Working Group on
Engineered Residual
Stress Implementation

Residual Stress Measurement Committee Annual Summary

16 February 2022

(These charts are a team product)

Eric Burba, committee lead

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Overview

Committee Logistics

- Typical Meeting Agenda
- Roster and Attendance
- Committee Mission and 2022 Goals

Update on Current Projects

- Texture and Anisotropy Sub-Team (Presenter: Dr. Mark Obstalecki, AFRL)
- 2inch Cx Residual Stress Determination for Process Simulation Validation (Presenter: Dr. Scott Carlson, Lockheed Martin)
- Contour Method Reproducibility Experiment A (CMRE-A) (Presenter: Dr. Mike Hill, UC Davis)
- Bulk RS Measurements in Cx Geometrically Large Holes (Presenter: Dr. Mike Hill)

Summary and Future Opportunities

Committee Logistics

Monthly Committee Meetings

- Meeting held on the first Wednesday of the month at 1400 Eastern
- Currently hosting meetings using ESRI's Zoom account
- Please contract Burba or DeWald if you would like to attend

Typical Meetings Agenda

Other ERSI Committee Updates

- Process Modeling Committee Update (DeWald)
- Risk Committee update (Ocampo)

Measurement Committee Projects & Updates

- Texture and Anisotropy Sub-Team (Obstalecki)
- Large Cx Hole Bulk Stress (Hill)
- Multi-Point Fracture Mechanics, AFRL (Burba)
- A-10 Best Practices Document (Pineault)
- Contour Method Reproducibility Experiment A (CMRE-A) (Hill)
- 2x2 Working Group (Carlson)

New Business

Around the Room

Committee Roster and Attendance

✓	Jeferson	Araújo de Oliveira	StressMap - Director	44 (0) 1908 653 452	Jeferson.Oliveira@stressmap.co.uk
✓	David	Backman	National Research Council Canada / Government of Canada	(613) 993-4817	david.backman@nrc-cnrc.gc.ca
	Ana	Barrientos Sepulveda	Northrup Grumman Aerospace Systems	321-361-2049	Ana.BarrientosSepulveda@ngc.com
	John	Bourchard	Professor of Materials Engineering Open University - Director of StressMap	44(0)7884 261484	john.bouchard@open.ac.uk
	Michael	Brauss	Proto Manufacturing Inc.	(734) 946-0974	mbrauss@protoxrd.com
✓	Dave	Breuer	Curtiss-Wright, Surface Technologies Division	(262) 893-3875	Dave.breuer@cwst.com
✓	Eric	Burba	U.S. Air Force (AFRL - RXC - Materials & Manufacturing Directorate)	(937) 255-9795	Micheal.Burba.1@us.af.mil
	Ralph	Bush	U.S. Air Force (Department of Engineering Mechanics, U.S. Air Force Academy)		ralph.bush@usafa.edu
✓	Scott	Carlson	Lockheed Martin Aero (F-35 Service Life Analysis Group)	(801) 695-7139	SCarlson01@gmail.com
	James	Castle	The Boeing Company (Associate Technical Fellow BR&T Metals and Ceramics)	(314) 563-5007	james.b.castle@boeing.com
	David	Denman	Fulcrum Engineering, LLC. (President & Chief Engineer)	(817) 917-6202	david@fulcrumengineers.com
✓	Adrian	DeWald	Hill Engineering, LLC	(916) 635-5706	atdewald@hill-engineering.com
	Daniele	Fanteria	Dipartimento di Ingegneria Civile e Industriale	(+)39.050.2217266	daniele.fanteria@unipi.it
	Eric	Greuner	Lockheed Martin Aeronautics - Integrated Fighter Group Airframe Stress and FEA	(817) 777-5453	eric.m.greuner@lmco.com
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✓	Eric	Lindgren	U.S. Air Force (AFRL - Materials and Manufacturing Directorate)	(937) 255-6994	Eric.Lindgren@us.af.mil
✓	Marcias	Martinez	Clarkson University (Department of Mechanical & Aeronautical Engineering)	(315) 268-3875	mmartine@clarkson.edu
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	Mike	Reedy	U.S. Navy (NAVAIR - Compression Systems Engineer)	(301) 757-0486	michael.w.reedy1@navy.mil
	Steven	Reif	AFLCMC/EZFS	937-656-9927	steven.reif@us.af.mil
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✓	Marcus	Stanfield	Southwest Research Institute (SwRI)	(801) 860-3831	marcus.stanfield@swri.org
✓	Mike	Steinzig	Los Alamos National Labs - Weapons Engineering Q17	(505) 667-5772	steinzig@lanl.gov
	Kevin	Walker	QinetiQ	+61457002775	kfwalker@qinetiq.com.au

Please contact Burba or DeWald if you would like to be added or removed from this rosters

What this Committee brings to ERSI

ERSI – RSM Committee has experts in a wide range of residual stress measurement techniques that are available to help ERSI stakeholders (e.g., end users and aircraft programs) design and implement fit-to-purpose residual stress measurement efforts

Established group of residual stress measurement professionals available to review, define, engage, and/or document:

- Repeatability of residual stress measurement data (in lab variability)
- Reproducibility of residual stress measurement data (lab-to-lab variability)
- Inter-method residual stress comparisons (e.g. ND to x-ray to contour)
- Measurement model comparisons (e.g. for CX holes)
- UQ/Statistical methods relative to residual stress data (connect to inter-method as well as model-measurement)

Measurement Committee's 2022 Goals

- Support the drafting of the Air Force Structures Bulletin, "Analytical Methods, Validation Testing, and Process Compliance Record Requirements for Explicit Utilization of Residual Stresses at Cold Expanded Fastener Holes in the Damage Tolerance Analysis of Metallic Structure"
- Review and provide feedback on the residual stress measurement section of the A-10 Best Practices document.
- Assess/Quantify/Define effects of texture and anisotropy on residual stress measurement, document, and seek means to improve.
- Develop and document exemplar datasets (leverage prior work and drive new work). Experimental residual stress datasets that have been implemented and published (use of 2x2 Cx hole dataset)

Texture and Anisotropy Sub-Team

Team:

Joshua Ward (AFRL)

Mark Obstalecki (AFRL)

Eric Burba (AFRL)

Mike Hill (Hill Engineering)

Mike Steinzig (LANL)

Zachary Sanchez (LANL)

James Pineault (Proto)

Mission Statement & Background

Quantify and incorporate the effects of crystallographic texture and elastic anisotropy in residual stress measurement workflows

- Focused on RS hole drilling
- Utilizing Ring and Plug samples
  - Assembled with interference fit
  - Assume isotropic elasticity
  - Equal biaxial stress spatially in plug

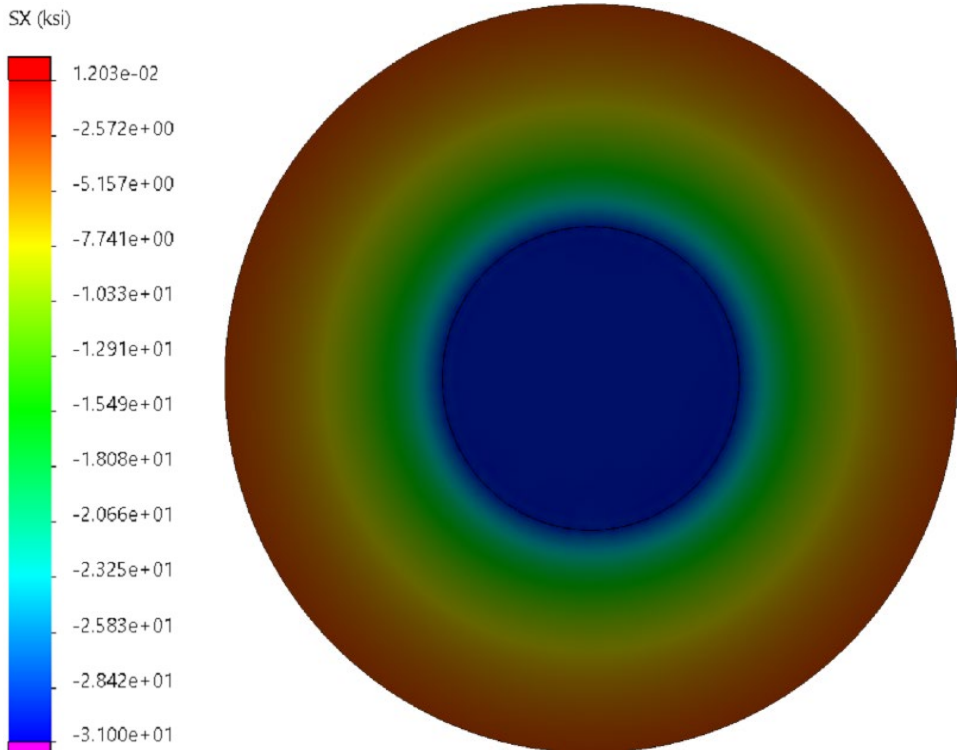


Figure 1: Radial stress of isotropic elastic material properties for stainless steel

Stainless Steel Ring and Plug Measurements

Figure 2: SSCAP ring/plug sample

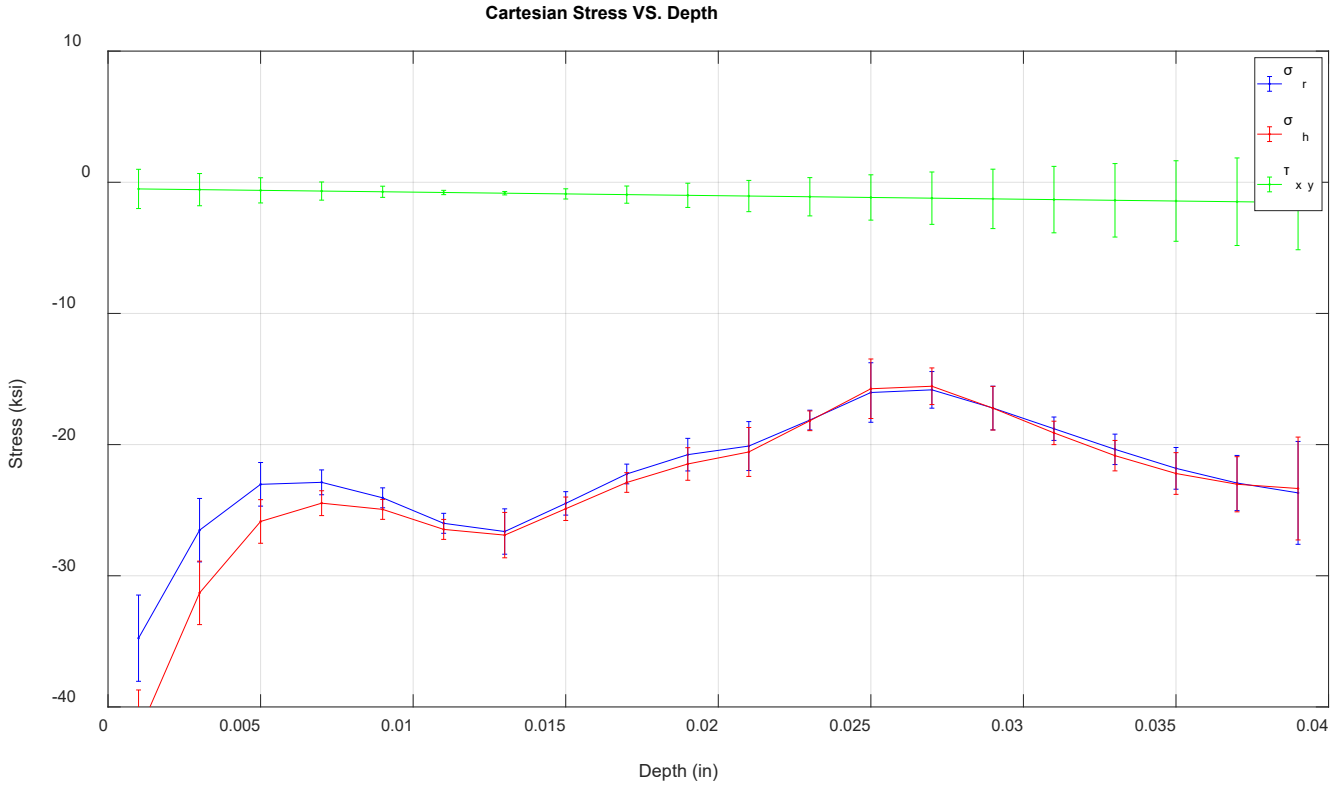


Figure 3: Stress VS. Depth graph of standard hole, circled in Figure 4

Stainless Steel Ring and Plug Measurements (Cont.)

