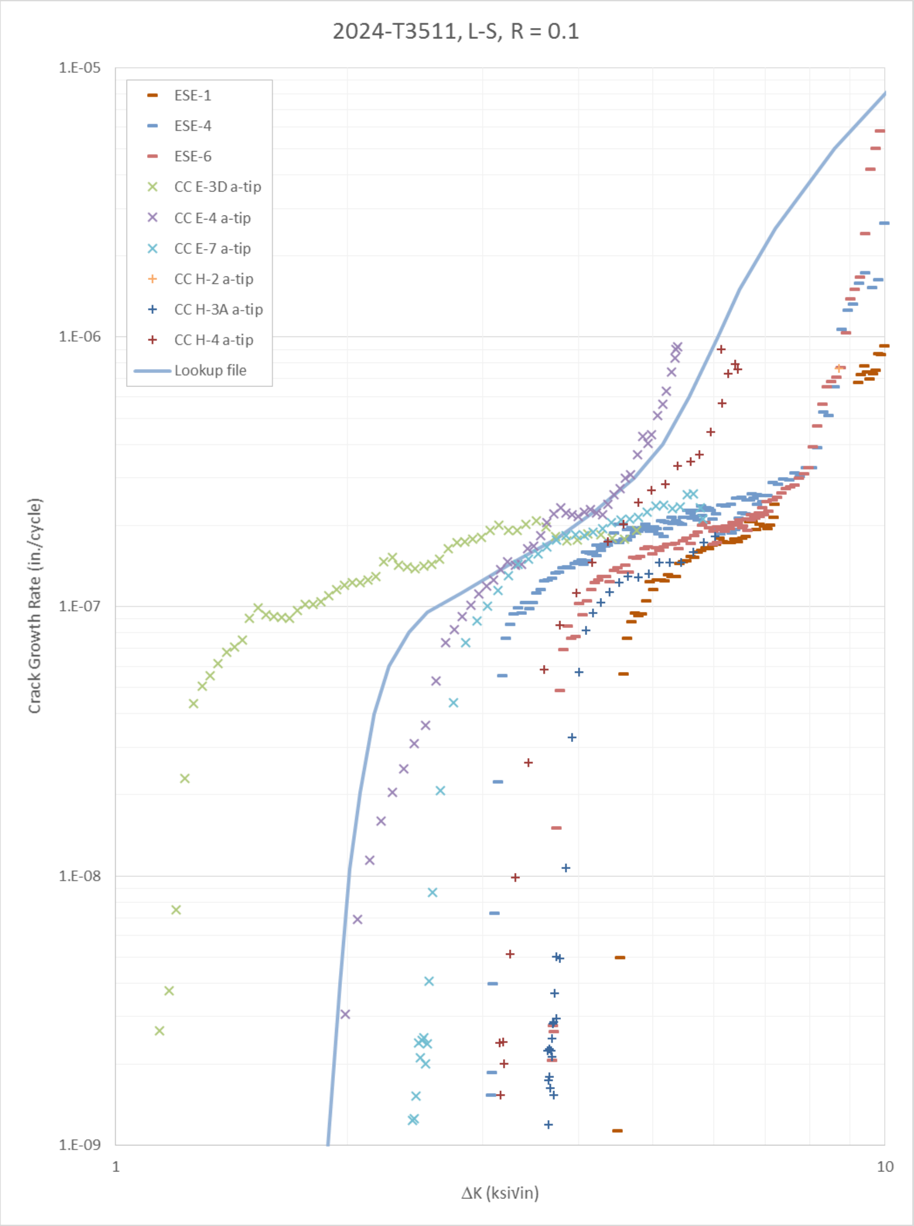
□ Edge corner L-T
○ Hole corner L-T
▲ C(T) L-T
◆ M(T) L-T
− ESE(T) L-S
× Edge corner L-S
+ Hole corner L-S
— Lookup file

Test results: T3511 L-T and L-S, R = 0.1



- L-S (a-tip and ESE(T)) and L-T (c-tip, C(T), and M(T)) data show similar threshold values
  - – Not including one outlier
- Corner crack and through crack data show lower rates than the AFGROW lookup file
  - – Lookup file is conservative, but not unrealistic
  - – Not including one outlier

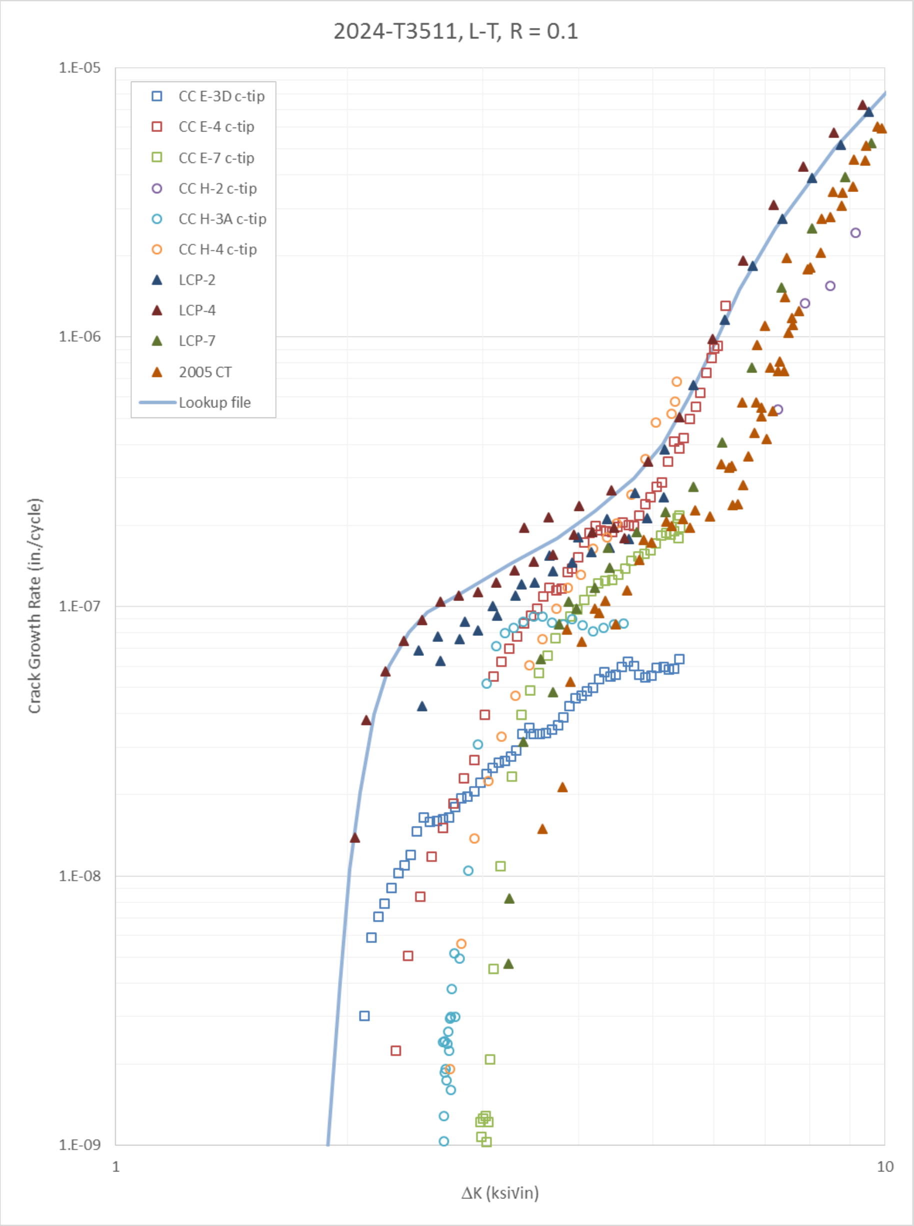
Test results: T3511 L-S, R = 0.1



- Edge corner crack data shows lower threshold than both ESE(T) and hole corner crack

☐ Edge corner L-T
○ Hole corner L-T
▲ C(T) L-T
◆ M(T) L-T
− ESE(T) L-S
× Edge corner L-S
\+ Hole corner L-S
— Lookup file

Test results: T3511 L-T, R = 0.1



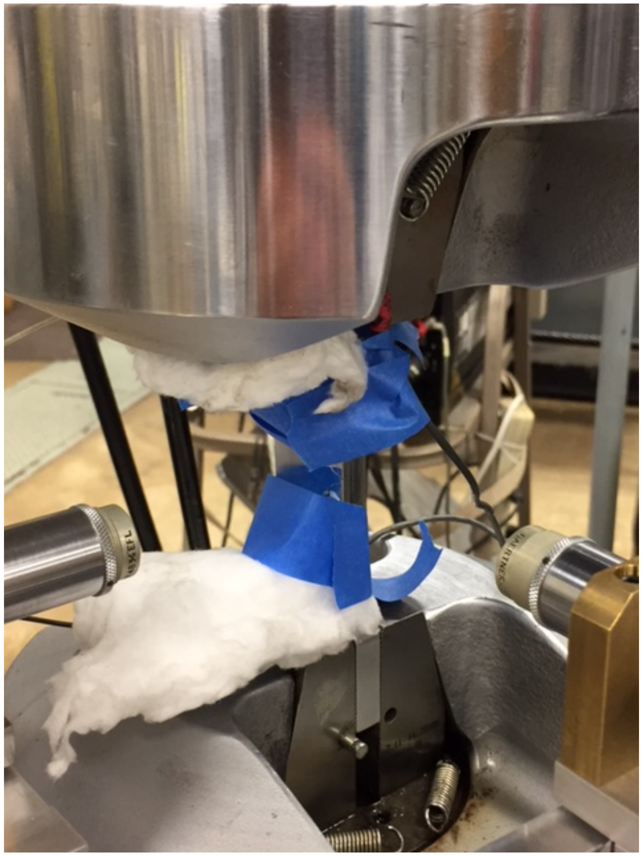
- Corner crack data consistent with C(T) and M(T) data

- Edge and hole corner crack rates are similar

☐ Edge corner L-T
○ Hole corner L-T
▲ C(T) L-T
◆ M(T) L-T
− ESE(T) L-S
× Edge corner L-S
\+ Hole corner L-S
— Lookup file

Conclusions

- Successfully developed near-threshold da/dN-ΔK curves from E647 testing using corner crack specimens
- Data developed for both L-T and L-S cracking
  - Simpler method for L-S data than using through crack specimens
  - Thin specimens possible
- Method did not decrease variability seen in near-threshold data
  - Cracked edge specimens more consistent and more in line with expectations than cracked hole specimens



TRI
AUSTIN

ERSI

Data Management and Quality Assurance

The Role of Capturing Quality Assurance Data for Deep Residual Stress Inducing Processes and How to Manage that Data for Future Use.

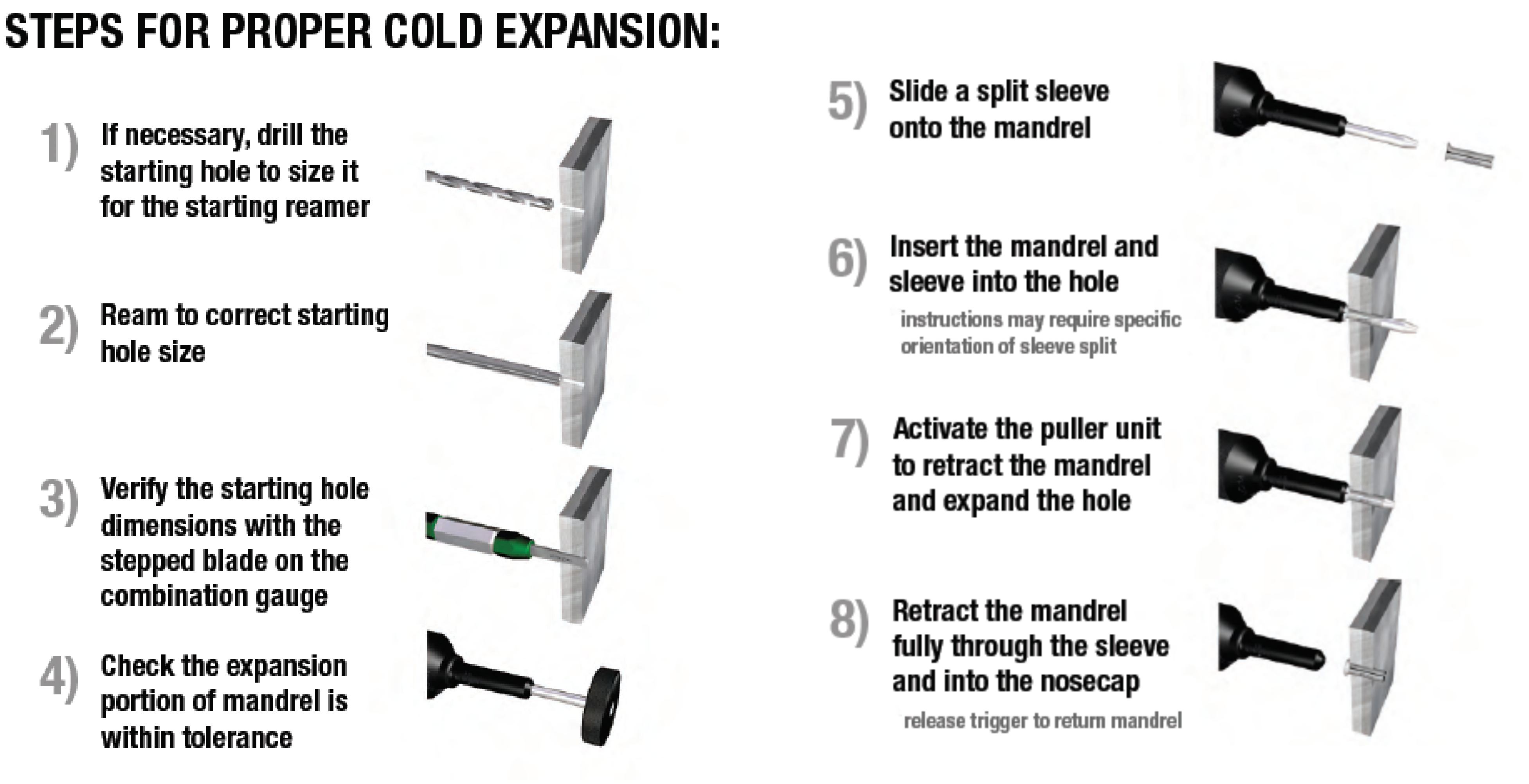
Outline

- Quality Assurance
- Data Management

DISCUSSIONS

1. What is the current state-of-the-art for capturing the proper application of the Cx process at fastener holes?
2. What are the technological gaps that still need to be overcome?
3. What type of governing document do you see the requirements for this type of quality assurance tool being placed for USAF usage?
    a. TO, Workspec, Planning documents????
4. How can the data produced via this method be stored and used?
5. Why is the capture and storage of this information so important for the implementation of residual stresses into the sustainment paradigm?

FTI process overview



STEPS FOR PROPER COLD EXPANSION:

1) If necessary, drill the starting hole to size it for the starting reamer

2) Ream to correct starting hole size

3) Verify the starting hole dimensions with the stepped blade on the combination gauge

4) Check the expansion portion of mandrel is within tolerance

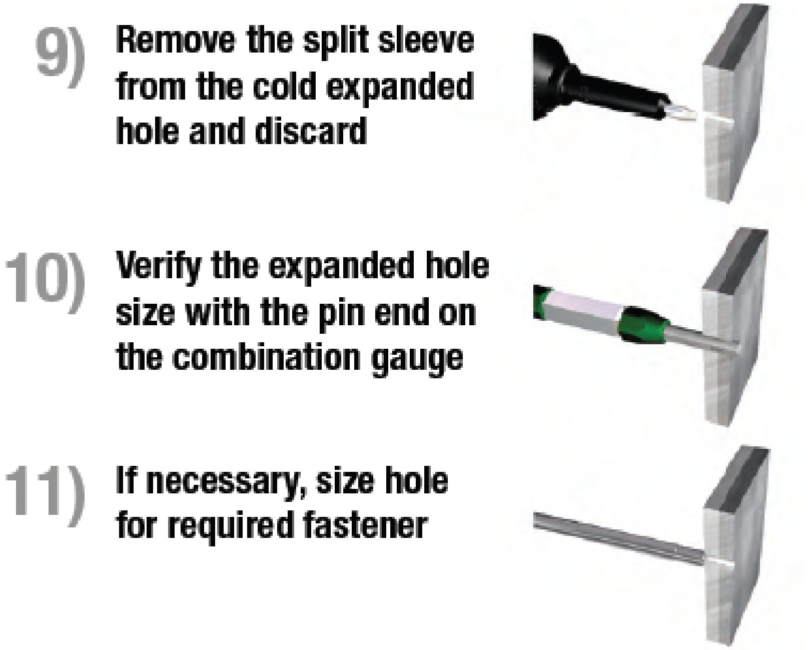
5) Slide a split sleeve onto the mandrel

6) Insert the mandrel and sleeve into the hole
instructions may require specific orientation of sleeve split

7) Activate the puller unit to retract the mandrel and expand the hole

8) Retract the mandrel fully through the sleeve and into the nosecap
release trigger to return mandrel

FTI process overview



9) Remove the split sleeve from the cold expanded hole and discard

10) Verify the expanded hole size with the pin end on the combination gauge

11) If necessary, size hole for required fastener

- Multiple QA steps built into this process.

2. Always observe these process quality steps:

- Use the combination gauge to verify hole size before and after cold working.
  - Use the stepped blade end of the gauge to check starting holes
  - Use the pin "go/no-go" end of the guage to verify that the hole has been properly cold expanded
- Use the mandrel check fixture to ensure that the major diameter of the mandrel is not worn beyond acceptable limits. A worn mandrel will result in insufficient cold expansion and life enhancement.

Why is more QA needed

- Technician uses feeler gauges to measure hole diameter during the process.
- Performed by the technician using manual gauge.
- If within spec, no record is required and process moves to the next step.
- Cx doesn’t get credit it deserves sometimes.
- Cx sometimes gets extra/wrong credit.
- If you are going to make lifing/risk decisions, you need to ensure CX has been done to your specifications.

Beyond residual stress

- If everything is “good”, no record exists
  - No news is good news

- Issue goes beyond residual stress to all NDI

- And even beyond NDI

Technology Gaps

- Depends on your requirements.

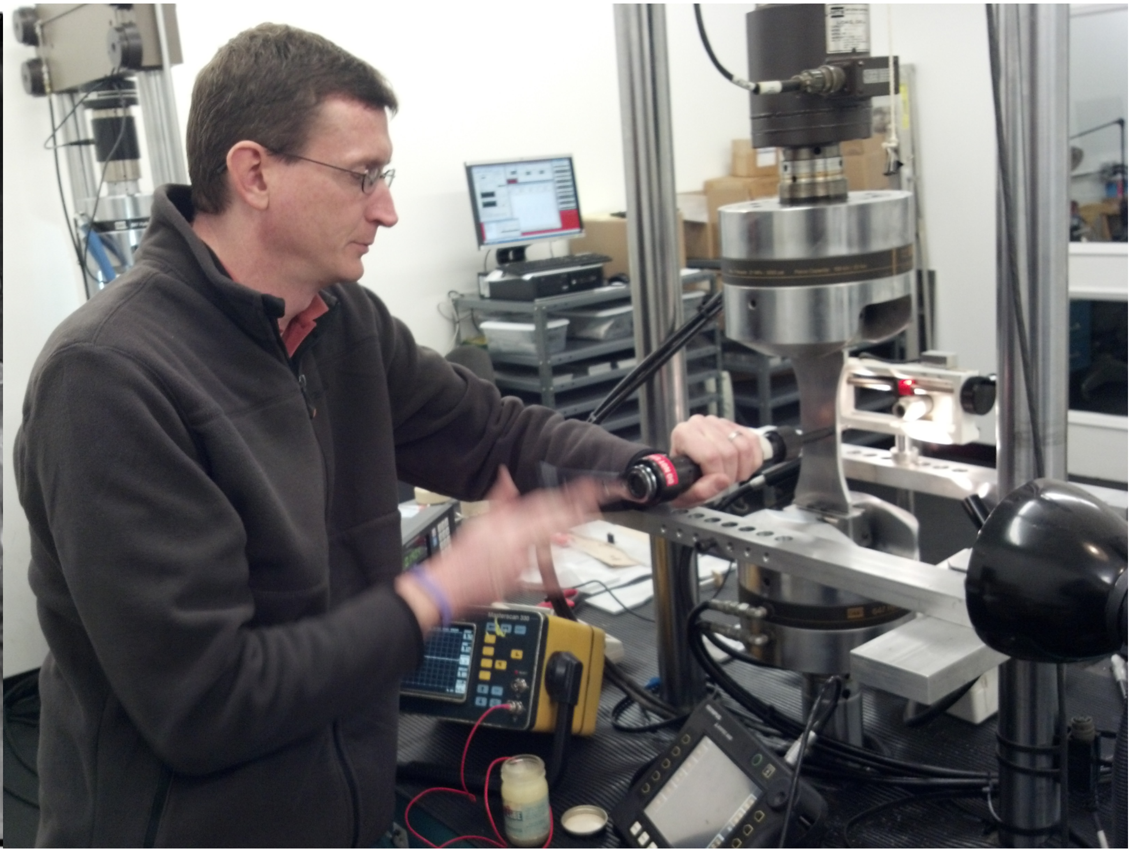
- IF you need auditable, quantitative measurement to show:
  a. Cx process was performed to spec
  b. residual stress amount was at least per spec.
  c. residual stress is X

QA requirements?

- What is the variability and uncertainty (not the same thing) that you can accept
  - in your processes of prediction
  - in your manufacture/depot process
- This drives the answer.
- Typical Cx hole expansions are in 3% to 5% range. How precise do you need to know for your particular application?
  - Validate your measurement capability w.r.t. your requirements.

Process performed to spec

- Could take a photo!



Residual stress amount was at least per spec.

- Basically a threshold. Easier than a precise measurement.

- Measure hole diameter before and after?
  - What is required precision, tooling to do this?

- Measure Cx
  - (Indirectly) Deformation due to process
  - (Directly) Surface residual stresses due to process

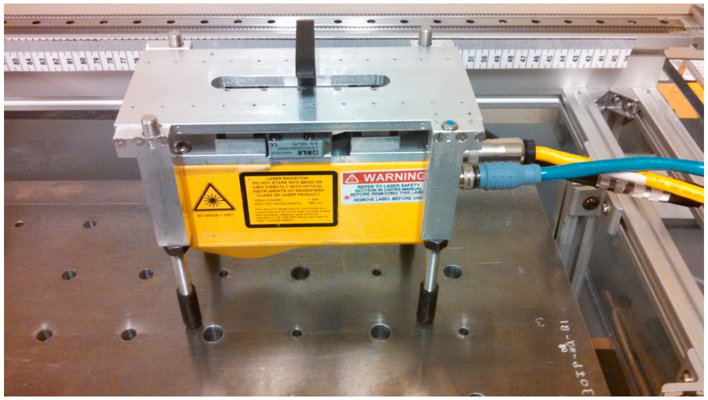
Variation with “spec”

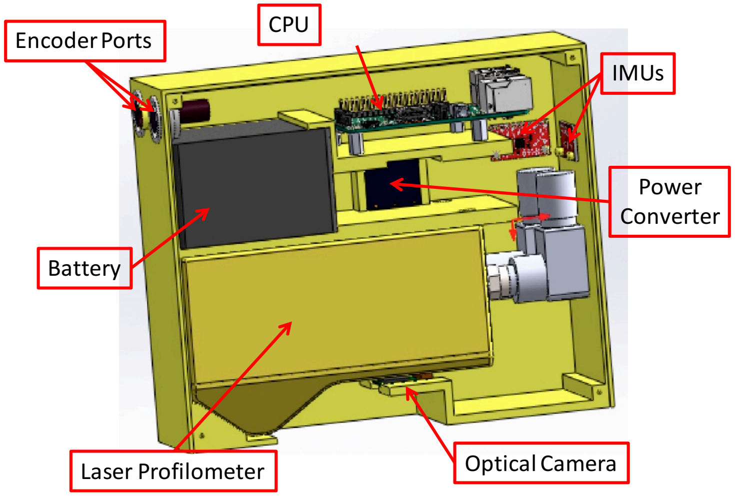
- Some examples of hole diameters and changes due to Cx.

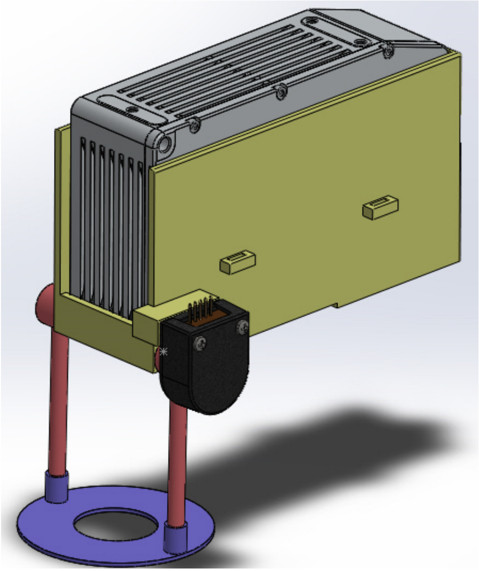
	MAX	MID	MIN	OUT
Hole Diameter	Hole 1 CX %	Hole 2 CX %	Hole 3 CX %	Hole 4 CX %
0.168”	4.75	3.98	2.80	1.40
0.246”	4.41	3.27	2.63	1.17
0.374”	3.99	3.42	3.00	1.20
0.494”	4.00	3.44	2.99	1.24
0.574”	3.63	3.20	2.93	1.07

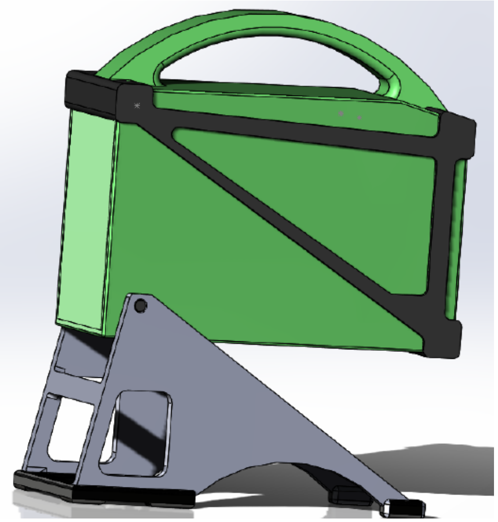
Measuring plastic deformation caused by Cx process

- TRI/Austin's FastenerCam™ evolution







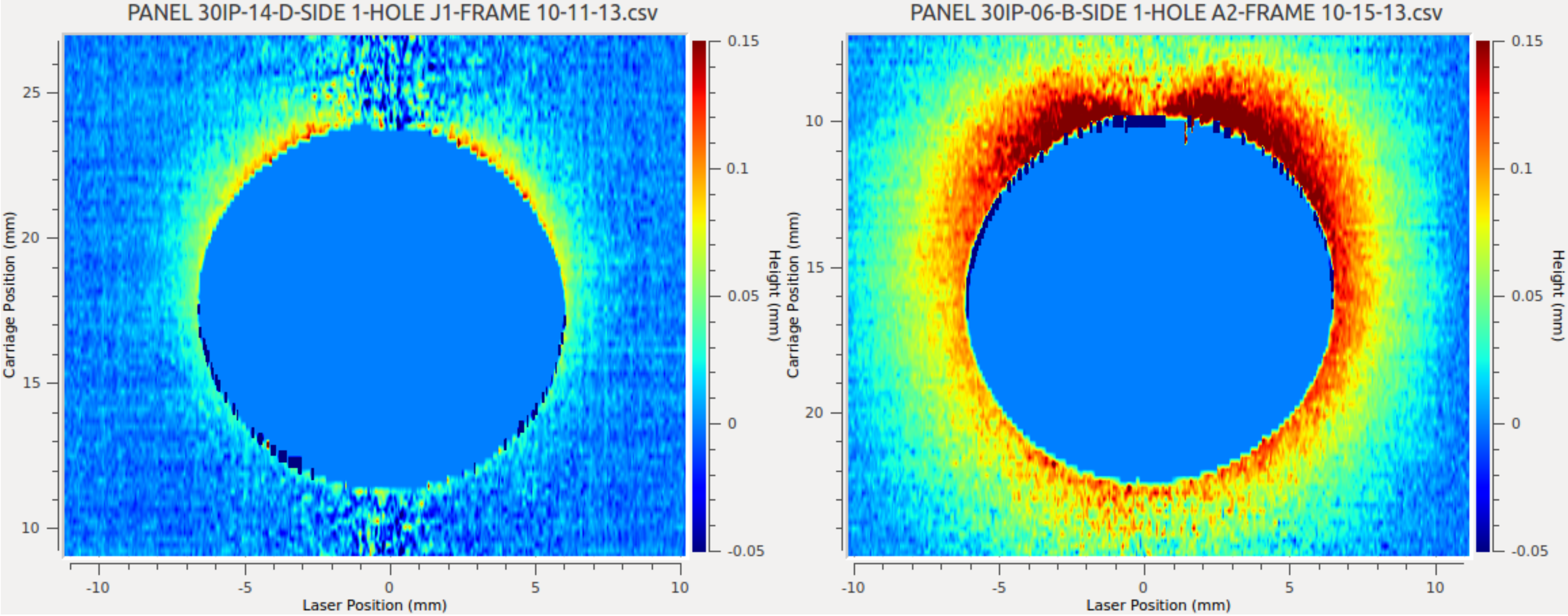


Measuring plastic deformation caused by Cx process

- TRI/Austin’s FastenerCam™

0.494” Diameter Straight Shank Holes

1.24% Cx 4.00% Cx



Measuring residual stresses caused by Cx process

- A system by Proto

MGR40 - RESIDUAL STRESS MEASUREMENT SYSTEM

Fully automated X, Y and Z axes for portable residual stress mapping

Portable, triaxial resi
measurement gonic

Measuring Residual Stress Inside a Bolthole

Measuring residual stresses caused by Cx process

Residual Stress Analysis Near a Cold Expanded Hole in a Textured Alclad Sheet Using X-ray Diffraction

by J.C.P. Pina, A.M. Dias, P.F.P. de Matos, P.M.G.P. Moreira and P.M.S.T. de Castro

Vol. 45, No. 1, February 2005 *© 2005 Society for Experimental Mechanics*

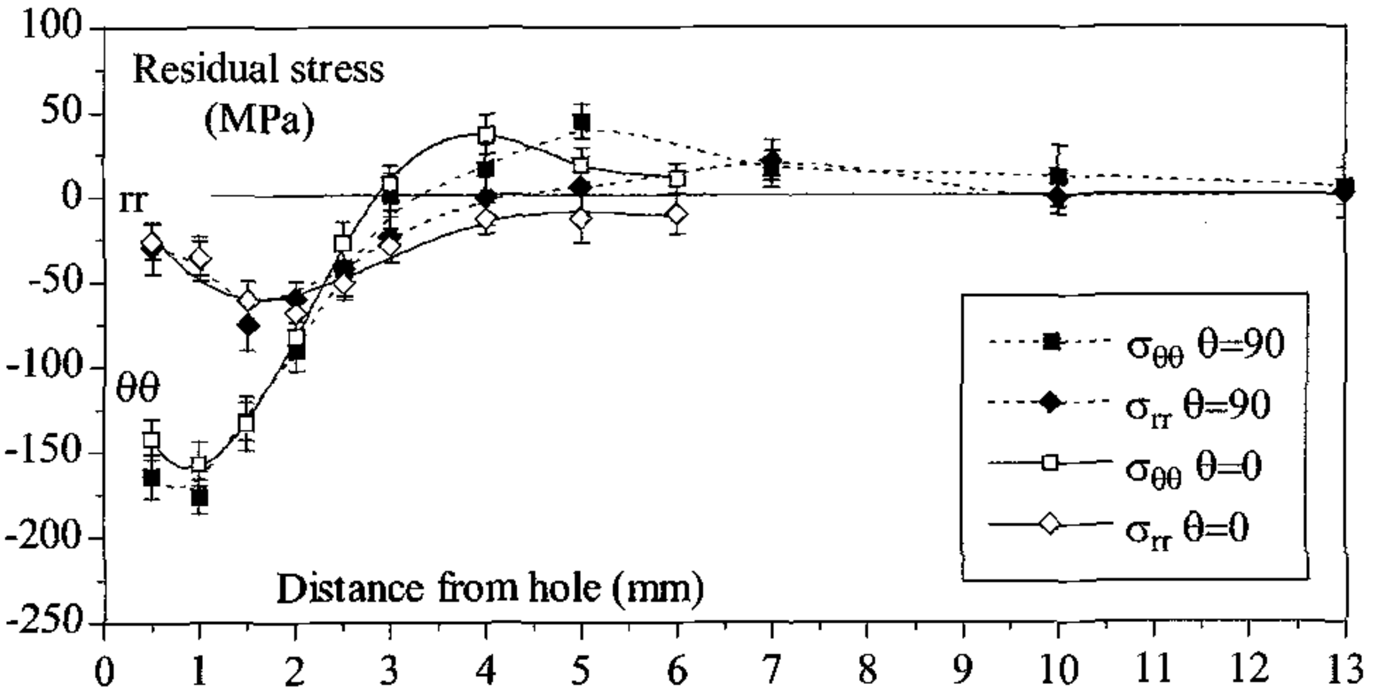


Fig. 6—Residual stresses determined on the entrance face of the aluminum sheet for θ = 90° and θ = 0°

Residual stress is X

- You have some model to convert the measured parameter to your residual stress.
  - Hole diameter, plastic deformation, surface residual stresses

- You really want to know stress tensor at all locations.
  - Modeling, experimental work described by previous speakers provides a means to infer this from simpler measurements

So are we there yet?

- That’s up to you to decide.
  - Does the system of measurement provide sufficient performance and variability to enable prediction of structural performance?
  - Is it affordable, practical for use?
- I don’t think we have solid answers for either the
  - structural performance prediction requirements
  - measurement system capabilities

Governing Docs

What type of governing document do you see the requirements for this type of quality assurance tool being placed for USAF usage?

a. TO, Workspec, Planning documents????

- This belongs to the owner. Discuss to your hearts' content, but you don't get to decide unless you are the owner.

Data Management

- This is a problem of the owner. Argue amongst yourselves. Manufacturing, depot, field all have their issues.
  - Must get IT involved

- Any of the processes described for QA provide digital data. You need to provide a receptacle for said data.
  - Must get IT involved

Why save data?

- Cx doesn’t get credit it deserves sometimes.
- Cx sometimes gets extra/wrong credit.
- If you are going to make lifing/risk decisions, you need to ensure Cx has been done to your specifications.

FINAL DISCUSSIONS

1. What is the current state-of-the-art for capturing the proper application of the Cx process at fastener holes?
2. What are the technological gaps that still need to be overcome?
3. What type of governing document do you see the requirements for this type of quality assurance tool being placed for USAF usage?
   a. TO, Workspec, Planning documents????
4. How can the data produced via this method be stored and used?
5. Why is the capture and storage of this information so important for the implementation of residual stresses into the sustainment paradigm?

Impact of Deep Residual Stress on NDI Methods

21 September 2017

AFRL HERITAGE | 1917–2017

100 YEARS OF U.S. AIR FORCE SCIENCE & TECHNOLOGY

John Brausch[1], David Stubbs[2]
Ward Fong[3]

[1]AFRL/RXSA, Systems Support Division
Materials and Manufacturing Directorate
Air Force Research Laboratory
Wright-Patterson AFB, OH 45433
[2]Universal Technology Corporation, Dayton, Ohio
[3] Ogden NDI Program Office, Hill AFB, UT

Integrity ★ Service ★ Excellence

Overview

- Summary of Current Knowledge
- Effect of Laser Peening on NDI of Fatigue Cracks in Aluminum Alloys
- Quantifying Ultrasonic “Dead Zone” in Cold Worked Holes
- Future Work

Acknowledgements

Dr. Adrian DeWald - Hill Engineering

Dr. Michael Hill - Hill Engineering

Dr. Mark Thomsen - A-10 ASIP Manager

Mr. Mark Bennett - Universal Technology Corporation

Mr. Brian Shivers – Southern Ohio Center for Higher Education

Summary of Current Knowledge

- Ultrasonic response from EDM and unloaded fatigue cracks differ by ~ 6dB for aluminum.
- Applied compressive stress reduces ultrasonic signal amplitude in aluminum by -6dB for every 4ksi for aluminum.
- **Applied compressive stresses** do not significantly affect BHEC or SECI on aluminum or titanium.
- Applied compressive stress affects fluorescent penetrant detection capability.
- CX of holes does not measurably affect BHEC on aluminum or titanium.
- CX of holes significantly affects SECI at the mandrel exit surface due to crack “tunneling”.

Summary of Current Knowledge (continued)

- CX of holes **reduces** ultrasonic detectability of fatigue cracks
  - Extent of ultrasonic dead zone not quantified or correlated to hole diameter or plate thickness.

- Deep residual stress surface treatments **do not** significantly affect SECI detectability in aluminum or titanium.

- Deep residual stress surface treatments significantly **affect** fluorescent penetrant detection capability.

What We Wanted to Know

(ERSI Workshop September 2016)

I. Quantify shear-wave ultrasonic detection capability for fatigue cracks propagating from CX holes.

- POD study for typical CX and no-CX countersink hole scenario
  - Semi-automated and manual scanning
- ***Develop model to address component geometry, plate thickness, hole diameter, % hole expansion, hole fill***
- ***Conduct empirical sensitivity studies to calibrate model***

II. Quantify effects of deep residual stress on crack closure and NDI of open surfaces.

- Ti-6-4 Beta peening study suggests compressive stress surrounding crack may be relieved, enabling penetrant to enter crack.
- ***Laser Peening study (Hill Engineering) should provide additional learning for Aluminum.***

Laser Shock Peening (LSP) Effects on NDI

Study Overview

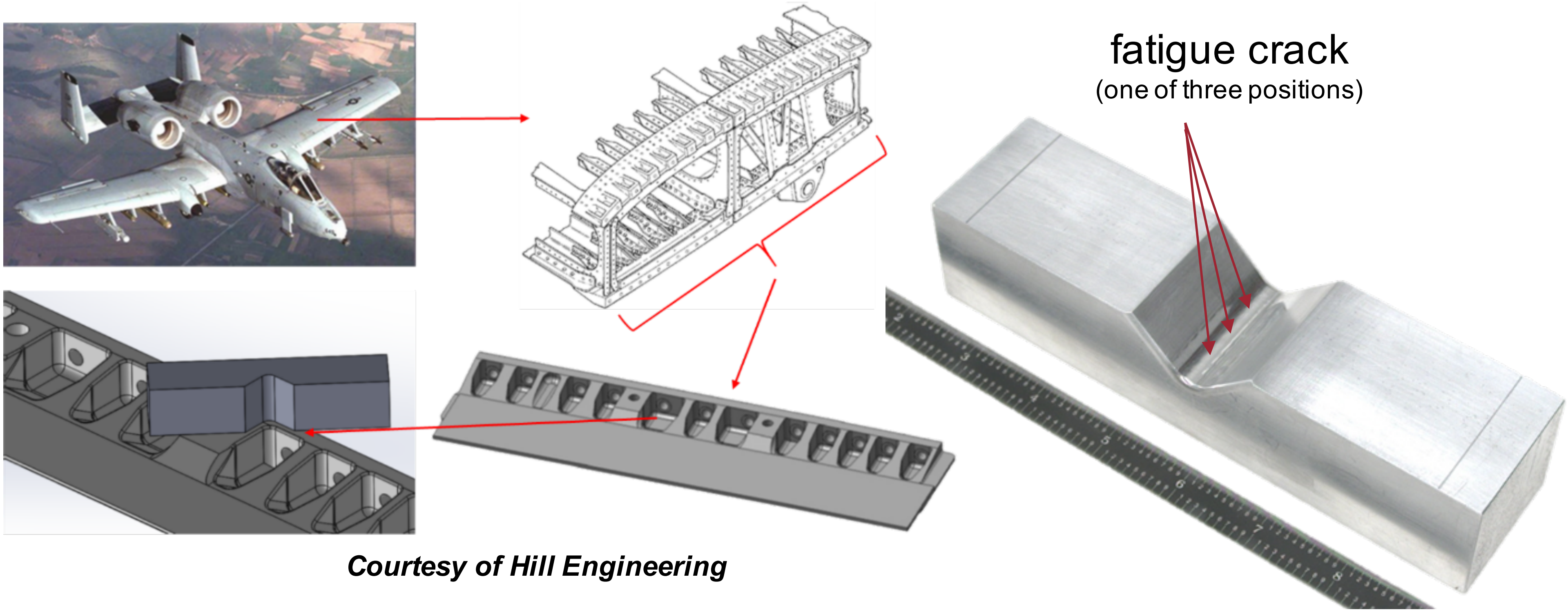
Objective

Quantify the effect of LSP on detectability of fatigue cracks in aluminum.

Approach

Measure and compare indication response on LSP treated and unpeened fatigue cracks specimens. Eddy current, fluorescent penetrant and ultrasonic methods evaluated.

7050-T7541 Specimen Configuration

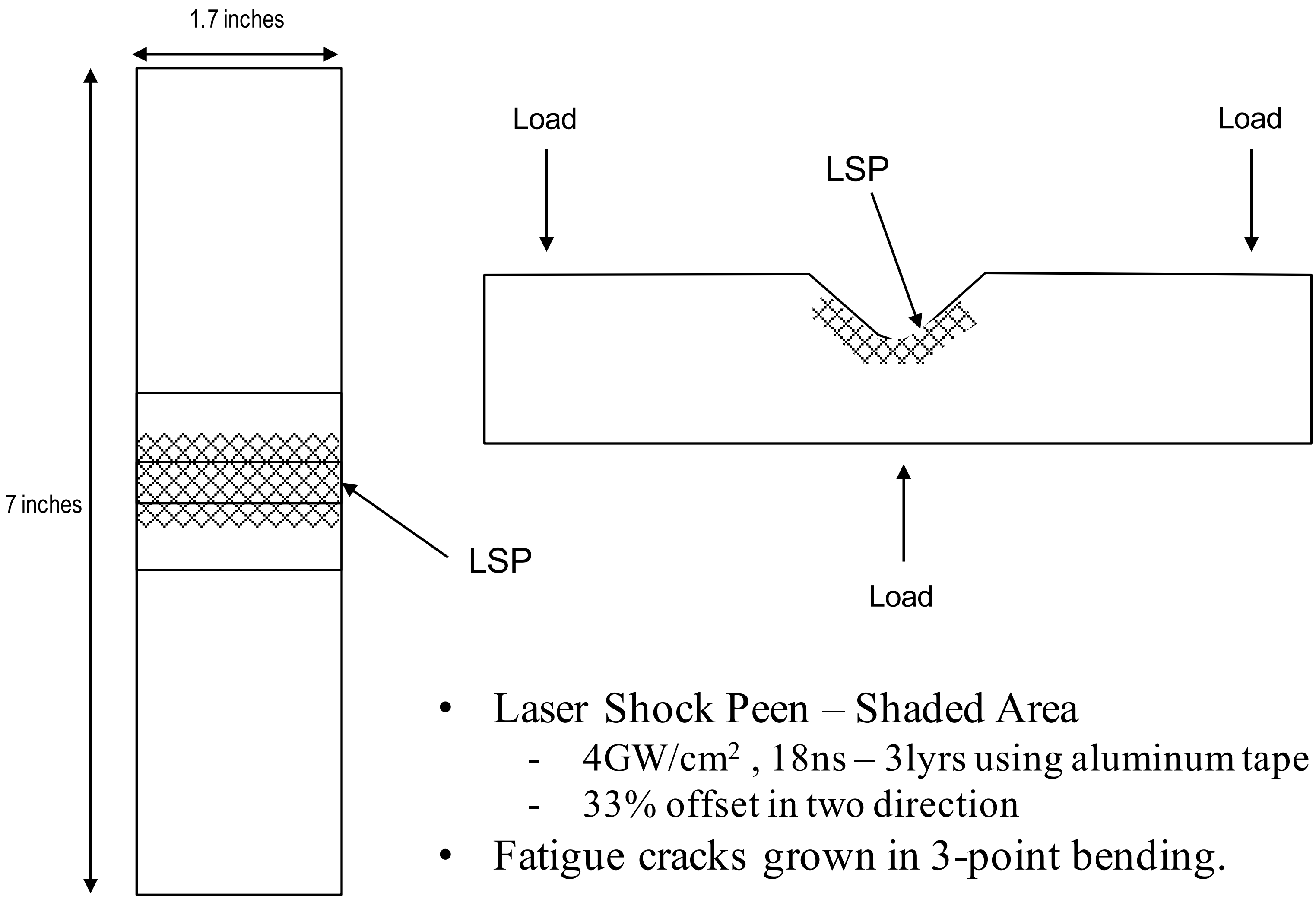


Courtesy of Hill Engineering

Fatigue Crack Specimens (***provided by Hill Engineering***)

- 20 ea. - Unpeened
- 20 ea. - LSP treated
- Precracked with 0.050 inch long x 0.025 inch deep electro-discharge machined (EDM) notches. EDM machined away then crack grown to target length.
- 0.070 inch – 0.300 inch target surface lengths

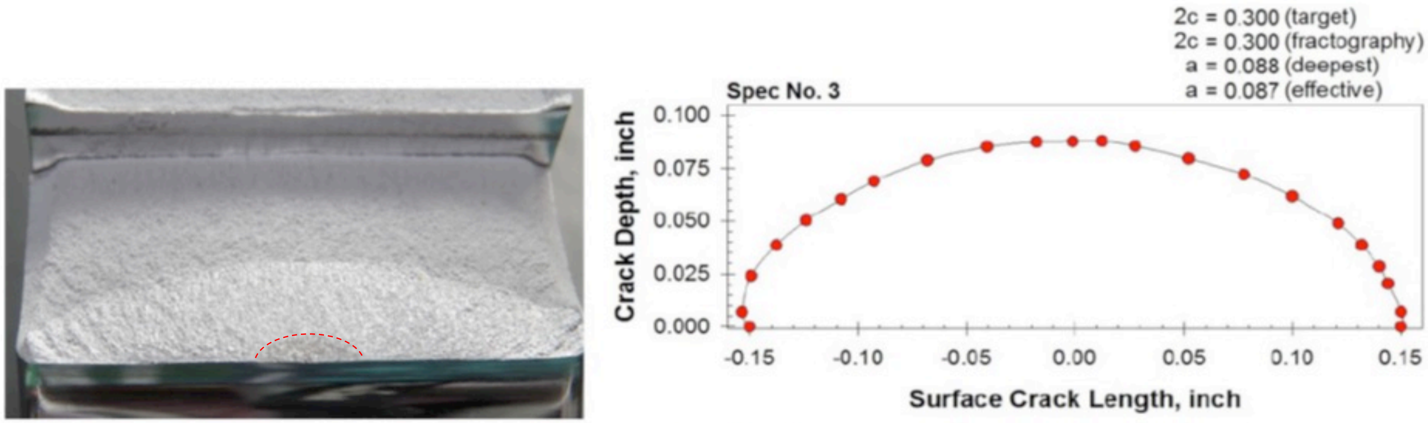
LSP Treatment



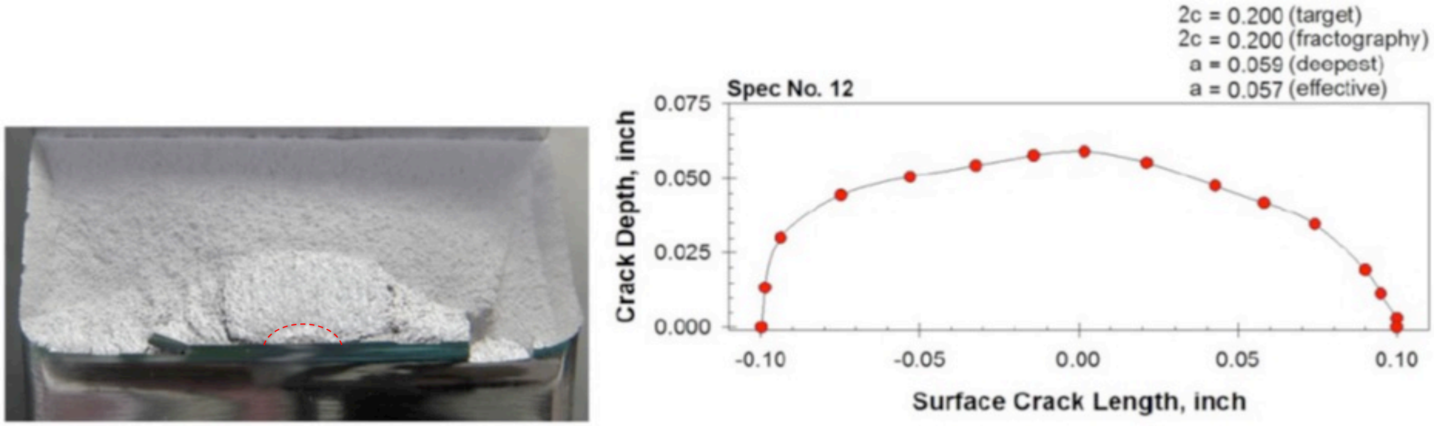
- Laser Shock Peen – Shaded Area
  - 4GW/cm^2 , 18ns – 3lyrs using aluminum tape ablative layer
  - 33% offset in two direction
- Fatigue cracks grown in 3-point bending.

Typical Aspect Ratios

Phase I Specimens



(a) Specimen No. 3

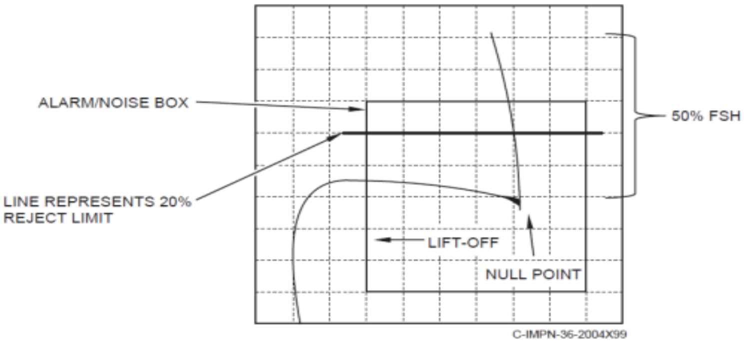


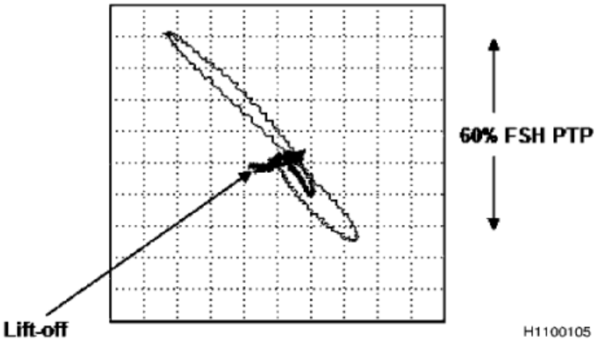
(b) Specimen No. 12

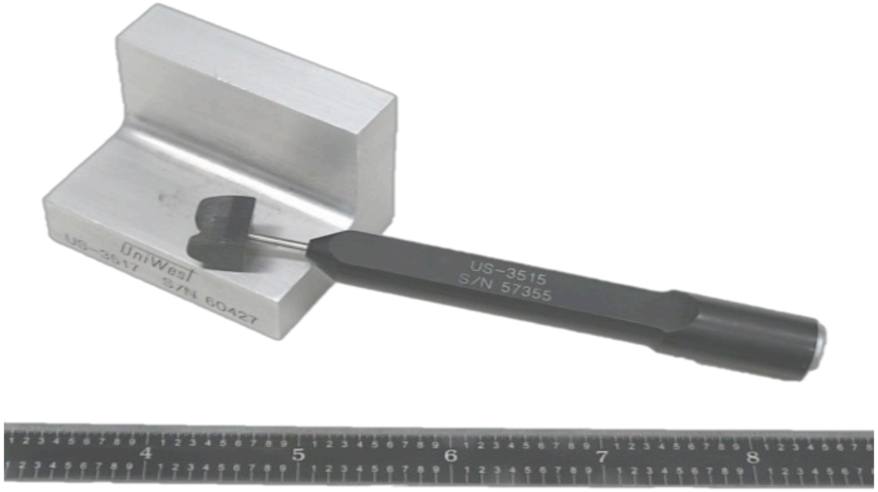
Courtesy of Hill Engineering

1.75 inch

Eddy Current Inspection Tools

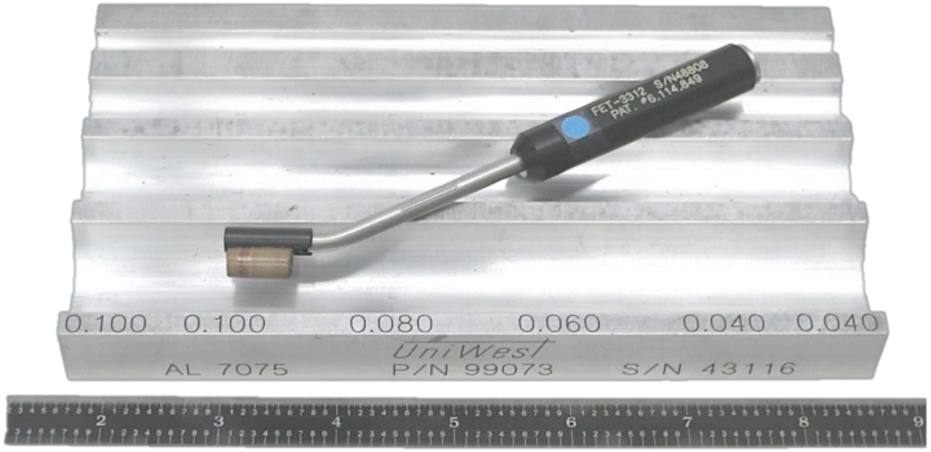






US-3515/3516 Probe

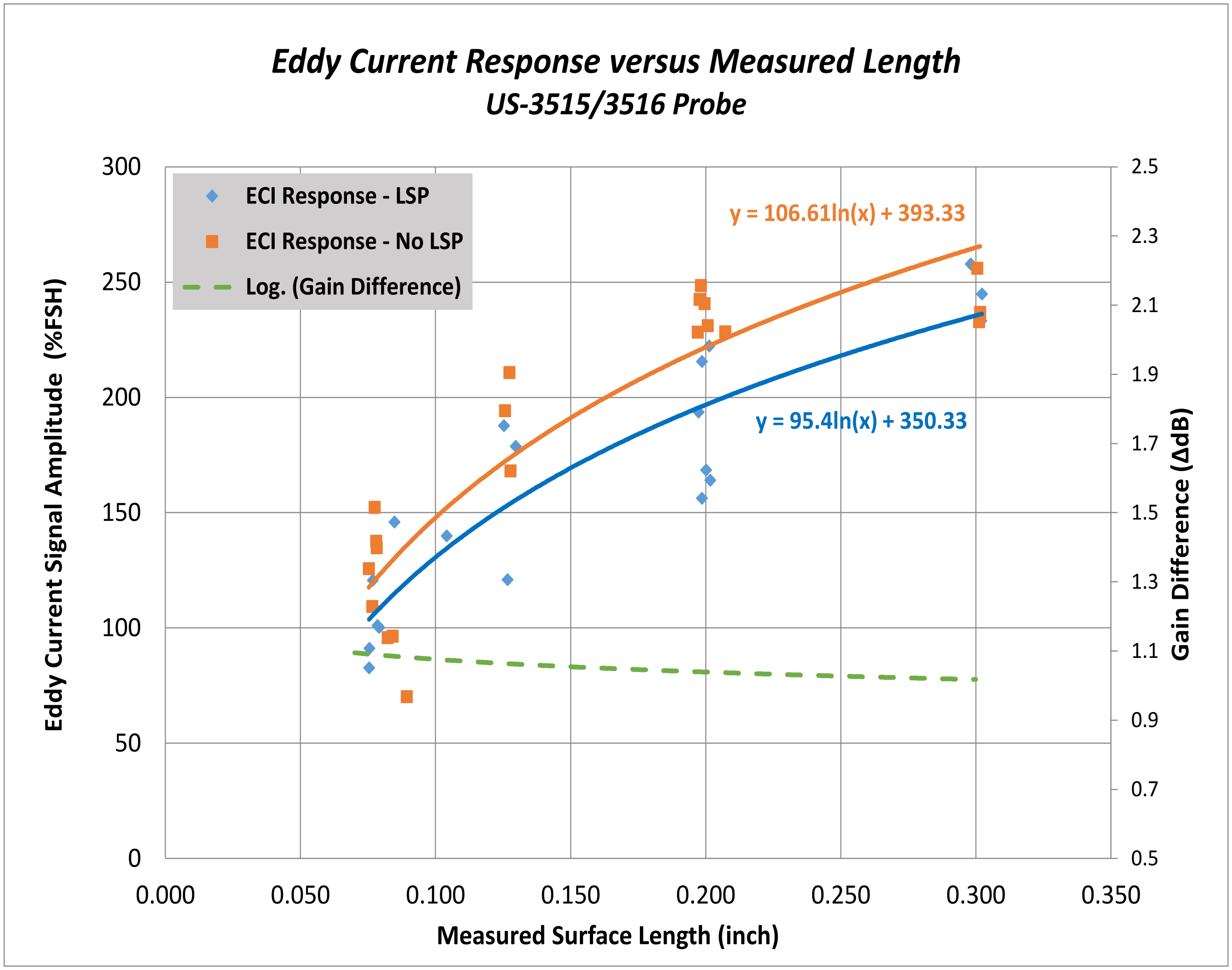
200 KHz



FET-3312 Probe

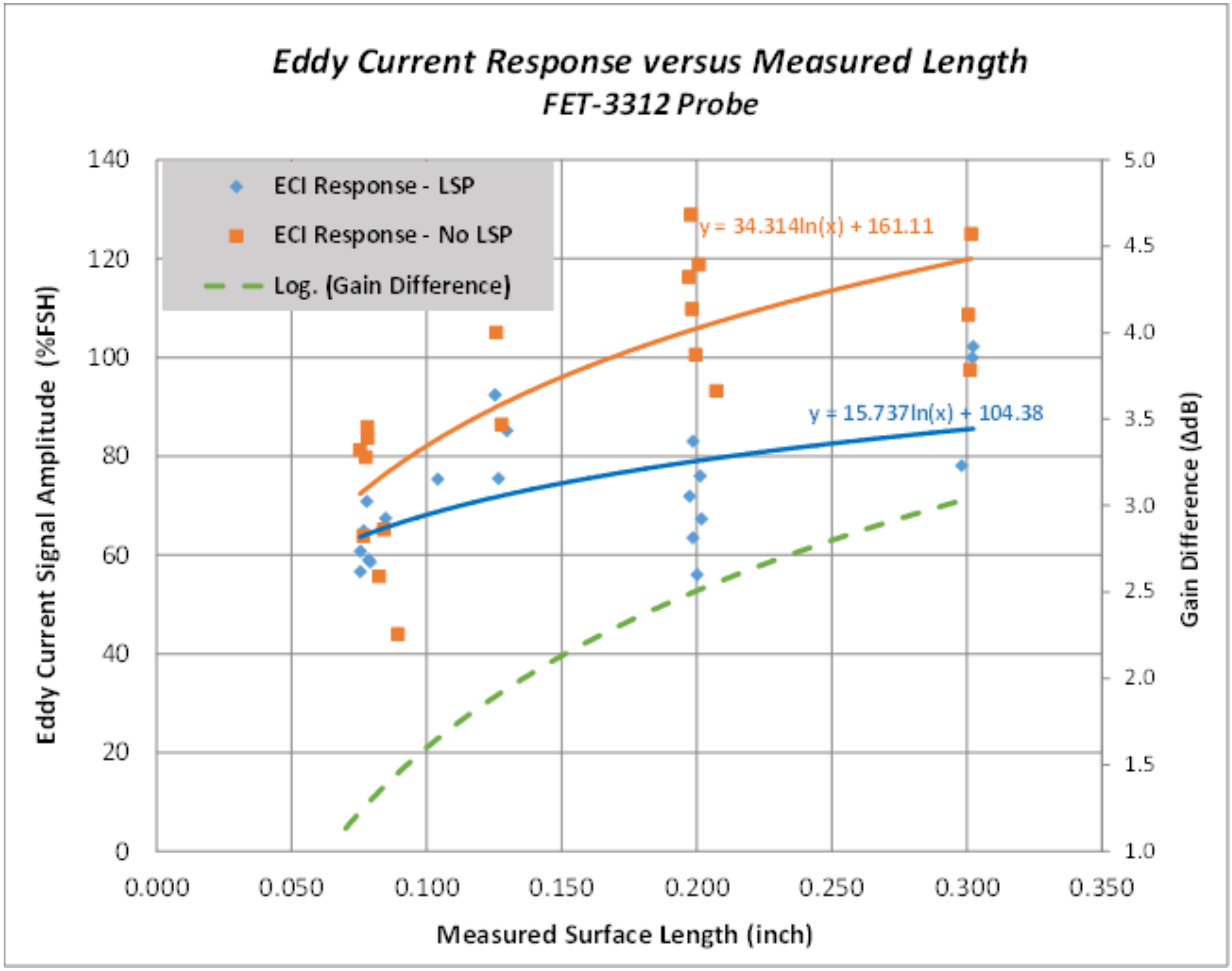
400 KHz

US-3515/3516 Probe Results



Distribution A: Approved for Public Release. Distribution unlimited. Case# 88ABW-2017-4459

FET 3312 Probe Results



FPI Indication Analysis

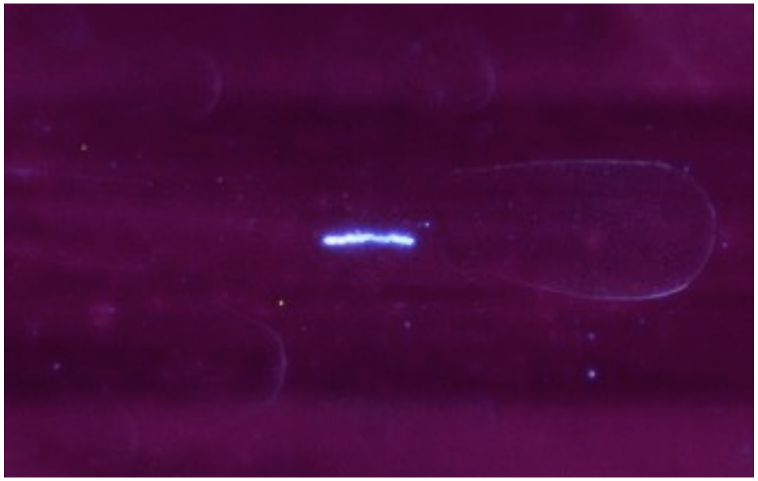
Calculation of FPI Indication Parameters using NIH Image J

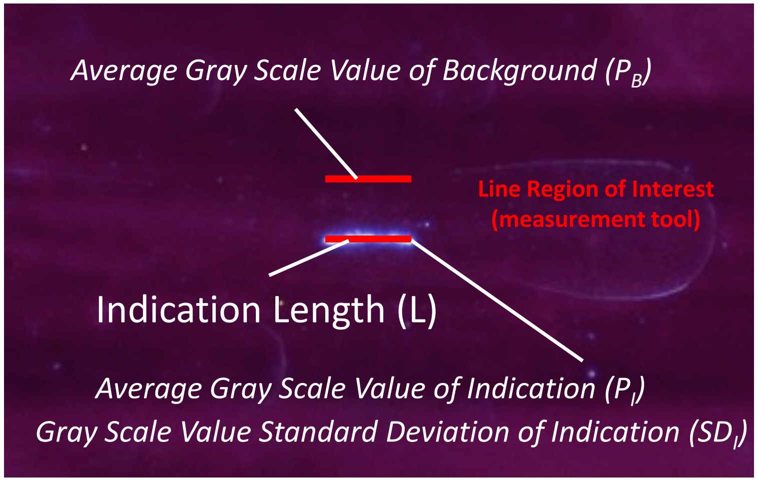
- Indication length (L)
- Average gray scale value along indication (PI)
- Standard deviation of gray scale value along indication (SDI)
- Background average gray scale value (PB)

Signal-to-noise (S:N) and factored length (LF) values were calculated and tabulated for each indication as follows:

