National Aeronautics and Space Administration
Marshall Space Flight Center

Overview of Fatigue and Damage Tolerance Performance of Powder Bed Fusion Alloy N07718

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ASTM/NIST Workshop on Mechanical Behavior in Additive Manufactured parts

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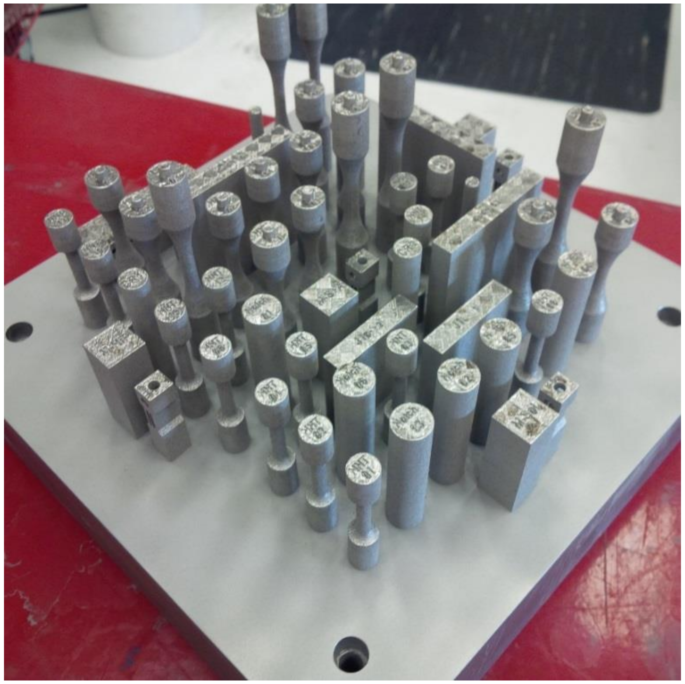
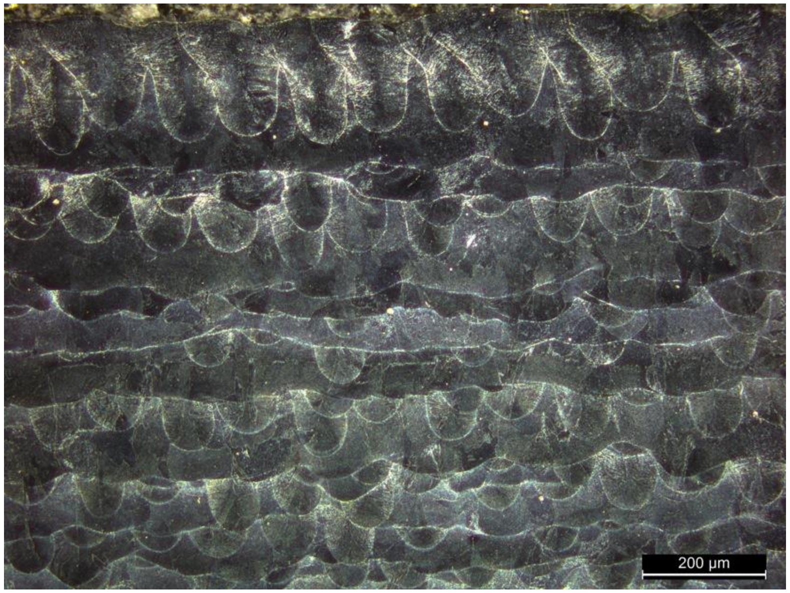
MSFC PBF Capability

- Selective Laser Melting (SLM)
  - Heat source is a 200 W laser
- Concept Laser M1 Cusing SLM machine
  - $250 \times 250 \times 250\ mm^3$ build volume

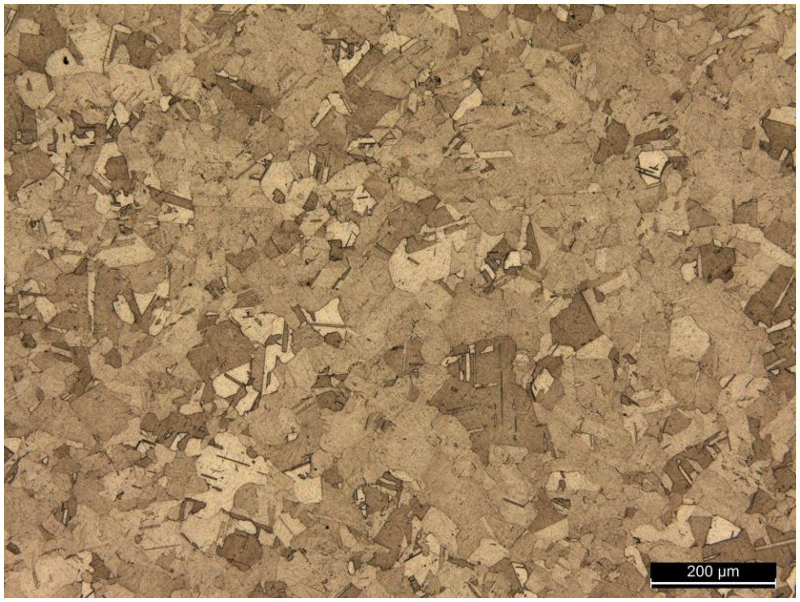


SLM 718 Post-Processing

- Stress Relief: 1065°C for 1.5 hours; furnace cool.
- HIP: 1165°C, 100 MPa, 3-4 hours
- Solution (AMS 5664): 1066°C for 1 hour; air cool.
- Age (AMS 5664): 760°C for 10 hours; furnace cool to 650°C; treat for total of 20 hours.



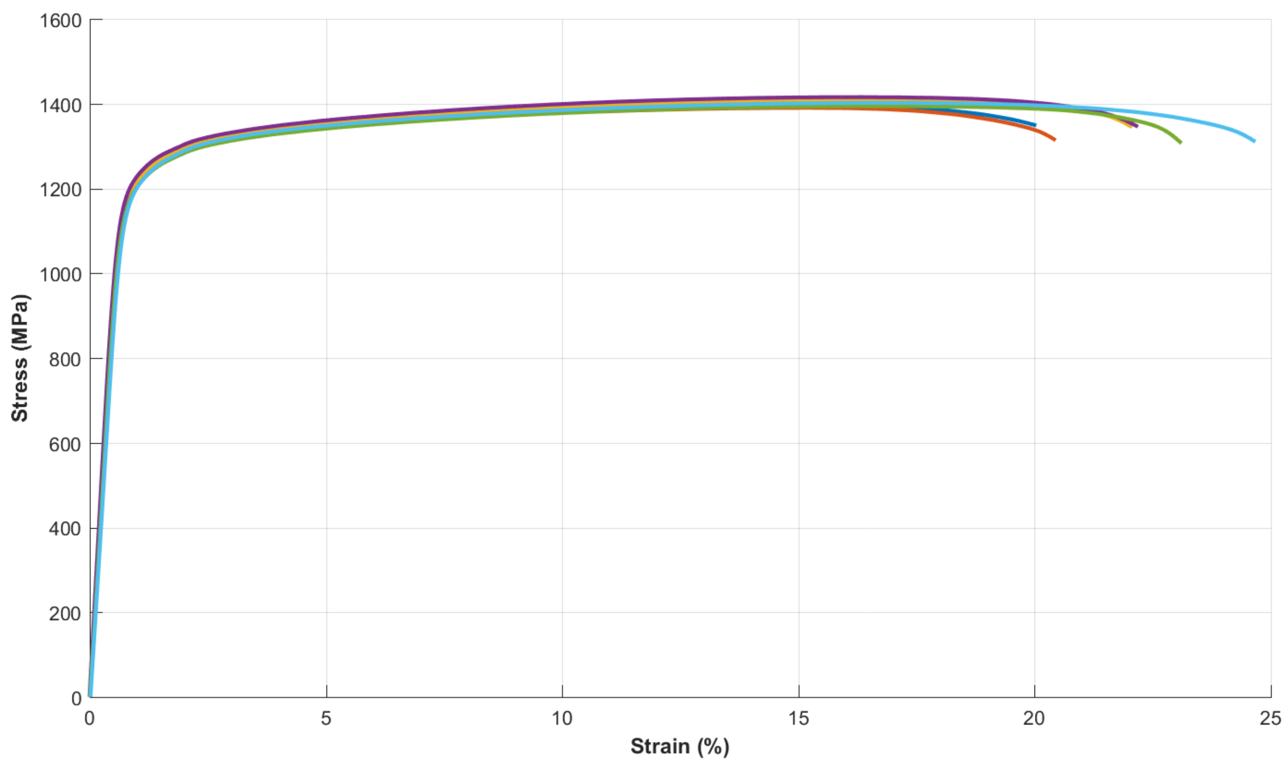
As-built microstructure



Heat treated microstructure

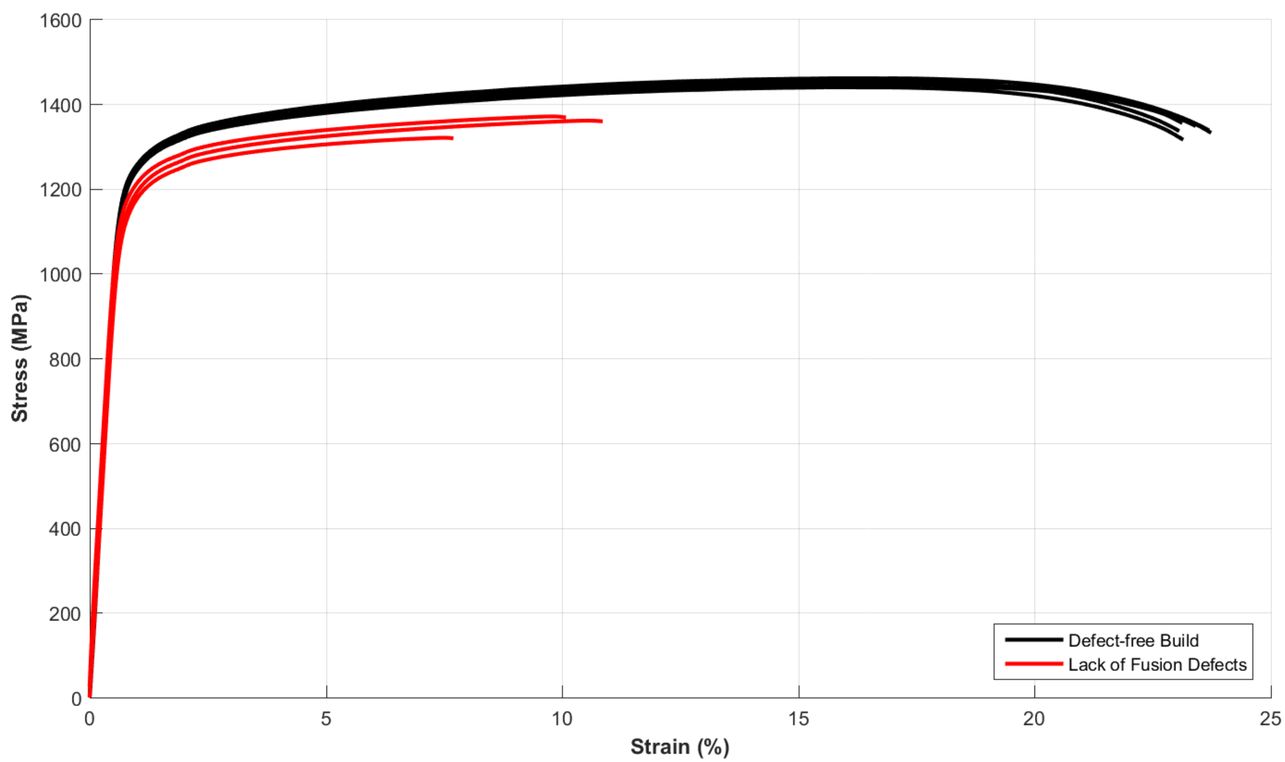
Typical Build Properties

- Typical tensile witness test curve for SLM 718.
  - Ultimate Tensile Strength: ~ 1380 MPa
  - Yield Strength: ~ 1170 MPa
  - Fracture Elongation: > 20%



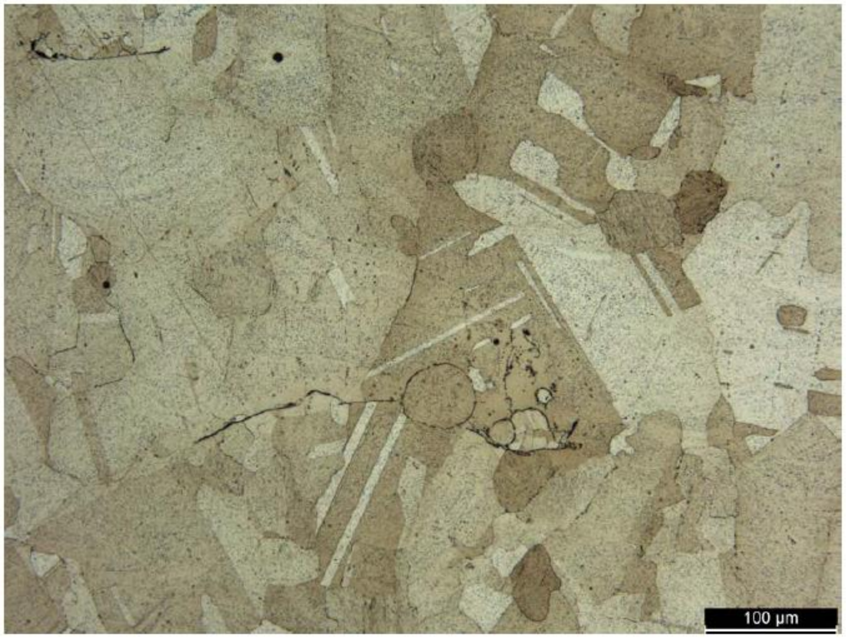
Defective Build

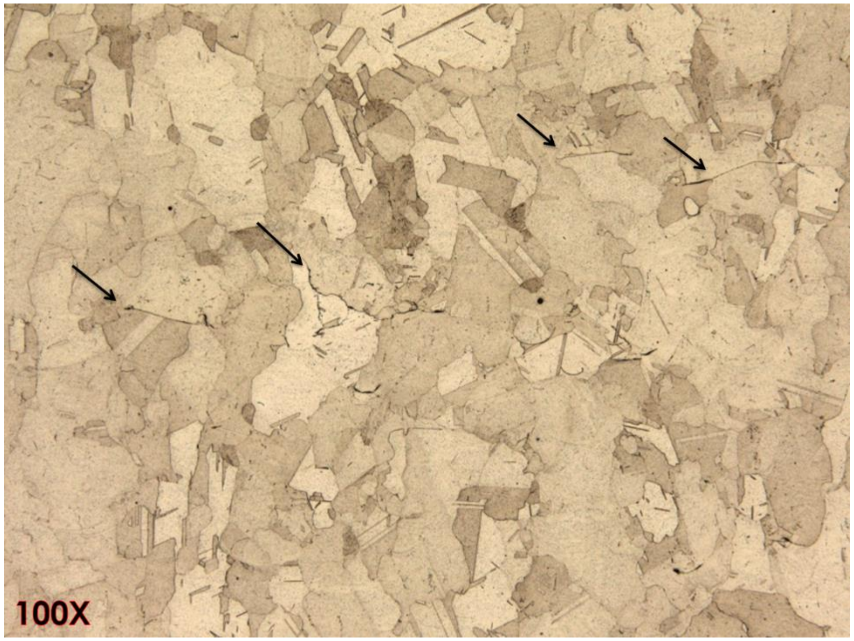
- A build of test specimens was produced; all indications were that the build was successful.
- Witness tensile testing revealed lower than expected material properties.



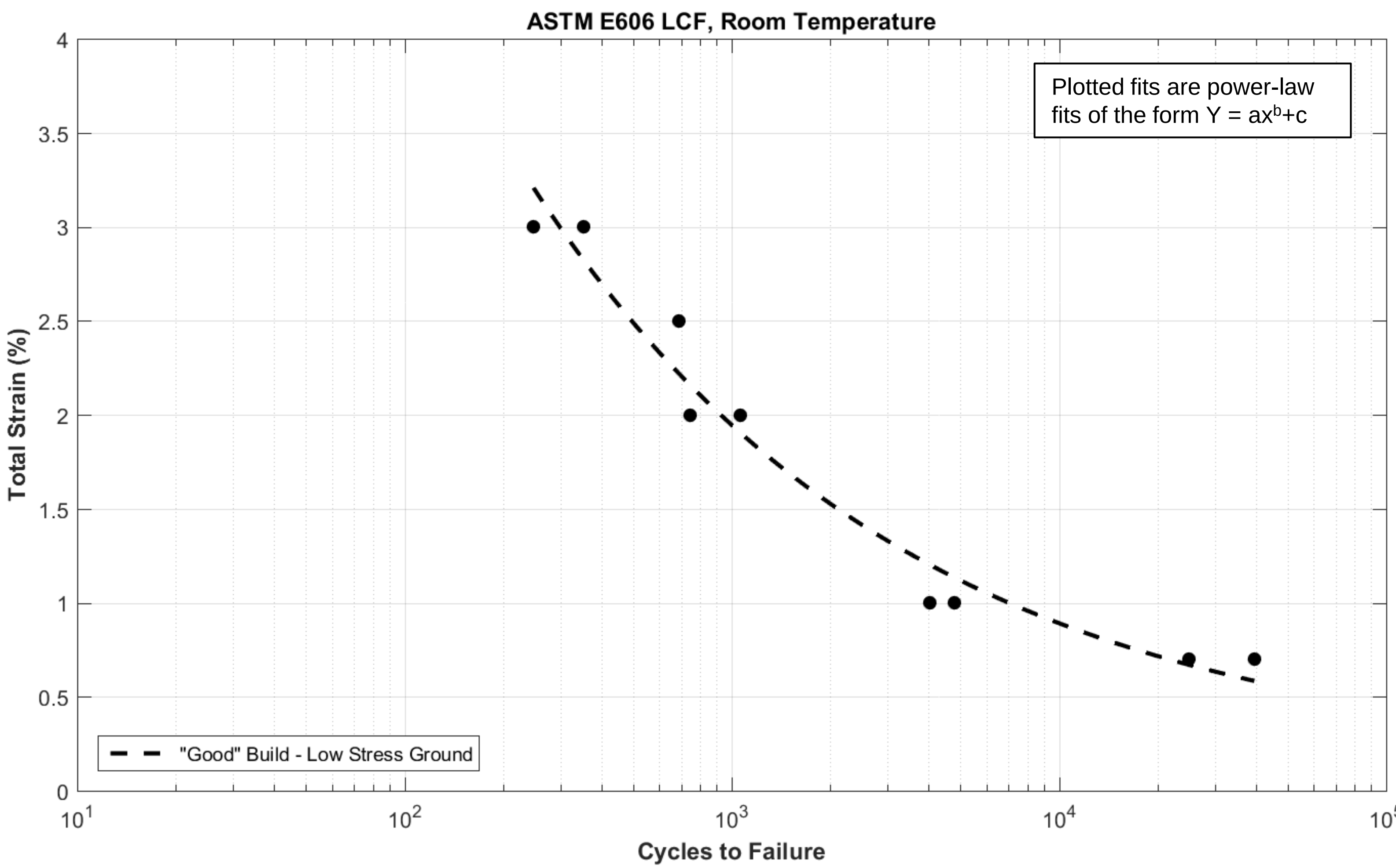
Defective Build

- Metallographic examination revealed lack of fusion defects in the material.
- Source was eventually determined to be a clogged ventilation duct that was allowing combustion by-products to settle on the powder bed.