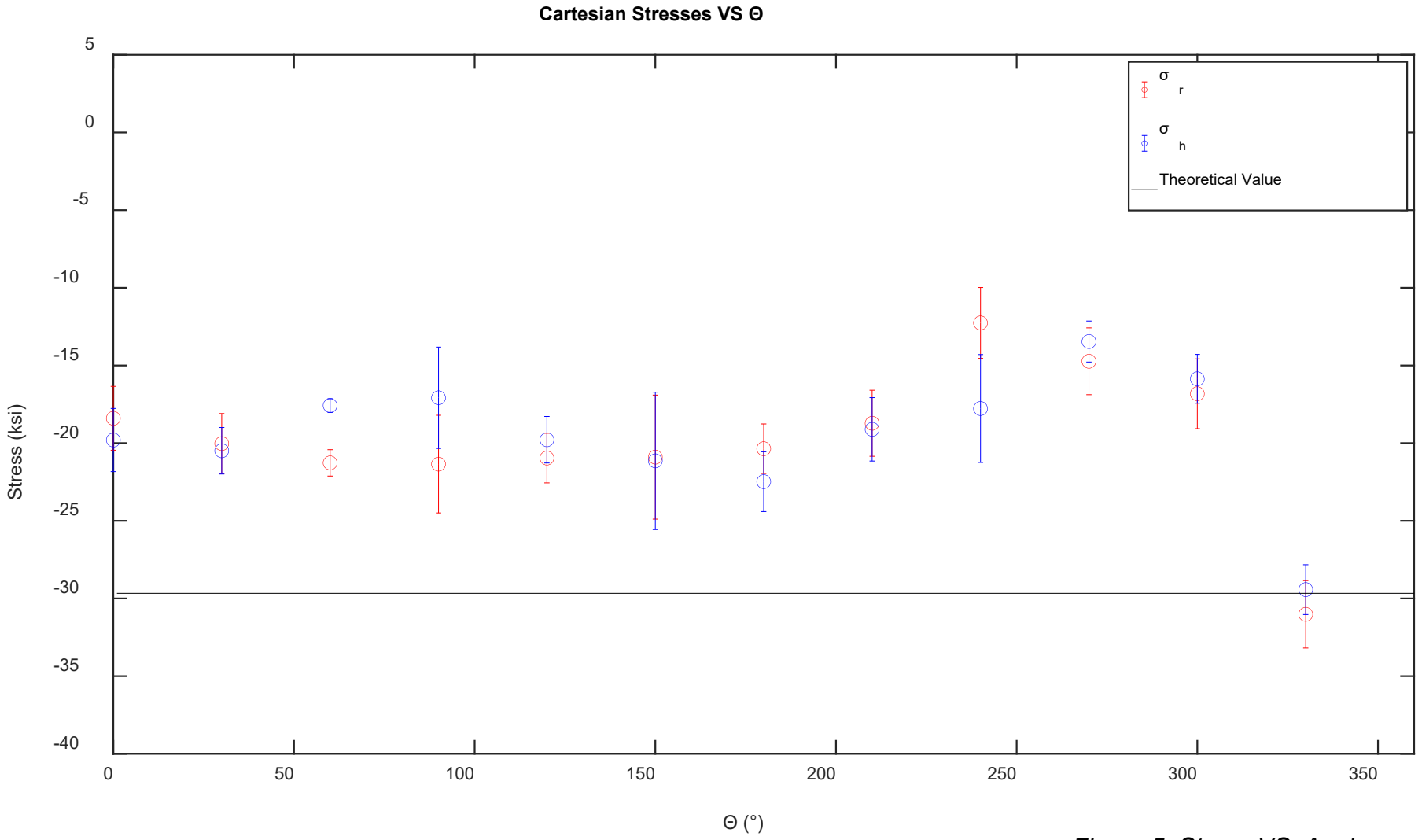
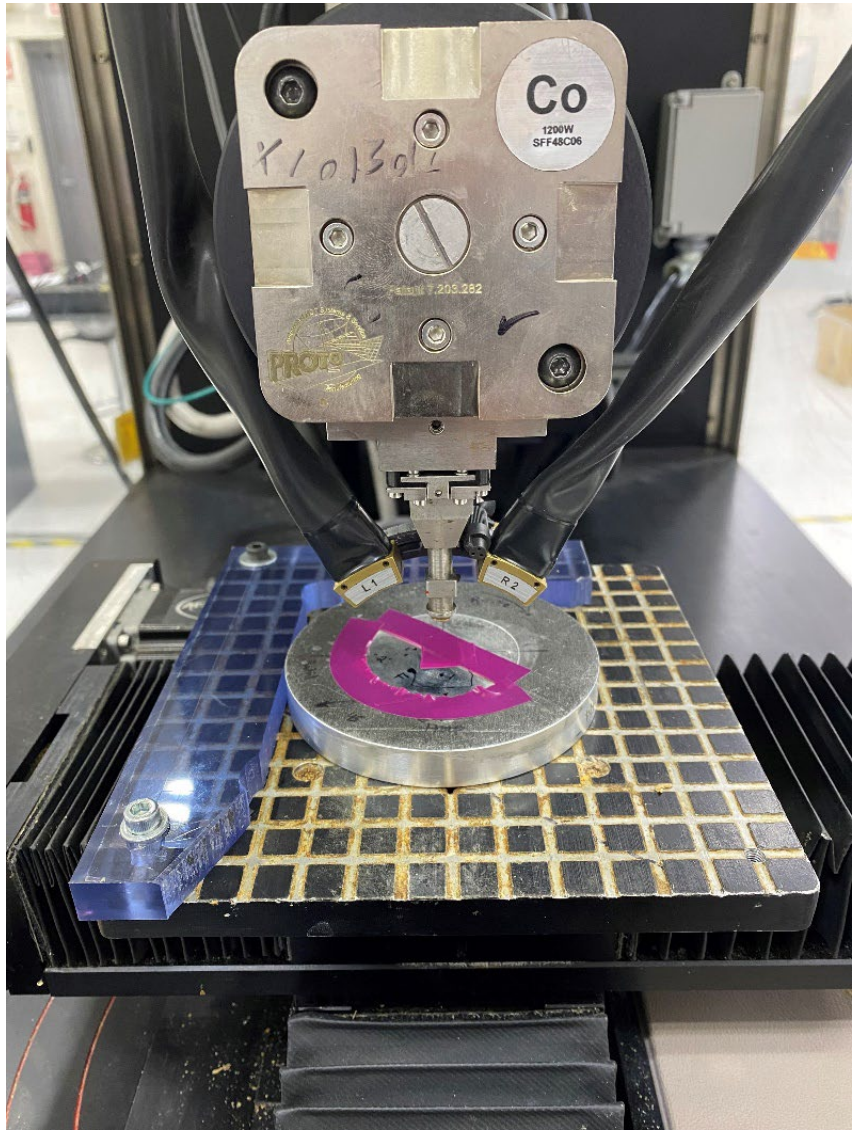
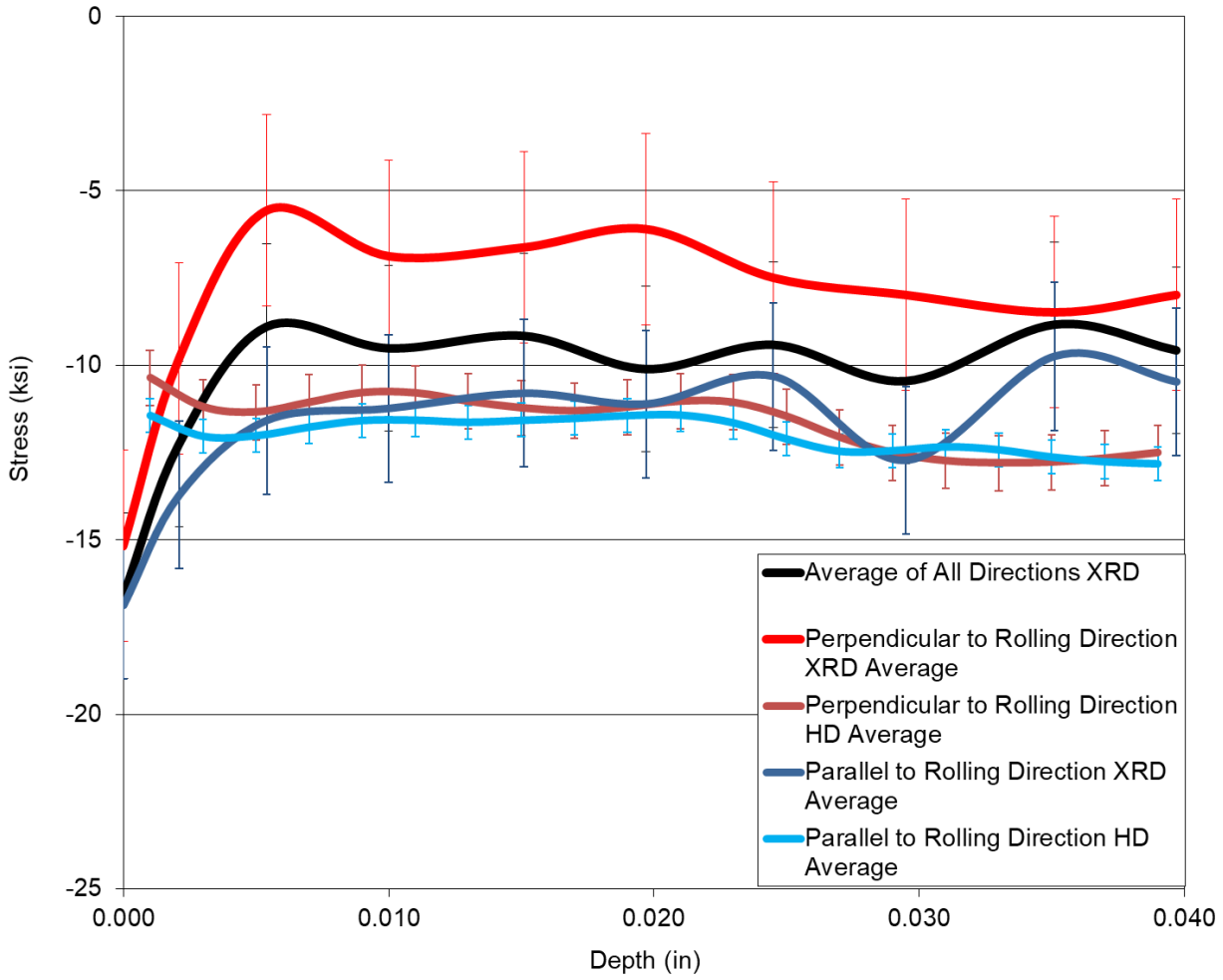


Figure 5: Stress VS. Angle around azimuth

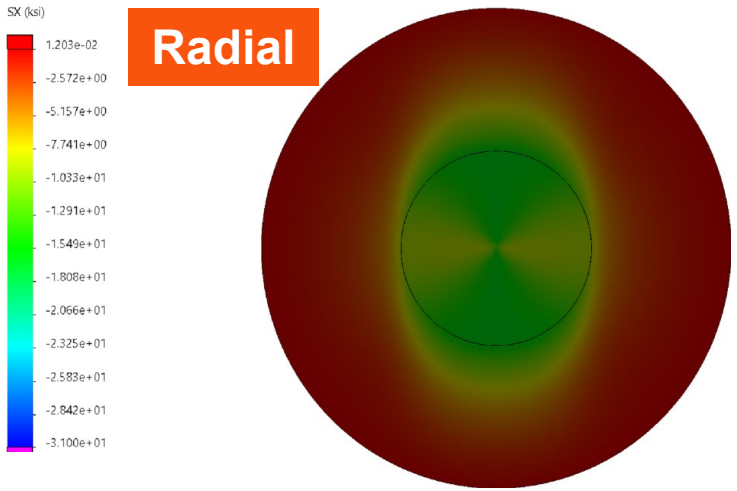
HD / XRD Round Robin (Aluminum)