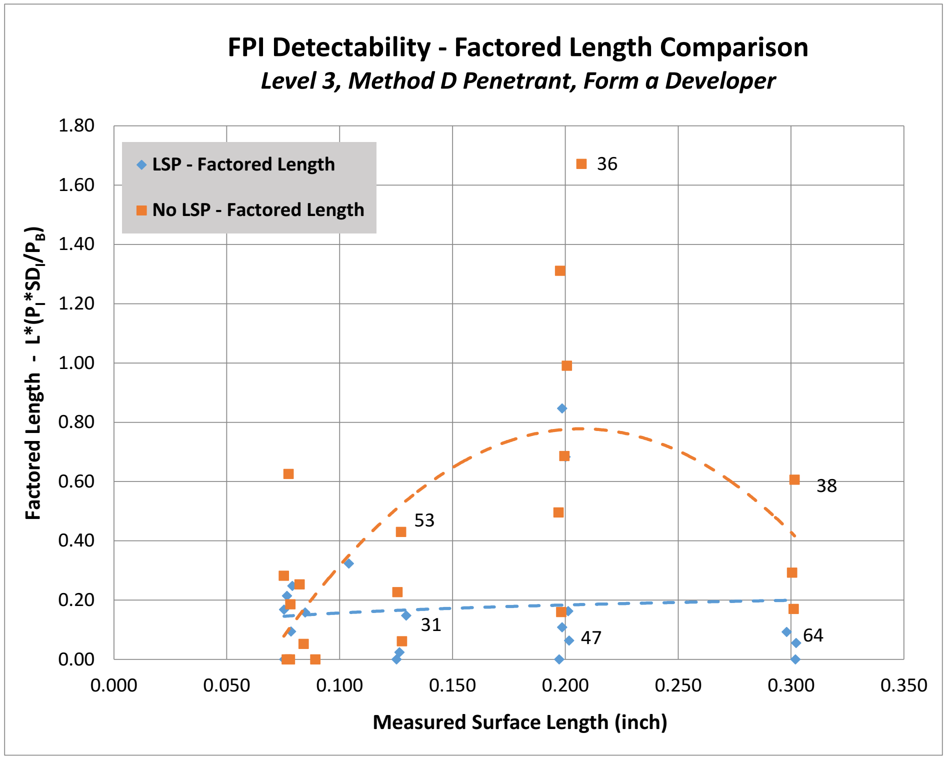
$S{:}N = (PI - SDI)/PB$ *Equation 2*

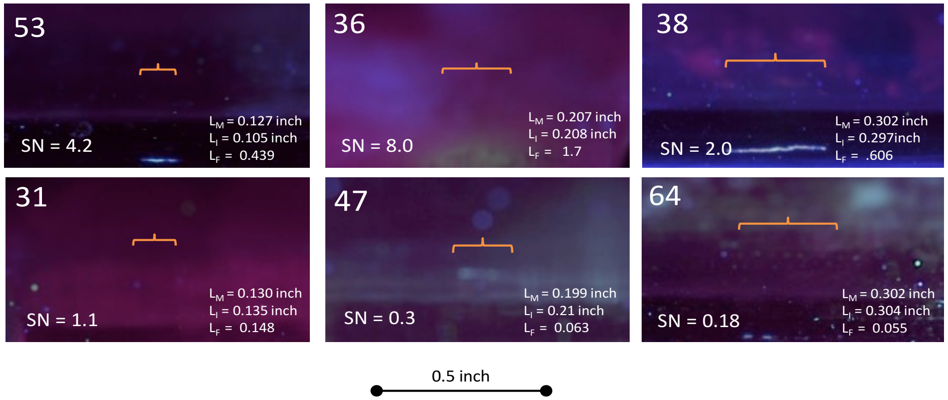
$\text{Factored Length (LF)} = L * S{:}N$ *Equation 3*





Level 3 FPI Process

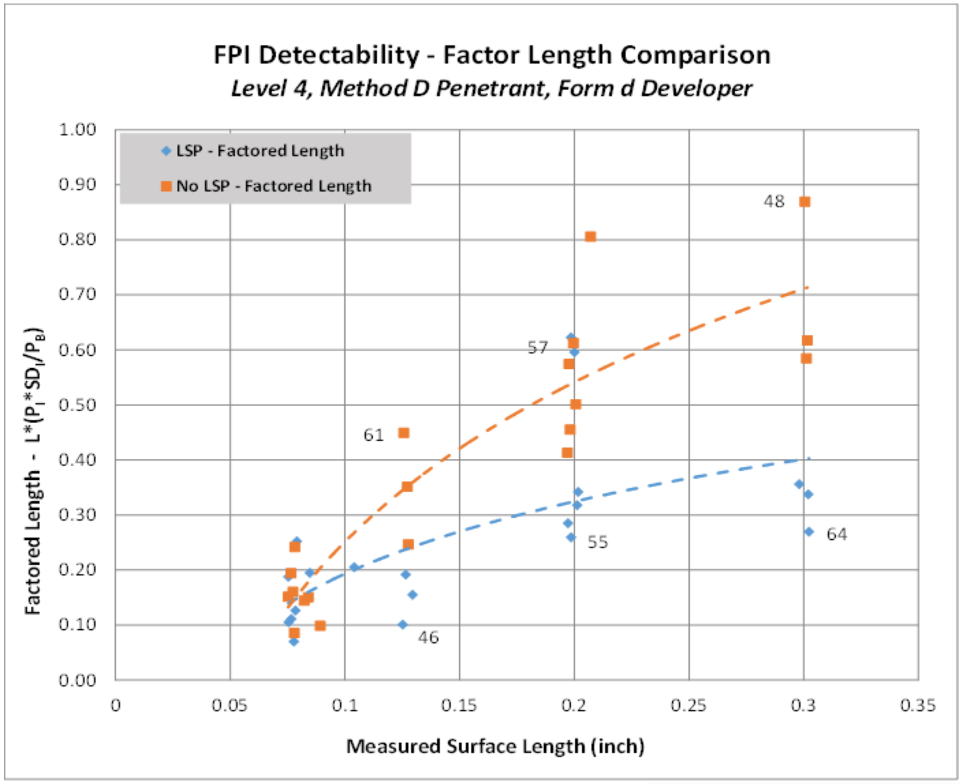




Level 3 FPI Process

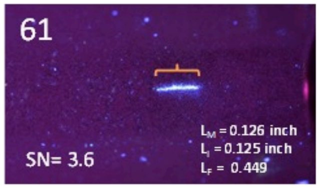
- Level 3 (high sensitivity penetrant)
- 30 minute penetrant dwell
- Method D (5% spray remover)
- Form a – dry powder developer
- 10 minute developer dwell

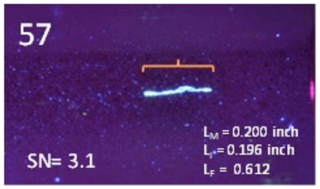
Level 4 FPI Process

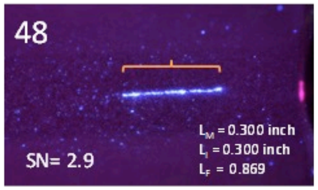


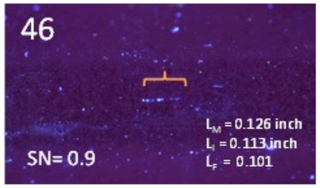
<u>Level 4 FPI Process</u>

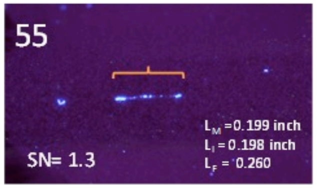
- Level 4 (ultrahigh sensitivity penetrant)
- 30 minute penetrant dwell
- Method D (5% spray remover)
- Form d – nonaqueous developer
- 15 minute developer dwell

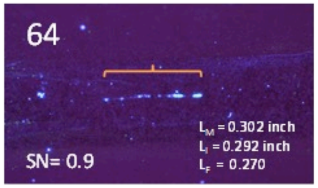






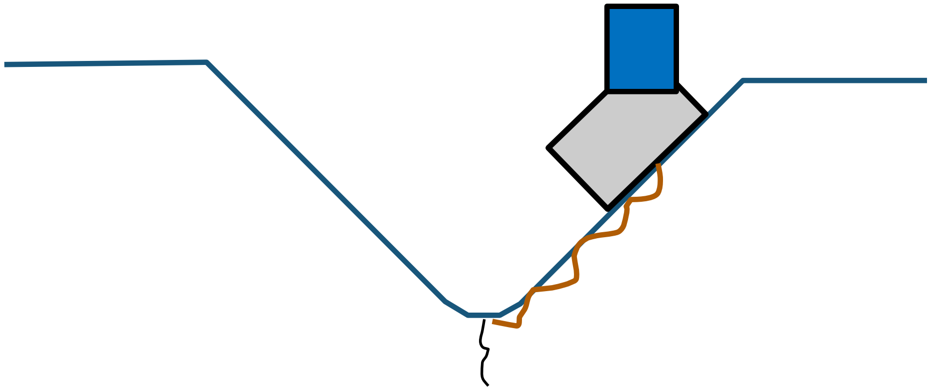






0.5 inch

Surface Wave Ultrasonics



Surface Wave Unit

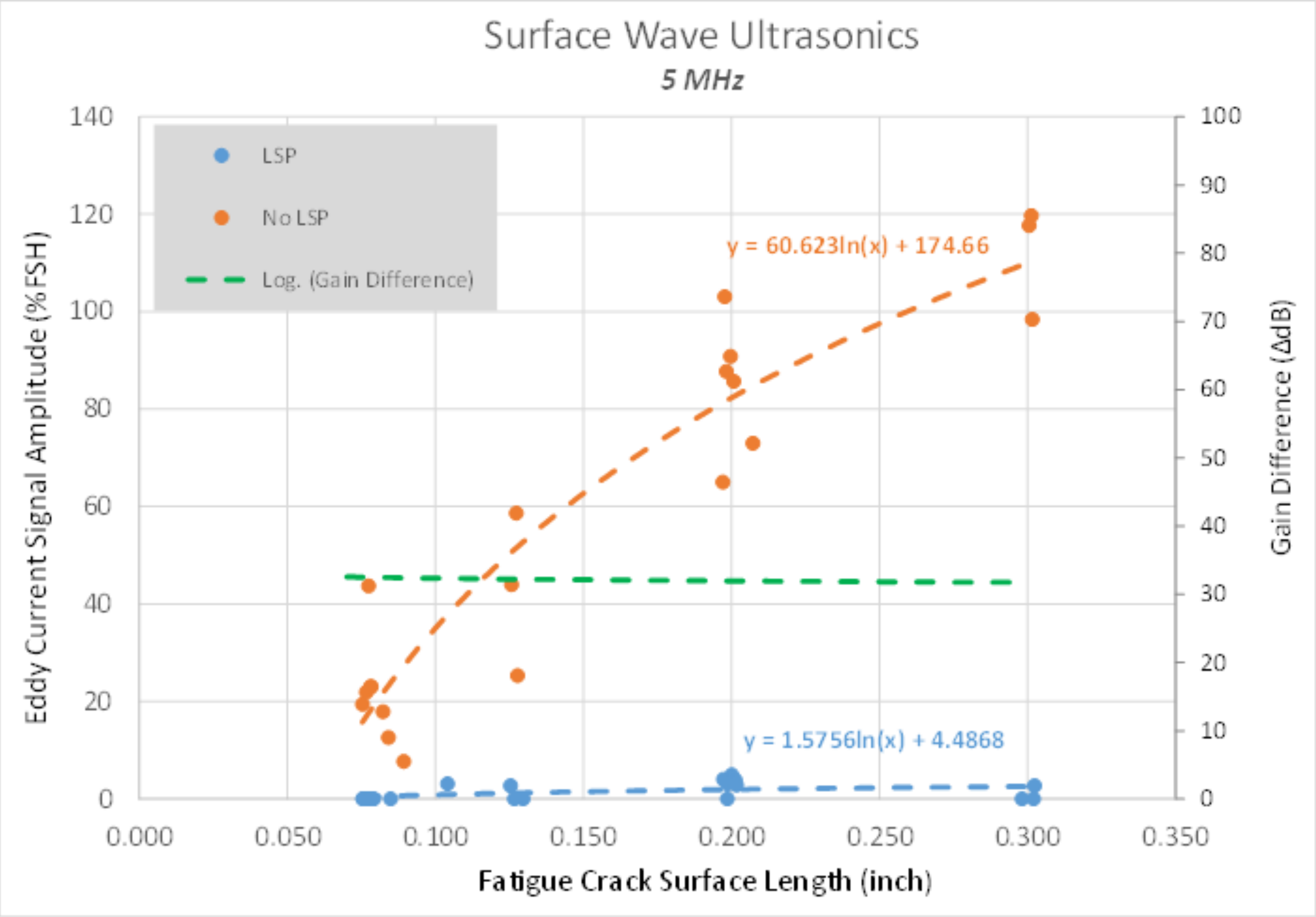
90º shear wedge

10 MHz, 0.25 inch diameter transducer

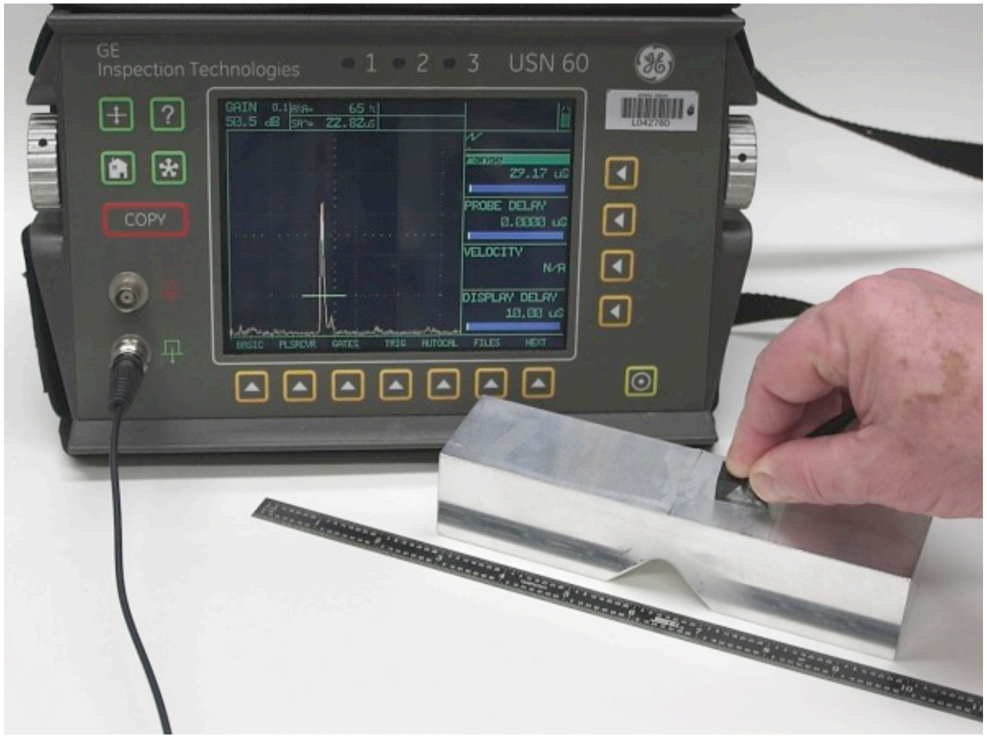
Calibration

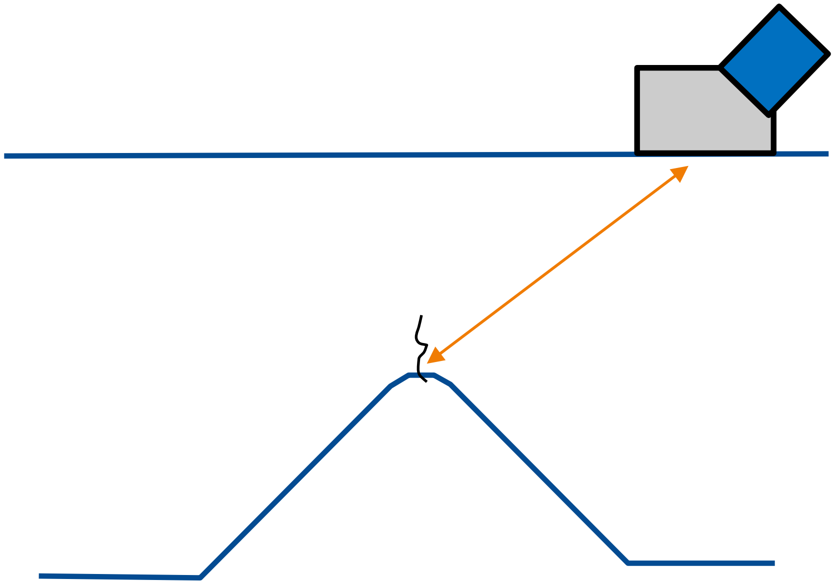
80%FSH from 0.02 x 0.01 inch notch
in a 7075-T7 reference plate

Surface Wave Ultrasonics Results



Shear-Wave Ultrasonics

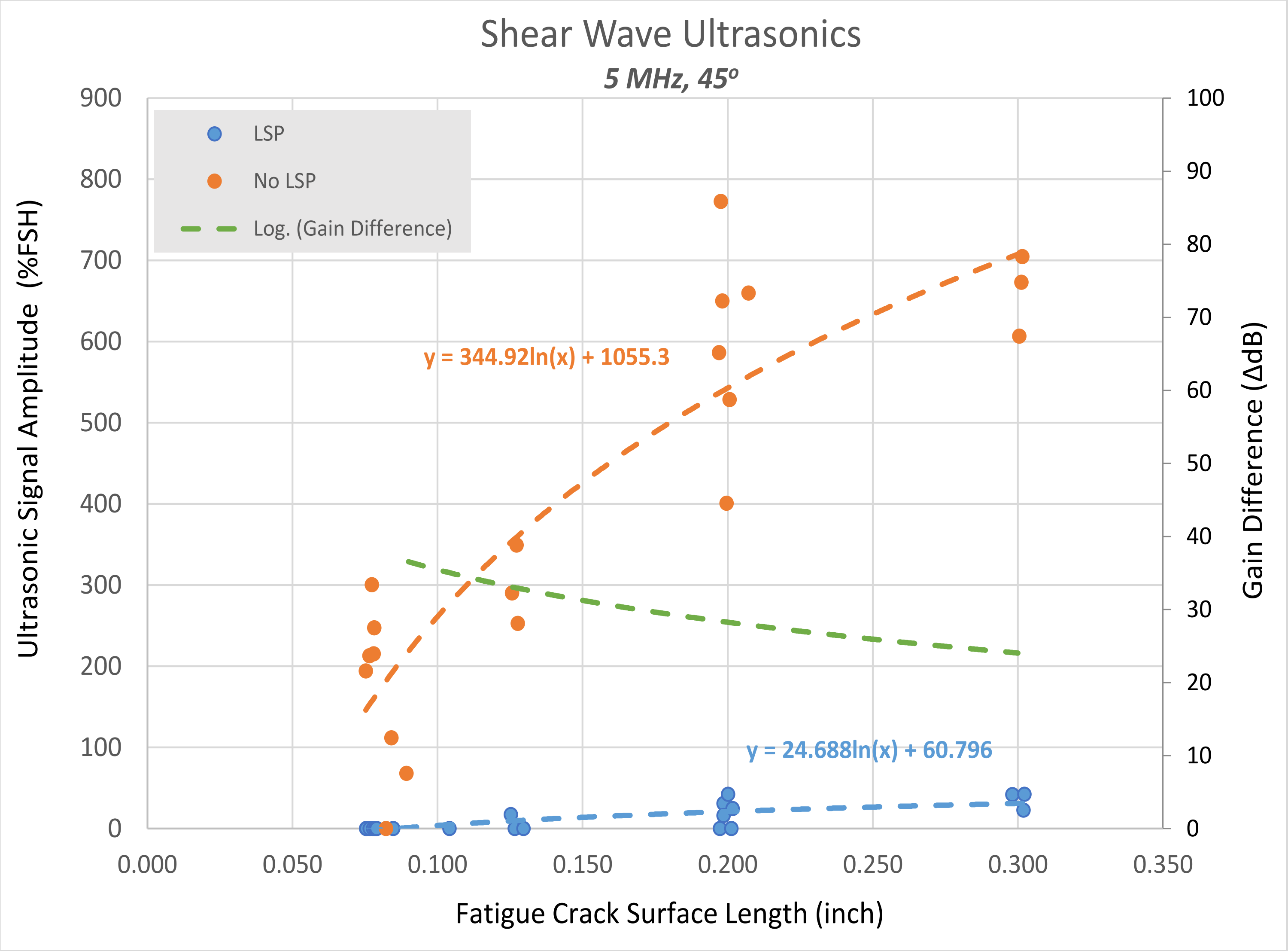




<u>Surface Wave Unit</u>
45^{o} shear wedge
10 MHz, 0.25 inch diameter transducer

<u>Calibration</u>
80%FSH from 0.02 x 0.01 inch notch
in a 7075-T7 reference plate

Shear-Wave Ultrasonics Results



Conclusions – LSP Effects

- LSP reduced ECI response from fatigue cracks by up to 1dB when the US-3515/3516 probe was used.
- LSP reduced ECI response from fatigue cracks by up to 3dB when the FET-3312 probe was used.
- Fluorescent penetrant detectability significantly degraded as a result of residual compressive loads imparted by LSP applied to 7050-T7541 aluminum.
- A combination of Level 4 (ultra-high sensitivity) fluorescent penetrant and focused eddy current will provide optimum detection capability.
- Surface and shear wave ultrasonics are not viable techniques to detect fatigue cracks in LSP aluminum surfaces. Ultrasonic responses from fatigue cracks were reduce by >26dB on LSP treated surfaces.

Quantifying Ultrasonic Dead Zone in Cold Worked Holes - Study Overview

Objective

Quantify extent of "ultrasonic dead zone" extending from hold worked holes. Establish correlations to hole diameter and/or plate thickness.

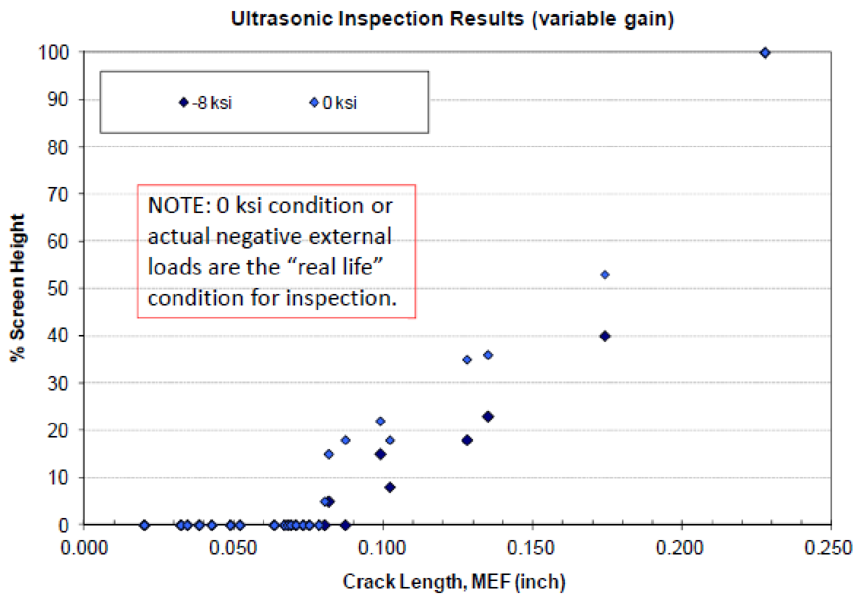
Approach

Measure, map and compare ultrasonic response of fatigue cracks extending from cold worked holes in various hole diameters and plate thicknesses.

Quantifying Ultrasonic Dead Zone in Cold Worked Holes - Study Overview

- CX of holes **reduces** ultrasonic detectability of fatigue cracks
- Crack must extend beyond compressive zone to be detectable by UT
- Previous efforts suggest compressive stress zone extended >0.075 inch beyond edge of hole for the scenario investigated by Forsythe and Mills.
- Correlation between hole diameter, plate thickness and compressive stress zone (i.e. ultrasonic dead zone) not well defined.
- Characterization of this effect is critical to:
  - ○ Optimizing inspection techniques
  - ○ Estimating UT detection capability

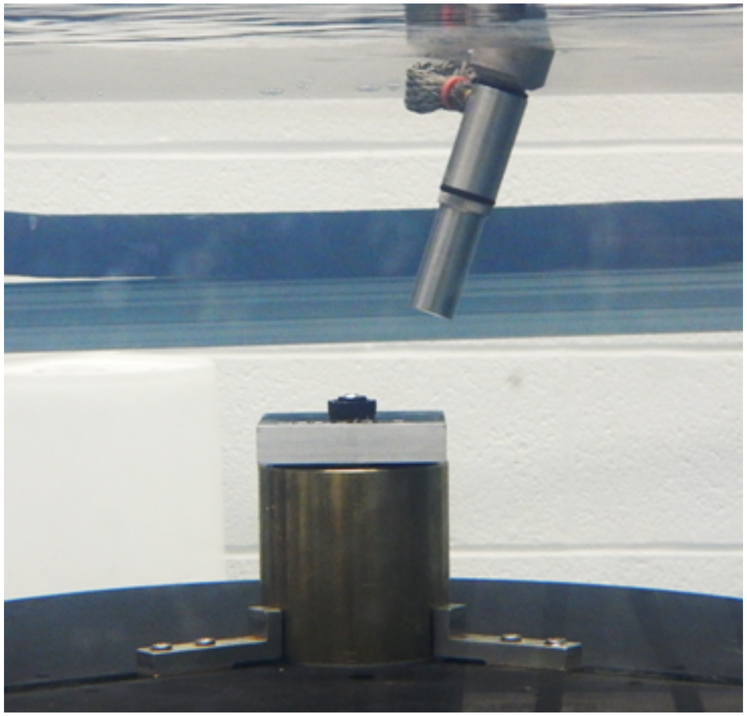
Forsythe, D., Mills, T. "Results of Study of Applied Stress and CX Process on Detectability of Fatigue Cracks"

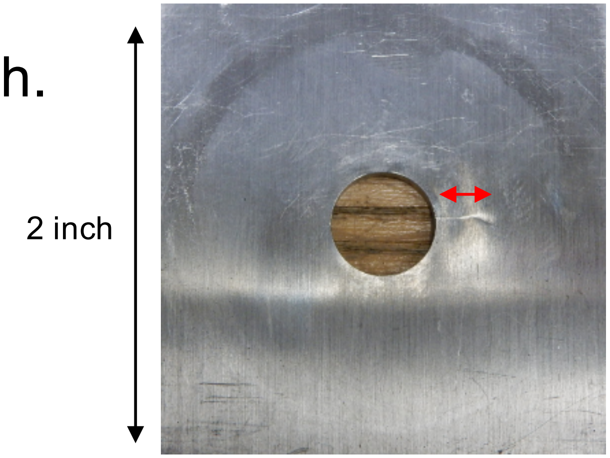


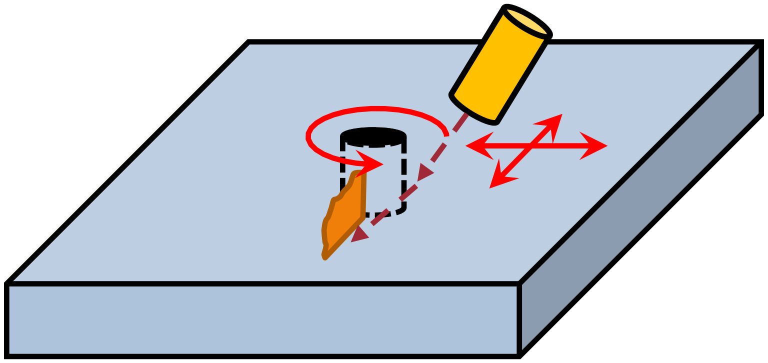
NOTE: 0 ksi condition or actual negative external loads are the "real life" condition for inspection.

Measurement Approach

- Map ultrasonic response along cracks grown in CX holes.
- Characterize “dead zone” for a range of hole diameters and plate thicknesses
  - Plate thicknesses: 0.100, 0.508 inch
  - Hole diameters: 0.280 inch, 0.450 inch, 0.540 inch
- Highly focused ultrasonic immersion inspection ≈ 0.020 inch focal spot
  - 45 degree shear, 10 MHz
- Map reflected ultrasonic energy along crack length.

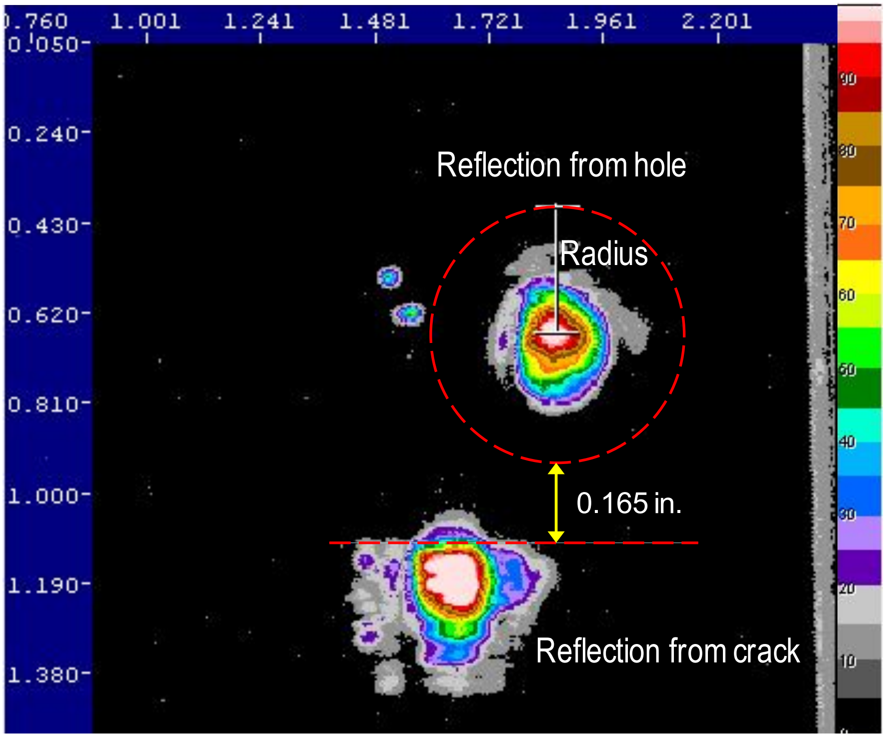






Ultrasonic C-scan Results

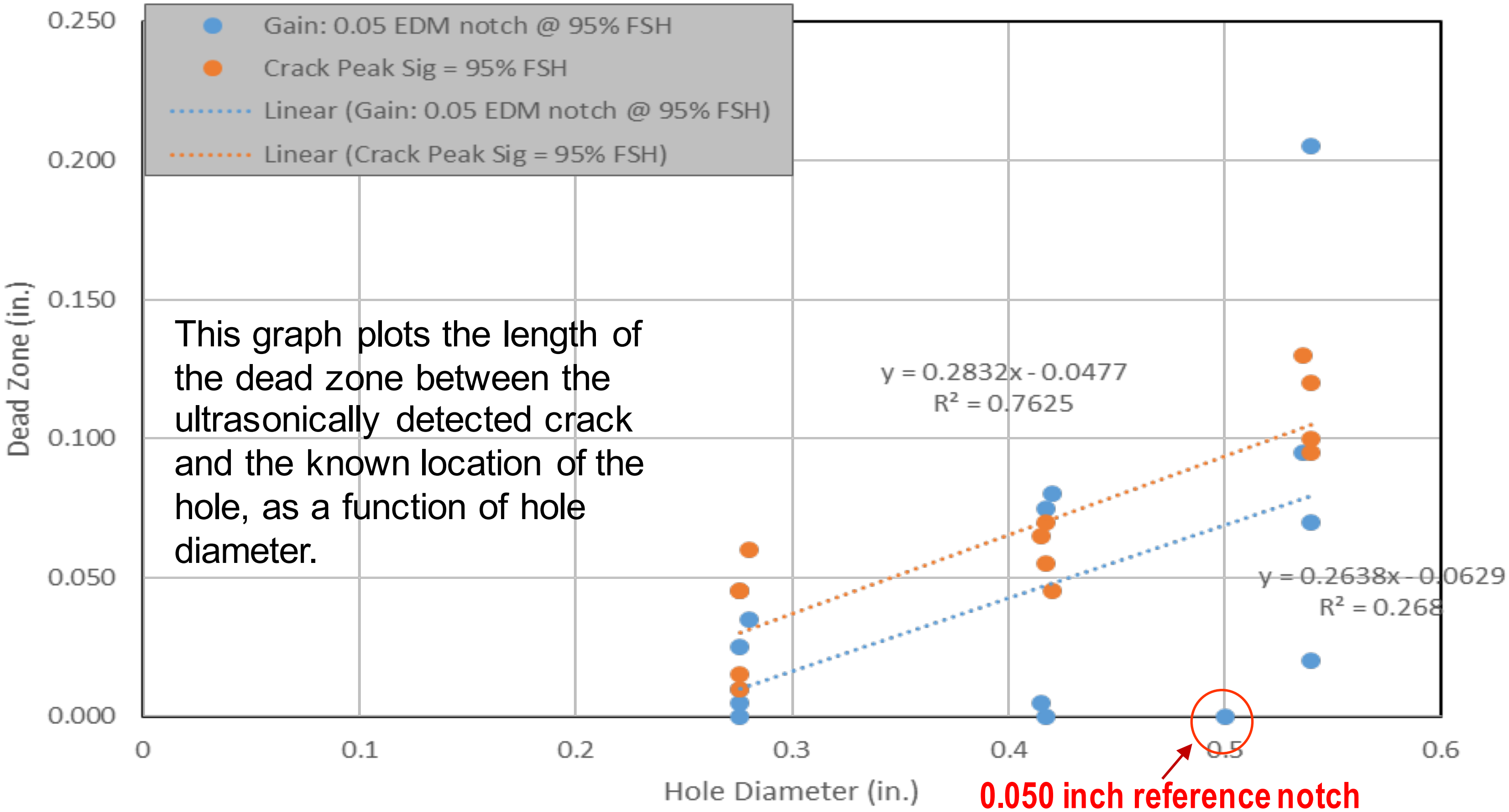
- Twelve fatigue crack specimens tested.
- The ultrasonic data were acquired by raster-scanning across the fatigue crack in 0.005” steps.
- Each ultrasonic “C-scan” contained an image of the hole as well as the crack.
- No reflection between the hole radius and the crack signal suggests the cold work suppresses a reflection from the crack.



In this C-scan image the crack signal begins 0.165 inches away from the hole. In this “dead zone” no ultrasound is reflected from the crack.

- 6dB drop defines edge of crack response.
- Dead zone measured twice:
  1) Reference gain set at peak response (95% screen height) from fatigue crack.
  2) Reference gain set at 95% screen height response from 0.050 inch corner EDM notch in 0.540 inch D hole, 0.508 inch thick sample.

Data Analysis



This graph plots the length of the dead zone between the ultrasonically detected crack and the known location of the hole, as a function of hole diameter.

0.050 inch reference notch

- The “dead zone” around each hole found to be proportional to the diameter of the hole **with significant scatter**.
- Similar analysis showed no dependence of the dead zone on thickness.

Conclusions – Cold Worked Holes

- Extent of ultrasonic dead zone correlates to hole diameter.
- No correlation to plate thickness observed.
- Significant scatter suggests variability in compressive stress profiles, crack morphology or closure.
- **Use upper bound of UT dead zone estimates to correct UT POD estimates for cold worked hole scenarios.**
- **Ultrasonic inspections of cold worked holes must be designed to interrogate beyond the tangency of the hole.**

Future Work
What We Still Wanted to Know

I. **Quantify UT dead zone in Cx holes**
  - Investigate cause of dead zone variability
  - Size UT dead zone for a range of Cx levels
  - Correlate UT dead zone to residual stress and fastener camera measurements
  - Define optimum UT system design for Cx holes
  - Develop Cx correction factors for UT POD estimates

II. **Investigate the impact of fastener installation on ultrasonic fatigue crack detectability?**
  - Taper-Lok fasteners
  - Interference fit fasteners
  - Interference fit fasteners installed in cold worked holes.

III. **Investigate the impact of deep residual stress treatments on fatigue crack detection capability?**
  - Laser shock peening on titanium alloys
  - Shot peening – aluminum and titanium (UT and FPI focus)

Questions?

ERSI WORKSHOP: RISK AND UQ SUBCOMMITTEE OVERVIEW

Laura Domyancic and Luciano Smith
Southwest Research Institute
September 2017

OUTLINE

- Objectives for the ERSI Risk Subcommittee
- Review types of uncertainty and random variables for risk assessment
- 2017 Workshop goals
- Presentation by Laura Domyancic on residual stress methods in DARWIN
- Presentation by Juan Ocampo on residual stress methods using SMART

RISK SUBCOMMITTEE OBJECTIVES

- **GOAL**: Develop methods and procedures that enhance the overall understanding of how residual stress affects life prediction analyses by using uncertainty quantification
- **Questions we'd like to answer**:
  - By how much, with quantified confidence, does the engineered residual stress process affect life?
  - What are the most significant variables in the ERS process?
    - How can we maximize/minimize the benefits/damages of these variables?

TYPES OF UNCERTAINTY

- **Aleatory**: Uncertainty relating to inherent variation of a property
  - Fracture toughness variation
  - Material yield stress variation
- **Epistemic**: Uncertainty due to incomplete or erroneous data, “lack of knowledge”
  - Model form uncertainty
  - Measurement error
  - Unknown physics
- Example: Taking into account aleatory uncertainty makes the yield stress a random variable. Taking into account epistemic uncertainty makes the mean and standard deviation *themselves* into random variables.

RISK ANALYSIS CONSIDERING ERS

From Min Liao's 2016 ERSI Pres.

RA Inputs	ERS Impact	Significance / Confidence	How to quantify uncertainty and variability
Initial crack size distribution (ICSD/IDS/EIFSD): related to material, geometry, manufacturing, usage/load, plus analytical method for EIFSD	Nucleation mechanism (sub-surface cracking, fretting etc.), EIFSD changed if DaDTA method changed too	High / ?	Discussion -- below
Crack growth a-t curve: material/ geometry/loads fracture mechanics (LEFM) modeling	Short crack growth, near threshold growth, high quality data. New a-t with ERS	High / ?	Discussion -- below
Maximum stress distribution: stress exceedance, loads/usage	Nominally no effect	None / None	Discussion ?
Fracture toughness (Kc) distribution or residual strength: material, geometry/thickness, analytical method	Bulk ERS may affect Kc or σ_{RS} (integral panel with ERS), self-equilibrating RS effect? conservative assumption?	Low-Med / High?	Discussion ?
POD data: over 20 factors including human factor	Lower POD, higher a90/95	High / ?	Discussion
Repaired crack size distribution: repair & modification (drilling/grind-out/cold-work/peening/bonding…)	Different RCSD (CW) from ICSD (non-CW), EIFSD also depending on DaDTA method/curve. New a-t curve, new POD	High / ?	combine EIFSD and POD discussion

2017 WORKSHOP

- The ERS process introduces additional variables and uncertainties. The subcommittee's goals for this workshop is to
  - Review current methods within risk analysis that address residual stresses
  - Identify method development that remains (gaps)
- Although software programs will be discussed, our final product is methodology recommendations

Random Residual Stress Modeling in DARWIN

Probabilistic Integration of Material Process Modeling and Fracture Risk Assessment Using Gaussian Process Models

AIAA SDM Conference
Boston, Massachusetts
April 8-11, 2013

Michael Enright, John McFarland,
Craig McClung
Southwest Research Institute

Wei-Tsu Wu, Ravi Shankar
Scientific Forming Technologies Corporation

Presented by:
Laura Domyancic
Southwest Research Institute

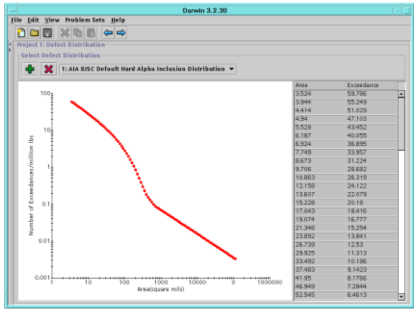
ERSI Workshop 2017

Acknowledgments

- Funding for this effort was provided by the US Air Force Research Laboratory
  - Rollie Dutton, AFRL Program Monitor
- Primary funding for DARWIN has been provided by the Federal Aviation Administration through a series of grants
  - Tim Mouzakis, FAA Engine and Propeller Directorate
  - Joe Wilson, FAA Technical Center
  - Industry Steering Committee (GE, Honeywell, P&W, Rolls-Royce)
- Technology implemented in DARWIN® software

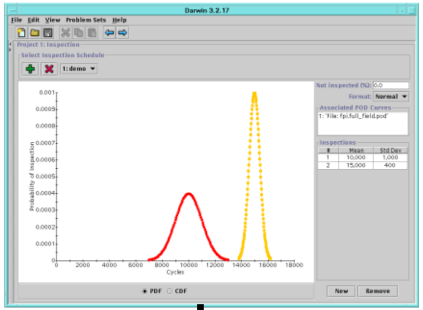
DARWIN Overview

Design **A**ssessment of **R**eliability **W**ith **IN**spection



1: AIA RISC Default Hard Alpha Inclusion Distribution

Area	Exceedance
3.524	59.786
3.944	55.249
4.414	51.029
4.94	47.103
5.528	43.452
6.187	40.055
6.924	36.895
7.749	33.957
8.673	31.224
9.706	28.682
10.863	26.319
12.158	24.122
13.607	22.079
15.228	20.18
17.043	18.416
19.074	16.777
21.348	15.254
23.892	13.841
26.739	12.53
29.925	11.313
33.492	10.186
37.483	9.1423
41.95	8.1766
46.949	7.2844
52.545	6.4613



1: demo

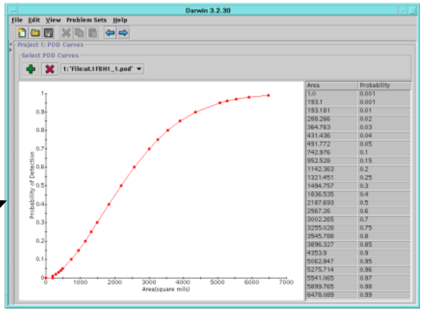
Not inspected (%): 0.0

Format: Normal

Associated POD Curves: 1: 'File: fpi.full_field.pod'

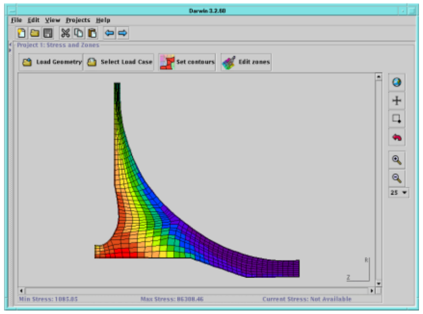
Inspections

#	Mean	Std Dev
1	10,000	1,000
2	15,000	400



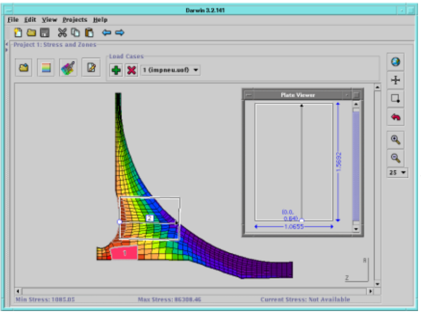
1: 'File:ut.1FBH1_1.pod'

Area	Probability
1.0	0.001
193.1	0.001
193.181	0.01
288.266	0.02
364.763	0.03
431.436	0.04
491.772	0.05
742.976	0.1
952.528	0.15
1142.363	0.2
1321.451	0.25
1494.757	0.3
1836.535	0.4
2187.693	0.5
2567.26	0.6
3002.265	0.7
3255.028	0.75
3545.788	0.8
3896.327	0.85
4353.9	0.9
5062.847	0.95
5275.714	0.96
5541.065	0.97
5899.765	0.98
6478.089	0.99



Min Stress: 1085.05 Max Stress: 86308.46 Current Stress: Not Available

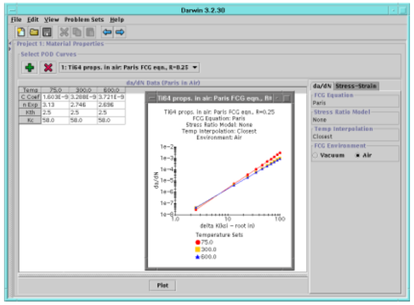
Stress Scatter



1 (impneu.uof)

Min Stress: 1085.05 Max Stress: 86308.46 Current Stress: Not Available

Life Scatter



1: Ti64 props. in air: Paris FCG eqn., R=0.25

Temp	75.0	300.0	600.0
C Coef	1.603E−9	3.288E−9	3.721E−9
n Exp	3.13	2.746	2.696
Kth	2.5	2.5	2.5
Kc	58.0	58.0	58.0

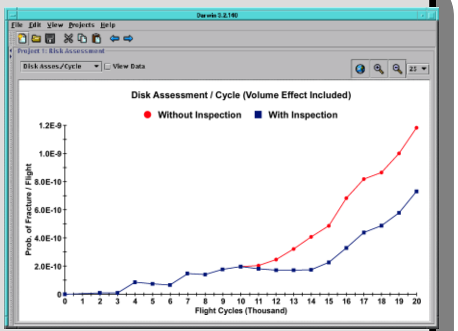
Ti64 props. in air: Paris FCG eqn., R=0.25
FCG Equation: Paris
Stress Ratio Model: None
Temp Interpolation: Closest
Environment: Air

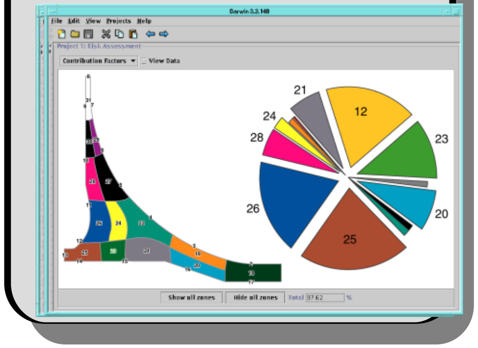
FCG Equation: Paris

Stress Ratio Model: None

Temp Interpolation: Closest

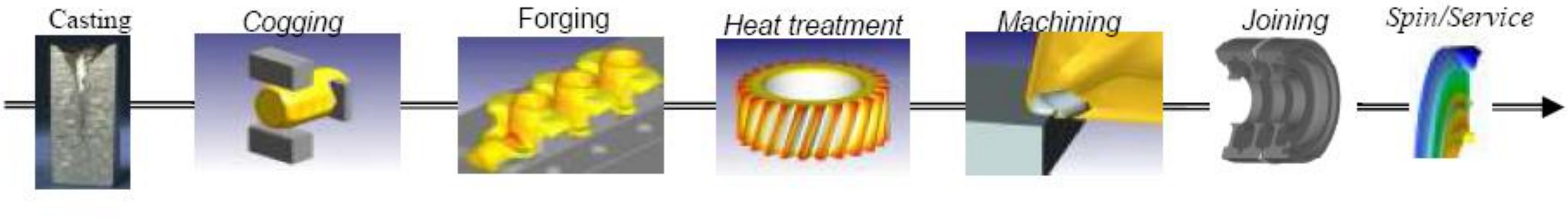
FCG Environment: ○ Vacuum ● Air





Total 97.62 %

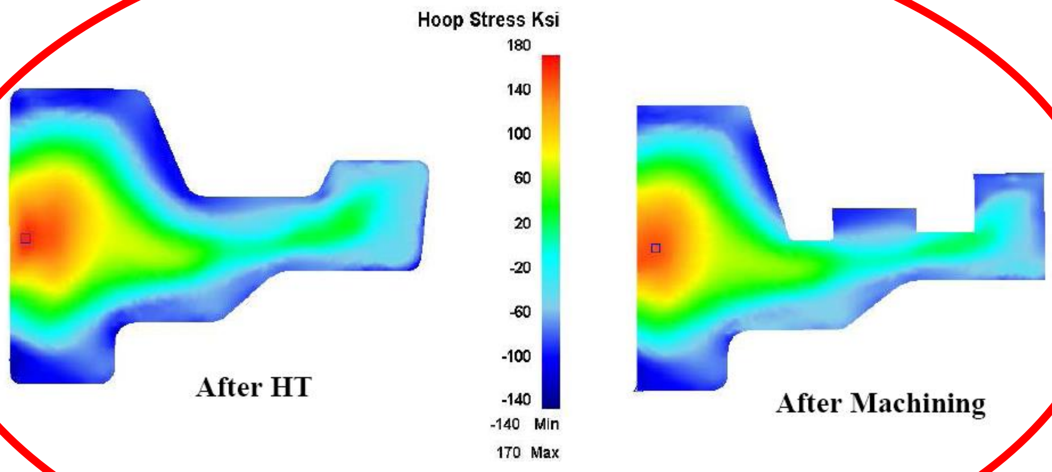
Integration with Manufacturing Process Simulation



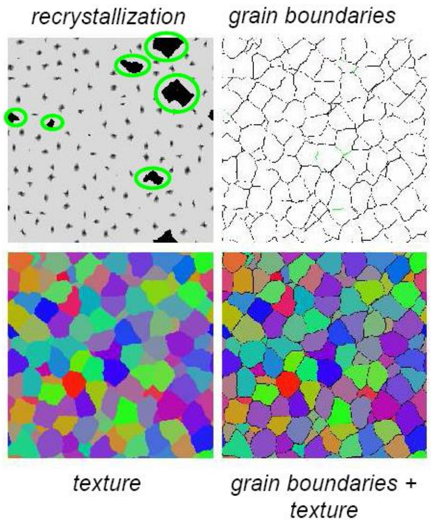
Link DEFORM output with DARWIN input

- Finite element geometry (nodes and elements)
- Finite element stress, temperature, and strain results
- Residual stresses at the end of processing / spin test
- Location specific microstructure / property data
- Tracked location and orientation of material anomalies

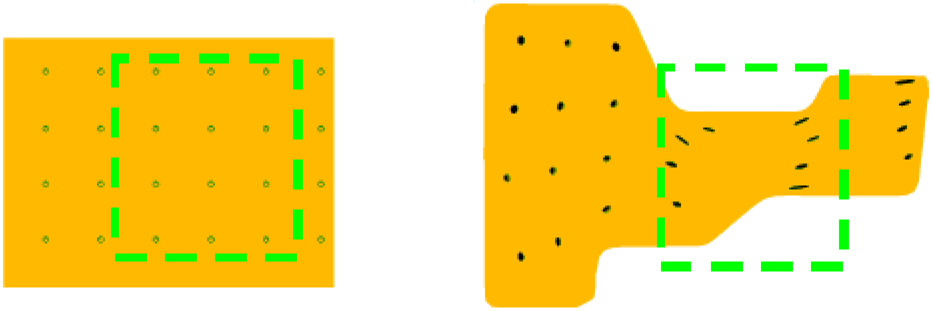
DARWIN-DEFORM Links



Residual Stresses



Microstructure



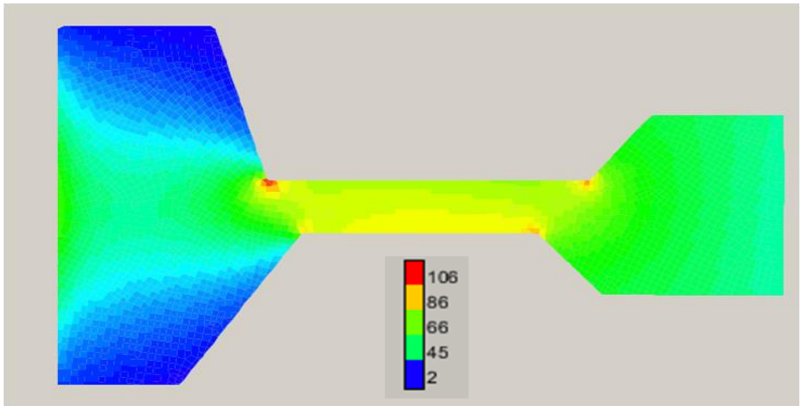
Anomaly Tracking and Deformation

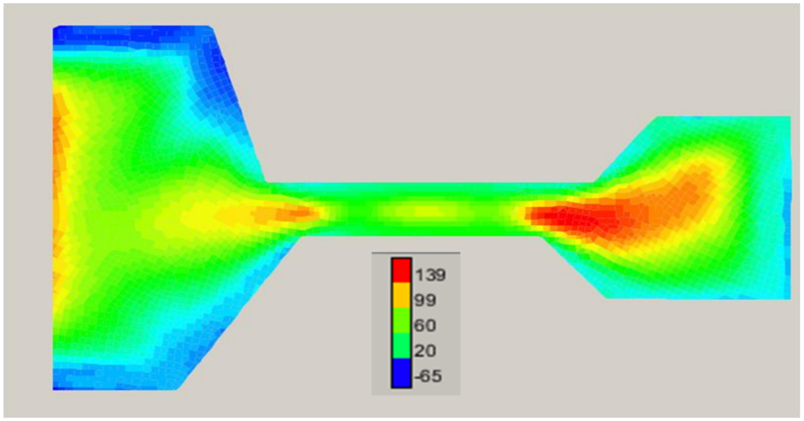
Effect of Material Processing Residual Stress on FCG Life

Without Residual Stress

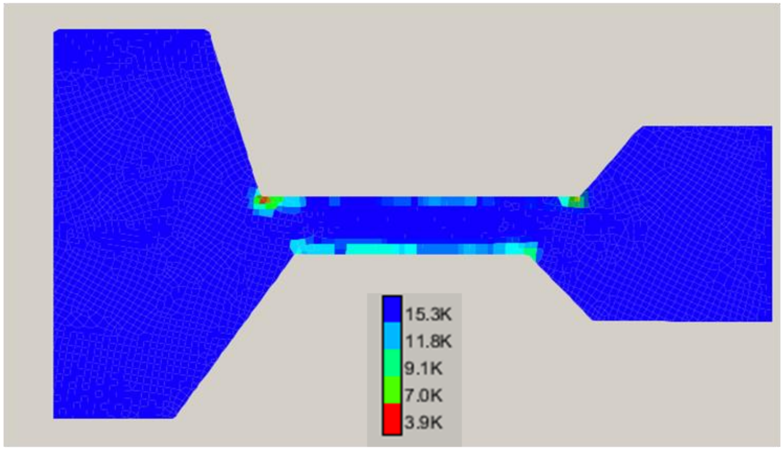
With Residual Stress

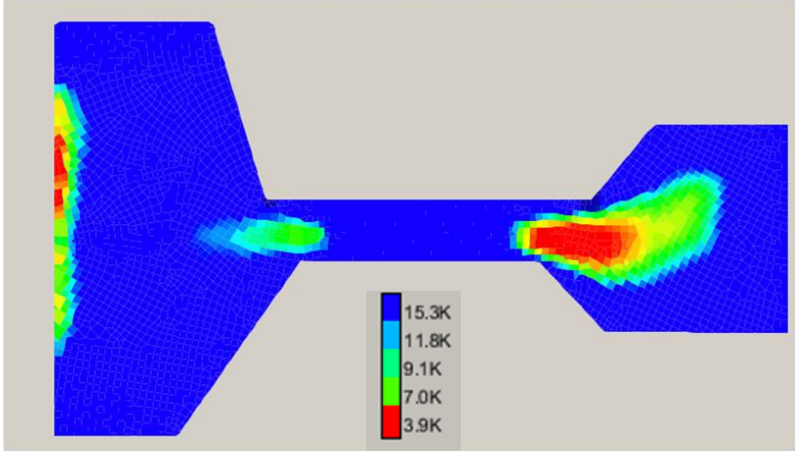
Stress





Life

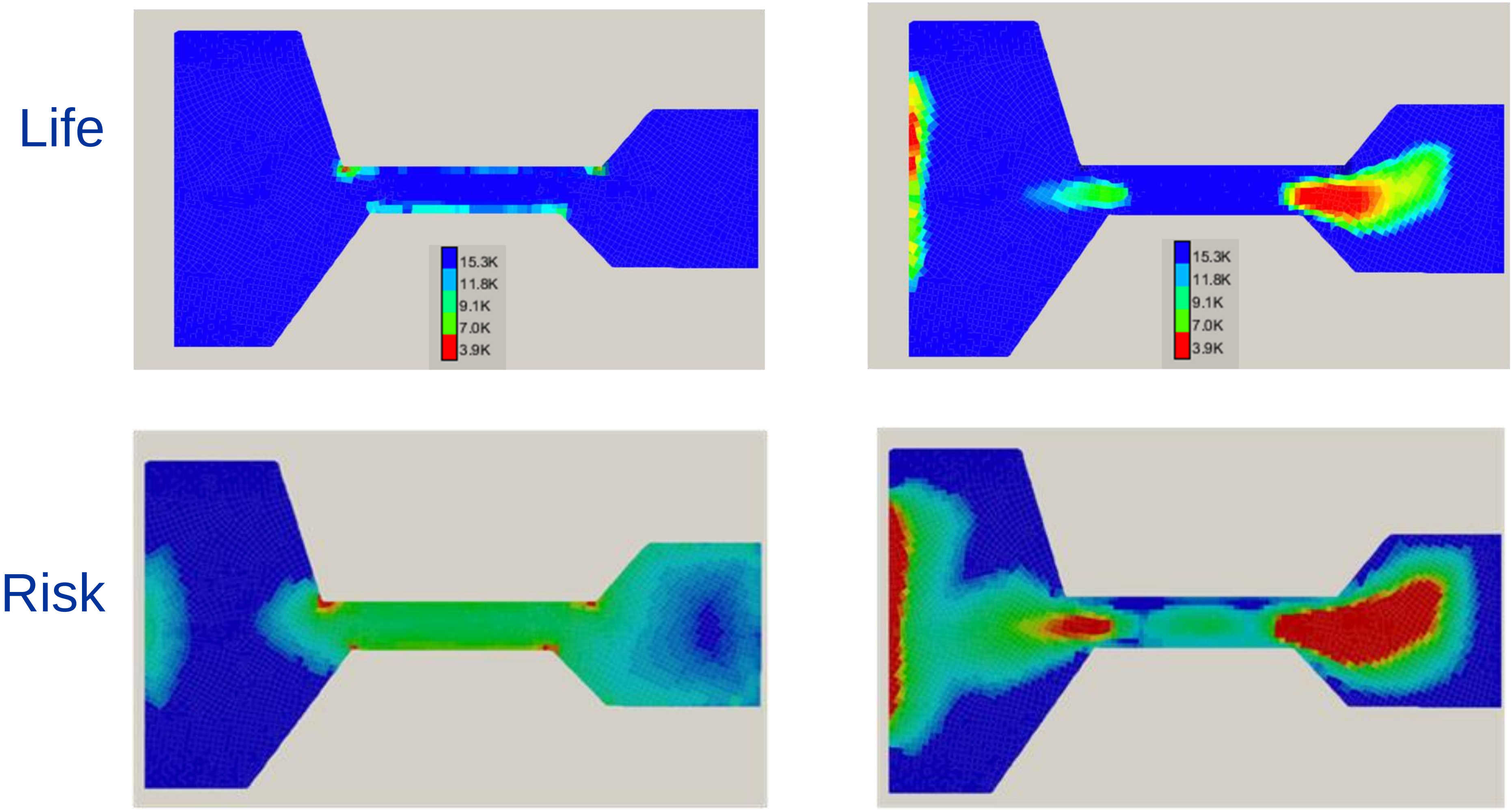




Effect of Material Processing Residual Stress on Risk

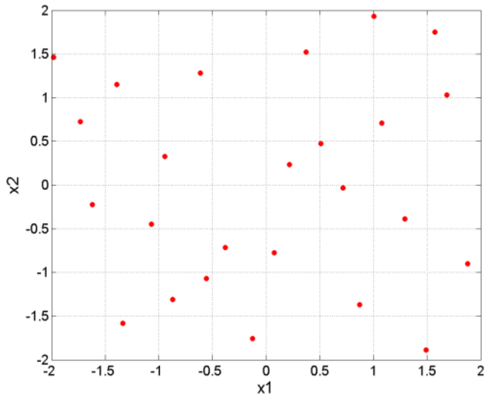
Without Residual Stress

With Residual Stress



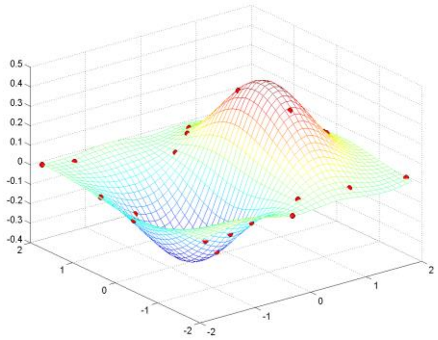
Phase II: Random Residual Stress Modeling

- Objective
  - Determine random residual stresses associated with material process modeling random input variables at any location within a component



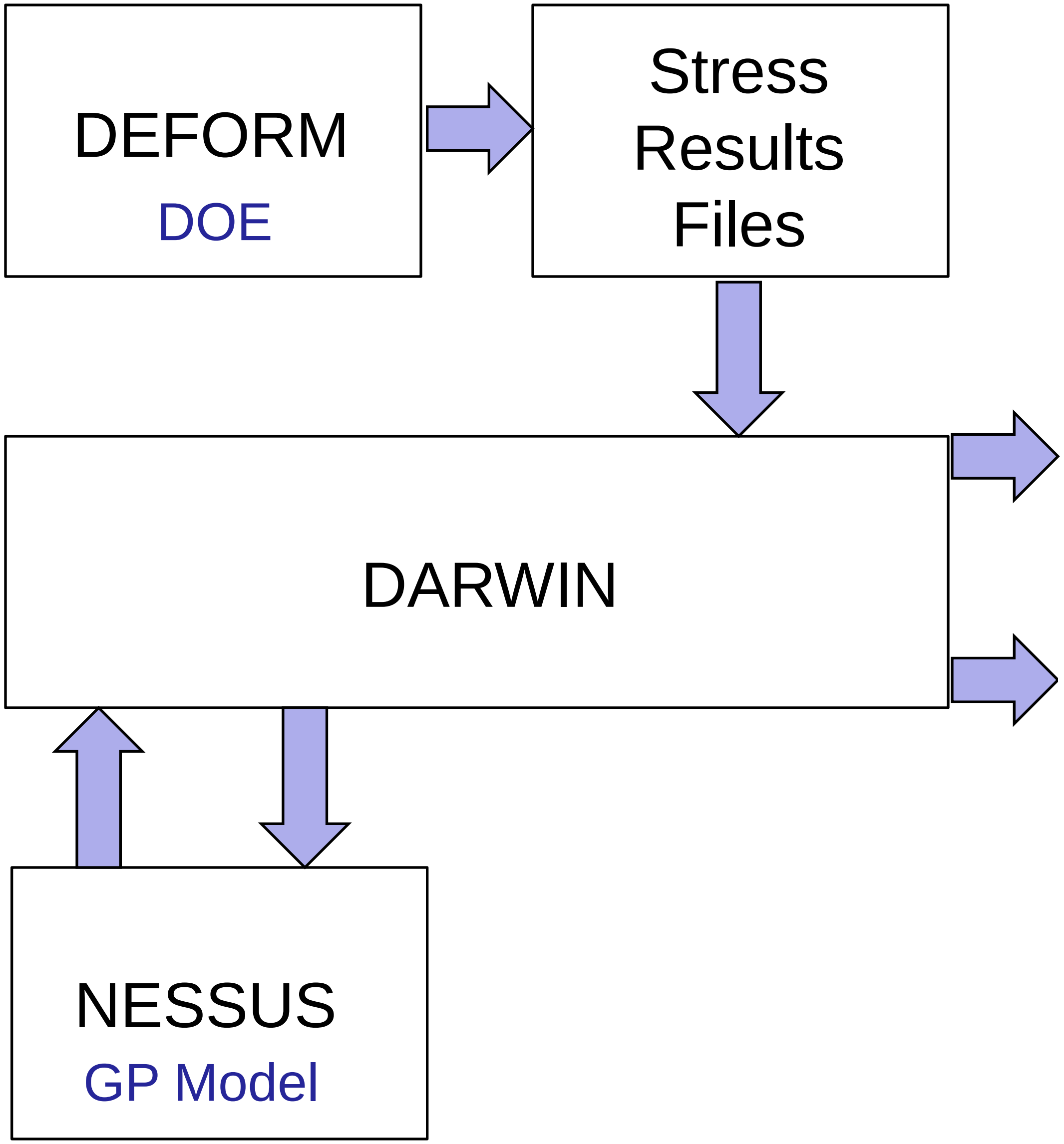
Design of Experiments

- Approach
  - Design of Experiments
    - Perform deterministic DEFORM runs to obtain residual stress values at all FE nodes
  - Response Surface Fitting
    - Determine the residual stress response using Gaussian Process (GP) model
  - Monte Carlo Simulation
    - Propagate random variables through response surface