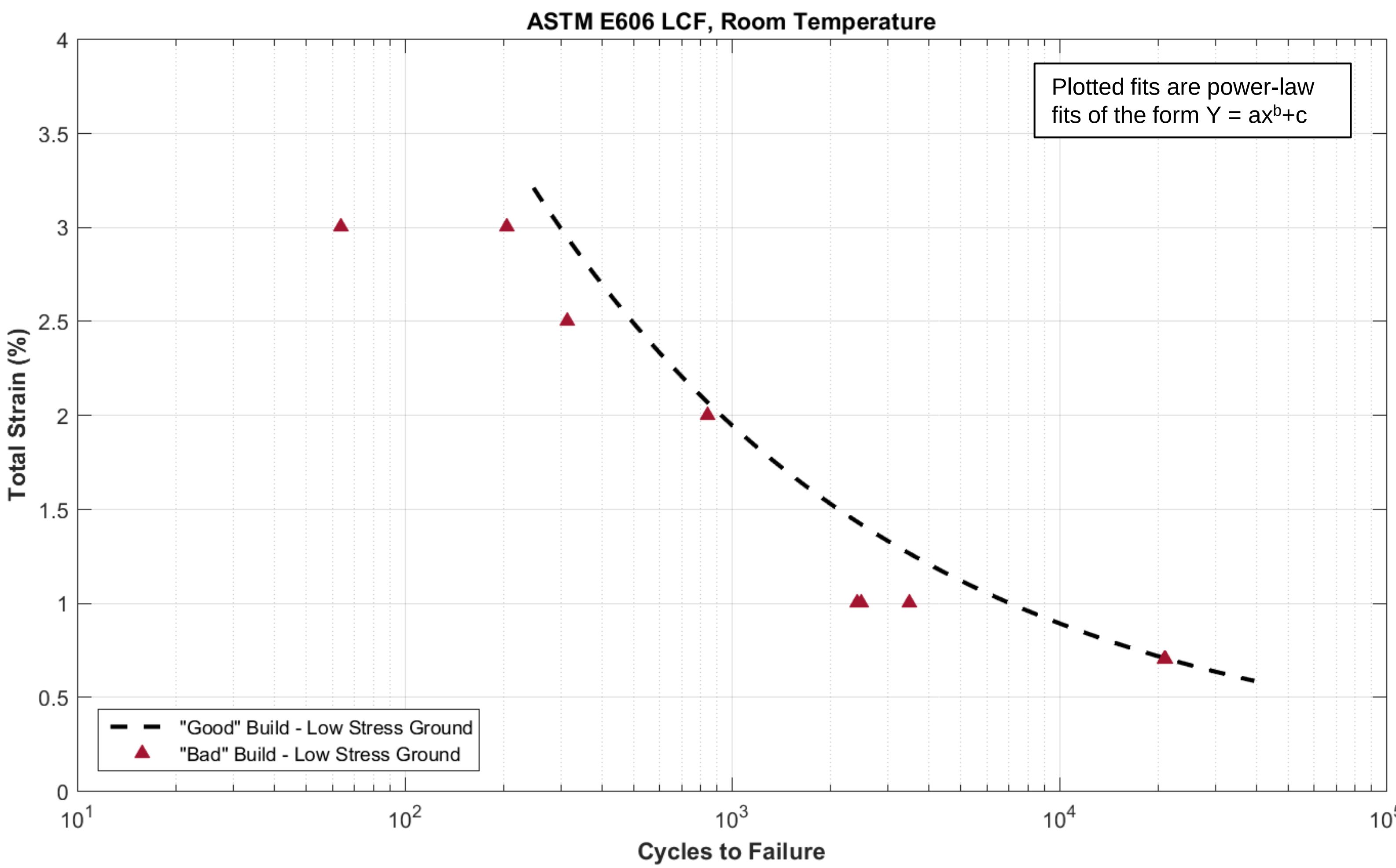


Low Cycle Fatigue of SLM 718



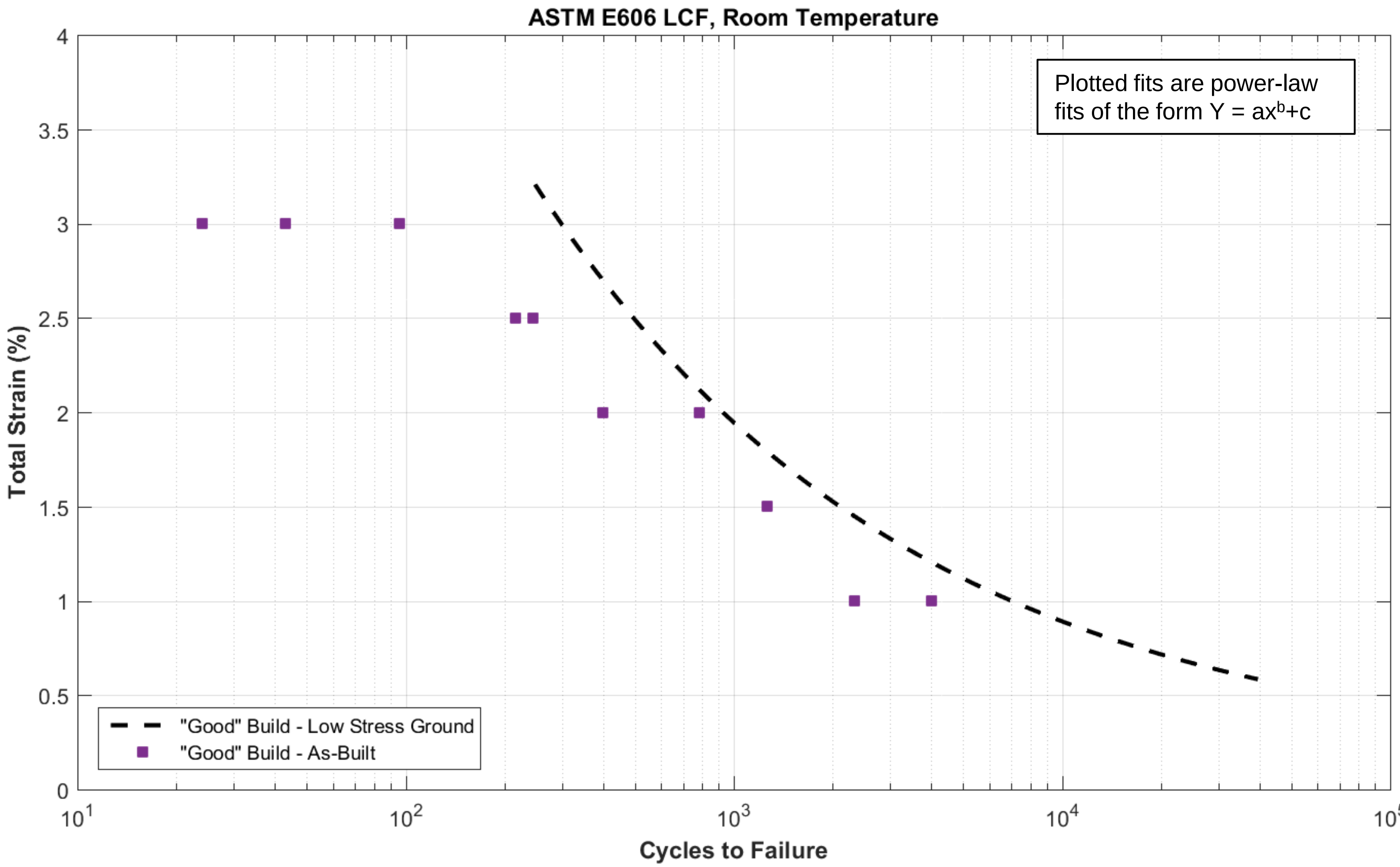
- "Reference" data – Low Stress Ground, R = -1, Defect-free build

Low Cycle Fatigue of SLM 718



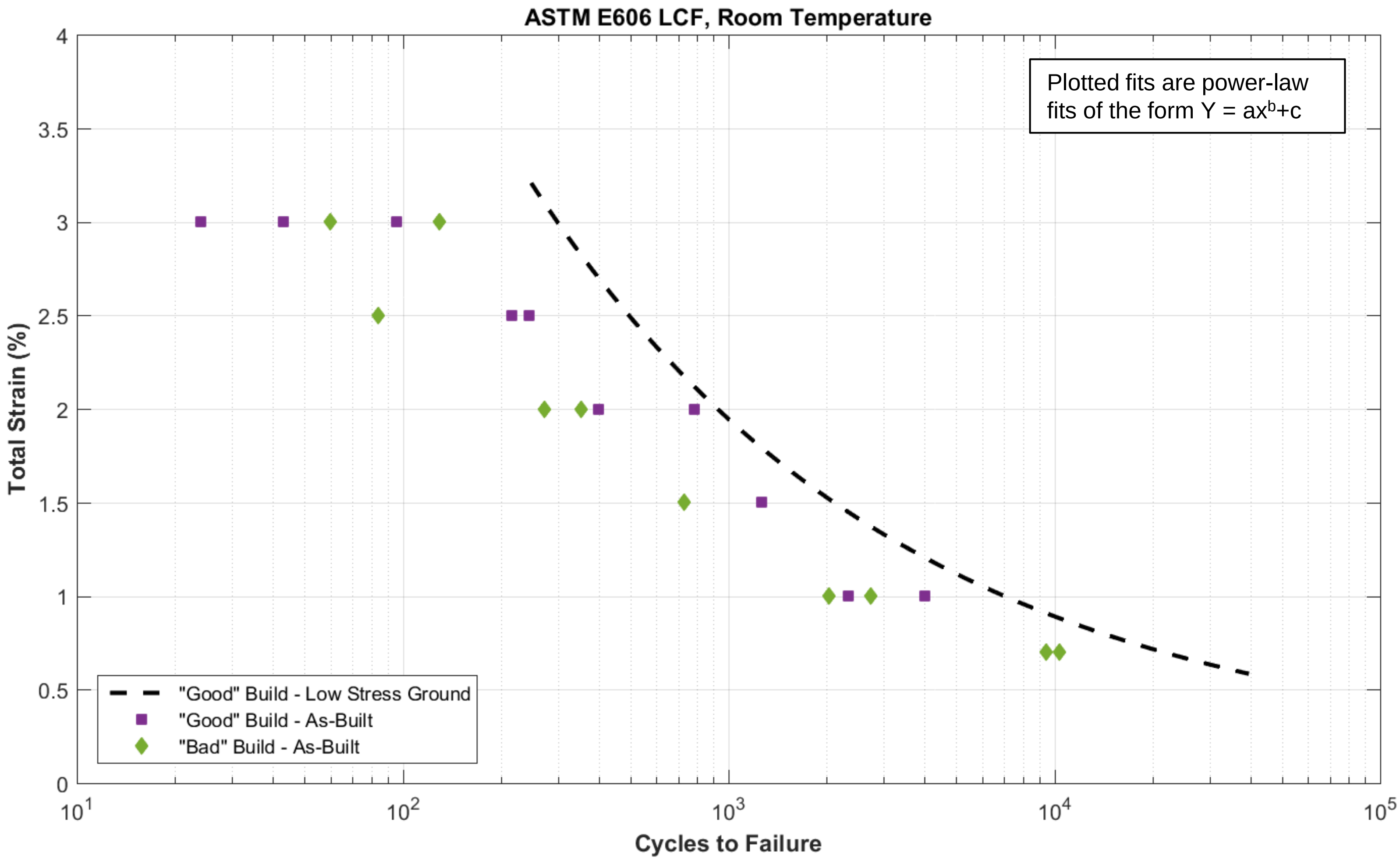
- Compare to build with defects – slightly lower fatigue life

Low Cycle Fatigue of SLM 718



- Defect-free build with as-built surface finish; fatigue life even lower

Low Cycle Fatigue of SLM 718

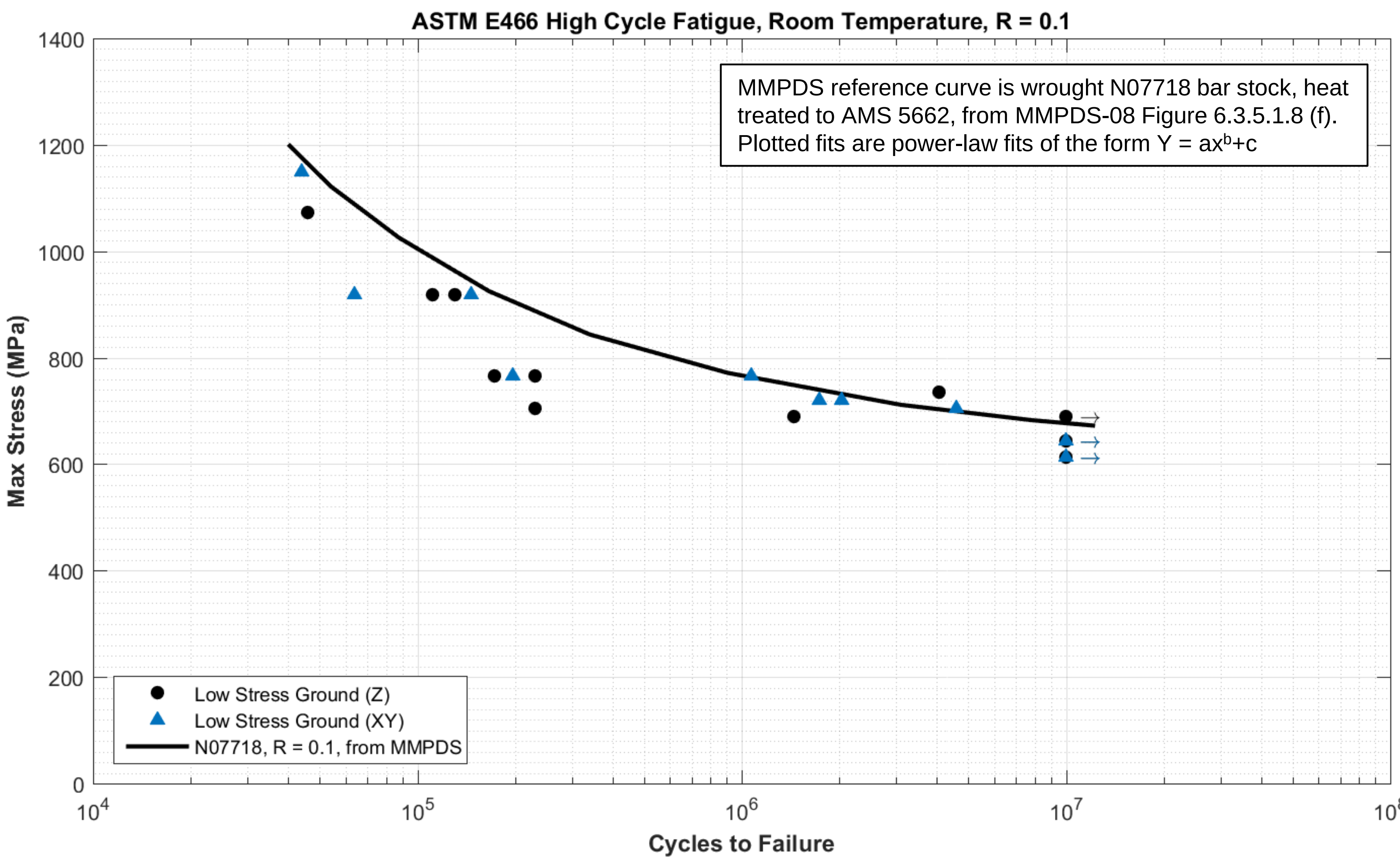


- As-built surface finish, with defects; surface finish has more effect than internal defects.

High Cycle Fatigue of SLM 718

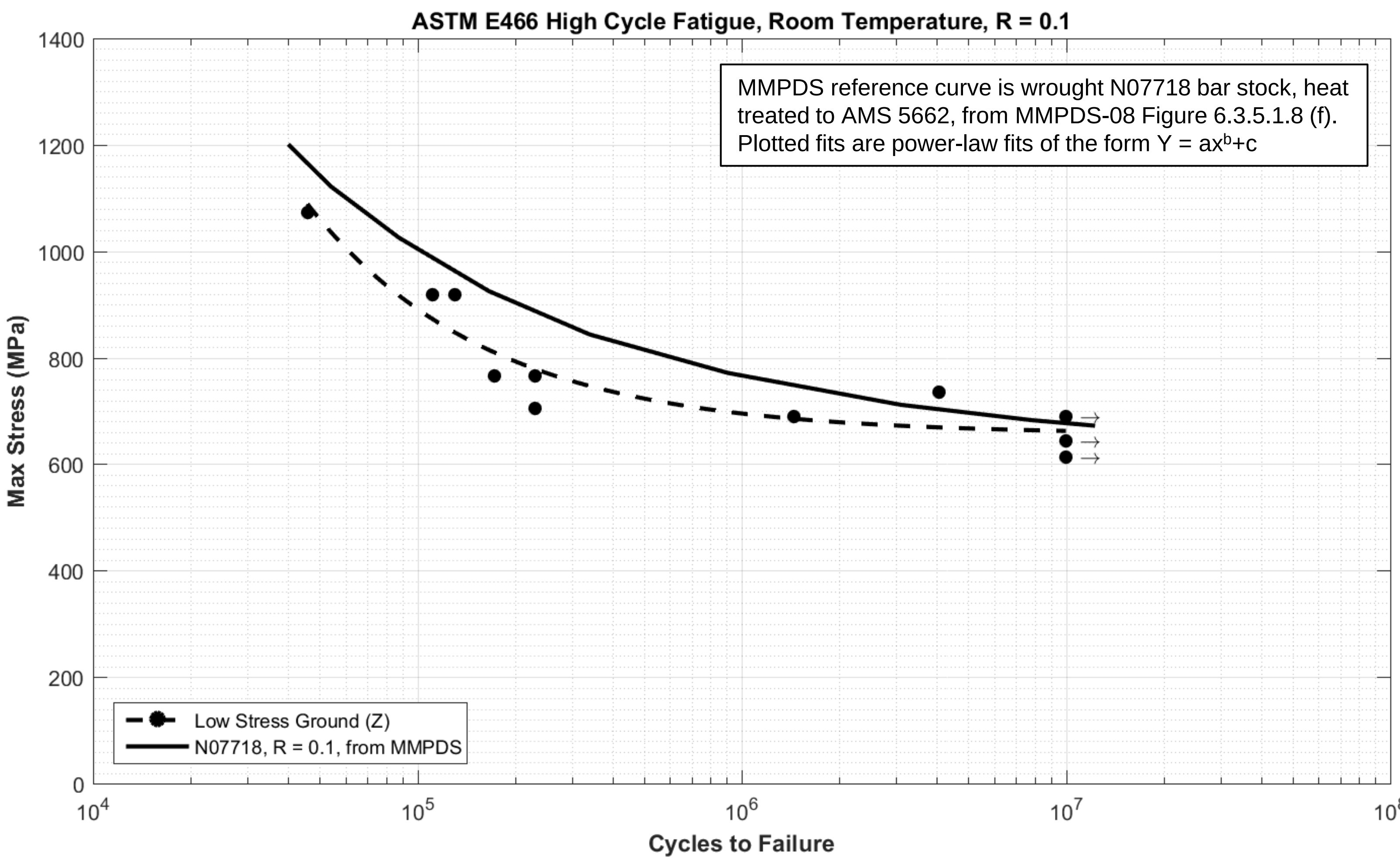
- Key Variables
  - Orientation
    - Z – loading axis perpendicular to powder bed plane.
    - XY – loading axis parallel to powder bed plane.
    - 45° – loading axis 45° from powder bed plane.
  - Surface Finish
    - Low Stress Ground – ASTM E466 finishing procedure
    - As-Built – Surface finish from the SLM machine
  - Temperature
    - Room Temperature (RT) – nominal lab conditions, 70-75°F
    - Liquid Nitrogen (-320°F)

High Cycle Fatigue of SLM 718



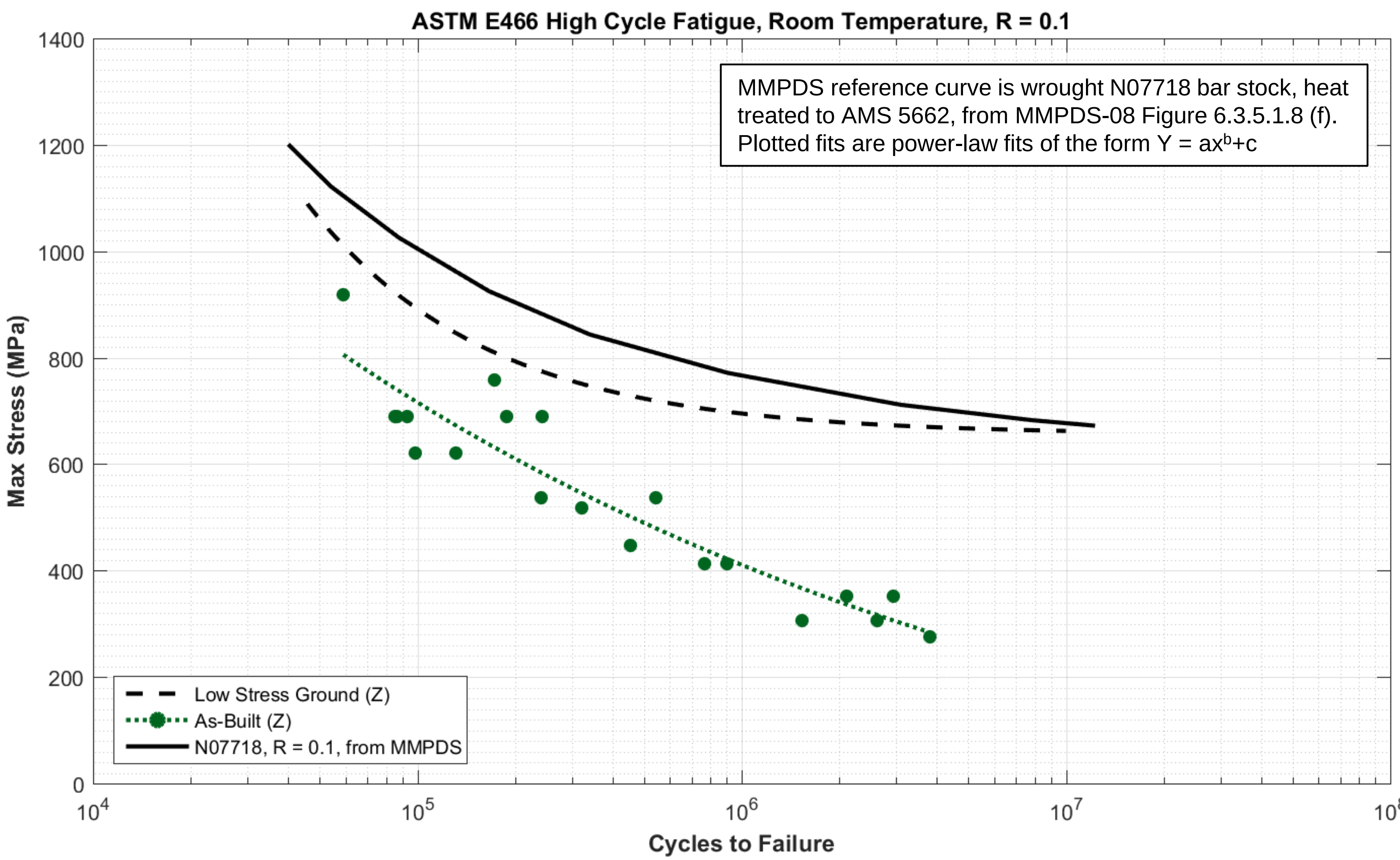
- Low stress ground; minimal effect from orientation