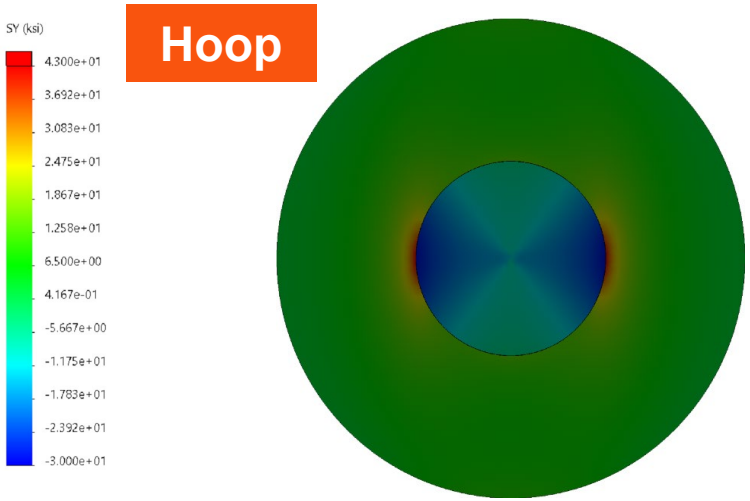




Analytical solution : -13 ksi

Gearing Toward Elastic Anisotropy

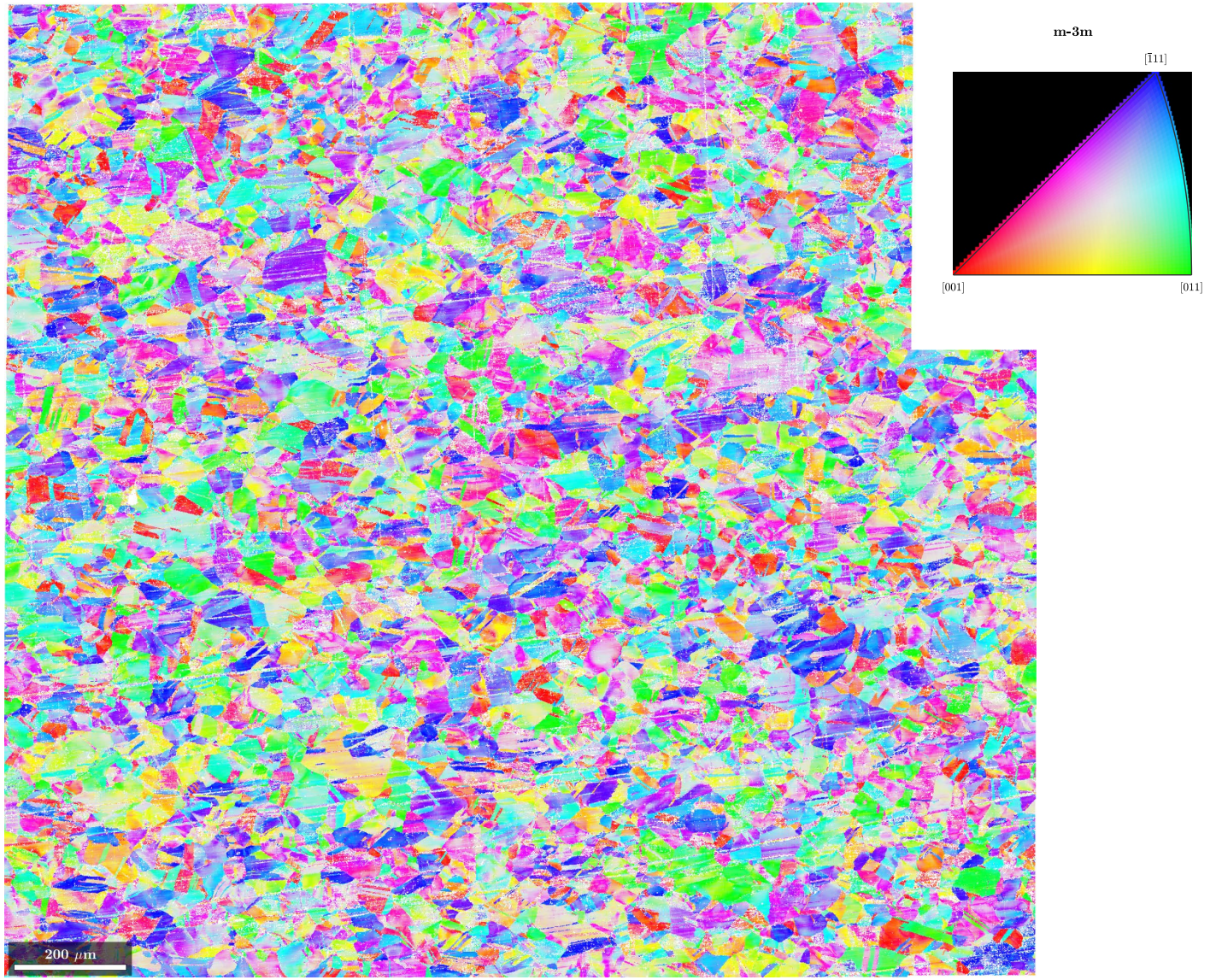




Plug \ Ring	Brass (260)	Stainless Steel (304)	Aluminum (6061)	Nickel (625)
Brass (260)				
Stainless Steel (304)				
Aluminum (6061)				
Nickel (625)				

EBSD Texture Analysis

- C260 Brass
- Texture index of T = 1.3198
- Indexed using FCC Copper parameters
- White horizontal lines are due to polishing error
- RD into page



Ongoing Efforts

- Design samples using rolled brass to maximize spatial stress variation within plug
- ‘Sharpen’ brass texture by rolling
- Quantify anisotropic elastic constants from EBSD
  - Make EBSD measurements of different rolled thickness samples
  - Same single crystal elastic constants
  - Using MTEX calculate differences in aggregate response based on texture change
- Quantify anisotropic elastic constants from RUS
- Build framework to simulate incremental hole drilling measurement in elastically anisotropic materials

2inch Cx Residual Stress Determination for Process Simulation Validation

2inch Cx Project Overview

- 2024-T351 & 7075-T651 Aluminum Plate
  - 0.25inch thick
  - 0.50inch diameter hole
  - 2inch wide

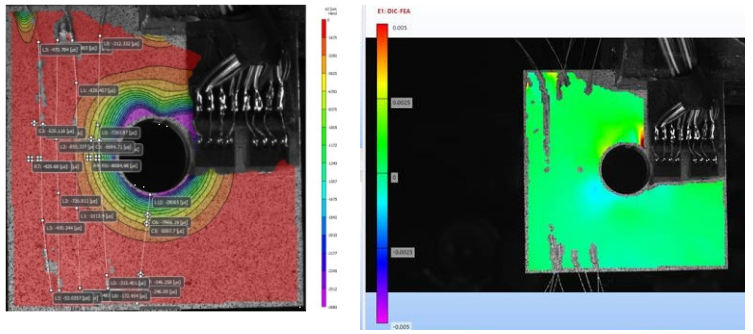
- Coupons Cold Expanded to the Max & Min of the Applied Expansion Range per the FTI Spec
  - 3.2% and 4.2%
  - High precision starting hole size
- One Set of Each Condition was Final Reamed for Future Use as a “Standard”
- During the Cx Process Surface Strain Measurements were Taken in ”Real-Time”
  - Strain gauges installed – Installed by FTI
  - LUNA Fiber optical strain gauge – Installed and monitored by Clarkson University
  - Digital Image Correlation – Installed and monitored by SwRI

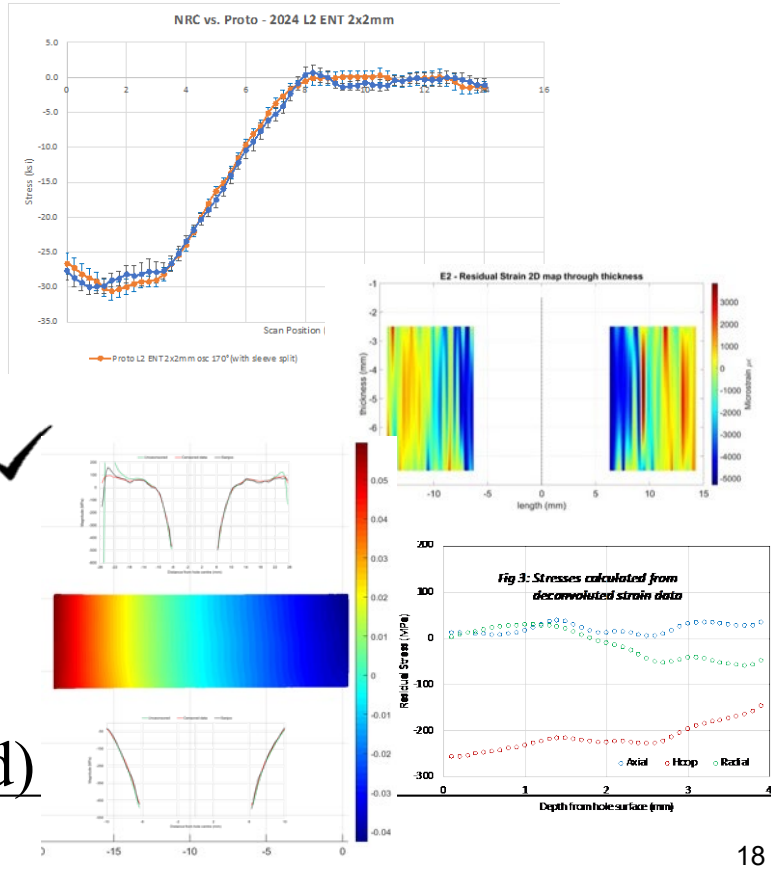
History of Program

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

Work Completed - Update

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





Future Work

- Complete Surface Strain Paper Comparison
  - Focused on FEA simulations, using multiple material models, to DIC/MatchID data
- Complete Data Processing of Neutron Diffraction Experiments
  - 2024 ”Low” and “High” have been completed the experiments – need to process data
  - 7075 “Low” and “High” are at Oakridge NL and need test plan defined and executed
- Complete Contour Method on Remaining 3 Coupons
- Develop Journal Papers on Through-Thickness Comparisons
  - Neutron vs. Contour
- Develop Method for Coupling Residual Stress Methods for Near-Surface and Away-from-Surface Stress Fields
  - Potential to use Neutron or XRD data near the bore of the hole and Contour data away from the hole
- Provide RS Field Data to Analysis Committee for Predictions of Test Conditions

Working Group on
Engineered Residual
Stress Implementation

ERSI RS Measurement

CMRE-A
and
Large Hole Bulk Stress

Mechanical and Aerospace Engineering
University of California, Davis

Contour Method Reproducibility Experiment A (CMRE-A)

Summary for ERSI

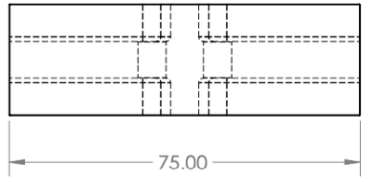
Initial version: February 15, 2022

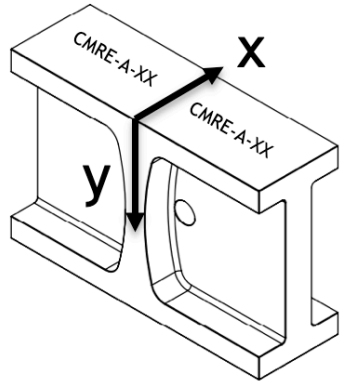
Christopher D'Elia, Research student (crdelia@ucdavis.edu)

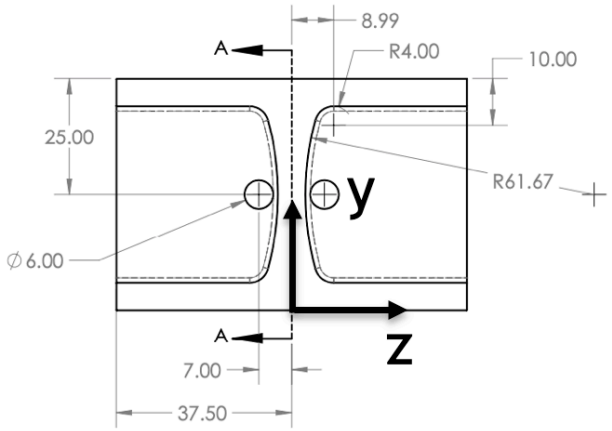
Professor Michael R Hill (mrhill@ucdavis.edu)

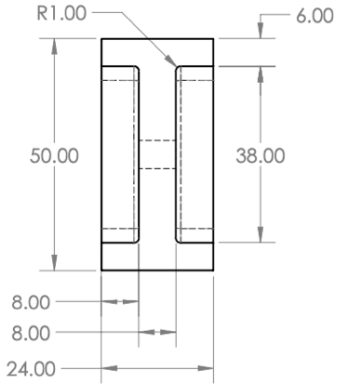
CMRE-A Sample

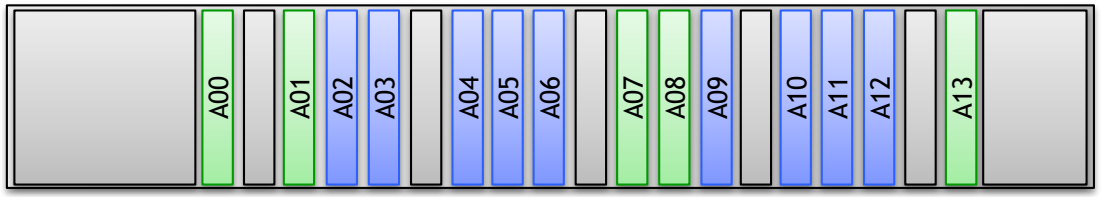
- **Interest in bulk stress fields, neglecting machining or other near-surface stresses**
- **Several blanks cut from a single residual stress bearing bar**
  - 7050-T74 high-strength aluminum alloy
  - Residual stress from quench/age of T74
- **Mill identical samples 50 x 75 x 24 mm**
  - Plane of interest A-A, 50 x 24 mm
  - Representative of heavy structural elements
- **Fabricated 14 samples A00 to A13**









