Working Group on
Engineered Residual
Stress Implementation

Measurement Committee Summary

(These charts are a team product.)

Dec 08, 2020

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Topics for Today

Committee Logistics:

- Typical Meeting Agenda
- Roster and Attendance

Topics of Note

- Active work items
- Status and accomplishments
- Summary of technical elements

Opportunities Ahead

- Applications at CHESS
  - Large hole coupons
- Continuation of active work
- Interactions with other ERSI Committees
- Interactions with field challenges

Meeting Agenda

X:00-X:05 Welcome and agenda (Mike H)

X:05-X:10 Update from Process Modeling committee (Adrian)

X:10-X:15 Update from 2x2WG (Marcus)

X:15-X:40 Old Business

- Project updates
  - Texture/Orientation/Anisotropy update (Mark, Mike S)
  - Exemplar Data Sets (Eric)
  - Large Hole Effort (Mike H and James)
- Potential activities at CHESS (Mark)
  - EDD for Large Hole coupons
- Documentation updates
  - Discussion of Best Practices Document updates

X:40-X:55 New business

- Quick updates (All)
- Open discussion (All)
- ERSI 2020 Virtual Meeting: Nov 17-19, 2020
- RS Measurement goals discussion

X:55-X:58 Action items

X:58-X:59 Closing

Example slide, typical meeting

Committee roster (recent changes in color)

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Summary of Meeting Attendance

Example slide, typical meeting

Nov 18, 2020
- Breuer, Burba, DeWald, Lindgr… Obstalecki, Oliveira, Pineault, Sp… Hill

Oct 14, 2020
- Backman, Breuer, Pineault, Oliveira, Bouchard, Burba, Martinez, Obstalecki, Hill

Sep 9, 2020
- Pineault, Burba, Obstalecki, DeWald, Harrison, Hill

Aug 19, 2020
- Burba, Pineault, Stanfield, DeWald, Obstalecki, Hill

July 8, 2020
- Lindgren, Burba, Bouchard, Carlson, DeWald, Pineault, Hill

June 10, 2020
- Lindgren, Burba, Bouchard, DeWald, Obstalecki, Pineault, Spradlin, Oliveira, Hill

May 13, 2020
- Burba, Obstalecki, Carlson, DeWald, Pineault, Hill, Backman, Steinzig, Bouchard, Harrison

April 8, 2020
- Harrison, Pineault, Burba, Hill, Hitchman (from Modeling group), Dave Breuer (CWST, guest of Harrison)

March 11, 2020
- …lin, DeWald, Carlson, Pineault, Obstalecki, …dgren, Burba, Hill

Sep 12, 2019 (…kshop)
- Pearce, Nyugen-Quoc, Barrientos, Greuner, Stanfield, Carlson, Bouchard, Dubberly, A Jones, Hitchman, DeWald, Steinzig, T Thompson, Pineault, Hill

March 13, 2019
- Spradlin, Lindgren, Pineault, Brauss, Steinzig, DeWald, Carlson, Grodzicki (guest), Hill

Feb 6, 2019
- Steinzig, Carlson, Penault, Grodzicki (guest), Pilarczyk, DeWald, Hill

Jan 9, 2019
- Spradlin, Carlson, Pilarczyk, Burba, Obstalecki, Lindgren, Martinez, Hill

Update from Process Modeling Committee

Adrian DeWald is point person fostering interaction with the Process Modeling Committee

Example slide, typical meeting

New items (Adrian)

- Notes from last meeting (9/17/20):
  - Planning to finish the summary of the first round robin modeling activity
    - Results to be presented at December ERSI general meeting
  - Holding on second round robin until after feedback from the December ERSI general meeting

From prior discussions

- First simulation round-robin is to be reported 9/25
  - Publication being considered
  - New round-robin activity is planned, but on hold pending feedback
- There is an opportunity to work with other ERSI Groups on methods for data comparison and data assessment
  - Basic questions:
    - When we have different 2D stress fields from given sources (e.g., measurements of different types, and/or models of different types) what are useful ways to compare them?
    - What are ways to assess uncertainty of 2D stress fields?
  - All groups have a stake in this area, but maybe these are key:
    - Data Management and Quality Assurance (Kaylon Anderson)
    - Risk Analysis and Uncertainty Quantification (Laura Hunt)
    - Residual Stress Measurement (Mike Hill)
    - Residual Stress Process Simulation (Keith Hitchman)

Update from 2x2 working group

Marcus Stanfield is point person fostering interaction with the 2x2 working group (2x2WG)

Example slide, typical meeting

New items (Marcus)

- Synchrotron data from APS needs to be processed (need a p
- XRD needs elastic constant (XEC) determined
- Neutron data from Japan is complete, Prof Bouchard preparing a publication
  - Post-meeting question: can this data be shared (to be held in the Committee)?
- 2x2WG priority is publication

From prior discussions

- Detailed update (Marcus, 19 Aug 20; see charts in email)
  - Opportunity to measure non-reamed CX holes (contact Marcus)
    + Limited to nondestructive measurements
    + Potential opportunity with at CHESS (USAF has a funded program)
  - Opportunity to help with analysis of prior EDXRD data (contact Scott C)
- Updates at July meeting (Bouchard, Pineault)
  - XRD data being worked on
  - Additional ND measurements active
  - Marcus Stanfield is current lead for this activity

Old business

On-going project updates

Example slide, typical meeting

- Texture/Orientation/Anisotropy (Mark/Mike S)
  - Current status
- Exemplar Data Sets (Eric)
  - Current status
    + Mike and Eric will develop a workflow for open publication of residual stress measurement data using DRYAD
      - Mike: data presented to the committee on June 10, 2020
      - Eric: USAF data to be identified (likely for shot peened materials)
    + DRYAD as opportunity for sharing data
      - https://datadryad.org/
- Large Hole Effort (Mike H)
  - Current status
    + James and Mike to provide update on recent measurement data in November

Potential activities at CHESS (Mark)

- Potential application of Energy Dispersive Diffraction (EDD) to the A-10 Large Hole coupons (good tie in to standing work)
  - Mark and Eric have the action on this?

