Overview of Fatigue and Damage Tolerance Performance of SLM Alloy 718

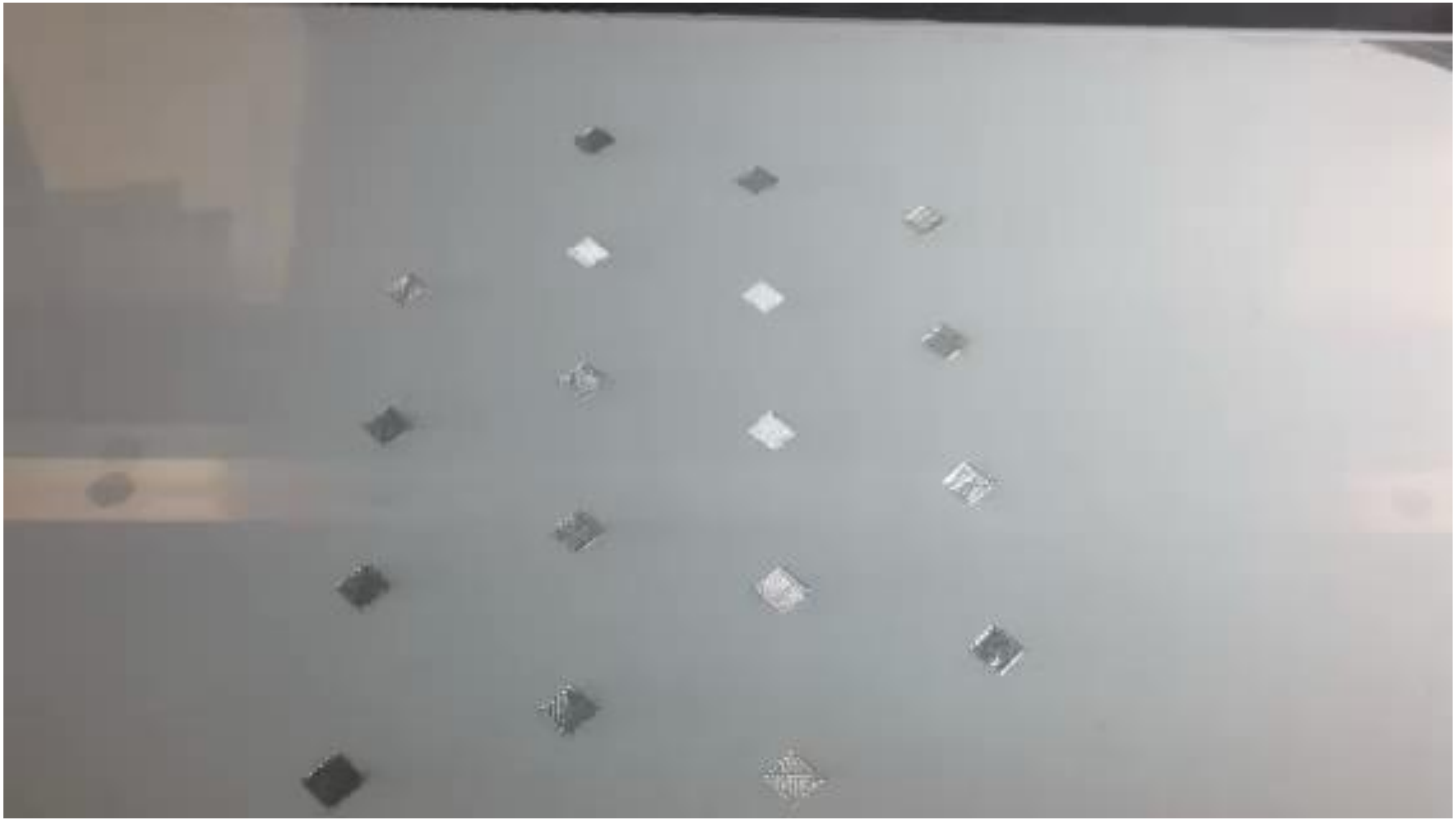
Kristin Morgan
MSFC Science and Technology Office
kristin.l.morgan@nasa.gov
256-544-1025

