2016 AFGROW Workshop

Application of Uncertainty Quantification for Residual Stress Measurement at a Cold Expanded Hole

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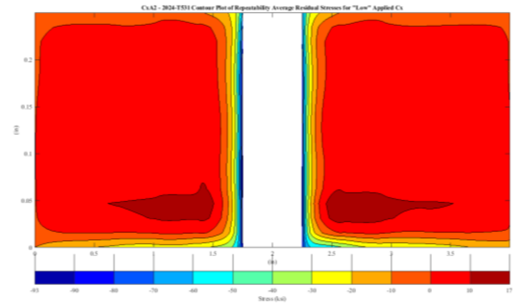
Presentation Outline

- Uncertainty and Implementation
- Contour Method – Sources of Uncertainty
- Residual Stress at Cx Holes – “Low” Applied Cx
- Results of Repeatability Measurement Uncertainty
  - Effects of uncertainty on fatigue crack growth predictions
- Results of Single Measurement Uncertainty
  - Effects of uncertainty on fatigue crack growth predictions
- Some Comments on Displacements to Stresses
- Future Work
- Conclusions

Keys to Implementation

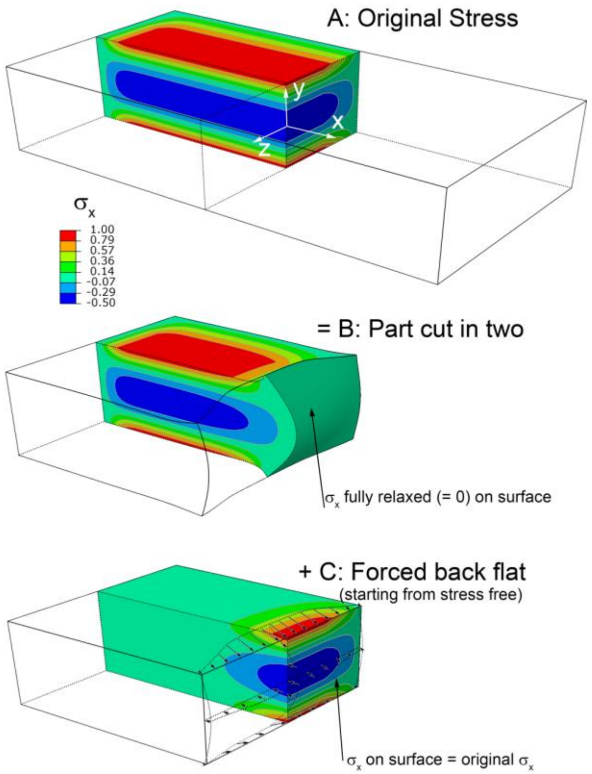
- Deep Residual Stresses/Self Stresses are a Physics-based Process
  - Plastic deformation
  - Local yielding



- Define/Quantify Parameters of Influence
  - Percent expansion
  - Local stress state
  - Applied loading (tension or compression dominated?)
- Understand and Quantify, **<u>Statistically</u>**, Bounds of Application
  - More accurate modeling of condition
  - Ability to more accurately assess risks and benefits

Contour Method

- Developed by Prime, M., Hill, M. at Los Alamos Labs
- First Published in 2001[1]
- Based upon the Bueckner's Superposition Principle of Stresses[2]
- Composed of 4 Major Steps
  - Cut using wire EDM
  - Measure using CMM or laser profilometer
  - Perform alignment, averaging, and fitting – [Johnson, G. Dissertation]
  - Apply final fit surface as boundary constraints to FEA
  - Solve for stresses within body



Idealized Conceptual Implementation of Contour Method[3]

Sources of Uncertainty in Contour

- Two Main Types of Uncertainty or Error
  - Random– *three main causes, lack of equipment sensitivity, noise in measurement, imprecise definition*
  - Systematic– *these can not be revealed through statistical analysis, bulge error, cutting irregularities, metrology*
- Two Types of Random "Uncertainty" Defined Looked at
  - "Modeling" or "Function" uncertainty
  - "Displacement" uncertainty
- Root Sum Square Uncertainty[4]

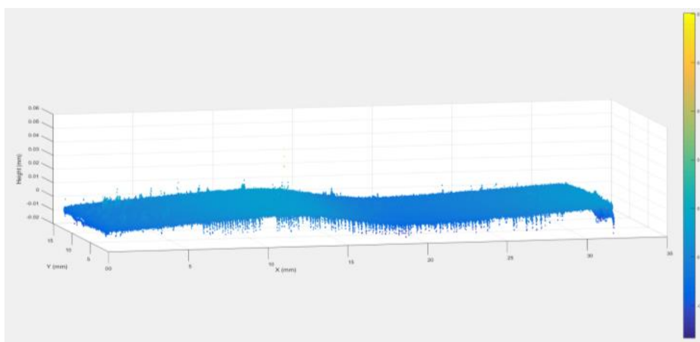
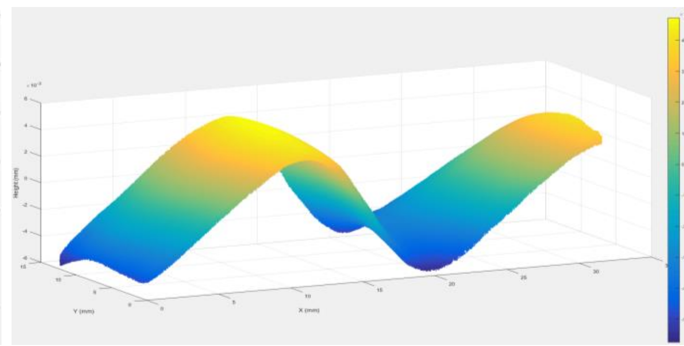
$$U_{RSS}(x,y) = \sqrt{U^2 U^2_{Disp}(x,y) + U^2_{Model}(x,y)}$$

Residual Stress Results – Key Parameters

- Data Reduction Key Parameters
  - Both sides of the hole solved together[3] – lesson learned
  - Outliers removed via Modified Thompson Tau method
  - Knot density – 4 knots along short side, 4 knots along long side
  - 3rd Order B-Splines within Matlab to fit between hard knot locations
  - 16 Elements through thickness
    - Element type – C3D8I – Incompatible mode eight-node brick
    - Convergence of mesh based on solution and time
  - All averages and standard deviations were solved at exact same node on each model
    - Enables easy calculations of averages and uncertainties

Removing Noise from Data Cloud

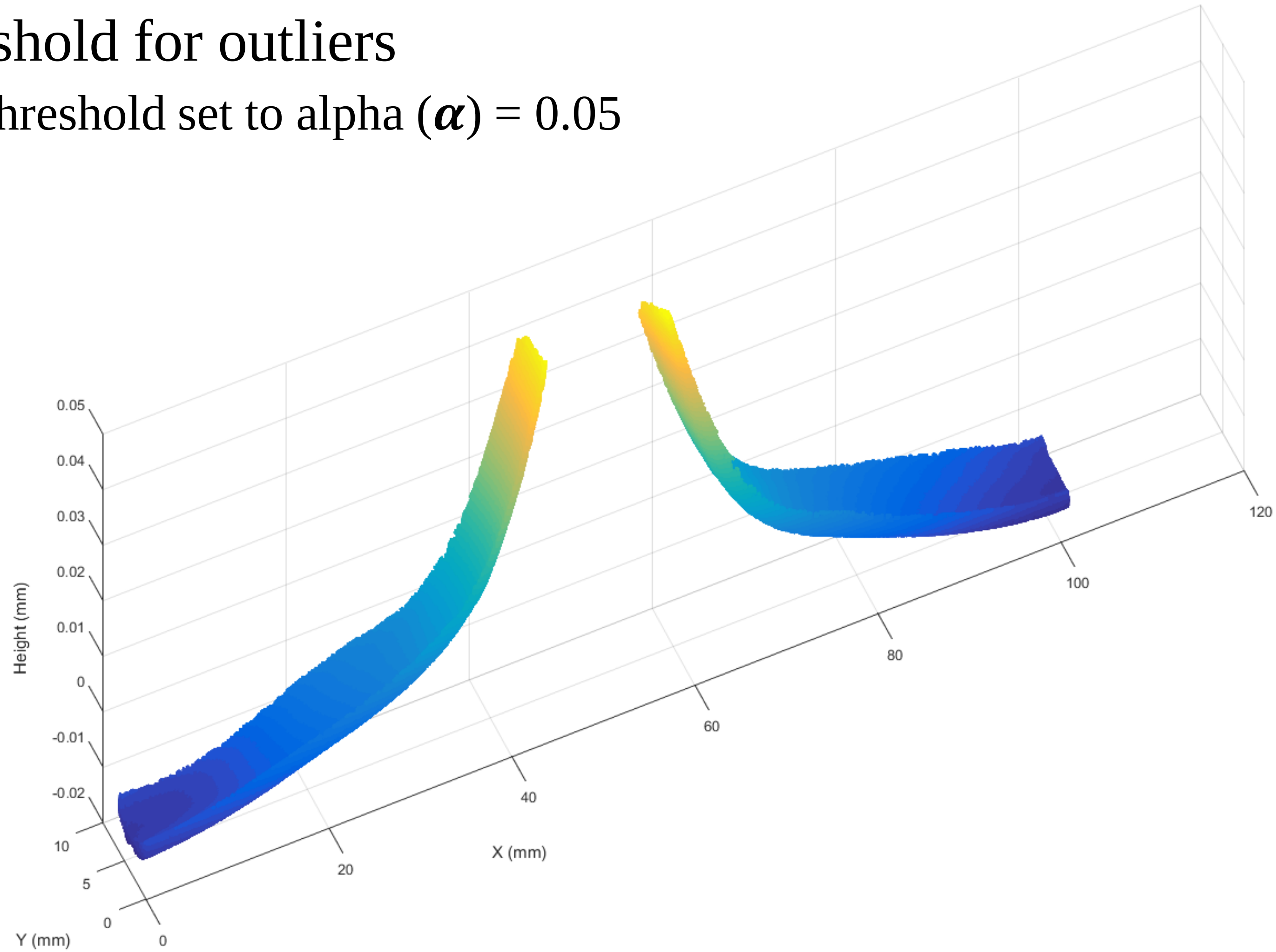
- How to Determine "Noise" from Appropriate Data
  - Data come with inherent noise from surface roughness, effects of the wire cutting, dust, noise from the measurement device
  - Outliers removed via Modified Thompson Tau Method

  - High potential to remove data that is valid without a process for removing "statistically significant outliers"
  - Original AFRL code required each point to be removed by hand and based on "engineering judgement"

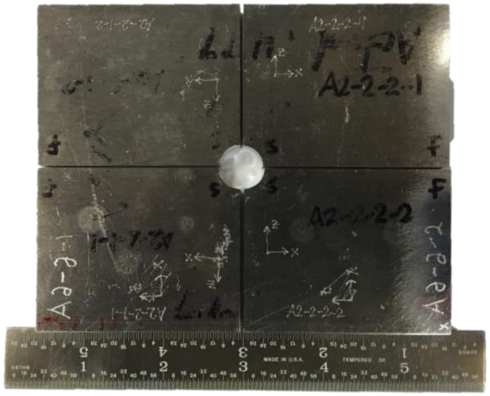
Modified Thompson Tau Method

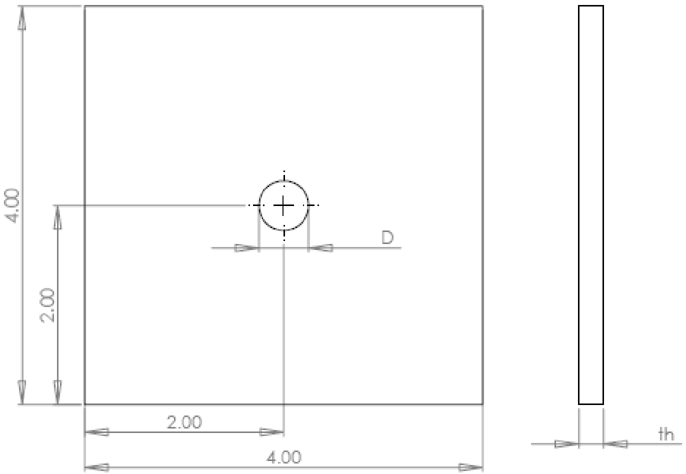
- Uses Hypothesis Testing to Determine Outliers
  - ASTM Standard E178 provides recommendations for selecting threshold for outliers
    - Threshold set to alpha ($\boldsymbol{\alpha}$) = 0.05



