Fatigue Testing and Validation

Fatigue Crack Growth in Engineered Residual Stress Fields

ERSI
Layton, UT

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Acknowledgments

- A-10 & T-38 ASIP
- AFRL
- SwRI
- ERSI Subcommittees

Contents

- Why do we test?
- Analysis data needs
- Peak Valley Load Excursion Effects at CX Holes
- Effect of Applied Stress Ratio on Crack Growth at CX Holes
- Equipment Inventories
- Future validation cases
- Crack Growth Material Data

ERS: Why do we test?

- Certification of a process for production / repair
- Iterate design (w/ desire for computational methods up front)
- Examine variability and interactions in a process
  - Uncover modeling needs
- Provide validation data for models
- Provide "foundation" data (e.g., crack growth rate data)
- Understand failure modes and evolution

Data to Support ERSI Analysis Group

- What are the big needs?
  - Most sensitive parameters to crack growth in RS fields:
    - Material data (da/dN vs. ΔK)
    - Stress distribution / redistribution
    - Closure phenomena
  - Validation cases
    - Primarily constant amplitude

Residual Stress (RS) Redistribution

Compression / Tension Overloads (OL)

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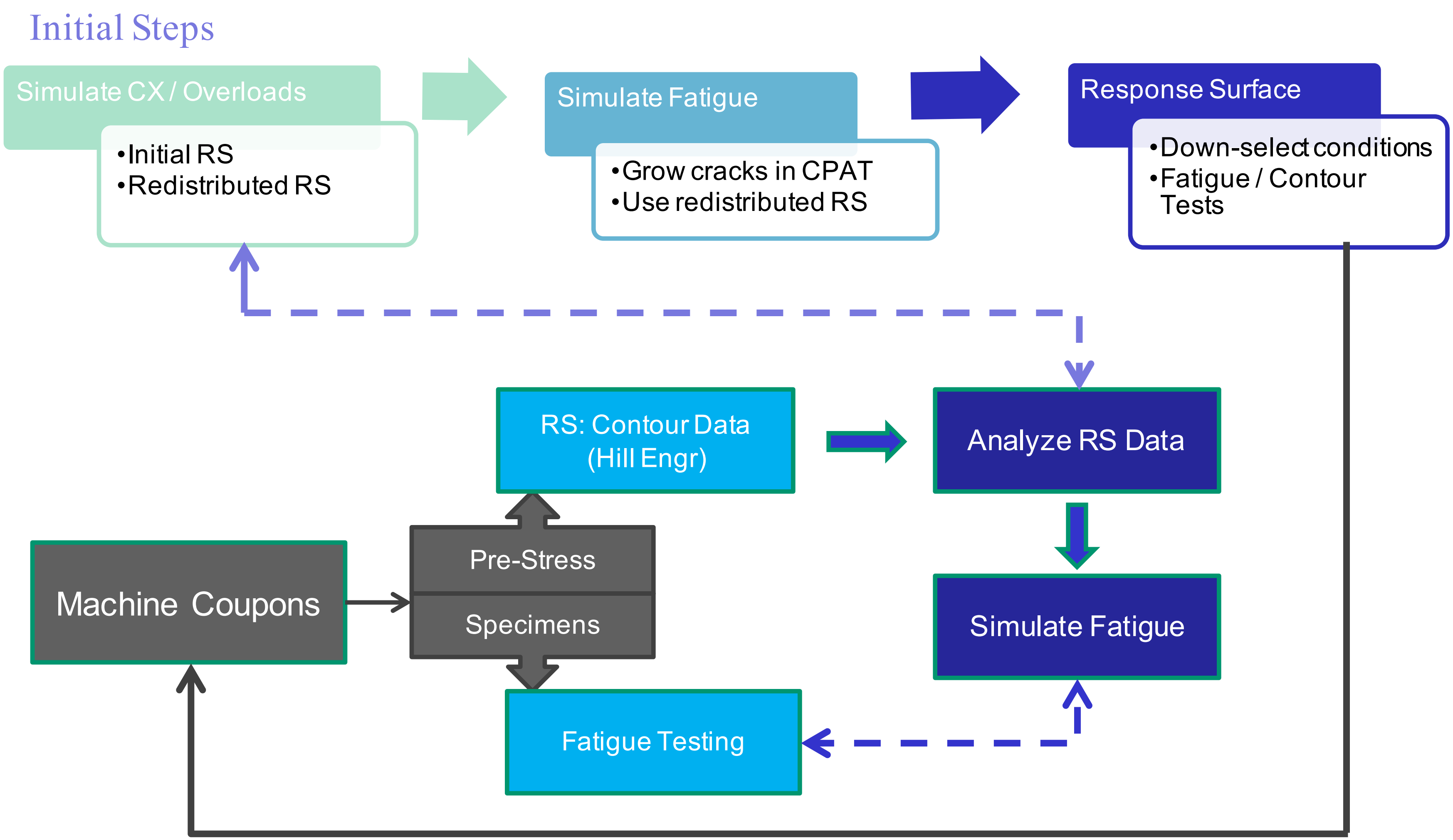
Task Process Flow

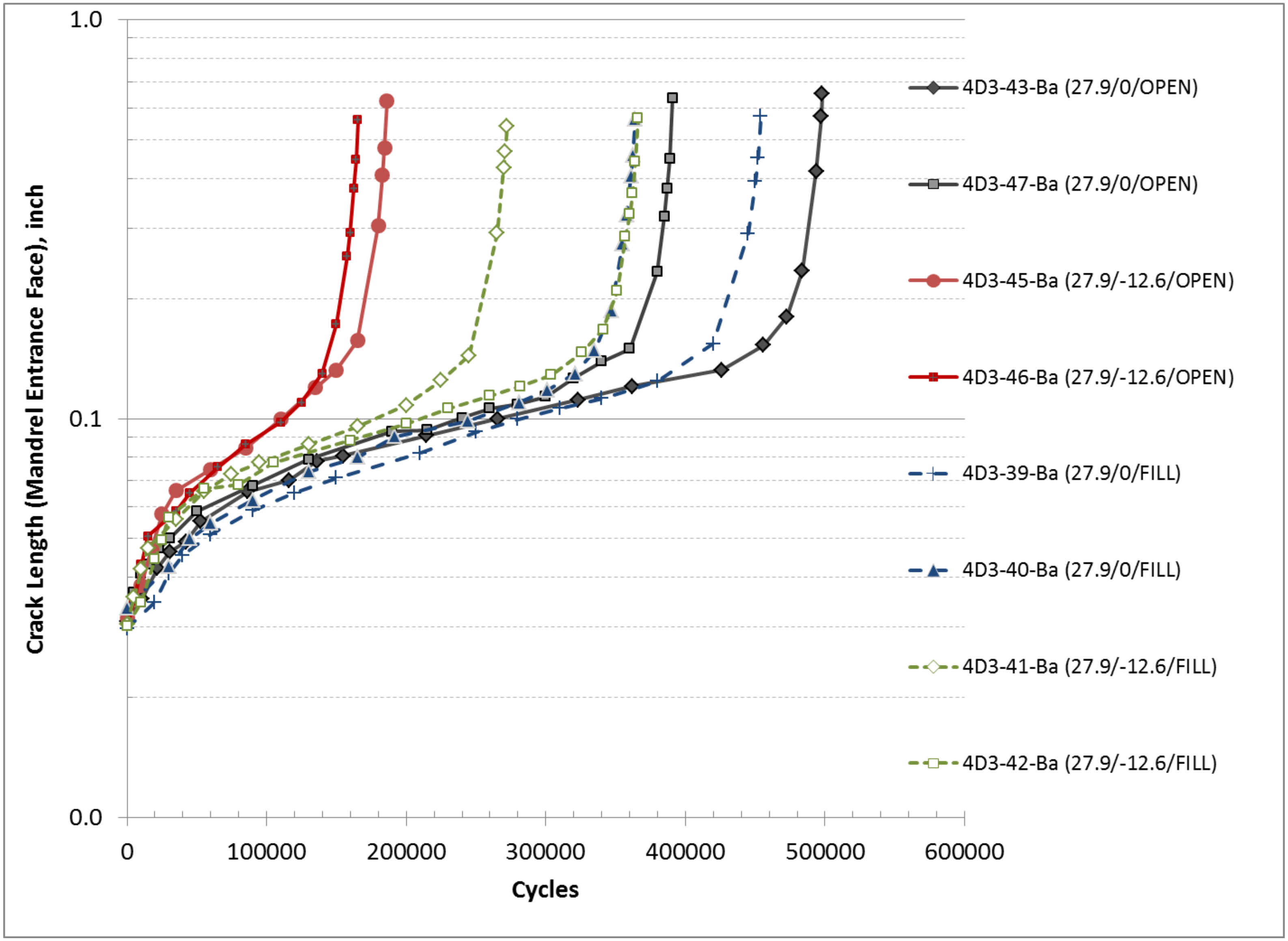


Test Matrix

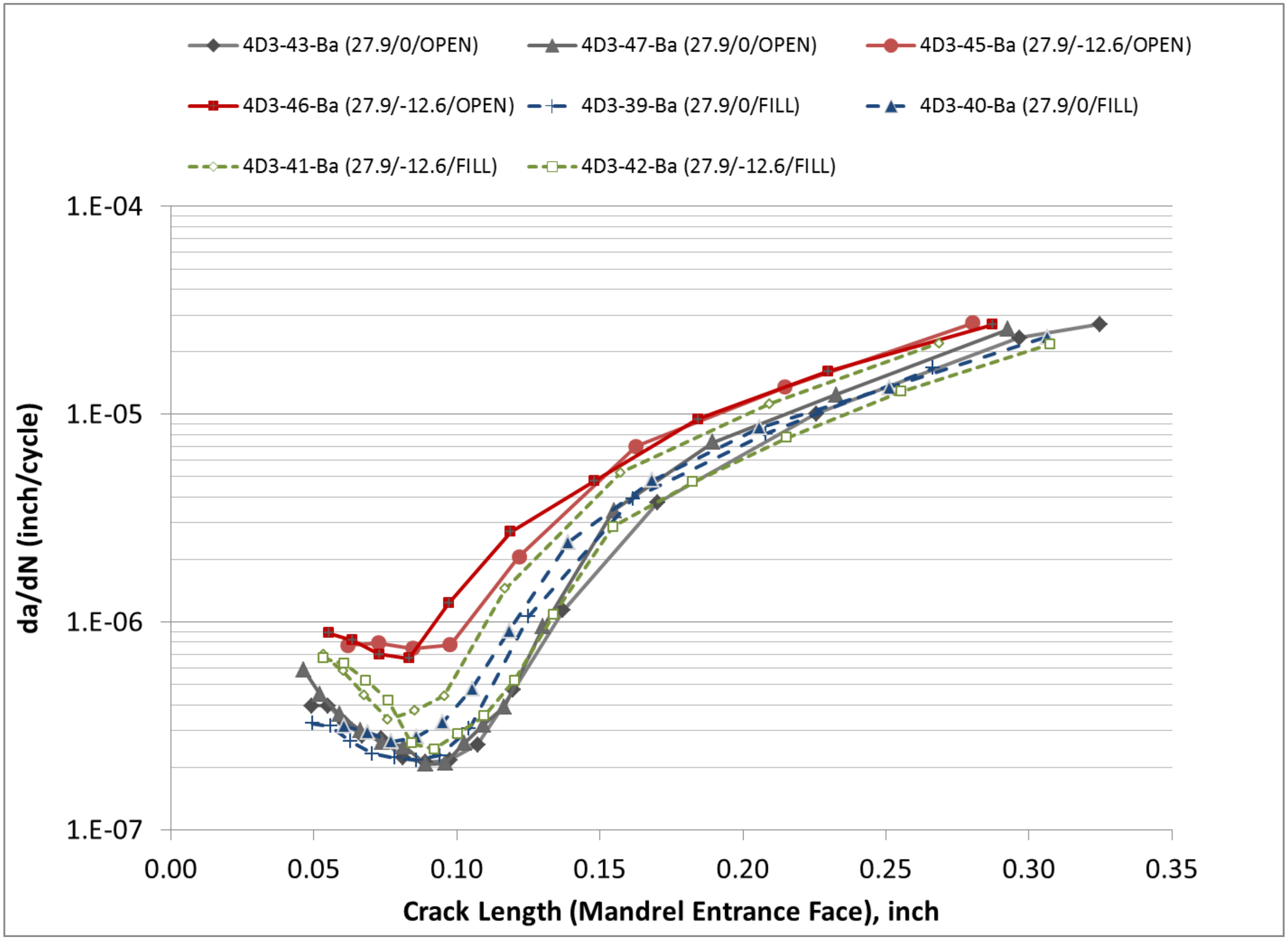
- 2024-T351 & 7075-T651Al
- Evaluate two open-hole and two filled-hole RS specimens using Contour Method
  - +27.9/0
  - +42.1/0
  - +27.9/-12.6
  - +42.1/-12.6
- Evaluate two open-hole and two filled-hole fatigue specimens without high tension OL
  - +27.9/0
  - +27.9/-12.6
- All fatigue tests conducted at 25 ksi, R + 0.1
  - Initial crack size approximately 0.03 inch x 0.045 inch
  - Initial ream diameter produced "max" interference, 4.3%

2024-T351
Fatigue Results

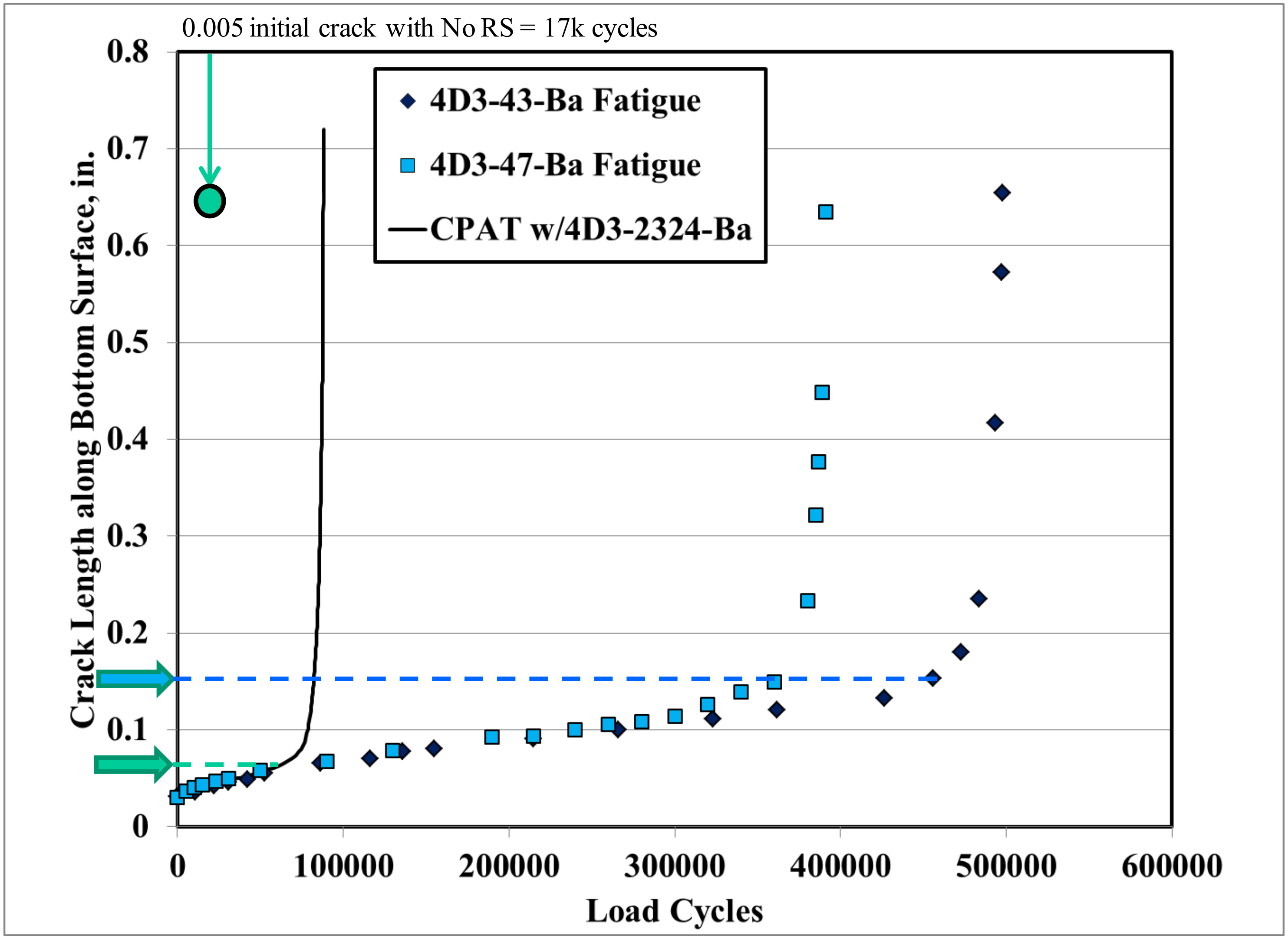
Underloads: a vs. N Data



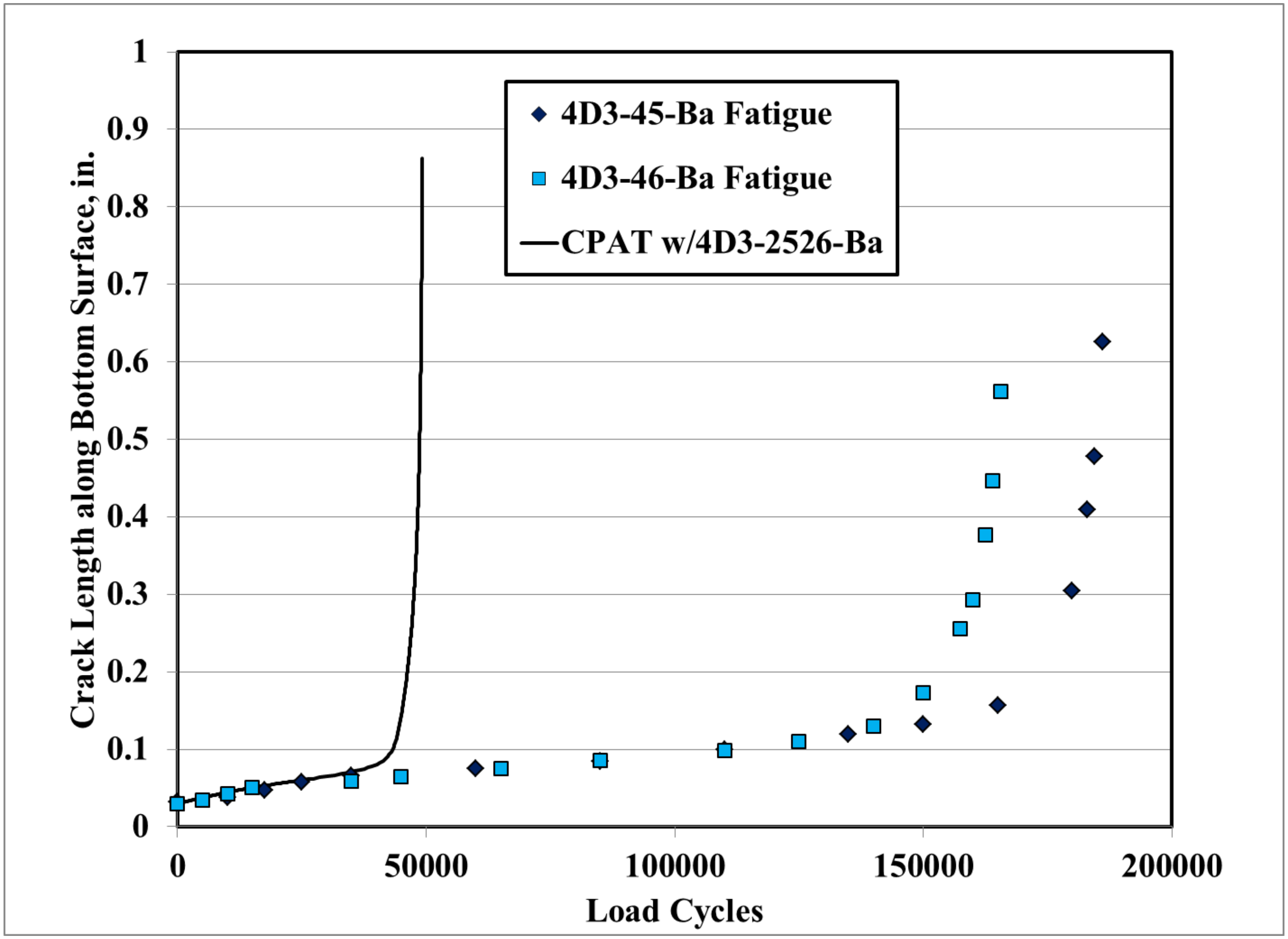
Underloads: da/dN vs. a (7-pt)



