Cold Expansion Effects on Cracked Fastener Holes under Constant Amplitude and Spectrum Loading in the 2024-T351 Aluminum Alloy

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AGENDA

- Cold Expansion
- Previous Research
- Research Objectives
- Test Procedure
- AFGROW Analysis
- Results
- Discussion
- Conclusions
- Recommendations
- References

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Cold Expansion

- Invented by Boeing in 1965
- Licensed technology to FTI

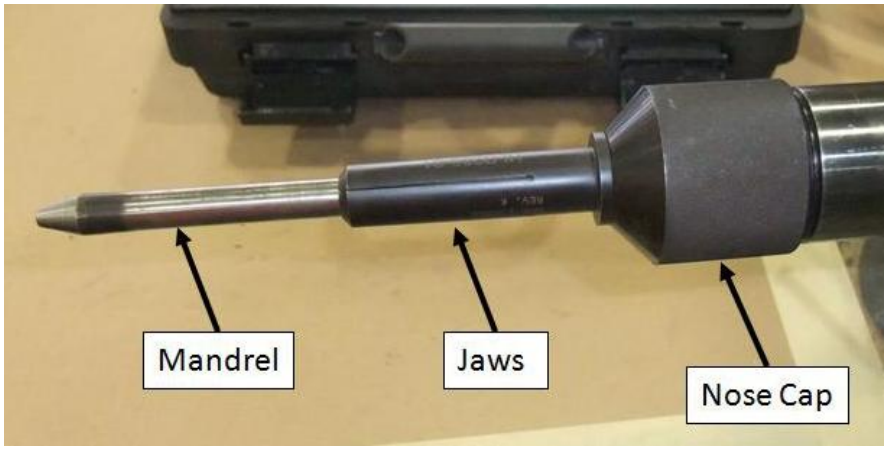

Fig. 1 Cold Expansion Equipment

Fig. 2 Cold Expansion Process

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Cold Expansion Effects

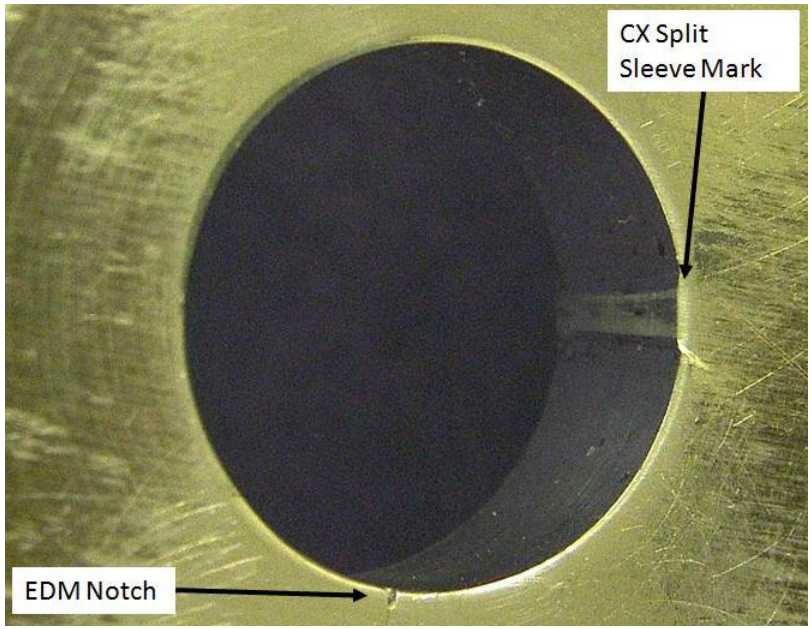

Fig. 3 Split Sleeve Mark from Cold Expansion

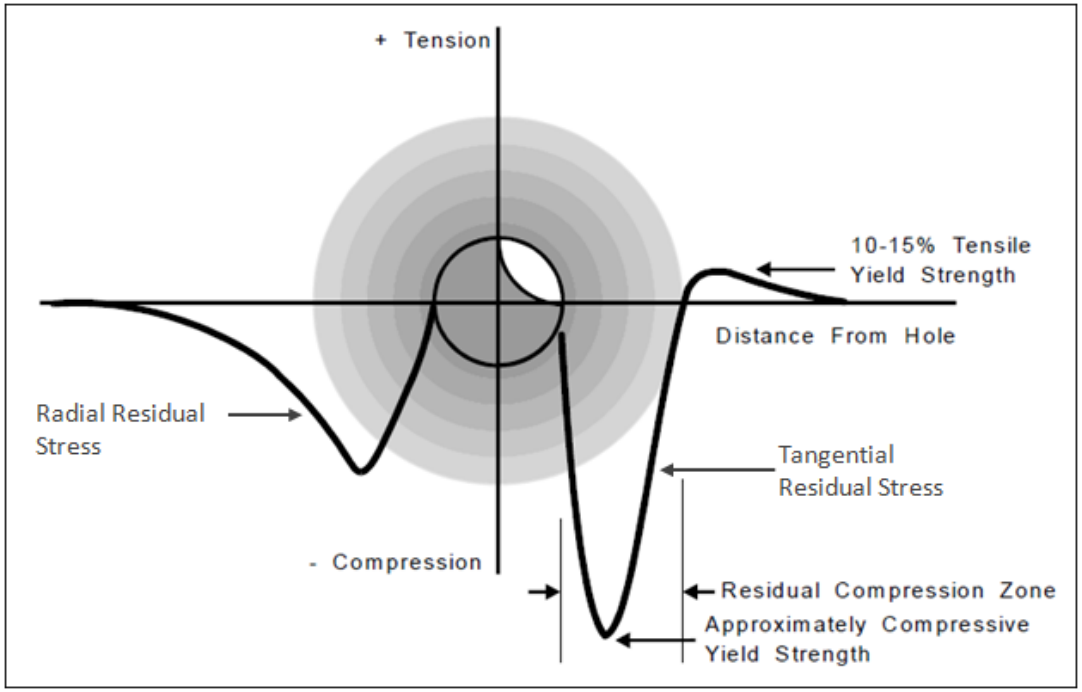

Fig. 4 Residual Stresses from Cold Expansion[1]

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Previous Research

- Cold Expansion (CX) does not benefit cracks larger than the hole radius.[2,3]
- CX only retards growth of cracks greater than 0.04".[4,5,6]
- Life benefit from CX is less for spectrum loading than constant amplitude loading.[3,7,8]
- Tensile overloads increase life, compressive overloads decrease life.[9]
- Residual stress models in AFGROW have good agreement with test data.[2,10]

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Research Objectives

- Validate test setup with ASTM E 647 standard
- Quantify life benefit of pre cracked (PC)-CX hole
- Compare life benefit of CX hole to PC-CX hole
- Evaluate agreement of test and 0.005” Initial Flaw Size (IFS) AFGROW prediction[11]

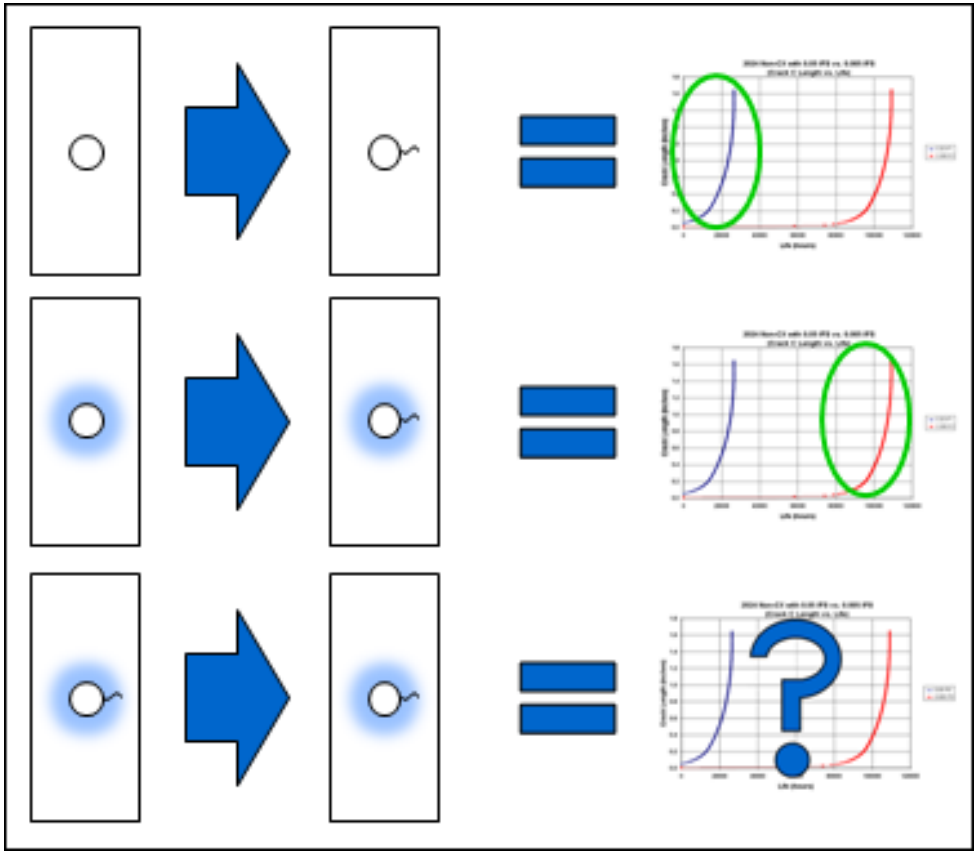

Fig. 5 Research Goal

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Test Procedure (Specimens)

- 2024-T351 Aluminum Plate
- 4” wide x 0.25” thick
- 0.5” final diameter hole
- Pre-cracked at 20 ksi
- ~0.05” fatigue pre crack
- Constant Amplitude
  - Stress Ratio = 0.1
  - Frequency = 20 Hz
  - Max Stress 25, 20 ksi
- Spectrum
  - A-10 wing spectrum
  - Load rate = 500,000 lbs/sec
  - Max Stress 25, 30, 33, 43 ksi

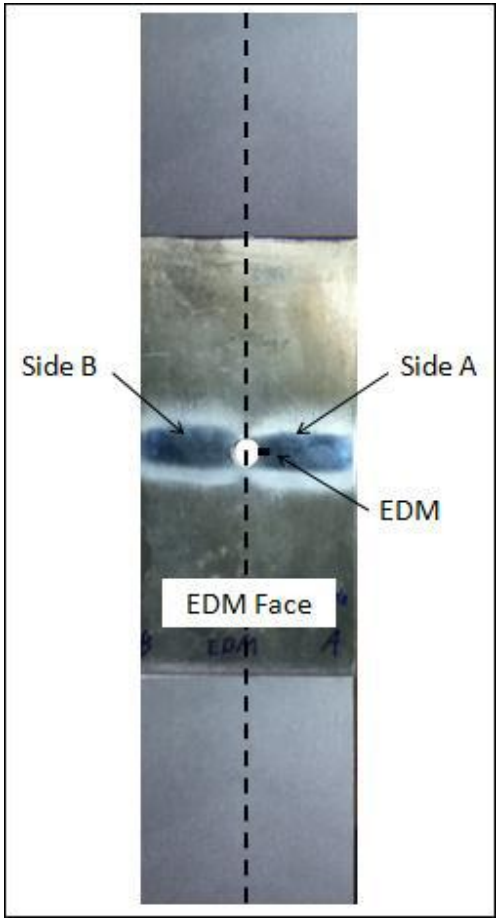

Fig. 6 Test Specimen

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Test Procedure (Test Equipment)

- Interlaken™ Load Frame
- MTS™ Grips and Intensifier
- Interface™ Load Cell
- Gaertner Scientific™ Scopes
- Instron 8800 FastTrack™ Controller
  - Random Loading v. 8.0.1
  - DADN v. 8.4.12