Results of "Low" Applied Cx

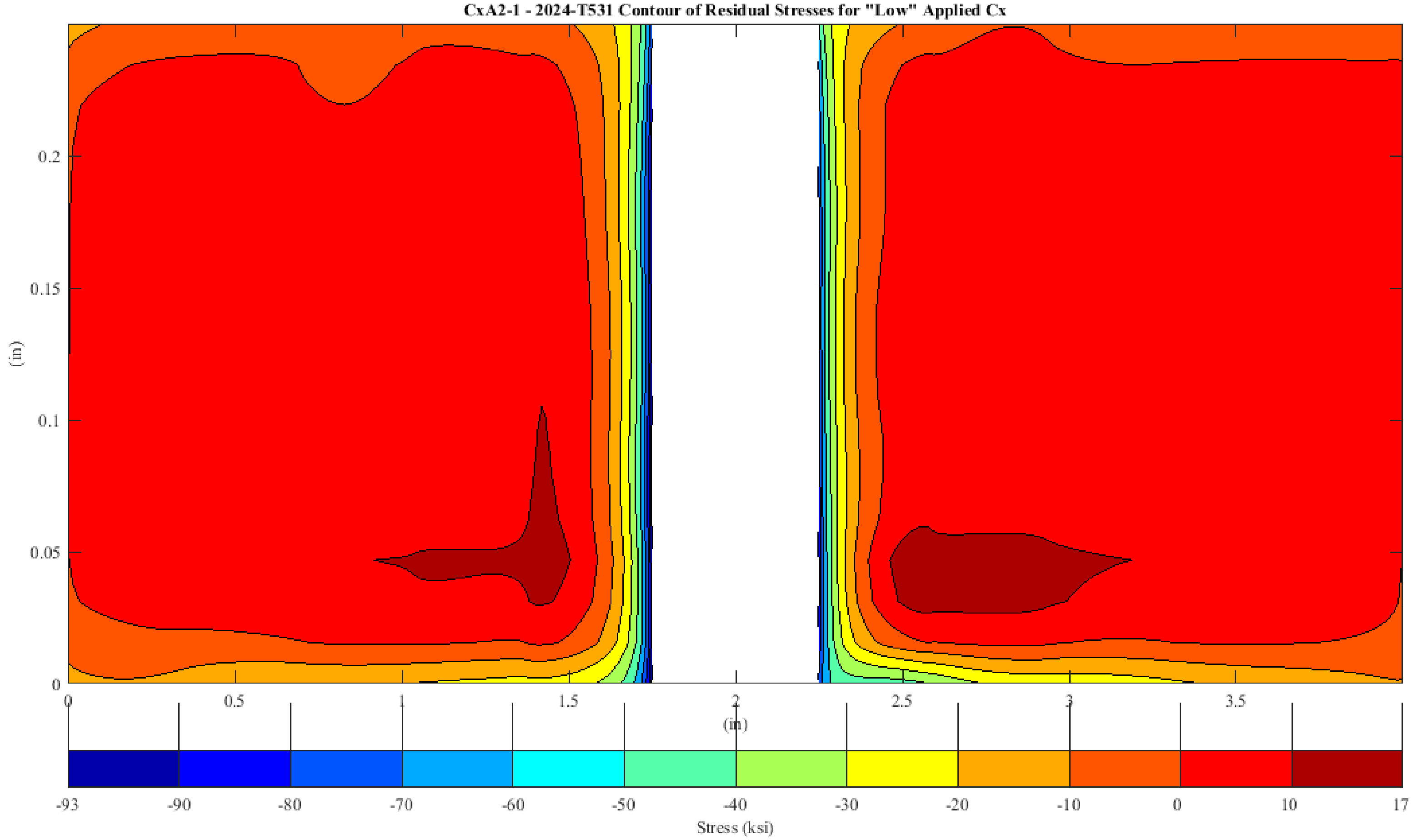
- 5 Replicates Were Produced for the "Low" Applied Cx Level in Al 2024-T351, 0.25in Thick, Approx. 0.50inch Hole Diameter
  - The "low" applied expansion represents 3.14-3.19%
  - Initial hole diameter = 0.4772-0.4774in
  - Mandrel diameter = 0.4684in with sleeve thickness = 0.0120in
  - Post Cx diameter = 0.4876-0.4884in
  - Avg. post Cx diameter = 0.48783-0.48835inch
  - Residual expansion = 2.33%-2.34%



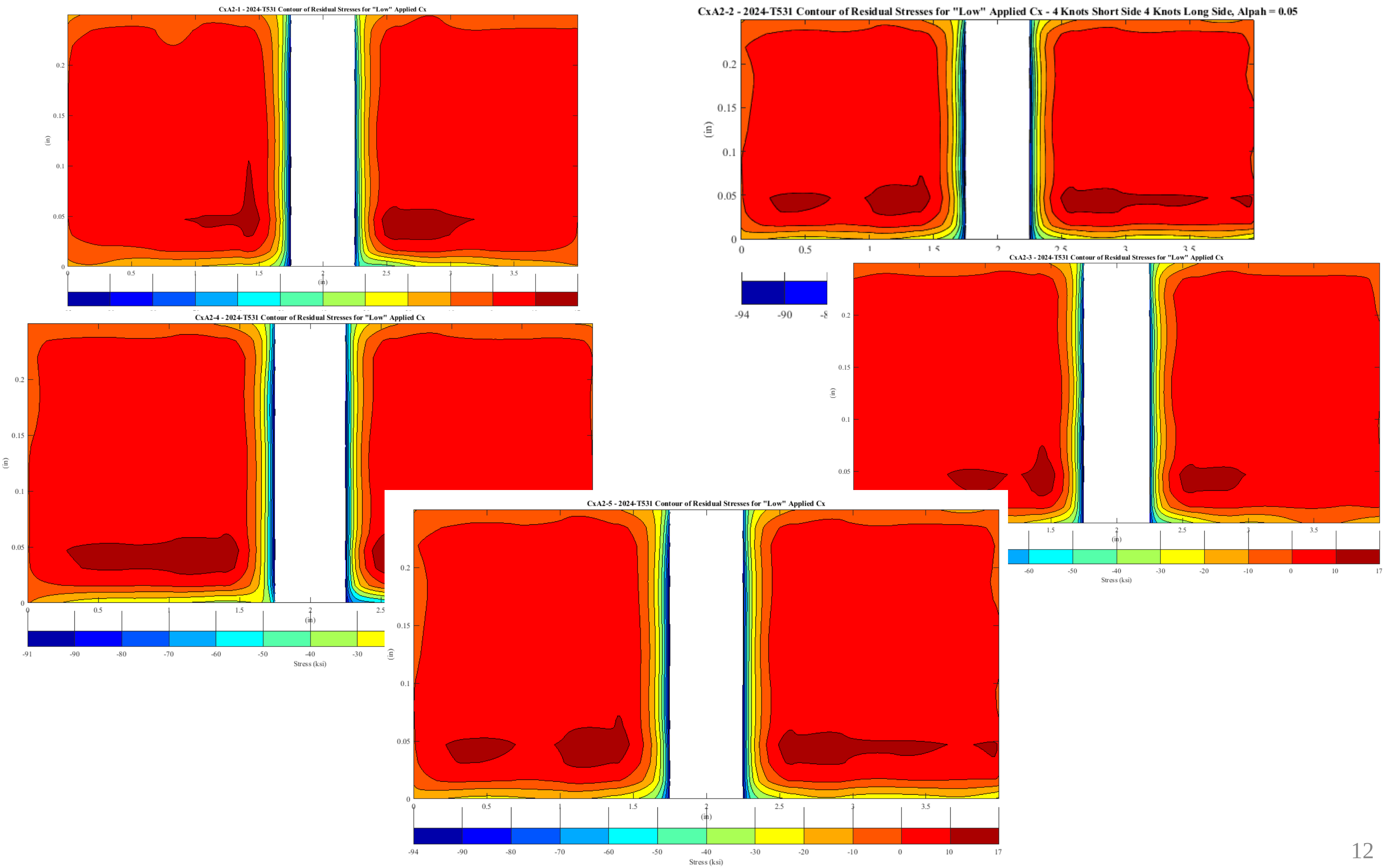


Repeatability Uncertainty

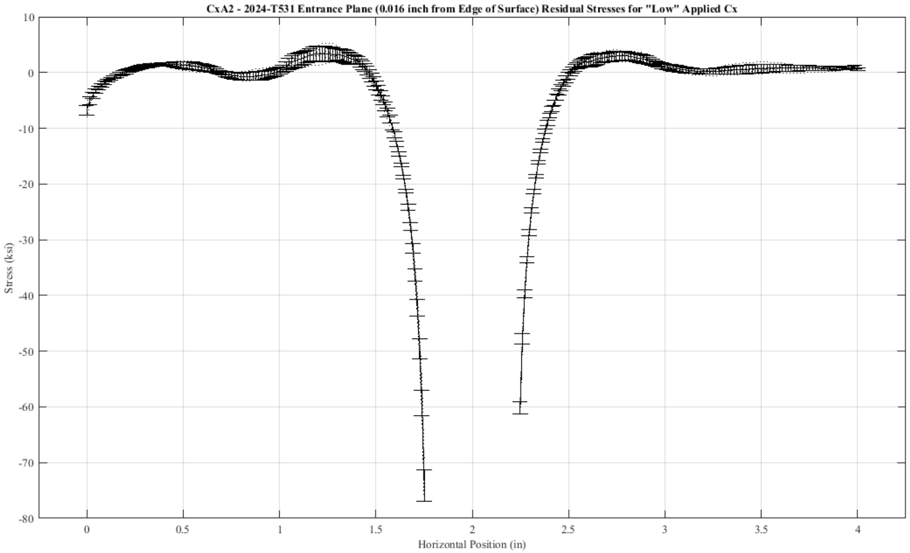
- From Replicate Conditions Each Contour Measurement was Performed Using Same Parameters
- Uncertainty of Single Standard Deviation from Mean

