2017 AFGROW Workshop

Implementation of Bi-Variant Polynomial Equations to Include the Effect of a Fatigue Crack on the Residual Stress and Life Prediction at Cx Holes

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

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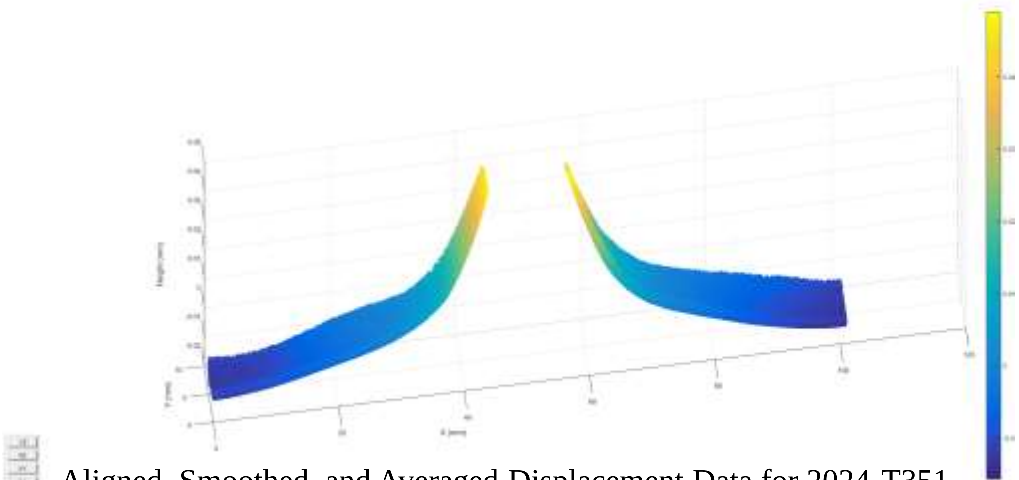
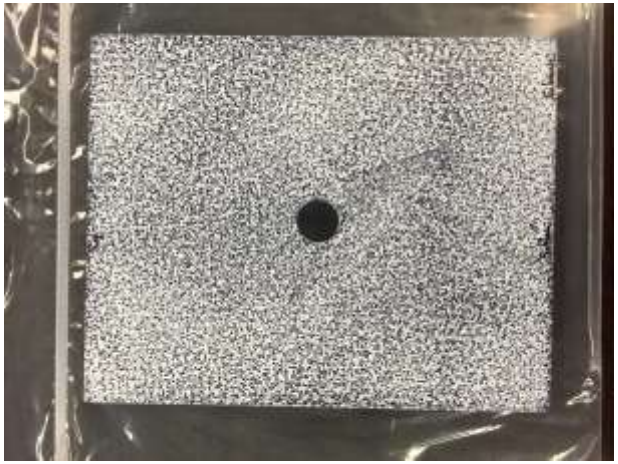
Questions Unanswered

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



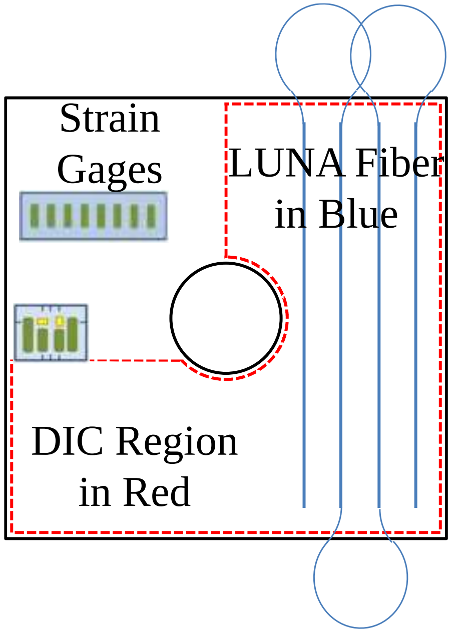
Aligned, Smoothed, and Averaged Displacement Data for 2024-T351, CxA2-1

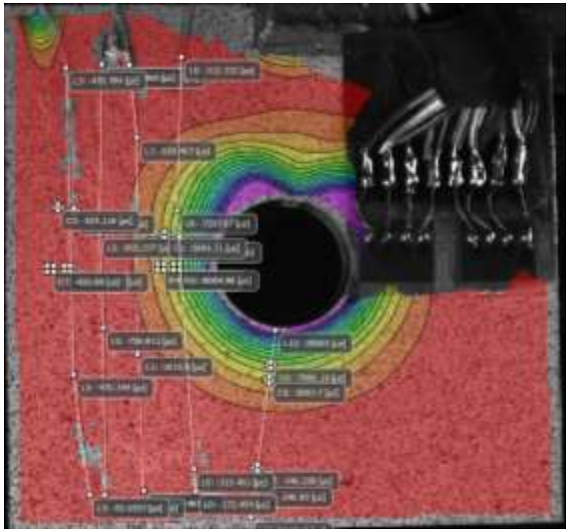


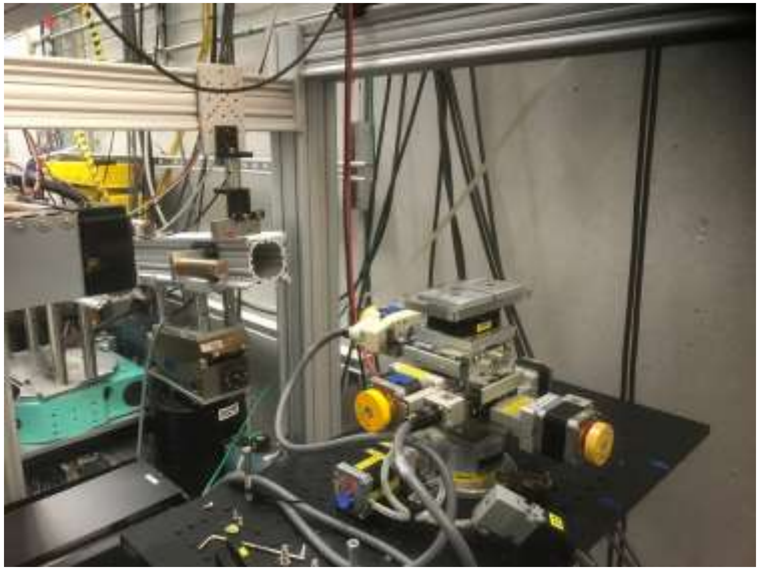
- Potential use of DIC to "Correct" for Surfaces
  - Causes higher compressive residual stresses than expected

Surface & Thru-Thickness

- Performed Surface Displacement Measurements
  - DIC, LUNA (fiber optics), and Strain Gages
- Performed Thru Thickness Displacement Measurements
  - High Energy X-ray Diffraction (Argonne) – DONE
  - X-ray Diffraction (NRC – Canada) - Currently
  - Neutron Diffraction (IMAT – UK)
  - Contour Method (Hill Engineering, LLC.)







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. LLC., 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

Inter-Laboratory Cx Work

- Provided FEA Simulation of 4-pt Bend and have Results
  - Post processing and comparing
- Currently in Prep for Two 4-pt Bend Tests

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

Acknowledgements

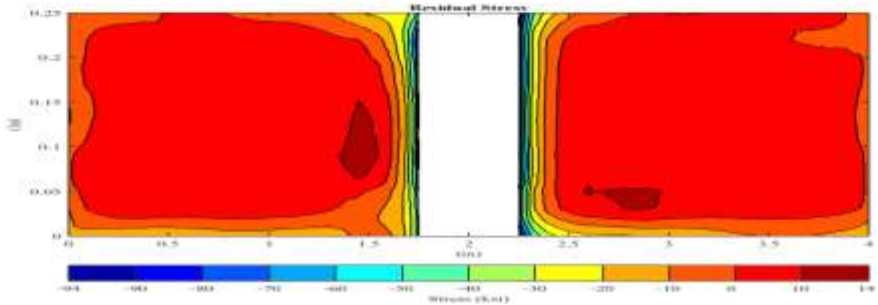
- Dr. Mark Thomsen – A-10 ASIP Manager
- Lucky Smith – SwRI Program Manager
- Joshua Hodges – Hill Engineering, LLC.
- Dr. Tom Mills - AP/ES Inc.

Agenda

- Perspective and Overview of Contour Method
- ***Influence of Fatigue Crack on Residual Stress Field***
  - ***Hypothesis and experiment set-up***
- Fatigue Crack Coupon Development
- Residual Stress Calculations for Cx Holes with Cracks
  - 2024-T351 & 7075-T651 “Low” Applied Cx
- ***Integration of Effected Residual Stress State into Fatigue Crack Growth Analysis***
  - Residual stress function’s effect on life predictions
  - Outputs to help make educated decisions for the future
- Conclusions and Recommendations

HOLSIP Perspective

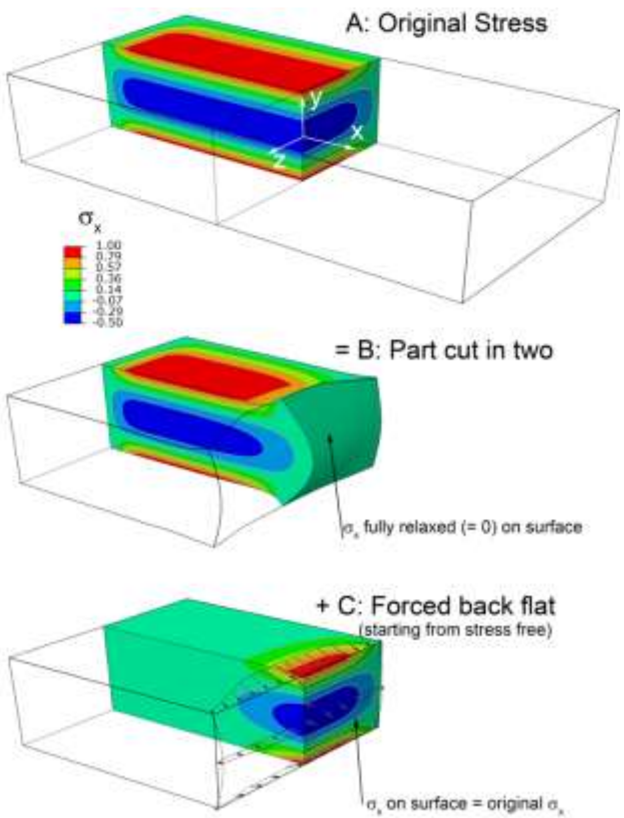
- Deep Residual Stresses/Self Stresses are a Physics-based Process
  - Plastic deformation
  - Local yielding



- Define/Quantify Parameters of Influence
  - Percent expansion
  - Local stress state
  - Applied loading (tension or compression dominated?)
- Understand and **Statistically** Quantify 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" or "smoothing" – Johnson, G. Dis
  - Apply final fit surface as boundary constraints to FEA
  - Solve for stresses within body



Idealized Conceptual Implementation of Contour Method[3]

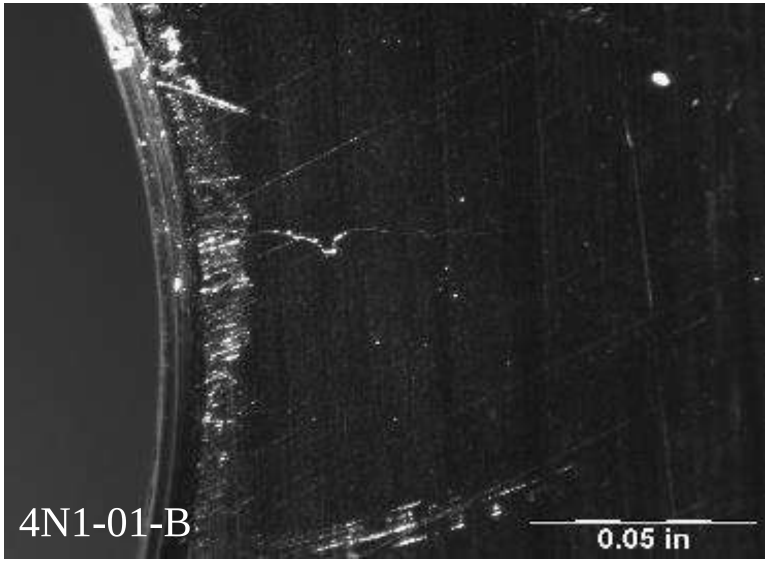
Influence of a Fatigue Crack

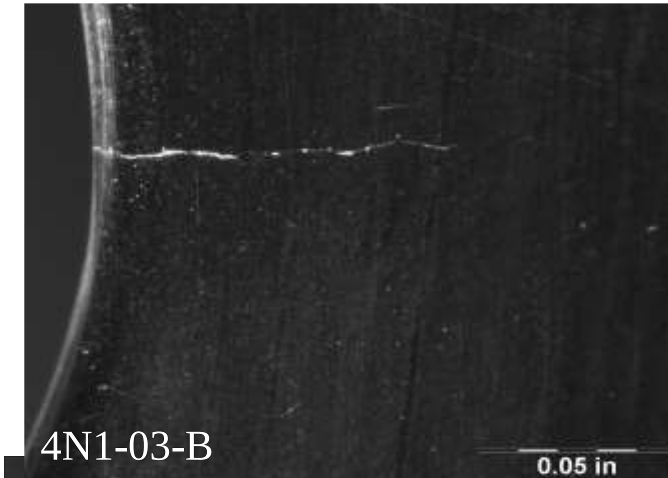
- Hypothesis:
  - *"The presence of a fatigue crack changes the residual stress field induced by the Cold Expansion (Cx) process within aerospace-grade aluminum alloys, namely 2024-T351 and 7075-T651"*
- Procedure for Testing Hypothesis
  - Develop baseline Cx coupons, no fatigue crack coupons
  - Develop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

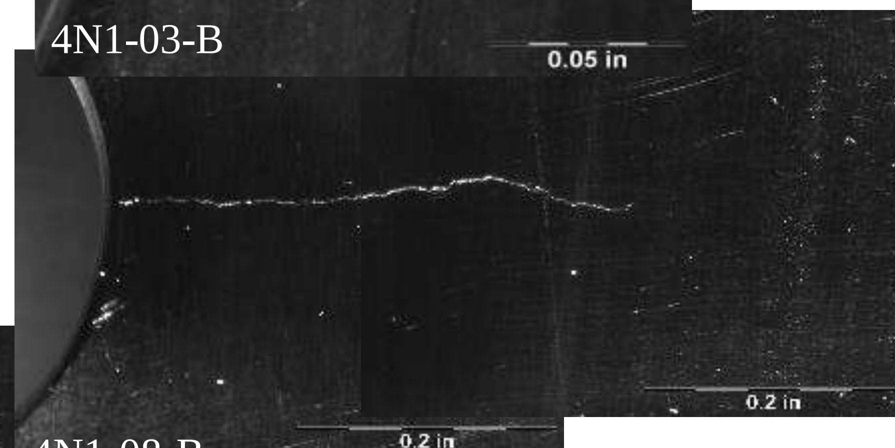
2024-T351 Coupons							
Specimen ID	Mandrel Entrance Face Crack (inch)	Gauge Width (inch)	Gauge Thickness (inch)	Initial Ream Diameter (CMM (inch)	% CX	Final Ream Diameter (inch)	RS Specimen Length (inch
4N1-01-B	0.0797	4.0000	0.2545	0.4771	3.23%	0.4990	5.0030
4N1-02-B	0.0798	4.0030	0.2550	0.4768	3.29%	0.4997	5.0035
4N1-03-B	0.0974	4.0025	0.2548	0.4772	3.21%	0.4997	5.0028
4N1-04-B	0.0962	4.0022	0.2555	0.4771	3.23%	0.4990	5.0022
4N1-05-B	0.1259	4.0027	0.2557	0.4771	3.23%	0.4980	5.0023
4N1-06-B	0.1214	4.0023	0.2555	0.4770	3.25%	0.4990	5.0025
4N1-07-B	0.2515	4.0020	0.2555	0.4770	3.25%	0.4995	5.0030
4N1-08-B	0.4974	4.0013	0.2550	0.4770	3.25%	0.4995	5.0030
AVERAGE		***4.0020***	***0.2552***	***0.4770***	***3.24%***	***0.4992***	***5.0028***
STDEV		***0.0009***	***0.0004***	***0.0001***	***0.03%***	***0.0006***	***0.0004***

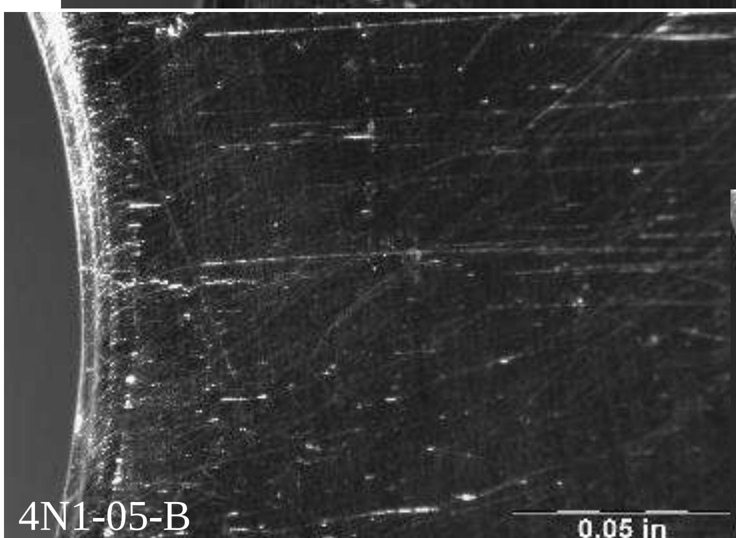
7075-T651							
Specimen ID	Mandrel Entrance Face Crack (in	Gauge Width (inch)	Gauge Thickness (inch)	Initial Ream Diameter (CMM) (inch	% CX	Final Ream Diameter (inch	RS Specimen Length (inch
4N1-01-D	0.0793	4.0028	0.2495	0.4766	3.34%	0.4988	5.0023
4N1-02-D	0.0807	4.0023	0.2510	0.4768	3.29%	0.4990	5.0022
4N1-03-D	0.0972	4.0017	0.2508	0.4769	3.27%	0.4993	5.0020
4N1-04-D	0.1015	4.0015	0.2500	0.4770	3.25%	0.4985	5.0025
4N1-05-D	0.1253	4.0020	0.2505	0.4769	3.27%	0.4992	5.0033
4N1-06-D	0.1235	4.0027	0.2507	0.4770	3.25%	0.4980	5.0020
4N1-07-D	0.2505	4.0020	0.2505	0.4767	3.31%	0.4983	5.0023
4N1-08-D	0.5017	4.0022	0.2512	0.4769	3.27%	0.4992	5.0030
AVERAGE		***4.0021***	***0.2505***	***0.4769***	***3.28%***	***0.4988***	***5.0025***
STDEV		***0.0005***	***0.0005***	***0.0001***	***0.03%***	***0.0005***	***0.0005***