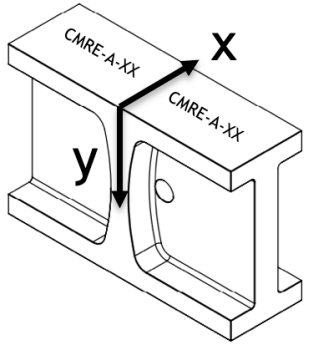


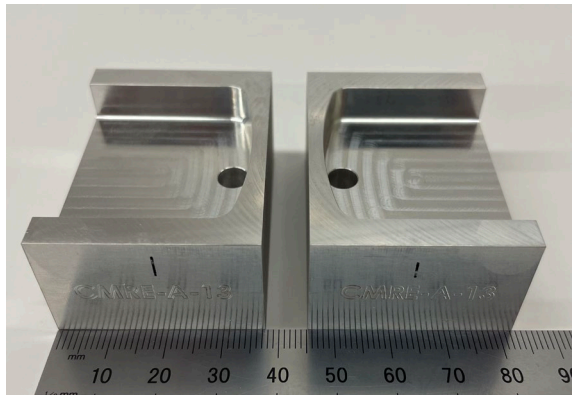
Not used
Planning
Participants

CMRE-A Measurements

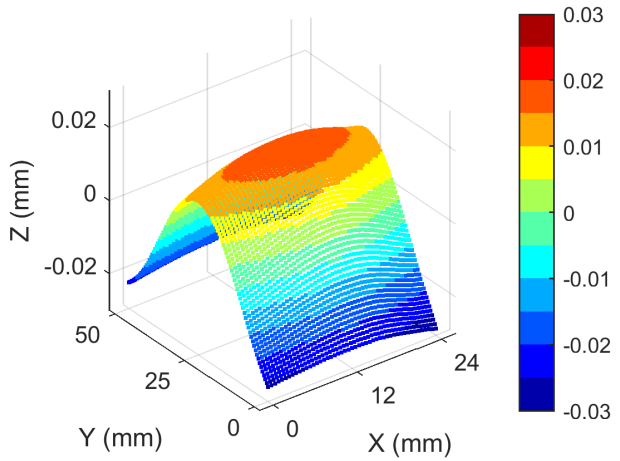
- **Planning Measurements:**
  - 3 contour measurements to assess uniformity of material condition and measurement repeatability (UC Davis) (Samples A01, A07, A13)
  - Neutron diffraction measurement at HFIR (Oak Ridge National Lab) (Sample A08)
  - Hole-drilling at surfaces (UC Davis) (Sample A00)
- **Participants Measurements:**
  - International group of 8 participants from industry and academia provide contour measurement results on Plane A-A

1) Cut the part (wire EDM)

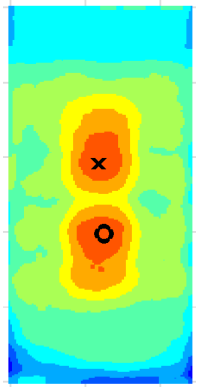


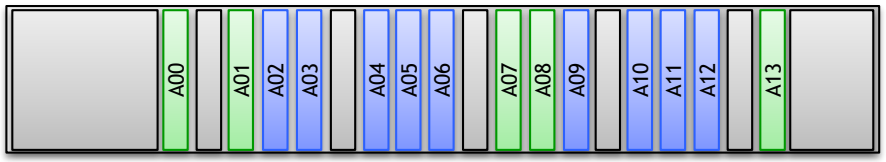


2) Measure the cut surface form



3) Compute RS (FEA)

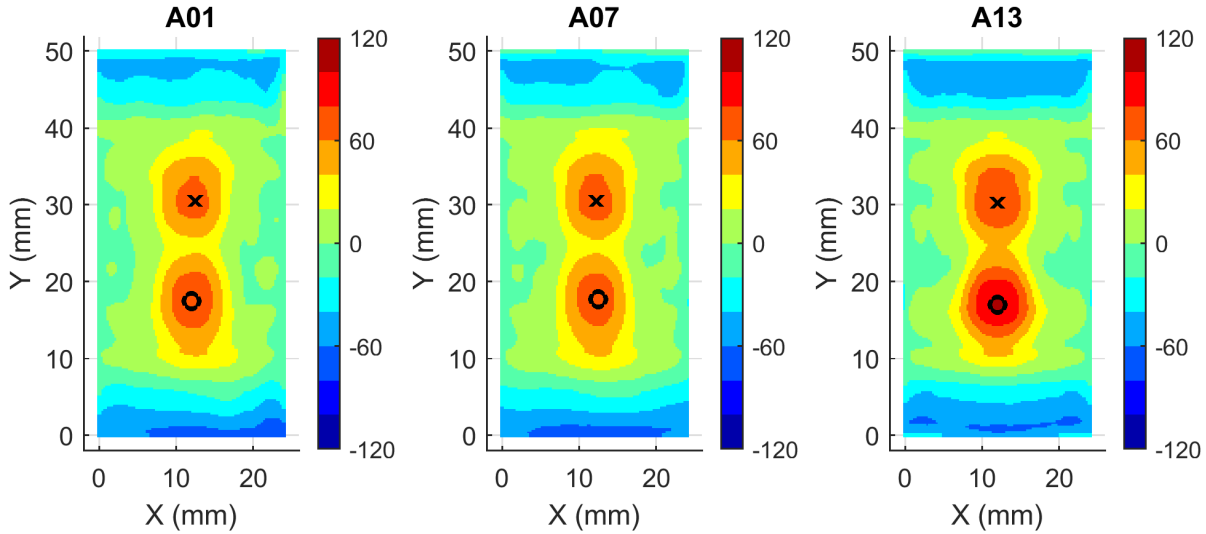


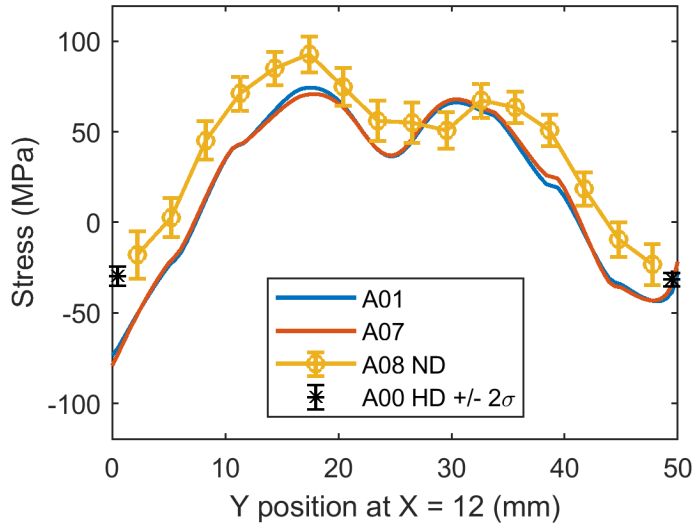


Not used
Planning
Participants

CMRE-A Planning Measurements

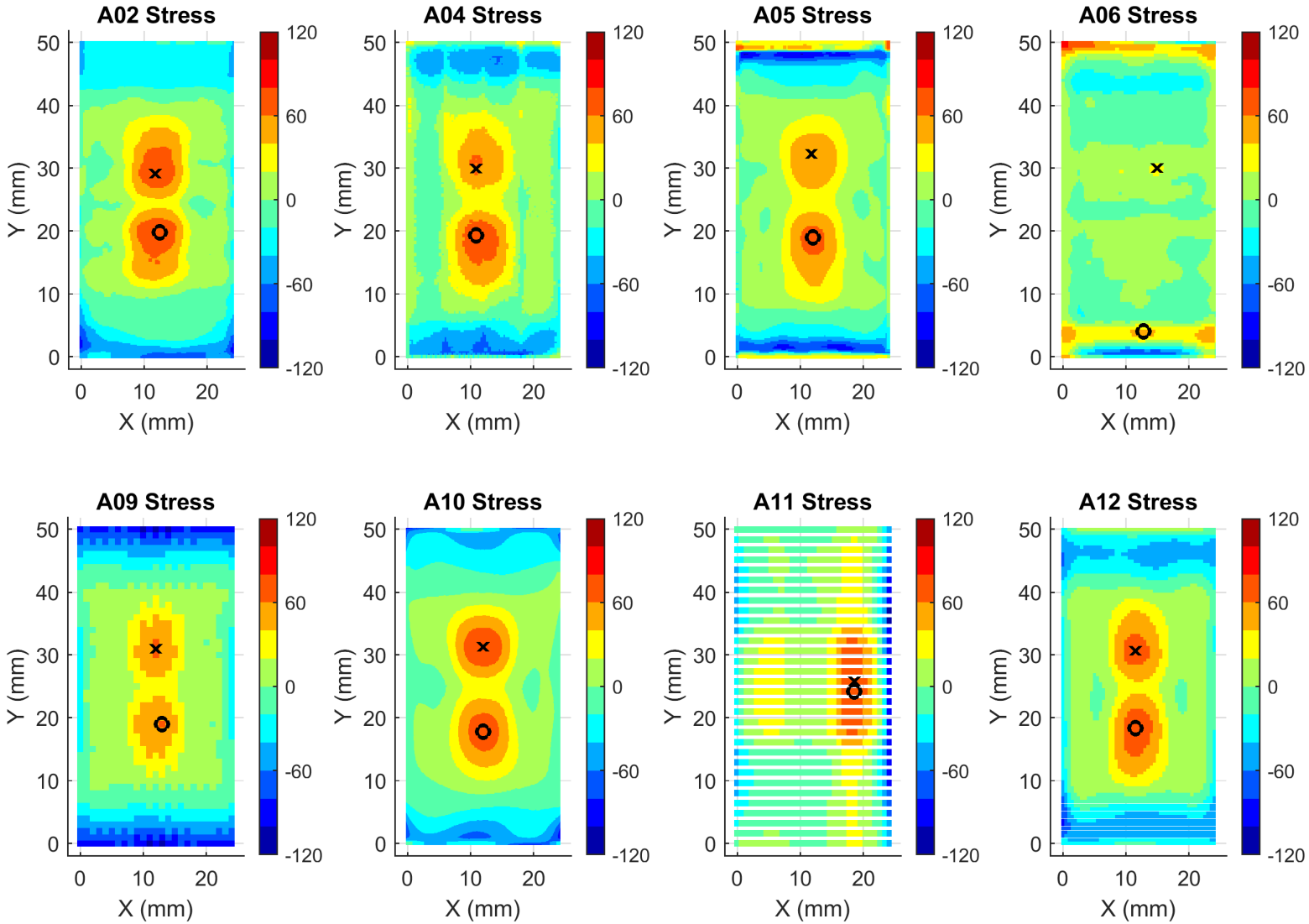
- **Contour results:**
  - A01 and A07 are nearly identical
  - Magnitude higher for A13
    - Likely due to proximity to end of bar (see Olson 2015)
    - Distant from participant samples
  - Spatial distribution of stress is similar along length of bar
- **Neutron diffraction results:**
  - Similar spatial form, offset of ~ 25 MPa (within expectation)
- **Hole-drilling results:**
  - Near surface stress symmetric





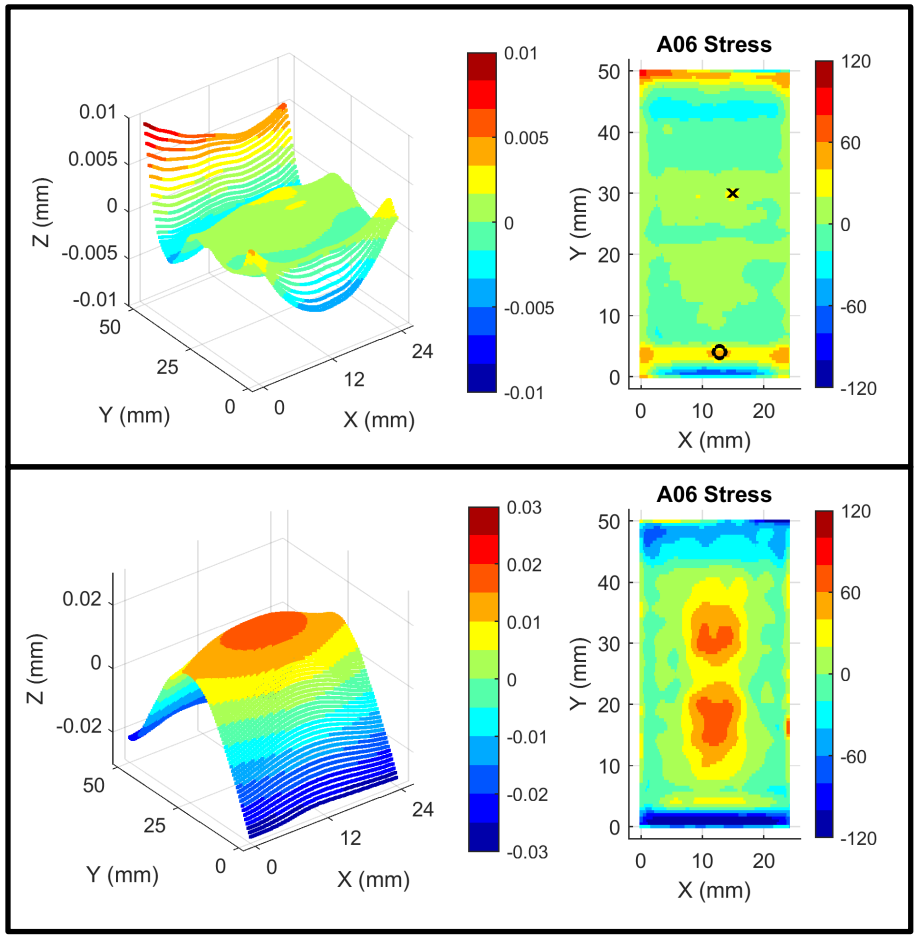
Olson, M.D., Hill, M.R. A New Mechanical Method for Biaxial Residual Stress Mapping. *Exp Mech* 55, 1139–1150 (2015). https://doi.org/10.1007/s11340-015-0013-5