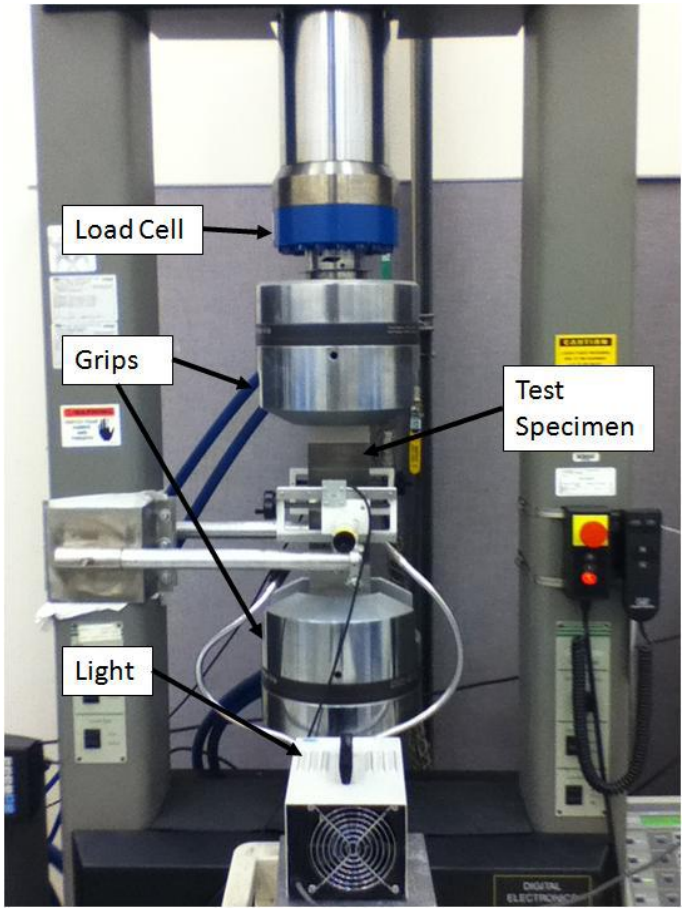

Fig. 7 Fatigue Test Equipment

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Test Procedure (Example Test, 40 ksi)

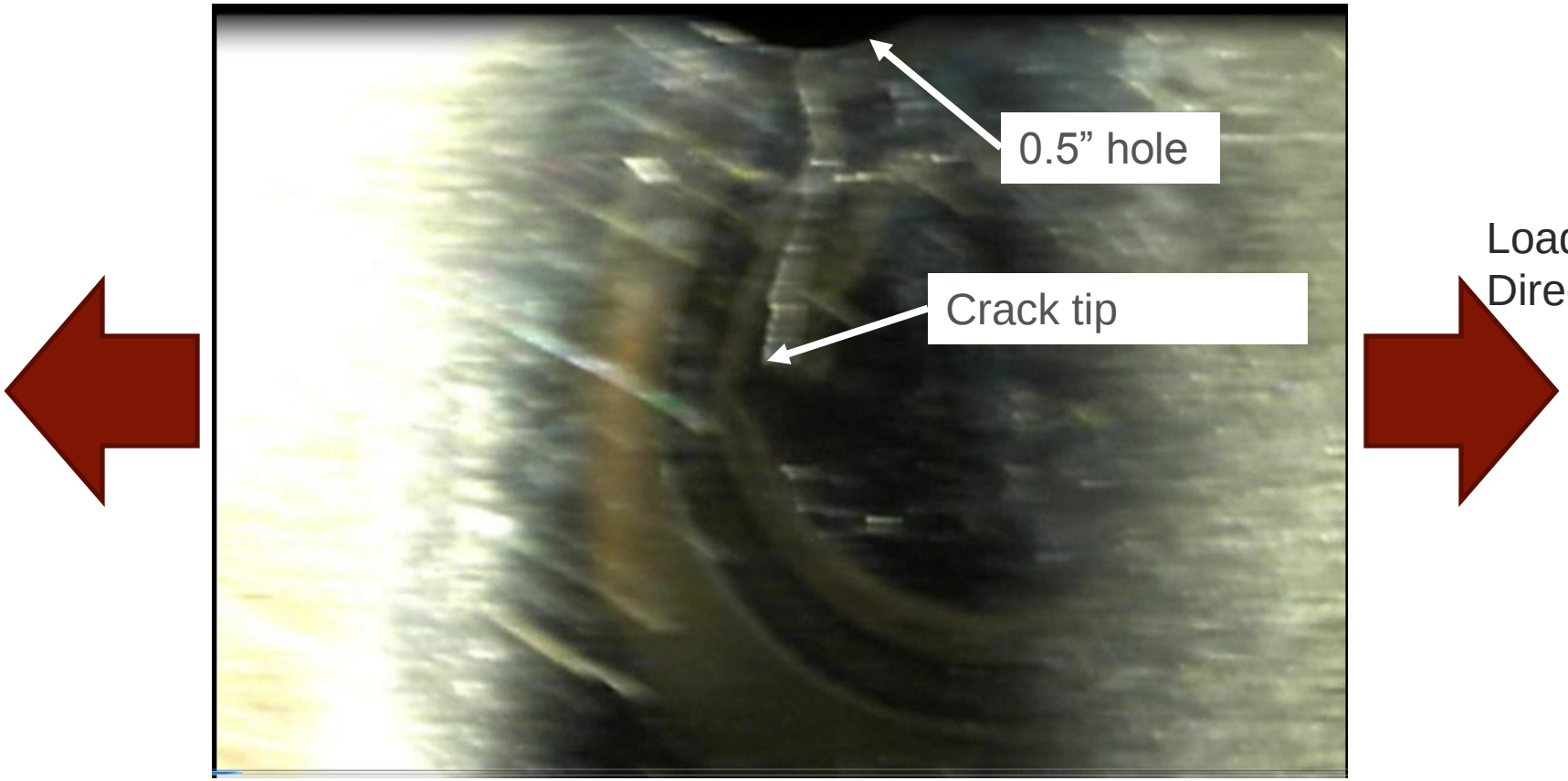

Fig. 8 Example Video Geometry

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Test Procedure (Example Test)

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AFGROW Analysis (Lookup File)

- ASTM E 647 lookup file baseline
  - Lookup file A (85% agreement): Always conservative
  - Lookup file B (90% agreement): More agreement with test, not always conservative

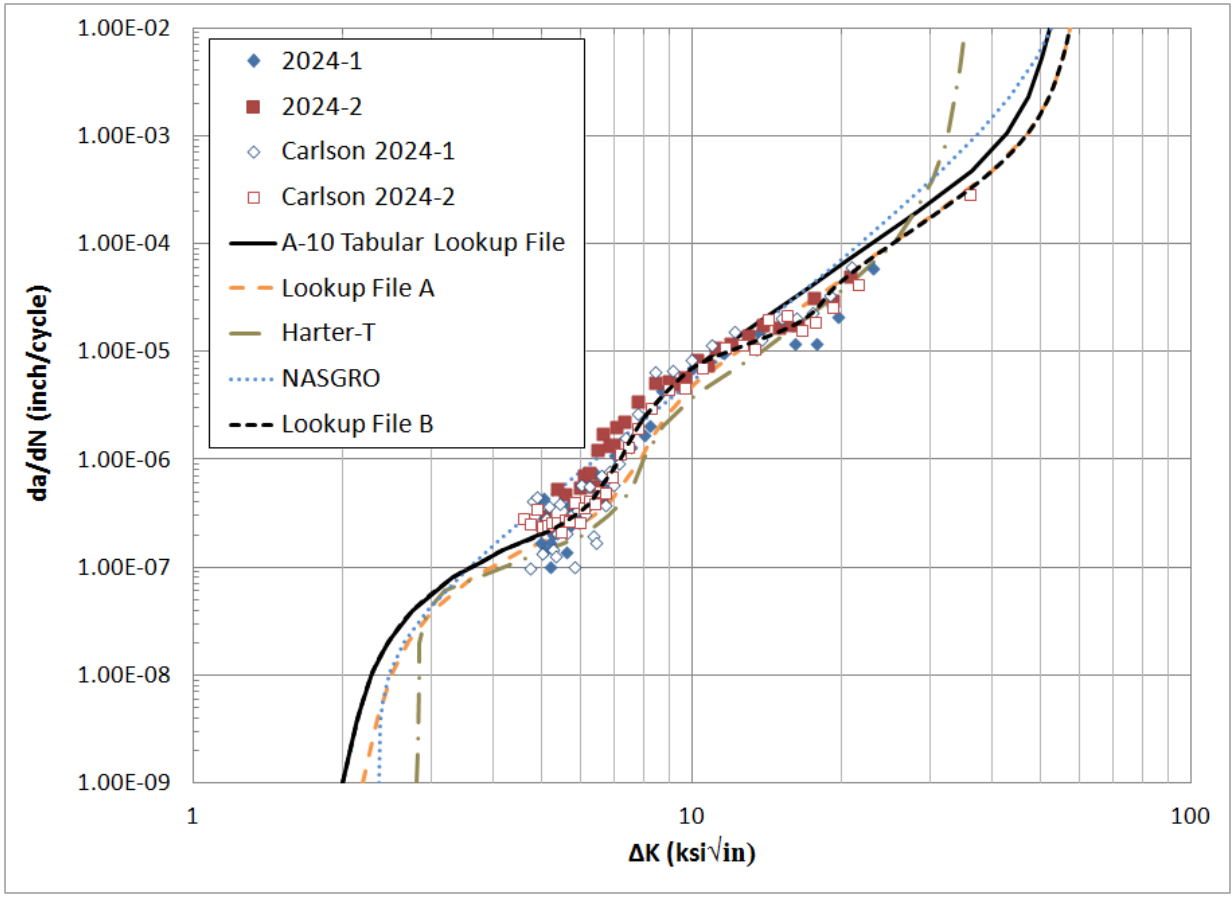

Fig. 9 Crack Growth Rate Graph[11]

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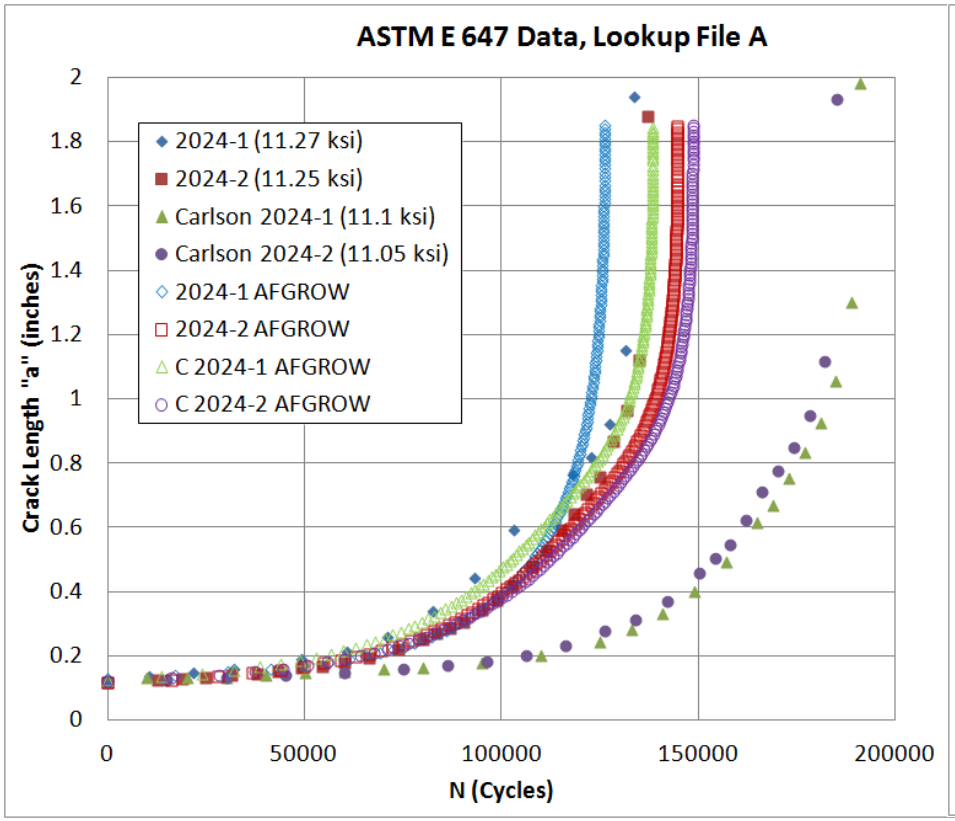
AFGROW Analysis (Lookup File)