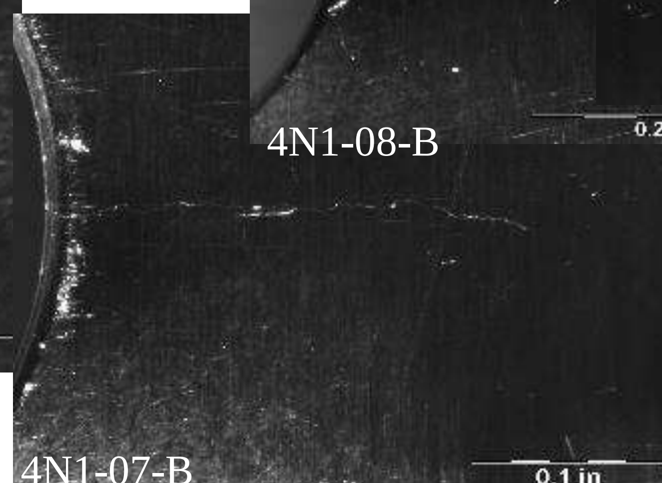
Fatigue Cracks in 2024-T351



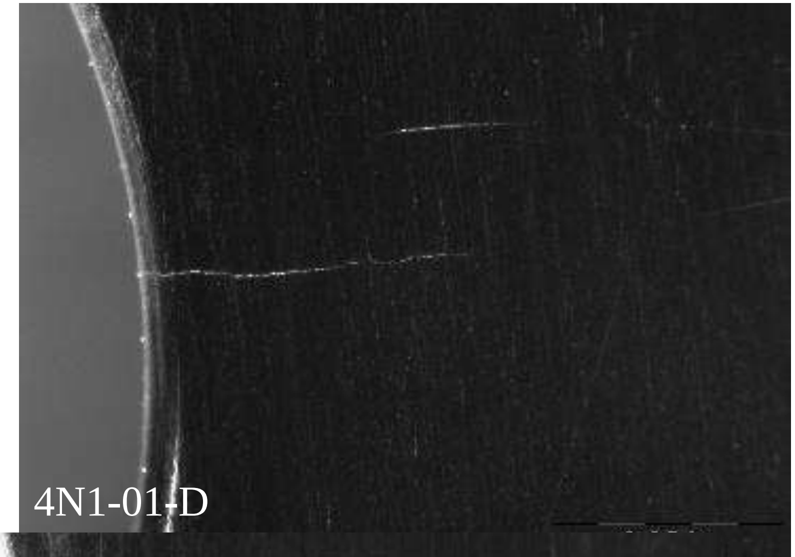


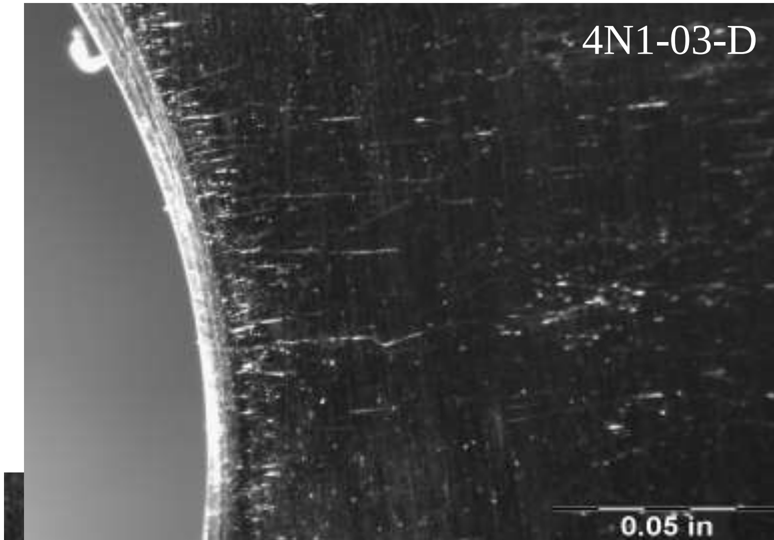


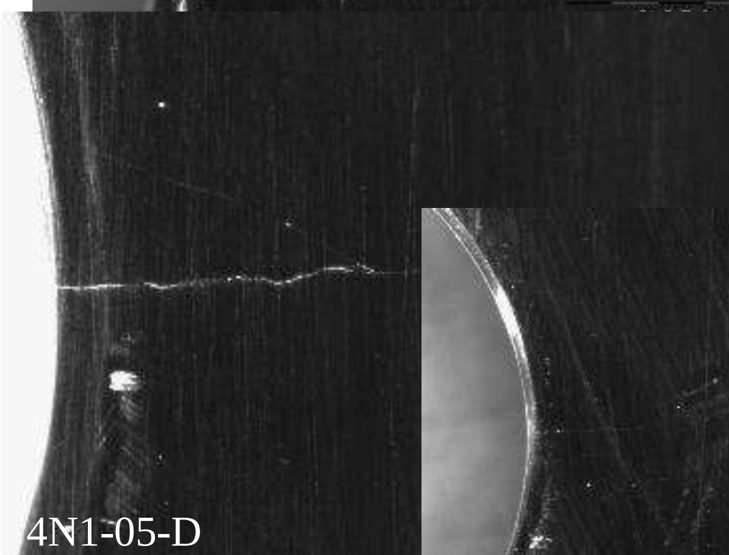


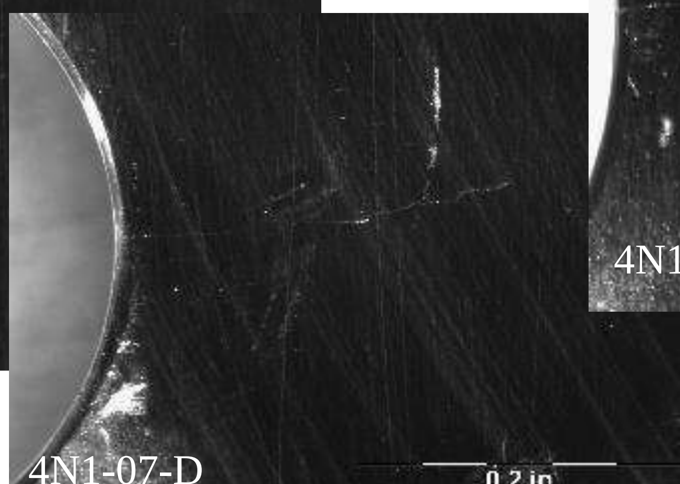


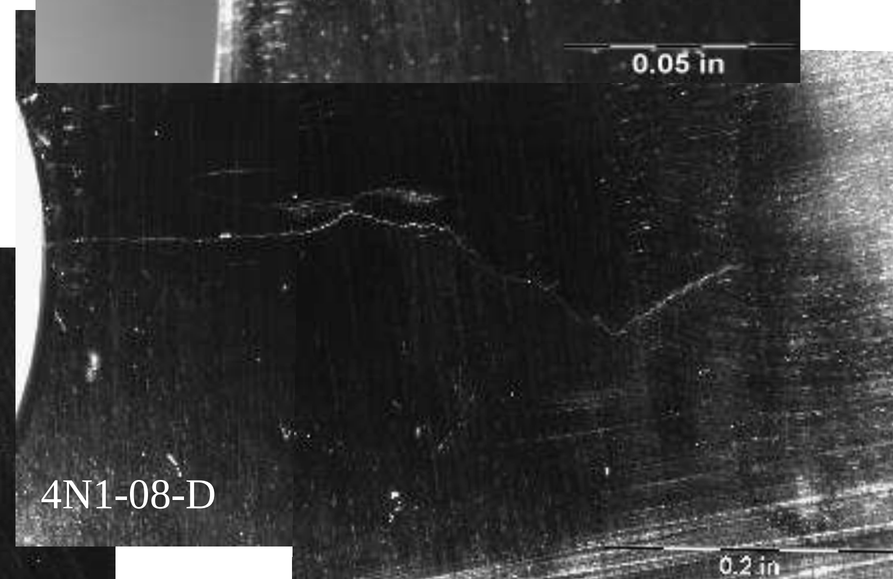
Fatigue Cracks in 7075-T651





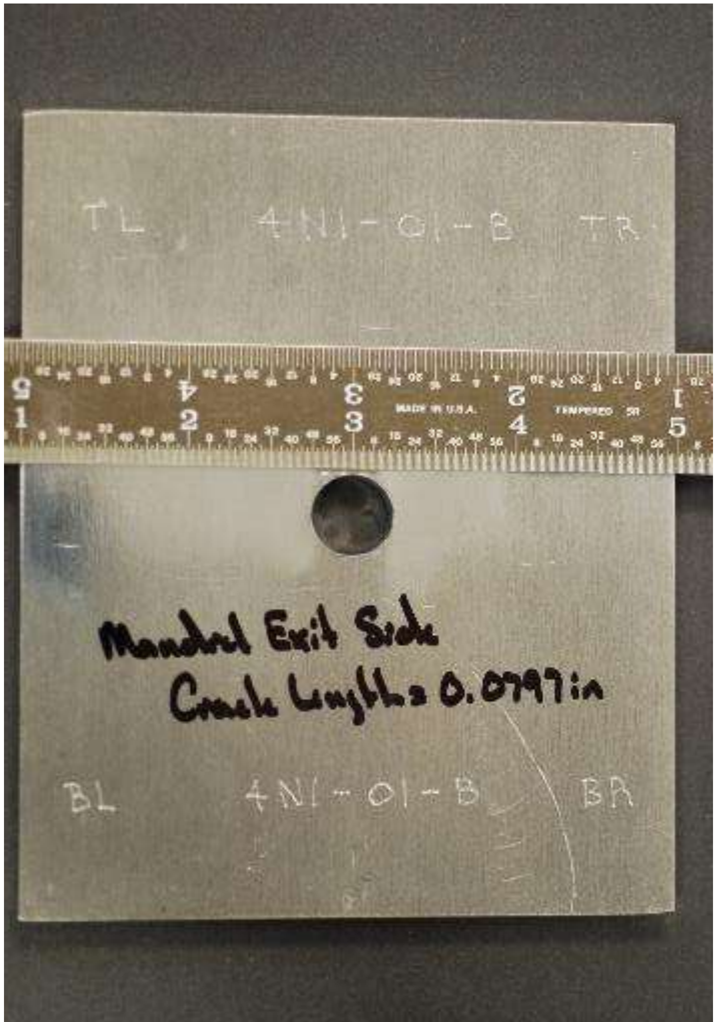


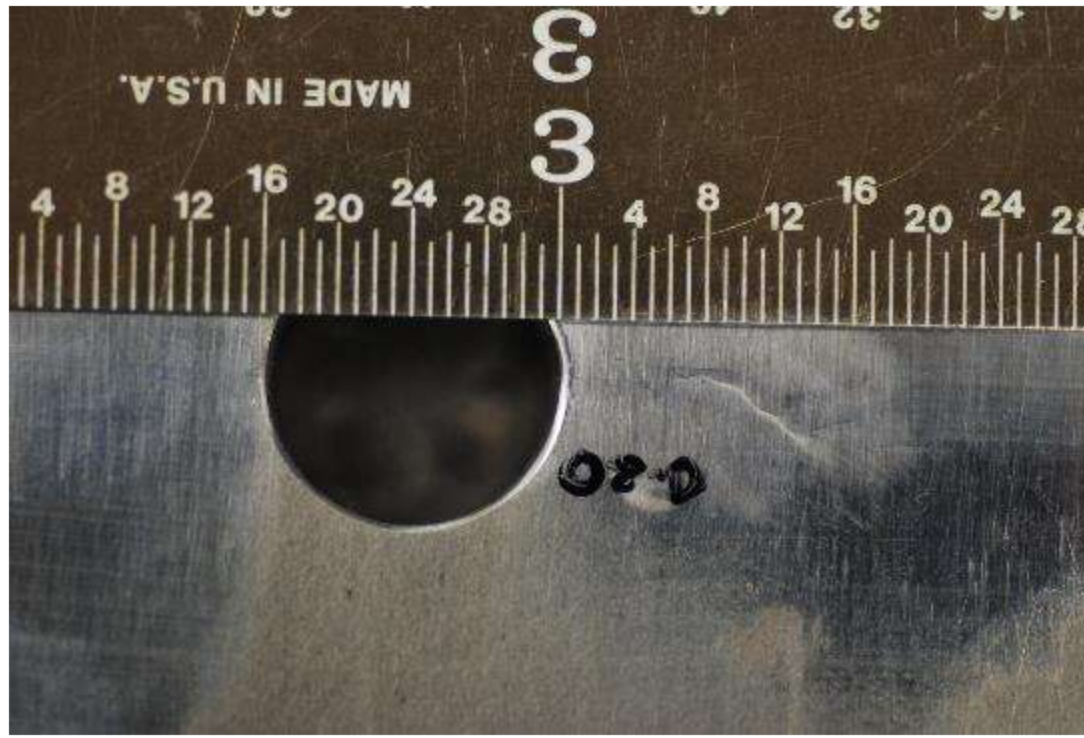




Displacement Measurements

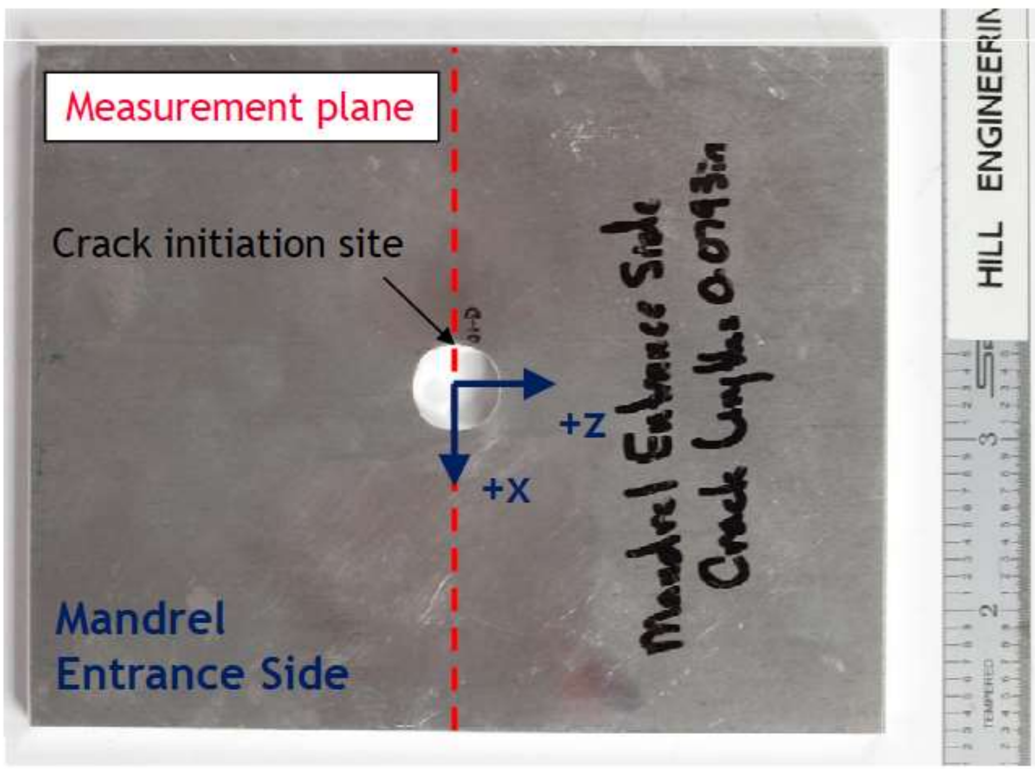
- Macro Images of Coupons





Displacement Measurements

- Contour Measurements at Crack Plane
  - Cutting of coupon initiated at fatigue cracked side
  - Cut plane was as close to plane of fatigue crack
    - For larger cracks approx. 0.25-0.50inch cracks were off plane



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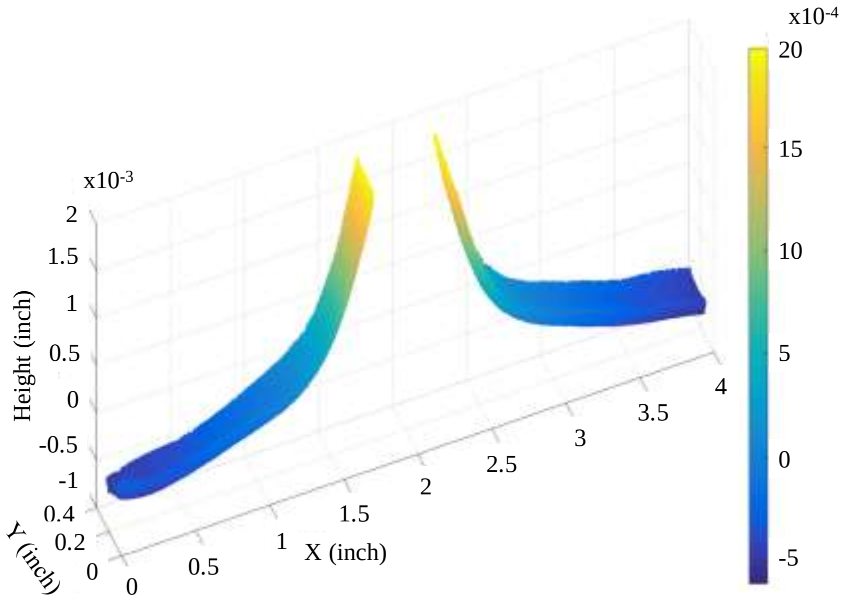
as shown here

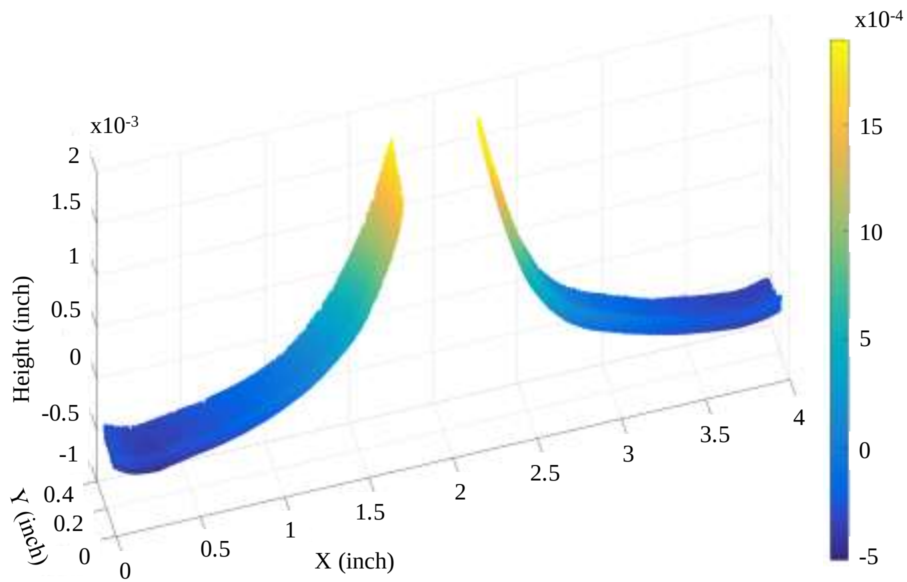
Image Courtesy of Hill Engineering, LLC.