High Cycle Fatigue of SLM 718



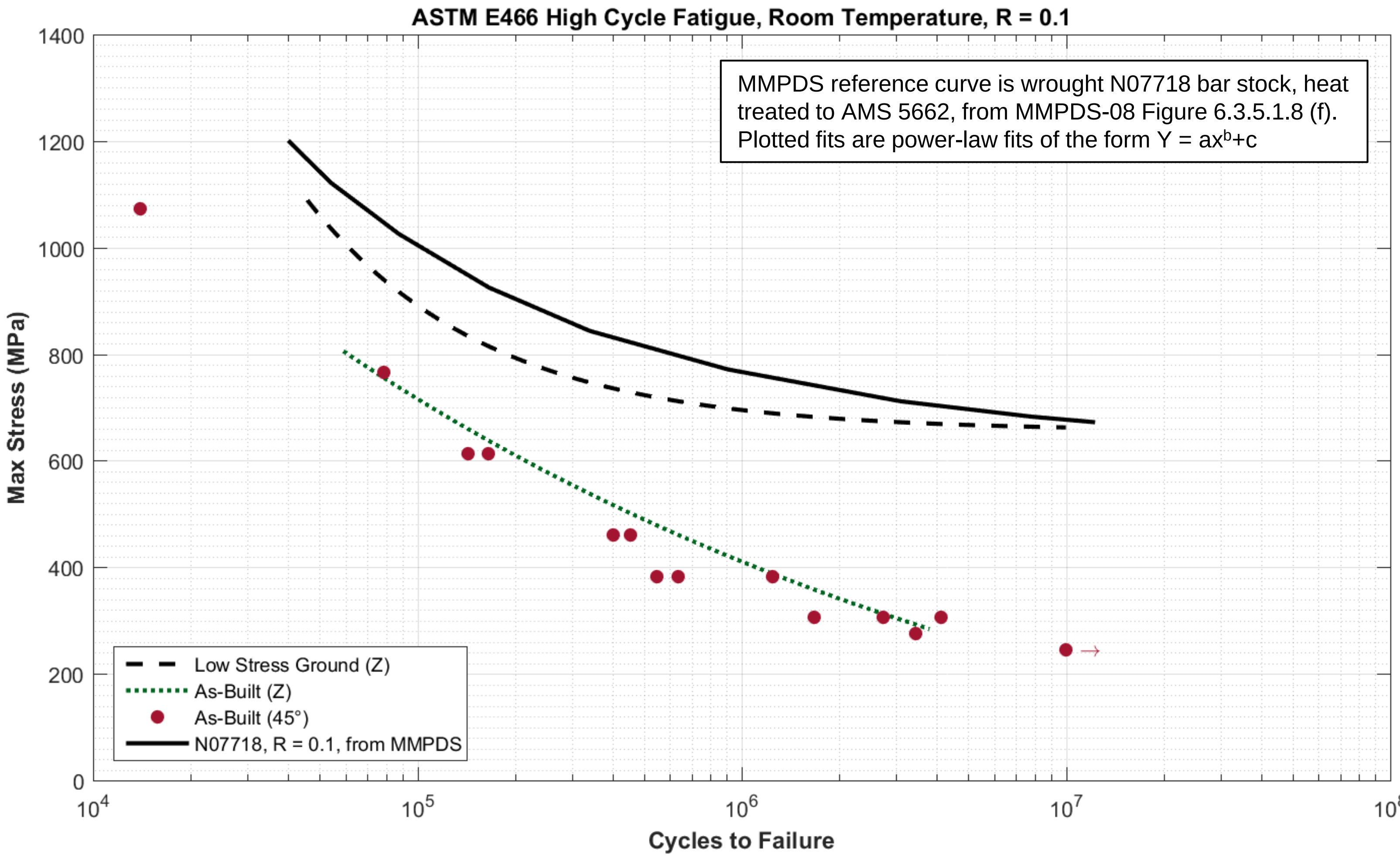
- "Reference" data – Low Stress Ground, Room Temperature, R = 0.1

High Cycle Fatigue of SLM 718



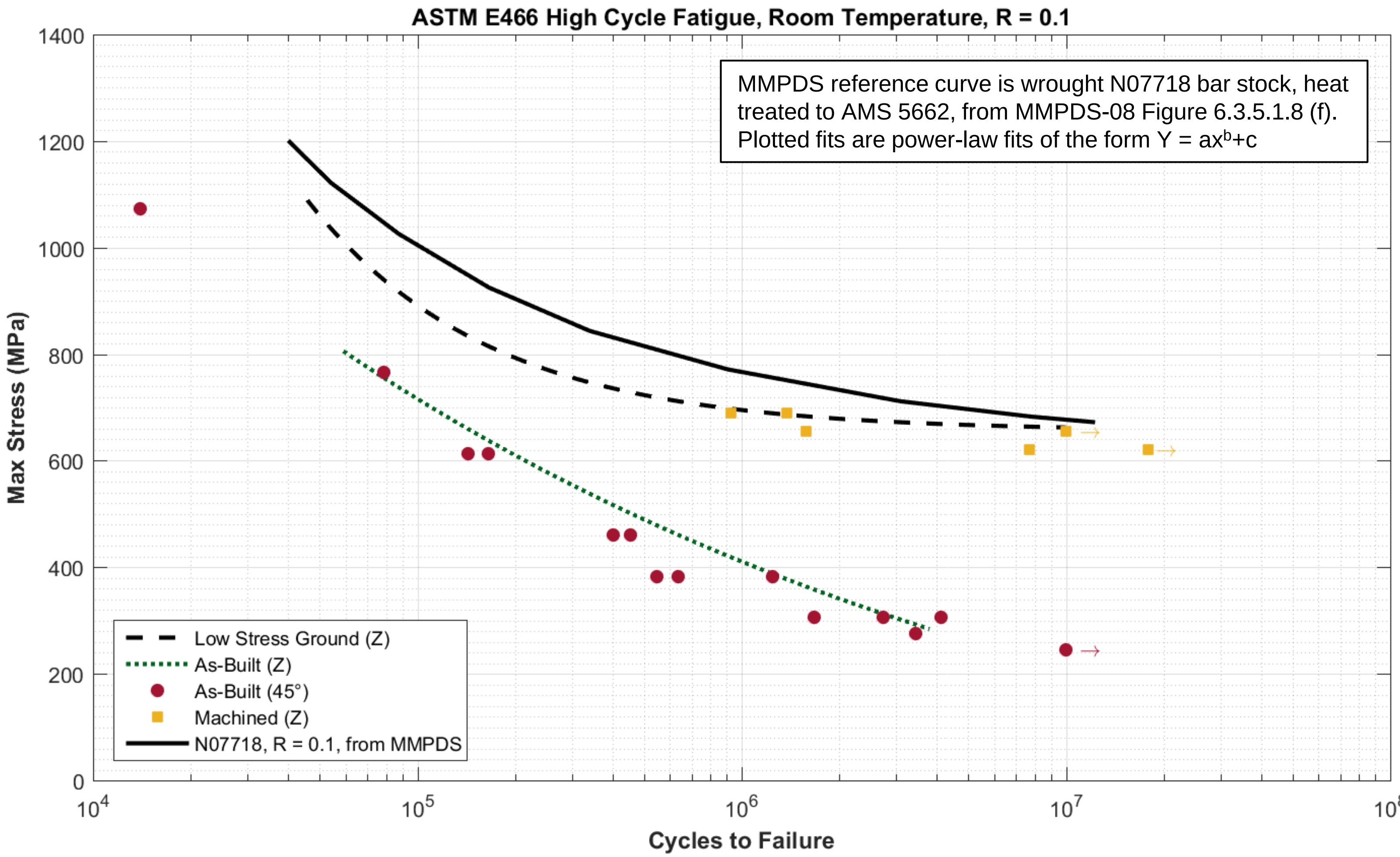
- Z-oriented, As-built surface finish; decreased fatigue life

High Cycle Fatigue of SLM 718



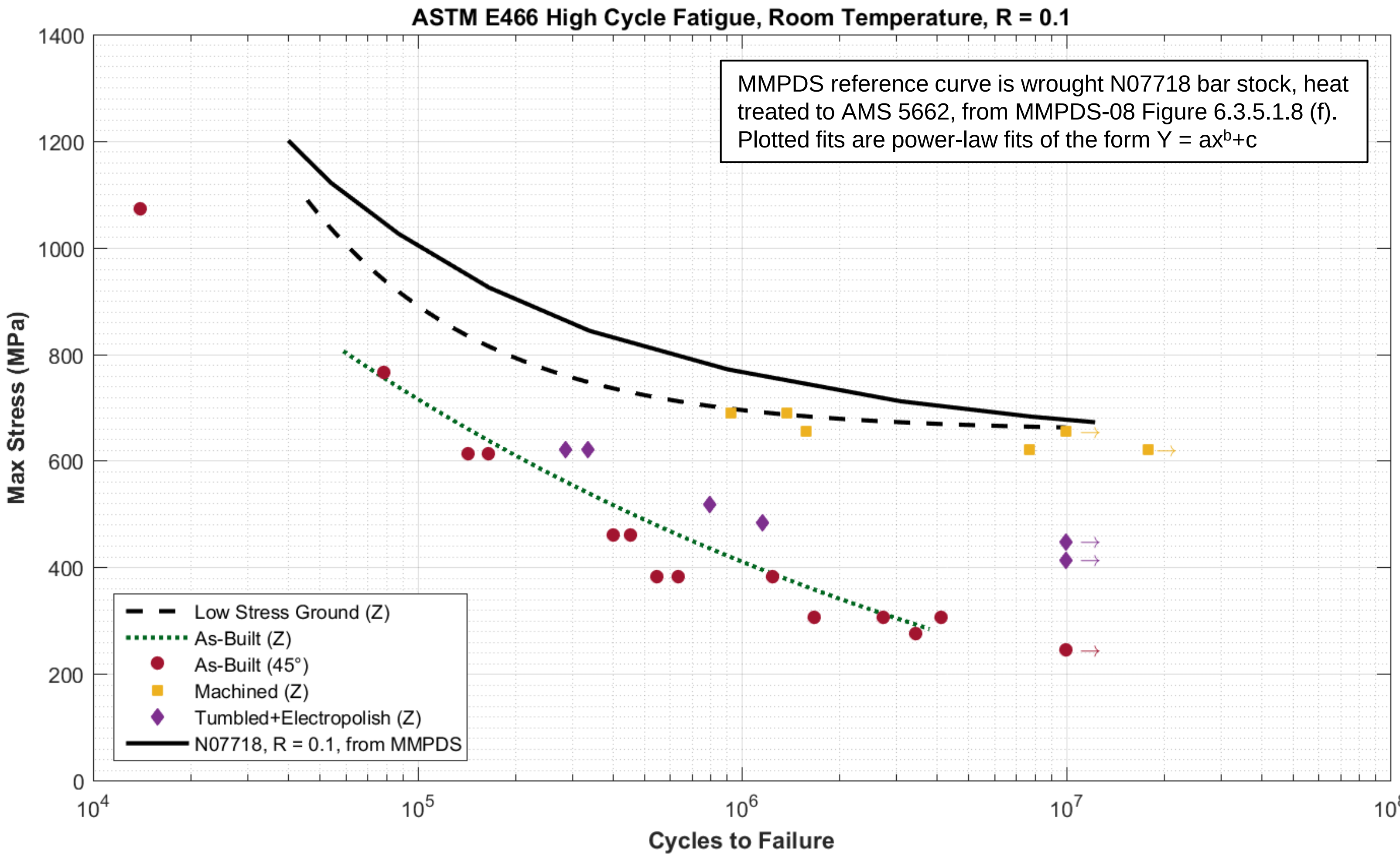
- 45°-oriented, As-built surface finish; similar fatigue life, 45° tend to be rougher than Z

High Cycle Fatigue of SLM 718



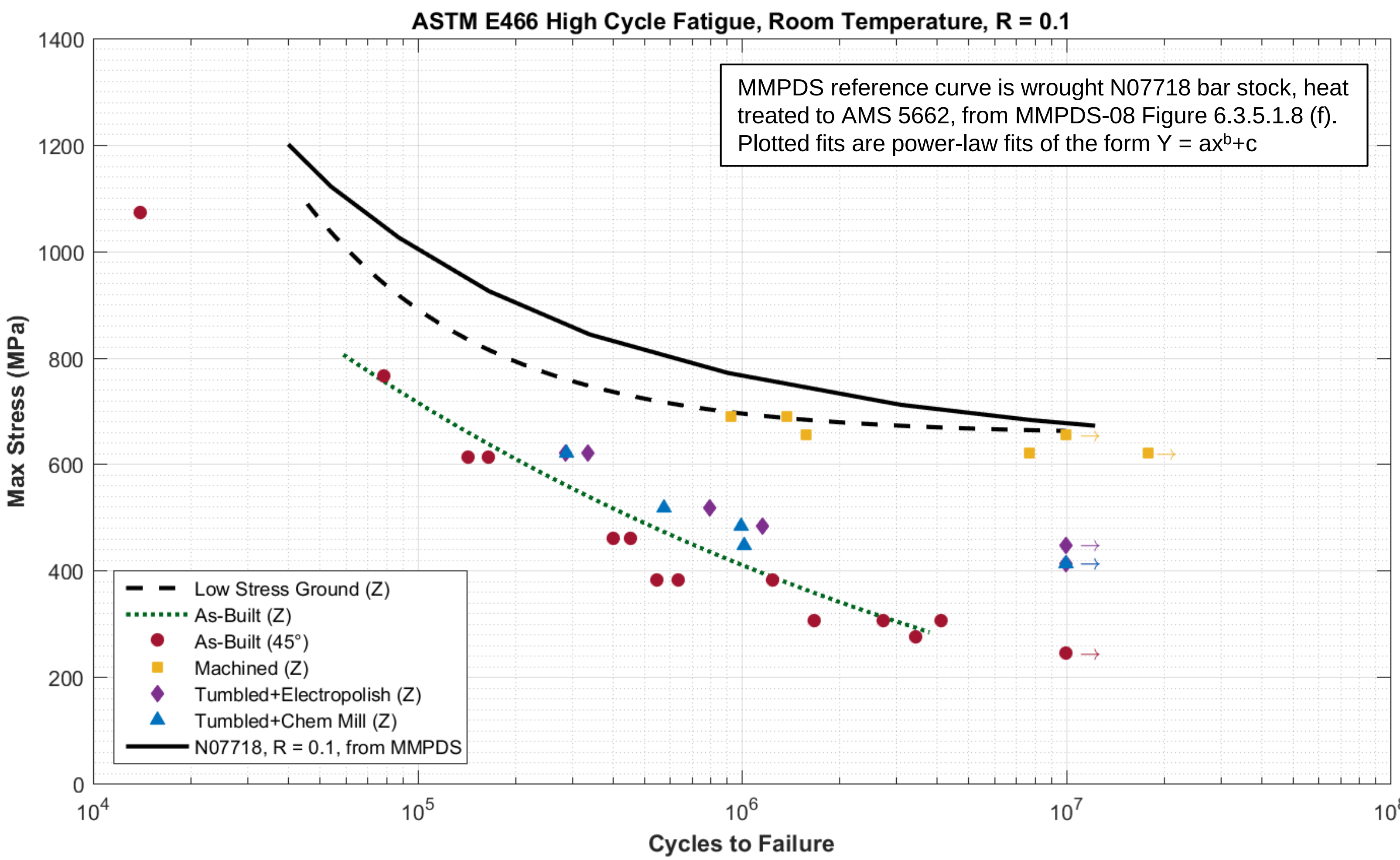
- Z-oriented, lathe-turned surface finish; quicker machining turnaround, slight decrease in life from low stress ground.

High Cycle Fatigue of SLM 718



- Z-oriented, Tumbled then Electropolished; investigated for part finishing.

High Cycle Fatigue of SLM 718

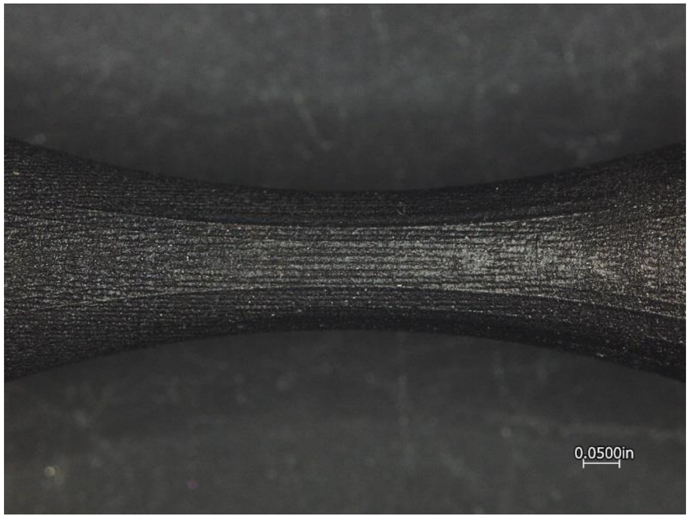


- Z Oriented, Tumbled then Chem Milled; investigated for part finishing.

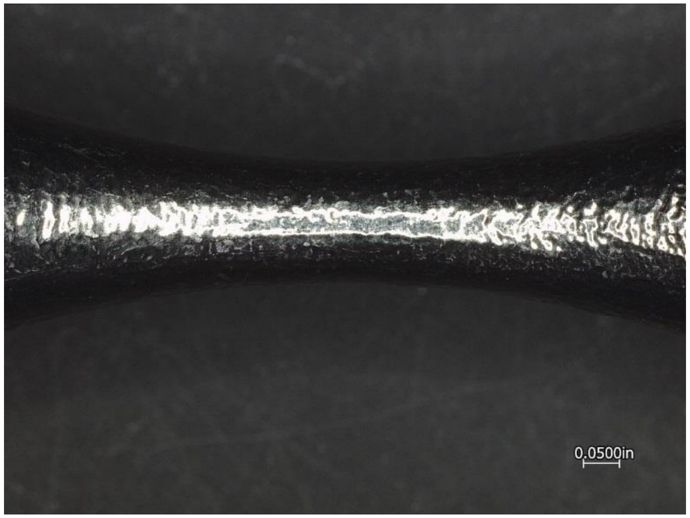
High Cycle Fatigue of SLM 718

- Fatigue life decreases with increasing surface roughness.