Response Surface

Demonstration Example: Modeling Random Residual Stresses

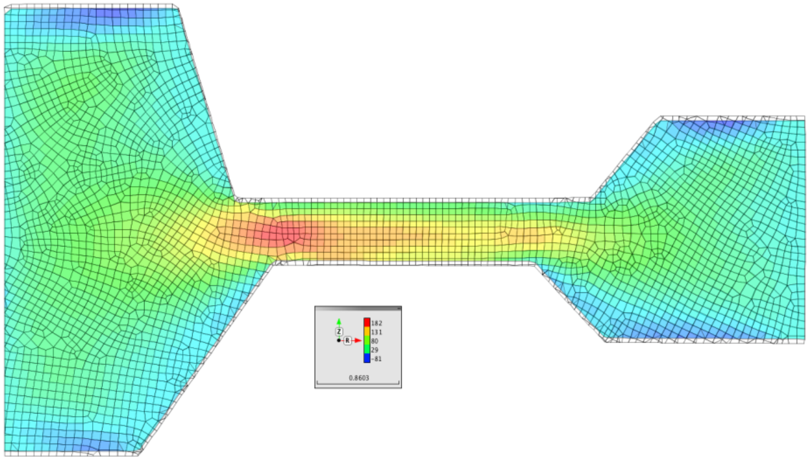


DEFORM
DOE

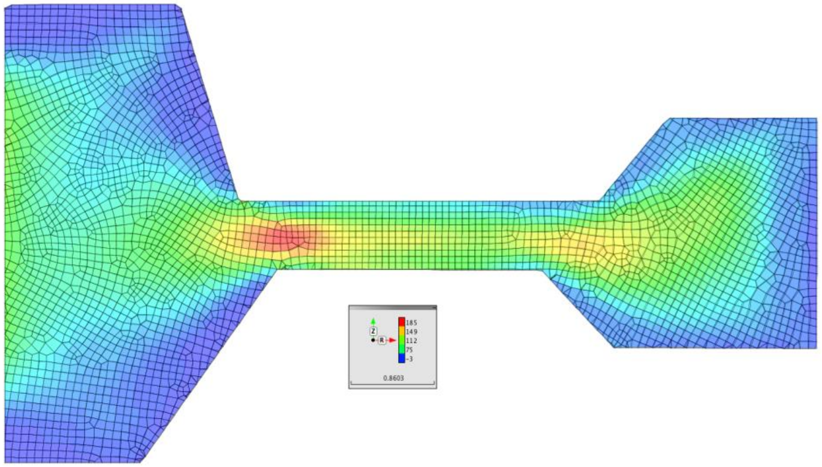
Stress Results Files

DARWIN

NESSUS
GP Model



residual stress DOE 1 contour

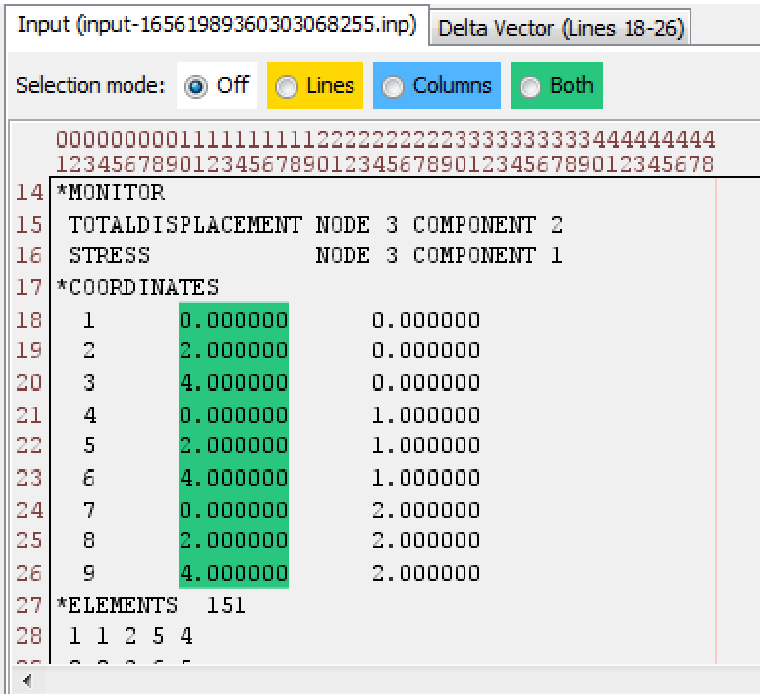


residual stress DOE 12 contour

Response Surface Generation

NESSUS software facilitates response surface generation:

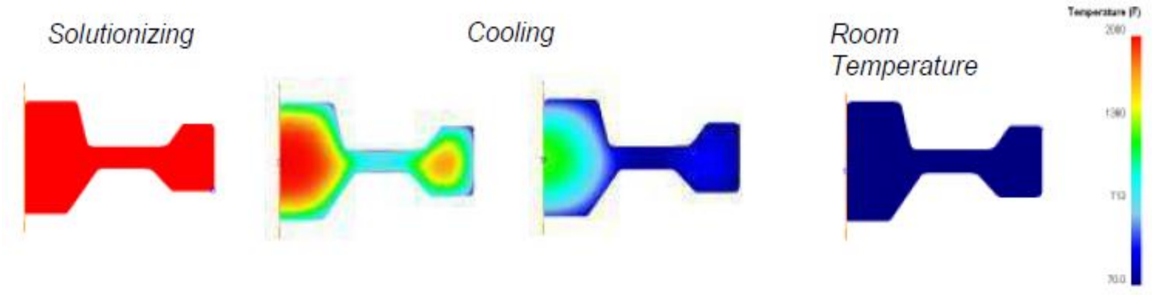
- Defines input ranges or distributions
- Generates a design of input values to run
  - ➢ Supports multiple DOEs
- Interfaces with external numerical model
  - ➢ Variables are graphically mapped to input file
  - ➢ NESSUS generates input deck for each run
  - ➢ NESSUS can execute model and extract outputs
- NESSUS can fit the response surface
  - ➢ 1st or 2nd order polynomial
  - ➢ Gaussian Process model



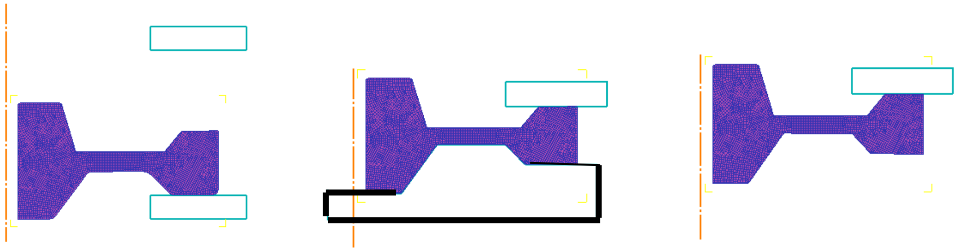
```
000000000111111111122222222223333333333444444444
123456789012345678901234567890123456789012345678
*MONITOR
 TOTALDISPLACEMENT NODE 3 COMPONENT 2
 STRESS            NODE 3 COMPONENT 1
*COORDINATES
  1      0.000000     0.000000
  2      2.000000     0.000000
  3      4.000000     0.000000
  4      0.000000     1.000000
  5      2.000000     1.000000
  6      4.000000     1.000000
  7      0.000000     2.000000
  8      2.000000     2.000000
  9      4.000000     2.000000
*ELEMENTS  151
 1 1 2 5 4
```

Residual Stress Model

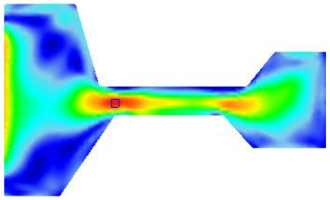
- Three DEFORM input random variables were considered:
  - Solution temperature



  - Material removal



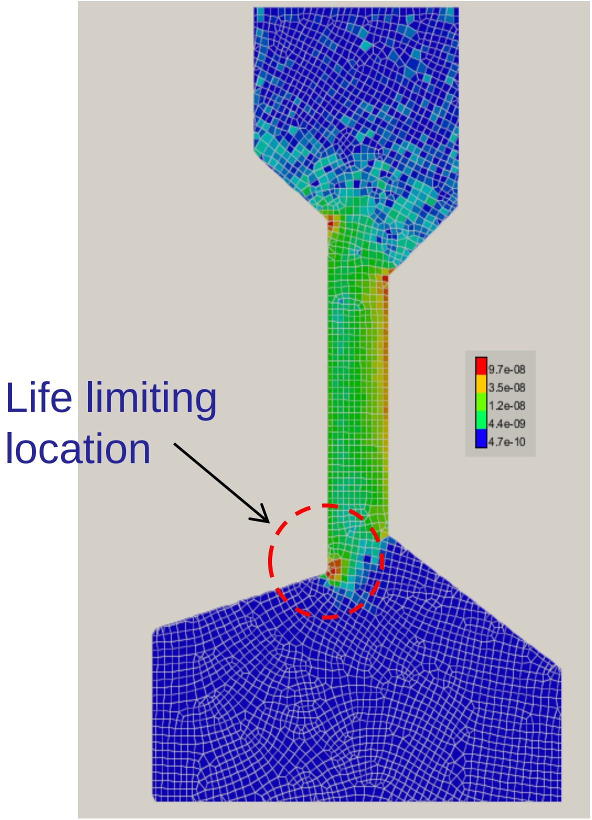
  - Spin test speed

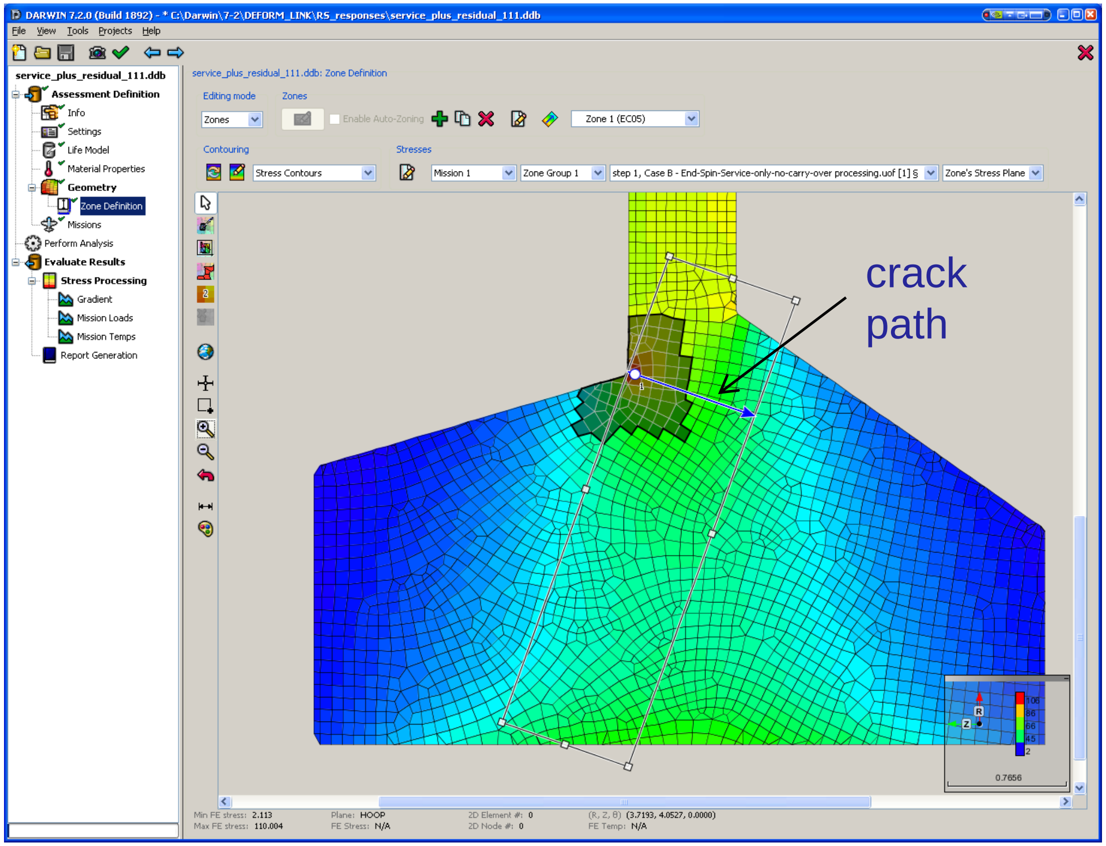


- DOE
  - Initial case: three-level full factorial design (Phase I results)
  - 27 training points – combined residual and service stress results

Demonstration Example

- Anomaly at life limiting location (service stress)
- Computed response surfaces for the following:
  - Individual locations – single response surfaces based on 27 training points each
  - Entire crack path - 100 locations along crack path





Editing mode: Zones

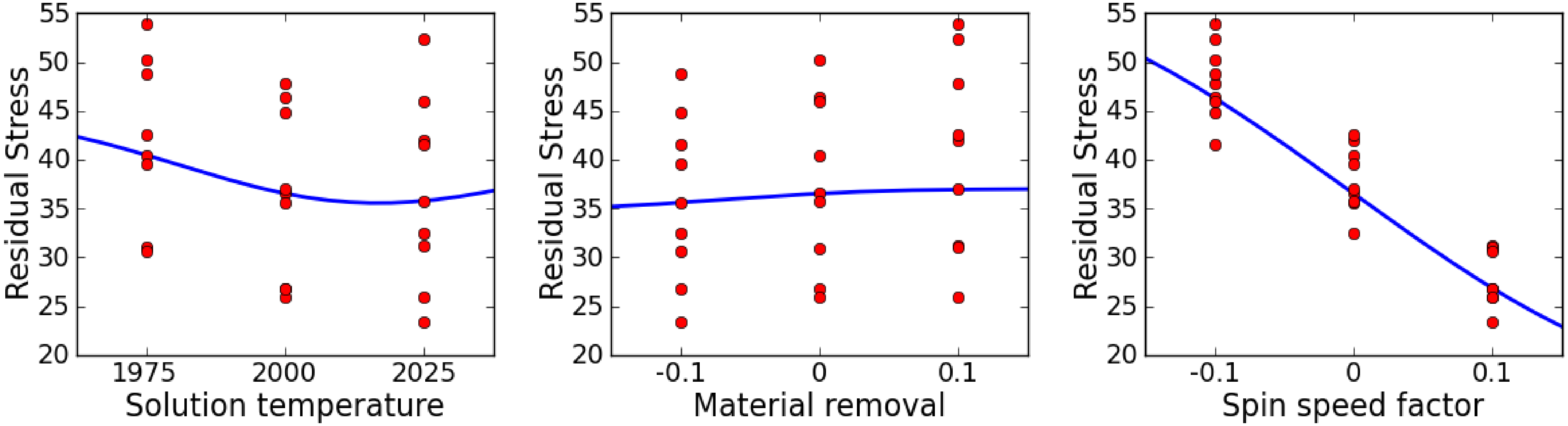
Zones: Zone 1 (EC05)

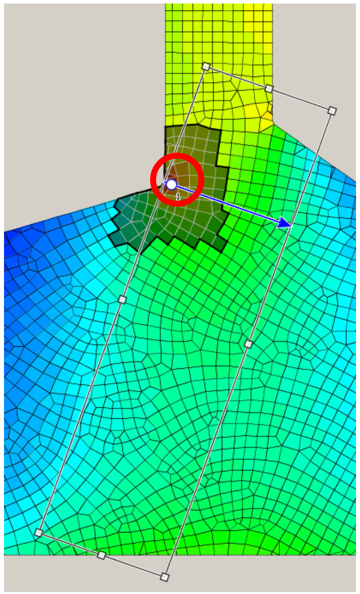
Contouring: Stress Contours

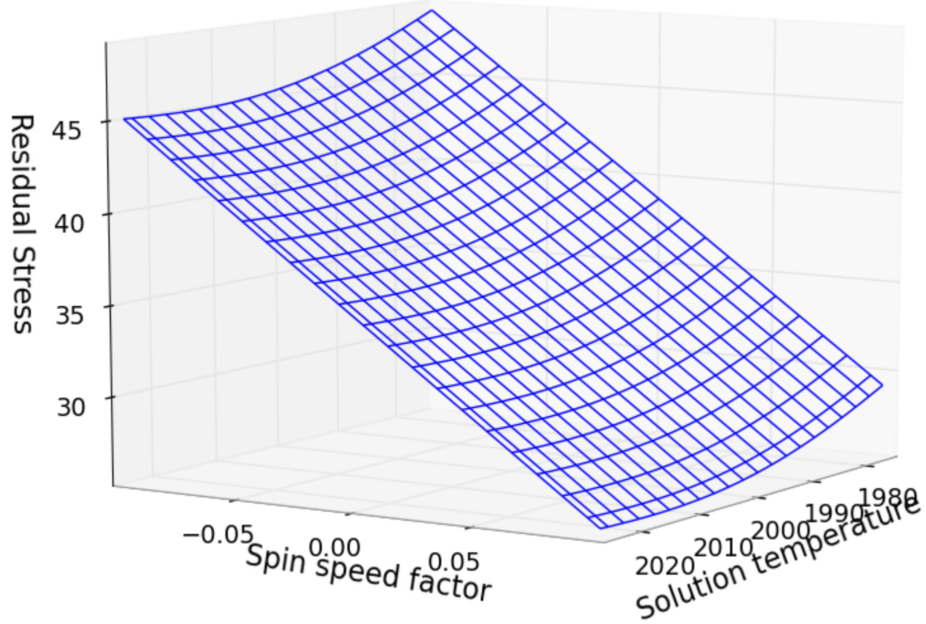
Stresses: Mission 1 | Zone Group 1 | step 1, Case B - End-Spin-Service-only-no-carry-over processing.uof [1] § | Zone's Stress Plane

Min FE stress: 2.113
Max FE stress: 110.004
Plane: HOOP
FE Stress: N/A
2D Element #: 0
2D Node #: 0
(R, Z, θ) (3.7193, 4.0527, 0.0000)
FE Temp: N/A

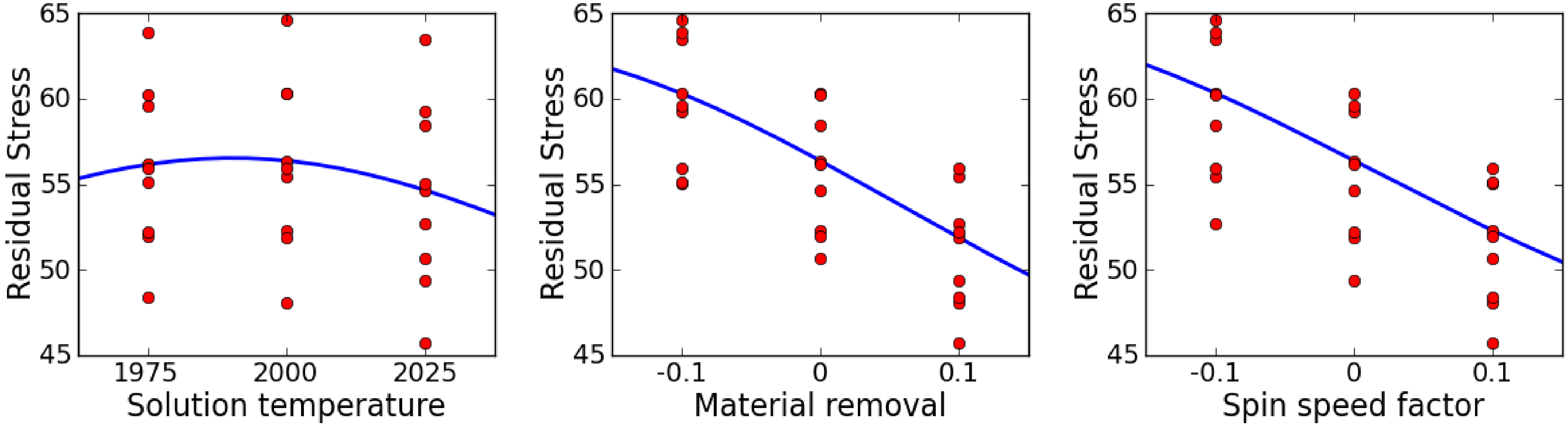
GP Response Surface at Location 1

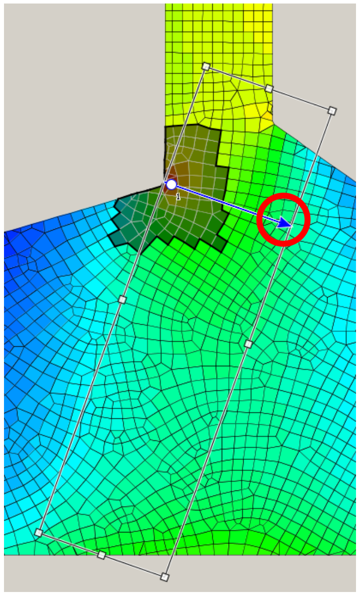


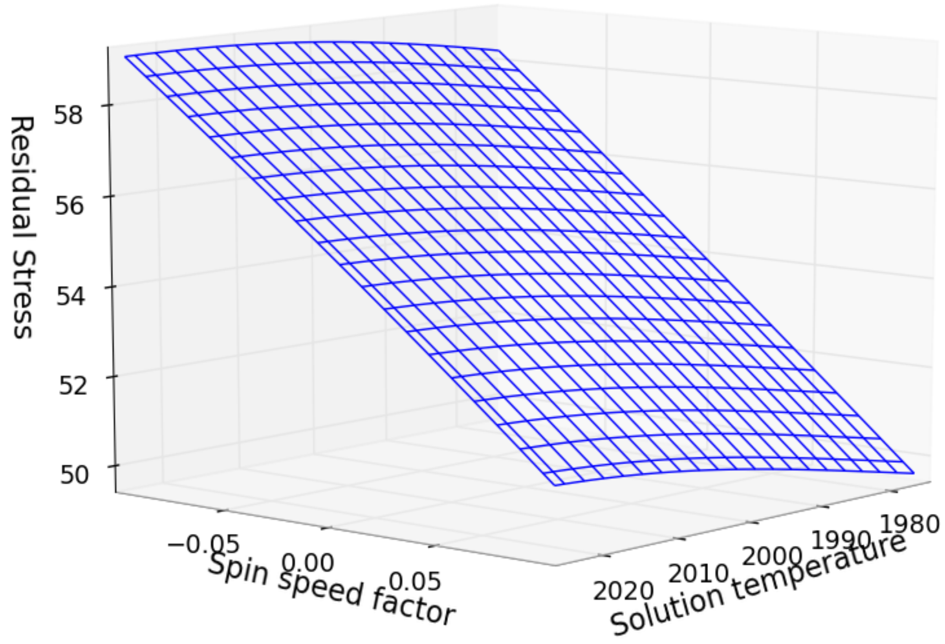




GP Response Surface at Location 100







Modeling the Stress Field Along the Entire Crack Path

- Principal Components Analysis (PCA) enables modeling of the variations in the high-dimensional stress field (100 locations) using a smaller number of coordinates (the principal components)
- The response surface models are used to relate the input variables to the principal components

One response surface for each principal component

$$\mathrm{RS}_1 : \mathbf{X} \to \alpha_1$$

$$\vdots$$

$$\mathrm{RS}_k : \mathbf{X} \to \alpha_k$$

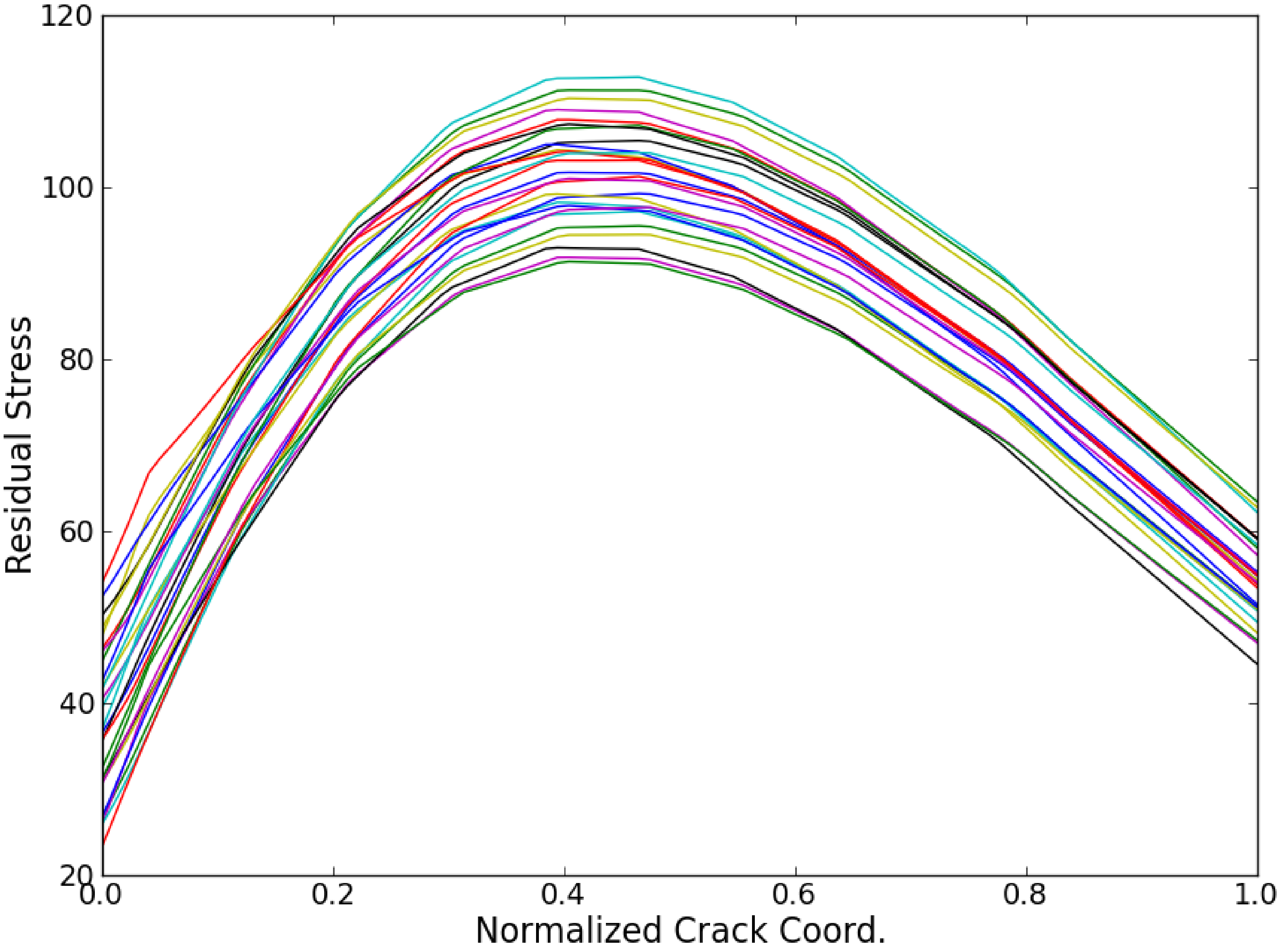
Project components back onto original space

$$\text{Stress Field} = \mathbf{U}^{(k)}\boldsymbol{\alpha}^{(k)} + \boldsymbol{\mu}$$

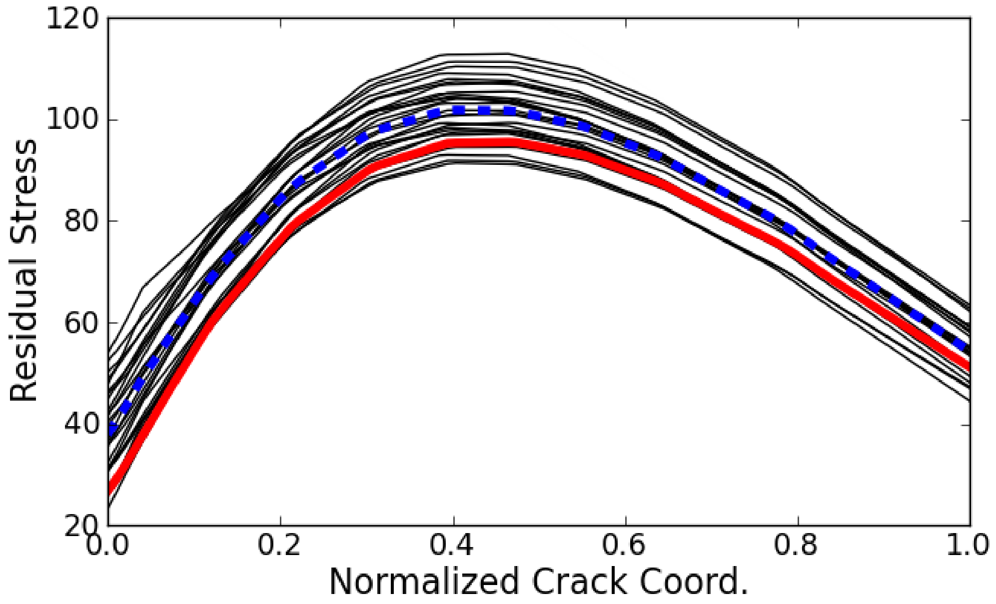
$\mathbf{U}^{(k)}$ contains first *k* eigenvectors of the covariance matrix

$\boldsymbol{\mu}$ is the stress field mean

Residual Stress Training Data (27 values) Along Crack Path



Principal Components Results

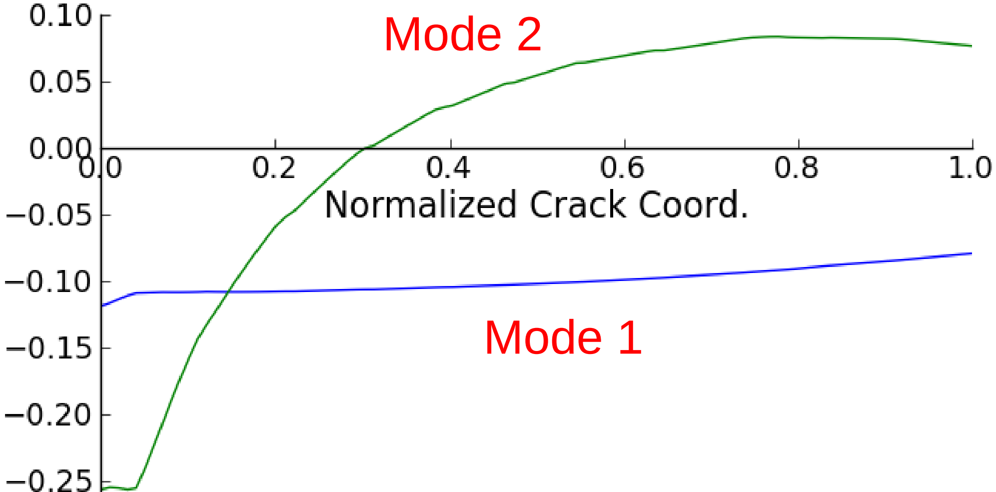


$$\text{Stress Field} = \mathbf{U}^{(k)}\boldsymbol{\alpha}^{(k)} + \boldsymbol{\mu}$$

Example: Case 2

α_2 = 16.6

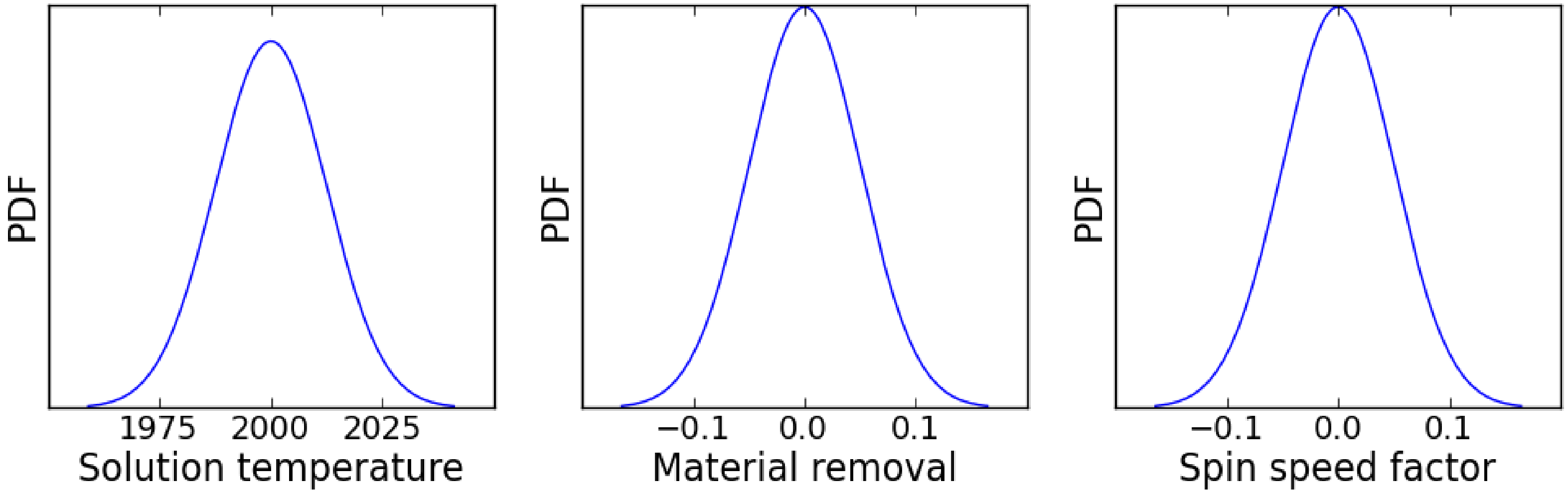
α_1 = 64.1



First two modes capture 99.0% of total variation

Probabilistic Analysis

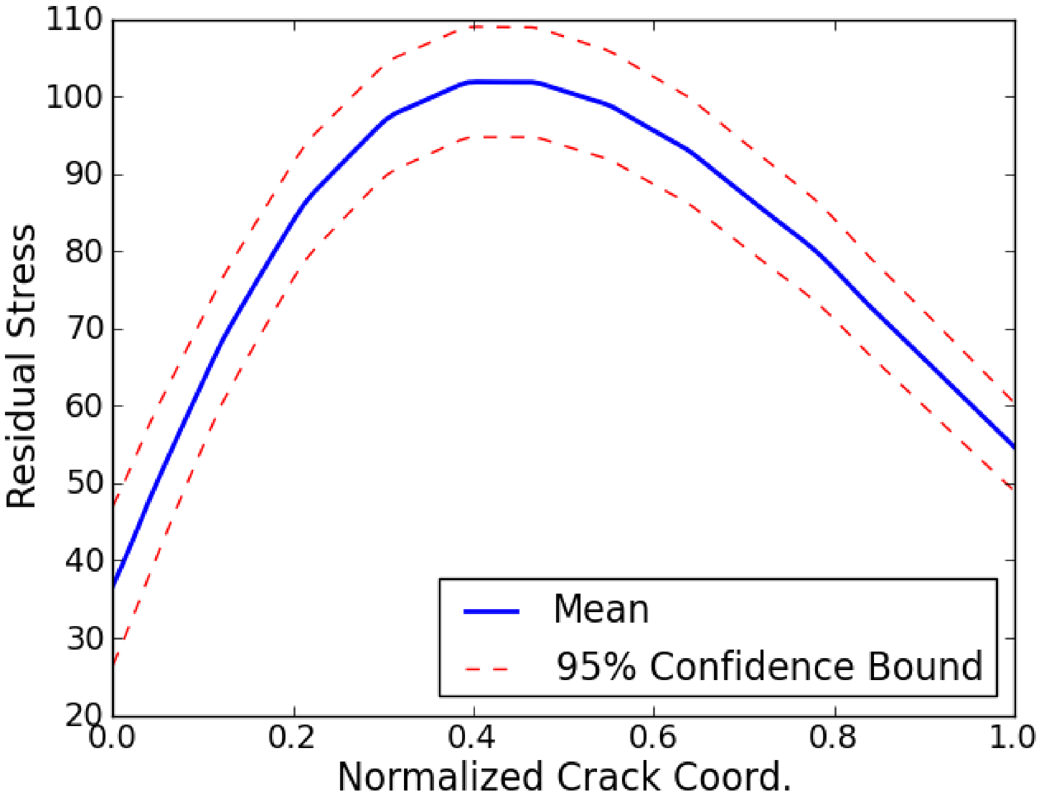
- The three input variables were modeled as normally distributed random variables:



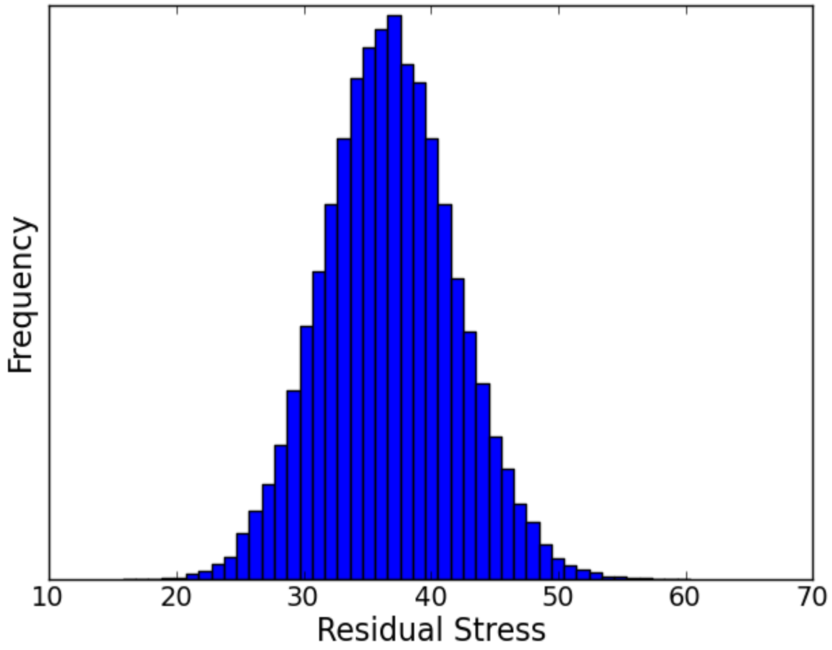
- Using Monte Carlo simulation, the random variables were propagated through the response surface
- The joint distribution of residual stress was identified at all 100 locations along the crack path

Random Residual Stress Results

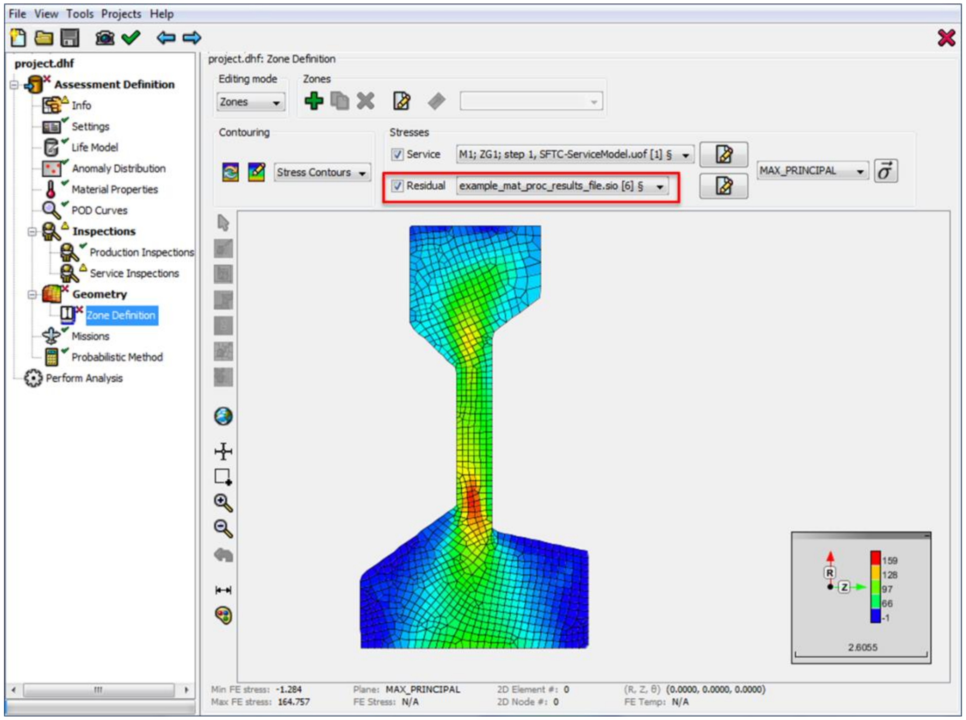
Mean and variation at all locations



Distribution at Coordinate 0



Visualizing Random Residual Stresses in DARWIN



project.dhf: Zone Definition

Editing mode: Zones

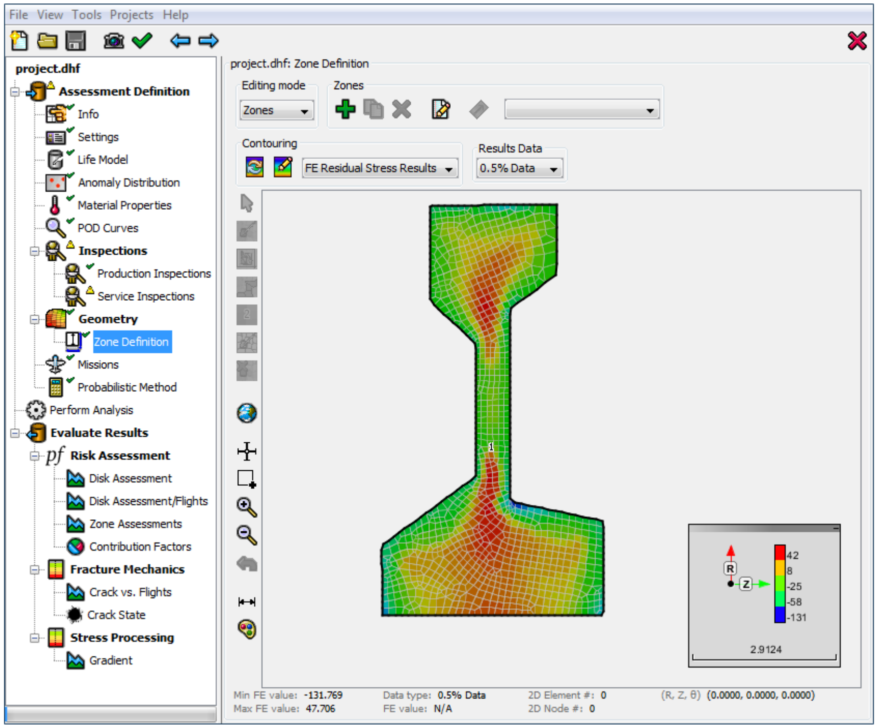
Contouring: Stress Contours

Stresses:
☑ Service: M1; ZG1; step 1, SFTC-ServiceModel.uof [1] §
☑ Residual: example_mat_proc_results_file.sio [6] §

MAX_PRINCIPAL

Min FE stress: -1.284
Max FE stress: 164.757
Plane: MAX_PRINCIPAL
FE Stress: N/A
2D Element #: 0
2D Node #: 0
(R, Z, θ) (0.0000, 0.0000, 0.0000)
FE Temp: N/A

DEFORM Training Data



project.dhf: Zone Definition

Editing mode: Zones

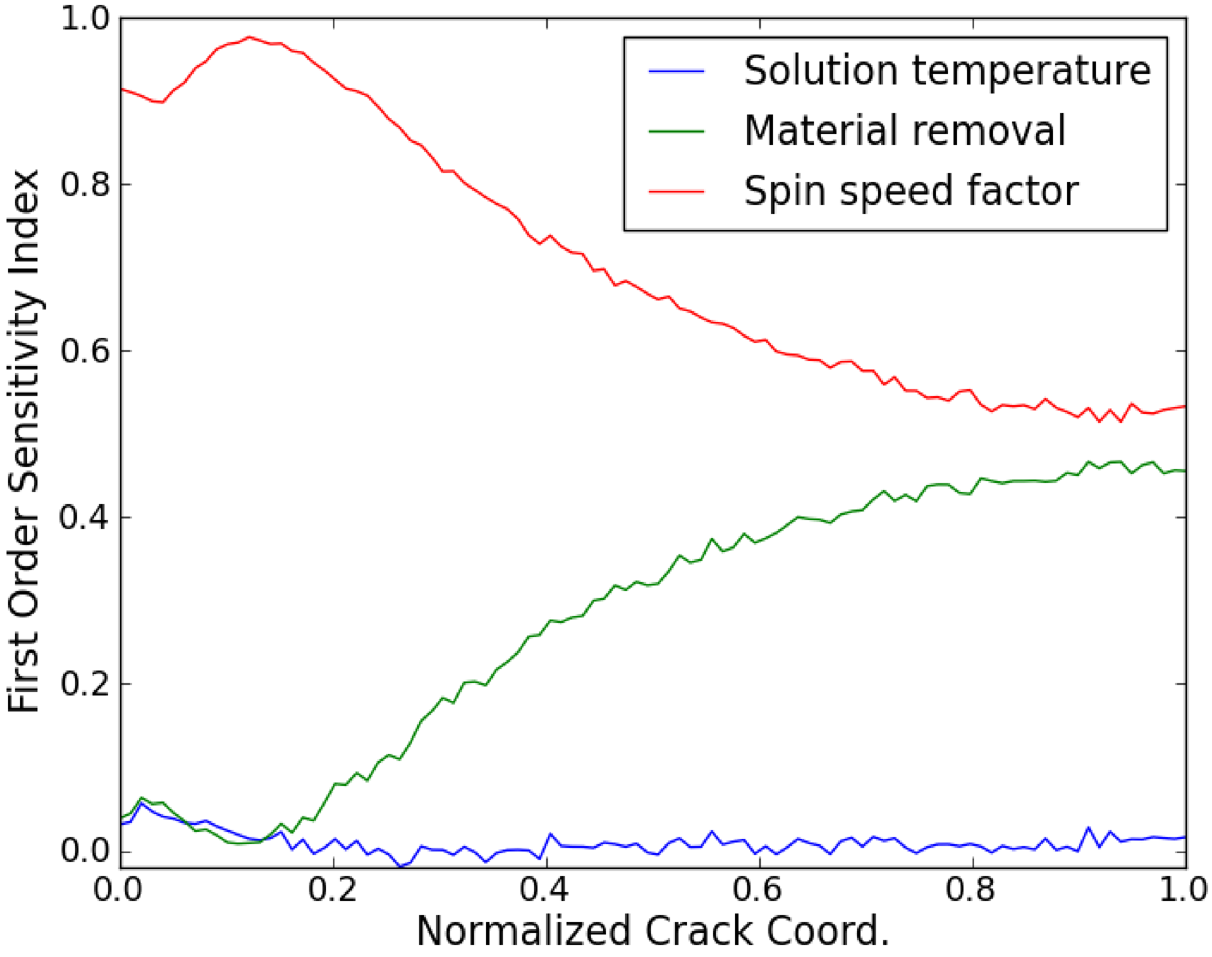
Contouring: FE Residual Stress Results

Results Data: 0.5% Data

Min FE value: -131.769
Max FE value: 47.706
Data type: 0.5% Data
FE value: N/A
2D Element #: 0
2D Node #: 0
(R, Z, θ) (0.0000, 0.0000, 0.0000)

95th Percentile Response

Sensitivity Analysis



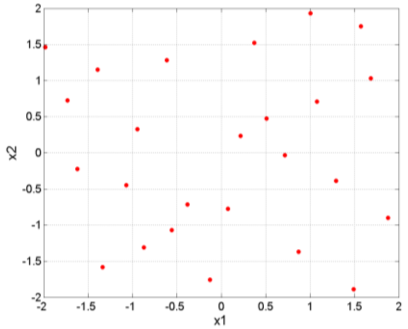
- First order sensitivity index describes fraction of variance in output attributed to each input

$$V\left(E\left(Y \mid X_i\right)\right)/V$$

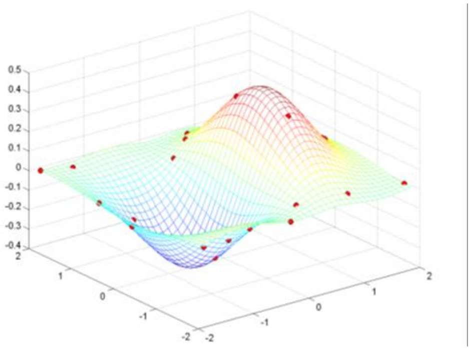
- Sensitivities are computed at each crack location

Summary: Random Residual Stress Modeling

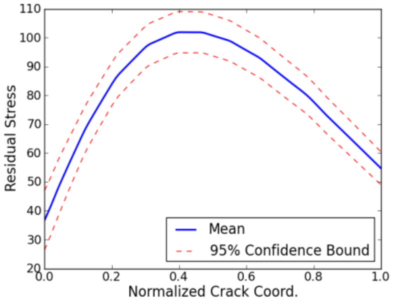
- Design of Experiments
  - Identify values of input variables for response surface construction in DEFORM using Latin Hypercube sampling
  - Perform deterministic DEFORM runs to determine residual stress values at all nodes within FE model
- Response Surface Fitting
  - Determine the residual stress response at selected locations within the FE model in DARWIN using Gaussian Process (GP) model
  - Determine response along the crack path in DARWIN using GP model combined with Principal Components Analysis
- Monte Carlo Simulation
  - Propagate random variables through response surface in DARWIN to determine the random residual stresses along the crack path and influence on life and risk values



Design of Experiments



Response Surface



Monte Carlo

Incorporating Residual Stresses into Probabilistic Damage Tolerance Analysis

Juan D. Ocampo and Alexander Horwath
St. Mary's University
Scott Carlson
University of Utah, Salt Lake City
Luciano Smith
Southwest Research Institute
Harry Millwater and Nathan Crosby
University of Texas at San Antonio

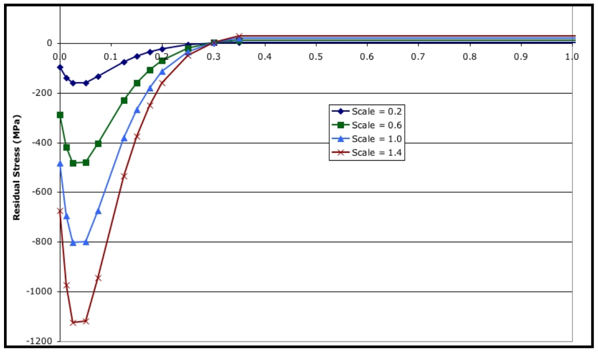
Engineered Residual Stress Implementation Workshop 2017
Salt Lake City, UT, September 21–22, 2017.

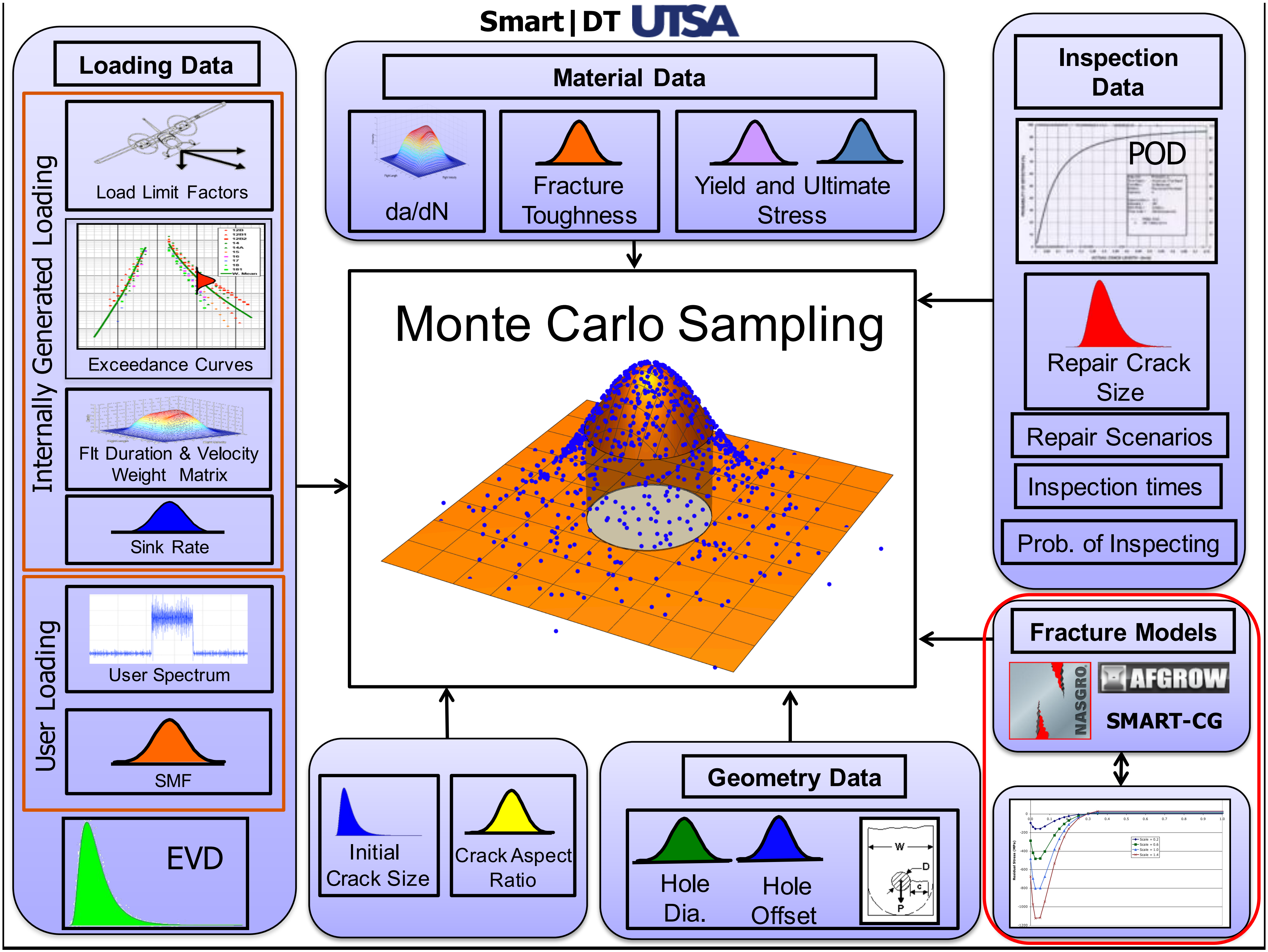
Outline

- ✓ SMART|DT Overview
- ✓ Residual Stresses Modeling Software
- ✓ Are RS needed in PDTA?
  - ✓ Sensitivity Study wrt. Remaining Useful Life
- ✓ Residual Stresses incorporated into PDTA
  - ✓ Deterministic Residual Stresses
- ✓ Future Plans

Probabilistic RS Profile

Deterministic RS Profile





Smart | DT UTSA

Loading Data

Internally Generated Loading

Load Limit Factors

Exceedance Curves

Flt Duration & Velocity
Weight Matrix

Sink Rate

User Loading

User Spectrum

SMF

EVD

Material Data

da/dN

Fracture
Toughness

Yield and Ultimate
Stress

Inspection Data

POD

Repair Crack
Size

Repair Scenarios

Inspection times

Prob. of Inspecting

Monte Carlo Sampling

Fracture Models

NASGRO

AFGROW

SMART-CG

Initial
Crack Size

Crack Aspect
Ratio

Geometry Data

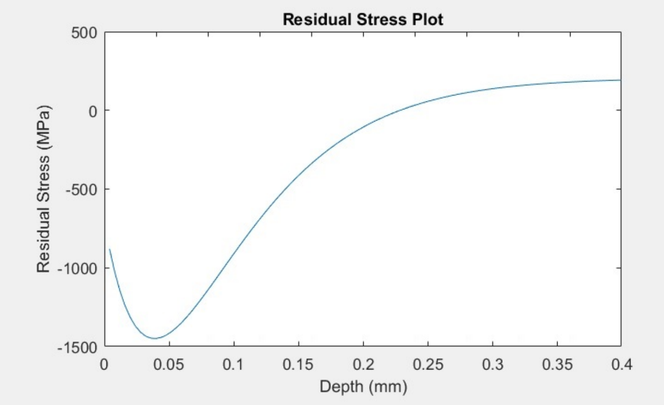
Hole
Dia.

Hole
Offset

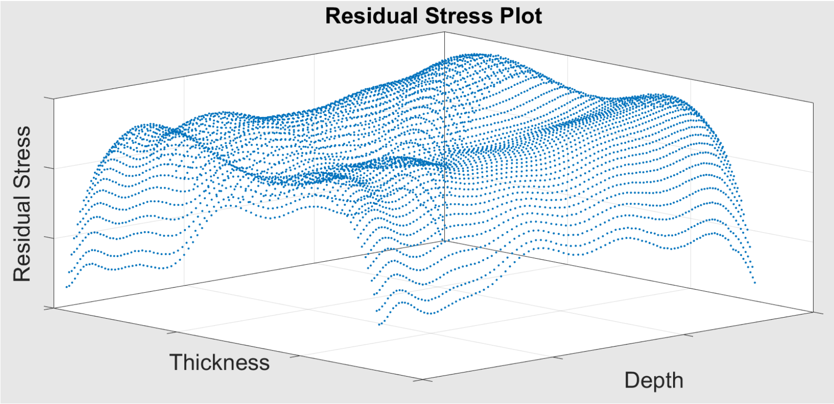
ERSI

Residual Stress Modeling Software

- Standalone executable to read experimental/ simulated data and find the best deterministic and probabilistic fit parameters.
  - 3 Models Available (Expandable)
  - 2D (Stress vs Depth) and 3D (Stress vs Depth vs Thickness).
  - Read input data in .txt & .csv format



2D



3D

Models

- Model I*

$$\sigma(x) = (ss - si + C_1 x)Exp(-C_2 x) + si$$

$$C_1 = \frac{\{(ss - si)\big(1 - Exp(-C_2 B)\big) + siBC_2\}C_2}{(C_2 B + 1)Exp(-C_2 B) - 1}$$

- Model II**

$$\sigma(x) = Asin(Bx + C)Exp\left(-\frac{x}{\lambda}\right)$$

- Model III (Polynomial Fit – Under Development)

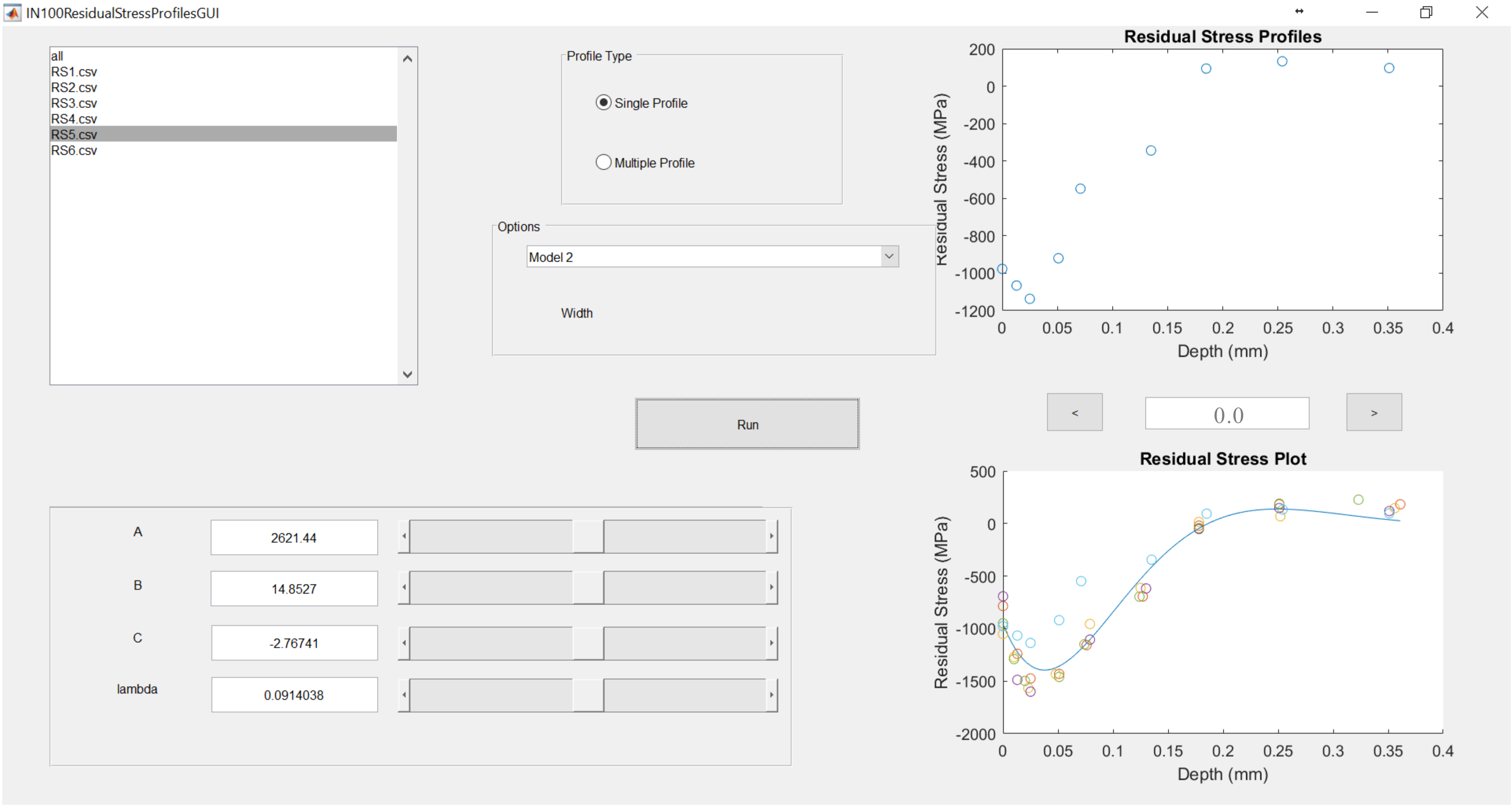
$$\sigma(x) = Ax^5 + Bx^4 - Cx^3 + Dx^2 - Ex - F$$

---

* *User Manual for ZENCRACK™ 7.1*, Zentech International Ltd., Camberley, Surrey, UK, September, 2003.

** R. VanStone, "F101-GE-102 B-1B Update to Engine Structural Durability and Damage Tolerance Analysis Final Report (ENSIP), Vol. 2," General Electric, p. 5-2-2.