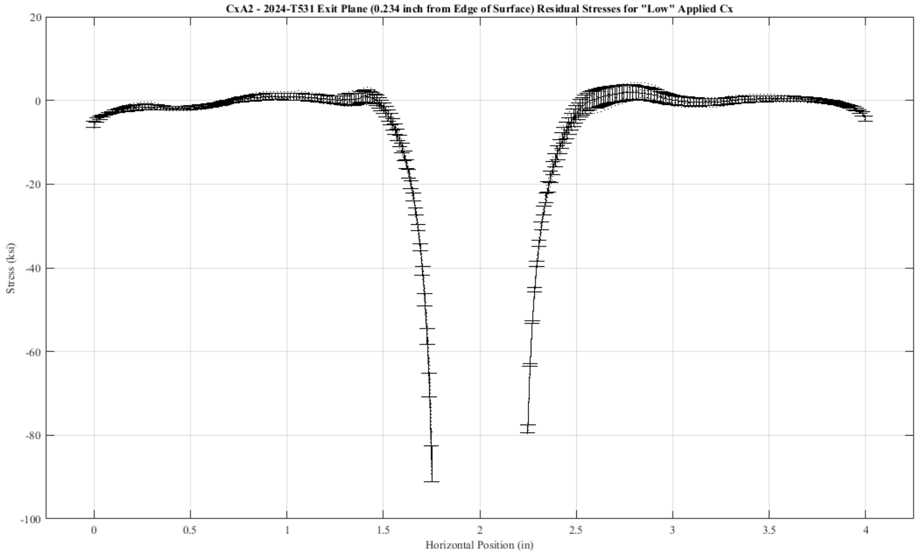


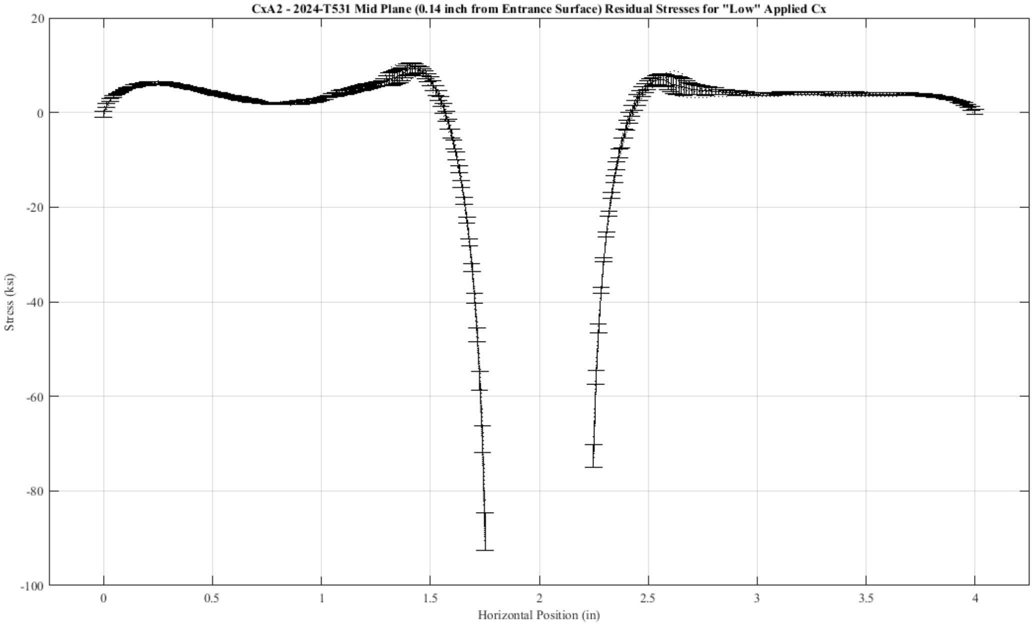
Residual Stress Results for 2024



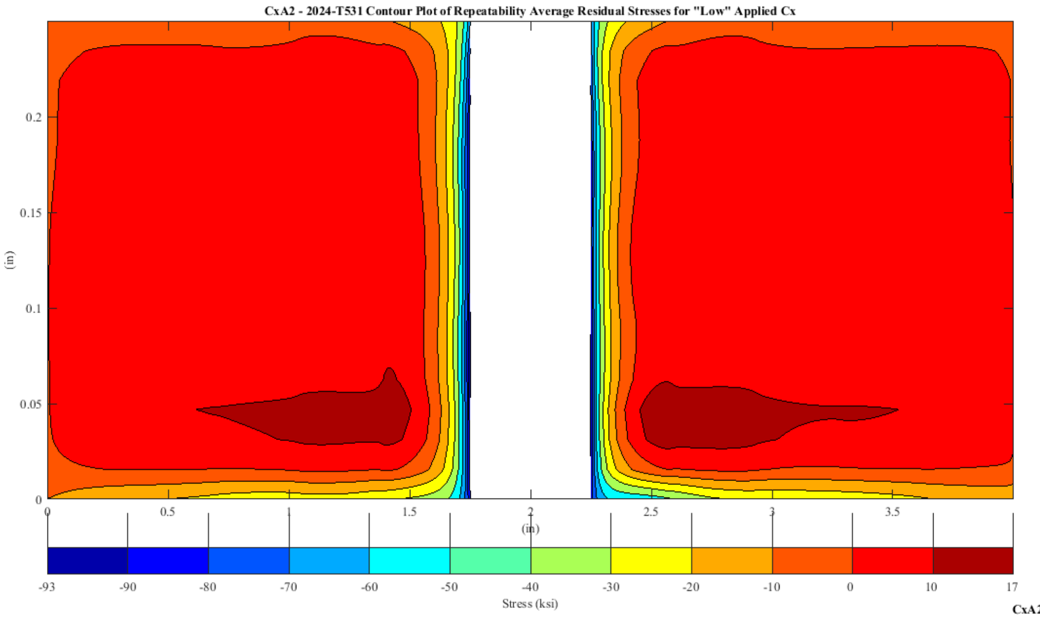
Residual Stress Results for 2024

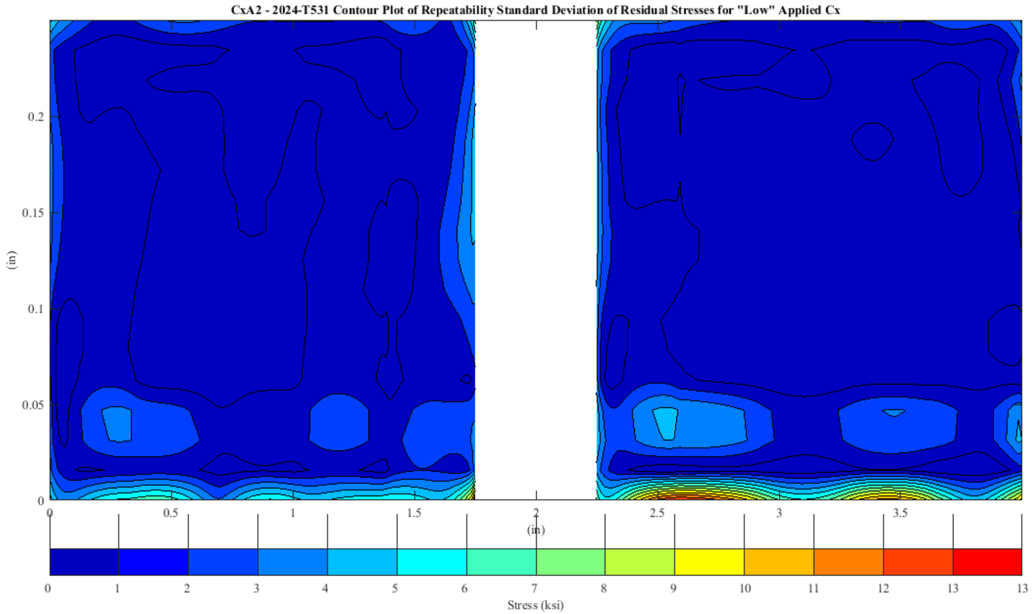






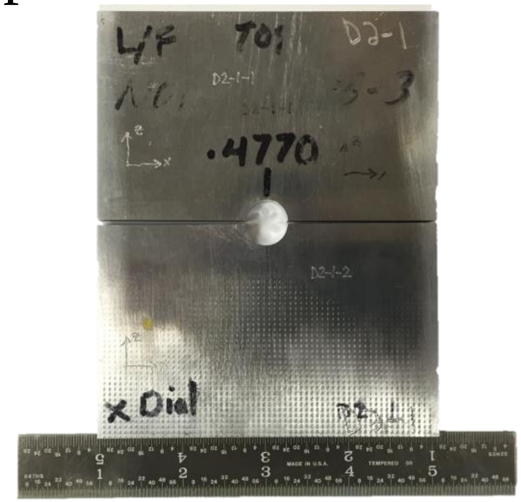
Average & Standard Deviation

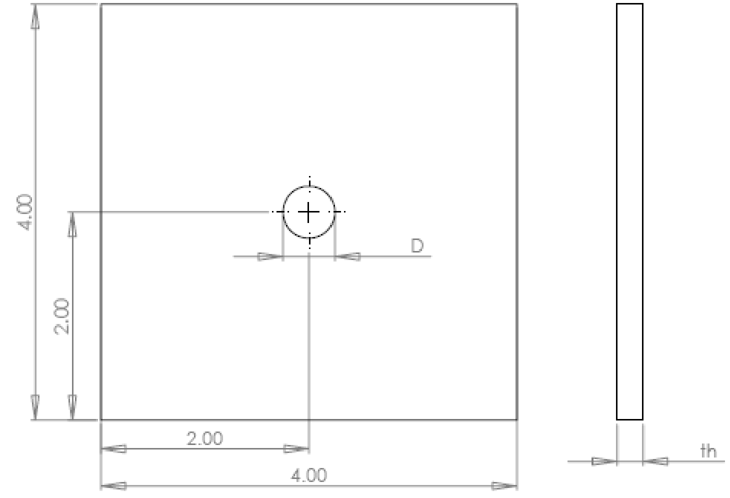




Results of "Low" Applied Cx

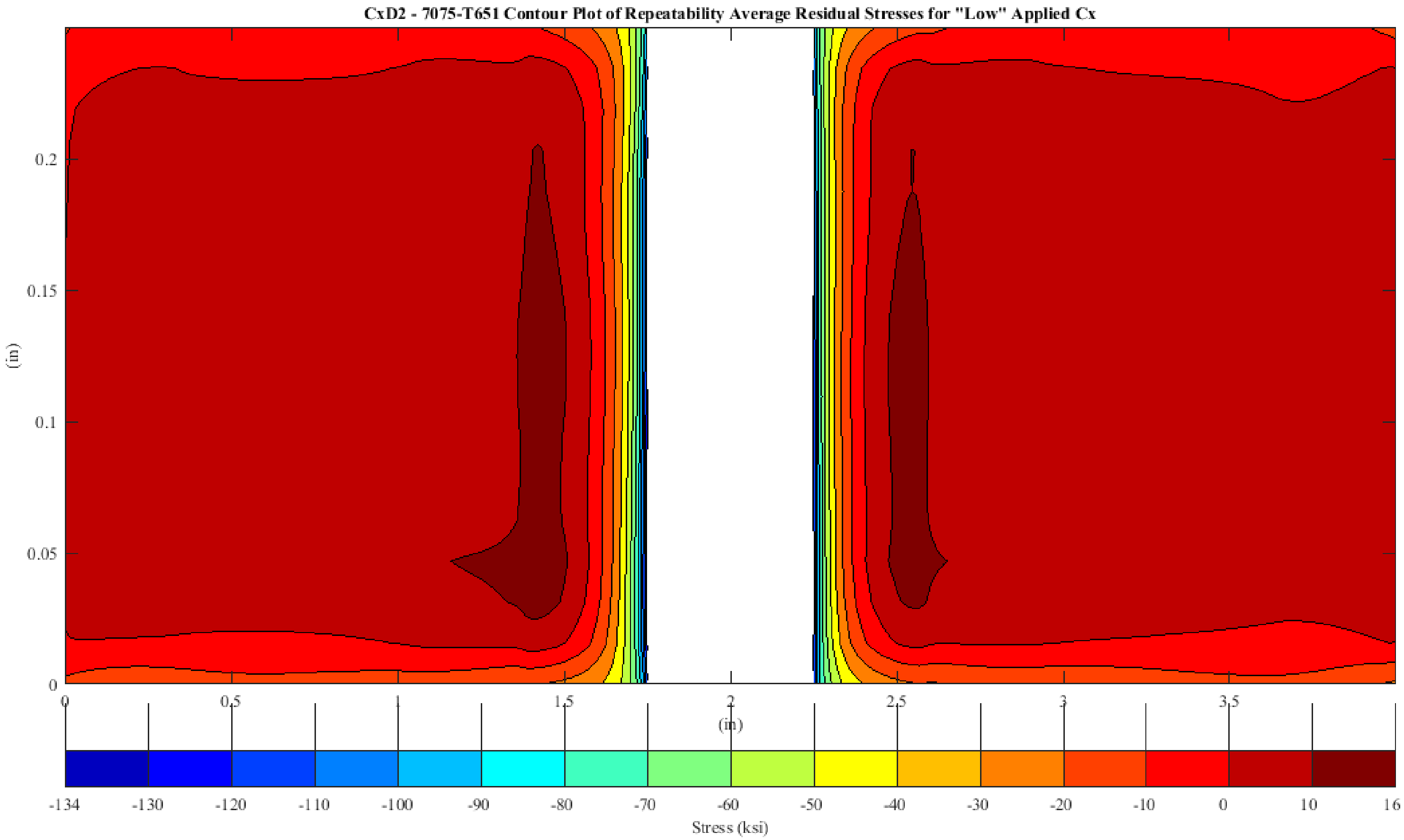
- 3 Replicates Were Produced for the "Low" Applied Cx Level in Al 7075-T651, 0.25in Thick, Approx. 0.50inch Hole Diameter
  - The "low" applied expansion represents 3.23%
  - Initial hole diameter = 0.4767-0.4769in
  - Mandrel diameter = 0.4684in with sleeve thickness = 0.0120in
  - Avg. post Cx diameter = 0.4859-0.4862in
  - Residual expansion = 1.87%-1.92%