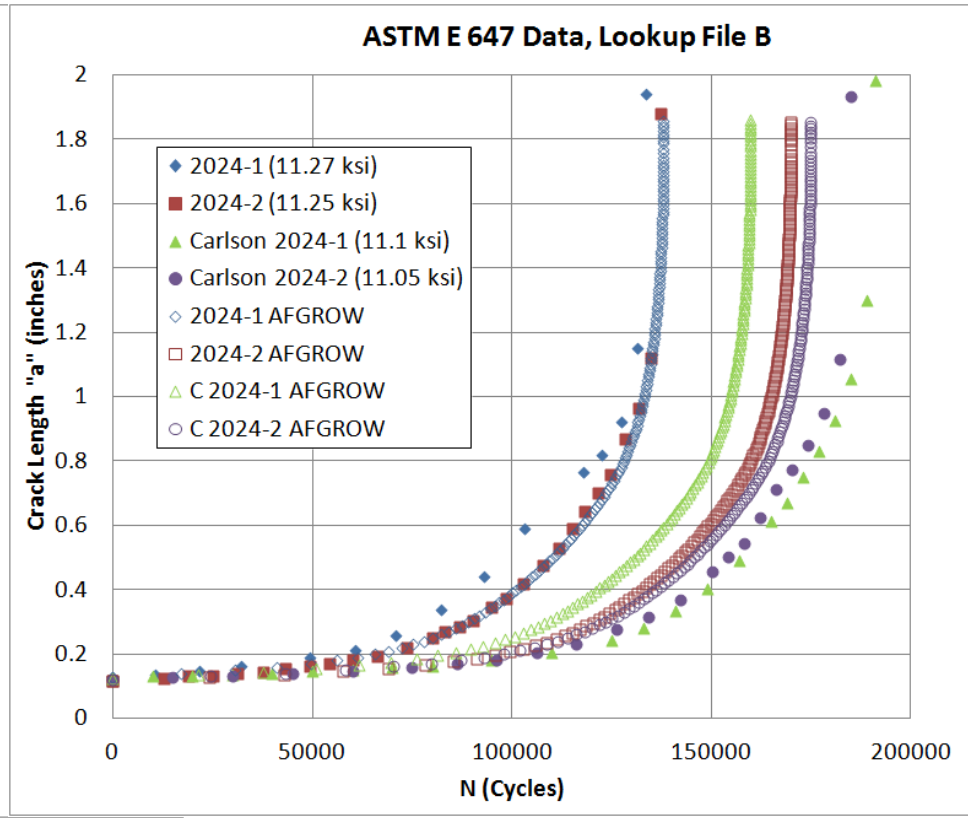


Fig. 10 ASTM E 647 Data and Predictions

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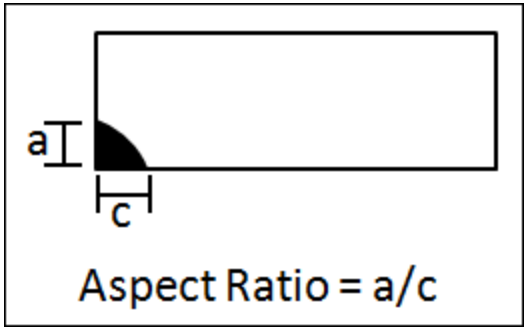
AFGROW Analysis

- Used non CX, Constant Amplitude (CA) data from Carlson's research.
- Optimized aspect ratio parameters
- Generalized Willenborg model used for spectrum retardation. Shutoff Overload Ratio (SOLR) is the only input parameter
- Optimized SOLR's for non CX Spectrum Tests



Percent Disagreement				
Specimen ID	Actual Crack Lengths		Average Crack Lengths	
	Vary a/c	Constant a/c	Vary a/c	Constant a/c
Scott NCX 2024-3	29.23%	51.15%	29.09%	1.46%
Scott NCX 2024-4	31.12%	22.98%	32.05%	11.69%
Average	30.18%	37.07%	30.57%	6.58%

Fig. 10 Aspect Ratio Optimization (Lookup File B)

Max Stress (ksi)	Average SOLR for Lookup File A	Average SOLR for Lookup File B	Average SOLR for A-10 Lookup File
25	1.88	1.82	1.68
30	1.85	1.79	1.64
33	1.83	1.78	1.62
43	1.94	1.90	1.69

Fig. 11 SOLR Optimization

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AFGROW Analysis

- Lookup File A always had best fit to test data

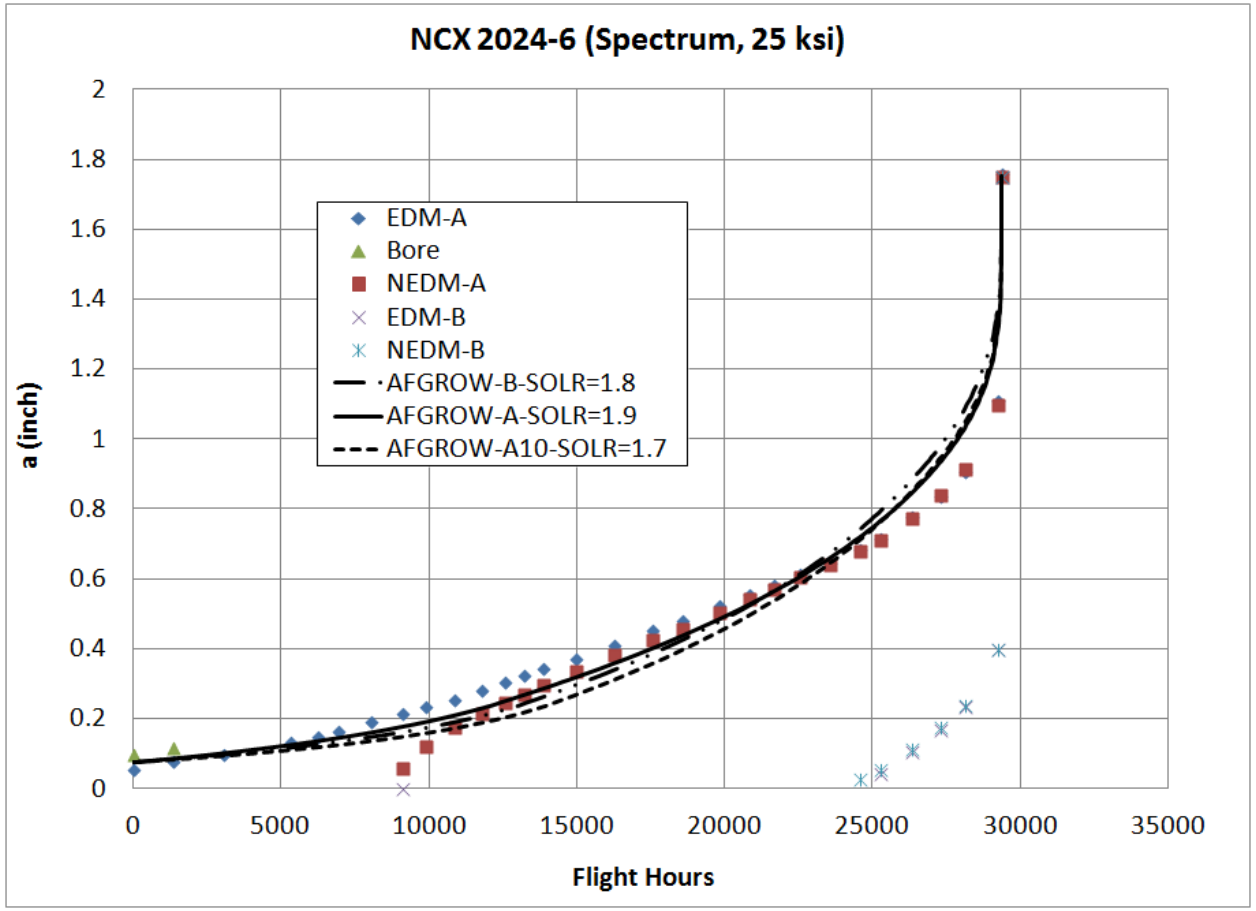

Fig. 11 Fit of Predictions

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Results (PC-CX, CA, 20 ksi)

- 2 grip failures
- Average PC-CX life 4,296,067 cycles
- Average Life Improvement Factor (LIF): 90.5
- Minimum LIF: 29.6
- Weibull β=1.6
- Prediction A: 52,606 cycles
- Prediction B: 55,099 cycles

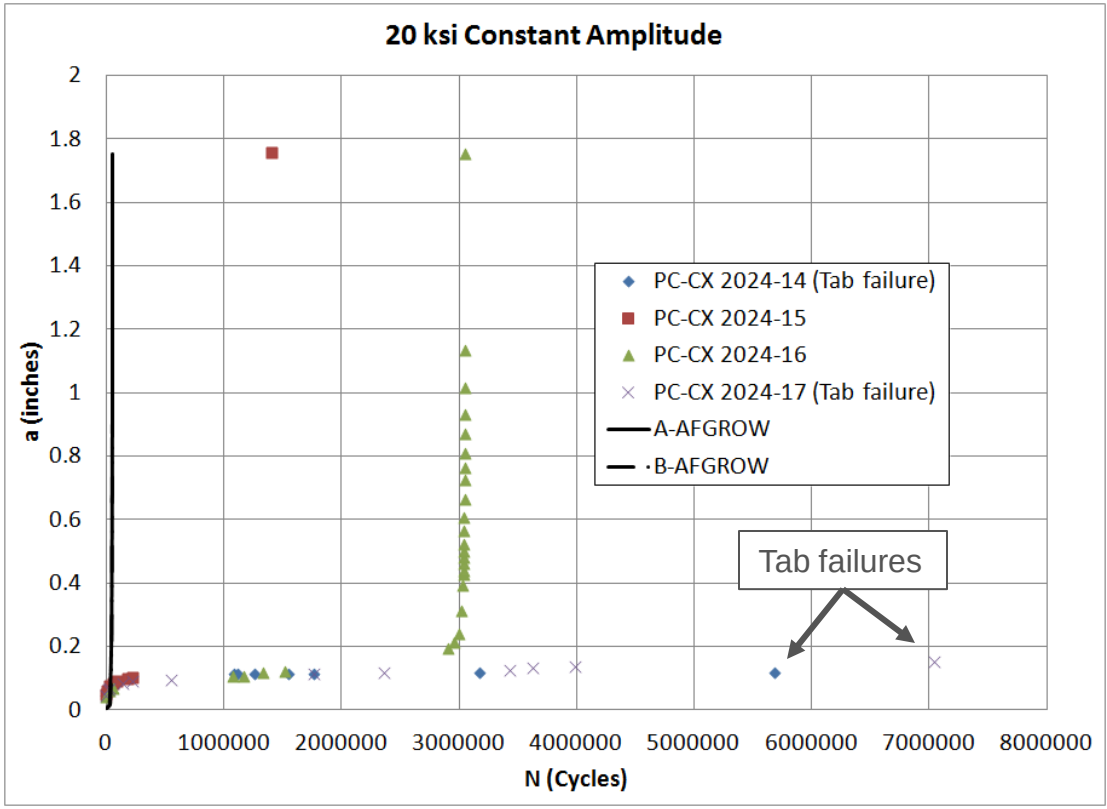

Fig. 12 Test Data and Predictions

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Results (PC-CX, CA, 25 ksi)

- CX life (Carlson)[12:] 531,776 cycles
- CX LIF: 71.4
- PC-CX life: 452,585 cycles
- PC-CX LIF: 60.8
- Weibull β=6
- Prediction A: 22,097 cycles
- Prediction B: 23,277 cycles

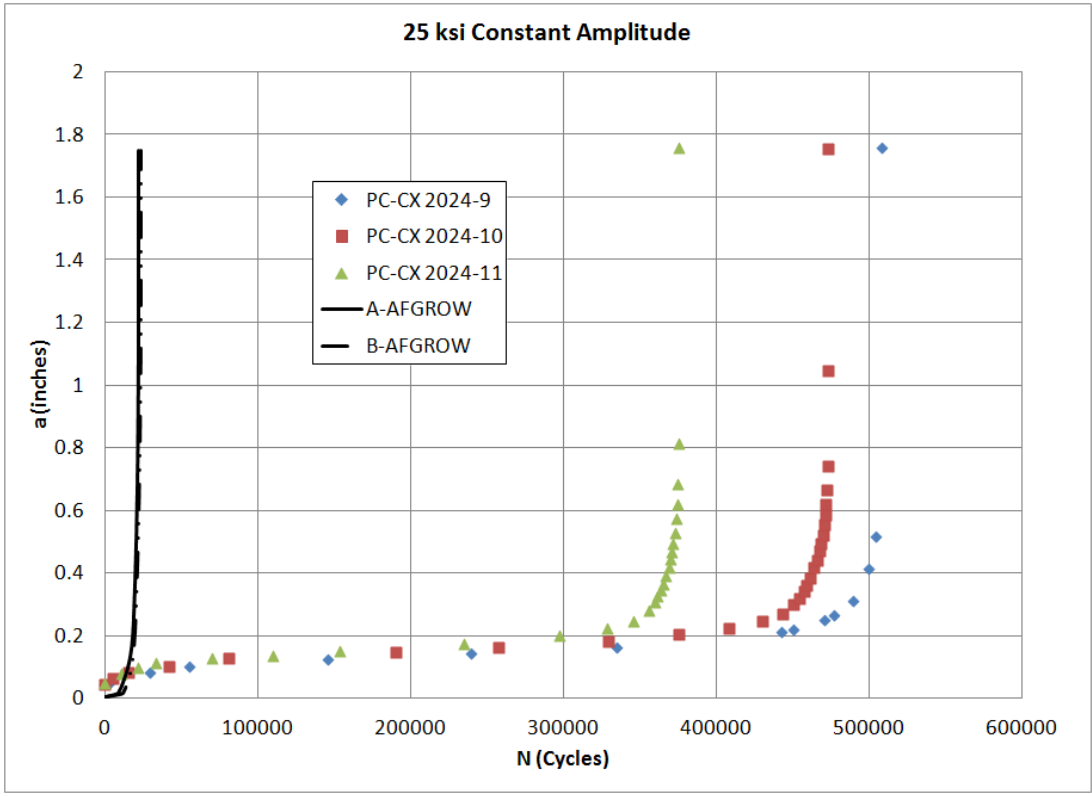

Fig. 13 Test Data and Predictions

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Results (NCX Spectrum)