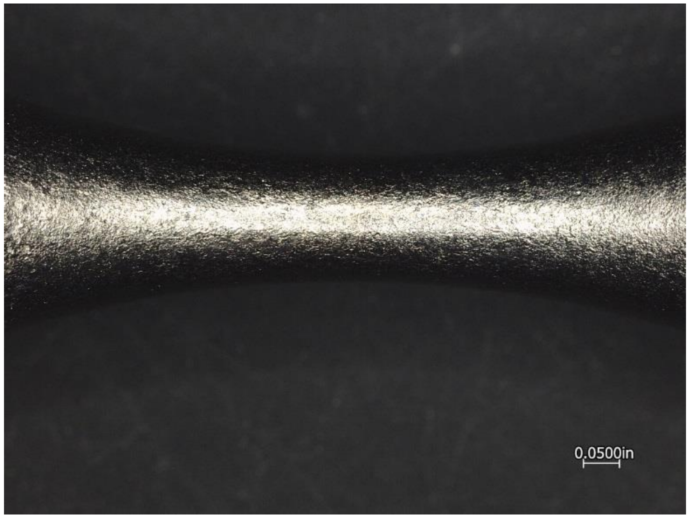
Low stress ground



As-built

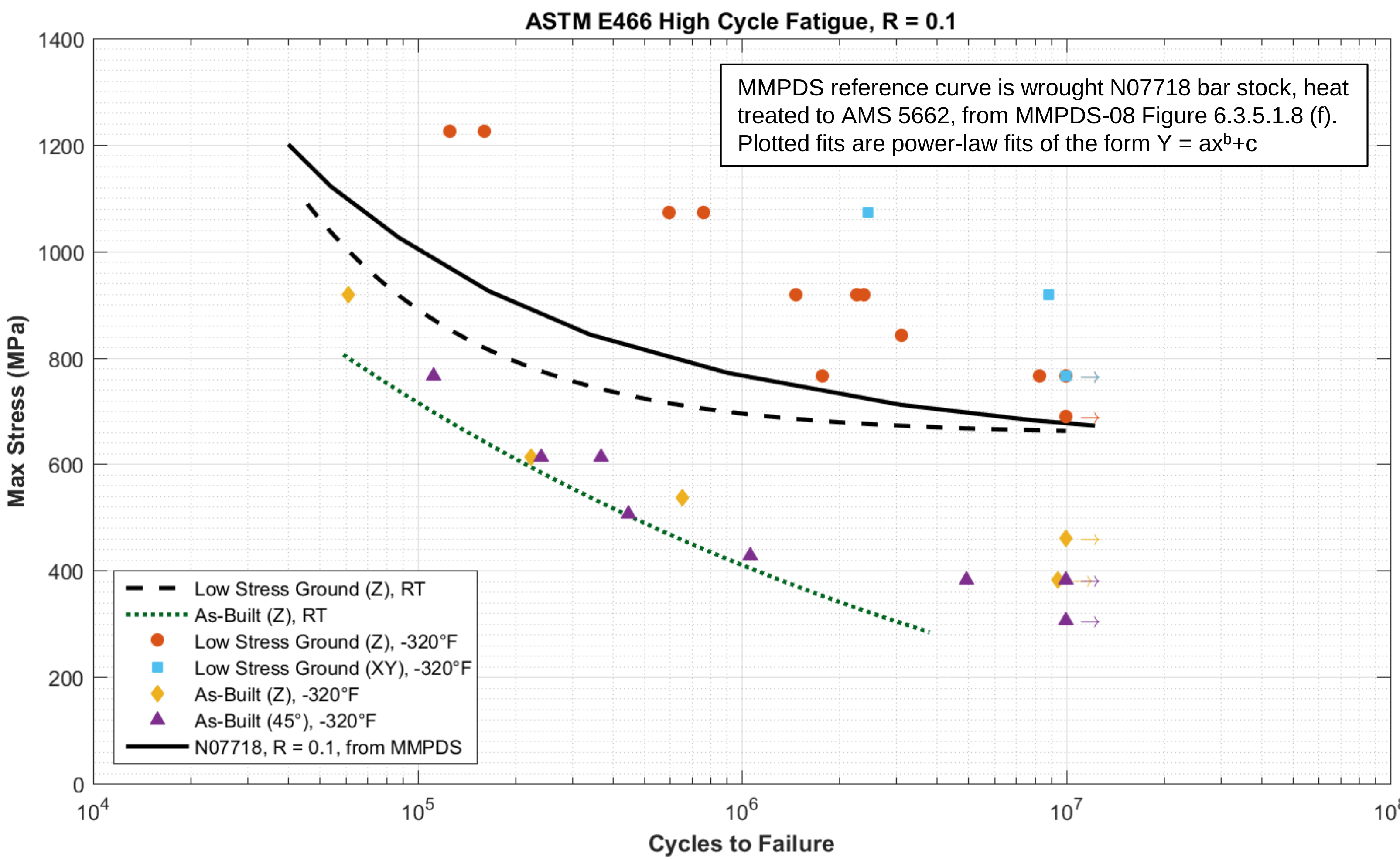


Tumbled & Electropolish



Tumbled & Chem Mill

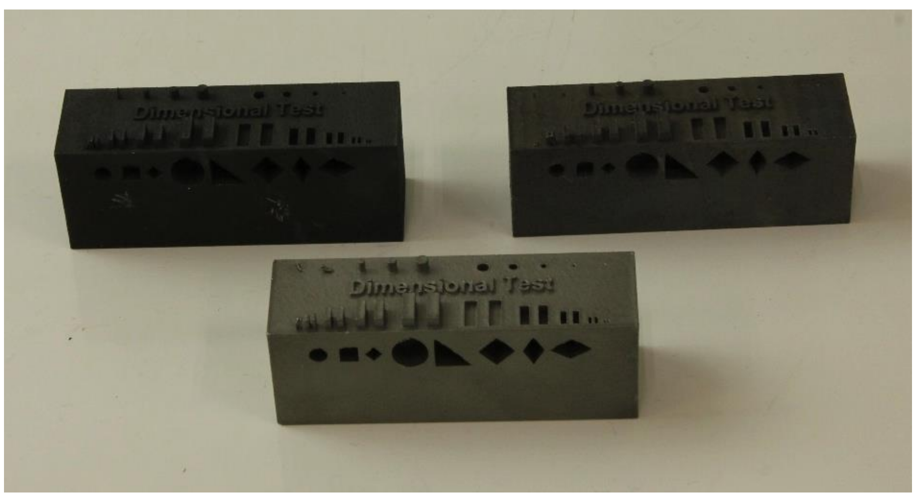
High Cycle Fatigue of SLM 718

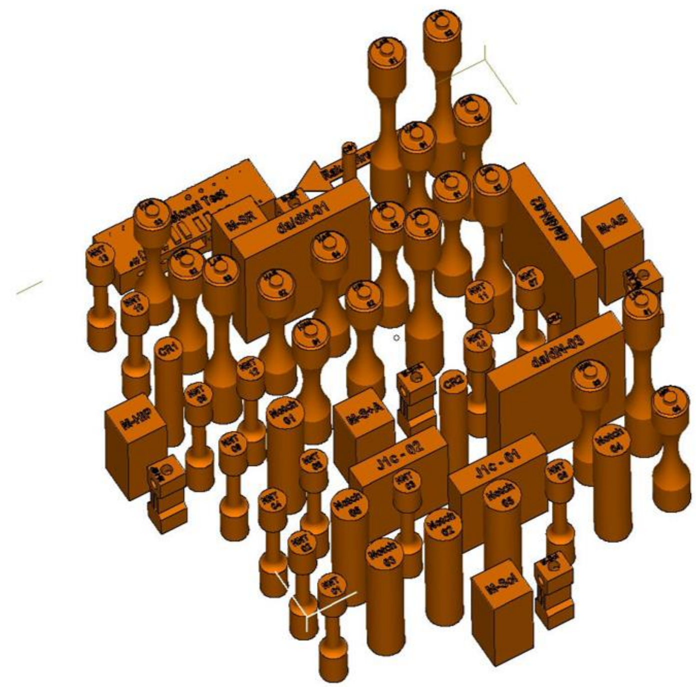


- Tests in LN_2 (-320°). Some increase in life for as-built surfaces; more increase for low stress ground.

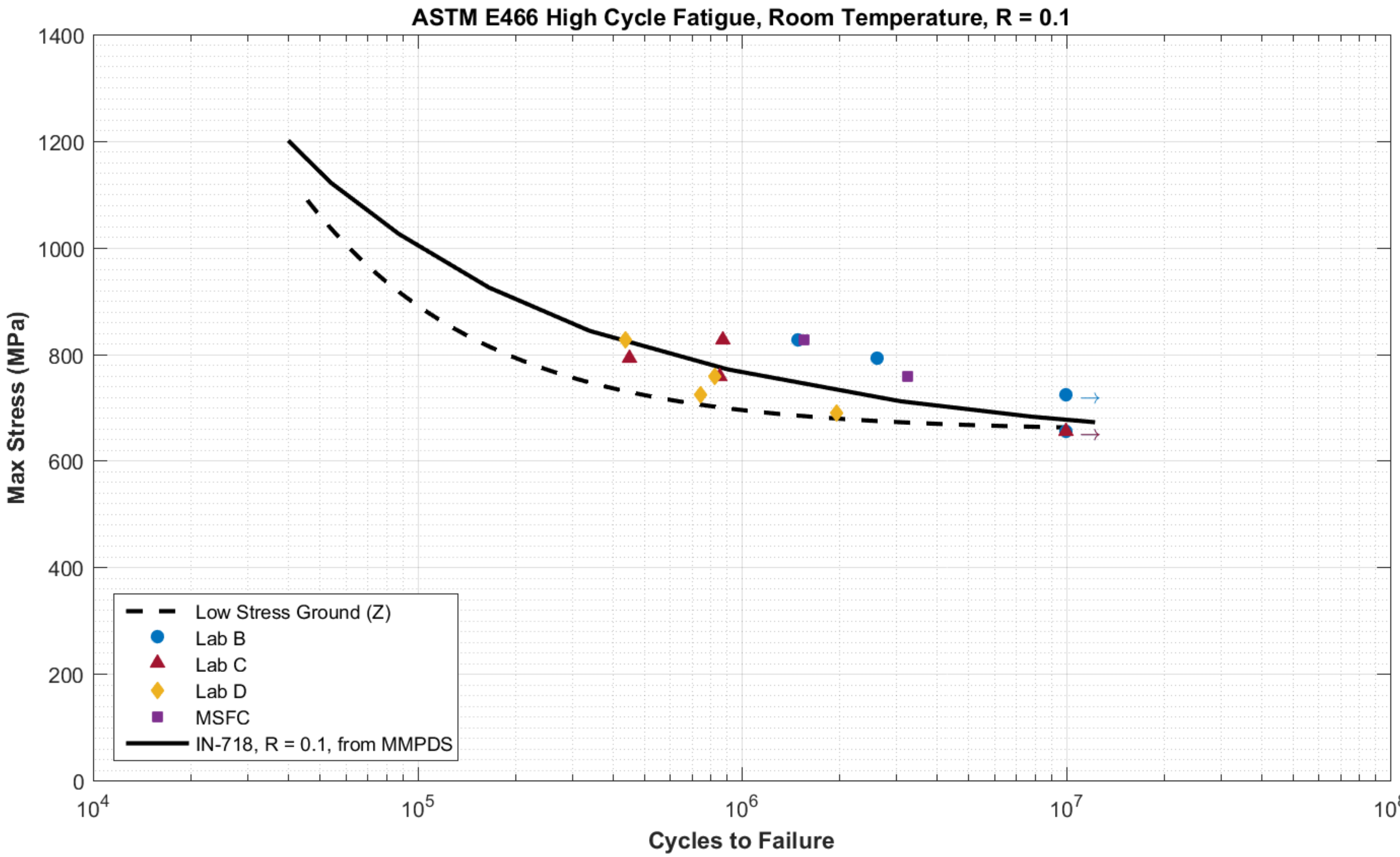
Vendor Round Robin

- Identical builds were procured from three third-party SLM vendors; one build was provided by MSFC.
- The specimens were heat treated per MSFC guidance, although allowances were made for vendors with existing mature processes.
- A series of comparison testing was done to evaluate the quality of the material.



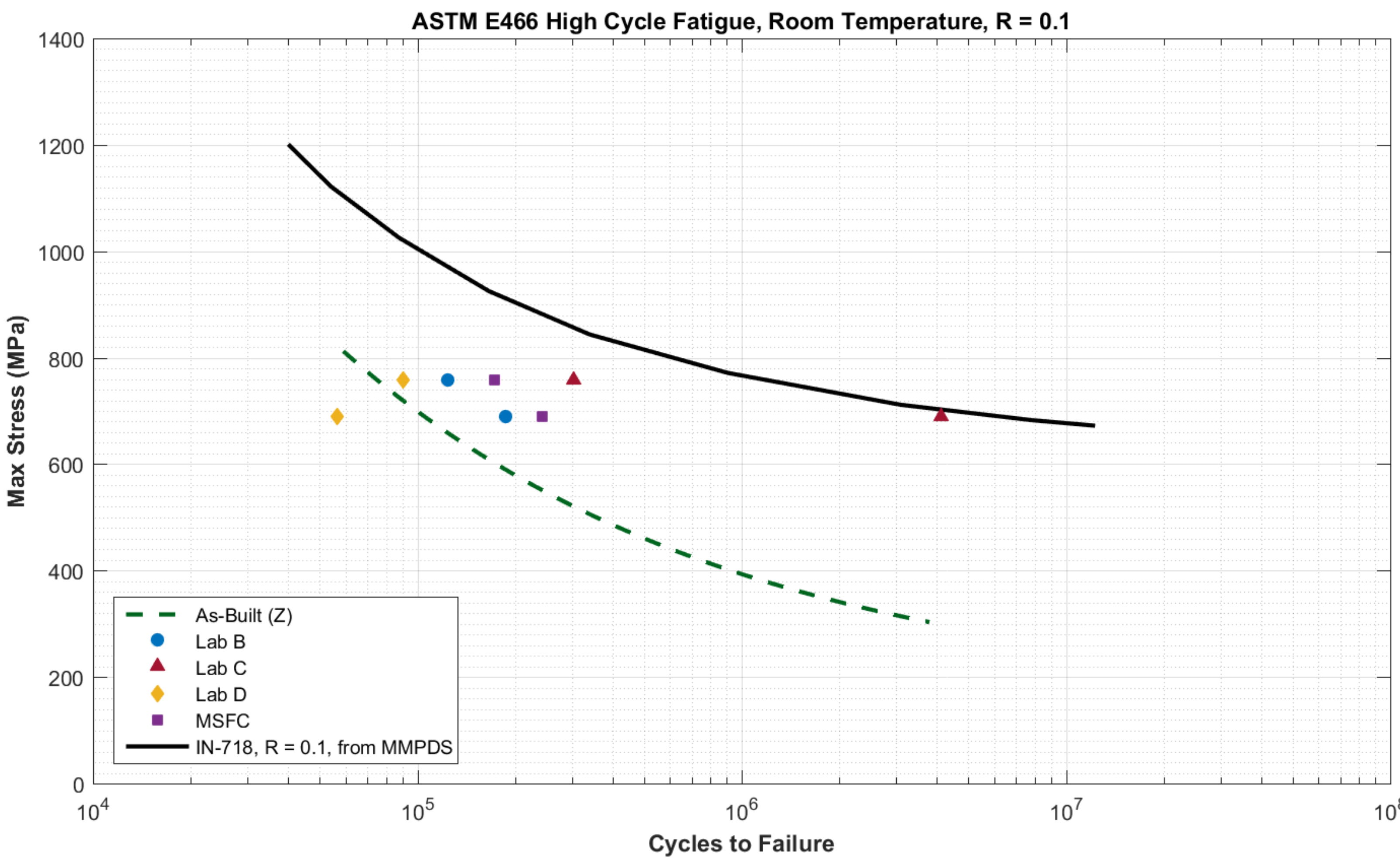


Round Robin Fatigue



- Z-oriented, low stress ground surface finish; compared to M1 and wrought reference curves

Round Robin Fatigue



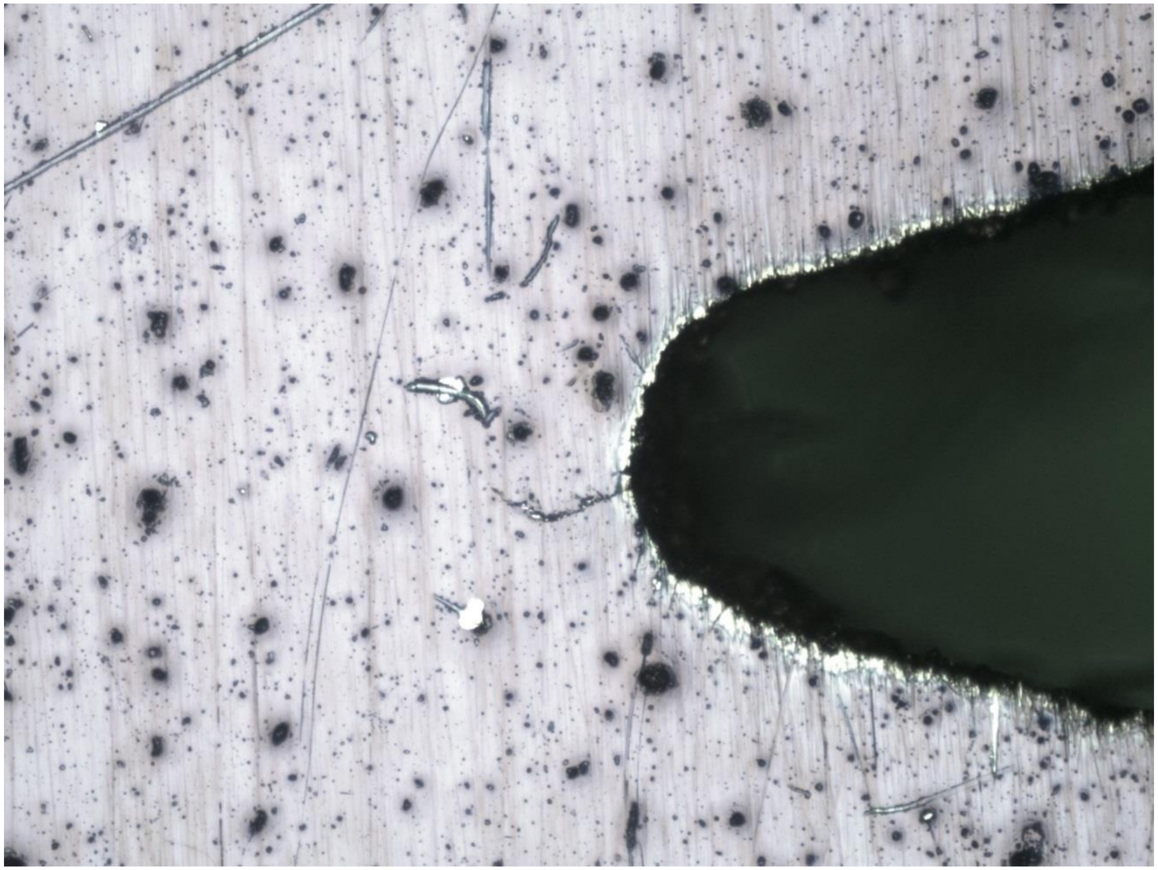
- Z-oriented, “as-provided” surface finish; compared to M1 and wrought reference curves

Fatigue Crack Growth Results

- Round Robin Results
  - 3 specimens from each build
  - Z-XY test orientation
  - Post-processing same as fatigue specimens
- Testing Methodology
  - Tested according to ASTM E647
    - “Standard Test Method for Measurement of Fatigue Crack Growth Rates”
  - R = 0.1 and R = 0.7 data shown
  - Compression pre-cracking procedure (CPC)

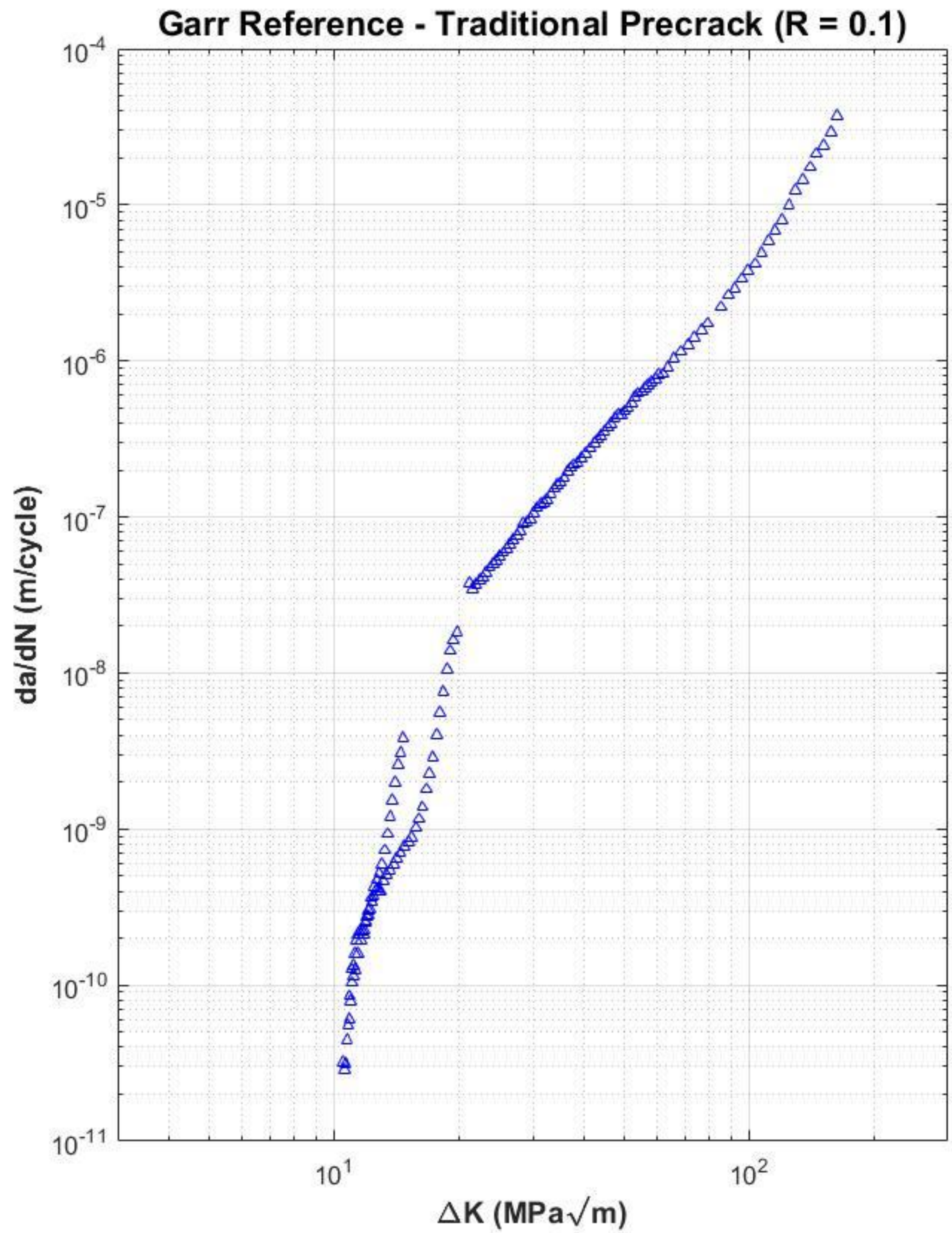
Compression Pre-Cracking

- Compression-compression loading used to generate a crack at the notch root of a c(T) specimen.
- May produce more conservative threshold and near-threshold crack growth rates.
- Following CPC procedure detailed by Newman and Yamada.