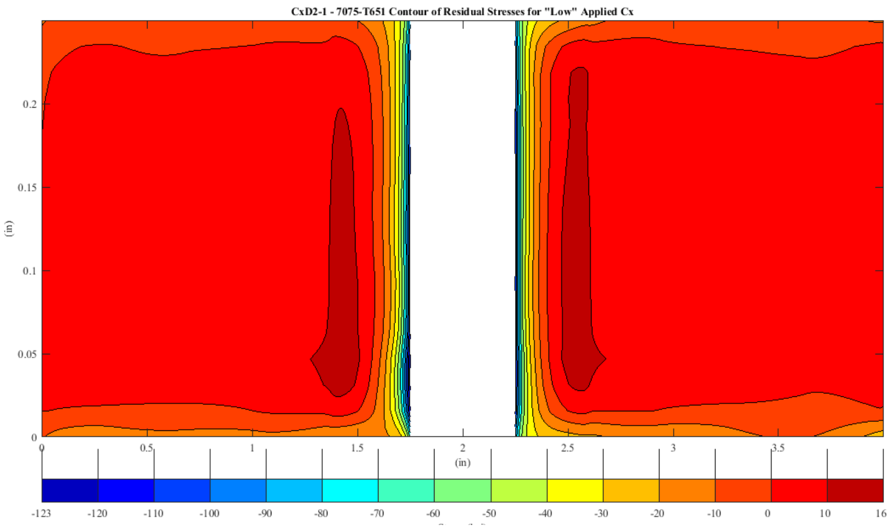


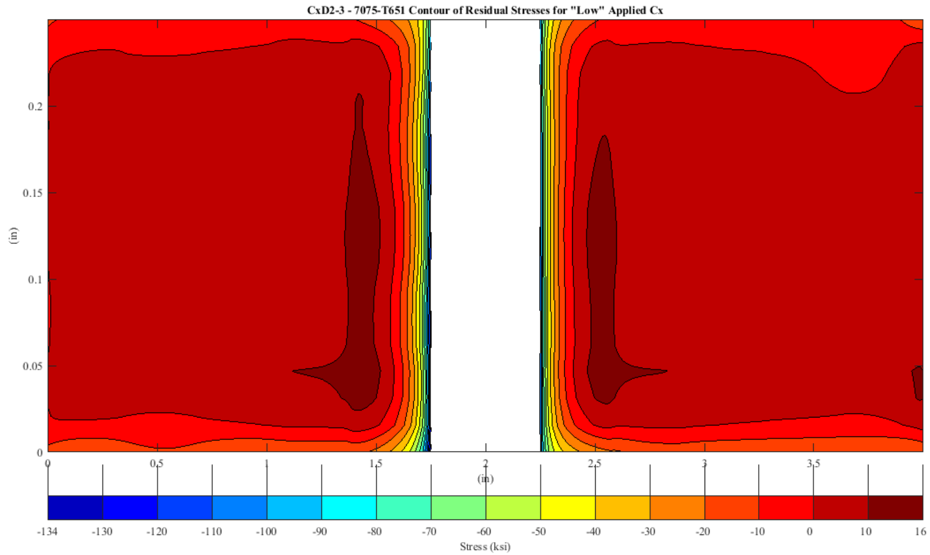
Repeatability Uncertainty

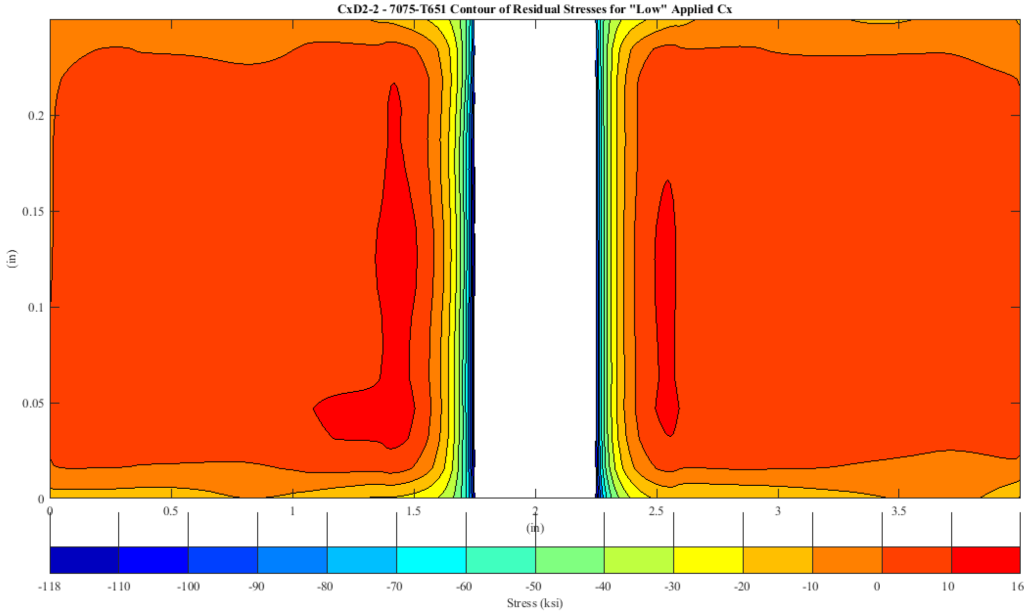
- From Replicate Conditions Each Contour Measurement was Performed Using Same Parameters
- Uncertainty of Single Standard Deviation from Mean