Douglas Wells
MSFC Damage Tolerance Branch
douglas.n.wells@nasa.gov
256-544-3300

2016 National Space and Missile Materials Symposium

21 June 2016

The SLM Process



MSFC SLM Capability

M1

Procured 2015

Build envelope
250 x 250 x 250 mm

Laser system
Fiber laser 400 W

No glovebox

M2

Procured 2012

Build envelope
250 x 250 x 280 mm

Laser system
Fiber laser 400 W

Inert atmosphere glovebox

XLine 1000R

Procured 2015

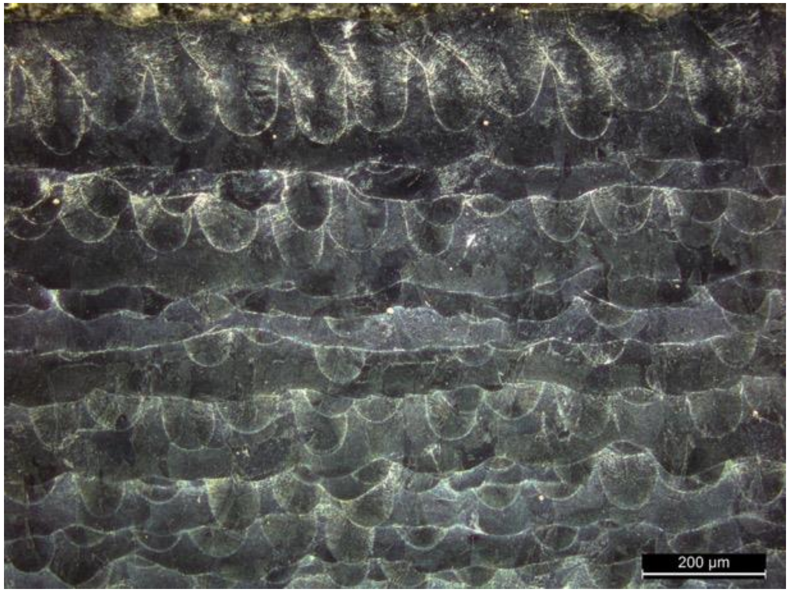
Build envelope:
630 x 400 x 500 mm

Laser system:
Fiber laser 1 kW

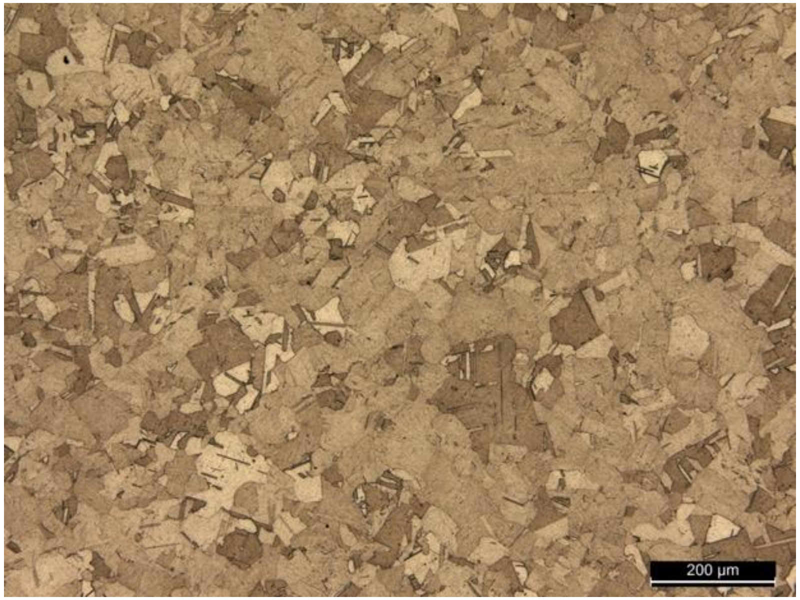
Inert atmosphere glovebox

Stable Alloy 718 Metallurgical Process

As-built microstructure



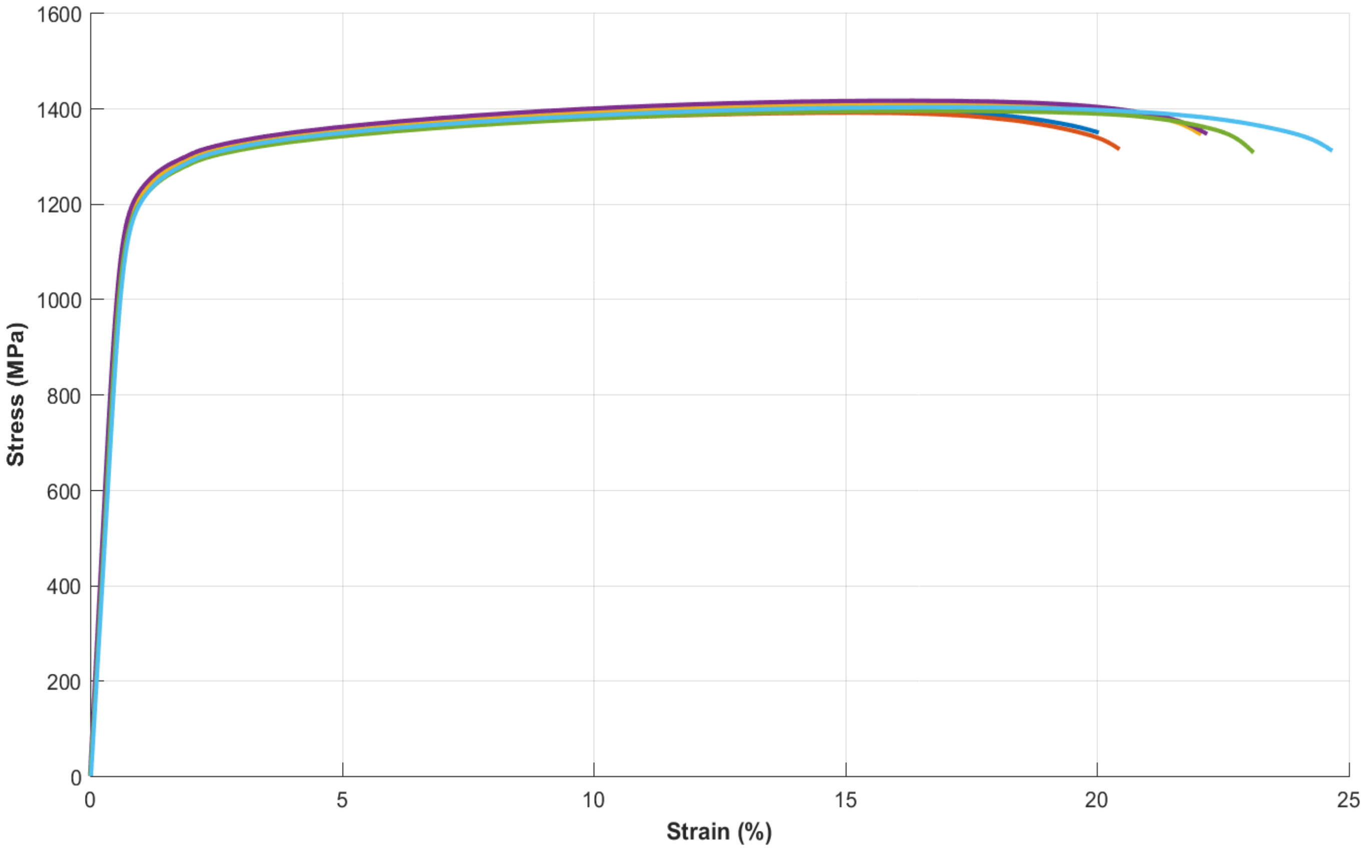
Heat treated microstructure



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

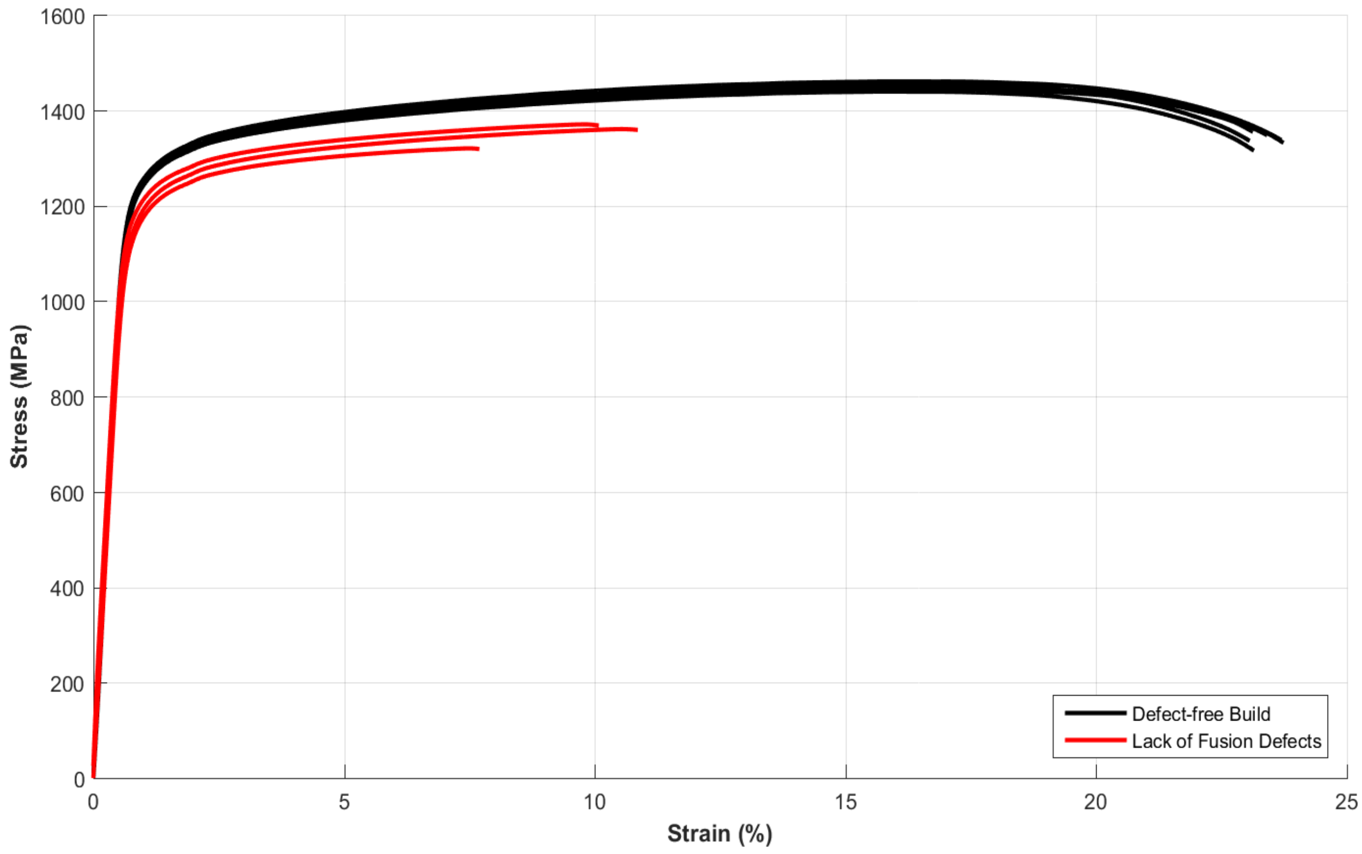
SLM Alloy 718 Typical Build Properties

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

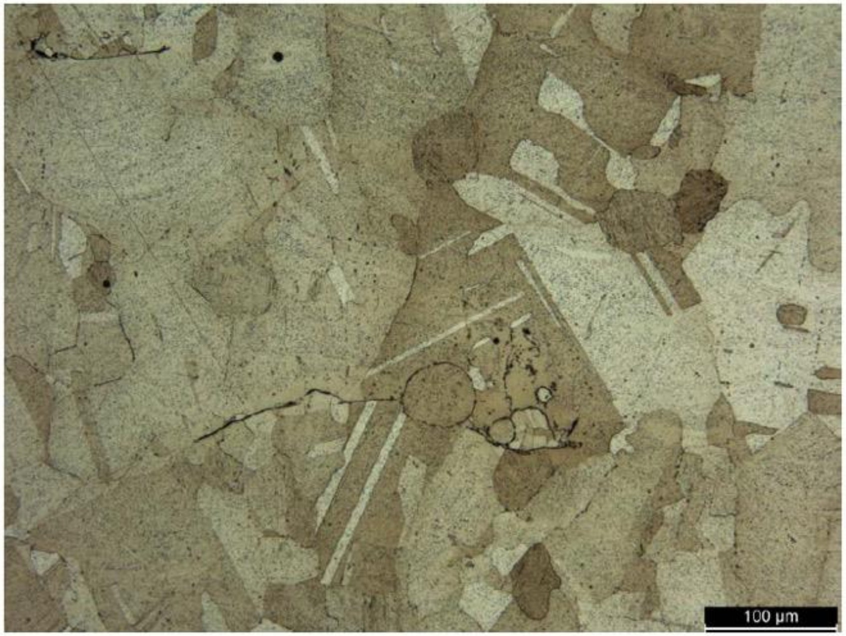


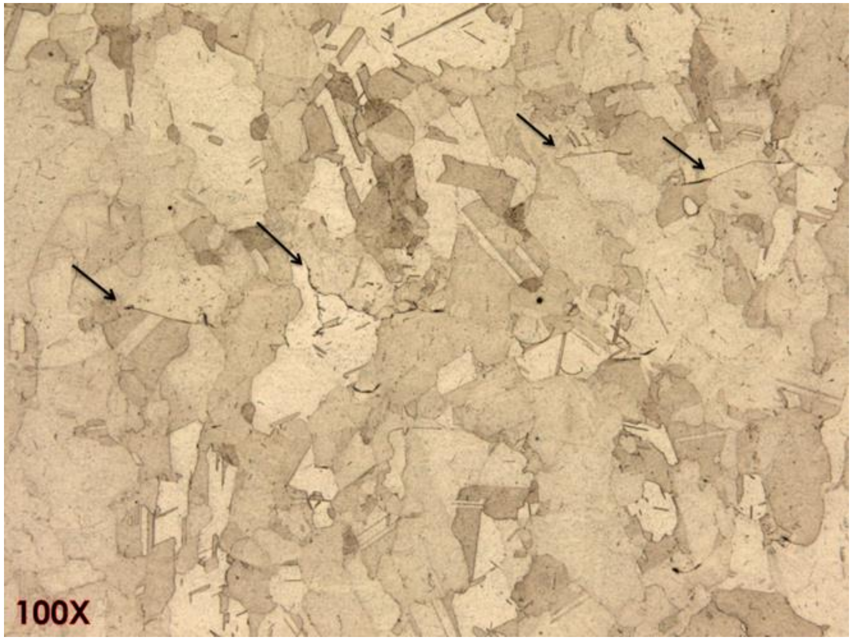
SLM 718 Defective Build

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



SLM 718 Defective Build





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

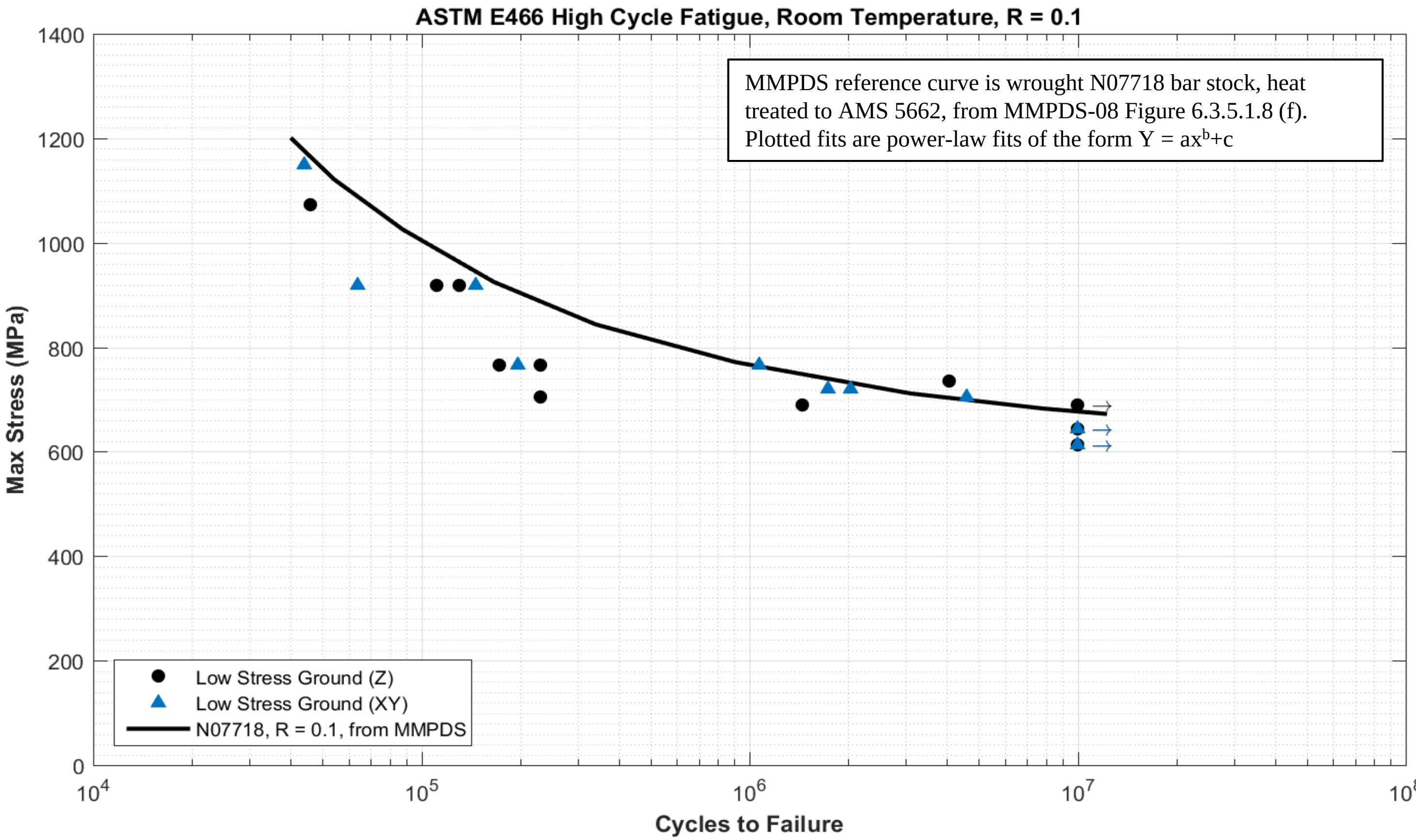
SLM 718 High Cycle Fatigue

Key Variables

1. 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.

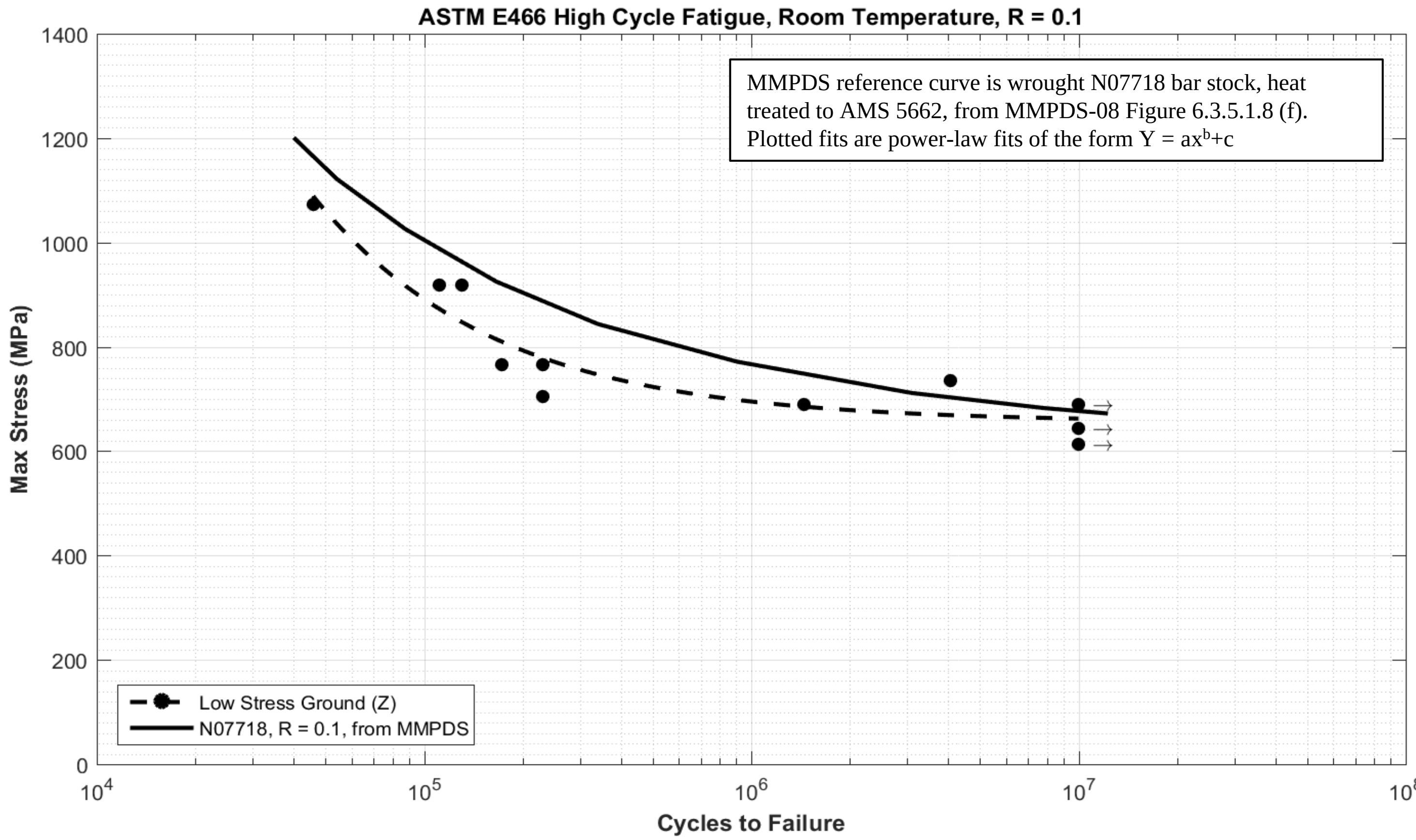
2. Surface Finish
   - Low Stress Ground – ASTM E466 finishing procedure
   - As-Built – Surface finish from the SLM machine

High Cycle Fatigue of SLM 718



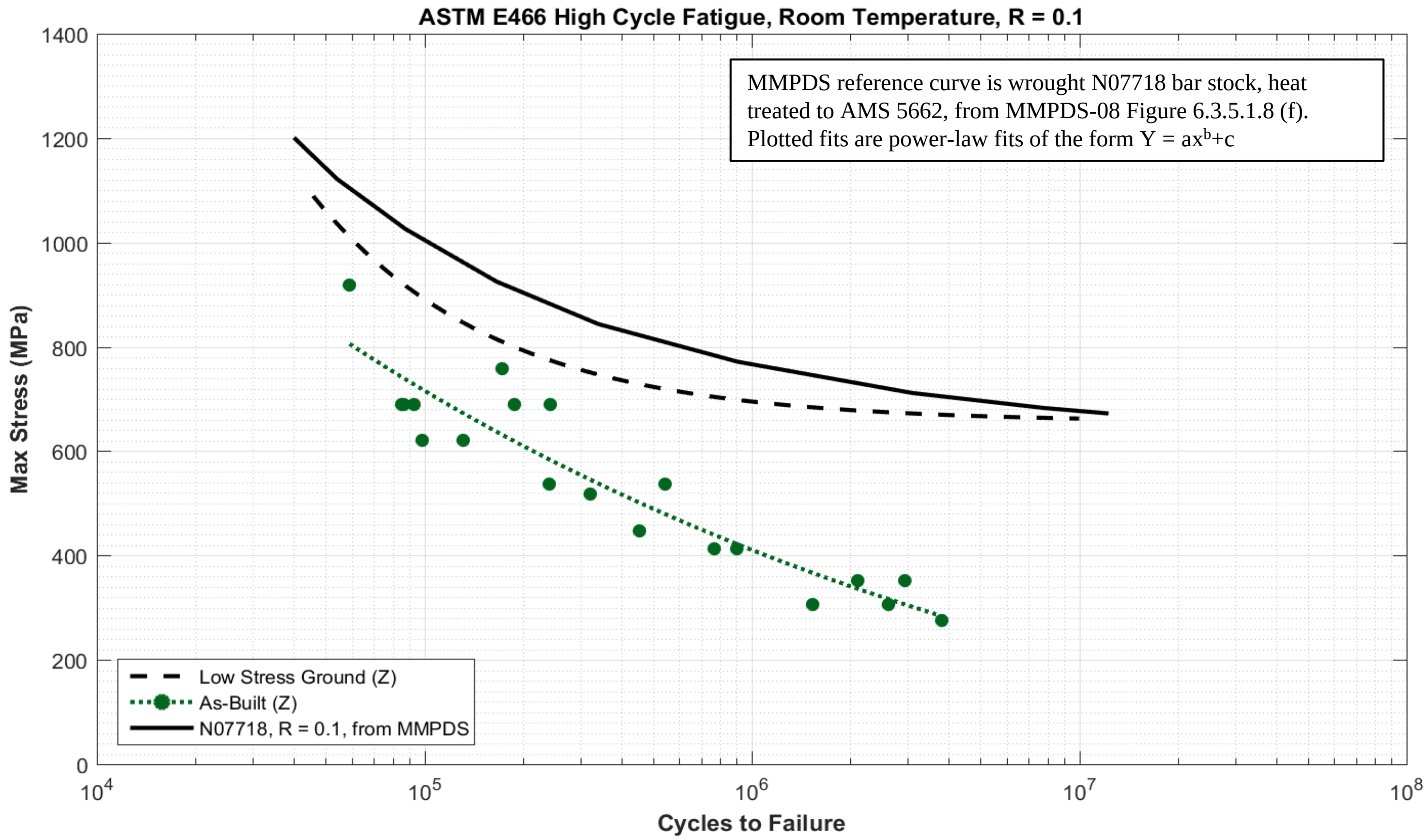
Low stress ground; minimal effect from orientation

High Cycle Fatigue of SLM 718



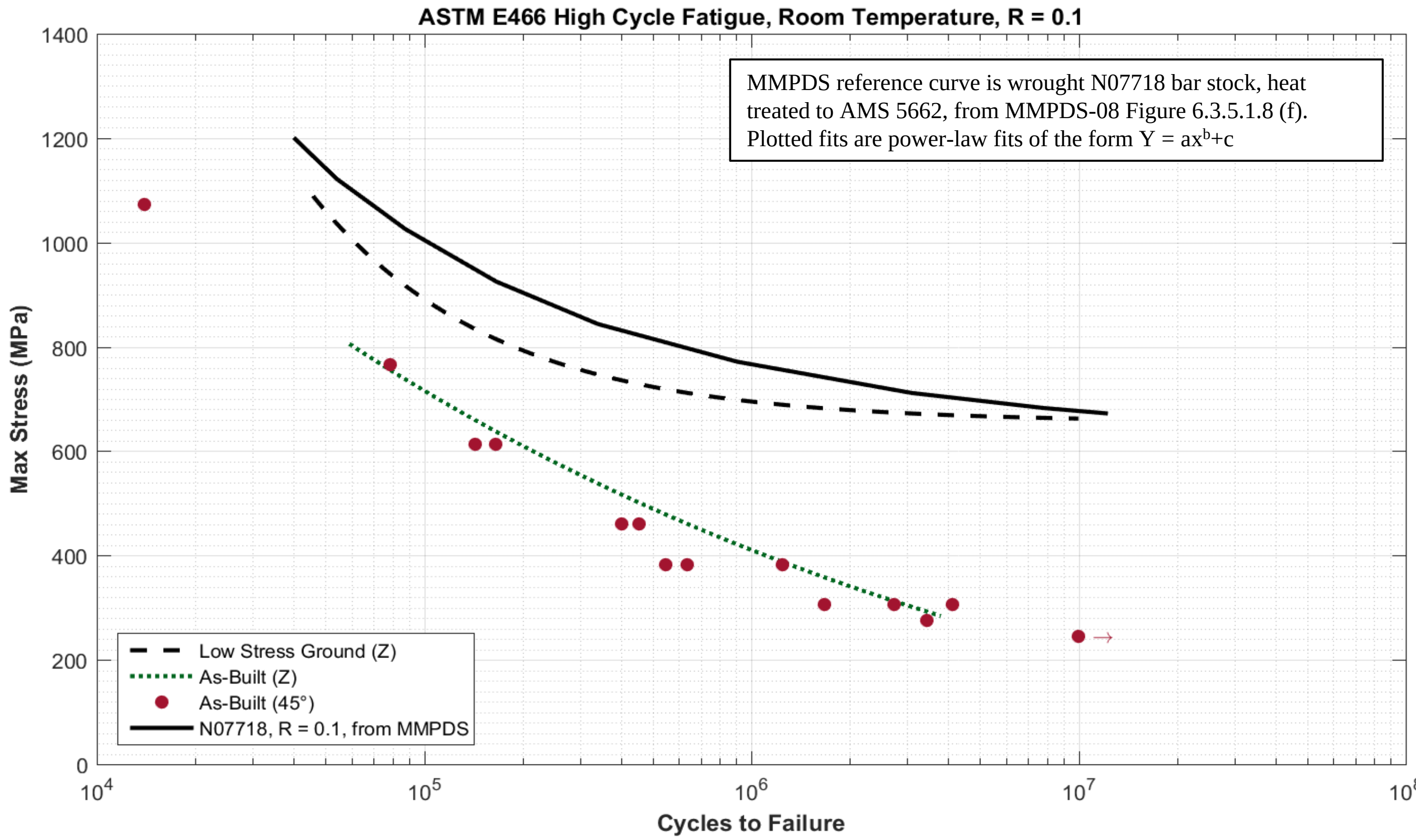
MMPDS Wrought data vs.
Low Stress Ground, Room Temperature, R = 0.1

