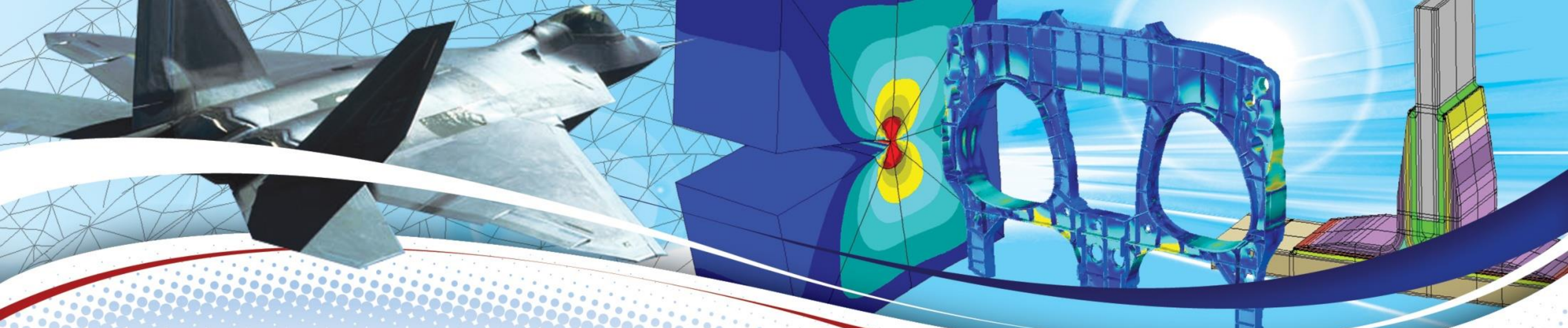

2015 AFGROW User's Conference
15-16 September 2015, Layton UT

Factors Affecting Fatigue Crack Propagation from Cold-Expanded Holes

Ricardo Actis ESRD, Inc.

16 September 2015

esrd

StressCheck

Outline

- Simulation
  - How we understand simulation
- Modeling fatigue crack propagation
  - Modeling assumptions and sources of error
- Model predictions
  - With & without cold-working
- Factors affecting predictions
  - Variation in residual stresses
- Summary and Conclusions

What is simulation?

- Simulation: The imitative representation of the functioning of one system by means of the functioning of another
  - Functioning of structural systems and the imitative representation by mathematical models
    - A mathematical model is a transformation of a set of data **D** based on a precisely formulated idea of physical reality **I** to the quantities of interest **F**

$$\mathbf{(D, I) \rightarrow F}$$

What is simulation?

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Physical reality. One should never confuse an idea of physical reality with physical reality itself:

The layman always means, when he says "reality" that he is speaking of something self-evidently known; whereas to me it seems the most important and exceedingly difficult task of our time is to work on the construction of a new idea of reality. – Wolfgang Pauli (Nobel Prize in Physics, 1945).

Our intellect does not draw its laws from nature but tries – with varying degrees of success – to impose upon nature laws which it freely invents. Theories are free creations of our own minds, the results of almost poetic intuition, of an attempt to understand intuitively the laws of nature. – Karl Popper (1902-1994) regarded as the one of the greatest philosopher of Science of the 20th century.

Uncertainties in Simulation

- Evaluation of the effects that uncertainties in **(D, I)** have on the data of interest **F**.
  - Two types of uncertainties
    - Aleatory (random) uncertainties associated with the statistical dispersion of model parameters
      - Residual stresses, crack propagation data, etc.
    - Epistemic (model-form) uncertainties
      - Associated with the definition of mathematical models

$$\mathbf{(D, I)} \rightarrow \mathbf{F}$$

Numerical Simulation

$(D, I) \rightarrow F \rightarrow F_{num}$

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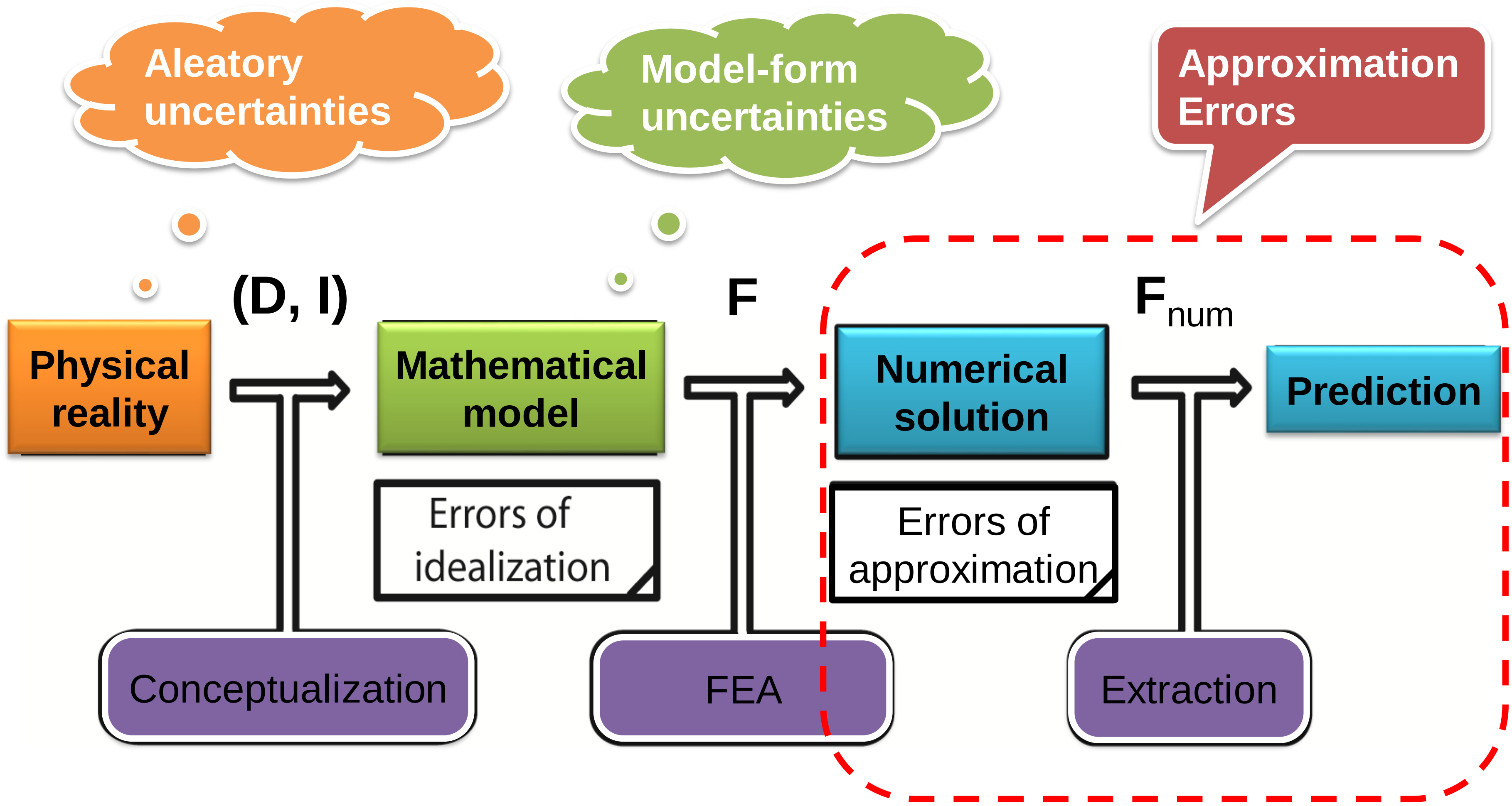

Modeling Crack Propagation **Assumptions**

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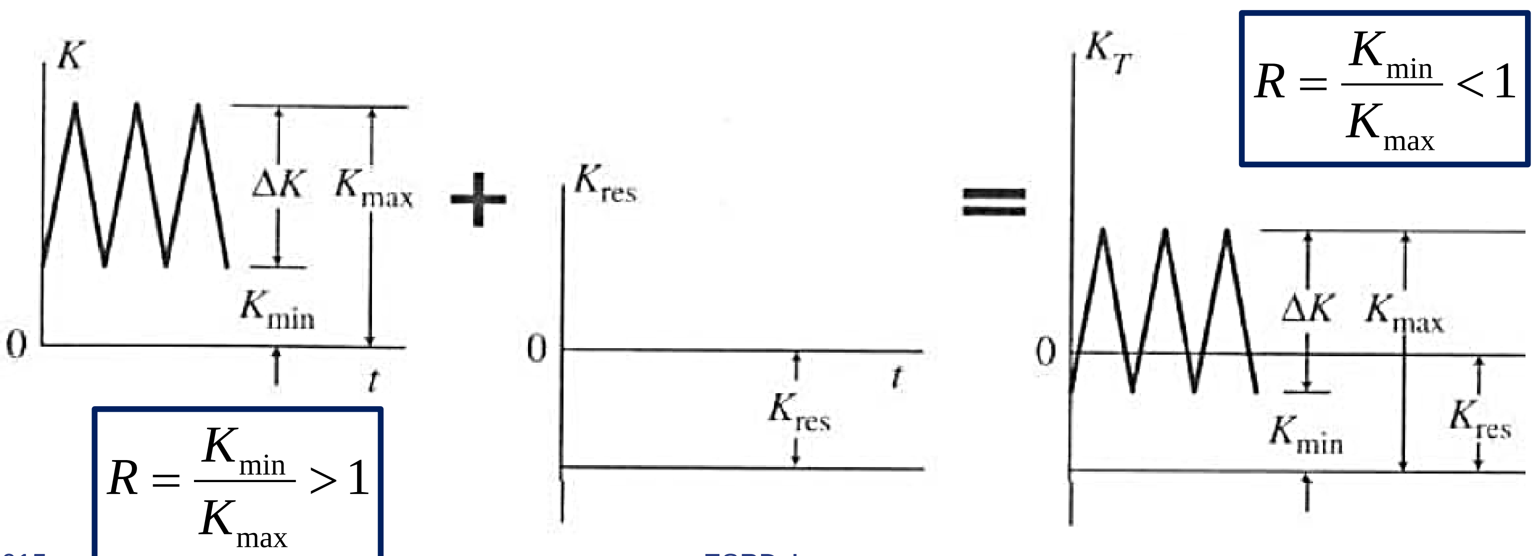
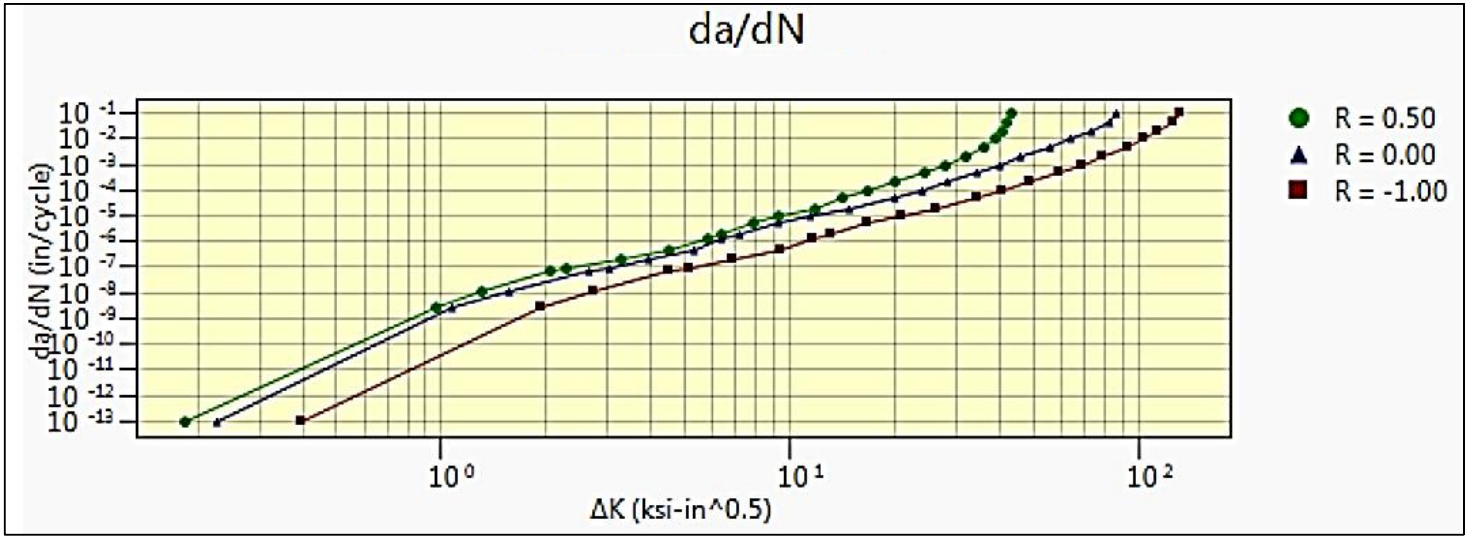
- The driver of fatigue crack propagation is the stress intensity factor amplitude ΔK_I
  - The principle of superposition is applicable (LEFM)
  - Residual stresses only affect the load ratio