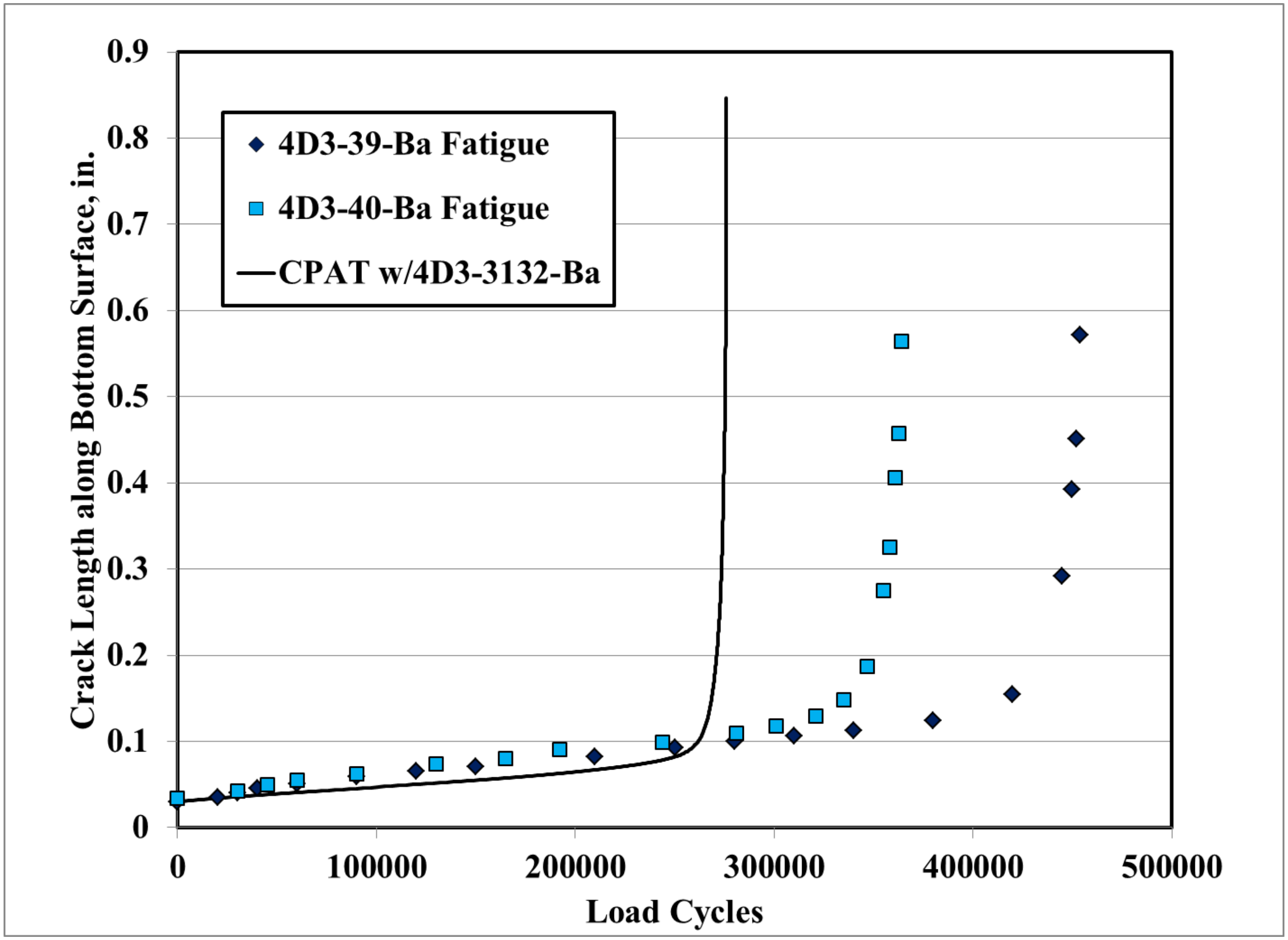
FCG using Contour Data 27.9 / 0 / OPEN



FCG using Contour Data 27.9 / -12.6 / OPEN



FCG using Contour Data 27.9 / 0 / FILL



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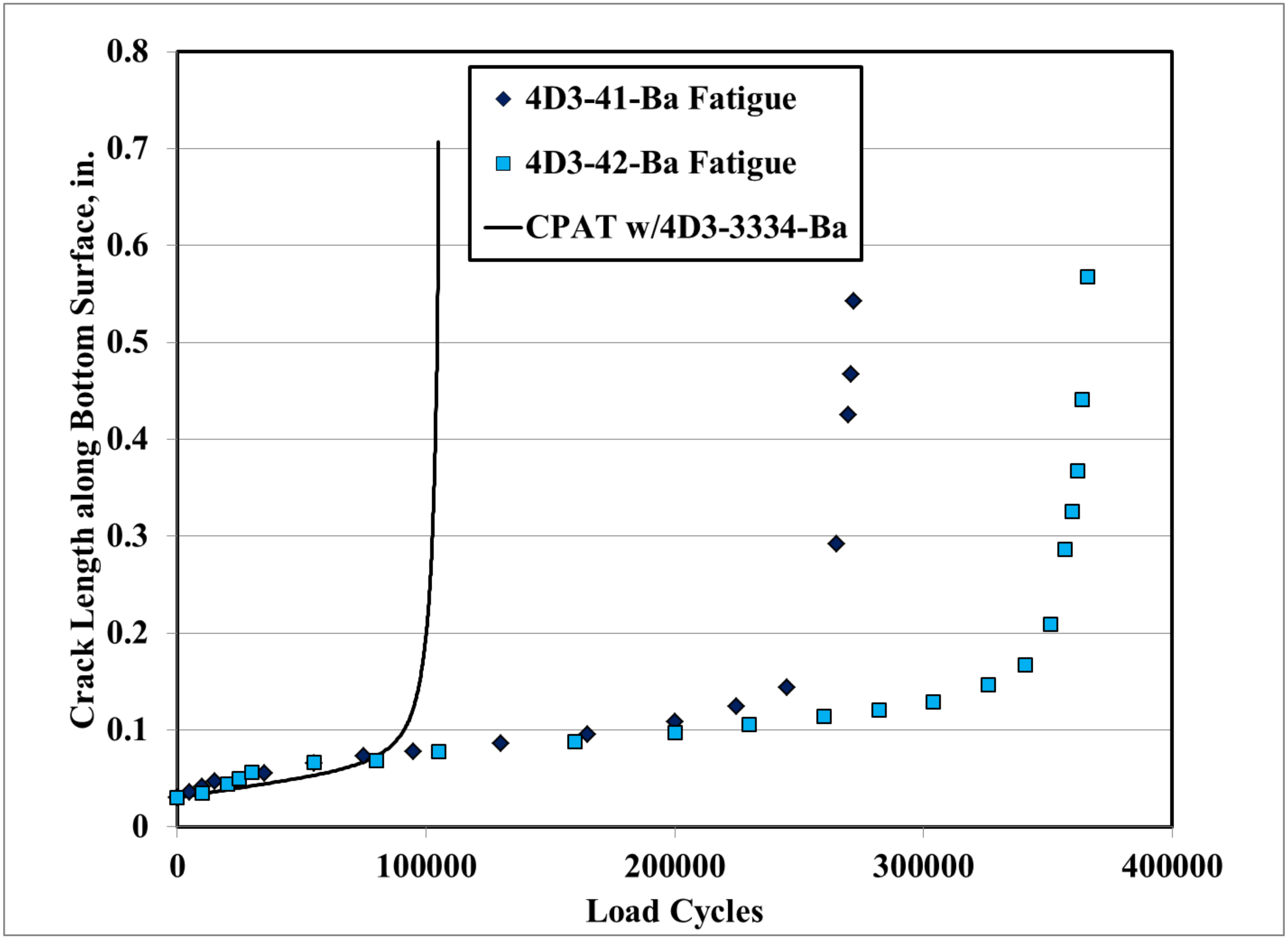
FCG using Contour Data 27.9 / -12.6 / FILL



7075-T651 Fatigue Results

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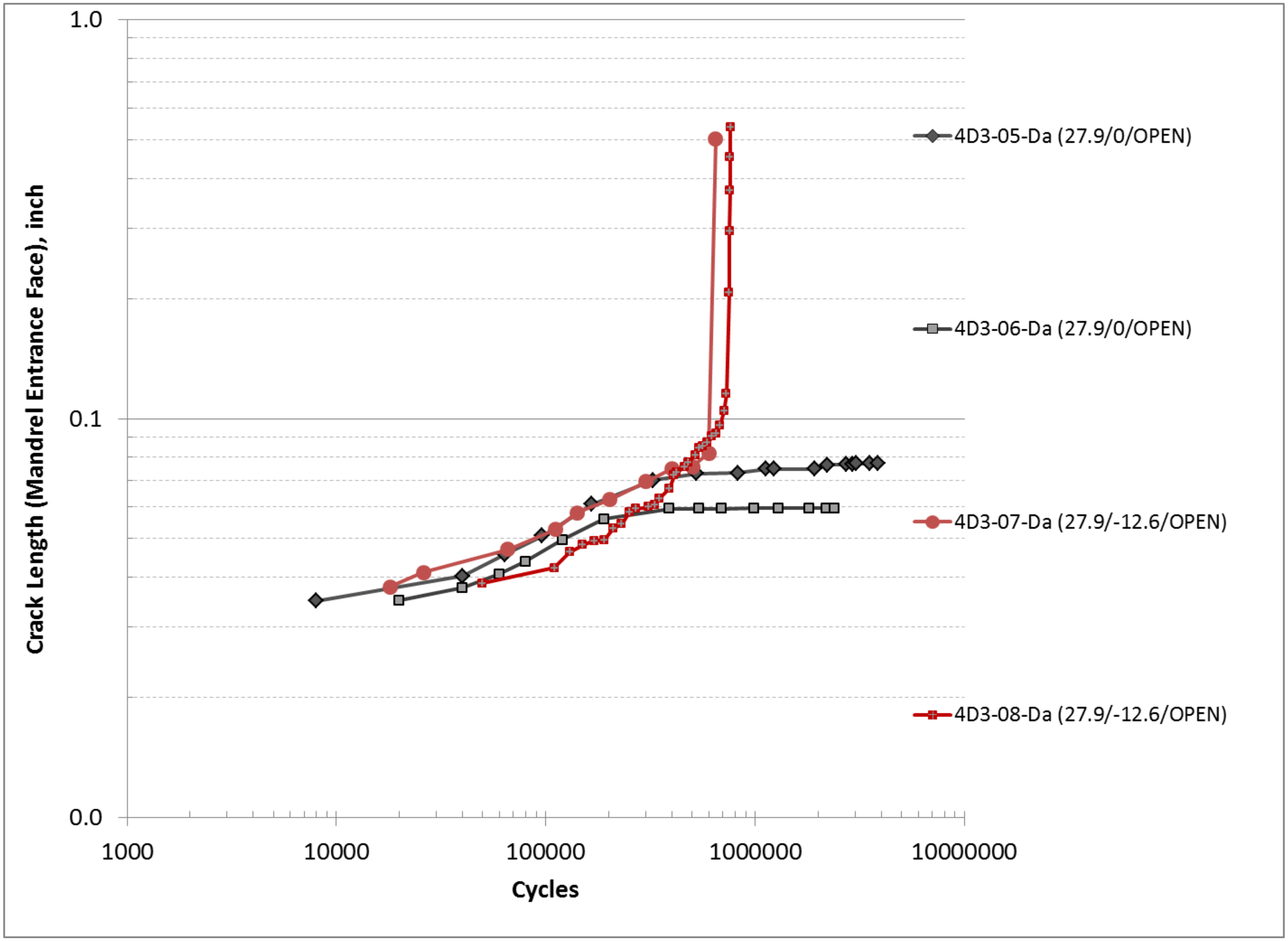
Underloads: a vs. N Data



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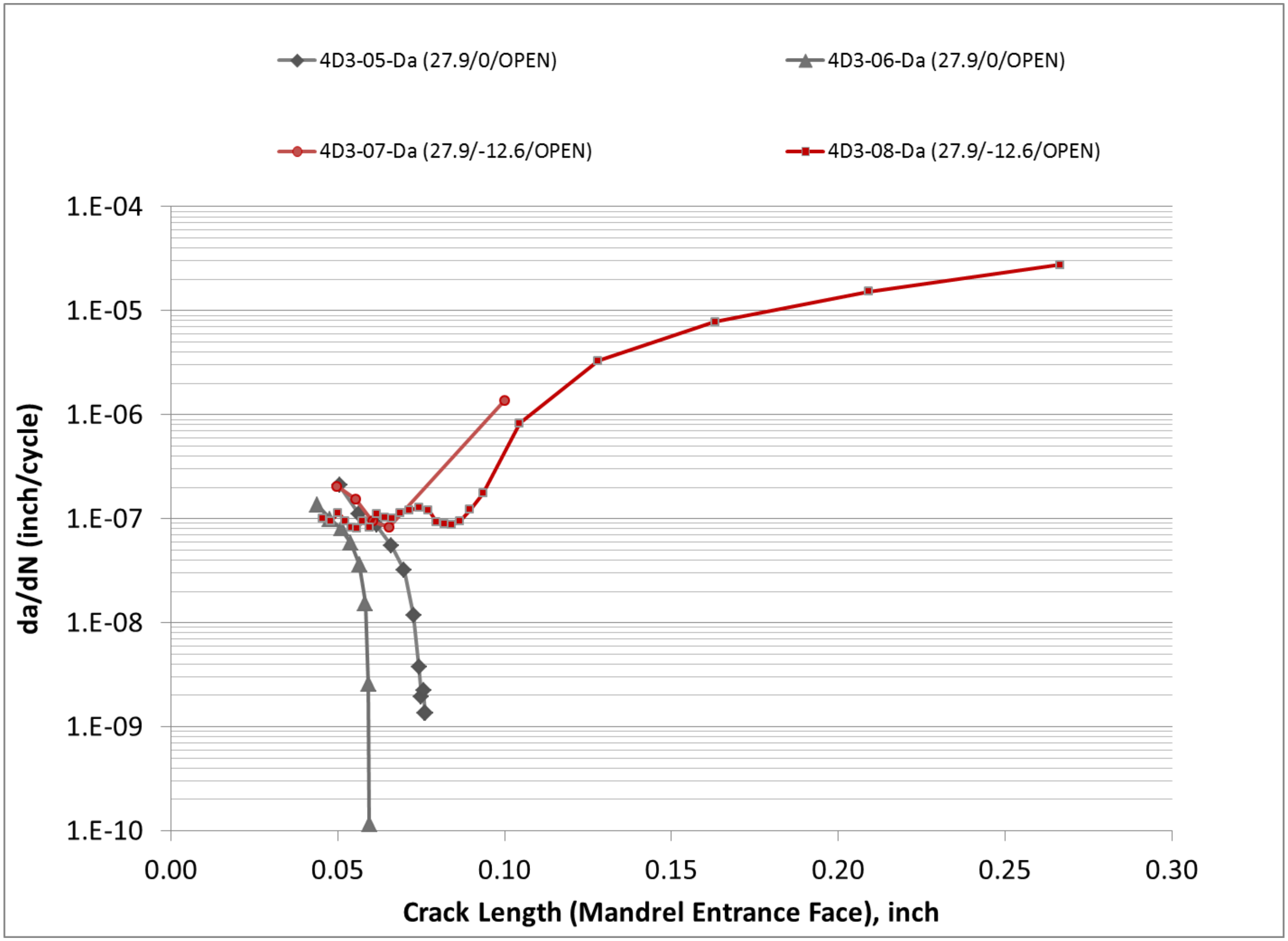
Underloads: da/dN vs. a (7-pt)



Redistribution: Observations

2024-T351 Aluminum

- Test life with compression preload was 37% of that without.
- Simulation life with compression preload was 55% of that without.
- Unfortunately, test lives were to 3x to 5x greater than computed lives.
- Valuable data sets for future simulations:
  - Well characterized residual stress
  - Well behaved crack growth in experiments
  - Tightly controlled processing during CX

7075-T651 Aluminum

- Compression preload allowed cracks to grow to failure.
- Remainder of specimens underwent crack arrest.
- Most models arrested--common problem with 7075.