High Cycle Fatigue of SLM 718



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

High Cycle Fatigue of SLM 718

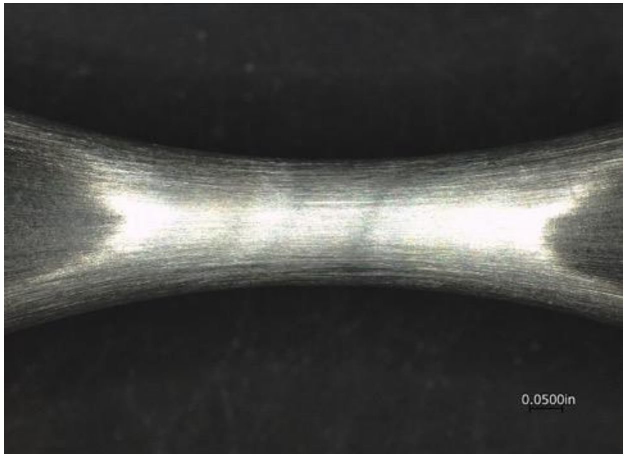


45°-oriented, as-built surface finish; comparable fatigue life

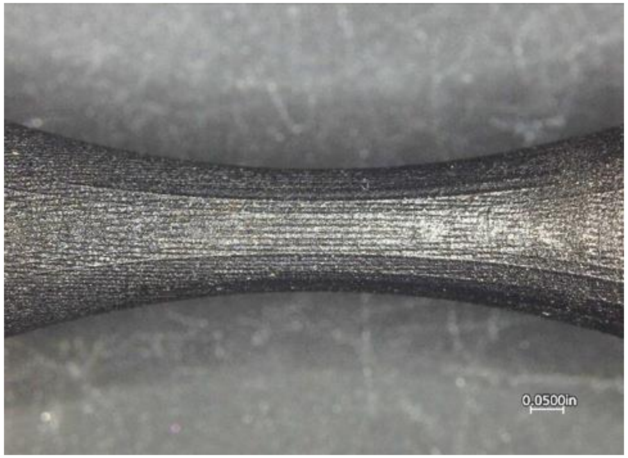
45° tend to be rougher than Z

High Cycle Fatigue of SLM 718

Fatigue life decreases with increasing surface roughness.

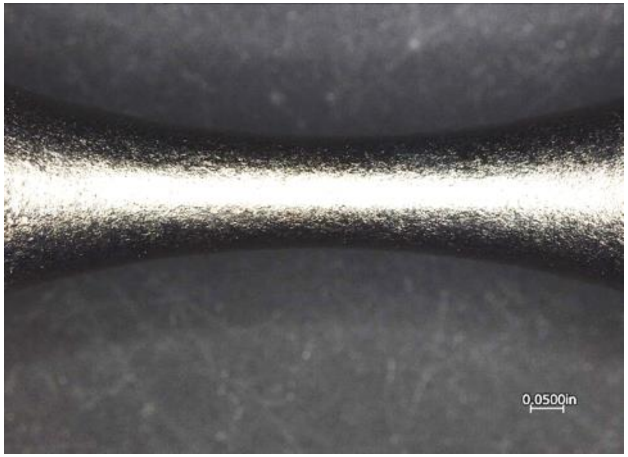


Low stress ground



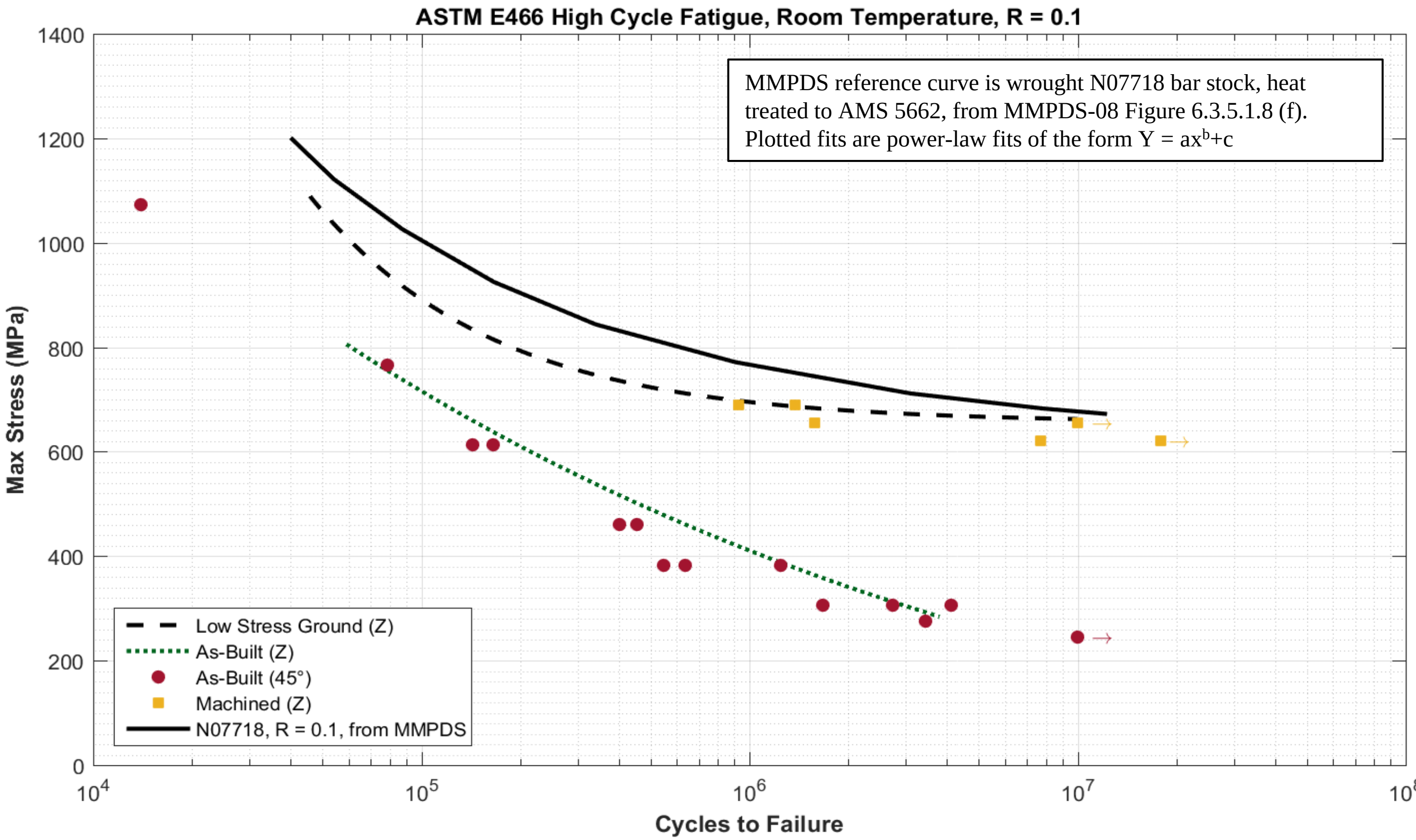
As-built

Tumbled & Electropolished



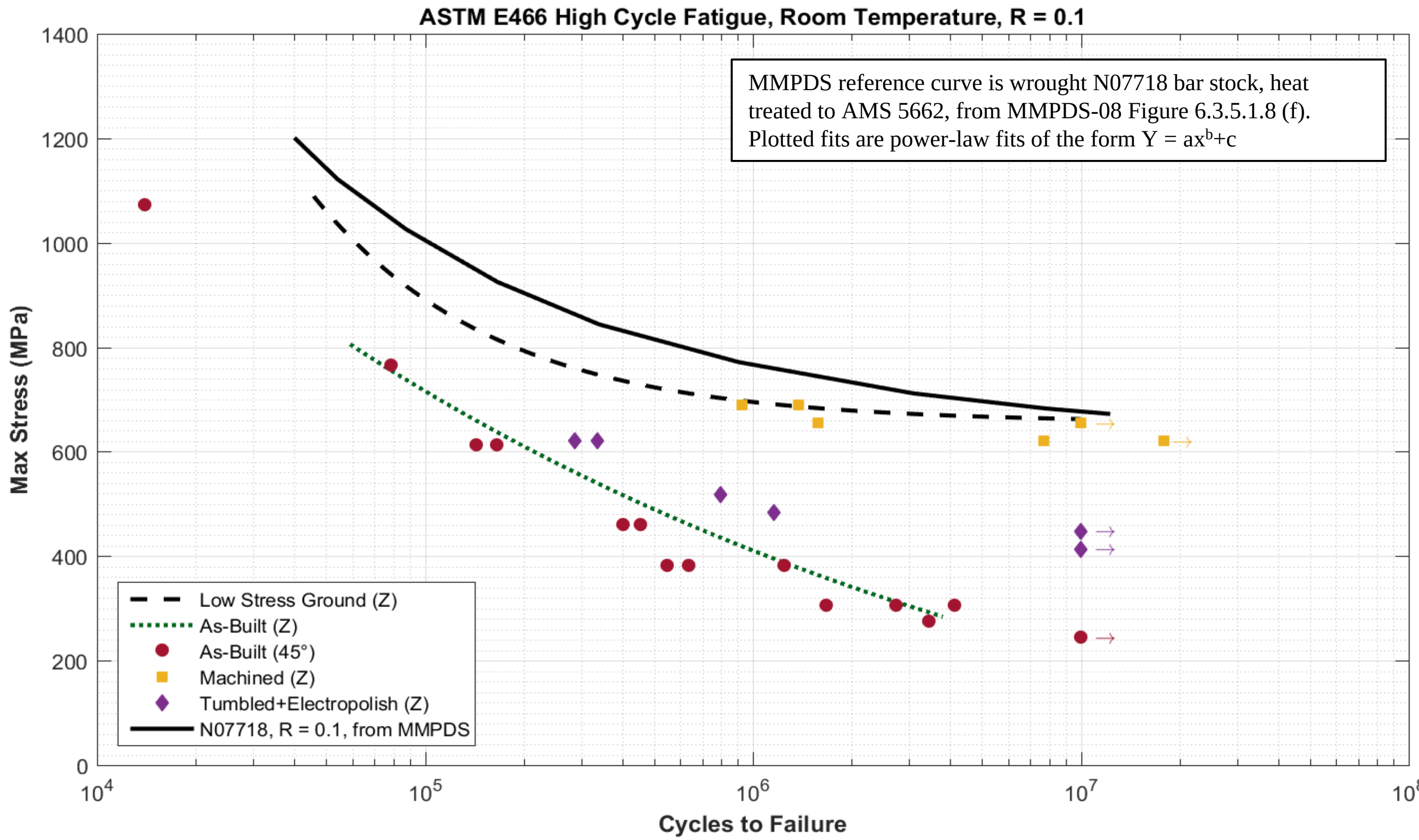
Tumbled & Chem Milled

High Cycle Fatigue of SLM 718



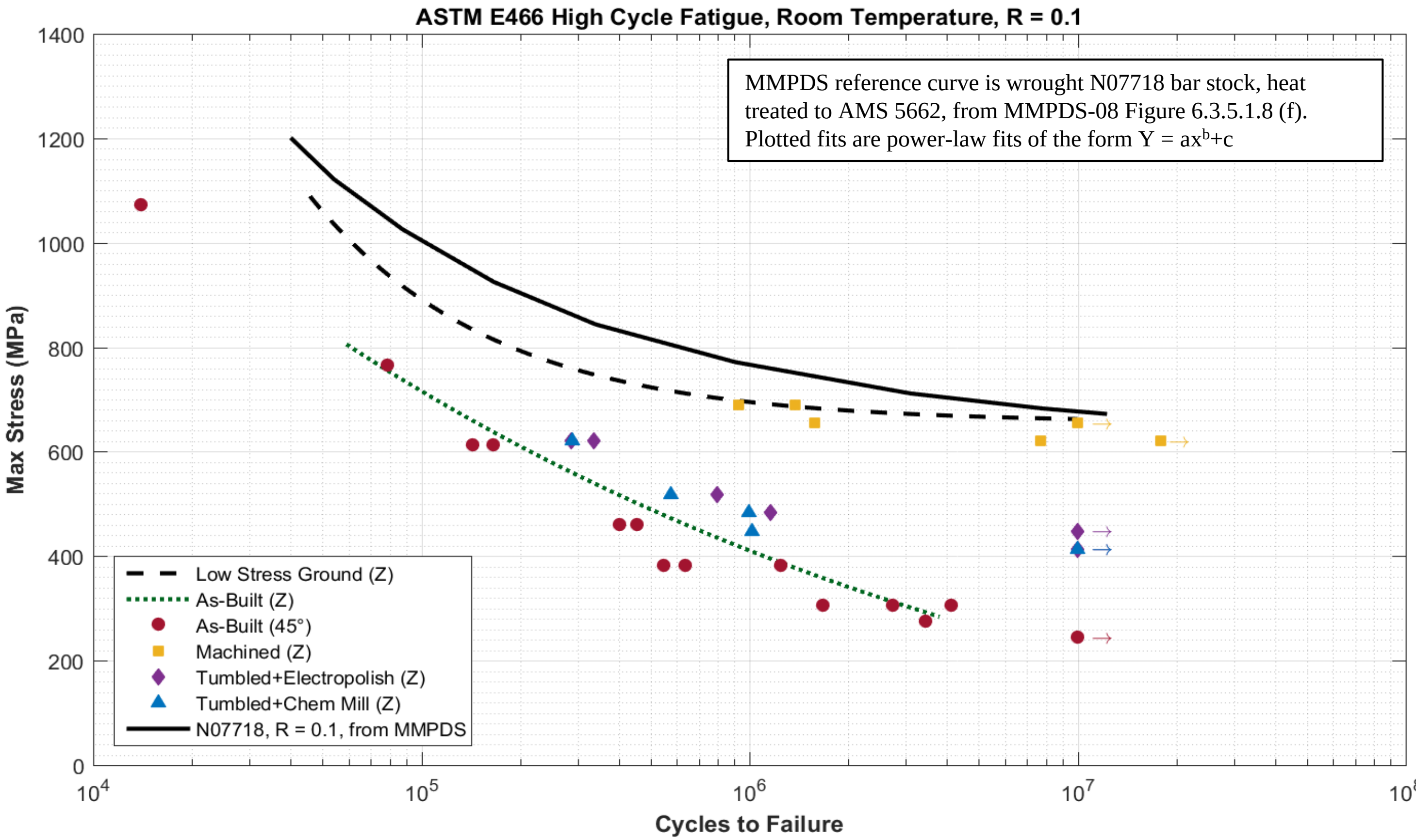
Z-oriented, lathe-turned surface for faster machining turnaround.
Slight decrease in life from low stress ground finish.