- NCX 25 ksi spectrum
  - Life: 31,521 flight hours
  - Weibull β=15.3
- NCX 33 ksi spectrum
  - Life: 12,200 flight hours
  - Weibull β=10.8
- NCX 43 ksi spectrum
  - Life: 4,657 flight hours

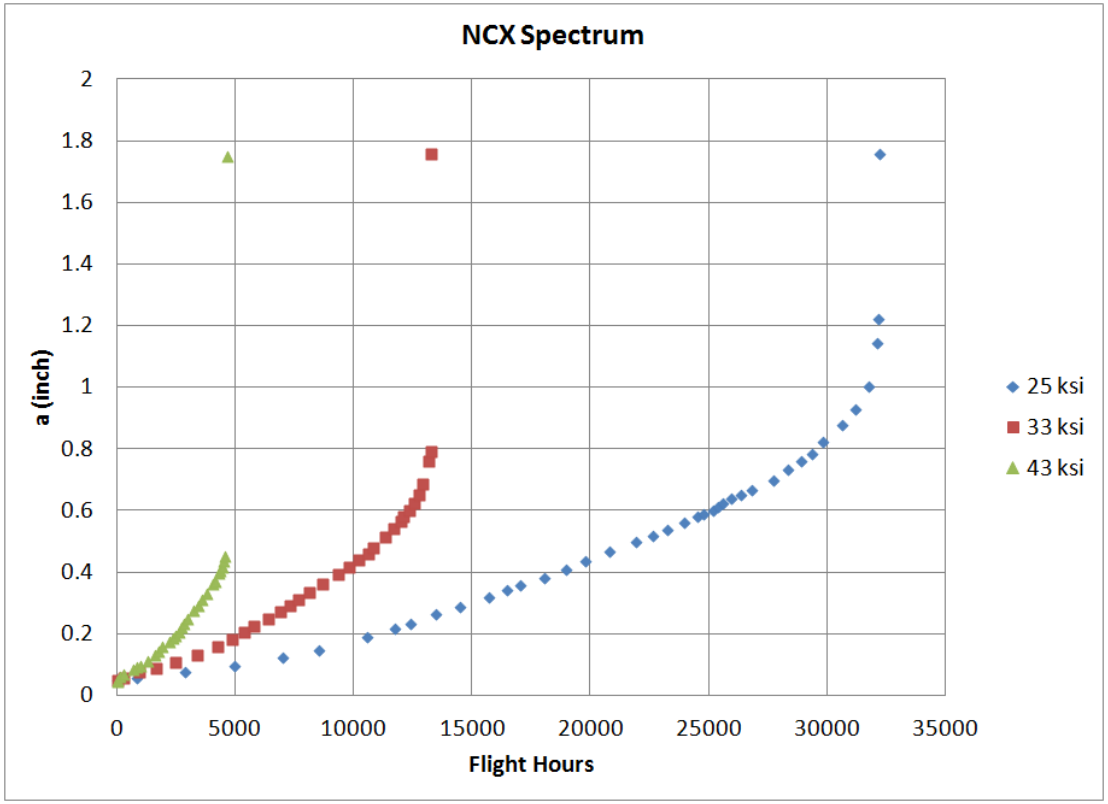

Fig. 14 Non CX Test Data

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Results (PC-CX, 25 ksi, Spectrum)

- PC-CX failed in grip after 704,450 flight hours
- LIF: 22.4
- Failed in the hole after 831,641 flight hours
- LIF: 26.4
- Prediction A: 86,611 flight hours
- Prediction B: 75,729 flight hours

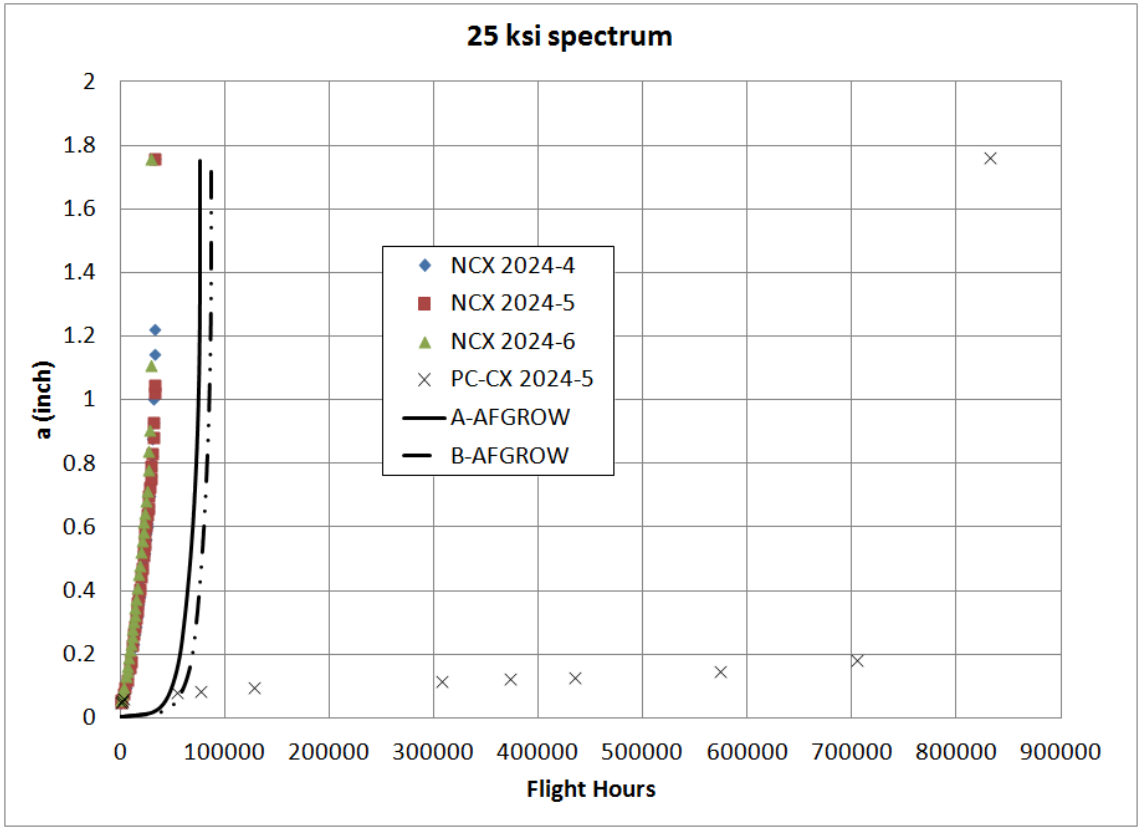

Fig. 15 Test Data

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Results (PC-CX, 30 ksi, Spectrum)

- PC-CX life: 194,950 flight hours
- Weibull β=7.3
- LIF: 9.9
- Prediction A: 43,923 flight hours
- Prediction B: 50,197 flight hours

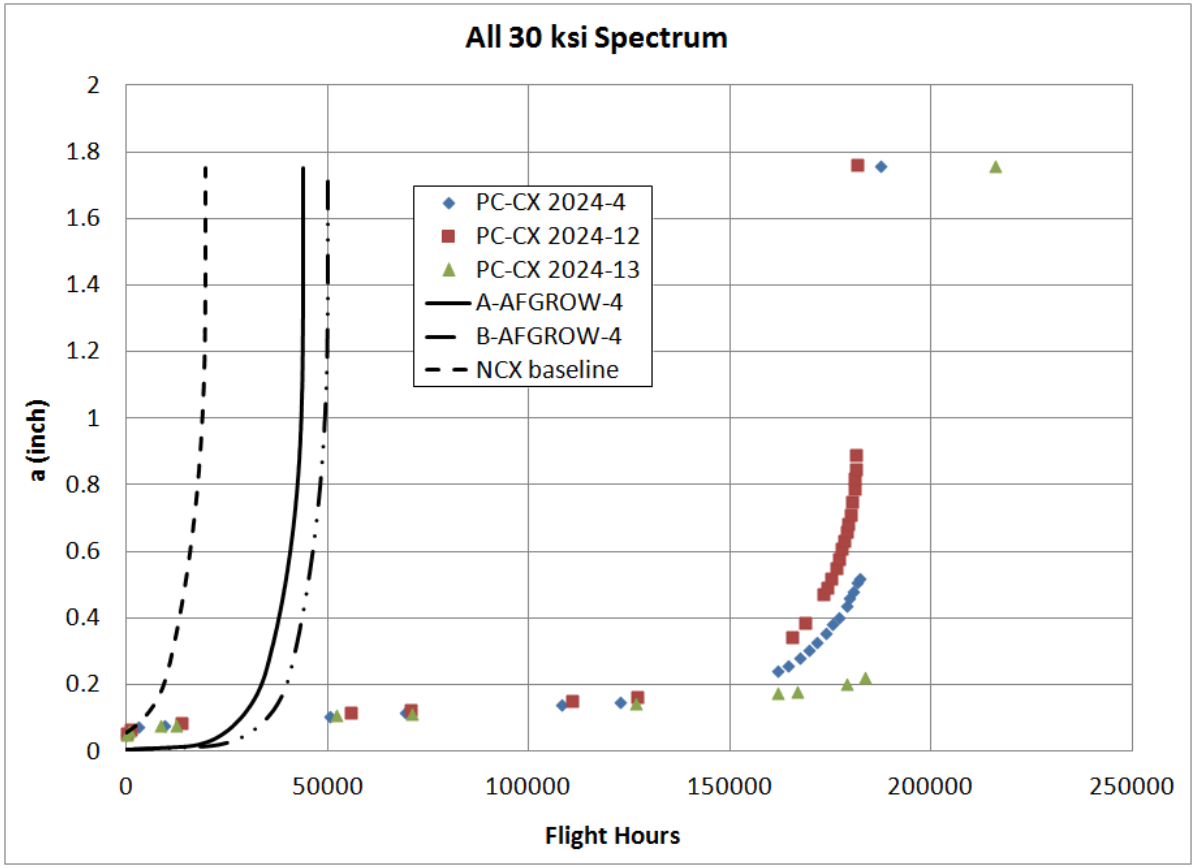

Fig. 16 Test Data

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Results (PC-CX, 33 ksi, Spectrum)

- PC-CX life: 80,220 flight hours
- Weibull β=8.7
- LIF: 6.6
- Prediction A: 32,677 flight hours
- Prediction B: 37,277 flight hours

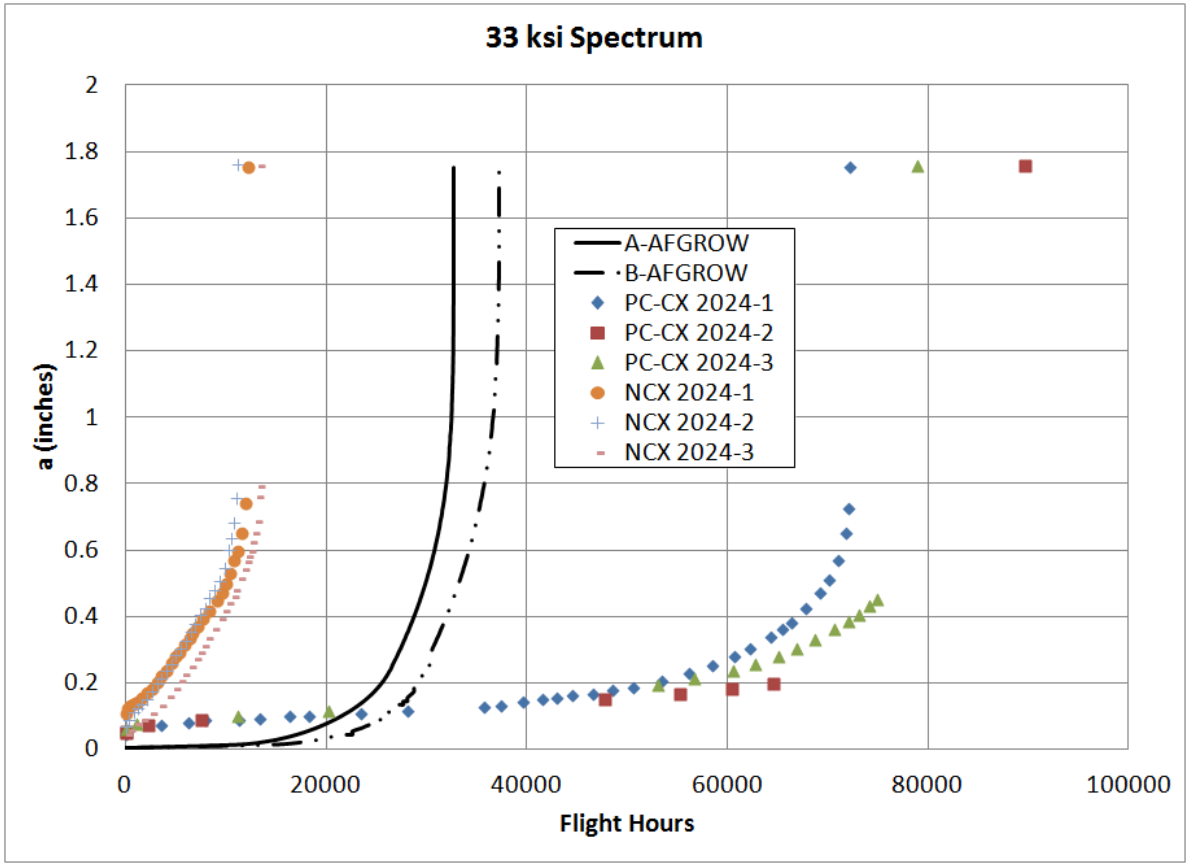

Fig. 17 Test Data

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Results (PC-CX, 43 ksi, Spectrum)