Old business (continued)

Documentation updates

- Current updates
  - Please provide feedback on best practices documents (
  - Received some detailed feedback (thanks, James!) on the A-10 [illegible]cument (see below)
    + Mike H and Eric will review, then feedback to Committee for consensus [illegible] to A-10
    + Watch for an action item on this by email
- Prior notes
  - New journal publication related to ERSI: Andrew, DL, Han, H-C, Ocampo, J, Alaeddini, A, Thomsen, M. Characterization of residual stresses from cold expansion using spatial statistics. *Fatigue Fract Eng Mater Struct*. 2020; 1–14. https://doi.org/10.1111/ffe.13334
  - New journal paper on contour method reproducibility
    + Available for all to read at https://rdcu.be/b4KpF
  - USAF Best Practices document being opened for updates (A-10 program) "Analytical Considerations for Residual Stress Best Practices and Case Studies"
    + Prior release available here: https://apps.dtic.mil/sti/citations/AD1084445
    + Feedback and suggestions are welcome
      - Provide comments back to Mike Hill for relay to program
  - ASTM Task Group writing industry guidance document
    + TG E08.04.06 - Residual Stress in Structural Design and Sustainment (T.J. Spradlin, TG Chair)
  - Forthcoming USAF Structures Bulletin
    + T.J. Spradlin accepting input
  - ERSI NDE/QA Committee is circulating a document framework for feedback
    + Send input to Mike Hill, Eric Burba, or Kaylon Anderson kaylon.anderson@us.af.mil

Example slide, typical meeting

Active work items

Communications and collaboration within ERSI

- 2x2 Working Group (2x2WG)
- Process Simulation Committee

Exemplar RS data sets

Large hole RS measurements

Anisotropy and preferred orientation

- Assess how residual stress measurement techniques perform in processed metals (typical and atypical material conditions)

Outward facing documents

- Develop measurement-specific documents
- Support overall ERSI documentation efforts
  - SB, A-10 Best Practices, ASTM, ASM
  - Focus currently on A-10 Best Practices
- List relevant publications and reports

Status and accomplishments

Established interfaces with other activities

- 2x2WG
- Process Simulation

Developed plan for posting exemplar data sets in open data repository

Developed RS data in large hole coupons

- Being discussed within Committee

Developed plan for studying anisotropic materials

Contributed to outward facing documents

- Engaged in developing draft material or revisions (ASTM, A-10 Best Practices)
- Noted relevant publications
  - Andrew, DL, et al., “Characterization of residual stresses from cold expansion using spatial statistics”. *Fatigue Fract Eng Mater Struct*. 2020; 1-14. https://doi.org/10.1111/ffe.13334
  - D’Elia, CR, et al., “Interlaboratory Reproducibility of Contour Method Data Analysis and Residual Stress Calculation”. *Experimental Mechanics*, 2020, https://rdcu.be/b4KpF

Summary of technical elements

2x2 working group (2x2WG)

- Contact Marcus Stanfield

Exemplar data sets: near surface stress profiles

- Contact Eric Burba

Large hole experimental work

- Contact Mike Hill

Anisotropy and preferred orientation

- Contact Mark Obstalecki

2x2 Working Group Overview

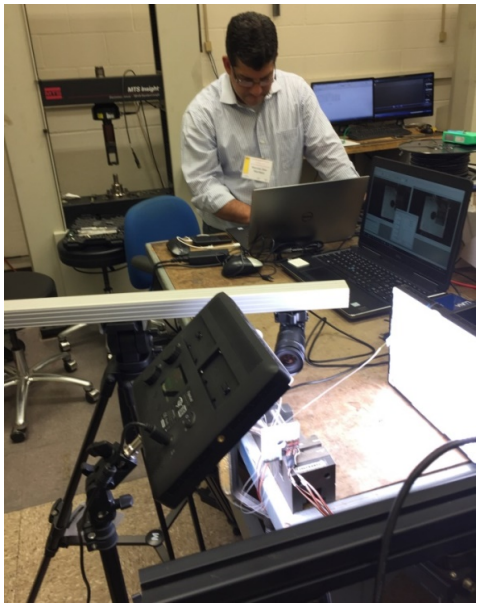
Schedule: 2016 - Ongoing

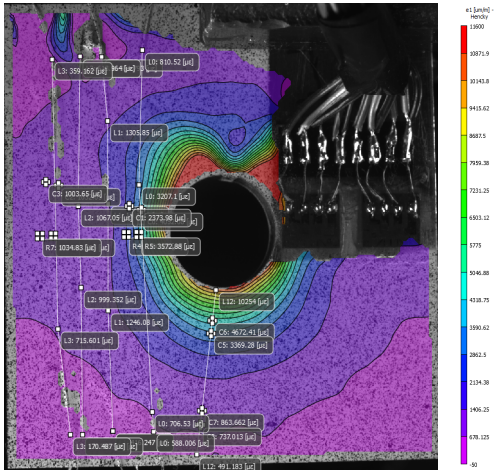
Members

- Research, Industry, Academia
- Multiple committee participation

Purpose

- Cx multiple aluminum alloys (2024-T351 & 7075-T651) at “Low” and “High” expansion levels for reamed and un-reamed configurations
- Characterize the residual stress/strain using multiple measurement techniques
  - Strain gauge, LUNA fiber optics, DIC
  - XRD, EDD, ND
  - Contour Method
- Develop a validation data set and framework for process simulations and NDI/QA
- Develop input data for FCG validation





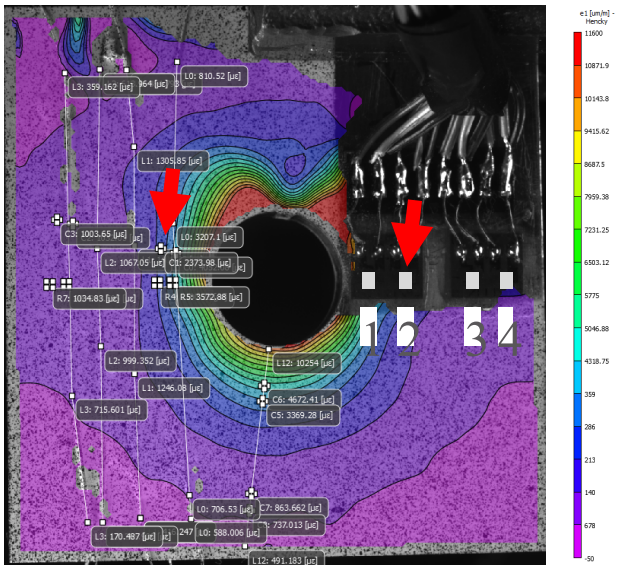
Surface Strain Highlights

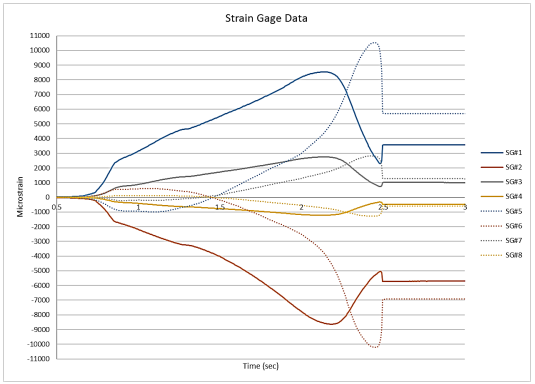
Multiple measurement cross validation

DIC/FEM comparison using MatchID

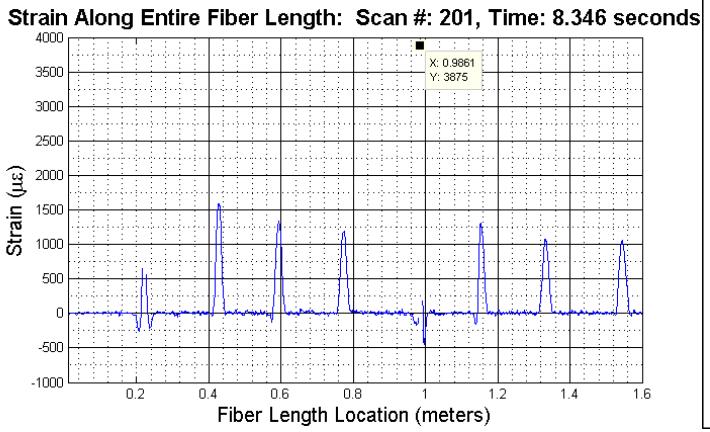
Validation metrics established (Zimmerman)