High Cycle Fatigue of SLM 718



Z-oriented, tumbled then electropolished.

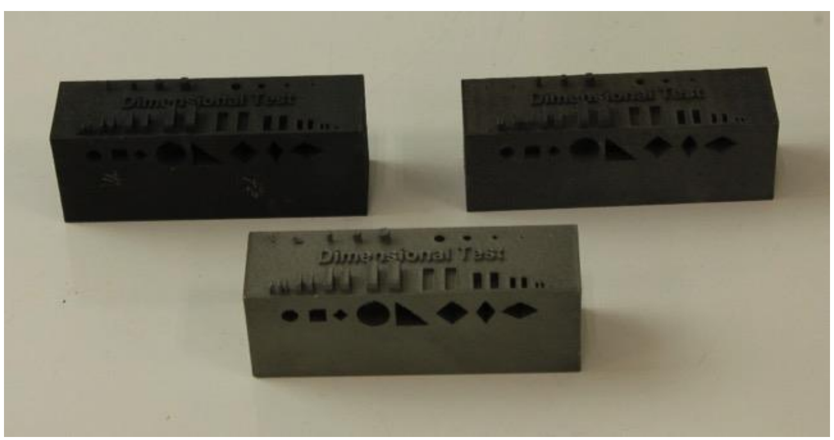
High Cycle Fatigue of SLM 718

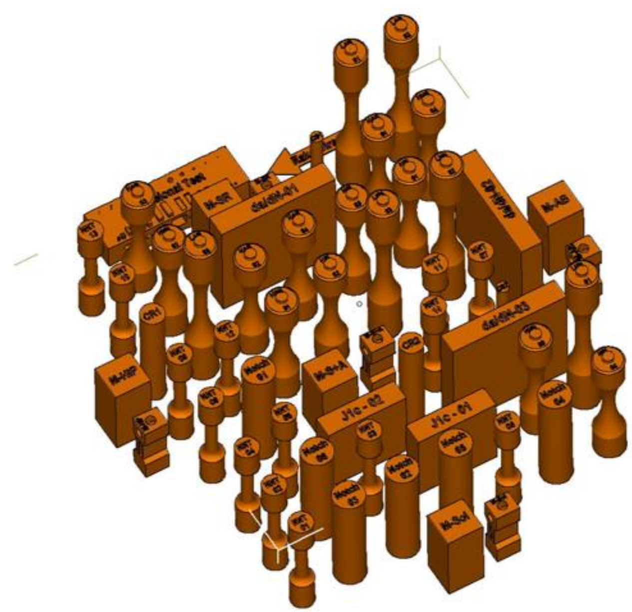


Z-Oriented, tumbled then chem milled.

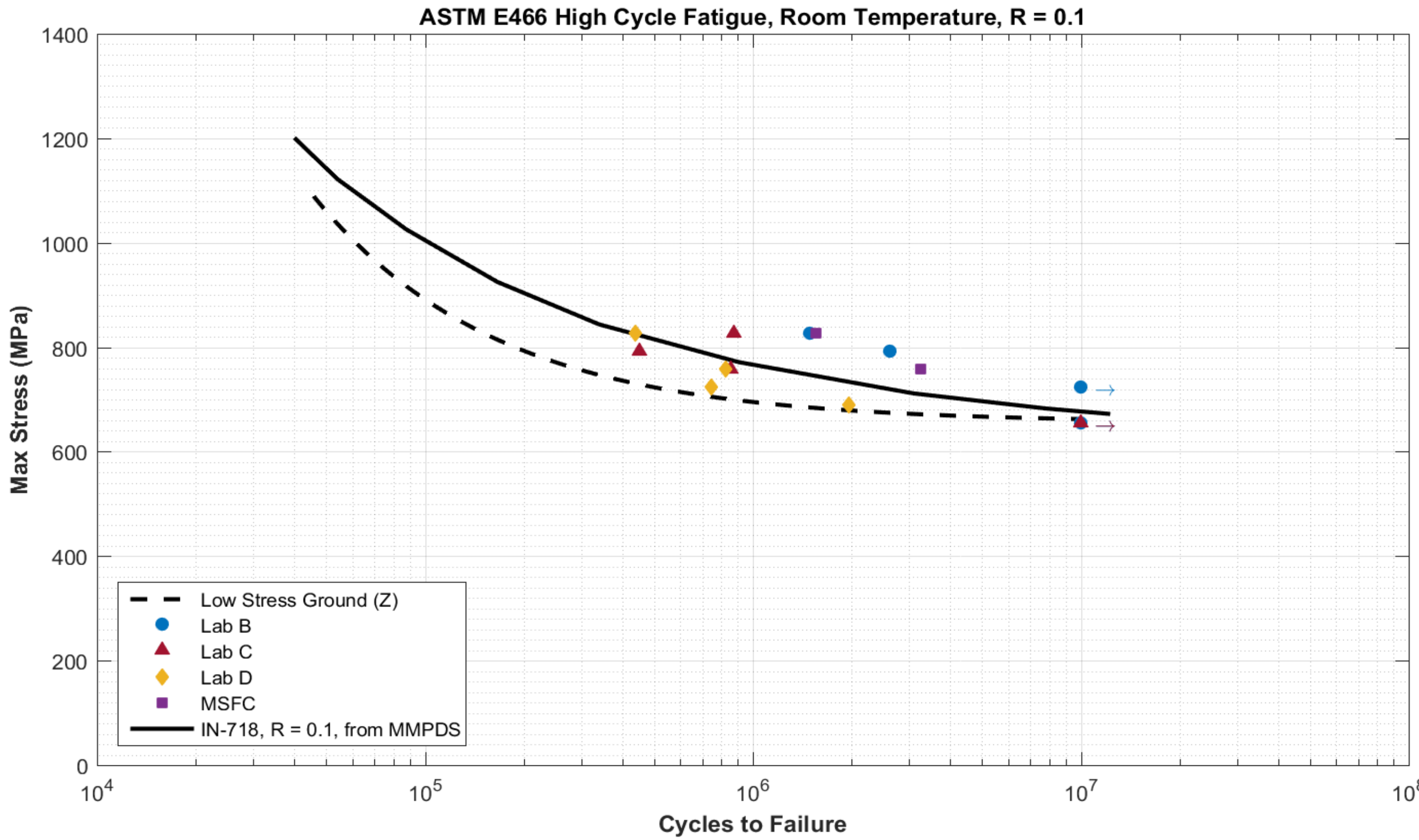
Vendor Round Robin

- 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 High Cycle Fatigue of SLM 718



Z-oriented, low stress ground surface finish.
Compared to M1 and wrought reference curves.

Fatigue Crack Growth of SLM 718

Round Robin Specifications

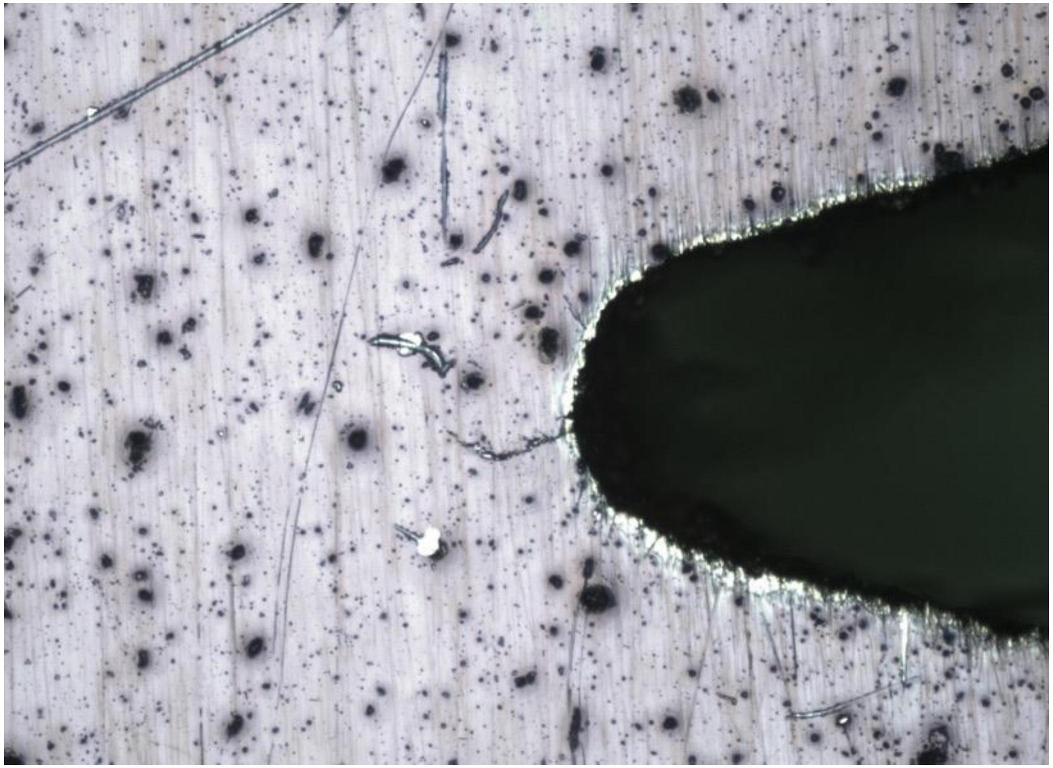
- 3 specimens from each build
- Z-XY test orientation
- Post-processing same as fatigue specimens

Testing Methodology

- Tested according to ASTM E647
- R = 0.1 and R = 0.7 data shown
- Compression pre-cracking procedure (CPC)

Compression Pre-Cracking

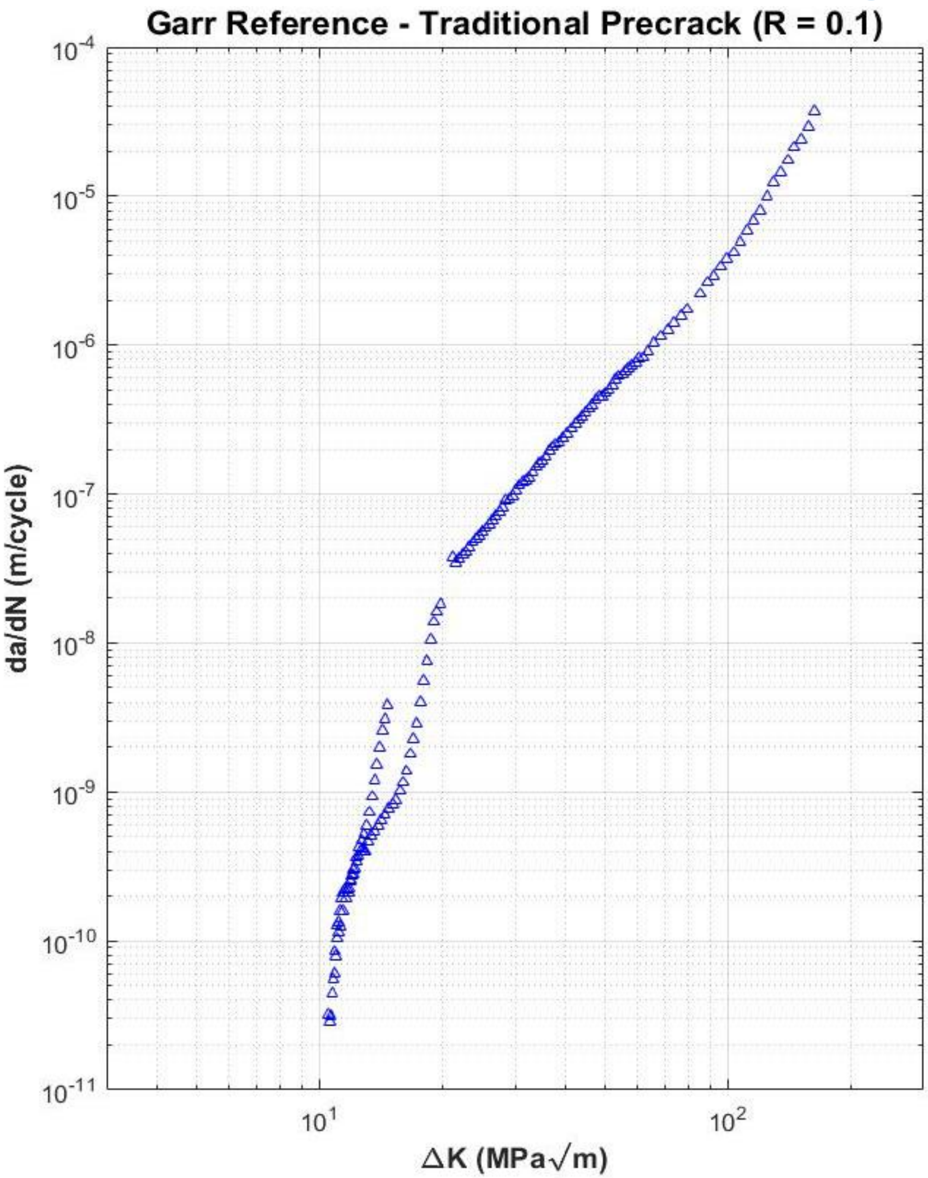
- Compression-compression loading used to generate a crack at the notch root of a c(T) specimen.
- May produce more conservative threshold and near-threshold crack growth rates.
- Following CPC procedure detailed by Newman and Yamada.



Reference: FCG of Wrought Alloy 718 at R = 0.1

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

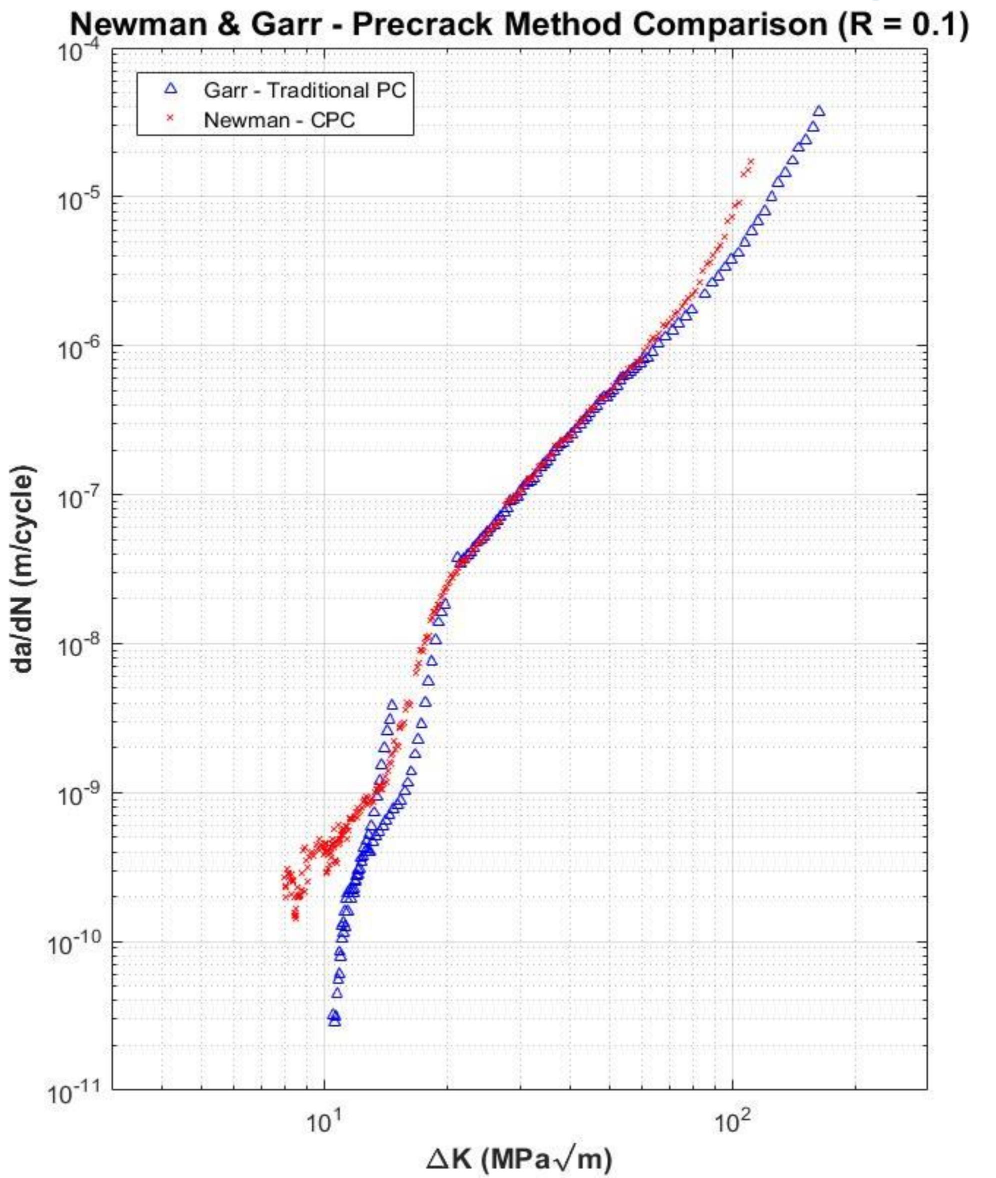
- Garr KR, Boeing-Rocketdyne Propulsion and Power Company, as referenced by Newman, J.C., Jr. and Yamada, Y., “Compression Precracking Methods to Generate Near-Threshold Fatigue-Crack-Growth-Rate Data”, International Journal of Fatigue, Vol. 32, 2010, p.879-885.