Single Profile Model I & II



IN100ResidualStressProfilesGUI

all
RS1.csv
RS2.csv
RS3.csv
RS4.csv
RS5.csv
RS6.csv

Profile Type

● Single Profile

○ Multiple Profile

Options

Model 2

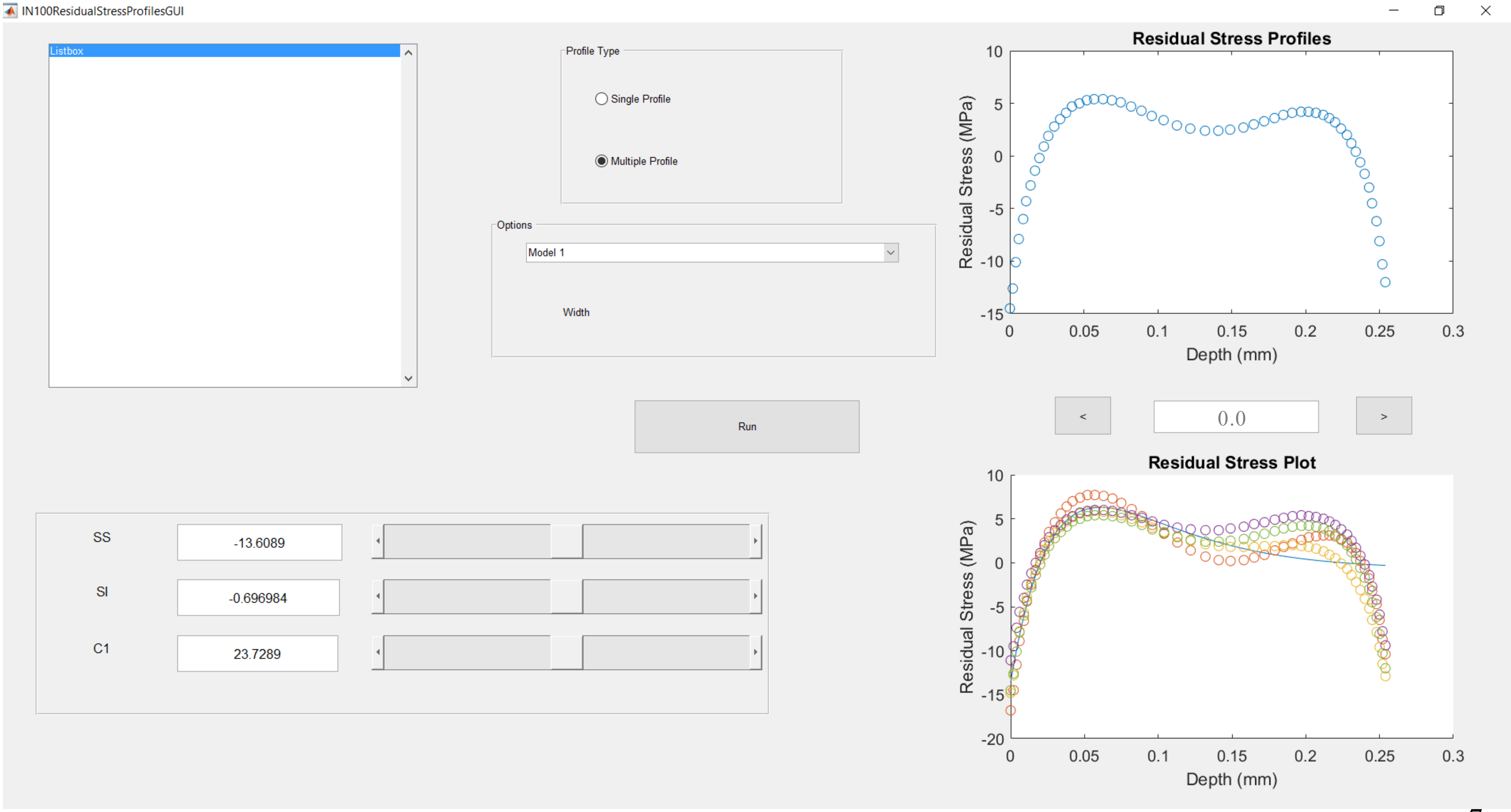
Width

Run

A	2621.44
B	14.8527
C	-2.76741
lambda	0.0914038

0.0

Mult. Profile Model I



○ Single Profile

● Multiple Profile

Options

Model 1

Width

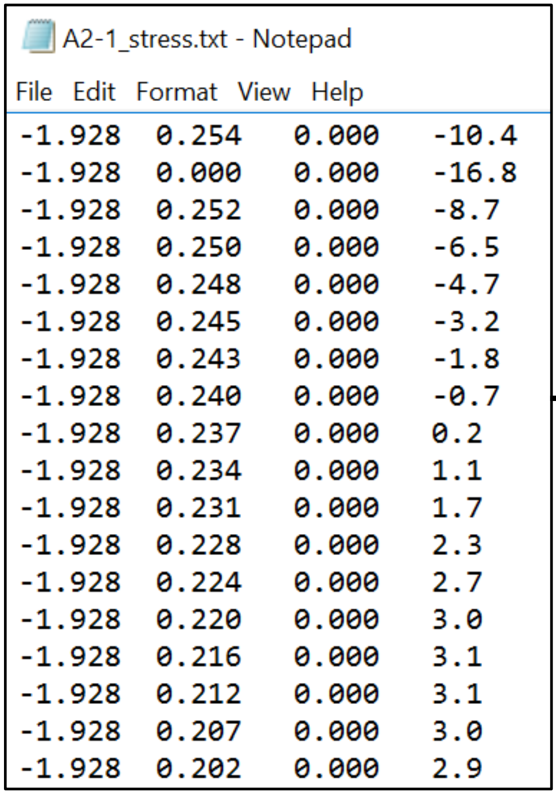
0.0

SS -13.6089

SI -0.696984

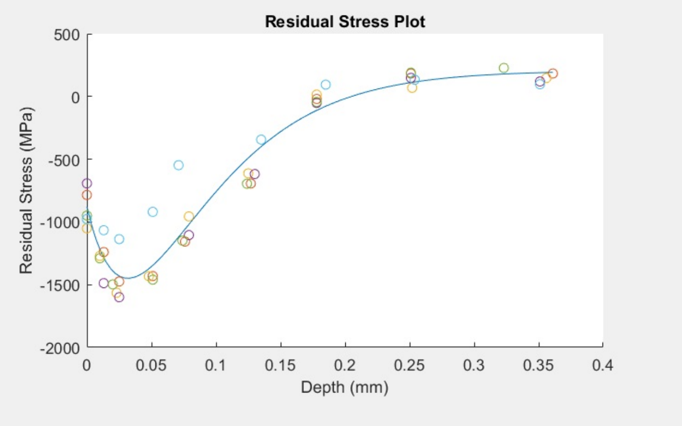
C1 23.7289

Input/Output



```
-1.928  0.254   0.000   -10.4
-1.928  0.000   0.000   -16.8
-1.928  0.252   0.000   -8.7
-1.928  0.250   0.000   -6.5
-1.928  0.248   0.000   -4.7
-1.928  0.245   0.000   -3.2
-1.928  0.243   0.000   -1.8
-1.928  0.240   0.000   -0.7
-1.928  0.237   0.000   0.2
-1.928  0.234   0.000   1.1
-1.928  0.231   0.000   1.7
-1.928  0.228   0.000   2.3
-1.928  0.224   0.000   2.7
-1.928  0.220   0.000   3.0
-1.928  0.216   0.000   3.1
-1.928  0.212   0.000   3.1
-1.928  0.207   0.000   3.0
-1.928  0.202   0.000   2.9
```

RS
Mod



Mean and Standard Deviation Parameters

	Mean	St dev
ss	-879.16	58.58
si	205.68	9.448
c2	20.872	1.050

Correlation Parameters

	ss	si	c2
ss	1	-0.214	0.402
si	-0.214	1	-0.796
c2	0.402	-0.796	1

Are probabilistic RS needed in PDTA?

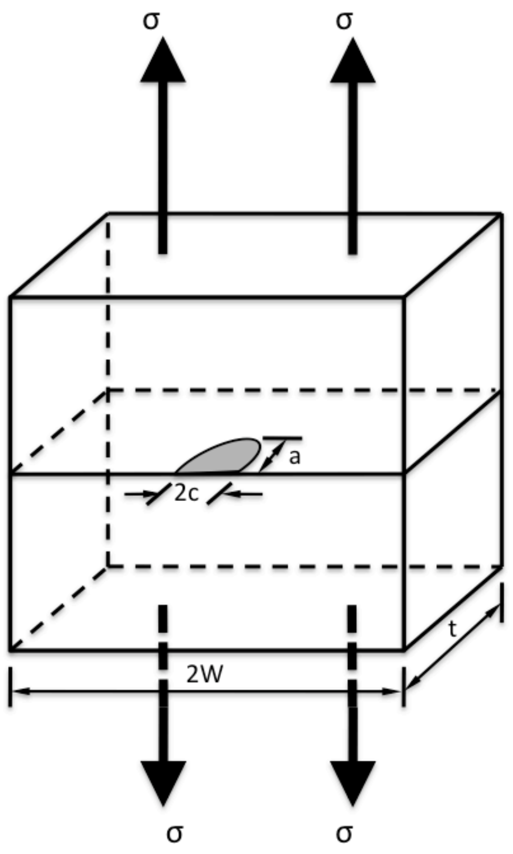
Sensitivity Study wrt Remaining Useful Life

Residual Stress Sensitivity Study

- Random variable sensitivity wrt remaining useful life

Variable Name	Type
Geometry (W)	Random
Geometry (t)	Random
Initial Crack Size (a)	Random
Initial Crack Size (c)	Random
Fracture Toughness (Kc)	Random
Residual Stress	Random
Paris Coefficients (C, m)	Random
Loading	Random
Walker m parameter	Deterministic
Stress Gradient (die out)	Deterministic
Threshold Kth	Deterministic

Residual Stress Sensitivity Study



Parameter	Mean (m)	COV
W = 2t	0.5	10%
t	0.25	10%

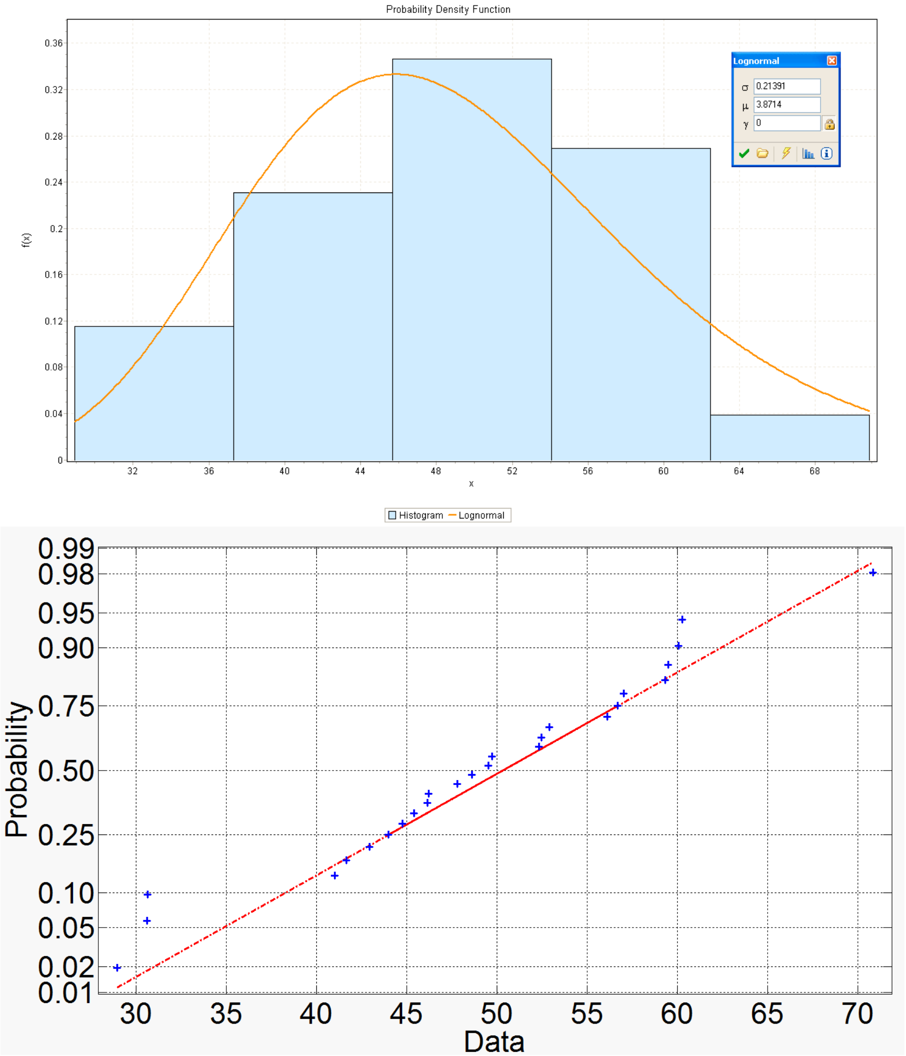
Residual Stress Sensitivity Study

Raw Data

Equivalent Semi-elliptical Crack Depth (a/c=1) (um)
42.94
43.98
28.93
48.63
52.48
60.26
52.32
47.82
44.75
59.34
70.83
59.49
41.65
56.68
49.72
41.01
30.65
45.40
57.04
52.90
46.20
49.53
56.11
60.08
46.14
30.60

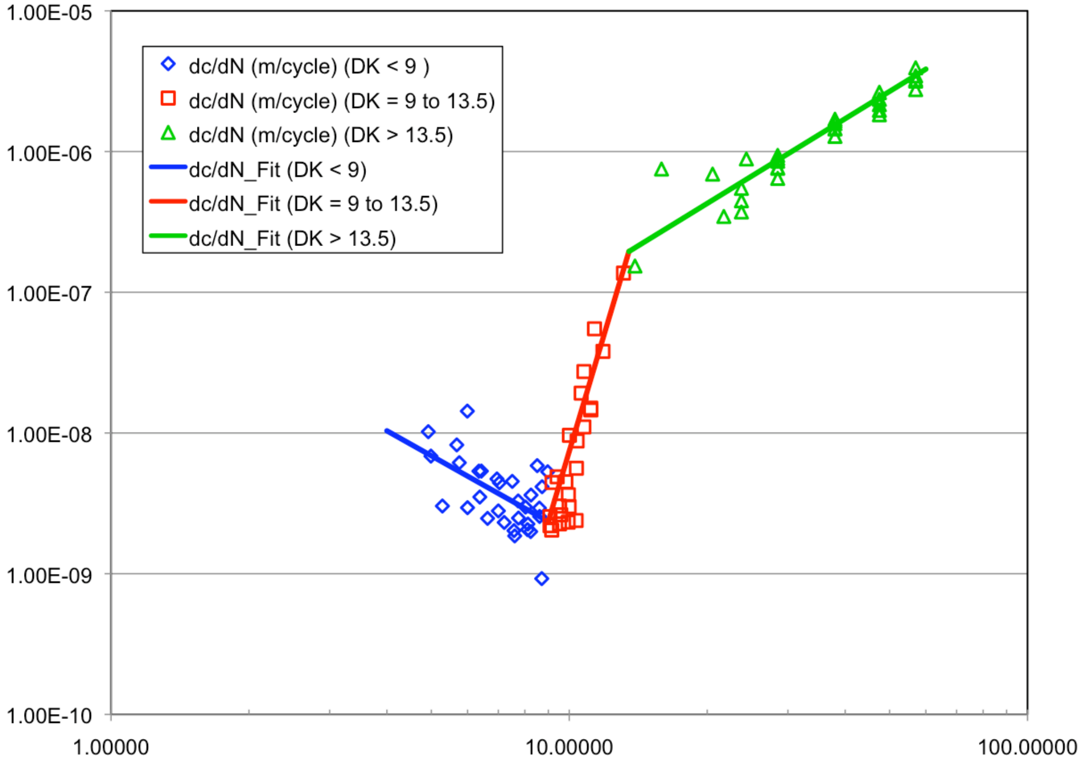
Lognormal distribution with histogram and lognormal probability plot

LN~(3.871, 0.23)



σ 0.21391
μ 3.8714
γ 0

Residual Stress Sensitivity Study



Curve Section	C	m
ΔK > 13	1.602E-09	1.8753
9 < ΔK < 13	2.425E-20	11.3580
ΔK < 9	1.306E-07	-1.8293

SAS Code to find the regression parameters and the variation on the parameters (Using simple linear regression)

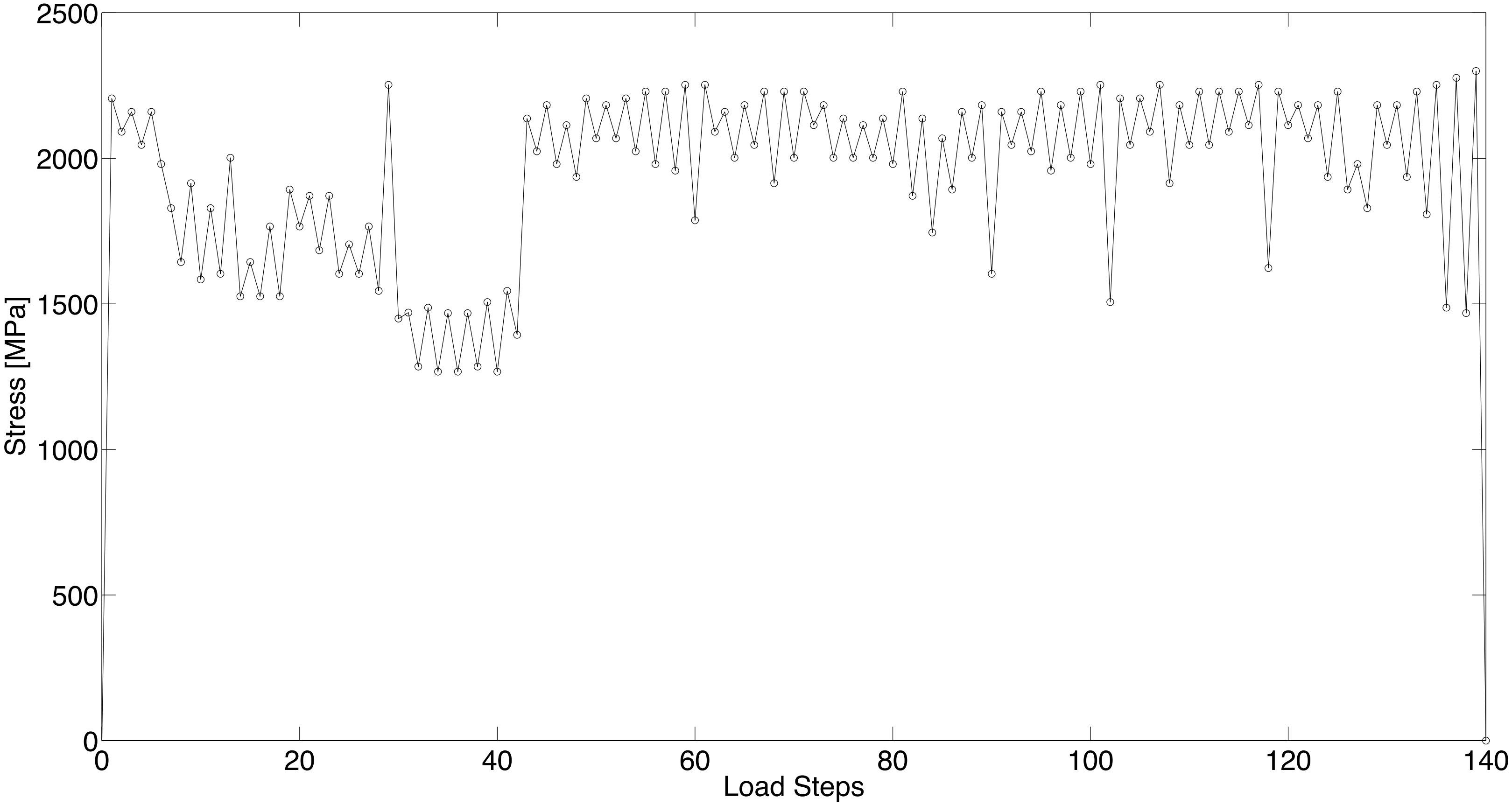
$$\frac{da}{dN} = C_1\left[(\Delta K)(1-R)^{(m-1)}\right]^{n_1} \qquad \Delta K < b$$

$$b = \frac{\log_{10}(C_1) - \log_{10}(C_2)}{n_2 - n_1}$$

$$\frac{da}{dN} = C_2\left[(\Delta K)(1-R)^{(m-1)}\right]^{n_2} \qquad \Delta K \geq b$$

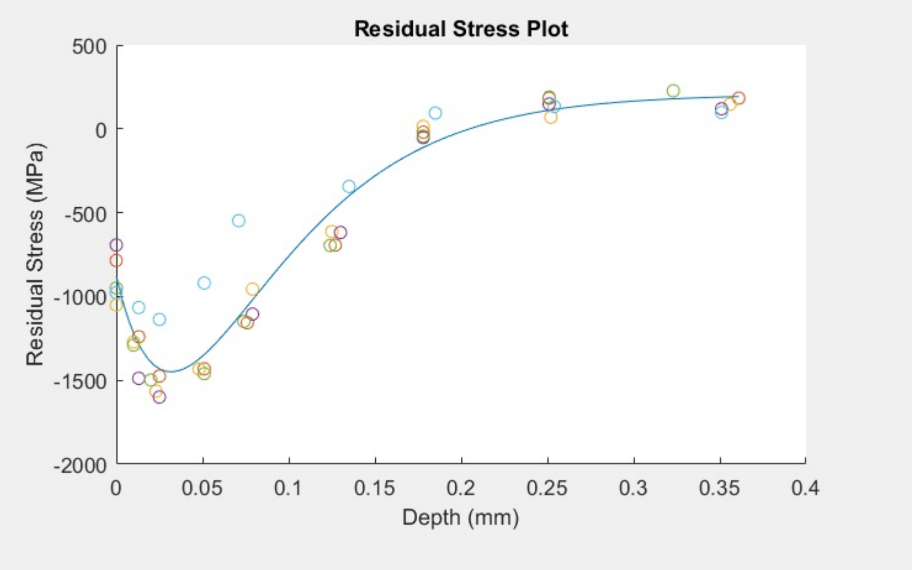
Residual Stress Sensitivity Study

Variable Amplitude Loading



Previous RS Sensitivity Study

- Shot Peening Residual Stress Profile (Random)



$$\sigma(x) = (ss - si + c_1 x)Exp[-C_2 x] + si$$

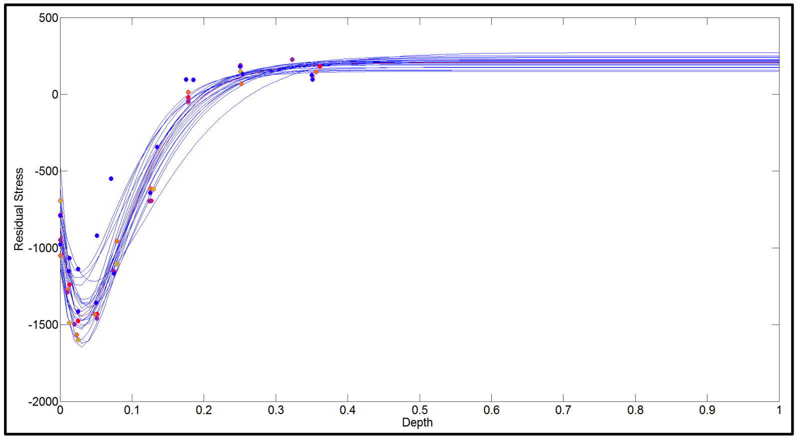
$$C_1 = \frac{\{(\sigma_s - \sigma_i)(1 - Exp[-C_2 B]) + \sigma_i B C_2\}C_2}{(C_2 B + 1)Exp[-C_2 B] - 1}$$

Mean and Standard Deviation Parameters

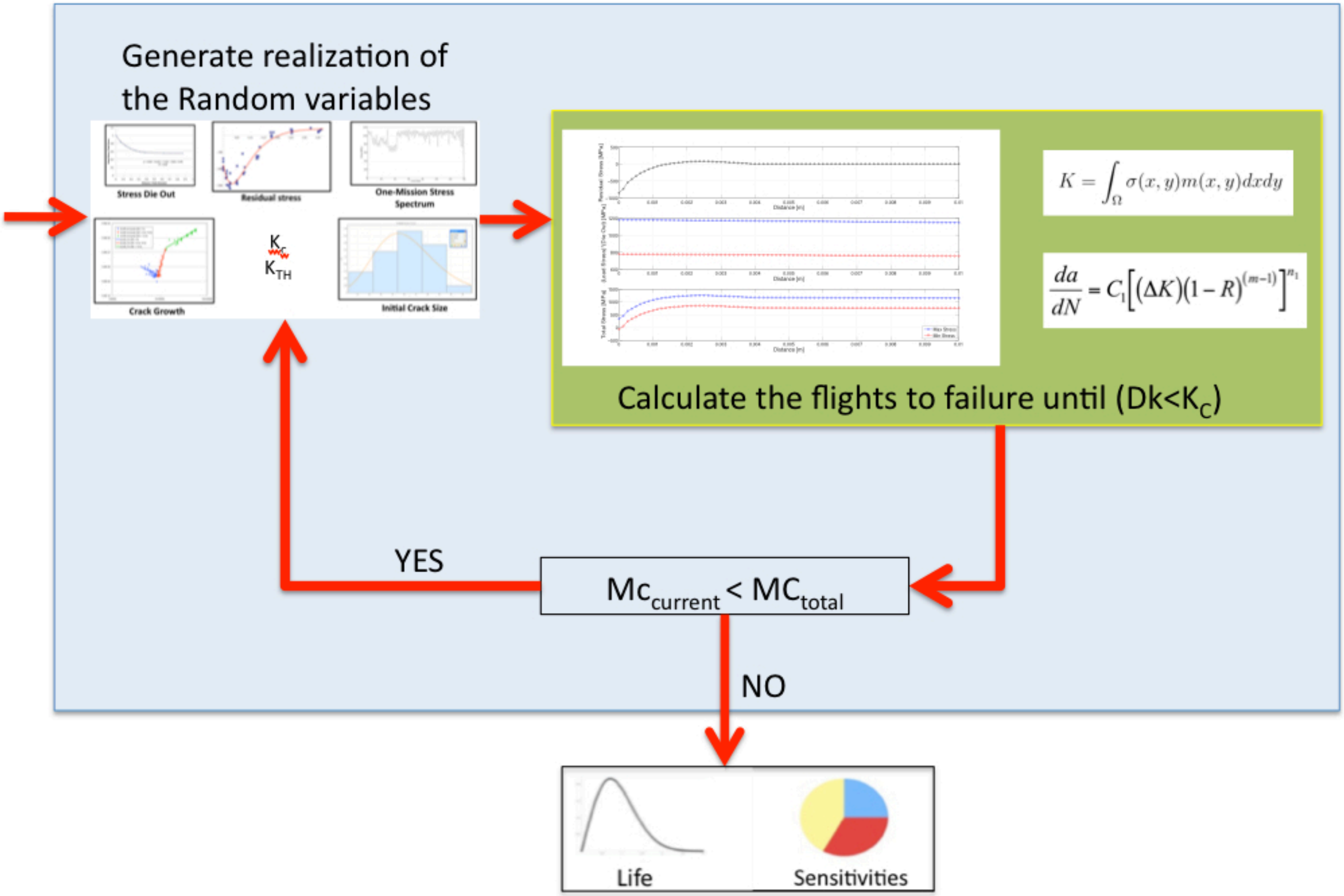
	Mean	**St dev**
ss	-879.16	58.58
si	205.68	9.448
c2	20.872	1.050

Correlation Parameters

	ss	**si**	**c2**
ss	1	-0.214	0.402
si	-0.214	1	-0.796
c2	0.402	-0.796	1



Residual Stress Sensitivity Study



Generate realization of the Random variables

$$K = \int_\Omega \sigma(x,y)m(x,y)dxdy$$

$$\frac{da}{dN} = C_1\left[(\Delta K)(1-R)^{(m-1)}\right]^{n_1}$$

Calculate the flights to failure until (Dk<K_C)

$Mc_{current} < MC_{total}$

YES

NO

ERSI

Sensitivity Results

$$\bar{S}_{\theta} = \frac{\partial P}{\partial \theta} \cdot \theta$$

$$S_i = \frac{V_{X_i}\left(E_{X\sim i}(Y/X_i)\right)}{V(Y)}$$

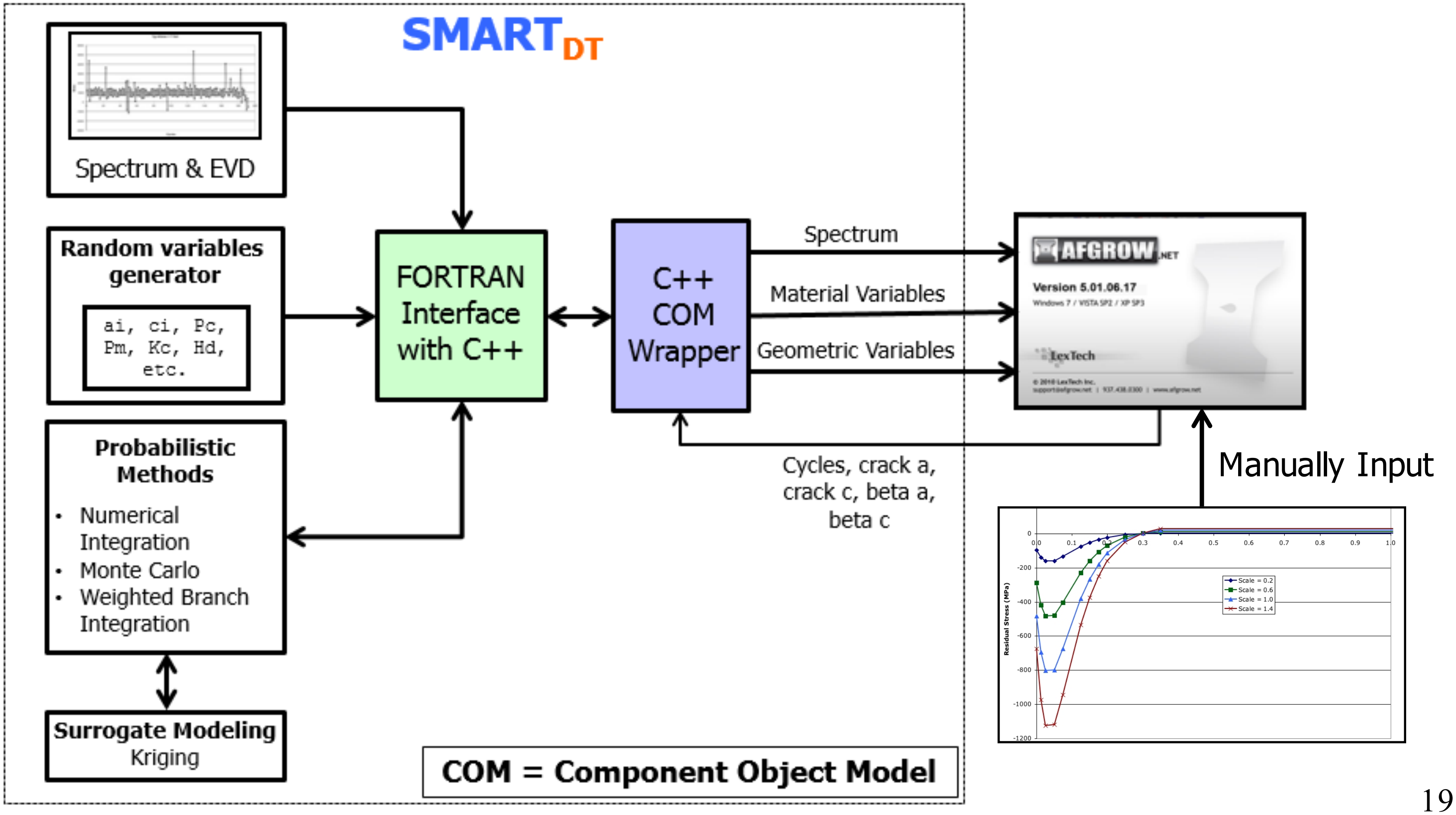
Input variable	Sensitivity Value	Importance	Sensitivity Value	Importance
C2	0.30	1	0.473479	1
Si	0.18	2	0.329348	2
Paris	0.16	3	0.150957	4
Ss	0.09	4	0.198532	3
ai	0.04	5	0.092150	5
Loading	0.01	6	0.014135	6
W	0.0026	7	0.003211	7
Kic	0.0009	8	0.001111	8
t	0.000009	9	1.11E-05	9

Results are problem dependent

Residual Stress Effect on SFPOF Using Deterministic Residual Stress Profile

Residual Stress Effect on SFPOF

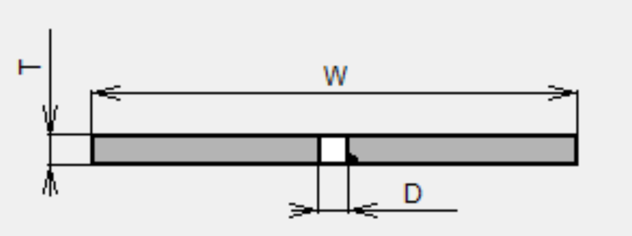
- SMART-AFGROW interface.



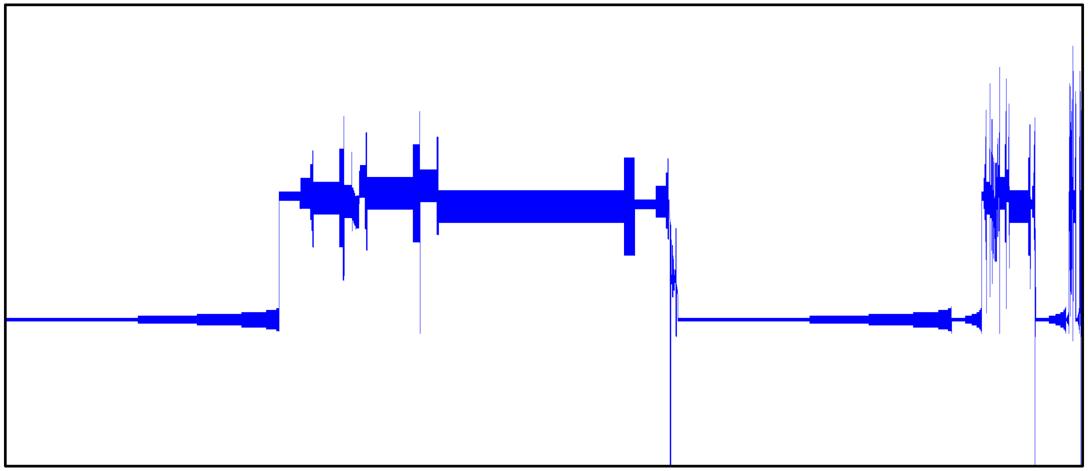
Input Parameters

Deterministic RS Example

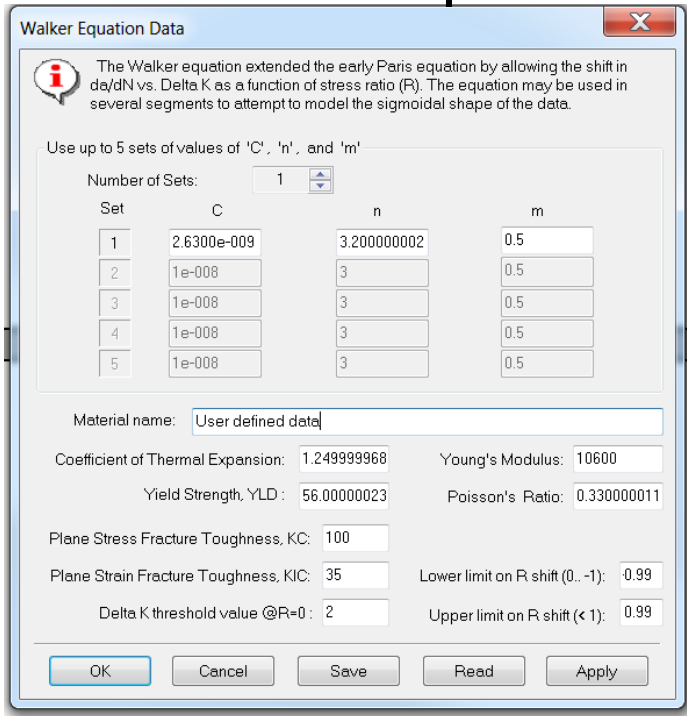
Corner crack @ hole



Parameter	Value
T	0.09 in
W	4.0 in
D	0.25 in



Mat. Prop.



The Walker equation extended the early Paris equation by allowing the shift in da/dN vs. Delta K as a function of stress ratio (R). The equation may be used in several segments to attempt to model the sigmoidal shape of the data.

Use up to 5 sets of values of 'C', 'n', and 'm'

Number of Sets: 1

Set	C	n	m
1	2.6300e-009	3.200000002	0.5
2	1e-008	3	0.5
3	1e-008	3	0.5
4	1e-008	3	0.5
5	1e-008	3	0.5

Material name: User defined data

Coefficient of Thermal Expansion: 1.249999968

Young's Modulus: 10600

Yield Strength, YLD : 56.00000023

Poisson's Ratio: 0.330000011

Plane Stress Fracture Toughness, KC: 100

Plane Strain Fracture Toughness, KIC: 35

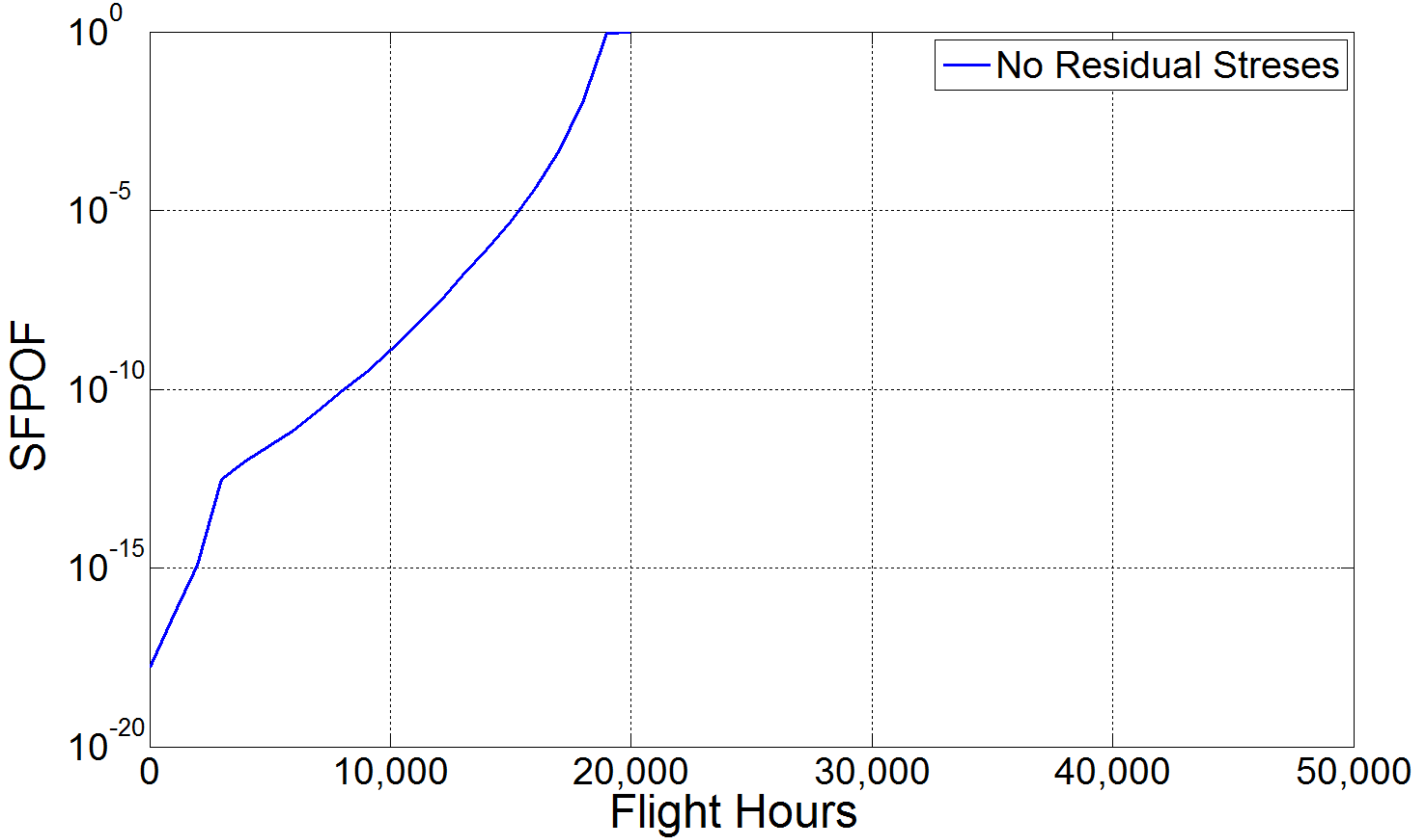
Lower limit on R shift (0.. -1): -0.99

Delta K threshold value @R=0 : 2

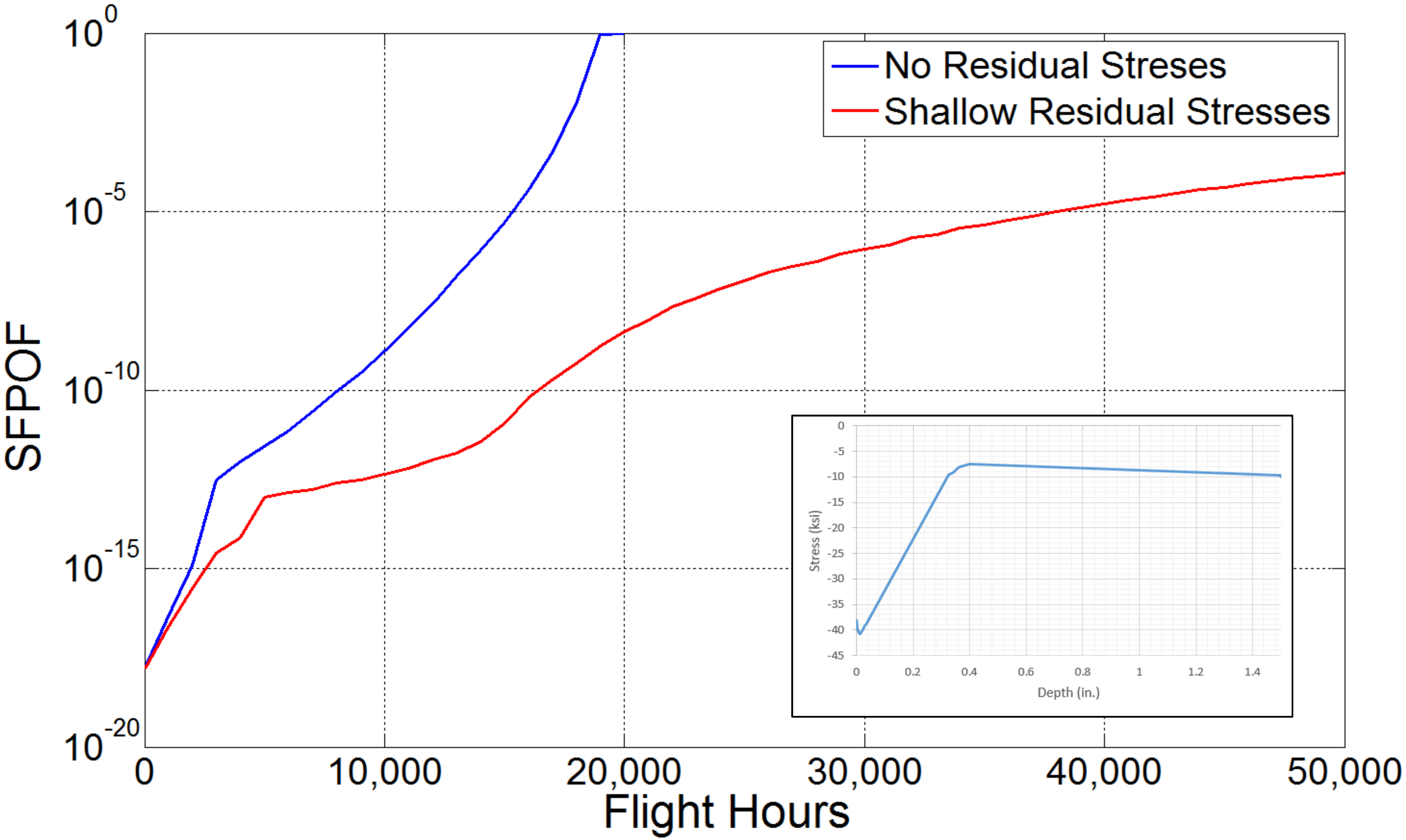
Upper limit on R shift (< 1): 0.99

Random Variables	Value
Fracture Toughness Distribution (Normal)	Mean = 34.5ksi√in, Standard Deviation = 3.8 ksi√in.
Initial & Repair Lognormal Size Distribution (a & c) (Lognormal)	Mean = 0.01 in, Standard Deviation = 0.001 in.
Extreme Value Distribution (Gumbel)	Location = 14.5, Scale = 0.8, and Shape = 0.0
Inspections (5,000 & 10,000)	POD Lognormal Mean = 0.07in, Standard Deviation = 0.06

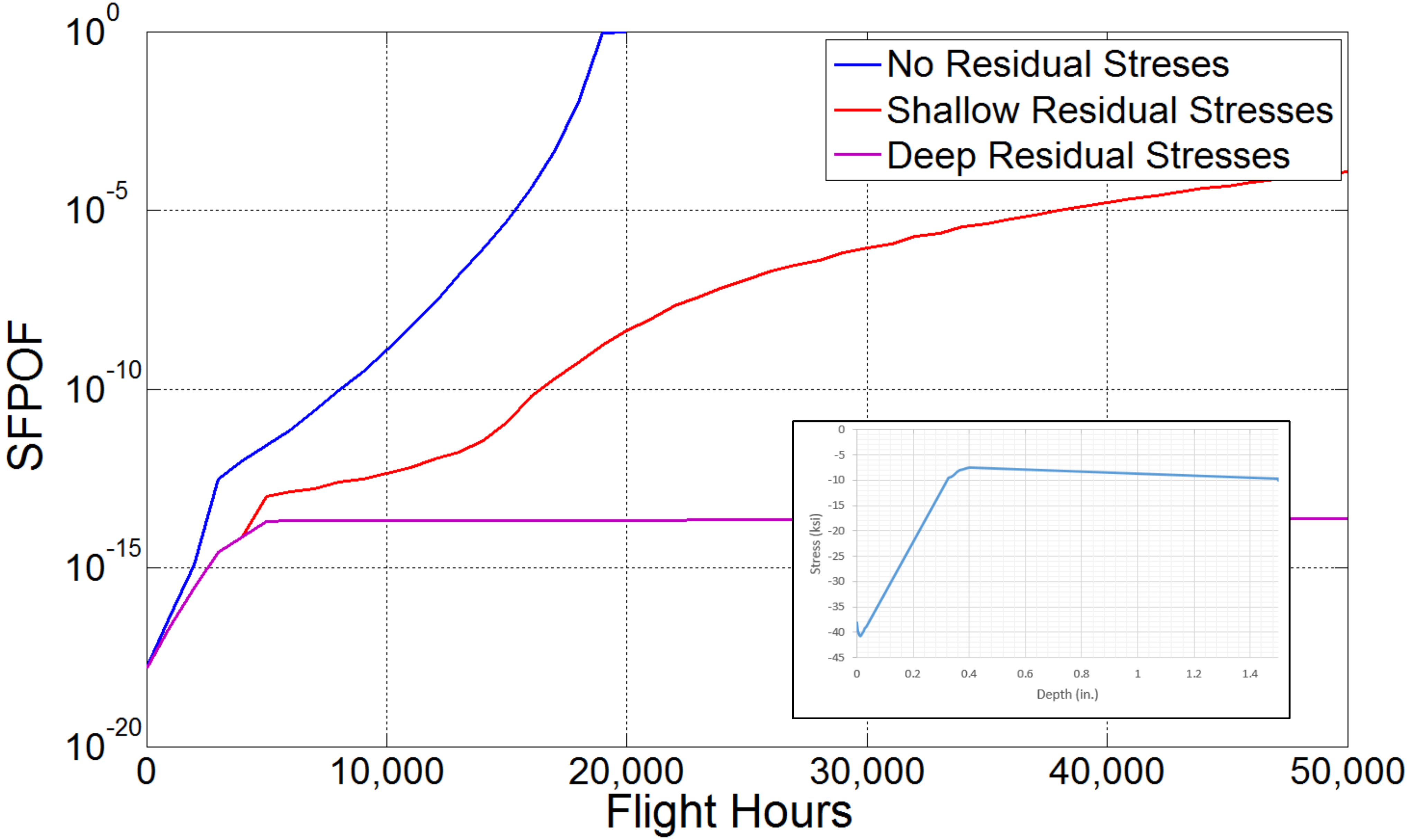
Results without Inspections



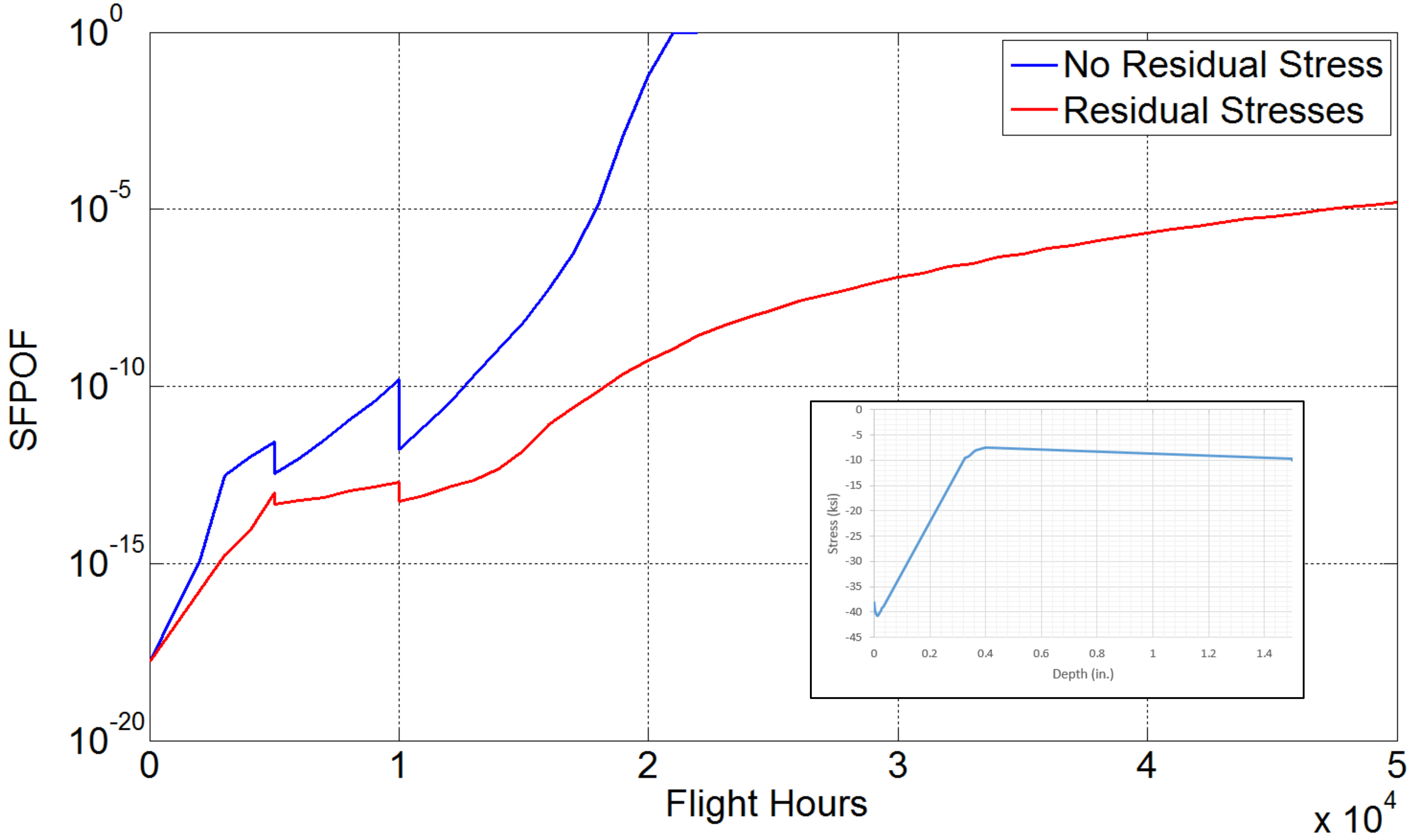
Results without Inspections



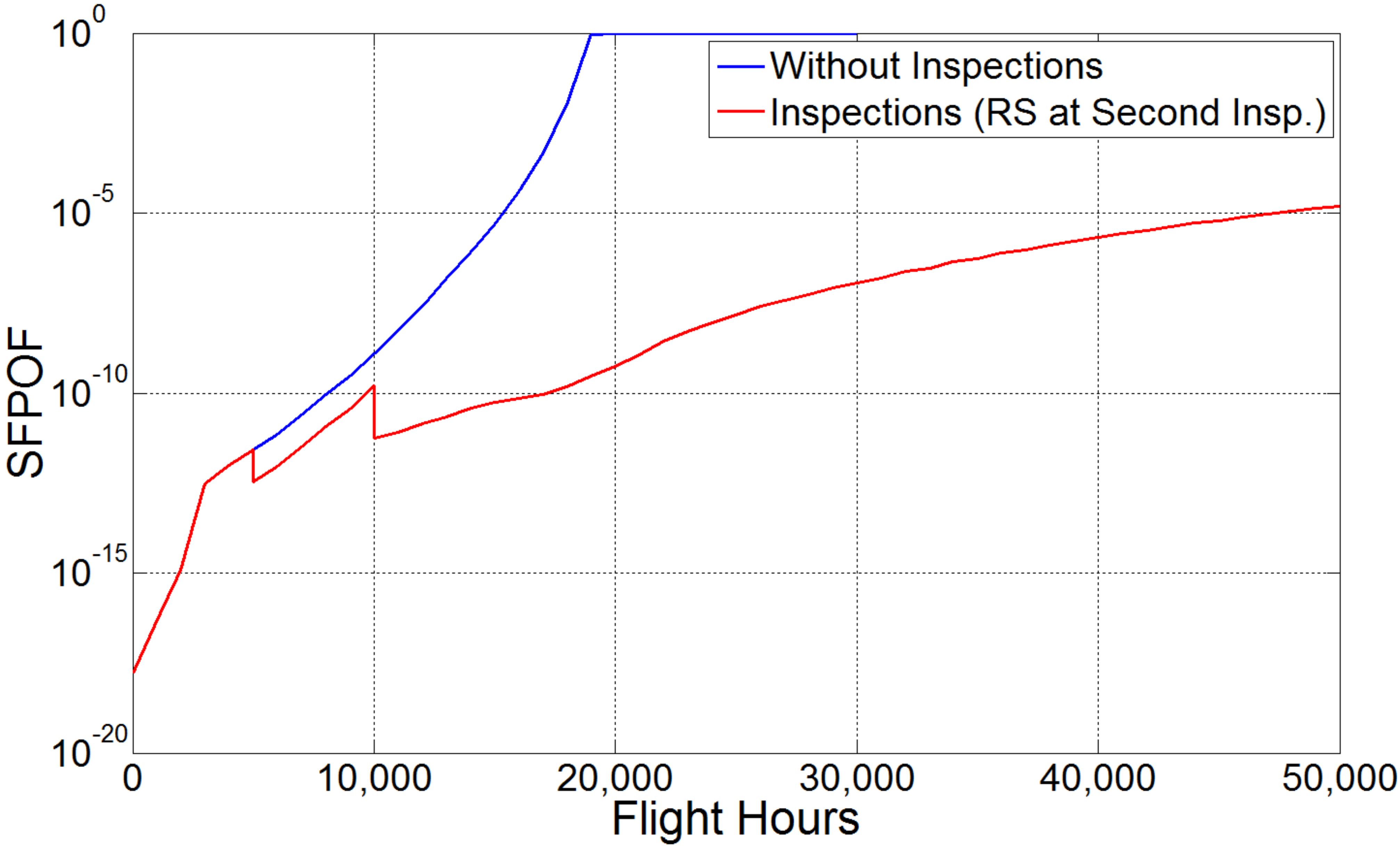
Results without Inspections



Results with Inspections



Inducing RS at the Second Inspections



SMART Internal Crack Growth Code

An Ultrafast Crack Growth Lifing Algorithm for Probabilistic Damage Tolerance Analysis

Harry Millwater, Nathan Crosby
University of Texas at San Antonio

Juan D. Ocampo
St. Mary's University, San Antonio

The Aircraft Airworthiness & Sustainment (AA&S) Conference
Jacksonville, FL. May– 2018.

Purpose

- Probabilistic damage tolerance analysis requires very small probabilities, e.g., 1E-9
- Previous methods allow for a deterministic crack growth curve and do not consider randomness in crack growth rate properties.
- Surrogate models, e.g., Kriging, can be used to speed up the analysis but are still very time consuming.
- Hence an ultrafast crack growth lifing code was developed.

Ultrafast Approach

1) Create an equivalent constant amplitude from an arbitrary spectrum
2) Use an *internal* adaptive time stepping RK algorithm to grow the crack
3) Collect the top 100 (or so) damaging realizations for further examination and potential reanalysis

Thank you!!

jocampo@stmarytx.edu

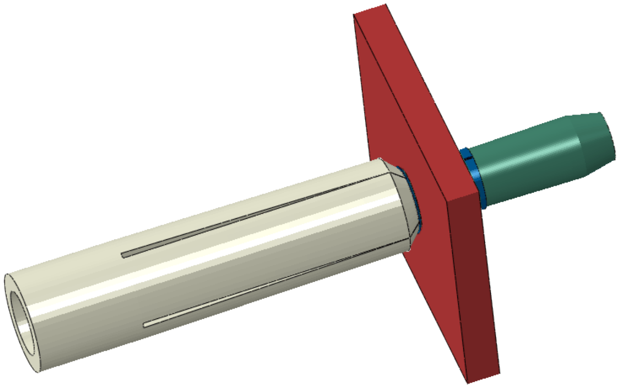
Residual Stress Process Simulation Subcommittee Progress Report

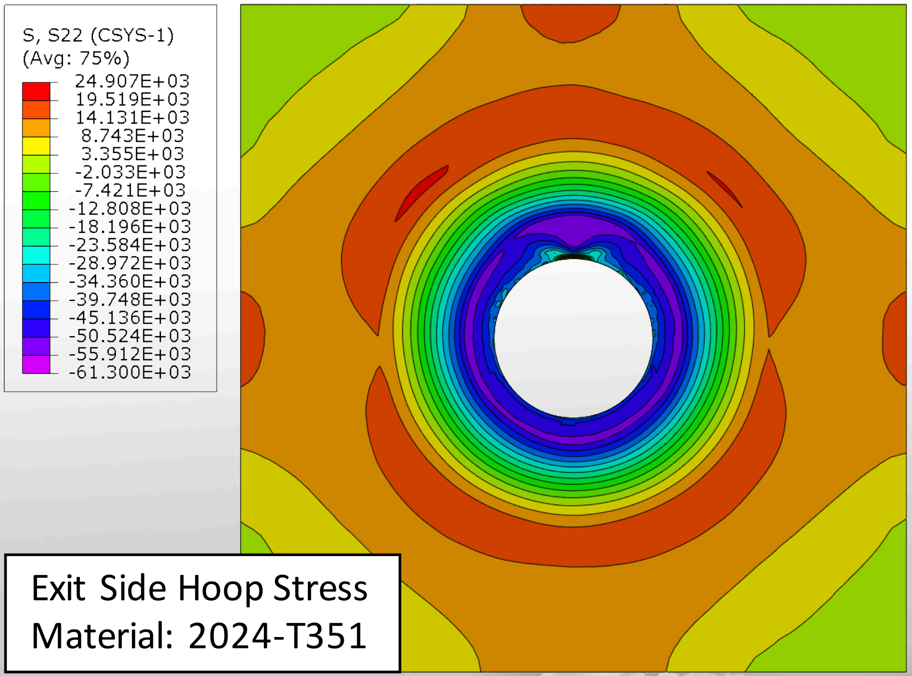
Engineered Residual Stress Implementation Workshop 2017
Layton, Utah, USA
September 21, 2017

Keith Hitchman - FTI

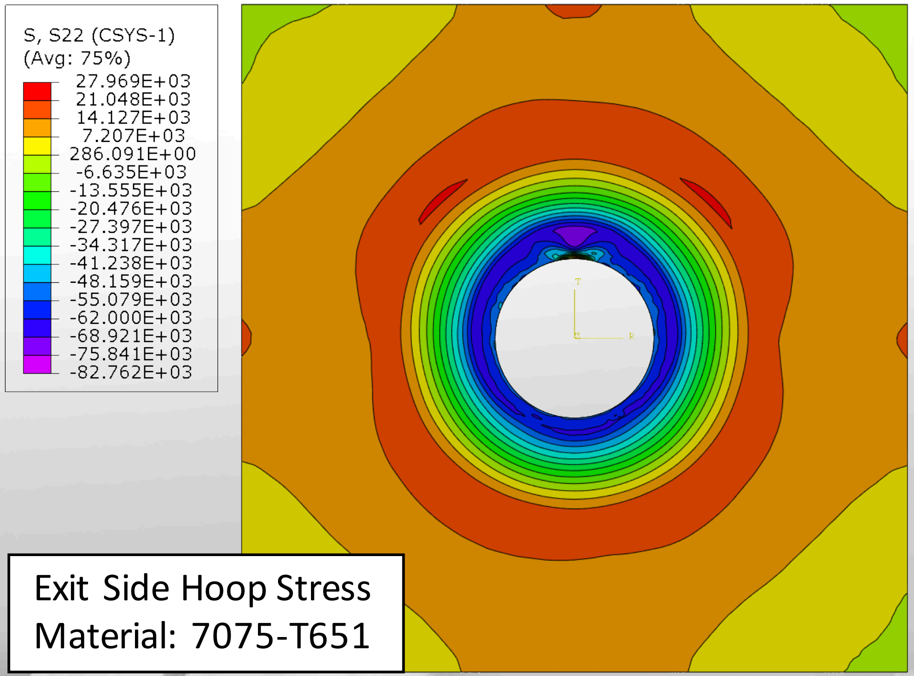
Outline

- RS Process Simulation Review
- Material Testing Progress
- RS Process Simulation Validation Progress



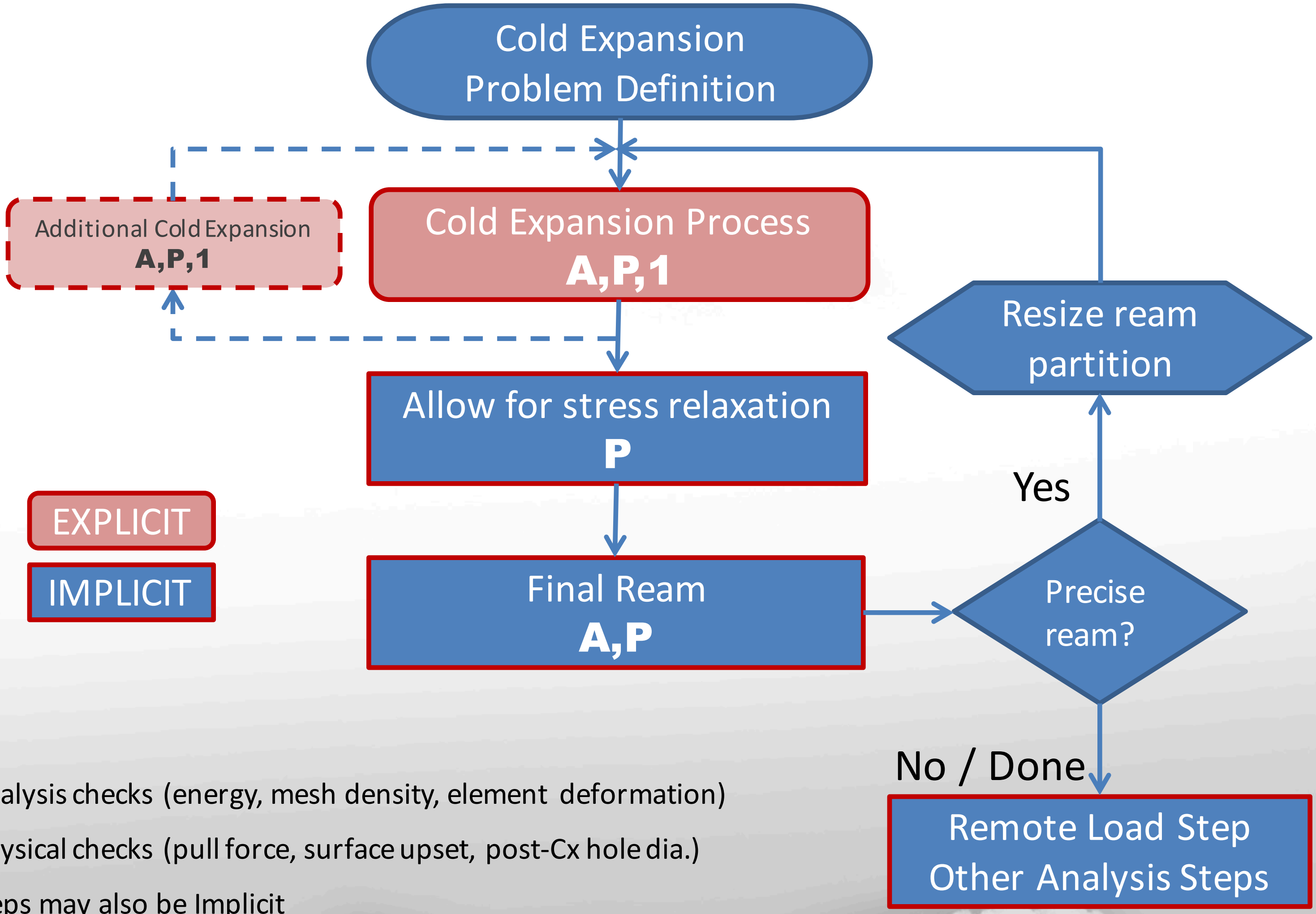


Exit Side Hoop Stress
Material: 2024-T351



Exit Side Hoop Stress
Material: 7075-T651

RS Process Simulation Review – Typical FEA Workflow



Cold Expansion Problem Definition

Additional Cold Expansion **A,P,1**

Cold Expansion Process **A,P,1**

Allow for stress relaxation **P**

Final Ream **A,P**

Precise ream?