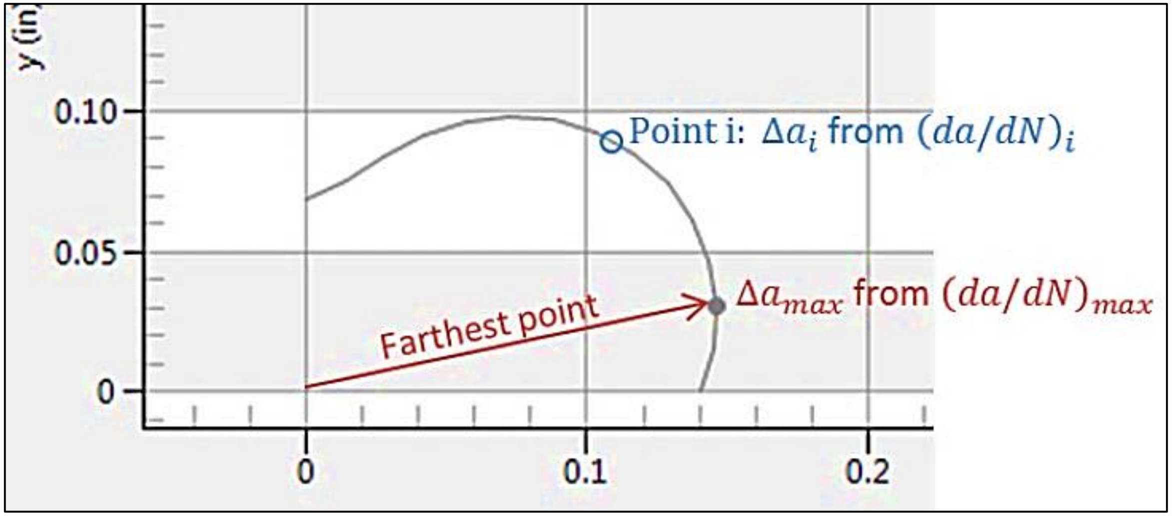
Modeling Crack Propagation **Assumptions**

- Crack propagation rates derived from da/dN – ΔK curves obtained from calibration experiments at fixed load ratios
  - Curves derived for thru-cracks are applicable for corner cracks
  - Interpolation for finding da/dN for load ratios not covered by the experimental data



Modeling Crack Propagation **Assumptions**

- The direction of crack growth is normal to the crack front
  - The crack grows in the plane of the initial flaw
  - Along the crack front the load ratio depends on the RS at the point
  - Only the residual stresses normal to the plane are needed to compute K_{res}
- The shape of the crack is controlled by the growth rate



Modeling Crack Propagation
Sources of Error

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Sources of Error – Model of Crack Propagation		
Aleatory	**Epistemic**	**Approximation**
Initial stresses before CX	Driver of crack propagation	Computation of SIFs with RS
Residual stresses data	Direction of crack extension	Computation of SIFs remote load
da/dN-ΔK data	Interpolation and fitting of test data	Numerical Integration to find ΔN $\Delta N_j = (da/dN)^{-1} \Delta a_j$
		Number of control points to define the crack shape

Model Predictions

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- Prediction using CP Model
  - Number of cycles to failure & shape of the crack front
    - 7075 Specimen with central hole – No CW
    - 2024 & 7075 Specimen with central hole – CW
- Uncertainty in predictions
  - Effect of variation in residual stresses
  - Spectrum load vs. equivalent constant amplitude loading

Prediction 7075-T6
Specimen Non Cold-Worked Hole

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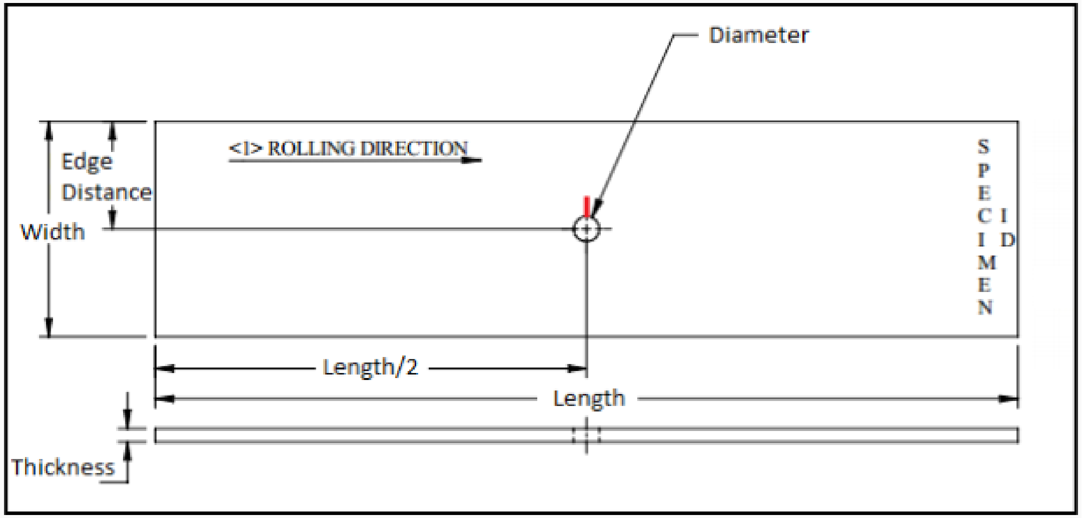


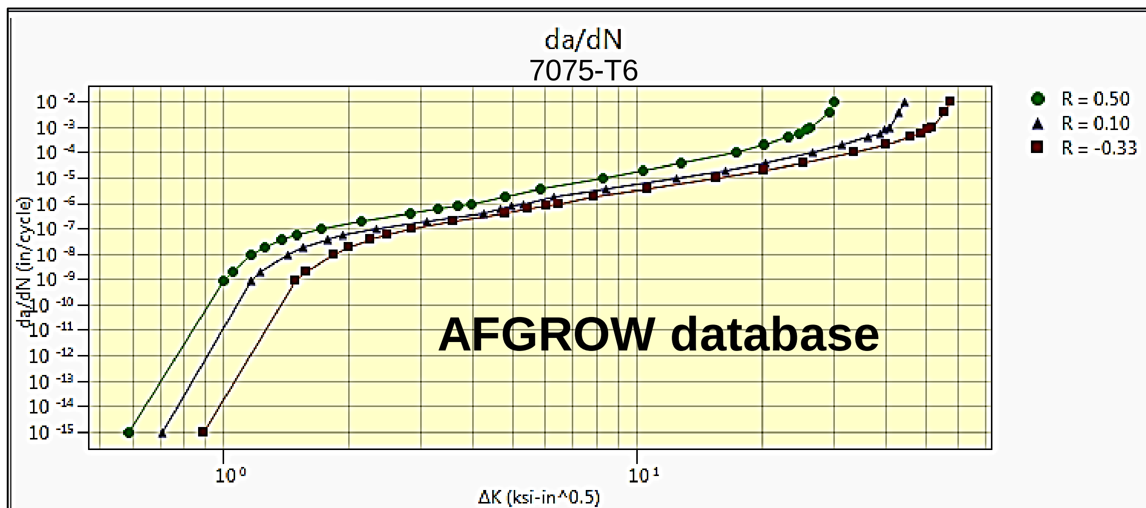
Constant Amplitude loading

Material Properties

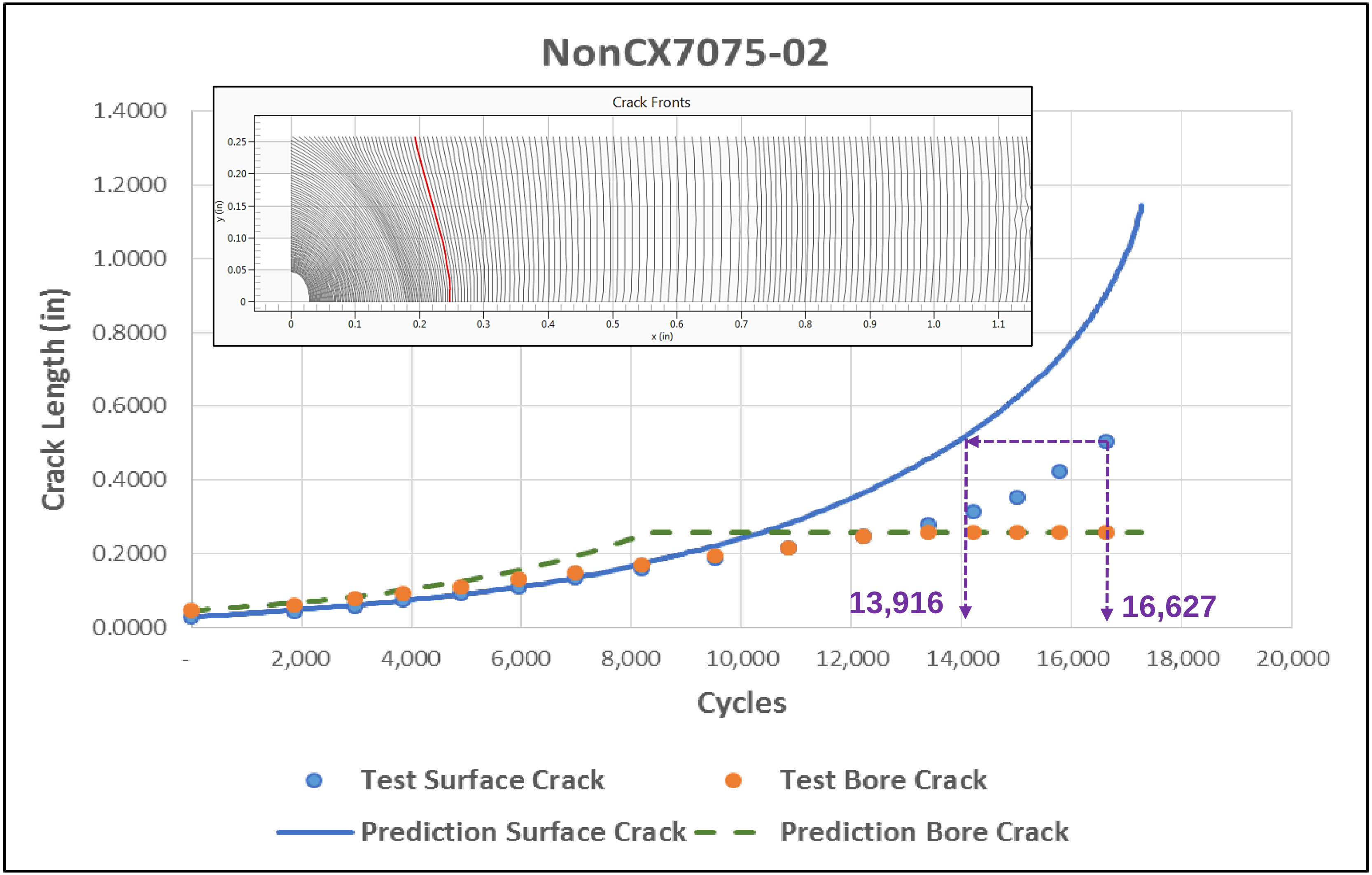
Name:	7075T6	
Modulus of elasticity:	10500	ksi
Poisson's ratio:	0.33	
Yield strength:	62	ksi
Plane strain toughness, KIc:	27	ksi-in$^{0.5}$
Plane stress toughness, Kc:	53	ksi-in$^{0.5}$

