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U.S. AIR FORCE

Investigation of Cold Expansion of Short Edge Margin Holes with Preexisting Cracks in 2024-T351 Aluminum Alloy

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AFGROW User Workshop 2012

Agenda

- Research Objectives
- Research Background Information
- Fatigue Test Specimen Preparation and Test Setup
- AFGROW Models
- Results
- Discussion
- Conclusions and Recommendations
- References

Research Objectives

- Compare Fatigue Crack Growth Life for Three Specimen Configurations:
  - Non-Cold Expanded
  - Cold Expanded
  - Precracked Cold Expanded
- Determine if Selected Hole Offset is Applicable for Cold Expansion in a Maintenance Environment
- Document Crack Front Shape
- Determine if the current USAF approach to account for fatigue life improvement due to cold expansion is conservative for the geometry and loading used in the tests

Thesis Research

Comparison of Fatigue Crack Growth Life

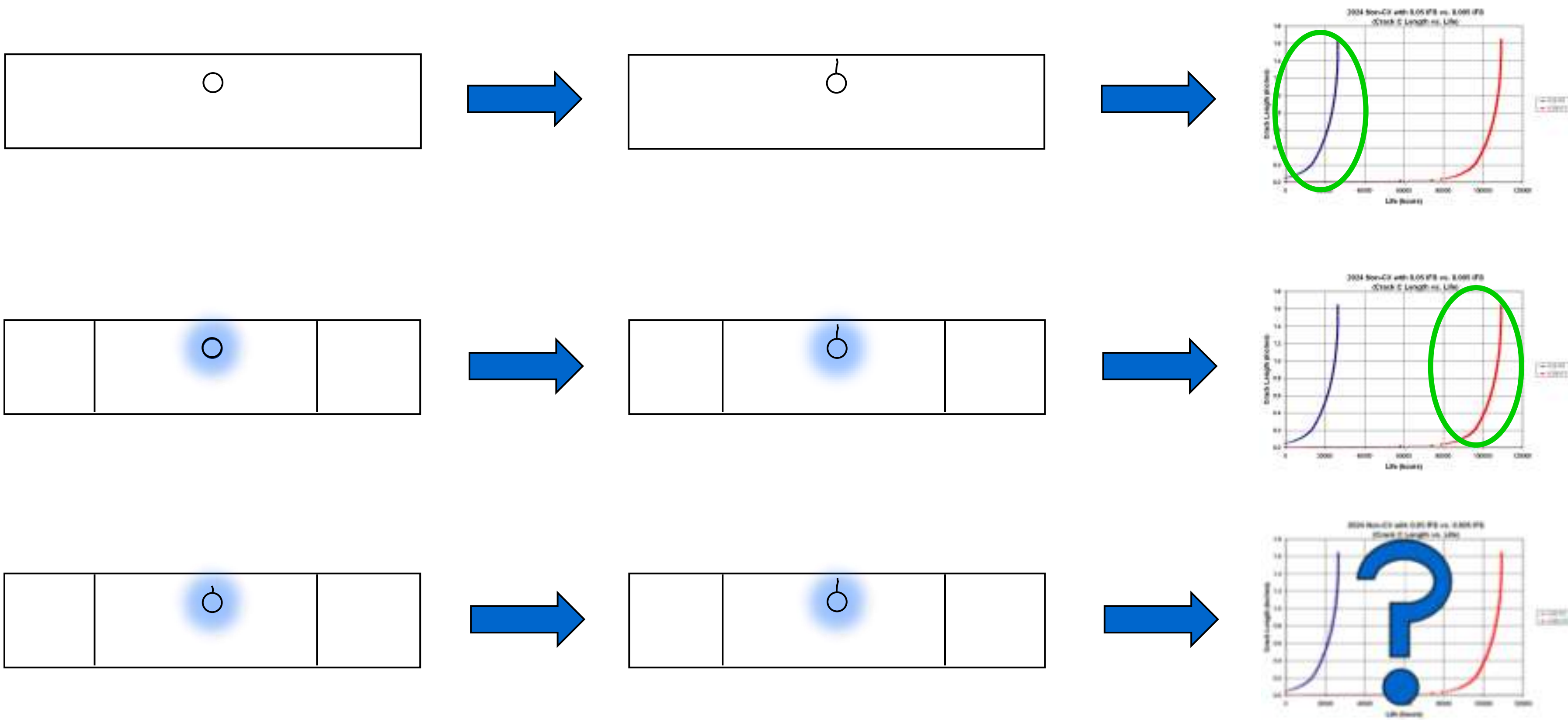
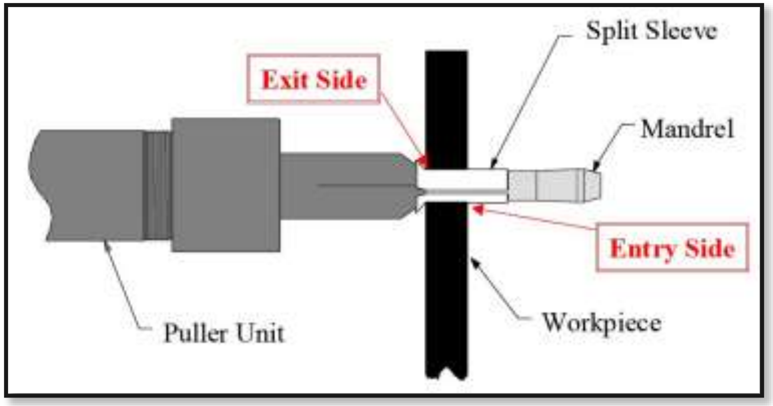


Fig. 1 Specimen Fatigue Crack Growth Life Comparison

Cold Expansion

- **Many Fatigue Issues are Located at Geometric Stress Concentrations – Fastener Holes**
- **Why Cold Expand a Hole?**
  - **Causes a Plastic Flow of Material**
  - **Results in Compressive Residual Stresses Adjacent to the Hole**
  - **Increases Fatigue Life and Retards Crack Growth**
  - **Low Cost / Low Tech Method**



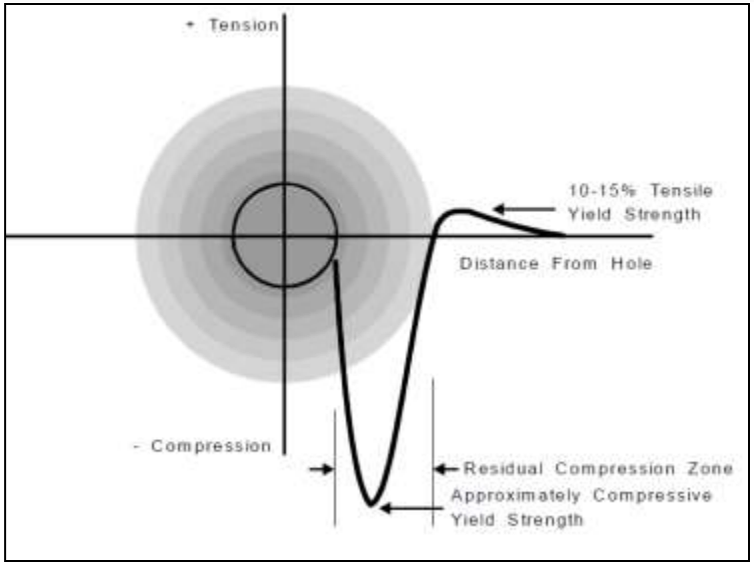


Fig.2 Top – FTI Split Sleeve Cold Expansion Process; Bottom –Residual Stress Profile Induced by FTI Split Sleeve Cold Expansion Process.[1]