Reference: FCG of Wrought Alloy 718 at R = 0.1

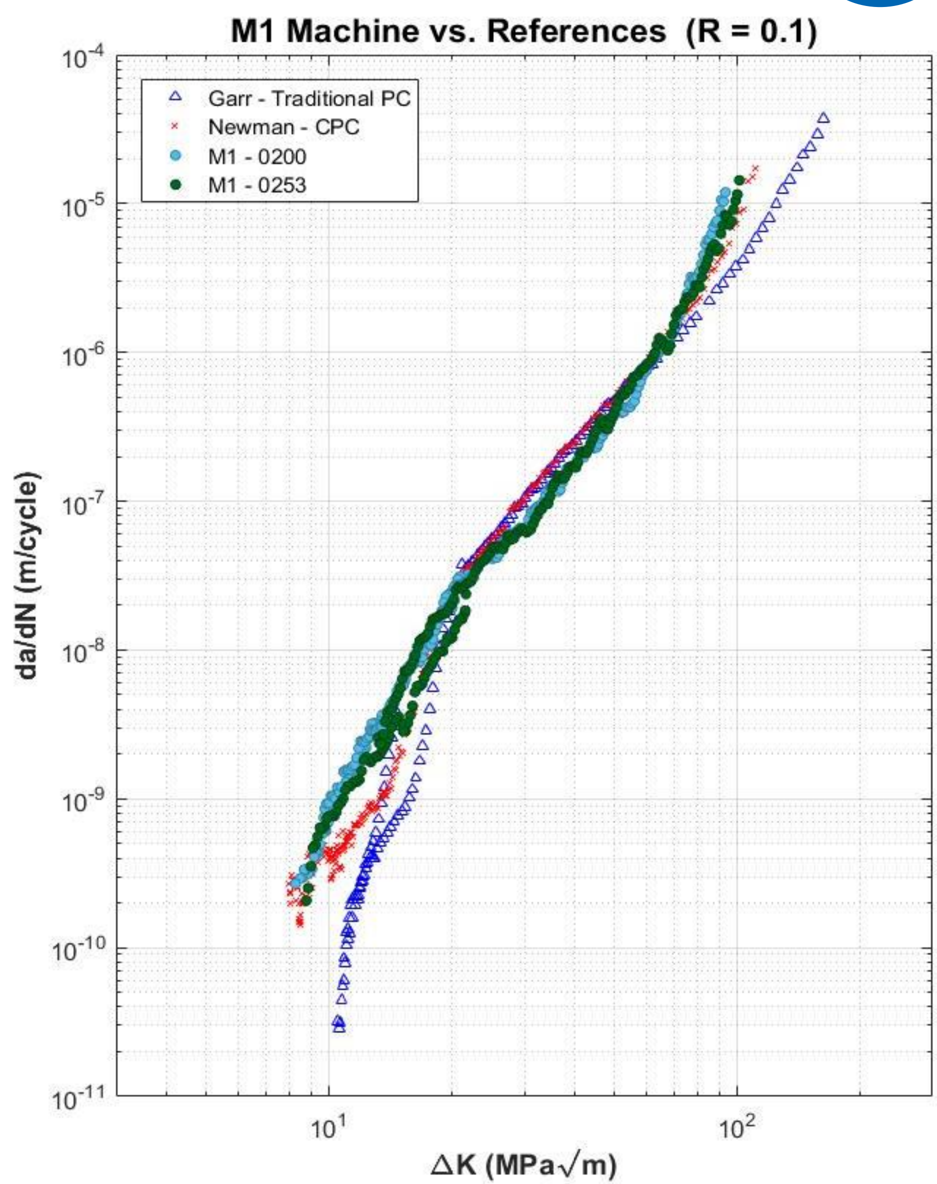
- Wrought Inconel-718 alloy obtained from Boeing-Rockwell. Tested using the CPCA loading.

- 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.



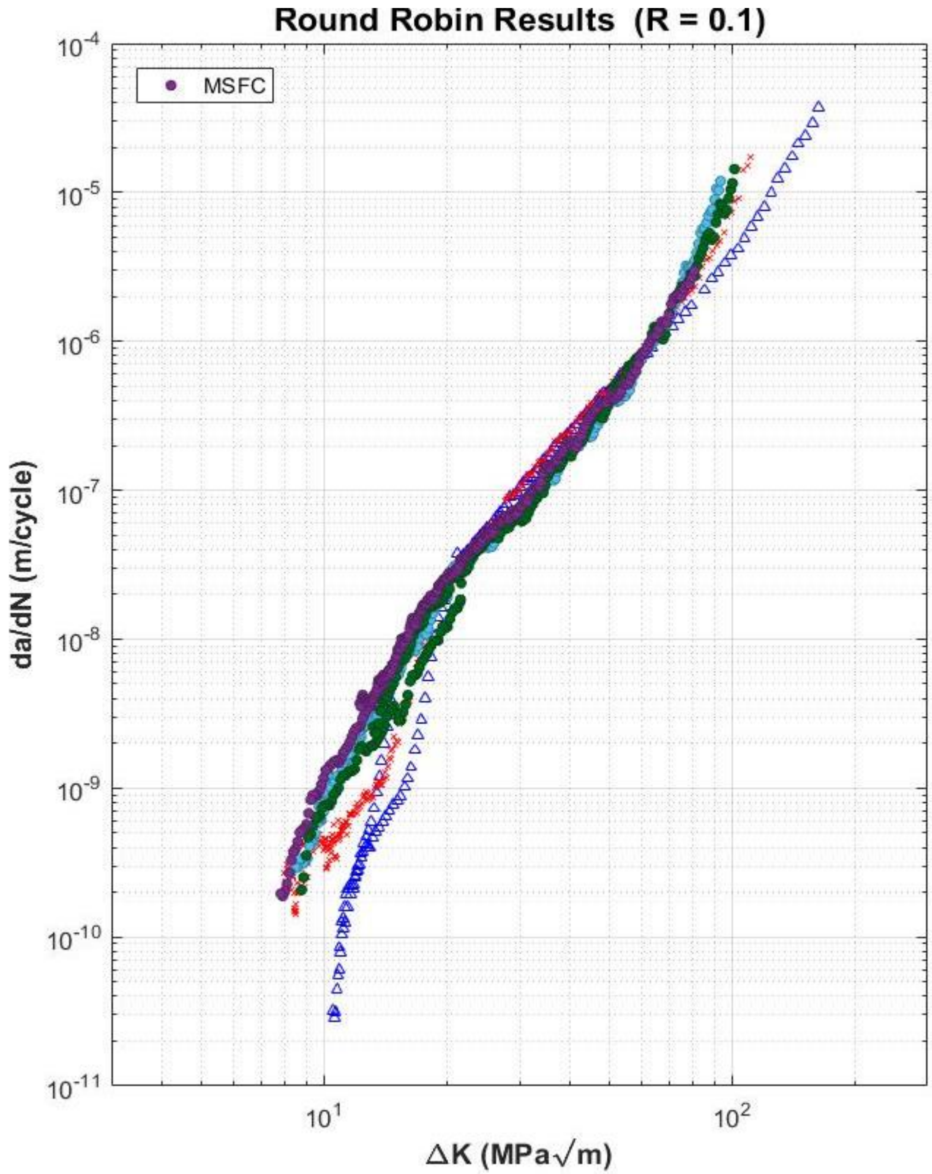
FCG of SLM 718 vs Wrought 718 at R = 0.1

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



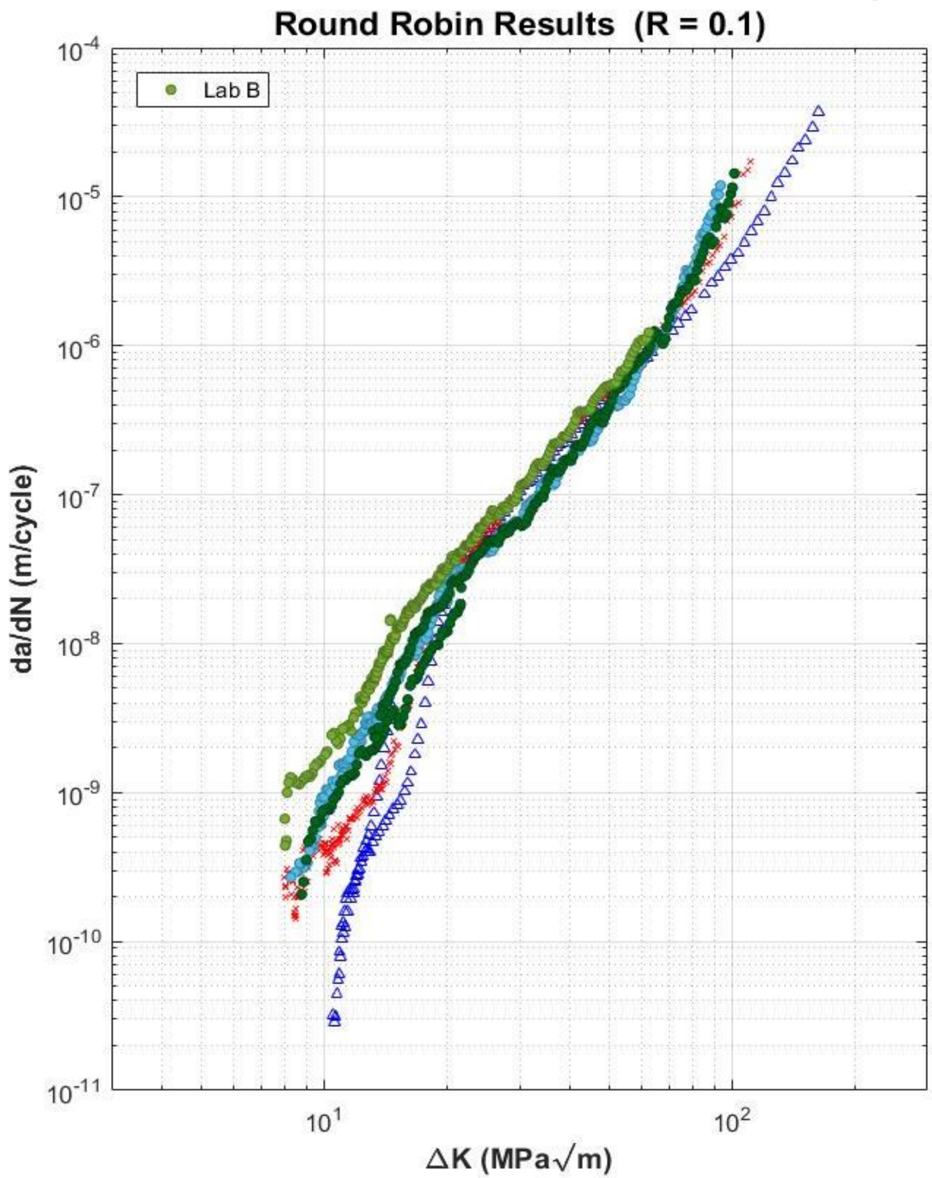
FCG of SLM 718: MSFC results at R = 0.1

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



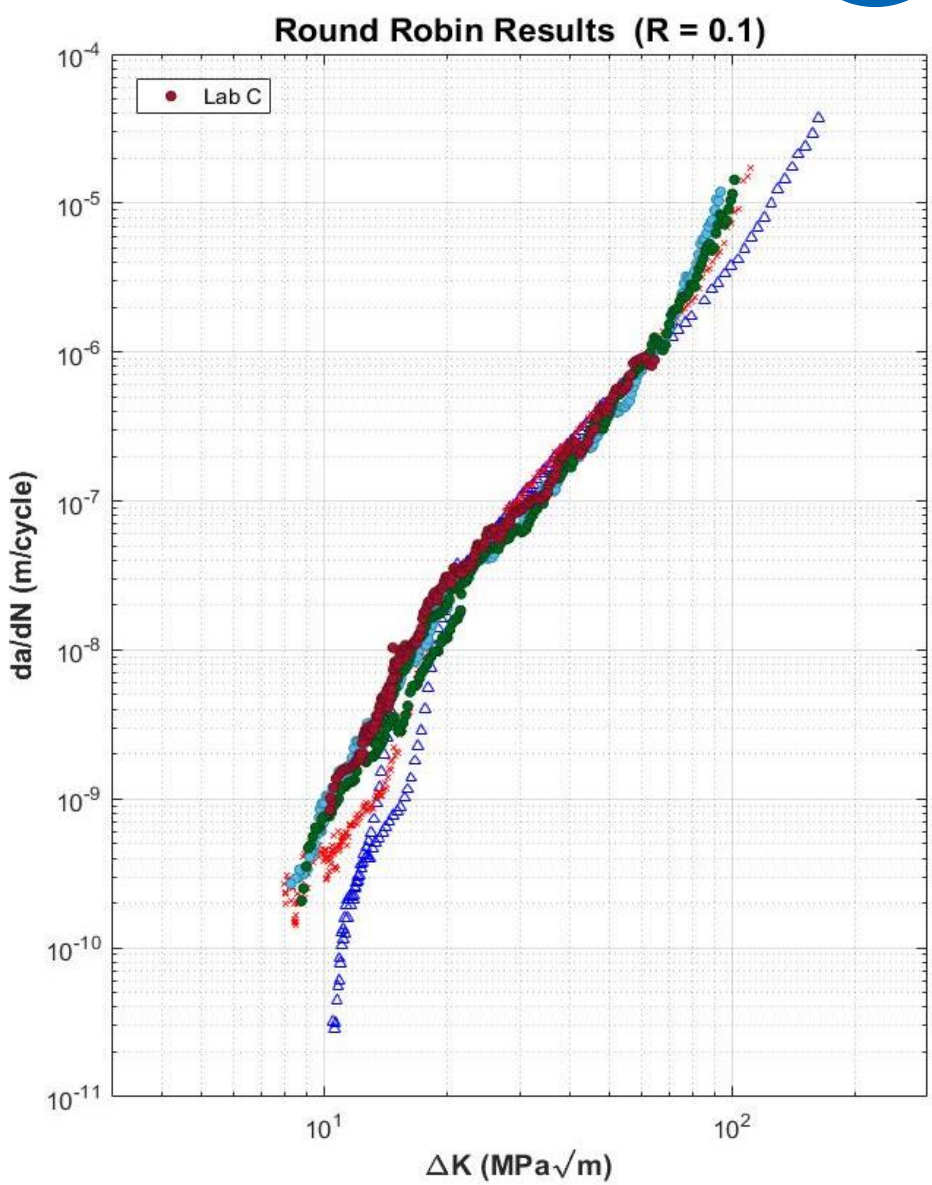
FCG of SLM 718: Lab B results at R = 0.1