Displacement Measurements

- All Displacements Provided by Hill Engineering LLC.
- Completed Data Reduction of Cracked Coupons
  - Followed same data reduction process for cracked coupons as with baseline coupons
    - Assumption: Lot-to-lot variability is negligible in these experiments

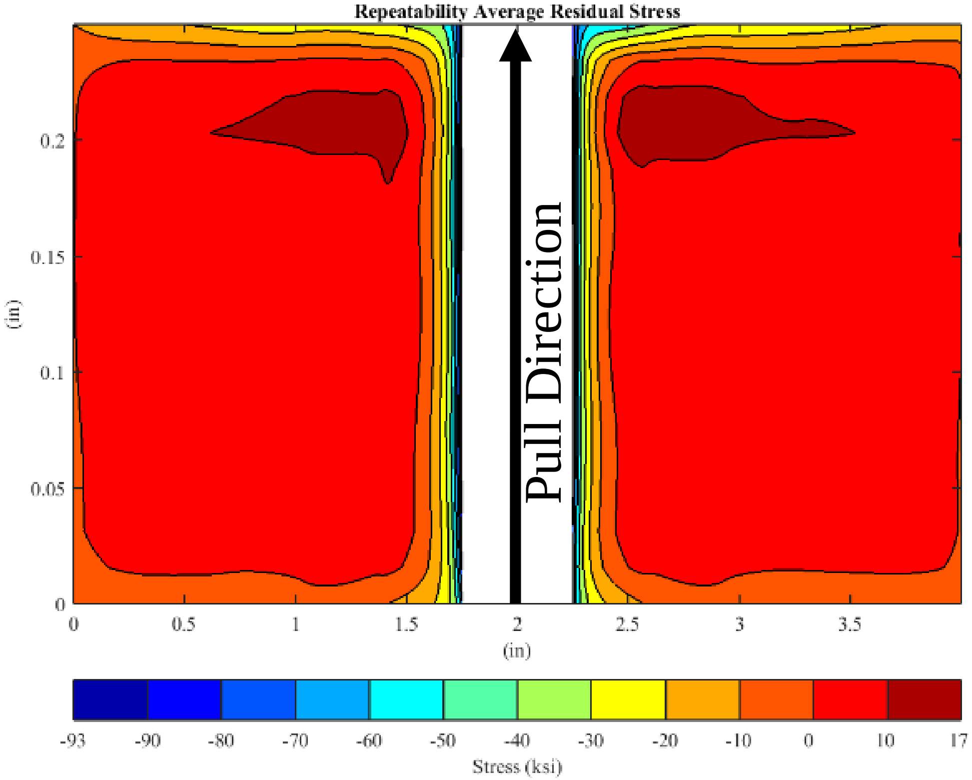


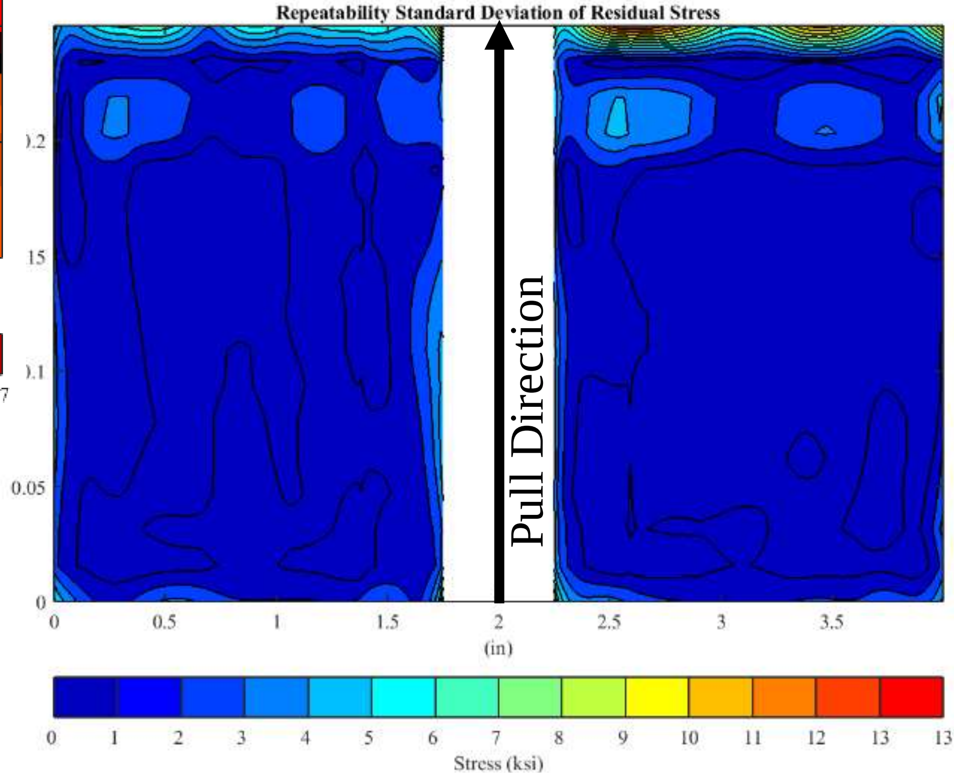
Cx-2024-T351 – Crack Size = 0.08inch



Cx-2024-T351 – Crack Size = 0.4974inch

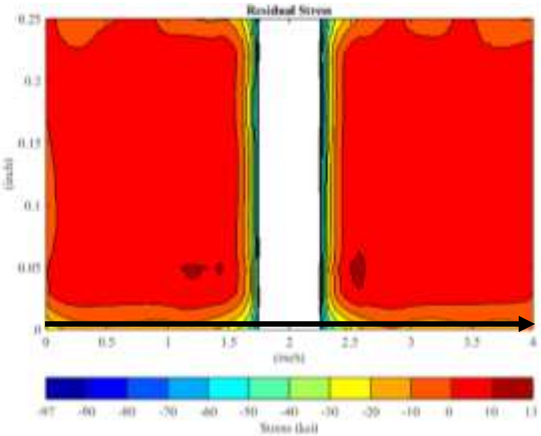
Average Baseline 2024-T351

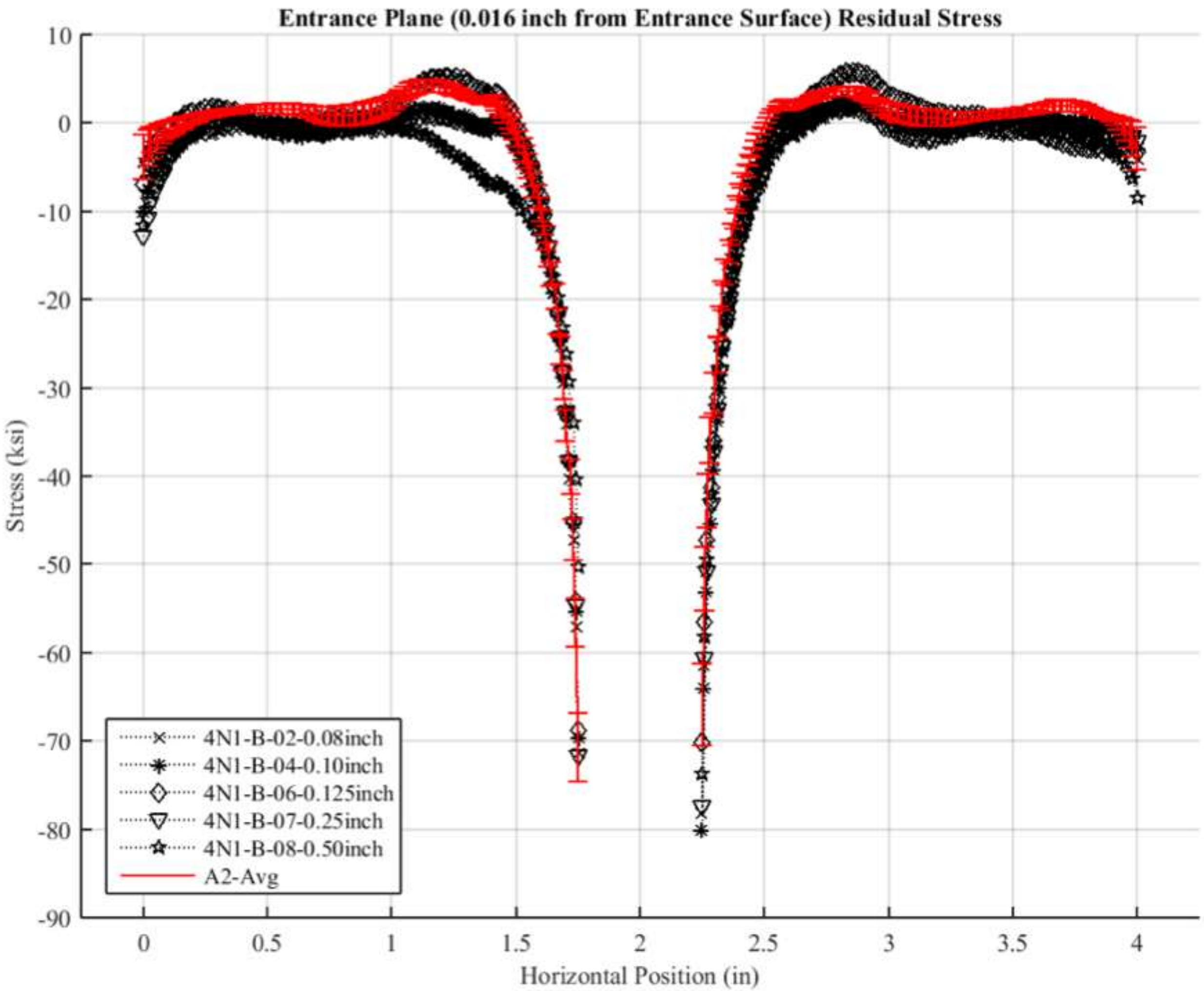




Residual Stresses in 2024-T351

- Line Plots of Stress Radially from Hole





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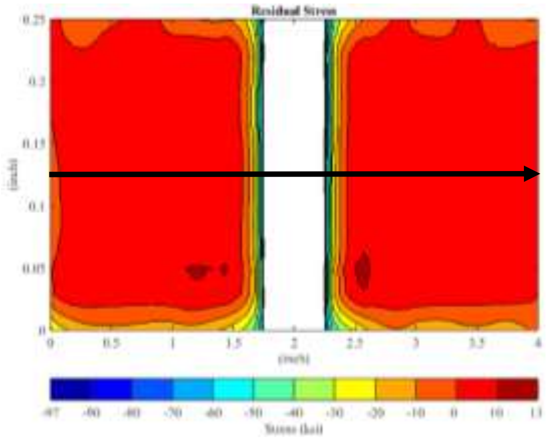