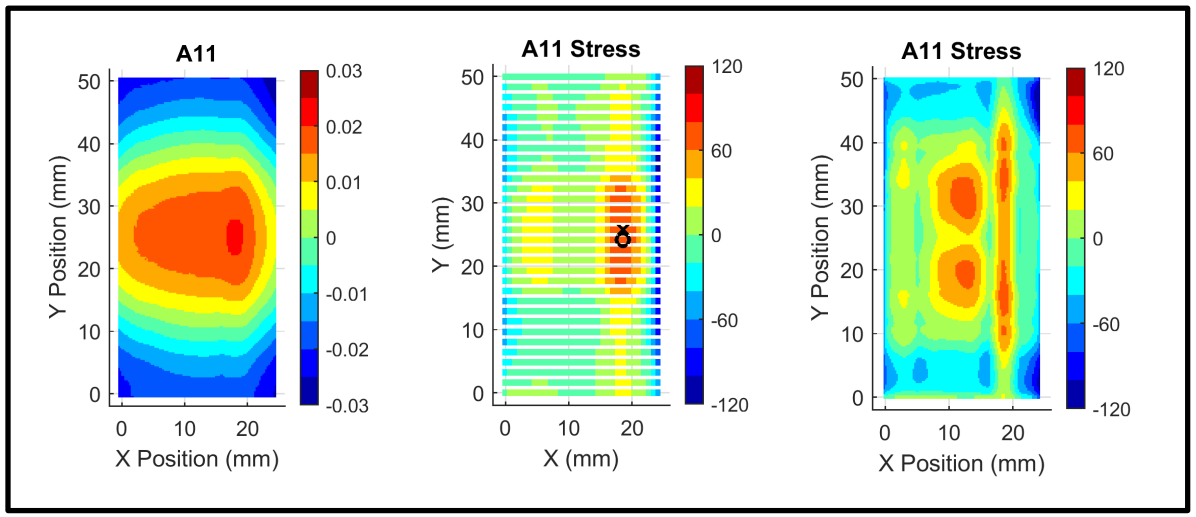
CMRE-A Results: Participant Reported Stress



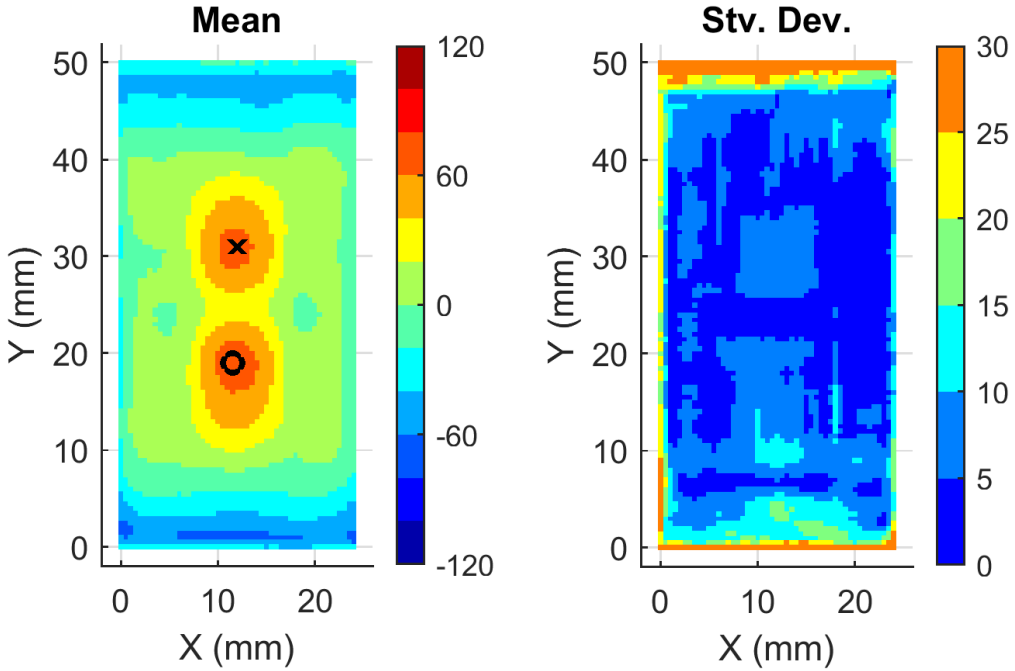
CMRE-A Results: Outliers

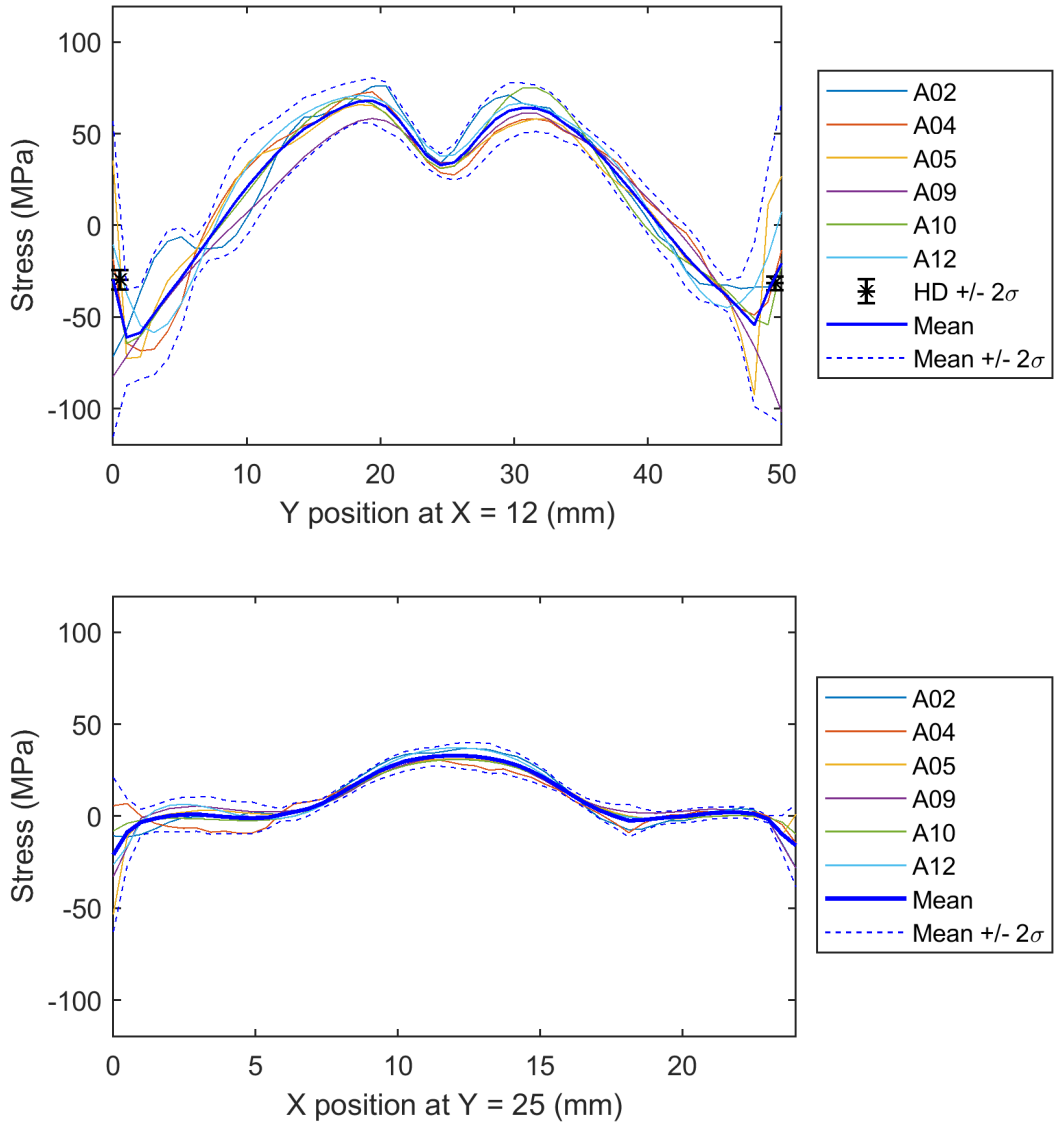
- **CMRE-A-06**
  - Surface measurement problem
  - New surface form measurements provided results consistent with others
- **CMRE-A-11**
  - Wire EDM cutting problem
    - Cut surface of stress-free material would be non-flat (called a “cutting artifact”)
  - Analysis problem
    - Overly simplistic geometry





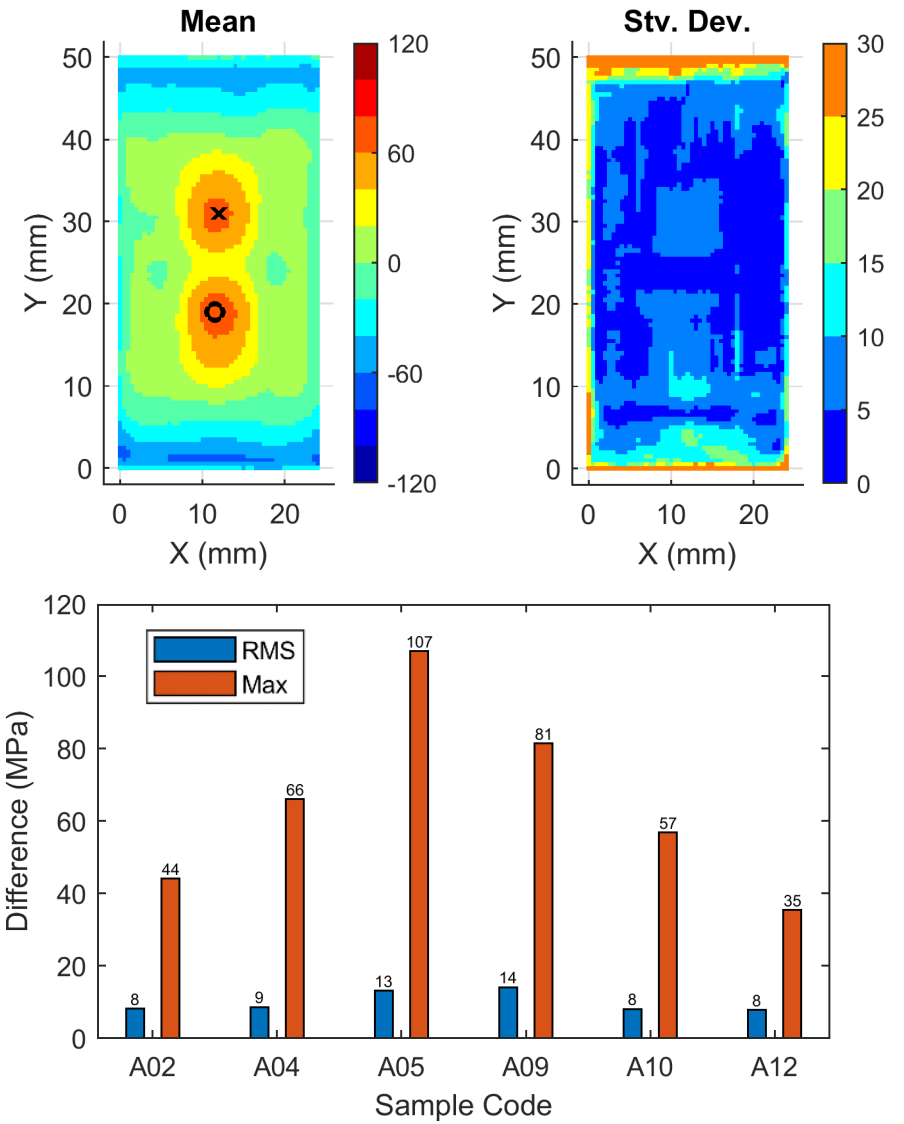
CMRE-A Results: Non-outlying





CMRE-A Results: Reproducibility (excluding outliers A06, A11)