Short Edge Margin

$e = .5325$

$D_{nom} = 0.25$

$(e/D)_{nom} = 2.13$

$(e/D)_{oversize} = 1.42$

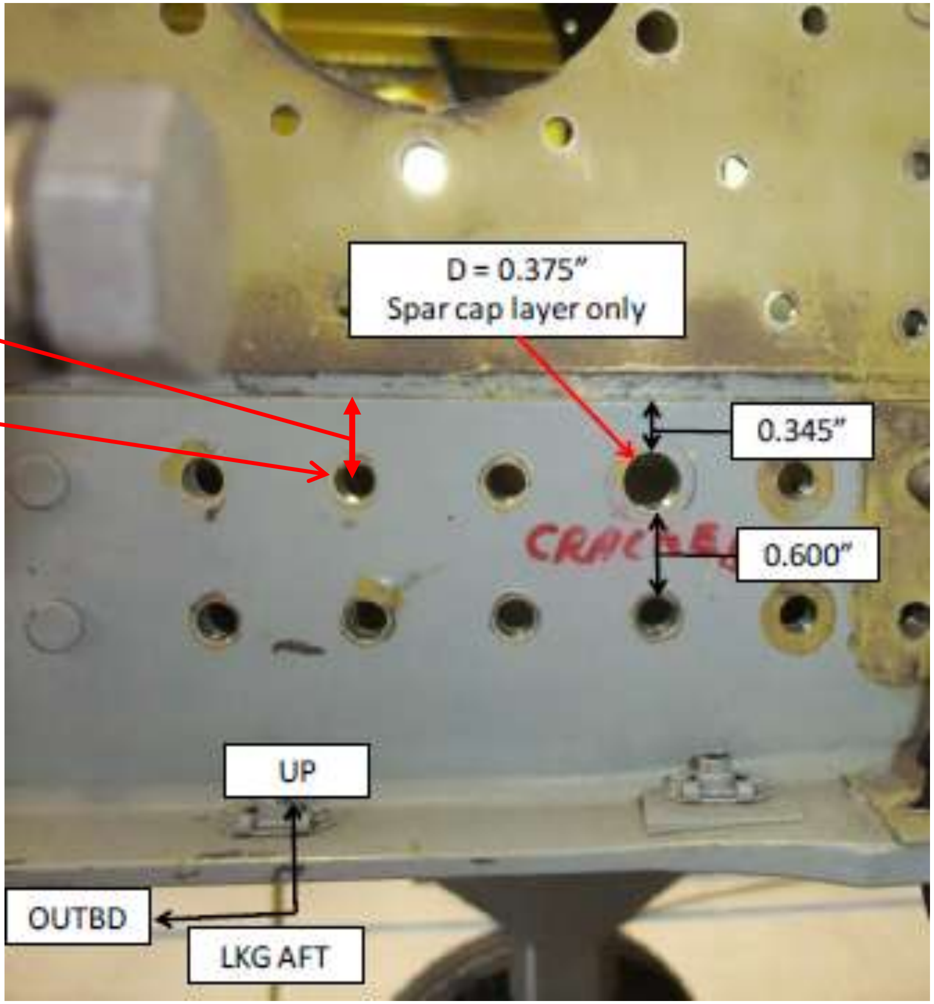


Fig. 3 Example of an oversized hole on an aircraft creating a short edge margin[2]

Fatigue Test Specimens

- **Material – AL 2024-T351**
  - **High Toughness / Low Strength Aerospace Grade Aluminum**
- **Constant Amplitude Loading**
  - **Max Stress 25 ksi and 10 ksi; R = 0.1**
- **Variable Amplitude Loading**
  - **Max Spectrum Stress = 33 ksi; A-10 Wing Spectrum**
- **Four Specimen Configurations Tested**
  - **2 ASTM E 647 Specimens**
    - **Verification of Test Setup, Operator Procedure, Material Behavior**
  - **6 Non Cold Expanded Specimens**
    - **Baseline Crack Growth Life**
  - **8 Cold Expanded Specimens**
    - **Baseline Crack Growth Life**
  - **10 Pre-Cracked Cold Expanded Specimens**
    - **Test Configuration**

Fig. 4 Cold Expanded Specimen

Specimen Configuration:
Non Cold Expanded: Baseline

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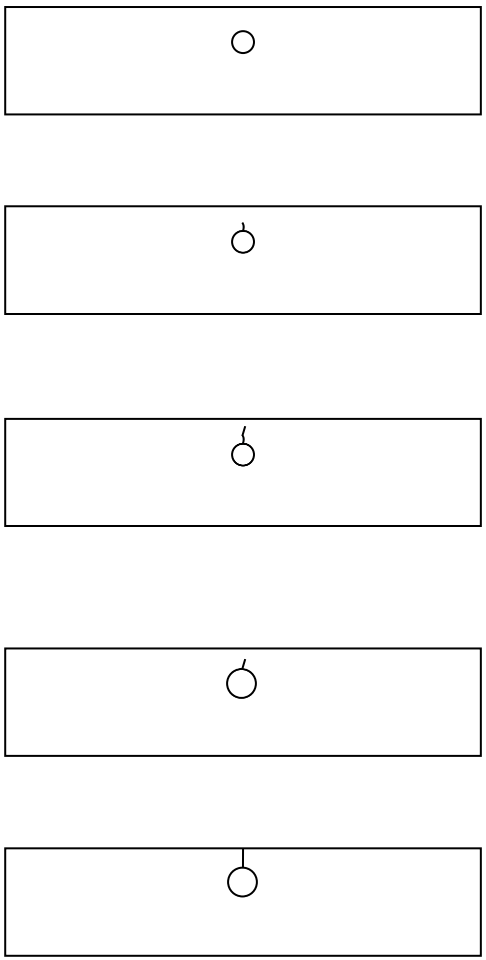


1. Drill and ream offset hole to initial diameter of 0.474-0.477 inch

2. EDM notch corner of hole to 0.020 inch by 0.020 inch

3. Precrack the specimen by constant amplitude loading to approximately 0.050 inch, to match minimum NDI detection threshold for bolt-hole eddy current probe

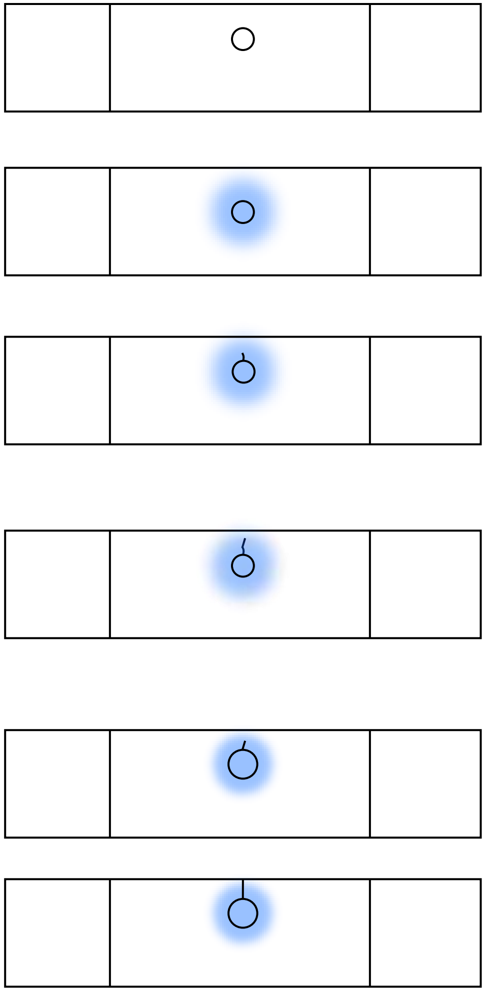
4. Final ream hole to 0.500 inch diameter

5. Fatigue test specimen to ligament failure

Fig. 5 Non-Cold Expanded Specimen Manufacturing Process Diagram

Specimen Configuration:

Cold Expanded: Baseline



1. Drill and ream offset hole to initial diameter of 0.474-0.477 inch
2. Cold expand hole
3. EDM notch corner of hole to 0.020 inch by 0.020 inch
4. Precrack the specimen by constant amplitude loading to approximately 0.050 inch, to match minimum NDI detection threshold for bolt-hole eddy current probe
5. Final ream hole to 0.500 inch diameter
6. Fatigue test specimen to ligament failure

