Nondestructive Inspection (NDI) Nondestructive Evaluation (NDE) Quality Assurance (QA) & Data Management (DM) Committee Overview

Engineered Residual Stress Implementation (ERSI) Workshop

8 December 2020

Subcommittee Leads

John Brausch[1], Dr. Eric Lindgren[1], Kaylon Anderson[2]

[1]Materials and Manufacturing Directorate, Air Force Research Laboratory, [2]A-10 Program Office, Hill AFB UT

Overview

- NDI/NDE/QA/DM Committee Membership
- Subcommittee Updates
  - Nondestructive Inspection (NDI) – John Brausch

    - Damage detection in residual stress fields
  - Nondestrutive Evaluation (NDE) – Eric Lindgren

    - Detection and quantification of residual stress fields
  - Quality Assurance (QA), Data Management (DM) – Kaylon Anderson

Committee Members

First Name	Last Name	Company/Organization
Kaylon	Anderson	U.S. Air Force (A-10 ASIP Analysis Group)
Dallen	Andrew	Hill Engineering, LLC
John	Brausch	U.S. Air Force (AFRL - NDE Lead Engineer, Systems Support)
Nicholas	Brunnell	Engineer, NDI SME AFSC/ENRB OL Robins
Dave	Campbell	U.S. Air Force (Tinker AFB NDI Program Office Lead)
Brandon	Dierschke	L3 MID (Sustainment Engineering)
Teodor	Dogaru	Southwest Research Institue (SwRI)
Ward	Fong	U.S. Air Force (Hill AFB NDI Program Office Lead)
Dave	Forsyth	Texas Research International (TRI) - Austin, Inc.
Leo	Garza	L3 Communications (RC-135 Fleet Manager)
Scott	Geller	GTC Machining
Tyler	Gruters	US. Air Force (F-15 Structures)
Bryce	Harris	U.S. Air Force (F-16 ASIP Manager)
Ian	Hawkings	US Navy (PAX river)
Mike	Hill	Hill Engineering, LLC
Joshua	Hodges	Hill Engineering, LLC
Phil	Hoefert	L3 Harris Aerospace Systems Division - Sustainment Engineering
Kim	Jones	U.S. Air Force (F-16 ASIP)
Chris	Kirkpatrick	L3 Harris Aerospace Systems Division - Sustainment Engineering
Eric	Lindgren	U.S. Air Force (AFRL - Materials and Manufacturing Directorate
Carl	Magnuson	Texas Research International (TRI) - Austin, Inc.
Doyle	Motes	Texas Research International (TRI) - Austin, Inc.
Mike	Reedy	U.S. Navy (NAVAIR - Compression Systems Engineer)
David	Rusk	U.S. Navy - NAVIAR Structures, AIR-4.3.3.5
Hazen	Sedgwick	U.S. Air Force (A-10 ASIP Analysis Group Manager)
Gregory	Shoales	Center for Aircraft Structural Life Extention, US Air Force Acad
Clint	Thwing	Southwest Research Institue (SwRI)
Jacob	Warner	U.S. Air Force (A-10 ASIP Analysis Group Lead)
David	Wilkinson	U.S. Air Force (C-5 ASIP Manager)
Sam	Zimmerman	Fatigue Technology Incorp. (FTI) - A PCC Company
Jude	Restis	PartWorks
Ian	Hawkings	US Navy
Edward	Bajeck	US Navy

33 Members

Nondestructive Inspection Sub-Committee

NDI Subcommittee Priorities

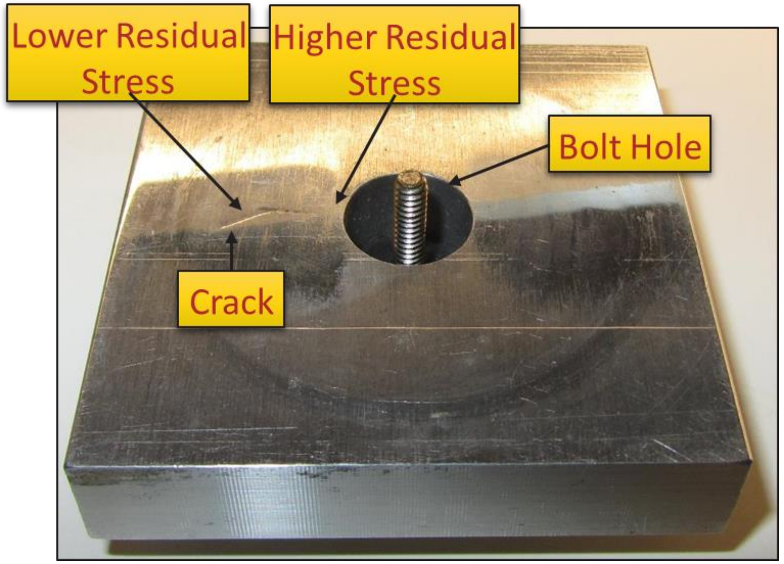
I. **Quantify ultrasonic dead zone in Cx holes**

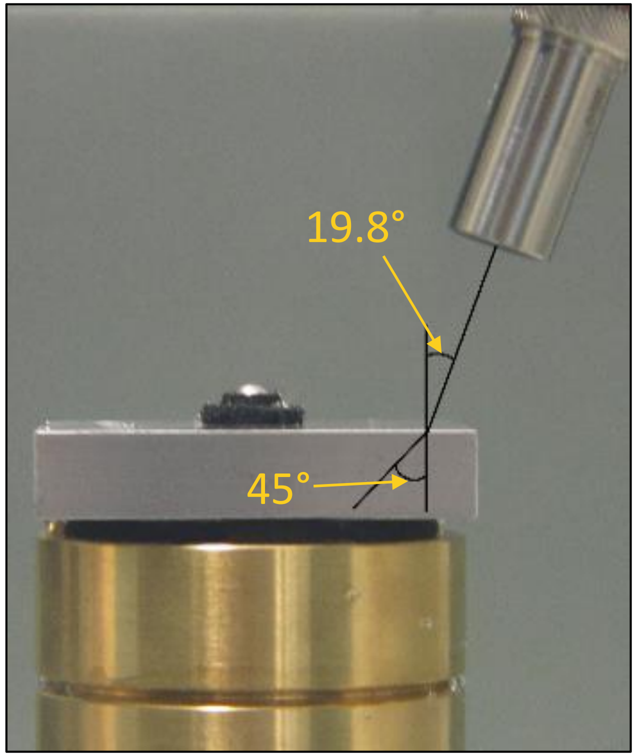
II. Evaluate Phased Array UT for inspection of Cx holes

III. Characterize impact of laser-peening of Titanium on eddy current, penetrant and eddy current detectability

Ultrasonic Dead Zone Characterization in Cx Holes

- Round Robin Testing
- Characterize effect of residual stresses on detectability of fatigue cracks with ultrasound
- 117 Specimens, 4% cold work holes – Courtesy of Apes Engineering
  - 3 hole diameters (0.278 inch D, 0.418 inch D, 0.538 inch D)
  - 3 plate thicknesses (0.100 inch, 0.313 inch, 0.500 inch)
  - Fatigue cracks: 0.020 inch – Thru-Thickness