Yes

Resize ream partition

No / Done

Remote Load Step
Other Analysis Steps

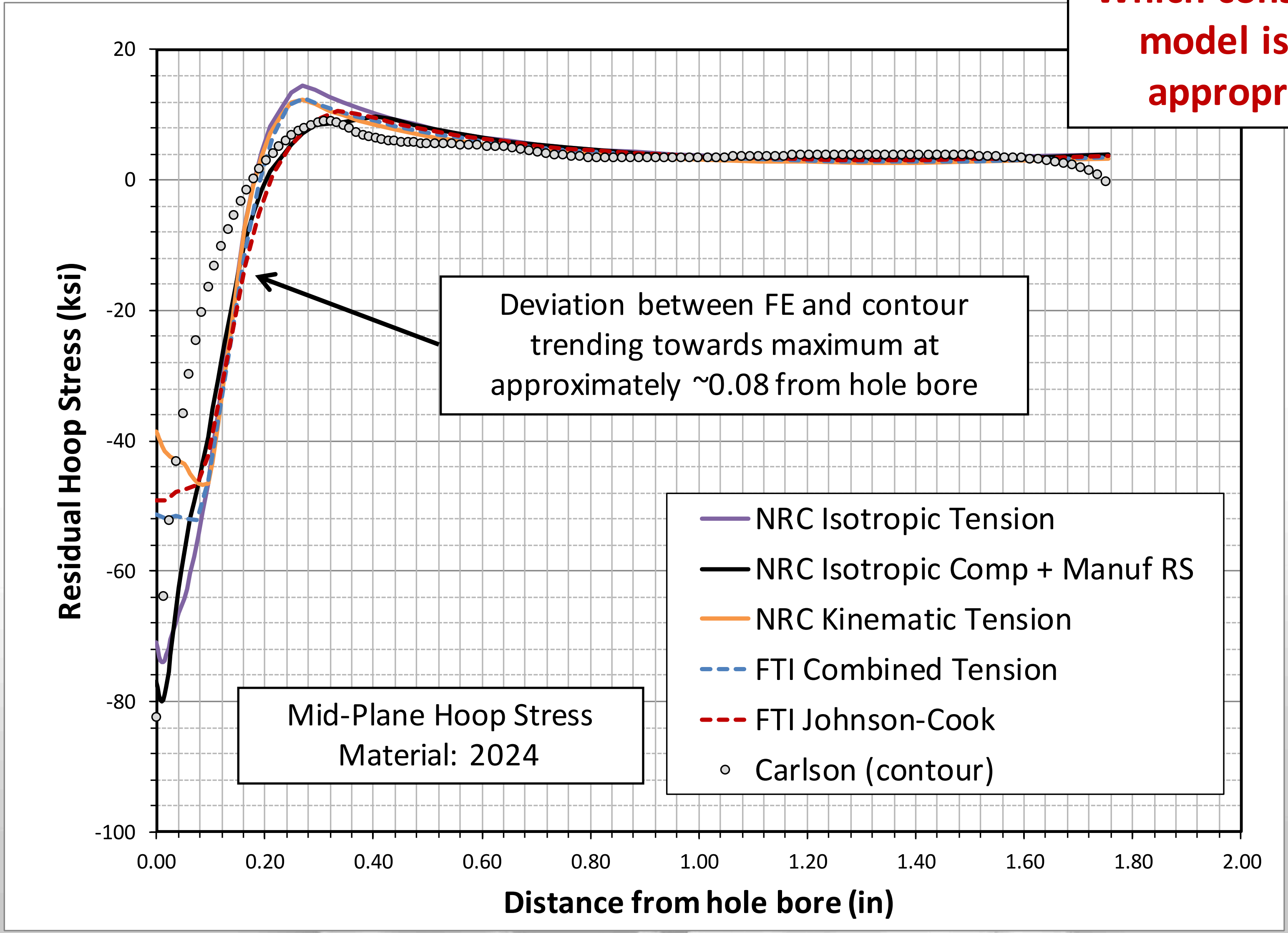
EXPLICIT

IMPLICIT

A: analysis checks (energy, mesh density, element deformation)
P: physical checks (pull force, surface upset, post-Cx hole dia.)
1: Steps may also be Implicit

Material Model Testing
Purpose of Program

Which constitutive model is most appropriate?

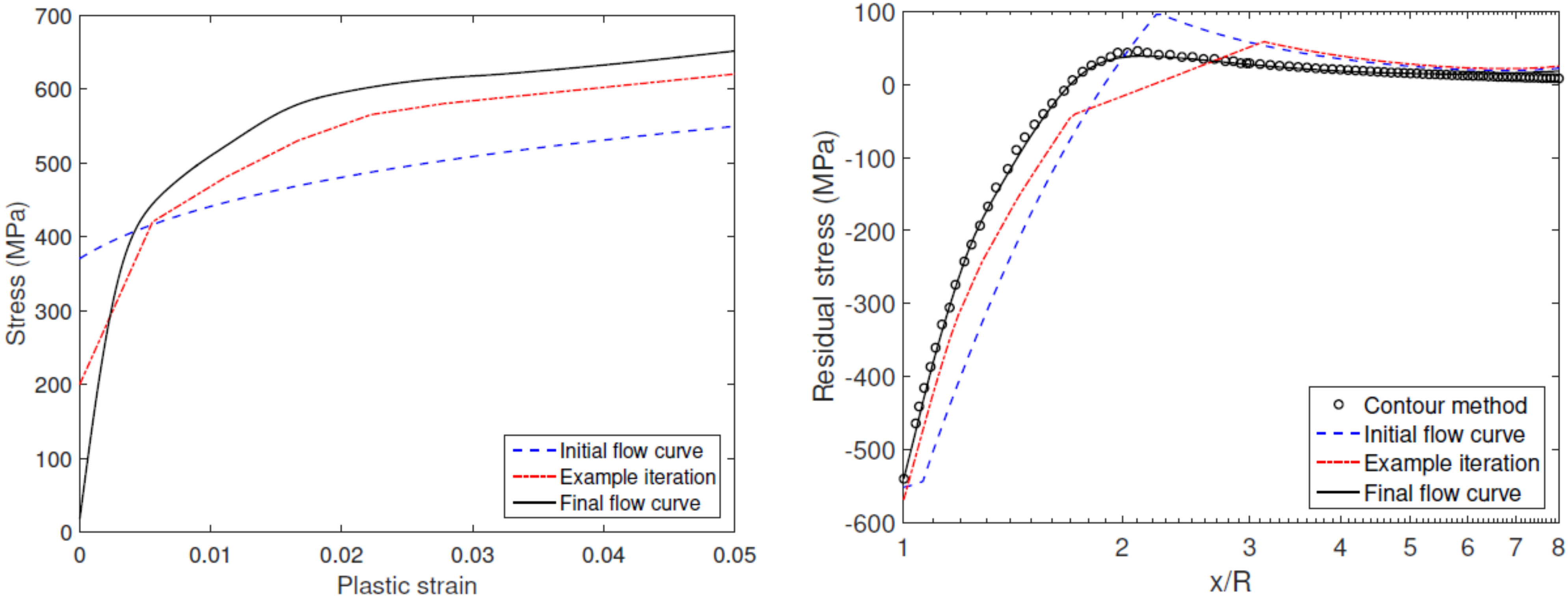


Deviation between FE and contour trending towards maximum at approximately ~0.08 from hole bore

Mid-Plane Hoop Stress
Material: 2024

Material Model Testing

Purpose of Program – Example



(a) (b)

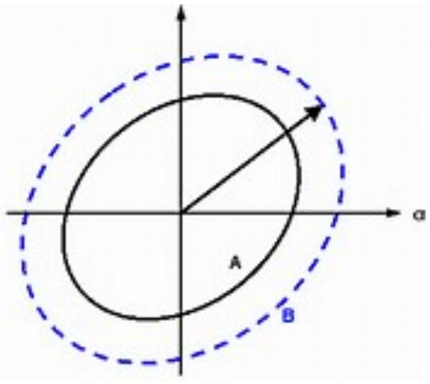
Figure 7 – (a) Flow curves tested, (b) resulting hoop residual stress ($\sigma_{\theta\theta}$); note log scale on x/R

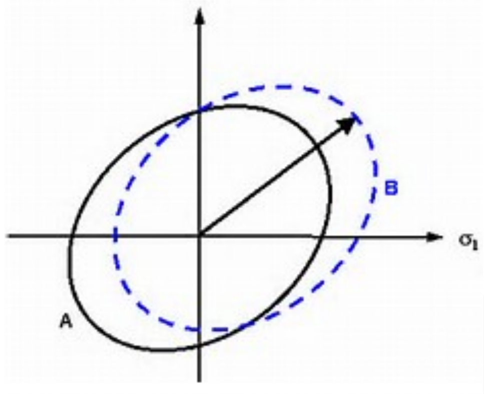
Ribeiro, Renan L., and Michael R. Hill. "Residual Stress From Cold Expansion of Fastener Holes: Measurement, Eigenstrain, and Process Finite Element Modeling." Journal of Engineering Materials and Technology 139.4 (2017): 041012. https://doi.org/10.1115/1.4037021

Material Model Testing

Material Models To Consider

- Isotropic
- Kinematic
- Combined
- Johnson-Cook (rate dep.)
- Triax/pressure dependence
  - Drucker-Prager (FTI)
  - Triax look-up (UMAT
- Anisotropic
  - Hill
  - Barlat (pressure dep./NRC)



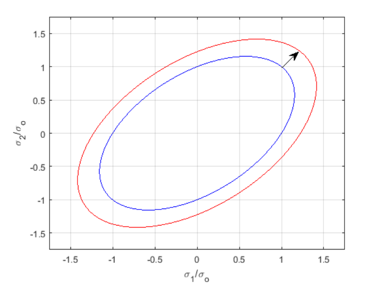


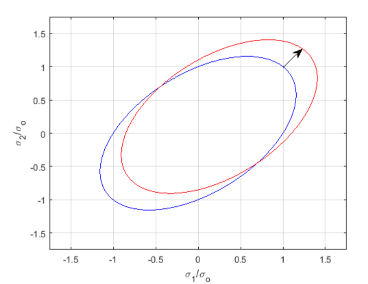
$$\sigma_{yield,effective} = \sigma_0 \left[1 - c_\eta \left(\eta - \eta_0\right)\right]$$

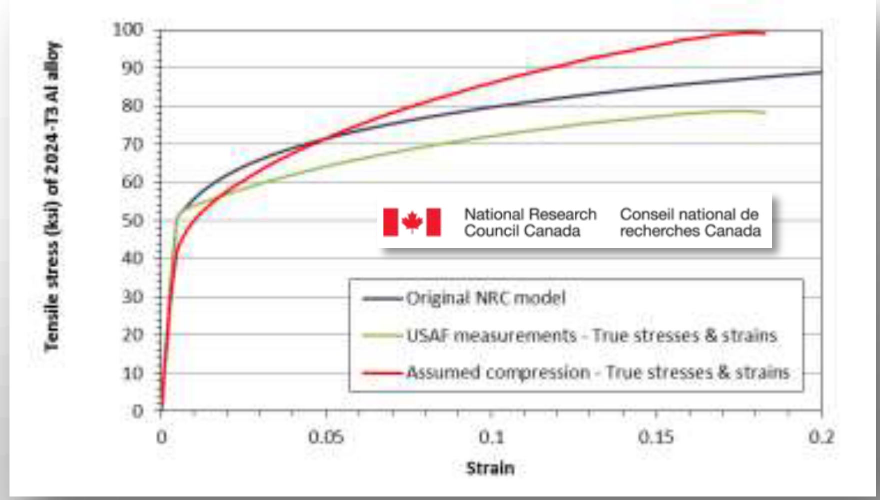
Material Model Testing

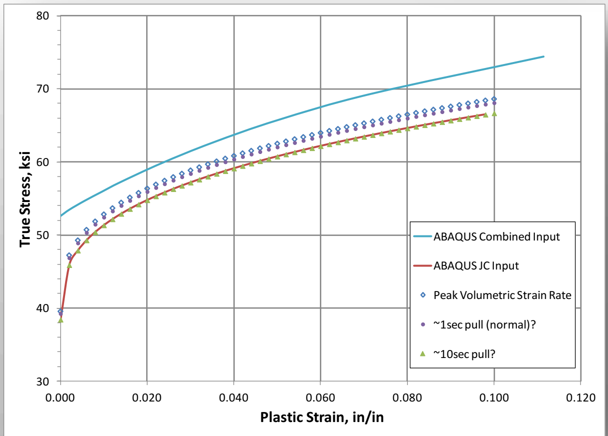
General Plan

- Based upon E606 LCF, up to ±4% in./in.
- Isolating current investigation to orthotropy
- Focusing on single-cycle reverse-yield behavior
- **Testing to be complete Fall 2017**





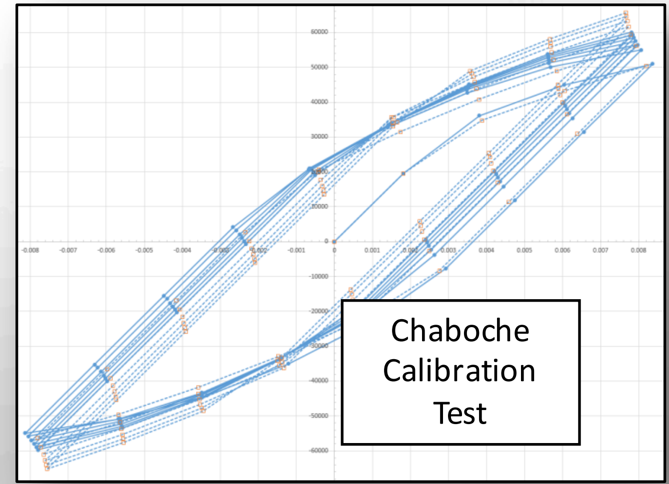




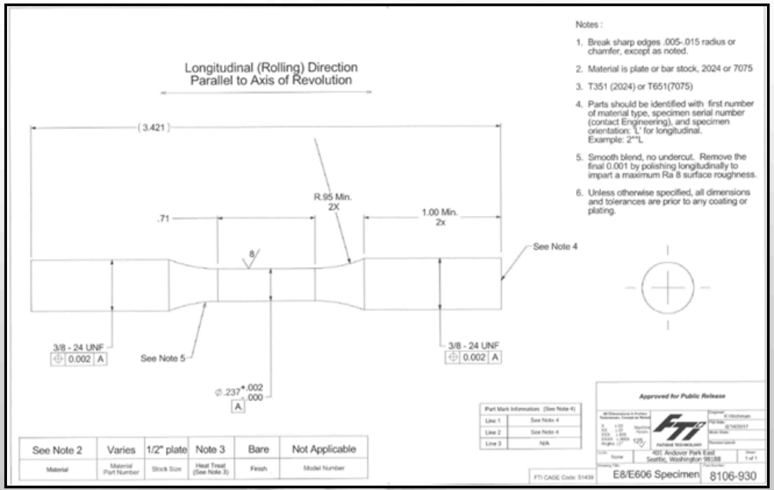
Material Model Testing

Experimental Matrix

Material and heat treat	Material Orientation	Specimens used for alignment + Spares	E8 specimens	E606 Specimens		
				R Ratio	Tension first	Compression first
2024-T351	L	4	2	-1	2	2
2024-T351	45-degrees	2	2	-1	2	2
2024-T351	LT	2	2	-1	2	2
7075-T651	L	4	2	-1	2	2
7075-T651	45-degrees	2	2	-1	2	2
7075-T651	LT	2	2	-1	2	2



Chaboche Calibration Test



Notes :

1. Break sharp edges .005-.015 radius or chamfer, except as noted.
2. Material is plate or bar stock, 2024 or 7075
3. T351 (2024) or T651(7075)
4. Parts should be identified with first number of material type, specimen serial number (contact Engineering), and specimen orientation: 'L' for longitudinal. Example: 2**L
5. Smooth blend, no undercut. Remove the final 0.001 by polishing longitudinally to impart a maximum Ra 8 surface roughness.
6. Unless otherwise specified, all dimensions and tolerances are prior to any coating or plating.

Material	Material Part Number	Stock Size	Heat Treat (See Note 3)	Finish	Model Number
See Note 2	Varies	1/2" plate	Note 3	Bare	Not Applicable

Part Mark Information: (See Note 4)	
Line 1	See Note 4
Line 2	See Note 4
Line 3	N/A

RS Process Simulation Validation
Purpose of Program

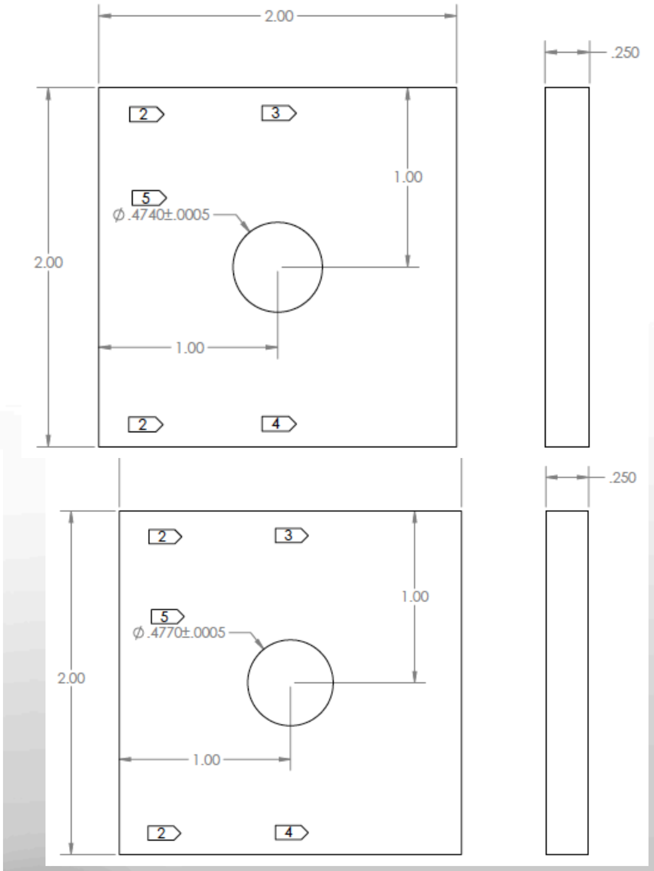
- Perform Experiments to Capture Surface and Through-Thickness Strains for FEA Process Simulation Validation
  - Quantification of residual stresses through process simulation is a critical path for future ERSI realization
  - Perform Residual Stress Validation Through Comparison of Techniques
  - Limited open literature on cross-comparison of residual stress measurement methods for Cx holes
  - Potential to complement through-thickness techniques with surface techniques for a more accurate understanding of the complete residual stress field
- Current work underway through Process Simulation Subcommittee, with the kind assistance of the ***Organization and Execution Group***:

  - Dr. TJ Spradlin (AFRL)
  - Keith Hitchman (FTI)
  - Dr. Marcias Martinez (Clarkson U.)
  - Marcus Stanfield (SwRI)
  - Prof. Michael Fitzpatrick (Coventry U.)
  - Scott Carlson (SwRI)
  - Dr. Min Liao (NRC)
  - Dr. Guillaume Renaud (NRC)
  - Dr. Mike Hill (Hill Engineering)

RS Process Simulation Validation

Experimental Matrix

- Material: 2024-T351 & 7075-T651
- Applied Expansion Levels:
  - “Low” (3.16%)
  - “High” (4.16%)
- Center Hole Diameter: 16-O-N Tool Set
  - 0.50inch final diameter
  - Hole not reamed

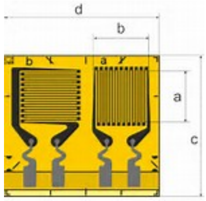


Coupon Name	Geometry Outer Size (inch)	Defined Applied Cx Level	Material
2024-Cx-DIC/LUNA/XRD/CM/SG-01-L1	2x2	Low	2024-T351
2024-Cx-DIC/LUNA/XRD/CM/SG-02-L2			
2024-Cx-DIC/LUNA/XRD/CM/SG-03-H1		High	
2024-Cx-DIC/LUNA/XRD/CM/SG-04-H2			
7075-Cx-DIC/LUNA/XRD/CM/SG-01-L1		Low	7075-T651
7075-Cx-DIC/LUNA/XRD/CM/SG-02-L2			
7075-Cx-DIC/LUNA/XRD/CM/SG-03-H1		High	
7075-Cx-DIC/LUNA/XRD/CM/SG-04-H2			

RS Process Simulation Validation

Strain Measurement Techniques

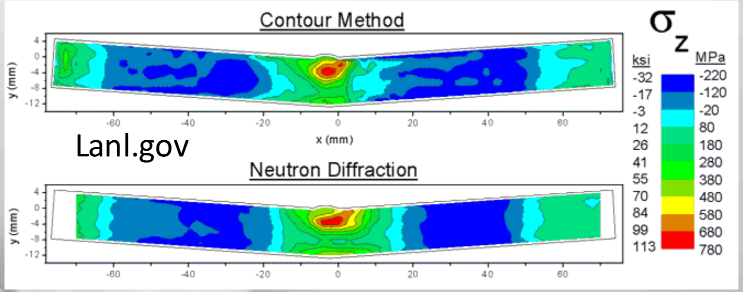
- Surface Strain Measurement Techniques (Performed on Exit and Entrance Surfaces)
  - Digital Image Correlation (DIC)
  - Fiber Optics (LUNA)
  - Strain gages
- Through-Thickness Measurement Techniques
  - High Energy X-ray Diffraction (XRD)
    - Argonne National Labs
  - Neutron Diffraction
    - Coventry University (UK)
  - Contour Method
    - Hill Engineering, LLC.



HBM.com

Lunainc.com

Argonne NATIONAL LABORATORY



Lanl.gov

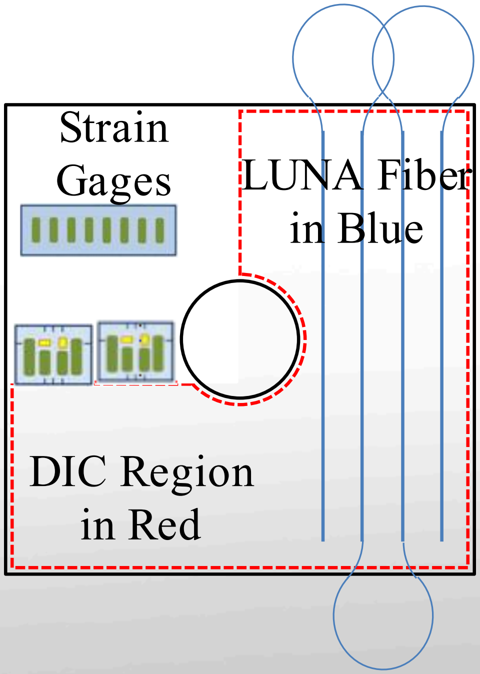
ERSI

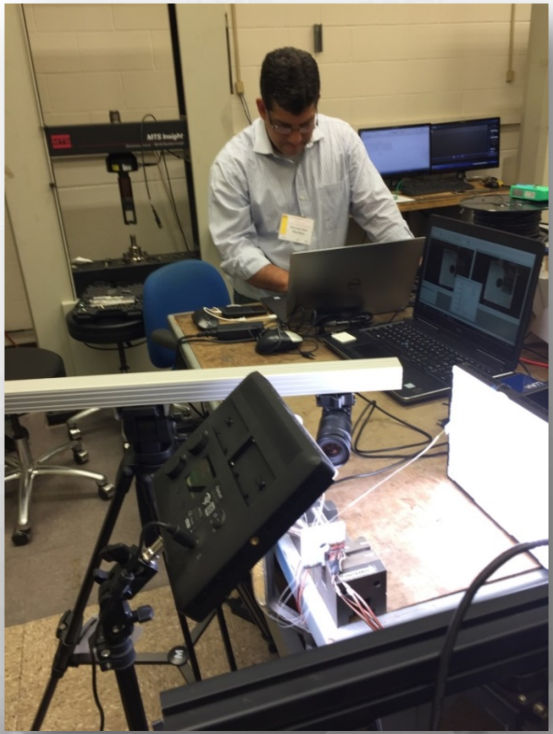
FTI FATIGUE TECHNOLOGY

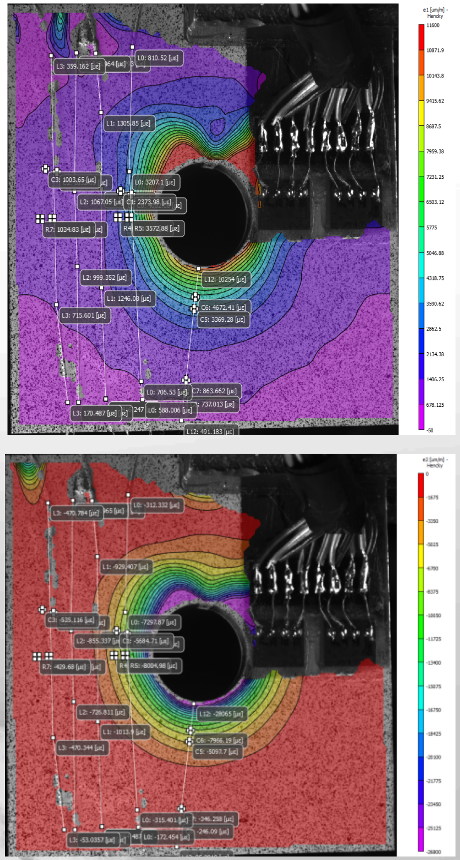
RS Process Simulation Validation

Surface Strain Measurements

- Measurements Performed at SwRI
- Both Entrance and Exit Surfaces Instrumented
- Able to Capture All Techniques Full-field Data for 6 of 8

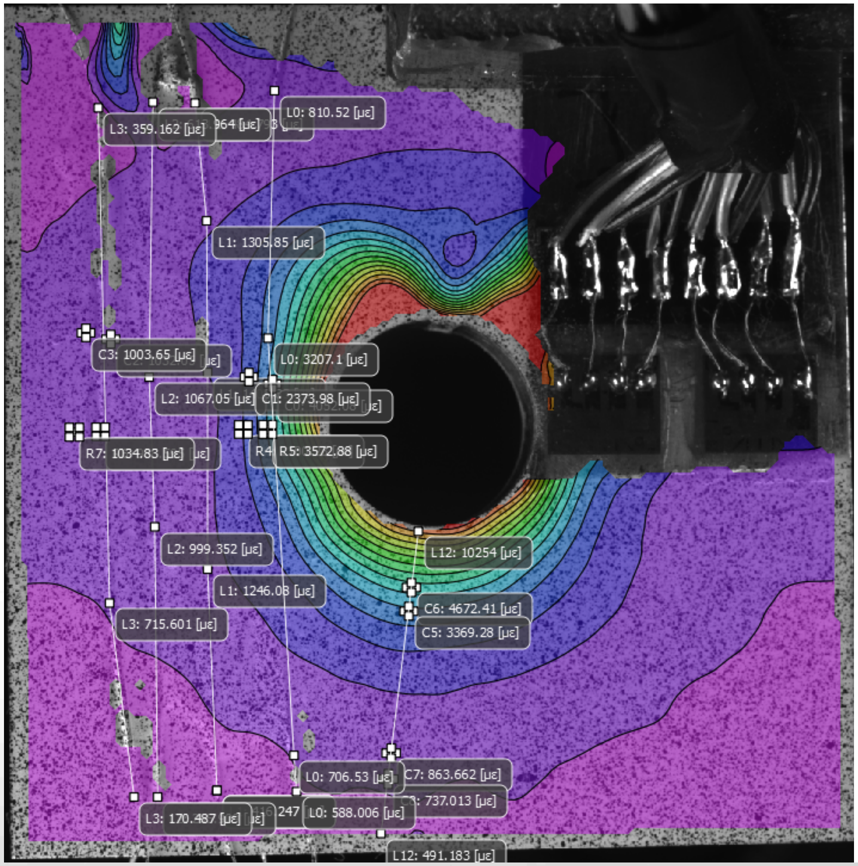




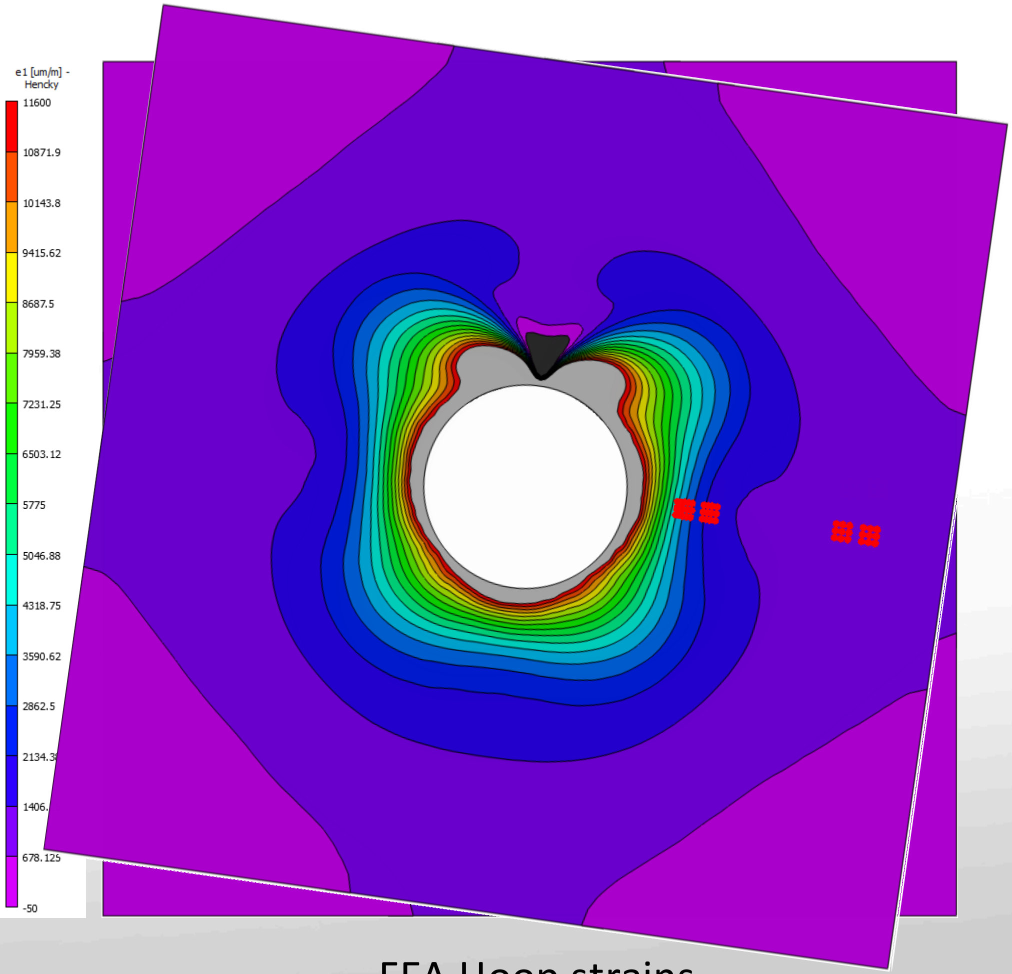


RS Process Simulation Validation

DIC vs Process Simulation Data



DIC Hoop strains



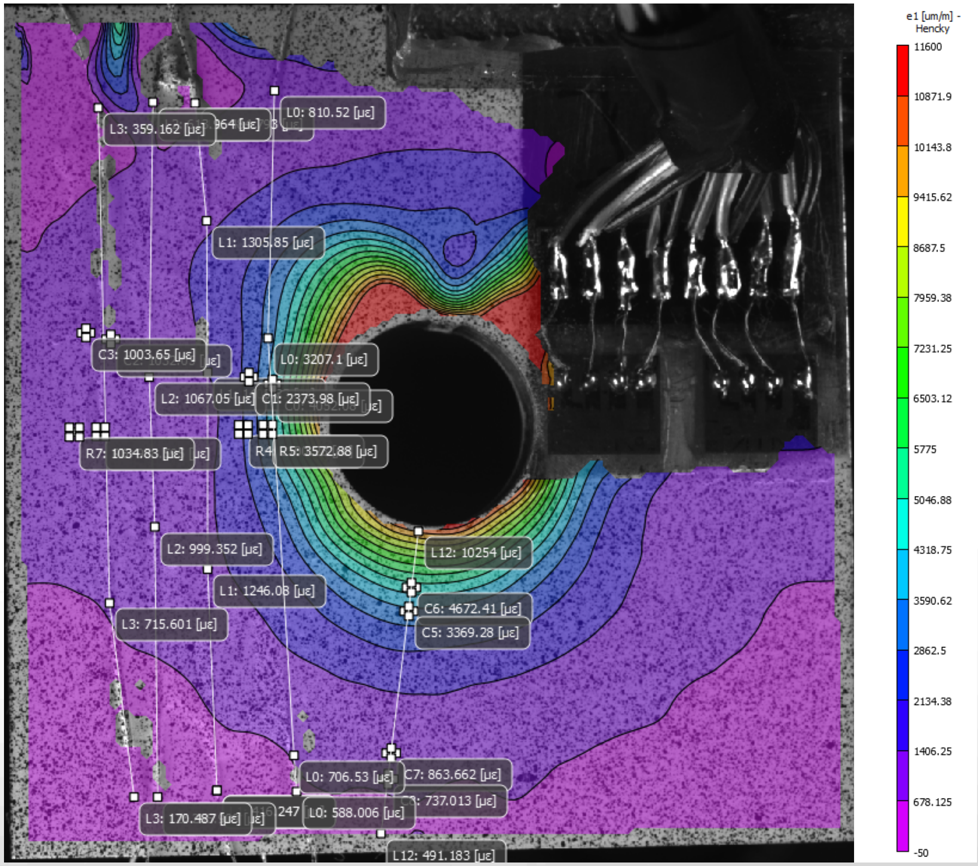
FEA Hoop strains
Combined Hardening

ERSI

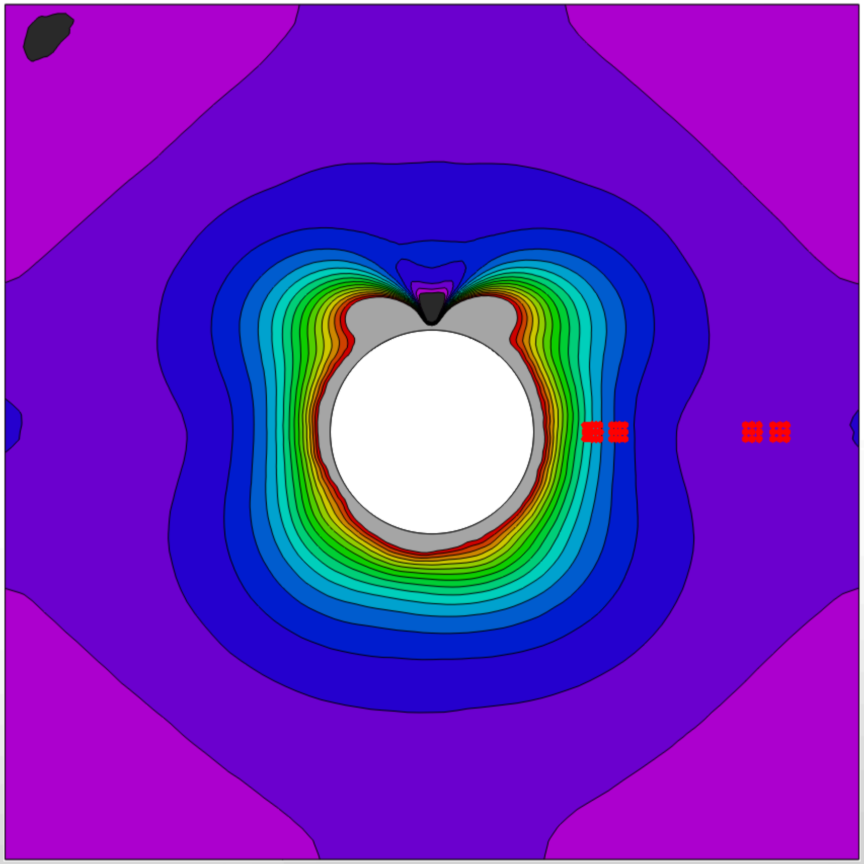
FATIGUE TECHNOLOGY

RS Process Simulation Validation

DIC vs Process Simulation Data



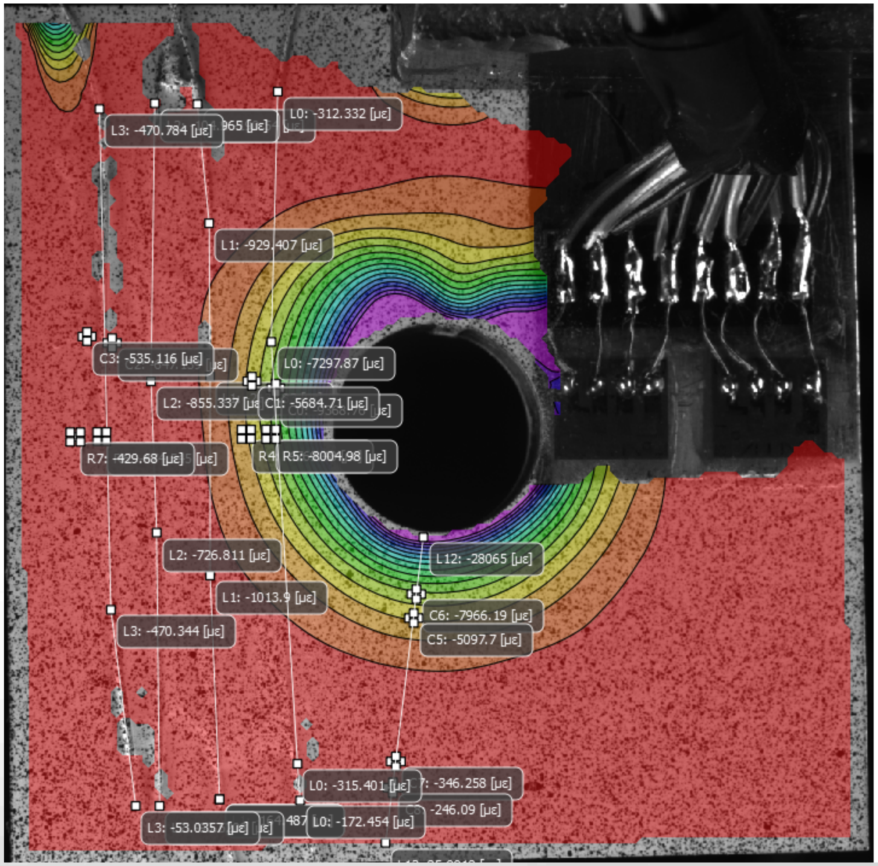
DIC Hoop strains



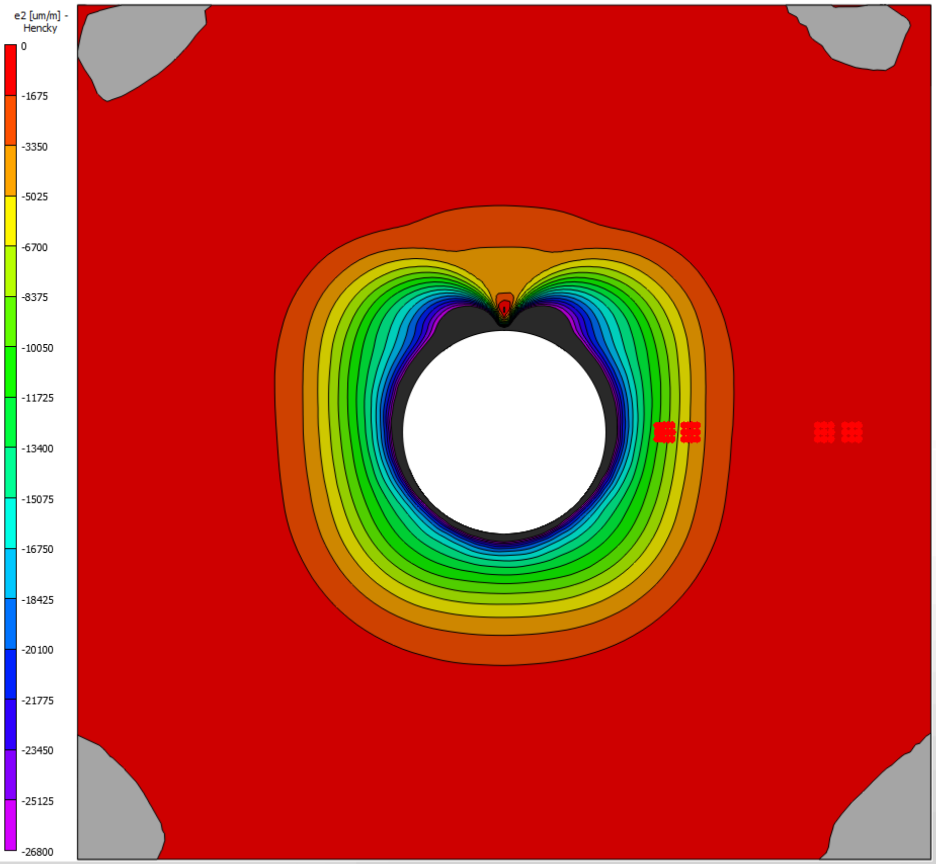
FEA Hoop strains
Chaboche Hardening

RS Process Simulation Validation

DIC vs Process Simulation Data



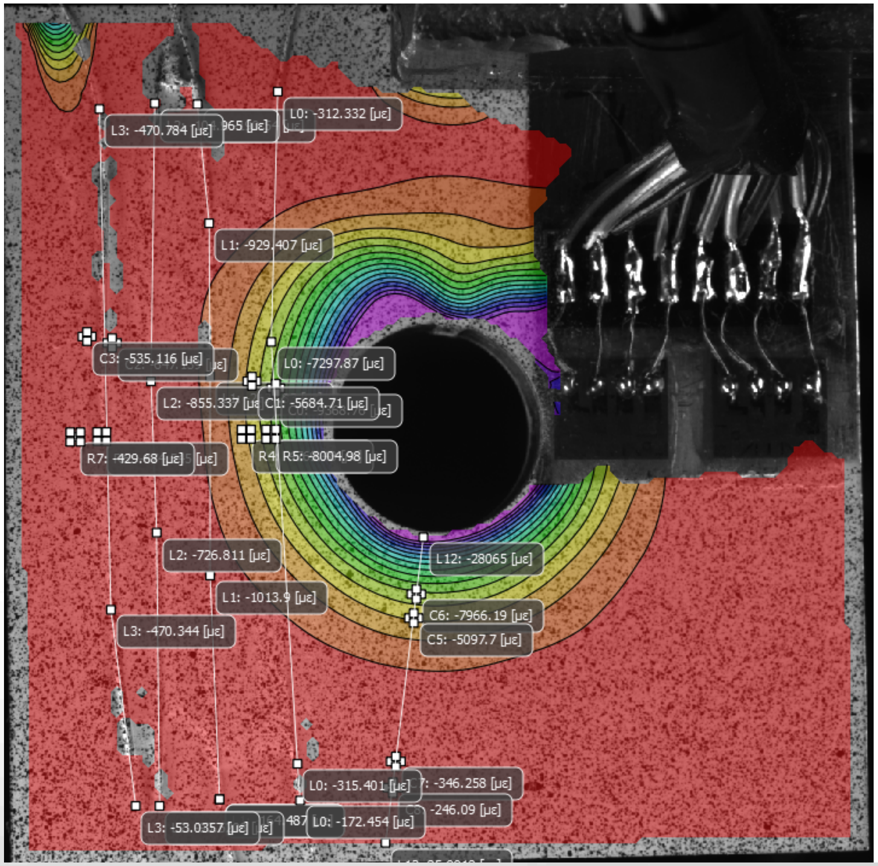
DIC Radial strains



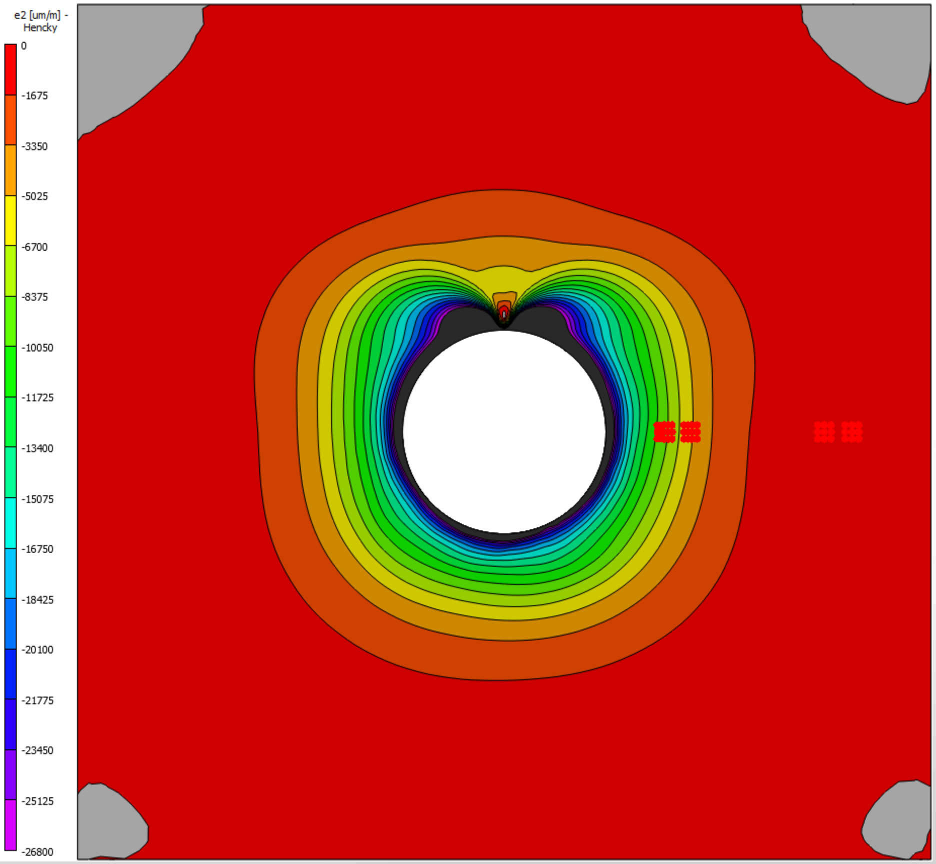
FEA Radial strains
Combined Hardening

RS Process Simulation Validation

DIC vs Process Simulation Data



DIC Radial strains

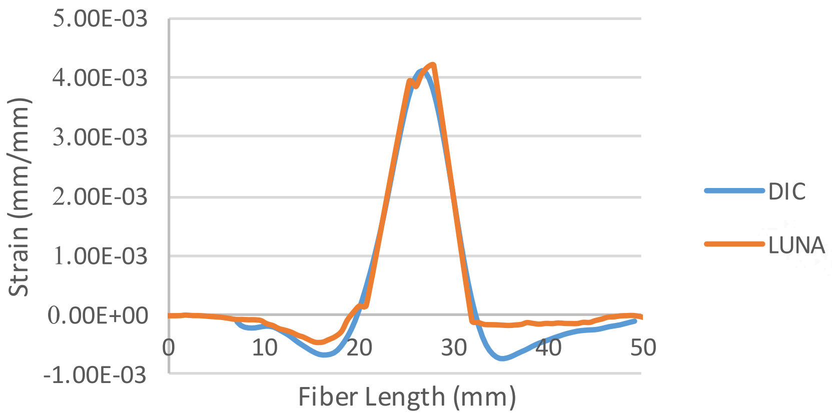


FEA Radial strains
Chaboche Hardening

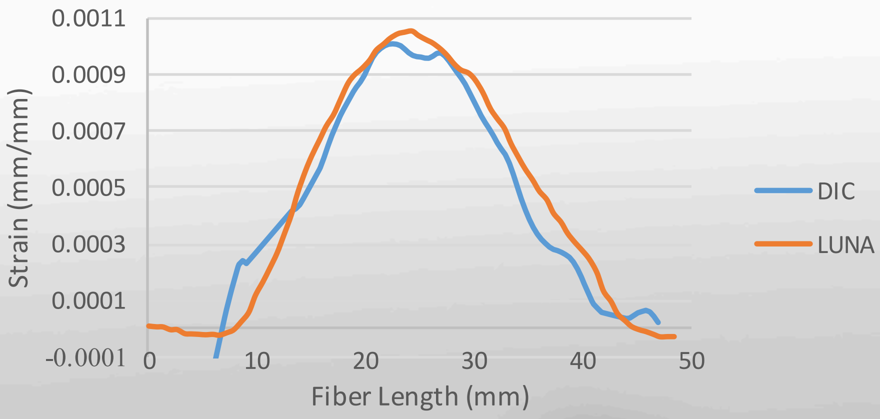
RS Process Simulation Validation

Luna/DIC vs Process Simulation Data

L0 Comparison

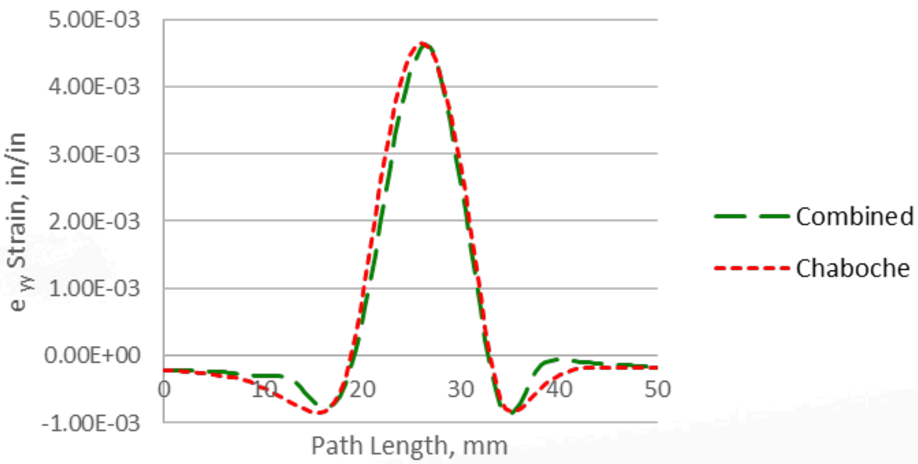


L3 Comparison

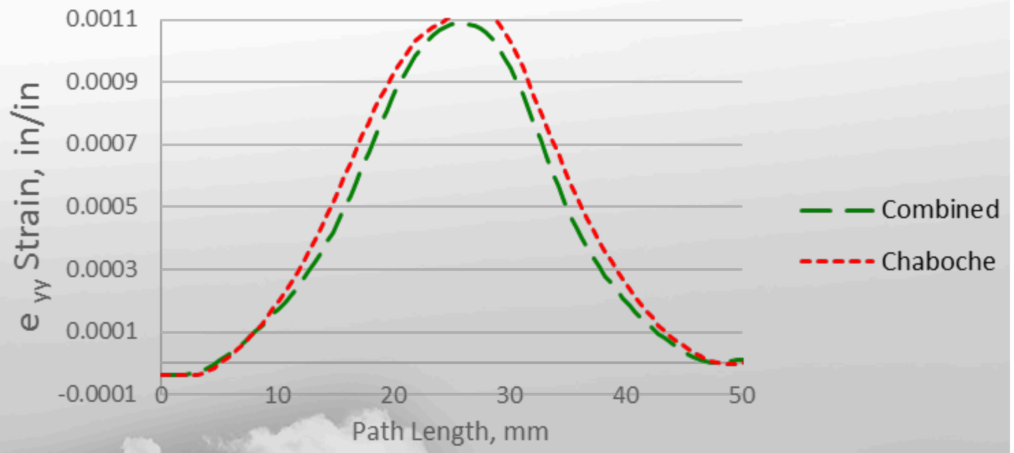


Luna/DIC e_{yy} strains

Luna Path L0, FEA Comparisons



Luna Path L3, FEA Comparisons

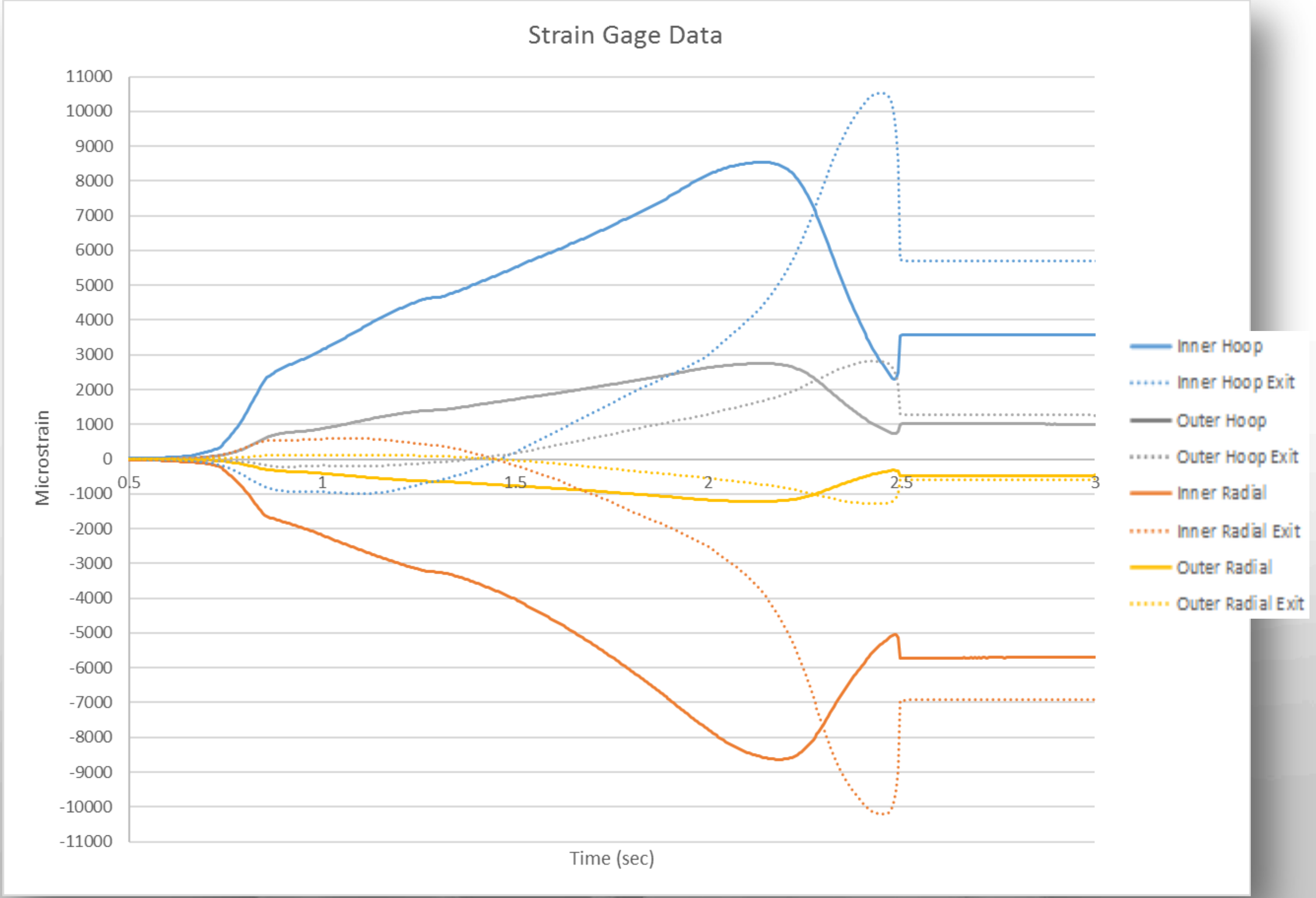


FEA e_{yy} strains

RS Process Simulation Validation

Strain Gage vs Process Simulation Data

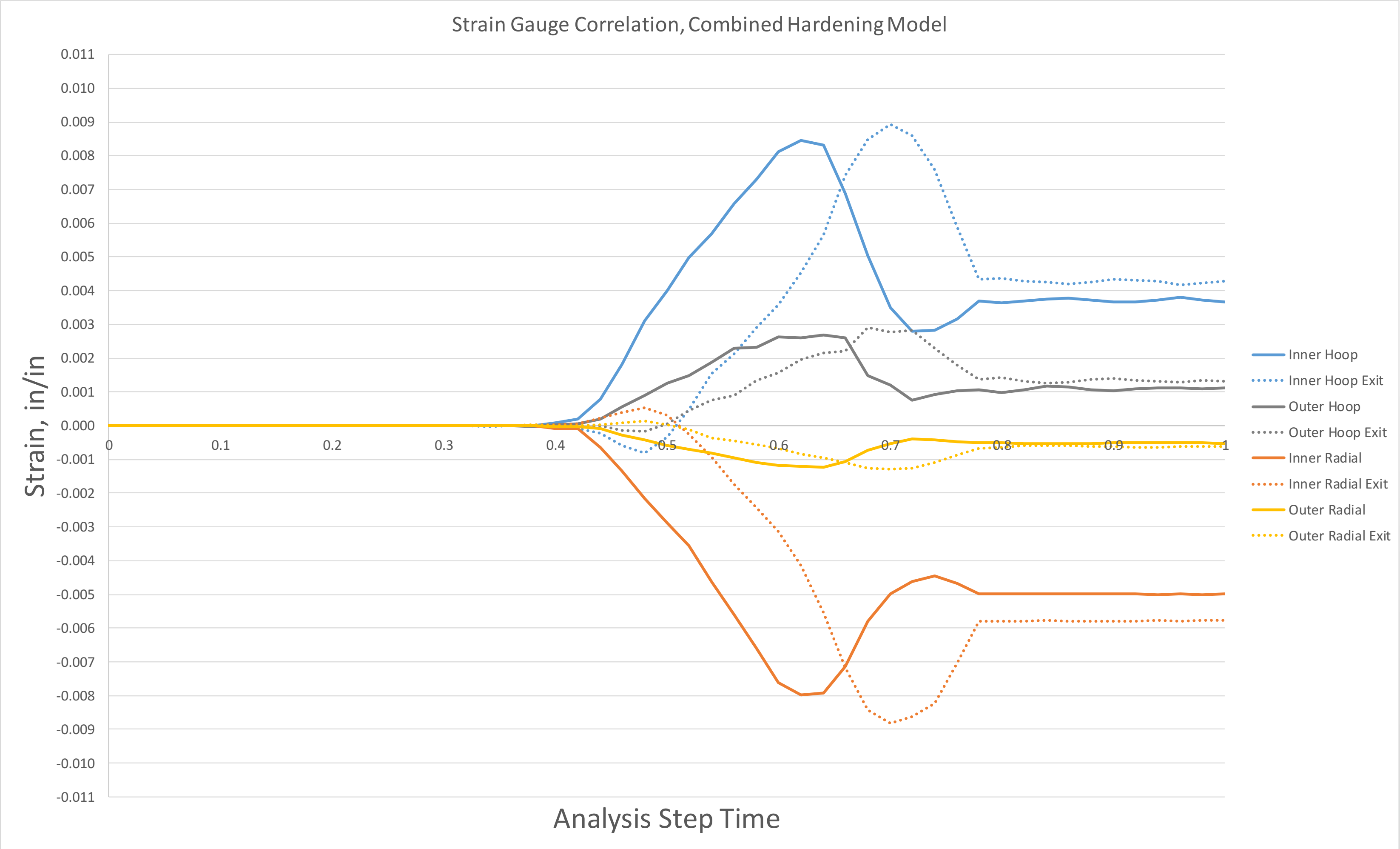
Solid Lines – Entrance **Dotted Lines – Exit**



RS Process Simulation Validation

Strain Gage vs Process Simulation Data

Solid Lines – Entrance **Dotted Lines – Exit**

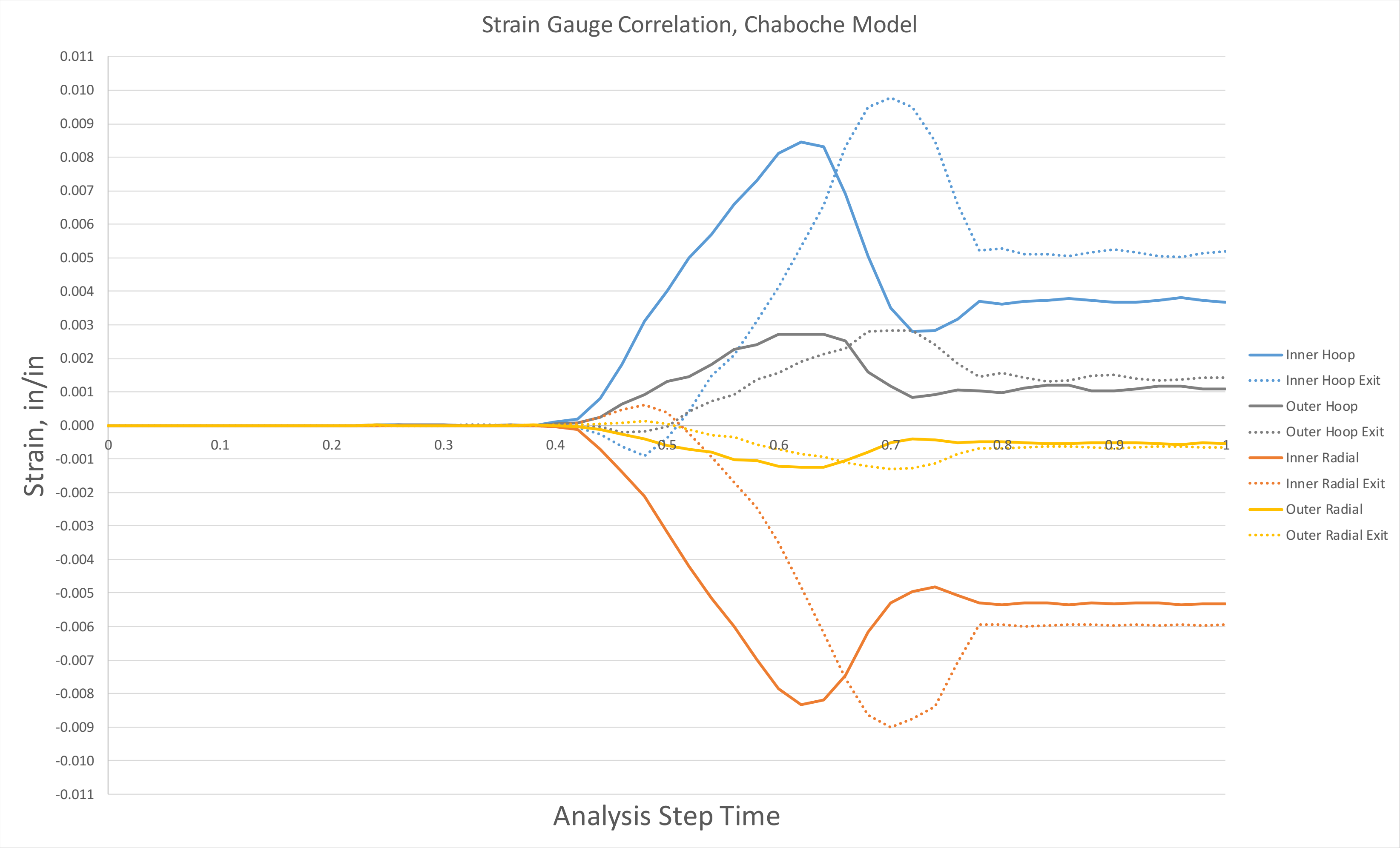


FATIGUE TECHNOLOGY

RS Process Simulation Validation

Strain Gage vs Process Simulation Data

Solid Lines – Entrance **Dotted Lines – Exit**



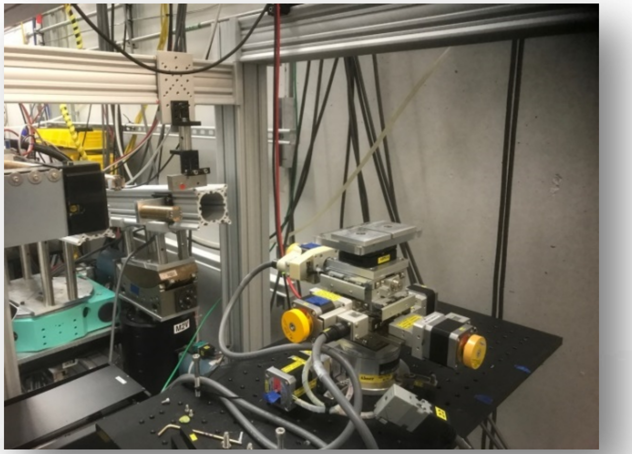
ERSI

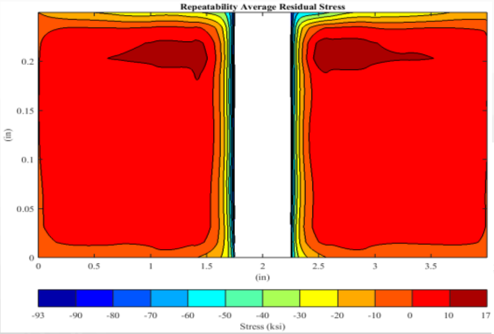
FATIGUE TECHNOLOGY

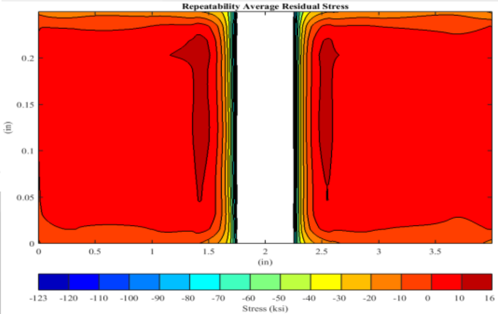
RS Process Simulation Validation

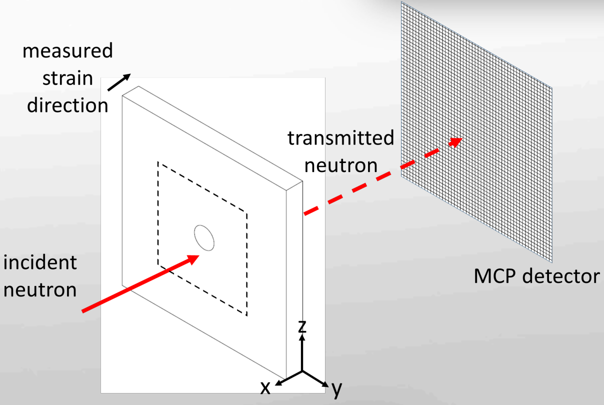
Next Steps: Thru-Thickness Measurements

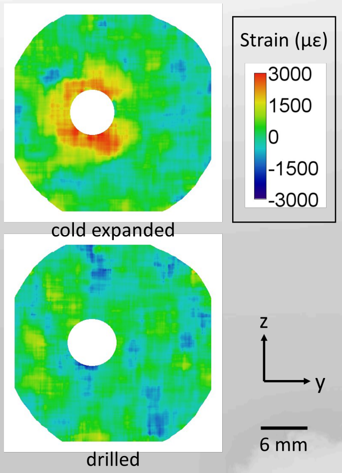
- Three Different Through-Thickness Techniques Planned:
  - High Energy X-ray Diffraction (HE-XRD); **Complete**
    - Argonne National Labs
  - Proto X-ray Diffraction; **October 2017**
    - NRC-Canada
  - Neutron diffraction; **December 2017**
    - Coventry University's IMAT
  - Contour Method; **February 2018**
    - Hill Engineering, LLC.