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



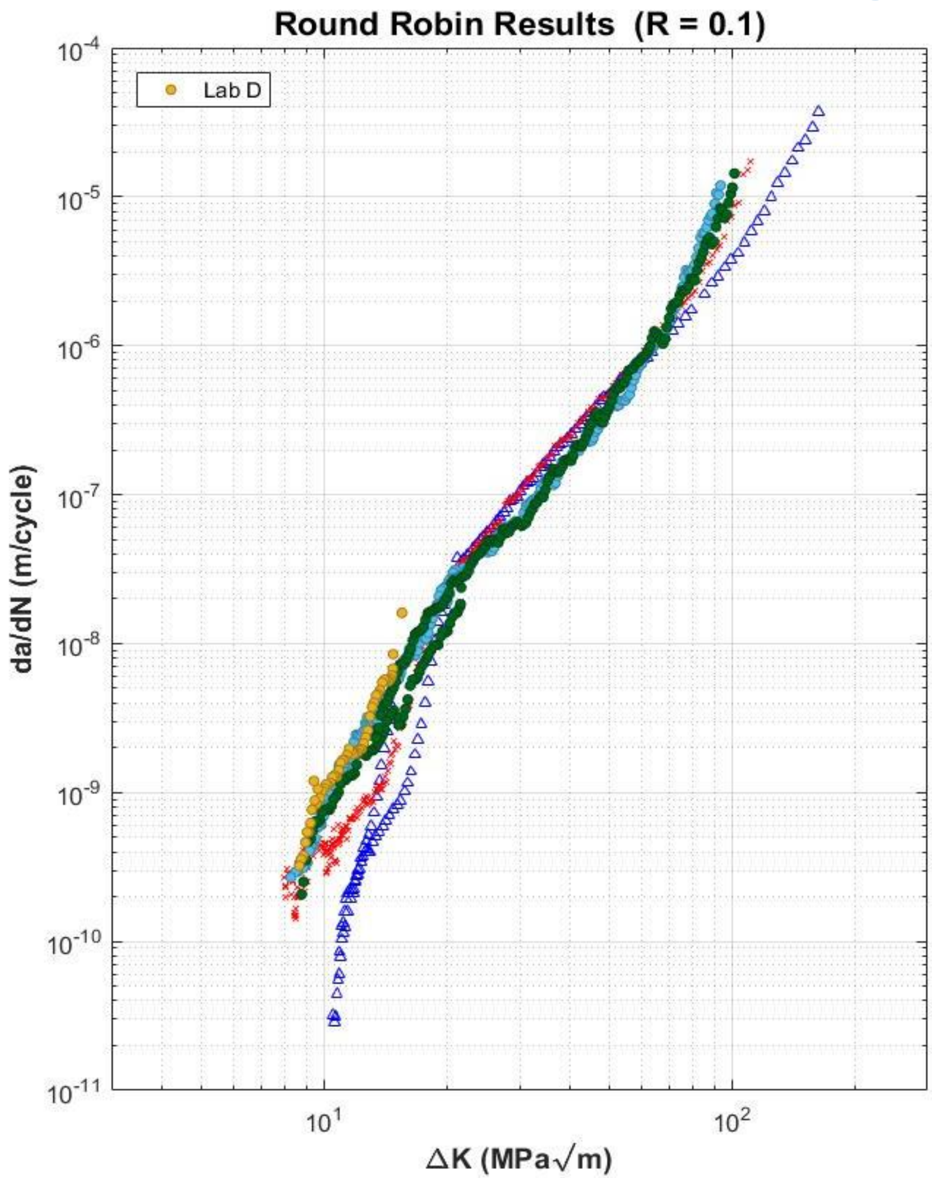
FCG of SLM 718: Lab C results at R = 0.1

- Lab C - Consistent with MSFC data.



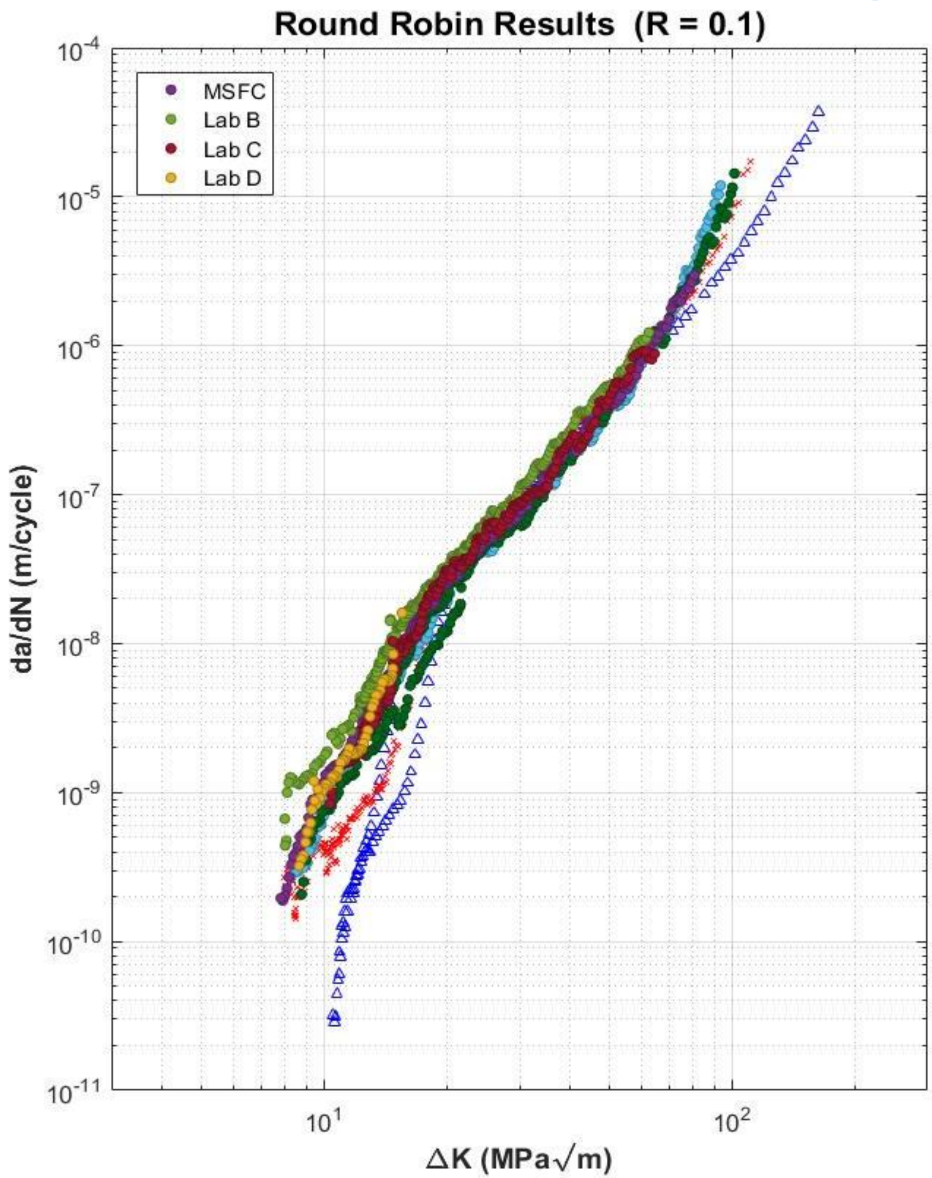
FCG of SLM 718: Lab D results at R = 0.1

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



FCG of SLM 718: All results at R = 0.1

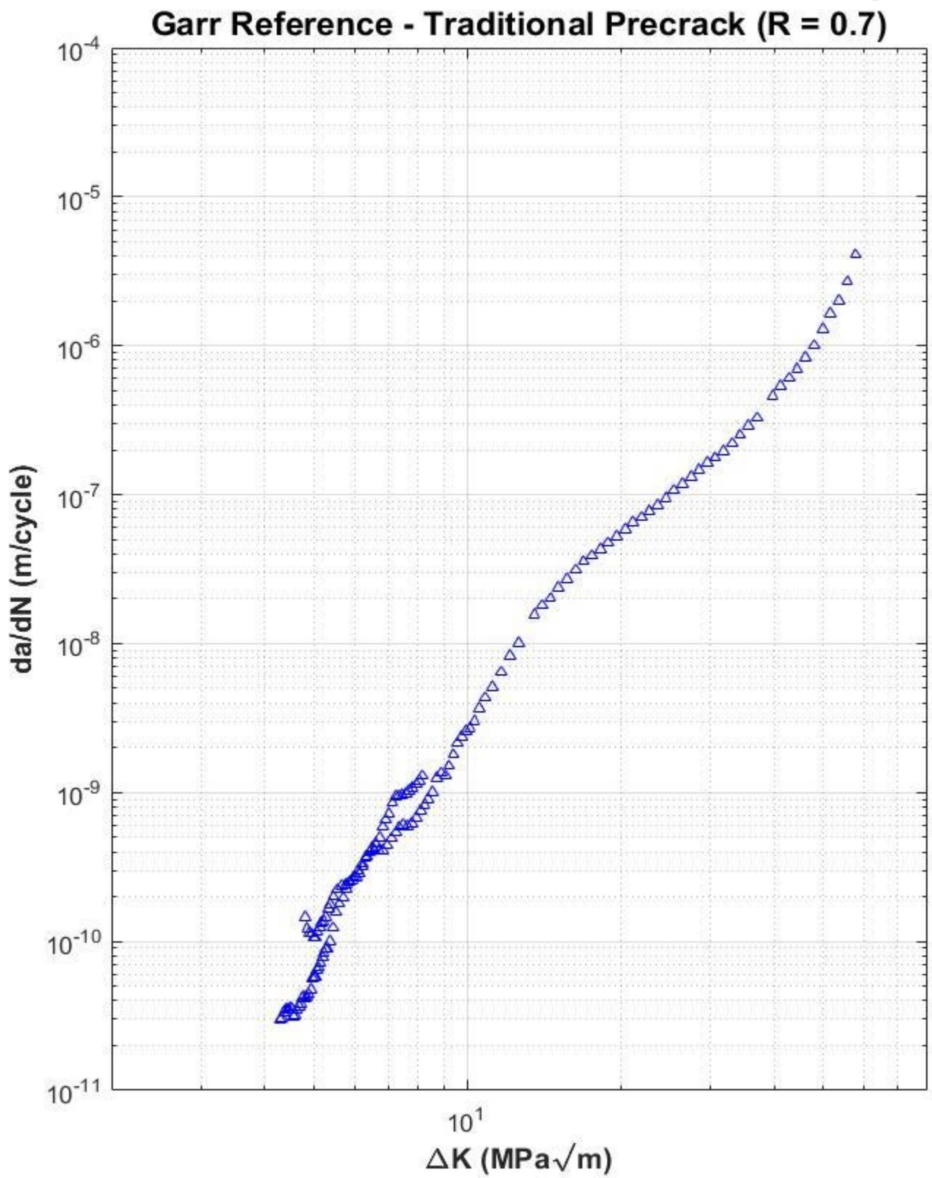
- Only Lab B varied from the MSFC data.
- All of the Round Robin data at R = 0.1 was self-consistent.



Reference: FCG of Wrought Alloy 718 at R = 0.7

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

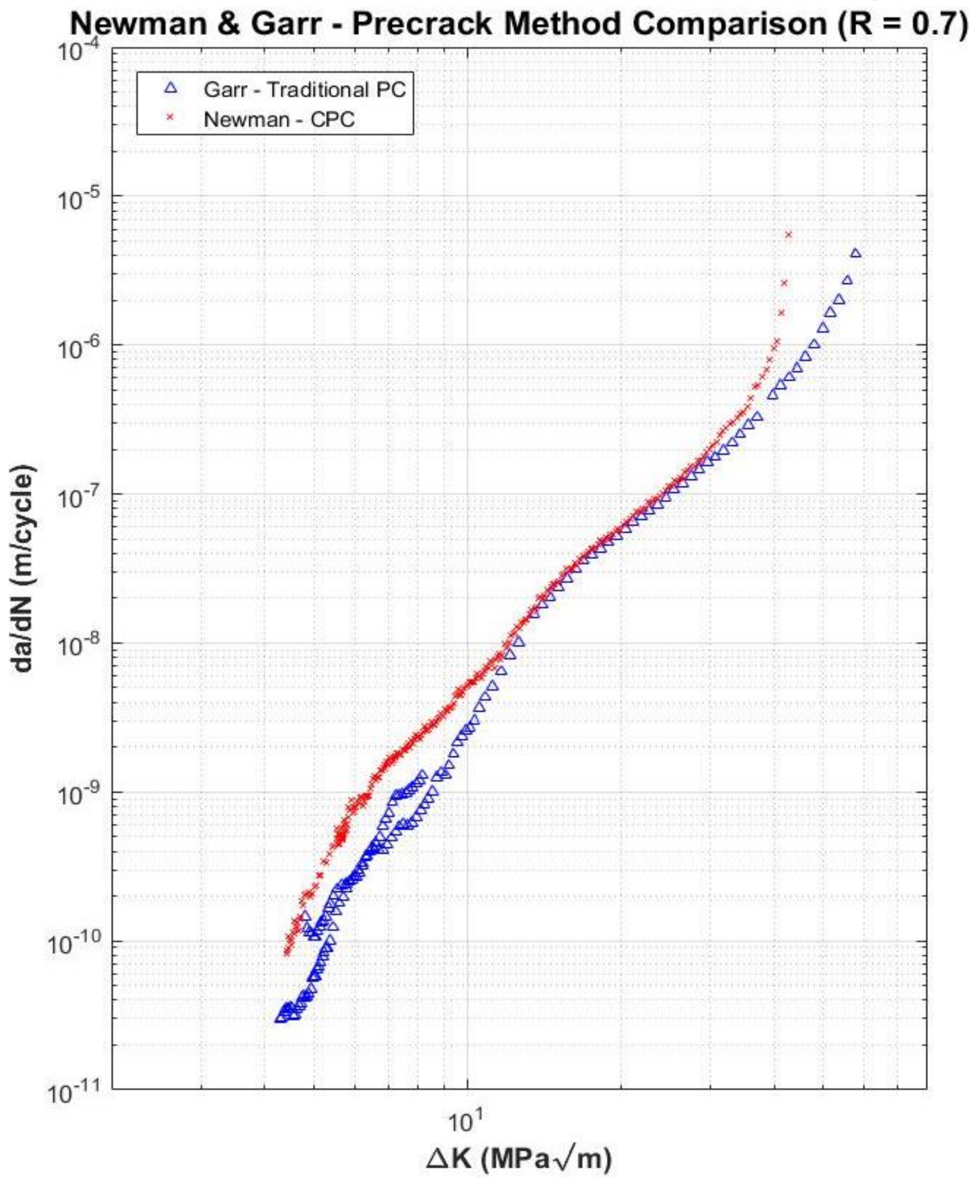
- Garr KR, Boeing-Rocketdyne Propulsion and Power Company, as referenced by Newman, J.C., Jr. and Yamada, Y., "Compression Precracking Methods to Generate Near-Threshold Fatigue-Crack-Growth-Rate Data", International Journal of Fatigue, Vol. 32, 2010, p.879-885.