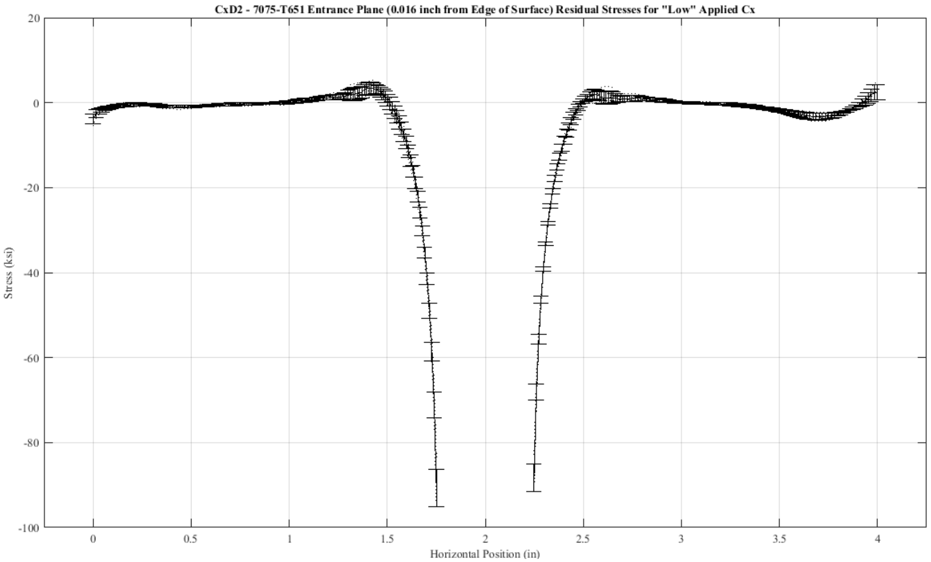
Residual Stress Results for 7075

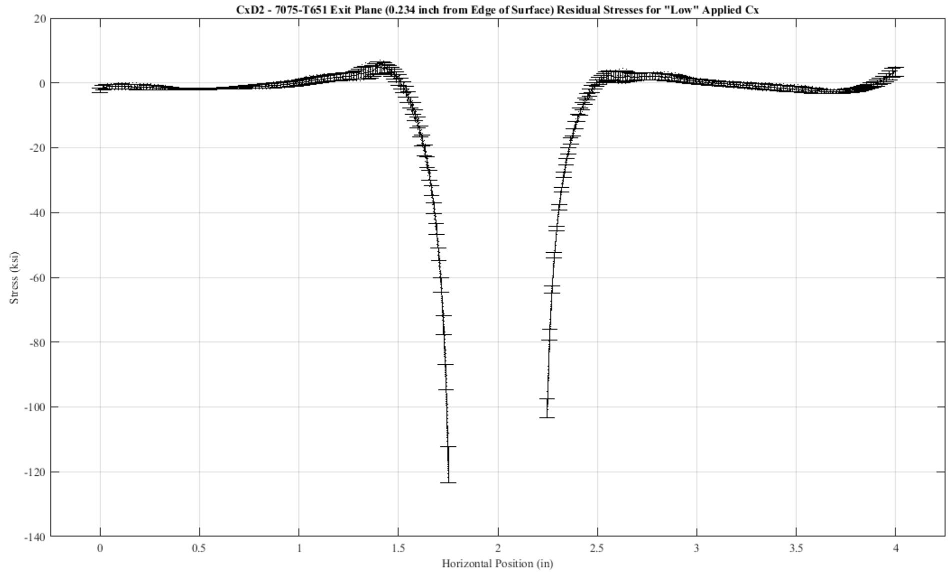


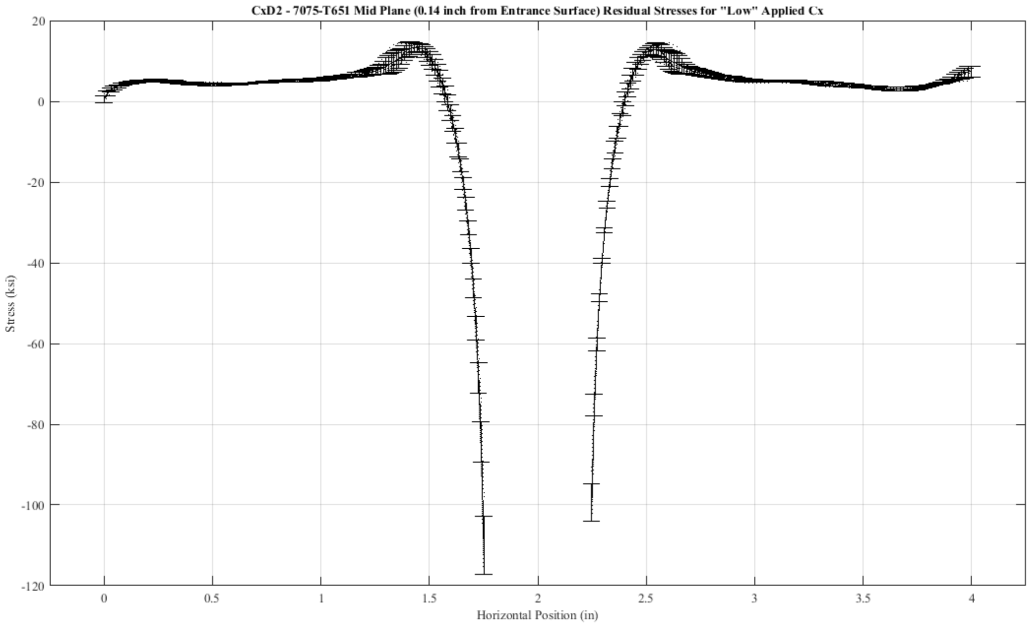




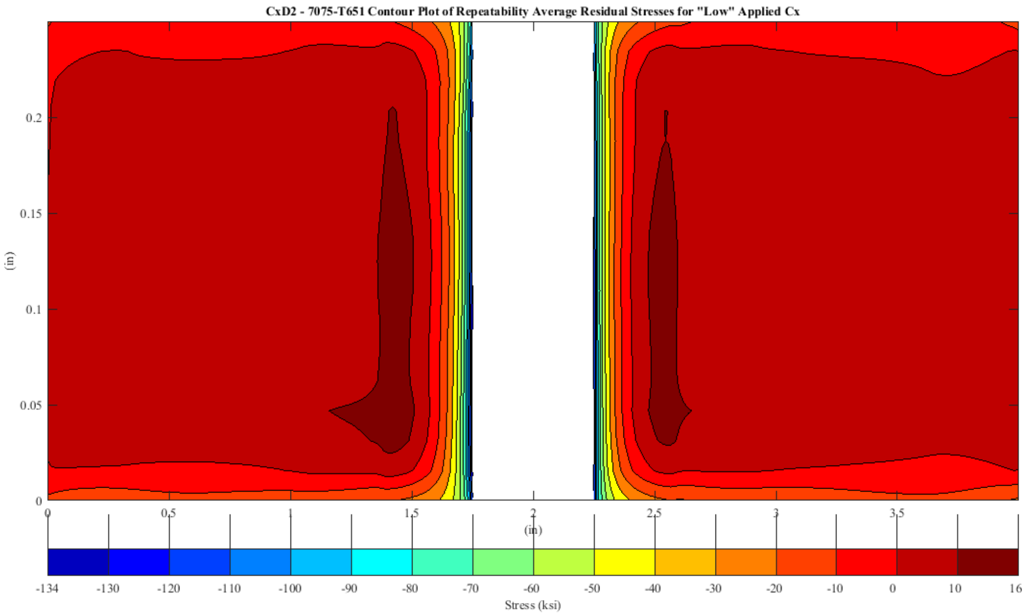
Residual Stress Results for 7075

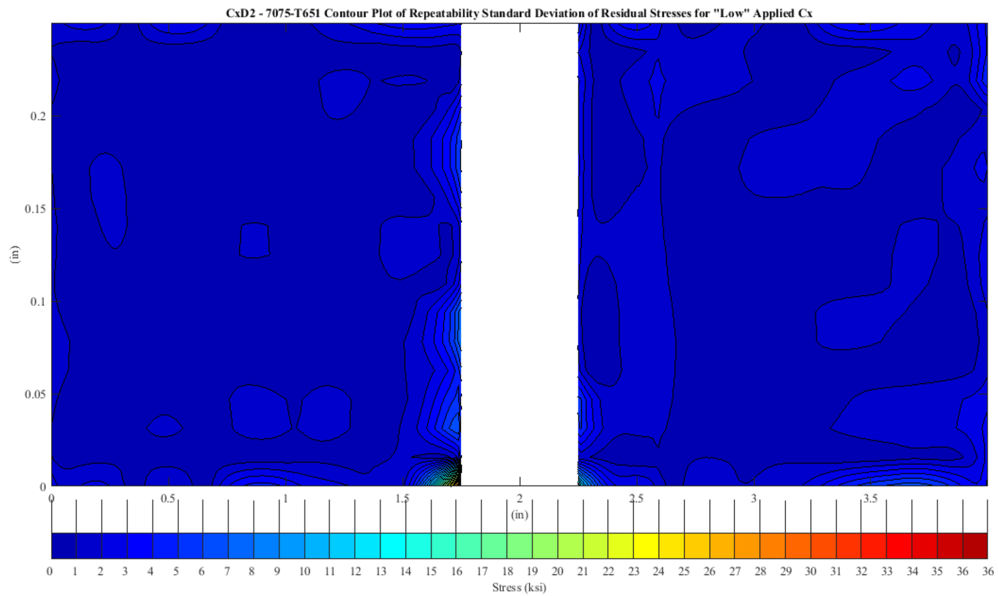






Average & Standard Deviation

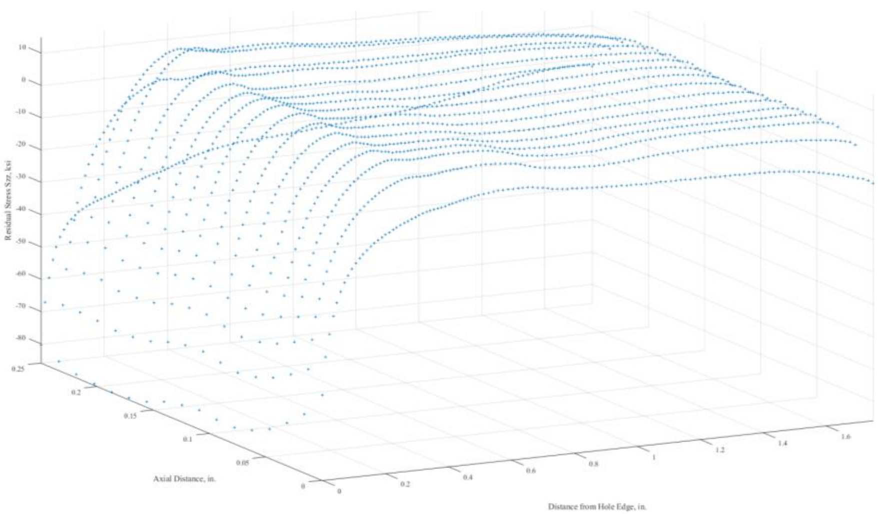




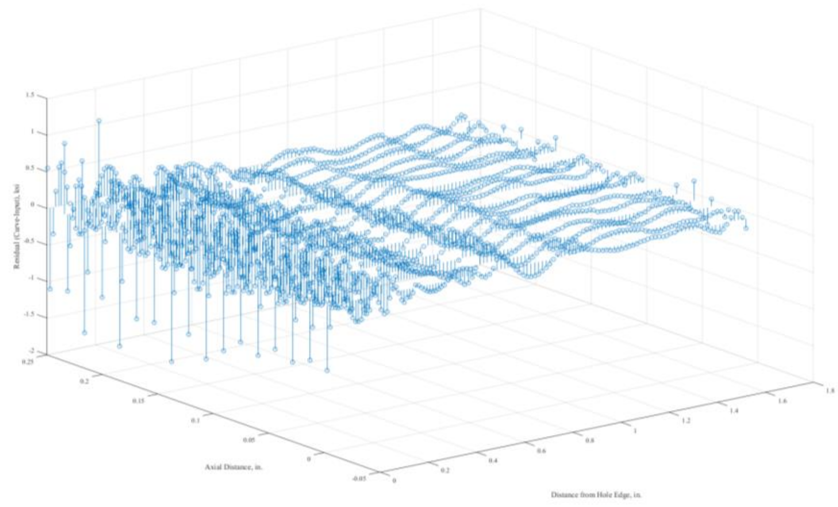
Crack Face Traction Function Developed

- Each Side Averaged Together for One Stress Field
- 15th Order Polynomial Used to Fit Residual Stress Field
- Optimized to Have <1ksi Residual Between Fit and Data
- Function Placed in StressCheck® Model for BAMF

Polynomial Function Fit to Residual Stress Field

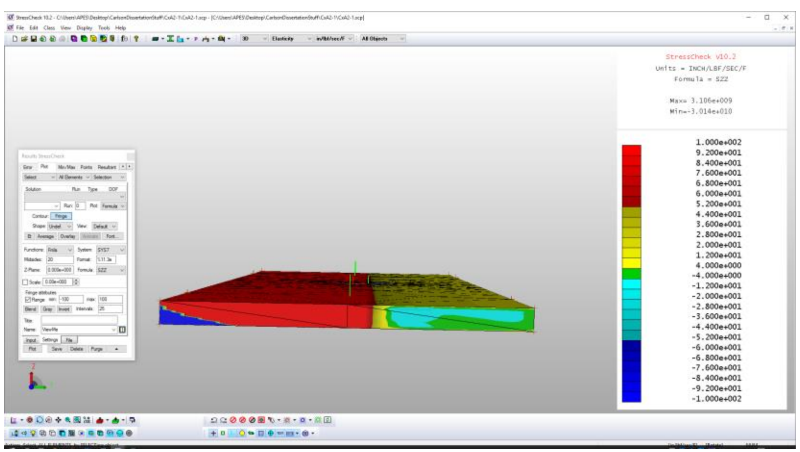


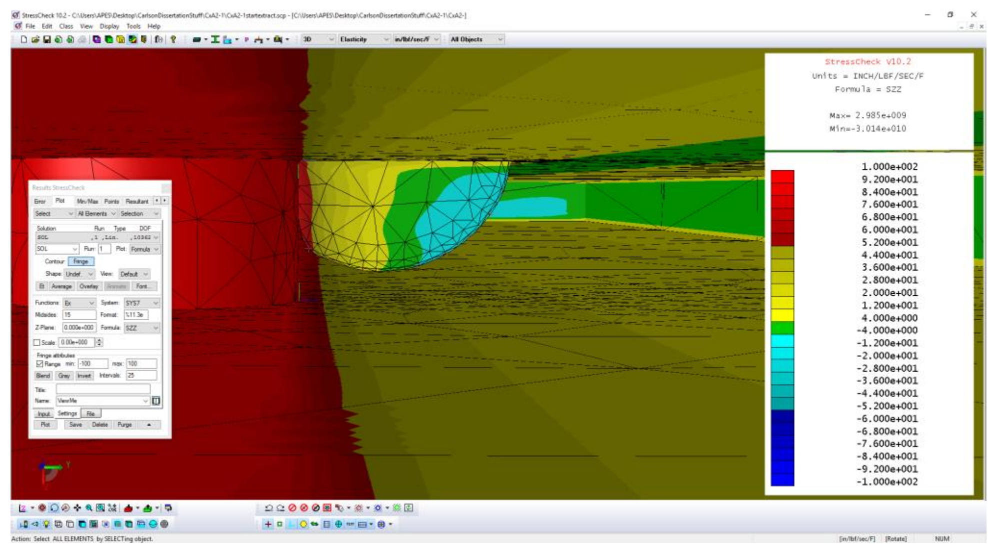
Residuals Between Fit and Actual



Application of MUCMUP BAMF

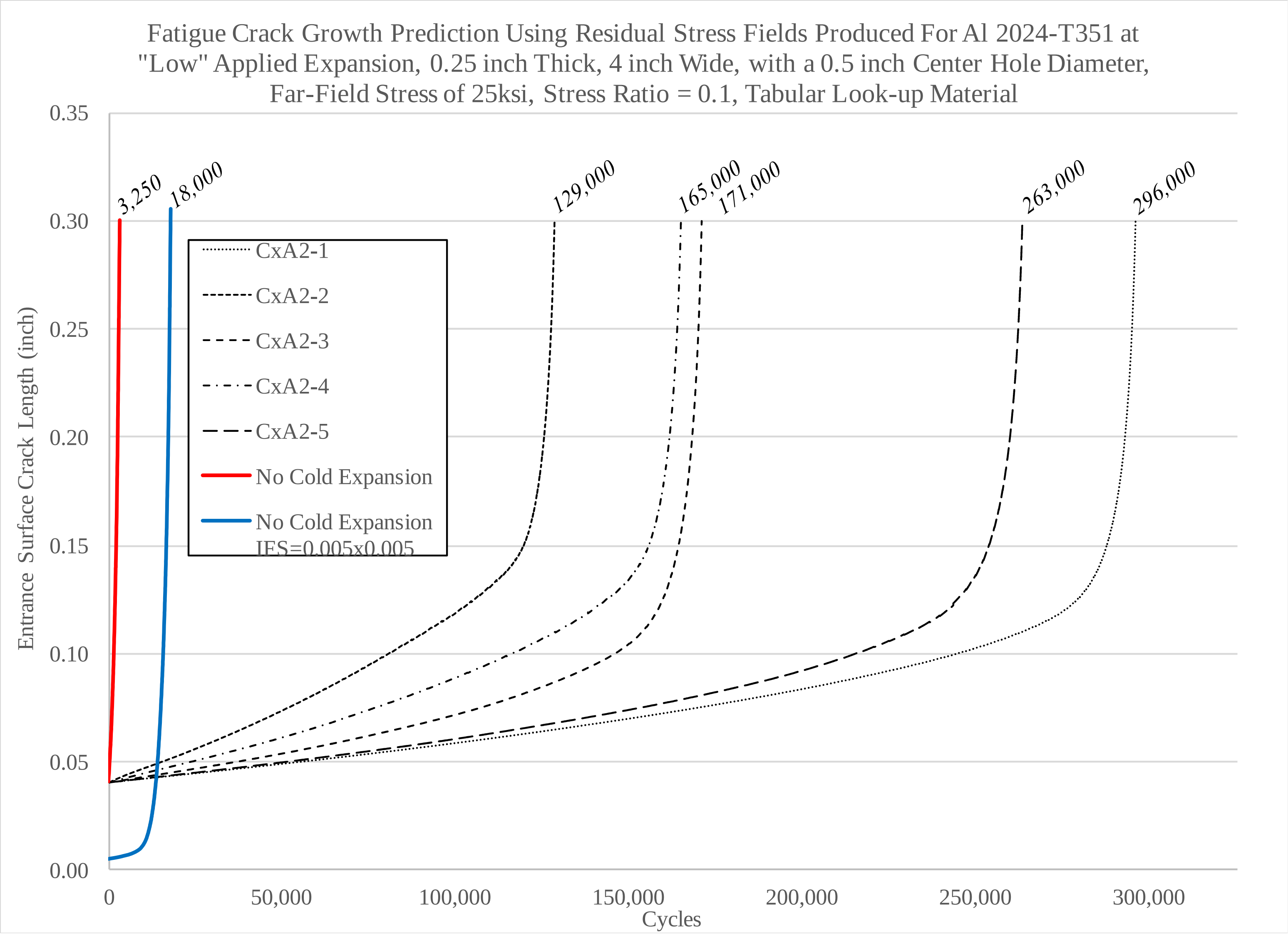
- Function Inserted at Crack Face as a Traction
- Material File for 2024-T351 – Tabular Look-up File
- Material File for 7075-T651 – Forman Equation
    - Extrapolated ΔK low to 0.001
- Loading – 25ksi, R=0.1
- All Cracks Nucleated on Entrance Side of Hole
- IFS for 2024 approx. 0.05x0.05, 7075 was 0.075x0.075