ERSI Residual Stress Process Simulation Sub Committee

- Dr. Scott Prost-Domasky, Analytical Processes/Engineering Solutions (AP/ES), Inc.
- Dr. Guillaume Renaud, National Research Council Canada
- Dr. Ralph Bush, United States Air Force Academy
- Marcus Stanfield, Southwest Research Institute
- Dr. Min Liao, National Research Council Canada
- Dr. Marcias Martinez, Clarkson University
- Dr. Adrian DeWald, Hill Engineering, LLC
- Dr. Keith Jones, Jones Engineering, LLC
- Robert Pilarczyk, Hill Engineering, LLC
- Dr. Mike Hill, Hill Engineering, LLC
- Matt Shultz, Fatigue Technology

Chair:
Keith Hitchman
Project Engineer, Analyst
Fatigue Technology
khitchman@fatiguetech.com
Phone: +1-206-701-7232
Mobile: +1-509-948-8240

Total Solar Eclipse
August 21, 2017
Culver, OR

HILL
ENGINEERING
Predict. Test. Perform.

ERSI

Measurements Sub-group Update

Michael R. Hill
Founder and CEO, Hill Engineering, LLC
mrhill@hill-engineering.com

Topics for Today

Measurements of stress at Legacy vs New CX holes (HE)

Measurements of Stresses at Cracked CX Holes (Carlson)

Recent Near-surface Stress Measurements (Castle)

Recent Near-bore Stress Measurements (HE)

Concept for Large Hole Experiments (HE)

Recent Cross-method Residual Stress Validations

- LSP, Al 7050T7451
- Die forgings, Al 7085-T74 and 7085-T7452

HILL
ENGINEERING
Predict. Test. Perform.

ERSI

Measurements Sub-group Update

Legacy vs New CX Residual Stress Evaluations

Legacy vs New CX Residual Stress Evaluations

Purpose: Compare coldworked holes from legacy assets to new manufactured coupons

- Legacy assets were all high hour wings and had mixed usages

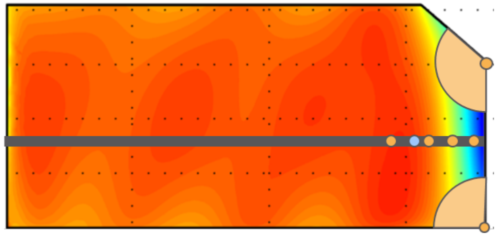
Performed ~200 measurements in teardown assets from 2 USAF aircraft types

- All assets had significant flight history

Performed ~100 measurements in new manufactured coupons

- That match geometry and materials in teardown assets

For each measurement complied:

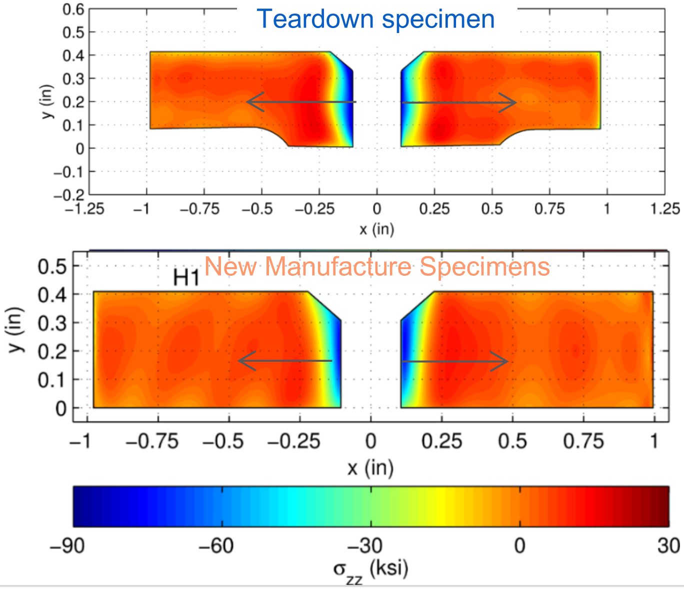


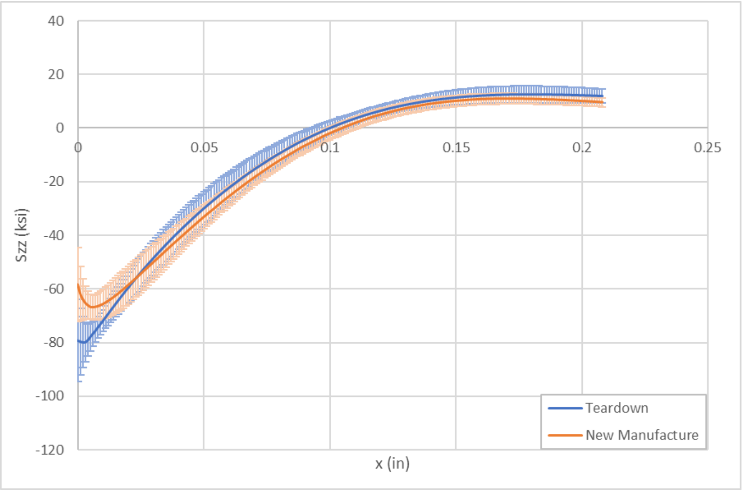
- Contour plot of residual stress
- Line plot of mid-thickness residual stress
- Tabulation of stress field characteristics
  - Stress at specific normalized distances: 0.125*r, 0.25*r, 0.50*r, 0.75*r
  - Depth of zero-crossing
  - Separate for LH and RH side, where geometry is different
  - Mean and standard deviation within 0.050” radial zone centered at:
    - Entry surface
    - Exit surface / countersink knee (if applicable)

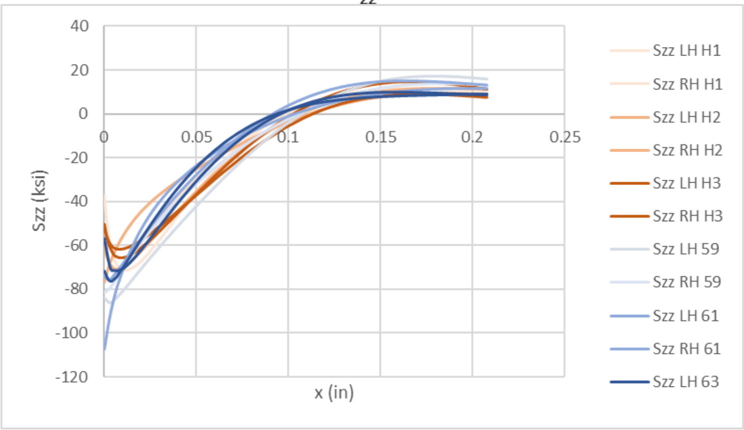
For each group of similar holes characterize differences:

- Statistical analysis: compare means and standard deviations
- Spatial field difference: Contour plots of difference between means of new manufacture and teardown

Legacy vs New CX Comparison #1

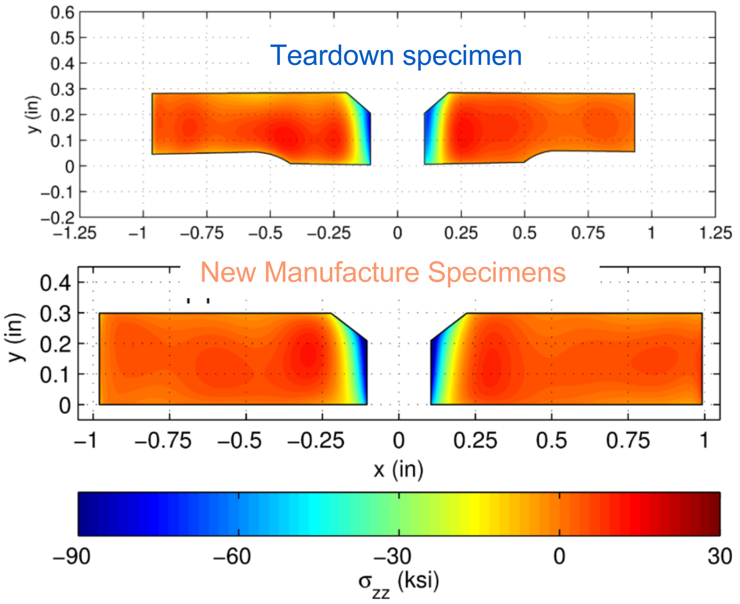


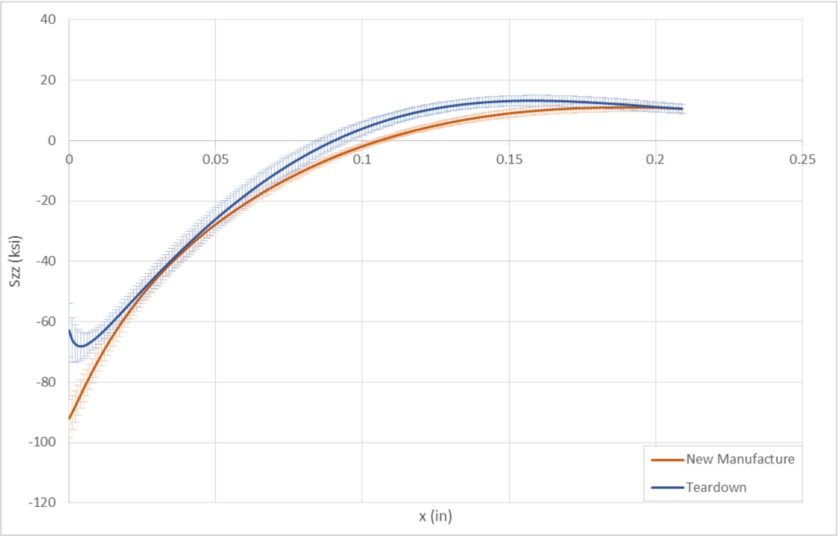


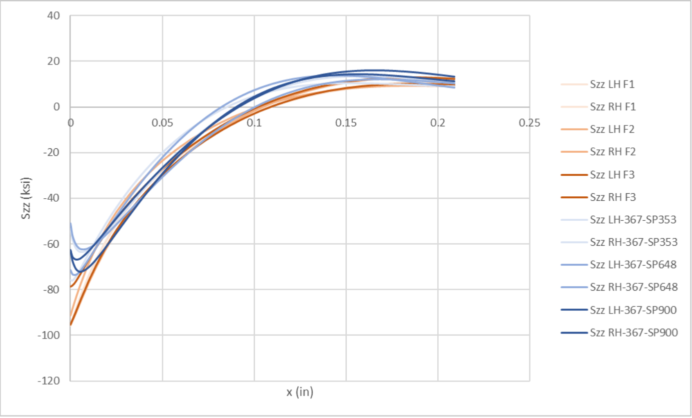


Sample ID	Midthickness 0.125*rad	Midthickness 0.25*rad	Midthickness 0.5*rad	Midthickness 0.75*rad	Depth at crossover (midthickness)	Point Value of Entrance	Avg RS in 0.05" Radius Entrance	Standard Deviation of Avg RS in 0.05" Radius CSK Entrance	Point Value CSK Knee	Avg RS in 0.05" Radius CSK knee	Standard Deviation of Avg RS in 0.05" Radius CSK Knee
L-59	-75.54	-62.37	-38.23	-17.06	0.11	-41.55	-42.52	12.53	-64.33	-67.77	8.86
R-59	-64.36	-50.39	-28.75	-12.05	0.11	-64.08	-30.42	14.86	-71.14	-54.33	12.20
L-61	-62.45	-48.14	-24.19	-5.89	0.09	-28.52	-34.95	9.23	-63.39	-59.91	10.61
R-61	-60.65	-41.99	-20.82	-7.91	0.10	-39.61	-33.14	13.49	-76.55	-60.63	14.44
L-63	-66.68	-53.25	-26.83	-7.67	0.10	-14.52	-37.40	8.14	-62.45	-61.08	10.12
R-63	-63.46	-46.85	-20.96	-5.06	0.09	-35.68	-34.90	11.51	-69.72	-56.33	13.47
L-H1	-65.31	-50.67	-26.36	-8.31	0.10	-20.19	-35.79	8.86	-62.90	-58.60	10.04
R-H1	-70.67	-60.17	-31.85	-9.90	0.10	-39.71	-33.49	9.47	-41.25	-62.40	8.67
L-H2	-50.49	-38.61	-23.31	-11.22	0.11	-34.93	-28.68	9.45	-69.66	-51.47	10.46
R-H2	-67.34	-55.92	-32.30	-13.30	0.11	-22.62	-35.97	9.23	-53.31	-66.29	8.02
L-H3	-60.45	-53.04	-34.46	-16.40	0.11	-40.85	-36.05	8.28	-57.51	-56.82	5.93
R-H3	-64.40	-55.64	-33.52	-13.27	0.10	-23.61	-32.05	6.60	-50.19	-65.40	8.68
Mean	**-65.52**	**-50.50**	**-26.63**	**-9.27**	**0.10**	**-37.33**	**-35.56**	**11.63**	**-67.93**	**-60.01**	**11.62**
Stdev	**4.84**	**6.32**	**5.93**	**4.12**	**0.01**	**14.94**	**3.76**	**2.33**	**5.03**	**4.23**	**1.94**
Mean	**-63.11**	**-52.34**	**-30.30**	**-12.07**	**0.11**	**-30.32**	**-33.67**	**8.65**	**-55.80**	**-60.17**	**8.63**
Stdev	**6.43**	**6.79**	**4.05**	**2.62**	**0.01**	**8.44**	**2.68**	**1.00**	**9.08**	**5.15**	**1.47**
Residuals (Td-NM)	**-2.41**	**1.84**	**3.67**	**2.79**	**-0.01**	**-7.01**	**-1.88**	**2.98**	**-12.13**	**0.16**	**2.98**

Legacy vs New CX Comparison #2



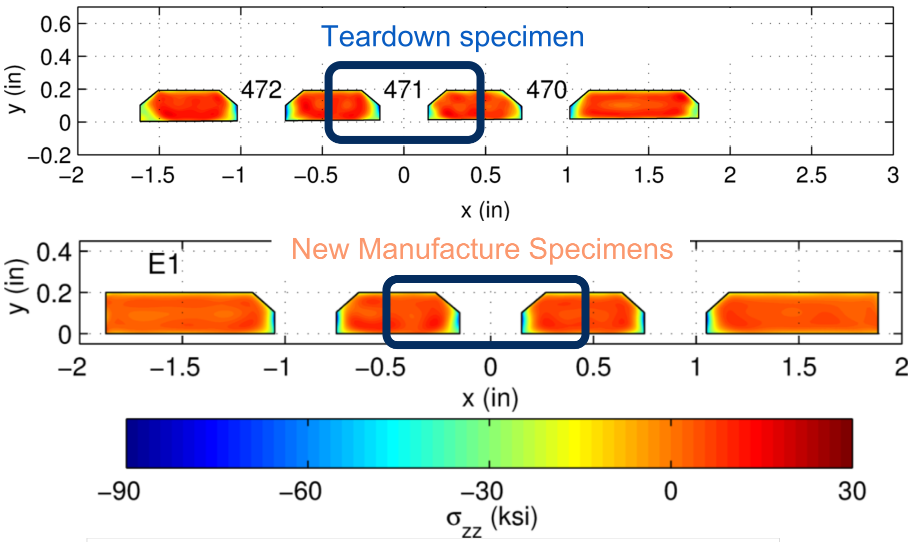


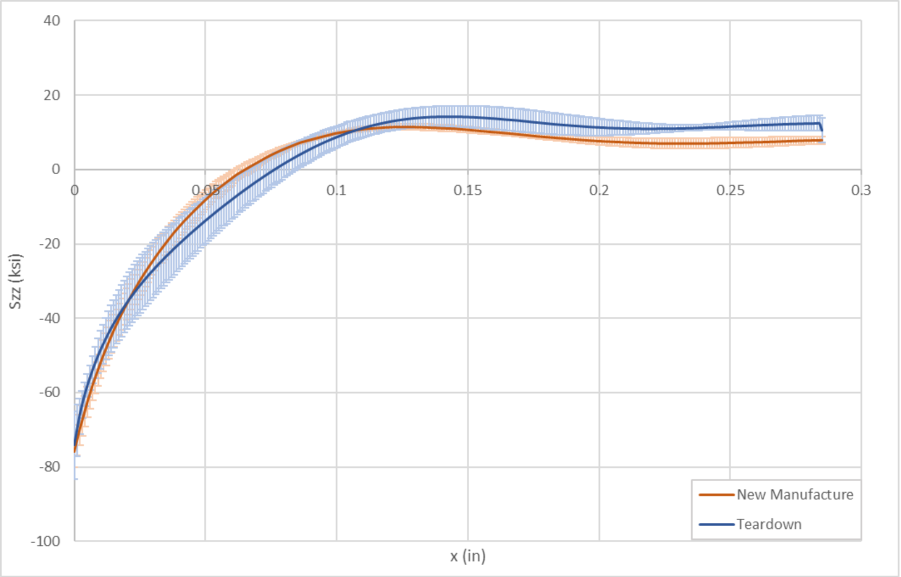


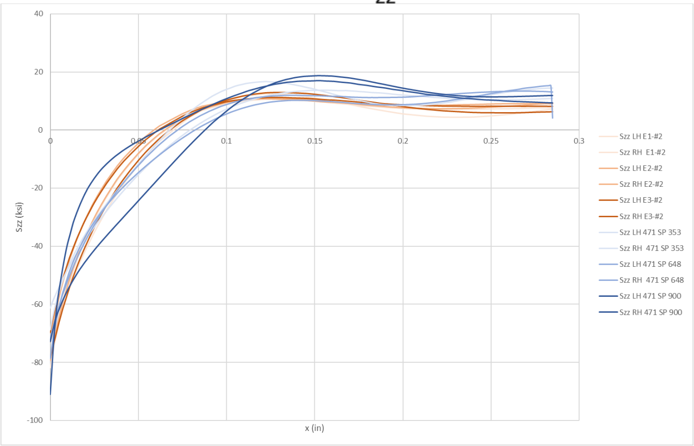
Sample ID	Midthickness 0.125*rad	Midthickness 0.25*rad	Midthickness 0.5*rad	Midthickness 0.75*rad	Depth at crossover (midthickness)	Point Value of Entrance	Avg RS in 0.05" Radius Entrance	Standard Deviation of Avg RS in 0.05" Radius	Point Value CSK Knee	Avg RS in 0.05" Radius CSK knee	Standard Deviation of Avg RS in 0.05" Radius
L-367-SP-353	-57.75	-40.98	-16.85	-1.76	0.09	-45.86	-39.54	11.79	-76.97	-55.74	14.75
R-367-SP-353	-59.44	-47.42	-23.56	-5.23	0.09	-28.27	-40.02	8.30	-60.03	-57.68	9.85
L-367-SP-648	-59.55	-49.30	-27.55	-9.76	0.10	-27.42	-43.94	9.54	-87.46	-58.51	12.76
R-367-SP-648	-61.16	-44.86	-18.70	-0.89	0.08	-39.95	-41.40	12.06	-51.24	-54.08	11.07
L-367-SP-900	-59.16	-46.32	-23.50	-5.73	0.09	-36.75	-34.98	10.61	-61.42	-57.69	9.70
R-367-SP-900	-66.43	-52.31	-25.40	-5.25	0.09	-17.48	-40.14	8.34	-68.11	-68.06	11.08
L-F1-A-1	-66.56	-48.51	-25.17	-10.31	0.11	-63.75	-44.42	15.80	-107.97	-68.49	19.65
R-F1-A-1	-66.81	-48.83	-25.43	-10.67	0.11	-57.40	-43.72	14.68	-106.92	-69.89	19.04
L-F2-A-1	-61.15	-43.57	-21.43	-7.87	0.10	-64.50	-45.22	14.04	-109.29	-69.40	18.99
R-F2-A-1	-70.03	-52.05	-27.35	-10.88	0.11	-51.73	-43.98	14.33	-96.44	-69.07	17.17
L-F3-A-1	-61.32	-46.53	-24.88	-9.58	0.10	-24.47	-36.79	8.08	-89.53	-63.45	15.88
R-F3-A-1	-69.31	-51.50	-27.41	-11.69	0.11	-70.21	-45.59	18.01	-98.54	-69.59	16.78
Mean	**-60.58**	**-46.86**	**-22.59**	**-4.77**	**0.09**	**-32.62**	**-40.00**	**10.11**	**-67.54**	**-58.62**	**11.54**
Stdev	**2.80**	**3.53**	**3.70**	**2.90**	**0.01**	**9.32**	**2.67**	**1.51**	**11.87**	**4.47**	**1.75**
Mean	**-65.86**	**-48.50**	**-25.28**	**-10.16**	**0.11**	**-55.34**	**-43.29**	**14.16**	**-101.45**	**-68.32**	**17.92**
Stdev	**3.50**	**2.88**	**1.99**	**1.21**	**0.00**	**14.98**	**2.98**	**3.02**	**7.18**	**2.22**	**1.38**
Residuals (Td-NM)	**5.28**	**1.63**	**2.69**	**5.39**	**-0.02**	**22.72**	**3.29**	**-4.05**	**33.91**	**9.69**	**-6.38**

HILL ENGINEERING

Legacy vs New CX Comparison #3







Sample ID	Midthickness 0.125*rad	Midthickness 0.25*rad	Midthickness 0.5*rad	Midthickness 0.75*rad	Depth at crossover (midthickness)	Point Value of Entrance	Avg RS in 0.05" Radius Entrance	Standard Deviation of Avg RS in 0.05" Radius	Point Value CSK Knee	Avg RS in 0.05" Radius CSK knee	Standard Deviation of Avg RS in 0.05" Radius
L-471-SP-353	-38.27	-23.51	-1.98	9.88	0.08	-32.82	-32.63	9.52	-85.89	-41.64	17.17
R-471-SP-353	-36.42	-20.73	4.01	16.06	0.07	-71.76	-32.80	12.26	-108.57	-30.08	22.33
L-471-SP-648	-37.22	-21.54	-2.28	8.35	0.08	-62.31	-42.46	15.71	-100.42	-33.44	18.77
R-471-SP-648	-38.21	-20.14	1.92	10.94	0.07	-114.88	-40.84	12.70	-76.90	-29.88	19.33
L-471-SP-900	-45.72	-32.40	-7.94	11.57	0.09	-38.19	-42.59	8.96	-104.07	-41.04	20.04
R-471-SP-900	-22.24	-8.55	3.94	13.42	0.06	-83.09	-32.75	16.34	-106.09	-25.65	24.46
L-F1-A-1	-41.79	-21.34	2.96	11.94	0.07	-52.82	-34.58	11.09	-74.22	-34.79	20.55
R-F1-A-1	-37.72	-16.80	3.93	10.29	0.07	-62.93	-37.82	14.91	-73.87	-33.44	21.08
L-E2-A-2	-30.98	-11.99	5.89	10.65	0.06	-82.34	-34.28	12.85	-69.24	-28.34	21.92
R-E2-A-2	-37.04	-16.46	4.25	10.75	0.07	-40.32	-40.24	11.91	-55.55	-33.76	20.10
L-E3-A-2	-31.14	-13.04	5.02	10.80	0.06	-88.50	-34.31	12.03	-70.76	-27.72	20.41
R-E3-A-2	-40.33	-19.53	3.55	12.17	0.07	-62.43	-40.65	12.49	-75.57	-32.47	20.94
Mean	**-36.35**	**-21.15**	**-0.39**	**11.70**	**0.08**	**-67.18**	**-37.35**	**12.58**	**-96.99**	**-33.62**	**20.35**
Stdev	**7.01**	**6.98**	**4.21**	**2.49**	**0.01**	**27.67**	**4.65**	**2.78**	**11.59**	**5.91**	**2.40**
Mean	**-36.50**	**-16.53**	**4.27**	**11.10**	**0.07**	**-64.89**	**-36.98**	**12.55**	**-69.87**	**-31.75**	**20.83**
Stdev	**4.16**	**3.29**	**0.96**	**0.70**	**0.00**	**16.44**	**2.74**	**1.19**	**6.75**	**2.72**	**0.58**
Residuals (Td-NM)	**0.15**	**-4.62**	**-4.66**	**0.60**	**0.01**	**-2.29**	**-0.37**	**0.03**	**-27.13**	**-1.87**	**-0.49**

HILL ENGINEERING

Legacy vs New CX Summary

Comparisons completed to date show no statistically significant difference between

Residual stresses at CX holes in teardown assets and

Residual stresses at CX holes in newly manufactured coupons

But, there are some differences in the data sets

- Largest differences are in areas of largest scatter in underlying populations
  - Scatter in populations may be due to combined effects of process variation and measurement uncertainty
- In single populations of replicate holes, sample-to-sample variations are similar in new manufacture and teardown
  - May indicate similar degree of process quality

In the present data, we see no measurable effect of service loading on residual stresses in cold worked holes

Finalizing work and completing comparisons (teardown vs. new manufacture)

Detailed investigation where "differences" are observed in Level I comparison

HILL
ENGINEERING
Predict. Test. Perform.

ERSI

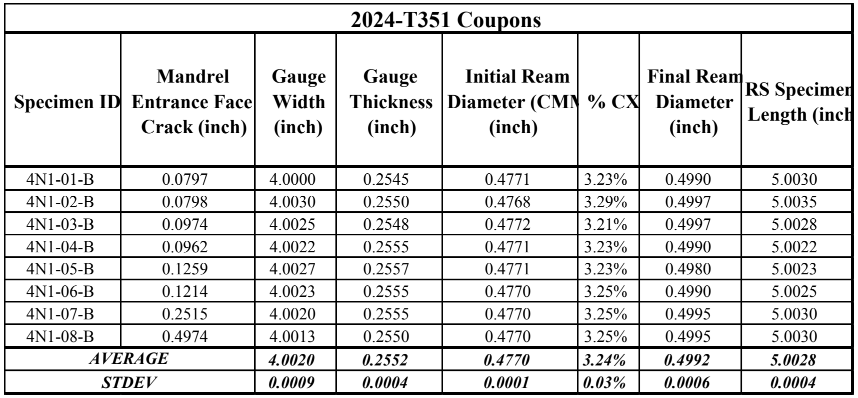
Measurements Sub-group Update

Contour Measurements in Cracked Coupons

Provided by Scott Carlson, SwRI

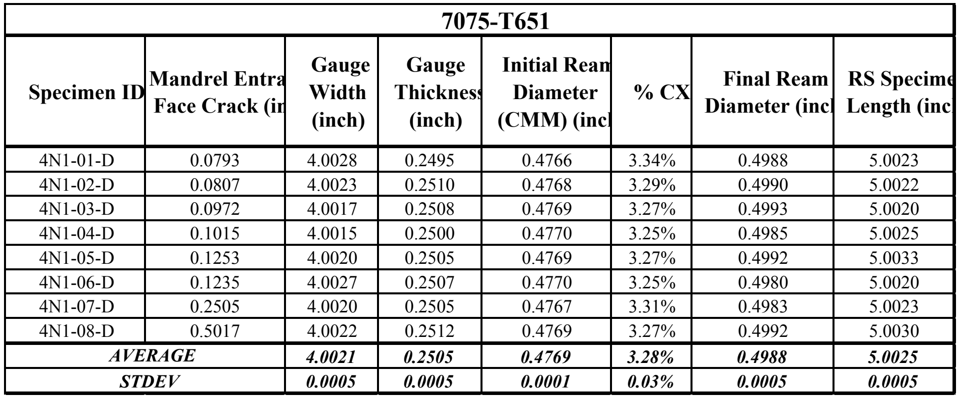
From Scott Carlson: Influence of a Fatigue Crack

- Hypothesis:
    - *"The presence of a fatigue crack changes the residual stress field induced by the Cold Expansion (Cx) process within aerospace-grade aluminum alloys, namely 2024-T351 and 7075-T651"*
- Procedure for Testing Hypothesis
    - Develop baseline Cx coupons, no fatigue crack coupons
    - Develop fatigue cracks via constant amplitude loading in identical Cx coupons
        - Range of crack sizes, stress = 25ksi or 26.5ksi, R = 0.1
    - Focus on "Low" applied expansion level for all Cx holes



2024-T351 Coupons

Specimen ID	Mandrel Entrance Face Crack (inch)	Gauge Width (inch)	Gauge Thickness (inch)	Initial Ream Diameter (CMM (inch)	% CX	Final Ream Diameter (inch)	RS Specimen Length (inch
4N1-01-B	0.0797	4.0000	0.2545	0.4771	3.23%	0.4990	5.0030
4N1-02-B	0.0798	4.0030	0.2550	0.4768	3.29%	0.4997	5.0035
4N1-03-B	0.0974	4.0025	0.2548	0.4772	3.21%	0.4997	5.0028
4N1-04-B	0.0962	4.0022	0.2555	0.4771	3.23%	0.4990	5.0022
4N1-05-B	0.1259	4.0027	0.2557	0.4771	3.23%	0.4980	5.0023
4N1-06-B	0.1214	4.0023	0.2555	0.4770	3.25%	0.4990	5.0025
4N1-07-B	0.2515	4.0020	0.2555	0.4770	3.25%	0.4995	5.0030
4N1-08-B	0.4974	4.0013	0.2550	0.4770	3.25%	0.4995	5.0030
AVERAGE		***4.0020***	***0.2552***	***0.4770***	***3.24%***	***0.4992***	***5.0028***
STDEV		***0.0009***	***0.0004***	***0.0001***	***0.03%***	***0.0006***	***0.0004***

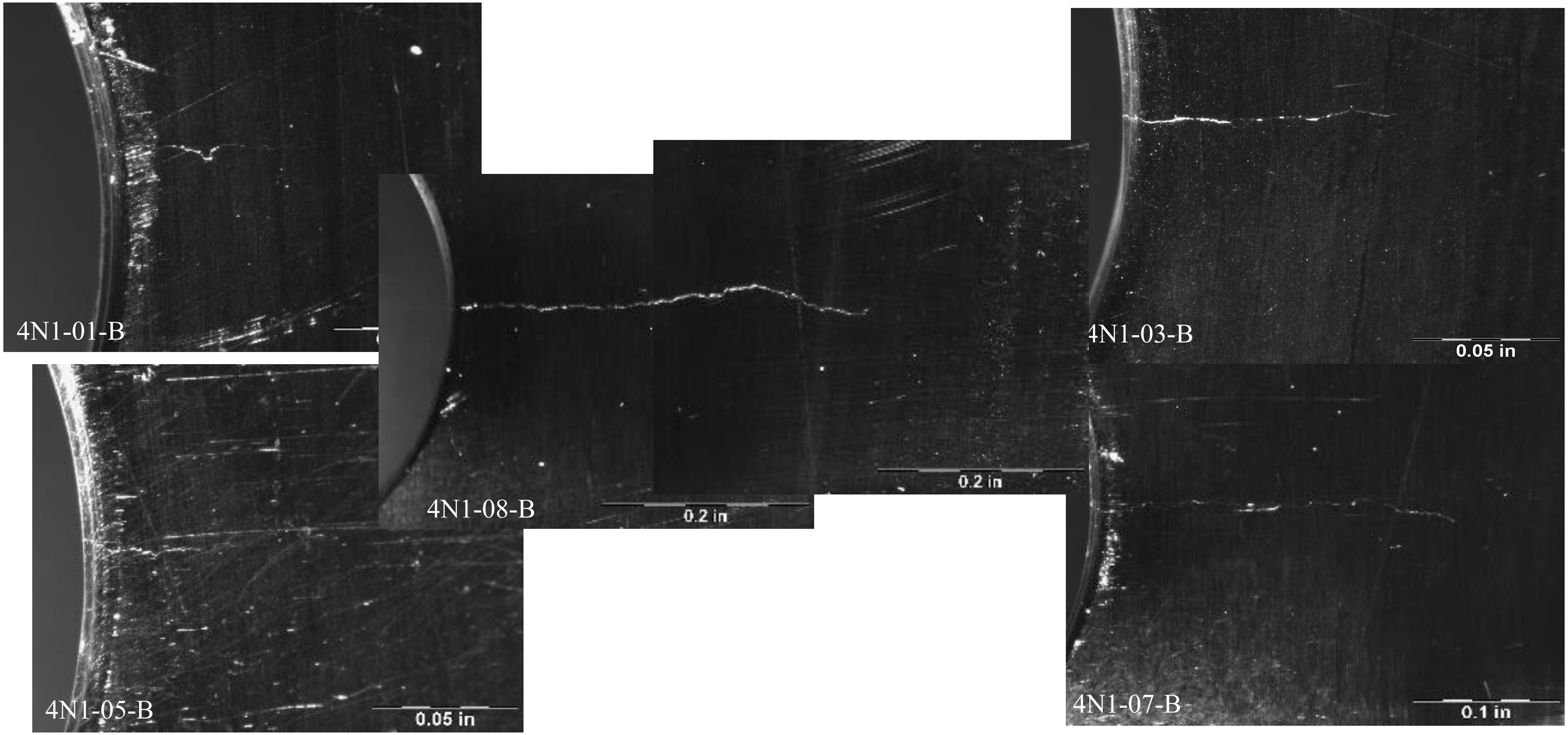


7075-T651

Specimen ID	Mandrel Entra Face Crack (in	Gauge Width (inch)	Gauge Thickness (inch)	Initial Ream Diameter (CMM) (incl	% CX	Final Ream Diameter (inc	RS Specime Length (inc
4N1-01-D	0.0793	4.0028	0.2495	0.4766	3.34%	0.4988	5.0023
4N1-02-D	0.0807	4.0023	0.2510	0.4768	3.29%	0.4990	5.0022
4N1-03-D	0.0972	4.0017	0.2508	0.4769	3.27%	0.4993	5.0020
4N1-04-D	0.1015	4.0015	0.2500	0.4770	3.25%	0.4985	5.0025
4N1-05-D	0.1253	4.0020	0.2505	0.4769	3.27%	0.4992	5.0033
4N1-06-D	0.1235	4.0027	0.2507	0.4770	3.25%	0.4980	5.0020
4N1-07-D	0.2505	4.0020	0.2505	0.4767	3.31%	0.4983	5.0023
4N1-08-D	0.5017	4.0022	0.2512	0.4769	3.27%	0.4992	5.0030
AVERAGE		***4.0021***	***0.2505***	***0.4769***	***3.28%***	***0.4988***	***5.0025***
STDEV		***0.0005***	***0.0005***	***0.0001***	***0.03%***	***0.0005***	***0.0005***

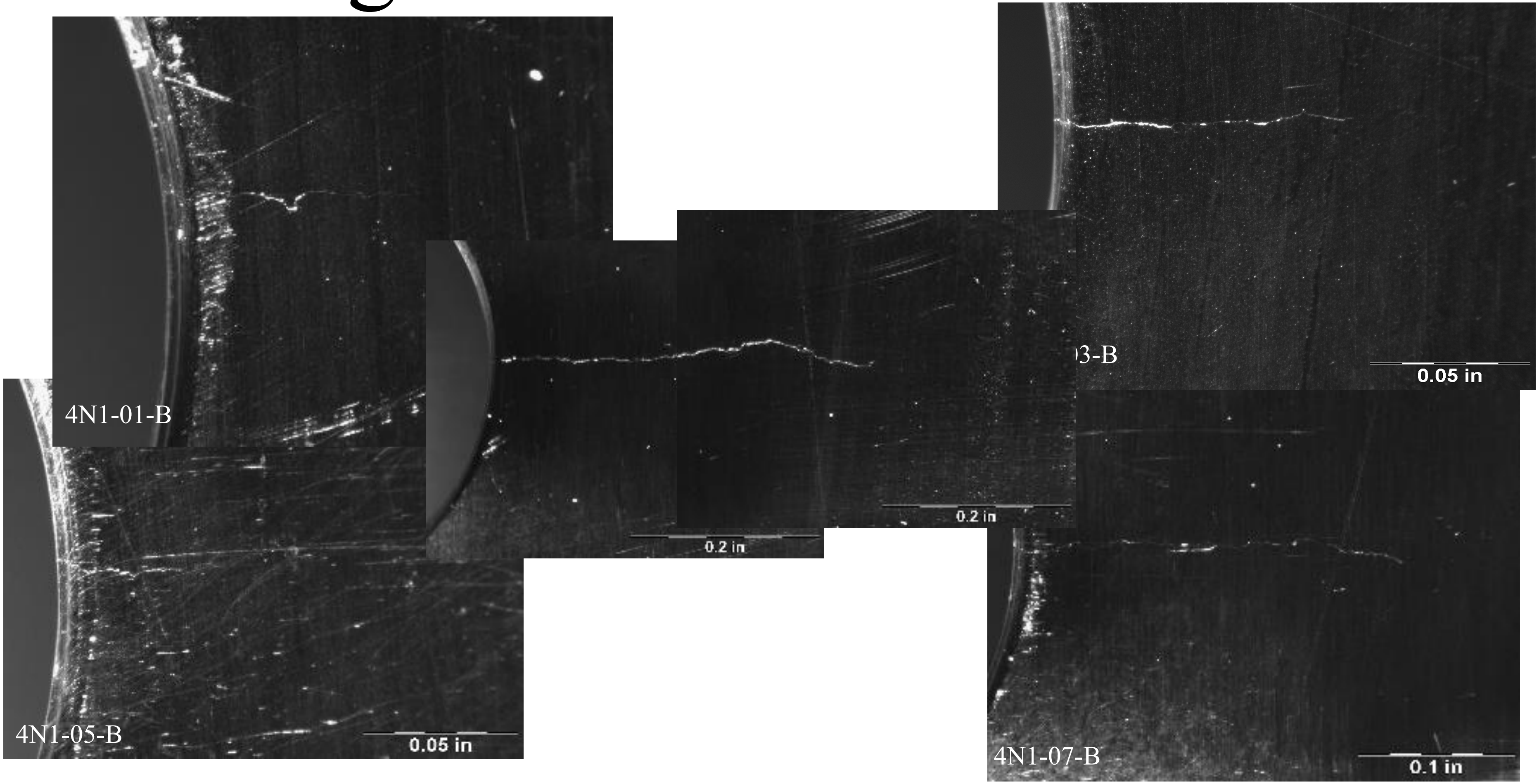
Provided by Scott Calrson

Fatigue Cracks in 2024-T351



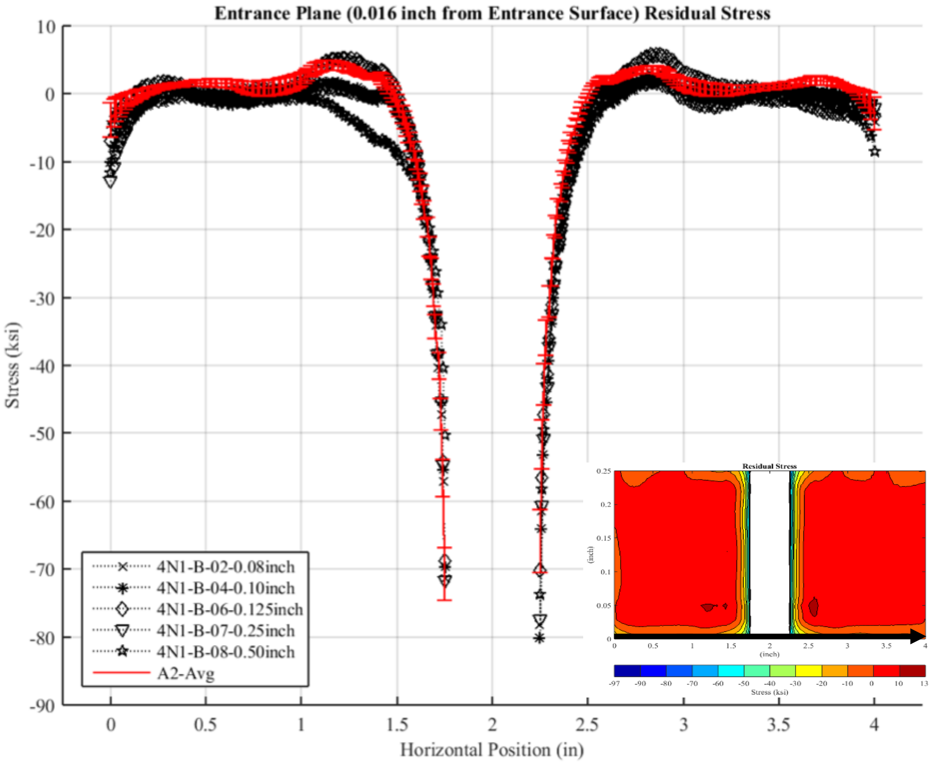
Provided by Scott Calrson

Fatigue Cracks in 7075-T651



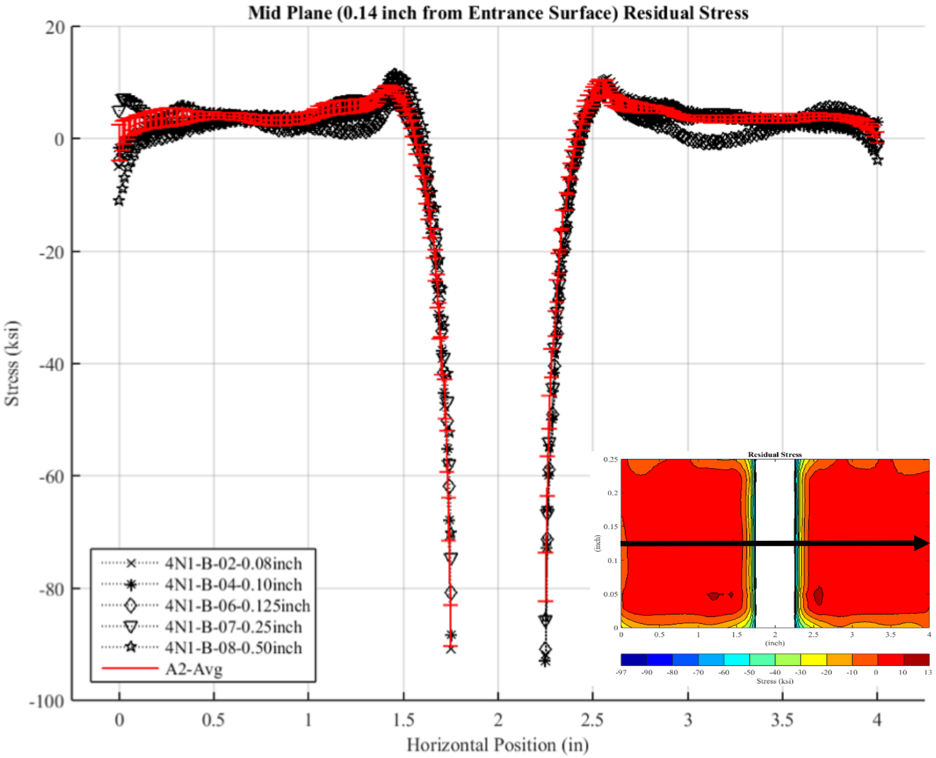
Provided by Scott Calrson

Residual Stresses in 2024-T351



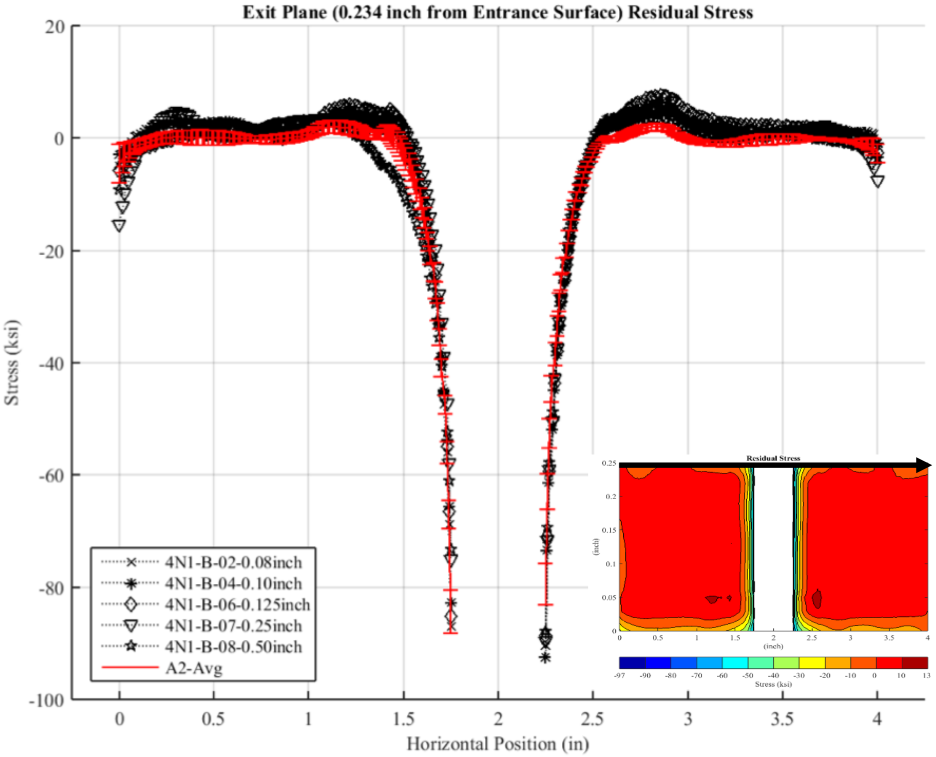
Provided by Scott Calrson

Residual Stresses in 2024-T351



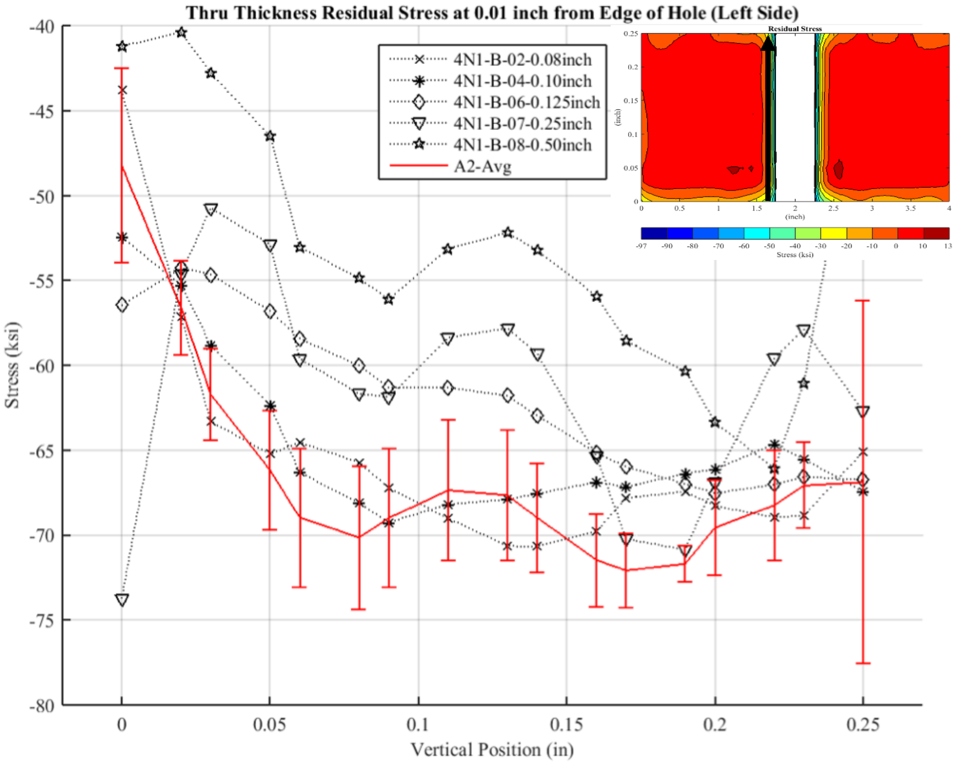
Provided by Scott Calrson

Residual Stresses in 2024-T351



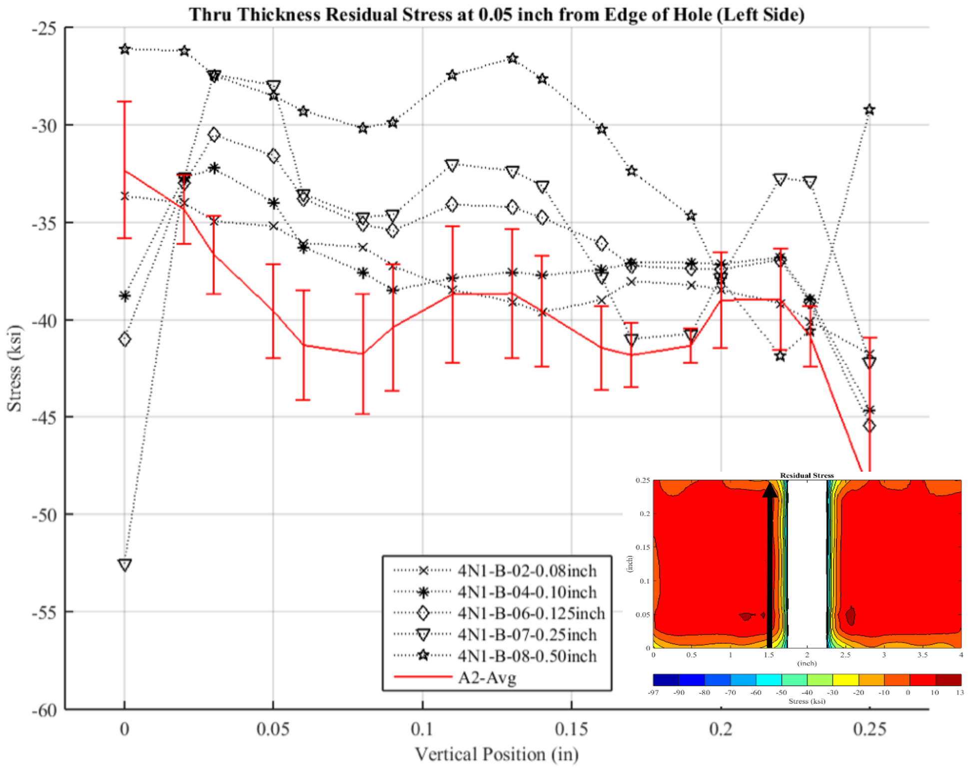
Provided by Scott Calrson

Residual Stresses in 2024-T351



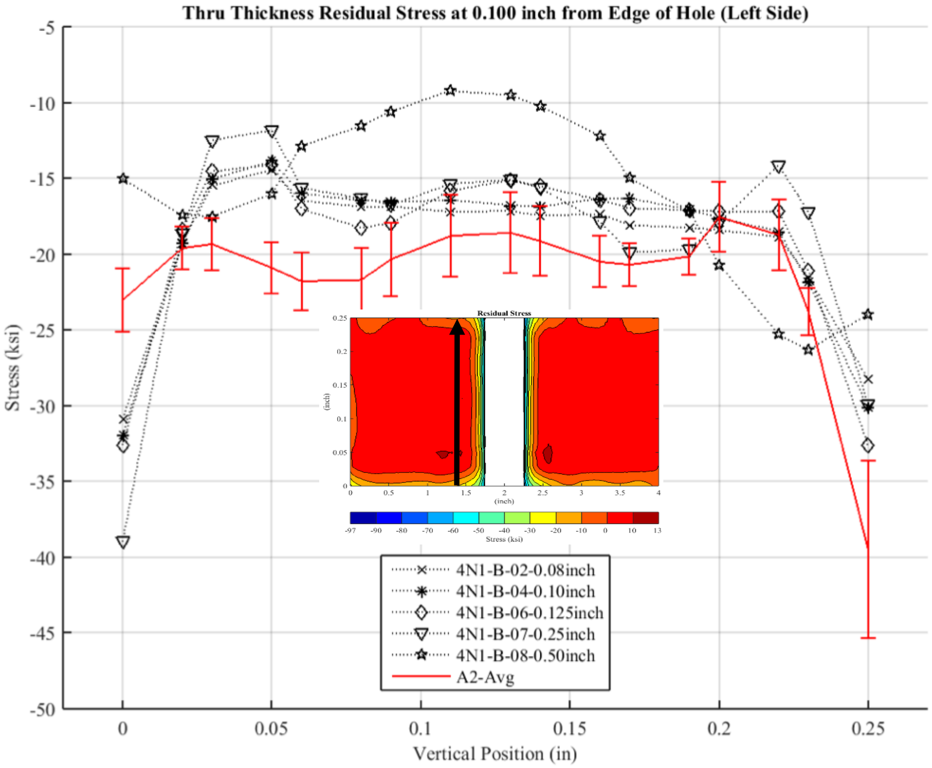
Provided by Scott Calrson

Residual Stresses in 2024-T351



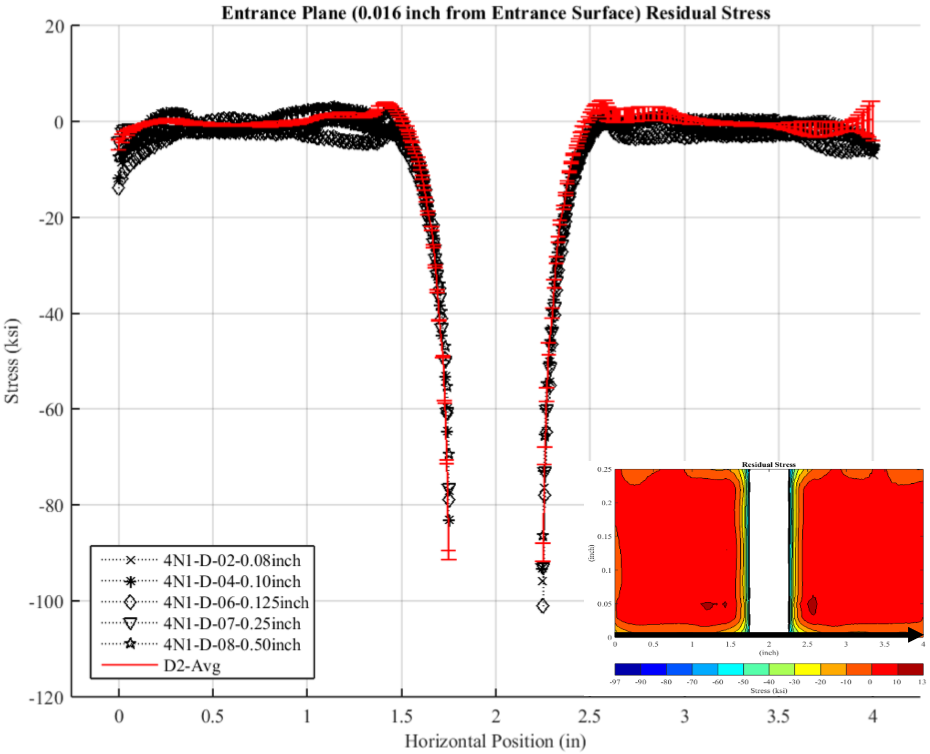
Provided by Scott Calrson

Residual Stresses in 2024-T351



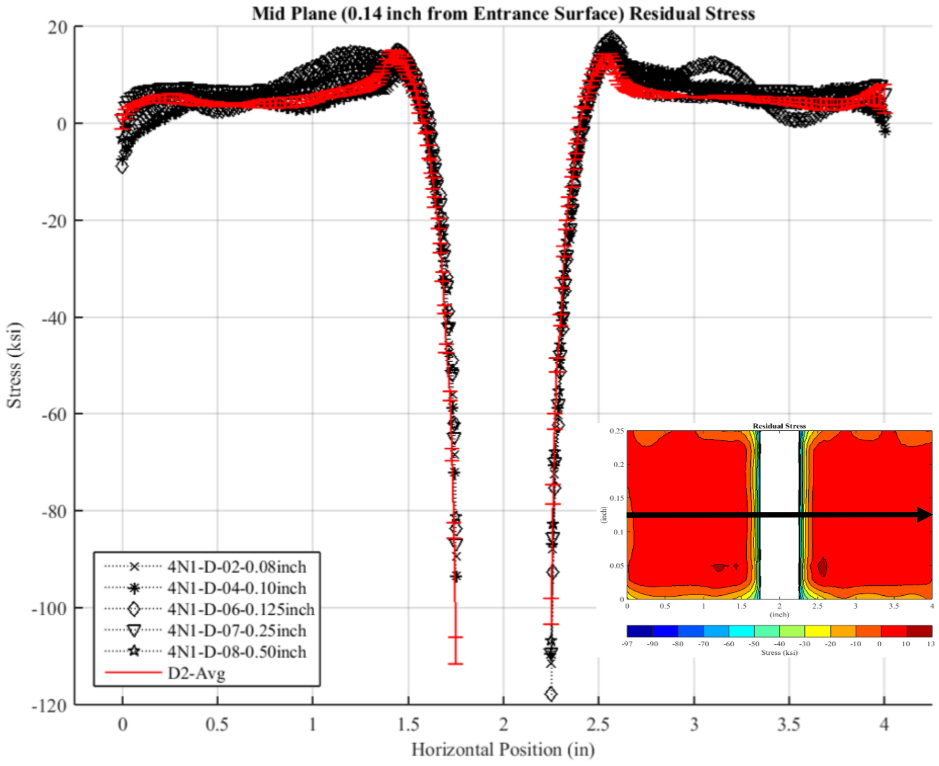
Provided by Scott Calrson

Residual Stresses in 7075-T651



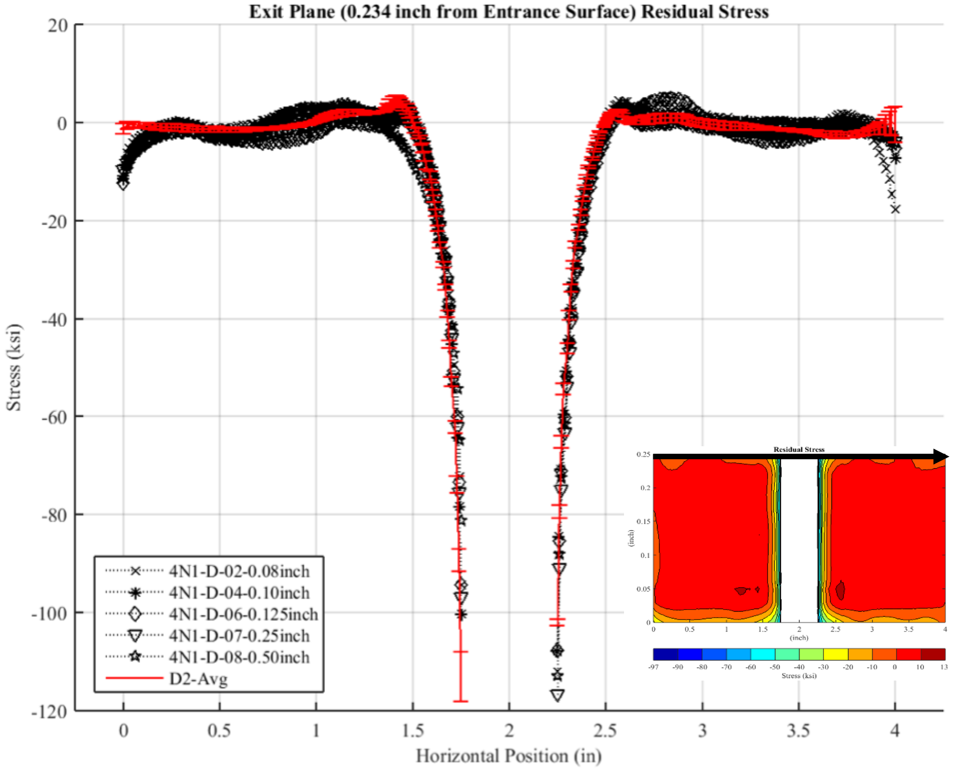
Provided by Scott Calrson

Residual Stresses in 7075-T651



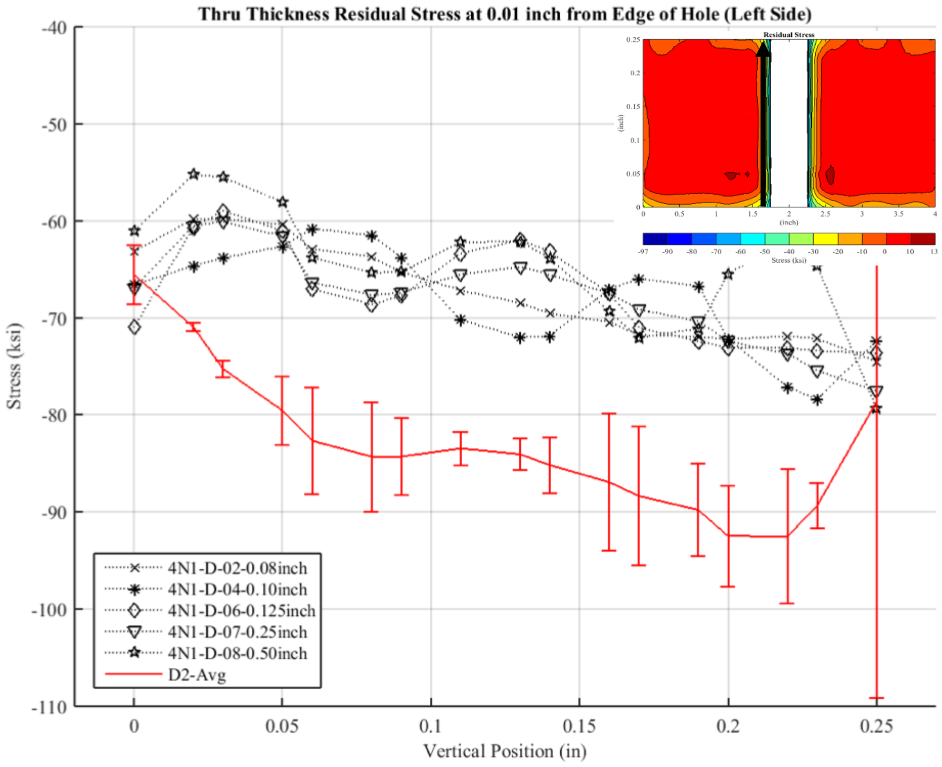
Provided by Scott Calrson

Residual Stresses in 7075-T651



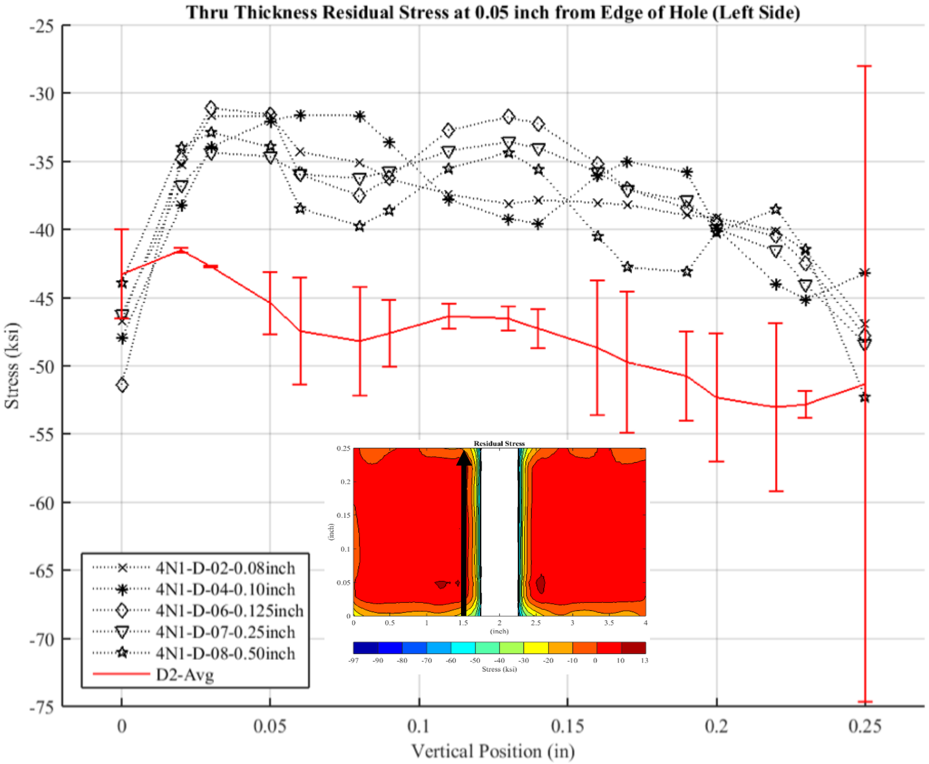
Provided by Scott Calrson

Residual Stresses in 7075-T651



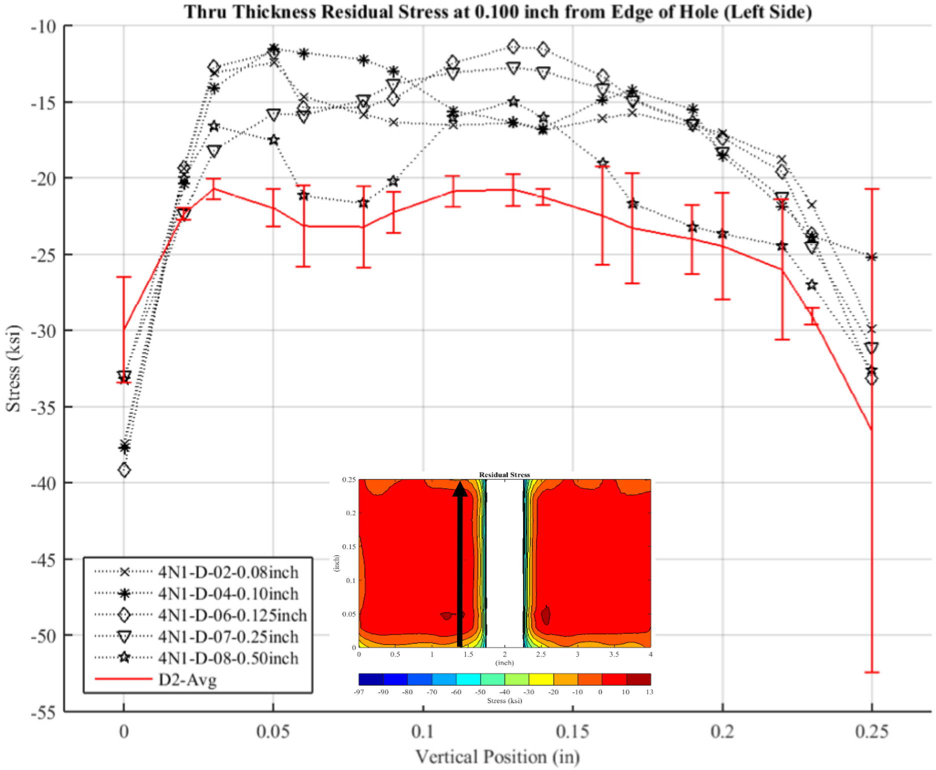
Provided by Scott Calrson

Residual Stresses in 7075-T651



Provided by Scott Calrson

Residual Stresses in 7075-T651



Provided by Scott Calrson

Conclusions

- It is possible to capture the effect of a fatigue crack via the Contour Method
- A fatigue crack has an effect on the residual stress field introduced via the Cold Expansion (Cx) process
  - For 2024-T351 the magnitude of the effect is related to crack size
  - For 7075-T651 the magnitude effect is does not seem to be related to the crack size

HILL
ENGINEERING
Predict. Test. Perform.