Reference: FCG of Wrought Alloy 718 at R = 0.7

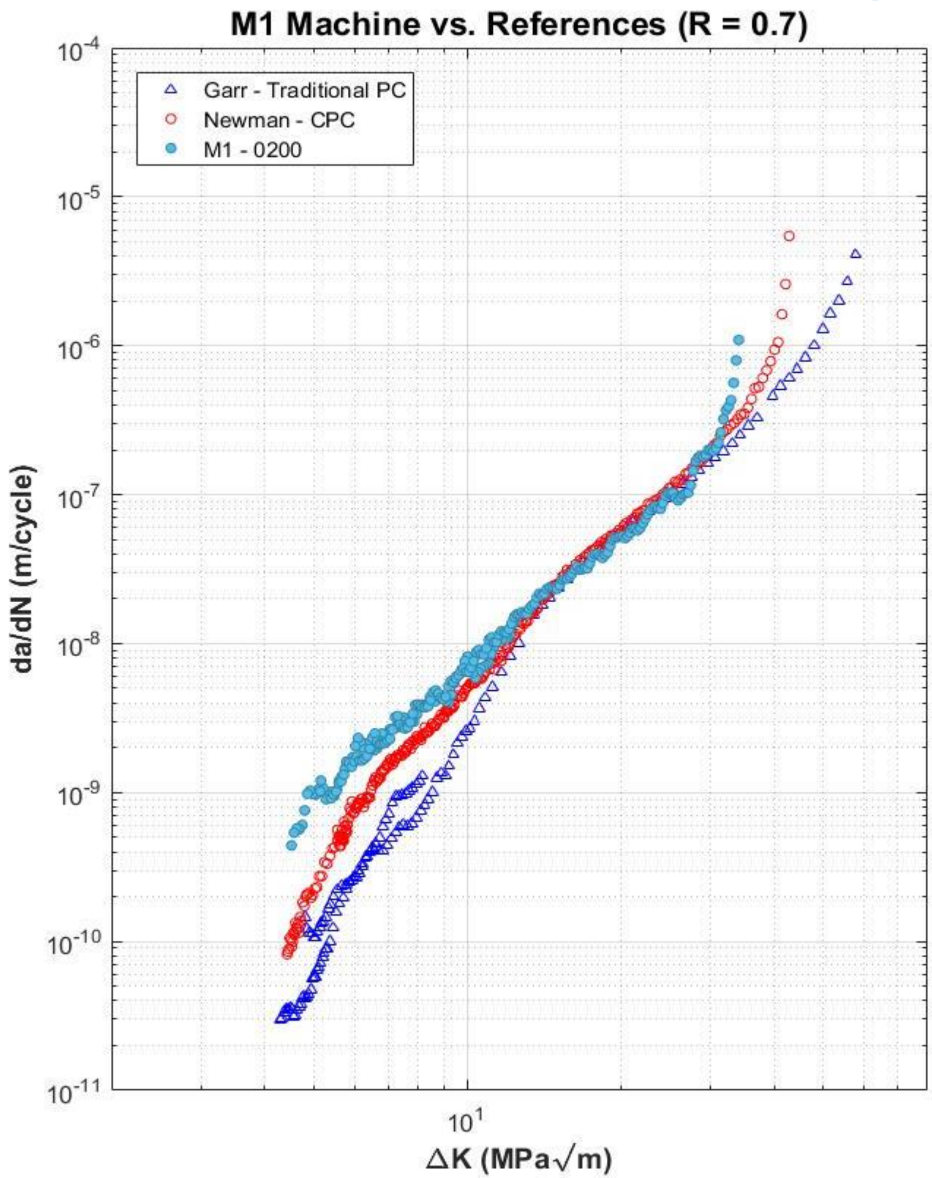
- Wrought Inconel-718 alloy obtained from Boeing-Rockwell. Tested using the CPLR test method and CA loading.

- 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.



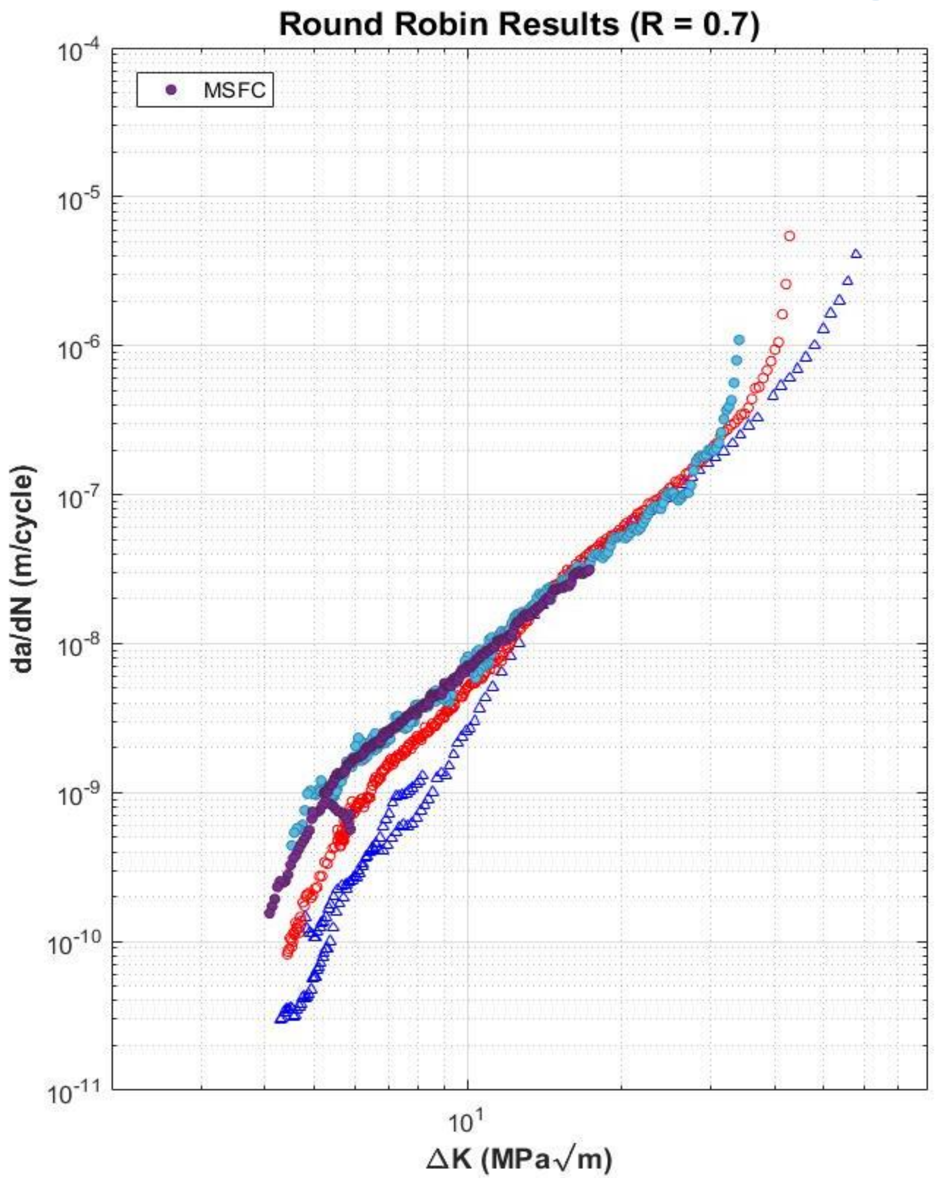
FCG of SLM 718 vs Wrought 718 at R = 0.1

- SLM 718 M1 data included as a reference. This data is not part of the Round-Robin.
- Produced using ASTM LR and CA loading.
- Higher observed growth rates compared to wrought 718 near-threshold.



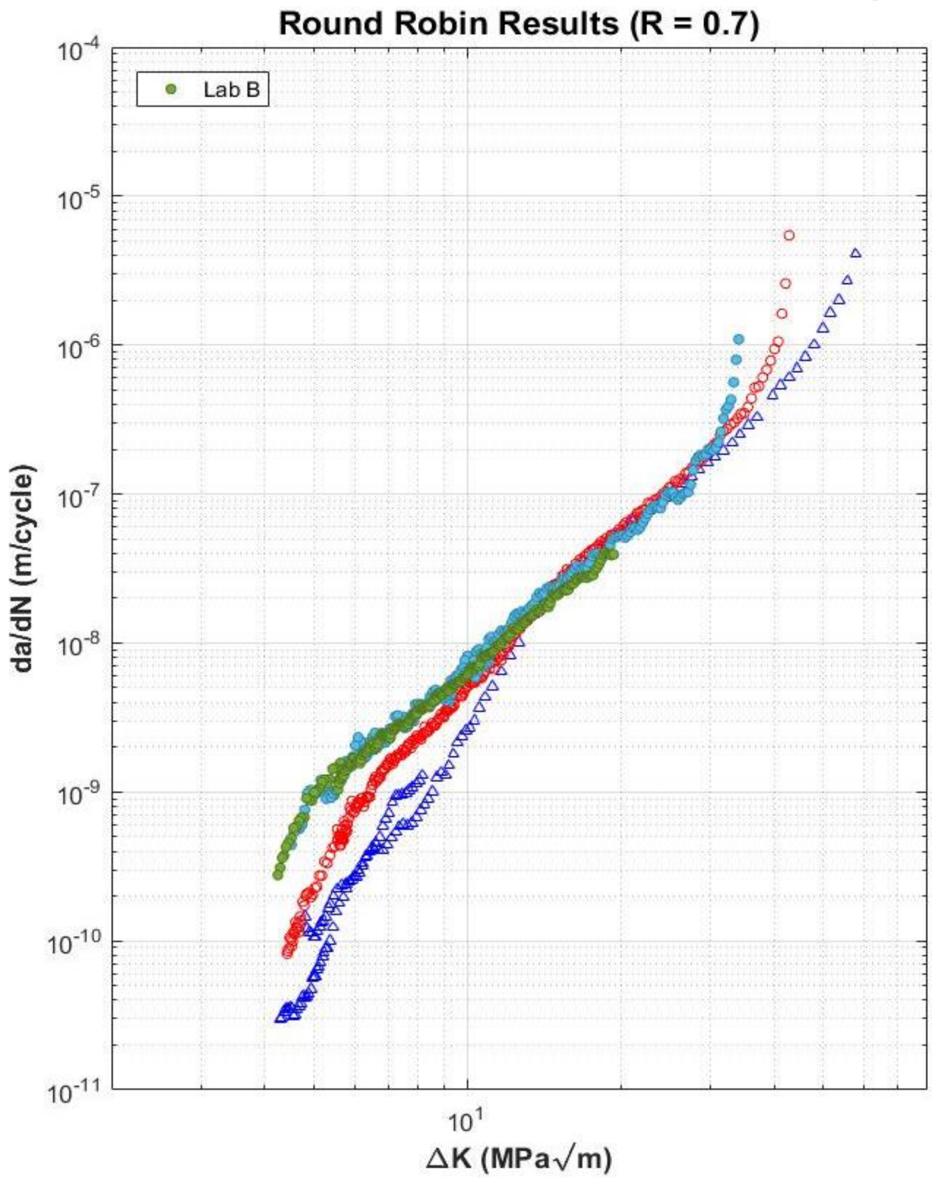
FCG of SLM 718: MSFC results at R = 0.7

- MSFC Round Robin Build is consistent with M1 data.



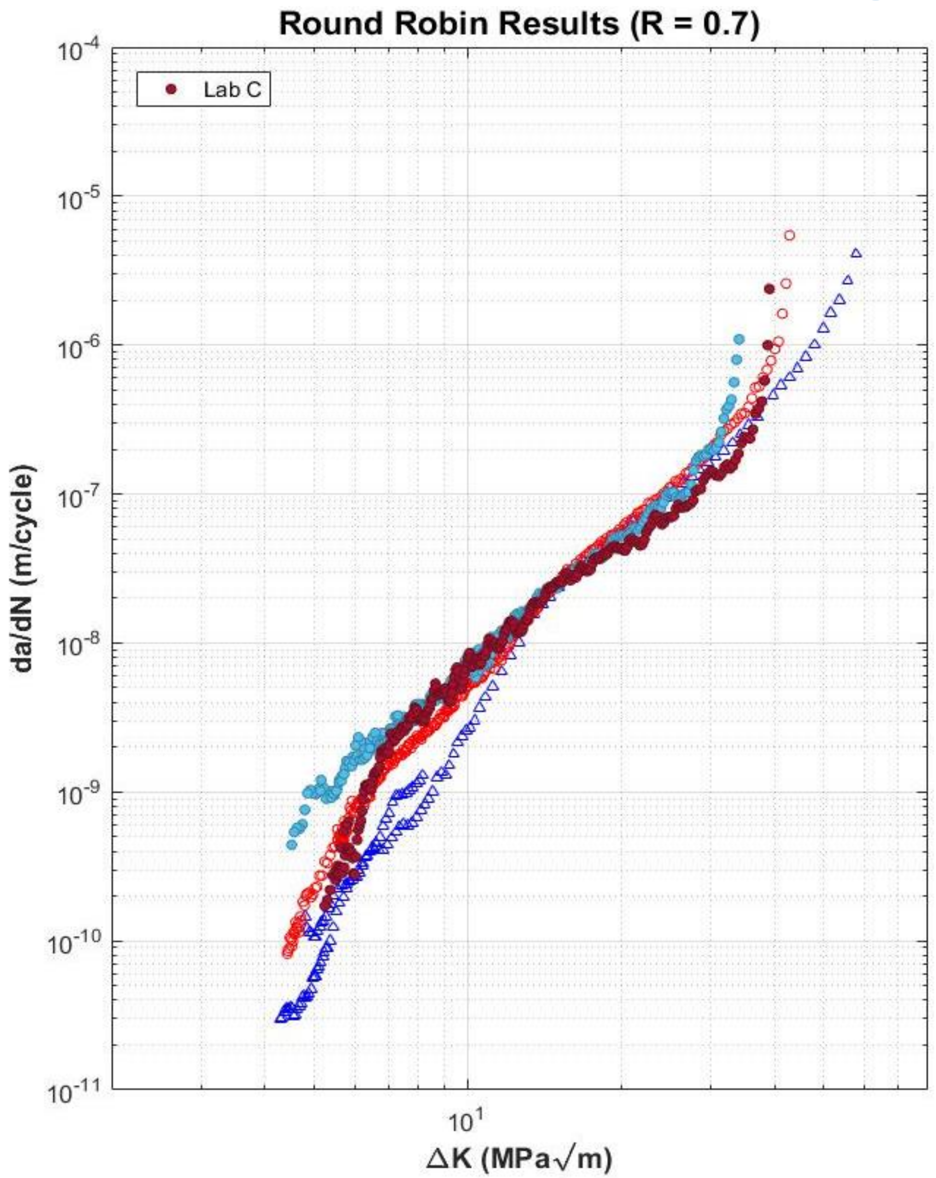
FCG of SLM 718: Lab B results at R = 0.7

- Lab B - Consistent with MSFC data at R = 0.7



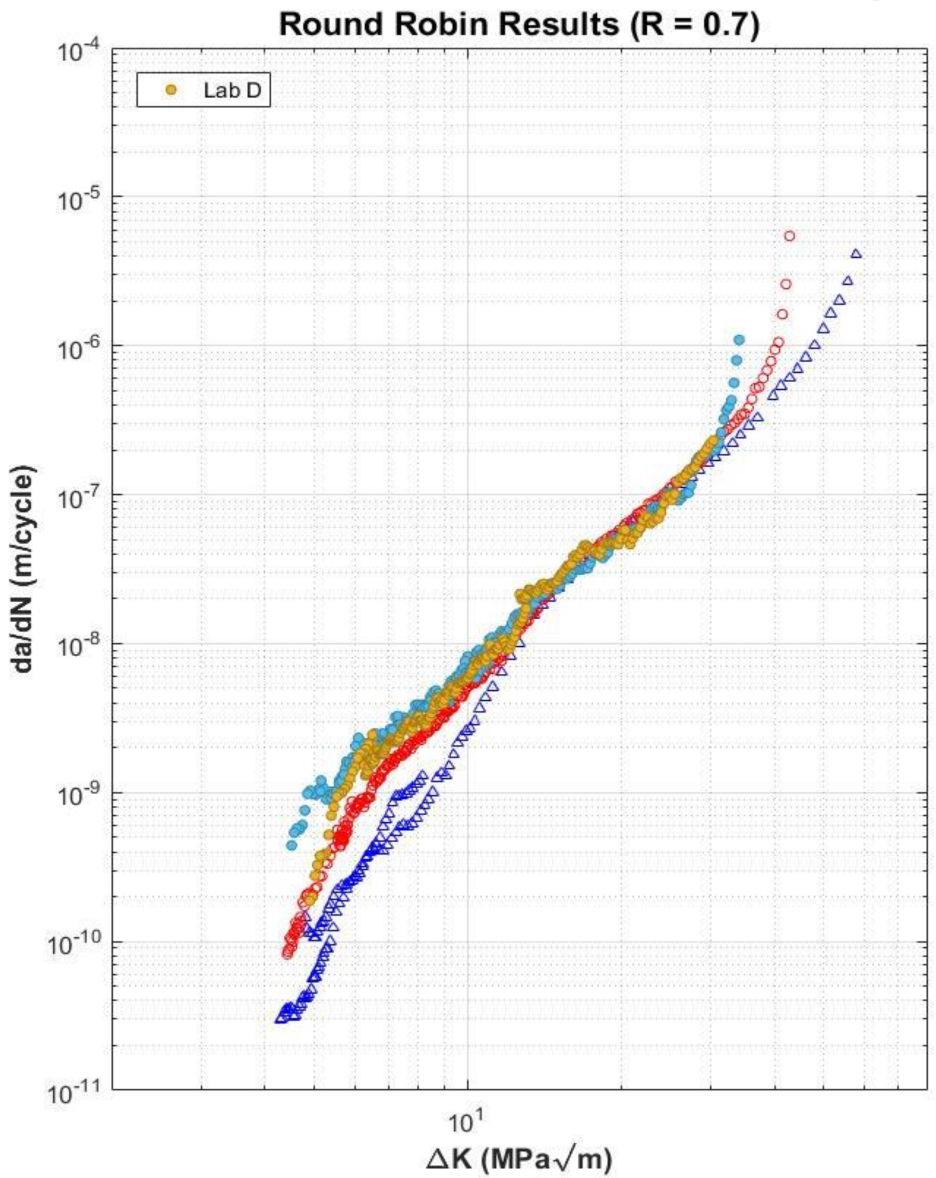
FCG of SLM 718: Lab C results at R = 0.7