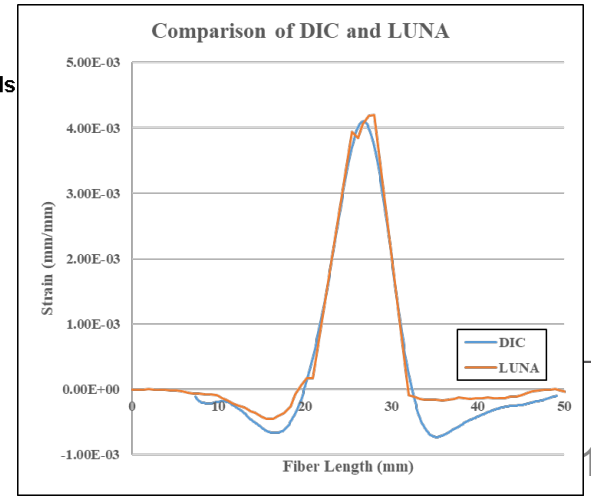
Multiple process simulation models (FTI/NRC)





Strain Comparison: Gauge vs. DIC			
Location	**Gauge**	**DIC**	**%Diff**
1	0.003571	0.003573	0.05%
2*	-0.005699	-0.005684	0.26%
3	0.000984	0.000969	1.54%
4	-0.000459	-0.000430	6.43%



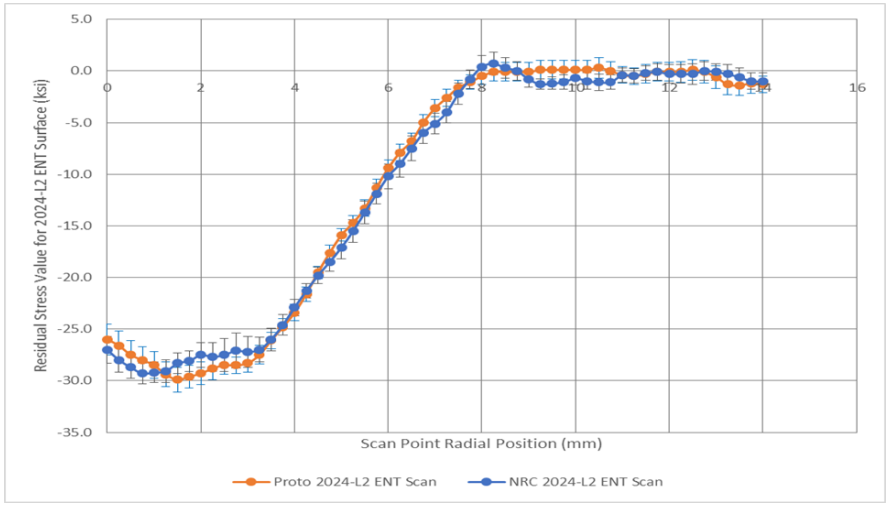


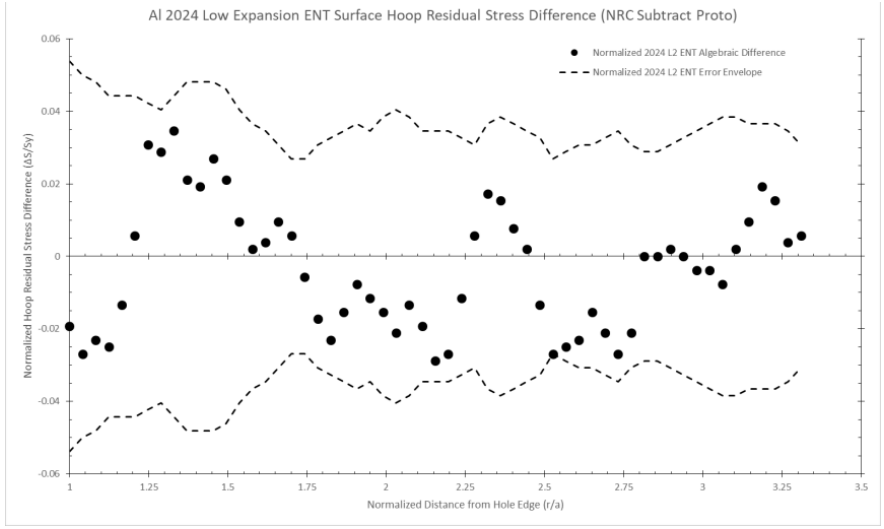
XRD Highlights

Inter and Intra laboratory studies (NRC & Proto Mfg.)

Optimize data collection parameters and take advantage of circumferential strain fields around CX holes to further improve measurement accuracy & precision

XEC determination for the specific 2024-T351 & 7075-T651 product forms studied is currently in progress



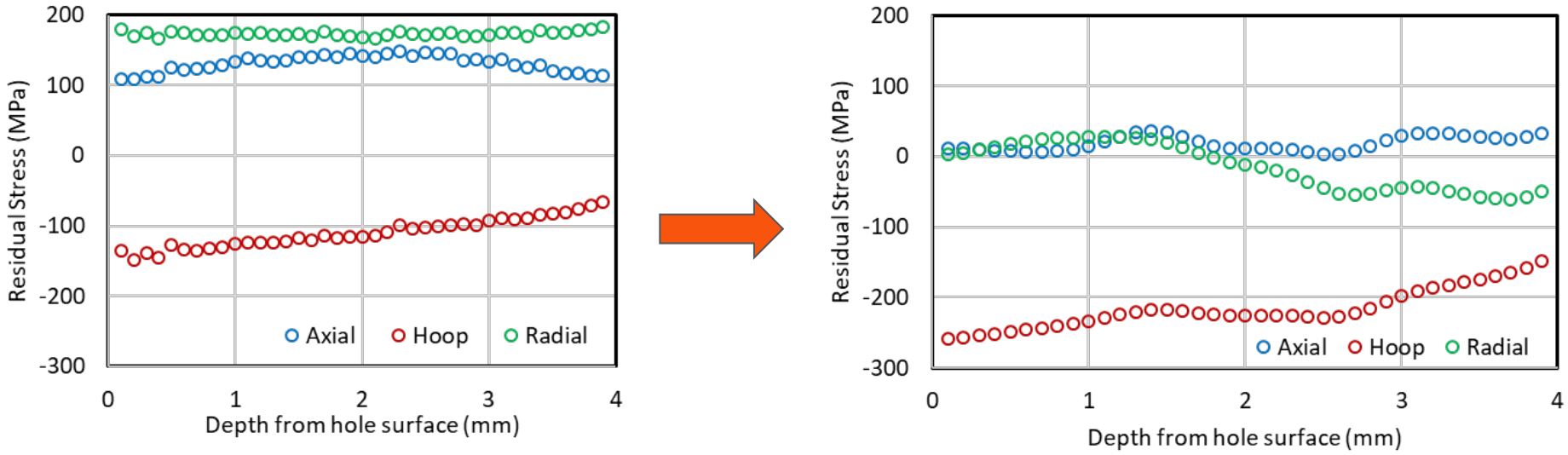


ND Highlights

Work performed by OpenU, Stress Space Ltd., CEAM, JAEA

Increased spatial resolution using a deconvolution algorithm

- Requires a thin foil for calibration
- Longer beam time



Status

Progress made

- Validation metrics and framework for simulation to data comparisons
  - Still to be discussed in committee
- XRD and ND “lessons learned” can be applied to similar applications
  - Accuracy improvements observed