ERSI

Measurements Sub-group Update

Near-surface Measurements at a CX Hole

Provided by James Castle, Boeing

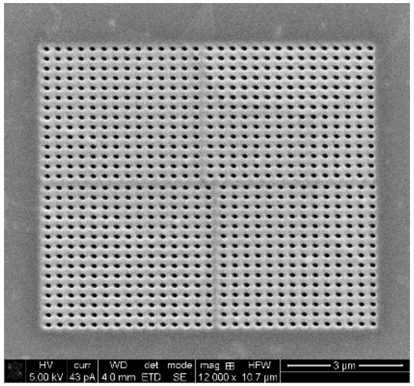
Reliable Measurement of Sub-Surface Residual Stress for Understanding Fatigue Performance

Elizabeth Burns[1,2], Joseph Newkirk[1], James Castle[2],
Jennifer Creamer[2], Matt Watkins[3]

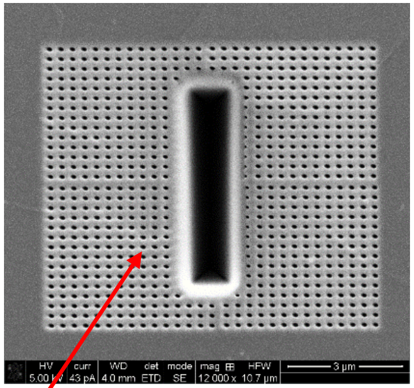
[1]Department of Materials Science & Engineering, Missouri University of Science and Technology, Rolla, MO USA
[2]Boeing Research and Technology, Saint Louis, MO, USA
[3]Engineering Software Research and Development (ESRD), Inc., Saint Louis, MO, USA

Micro-slotting method

1. Milled pattern of small surface dots and obtained electron image
2. Milled slot and obtained electron image
3. Determined original stress state of imaged region:
    - Input images and text file of FE surface displacements for reference stress into MATLAB DIC program

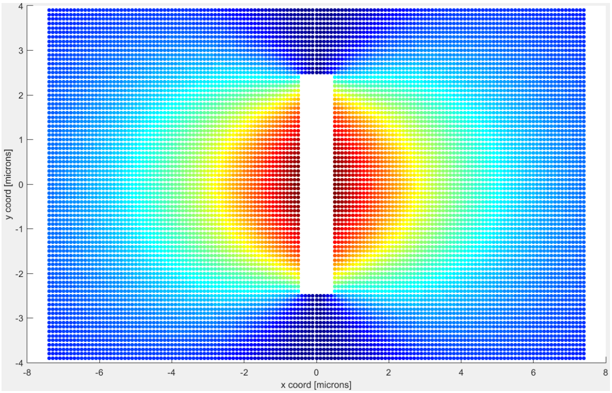


1



2

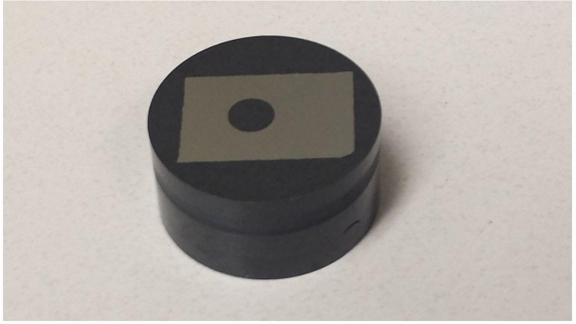
Micro-slot length:
0.005 mm

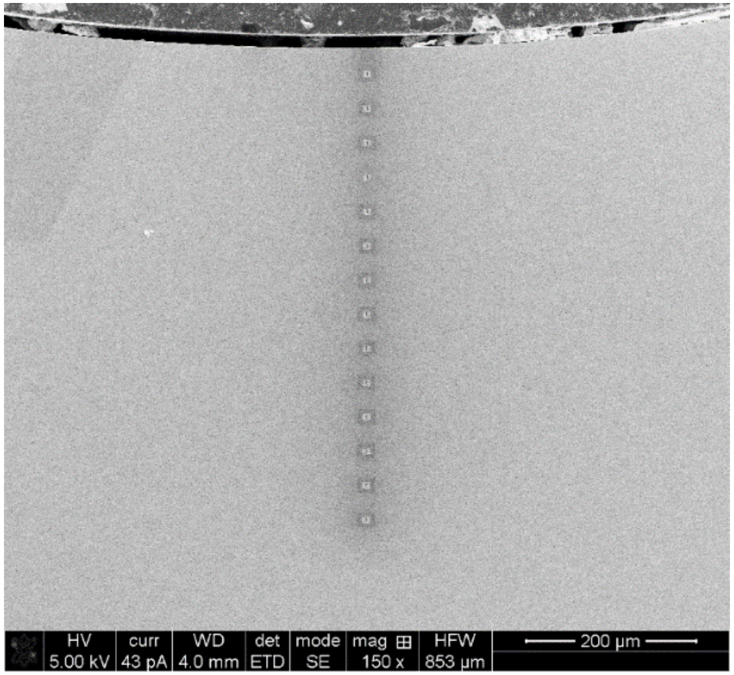


3

Micro-slotting Procedure

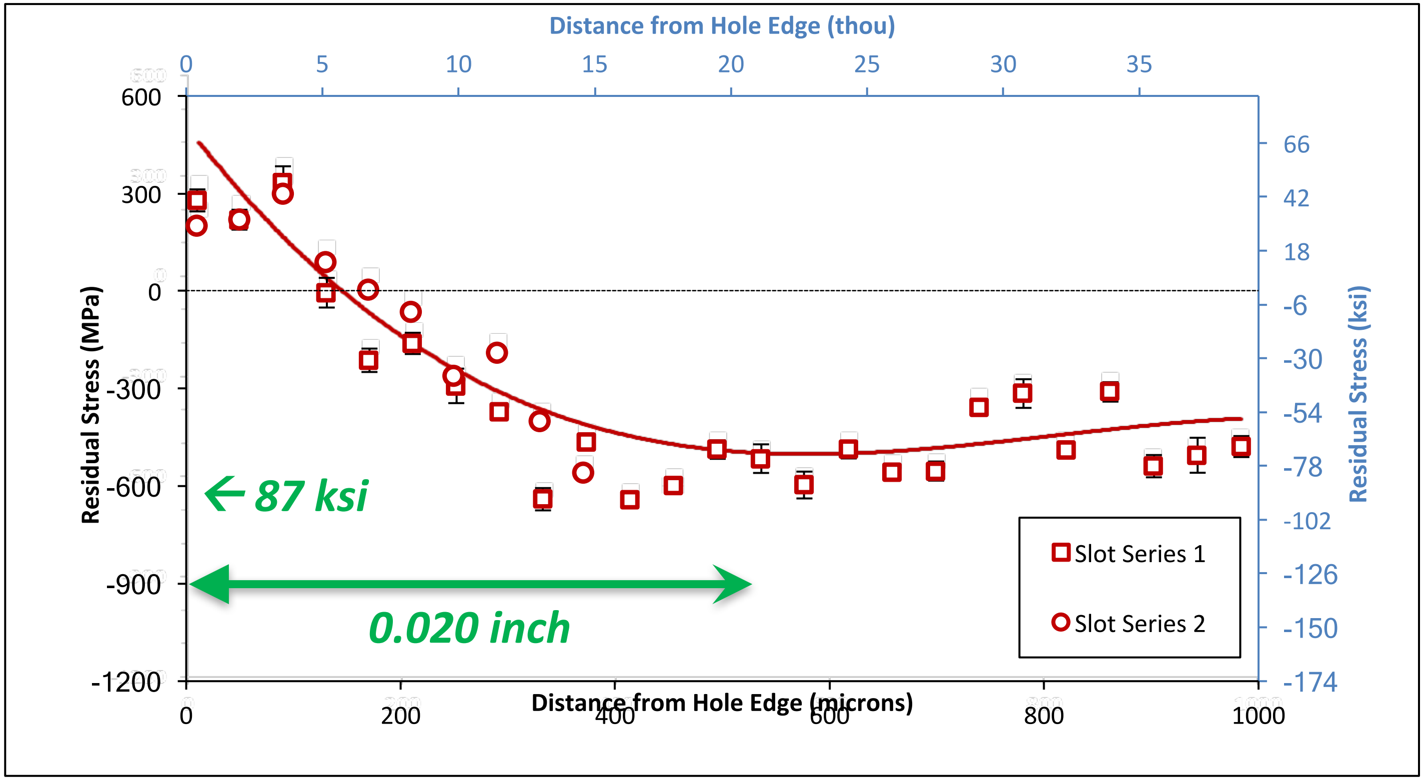
- Processed coupons were sectioned and polished
- Series of slots were milled using "best practice" procedure
    - Planar samples – as a function of distance below the surface
    - Hole samples – as a function of distance from the hole edge
- Slot size: 5x1x7 µm
- Slots were vertically spaced ≥ 25 µm (~1 thou)





Cold worked hole with reaming step

Measurements are reported as an average and standard deviation of residual stress for each slotted region



Two series of measurements superimposed show a small tensile stress at hole edge (most likely due to reaming process) followed by deep compressive stress

HILL
ENGINEERING
Predict. Test. Perform.

ERSI

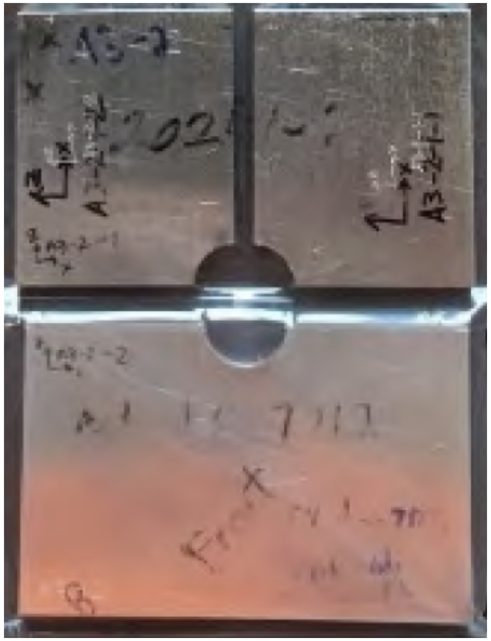
Measurements Sub-group Update

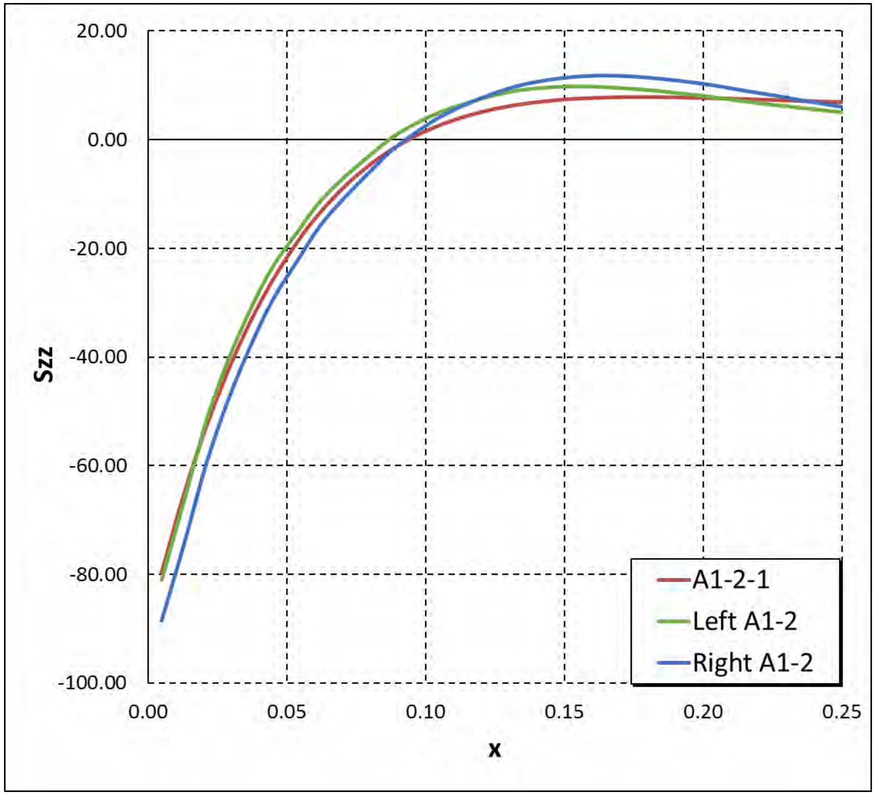
Near-bore Measurements at CX Hole

Measurements of near-bore residual stress

Slitting method measurements following contour

- Corrected for prior contour measurement
- For 2024-T351, no significant difference in results

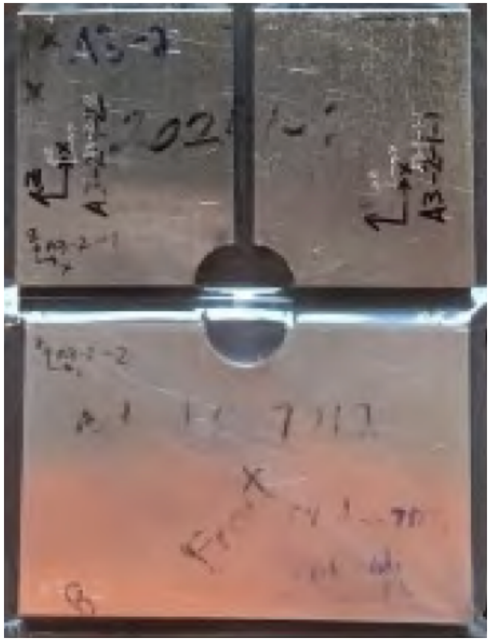


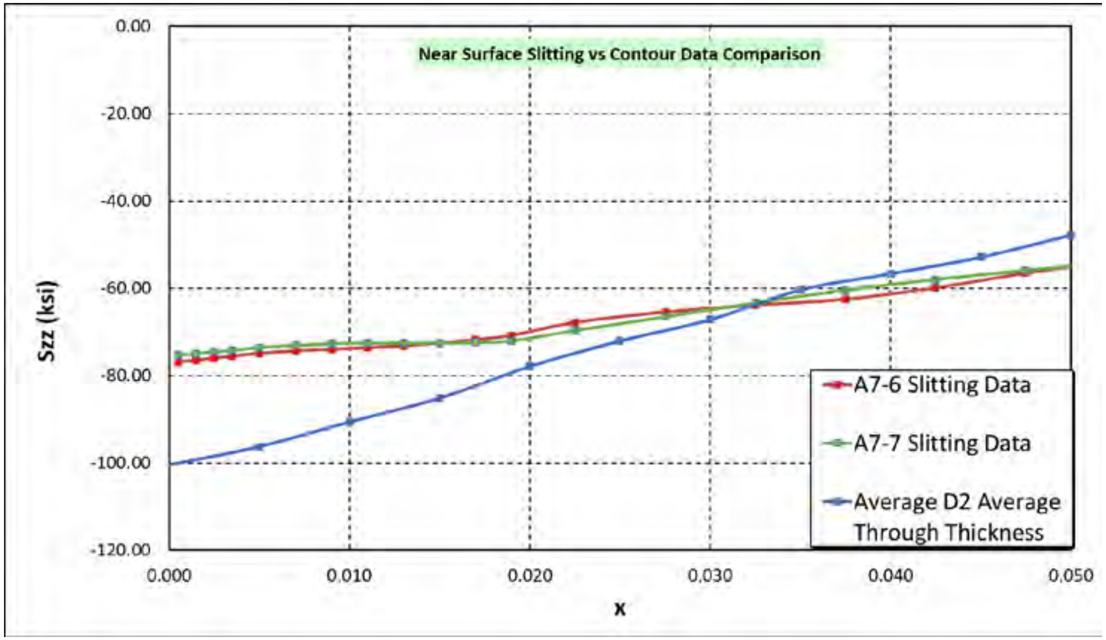


Measurements of near-bore residual stress

Slitting method measurements following contour

- Corrected for prior contour measurement
- For 7075-T651 significant difference in results within 0.020” of the bore





HILL ENGINEERING

HILL
ENGINEERING
Predict. Test. Perform.

ERSI

Measurements Sub-group Update

Large Hole CX Evaluation

Coupon Design

Objective

- Develop a coupon that scales-up the stress field
- Develop and interrogate measurement data

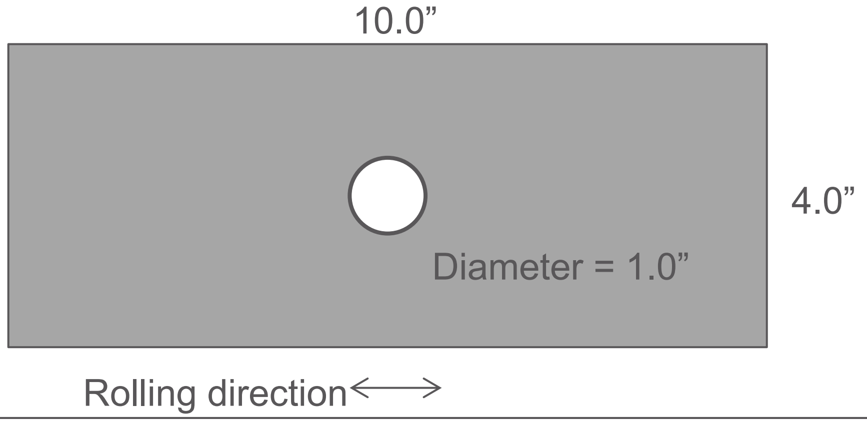
Coupon attributes

- Large diameter
  - Maximize length scale of “near-surface” and “near-bore” regions
- Long enough to facilitate fatigue testing
- Wide enough to minimize edge margin effects

Material types

- 7075-T651
- 2024-T351

Comments from group?



HILL
ENGINEERING
Predict. Test. Perform.

ERSI

Measurements Sub-group Update

Recent Cross-Method Validations

Quality of residual stress data (model or measurement)

Judging the quality of residual stress data is difficult

- Models are non-linear and model inputs are uncertain
- Direct residual stress measurements are not possible
  - Always determined indirectly
    - Lattice spacing, cut-induced deformation, correlation with magnetic properties
  - No one method meets all needs (e.g., bulk vs near-surface)
    - Use multiple techniques, data fusion
- Lack of truth data

Three approaches to assessing quality of measurement data

- Measurement repeatability – determines precision (but not accuracy)
  - Intralaboratory (repeatability)
  - Interlaboratory (reproducibility)
- Cross-method validation – shows consistency (but not accuracy)
  - Best when methods use different physics (e.g., mechanical and diffraction)
- Phenomenological correlation – shows usefulness
  - Provides the most relevant truth data
  - Focused on impact of residual stress on component
    - e.g., Fatigue life or Distortion

Residual stress measurement

Residual stress measurement is challenging

- Impossible to “see” residual stress
- Requires indirect measurement
  - Measure something else (e.g., strain release) and “infer” residual stress

Many “accepted” RS measurement methods

- Each method has advantages and disadvantages
- No gold standard
- “Best method” depends on specific application

Selection of RS measurement technique

Depth of RS measurement
Magnitude of stress gradients
Number RS components
Geometry
Destructiveness
Measurement time
Portability
Material handling

Required accuracy
Spatial variation of RS
Material property variations
Application specific concerns
Required equipment
Cost
Required expertise

Important questions to consider

- What does anticipated residual stress field look like?
- How will the measurement data be used?

Experimental technique is important

Consider replicate measurements

Consider multiple methods

HILL
ENGINEERING

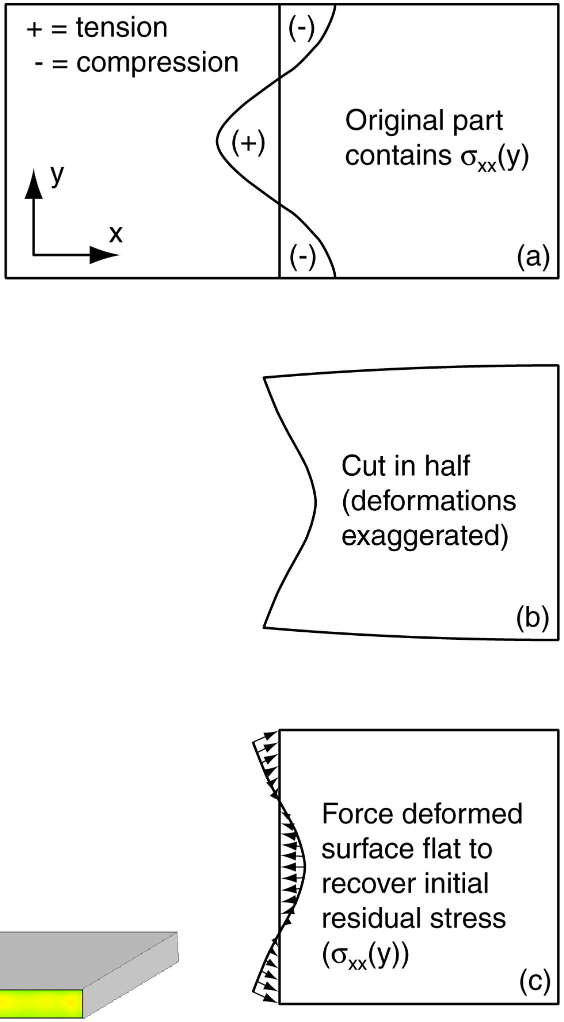
38

Contour method overview

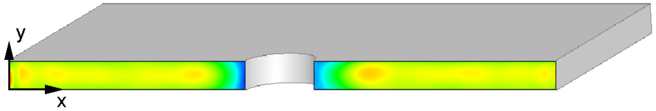
Contour method steps

- Part contains unknown RS (a)
- Cut part: stress release ⇒ deformation (b)
- Measure deformation of cut surfaces
- Apply reverse of average deformation to FE model of body (c)
- Map of RS normal to surface determined
- Same procedure holds for 3D

Cut → measure → FEM → residual stress



- Contour method can generate a 2D map of residual stress normal to a plane



Diffraction methods principle

Subject a crystalline material to incident radiation

Radiation will diffract from crystal lattice planes via Bragg's law

- $\lambda = 2d\sin\theta$

By measuring θ and knowing λ we can obtain lattice spacing *d*

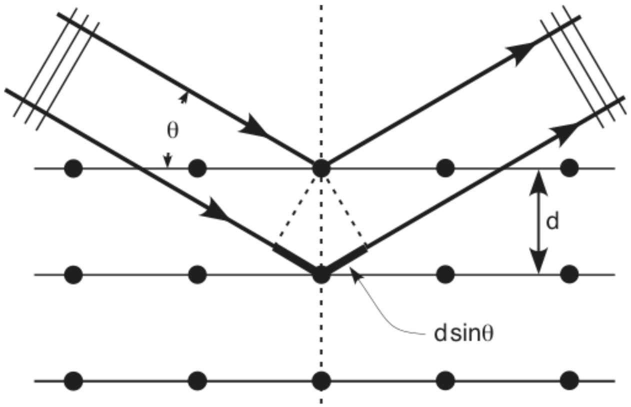
Compare with unstressed lattice spacing d_0

Get elastic strains

Calculate stress

Requires statistics – average over many diffracting grains

Map fields by making multiple point measurements



public domain image via Wikipedia Creative Commons

$$\varepsilon_i = \frac{d \;\; - d^0}{d^0}$$

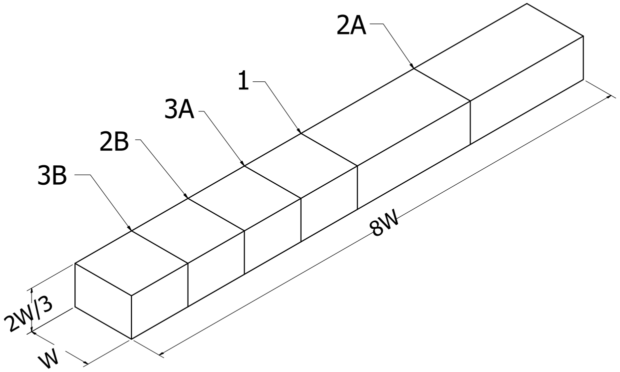
$$\sigma_i = \frac{E(1-\nu)}{(1+\nu)(1-2\nu)}\left[\varepsilon_i + \frac{\nu}{1-\nu}(\varepsilon_j + \varepsilon_k)\right]$$

HILL ENGINEERING

40

Repeatability: contour in quenched bar

Contour method stress mapping



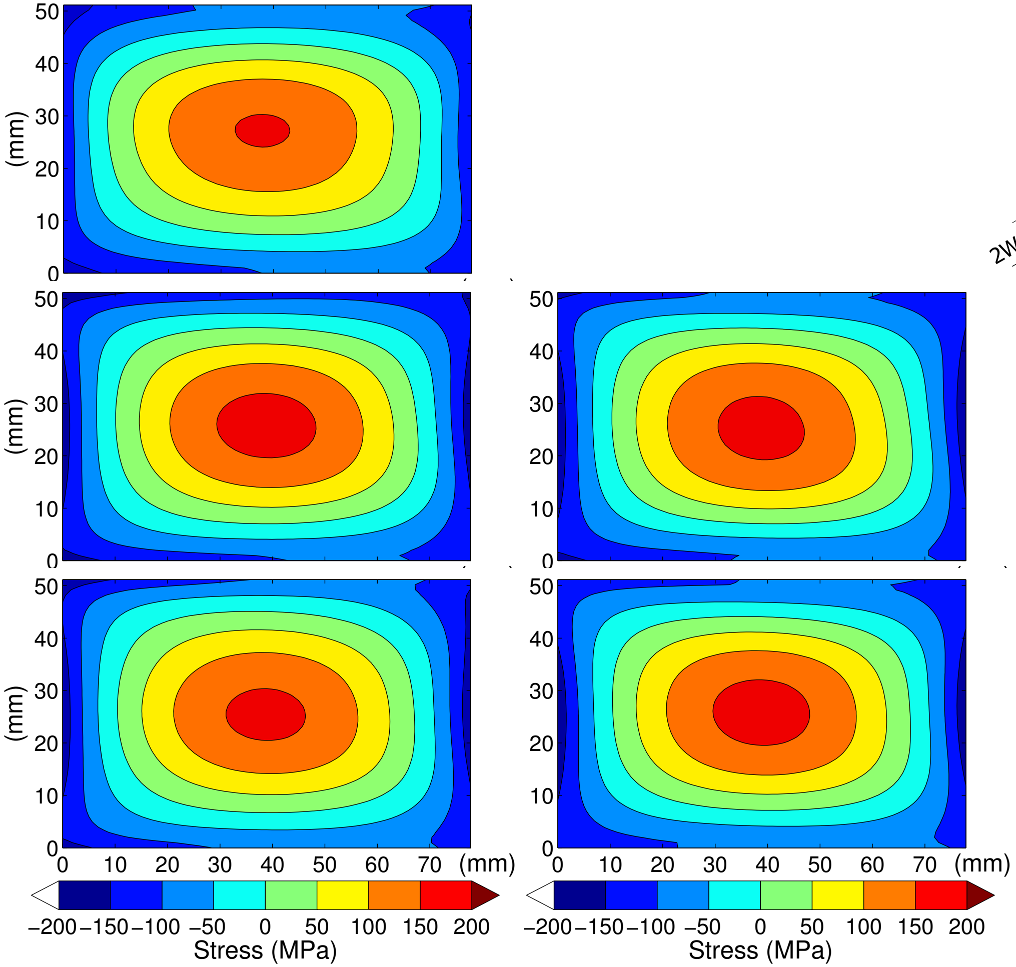
Cut 1

Cut 2A

Cut 2B

Cut 3A

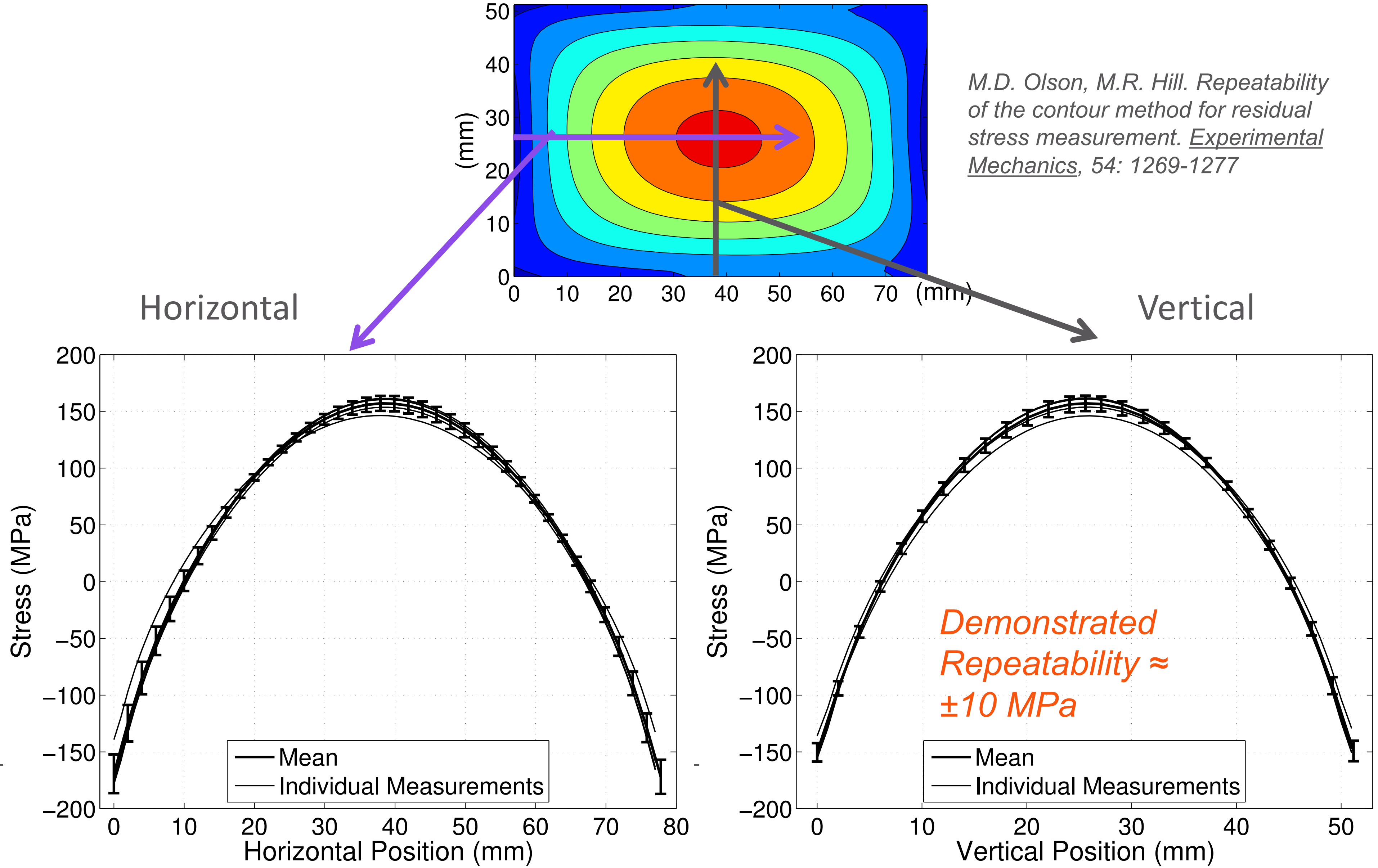
Cut 3B



M.D. Olson, M.R. Hill. Repeatability of the contour method for residual stress measurement. Experimental Mechanics, 54: 1269-1277

Repeatability: contour in quenched bar

M.D. Olson, M.R. Hill. Repeatability of the contour method for residual stress measurement. Experimental Mechanics, 54: 1269-1277



Demonstrated Repeatability ≈ ±10 MPa

Example: cross-method validation in peened plate

Uniformly LSP entire surface of Ti-6Al-4V plate

Cut into 4 block coupons

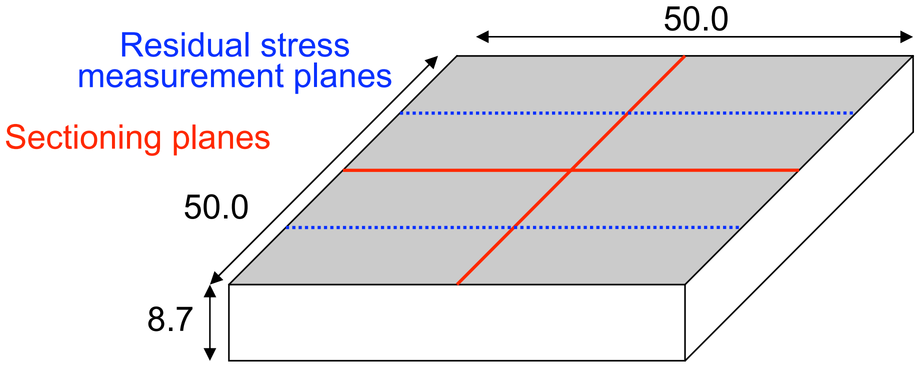
- Each 25 x 25 x 8.7 mm

Measure residual stress

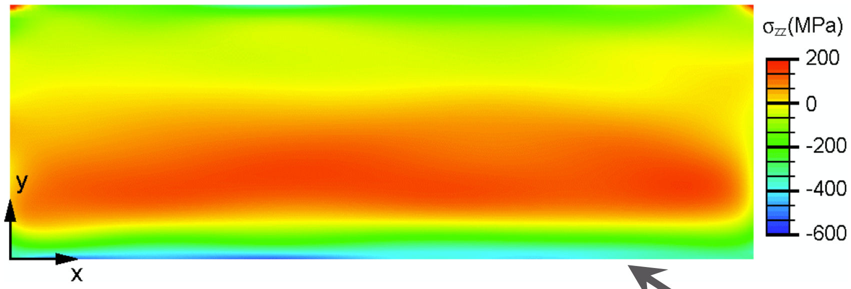
- Slitting, Contour, X-ray diffraction

Good agreement in methods

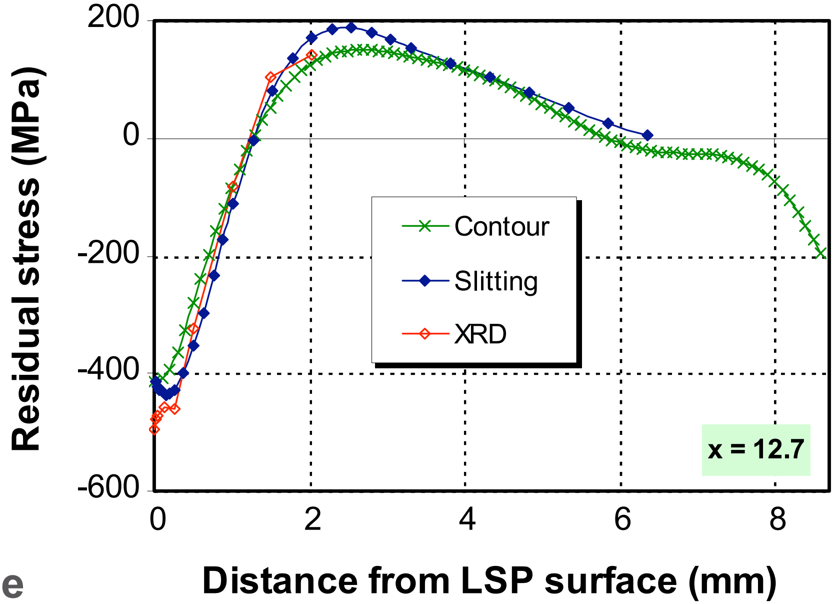
- Residual stress field that meets assumptions of methods
- Uniform microstructure, equiaxed grains



Dimensions in mm



LSP Surface



Example: cross-method validation in ring and plug

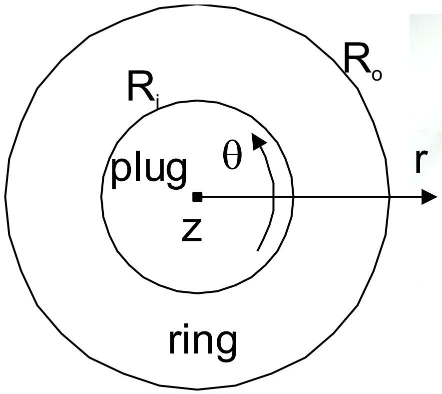
Ring and plug specimen

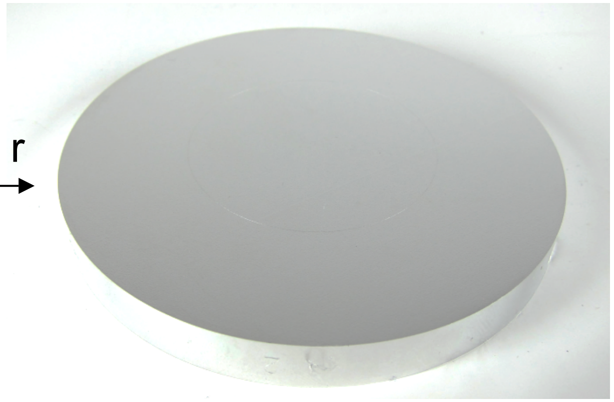
- 2.0 inch diameter plug
- 4 inch diameter ring
- AA2024-T351

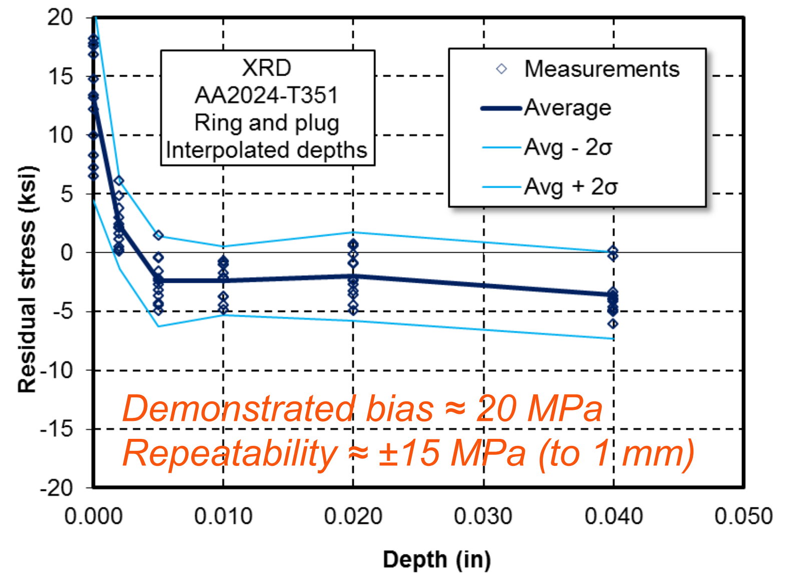
Expect -6.0 ksi in “plug” (40 MPa)

12 replicate measurements

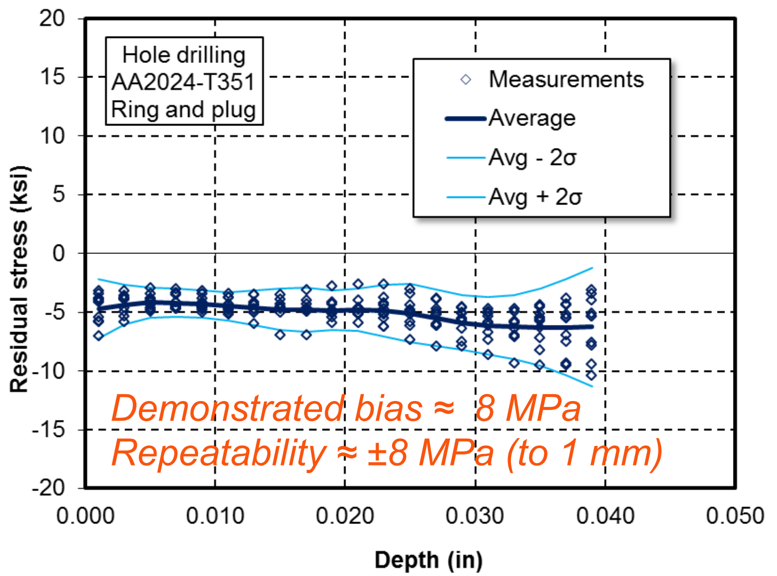
- Depth profiles to 1 mm







Demonstrated bias ≈ 20 MPa
Repeatability ≈ ±15 MPa (to 1 mm)



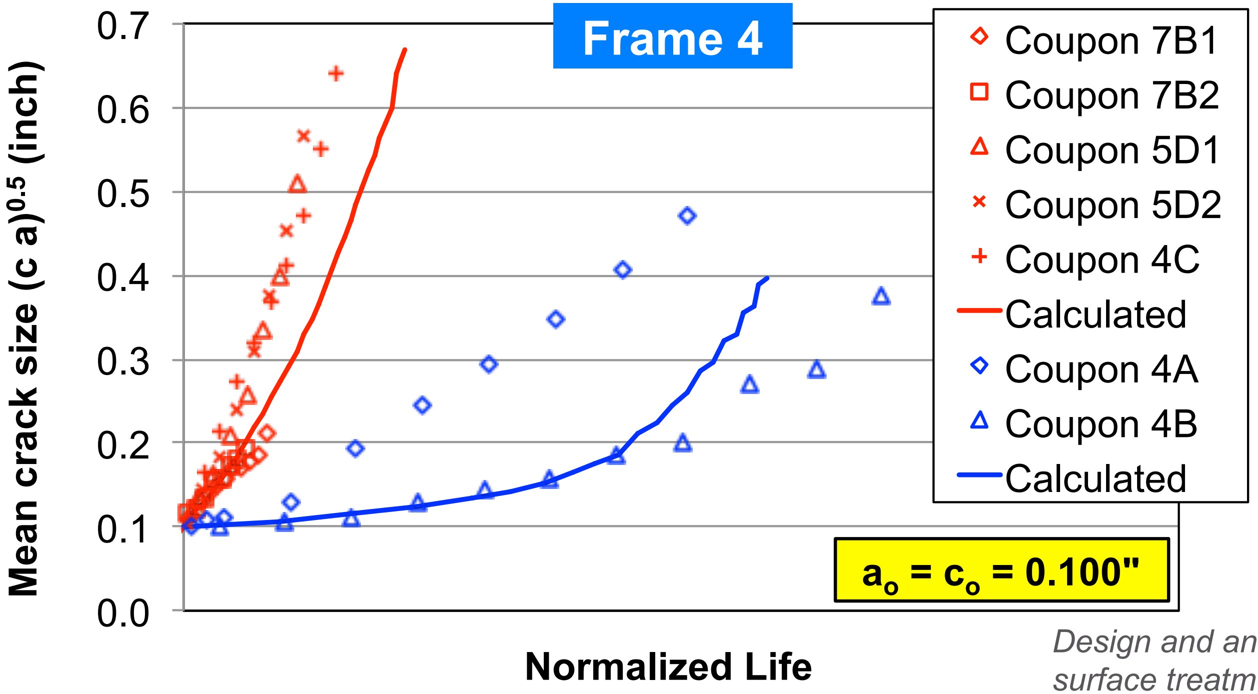
Demonstrated bias ≈ 8 MPa
Repeatability ≈ ±8 MPa (to 1 mm)

Fatigue test correlation

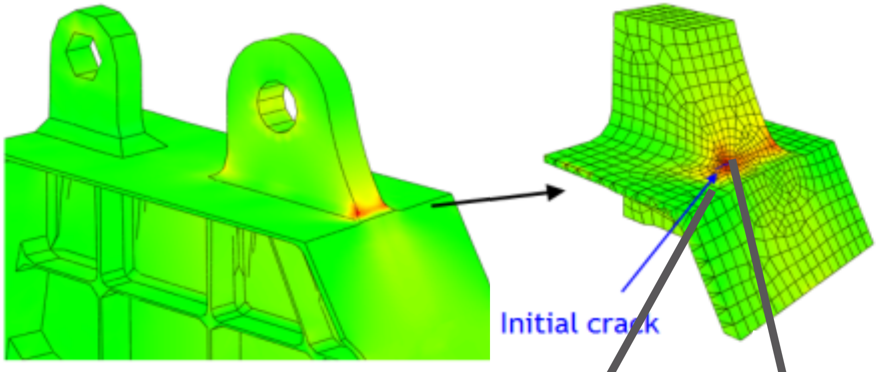
F-22 fatigue life improvement

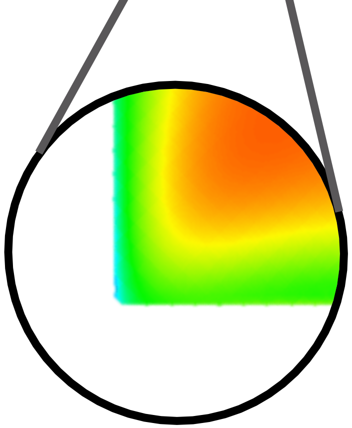
RED = Baseline

BLUE = LSP over crack



$a_o = c_o = 0.100"$





Compressive RS from laser shock peening

Design and analysis of engineered residual stress surface treatments for enhancement of aircraft structure, M.R. Hill, et al, 2012 ASIP Conference, San Antonio, TX

Some prior cross-method validation in Al 7XXX

References:

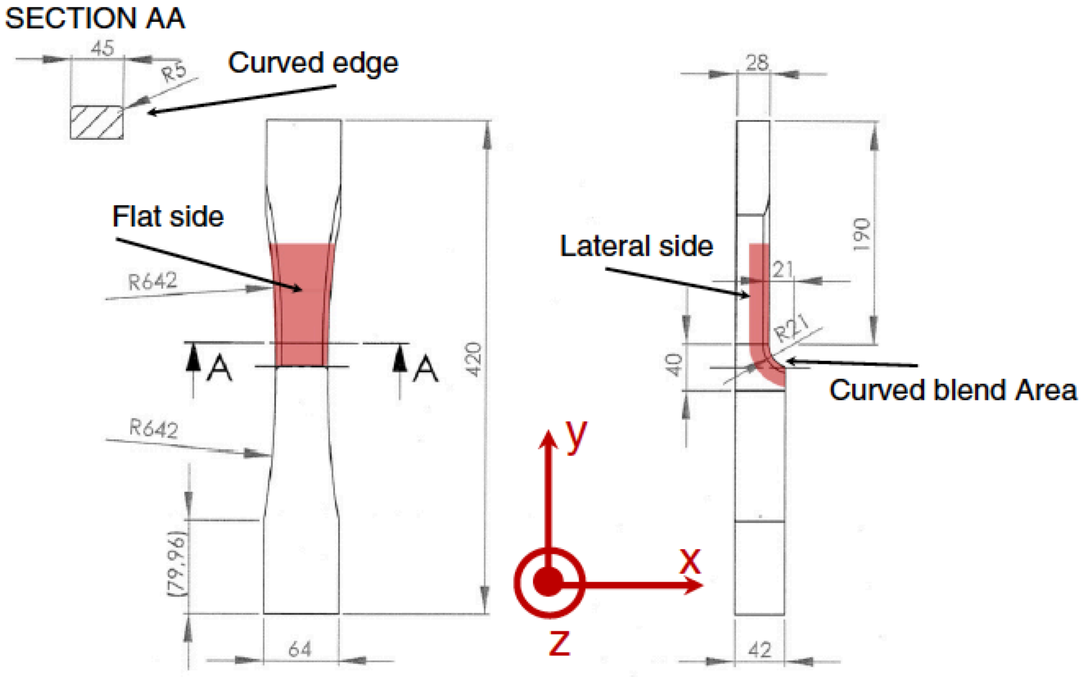
- Coratella, et al (Fitzpatrick group in UK)
  - Laser shock peened aluminum (7050 T7451)
  - http://dx.doi.org/10.1016/j.surfcoat.2015.03.026
- Hill Engineering work supported by AFRL
  - Cold compression stress relief in aluminum die forgings (7085 T7452 and T74)
  - “Engineering Residual Stress in Aerospace Forgings,” Proceedings of the International Conference on Residual Stress, Sydney, July 2016.

LSP 7050 aluminum

Evaluation RS from LSP

Residual stress data from

- Eigenstrain model
- Bulk measurements
  - Contour
  - Synchrotron XRD
  - Neutron diffraction
- Near surface measurement
  - Hole drilling
  - Lab XRD



Good care in work

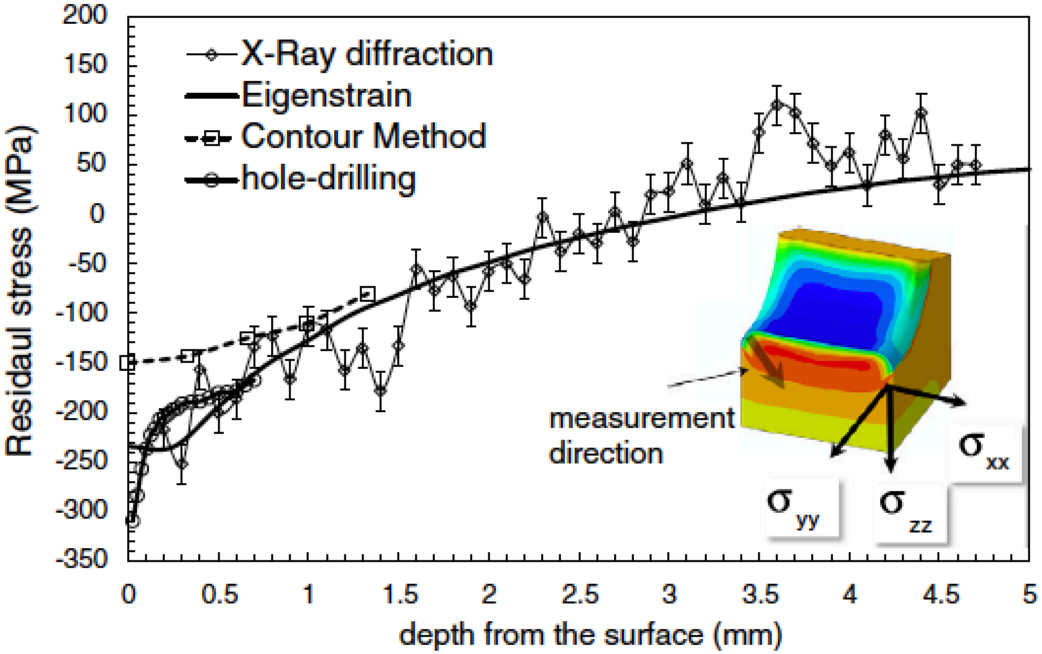
Reasonable correlation between data sets

Read the paper if you have time

LSP 7050 aluminum: Example results

Overall reasonably good correlation

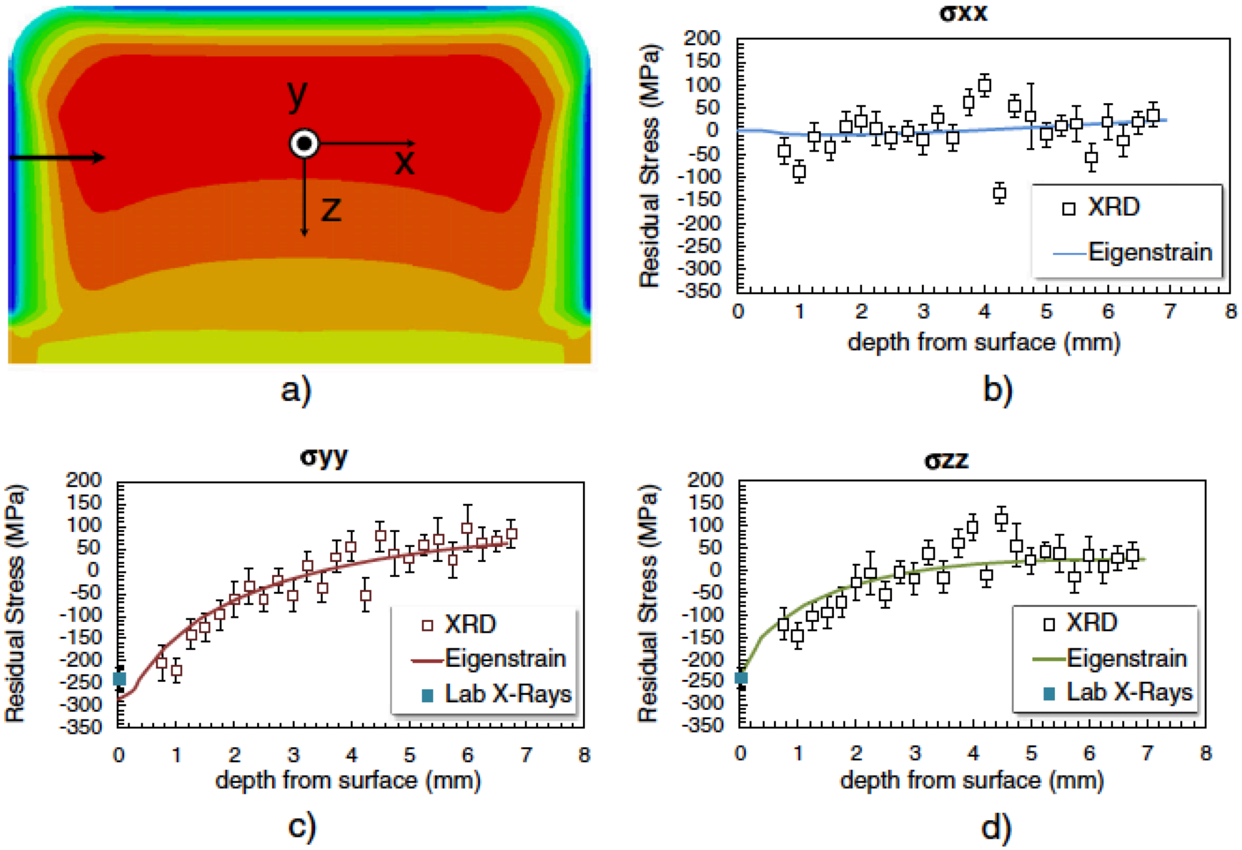
Substantial differences point-wise and in trend



LSP 7050 aluminum: Example results

Overall reasonably good correlation

Substantial differences point-wise and in trend



a)

b)

c)

d)

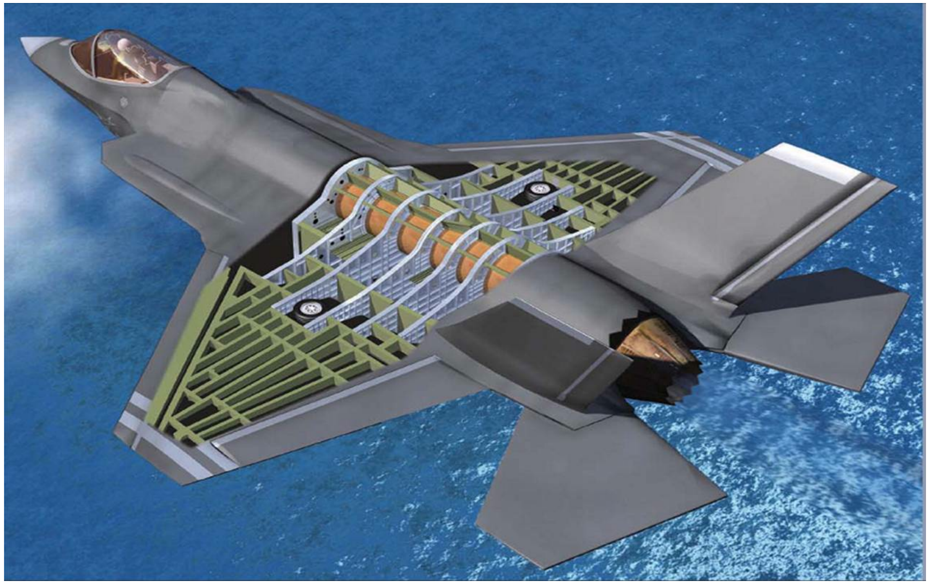
7085 T7452 die forgings

Cold compressed die forgings

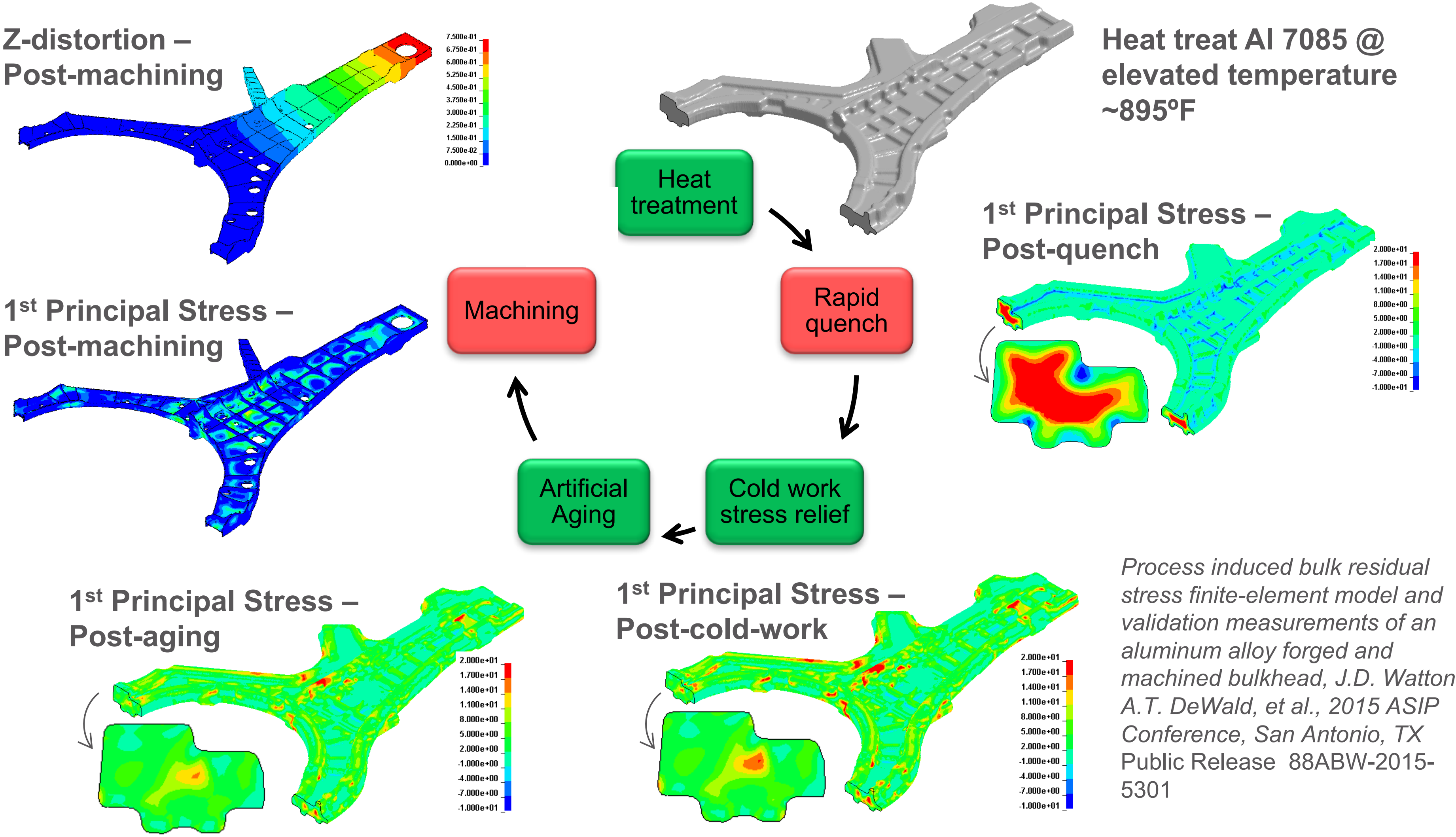
- Before cold compression: relatively high stress (±30 ksi)
- After cold compression: relatively low level of stress (±10 ksi)
- Large parts

Large Forged Bulkhead (19.5 x 6.5 ft)

http://www.alcoa.com/



Alcoa model for aluminum forgings



Z-distortion – Post-machining

Heat treat Al 7085 @ elevated temperature ~895ºF

1st Principal Stress – Post-quench

1st Principal Stress – Post-machining

Heat treatment → Rapid quench → Cold work stress relief → Artificial Aging → Machining

1st Principal Stress – Post-aging

1st Principal Stress – Post-cold-work

Process induced bulk residual stress finite-element model and validation measurements of an aluminum alloy forged and machined bulkhead, J.D. Watton, A.T. DeWald, et al., 2015 ASIP Conference, San Antonio, TX