- **Observed interlaboratory reproducibility**
  - 8.1 MPa average for all locations
  - 6.1 MPa on interior
  - 17.6 MPa near boundary (within 1 mm)
- **Observed reproducibility similar to intralaboratory repeatability reported earlier (Olson, et al, 2018)**
  - 9.0 MPa on interior
  - 18 MPa near boundary
- **Differences from group mean vary among participants**
  - RMS differences range 7.8 to 14.1 MPa
  - Maximum differences range 35.5 to 107 MPa



Olson, MD, DeWald, AT, & Hill, MR. Repeatability of contour method residual stress measurements for a range of materials, processes, and geometries. *Mater Perform Charact*, 7(4), 20170044-20170044, 2018. http://dx.doi.org/10.1520/MPC20170044

CMRE-A Study Results Submitted for Publication in Experimental Mechanics

- Submitted Feb 2022

Interlaboratory Reproducibility of Contour Method Data in a High Strength Aluminum Alloy

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ABSTRACT

Background: The contour method for residual stress measurement has seen significant development, but an experimental reproducibility study has not been published. Objective: A double-blind reproducibly study is reported, having scope beginning with EDM cutting and ending with residual stress calculation. Methods: A reinforced I-beam sample geometry is identified for its unique residual stress profile when extracted from residual stress bearing quenched aluminum bar (7050-T74). Contour measurements are prescribed on a midplane of symmetry with dimensions 24 mm by 50 mm. Fourteen identically prepared samples are fabricated from a single long bar with well characterized and uniform residual stress. Five

Working Group on
Engineered Residual
Stress Implementation

Bulk RS Measurements in Cx Geometrically Large Holes 7075-T651 and 7050-T7451

Residual stress measurements supported by process finite element modeling

Team

Organized under ERSI-RSM

Contributors:

- Hill Engineering (HE)
  - Renan Ribeiro, Bob Pilaczyk, Adrian DeWald
- US Air Force Research Lab (AFRL)
  - Eric Burba, Mark Obstalecki, Paul Shade
- Fatigue Technologies (FTI)
  - Matt Shultz
- Los Alamos National Lab (LANL)
  - Don Brown, Bjørn Clausen
- Cornell High Energy Synchrotron Source (CHESS)
  - Chris Budrow
- University of California, Davis (UC Davis)
  - Nick Bachus, Mike Hill

Working Group on
Engineered Residual
Stress Implementation

Background and Objectives

Background:

- Existing prior data for large (D = 1 inch) Cx holes in 7075-T651
  - Residual stress measurements (contour)
  - Residual stress outputs from nonlinear process model
- Disagreement between measurement results and model outputs

Objectives:

- Fabricate coupons for measurements in D = 1 inch Cx holes
  - Samples cut from 7050-T7451 2” thick plate (AFRL)
  - 100% processed and 50% processed (FTI)
- Develop process model outputs for coupon conditions (Hill Engineering)
- Assess bulk RS in coupons
  - Neutron Diffraction (ND) at SMARTS (LANL, UCD)
  - Synchrotron X-ray Diffraction (EDXRD) (CHESS, AFRL, UCD)
  - Contour (Hill Engineering)
- Report findings in a joint journal publication (e.g., Experimental Mechanics)

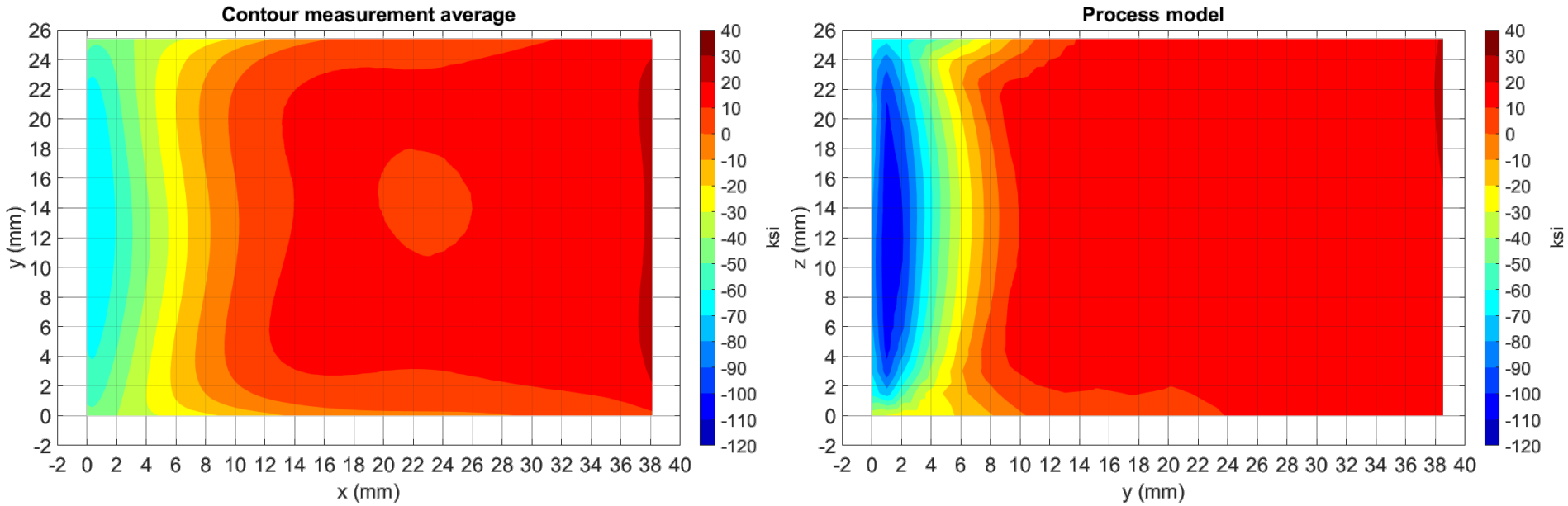
Today: Describe data gathered to date

Prior work: Measurement and model comparisons

Contour maps of the hoop residual stress below

- Results shifted to start at the hole edge
- Dimensions in mm, stress in ksi (same color scale)
- Significantly higher magnitude of residual stress from model compared to measurement average

7075-T651



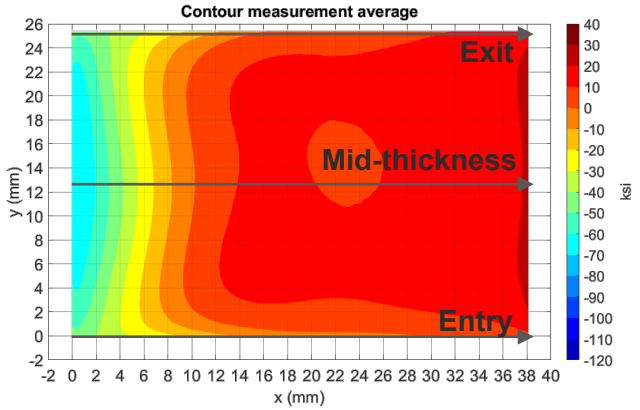
Prior work: Measurement and model comparisons

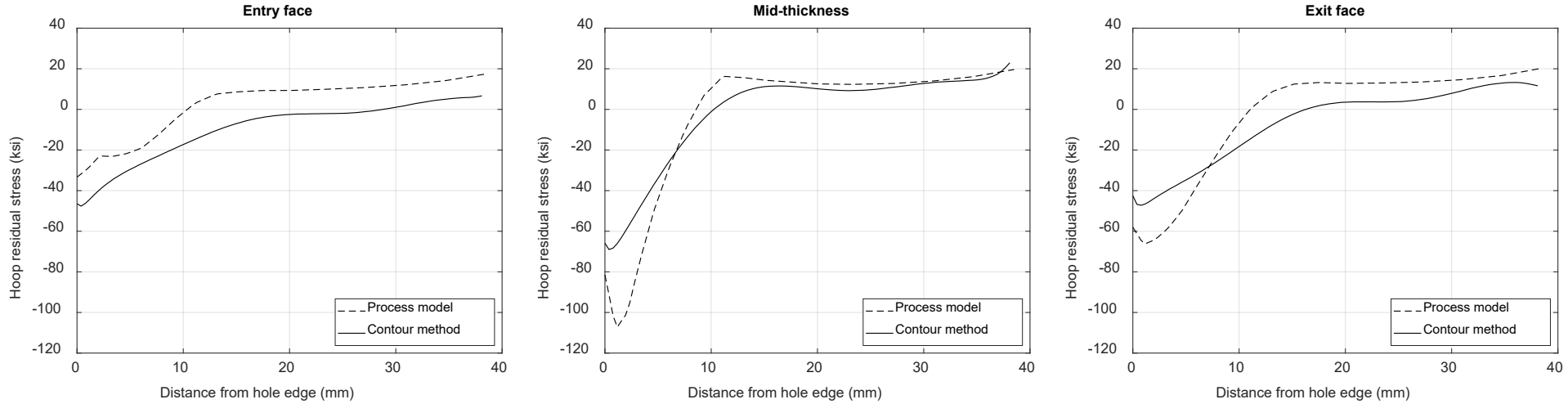
Comparisons below along entry surface, mid-thickness, and exit surface

Model results show

- Lower compressive residual stress on entry surface than measurement
- Higher magnitudes of compressive residual stress near the hole and on mid-thickness and exit surface than measurement

7075-T651





Samples for experiments

Samples reflect the conditions in the prior charts, but are in a new material and geometry

Material is AA7050-T7451 plate, 2 inch thick

Sample geometry (inches)

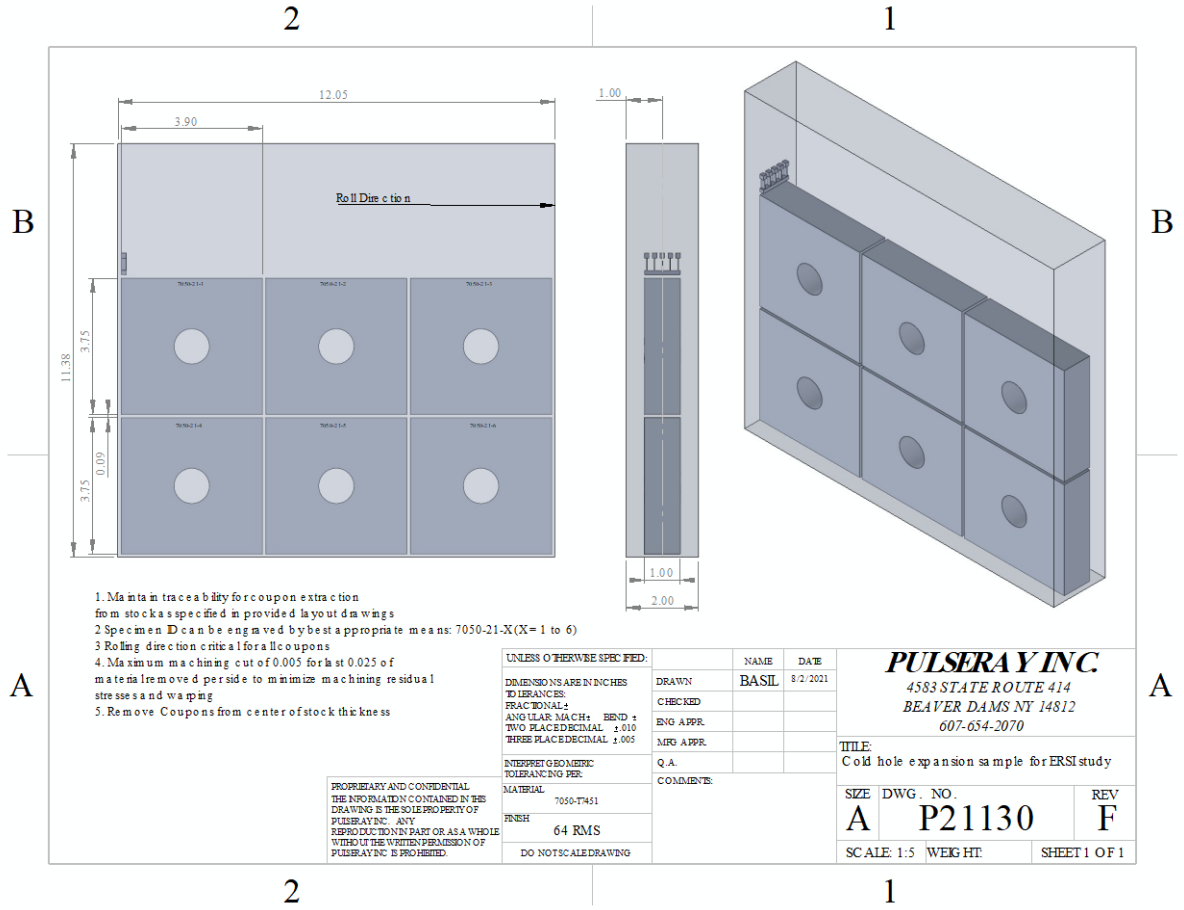
- Plates, L = 3.90 (along L), W = 3.75 (along LT), and T = 1.0 (along ST)
  - 1.0 dimension at plate mid-thickness to reduce texture
- Centered hole, D = 1.00