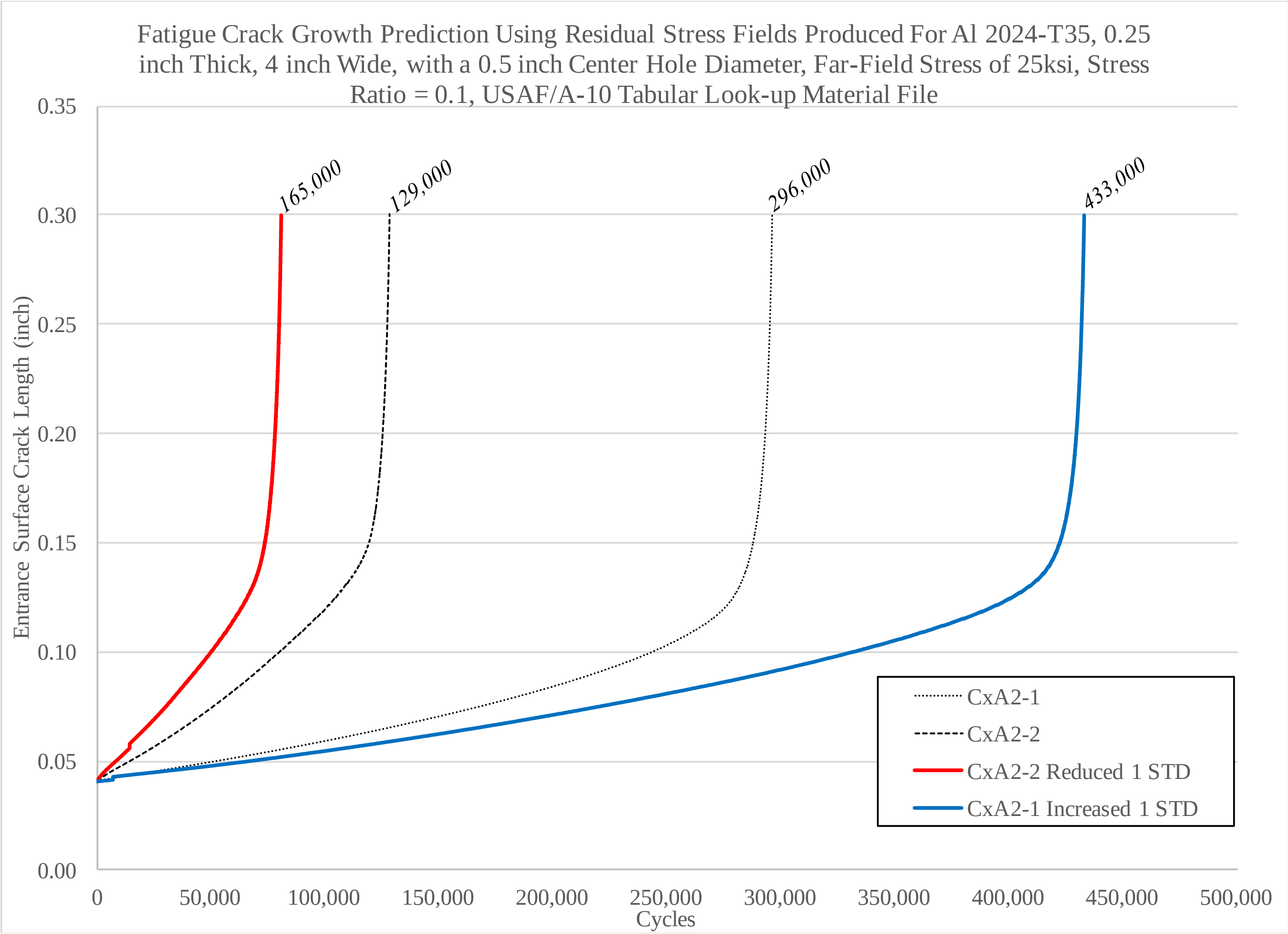
Fatigue Life Predictions

- All 2024-T351 Residual Stress Fields



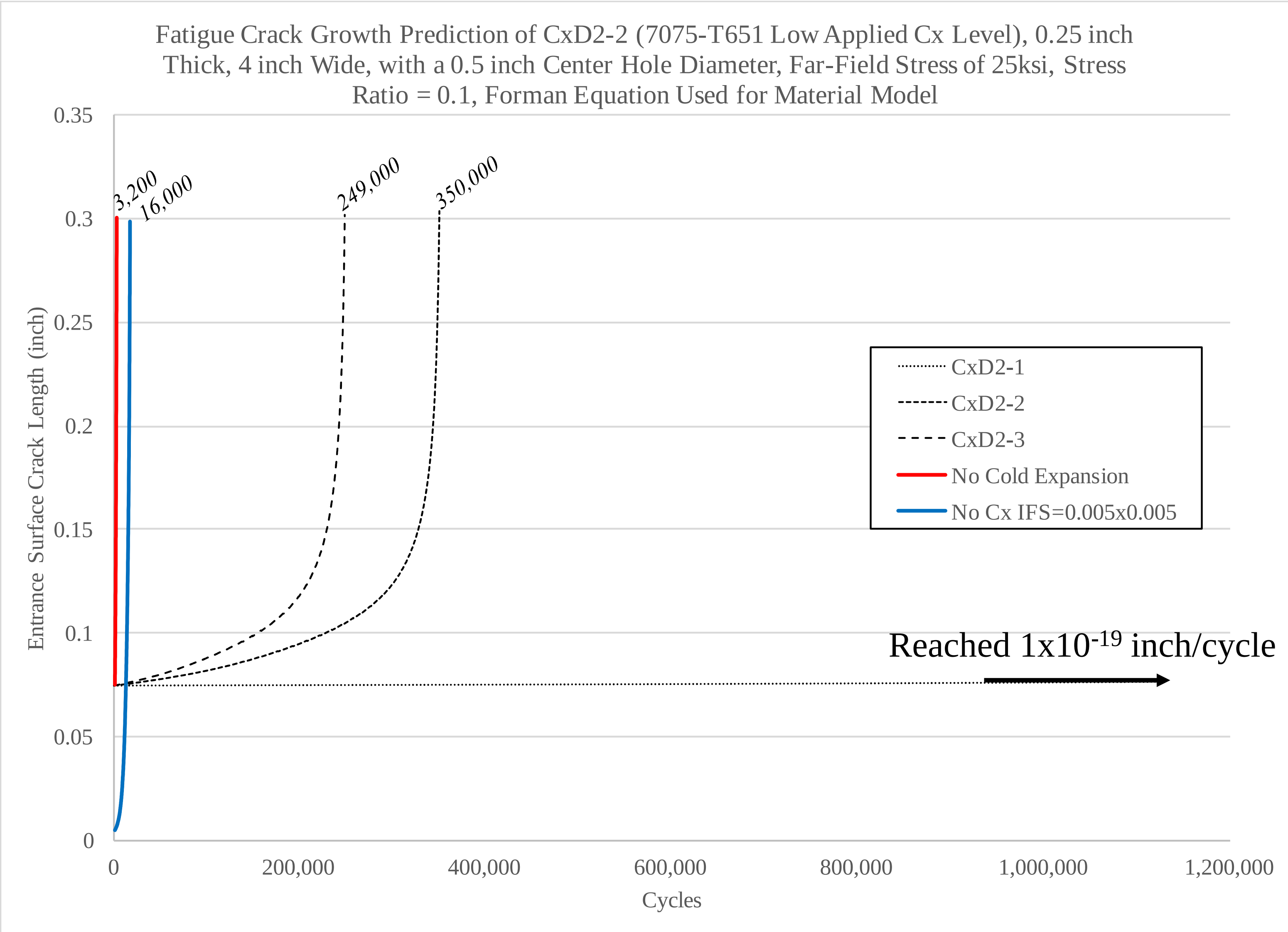
Fatigue Life Predictions

- Adjust Shortest and Longest Life Residual Stress Fields by 1 Standard Deviation



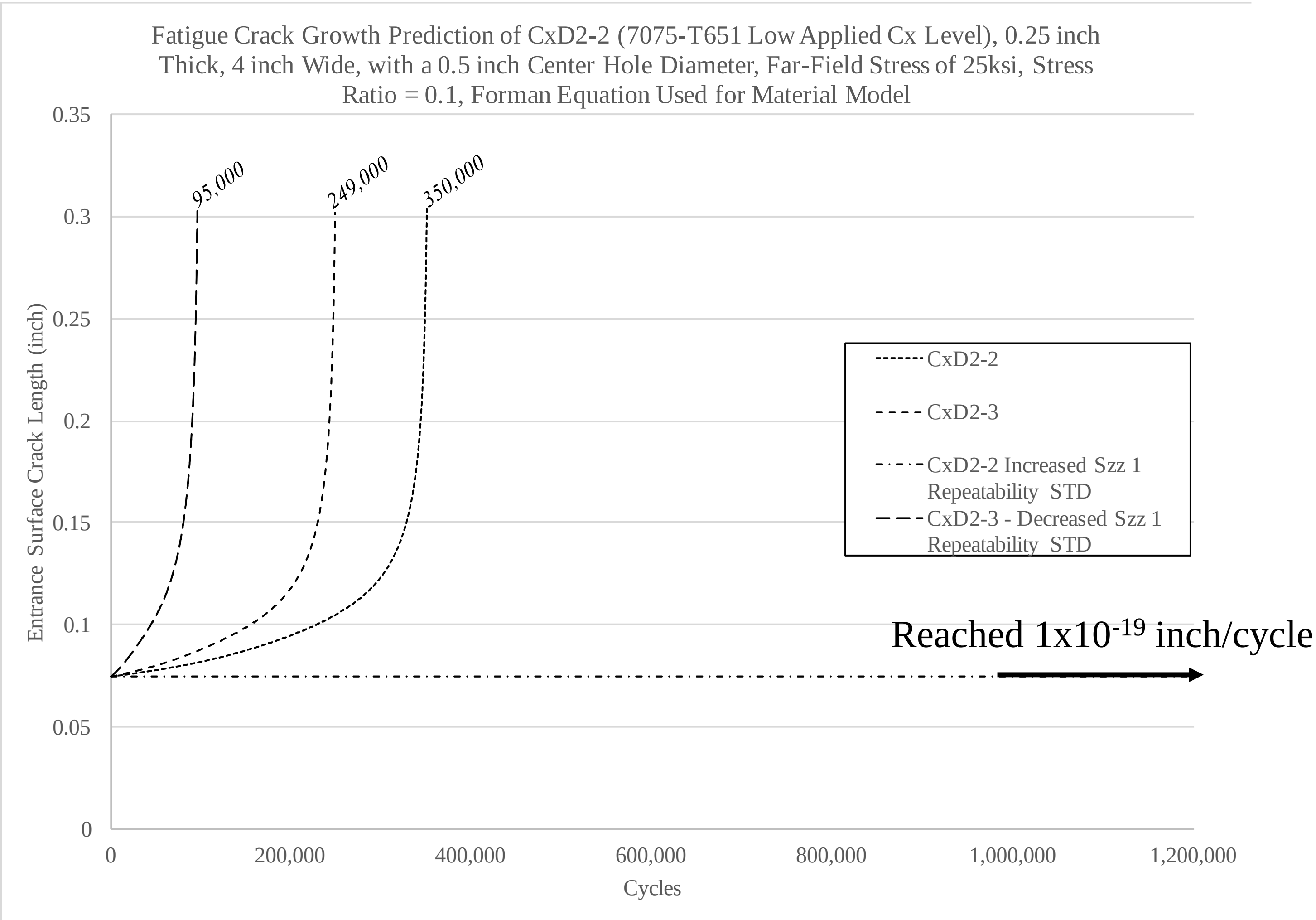
Fatigue Life Predictions

- All 7075-T651 Residual Stress Fields



Fatigue Life Predictions

- Adjust Shortest and Longest Life (that would run) Residual Stress Fields by 1 Standard Deviation