- PC-CX life: 6,201 flight hours
- Weibull β=18.7
- LIF: 1.3
- Prediction A: 9,357 flight hours
- Prediction B: 10,031 flight hours

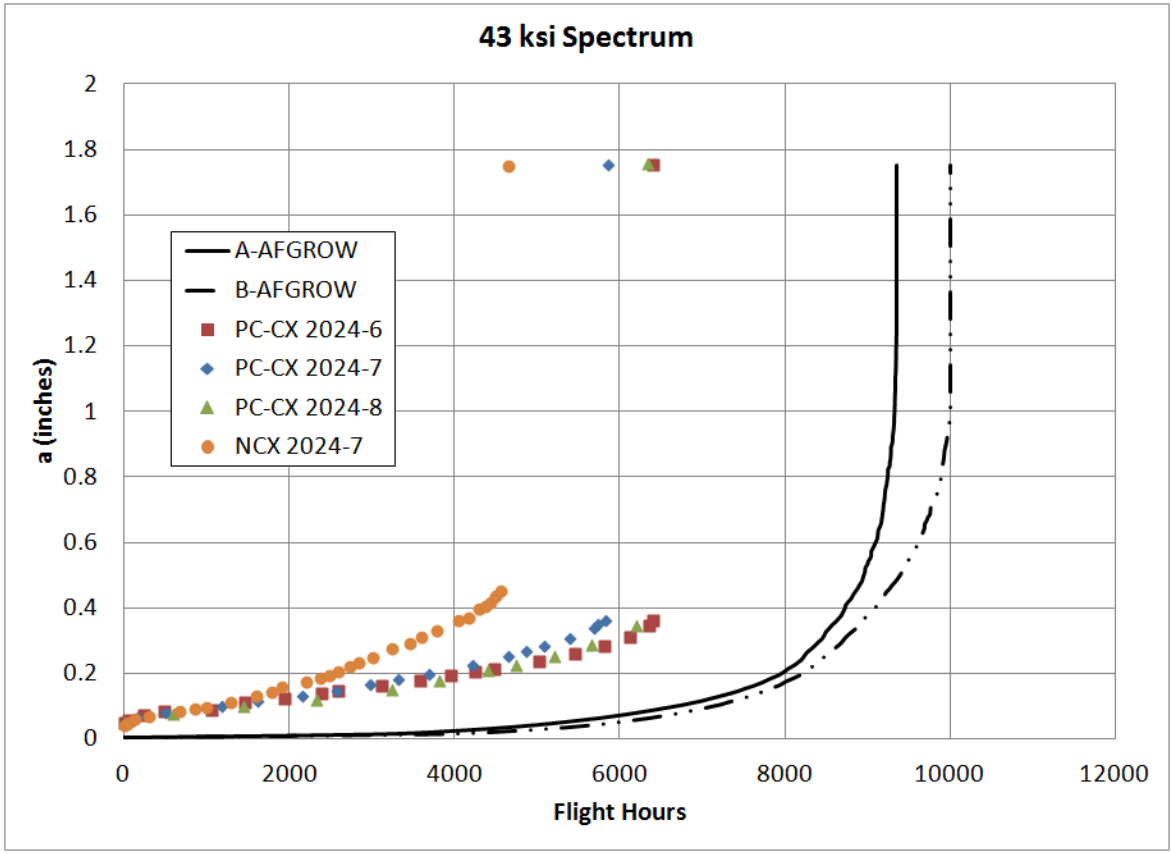

Fig. 18 Test Data

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Discussion

- LIF decreases with increasing stress

Loading	Max Stress (ksi)	Non-CX Life (cycles)	PC-CX Life (cycles)	LIF NCX to PC-CX
Constant Amplitude	20	47443	4296067	90.6
	25	7443	452585	60.8
Spectrum	25	31521	704450	22.3
	30	N/A	194950	10.3
	33	12201	80220	6.6
	43	4658	6201	1.3

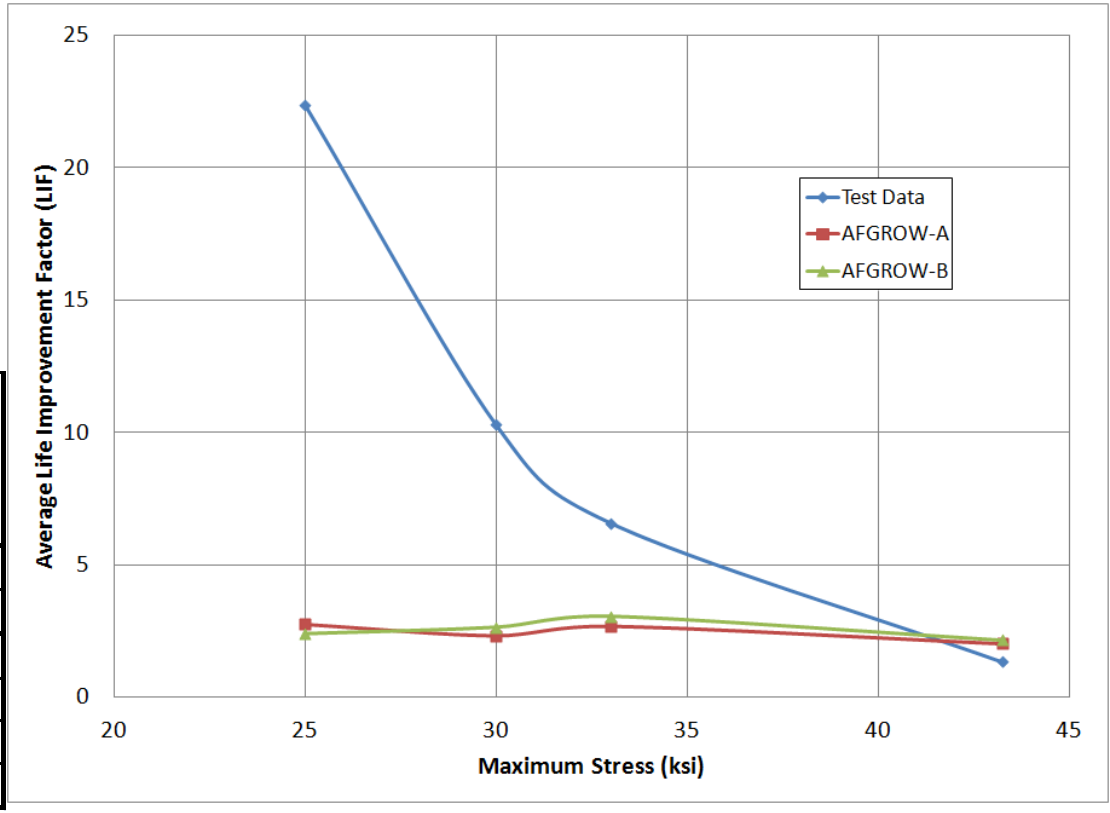

Fig. 19 LIF Plot

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Discussion

- 0.005” IFS is non conservative at 43 ksi max stress, even with a conservative lookup file

Loading	Max Stress (ksi)	Average Ratio ofTested Life to Predicted Life Lookup File A	Average Ratio of Tested Life to Predicted Life Lookup File B
Constant Amplitude	20	81.60	77.92
	25	20.49	19.45
Spectrum	25	8.13	9.30
	30	4.44	3.88
	33	2.45	2.15
	43	0.66	0.62

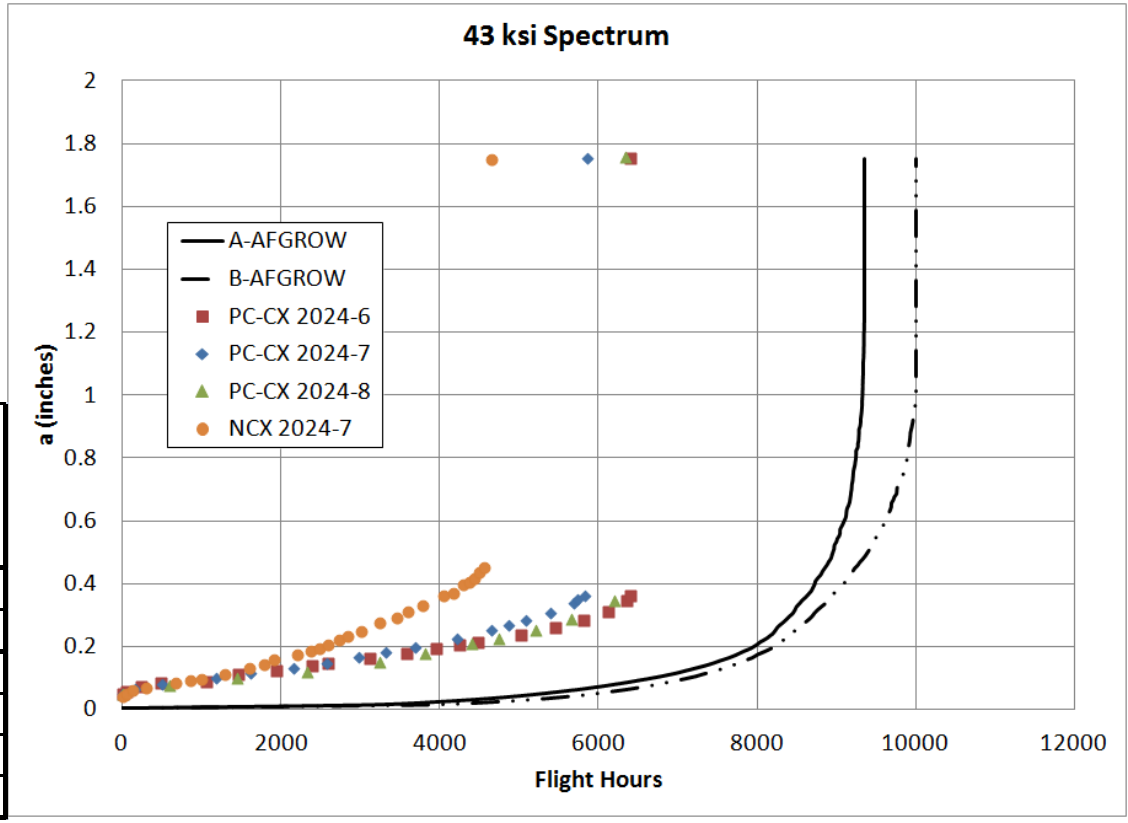

Fig. 20 Non Conservative Prediction

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Discussion

- Material Yield Strength: 48.1 ksi
- Yield for K_t=3: 16 ksi
- Ultimate Strength: 68.4 ksi

Max Stress (ksi)	Average Stress	RMS Stress	3rd Quartile Stress
25.00	6.31	7.49	8.85
30.00	7.58	8.99	10.62
33.00	8.33	9.87	11.68
43.25	10.92	12.96	15.31

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Discussion

- Crack growth due to CX
  - ~0.0014” growth on surface
  - ~0.003” growth down bore
- CX benefit dropped 15% for 0.05” pre-existing crack
- Average absolute error in spectrum less than 2.5%

$$\textit{Damage Parameter} = \Gamma = \left(\frac{P_{actual}}{P_{command}}\right)^{m}$$

Max Stress (ksi)	Load Rate (kip/sec)	Average Absolute Percent Error	Average Damage Parameter
43	500	1.18%	1.04
33	500	1.66%	1.05
	200	2.50%	1.01
	100	2.50%	0.97
30	500	1.52%	1.00
	200	1.35%	0.98
	100	1.81%	0.97
25	500	2.10%	1.00
	200	1.56%	0.99
	100	2.02%	0.97

Fig. 21 Error Loading[13]

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Conclusions

- Test data is valid as per ASTM E 647 standard
- Fatigue life of PC-CX holes were quantified for constant amplitude and spectrum loading
- LIF of a CX hole is decreased by ~15% due to a pre-existing 0.05” crack
- AFGROW models using 0.005” IFS were compared with test data.
- AFGROW predictions become non conservative for spectrum tests with 43 ksi max stress
- The LIF from cold expansion is greater for constant amplitude loading than spectrum loading

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Recommendations

- Employ physics based model to account for residual stresses in cold expanded holes
- Conduct further testing at various stress levels to identify when the 0.005” IFS assumption becomes non conservative
- Test various edge margins to identify the stress and edge margin limits where the 0.005” IFS assumption becomes non conservative
- Investigate residual stress models available in AFGROW to determine whether one is suitable for predicting cold expanded holes
- Test the effects of common fastener systems in cold expanded holes
- Quantify the residual stress from cold expansion, especially at the crack tip
- Test the effects of other pre-existing discontinuities on cold expansion
  - Gouges, discontinuities from fretting and wear, etc.