Applied R Effects

2024-T351 (APES)

7075-T7351 (SwRI)

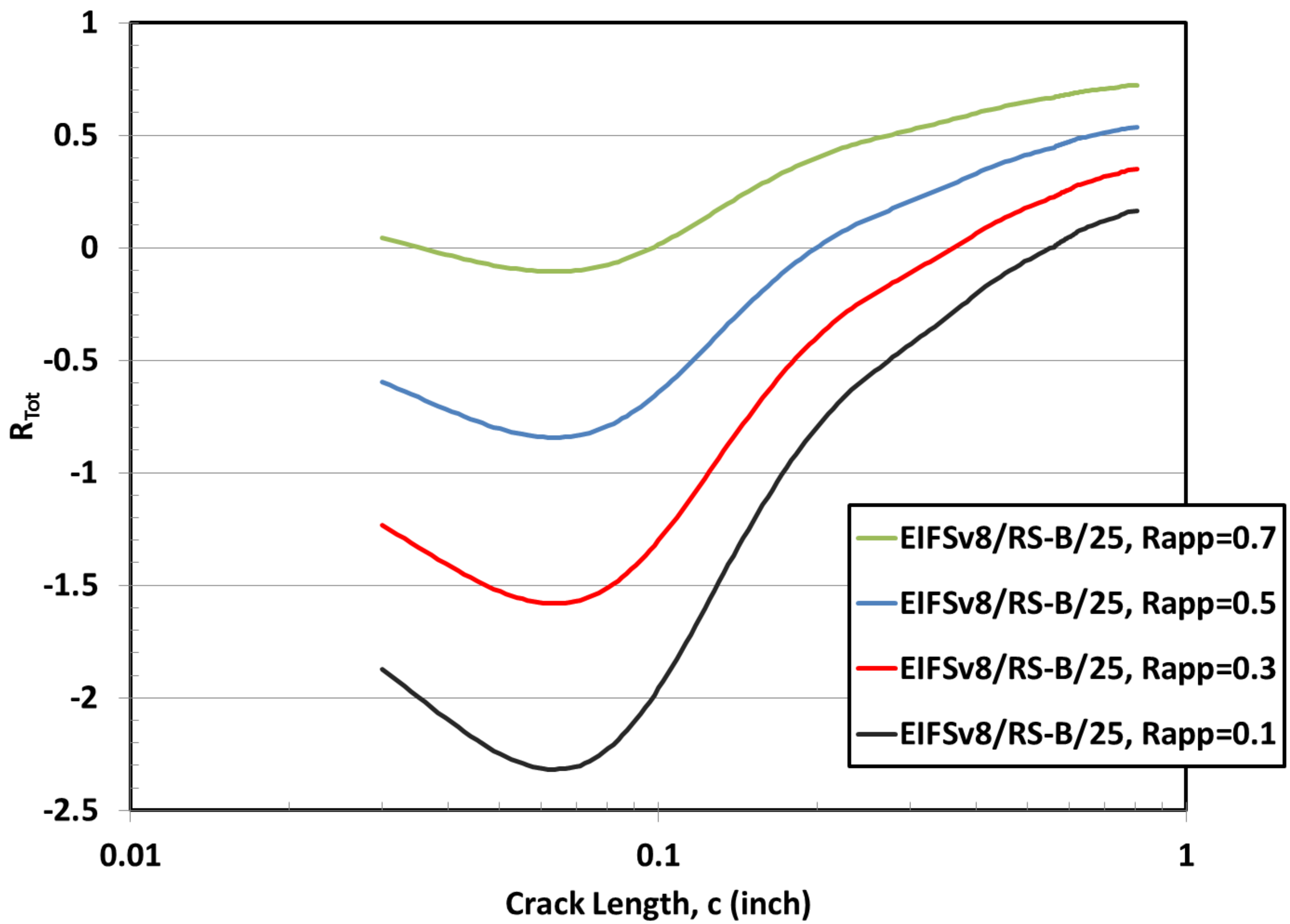
Test Conditions and Goal

- Goal: examine behavior of CX crack growth under various applied R

- APES (2024-T351)
  - Five replicates at
  - R_{app} = 0.1, 0.3, 0.5, 0.7

- SwRI (7075-T7351)
  - Four replicates at
  - R_{app} = 0.02, 0.1, 0.4, 0.6, 0.7, 0.8

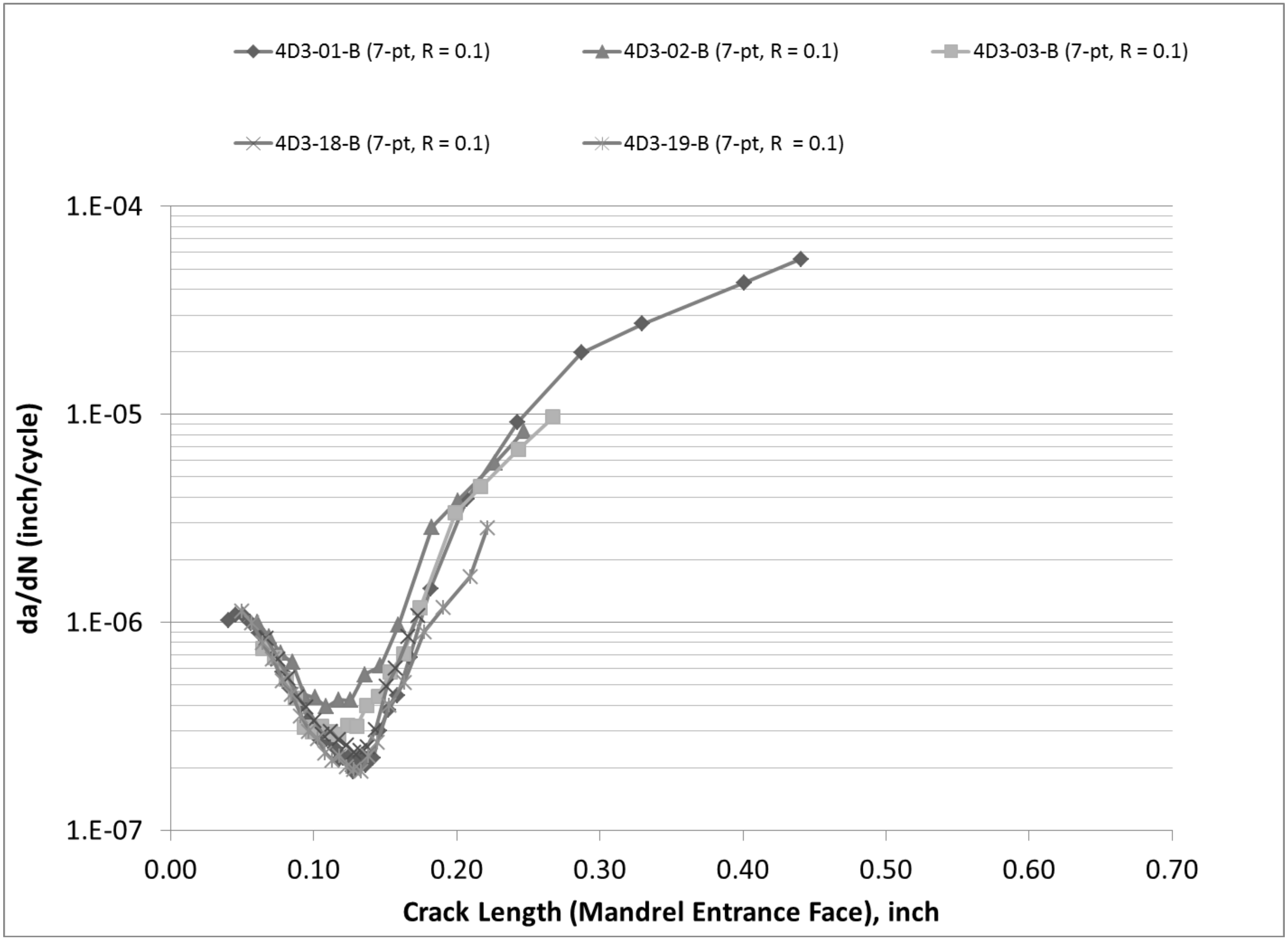
R_{Tot} vs. Crack Length



2024-T351

R Effects: Flip Chart

2024-T351: R_{app} = 0.1



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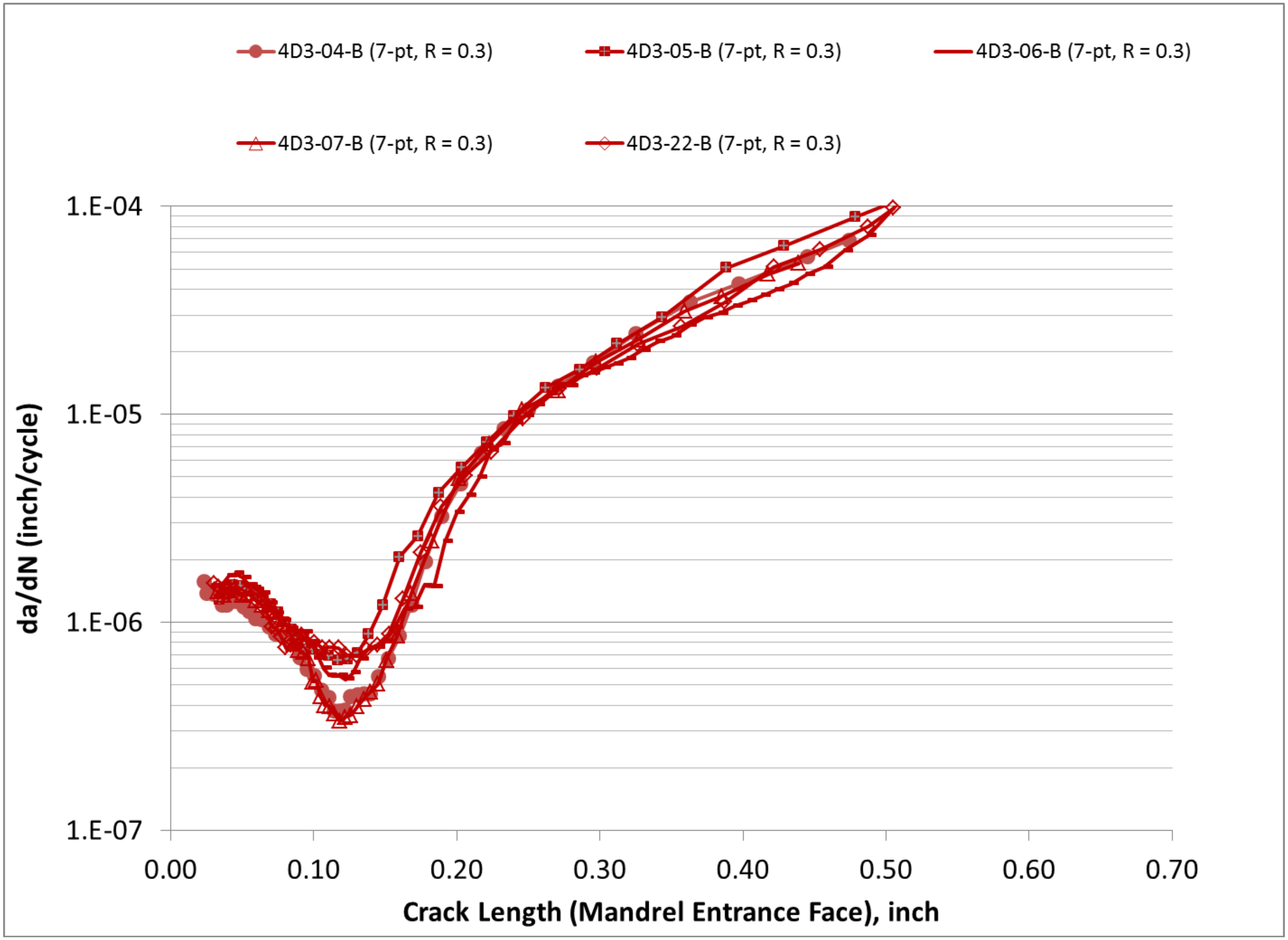
2024-T351: R_{app} = 0.3



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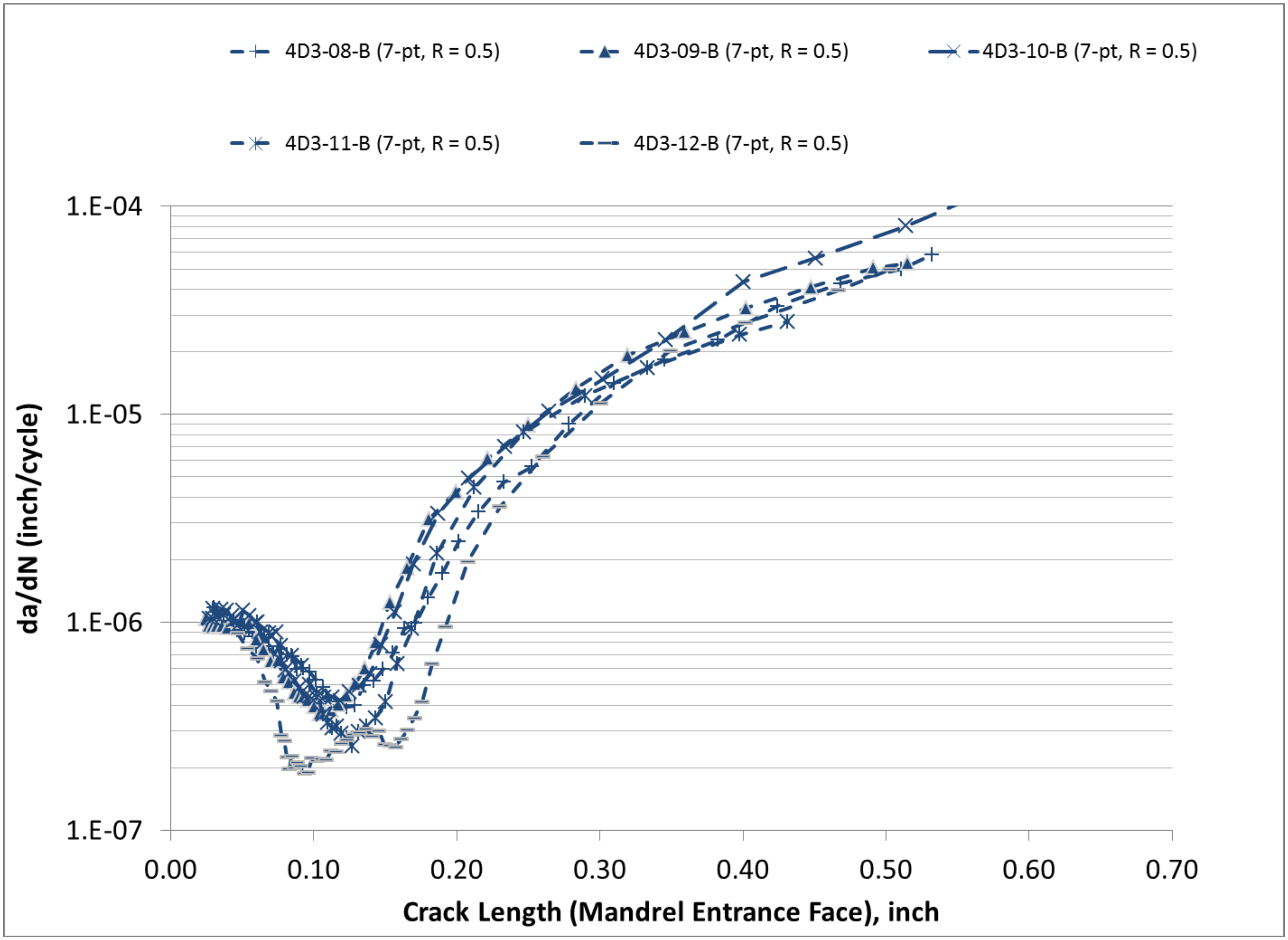
2024-T351: R_{app} = 0.5