Fig. 6 Cold Expanded Specimen Manufacturing Process Diagram

Specimen Configuration:
Precracked Cold Expanded

1. Drill and ream offset hole to initial diameter of 0.474-0.477 inch
2. EDM notch corner of hole to 0.020 inch by 0.020 inch
3. Precrack the specimen by constant amplitude loading to approximately 0.050 inch, to match minimum NDI detection threshold for bolt-hole eddy current probe
4. Cold expand hole
5. Final ream hole to 0.500 inch diameter
6. Fatigue test specimen to ligament failure

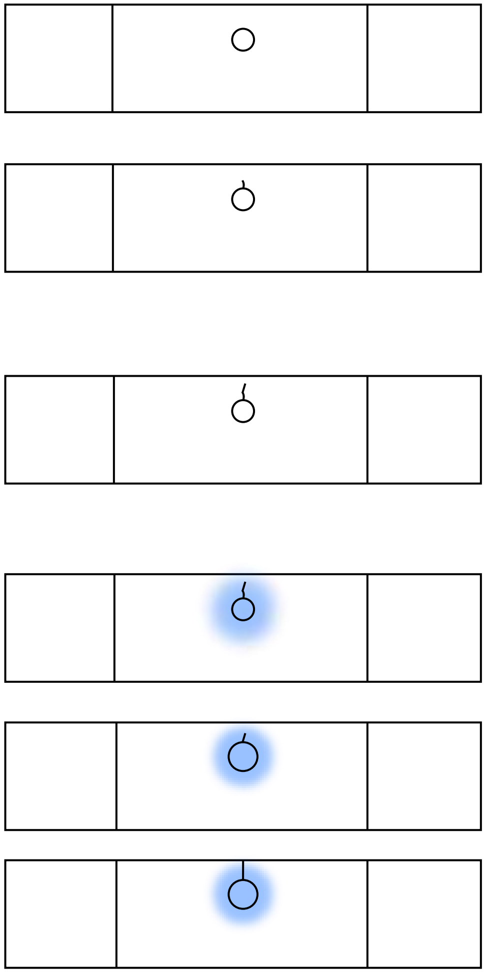


Fig. 7 Precracked Cold Expanded Specimen Manufacturing Process Diagram

AFGROW Models

- **ASTM E 647 Specimens**
  - **Validate da/dN vs. ΔK Curve Fit**
- **Non Cold Expanded Constant Amplitude Specimens**
  - **Establish and Validate Modeling Procedures**
- **Non Cold Expanded Variable Amplitude Specimens**
  - **Establish Retardation Parameter**

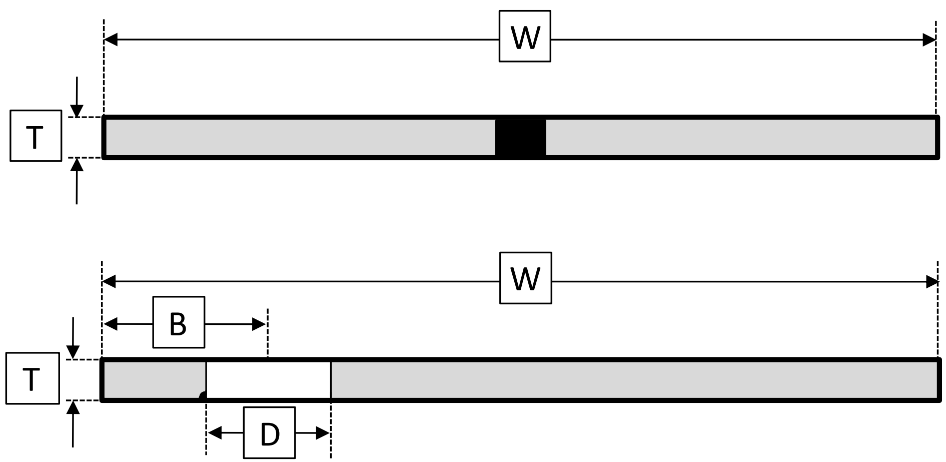


Fig. 8 Cross-sectional view of AFGROW Models Used to Baseline Fatigue Life Predictions/Postdictions[4]

Results

ASTM E 647 Specimens – da/dN vs. ΔK

- Constant Amplitude Loading
  - σ_{max} = 11.4 ksi
  - R = 0.1
  - *f* = 20 Hz
- Harter T & NASGRO Equations from AFGROW[4]

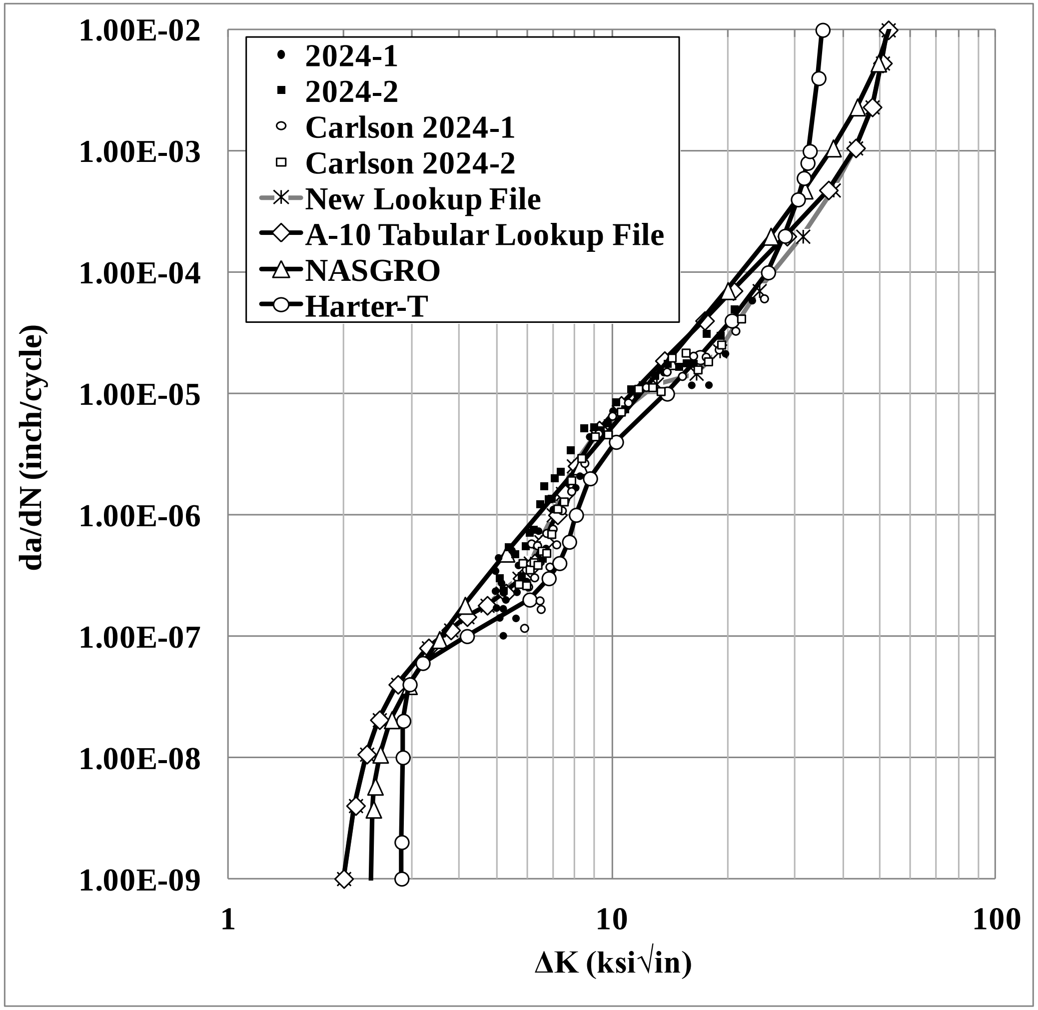
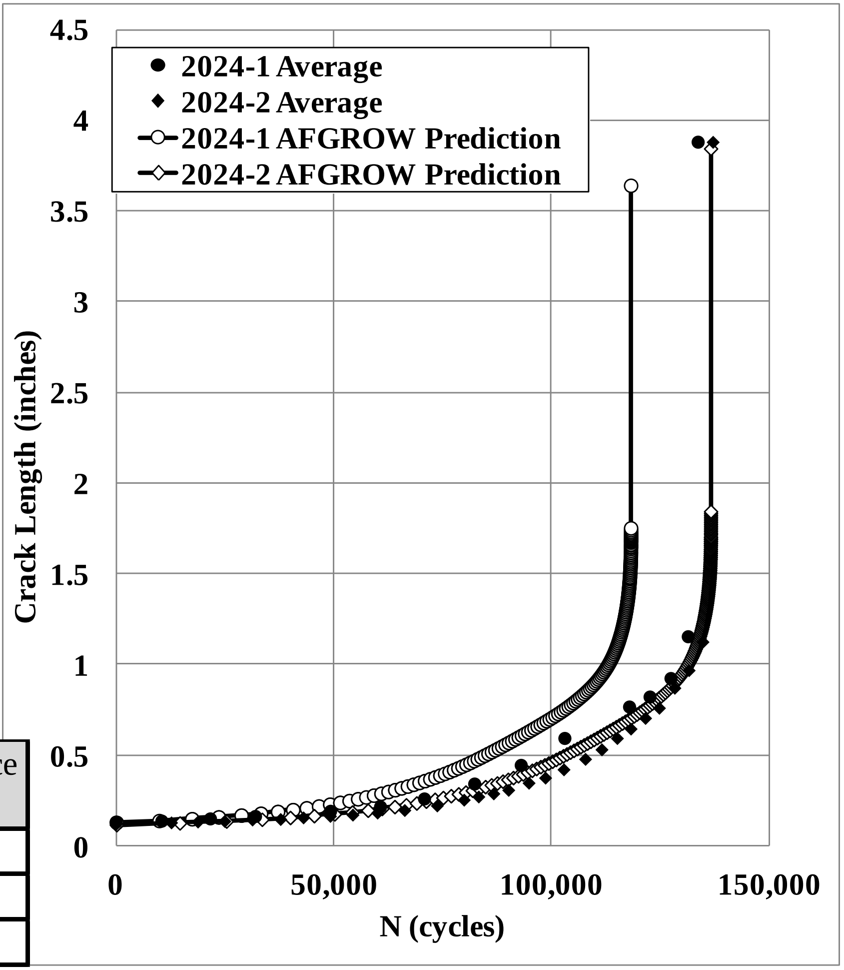