Public Release 88ABW-2015-5301

Measurement precision: repeatability in quenched bar

Contour method stress mapping

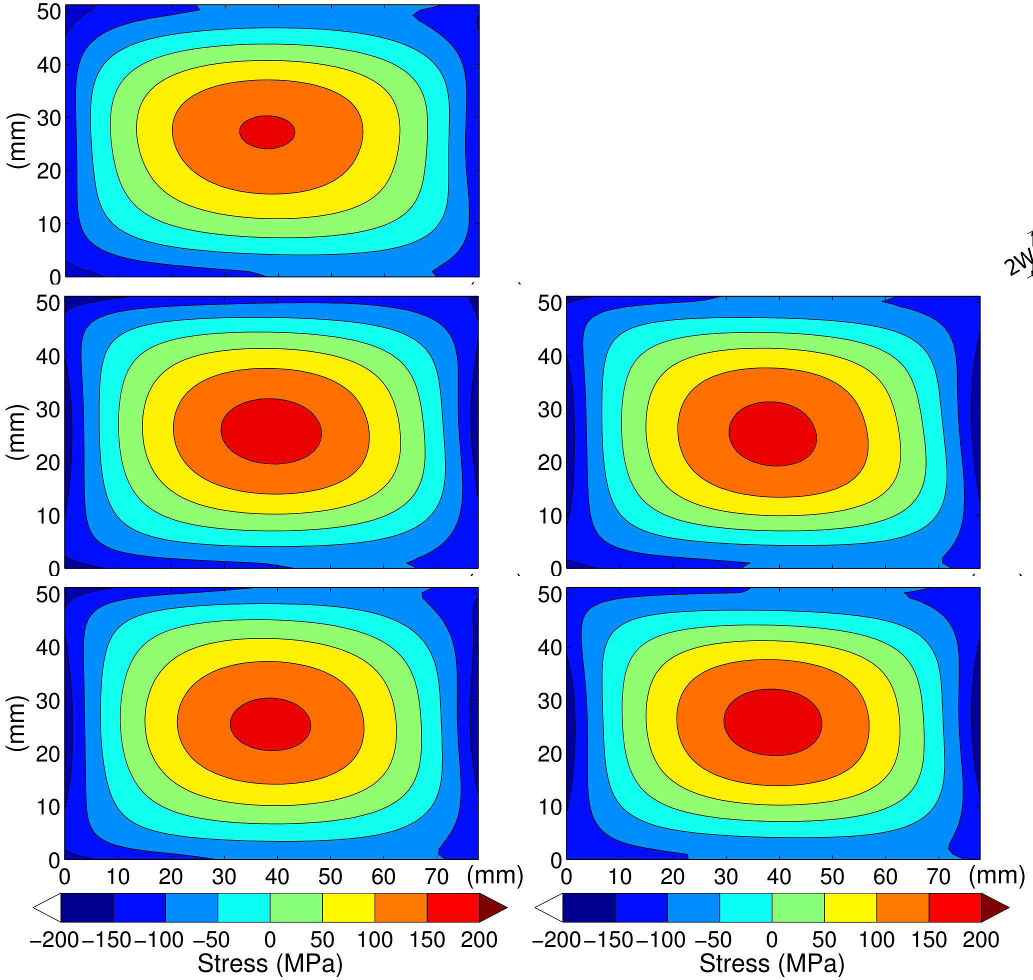
Cut 1

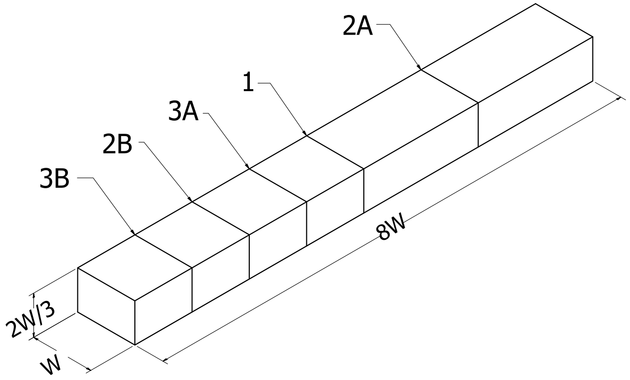
Cut 2A

Cut 2B

Cut 3A

Cut 3B





M.D. Olson, M.R. Hill. Repeatability of the contour method for residual stress measurement. *Experimental Mechanics*, *54: 1269-1277*

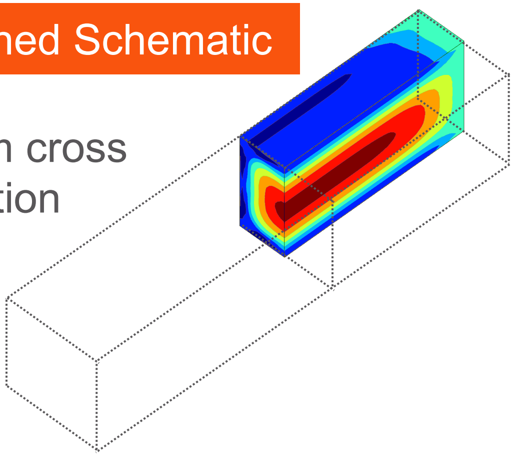
Cross-method validation in large hand forging

200 mm square-section quenched bar

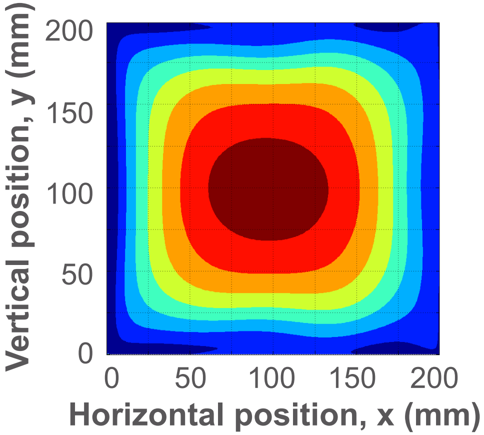
Validation of Residual Stress Fields Determined from Material Process Models, M.R. Hill. A.T. DeWald, 2012, MS&T Symposium on ICME, Pittsburgh, PA

As-Quenched Schematic

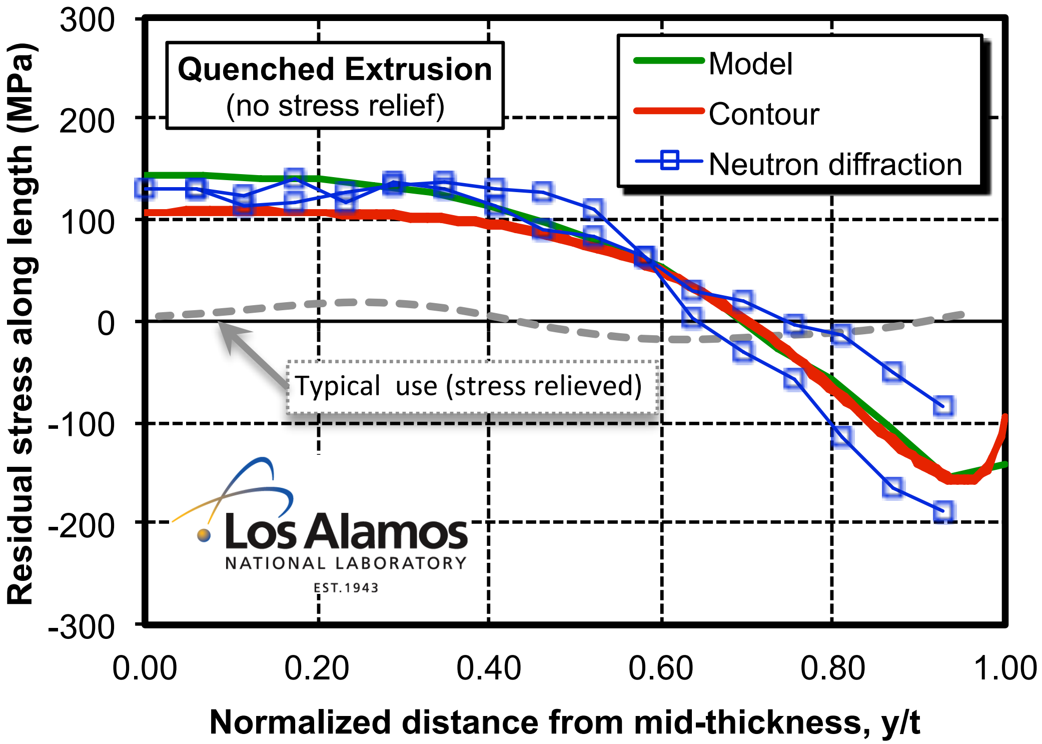
200 mm cross section



Contour measurement



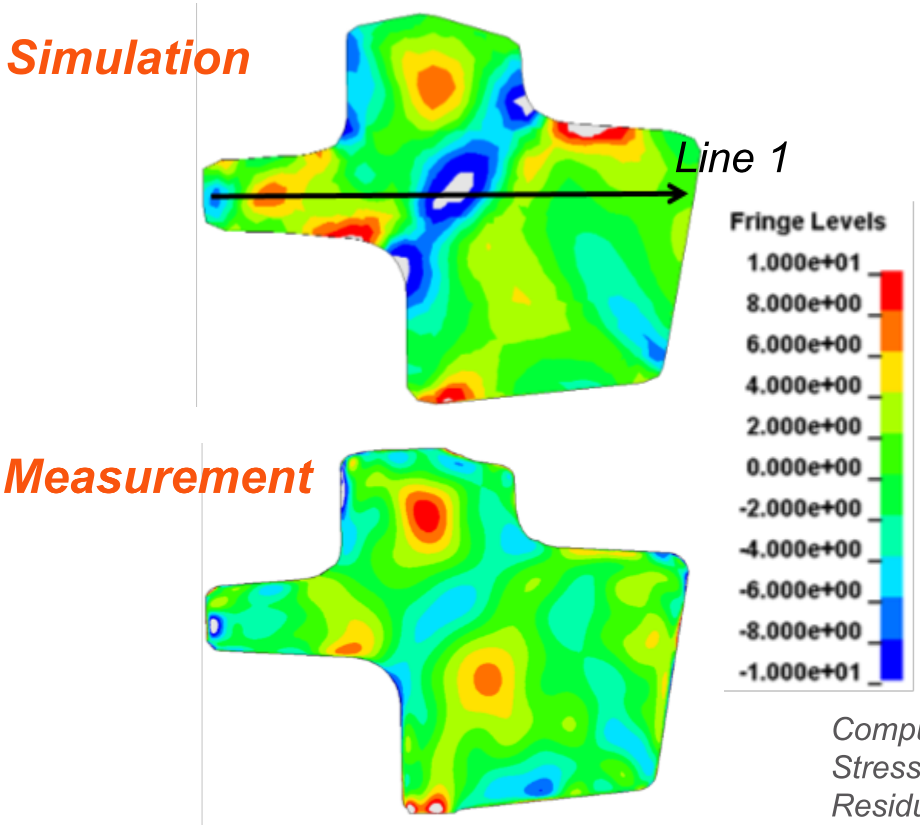
Validation: Quench model (Alcoa), Contour (HE), and Neutrons (LANL, UC Davis)

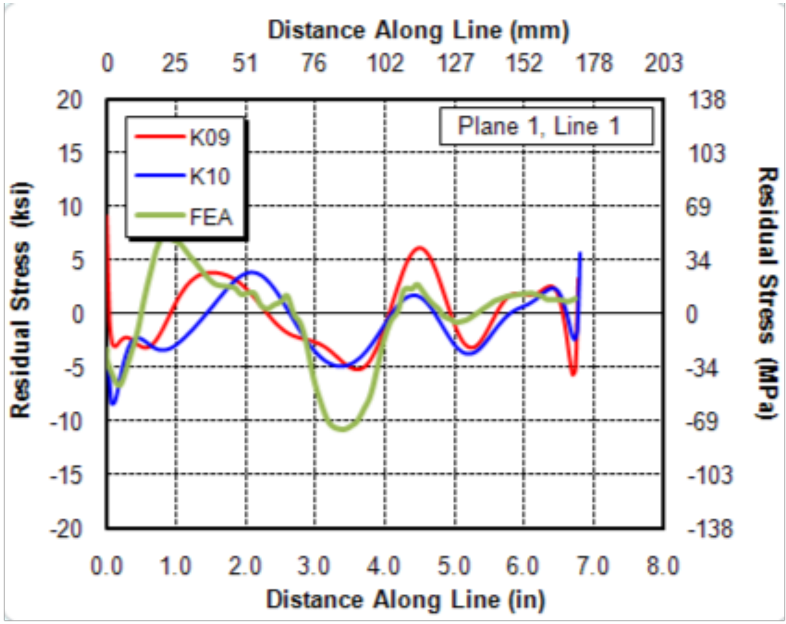


Model validation in aerospace die forging

Model to measurement correlation – small, 7085 die forgings
Stress relieved condition

- Not shown, but important: measurement precision, model uncertainty



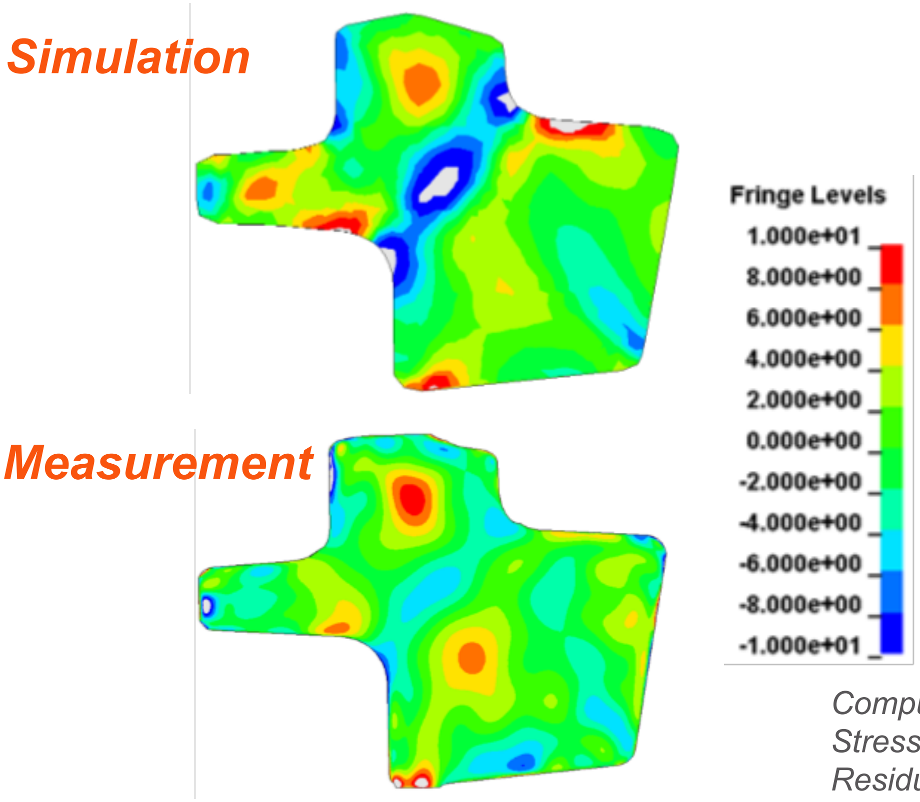


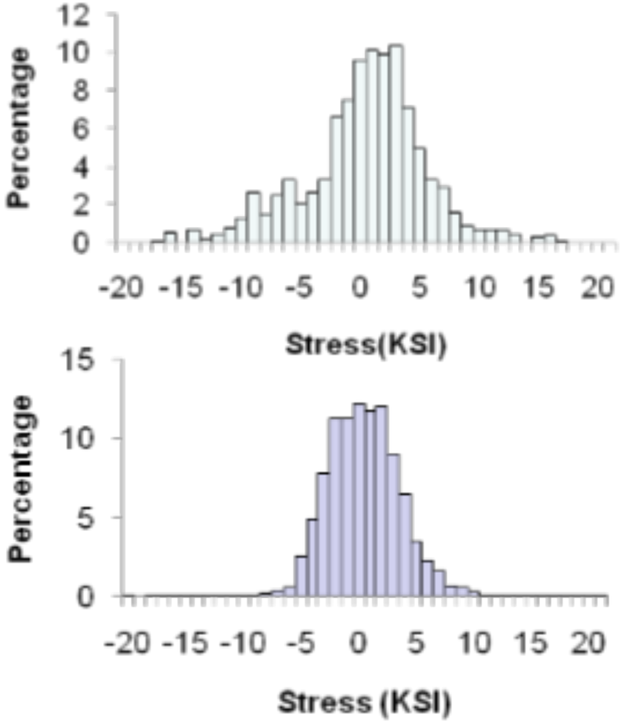
Computational Modeling and Optimization of Bulk Residual Stress in Monolithic Aluminum Die Forgings, J.D. Watton, 2010 Residual Stress Summit, Tahoe City, CA

Model validation in aerospace die forging

Model to measurement correlation – small, 7085 die forgings
Stress relieved condition

- Measurements confirm ability of model to estimate residual stress levels and distribution



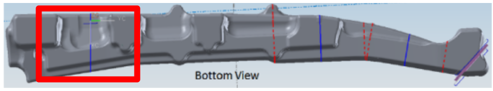


Computational Modeling and Optimization of Bulk Residual Stress in Monolithic Aluminum Die Forgings, J.D. Watton, 2010 Residual Stress Summit, Tahoe City, CA

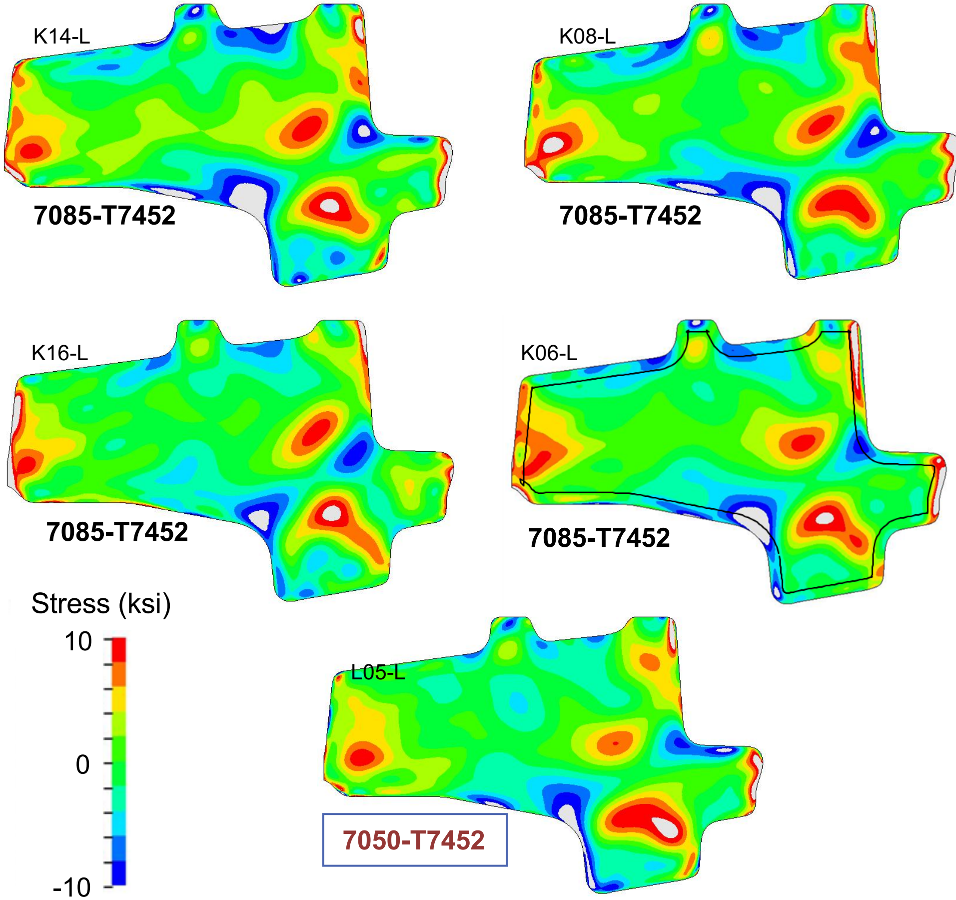
Process consistency in aerospace die forging

Contour measurements in 6 forgings

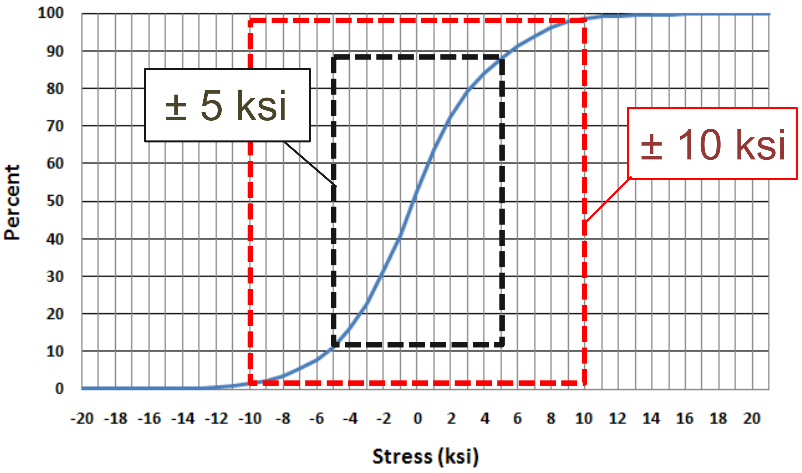
(Mark James, Alcoa, 2012 Aeromat)



MAI Export Control Clearance:
88ABW-2012-3018



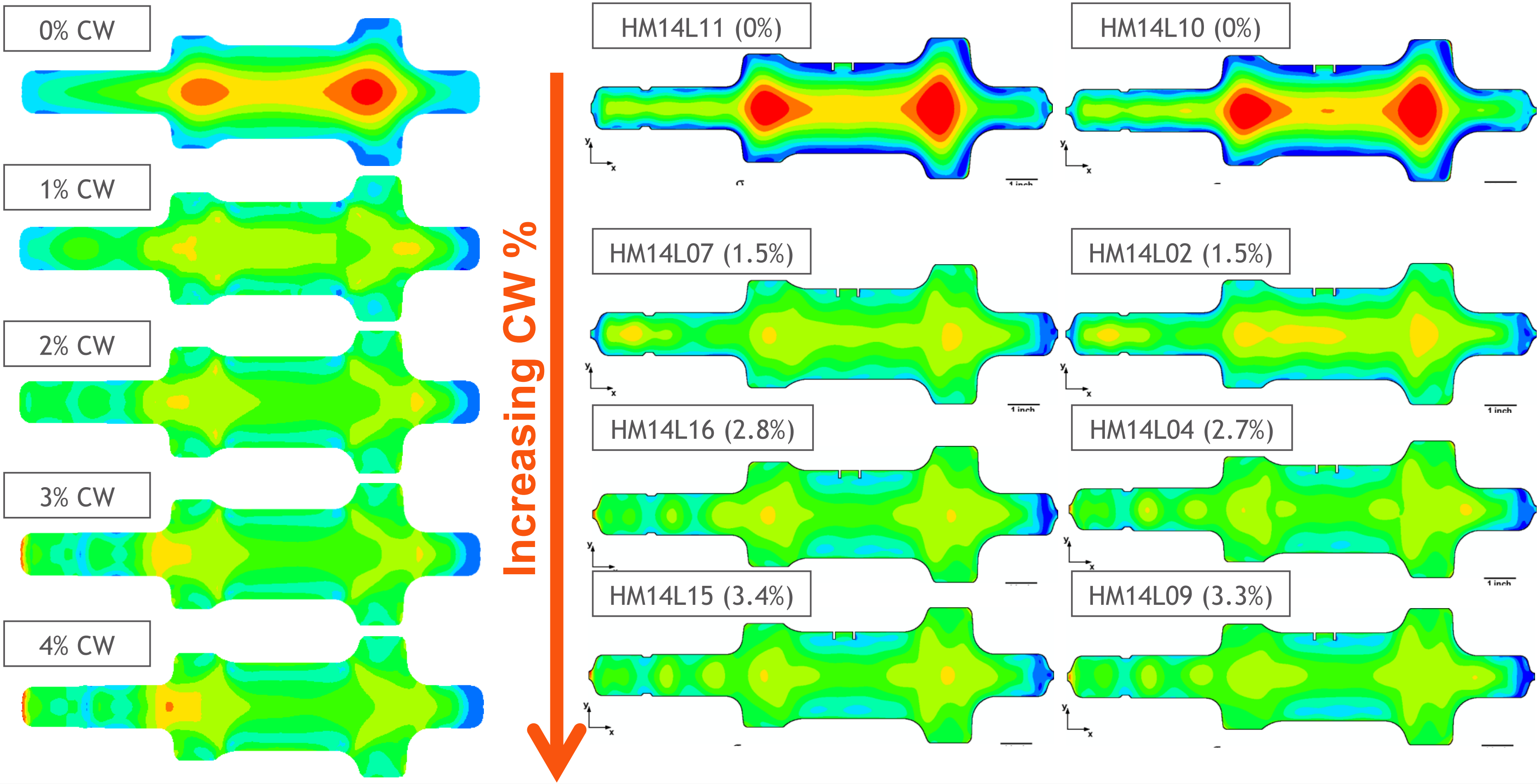
Cumulative stress distribution in left section of six latch beams excluding perimeter data



Validation of process sensitivity in aero die forging

Process model

Measurements



0% CW

1% CW

2% CW

3% CW

4% CW

Increasing CW %

HM14L11 (0%)

HM14L10 (0%)

HM14L07 (1.5%)

HM14L02 (1.5%)

HM14L16 (2.8%)

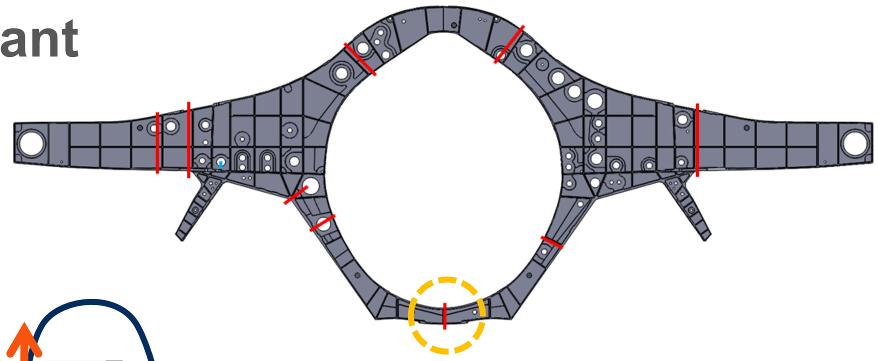
HM14L04 (2.7%)

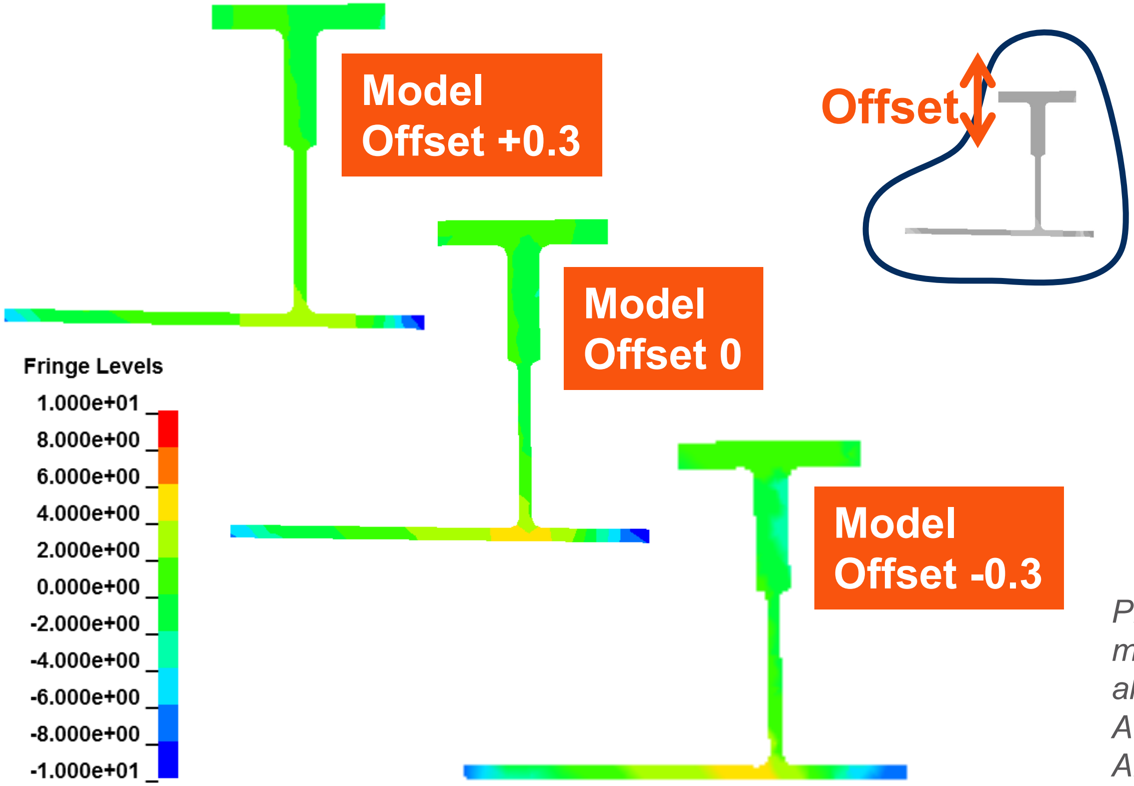
HM14L15 (3.4%)

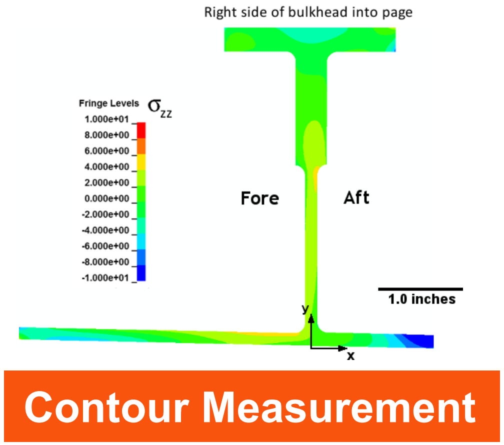
HM14L09 (3.3%)

Validation of residual stress in machined parts

Part placement (offset) has a significant effect on RS model output





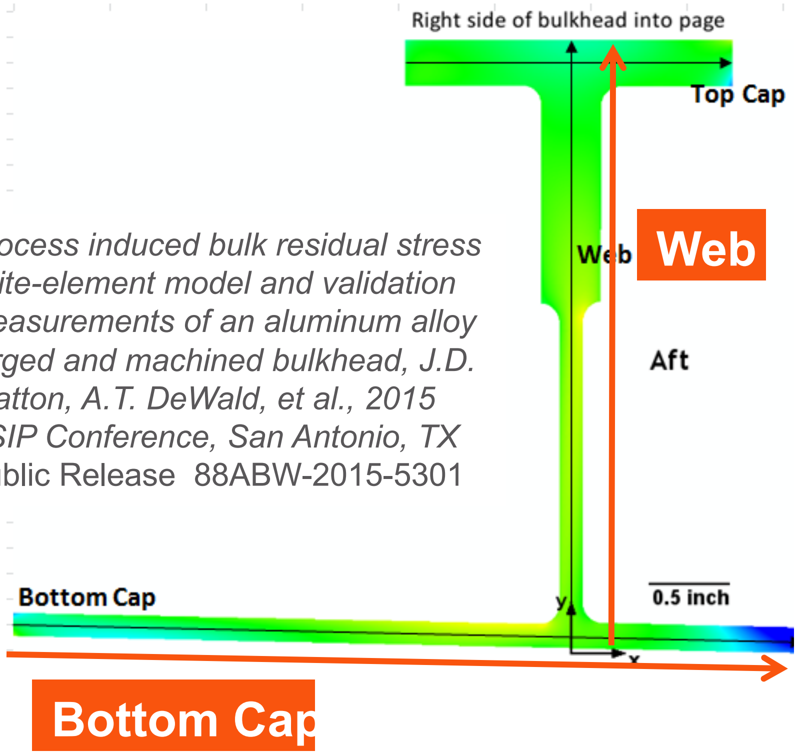


Process induced bulk residual stress finite-element model and validation measurements of an aluminum alloy forged and machined bulkhead, J.D. Watton, A.T. DeWald, et al., 2015 ASIP Conference, San Antonio, TX Public Release 88ABW-2015-5301

Validation of residual stress in machined parts

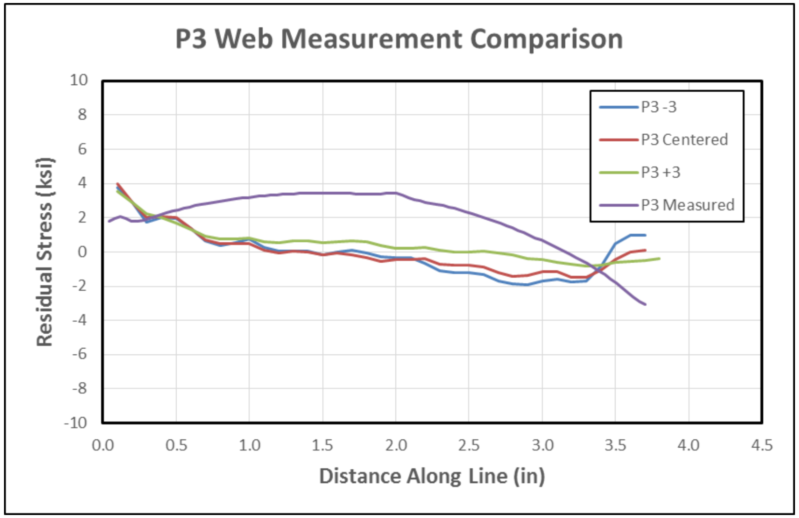
Validation of residual stress in machined component

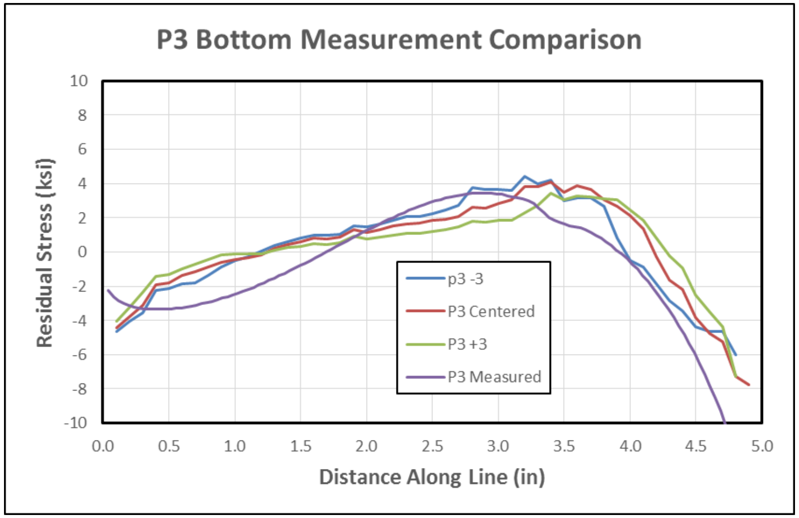
- Agreement within ±3 ksi



Process induced bulk residual stress finite-element model and validation measurements of an aluminum alloy forged and machined bulkhead, J.D. Watton, A.T. DeWald, et al., 2015 ASIP Conference, San Antonio, TX

Public Release 88ABW-2015-5301

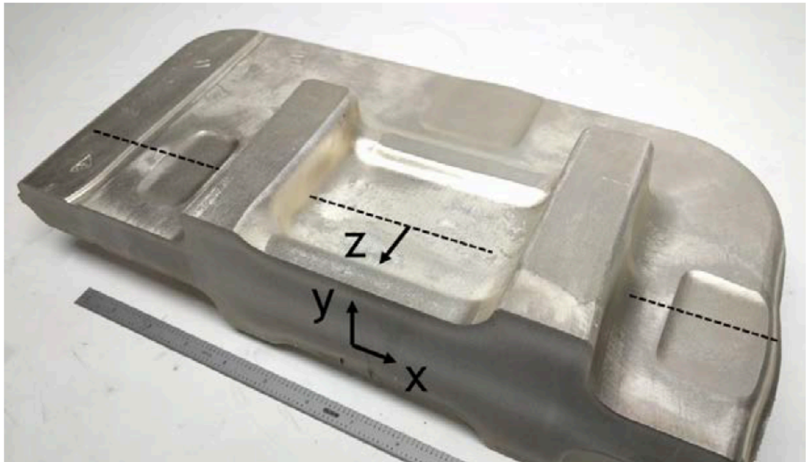


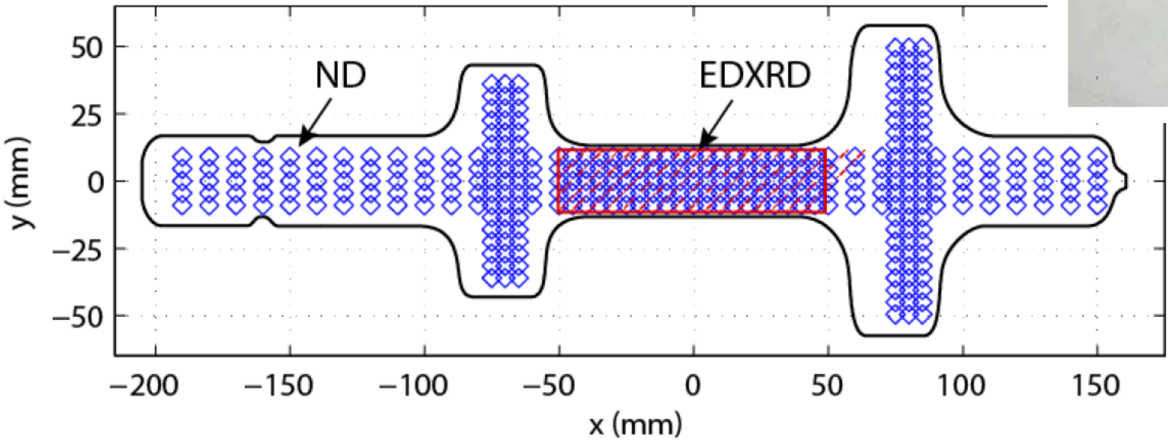


Die Forgings: Recent cross-method validation

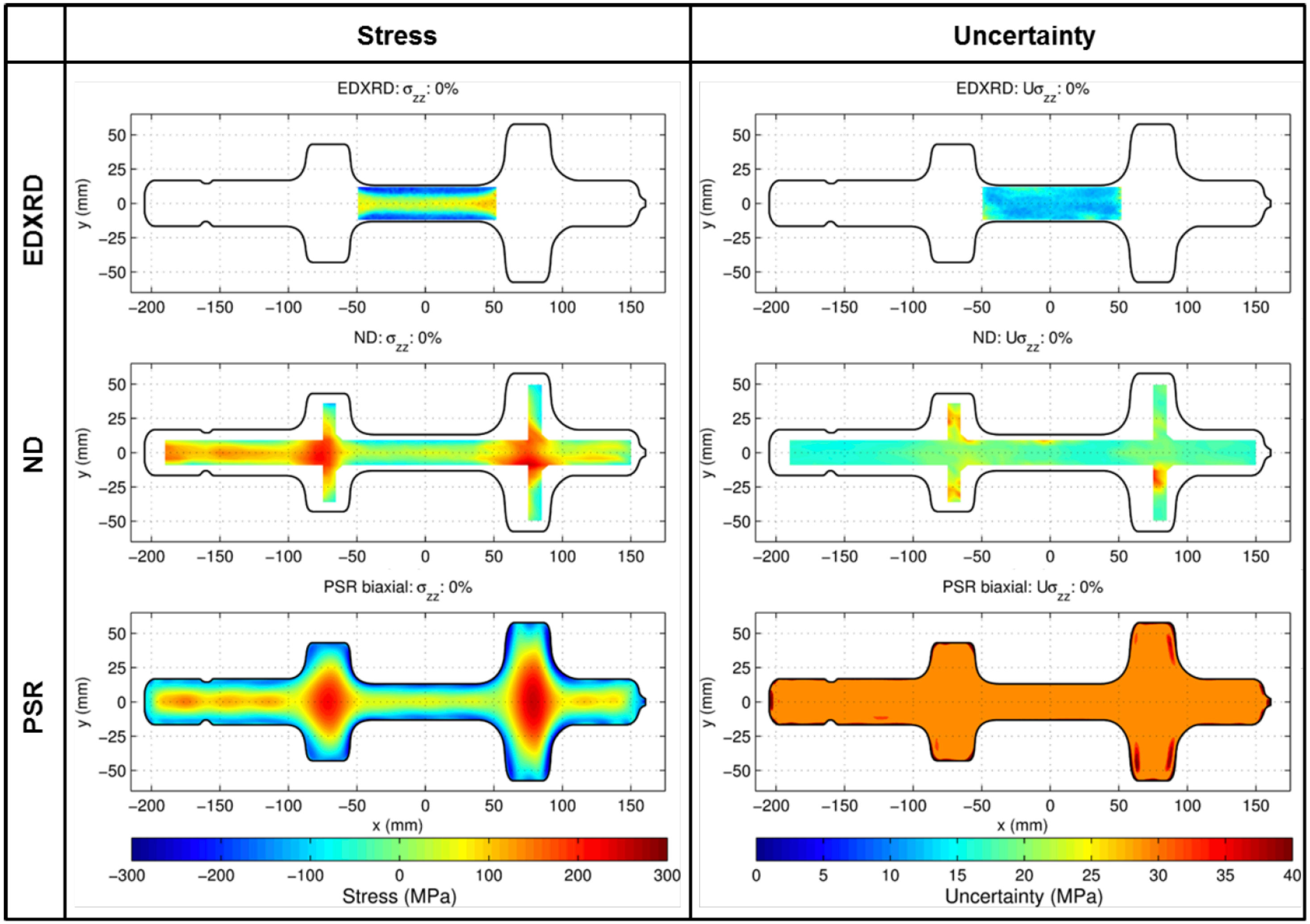
Ref: Olson, Spradlin, et al, 2017, Multi-Technique Residual Stress Measurement Comparison in 7085-T7452 Aluminum Die Forgings (to appear)

- PSR biaxial mapping (HE)
  - Contour + Slitting
- Neutron diffraction (SNS)
  - Sampling volume: 5 x 5 x 5 mm
- EDXRD (synchrotron, APS)
  - Sampling volume: 0.1 mm x 1 mm x 7°

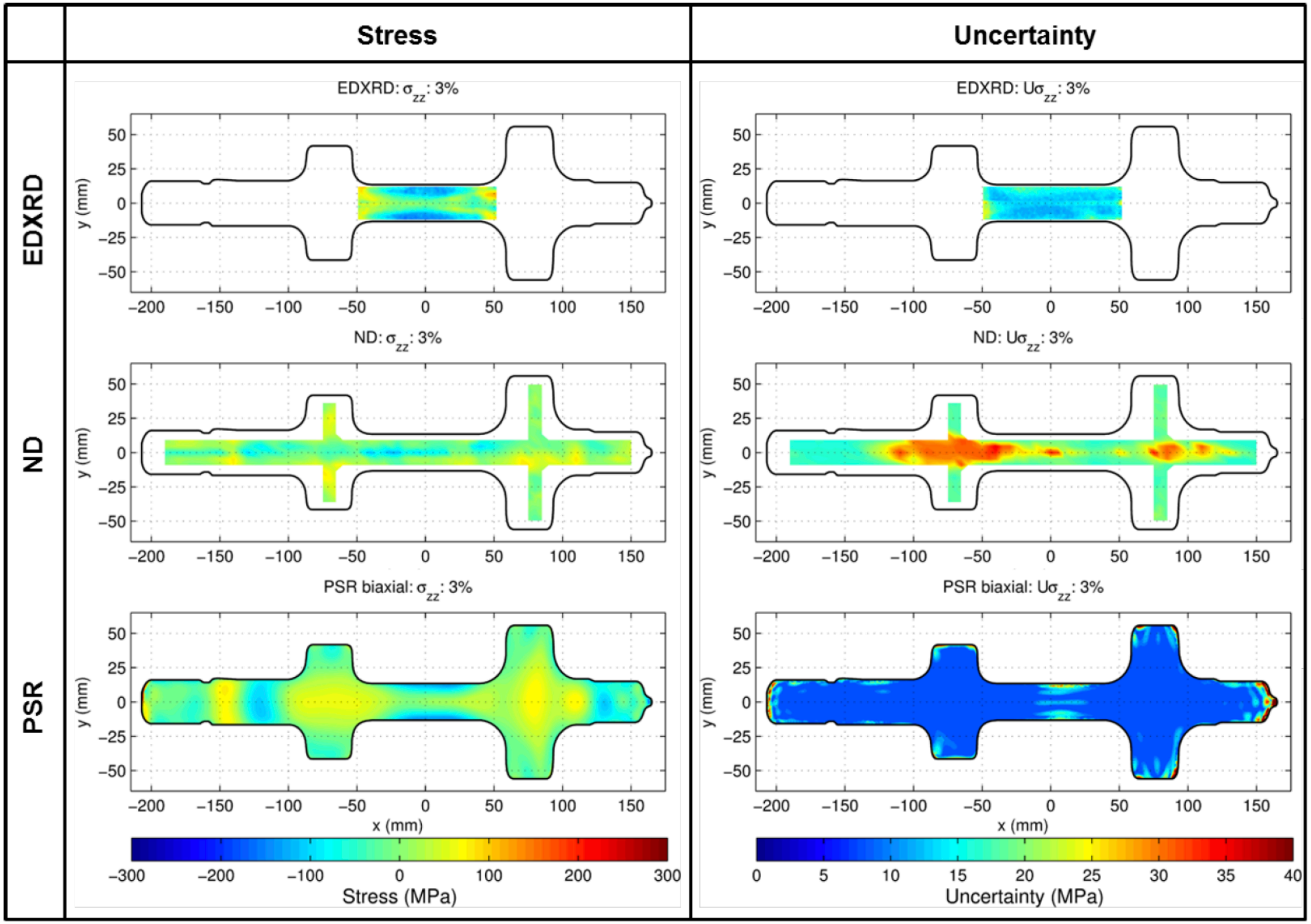




Die Forgings: AQ σ_{zz} inter-method comparison



Die Forgings: 3% CW σ_{zz} inter-method comparison



Die Forgings: 3% CW σ_{zz} inter-method comparison

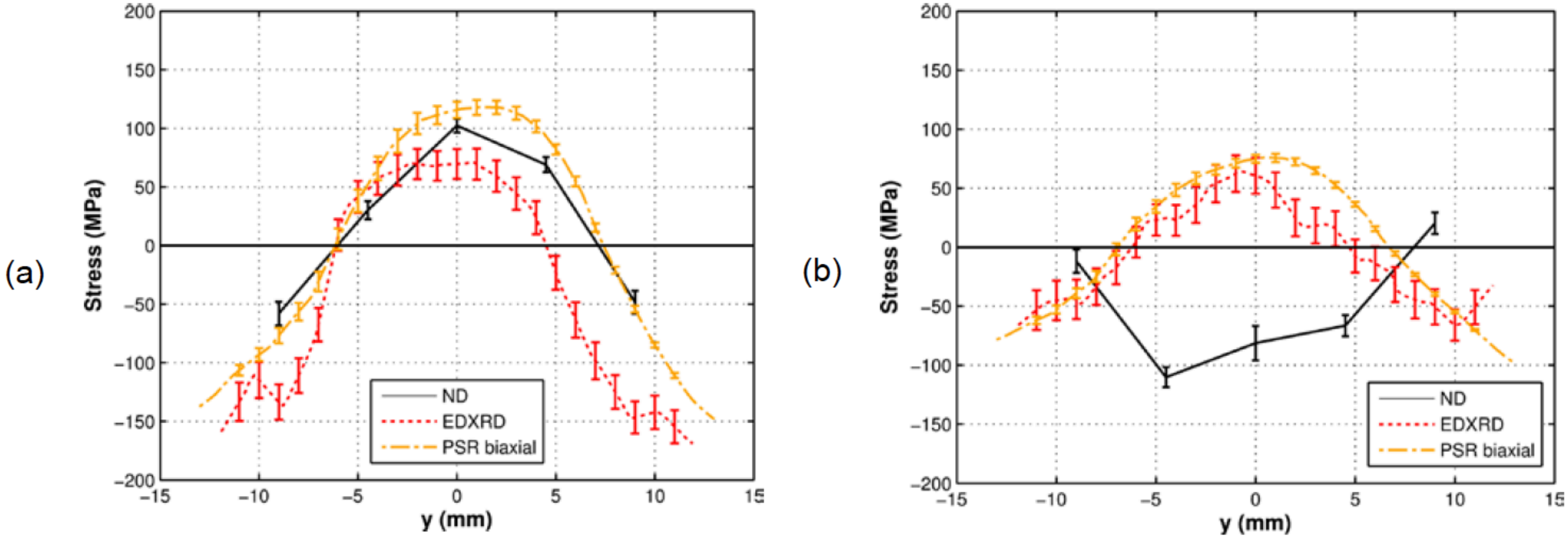


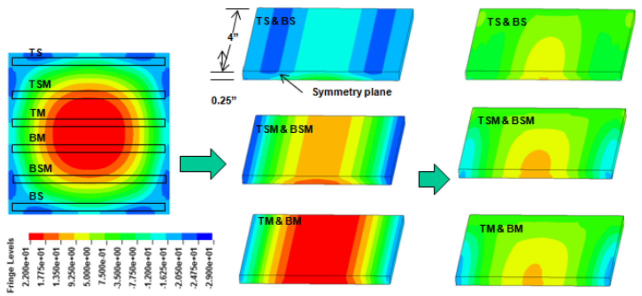
Figure 14: Line plots of the σ_{xx} stress from each of the measurement techniques along the line at x = 0 for the (a) 0% and (b) 3% cold-working conditions

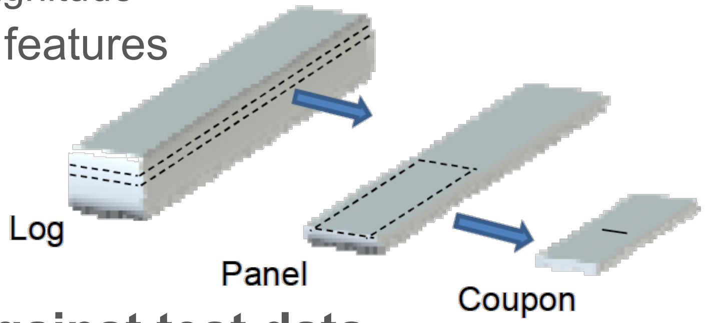
Validation of the impact of RS on fatigue analysis

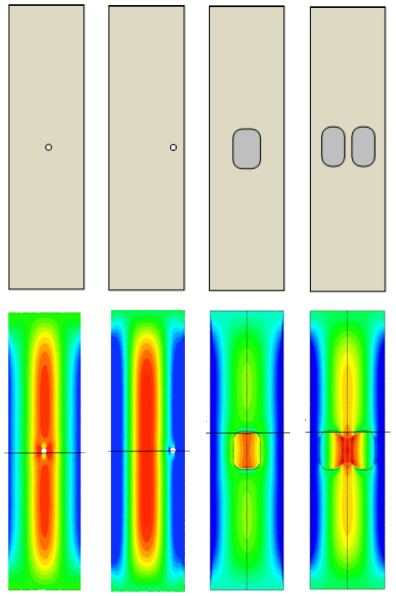
Fatigue crack initiation and crack growth tests

Develop set of coupons with range of residual stress

- Start with large quenched log with high residual stress (up to 150 MPa)
- Remove panels at various positions
  - Range of residual stress magnitude
- Make coupons with design features
  - Centered hole (+RS)
  - Offset hole (–RS)
  - Center pocket (+RS)
  - Double pocket (+RS)







Validate fatigue analysis against test data

- Crack initiation
- Crack growth

Include or ignore residual stress in analysis

The Impact of Forging Residual Stress on Fatigue in Aluminum, D.L. Ball, M.A. James, et al. http://arc.aiaa.org/doi/abs/10.2514/6.2015-0386

Validation of the impact of RS on fatigue analysis

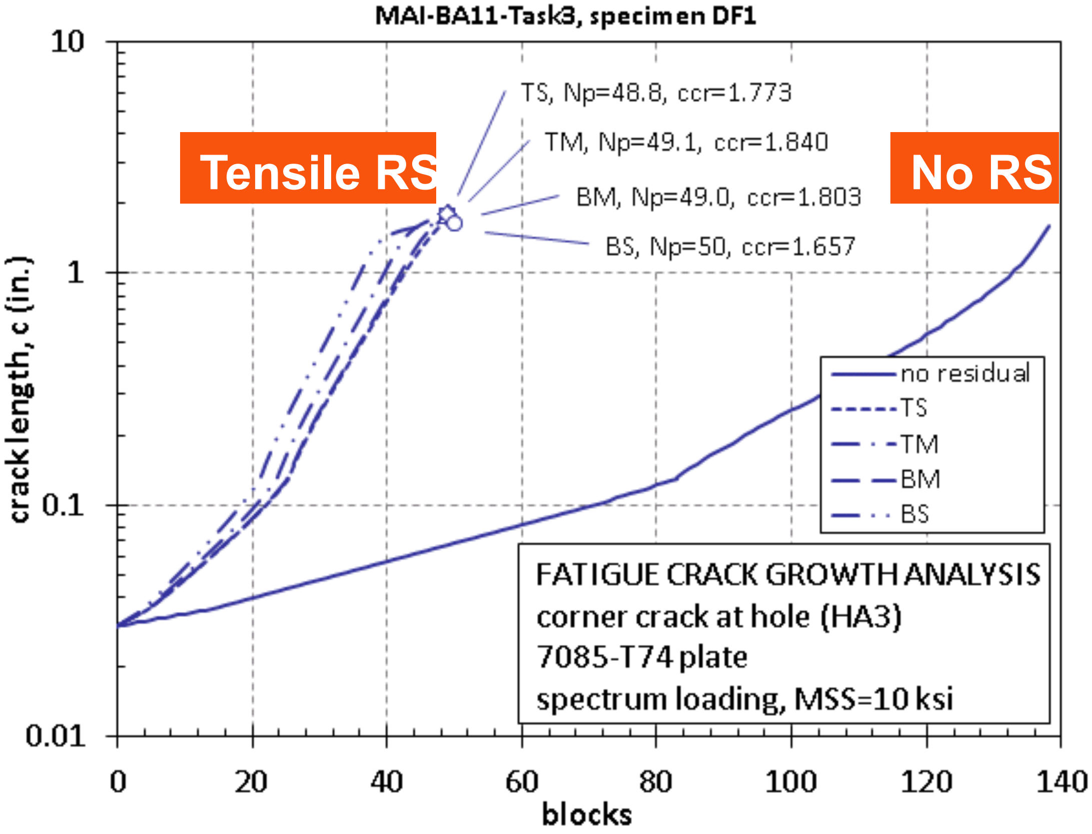
Fatigue Crack Growth Analysis

- Use superposition to include residual stress in LEFM analysis
- Most accurate for tensile residual stress

Tensile RS can cause significant increase in crack growth rate

- Decrease in life compared to baseline (no RS)

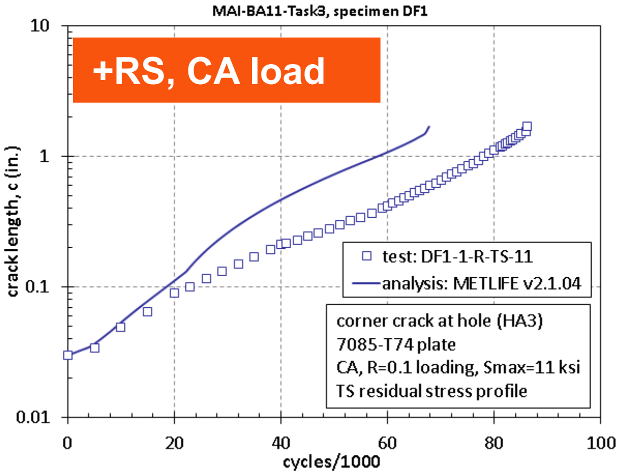
The Impact of Forging Residual Stress on Fatigue in Aluminum, D.L. Ball, M.A. James, et al. http://arc.aiaa.org/doi/abs/10.2514/6.2015-0386

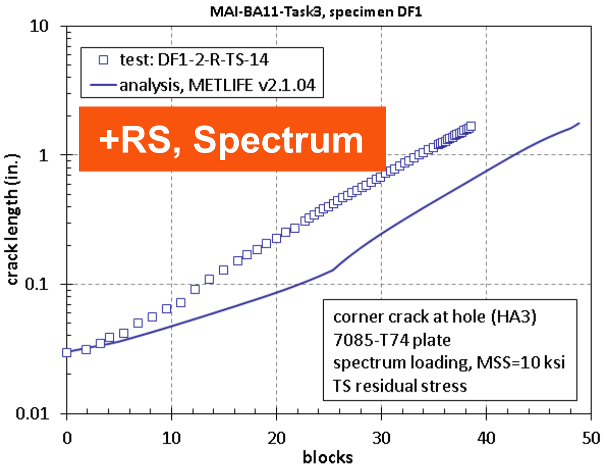


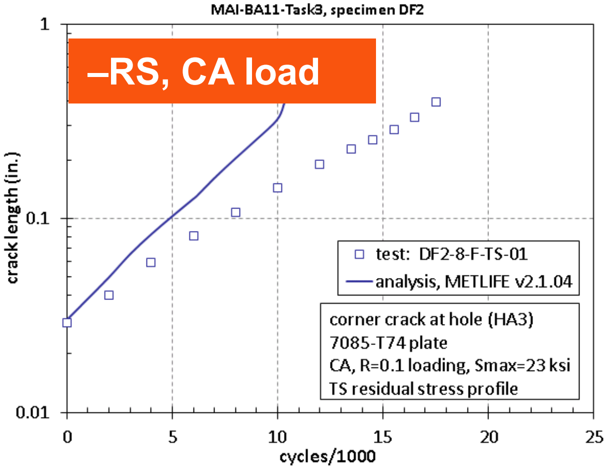
Validation of the impact of RS on fatigue analysis

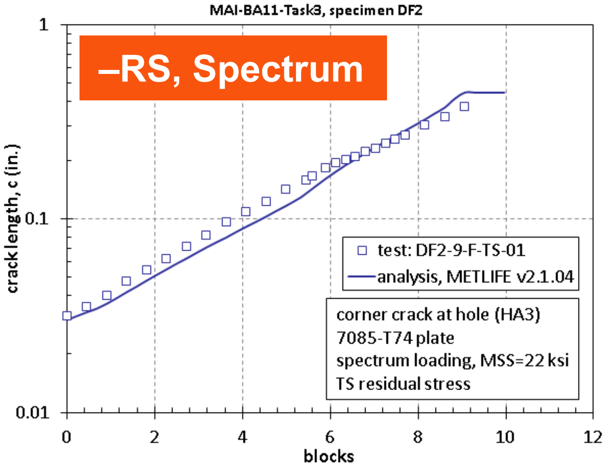
FCG models correlate reasonably well with test data

- Residual stress
  - Tensile
  - Compressive
- Loading
  - Spectrum
  - Constant Amplitude





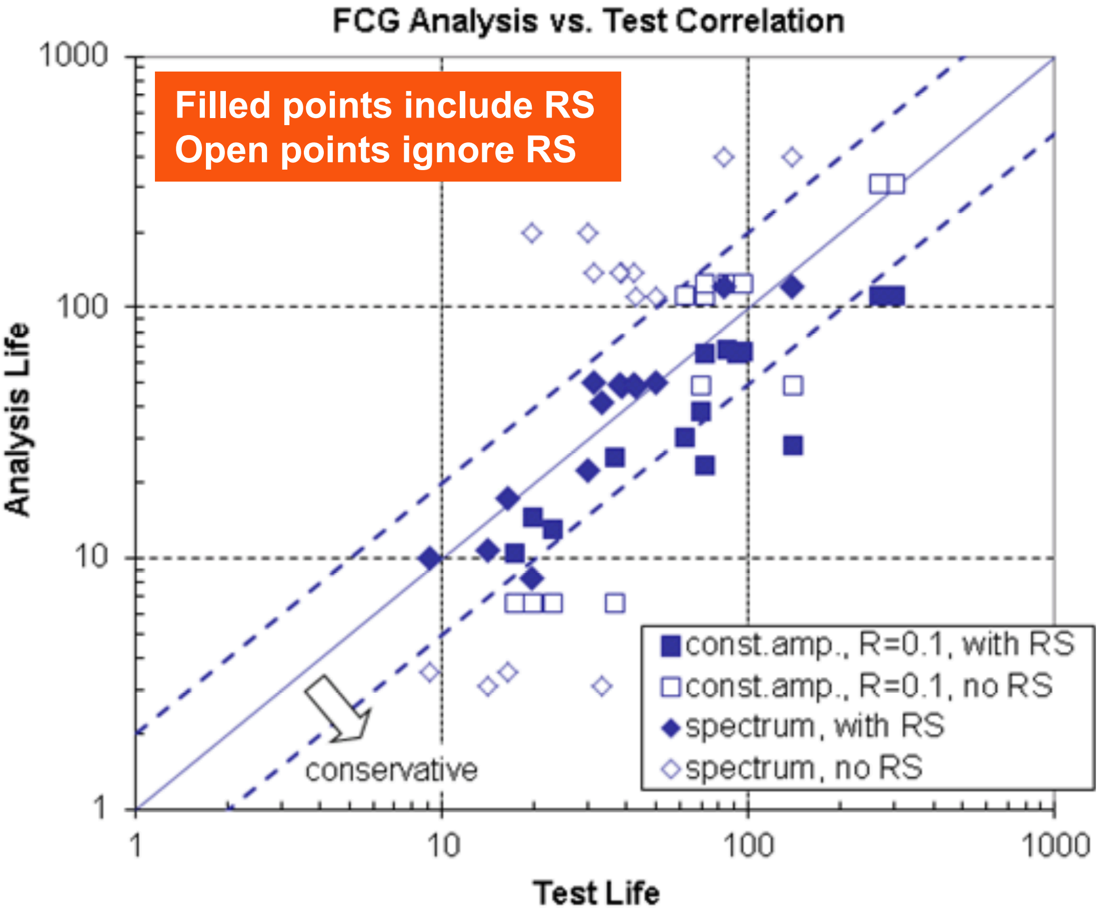




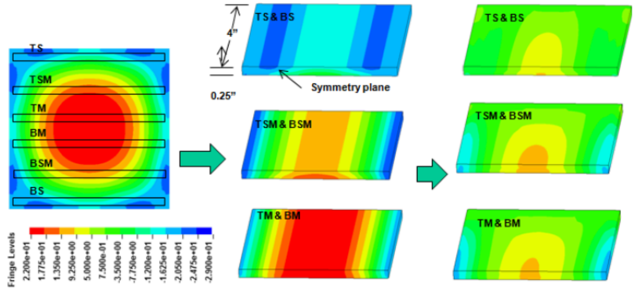
The Impact of Forging Residual Stress on Fatigue in Aluminum, D.L. Ball, M.A. James, et al. http://arc.aiaa.org/doi/abs/10.2514/6.2015-0386

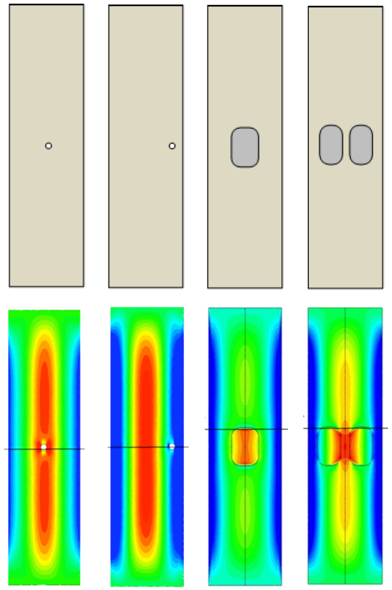
Validation of fatigue in parts removed from forgings

Fatigue crack growth tests: correlation of 6 unique coupon types in material with high residual stress



Filled points include RS
Open points ignore RS





The Impact of Forging Residual Stress on Fatigue in Aluminum, D.L. Ball, M.A. James, et al. http://arc.aiaa.org/doi/abs/10.2514/6.2015-0386

Summary of Topics for Today

Measurements of stress at Legacy vs New CX holes (HE)

- Data to date suggest legacy CX consistent with lab practices
- Data to date suggest no effect of service loading on RS (lower skin)

Measurements of Stresses at Cracked CX Holes (Carlson)

- Residual stress in cracked CX holes is changed from stress in new holes
  - Effect related to crack size in 2324-T351, but not related to crack size in 7075-T651

Recent Near-surface Stress Measurements (Castle)

- Near-surface stresses, near the bore edge may be tensile in a small area

Recent Near-bore Stress Measurements (HE)

- Slitting data for 2324-T351 CX holes consistent with contour data
- Slitting data for 7075-T651 CX holes less compressive than contour data with 0.02” of the bore

Concept for Large Hole Experiments (HE)

- Large holes with lower gradients that will be easier to measure

Recent Cross-method Residual Stress Validations (LSP and Die forgings)

- Provided data from prior programs to convey challenges and opportunities in cross-method residual stress validation data