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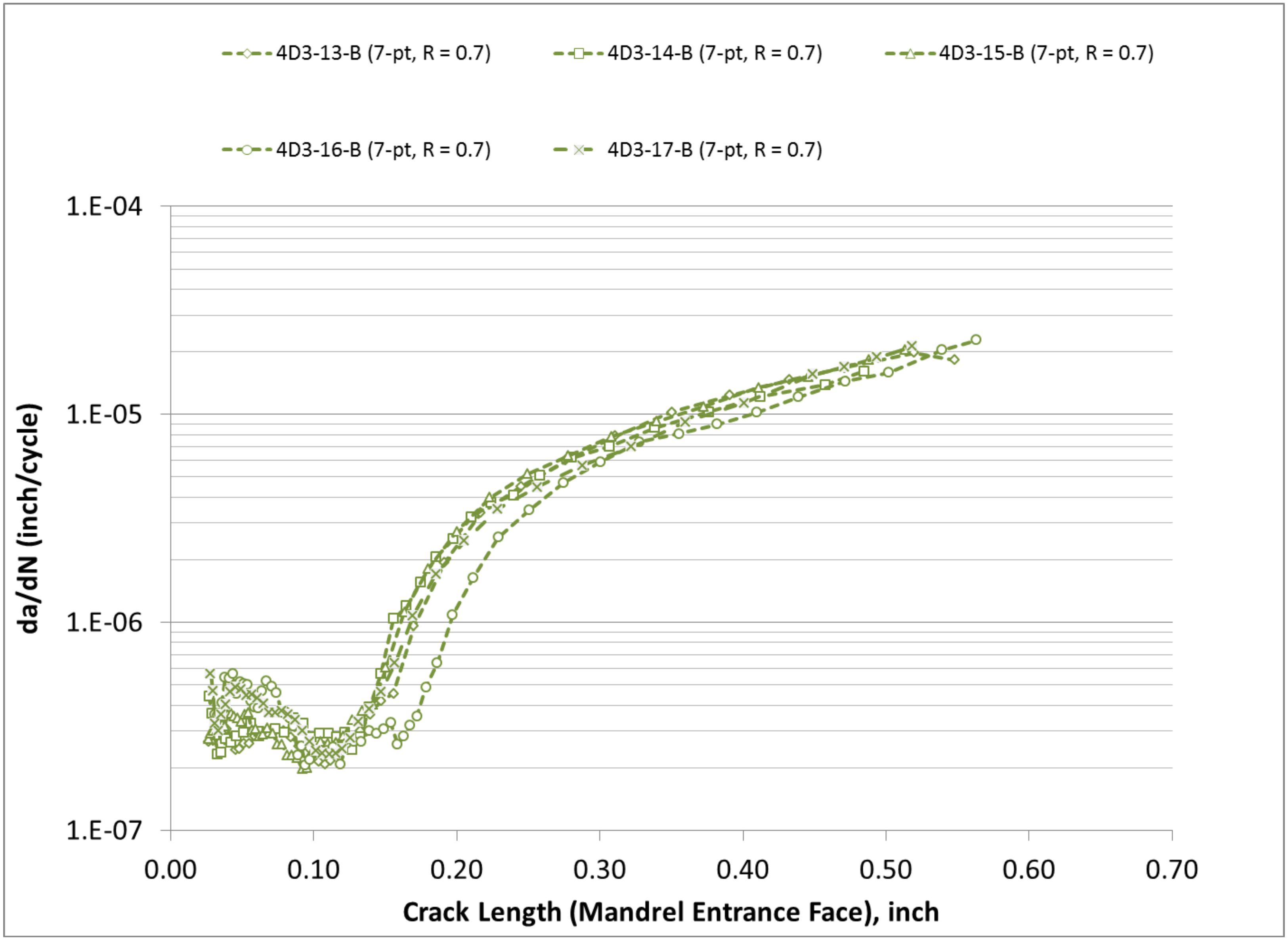
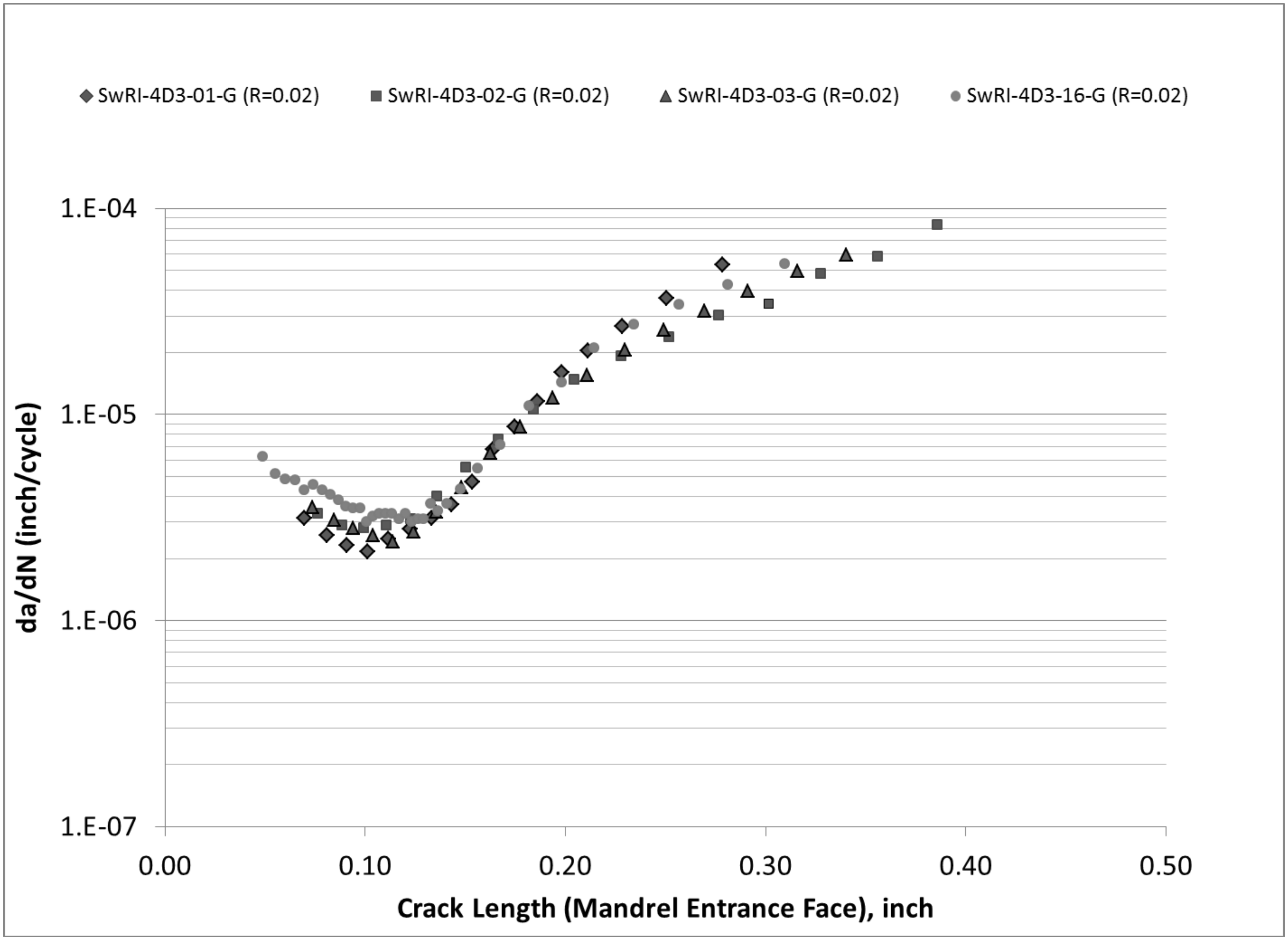
2024-T351: R_{app} = 0.7



7075-T7351

R Effects: Flip Chart

7075-T7351: $R_{app} = 0.02$



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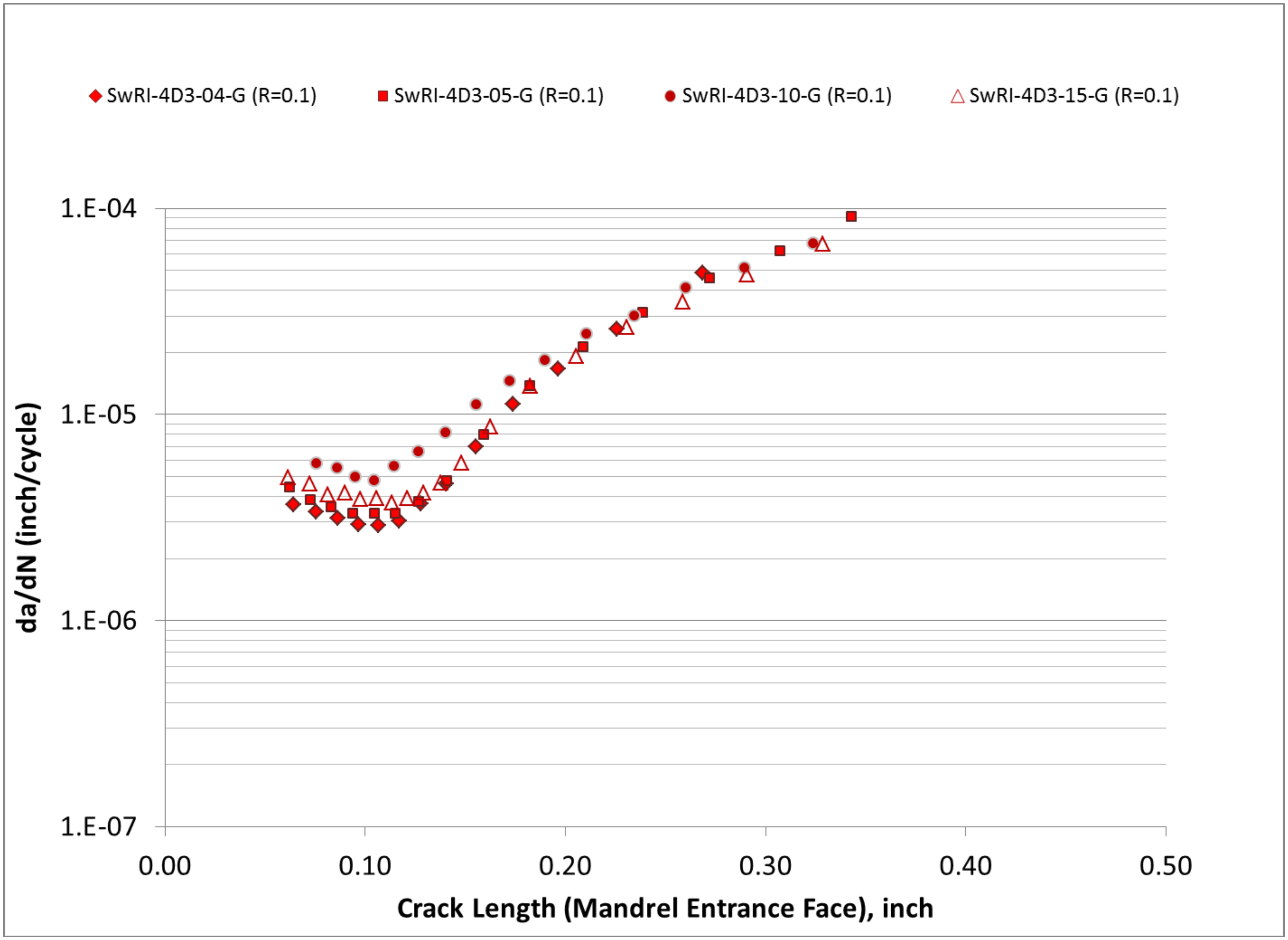
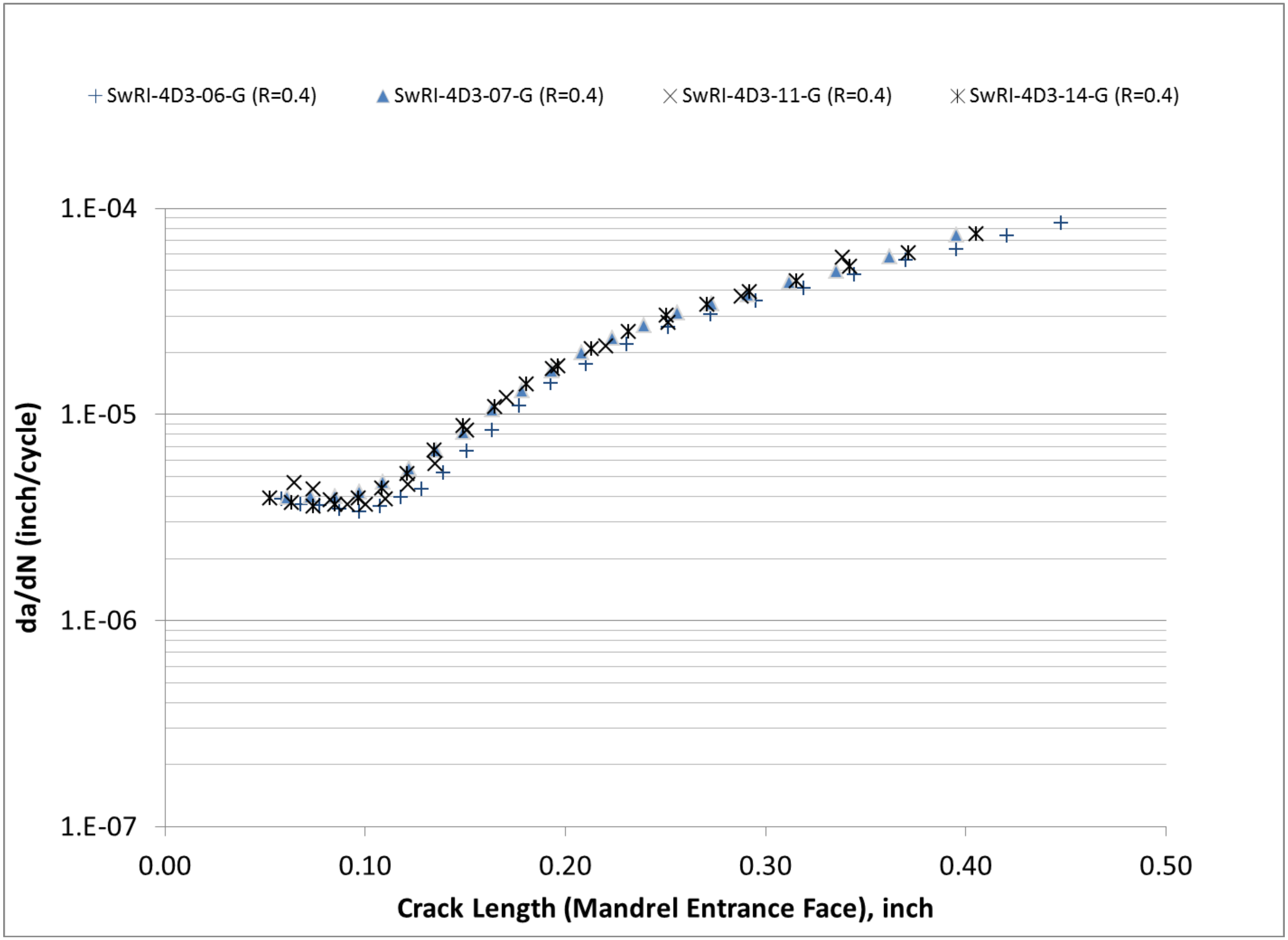
7075-T7351: R_{app} = 0.1