Fig. 9 da/dN vs. ΔK Test Data and Several Curve Fits[3]

Results

ASTM E 647 Specimens Crack Growth Curves

- Constant Amplitude Loading
  - σ_{max} = 11.4 ksi
  - R = 0.1
  - f = 20 Hz
- AFGROW Model
  - Averaged Crack Length



Specimen ID	Constant/Variable Amplitude Loading	Test Life (cycles)	Prediction Life (cycles)	% Difference in Life
2024-1	Constant	133769	118198	-11.64%
2024-2	Constant	137224	136574	-0.47%
Constant Amplitude Average:				-6.06%

Fig. 10 ASTM E 647 Specimens Crack Growth Test Data and AFGROW Postdictions

Results

Non Cold Expanded Specimens Crack Growth Curves

- Constant Amplitude Loading
  - σ_{max} = 10 ksi
  - R = 0.1
  - f = 20 Hz
- AFGROW Model
  - Averaged Crack Length
  - a/c=1 Held Constant

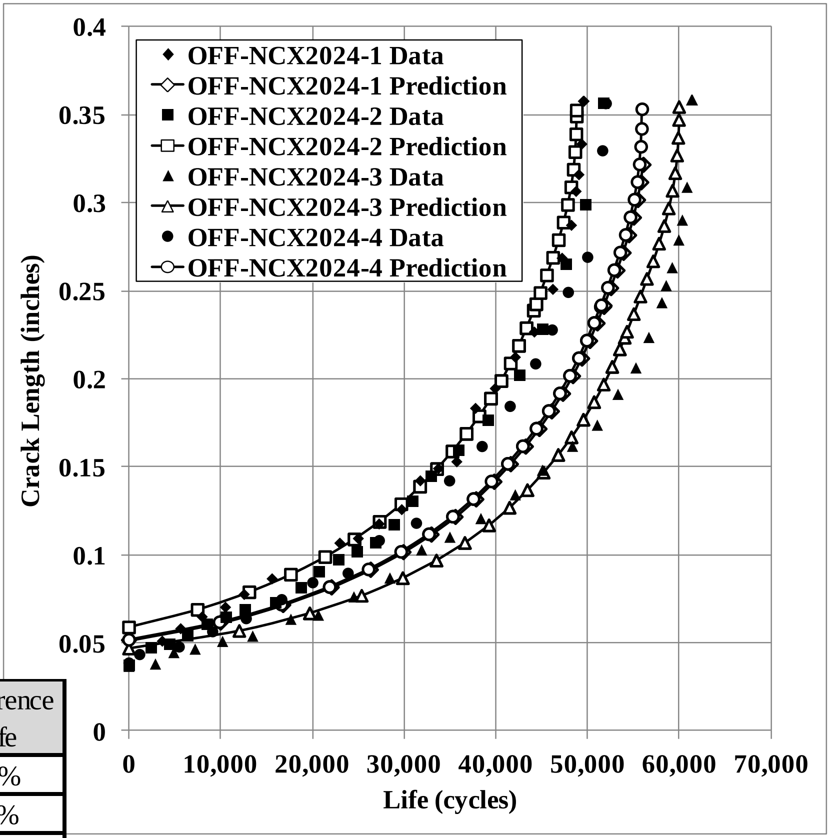


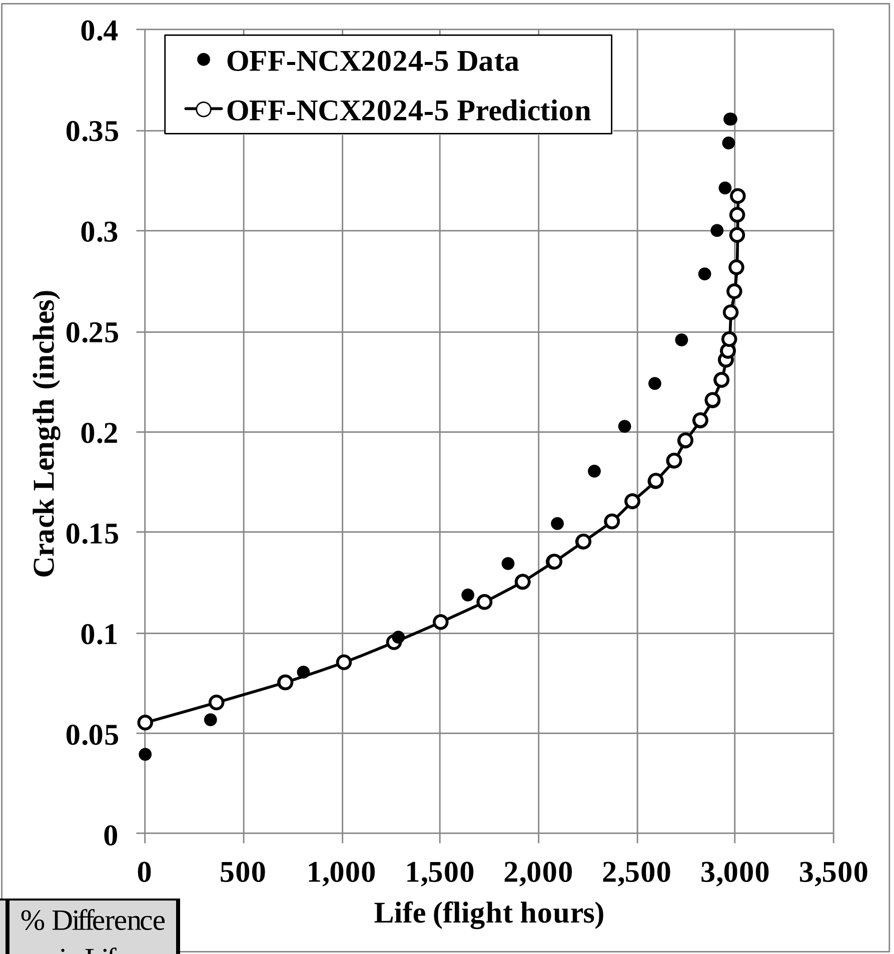
Fig. 11 Non Cold Expanded Constant Amplitude Specimen Crack Growth Test Data and AFGROW Postdictions