Fatigue Crack Growth

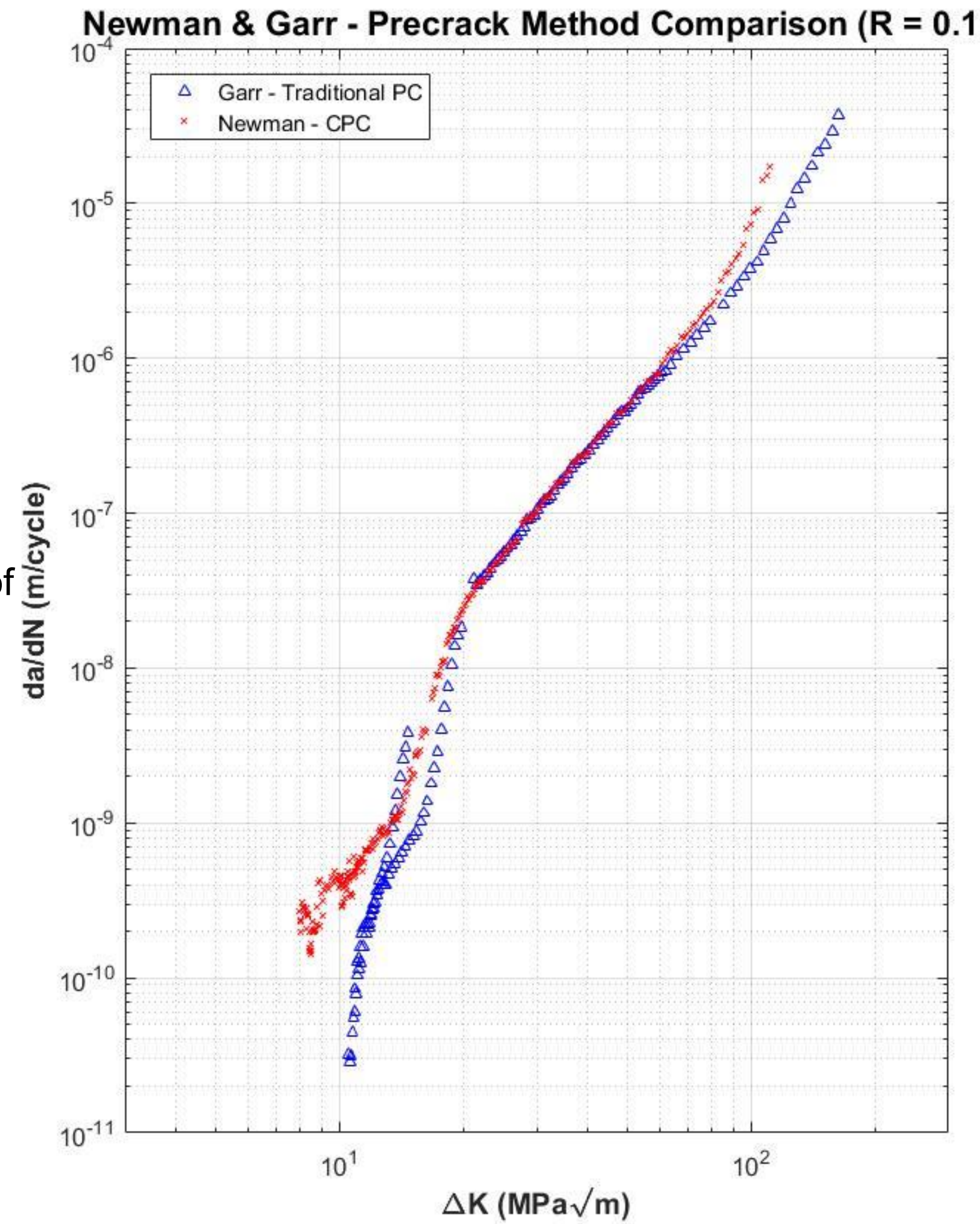
- Wrought Inconel-718 alloy obtained from Boeing-Rockwell. Tested using the ASTM LR test method and CA loading.
- Garr KR, Boeing-Rocketdyne Propulsion and Power Company, private communication; 2004.



Fatigue Crack Growth

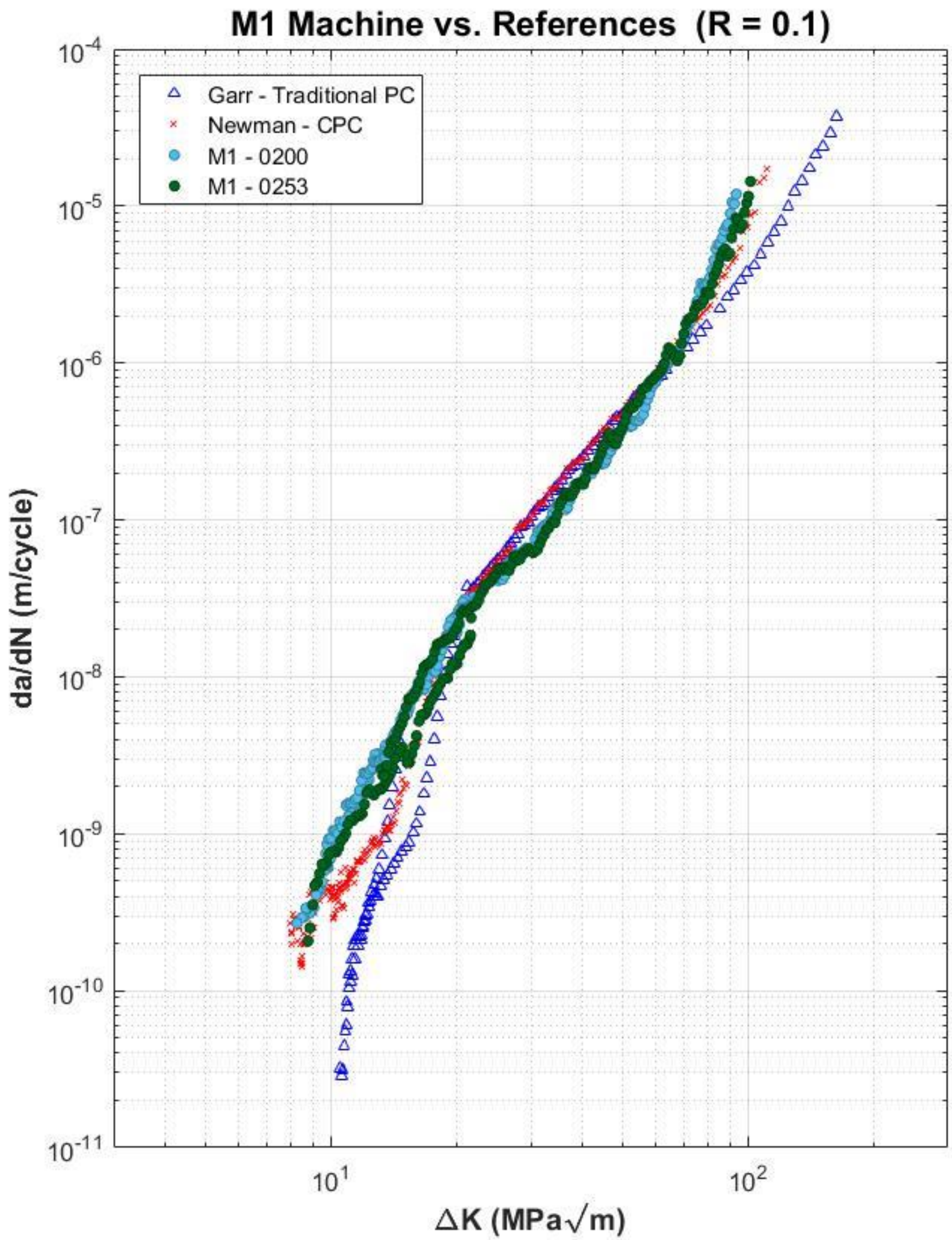
- Wrought Inconel-718 alloy obtained from Boeing-Rockwell. Tested using the CPLR test method and CA loading.

- Newman, J.C., Jr. and Yamada, Y., “Compression Precracking Methods to Generate Near-Threshold Fatigue-Crack-Growth-Rate Data”, International Journal of Fatigue, Vol. 32, 2010, p.879-885.



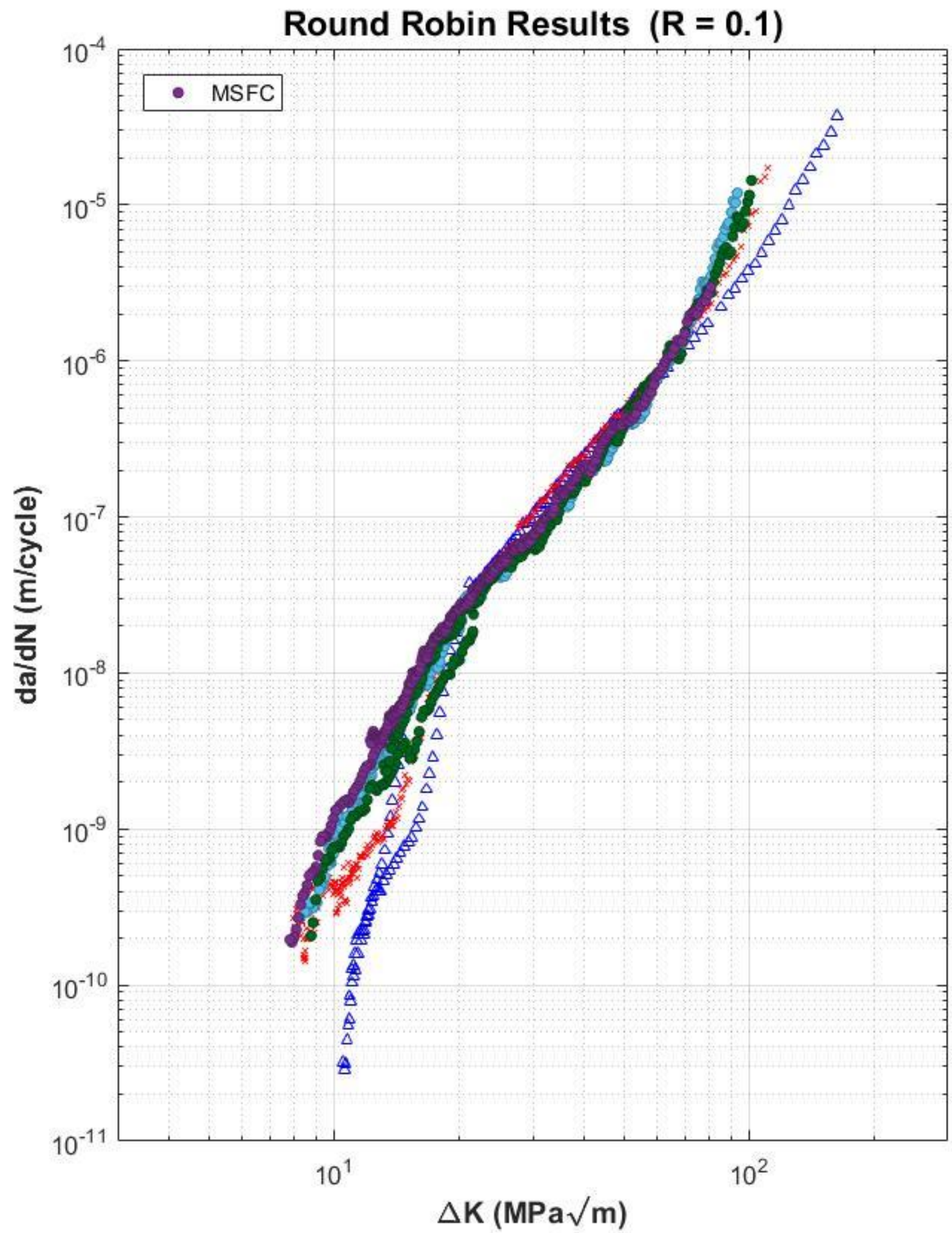
Fatigue Crack Growth

- SLM 718 M1 Machine included as a reference. This data is not part of the Round-Robin.
- Produced using ASTM LR and CA loading.



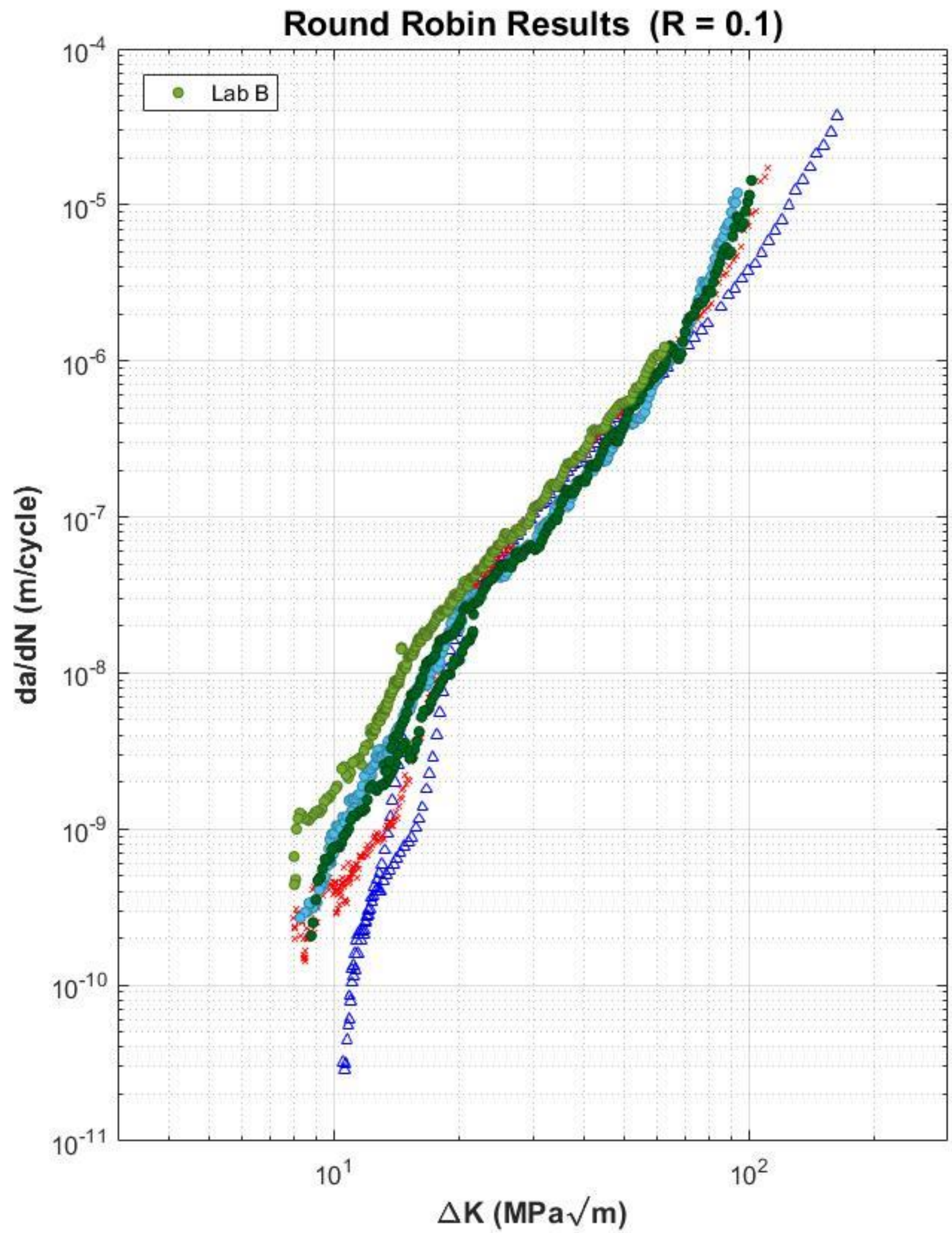
Fatigue Crack Growth

- MSFC Round-Robin data. Consistent with M1 data.



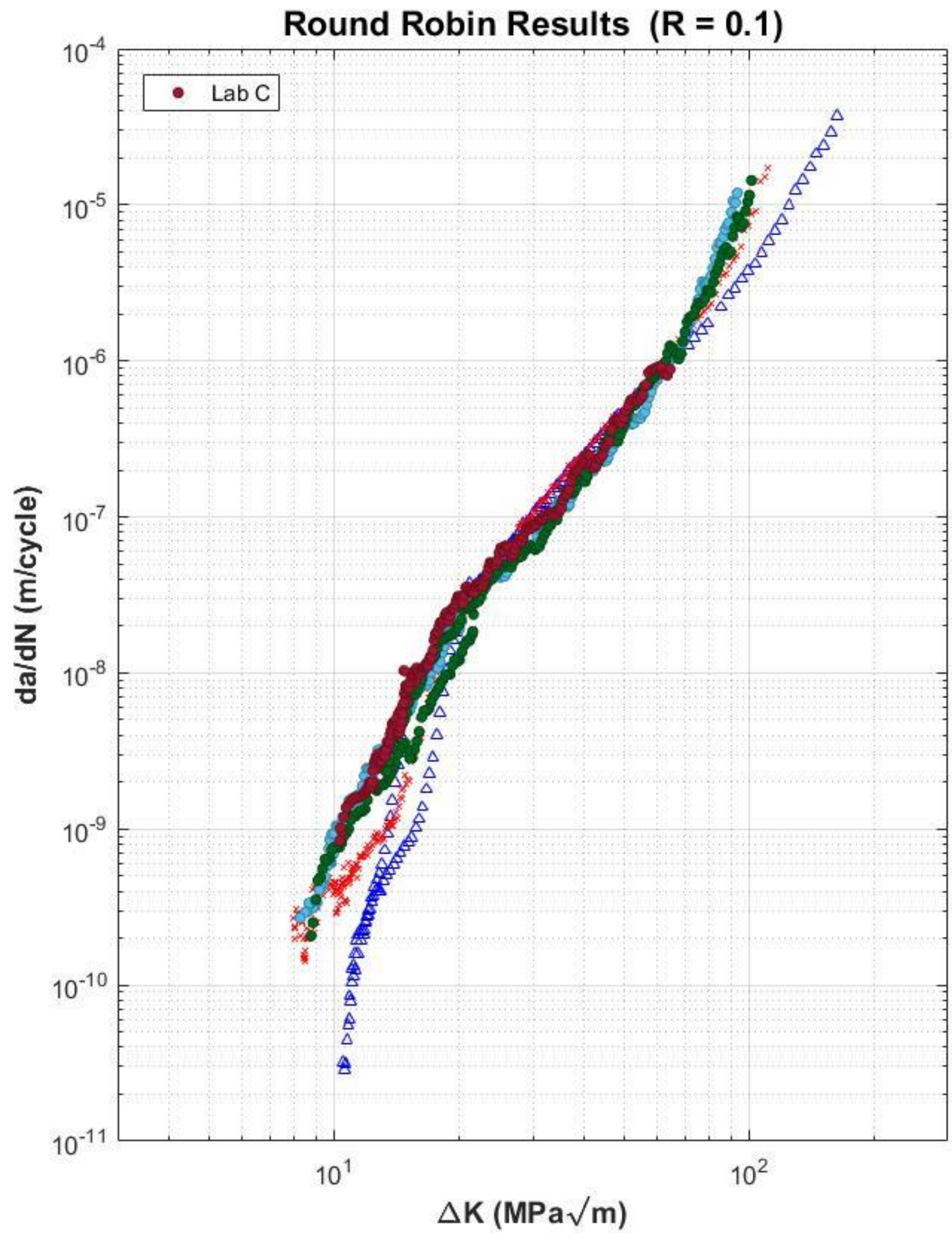
Fatigue Crack Growth

- Lab B - Higher observed growth rates than M1 data.