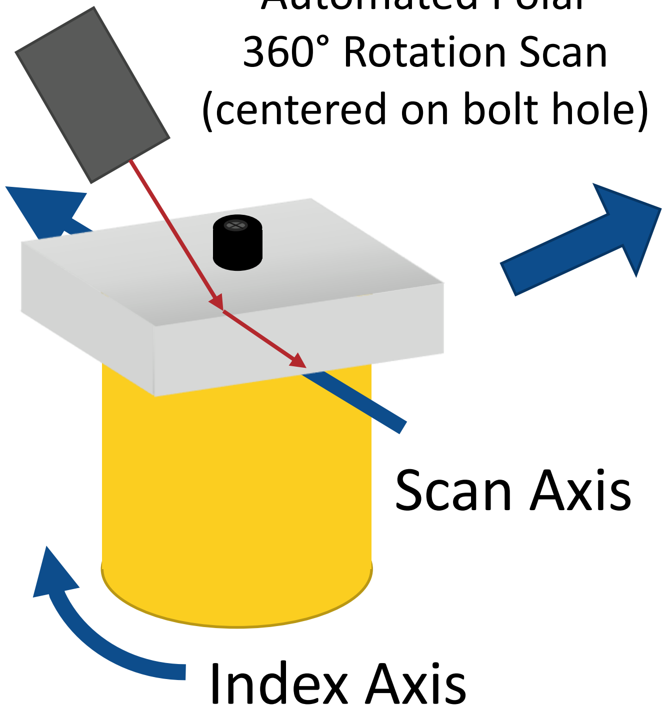


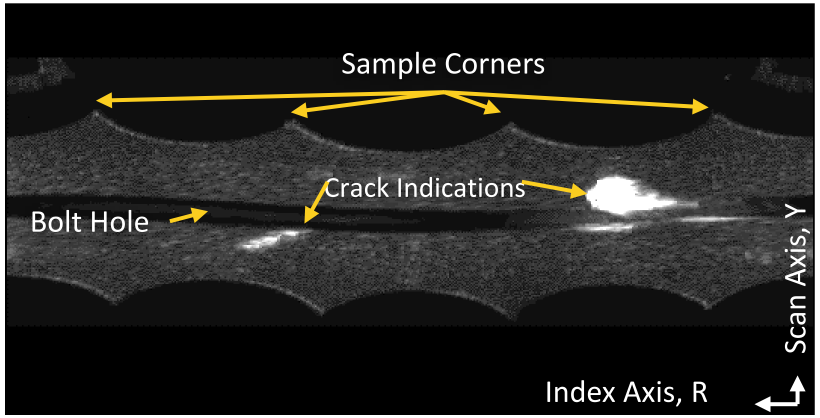
Research performed UDRI On-Site Personnel (Tyler Lesthaeghe, David Zainey & Tineka Witt)

Ultrasonic Dead Zone Characterization in Cx Holes

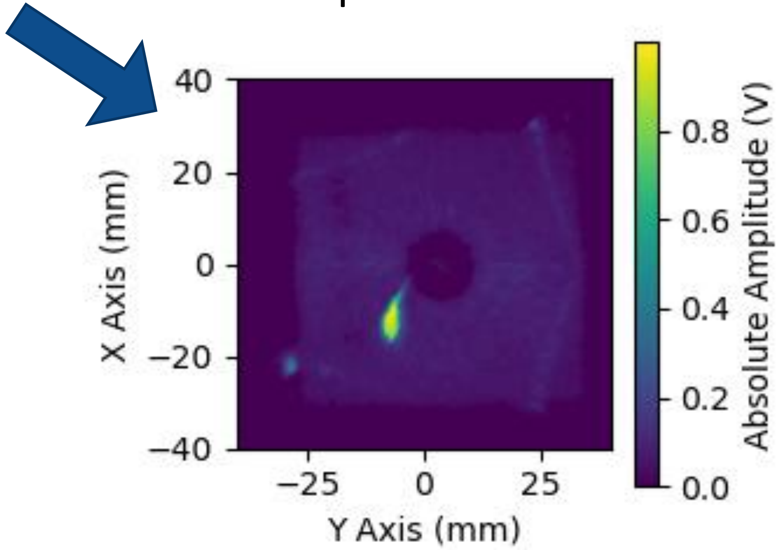
Sample Screening using Polar Scanning Process

Automated Polar
360° Rotation Scan
(centered on bolt hole)





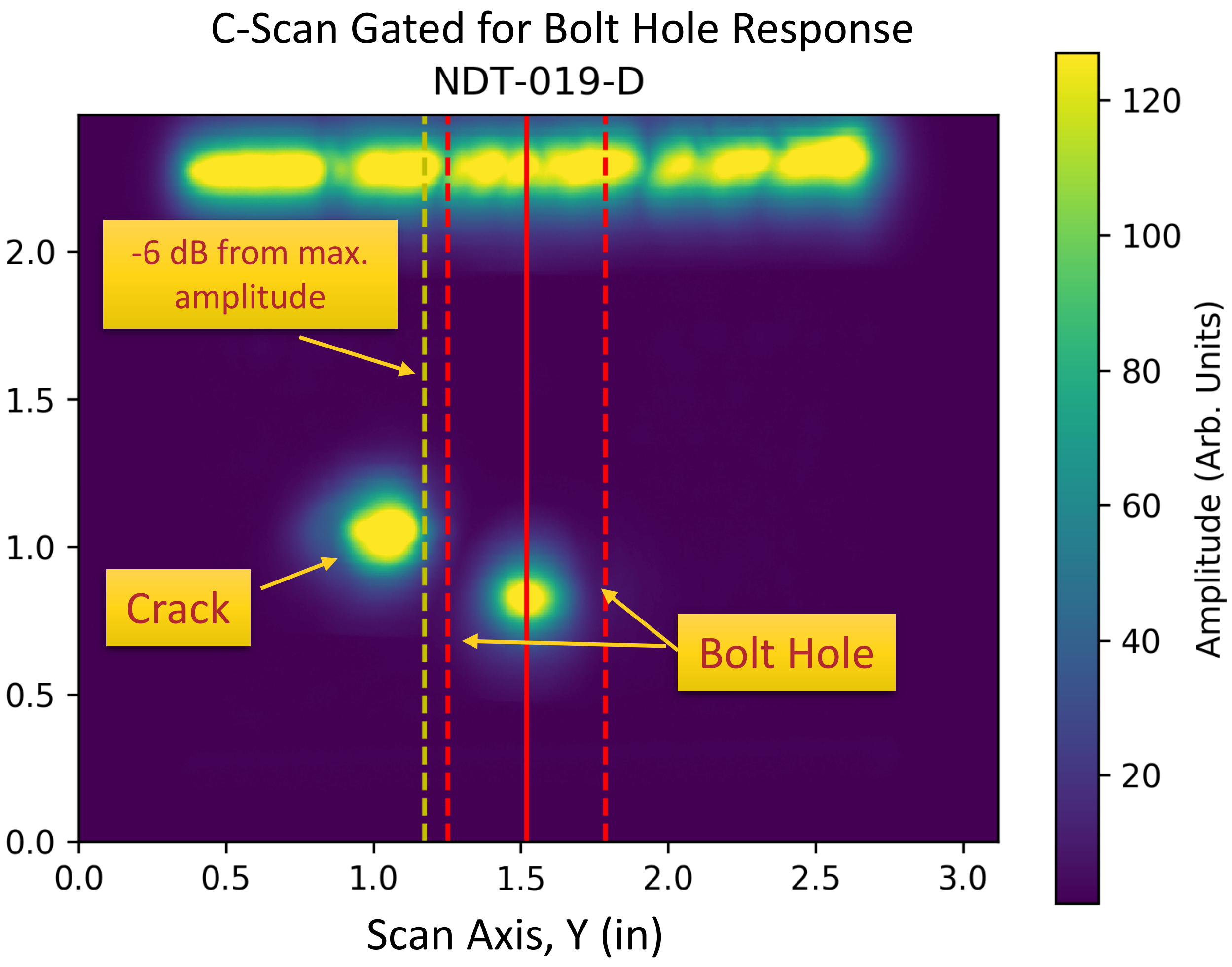
Warping Procedure To
Create C-scan Image For
Easier Interpretation