Work planned

- Additional ND and Contour Method measurements in Q1 & Q2 of 2021
- Residual stress data sets for FCG inputs should be established by Q4 2021
- Reamed coupons reserved for NDI and QA techniques
- Multiple journal papers in work

Exemplar data sets: near-surface stress profiles

Exemplar data sets objective:

- Identify examples of residual stress measurement data that are typical of good practice in aerospace materials
- Seek data showing comparisons of different experimental methods applied to the same parts or samples
- Post these data to an open repository for access by the community

Methods:

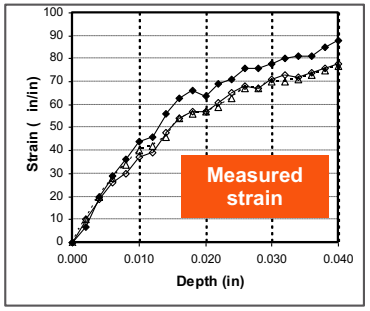
- Identify data through committee members and their networks
  - Prior publications, contract reports, ERSI studies, et cetera
- Employ open data sharing platform
  - DRYAD https://datadryad.org/
    + Any field. Any format. Quality control and assistance. Community-led.
    + Currently developing posting workflow

First example: near-surface stress profiling

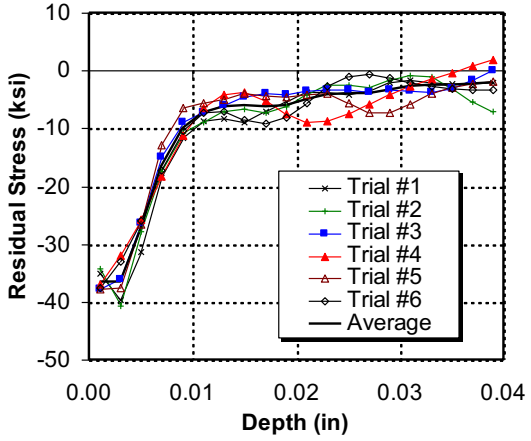
- Inter-method comparison of near-surface stress profiling
  - *Ref: "Measurement of residual stresses near the surface of metals," M.R. Hill, A.T. DeWald, T.A. Wong, 10th European Conference on Residual Stresses, Leuven BE*

Near-surface stress profiling methods

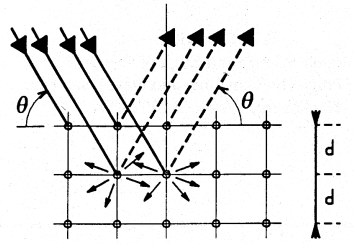
Hole-drilling



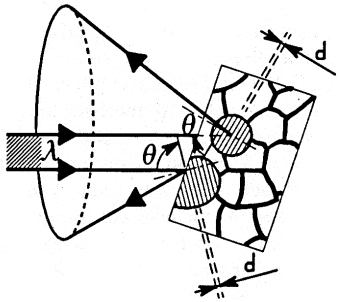
3 stress components

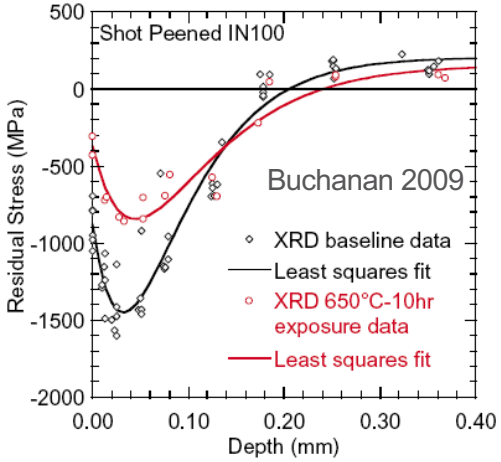


XRD

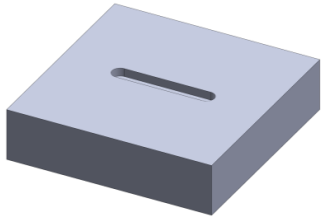


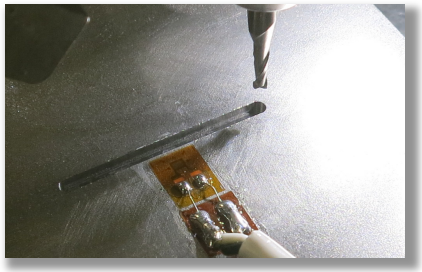
J. Lu, Handbook of Meas. of RS, 1996.

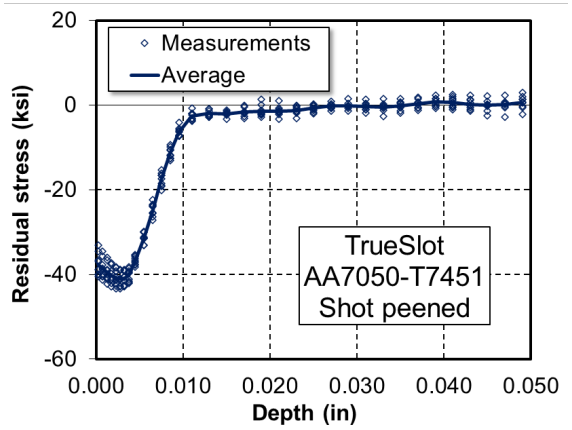




Slotting (TrueSlot®)