7075-T7351: R_{app} = 0.4



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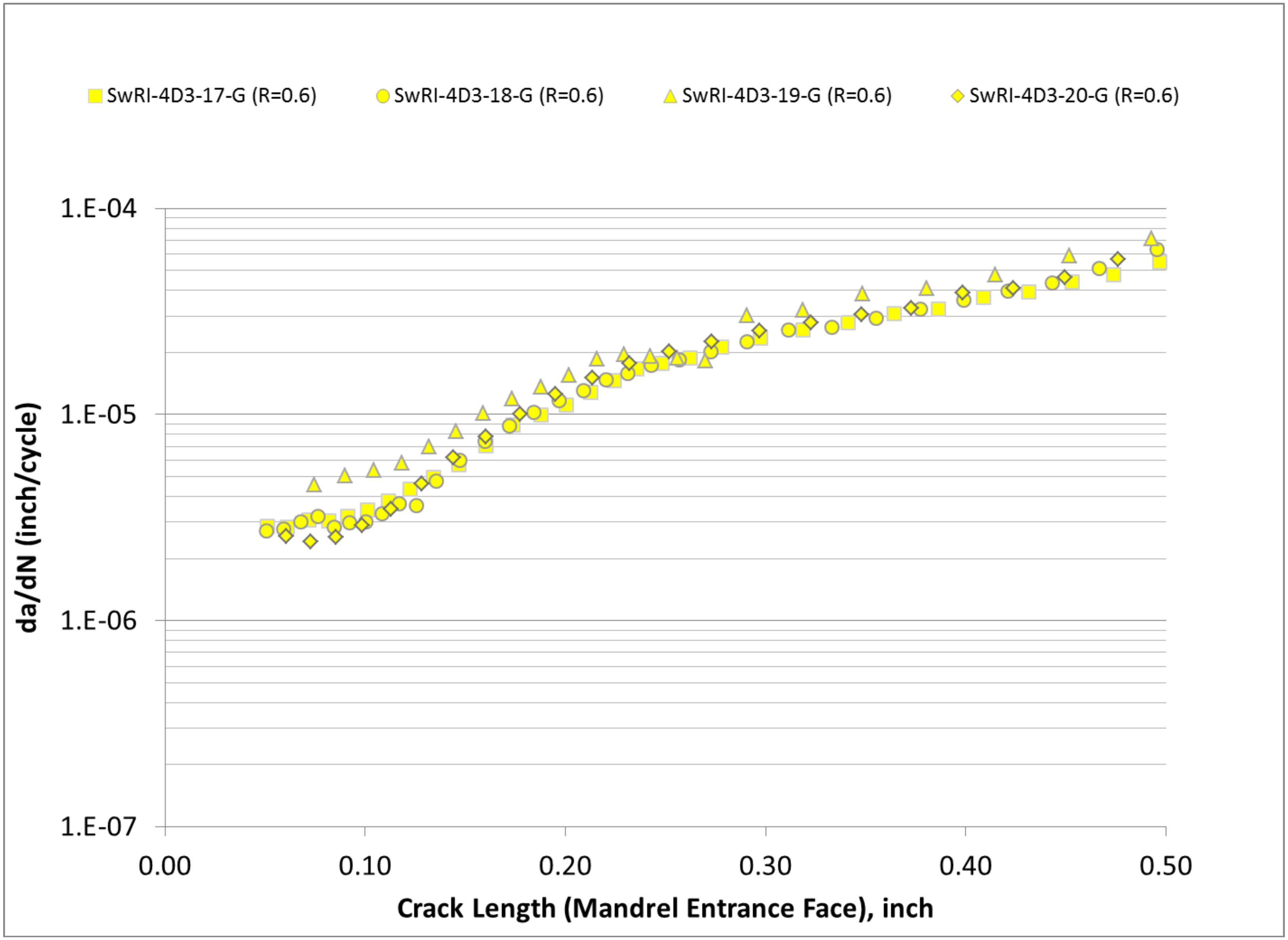
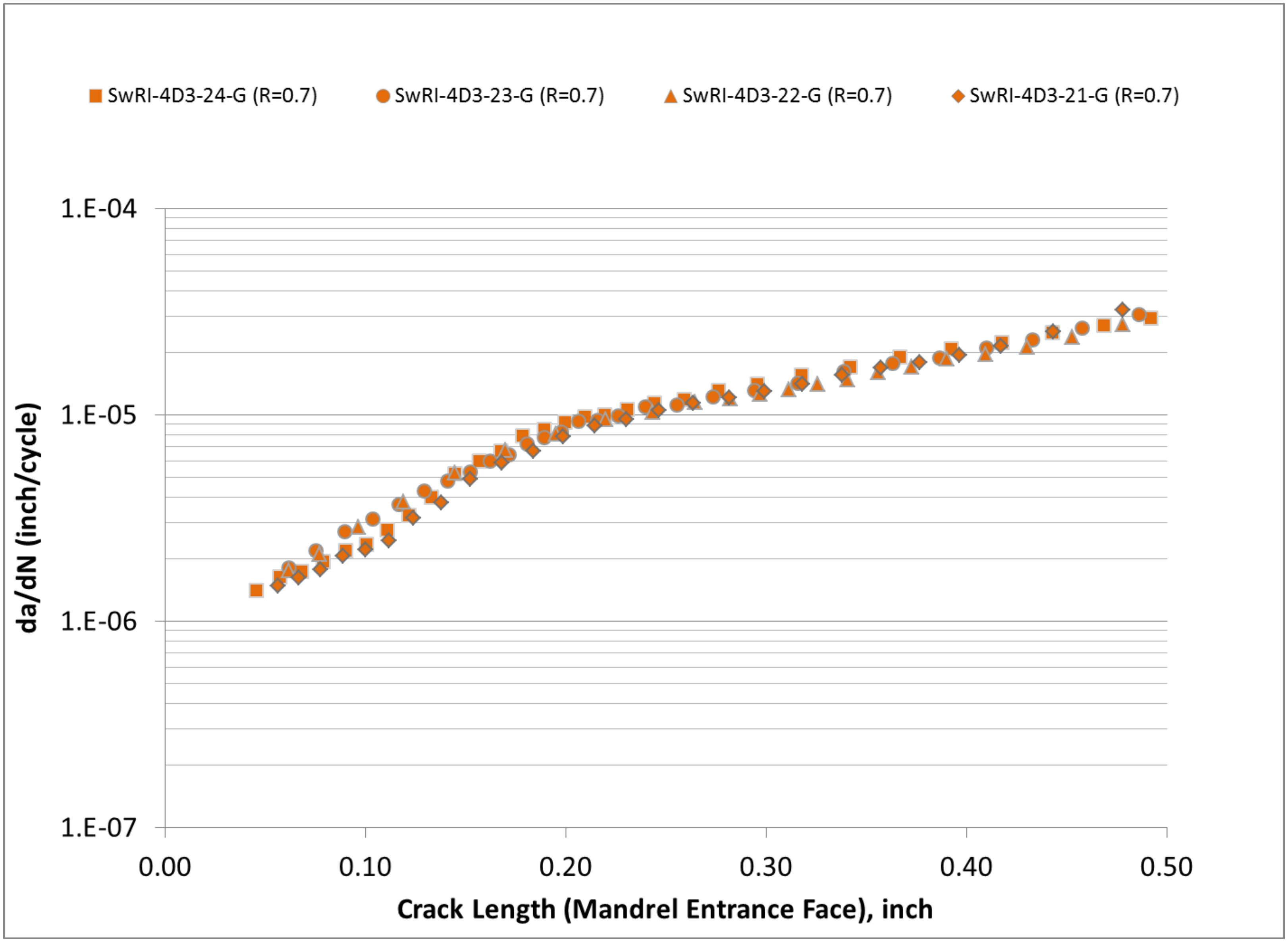
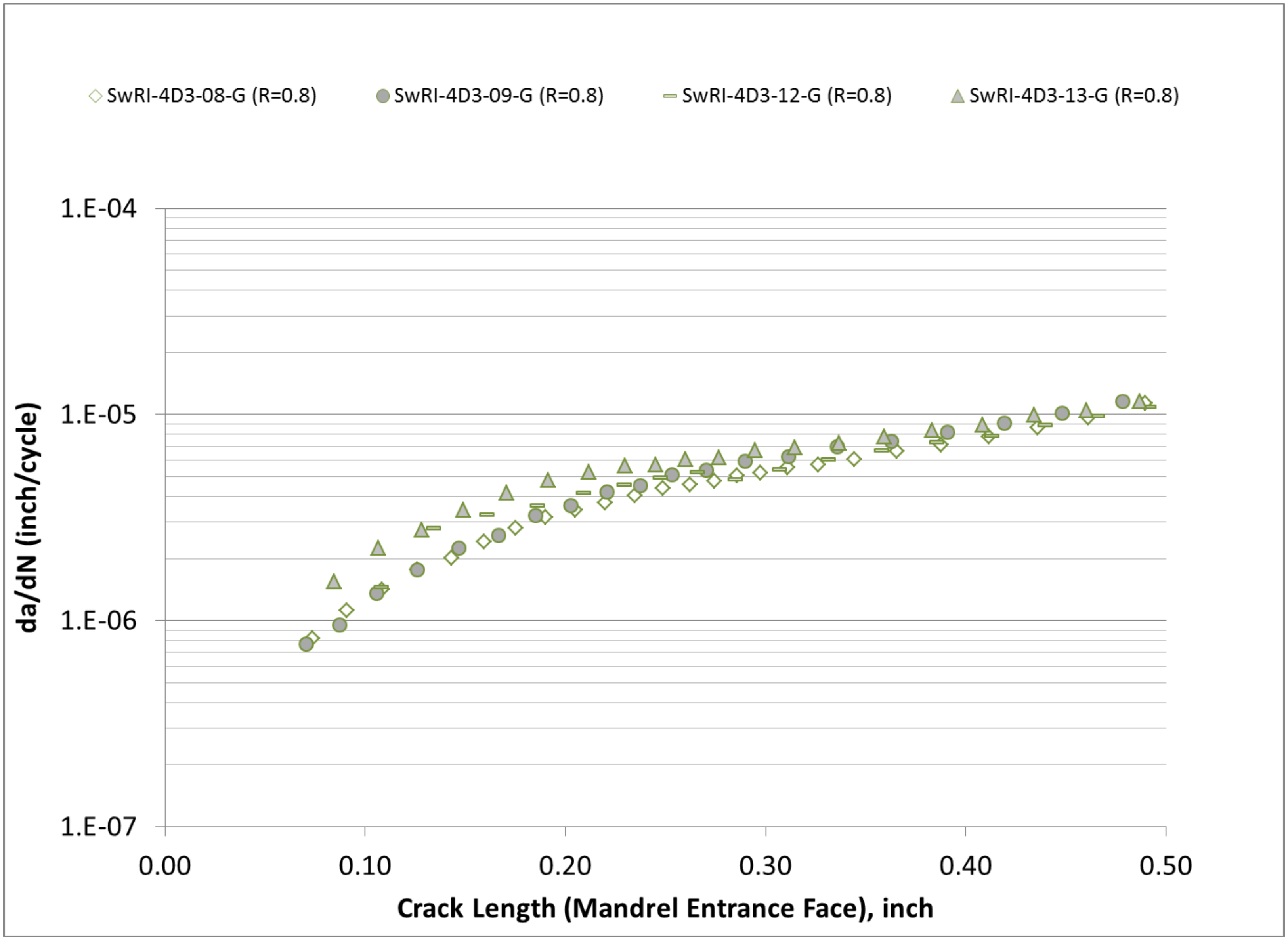
7075-T7351: R_{app} = 0.6