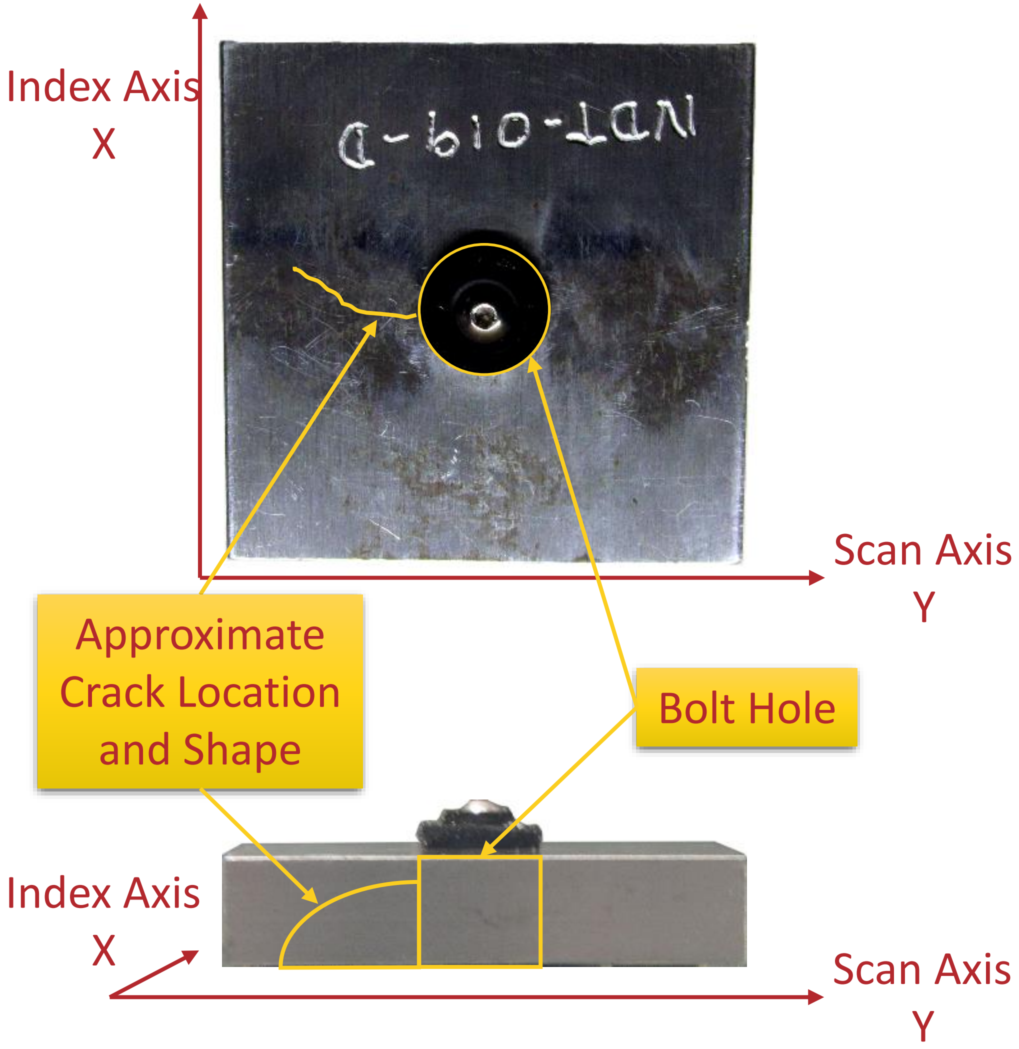


Employed automated scanning to screen for samples with detectable cracks

- 117 Samples, most did not have detectable cracks

Procedure for Dead Zone Measurement

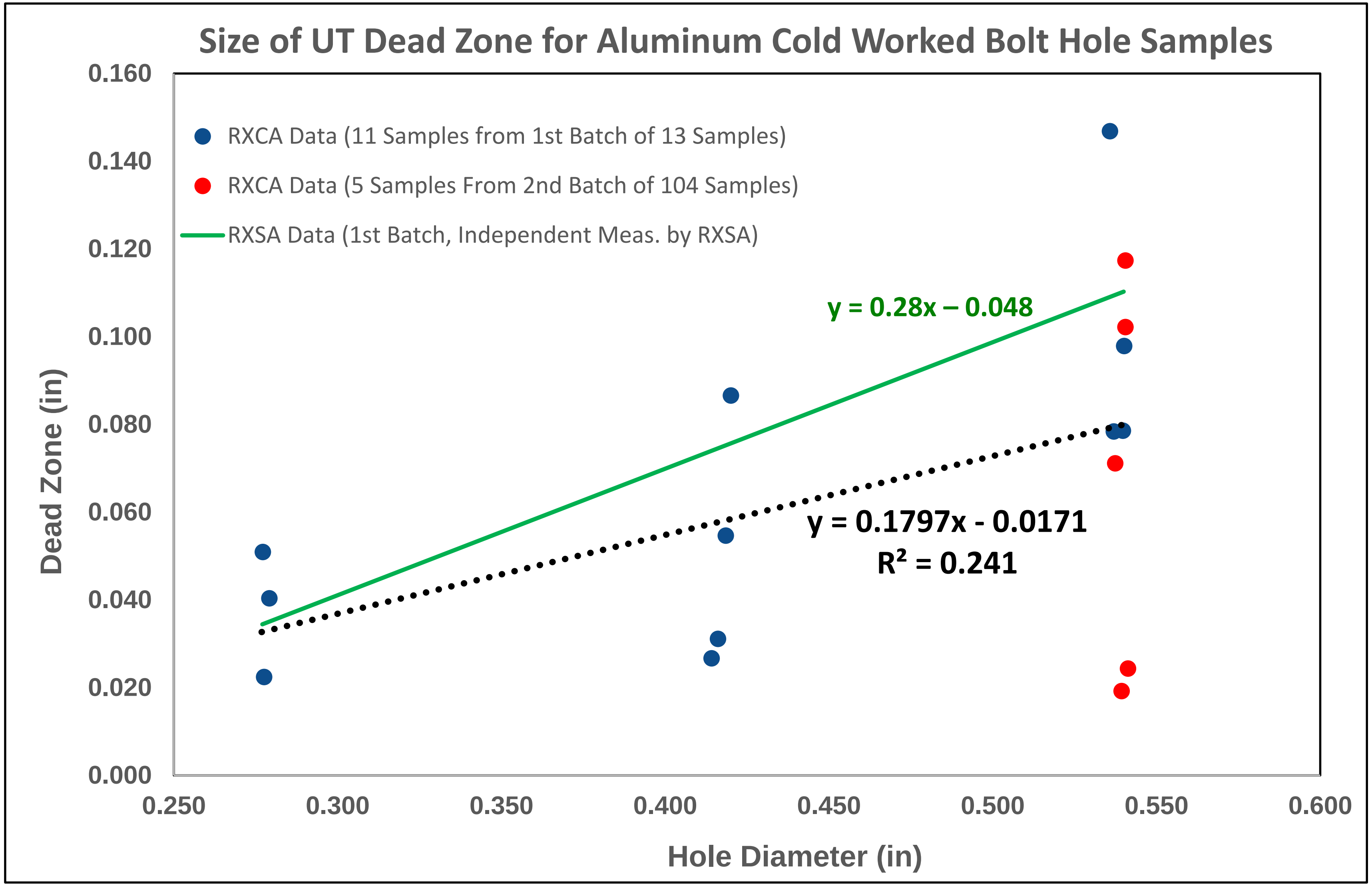




Python Scripts used to Semi-Automate Dead Zone Measurements

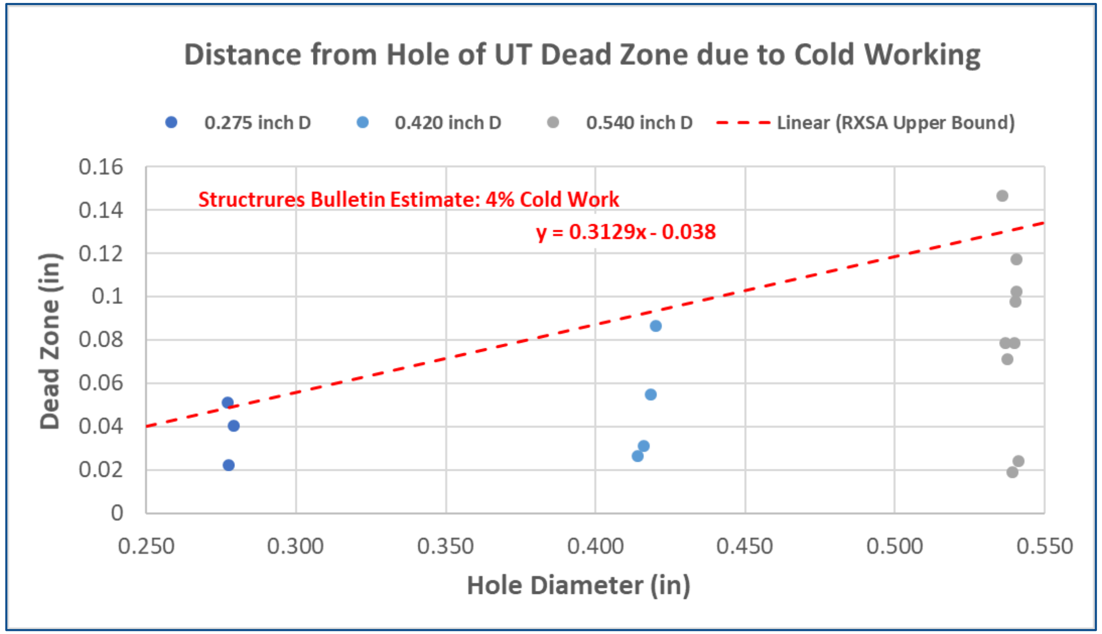
Summary of RXCA Results

- 117 Samples Examined
- Measurable Dead Zone in only 16 samples
  - Used similar procedure as RXSA to size dead zone
  - Samples with no dead-zone not shown
- Similar trend of Dead Zone Size Proportional to Hole Dia. as found by RXSA
  - On average, RXCA results report smaller dead zone compared to RXSA measurements