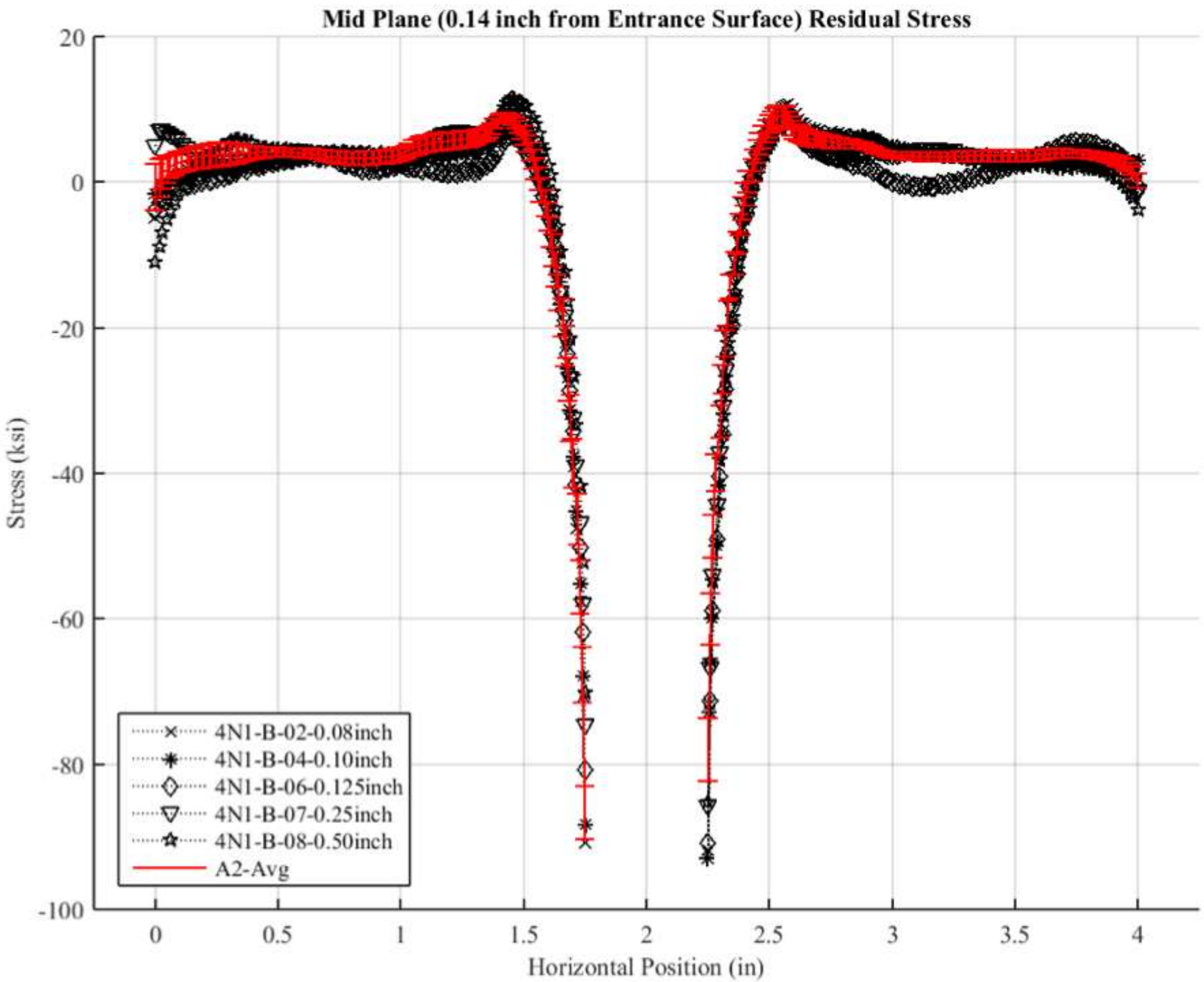

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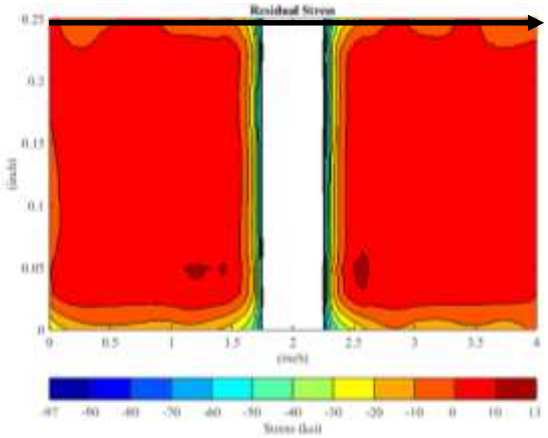
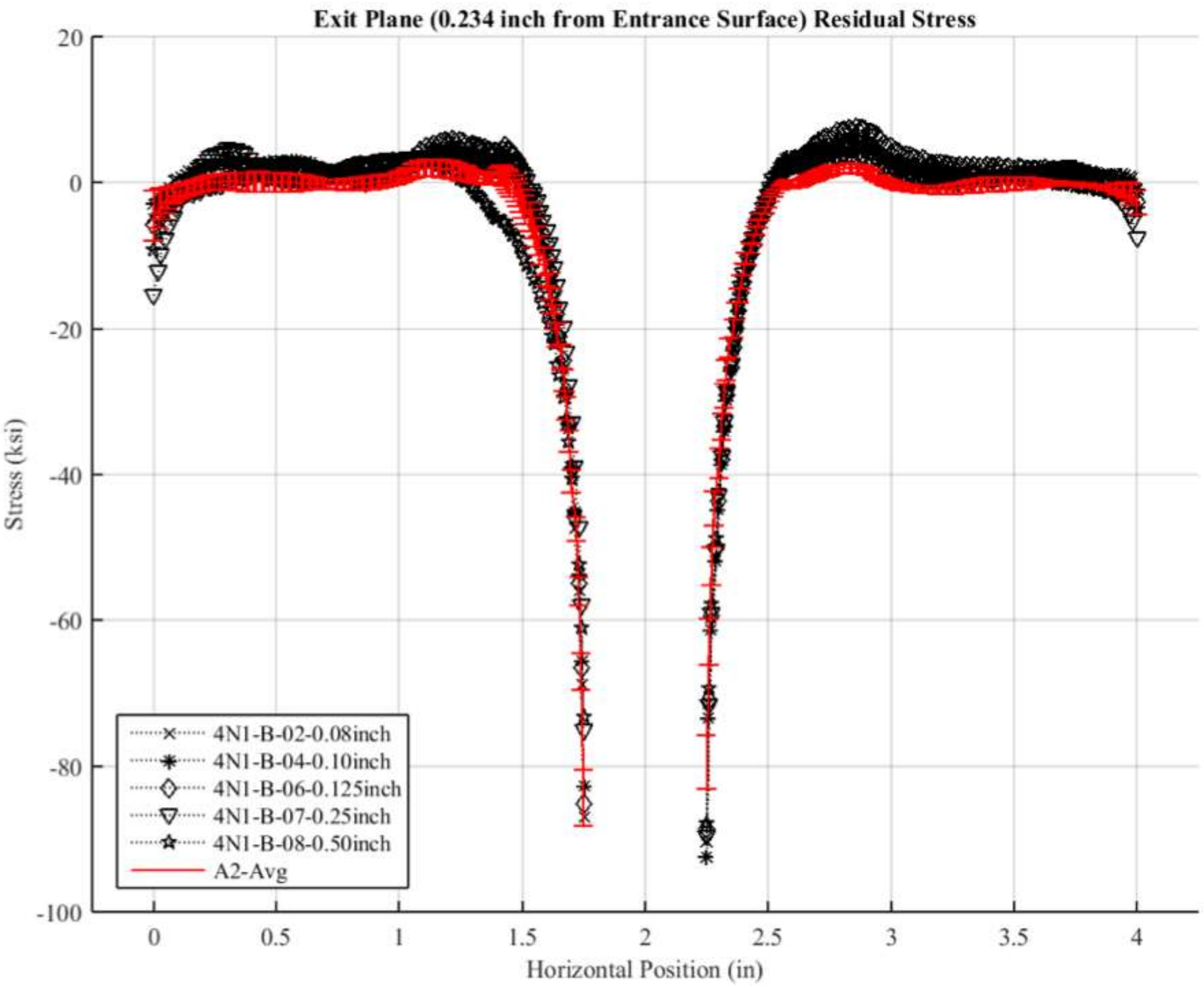
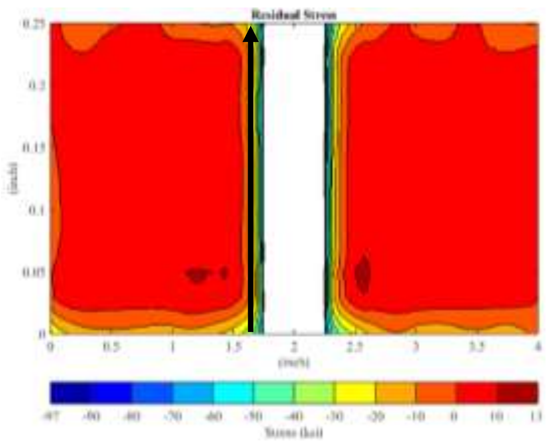
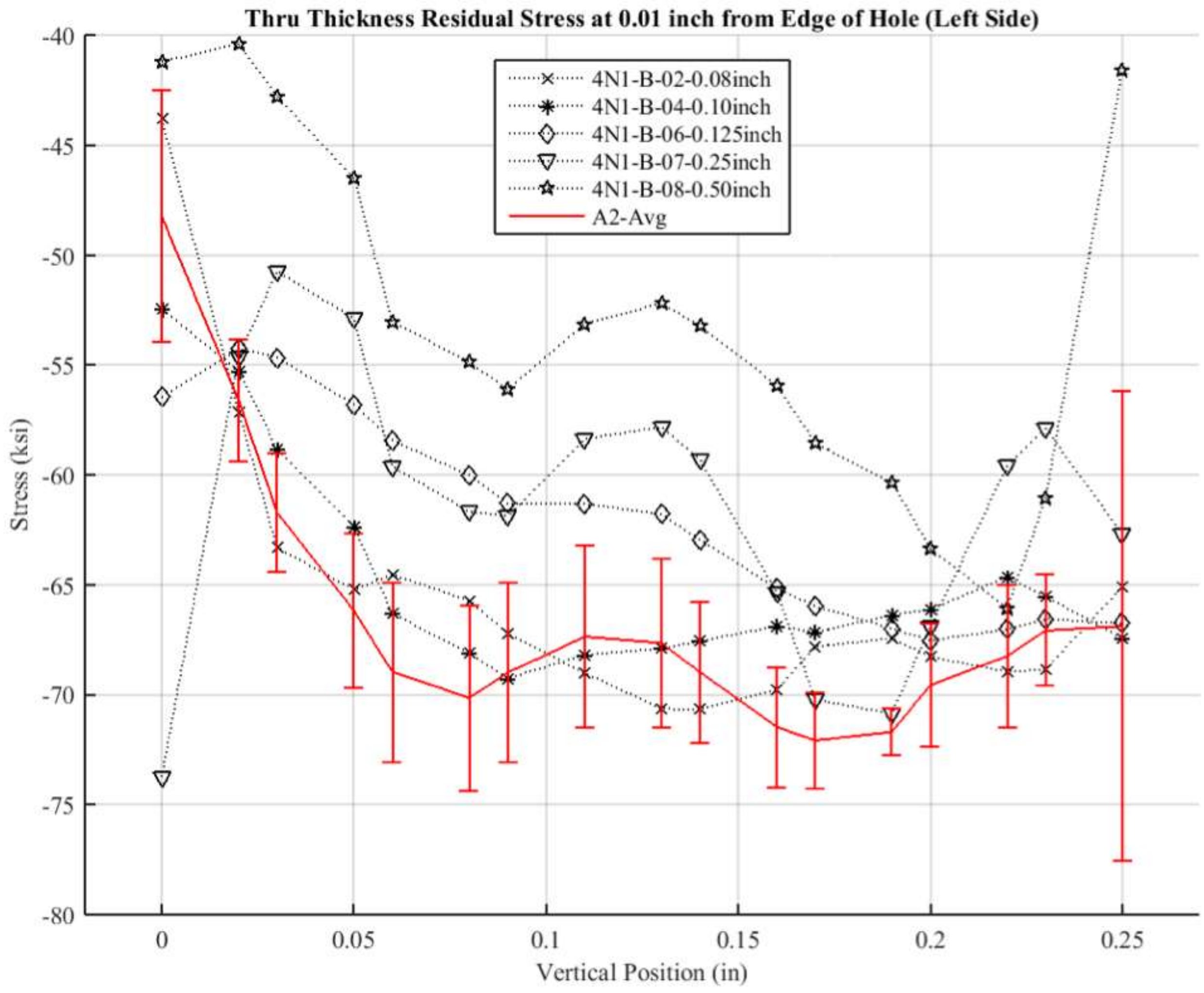




Residual Stresses in 2024-T351

- Line Plots of Stress Through Thickness Near Hole





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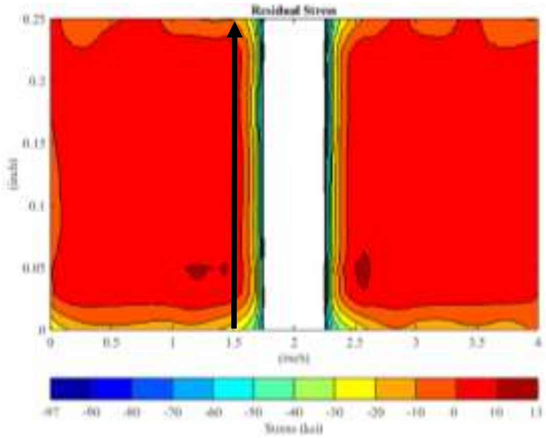

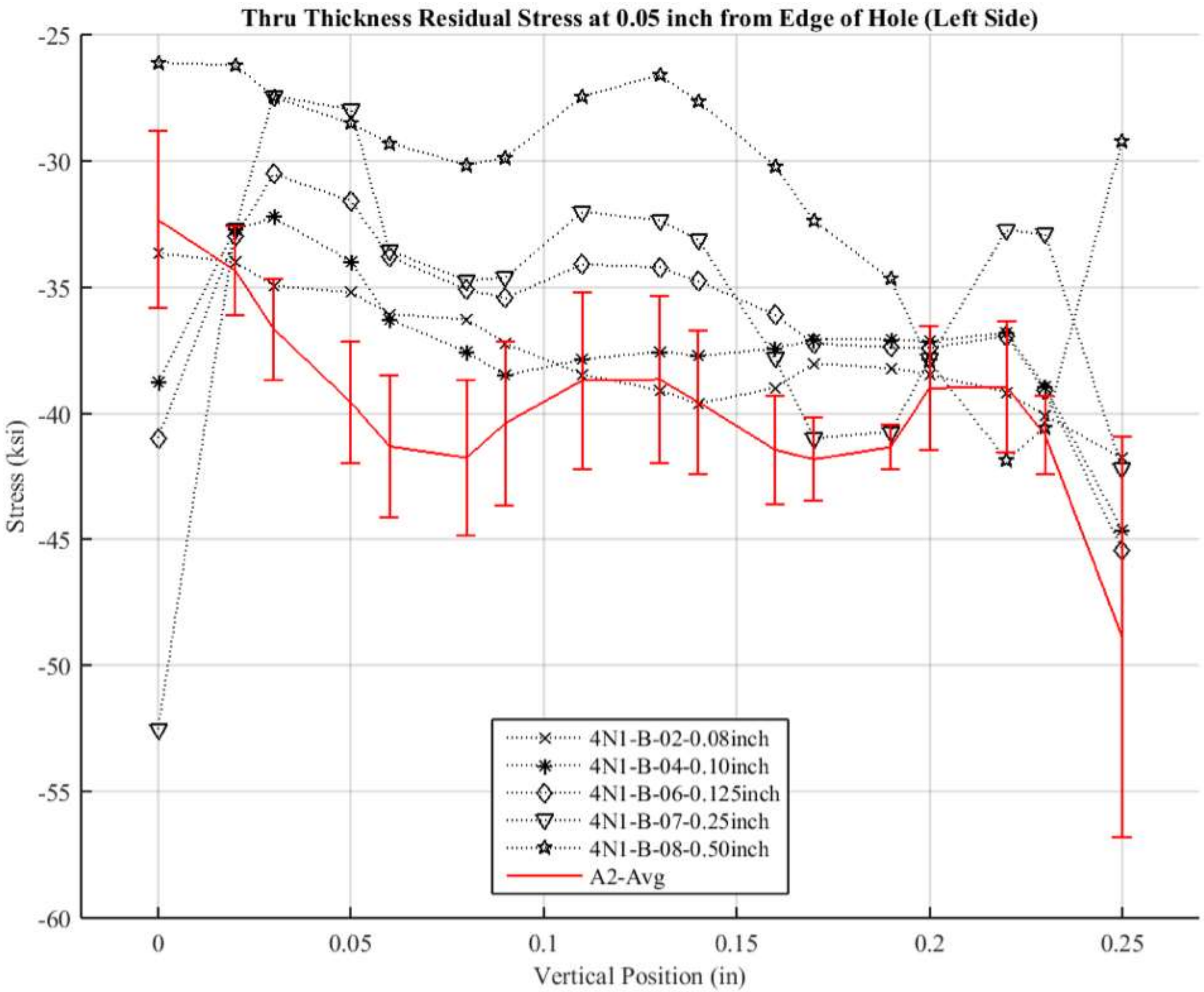

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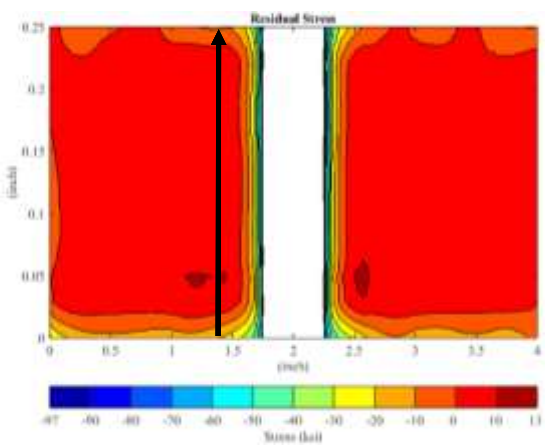
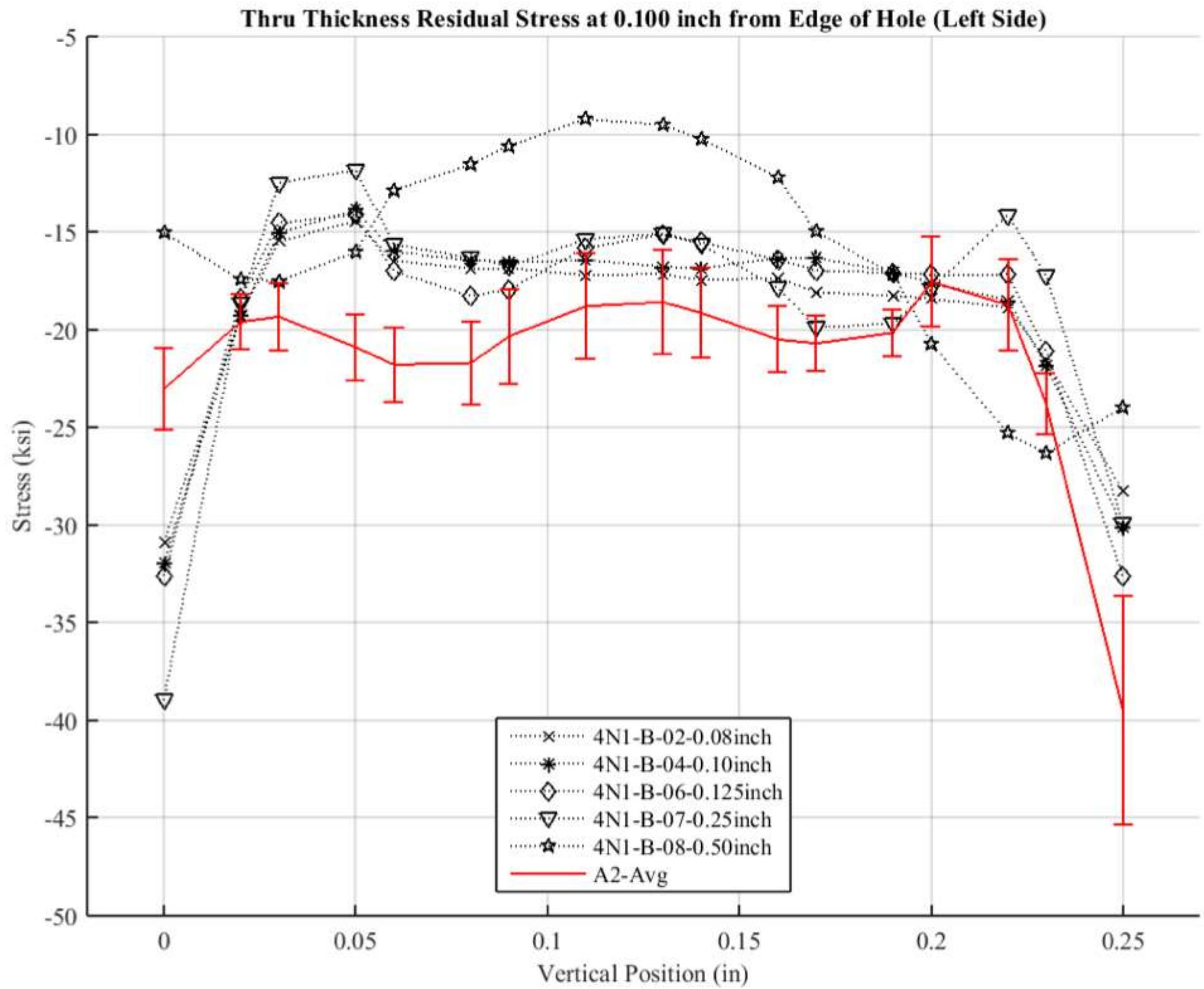
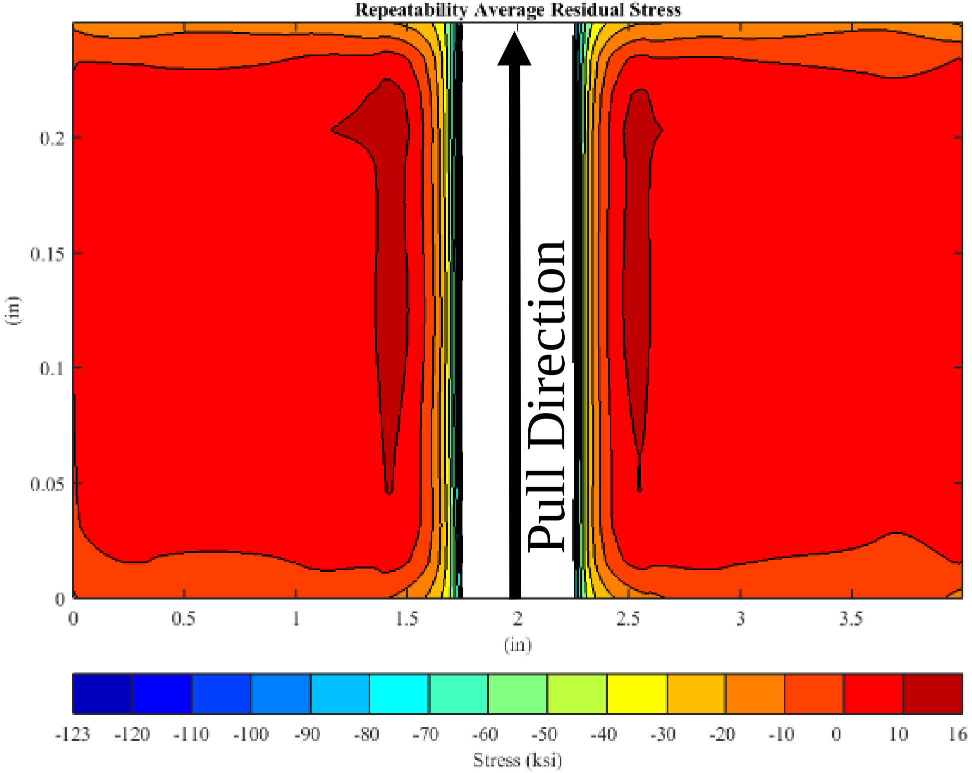
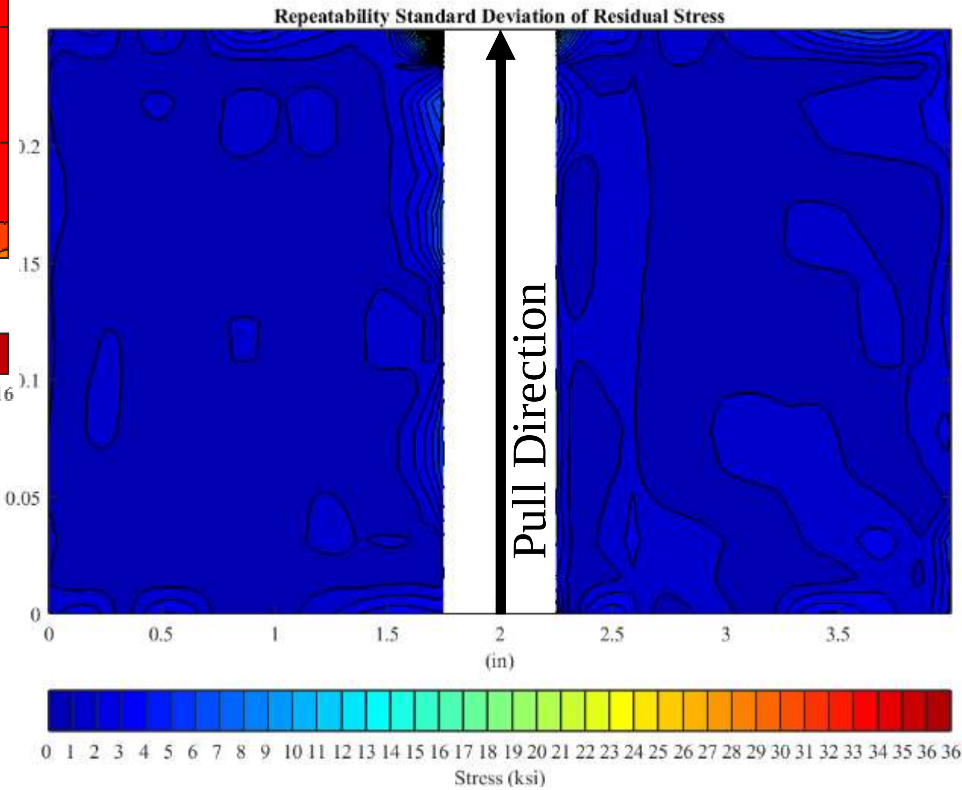