Specimen ID	Constant/Variable Amplitude Loading	Test Life (cycles/flight hours)	Prediction Life (cycles/flight hours)	% Difference in Life
OFF-NCX2024-1	Constant	49631	56415	12.0%
OFF-NCX2024-2	Constant	51797	48839	-5.7%
OFF-NCX2024-3	Constant	61441	60002	-2.3%
OFF-NCX2024-4	Constant	52051	55974	7.5%
Constant Amplitude Average:				2.9%

Results

Non Cold Expanded Specimen Crack Growth Curve

- **Variable Amplitude Loading**
  - **σ_{max} = 33 ksi**
  - **A-10 Wing Spectrum**
  - ***f* = 20 Hz**
- **AFGROW Model**
  - **Averaged Crack Length**
  - **a/c=1 Held Constant**
  - **SOLR = 2.11**



Specimen ID	Constant/Variable Amplitude Loading	Test Life (cycles/flight hours)	Prediction Life (cycles/flight hours)	% Difference in Life
OFF-NCX2024-5	Variable	2979	3014	1.2%

Fig. 12 Non Cold Expanded Variable Amplitude Specimen Crack Growth Test Data and AFGROW Postdiction

Results

Constant Amplitude Fatigue Life Differences

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Type of Loading	Precracked Cold Expanded Specimens (X Times Increase in Life)	Cold Expanded Specimens (X Times Increase in Life)
Constant Amplitude Average	3.60	6.75

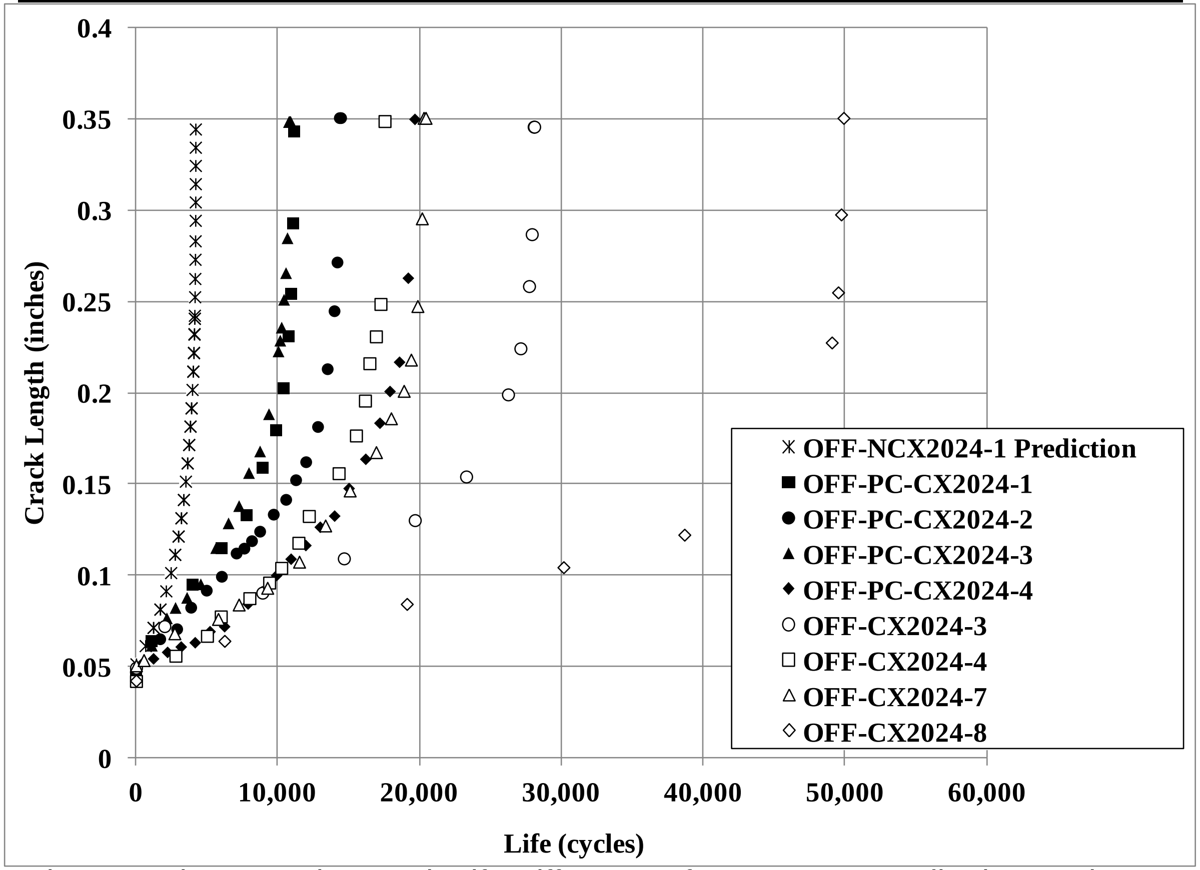


Fig. 13 Fatigue Crack Growth Life Differences for Constant Amplitude Specimens

Discussion

Constant Amplitude Fatigue Life Differences

Type of Loading	Precracked Cold Expanded Specimens (X Times Increase in Life)	Cold Expanded Specimens (X Times Increase in Life)
Constant Amplitude Average	3.60	6.75