7075-T7351: R_{app} = 0.7

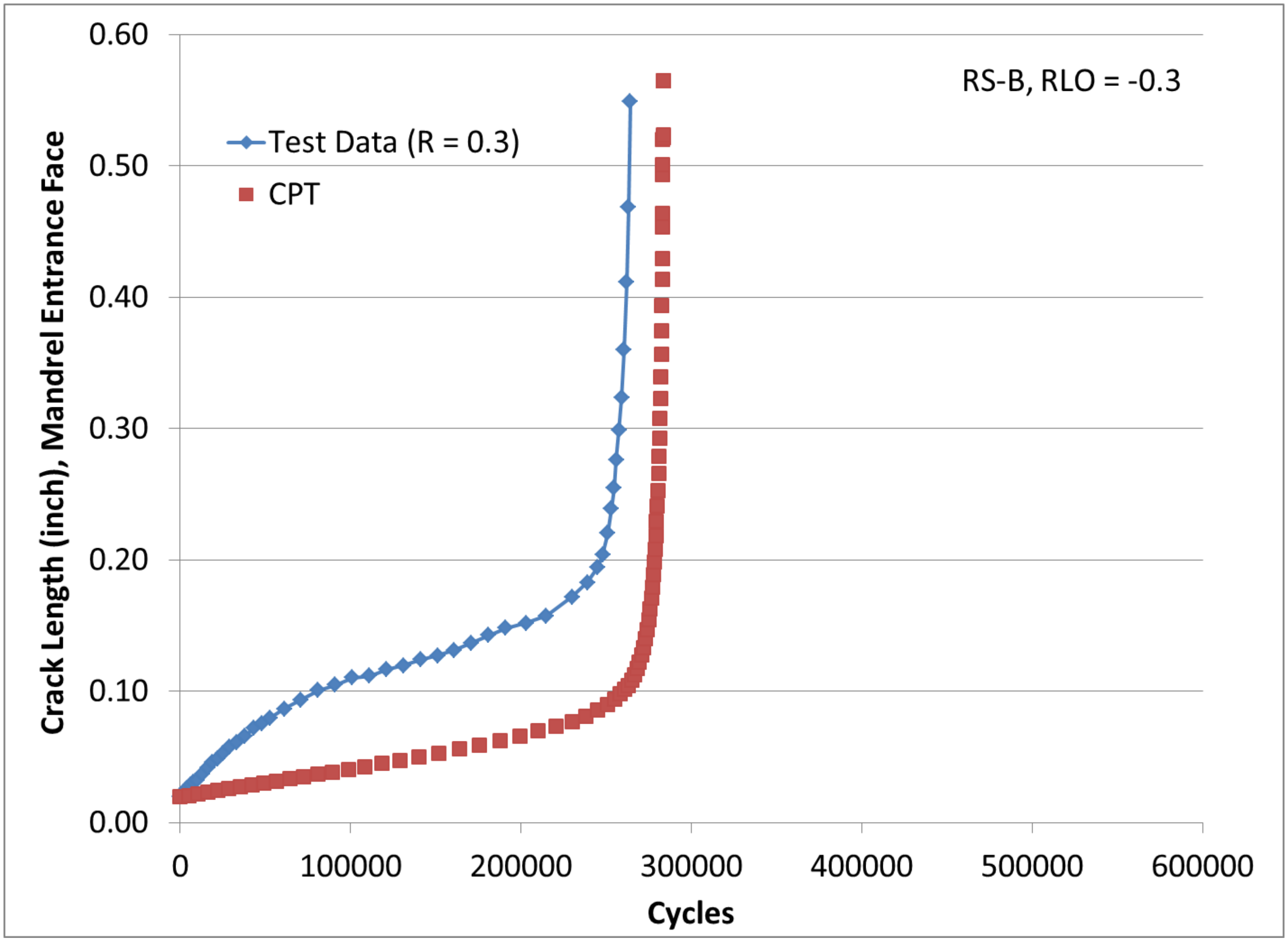


7075-T7351: R_{app} = 0.8

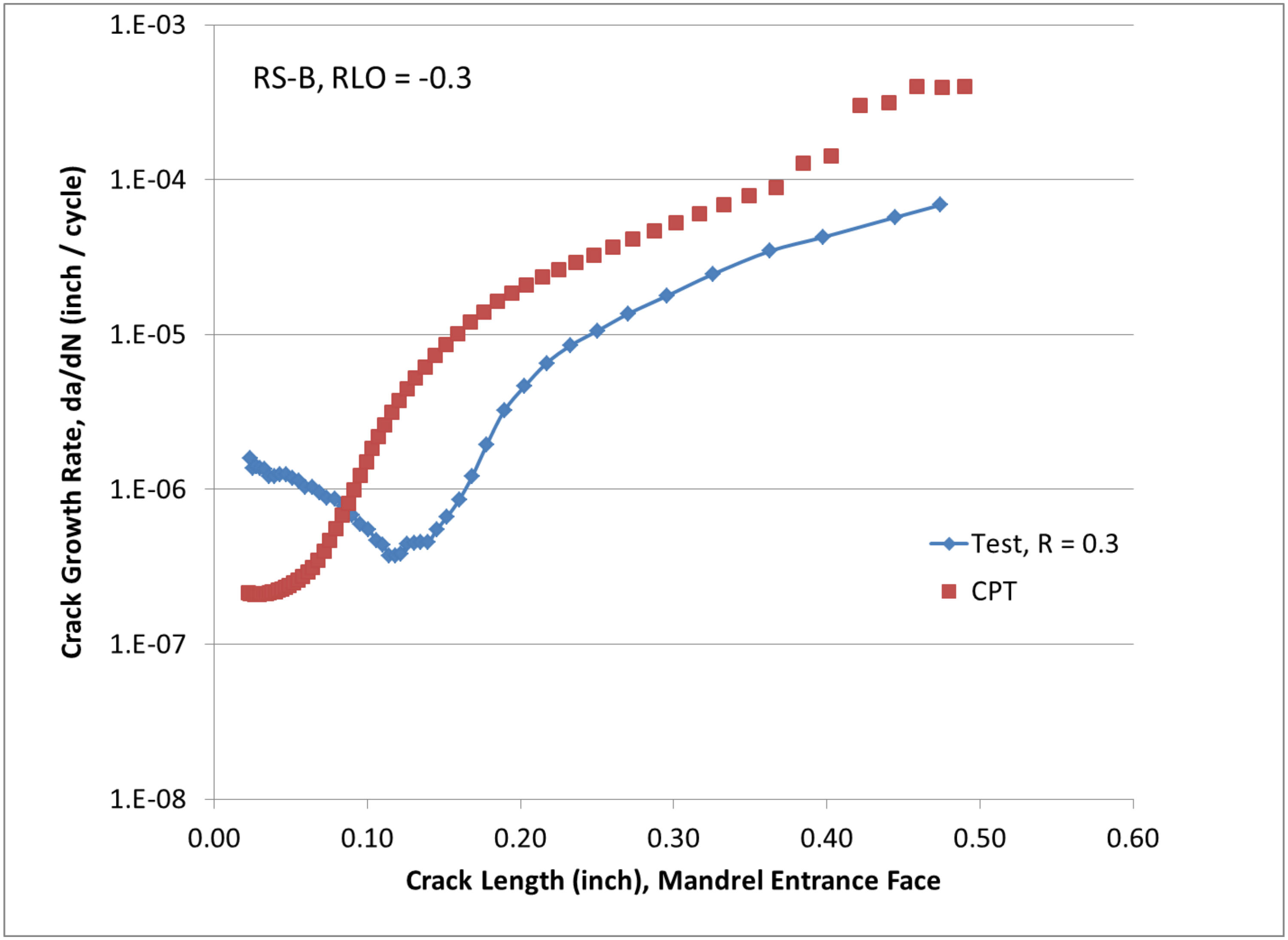


Simulation Results

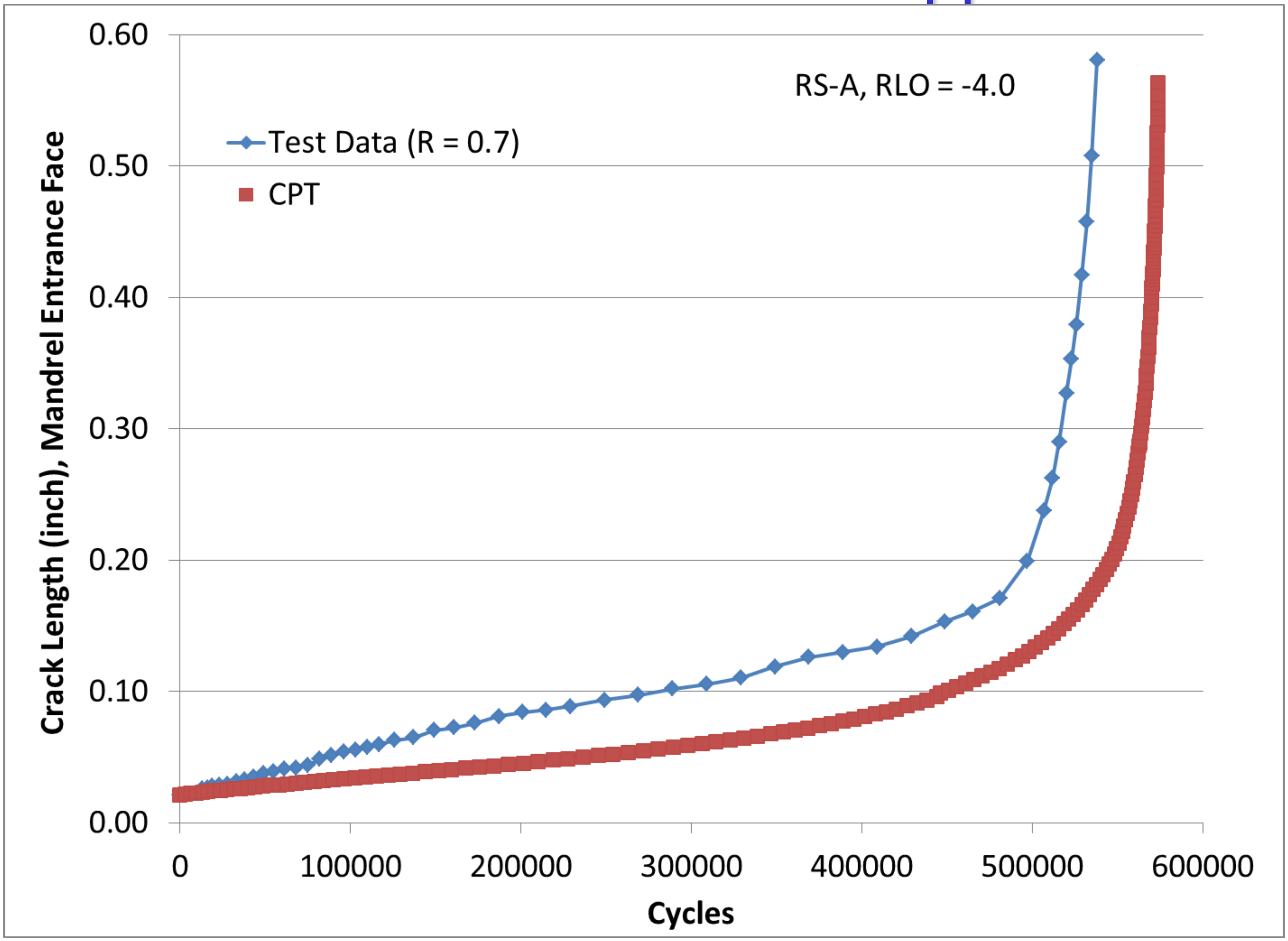
Crack Growth, R_{app} = 0.3



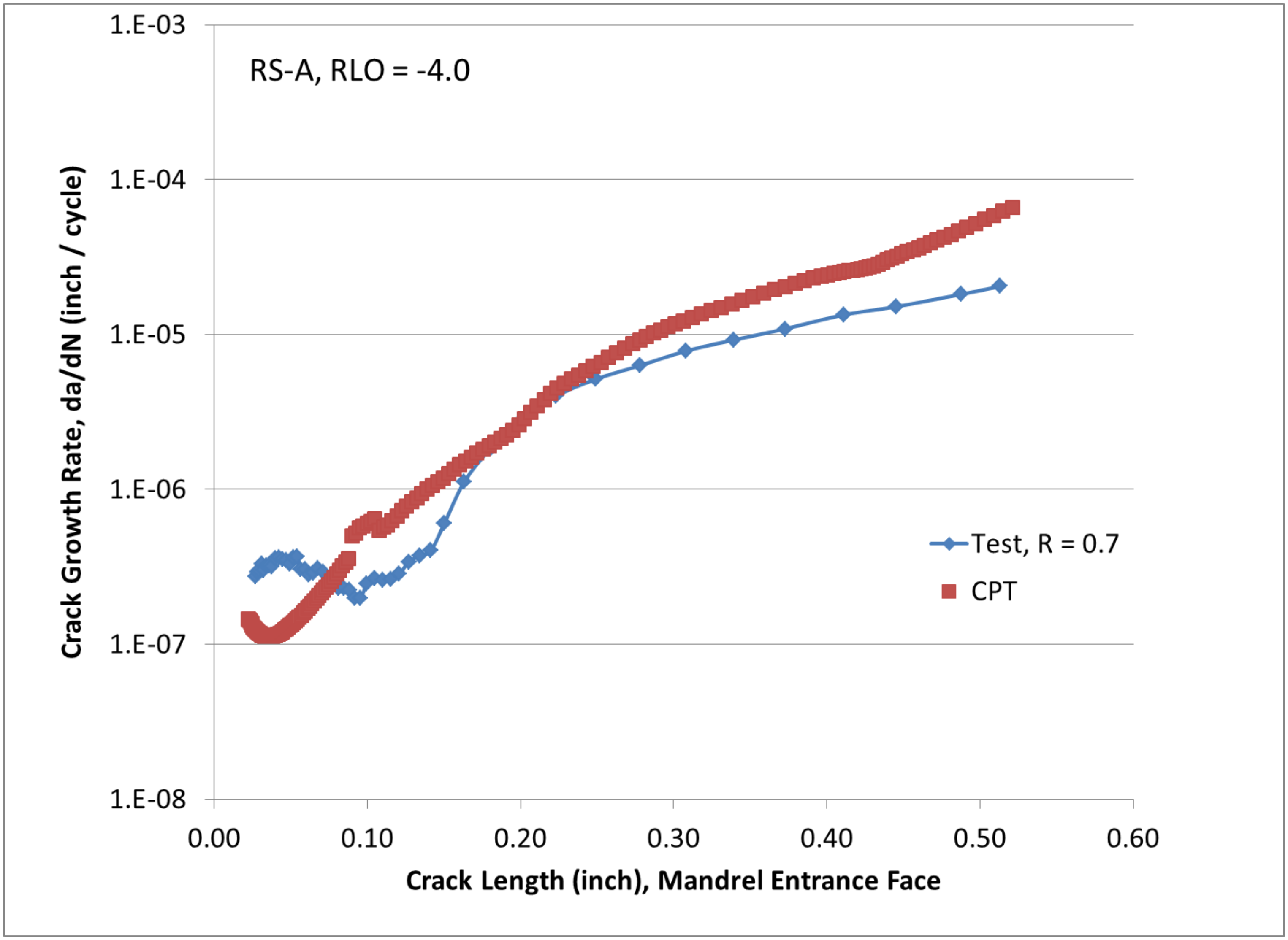
Growth Rate, R_{app} = 0.3



Crack Growth, R_{app} = 0.7



Growth Rate, R_{app} = 0.7



R Effects: Observations

- R Effects
  - Dip in da/dN vs. ‘a’ at lower applied R
  - Dip lessons or disappears at higher applied R depending on alloy
  - Dip more prominent in lower yield strength material: 2024-T351
- CRACK CLOSURE: Quite possibly the single biggest factor in discrepancies between predicted lives and test data
- High priority item for addressing life prediction accuracy
- **Future work** to focus on closure, stress redistribution in front of active crack, and Negative R crack growth data
  - Funded by AFRL and A-10 ASIP

Miscellaneous Items

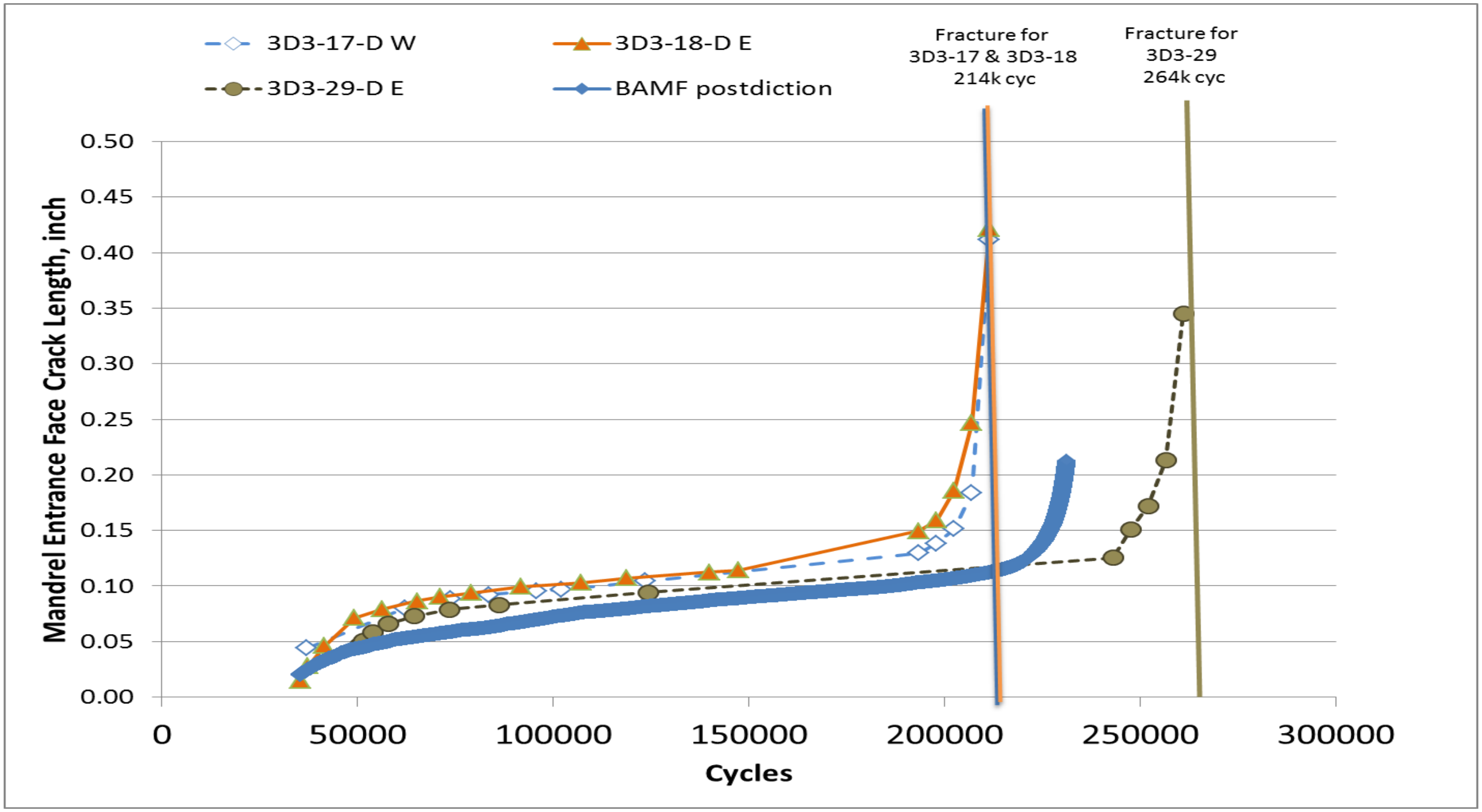
- Test equipment inventory
- CX equipment inventory
- Examining available residual stress data to pick candidates for additional modeling round robin work.
  - Requires corresponding fatigue data
  - Work in conjunction with CAStLE as a possible way to provide new fatigue data sets
  - More on this tomorrow….

Material Models

Crack Growth Data

- General consensus that we need to revisit our material models (da/dN vs ΔK)
- Best practices for reducing artificial threshold effects
    - Understanding how data are generated
    - Part-through cracks vs. through cracks
  - Proper understanding of negative R data
    - Cx holes typically have negative R_{tot} except in cases of higher applied (R_{app} > 0.7)

Material Model Sensitivity



- BAMF results predicted average behavior of coupon group
- Predicted life here is 70% of that predicted by APES (330k)

Development of Fatigue Crack Growth Rates from Corner Crack Tests

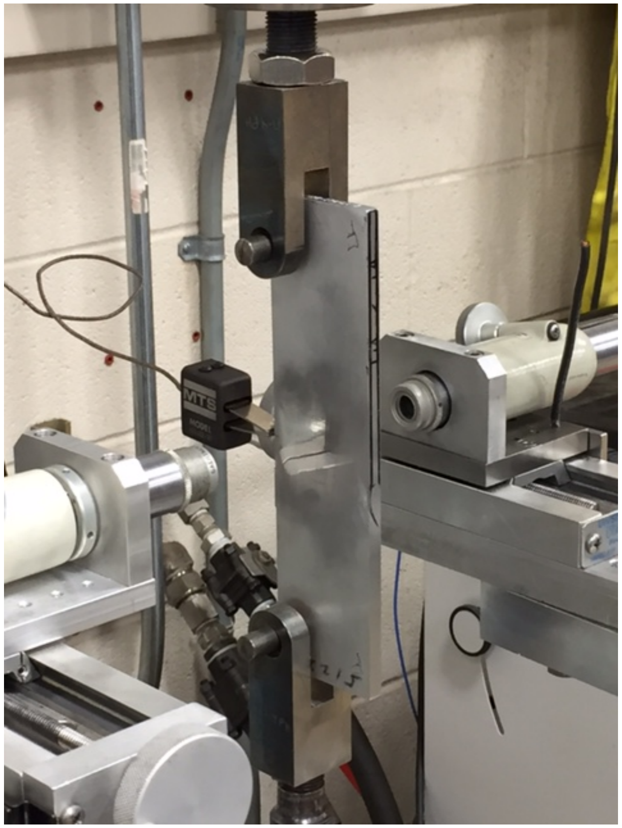
SOUTHWEST RESEARCH INSTITUTE®

Luciano Smith, James Feiger, and Mark Thomsen
ERSI Workshop
September 2017

Distribution A: Approved for public release; unlimited distribution.
Reference Number: 2017-08-30_WWA-004, Case #75ABW-2017-0044

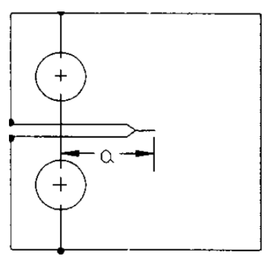
ASTM E647

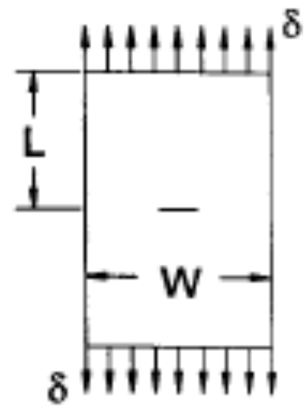
- Standard Test Method for Measurement of Fatigue Crack Growth Rates
  - Specimen configuration
  - Test procedure
  - Calculation of growth rates
  - Reporting requirements

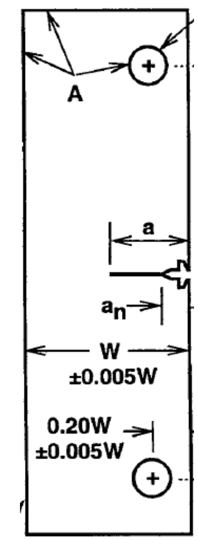


ASTM E647

- Standard Test Method for Measurement of Fatigue Crack Growth Rates
  - Specimen configuration
    - Three specimens are defined:
      - Eccentrically-loaded single edge crack tension: ESE(T)
      - Middle tension: M(T)
      - Compact: C(T)



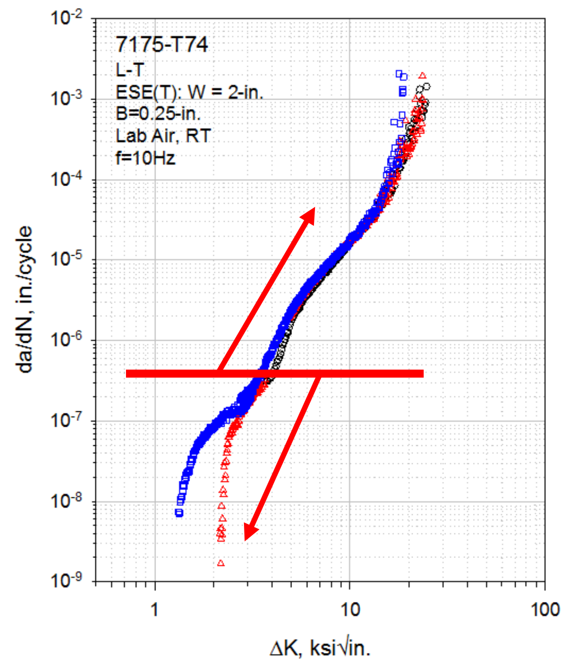




    - Any specimen type is allowed if the K solution is known
      - "Specimen configurations other than those contained in this method may be used provided that well-established stress-intensity factor calibrations are available"

ASTM E647

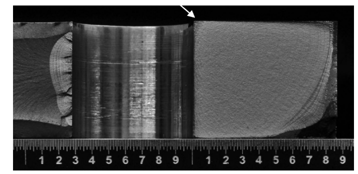
- Standard Test Method for Measurement of Fatigue Crack Growth Rates
  - Specimen configuration
  - Test procedure
    - Number of tests
    - Precracking method
    - Application of load



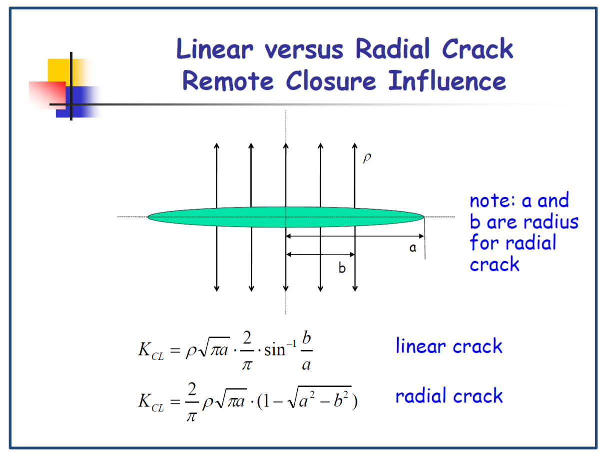
  - Constant force-amplitude or K-control for rates above 10^{-8} m/cycle
  - K-decreasing for rates below 10^{-8} m/cycle (near-threshold)

Motivations for corner crack testing

- Ability to gather L-T and L-S growth rate data in one test
- The standard specimens used for crack growth rate testing are all one-dimensional through cracks
  - The majority of analysis life is as corner crack



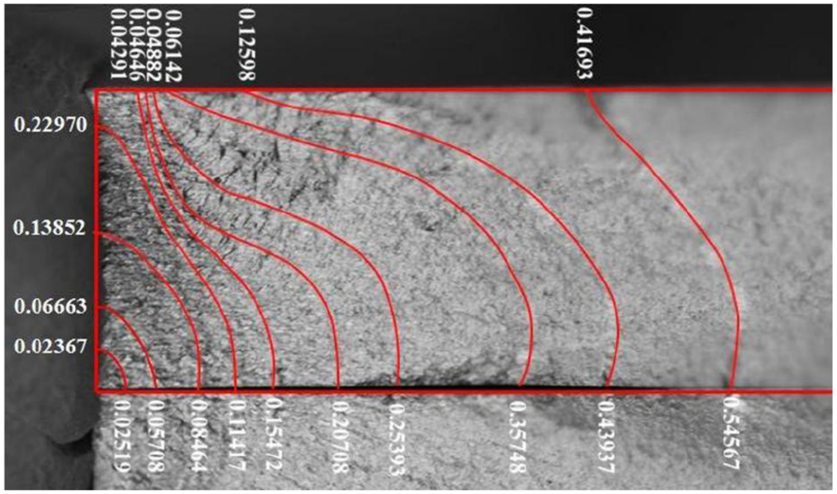
- When loading history is properly accounted for (minimizing plasticity induced crack closure), roughness induced closure dominates at low ΔK
  - Closure effect is smaller for radial crack versus linear crack (bulk material constraint)