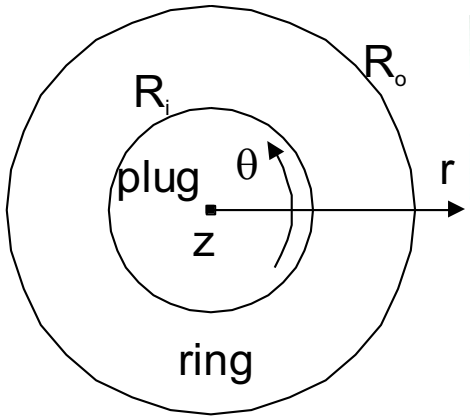


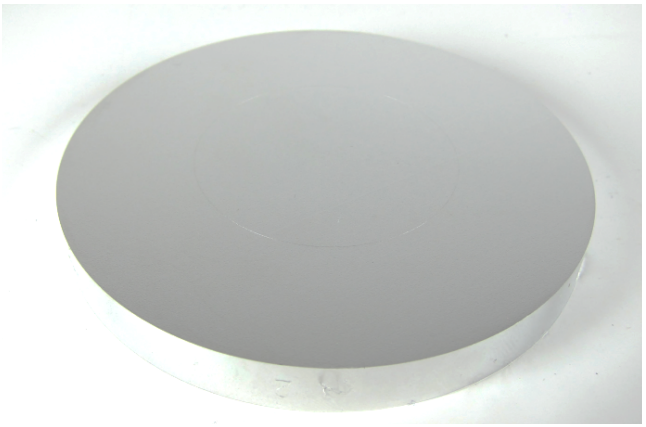


Sample type 1: Ring and plug

Ring and plug specimen

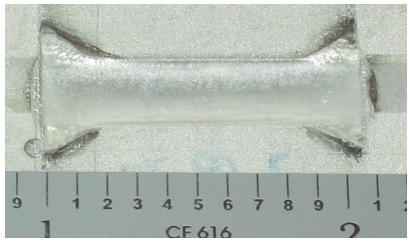
- 2.0 inch diameter plug
- 4 inch diameter ring

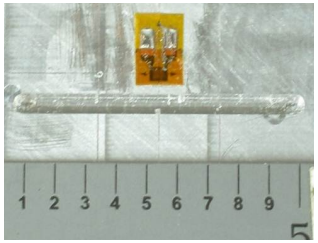


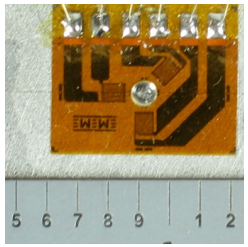


Material properties:

- AA2024-T351
- E = 10,400 ksi
- ν = 0.33
- Expect -6.0 ksi stress in the plug equibiaxial



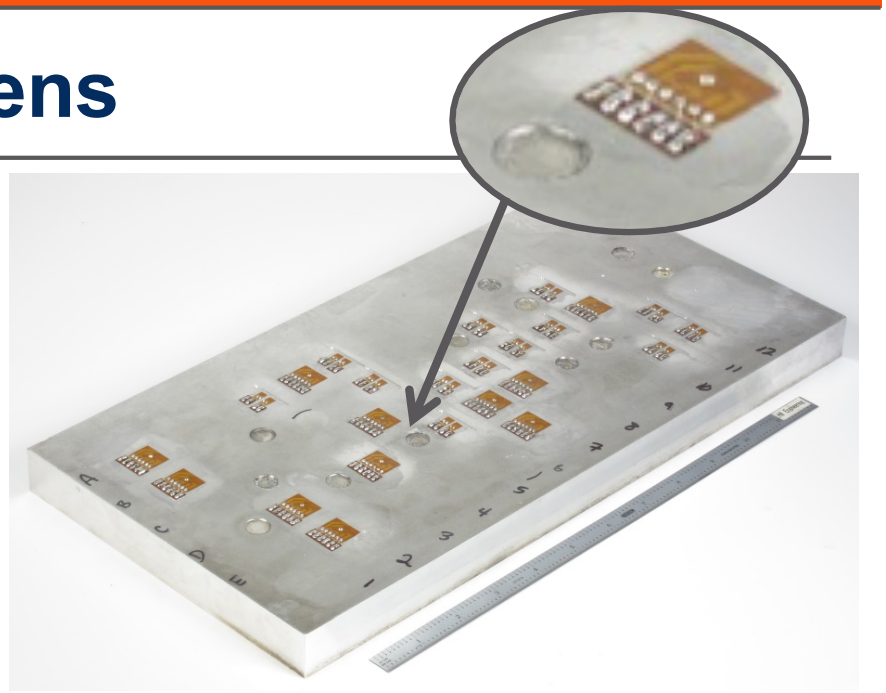




Measurement order

- First: XRD
- Second: HD
- Third: slotting

Sample type 2: Plate specimens



Nominally 15 x 7.5 x 1 inch (380 x 190 x 25.4 mm)

Three plate conditions

- Shot peened AA7050-T7451
  - SAE 230-280 cast steel shot, 6 A, 200%
- Shot peened Ti-6Al-4V (mill-annealed)
  - SAE 170 cast steel shot, 6-9 A, 100%
- Quenched AA7050-T74

12 replicate measurements

- Randomize locations

Measurement order

- First: XRD
- Second: HD
- Third: slotting

Description	Material Properties
Shot peened Al plate	Aluminum alloy 7050-T7451 E = 10,400 ksi ν = 0.33
Shot peened Ti plate	Titanium alloy Ti-6Al-4V E = 16,500 ksi ν = 0.34
Quenched Al plate	Aluminum alloy 7050-T74 E = 10,400 ksi ν = 0.33