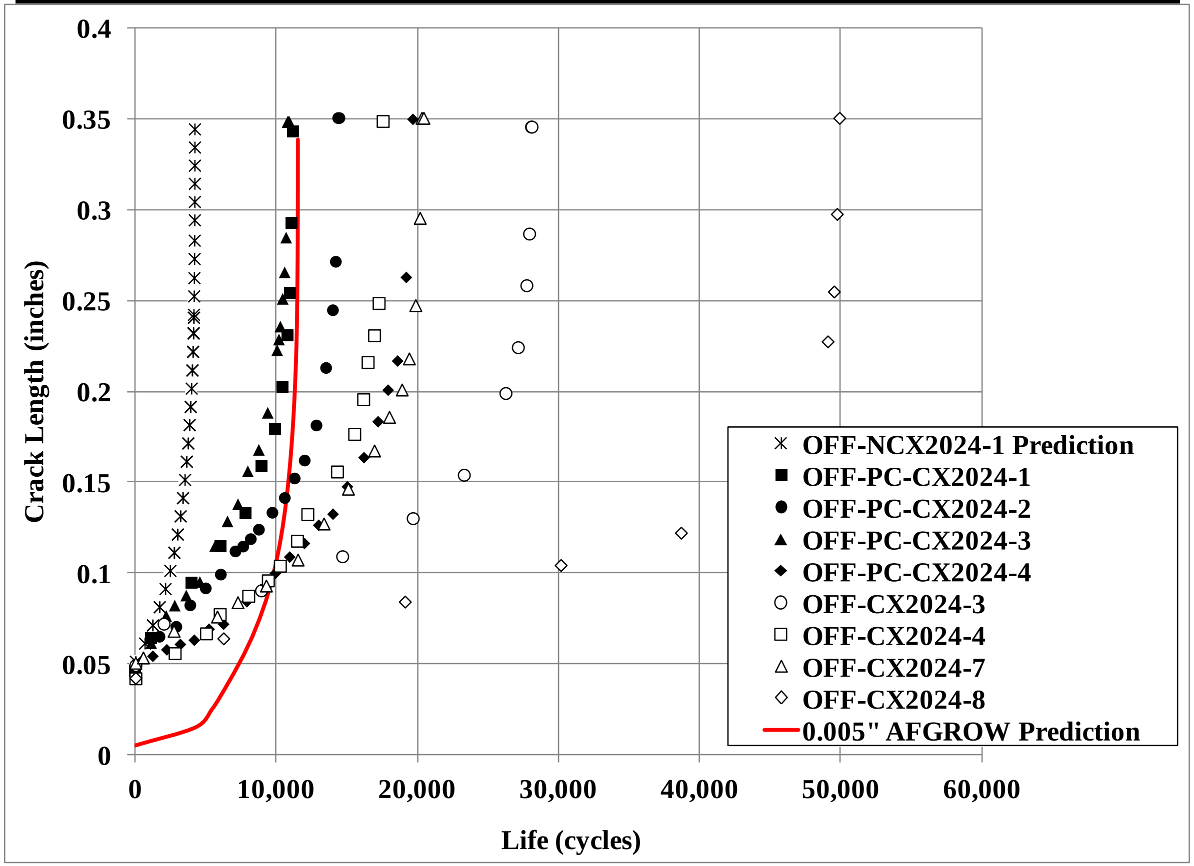


Fig. 14 Fatigue Crack Growth Life Differences for Constant Amplitude Specimens

Results

Variable Amplitude Fatigue Life Differences

Type of Loading	Precracked Cold Expanded Specimens (X Times Increase in Life)	Cold Expanded Specimens (X Times Increase in Life)
Variable Amplitude Average	2.27	3.26

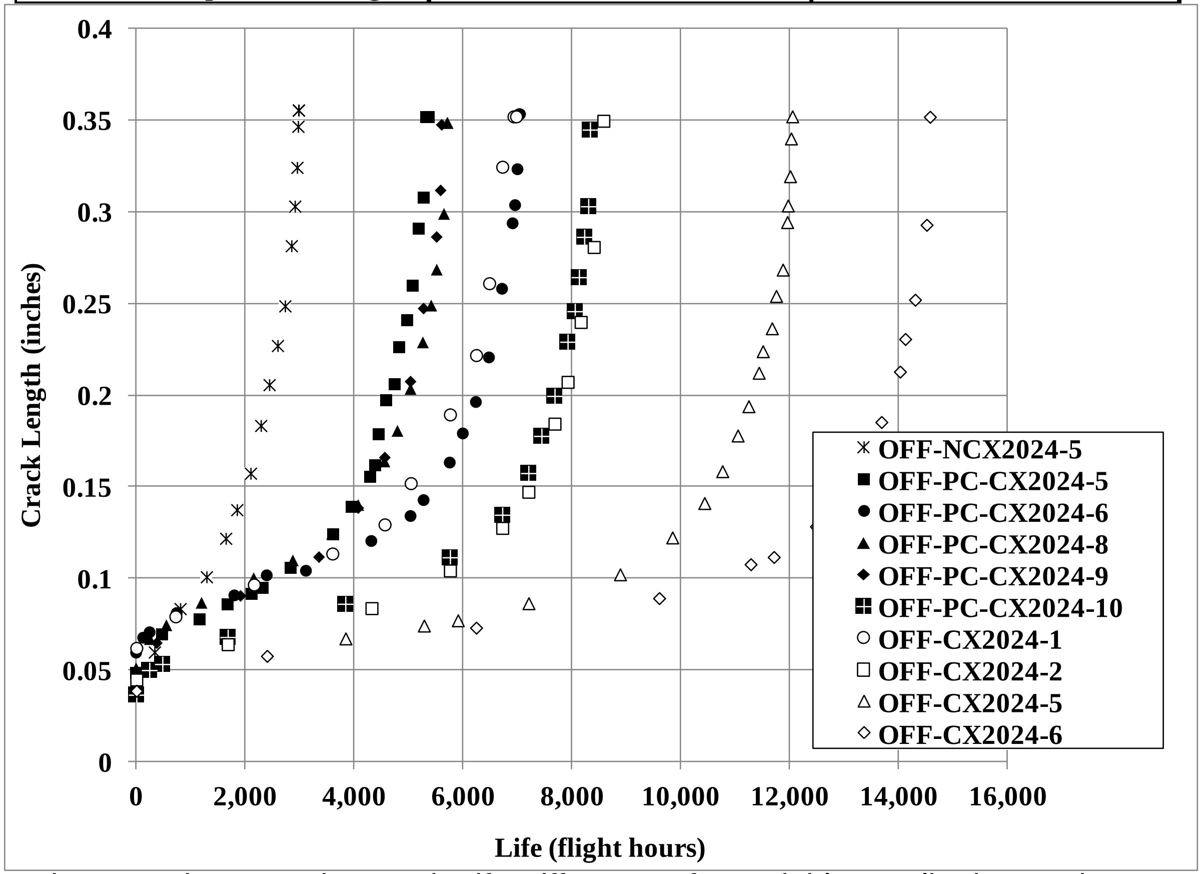


Fig. 15 Fatigue Crack Growth Life Differences for Variable Amplitude Specimens

Discussion

Variable Amplitude Fatigue Life Differences

Type of Loading	Precracked Cold Expanded Specimens (X Times Increase in Life)	Cold Expanded Specimens (X Times Increase in Life)
Variable Amplitude Average	2.27	3.26

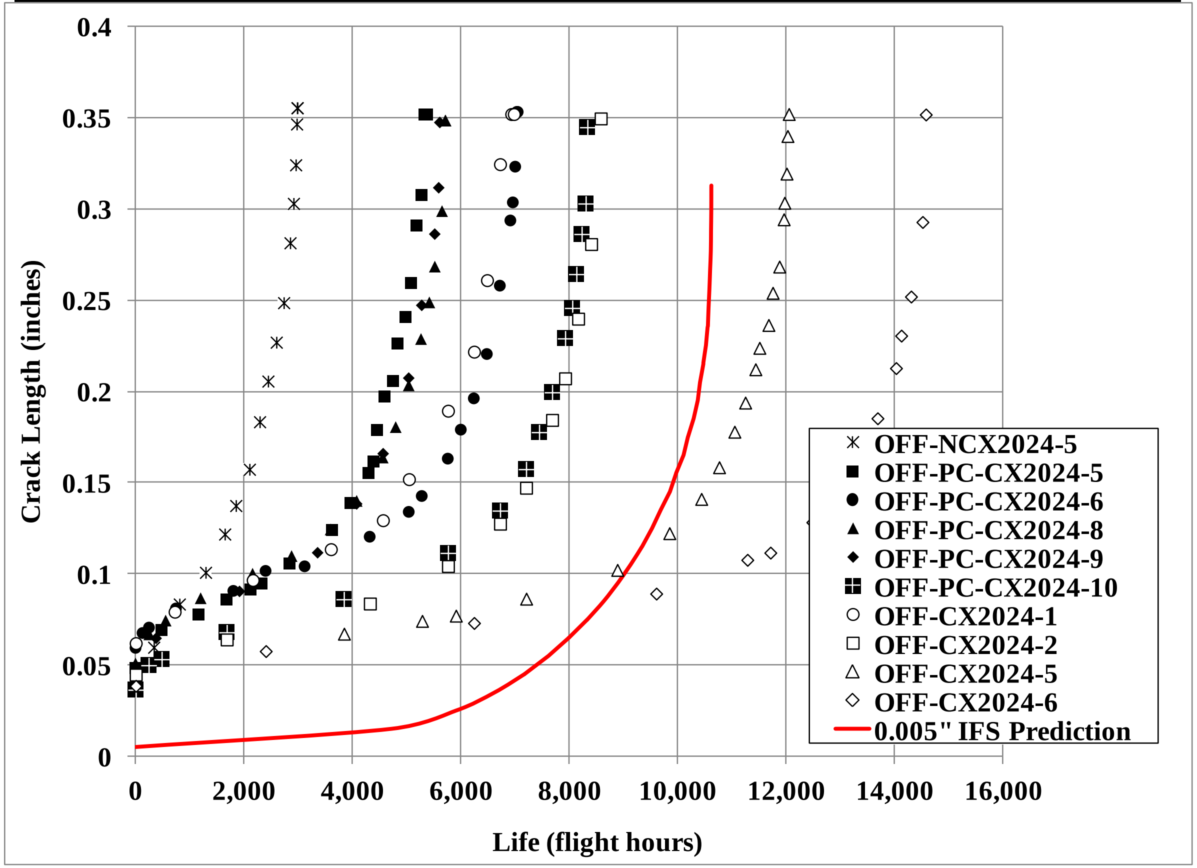
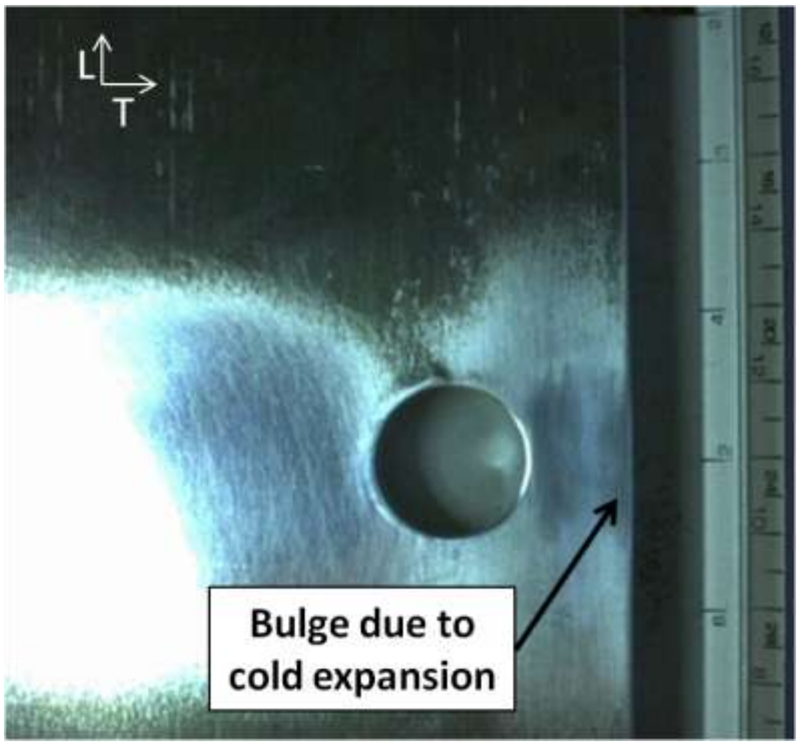