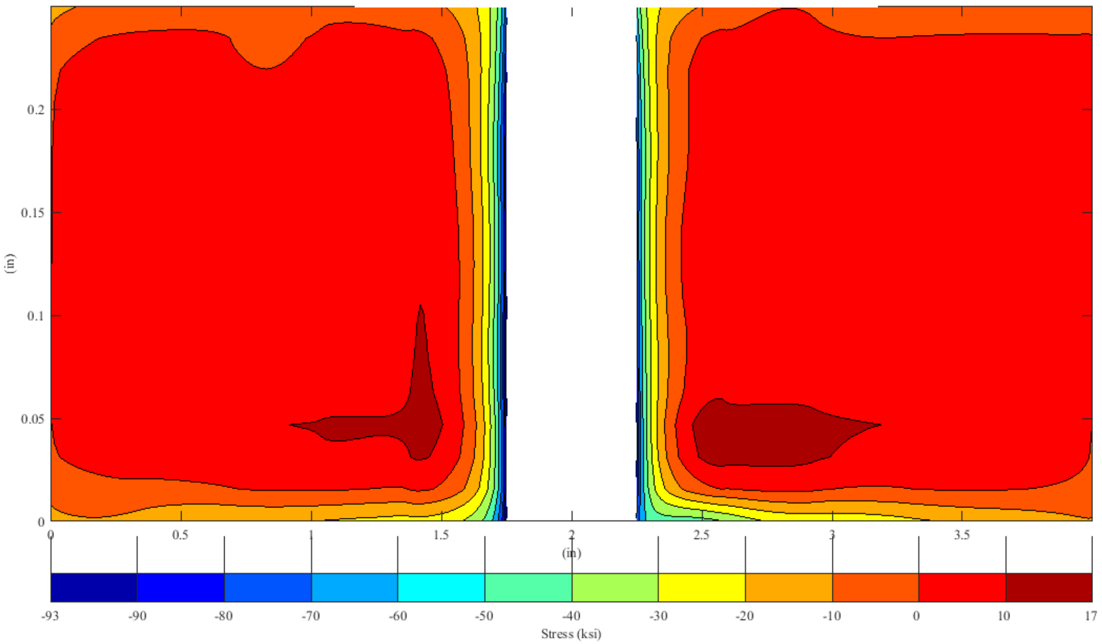
Single Measurement Uncertainty

- Application of Single Measurement Uncertainty
  - Adjust knot density along short and long side from optimal knot density
    - Short side knot density = 4
    - Long side knot density = 4
    - Adjusted knot densities for short and long sides 3-4, 4-3, 4-4, 4-5, 5-4
    - Total of 5 individual data reductions performed
  - Performed Monte Carlo simulation of optimal condition with added, normally distributed "Noise" to averaged-smooth displacement surface
    - Noise represents "the inherent surface roughness of the EDM cuts as well as the measurement error present in the displacement measurement signal."[4]
    - Convergence criteria – 50 simulations were performed

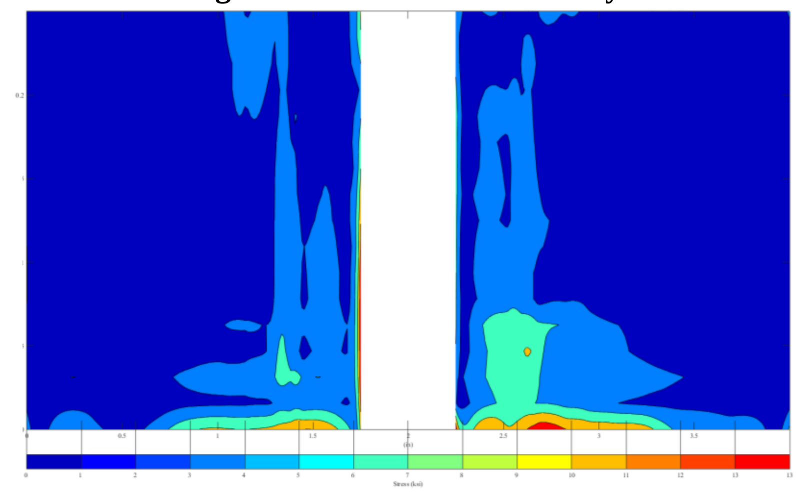
Total Single Measurement Uncertainty

- 2024-T351 Measurement for A2-1
  - 1st 2024-T351 part measured

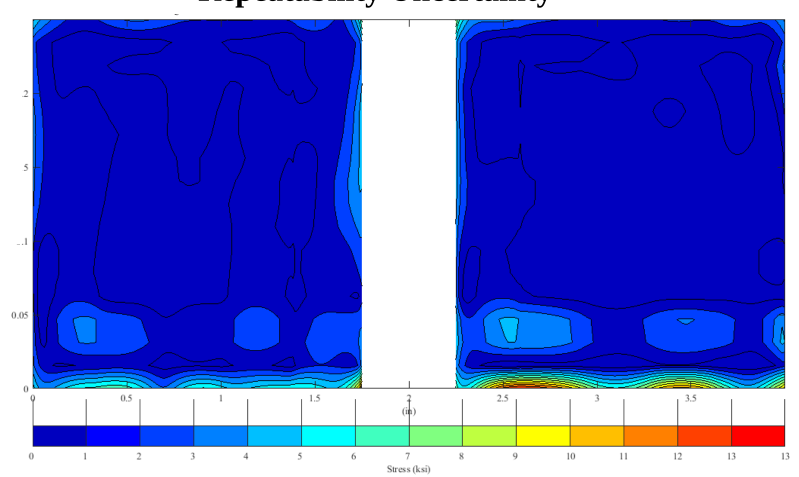
Measured Residual Stress



Single Measurement Uncertainty

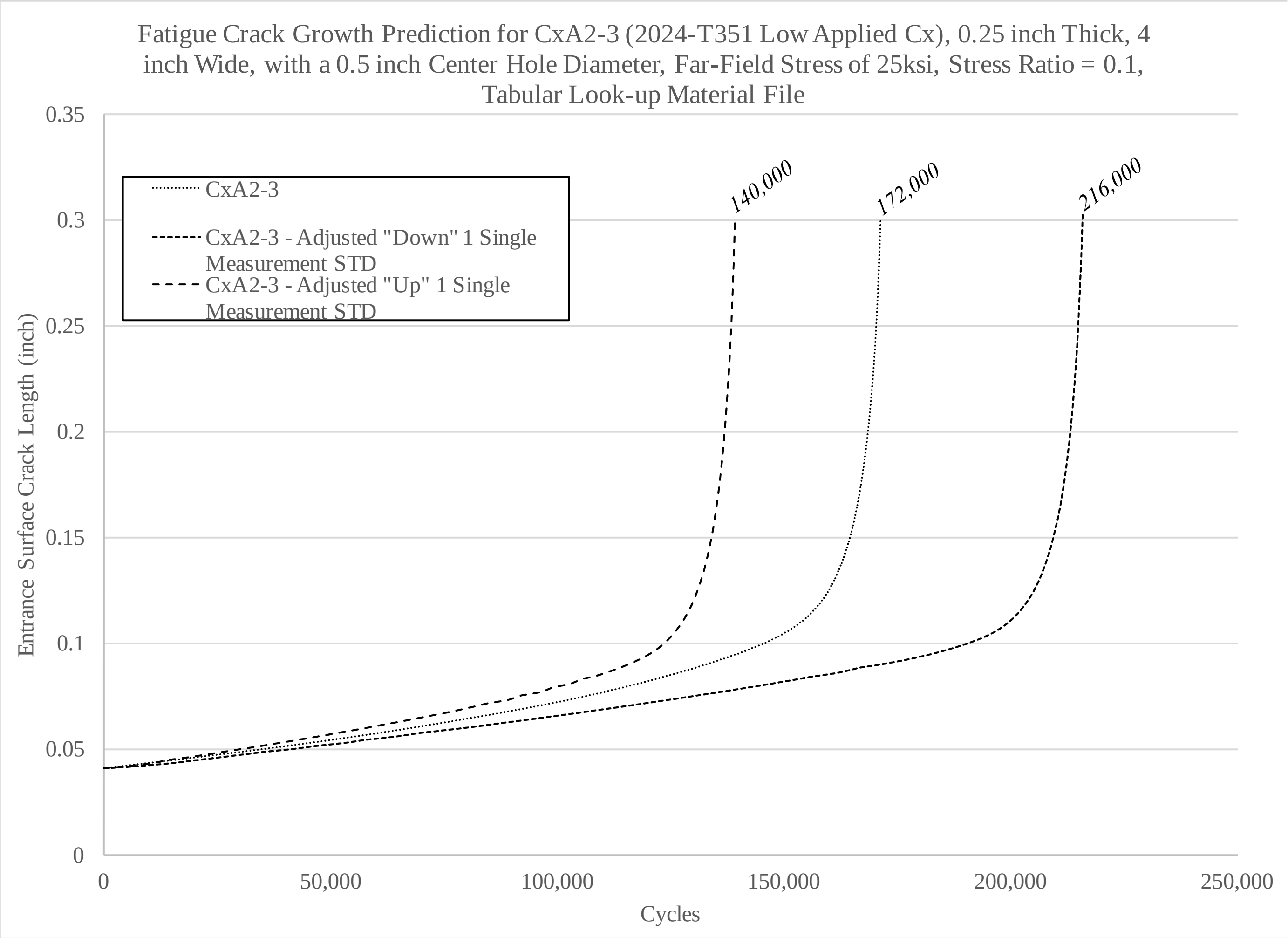


Repeatability Uncertainty



Impacts to Fatigue Life Predictions

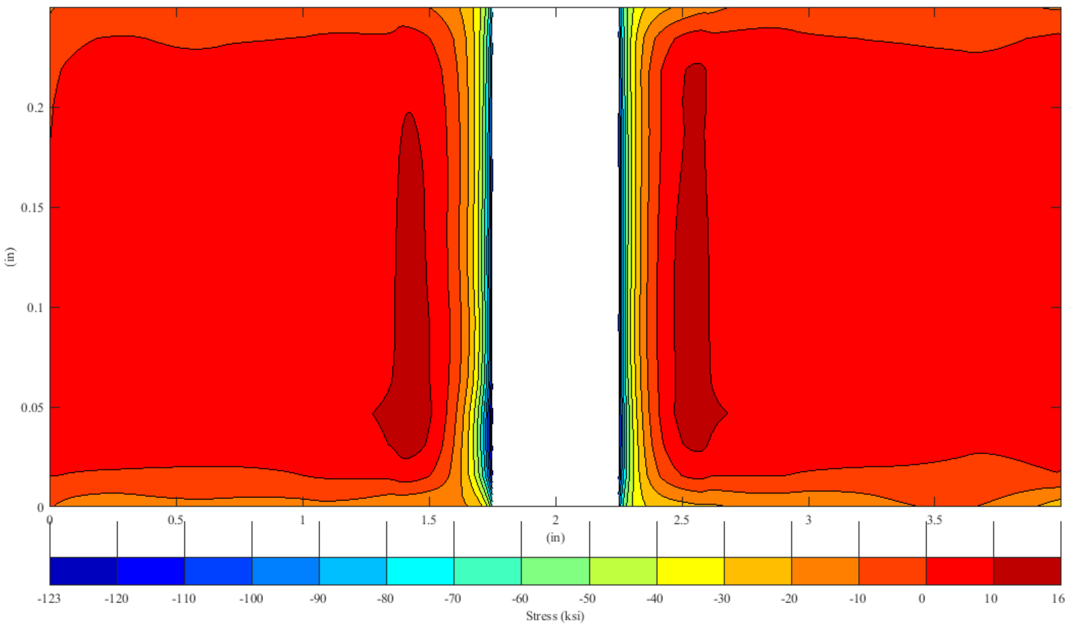
- 2024-T351 Measurement for A2-1
  - Adjusted A2-1 residual stress field "up" and "down" one STD