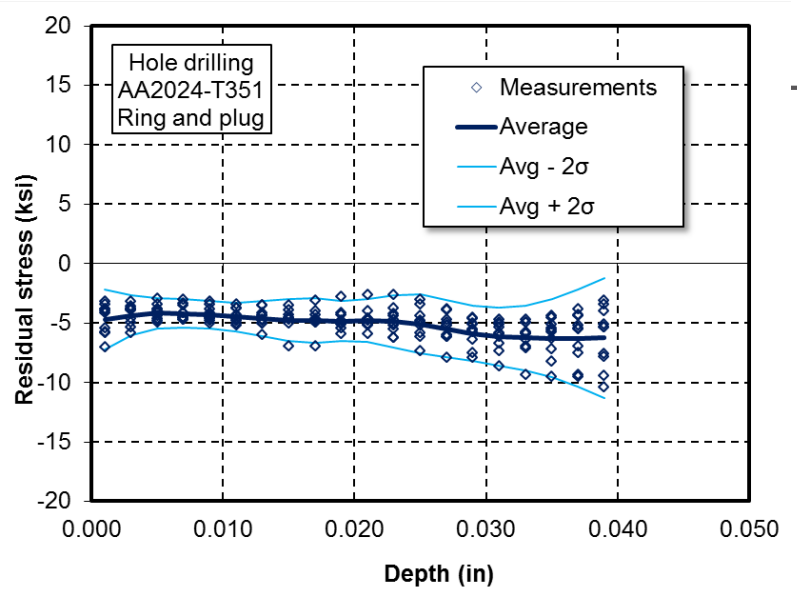
Ring and plug results

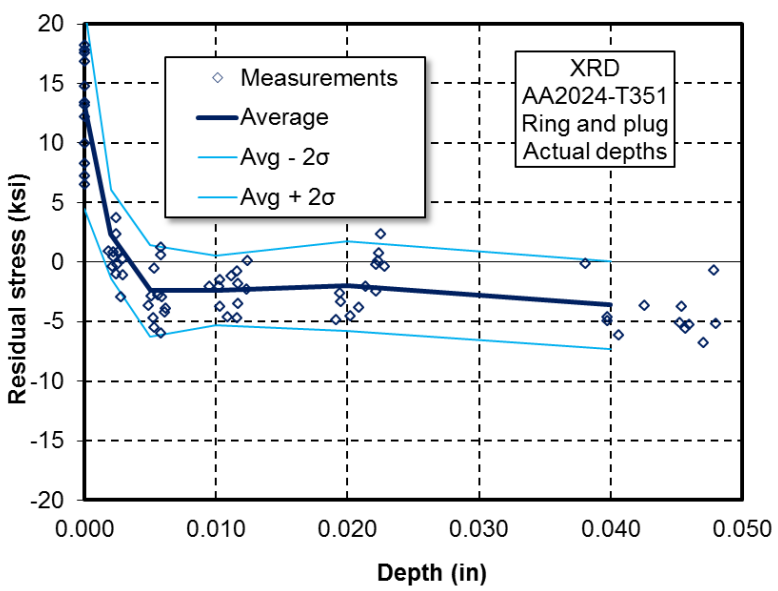
Summary of results

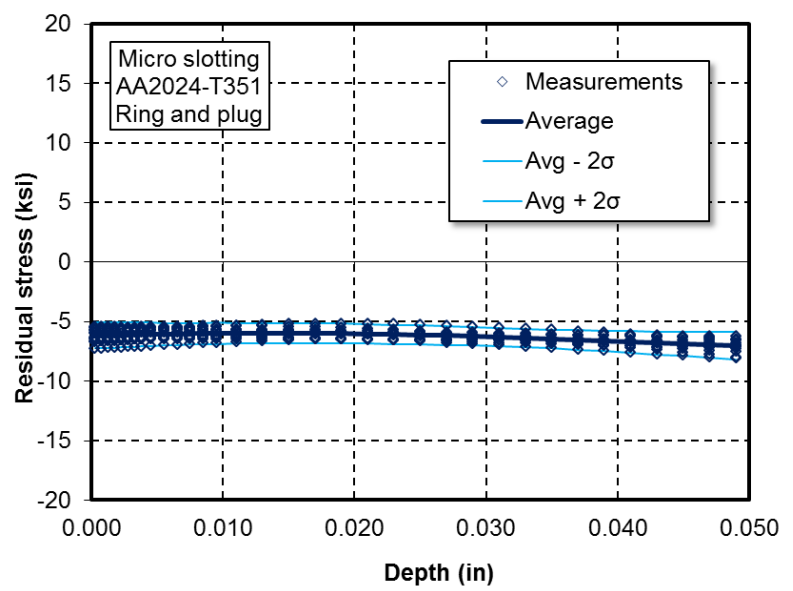
- Near uniform compressive RS
- Similar to expected value of -6 ksi

Data analysis

- Compute average and standard deviation at set of depths
- Use linear interpolation to consistent depths







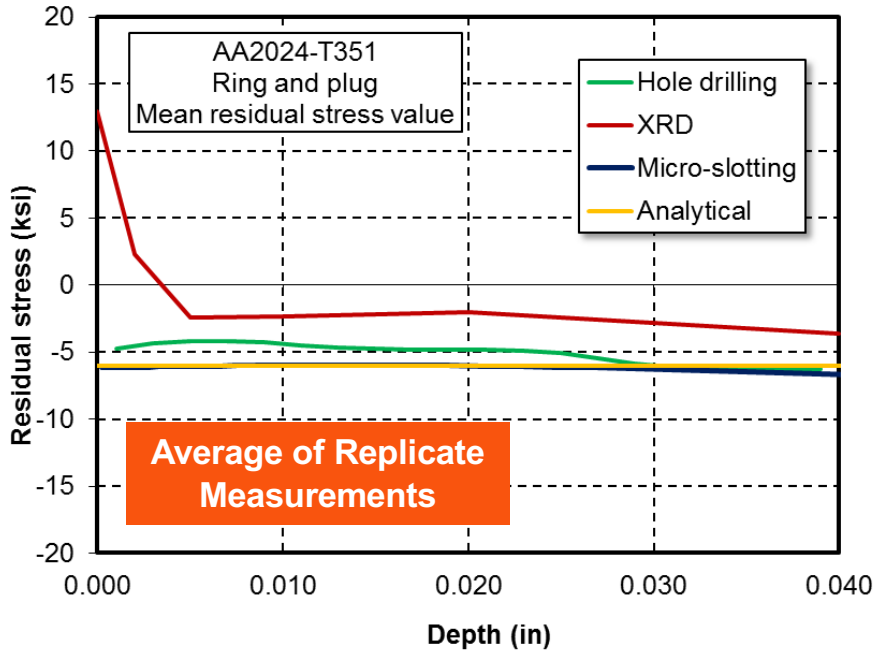
Ring and plug results

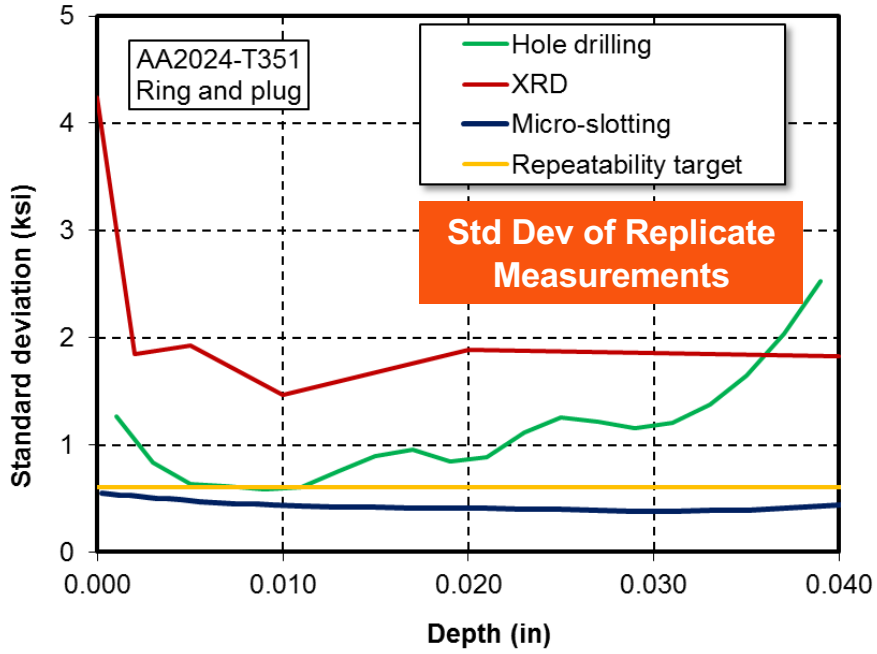
Comparison of average residual stress

- Slotting closely matches expected residual stress
- Hole-drilling has similar shape, slightly different magnitude
- XRD has different surface value and sub-surface bias (different value)

Residual stress repeatability (standard deviation) versus depth

- Slotting repeatability better than 0.5 ksi (average); hole-drilling somewhat higher, and XRD largest





Near-surface profiling study summary

Documented repeatability of residual stress measurement

- In relevant materials and stress states
- Summary data are tabulated below
- Full data to be posted on DRYAD