Fig. 16 Fatigue Crack Growth Life Differences for Variable Amplitude Specimens

Discussion

Deformation of Free Edge



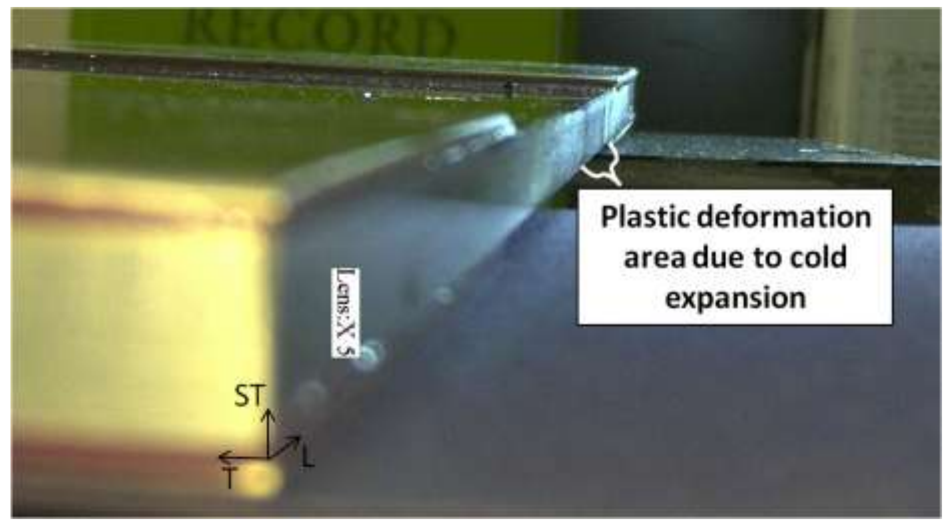


Fig. 17 Digital Microscope Image (5X Magnification) Showing Bulge Created on the Free Edge of the Specimens During the Cold Expansion Process

Discussion

Marker Band Specimen

- **Documentation of Crack Front Shape**

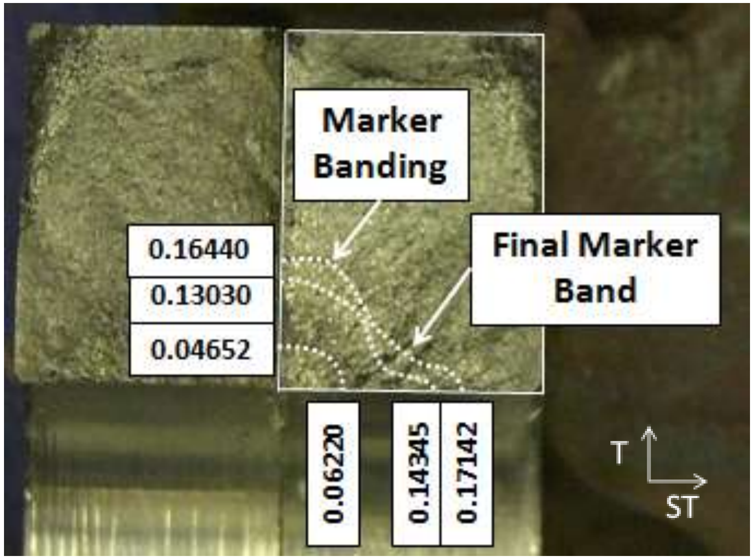


Fig. 18 Marker Banding on Precracked Cold Expanded Specimen OFF-PC-CX2024-7

Conclusions

- **Compare Fatigue Crack Growth Life for Three Specimen Configurations:**
  - **Non-Cold Expanded**
  - **Cold Expanded**
  - **Precracked Cold Expanded**
- **Determine if Selected Hole Offset is Applicable for Cold Expansion in a Maintenance Environment**
- **Document Crack Front Shape**
- **Determine if the current USAF approach to account for fatigue life improvement due to cold expansion is conservative for the geometry and loading used in the tests**

This Research Quantifies Fatigue Life Due to Cold Expansion of Cracked Hole with a Short Hole Offset