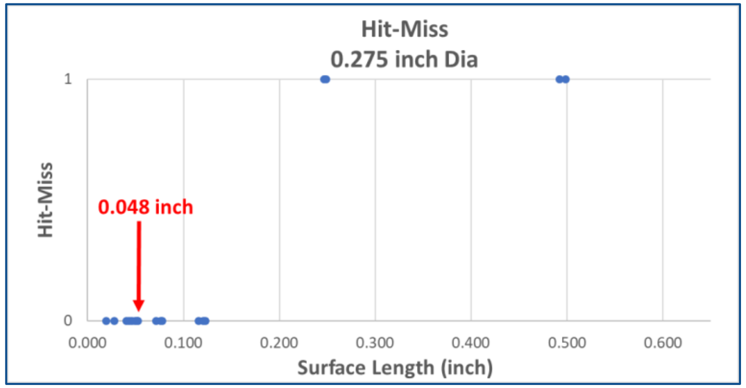


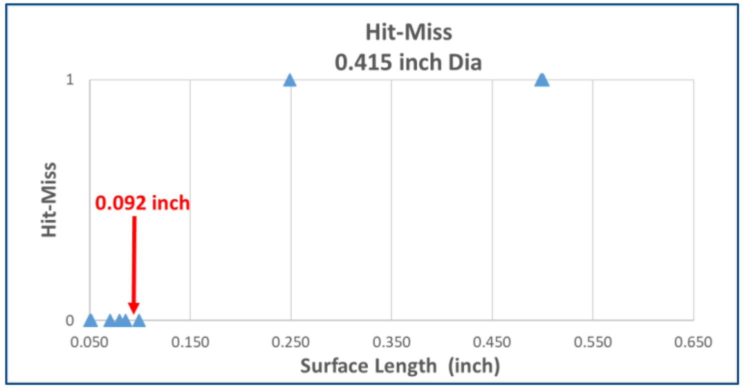
Comparison to Current Assumptions

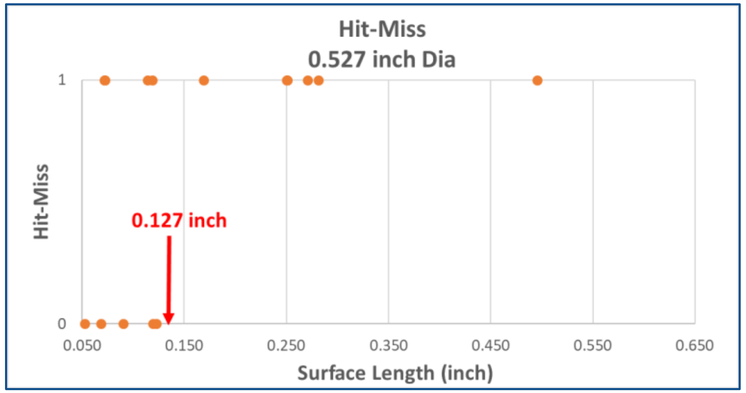
Data for Detectable Cracks (16 samples)



All Cracks (56 samples)







- Considerable variability in results
- Missed cracks greater than prediction are concerning
  - Further analysis of 0.275 in diameter hole samples initiated
- Next: Correlate dead zone estimates to residual stress profiles – collaboration required

NDI Implementation Strategy

- Capability impacts documented in EN-SB-008-012
- Impacts incorporated into ultrasonic probability of detection models
- Inspection limitations to be documented in ERSI Best Practices
- Documentation of inspection process best practices in general procedures of T.O. 33B-1-2 where applicable

Nondestructive Evaluation Sub-Committee

Nondestructive Evaluation to Detect and Quantify Residual Stress Fields in Cold Worked Holes

Eric Lindgren

Materials State Awareness Branch
Materials and Manufacturing Directorate

December 8, 2020

Objective / Motivation / Impact

Objective

- **Nondestructive Evaluation (NDE) to quantify residual stress field at cold worked fastener holes**
  - **Verify Engineered Residual Stress (ERS) is present**
  - **After in-service and possibly for quality assurance**

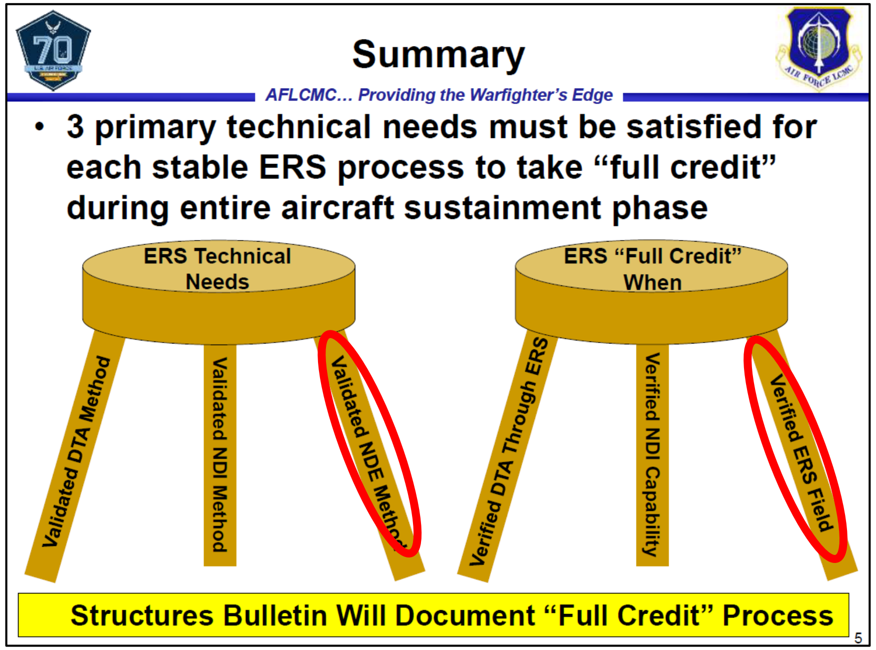
Motivation

- **One of three primary technical needs to take full credit during entire sustainment phase**

Impact

- **Enables enhanced life management**
- **Enables life extension**
- **Both while not compromising safety**

Engineering Residual Stress Integration



From "ASIP Perspective on Accounting for Engineered Residual Stress (ERS) in Damage Tolerance Analysis," C.A. Babish, ASIP Conference 2017

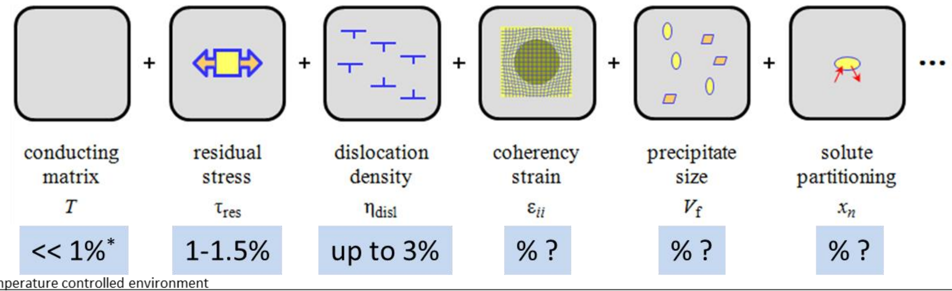
Background / Challenges

Background

- Multiple NDE-based methods sensitive to residual stress
  - X-ray diffraction, ultrasound, eddy current, neutron diffraction
- Previous research addresses predominantly shot-peened metals
  - Multiple for turbine engine applications

Challenges

- Confounding factors can exceed residual stress effect on NDE measurements
- In service: manufacturing (e.g. fit-up stresses), maintenance, repair, usage
- Macro-scale: temperature, geometry, material
- Micro-scale: dislocation density, coherency strain, precipitates, solute positioning



*Temperature controlled environment

Approach

Develop comprehensive inversion methodology:

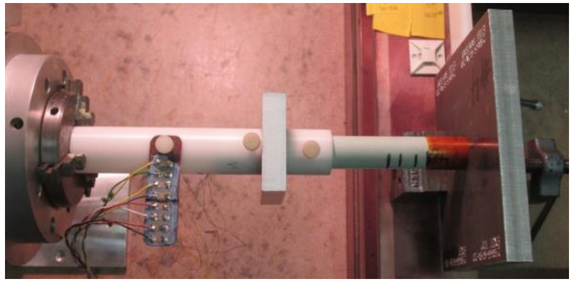
- **Focus: cold worked fastener holes**
- **Includes: multi-frequency, multi-probe approaches**
  - **Initial focus on eddy current methods**
  - **Ultrasonic techniques being evaluated**
- **Leverages modeling: macro and micro effects in aluminum alloys first**
- **Integrates uncertainty quantification:**
  - **Required to provide quantitative answer**
- **Year one of four year program complete**

HILL ENGINEERING
Predict. Test. Perform.