Dimensions

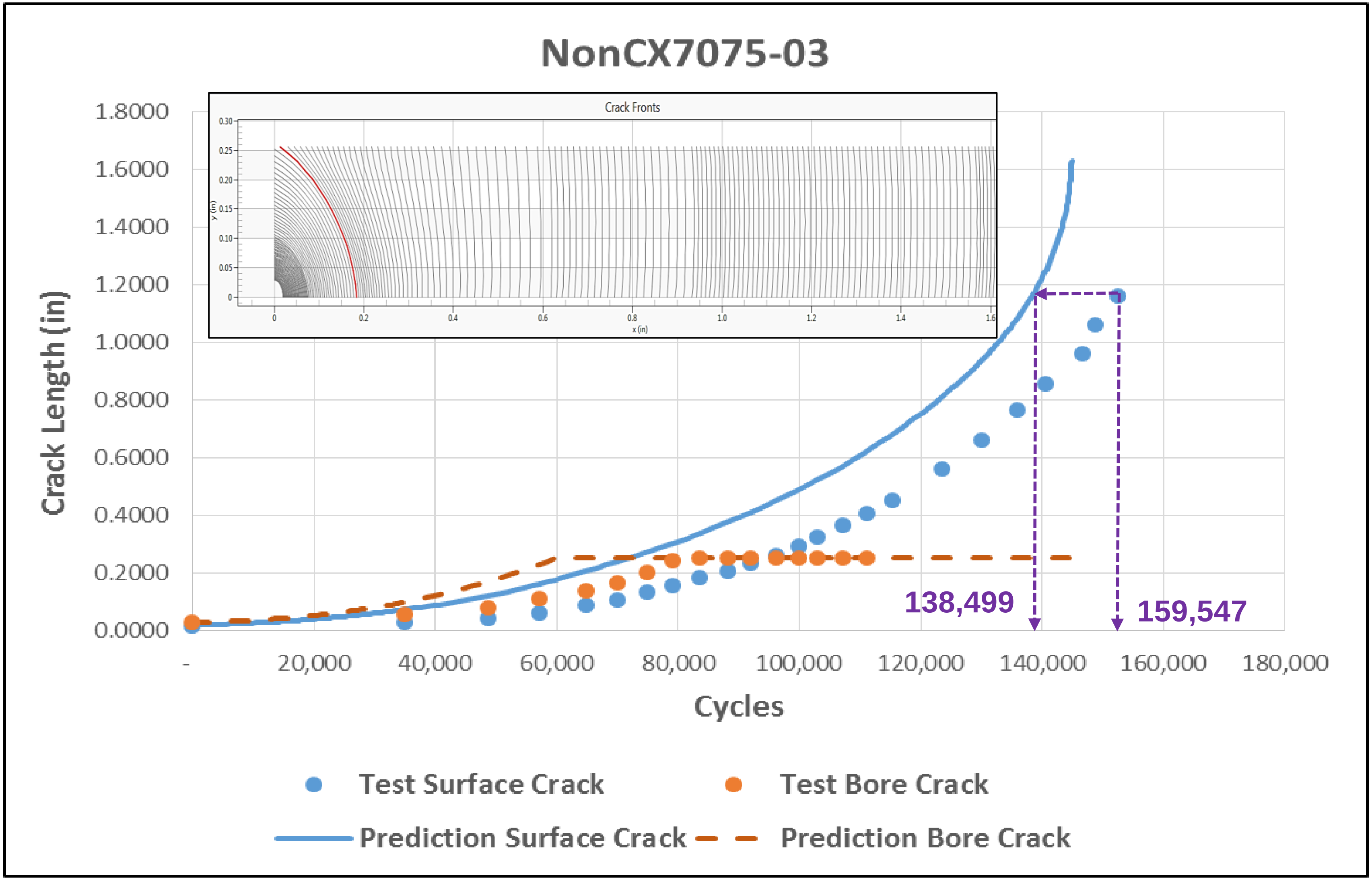
Diameter:	0.50079	in
Test section width:	4	in
Thickness:	0.256	in
Edge distance:	2	in
Length:	16	in



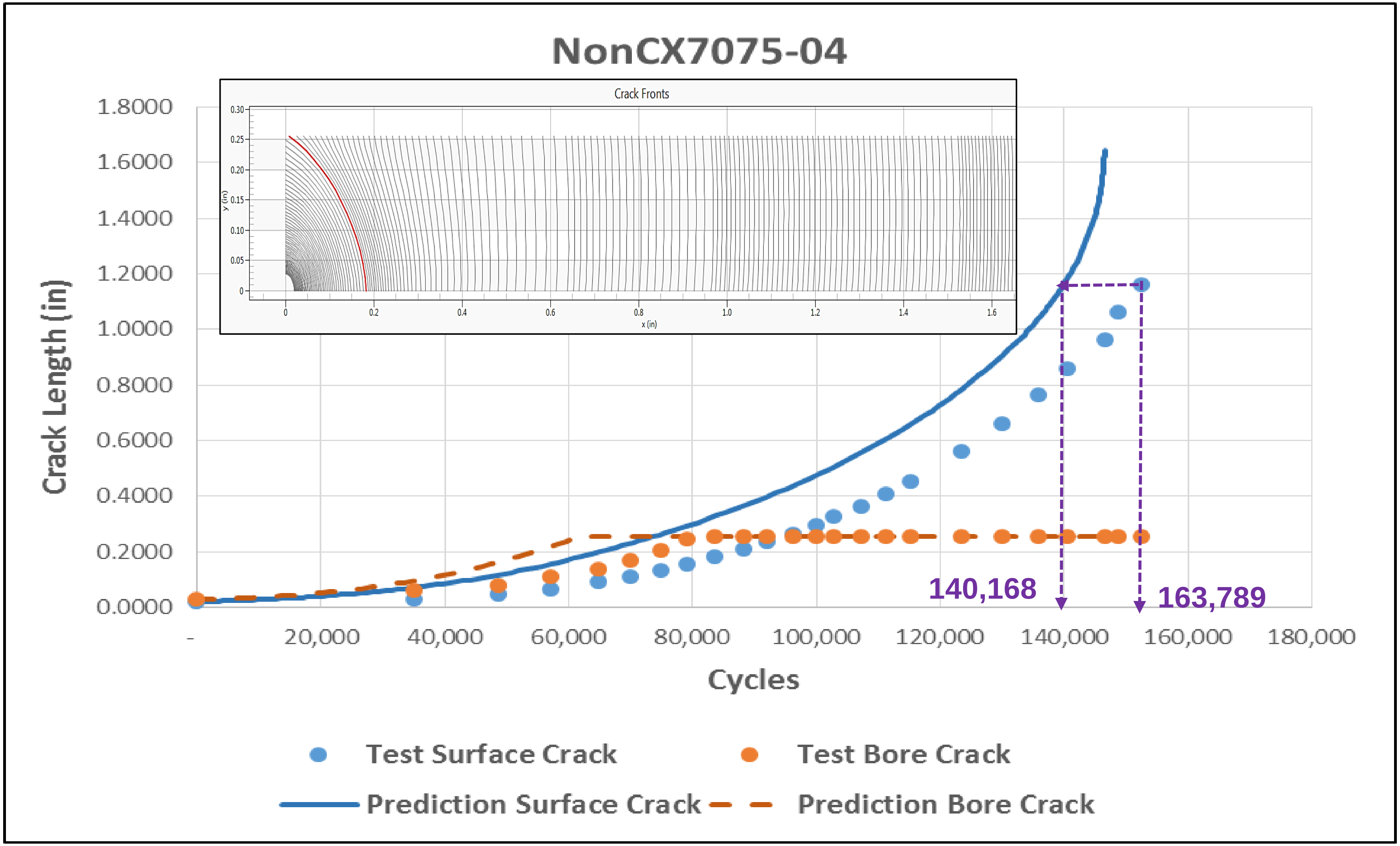
Prediction 7075-T6
Specimen NonCX7075-02



Prediction 7075-T6
Specimen NonCX7075-03



Prediction 7075-T6
Specimen NonCX7075-04



Prediction 2024-T3
Specimen with Cold-Worked Hole

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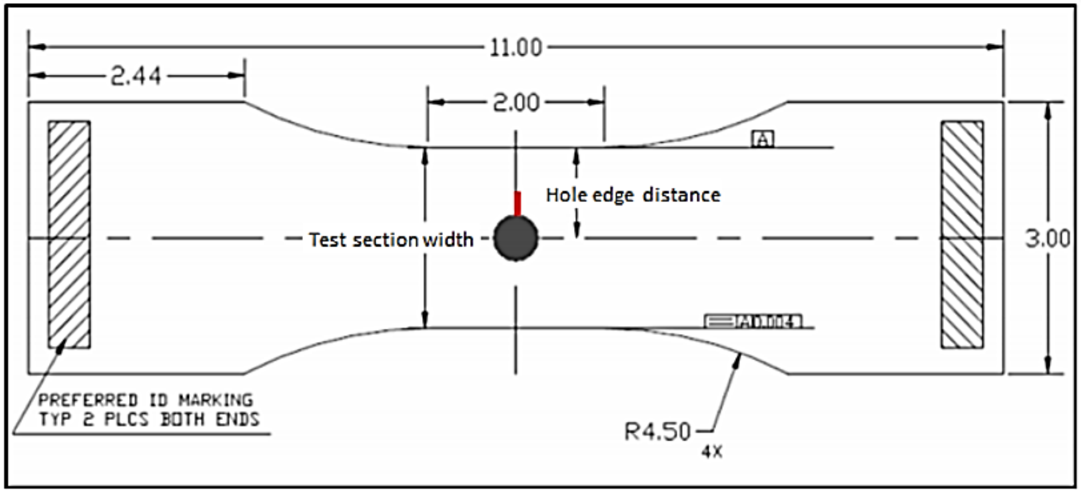
Constant Amplitude loading

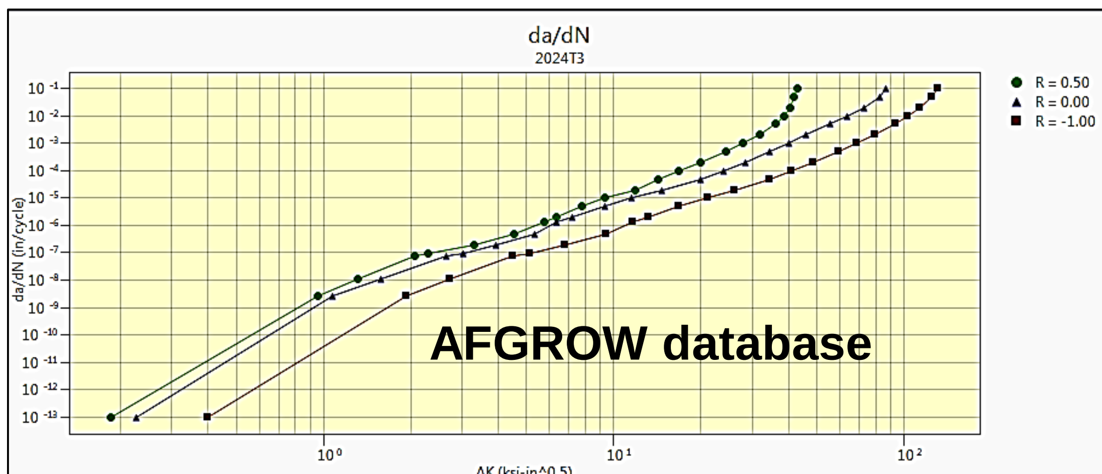


Material Properties

Name:	2024T3	
Modulus of elasticity:	10000	ksi
Poisson's ratio:	0.3	
Yield strength:	48	ksi
Plane strain toughness, KIc:	35	ksi-in$^{0.5}$
Plane stress toughness, Kc:	90	ksi-in$^{0.5}$