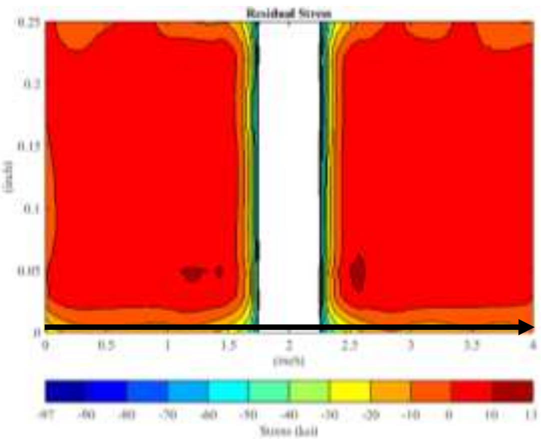
Average Baseline 7075-T651

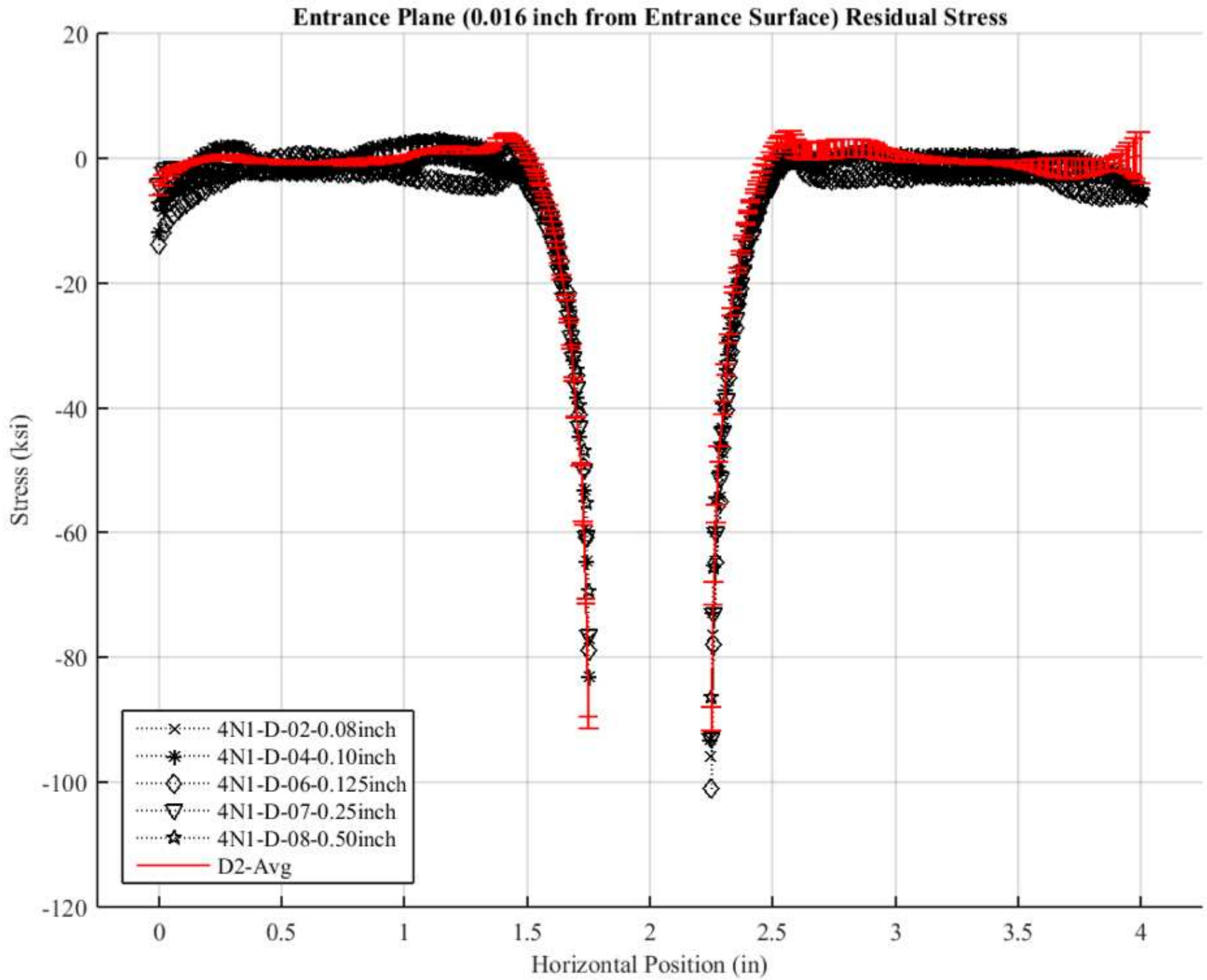




Residual Stresses in 7075-T651

- Line Plots of Stress Radially from Hole





Residual Stresses in 7075-T651

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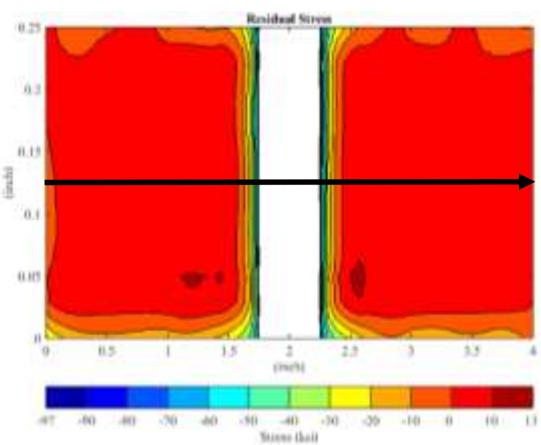

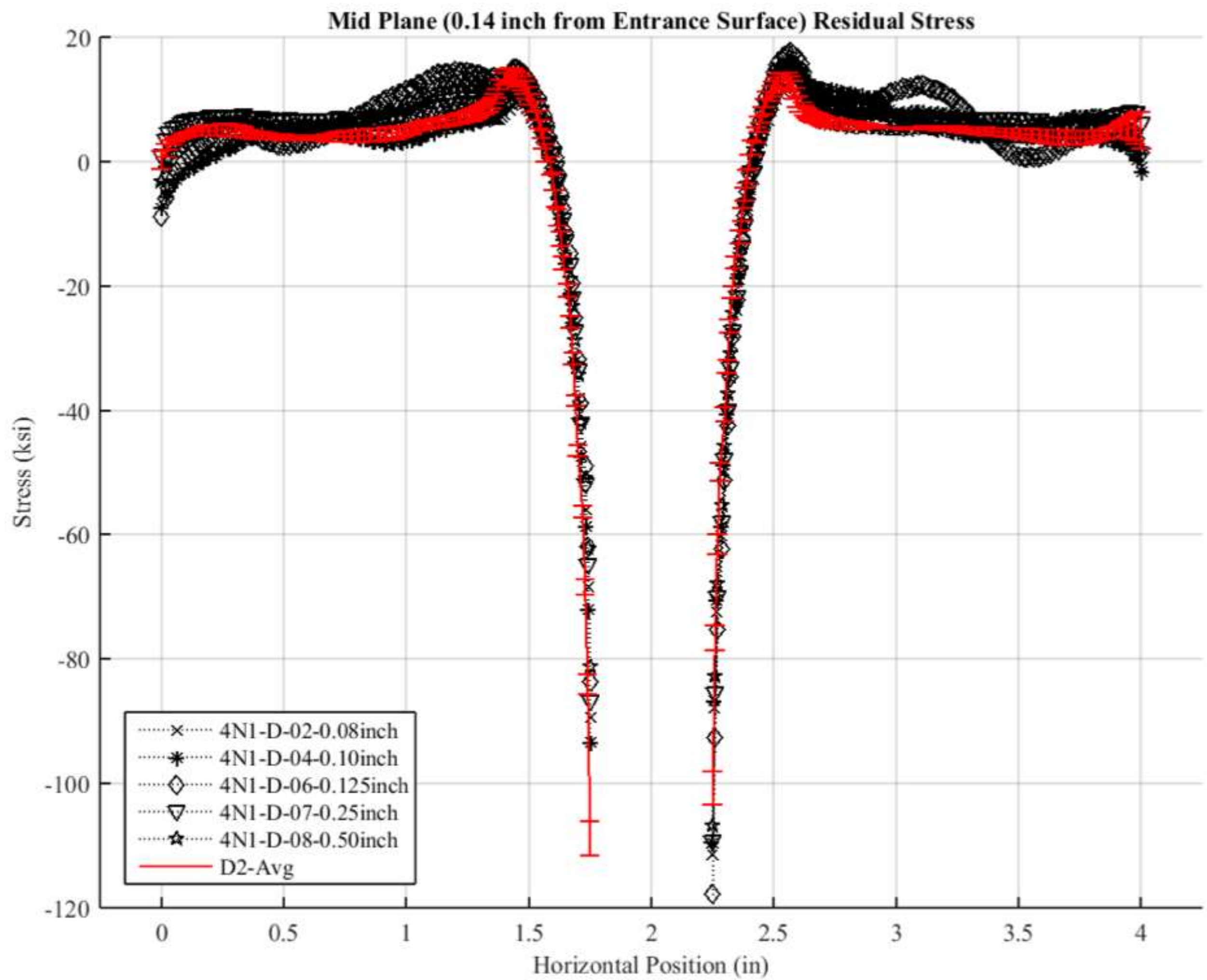

Residual Stresses in 7075-T651

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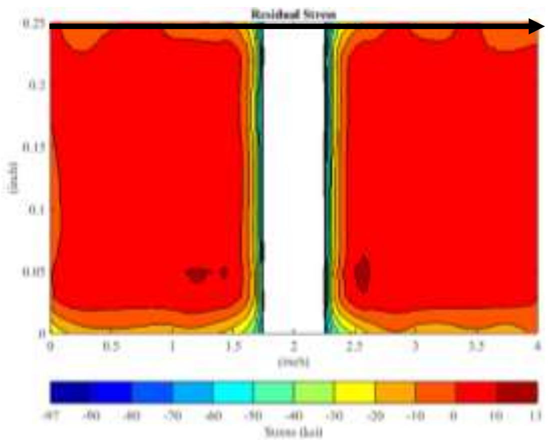
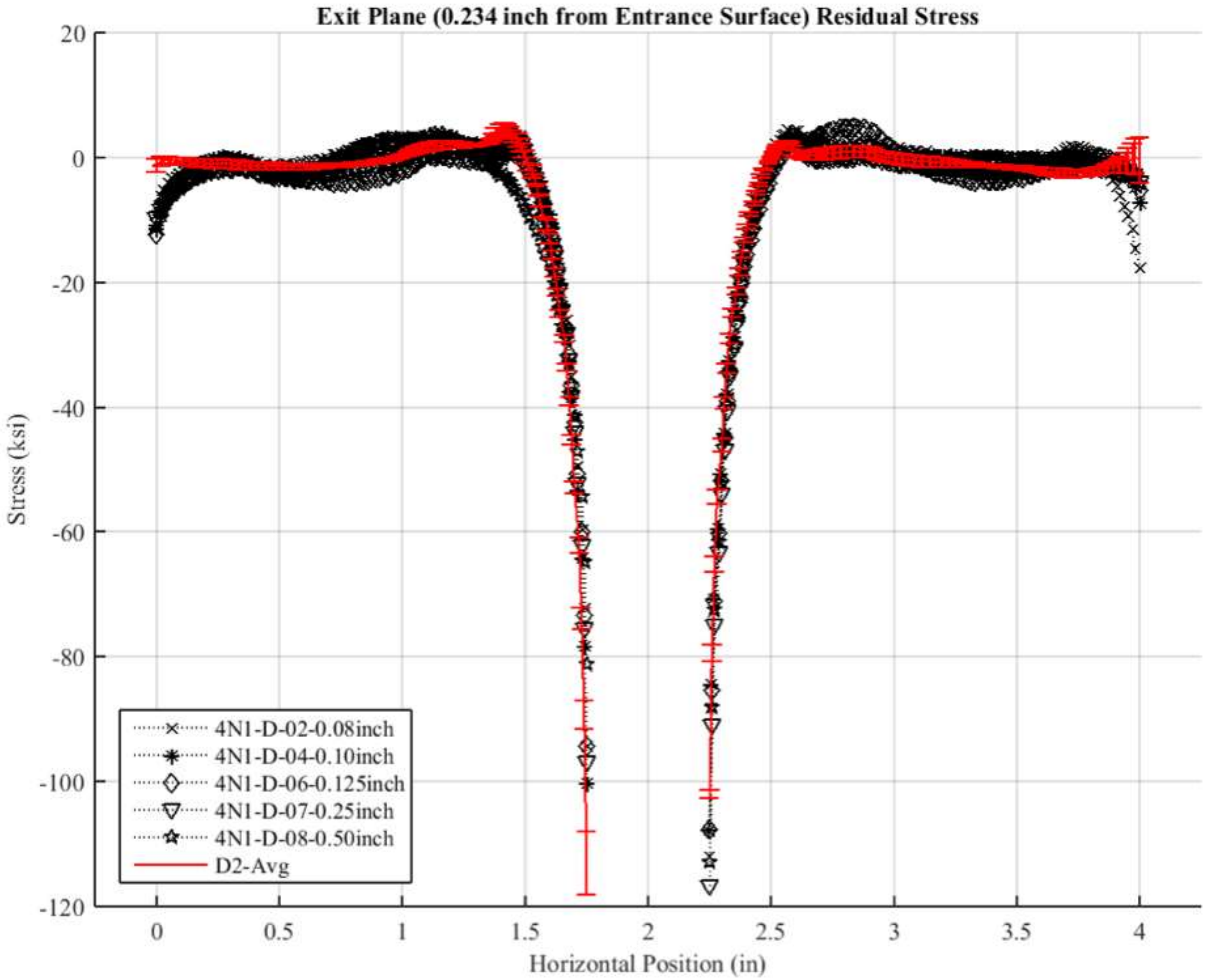
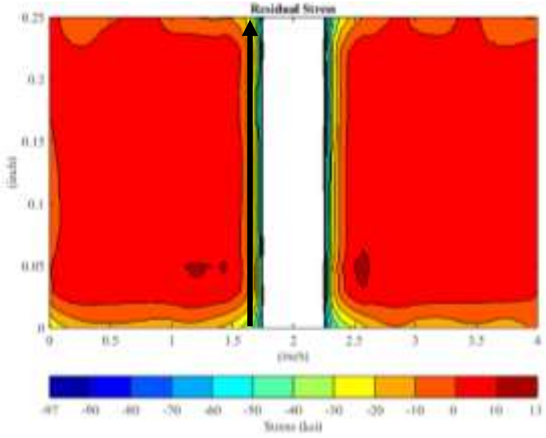
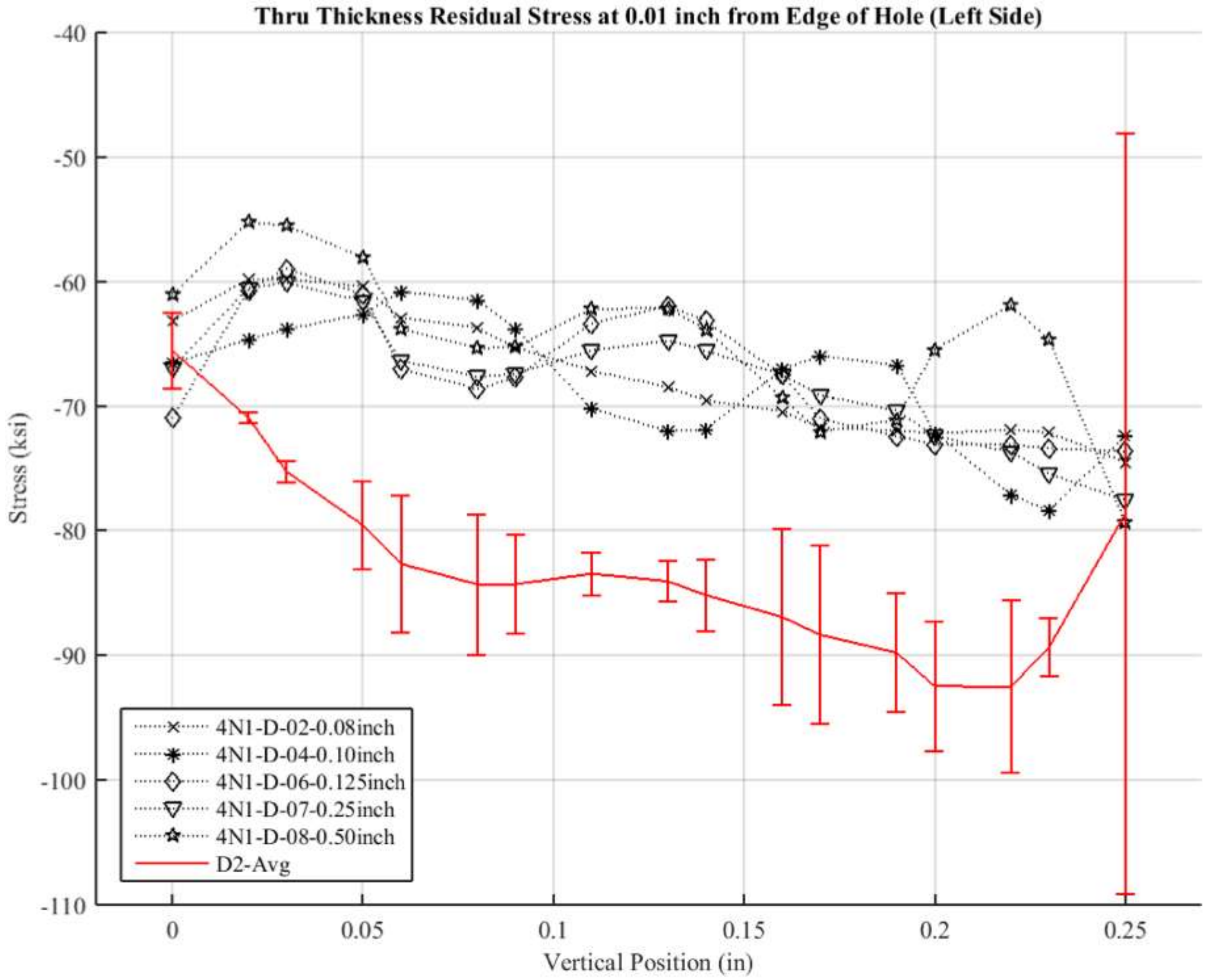