SwRI

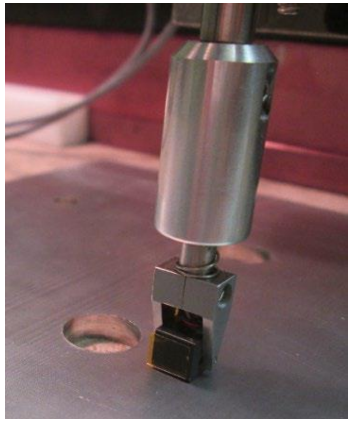
ERSI

Progress to Date



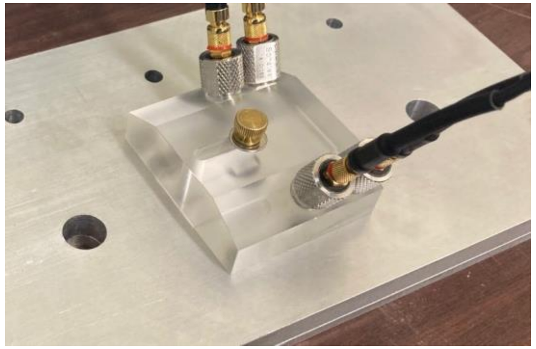
Initial Exploration:

- In-hole eddy current probe
- Specialized eddy current surface probe
- Ultrasonic probes



Structured Approach:

- Confounding factor assessment
- Rigorous test matrices
- Initial sample sets
- Will integrate structural variability



Preliminary Results:

- All methods sensitive to controlled residual stresses
- Changes measured are small – promising for QA
- Start to address hard problem: quantification

Summary

- Quantitative NDE methods required for "full credit" for ERS
  - QA and Surveillance
- Extensive past R&D focused on NDE
  - Multiple methods can measure ERS
  - Success limited to differential measurements
  - Quantitative results hindered by confounding factors: there are many!
- New program leveraging past experience
  - Ambitious objectives
  - Eddy current and ultrasonic based approaches
  - Addresses QA and surveillance
  - Includes components with 10 and 20 year service life

Nondestructive Inspection Executive Working Group

Air Force Research Laboratory

RXCA
Research, Development, Transition

RXSA
Advanced Engineering, Rapid Response

AF Life Cycle Management Center

EZPT, EZF, LPS, SPOs
Field Support, Engineering Support, and Requirements

NDI EWG
Includes MAJCOM NDI Functionals

AF Sustainment Center

AFSC NDI Program Manager
Complex NDI Managers
Depot/Field/SPO Support

AIR FORCE LCMC

AIR FORCE RESEARCH LABORATORY

AF SUSTAINMENT CENTER

Material Assessment for Integrity Assurance

Quality Assurance and Data Management Sub-Committee

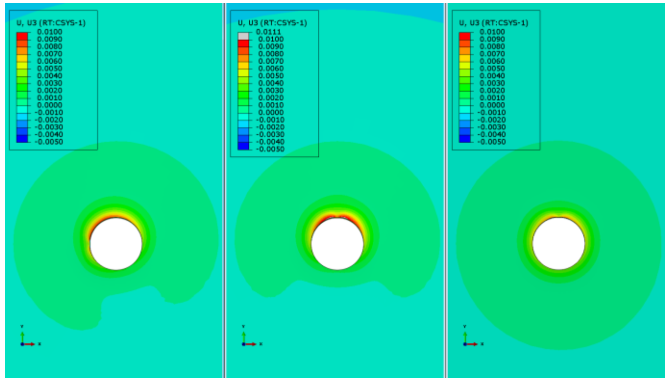
FastenerCam for QA/QC of Cold-Expanded Fastener Holes – 2020 ERSI Update and Summary

Doyle Motes,
Texas Research Institute (TRI) Austin, Inc.

8 December 2020

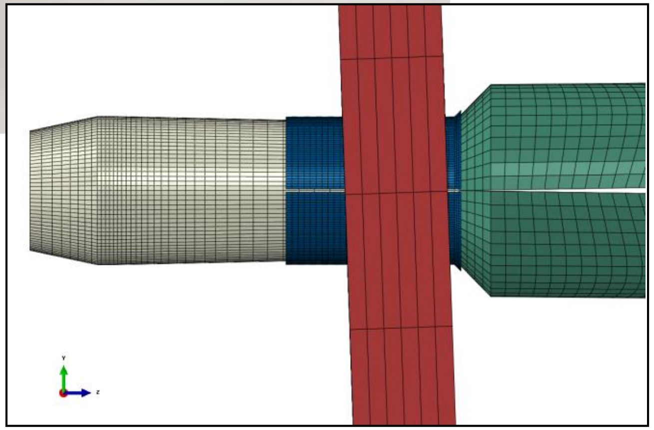
What is FastenerCam™?

- Developed out of RIF and subsequent SBIR efforts
- Handheld laser profilometer and software package (open source Python)
- Measures cold expansion around cold-worked fastener holes (quality assurance)
  - New install
  - Legacy analysis
  - What is unique to our approach
- Provides options for:
  - Good/Bad (Green light/red light)
  - Full data capture (entire set of profile data)
  - Interfaces with NLign for reporting



Current Status of FastenerCam™

- Ruggedized manufacturing prototype has been developed (TRL 6)
- Positioned to start LRIP for fieldable units
- Use cases include:
  - Straight shank holes
  - Multiple layers
  - Off-angle pulls
  - 2024 and 7075 Al alloys
- Meets MIL-STD-810F, -1472F, - 461G
- 8 hr battery, 2 TB HD, integrated touchscreen tablet



ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Next Steps to Develop FastenerCam™

- Develop and implement profilometry capabilities (scanning and analysis) for countersunk CX holes
- Manufacture an upgraded FastenerCam™ (for straight and countersunk holes)
- Repeatability and reliability (R&R) study to integrate FastenerCam™ into tech orders for aircraft of interest

Digitalex background

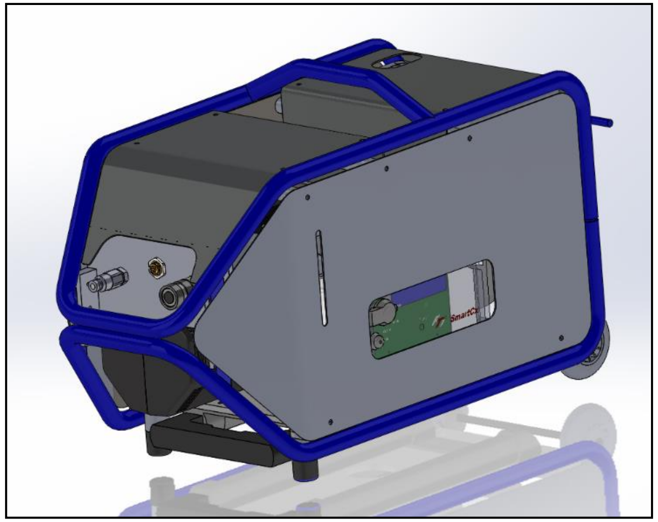
Sam Zimmerman,
Fatigue Technologies, Inc.

8 December 2020

Next-generation split sleeve instrumented Cx tooling

New Hydraulic Puller and PowerPak integrating instrumentation with proprietary data analysis

- Fully electric operation,
- Monitors load vs piston stroke data,
- Integrated process validation (Go/No Go),
- Process data logging for archive records,
- Allows tool life tracking, lockout and other digitized tool management
- Integration to networked factory (IoT),
- Compatible with legacy FTI processes,
- Compatible with Data Spatial Positioning (DSP) systems.