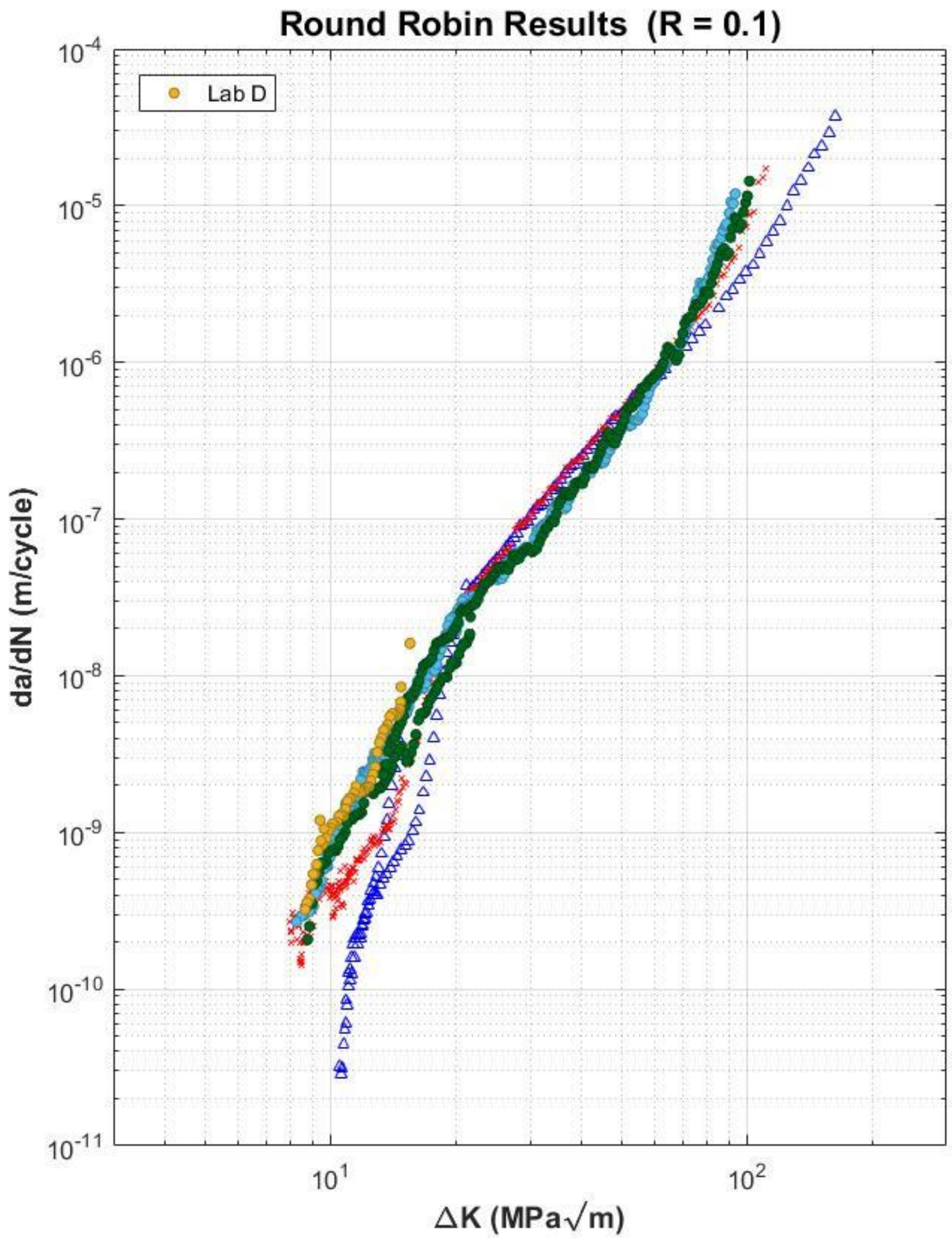
Fatigue Crack Growth

- Lab C - Consistent with M1 data.



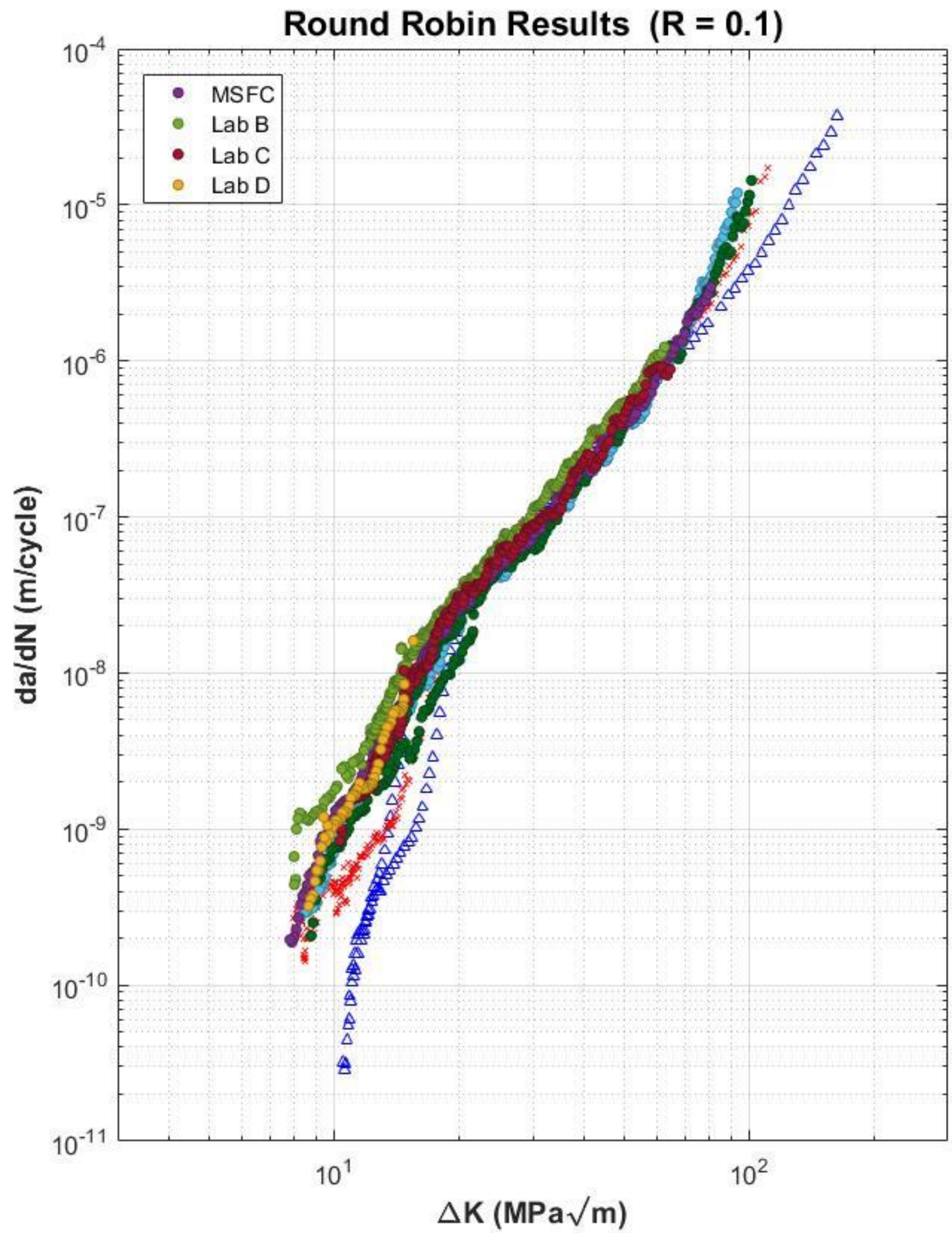
Fatigue Crack Growth

- Lab D - Consistent with M1 data. CPLR only.



Fatigue Crack Growth

- Only Lab B had any distinction from the M1 data.



Fatigue Crack Growth

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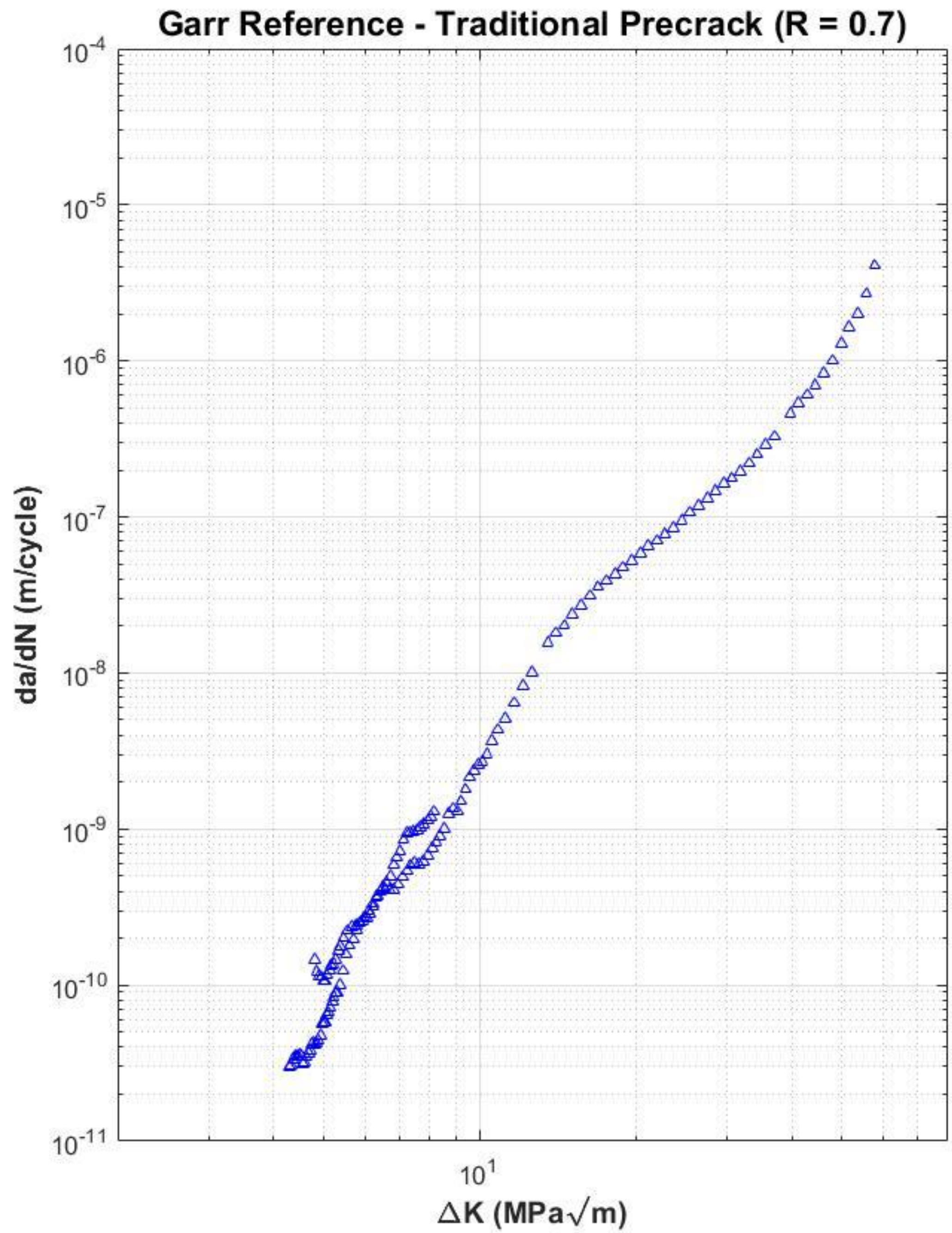

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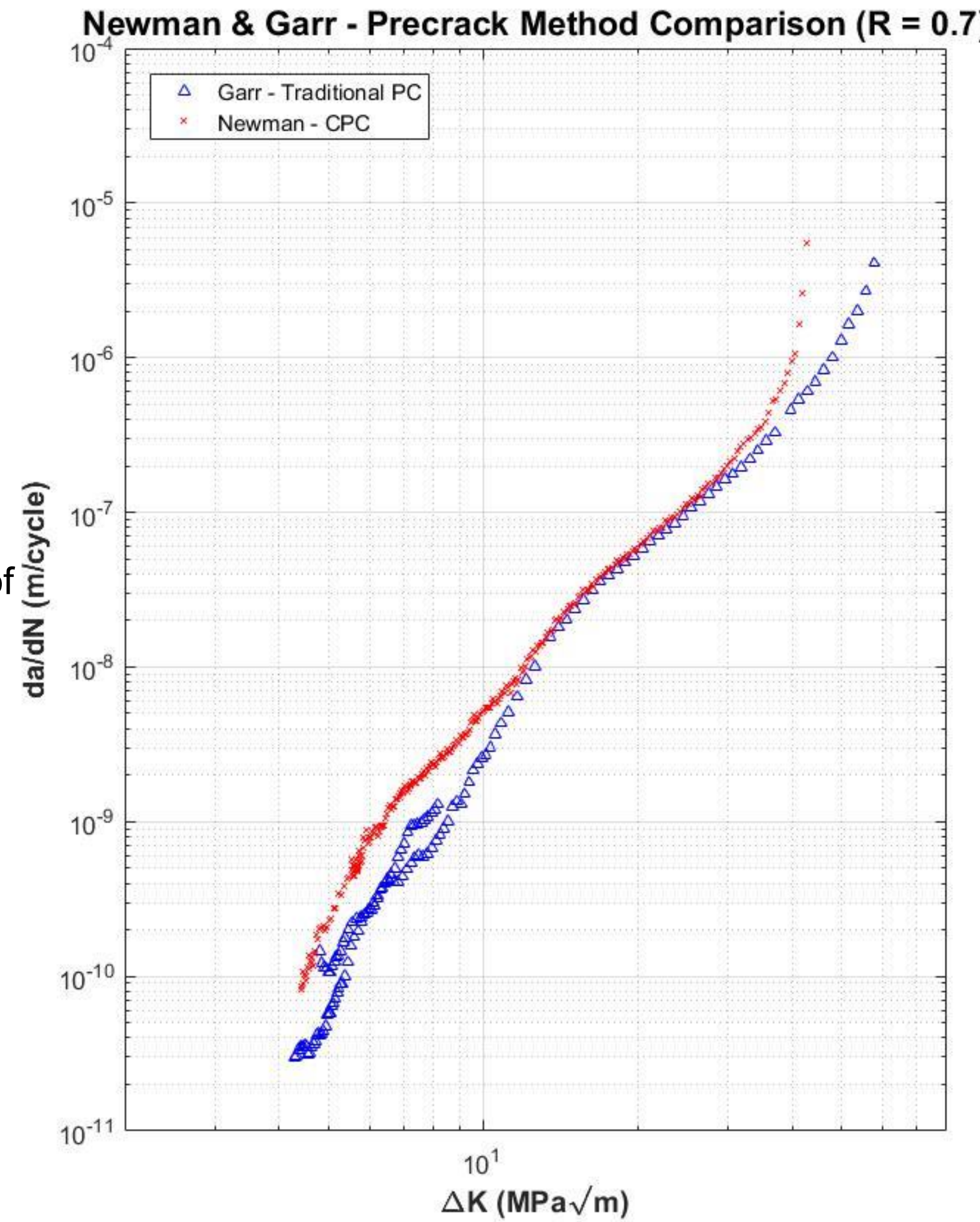
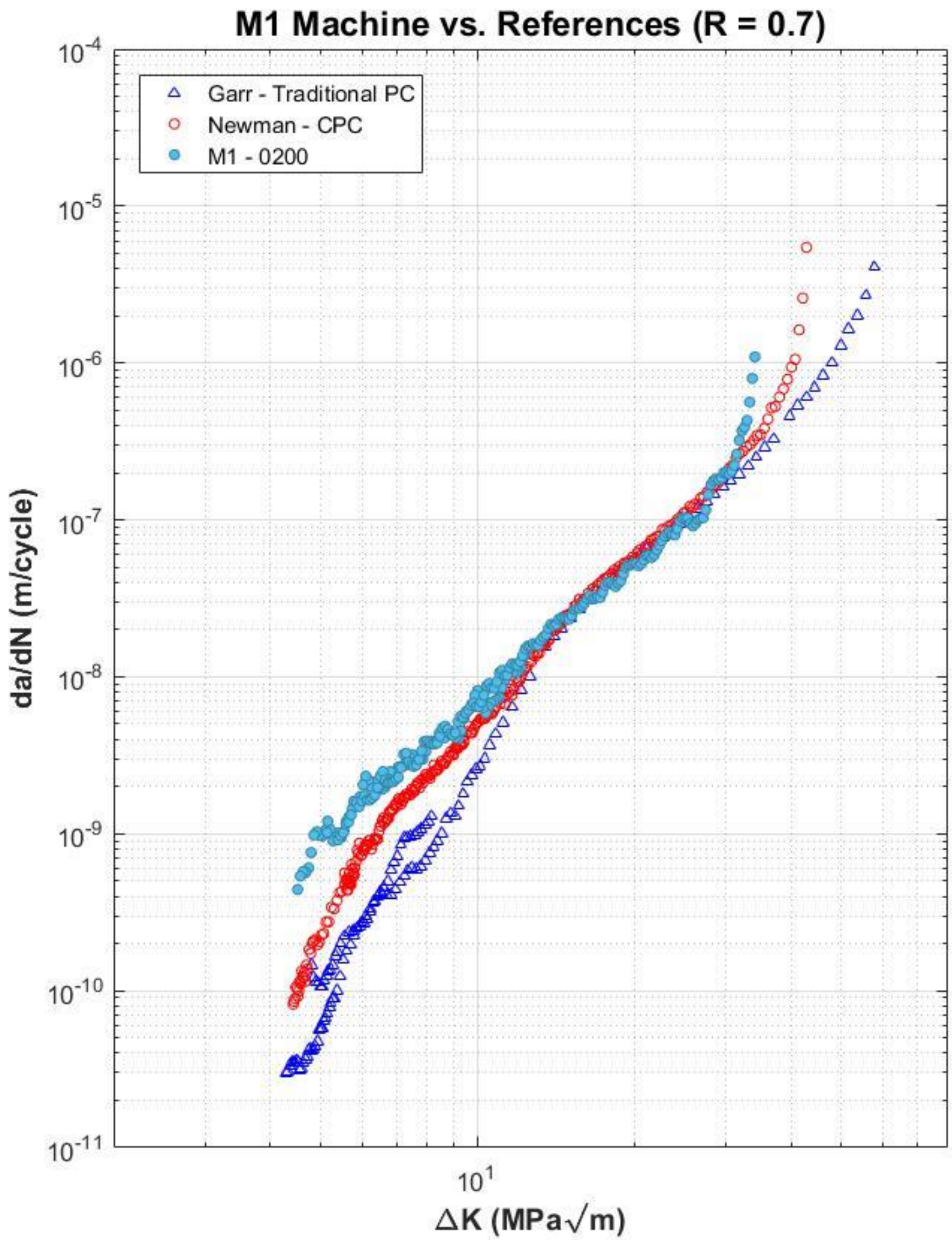


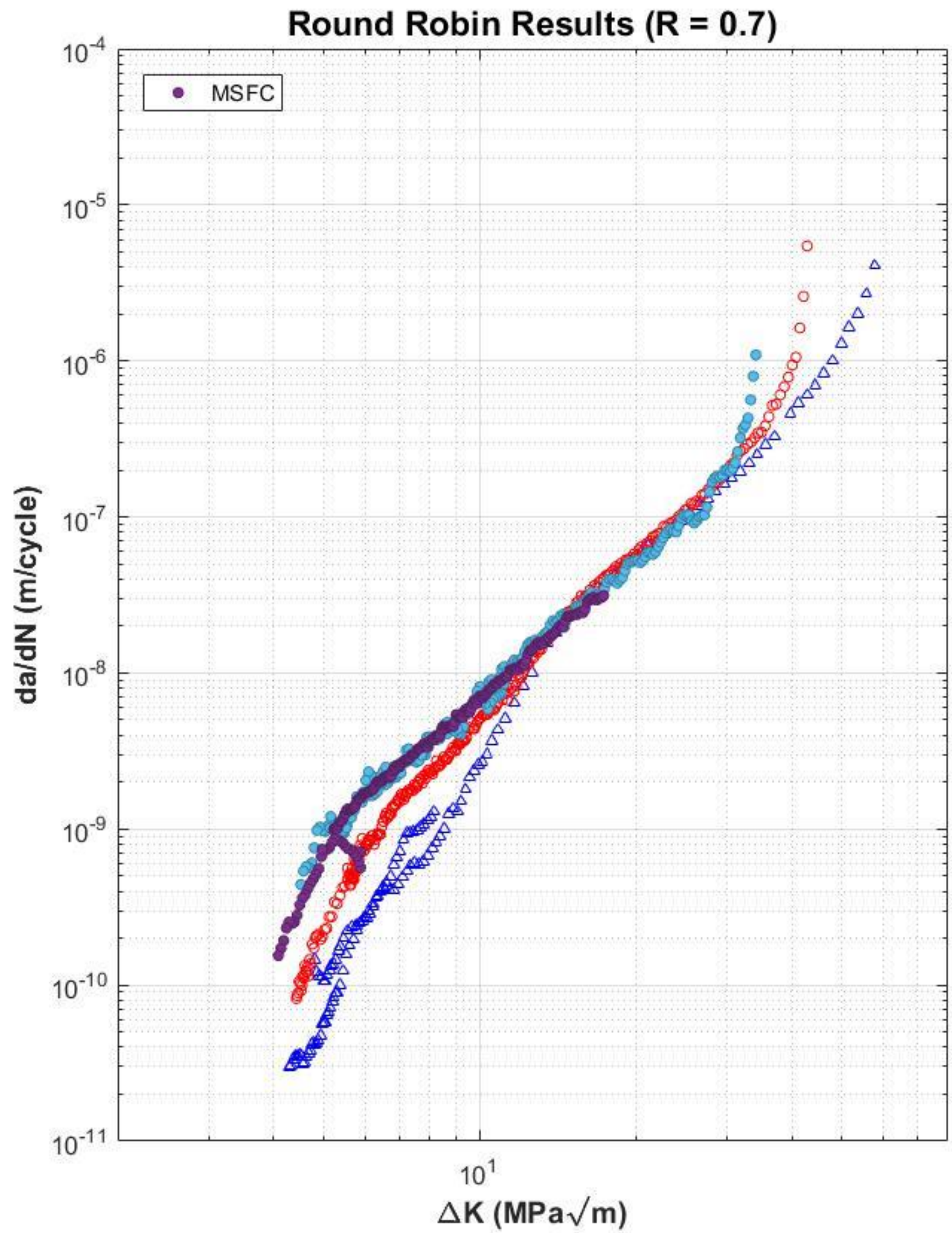
Fatigue Crack Growth

- Higher observed growth rates compared to wrought 718 near-threshold.