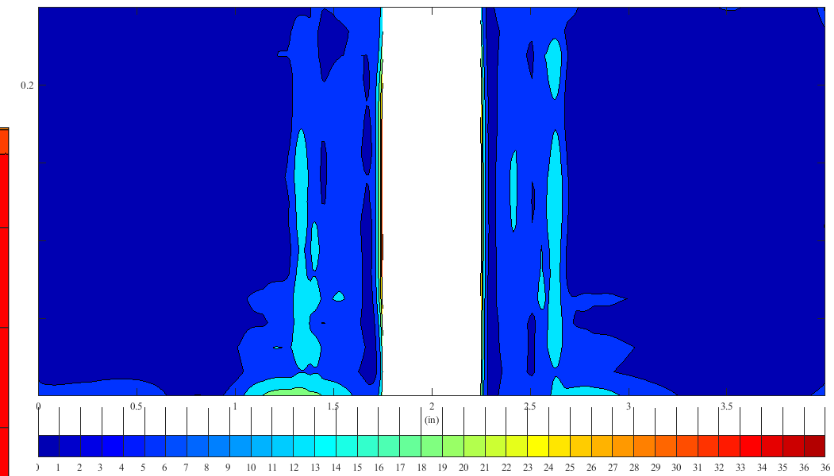
Total Single Measurement Uncertainty

- 7075-T651 Measurement for D2-1
  - 1st 7075-T651 part measured

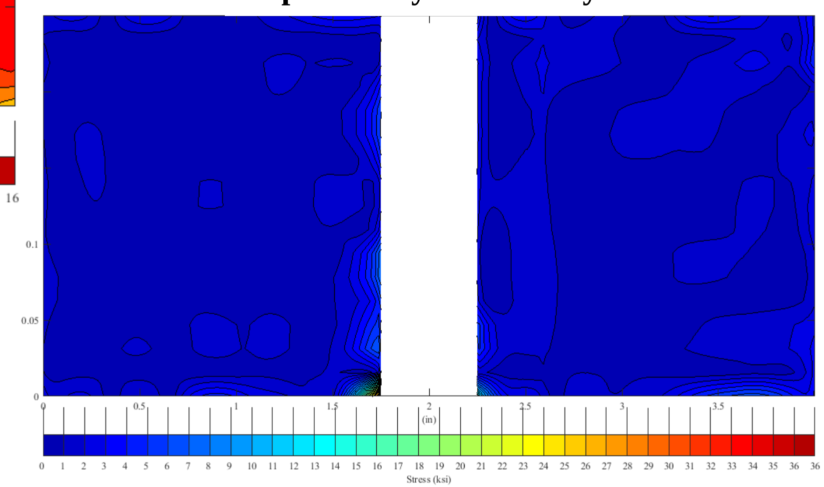
Measured Residual Stress



Single Measurement Uncertainty

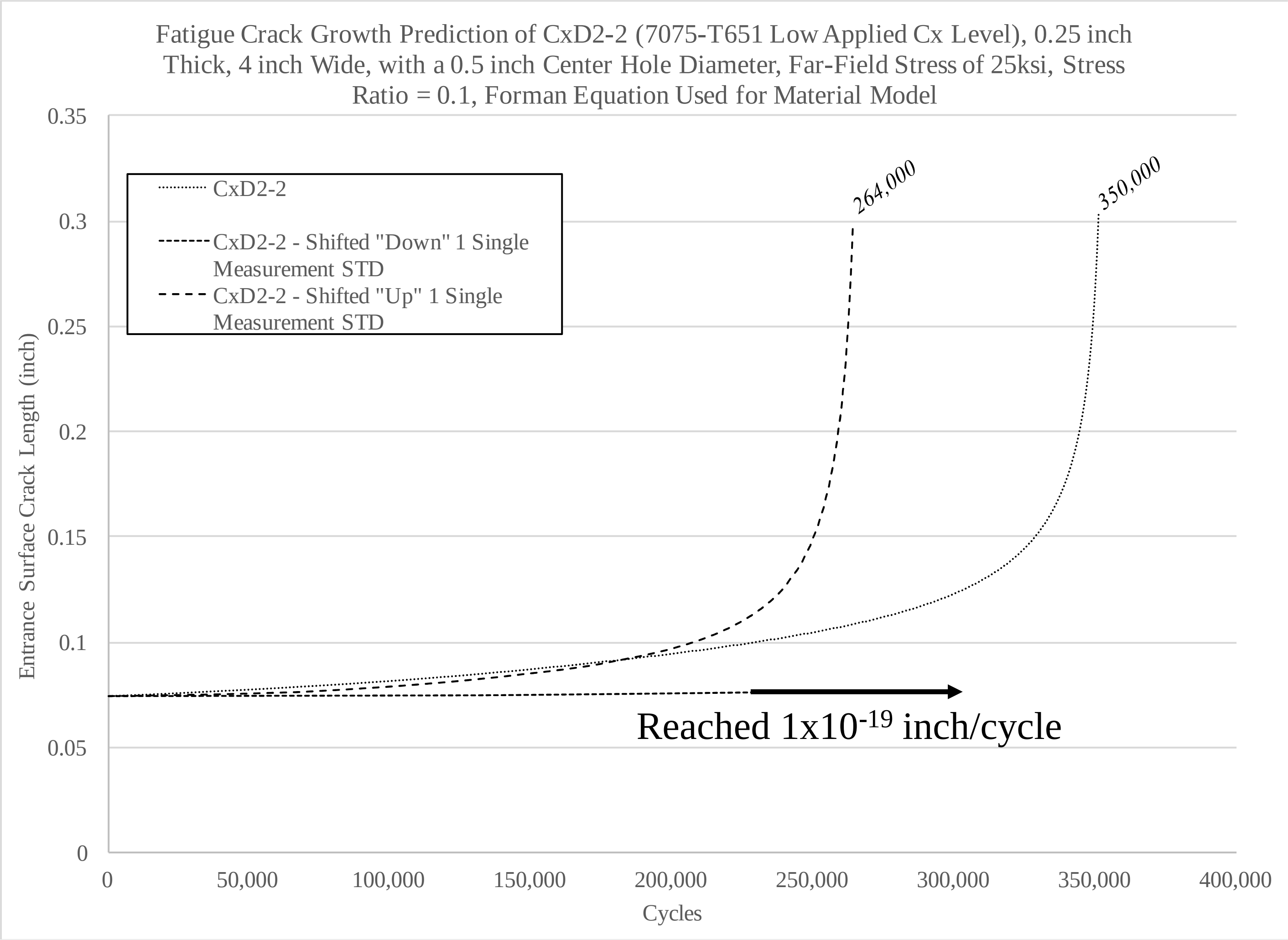


Repeatability Uncertainty



Total Single Measurement Uncertainty

- 7075-T651 Measurement for D2-1
  - Adjusted D2-1 residual stress field “up” and “down” one STD



Conclusions from Repeatability UQ

- Higher Levels of Uncertainty are Found at ”Near-Surface” and Very ”Local” Locations
  - Range of repeatability uncertainty for 2024-T351 = <1 – 13ksi
  - Range of repeatability uncertainty for 7075-T651 = <1 – 36ksi
- Effect of Shift of Repeatability STD on Fatigue Life Prediction
  - 2024-T351 life prediction range from 165,000 – 430,000 cycles
  - 7075-T651 life prediction range from 95,000 cycle – infinite life

Important Note: All BAMF Runs with 7075-T651 Tabular Look-up Files Produced Infinite Life – Why Forman Equation was Used – Provides a Starting Point for Life Predictions – Work Continues

Conclusions from Single Measurement UQ

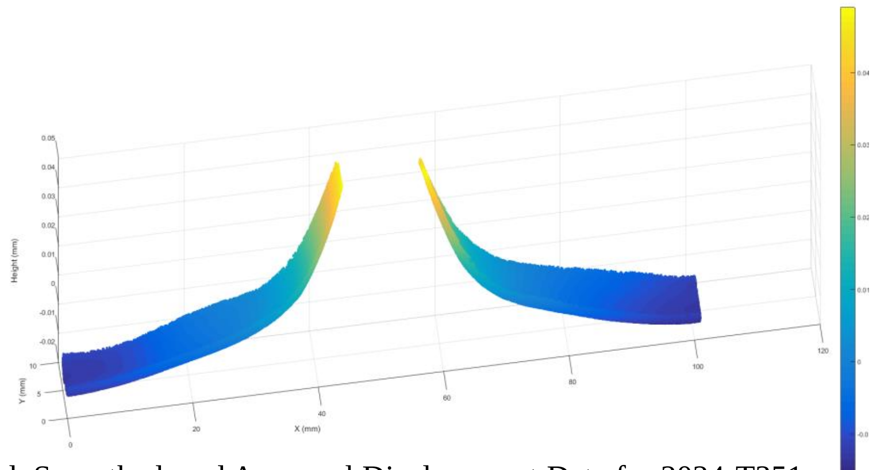
- Magnitudes of Uncertainty Similar to Repeatability Uncertainty
  - Total uncertainty driven by “Modeling” uncertainty
  - “Displacement” uncertainty symmetric around hole
- Locations of Peaks Not the Same
- Effect of Shift of Repeatability STD on Fatigue Life Prediction
  - 2024-T351 life prediction range from 140,000 – 216,000 cycles
    - Starting life cycle number = 172,000 cycles
  - 7075-T651 life prediction range from 264,000 cycle – infinite life
    - Starting life cycle number = 350,000 cycles

General Conclusions

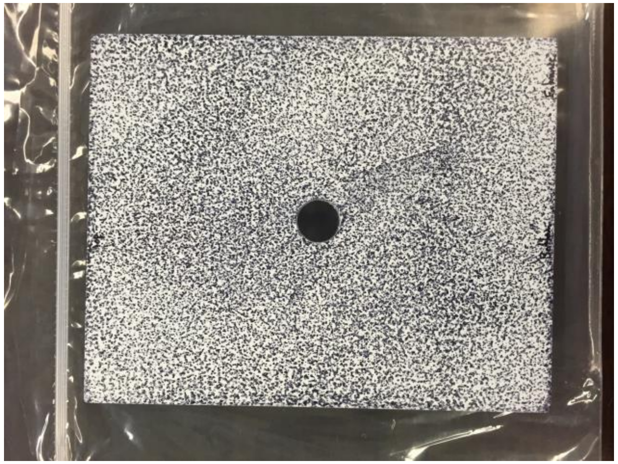
- Single Measurement does not Capture Breadth of Uncertainty Seen in Repeatability Uncertainty
  - Looks like it's better to have multiple measurements
- Single Measurement and Repeatability are Statistically Not Equal and are Independent via Chi-Squared Test
  - Potential to combine to capture uncertainty associated with Cx process and data reduction process "contour method"
- Confirming Independence via Hypothesis Testing on Differences of Means
- Repeatability Shifts of STD Create Greater Difference in Fatigue Life Predictions
- 7075-T651 is More Sensitive to these Shifts
  - Material model is a problem now – working on that

Questions Unanswered

- Large Displacements Along Entrance and Exit Surfaces
  - Potentially due to plane stress/plane strain effect from cutting



Aligned, Smoothed, and Averaged Displacement Data for 2024-T351, CxA2-1



- Potential use of DIC to "Correct" for Surfaces
  - Causes higher compressive residual stresses than expected

Inter-Laboratory Cx Work

- Working to Have Multiple Labs Perform Residual Stress Measurement of Cx Condition
  - Does data processing methods make significant impact?
  - Does cutting methods cause significant impact on stress results?
- Working with 5 Labs for Inter-Laboratory Data Reduction of 4-Pt. Bend Condition[7,8]
  - Coupons tested at SwRI, cut at Hill Eng. LLC.
  - Data sent to individuals at Hill Eng., Los Alamos Labs, StressMap (UK), Hill AFB, Hydro-Quebec Research Institute
  - Is not trying to capture cutting and displacement measurement errors
- Need to Provide Users with Understanding of Uncertainty if Contract goes to *"Lowest Cost, Technically Acceptable"*
- Potential to have Inter-Laboratory Total Uncertainty "Too High" – Would Limit Usefulness of Method

Future Work

- Quantification of Total Uncertainty is Essential for Future Work
  - Enables confidence in isolating out effect being investigated
- Effect of a Fatigue Crack on the Residual Stress Field
- Effect of Peak Compression Cycles on Residual Stress Field
- Effect of Steel Pin Installation During Cyclical Loading
- Effect of Bearing & Bypass Loading
- Application of DIC for Measurement of Strain/Stress During Cx-Through-Testing-Crack Propagation Process
  - Look to correlate to Contour Method data
  - Potential for surface correction to improve Contour Method data
- Integrate all Aspects into Fatigue Life Prediction at Critical Airframe Locations Across Fleet - USAF-wide

Questions?

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