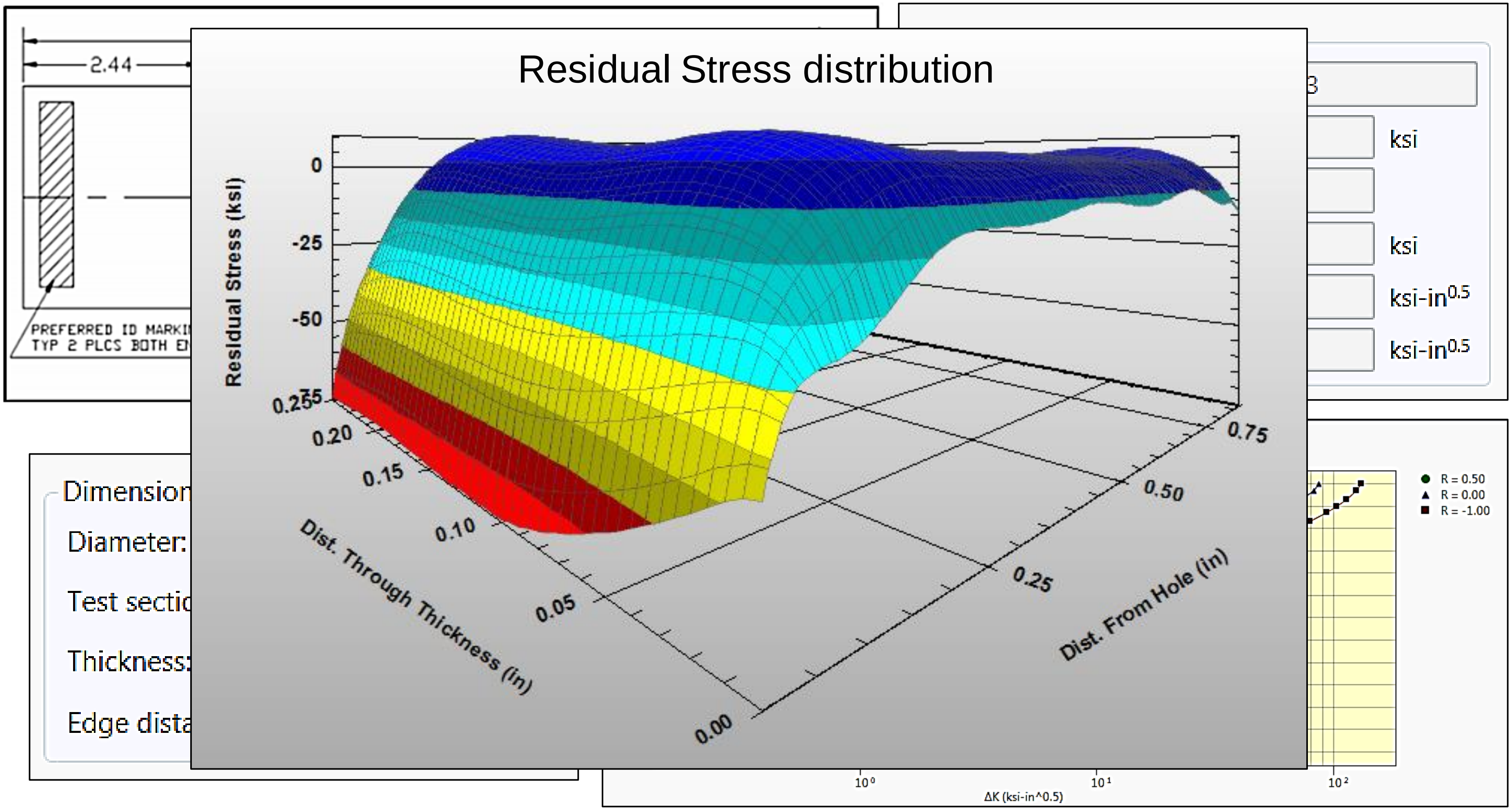
Dimensions

Diameter:	0.25	in
Test section width:	2	in
Thickness:	0.25	in
Edge distance:	1	



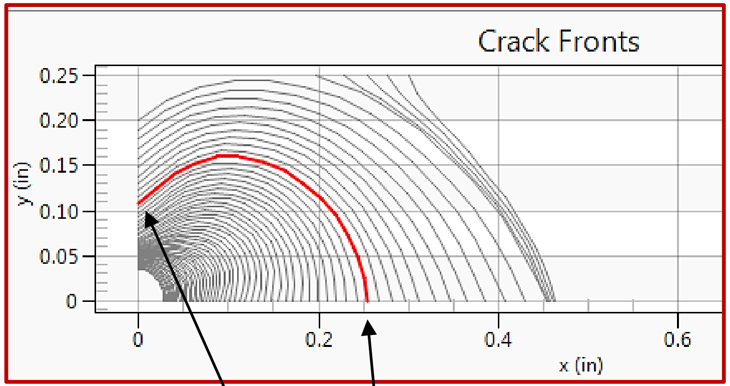
Prediction 2024-T3
Specimen with Cold-Worked Hole

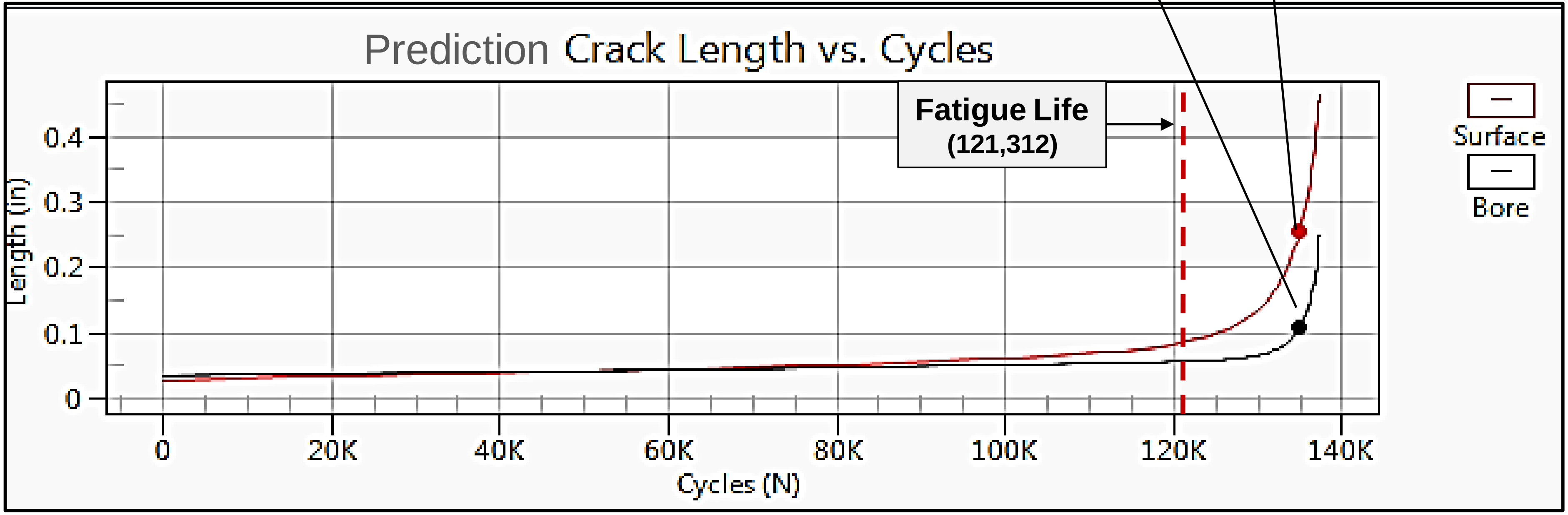
Constant Amplitude loading



Prediction 2024-T3
Cold-Worked & Pre-Cracked

Coupon	Surface Pre-crack, in.	Bore Pre-crack, in.	Fatigue Life, Cycles
1	0.02810	0.03486	121312
2	0.02166	0.04136	65890
3	0.02200	0.03204	126587
4	0.02032	0.02936	180066





Prediction 2024-T3
Cold-Worked & Pre-Cracked

Coupon	Surface Pre-crack, in.	Bore Pre-crack, in.	Fatigue Life, Cycles
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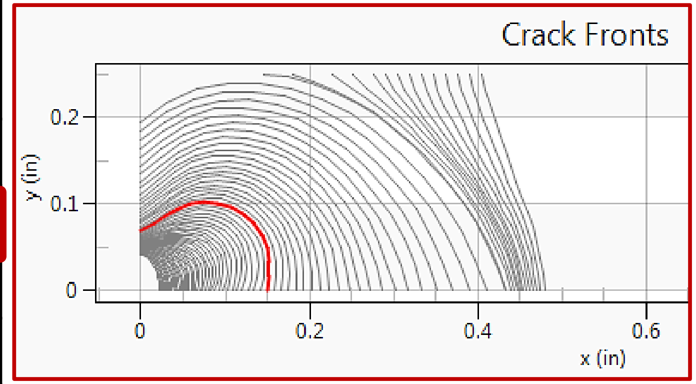

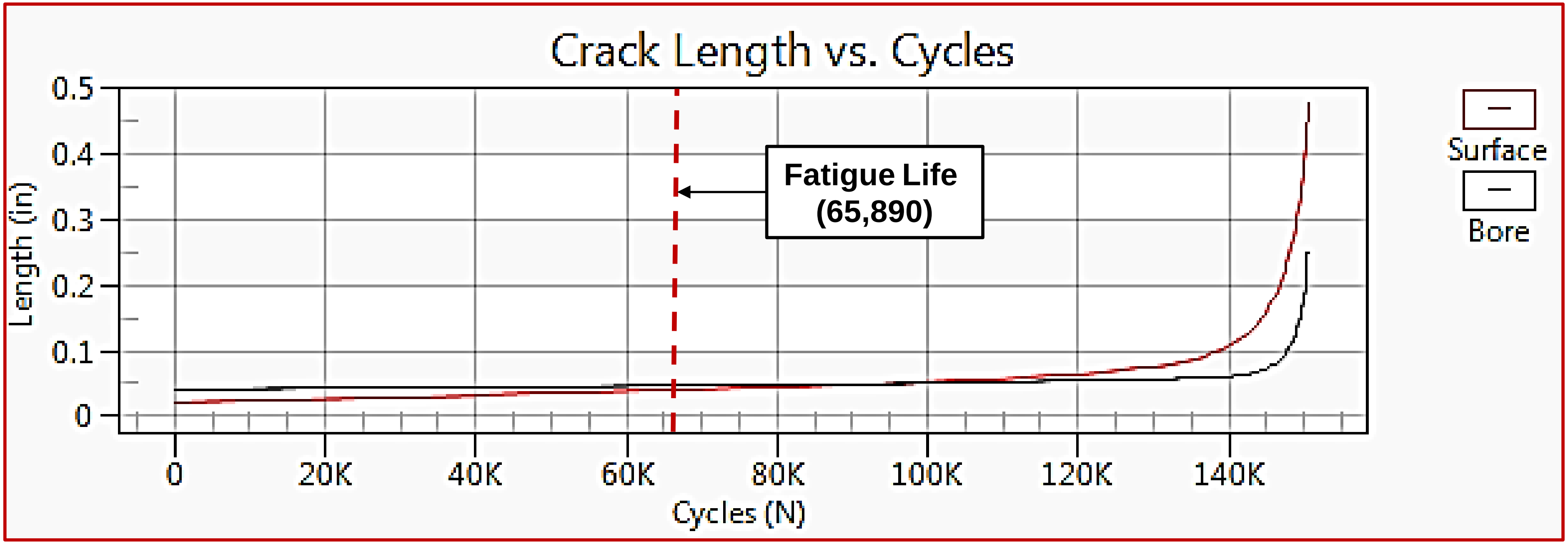

Prediction 2024-T3
Cold-Worked & Pre-Cracked

STRESSCHECK

Coupon	Surface Pre-crack, in.	Bore Pre-crack, in.	Fatigue Life, Cycles
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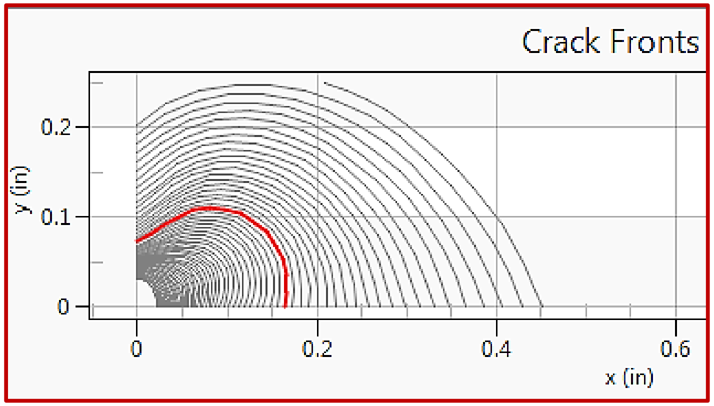