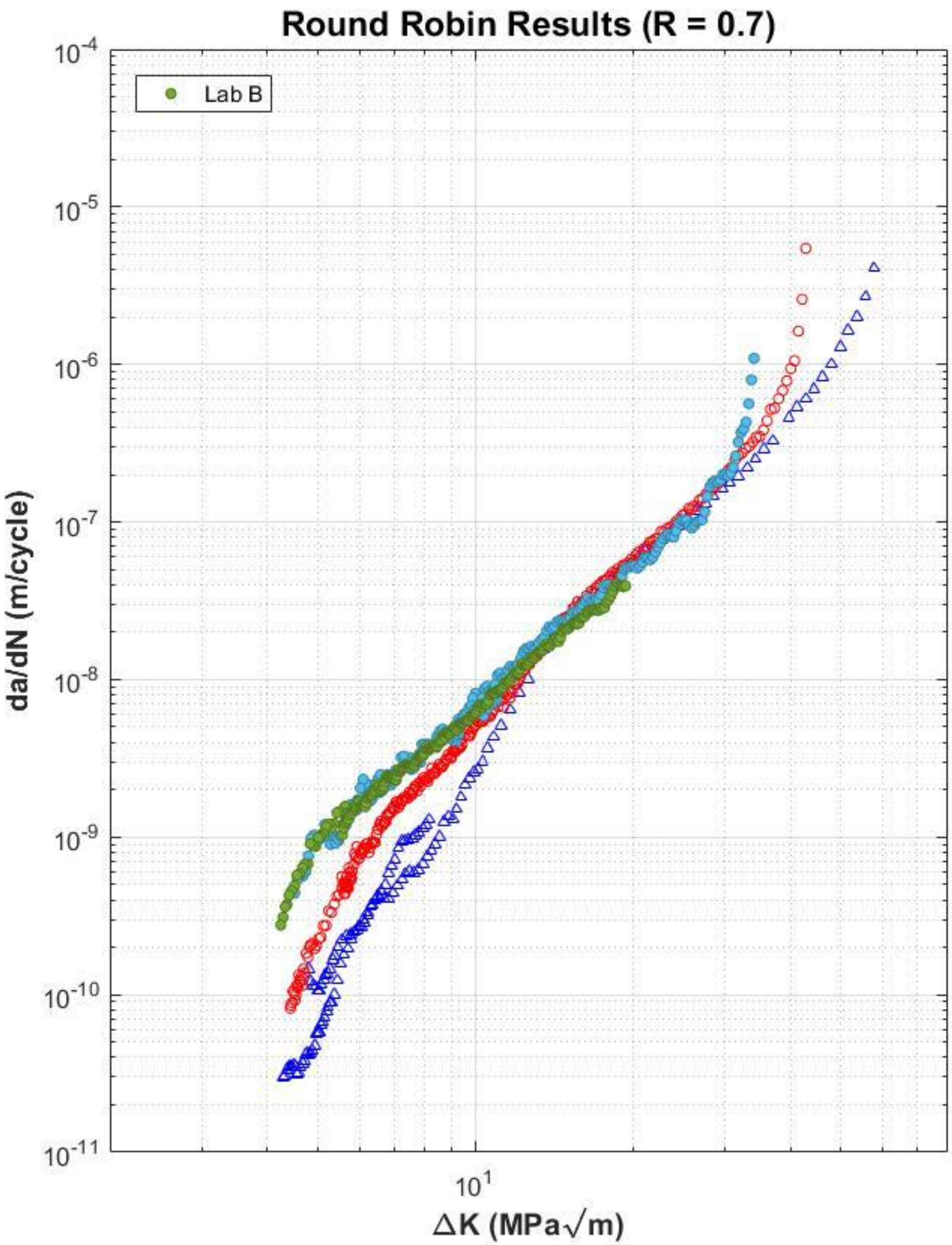
Fatigue Crack Growth

- MSFC - Consistent with M1 data.



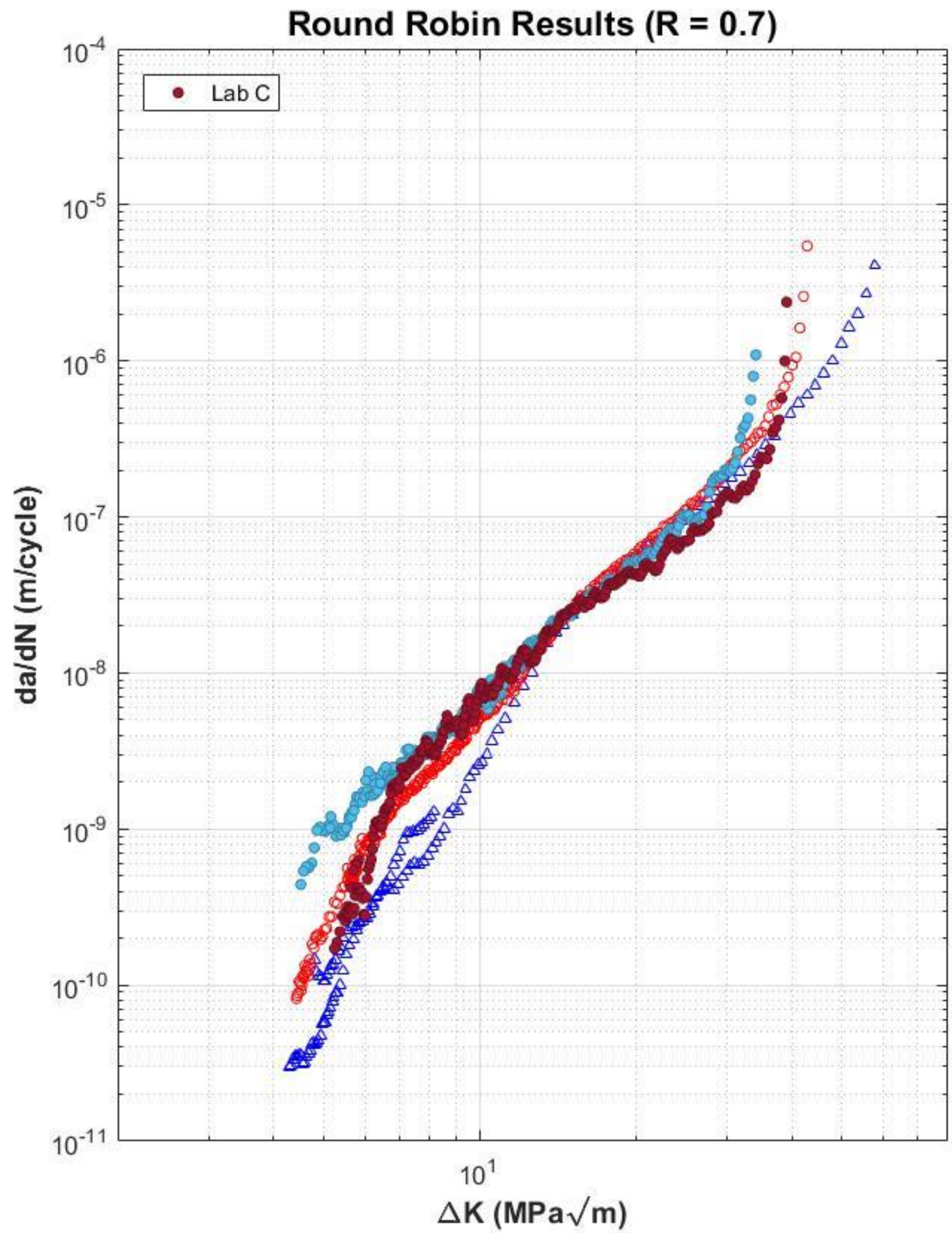
Fatigue Crack Growth

- Lab B - Consistent with M1 data.



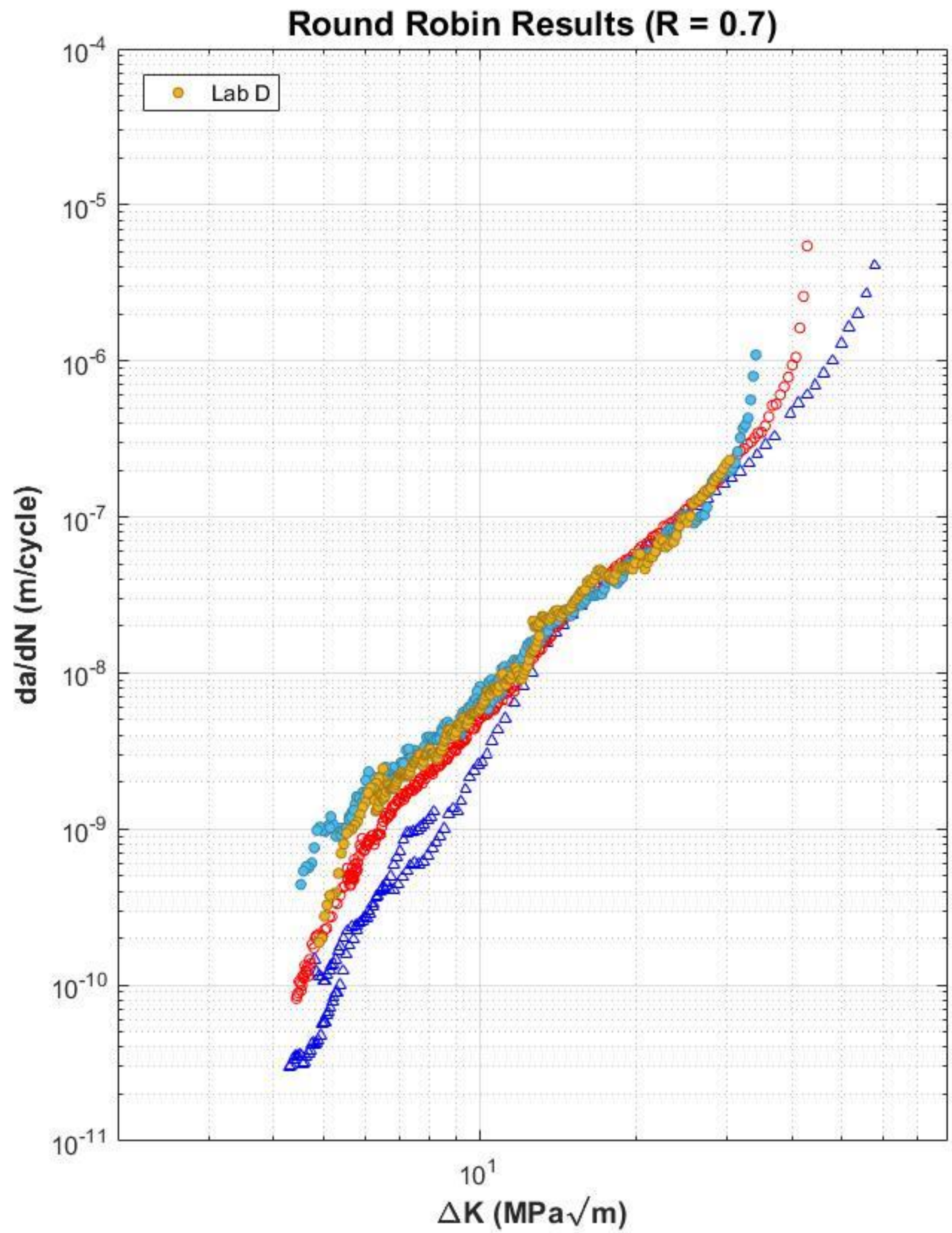
Fatigue Crack Growth

- Lab C - Lower crack growth rates near-threshold compared to M1 data. More closely follows Newman data.



Fatigue Crack Growth

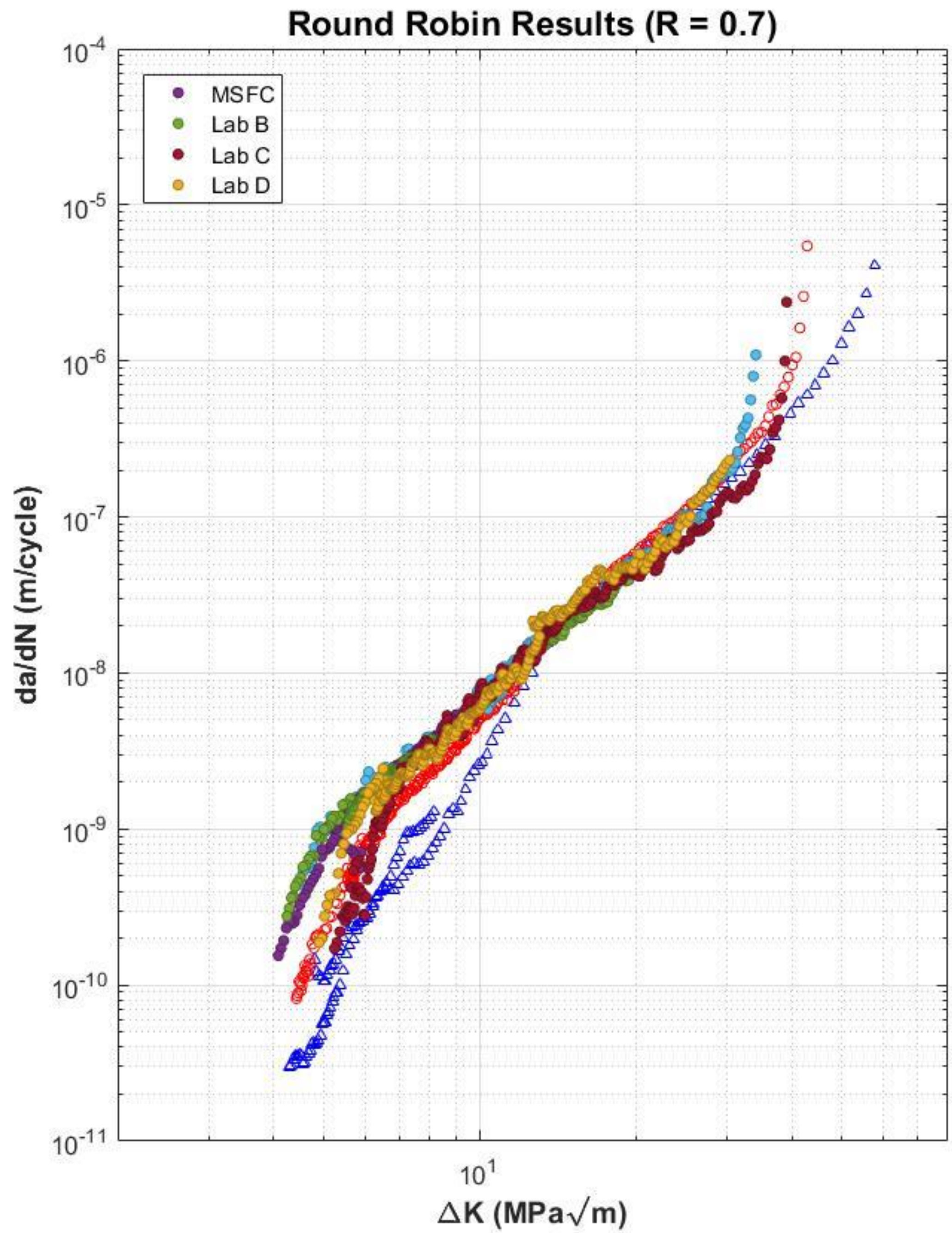
- Lab D - Lower crack growth rates near-threshold compared to M1 data. More closely follows Newman data.