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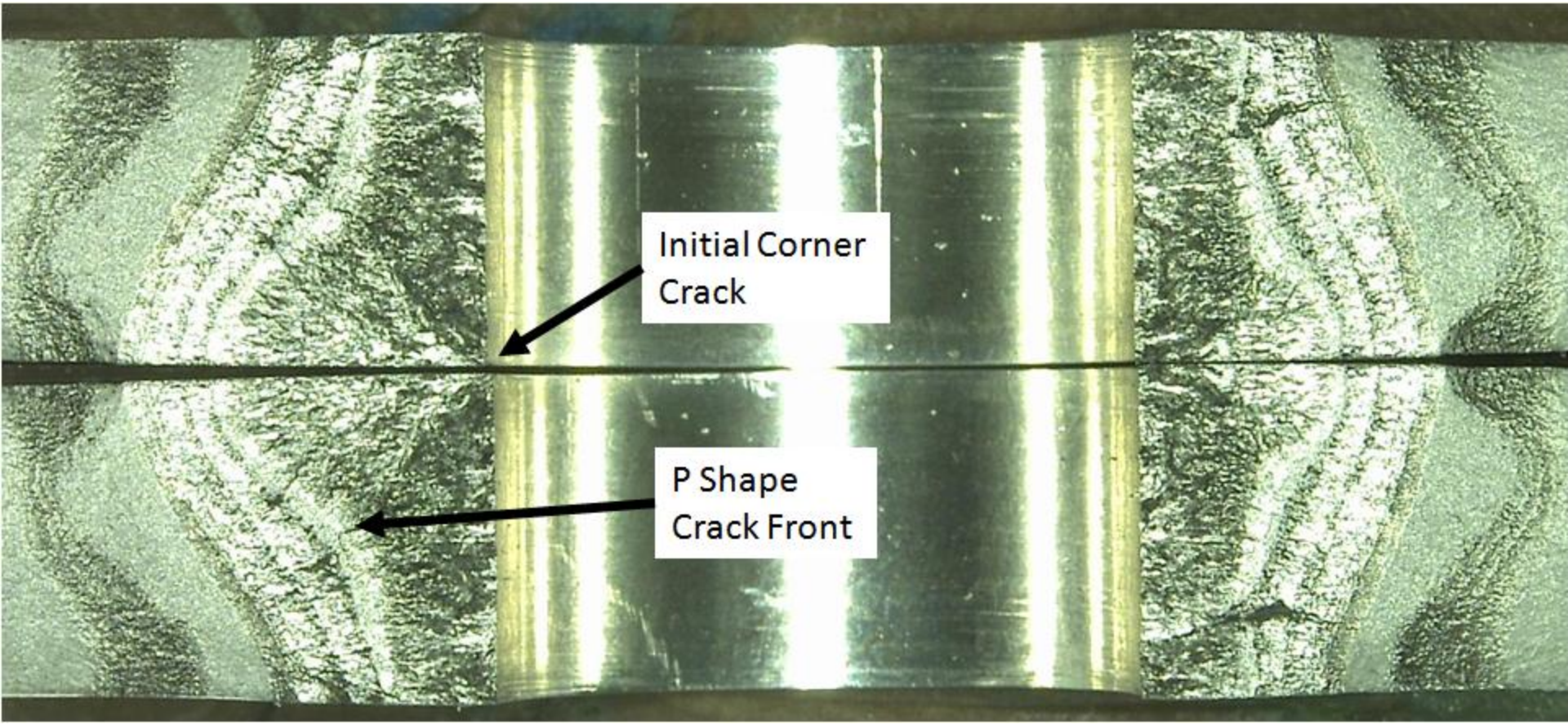
Questions?



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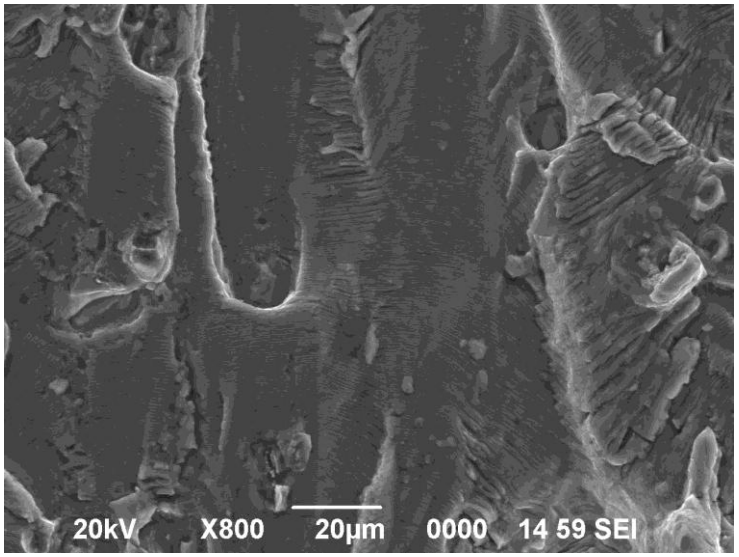

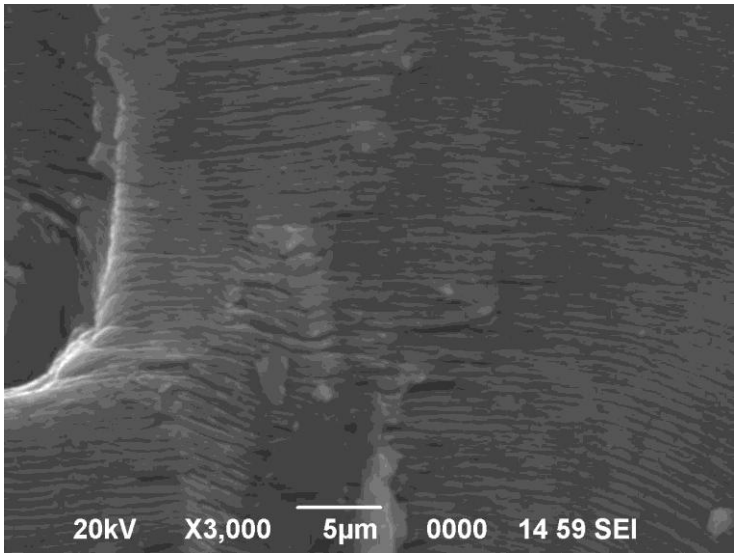

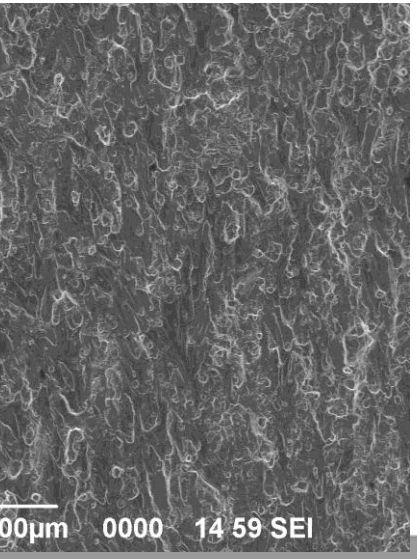

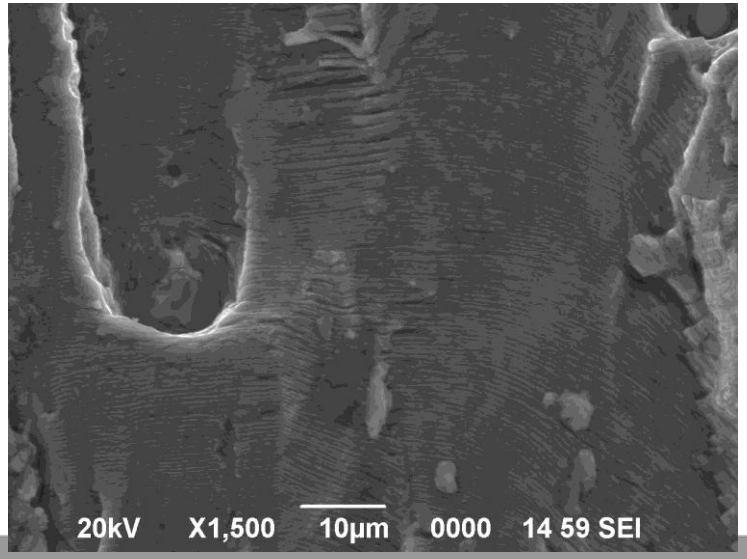

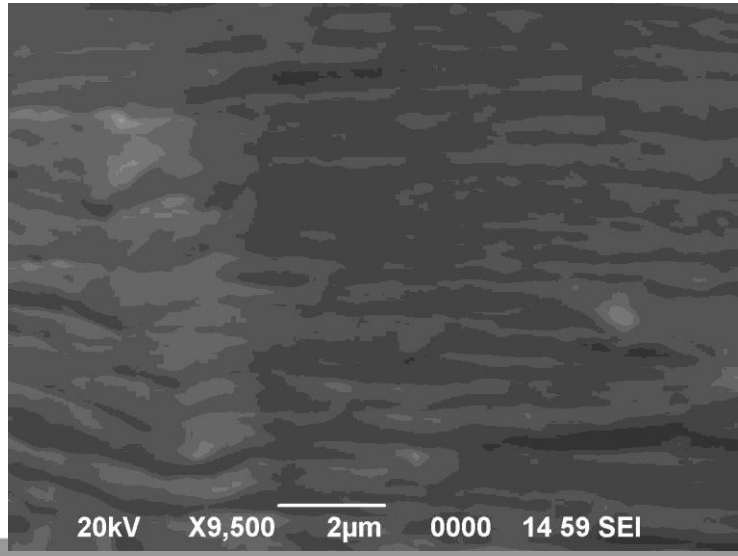

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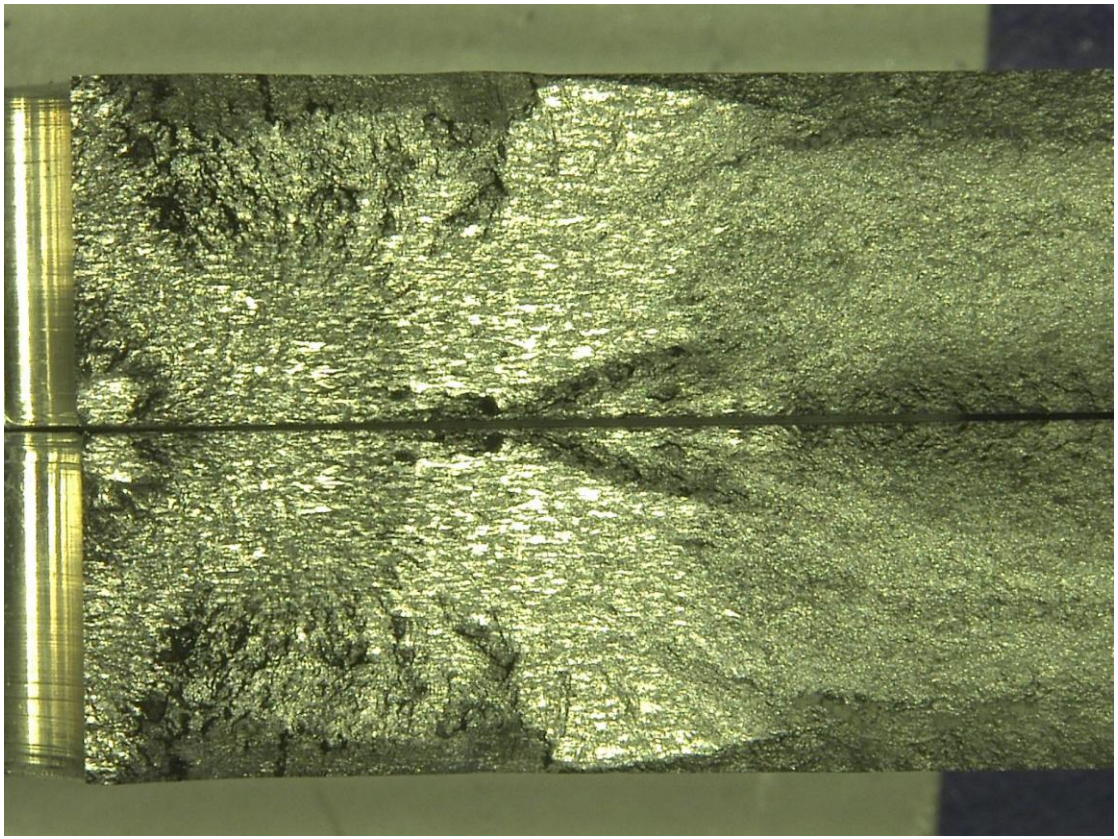