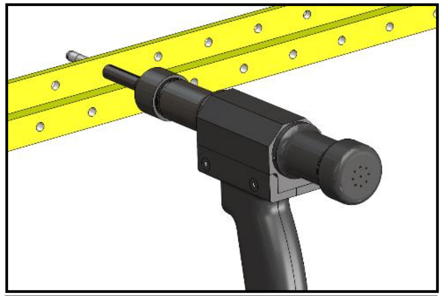


ERSI
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

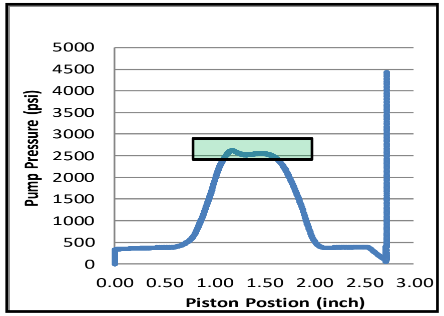
Vision for digitized cold expansion tools

QUALITY

- Increased process confidence and reduced quality risk
- Integrated process check ("Instant" Go/No Go)



FTI Instrumented SsCx Tooling



PROCUREMENT

- Real-time tooling and consumables data
- Advanced tool tracking

PLANNING

- Pre and Post Cx process data sharing
- Active monitoring of KPI's and advanced analytics

ENGINEERING

- Greater confidence in design allowables
- Traceable digital Cx data records (Digital Twin)

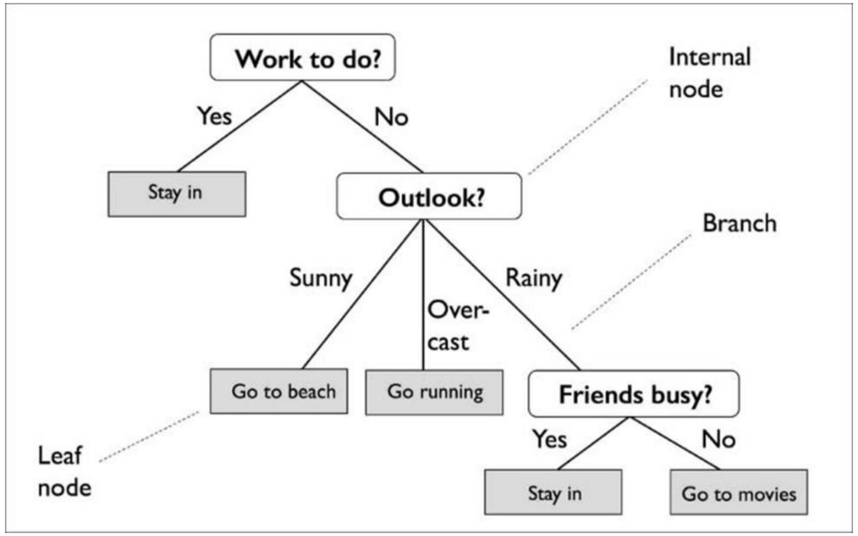
CUSTOMER SATISFACTION

- Increased quality at higher rates
- Potential for extended PM schedules
- Traceability and advanced data

Decision Tree Go/No-go

Process description

- Data is curve fit to both a flat-top Gaussian and a skew Gaussian
- Curve fit parameters are fed into decision tree classifier
- Planned schedule: Available on DSP program unit
  June 2020



In-depth method – Curve Fit

- Two curve fit equations:

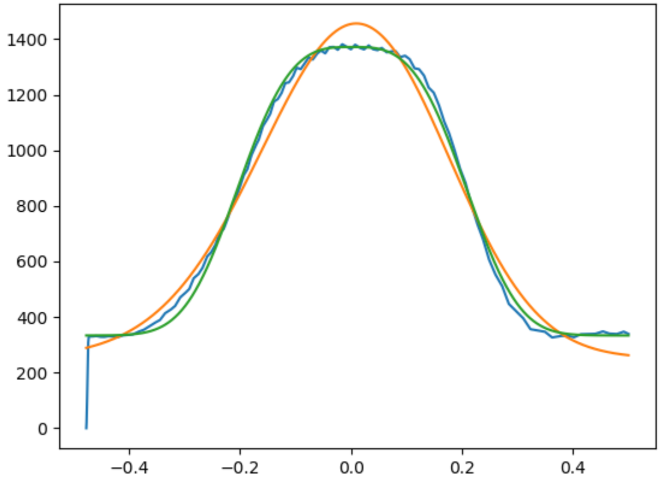
$$PDF(x) = \frac{1}{\sqrt{2\pi}} e^{-x^2/2}$$

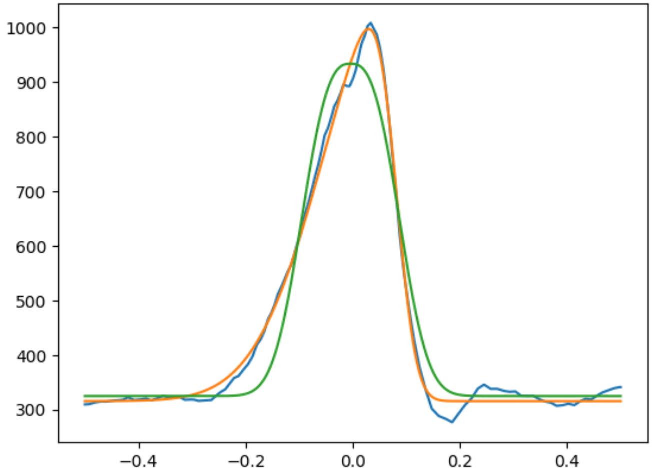
$$CDF(x) = \frac{1 + \text{erf}\left(x/\sqrt{2}\right)}{2}$$

Equations:

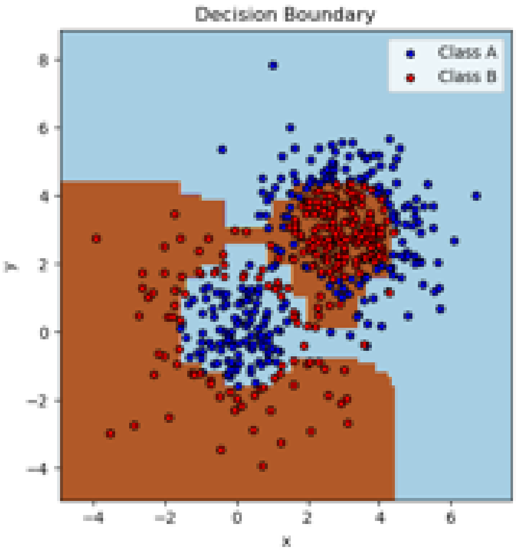
$$S(x) = \alpha\left(PDF\left(\frac{x-m}{\sigma}\right) CDF\left(\frac{\beta(x-m)}{\sigma}\right)\right) + \gamma$$

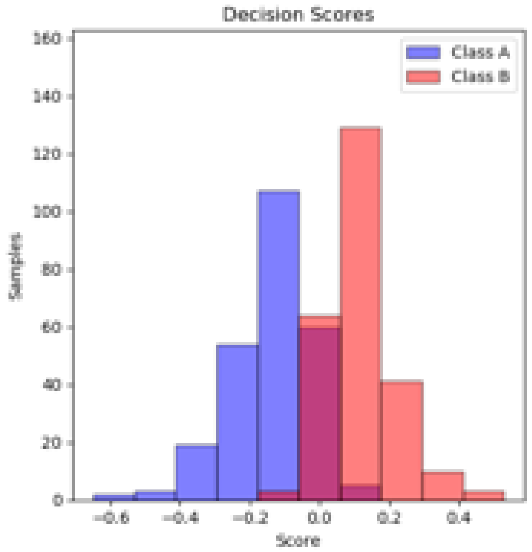
$$F(x) = \alpha\left(PDF\left(\left(\frac{x-m}{\sigma}\right)^{\varphi}\right)\right) + \gamma$$