Residual Stresses in 7075-T651

- Line Plots of Stress Through Thickness Near Hole





Residual Stresses in 7075-T651

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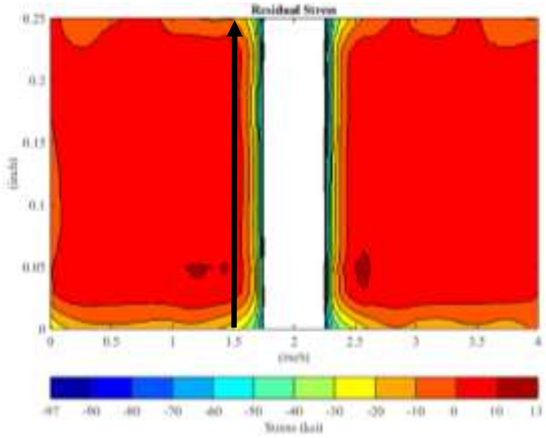
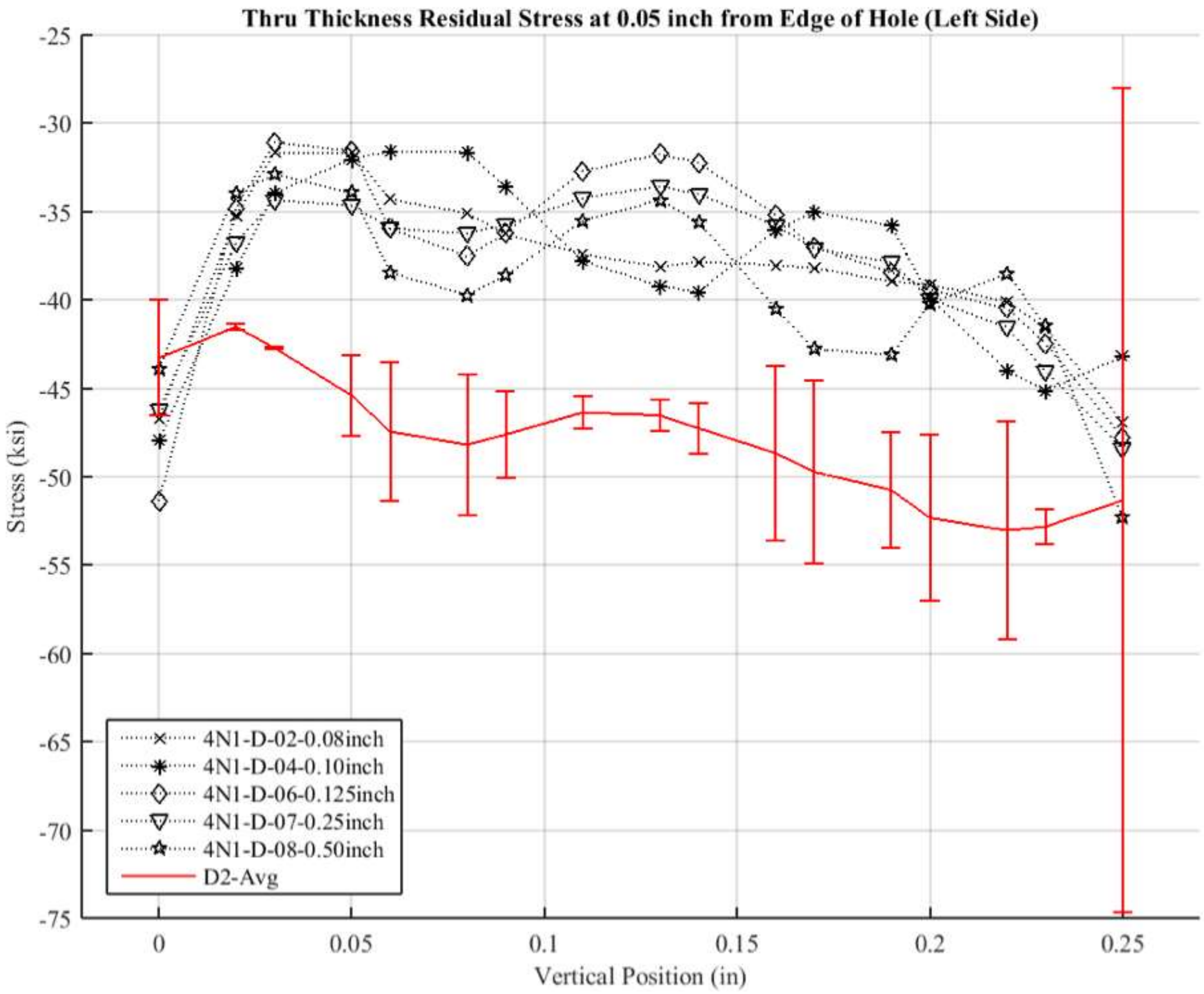
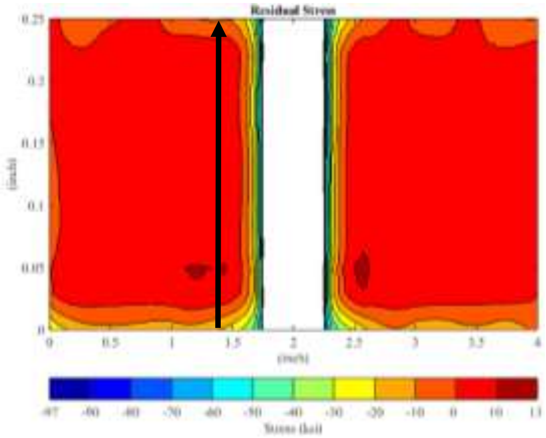
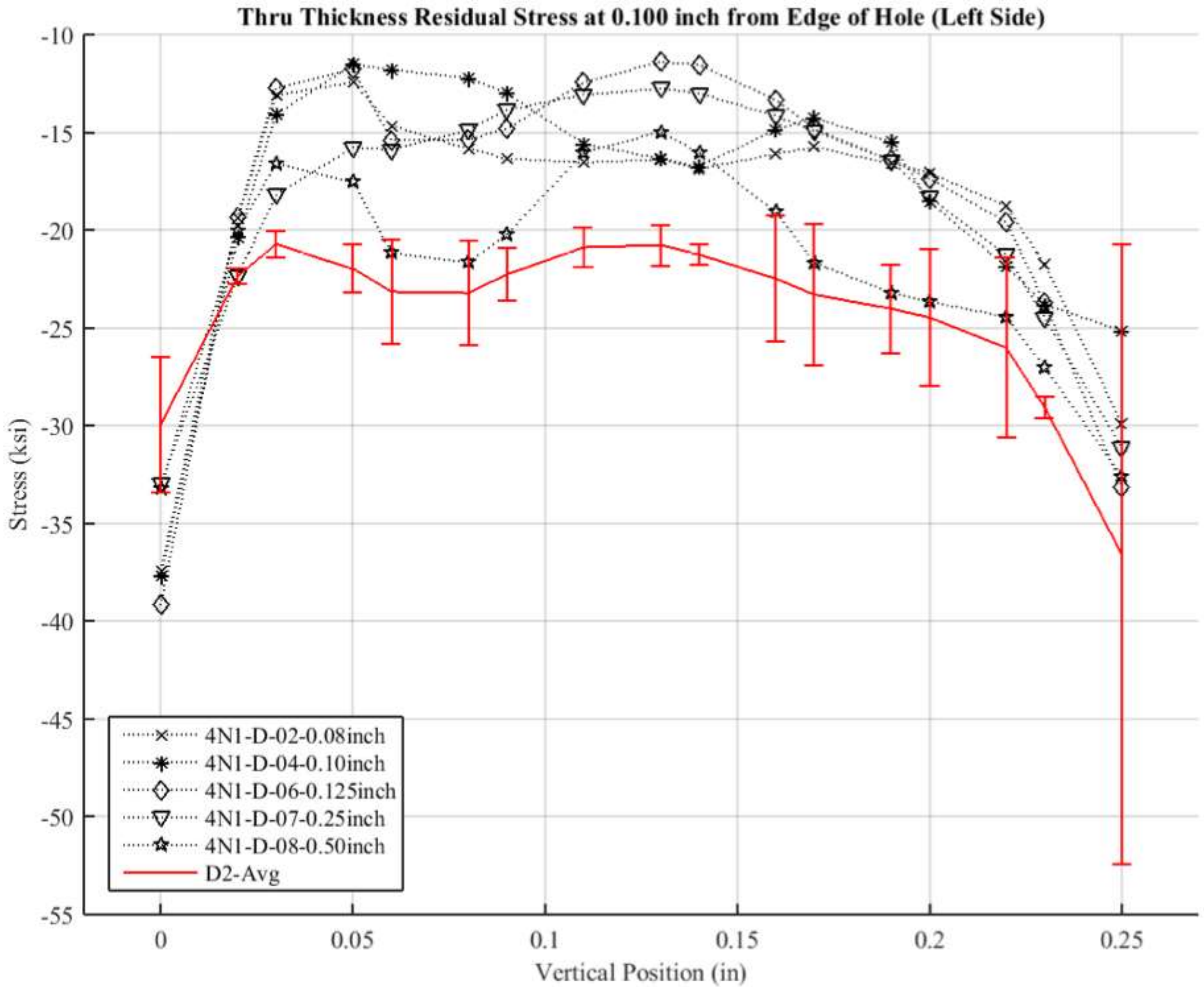




Residual Stresses in 7075-T651

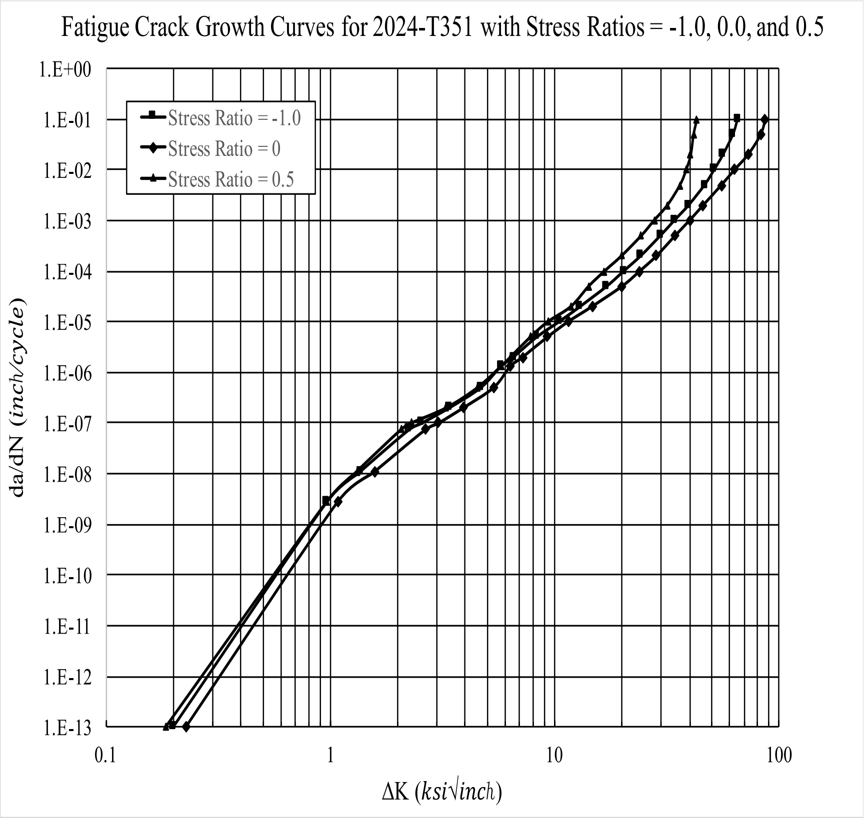
- Line Plots of Stress Through Thickness Near Hole

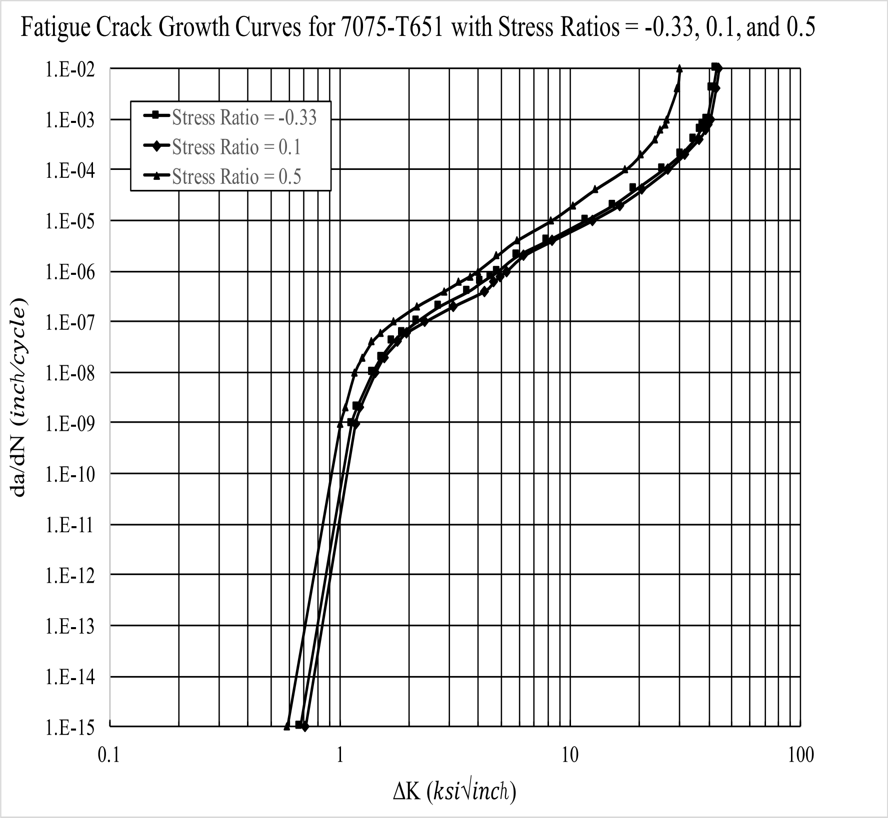




Application of MuPMuC BAMF

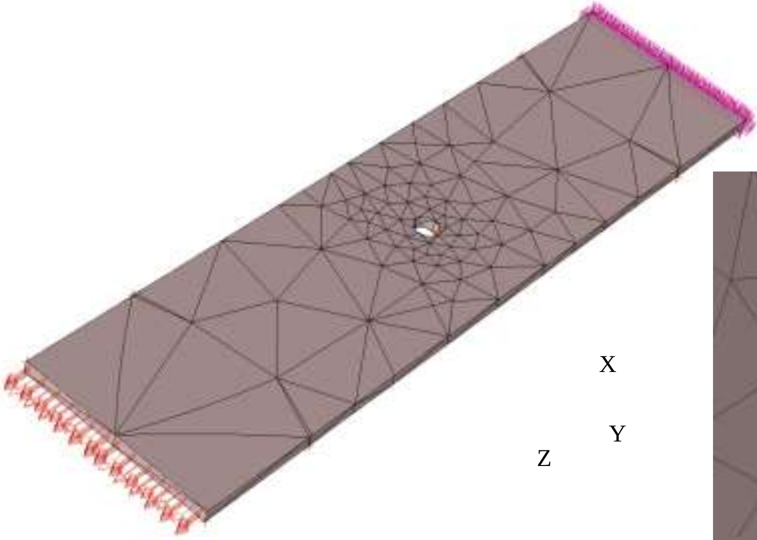
- AFGROW Inputs
  - Material file – Tabular look-up file for 2024-T3 and 7075-T6
  - Loading – Constant amplitude, R = 0.1, 25ksi & 26.5ksi
  - Growth increment = 3%