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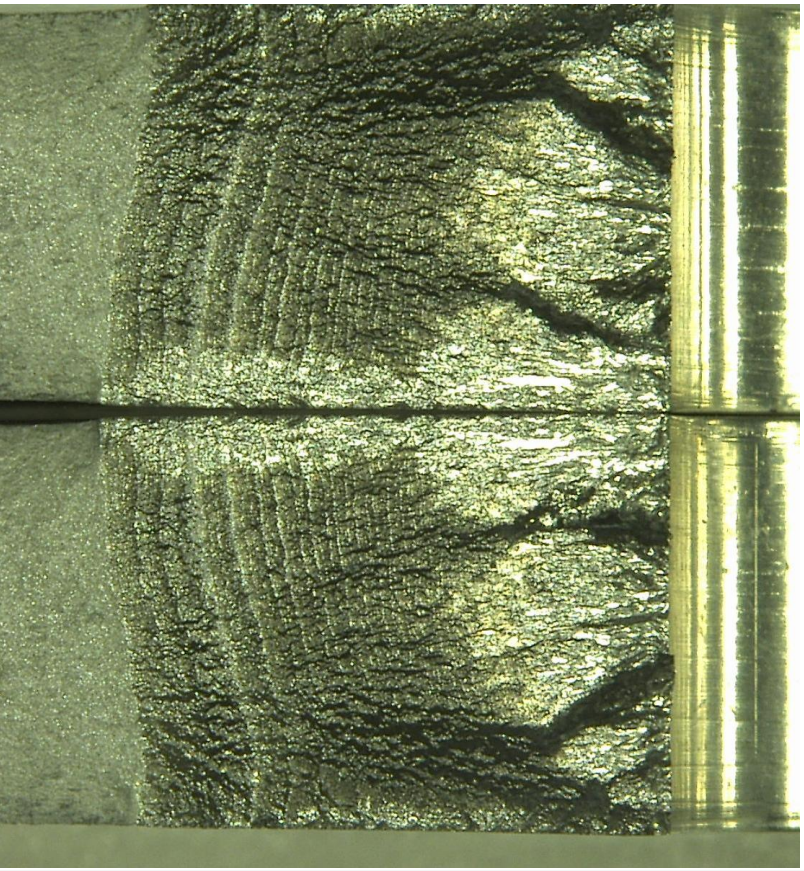

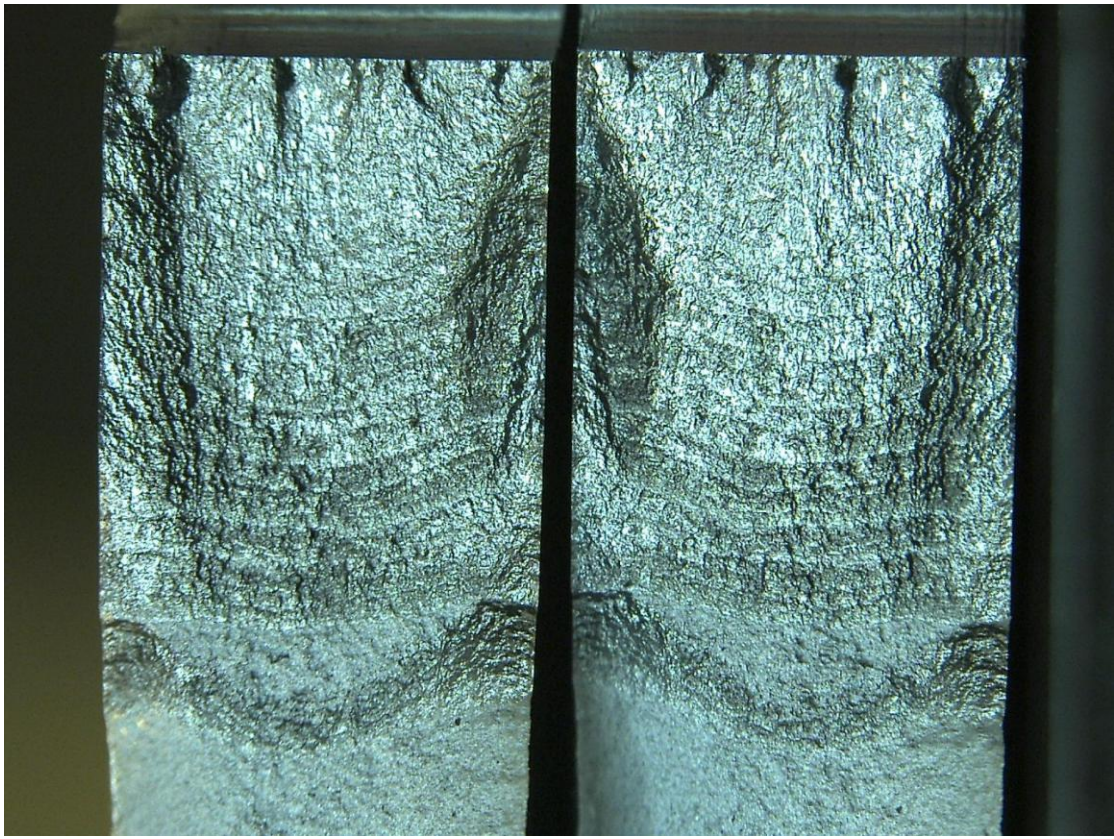

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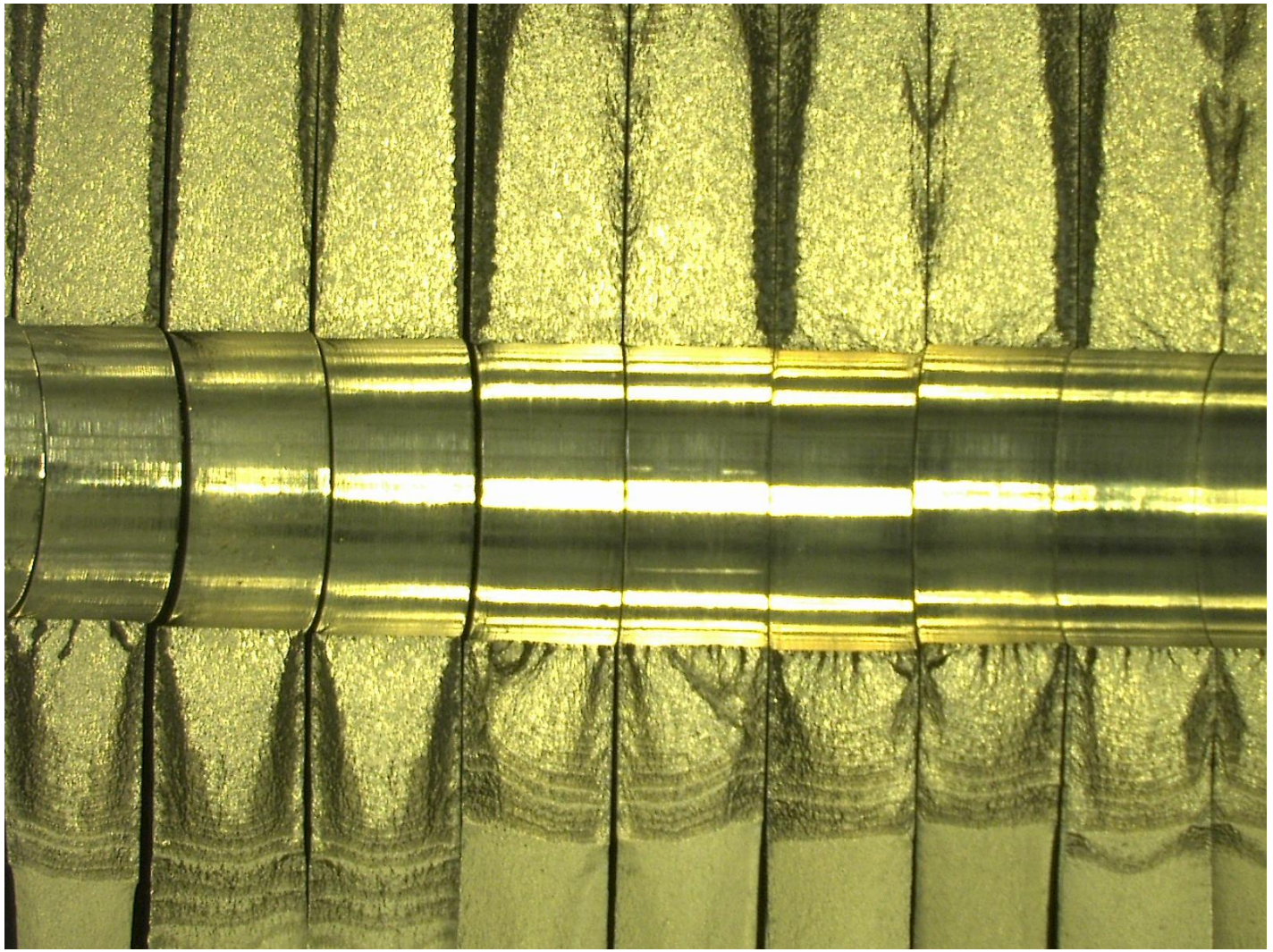

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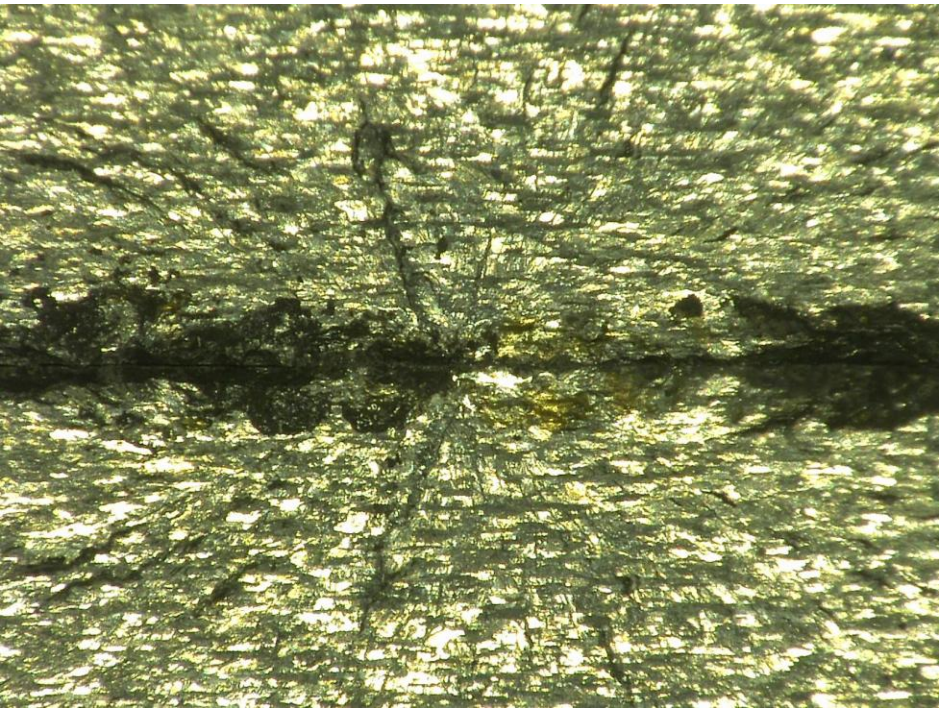