(Ref: ASTM E08.06.06 meeting minutes, November 15, 2016

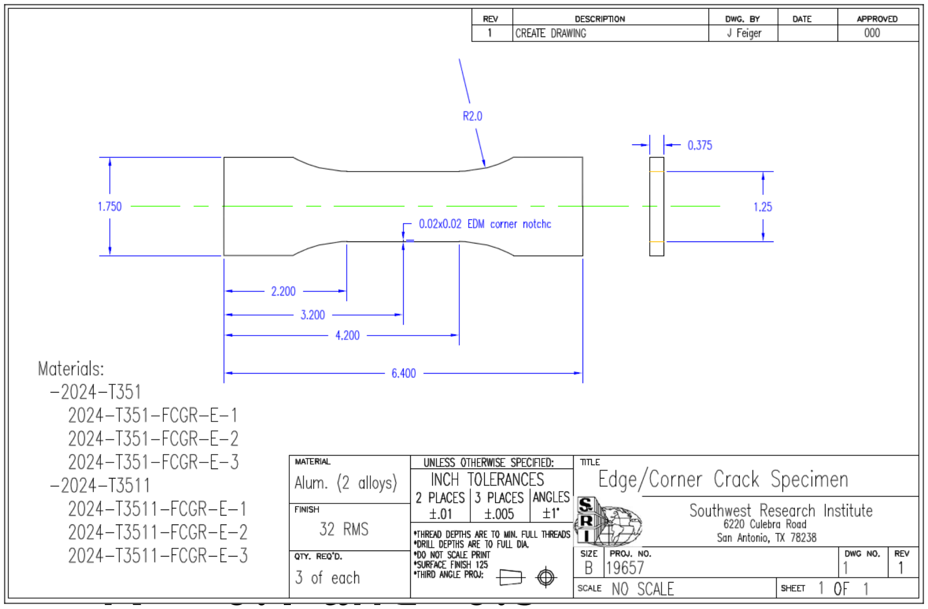
Motivations as related to ERSI

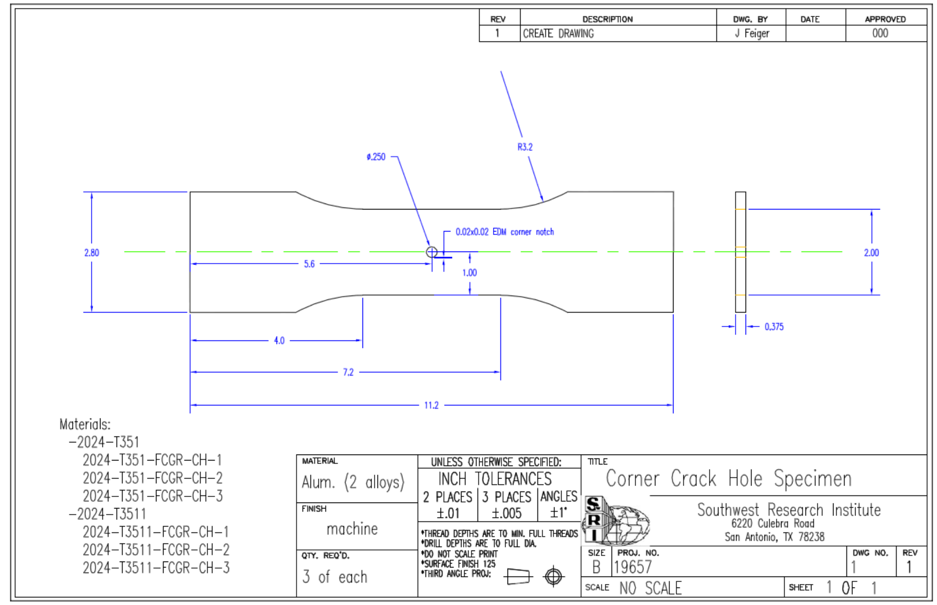
- L-S rates:
  - Through-thickness rates are critical for accurately predicting corner crack aspect ratios
- Corner crack rates:
  - The *vast* majority of coldworked hole life is as corner crack
- Low ΔK rates:
  - Compressive residual stresses shift us onto the lower end of the growth rates curves



Description of corner crack testing

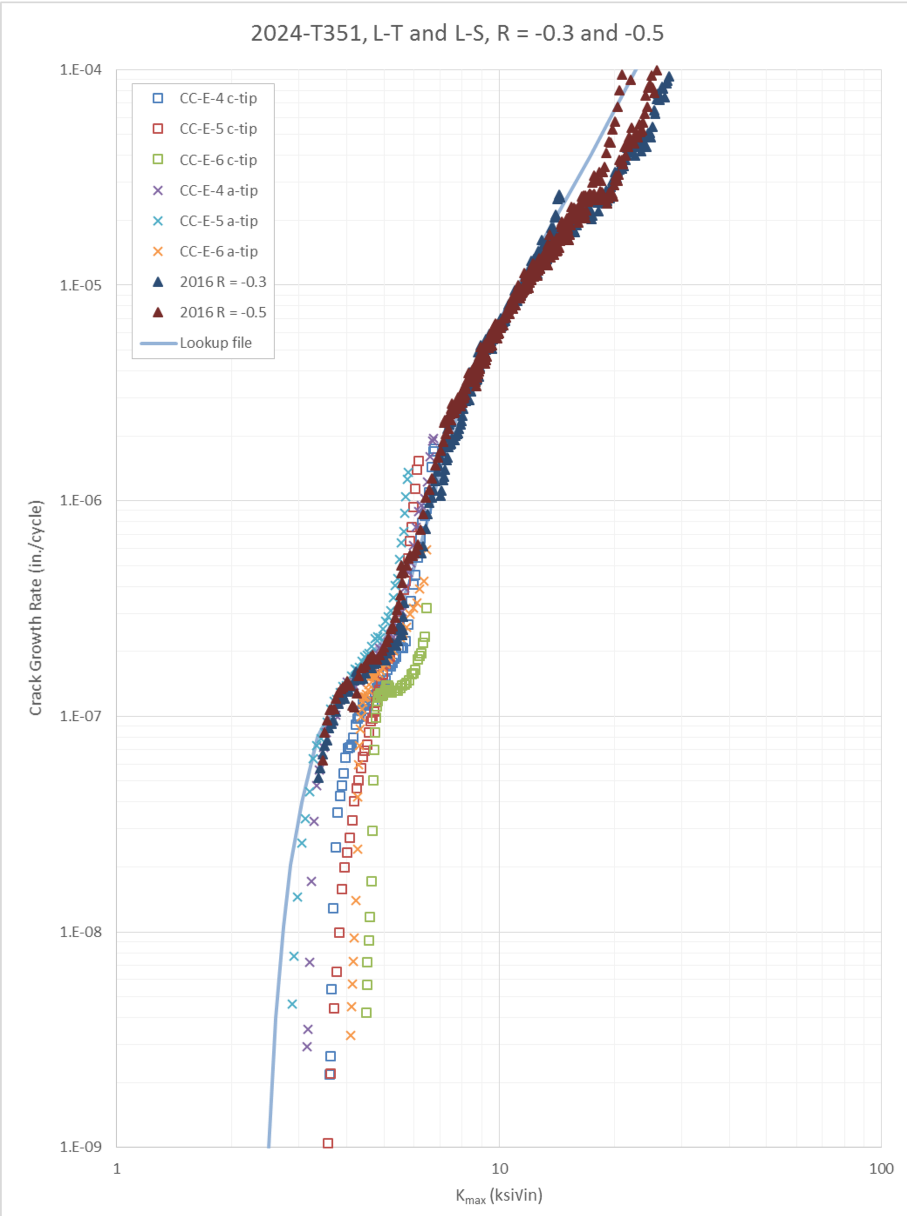
- All procedures follow E647, with two non-standard specimens



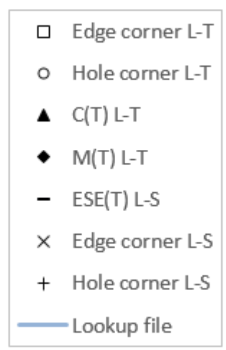


- Load shedding controlled by DCPD
  - $C = -4\ in^{-1}$ $(0.035 < -C\ (K_{max,i} / \sigma_y)^2 < 0.097)$
  - Pre-test assumption of aspect ratios for a-tip K input
  - Post-test correction of applied K for da/dN-ΔK curves

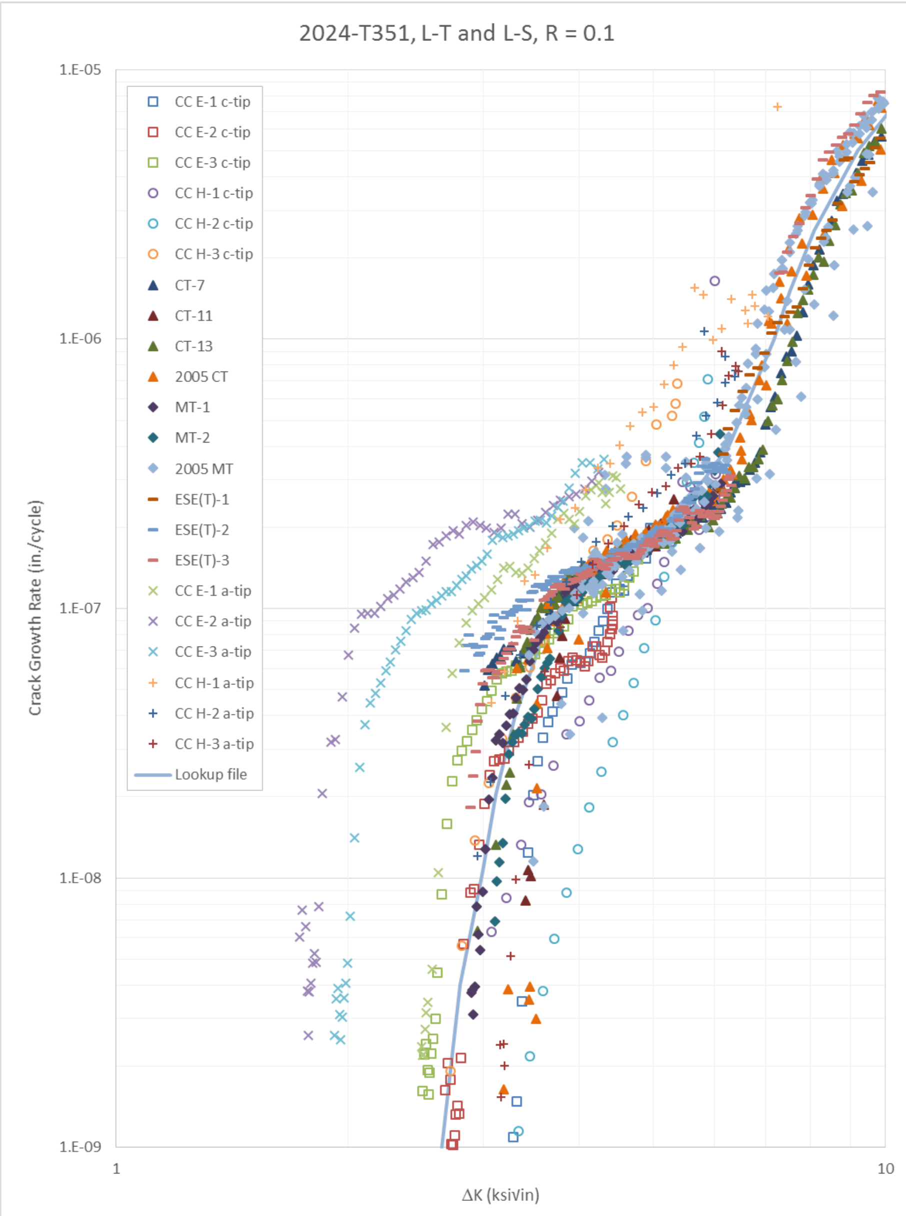
Test results: T351 L-T and L-S, R = -0.3



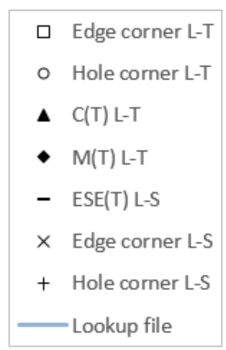
- Mostly consistent with M(T) data
- L-S (a-tip) data shows lower threshold than L-T (c-tip)
  - Very slightly lower than M(T)



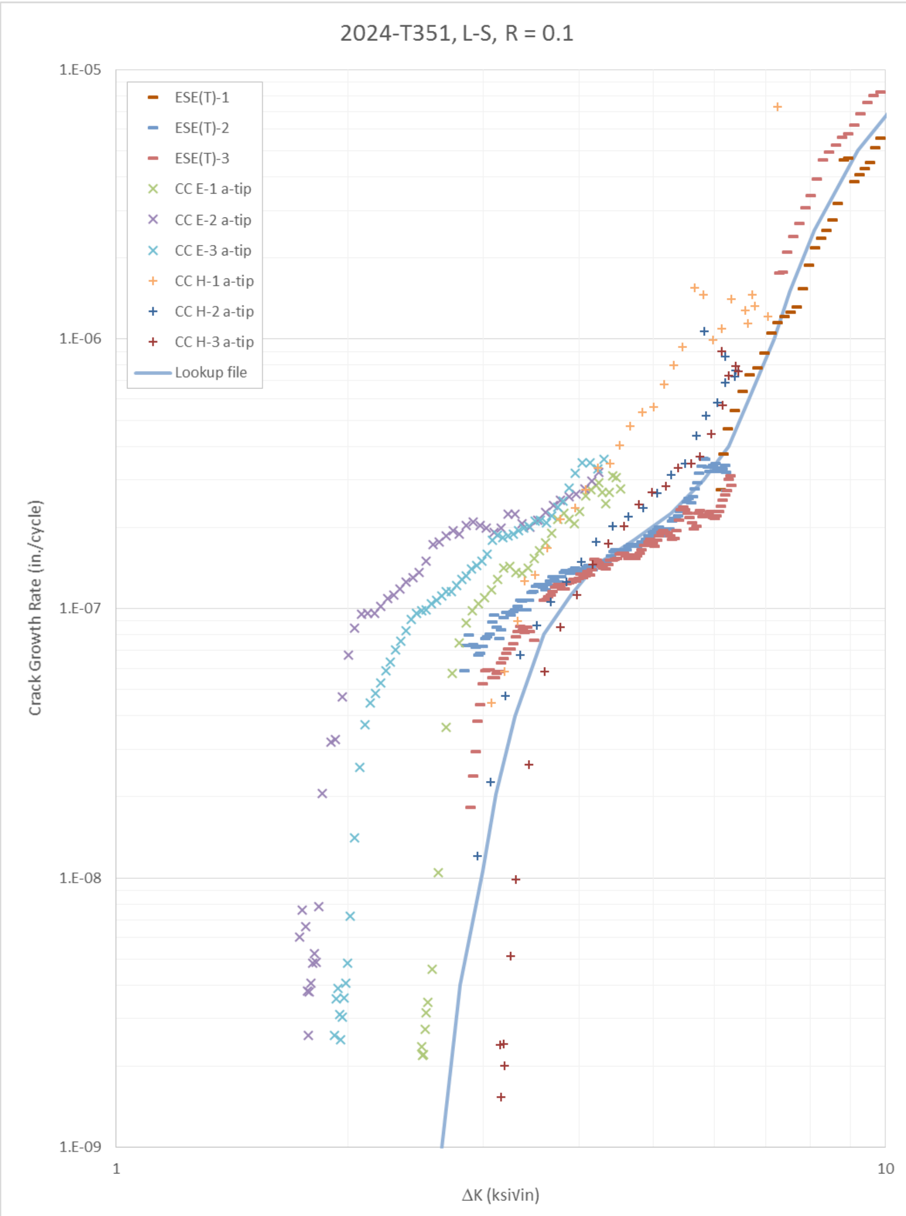
Test results: T351 L-T and L-S, R = 0.1



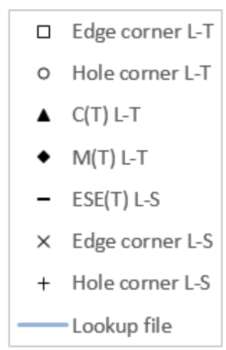
- L-S (a-tip and ESE(T)) data shows lower threshold than L-T (c-tip, C(T), and M(T)) data
- L-S data shows faster rates than the AFGROW lookup file
  - Potential for improved accuracy in corner crack aspect ratios



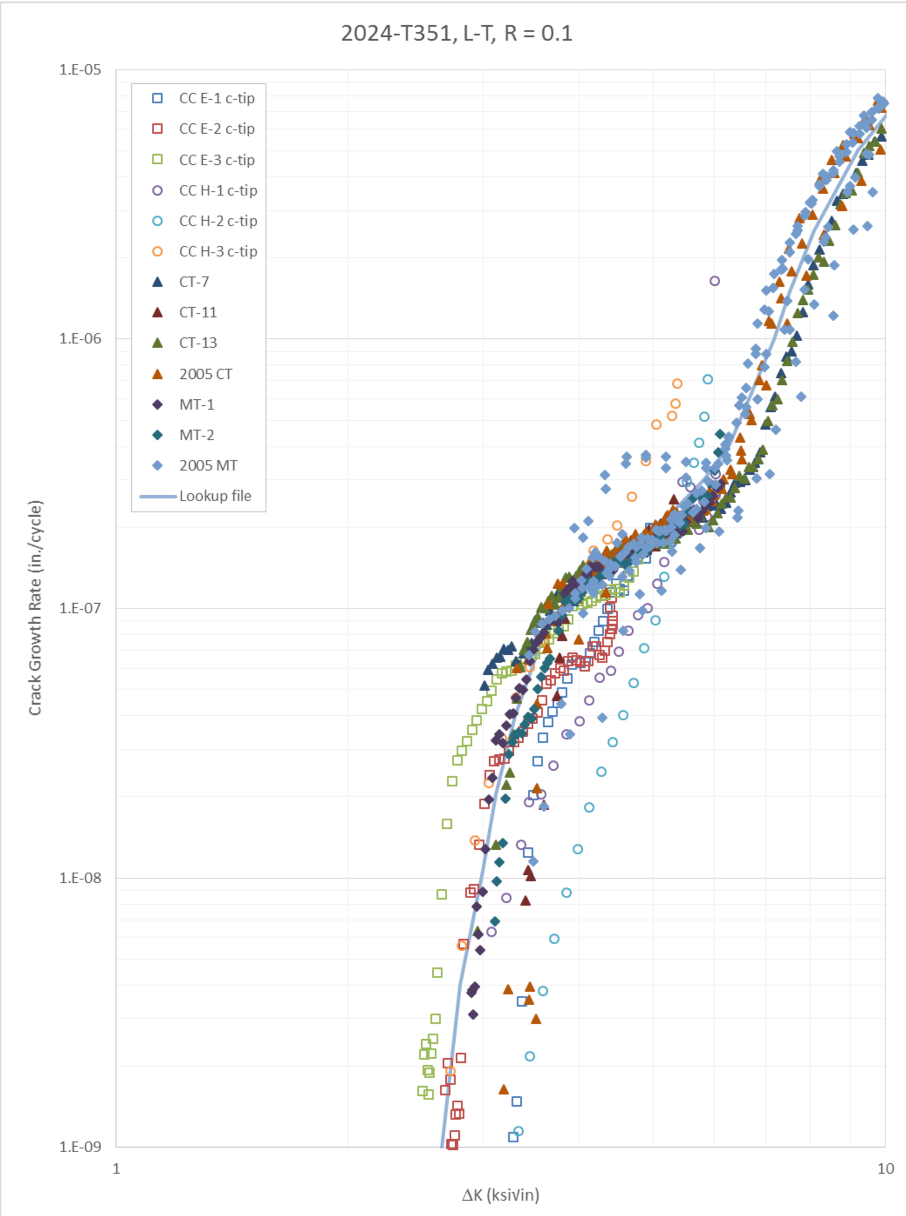
Test results: T351 L-S, R = 0.1



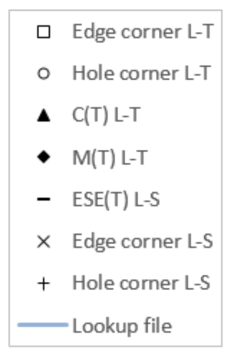
- Edge corner crack data shows lower threshold than both ESE(T) and hole corner crack