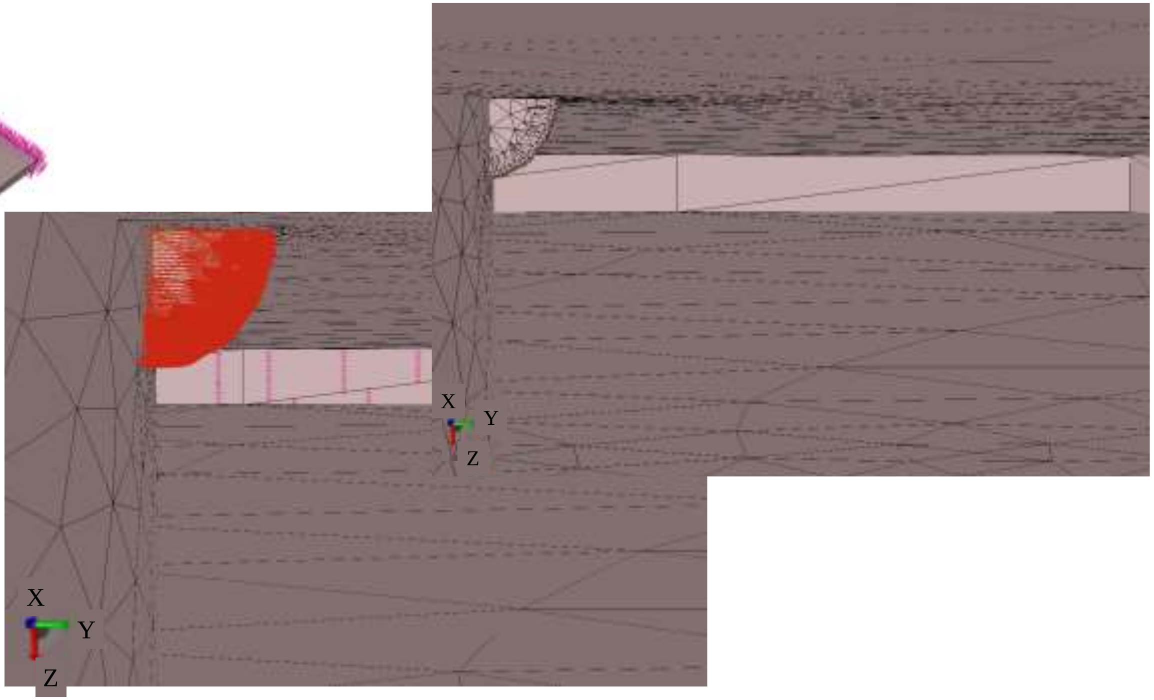




Application of MuPMuC BAMF

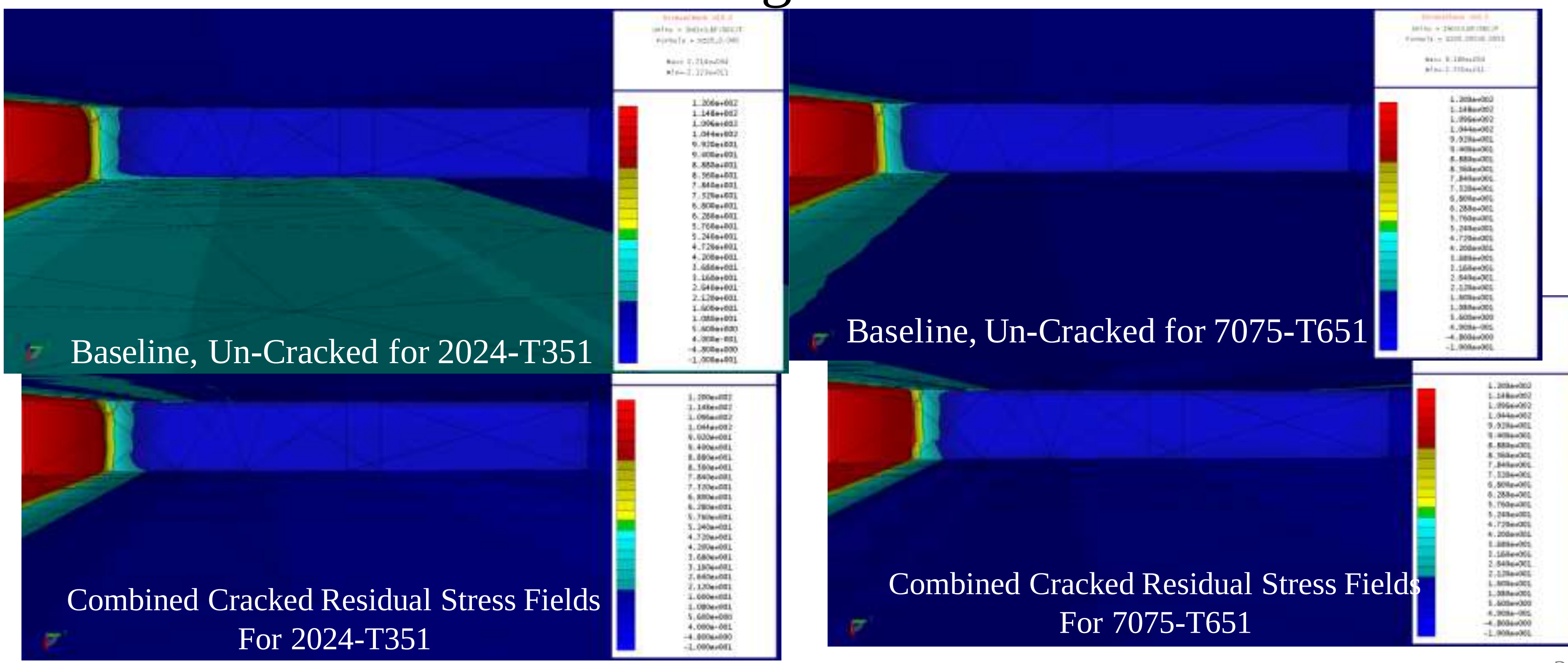
- StressCheck® Inputs
  - Initial flaw size = 0.0408x0.0486inch (derived via fractography from APES RIF)
  - Fixed constraint and far field traction
  - Meshing defined by BAMF
  - Residual stress applied as a “Crack Face” traction





Development of R.S. Function

- Bi-variant, High Order Polynomial Residual Stress
  - Four variants of residual stress function
    - Baseline, un-cracked
    - Inclusion of effect of fatigue crack
- All Stresses are the Average for the Given Condition



Baseline, Un-Cracked for 2024-T351

Baseline, Un-Cracked for 7075-T651

Combined Cracked Residual Stress Fields For 2024-T351

Combined Cracked Residual Stress Fields For 7075-T651

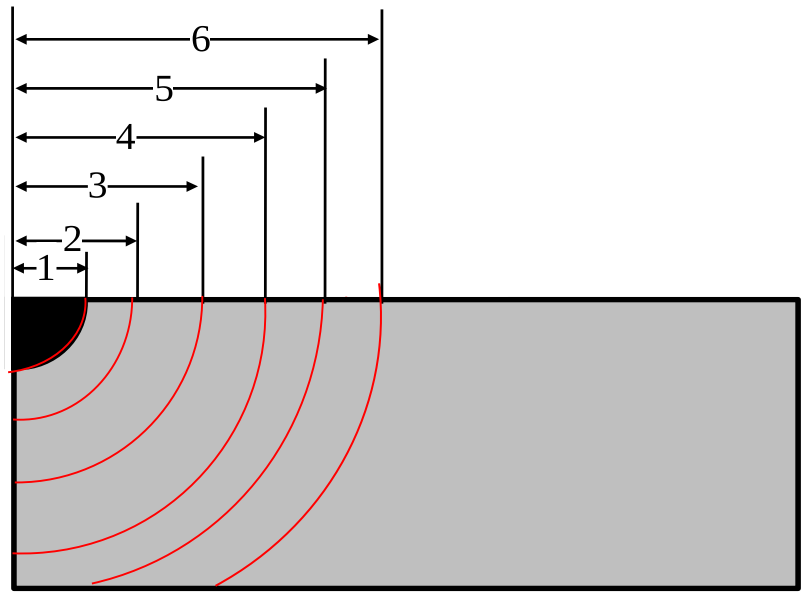
Development of R.S. Function

- Functions were Adjusted to Investigate the Effect of Including the Cracked Residual Stress Fields
  - Approximated shape as quarter-circular (assumption)

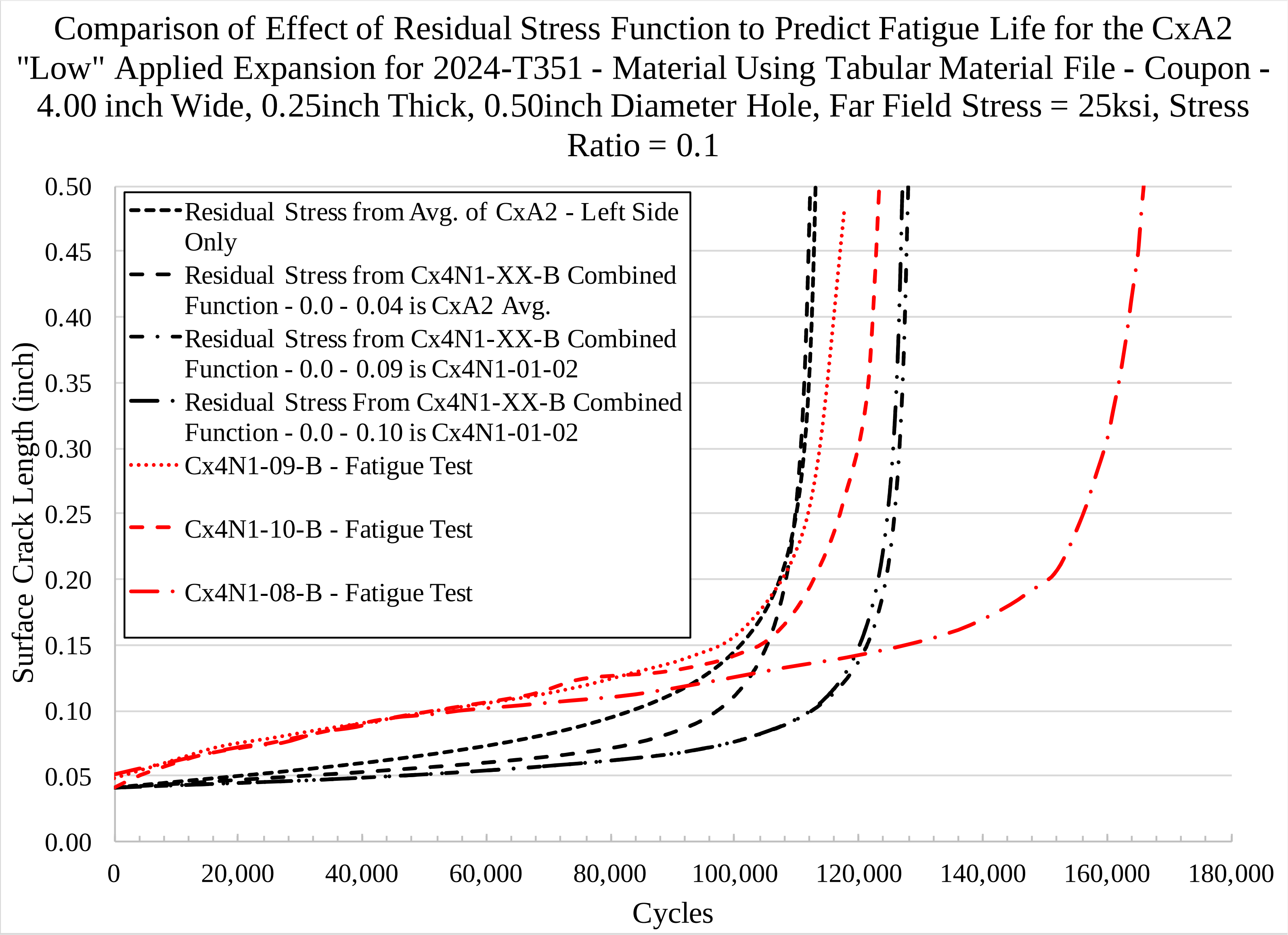
Plot Number	Residual Stress from Faituge Cracked Coupons	Distance Applied
1	Baseline Non-Cracked Residual Stress	0.00 - 0.04inch
2	Residual Stress for -01-02 (0.08inch) Crack Length	0.04 - 0.09inch
3	Residual Stress for -03-04 (0.10inch) Crack Length	0.09 - 0.1125inch
4	Residual Stress for -05-06 (0.125inc) Crack Length	0.1125 - 0.1875inch
5	Residual Stress for -07 (0.25inch) Crack Length	0.1875 - 0.375inch
6	Residual Stress for -08 (0.5inch) Crack Length	0.375 - 0.75inch

Plot Number	Residual Stress from Faituge Cracked Coupons	Distance Applied
1 2	Residual Stress for -01-02 (0.08inch) Crack Length	0.00 - 0.09inch
3	Residual Stress for -03-04 (0.10inch) Crack Length	0.09 - 0.1125inch
4	Residual Stress for -05-06 (0.125inc) Crack Length	0.1125 - 0.1875inch
5	Residual Stress for -07 (0.25inch) Crack Length	0.1875 - 0.375inch
6	Residual Stress for -08 (0.5inch) Crack Length	0.375 - 0.75inch

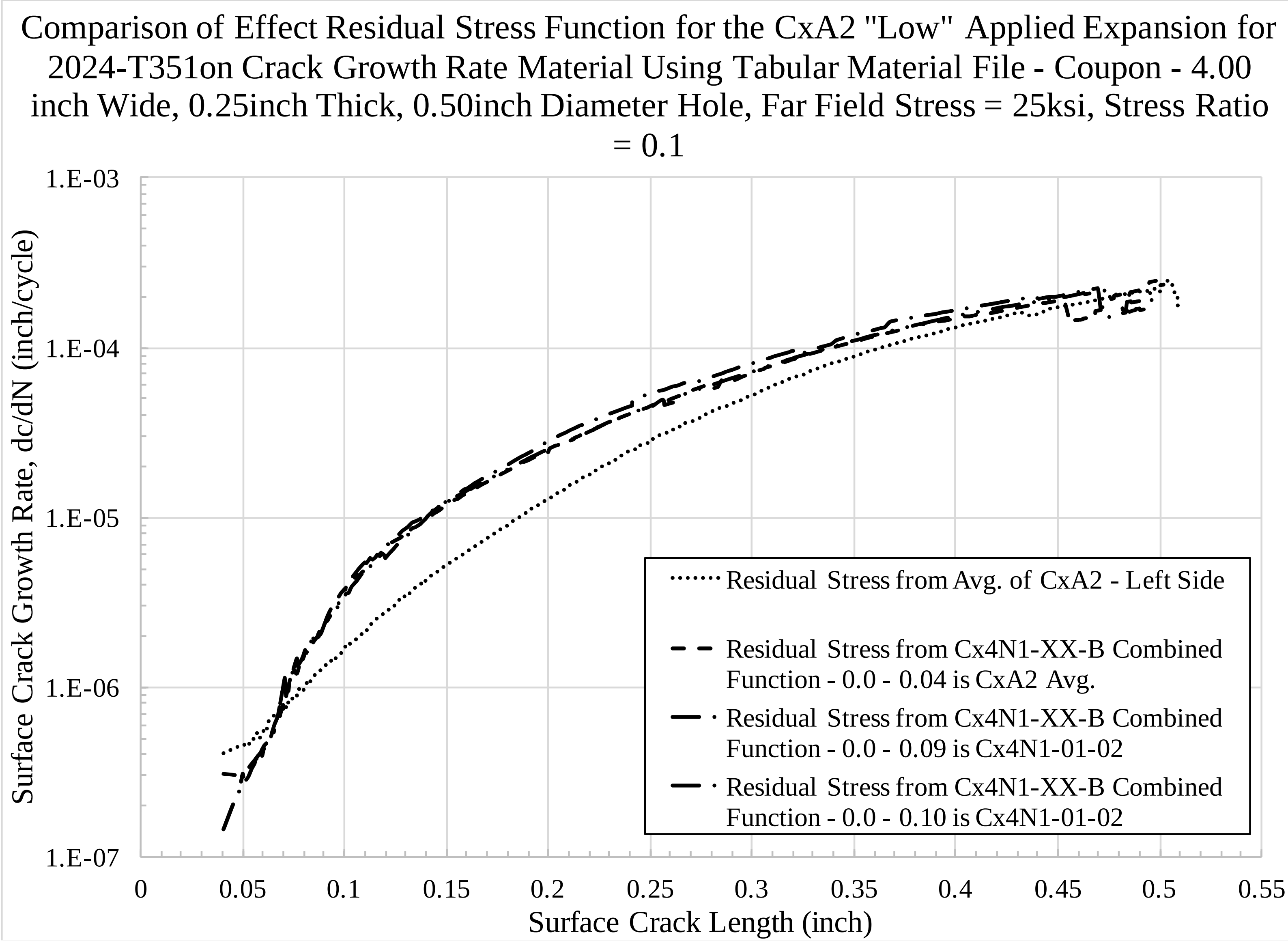
Plot Number	Residual Stress from Faituge Cracked Coupons	Distance Applied
1 2	Residual Stress for -01-02 (0.08inch) Crack Length	0.00 - 0.10inch
3	Residual Stress for -03-04 (0.10inch) Crack Length	0.10 - 0.125inch
4	Residual Stress for -05-06 (0.125inc) Crack Length	0.125 - 0.25inch
5	Residual Stress for -07 (0.25inch) Crack Length	0.25 - 0.50inch
6	Residual Stress for -08 (0.5inch) Crack Length	0.50 - 0.75inch