Results show hole-drilling, XRD, and slotting provide similar results, with differences in bias and precision

- Results dependent on specific materials, geometry, stress state, and methods

	Repeatability Std Dev (ksi) Average 0.00 to 0.04 inch			Repeatability Std Dev Normalized by Slotting		
Specimen	**XRD**	**HD**	**Slotting**	**XRD**	**HD**	**Slotting**
Aluminum ring and plug	2.2	1.1	0.4	5.5	2.7	1.0
Shot peened aluminum	2.5	3.0	1.1	2.3	2.7	1.0
Shot peened titanium	8.7	3.7	4.1	2.1	0.9	1.0
Quenched aluminum	2.0	1.4	1.0	2.0	1.4	1.0

Large Hole CX Evaluation

Objective

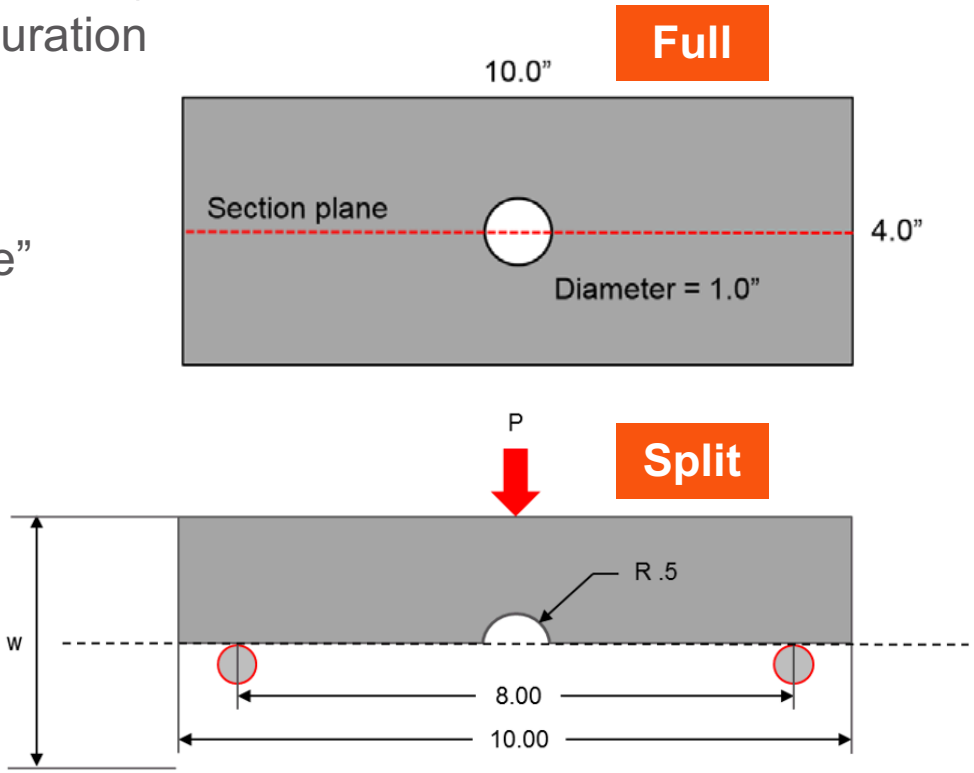
- Develop a coupon that scales-up the stress field
- Develop and interrogate residual stress measurement data
  - Full configuration
  - Split configuration (split along 10” dimension)
- Develop crack growth data in split configuration

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



Large Hole Status

Study design

- Complete (HE and A-10)

Coupon fabrication

- Complete (HE)

Planned residual stress measurements

- Contour: complete (HE)
- Hole drilling: complete (HE)
- XRD: complete (Proto)
- Comparison and assessment: in-process (Team)

Fatigue crack growth testing of split samples

- Straight bend: complete (A-10)
- Corner bend: unknown

Reporting

- To be defined

HILL ENGINEERING

PROTO MANUFACTURING

ERSI Texture & Anisotropy Team

Objective: Incorporate elastic anisotropy into standard industry residual stress measurement workflows

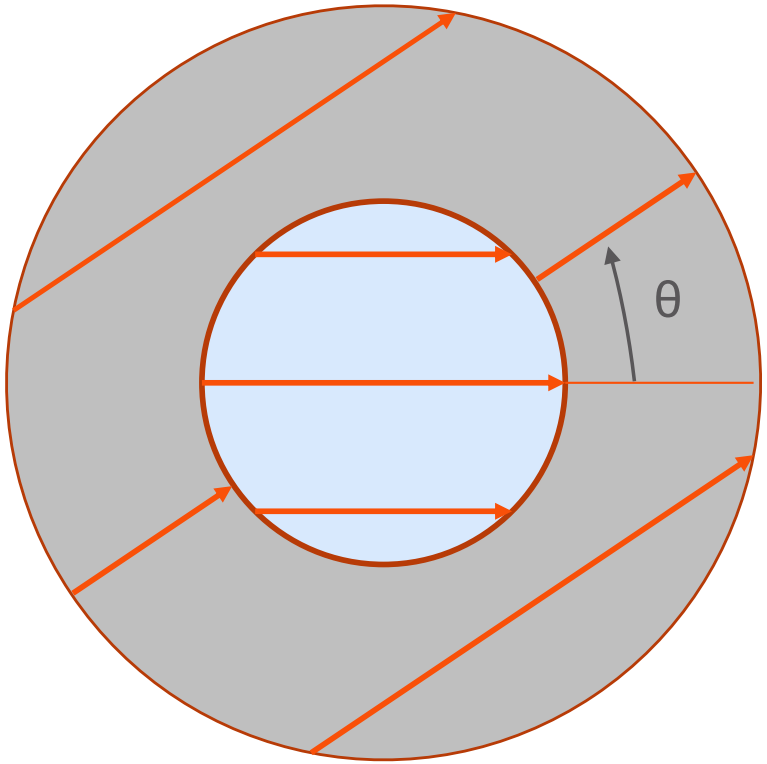
Methods: Develop combined modeling and experimental approach to (1) demonstrate impact of elastic anisotropy on current RS measurement techniques, (2) enable incorporation of microstructure into existing workflows, and (3) support round robin sample sharing

Schedule:

- Nov 2020 – First 'official' biweekly meeting
- Dec 2020 – LANL prepares ring/plug samples
- Jan 2021 – AFRL begins hole drilling measurements
- FY21 – Anisotropic FE ring/plug model development
- FY21 – Measurement of 'optimized' anisotropic ring/plug samples

Team:

- Mike Steinzig & Zac Sanchez Archuleta – LANL
- Mike Hill – Hill/UC Davis
- Mark Obstalecki & Eric Burba – AFRL



- Arrows indicate the dominate texture direction in each component
- Model anisotropic material properties to determine theta with the greatest effect on plug/ring interaction