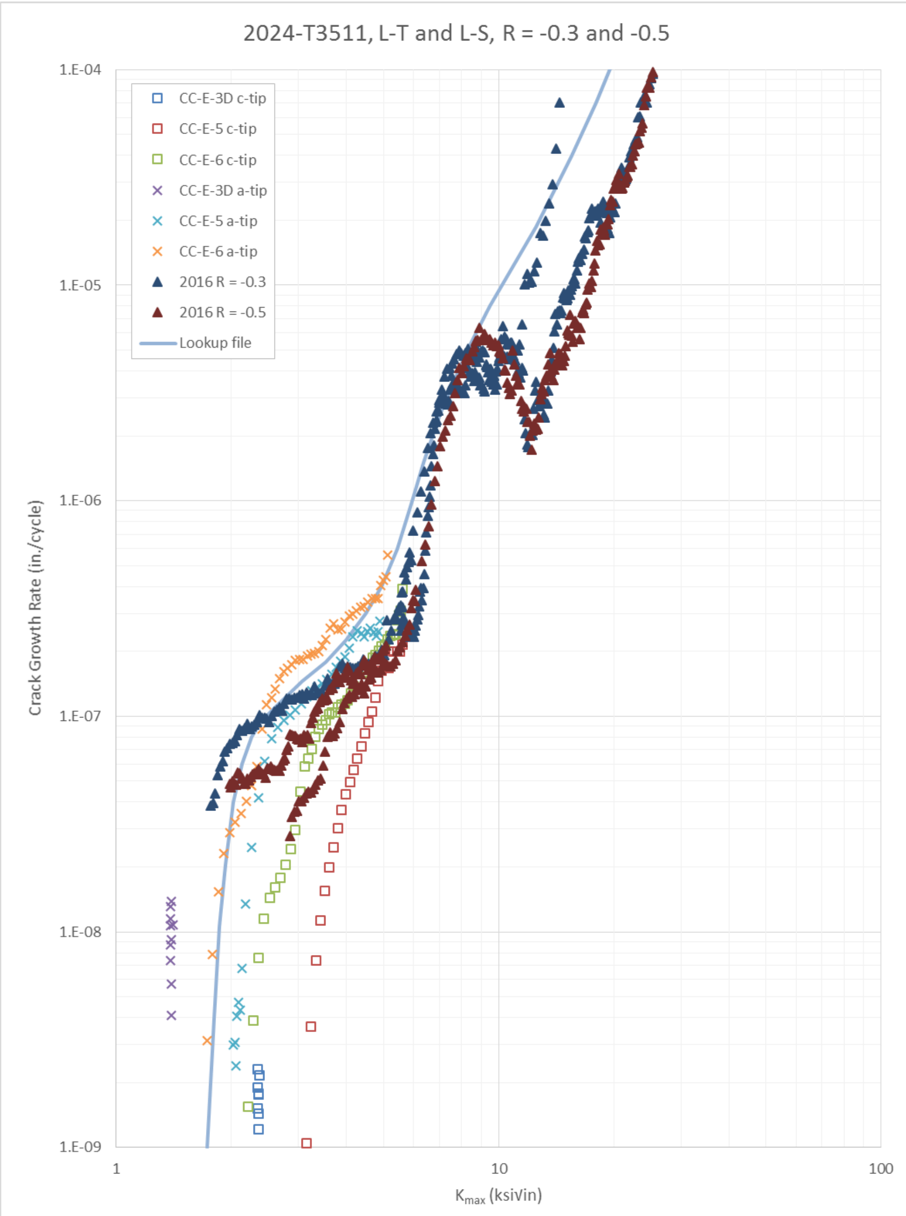
Test results: T351 L-T, R = 0.1



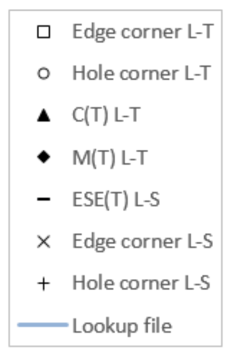
- Corner crack data consistent with C(T) and M(T) data
- Edge corner crack data shows lower threshold than hole corner crack



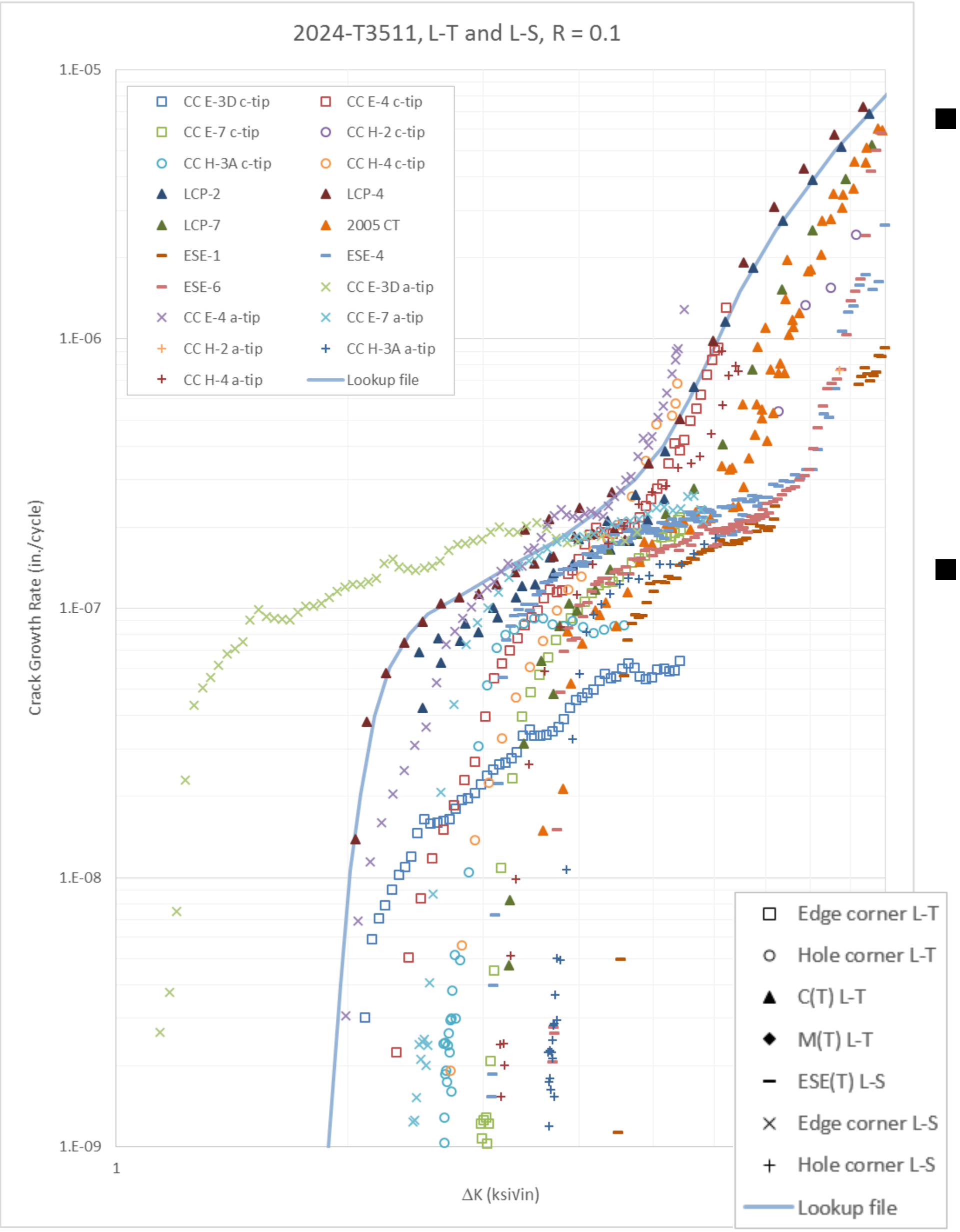
Test results: T3511 L-T and L-S, R = -0.3



- Mostly consistent with M(T) data
- L-S (a-tip) data shows lower threshold than L-T (c-tip)

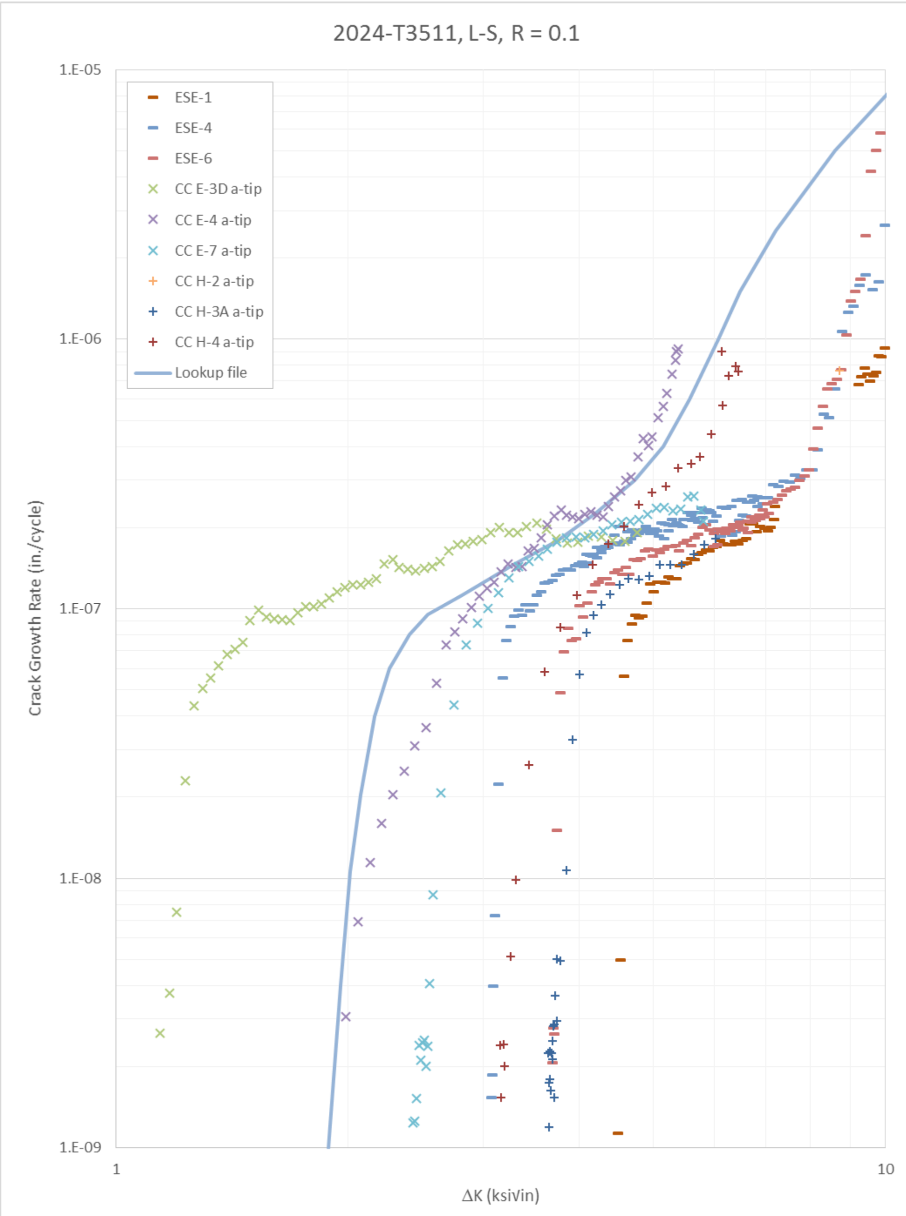


Test results: T3511 L-T and L-S, R = 0.1

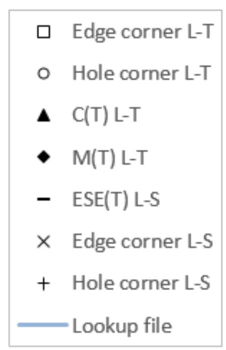


- L-S (a-tip and ESE(T)) and L-T (c-tip, C(T), and M(T)) data show similar threshold values
  - Not including one outlier
- Corner crack and through crack data show lower rates than the AFGROW lookup file
  - Lookup file is conservative, but not unrealistic
  - Not including one outlier

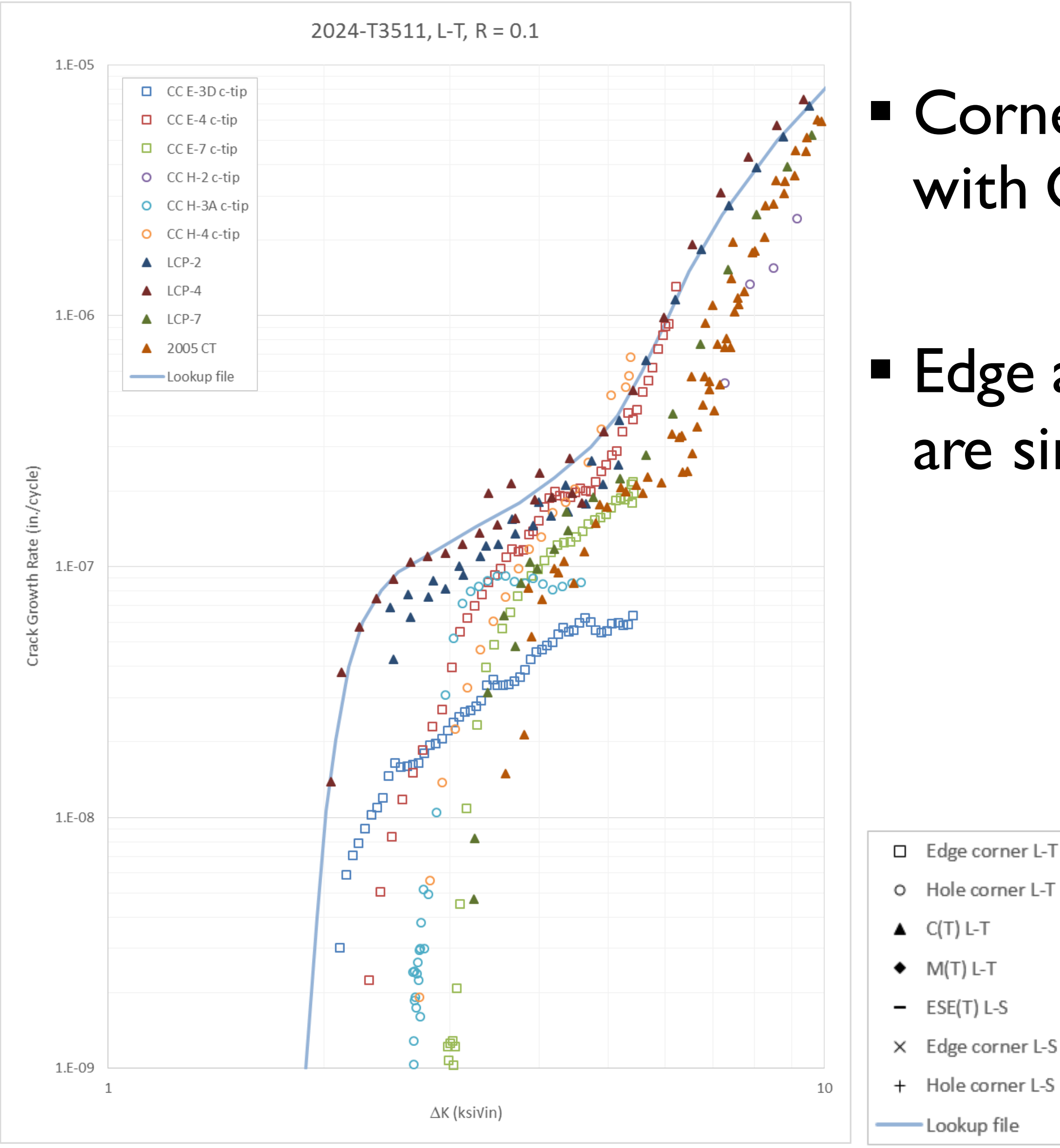
Test results: T3511 L-S, R = 0.1



- Edge corner crack data shows lower threshold than both ESE(T) and hole corner crack



Test results: T3511 L-T, R = 0.1



- Corner crack data consistent with C(T) and M(T) data
- Edge and hole corner crack rates are similar

Conclusions

- Successfully developed near-threshold da/dN-ΔK curves from E647 testing using corner crack specimens
- Data developed for both L-T and L-S cracking
  - Simpler method for L-S data than using through crack specimens
  - Thin specimens possible
- Method did not decrease variability seen in near-threshold data
  - Cracked edge specimens more consistent and more in line with expectations than cracked hole specimens