Conclusions

Correlation Ratio – Constant Amplitude

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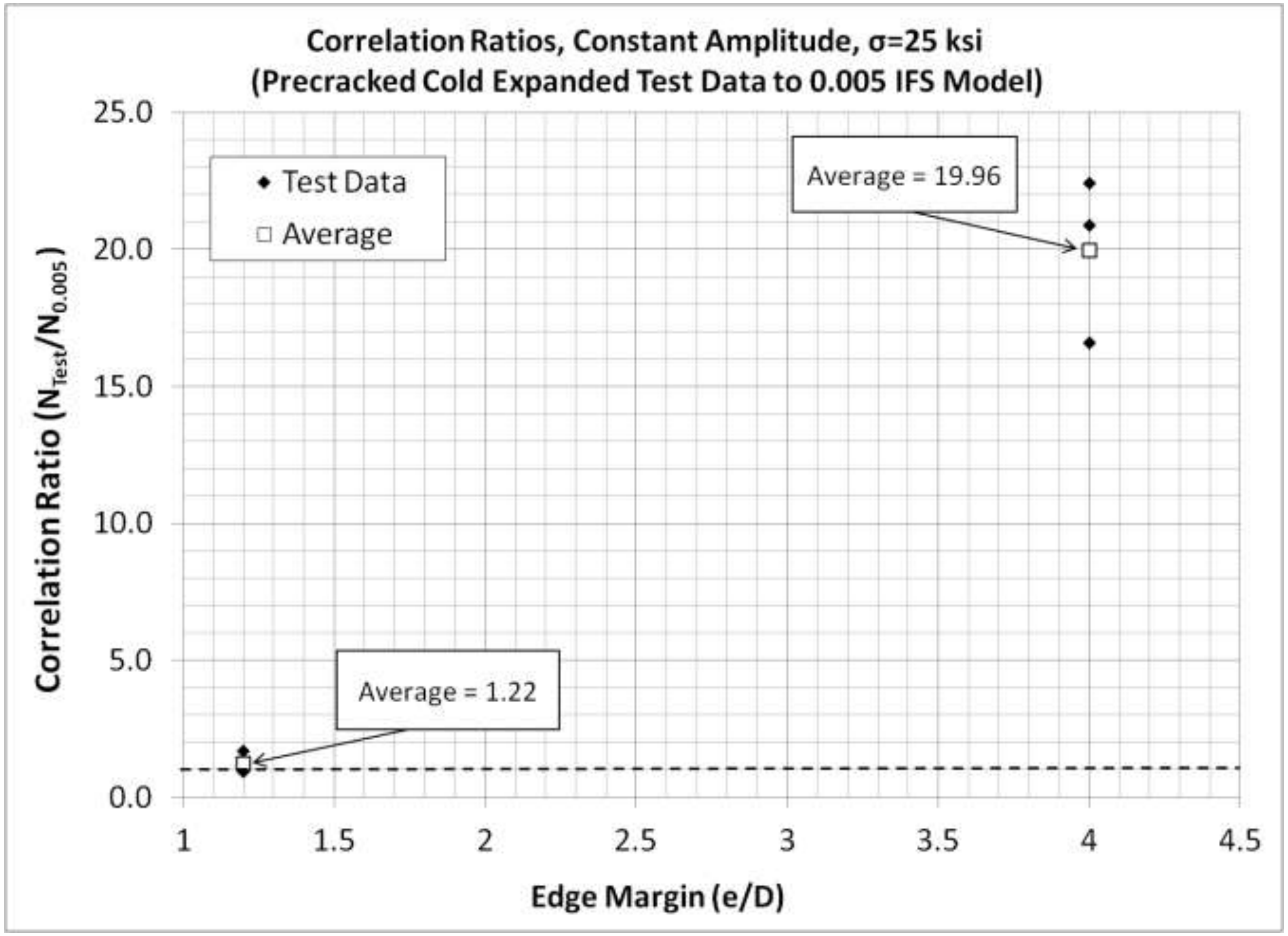

Fig. 19 Correlation Ratios for Constant Amplitude Test Data compared to a 0.005 IFS Prediction

Conclusions

Correlation Ratio – Variable Amplitude

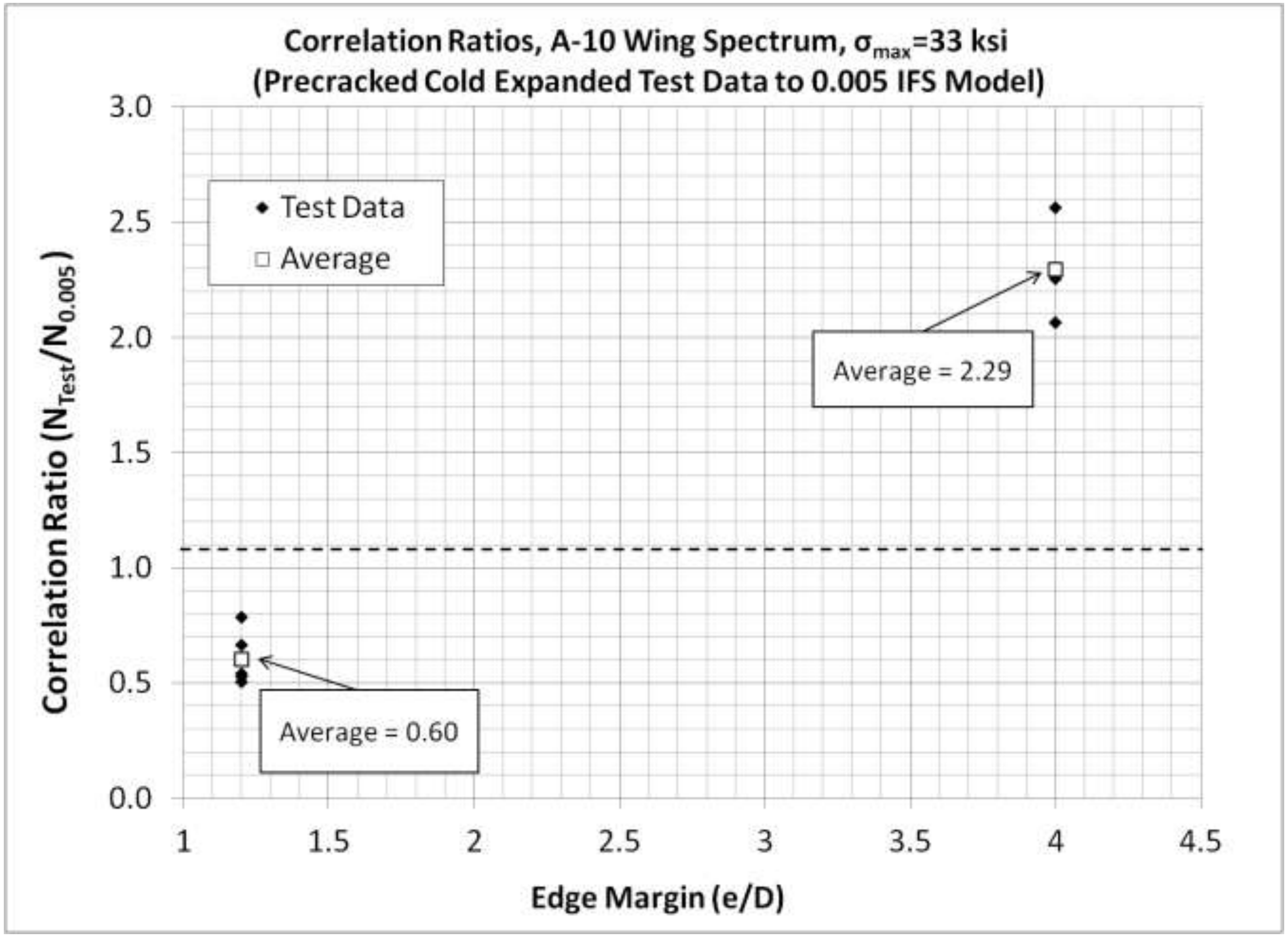

Fig. 20 Correlation Ratios for Variable Amplitude Test Data compared to a 0.005 IFS Prediction

Recommendations

- Additional Fatigue Testing
  - Vary Specimen Geometry Such As Hole Offset, Hole Diameter, Thickness, Etc.
  - Variation of Initial Crack Length Prior to Cold Expansion
  - Variation of Initial Discontinuity State (IDS)
    - EDM size, Razor Notches, Corrosion Pits, Scratches, Gouges, Etc.
  - Using Different Stresses for Both Constant and Variable Amplitude Loading
- Application of Beta Corrections
- Implementation of a residual stress field into a model

References

1. FTI Process Specification 8101D Cold Expansion of Holes Using the Standard Split Sleeve System and Countersink Cold Expansion (CsCx™), Fatigue Technology Inc., Seattle, WA, 2002.

2. Andrew, D. (2010) A3G-2009-182752, “Lower Forward Spar Cap & Web OS Holes ”, 6 January 2010.

3. Carlson, S. (2008). Experimentally derived beta (β) corrections to accurately model the fatigue crack growth behavior at cold expanded holes in 2024-T351 aluminum alloys. Mechanical Engineering. University of Utah, Salt Lake City, 219.

4. LexTech Inc., AFGROW (Fracture Mechanics and Fatigue Crack Growth Analysis Software), version 5.1.5.16, 2010.

Questions?

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