Fatigue Crack Growth

- MSFC & Lab B: Consistent with M1 data

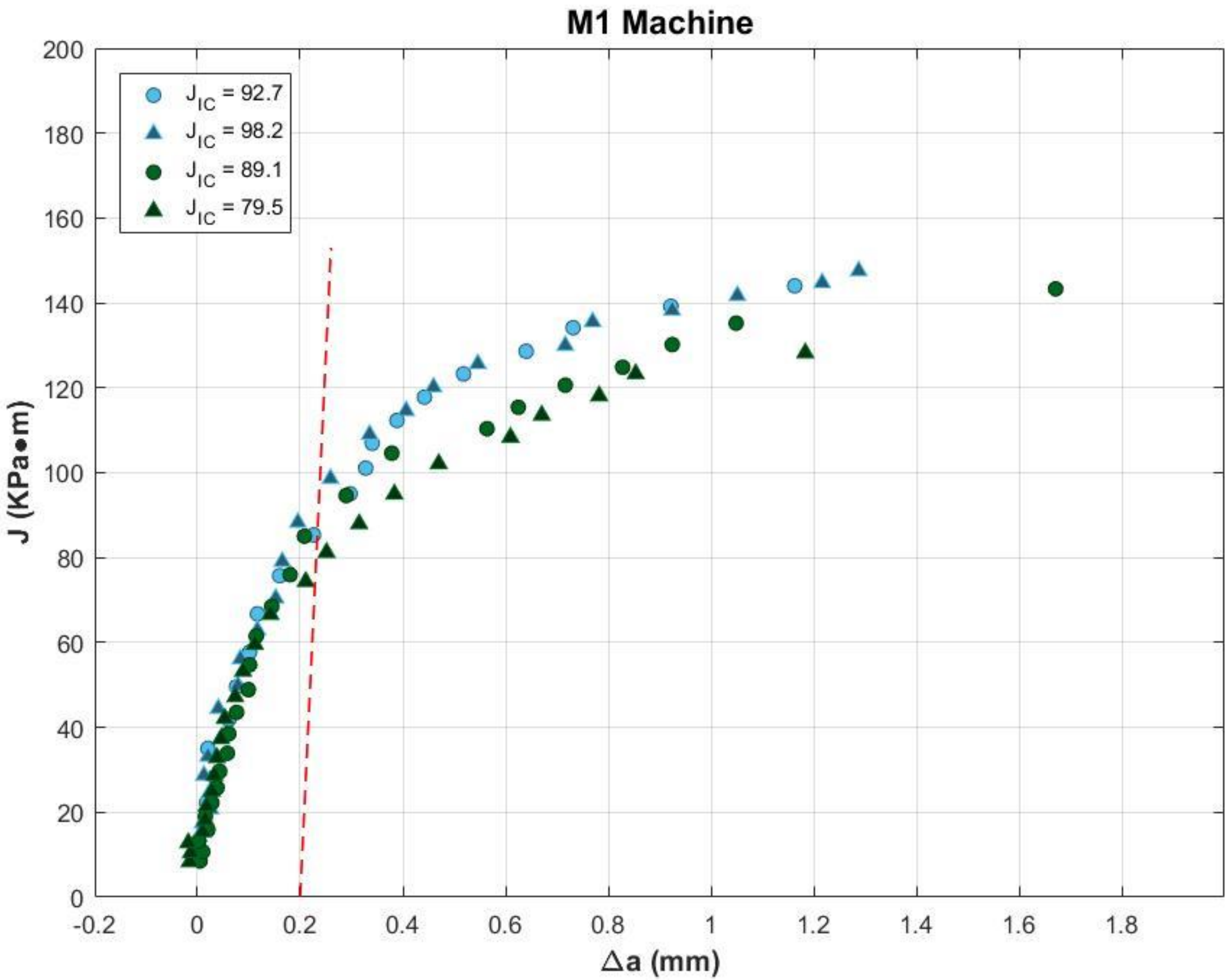
- Lab C & Lab D: Consistent with Newman data



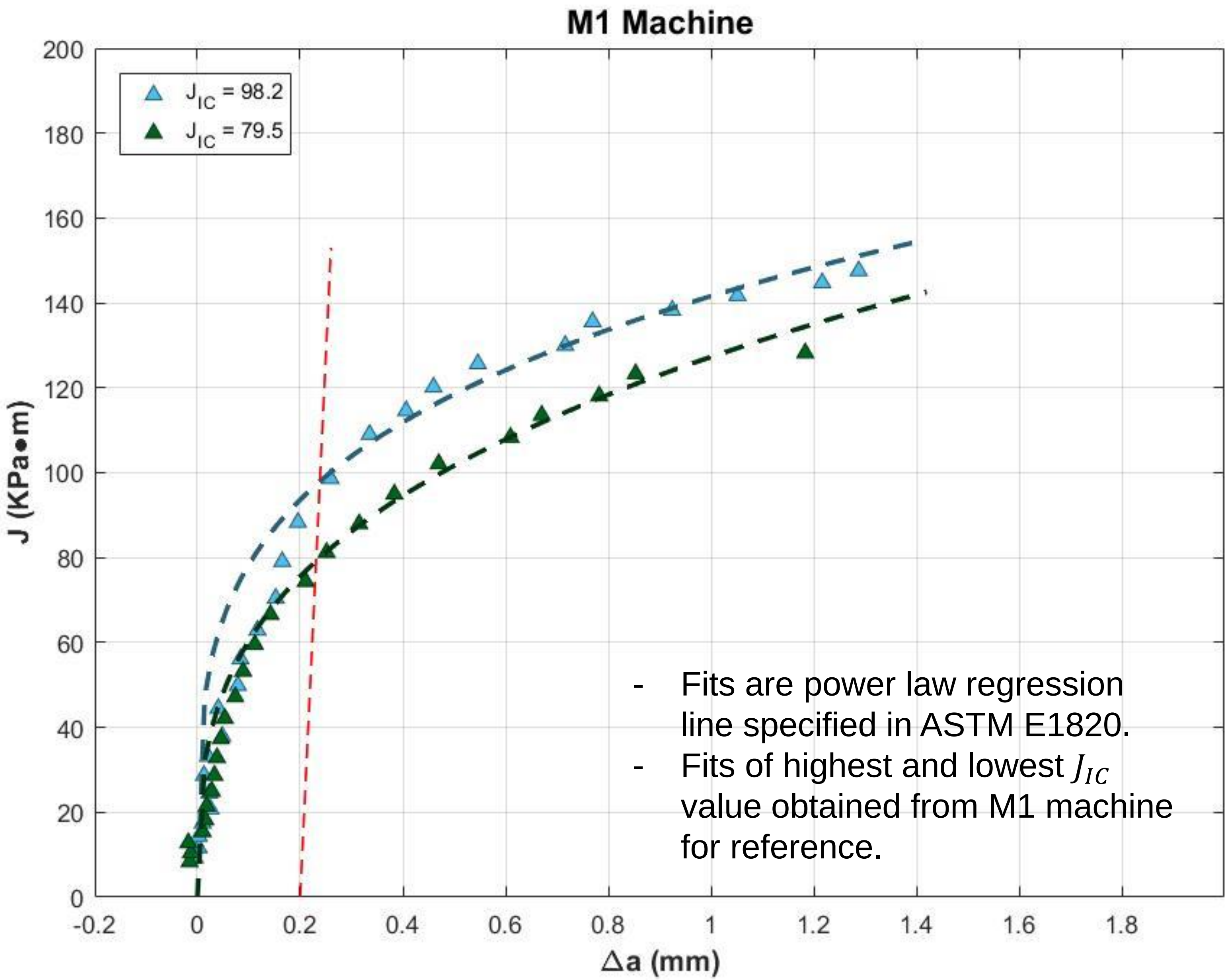
Fracture Toughness Results

- Round Robin
- SLM 718
  - Stress relief, HIP, ASM 5664 Heat Treatment
- ASTM E1820
  - J-R vs Δa
  - Legend lists J_{IC} value obtained from ASTM E1820

Fracture Toughness Results

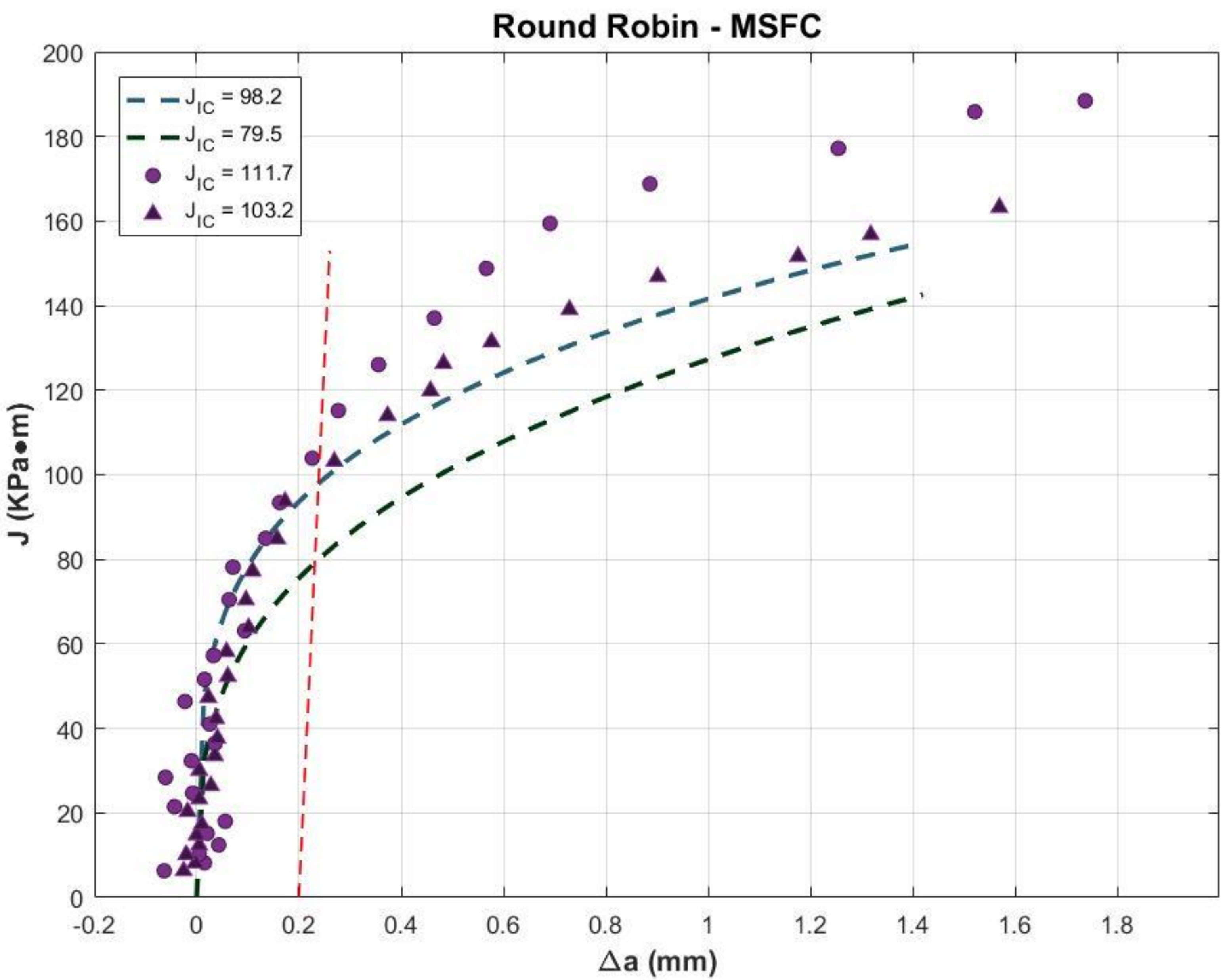


Fracture Toughness Results

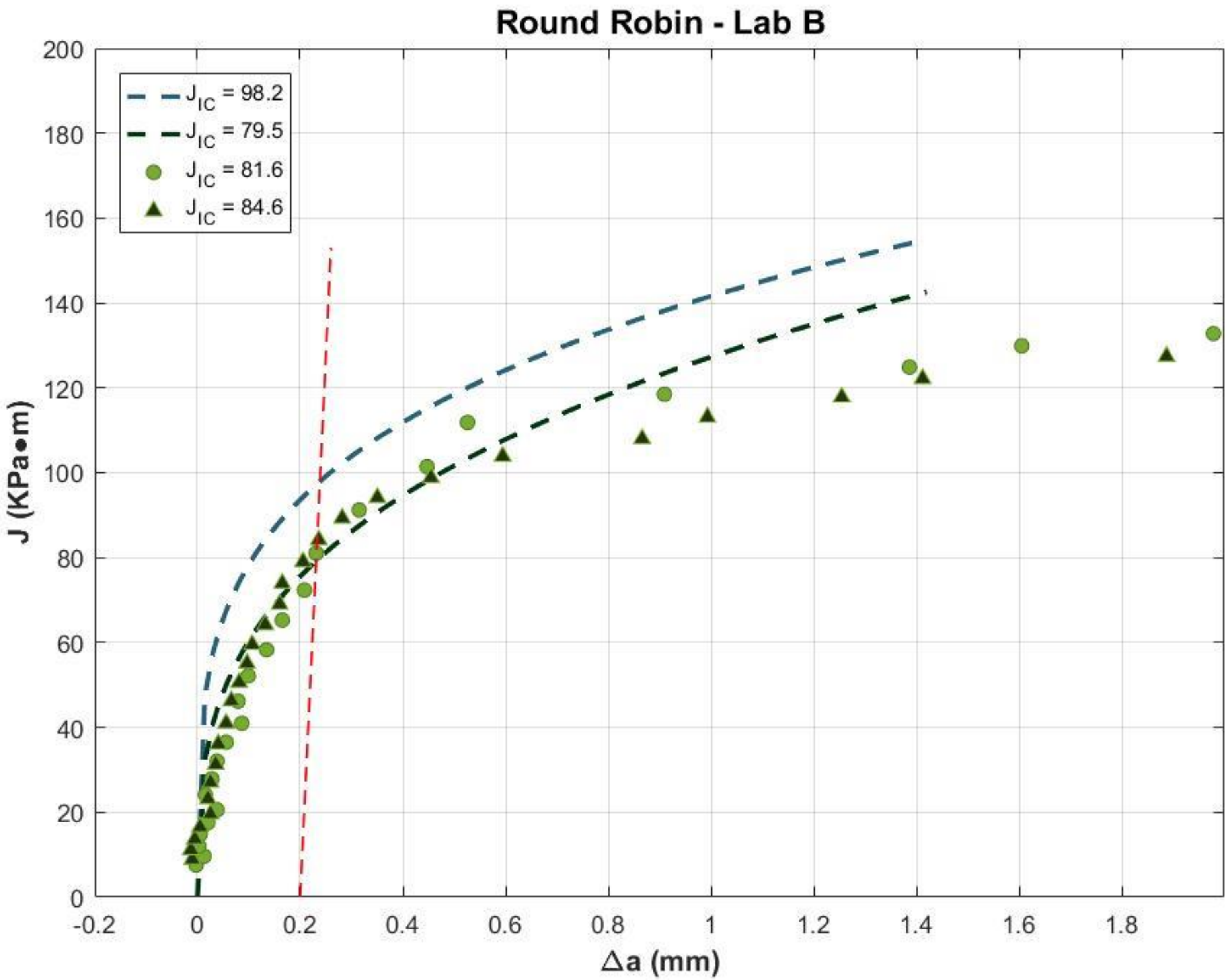


- Fits are power law regression line specified in ASTM E1820.
- Fits of highest and lowest J_{IC} value obtained from M1 machine for reference.

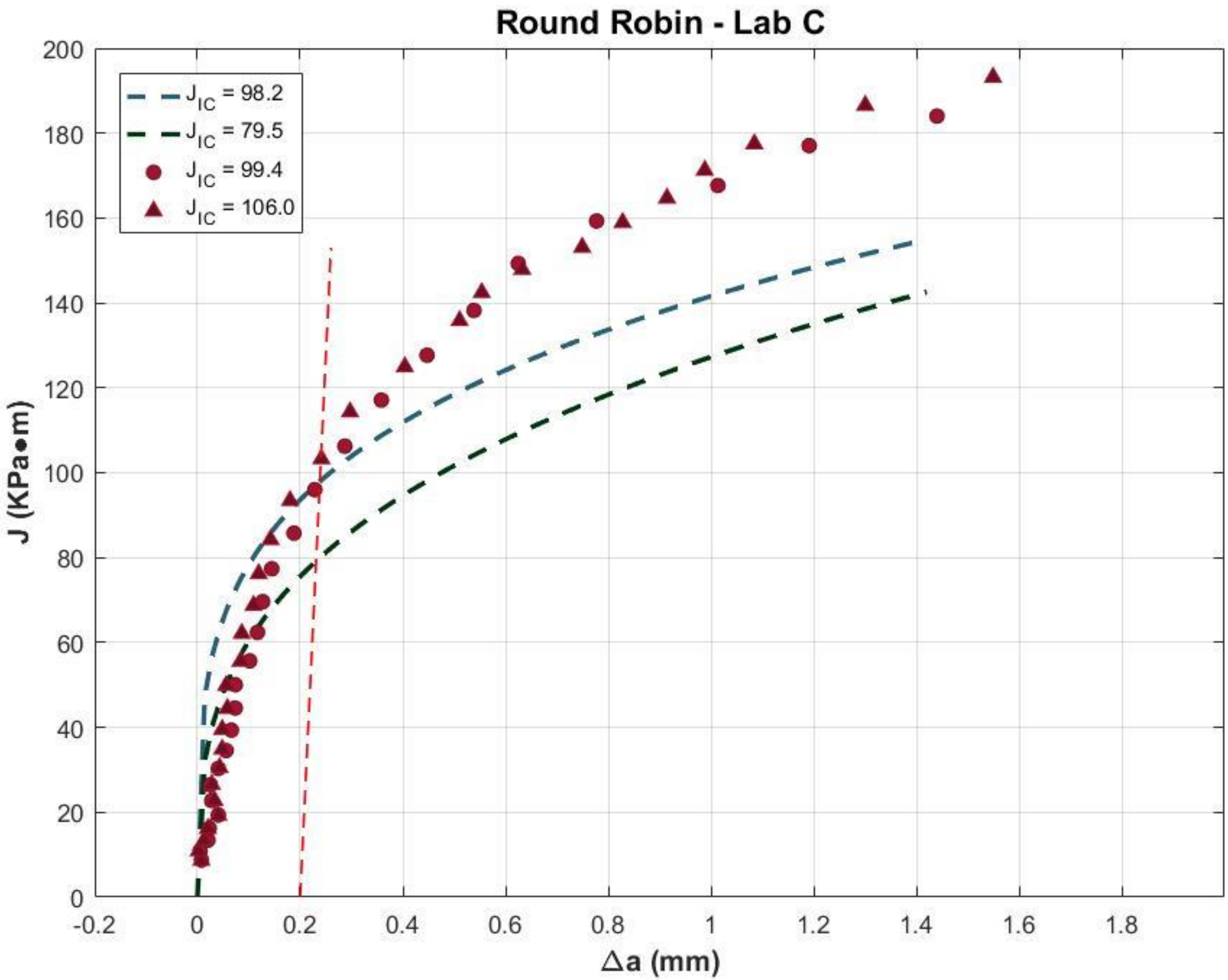
Fracture Toughness Results



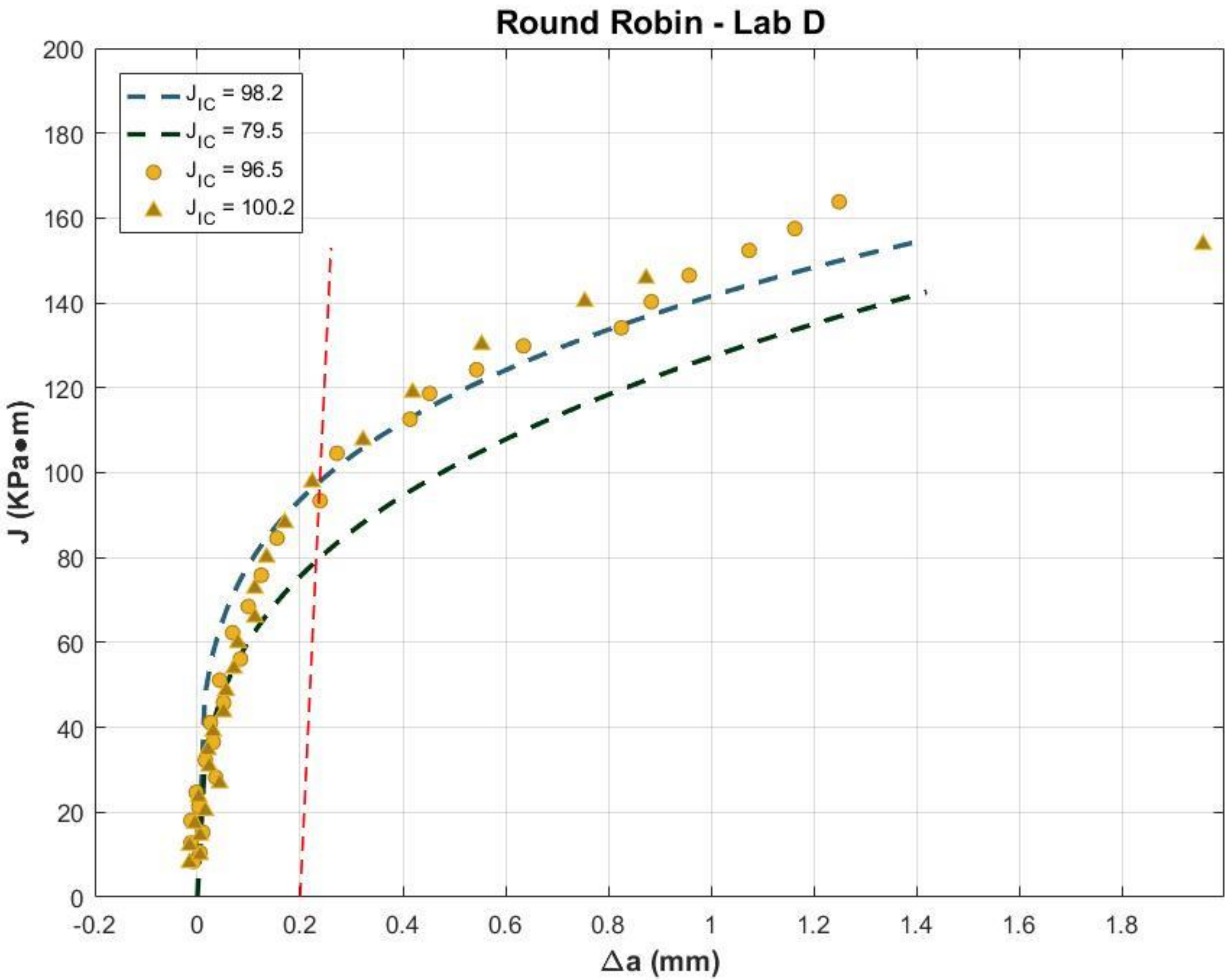
Fracture Toughness Results



Fracture Toughness Results



Fracture Toughness Results



Fracture Toughness Results