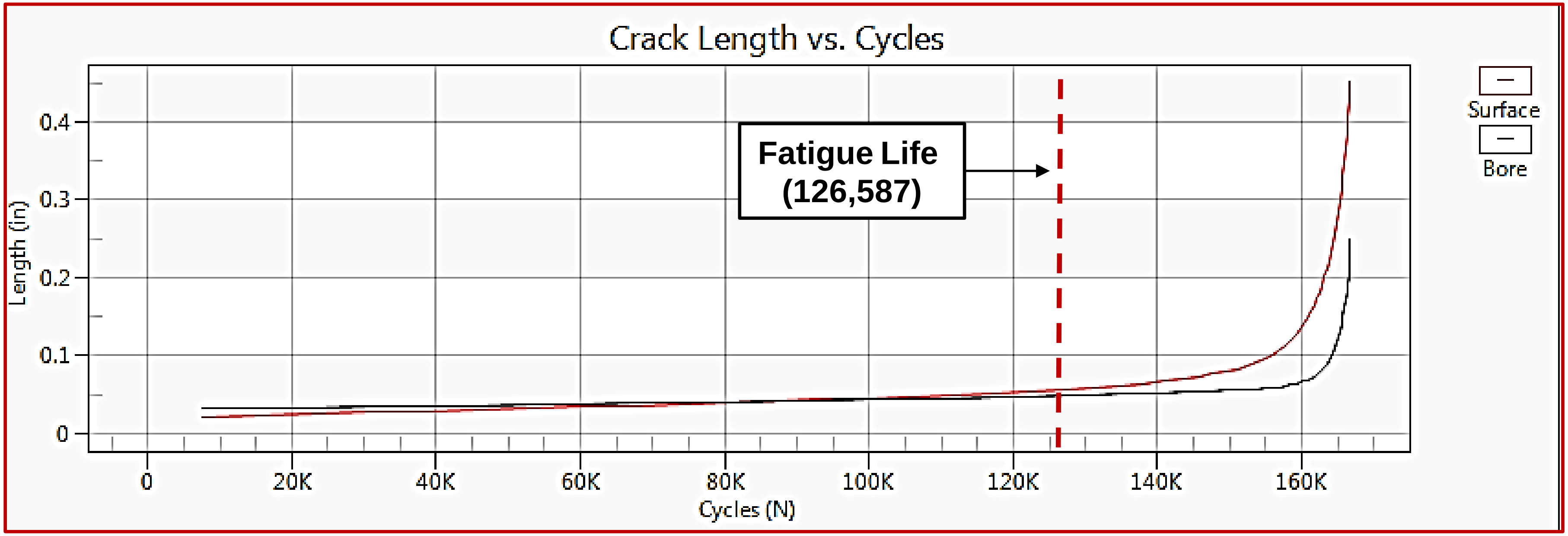

Prediction 2024-T3
Cold-Worked & Pre-Cracked

Coupon	Surface Pre-crack, in.	Bore Pre-crack, in.	Fatigue Life, Cycles
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2	0.02166	0.04136	65890
3	0.02200	0.03204	126587
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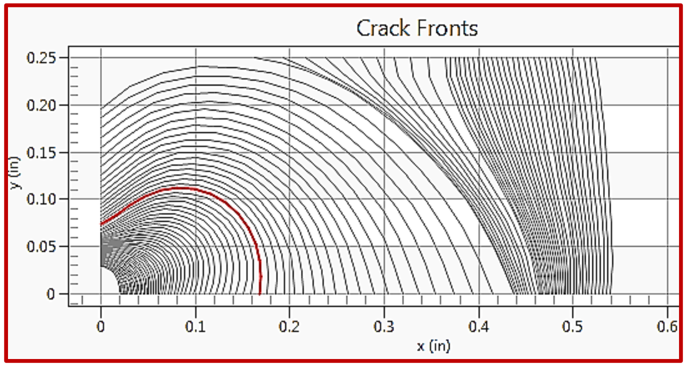
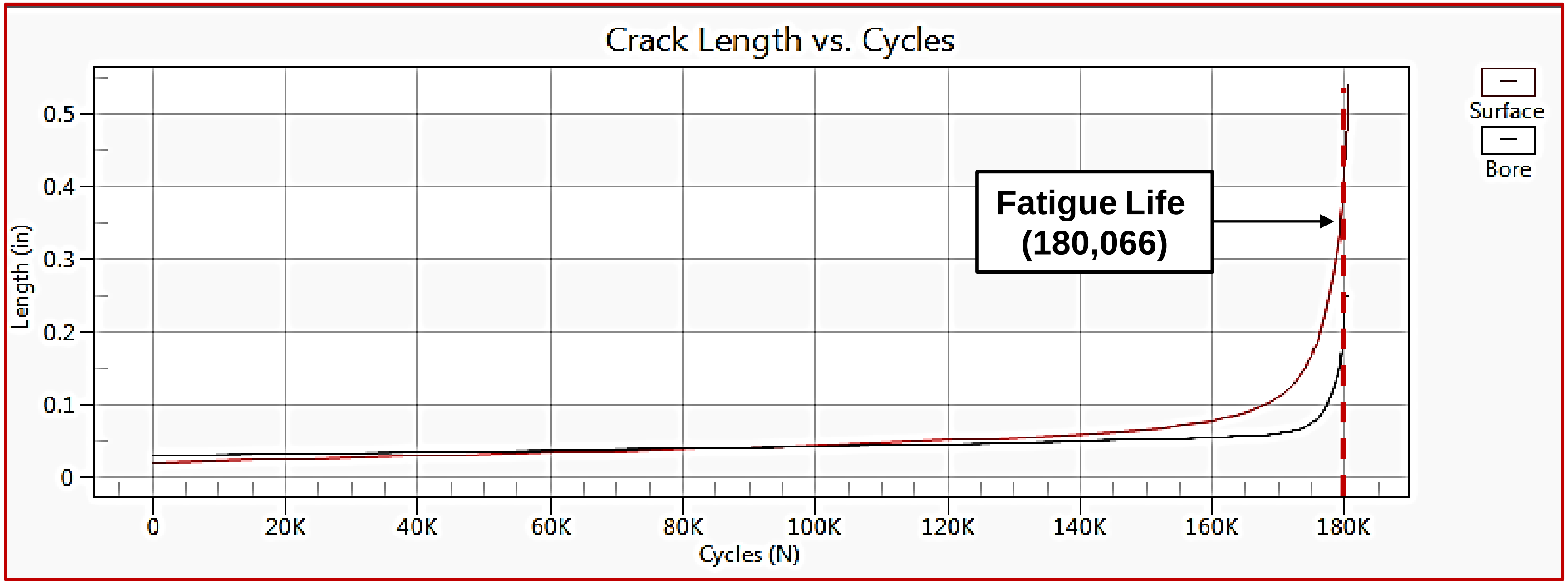
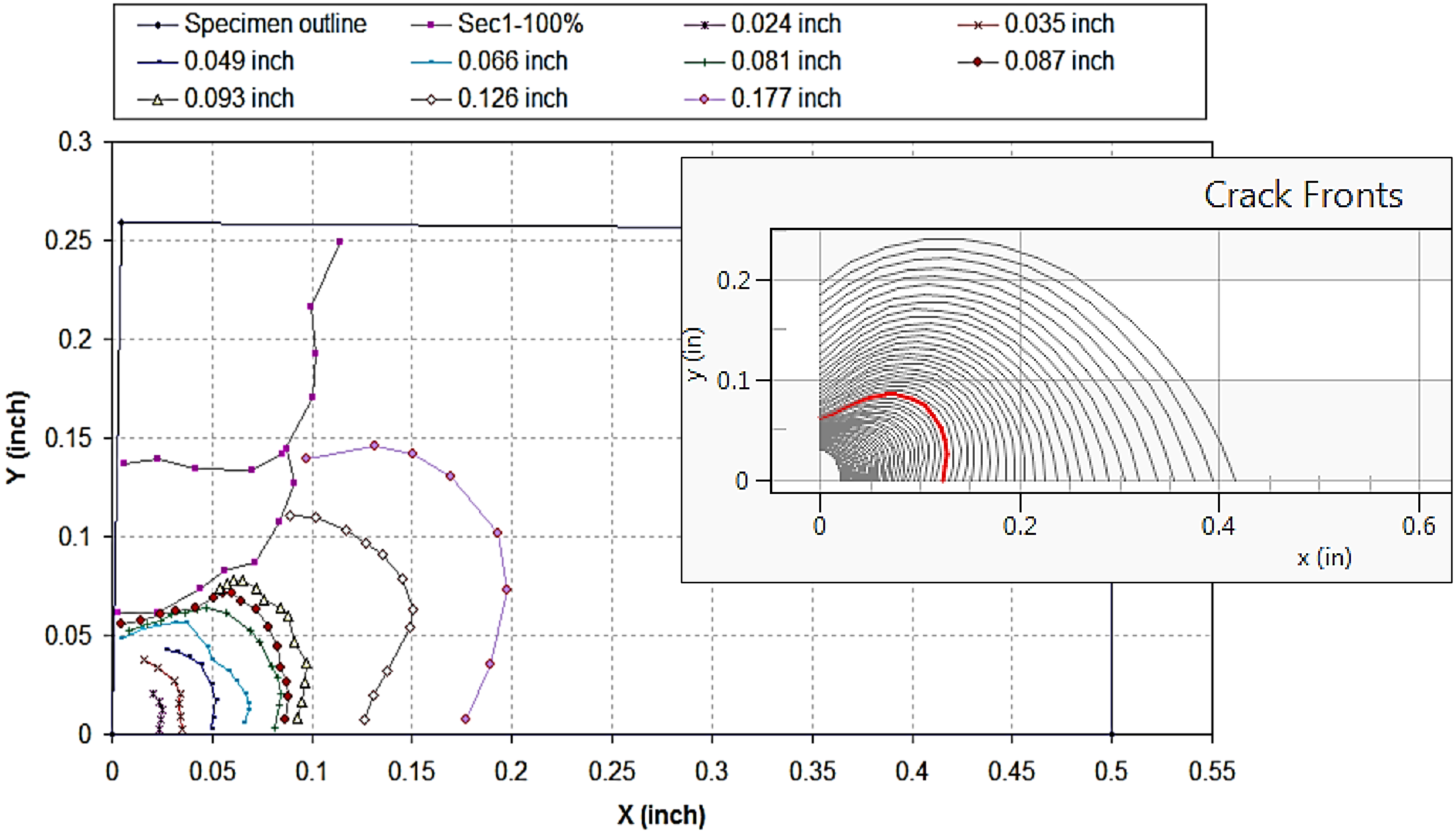




Typical Crack Propagation Map



Effect of Variations in RS

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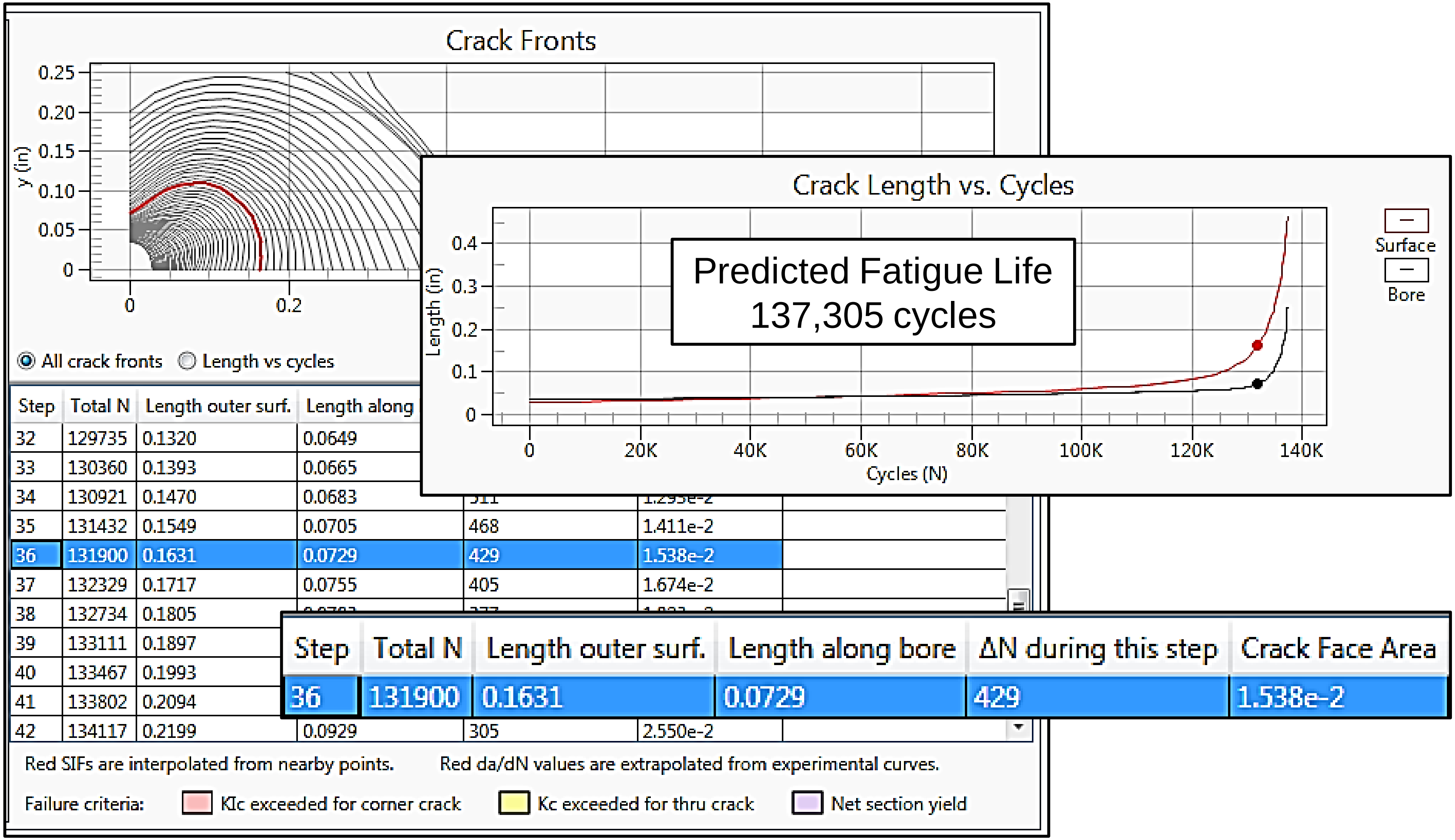
- Assessment of the effect of aleatory uncertainty in the prediction of the fatigue life
- Specimen 1 (CX & pre-crack) was analyzed with 3 RS distributions
  - RS as measured
  - RS 10% lower than measured
  - RS 10% higher than measured