Fabricated 6 samples (AFRL)

- 7050-21-1 to 7050-21-6

Processing (FTI)

- Cx to 3.43 to 3.45% (see data)
- 7050-21-1: 100% Cx (ND complete)
- 7050-21-2: 100% Cx
- 7050-21-3: 50% Cx (ND complete)

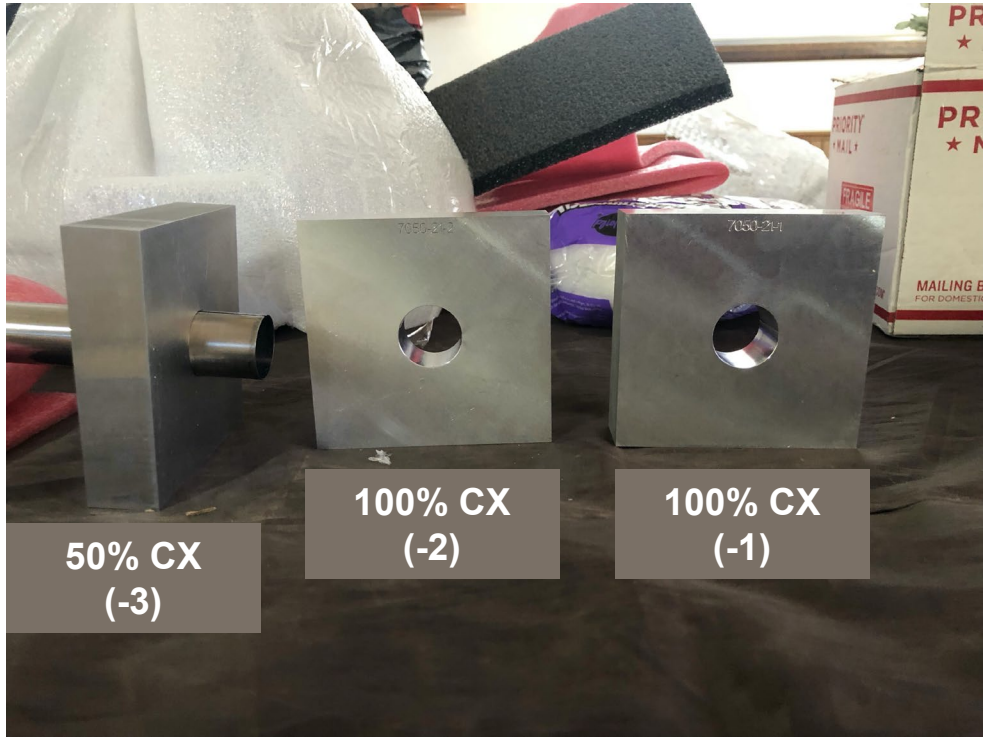


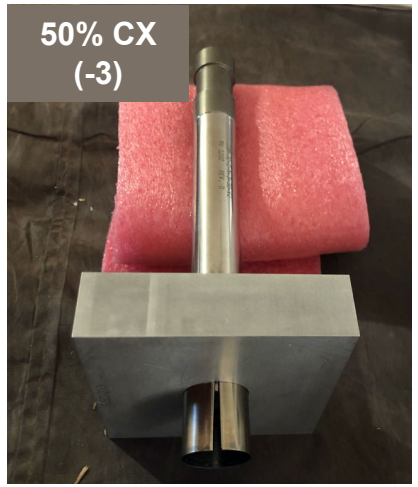
Processed samples at LANL

7050-21-1 – 100% CX (ND complete)

7050-21-2 – 100% CX (spare now, use for contour)

7050-21-3 – 50% CX (ND complete)



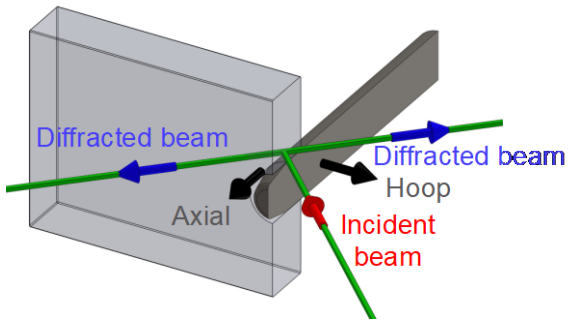


ND Setup and measurement locations (concept)

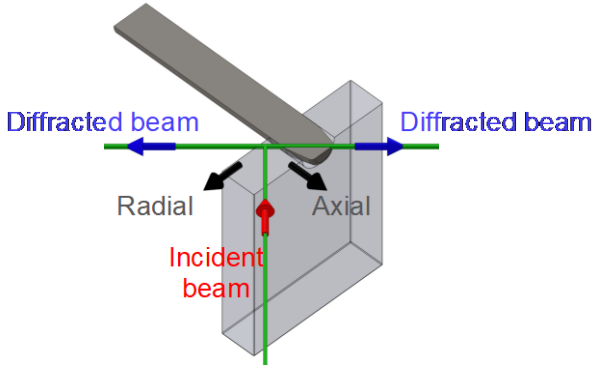
Note: ND measurements are complete

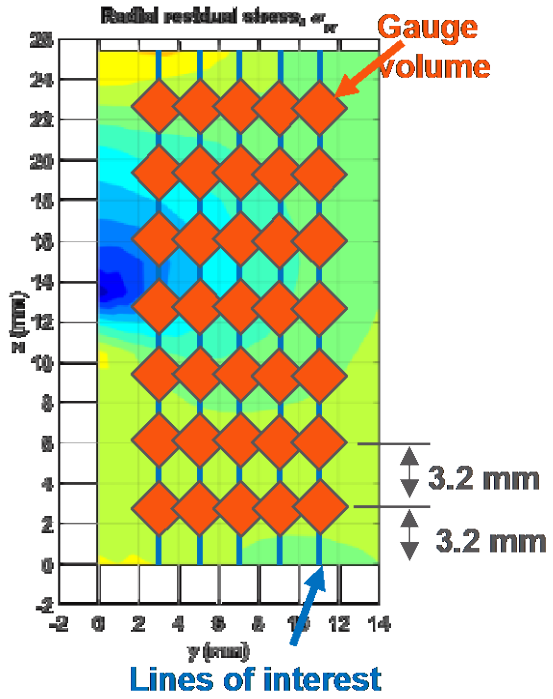
2 mm cubic gage volumes

Horizontal orientation

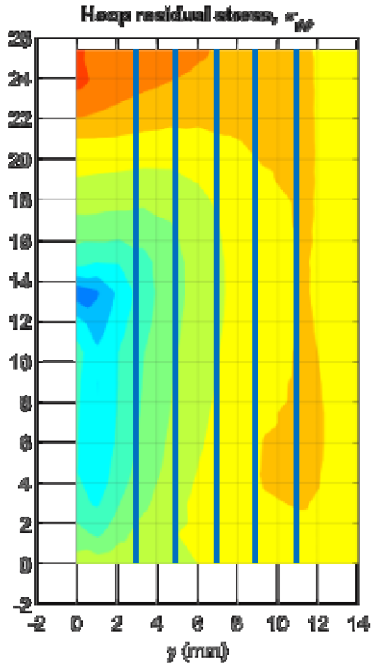


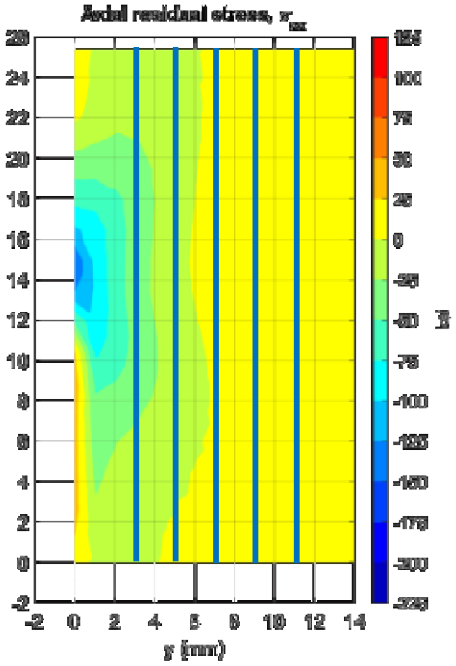
Vertical orientation





Background contours: Stress for 7075-T651 (50%)





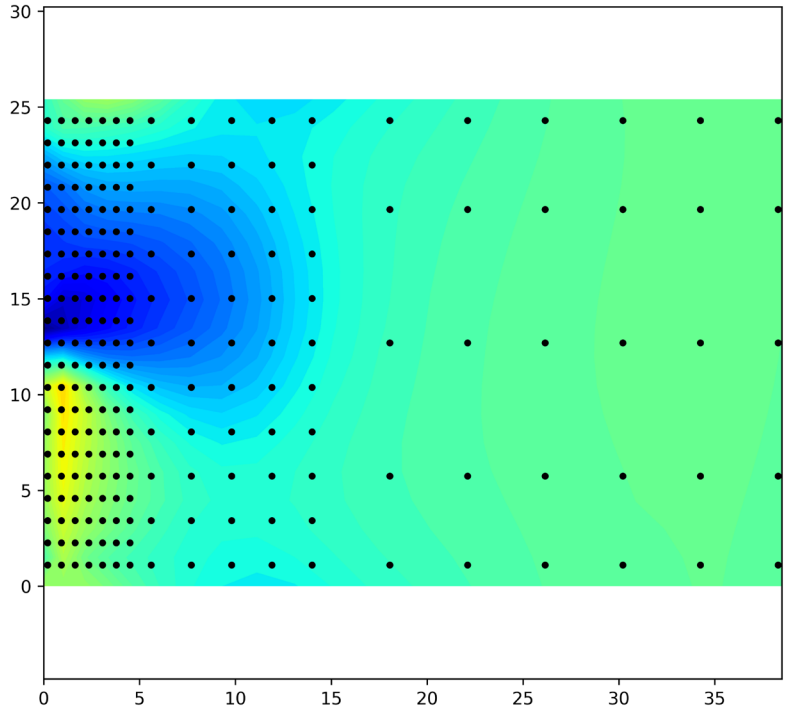
EDXRD measurement locations (concept)

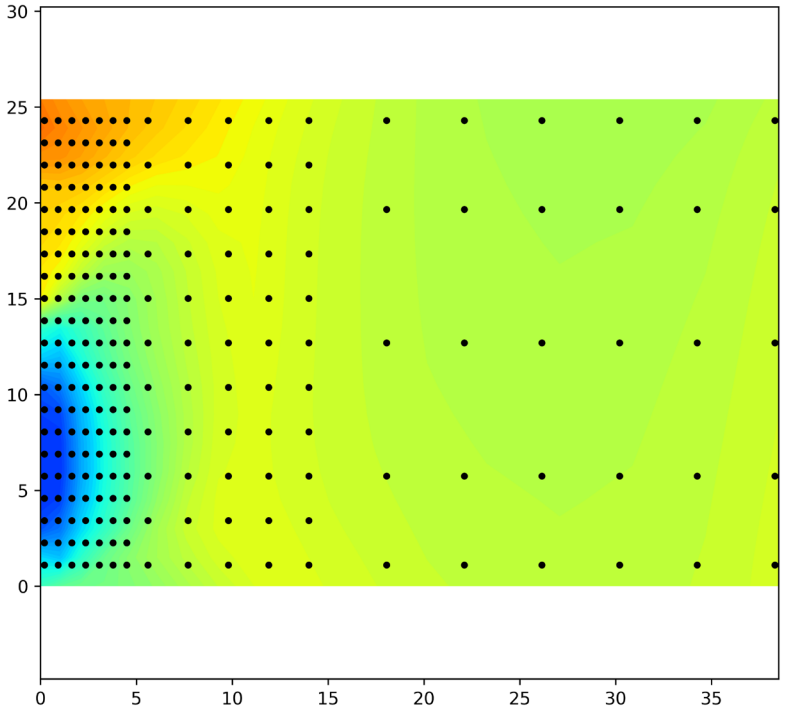
Note: EDXRD measurements are to begin Feb 16, 2022

Compared to ND, EDXRD allows for:

- More locations (faster per point)
- Closer spacing (smaller gage volume)

Background contours:
Elastic strain for 7050-T7451 (50%)