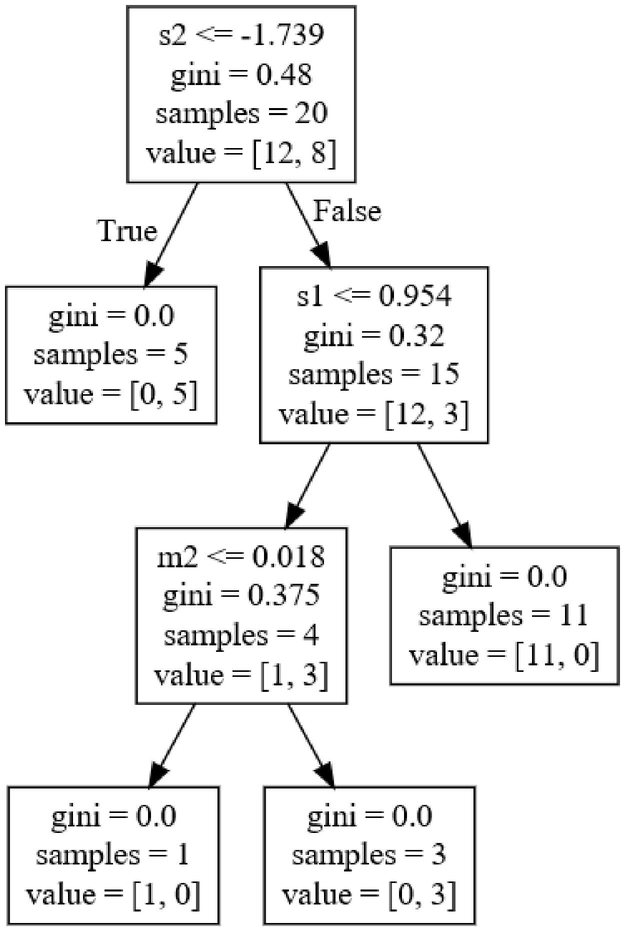
In-depth method – Decision Tree Classification





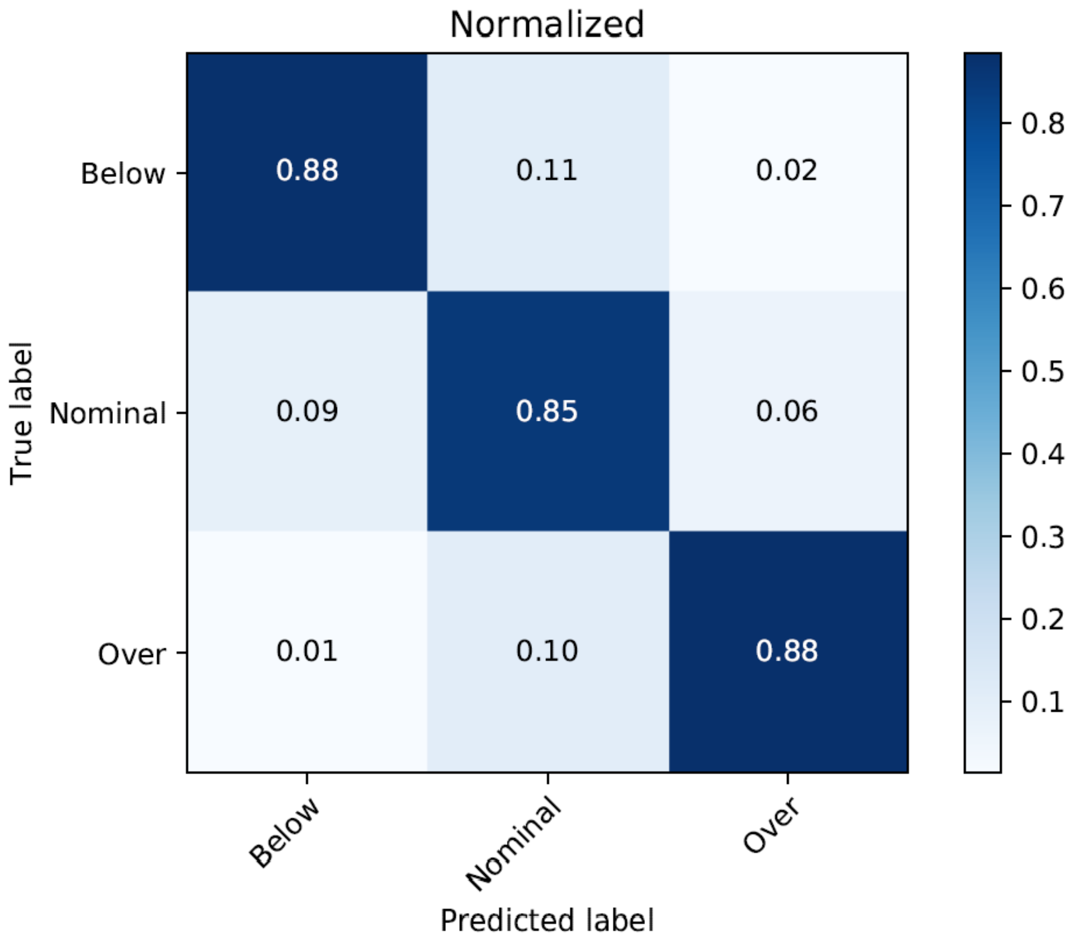
- Separate parameter space into rectangular "regions" split by branches
- Regions are continually split into smaller and smaller rectangles at each branch

Optimization process



- At each branch, minimize Gini index.
  - Gini measures how "pure" each category is
- Pruning
  - After building tree, remove unnecessary branches
- Bootstrapping
  - Build multiple trees and take the median of all of them

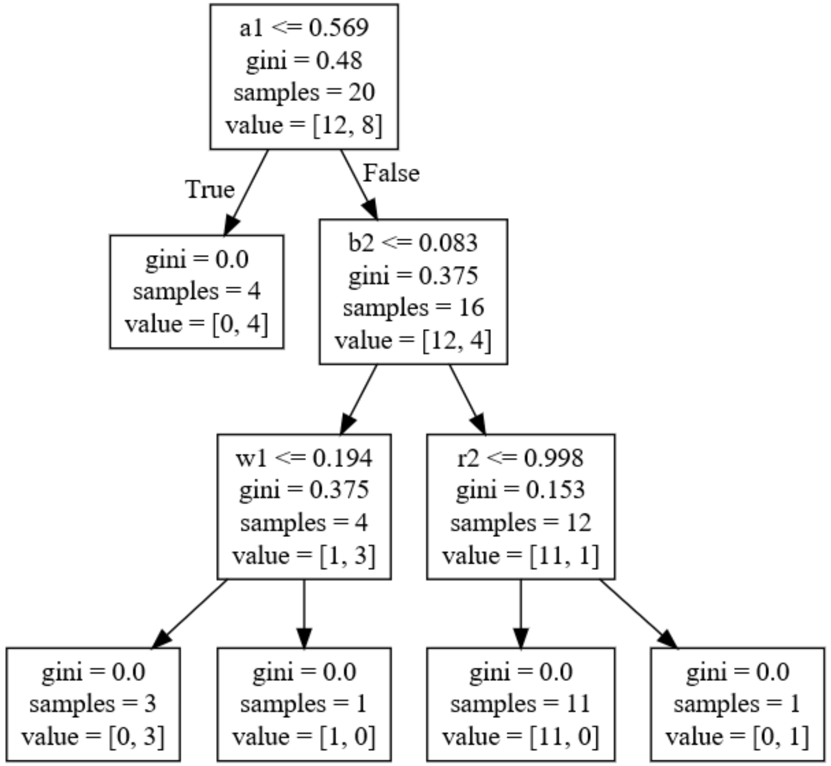
Results



Classification rate with built-in 90% confidence interval

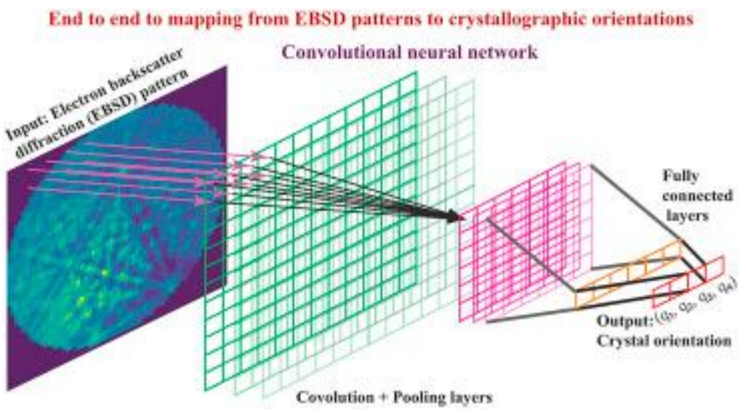
Discussion

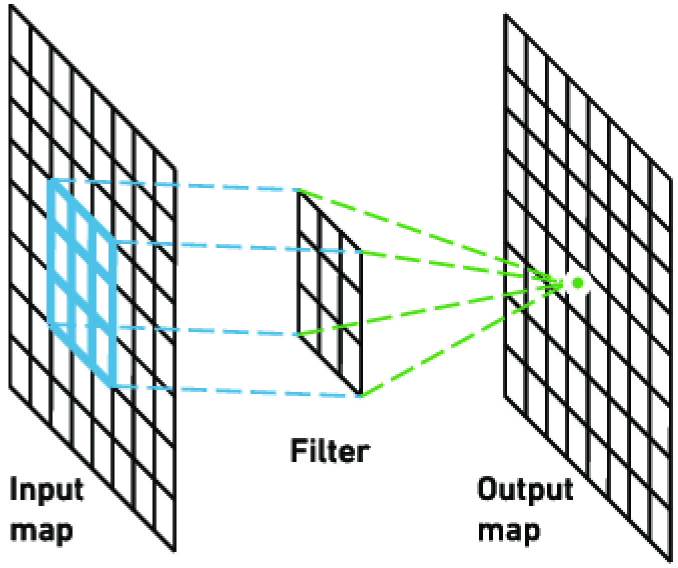
- Process can account for lots of different data configurations and styles
- Better configuration with LOTS more data
- Need to fine-tune pruning options to help clean up excessively large trees