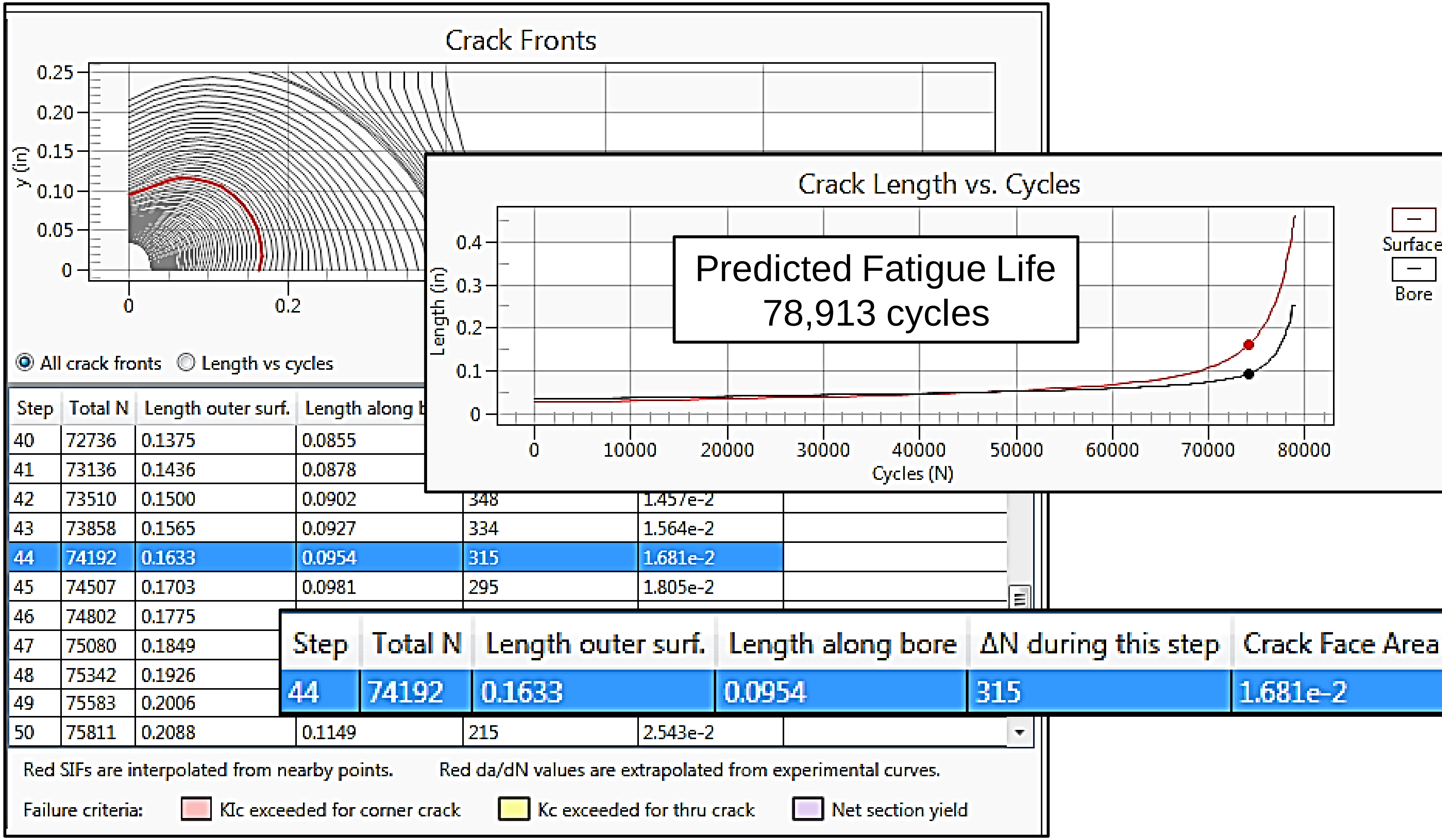
Prediction 2024-T3
Specimen 1 – RS as Measured



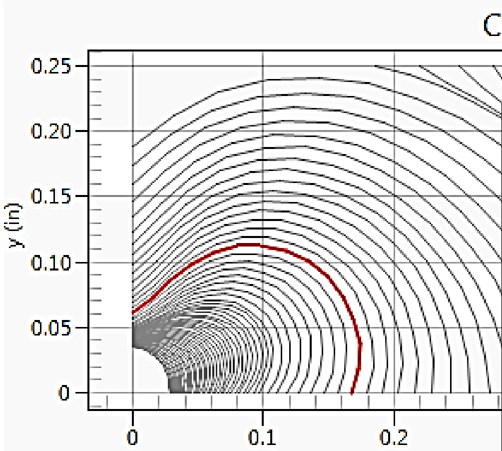
Step	Total N	Length outer surf.	Length along		
32	129735	0.1320	0.0649		
33	130360	0.1393	0.0665		
34	130921	0.1470	0.0683		
35	131432	0.1549	0.0705	468	1.411e-2
36	131900	0.1631	0.0729	429	1.538e-2
37	132329	0.1717	0.0755	405	1.674e-2
38	132734	0.1805			
39	133111	0.1897			
40	133467	0.1993			
41	133802	0.2094			
42	134117	0.2199	0.0929	305	2.550e-2

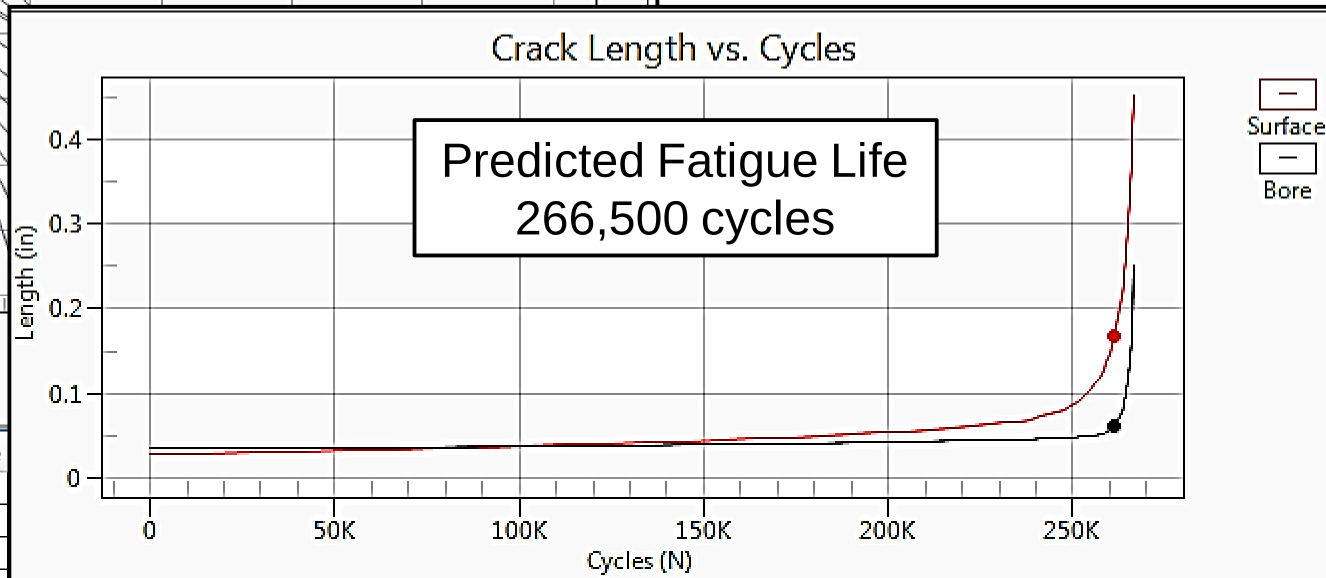
Step	Total N	Length outer surf.	Length along bore	ΔN during this step	Crack Face Area
36	131900	0.1631	0.0729	429	1.538e-2

Prediction 2024-T3
Specimen 1 – RS 10% Lower



Prediction 2024-T3
Specimen 1 – RS 10% Higher





Step	Total N	Length outer surf.	Length along bore		
37	257157	0.1182	0.0508		
38	258190	0.1269	0.0521		
39	259104	0.1363	0.0537		
40	259906	0.1462	0.0556	[illegible]	[illegible]
41	260621	0.1567	0.0581	638	1.452e-2
42	261259	0.1677	0.0613	566	1.628e-2
43	261825	0.1791	0.0650	509	1.820e-2
44	262334	0.1908			
45	262793	0.2031			
46	263214	0.2158			
47	263601	0.2291			
48	263959	0.2431	0.0910	327	3.091e-2
49	264286	0.2577	0.0979	297	3.421e-2

Step	Total N	Length outer surf.	Length along bore	ΔN during this step	Crack Face Area
42	261259	0.1677	0.0613	566	1.628e-2

Red SIFs are interpolated from nearby points. Red da/dN values are extrapolated from experimental curves.

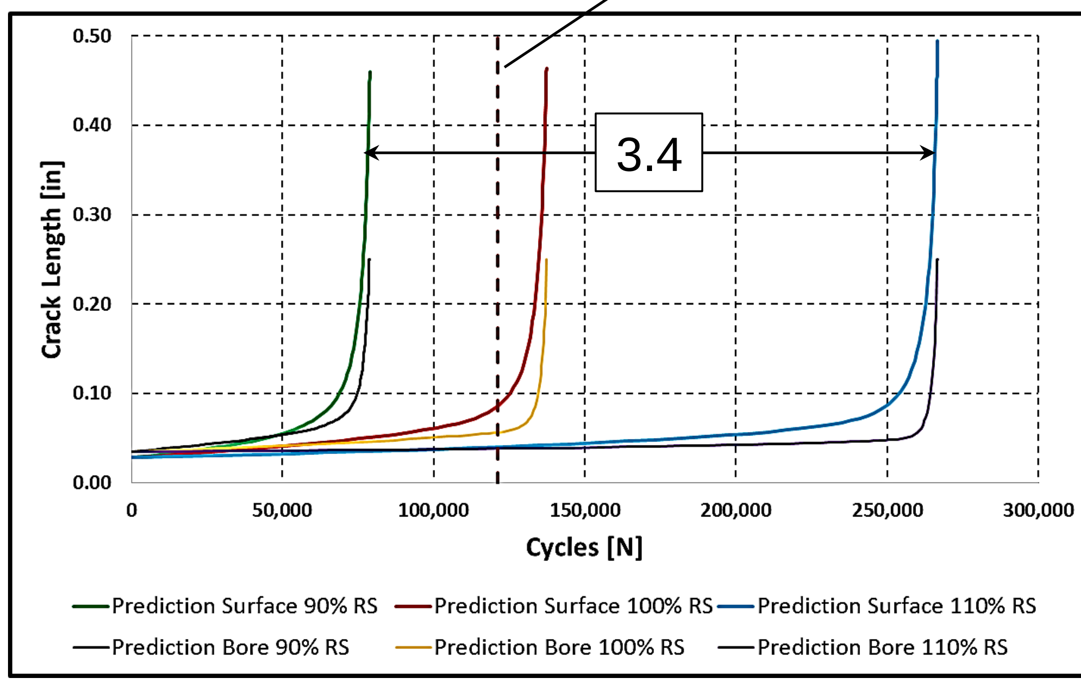
Failure criteria: KIc exceeded for corner crack · Kc exceeded for thru crack · Net section yield

Prediction 2024-T3
Sensitivity to Input RS

Predicted Life [Cycles]			Fatigue Life [Cycles]
90% RS	100% RS	110% RS	
78,913	137,305	266,500	121,312