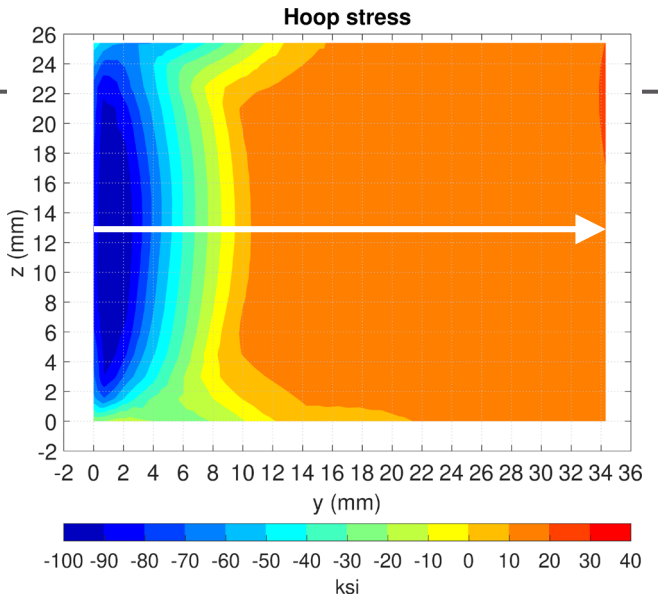


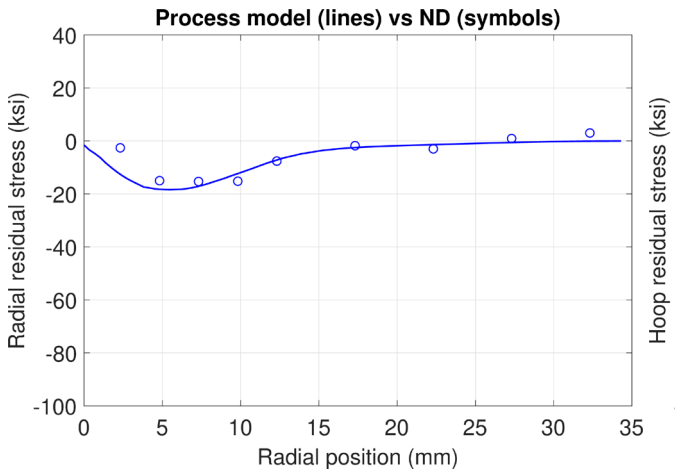


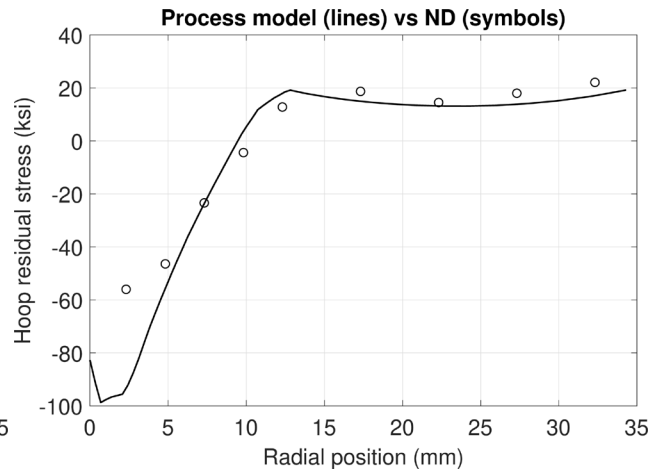
Results: Model and ND (100%)

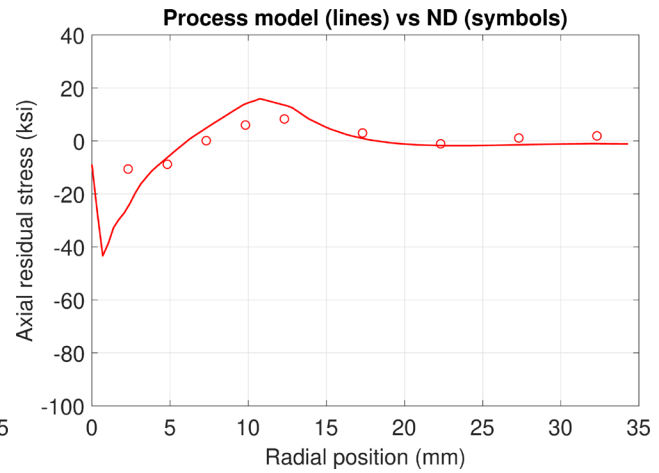
7050-T7451

- Line plots comparing model output and neutron diffraction (ND) measurements below
- At the mid-thickness vs position from the hole bore
- Radial, hoop, and axial residual stress results shown







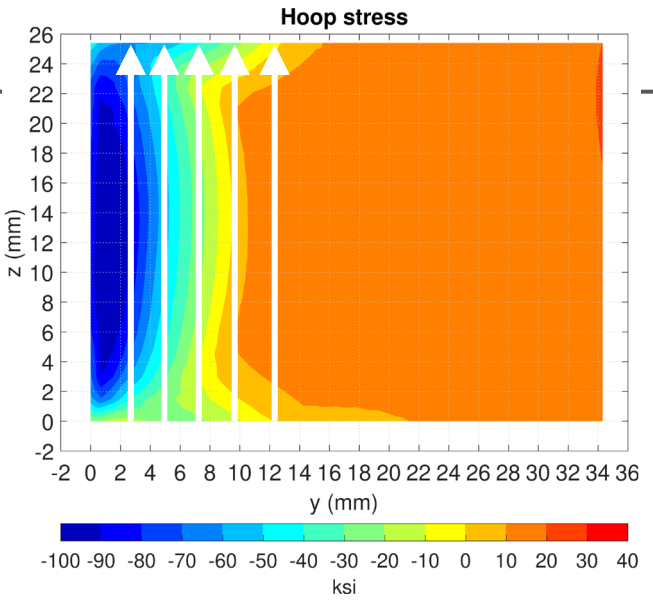


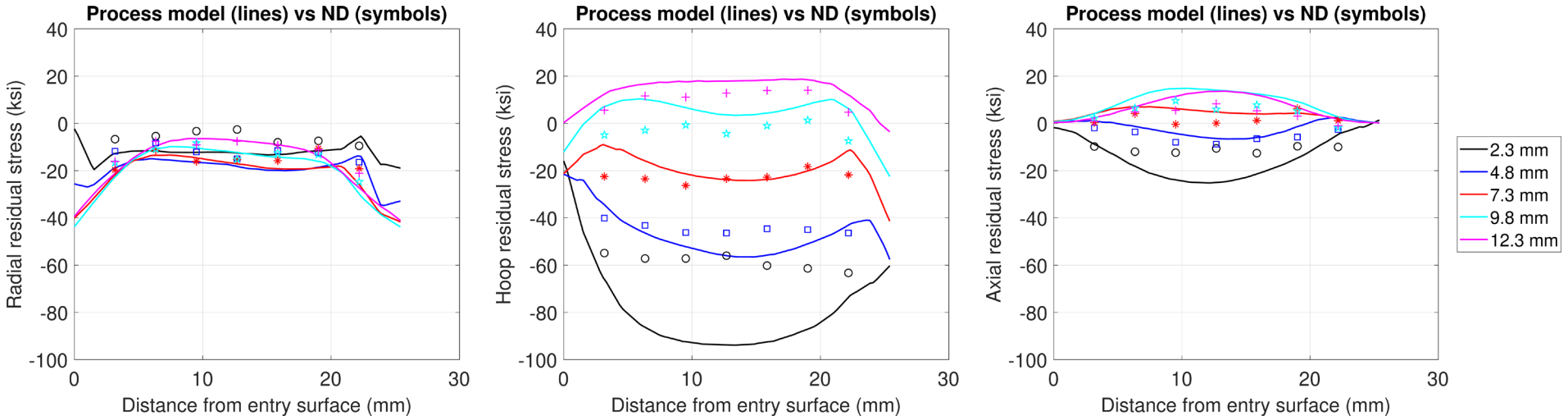
Results: Model and ND (100%)

7050-T7451

Line plots comparing model and neutron diffraction (ND) measurements below

- Through the thickness from the cx entry surface
- Radial, hoop, and axial residual stress results shown



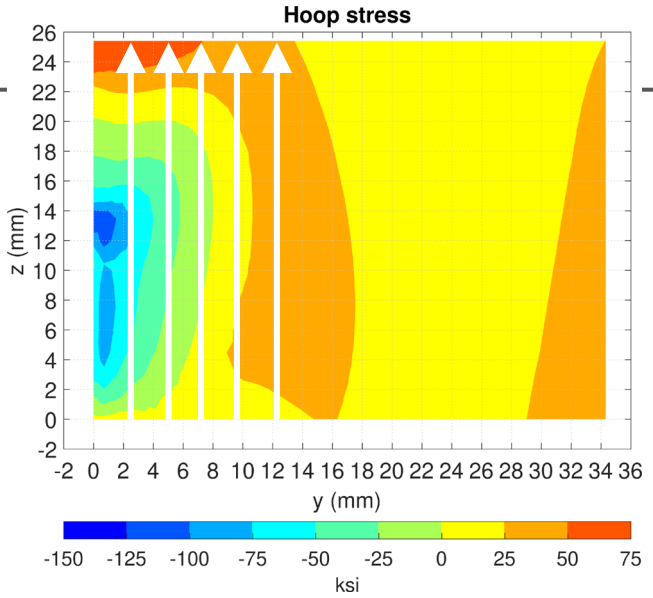


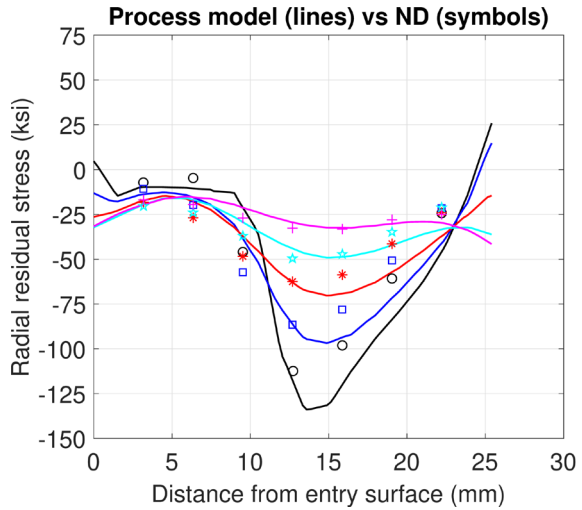
Results: Model and ND (50%)

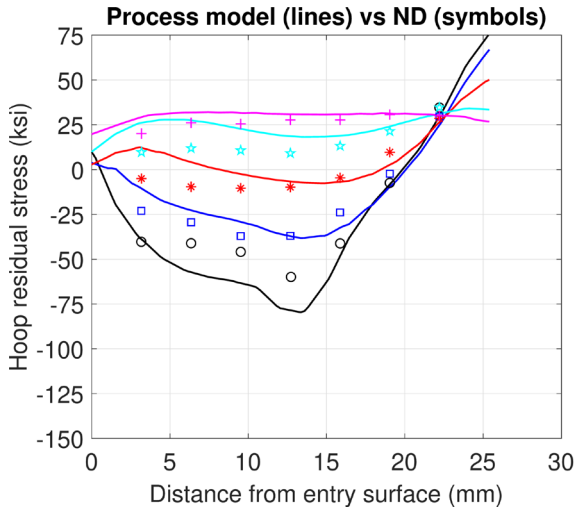
7050-T7451

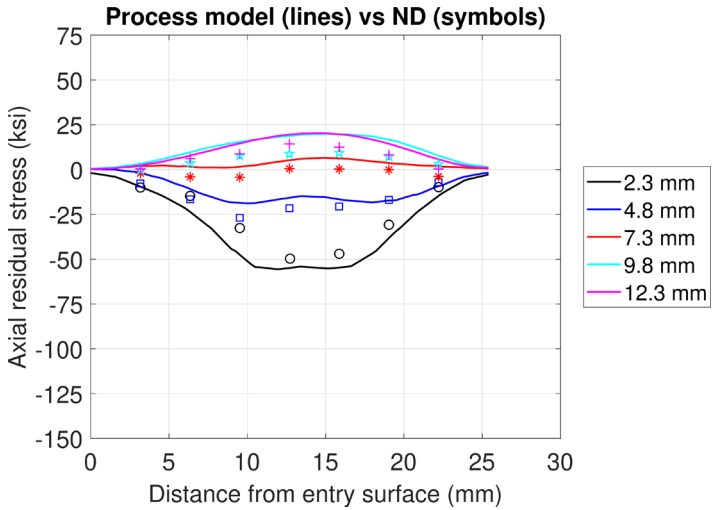
Line plots comparing model and ND measurements below

- Through the thickness from the cx entry surface
- Radial, hoop, and axial residual stress results shown









To be continued

EDXRD measurements this week (Feb 16-23, 2022)

Contour measurements to follow (Spring 2022)

Publication to be completed (Summer 2022)

Summary and Future Opportunities

Committee logistics

Active work

Opportunities in store

- Applications at CHESS
  - Large hole samples
- Continuation of active work
  - Communications and collaboration within ERSI
  - Exemplar RS data sets
  - Large hole RS measurements
  - Anisotropy and preferred orientation
  - Outward facing documents
- Interactions with other ERSI committees
  - Leverage ERSI member experience
- Interactions with field challenges
  - AFRL Multi-point Fracture Mechanics program (MAI)
  - Bring us your problems!