Machine Learning
Applied Expansion Estimation

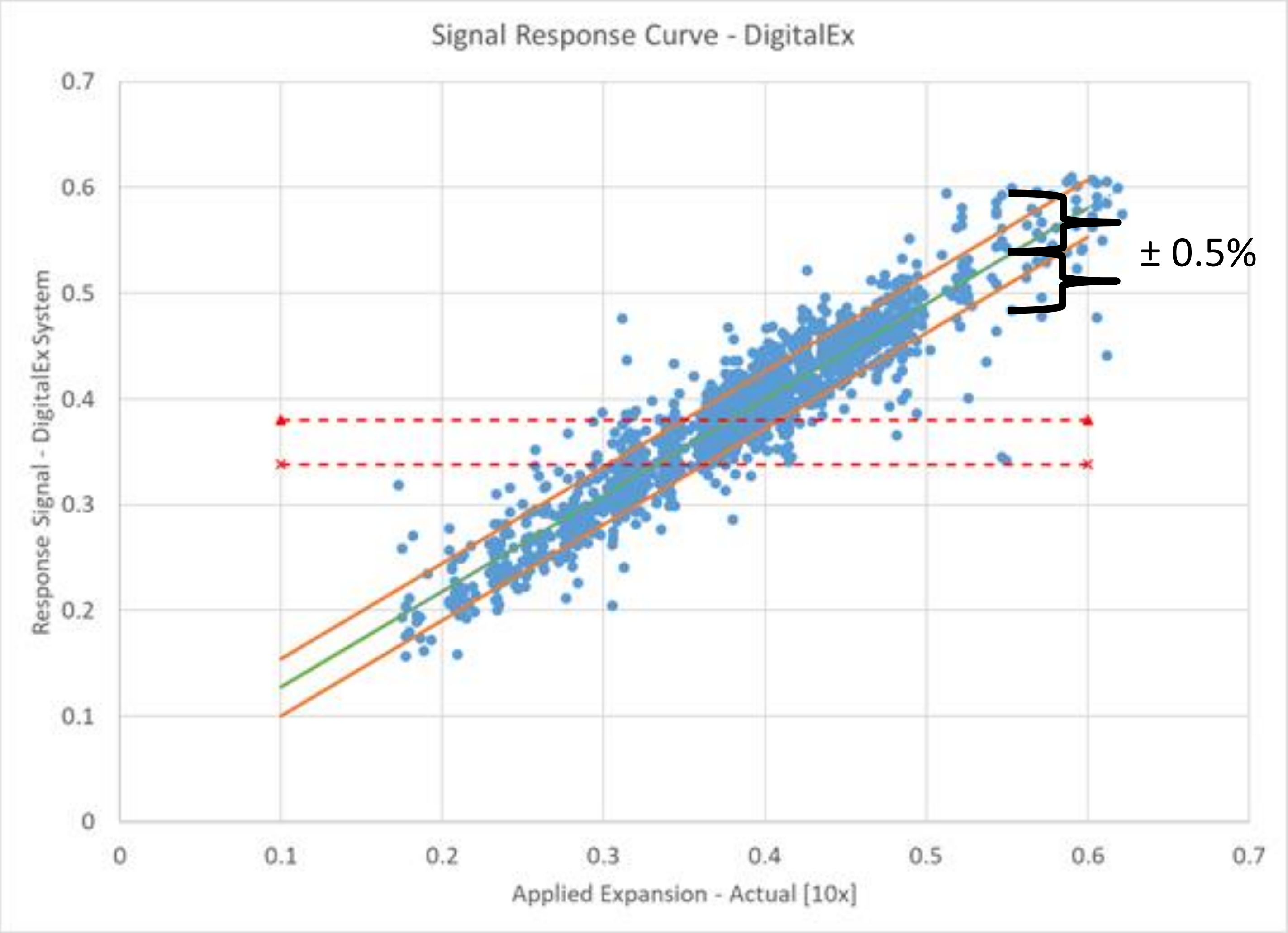
Convolution Network





- Convolution NN iteratively determines filters
- Filters are optimized using error back-propagation
- Consecutive layers detect important combinations of features

Results


Signal Response Curve - DigitalEx
Response Signal - DigitalEx System
Applied Expansion - Actual [10x]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
± 0.5%

Discussion

- Present capabilities are useful but not universal
  - Needs significantly more testing before final roll-out
- Better for processing prediction, not as useful for QA control
  - Since QA is not driven by expansion, cannot *currently* use expansion as true QA metric
- Expected timeline – May/June 2021

ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Update on Best Practices Document

Dallen L. Andrew, Ph.D.
Hill Engineering LLC

8 December 2020

s Update

- Significant progress was made to the NDI/NDE/QA/Data Management Best Practices document
- Feedback has been gathered from ERSI committee members and revisions are in-work
- An outline of the revised sections is included for reference

ERSI ENGINEERED RESIDUAL
STRESS IMPLEMENTATION

OUTLINE

Nondestructive Evaluation, Quality Assurance, and Data Management Considerations for Residual Stress: Best Practices

Prepared by:
Dallen L. Andrew, Ph.D.
Hill Engineering, LLC

Prepared for:
ERSI QA/Data Management Committee

3 November 2020

ERSI 1

s Update

1. NONDESTRUCTIVE INSPECTION

- 1.1 Inspection methods for metallic structures
  - 1.1.1 Eddy current
    - *1.1.1.1* Conventional surface eddy current
    - *1.1.1.2* Bolt-hole eddy current
    - *1.1.1.3* Conformal eddy current
    - *1.1.1.4* Eddy current arrays
  - 1.1.2 Ultrasonic
    - *1.1.2.1* Compression-Wave
    - *1.1.2.2* Shear-Wave
    - *1.1.2.3* Phased Array
  - 1.1.3 Fluorescent penetrant
  - 1.1.4 Radiography
    - *1.1.4.1* Film
    - *1.1.4.2* Computed radiography
    - *1.1.4.3* Computed tomography
- 1.2 NDI impacts due to applied stress
- 1.3 NDI impacts for cold expanded holes
  - 1.3.1 Eddy current
    - *1.3.1.1* Rotary bolt hole eddy current
    - *1.3.1.2* Surface eddy current inspections
  - 1.3.2 Ultrasonic
  - 1.3.3 Fluorescent penetrant
- 1.4 NDI impacts for laser shock peened surfaces
  - 1.4.1 Eddy current
  - 1.4.2 Ultrasonic
  - 1.4.3 Fluorescent penetrant
- 1.5 Methods for quantifying impact of ERS on POD
  - 1.5.1 POD estimation methods
    - *1.5.1.1* Hit-Miss
    - *1.5.1.2* Amplitude versus flaw size
  - 1.5.2 EDM versus naturally occurring cracks under influence of residual stress
  - 1.5.3 Crack aspect ratio considerations
  - 1.5.4 Capability modeling
  - 1.5.5 POD correction methods – transfer functions
  - 1.5.6 Cx considerations
  - 1.5.7 LSP considerations
- 1.6 Recommendations and policy
- 1.7 Future considerations
  - 1.7.1 Material dependency
  - 1.7.2 Impact of installed fasteners
  - 1.7.3 Advanced inspection methods
  - 1.7.4 NDI and Teardown Evaluations of Post-Service Structure
  - 1.7.5 Terminology:

ENGINEERED RESIDUAL STRESS IMPLEMENTATION

…s Update

ENGINEERED RESIDUAL STRESS IMPLEMENTATION

2. QA AND NDE

Questions

- NDI: J. Brausch committed to fill-in any of this chapter?
- QA and NDE: Does anyone want to help fill-in any of this chapter?
  - Will likely need support at least from:
    - FTI (Sam?) for instrumented puller
    - TRI-Austin (Doyle?) for FastenerCam