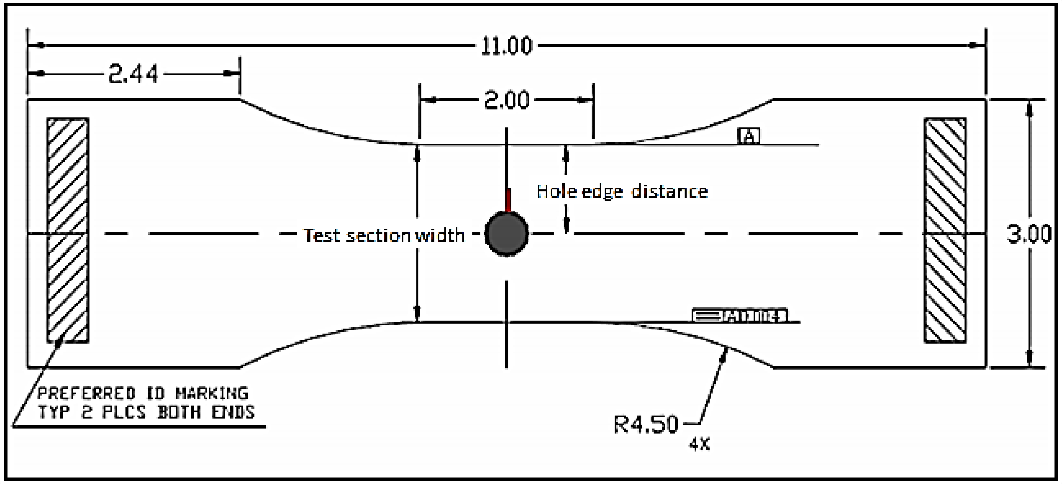
+/-10% variation in RS

Prediction → 137,305 { + 94% / – 43%



Prediction 7075-T6
Specimen with Cold-Worked Hole

Constant & Variable Amplitude loading

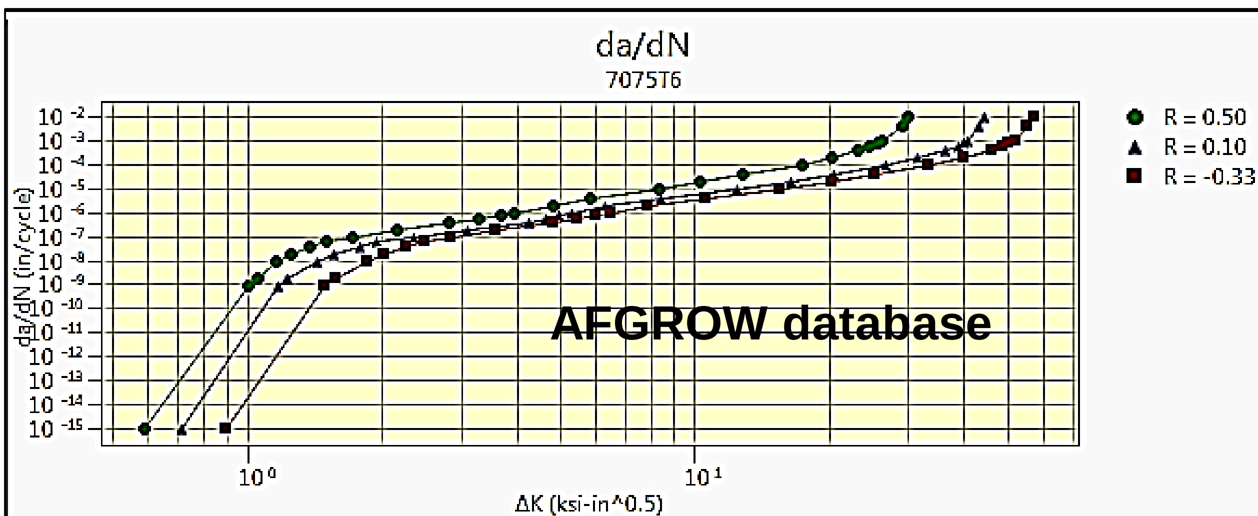


Material Properties

Name:	7075T6	
Modulus of elasticity:	10500	ksi
Poisson's ratio:	0.33	
Yield strength:	62	ksi
Plane strain toughness, KIc:	27	ksi-in$^{0.5}$
Plane stress toughness, Kc:	53	ksi-in$^{0.5}$

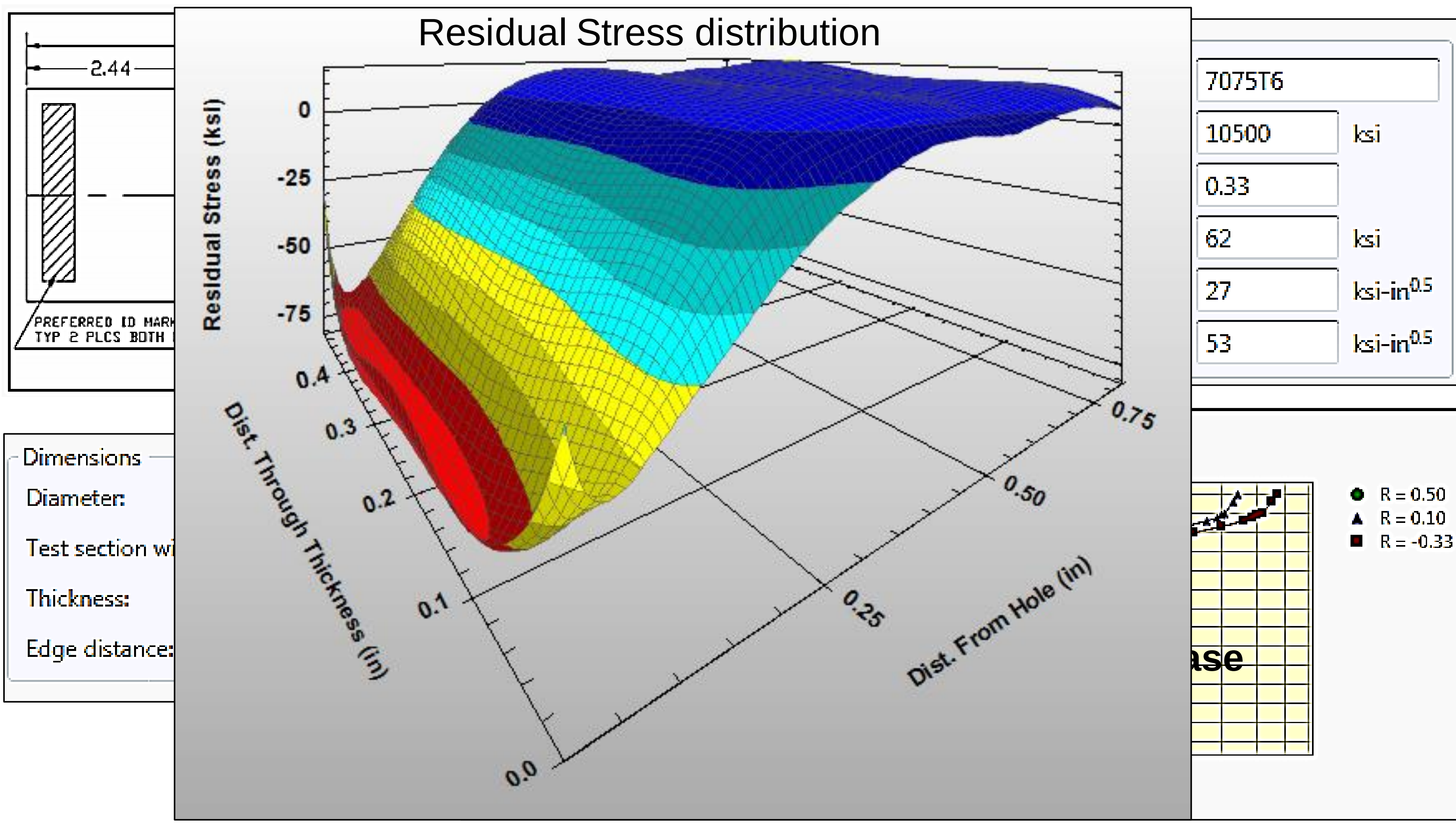
Dimensions

Diameter:	0.5	in
Test section width:	2.4	in
Thickness:	0.5	in
Edge distance:	1.2	in

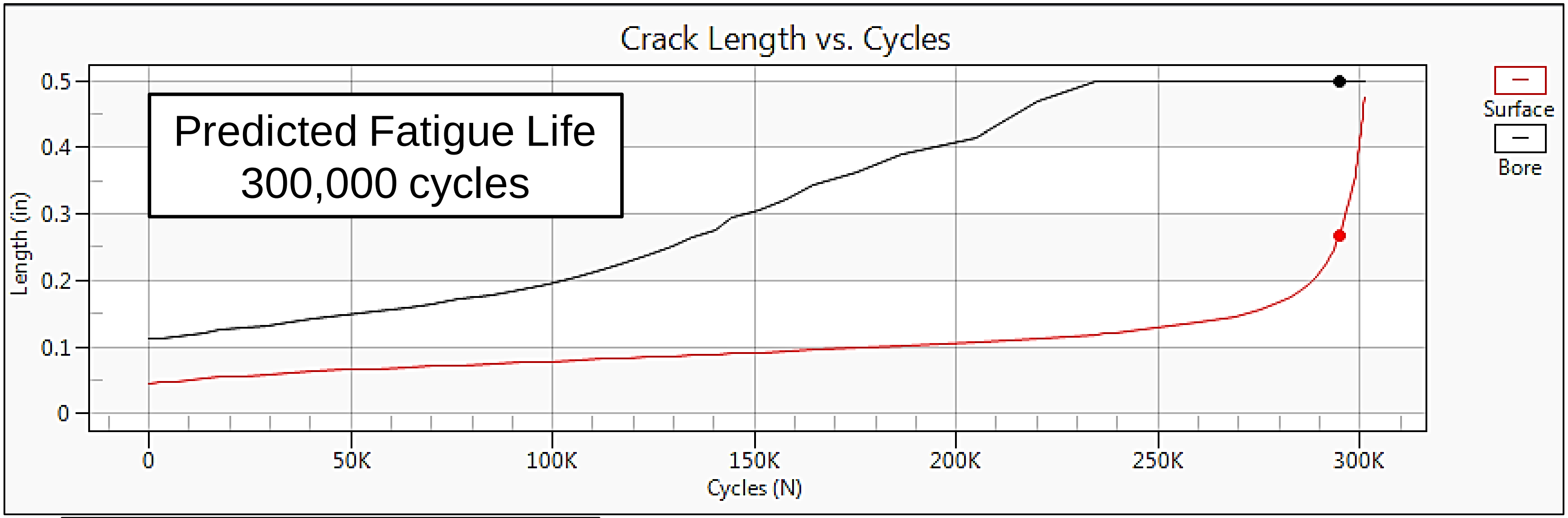


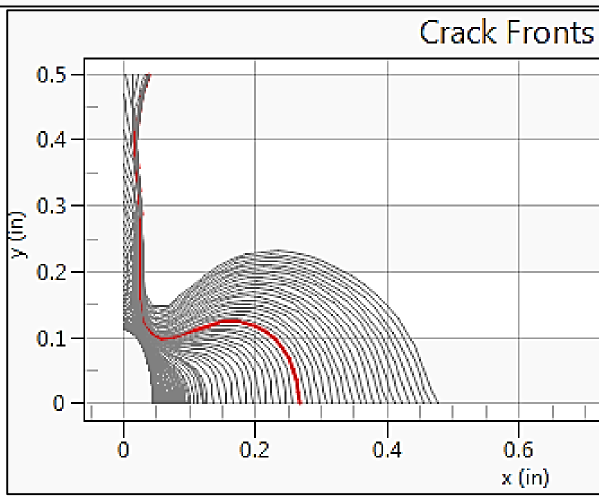
Prediction 7075-T6
Specimen with Cold-Worked Hole