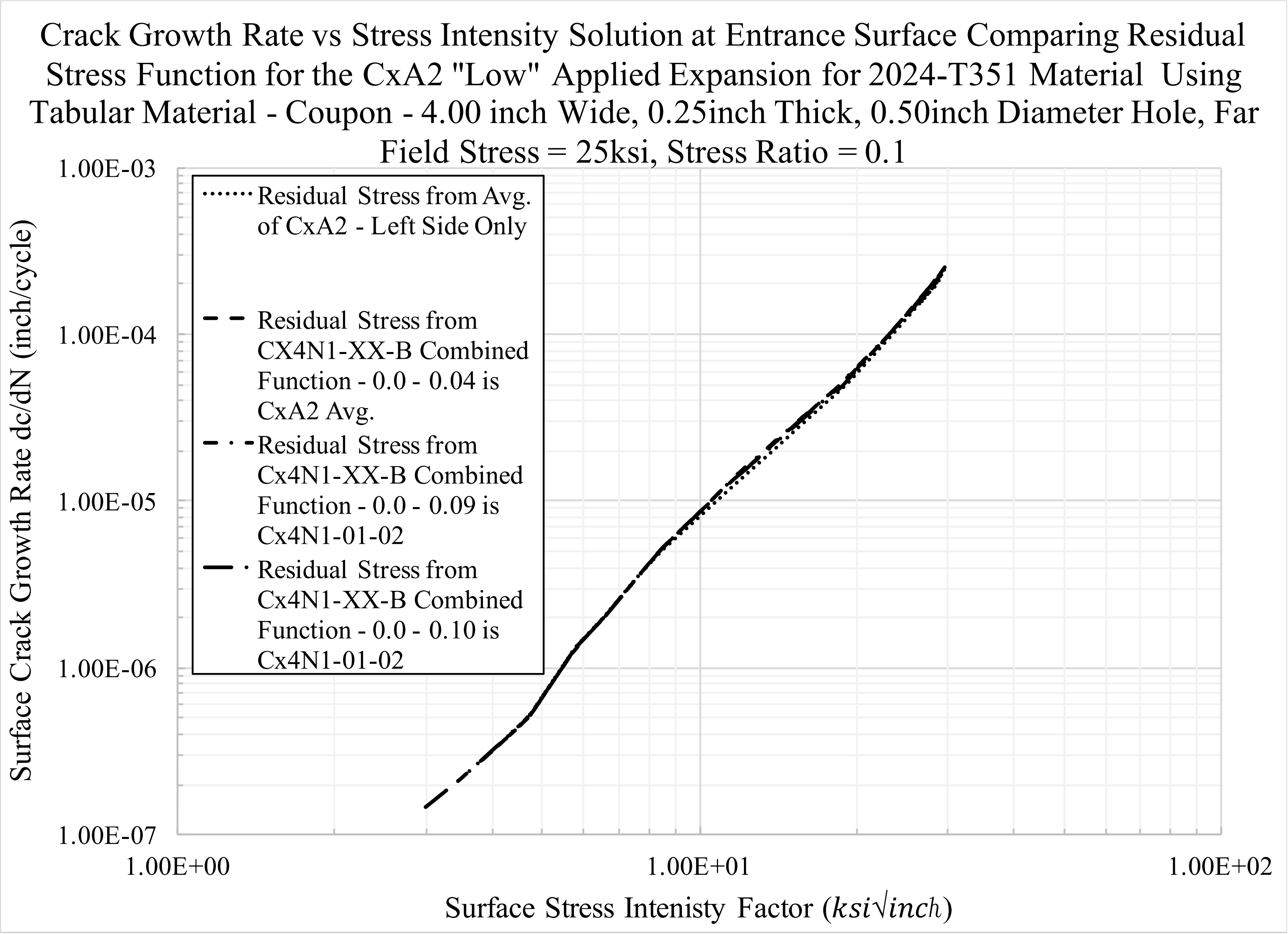
Fatigue Life Predictions



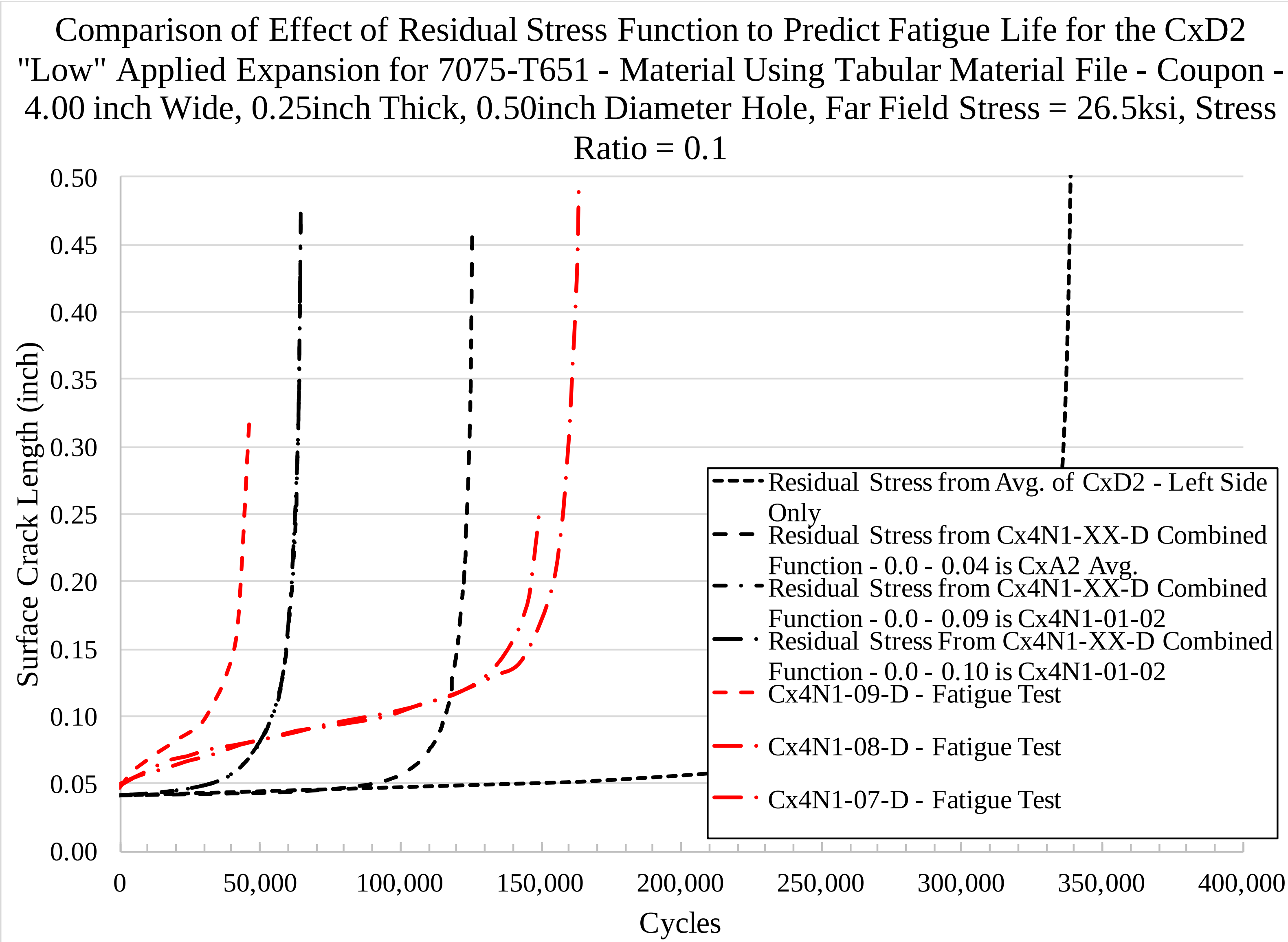
Fatigue Life Predictions



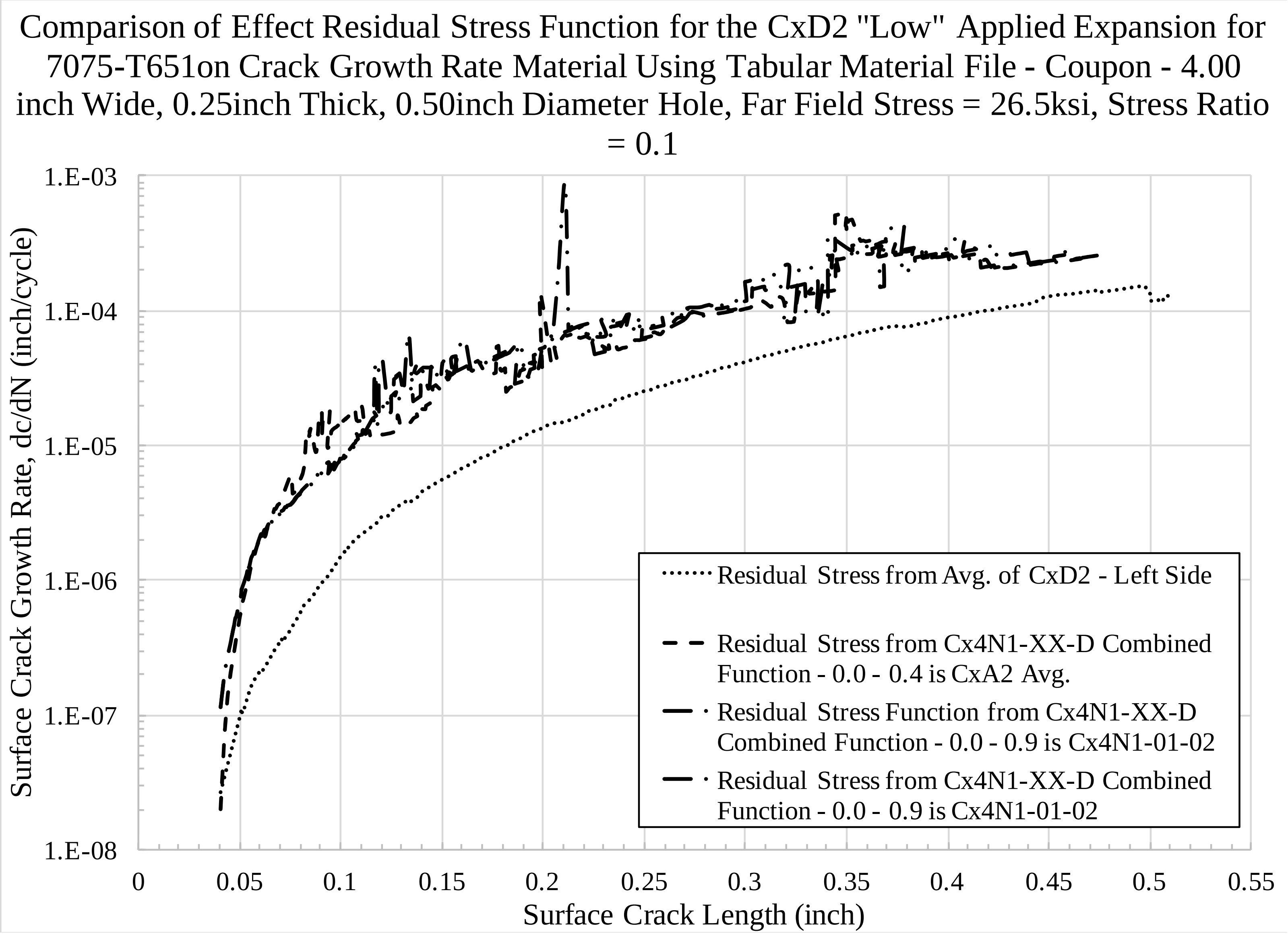
Fatigue Life Predictions



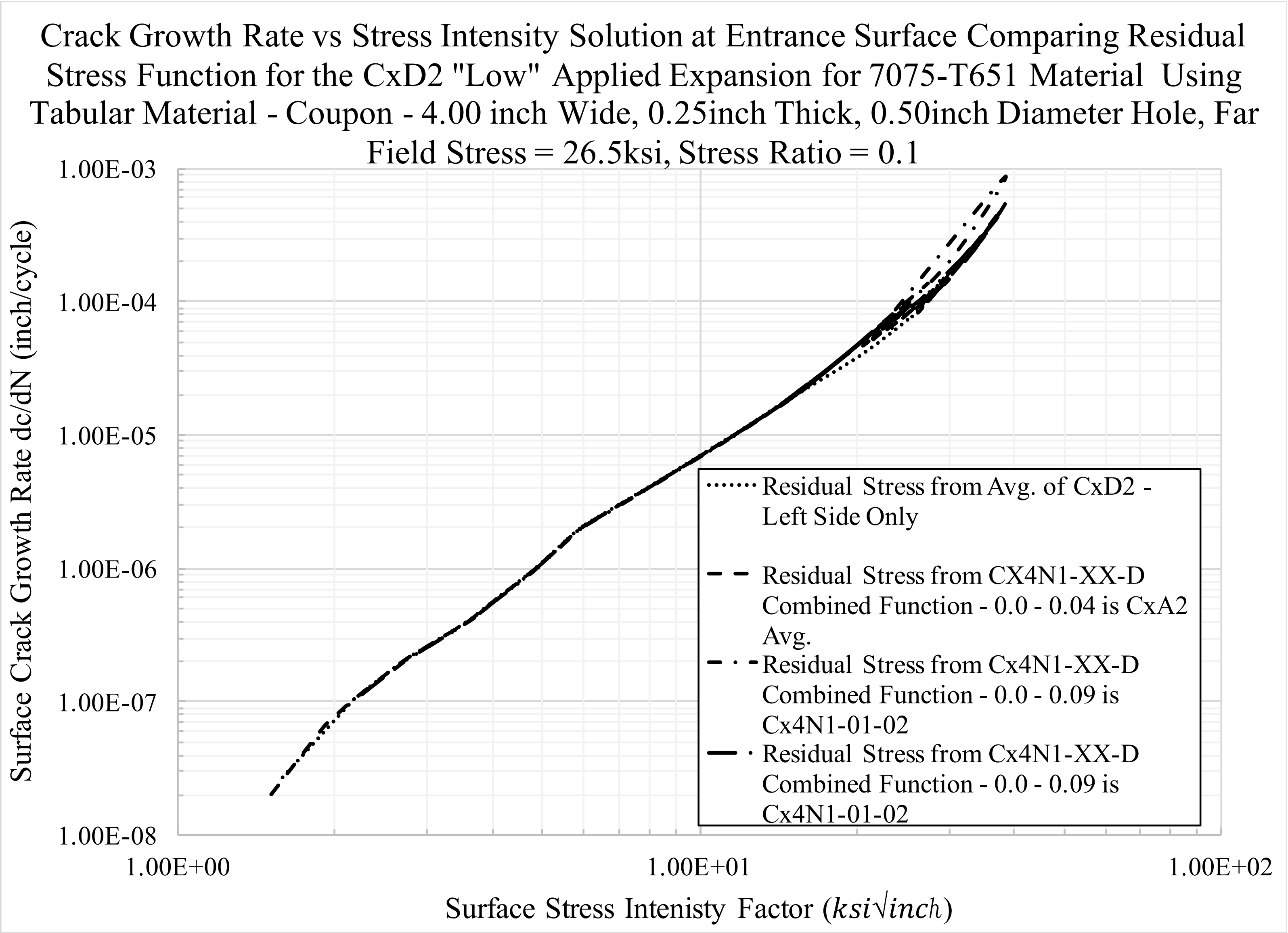
Fatigue Life Predictions



Fatigue Life Predictions



Fatigue Life Predictions



Conclusions

- It is Possible to Capture the Effect of a Fatigue Crack via the Contour Method
- A Fatigue Crack has an Effect on the Residual Stress Field Introduced via the Cold Expansion (Cx) Process
  - For 2024-T351 the magnitude of the effect is related to crack size
  - For 7075-T651 the magnitude effect is does not seem to be related to the crack size
- Inclusion of the Modified Residual Stress State into a Fatigue Life Prediction Adjusts the Life
  - For both the 2024-T351 and 7075-T651 the effect moves the prediction closer to the average tested fatigue life

Recommendations

- Develop Standard Statistical Methods for Quantifying “Difference” in 2D and 3D Data Fields
- Perform Additional Design Space Measurements of Cracked Coupons to Determine the Bounds of Application
- Develop Mathematical Representation of Effect of Crack in 3D Space
  - Develop methods for adjusting residual stress field to account for the effect of the crack, thus reducing the extensive “measurement” burden
- Look at Different Shape Approximations for Effected Residual Stress Field

Questions?

References

1. Prime, M.B., (2001). "*Cross-Sectional Mapping of Residual Stresses by Measuring the Surface Contour After a Cut*", Journal of Engineering Materials and Technology, Vol. 123, Issue 2, pg. 162-168.
2. Bueckner, H., (1958). "*The Propagation of Cracks and the Energy of Elastic Deformation*", Transactions of the American Society of Mechanical Engineers, Vol. 80, pg. 1225-1230.
3. Prime, M.B., DeWald, A.T., (2013). The Contour Method, Chapter 5, Practical Residual Stress Measurement Methods, John Wiley & Sons Ltd., West Sussex, United Kingdom.