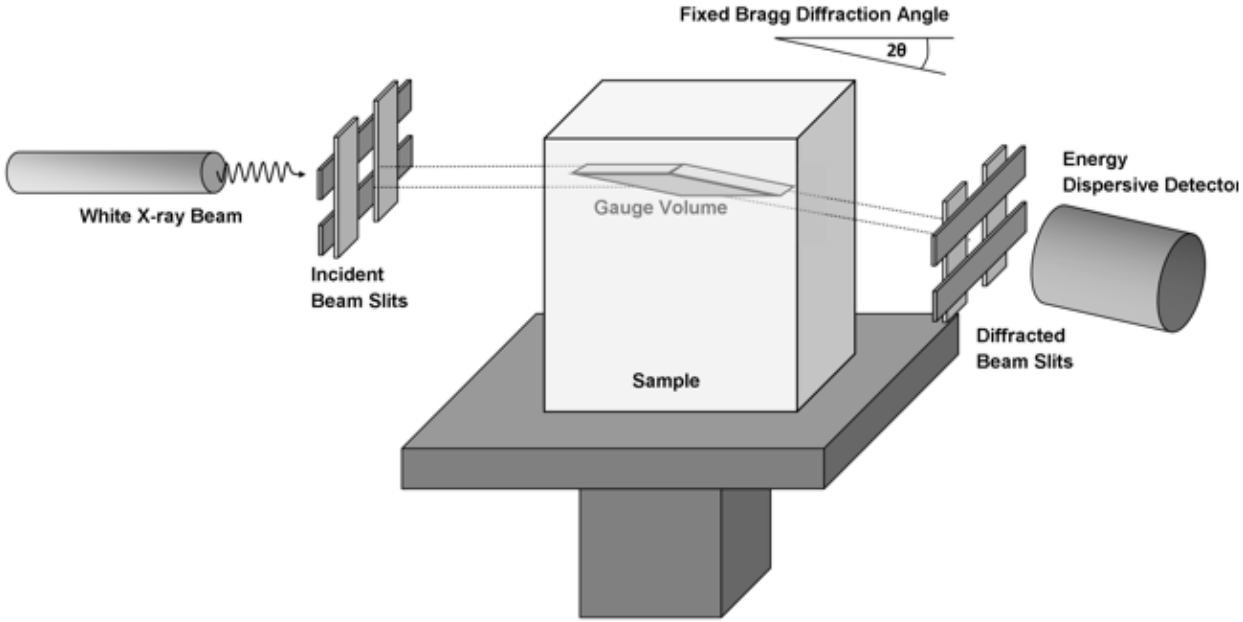
Cornell High Energy Synchrotron Source

Cornell University
Ithaca, NY

Synchrotron X-ray Menu

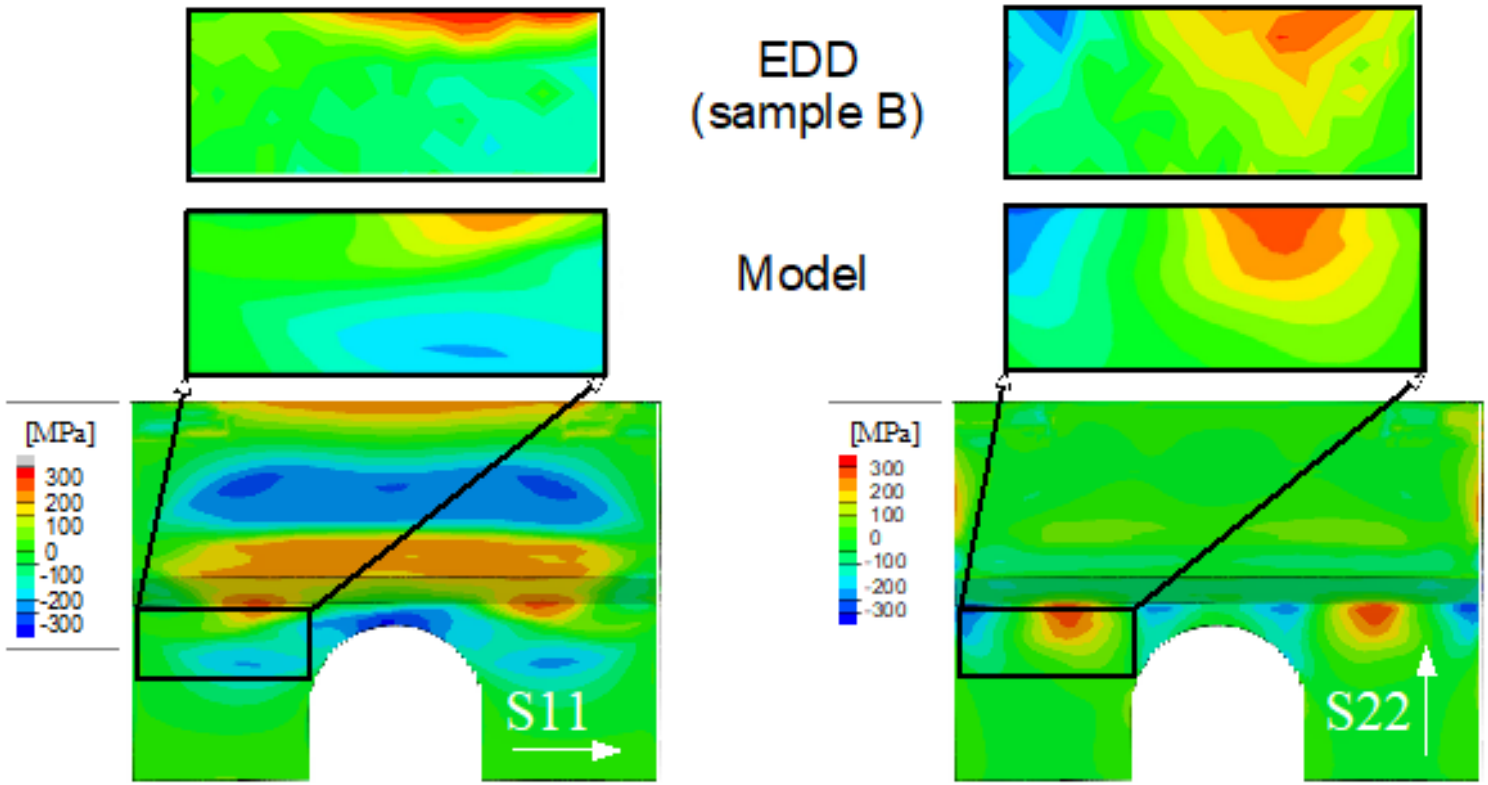
- **High Energy Diffraction Microscopy (HEDM)**
  - **Far-field:** grain average orientation, position, and strain
  - **Near-field:** grain orientation map
- **Transmission Powder Diffraction**
  - texture and strain pole figures
- **Energy Dispersive Diffraction**
  - volume averaged strain

Energy Dispersive Diffraction (EDD)



- EDD enables measurement of spatially resolved distributions of strain in large volumes (in)
- Polychromatic x-rays ranging from 50-200 keV
  - Can penetrate through bulky samples & sample environments
- Measurement time: 60 sec to 30 min per point
- Works best with fine grained materials, but heavily textured materials can be problematic
- Energy sensitive point detector

Residual Stress Mapping Example



Mach, et. al., JOM, (2017)

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!