Constant & Variable Amplitude loading



Prediction 7075-T6
Specimen 100% RS – CA Loading



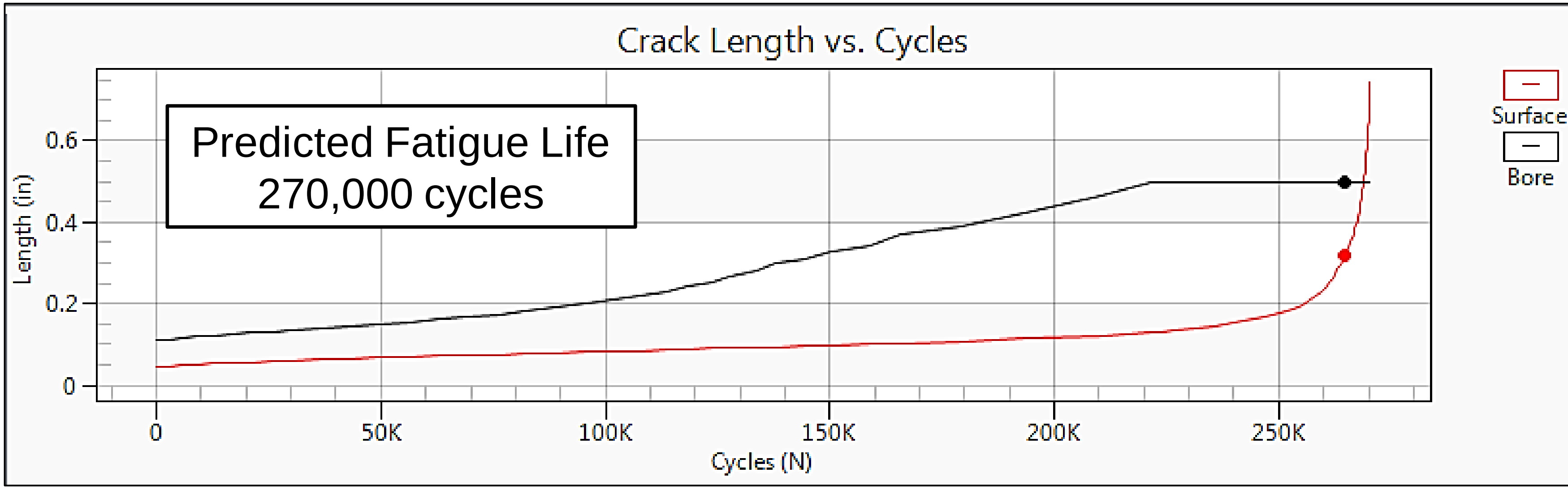


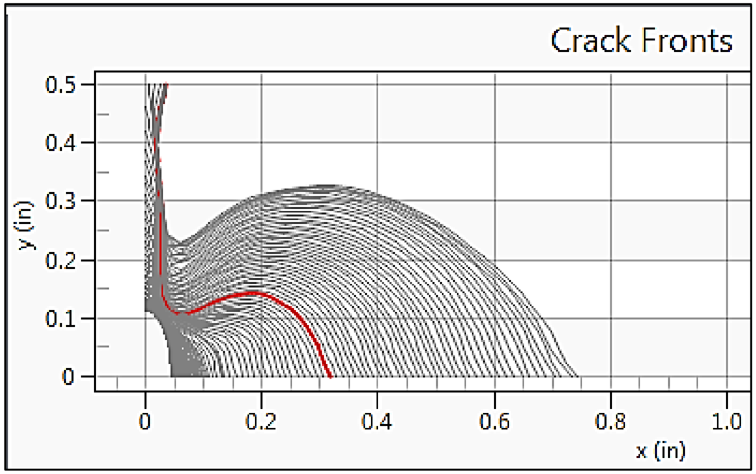
Equivalent Constant Amplitude loading

Test Section Load

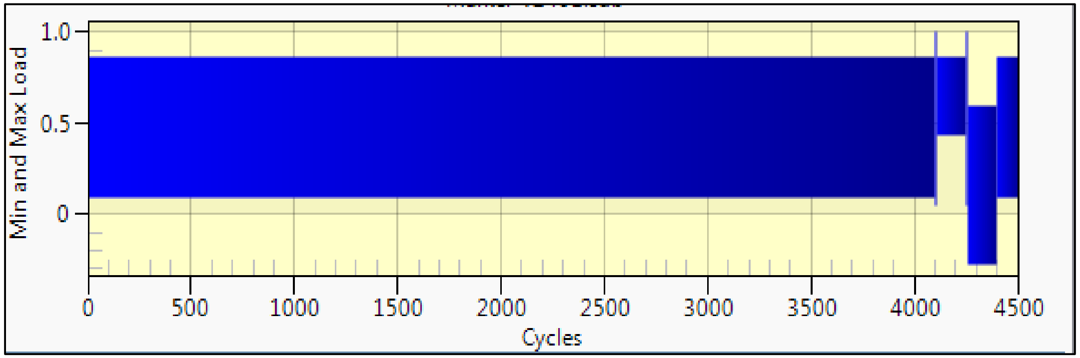
Peak load:	26.3	ksi
R-ratio:	0.1	

Prediction 7075-T6
Specimen 100% RS – VA Loading





Spectrum Loading



Prediction 7075-T6
Specimen 95% RS – CA Loading

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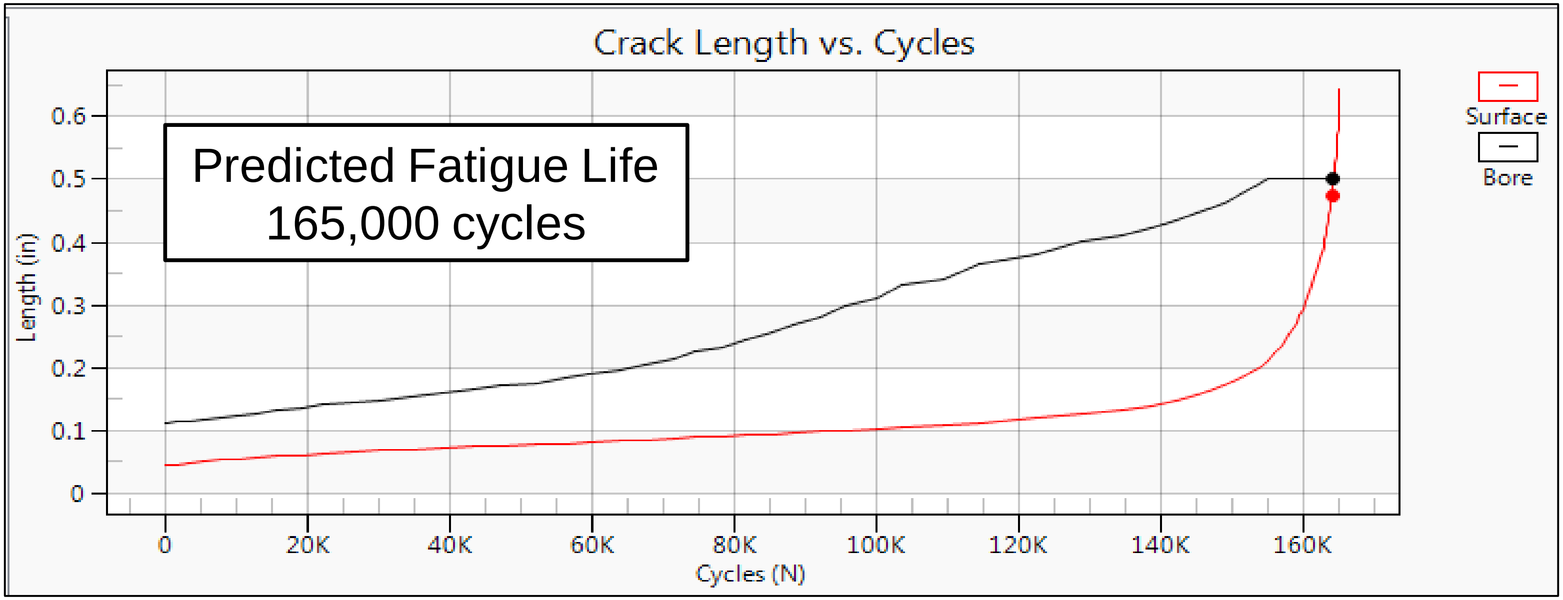
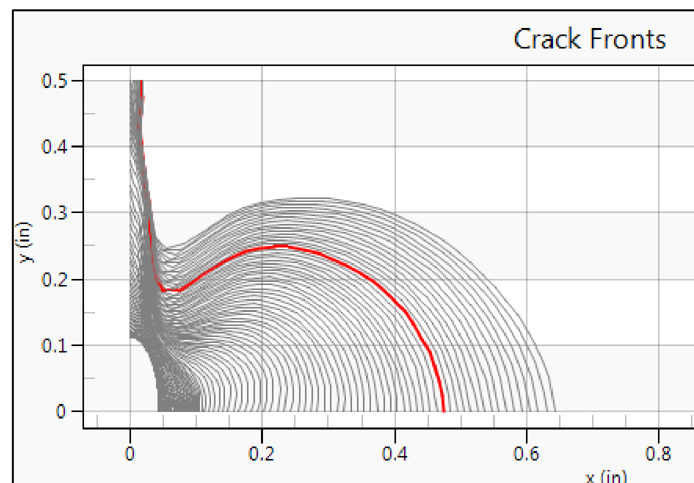


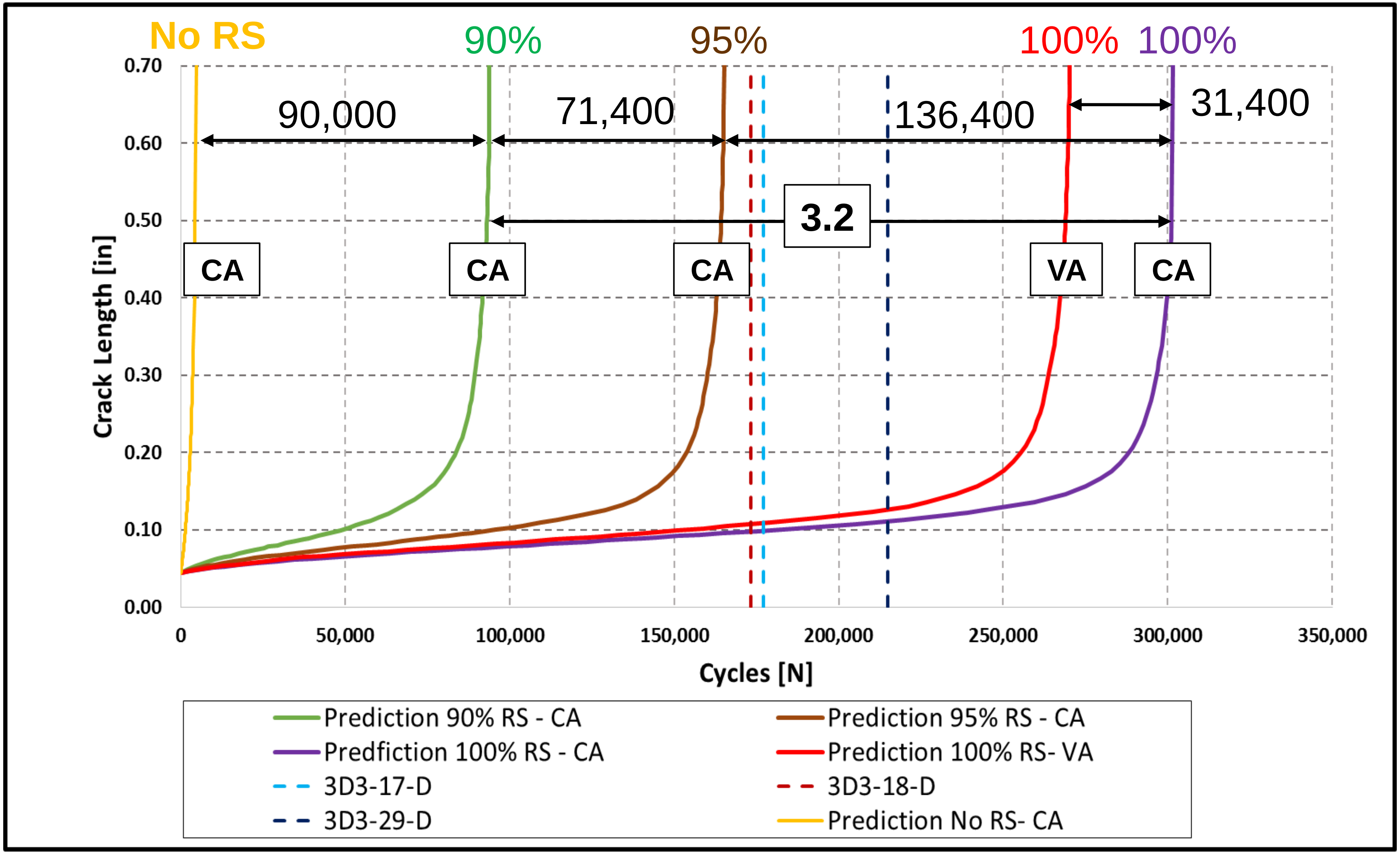
Equivalent Constant Amplitude loading

Test Section Load

Peak load:	26.3	ksi
R-ratio:	0.1	



Prediction 7075-T6
Sensitivity to Input RS & Loading



Summary & Conclusions

- The prediction of fatigue life for crack in cold-worked holes is affected by
  - The statistical dispersion of the input data (**D**)
    - Residual stress and crack propagation data
  - Our idea of reality (**I**)
    - Which serves as the basis for the formulation of the mathematical model
  - The mathematical model used for the computation of the data of interest (**K**, $\mathbf{K_{res}}$)
    - The control of the errors of approximation when computing $\mathbf{K_{num}}$.

Summary & Conclusions

- The prediction of fatigue life is strongly affected by variation in residual stresses
  - ±10% variation in RS → factor > 3.0 in fatigue life estimates for the 2024 & 7075 specimens considered
- The prediction of fatigue life was much less affected by the loading
  - 11% variation when comparing the equivalent constant amplitude load cycle with the spectrum load cycle with 100% RS for the 7075 specimen