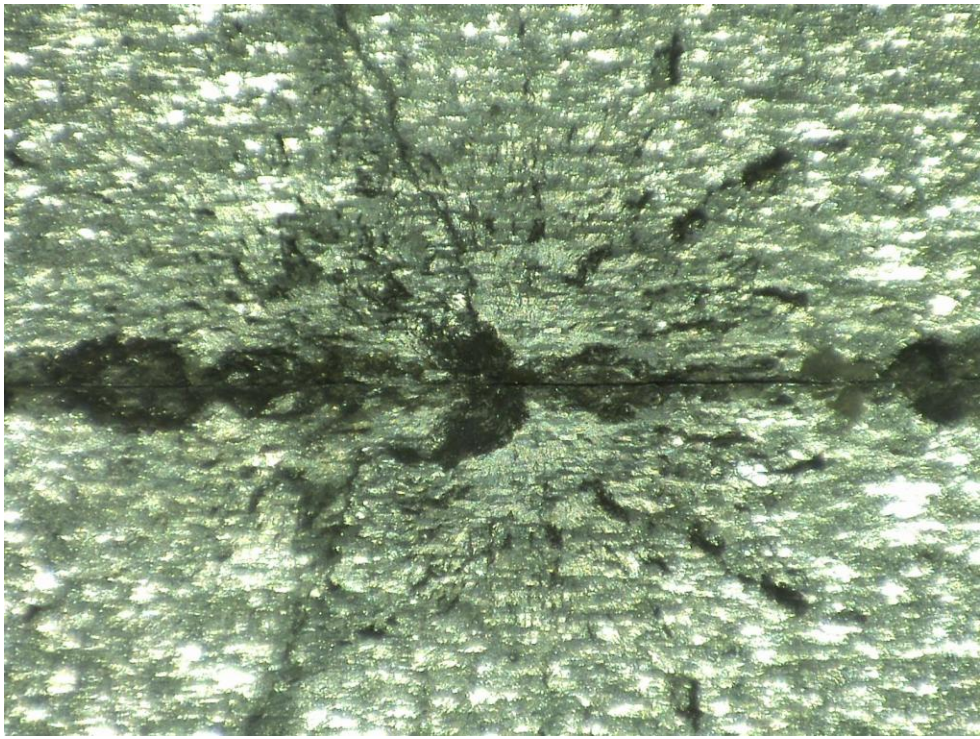

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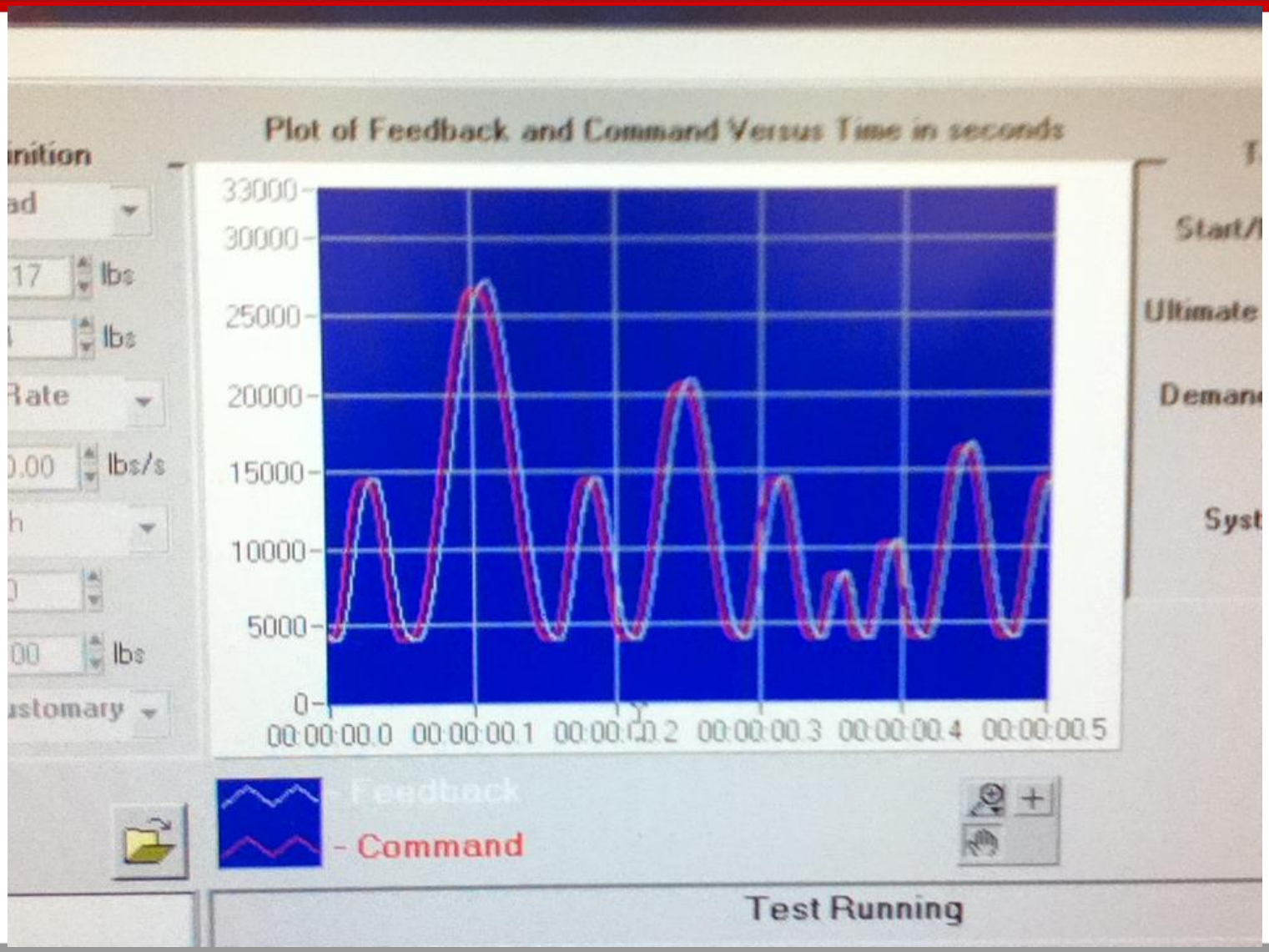

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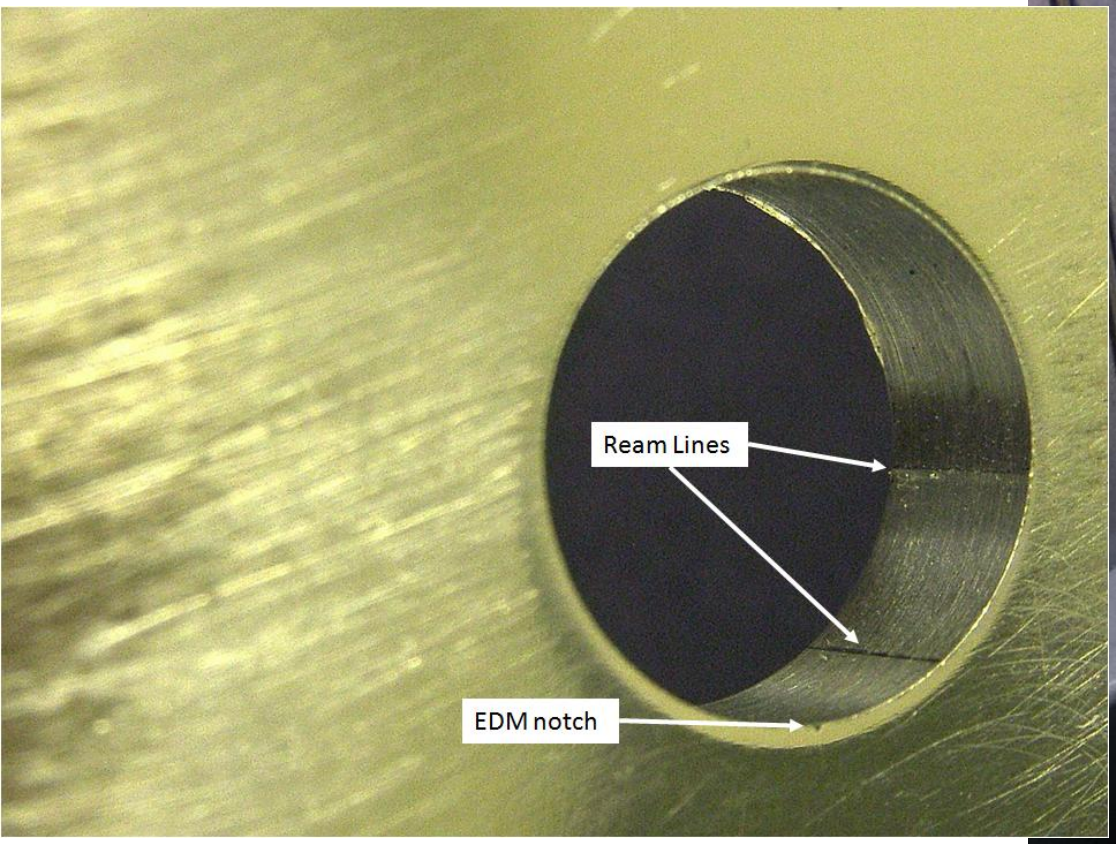

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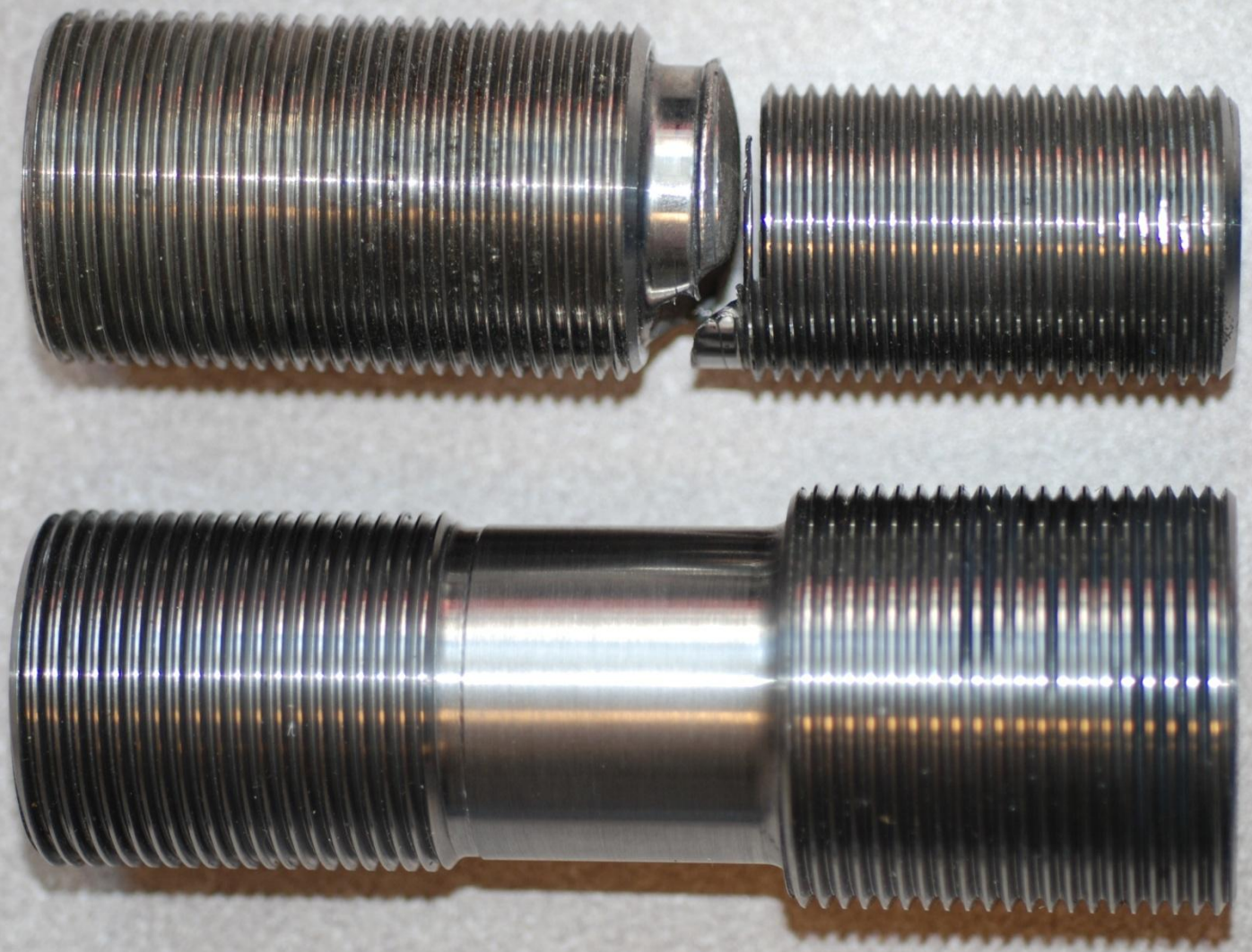

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