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



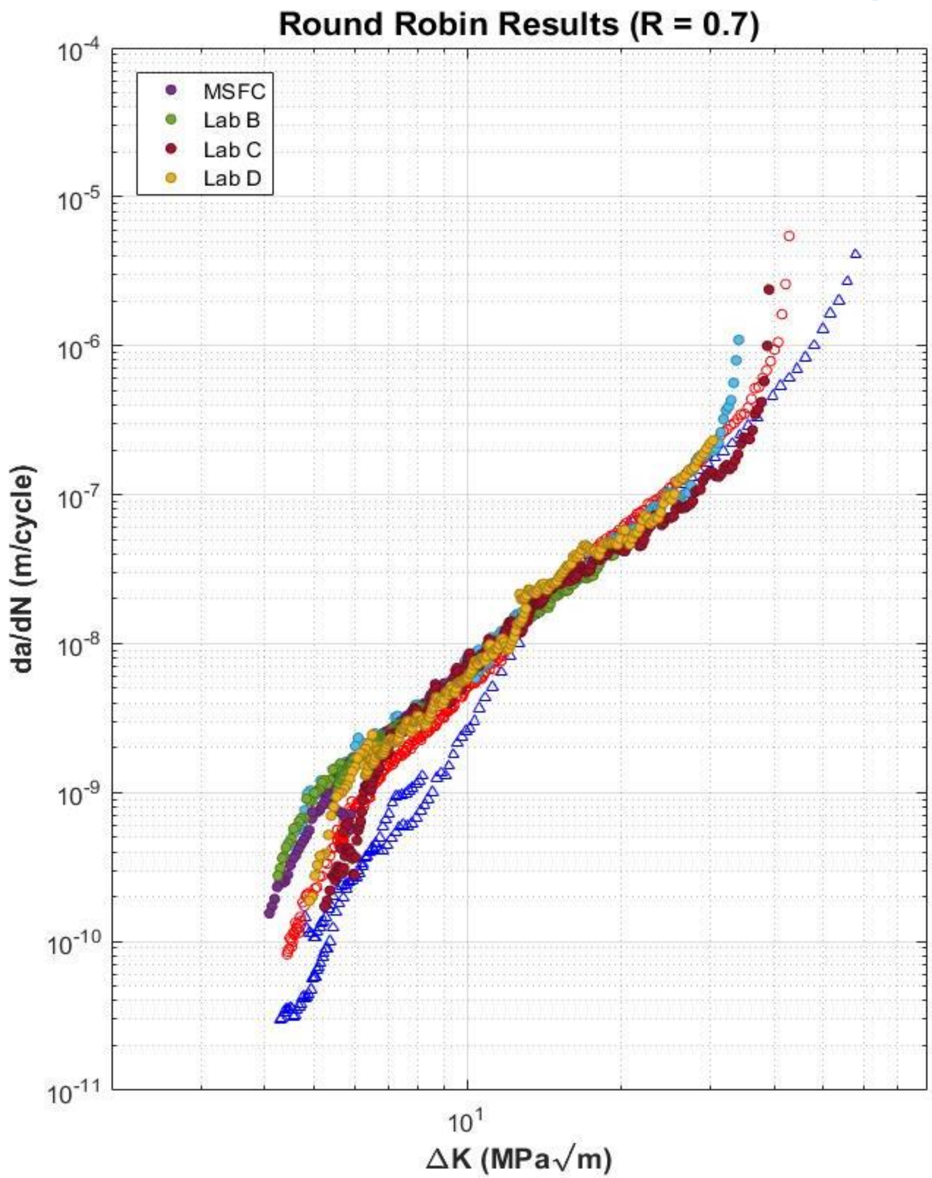
FCG of SLM 718: Lab D results at R = 0.7

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



FCG of SLM 718: All results at R = 0.7

- MSFC & Lab B: Consistent with M1 data
- Lab C & Lab D: Consistent with Newman data



Fracture Toughness of SLM Alloy 718

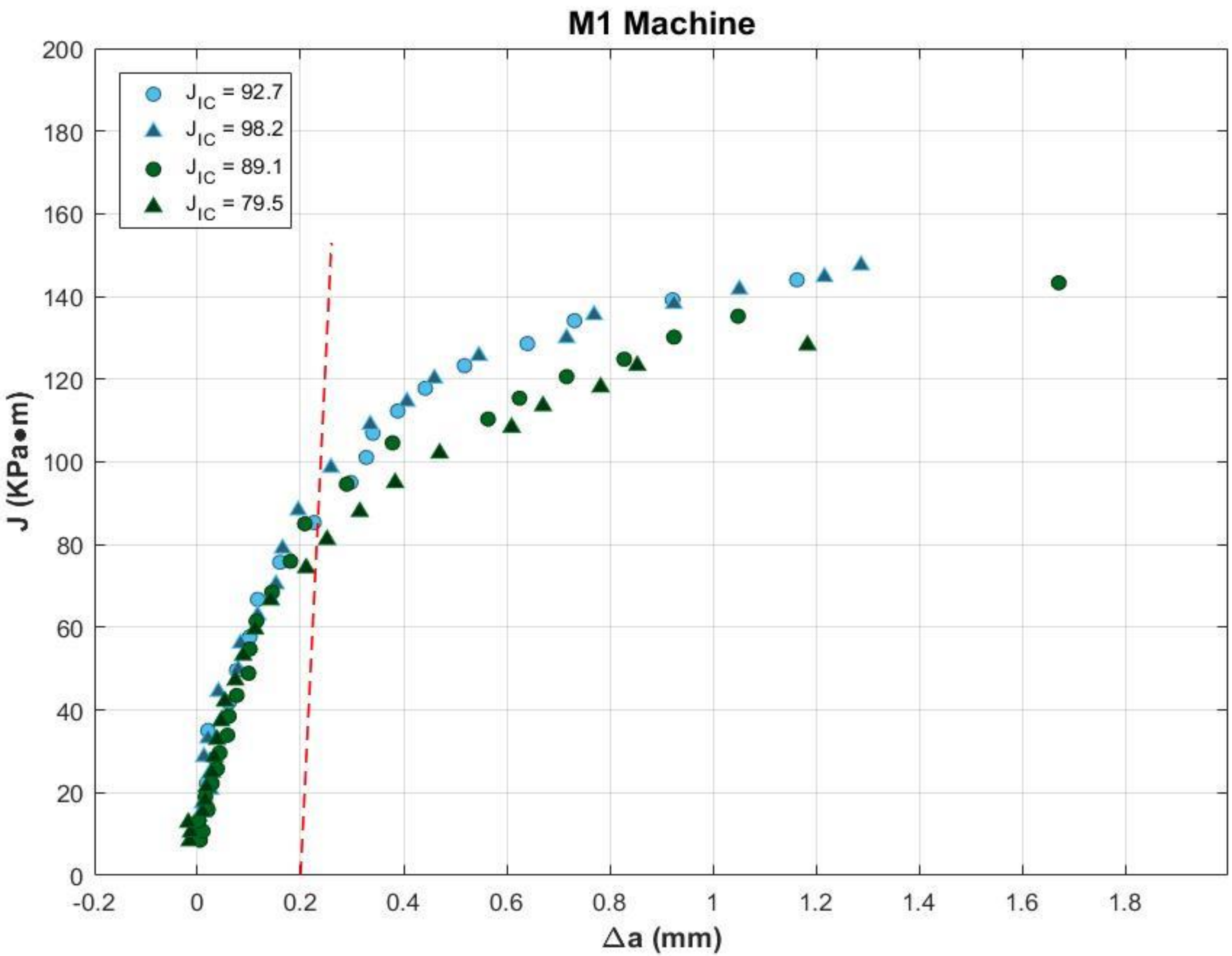
Round Robin Specifications

- 2 specimens from each build
- Z-XY test orientation
- Post-processing same as fatigue specimens

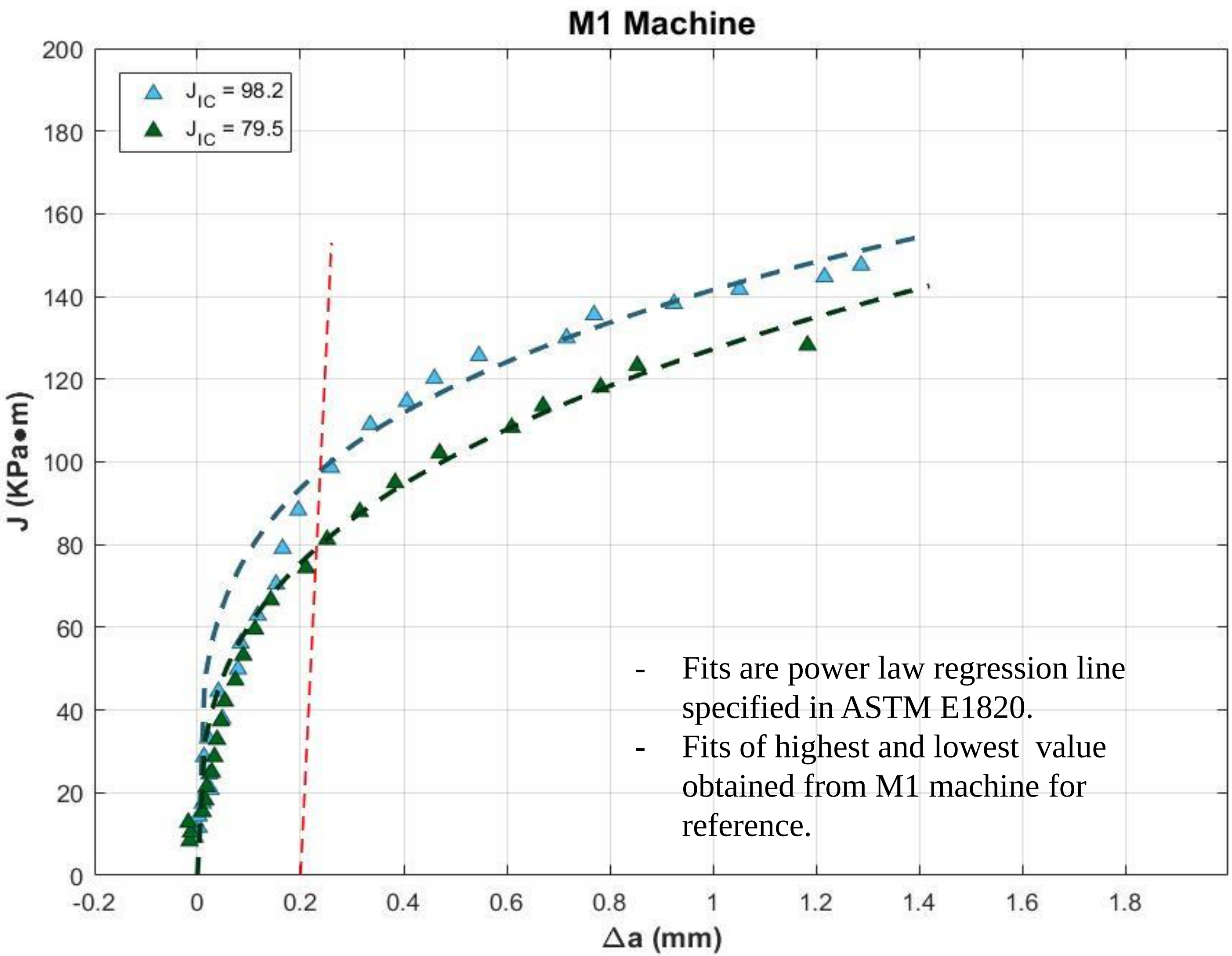
Test Methodology

- Tested according to ASTM E1820

Reference: Fracture Toughness of SLM Alloy 718

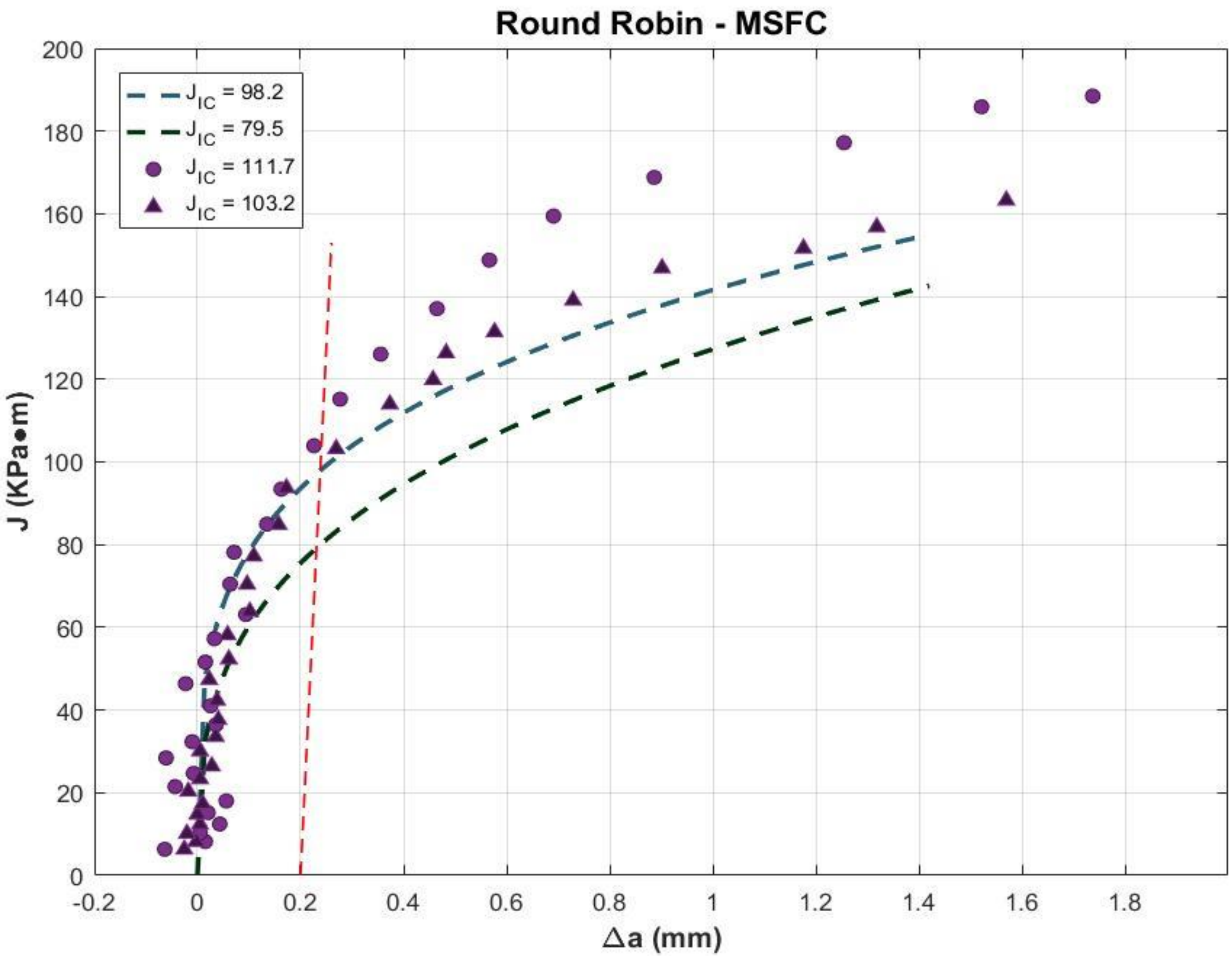


Reference: Fracture Toughness of SLM Alloy 718

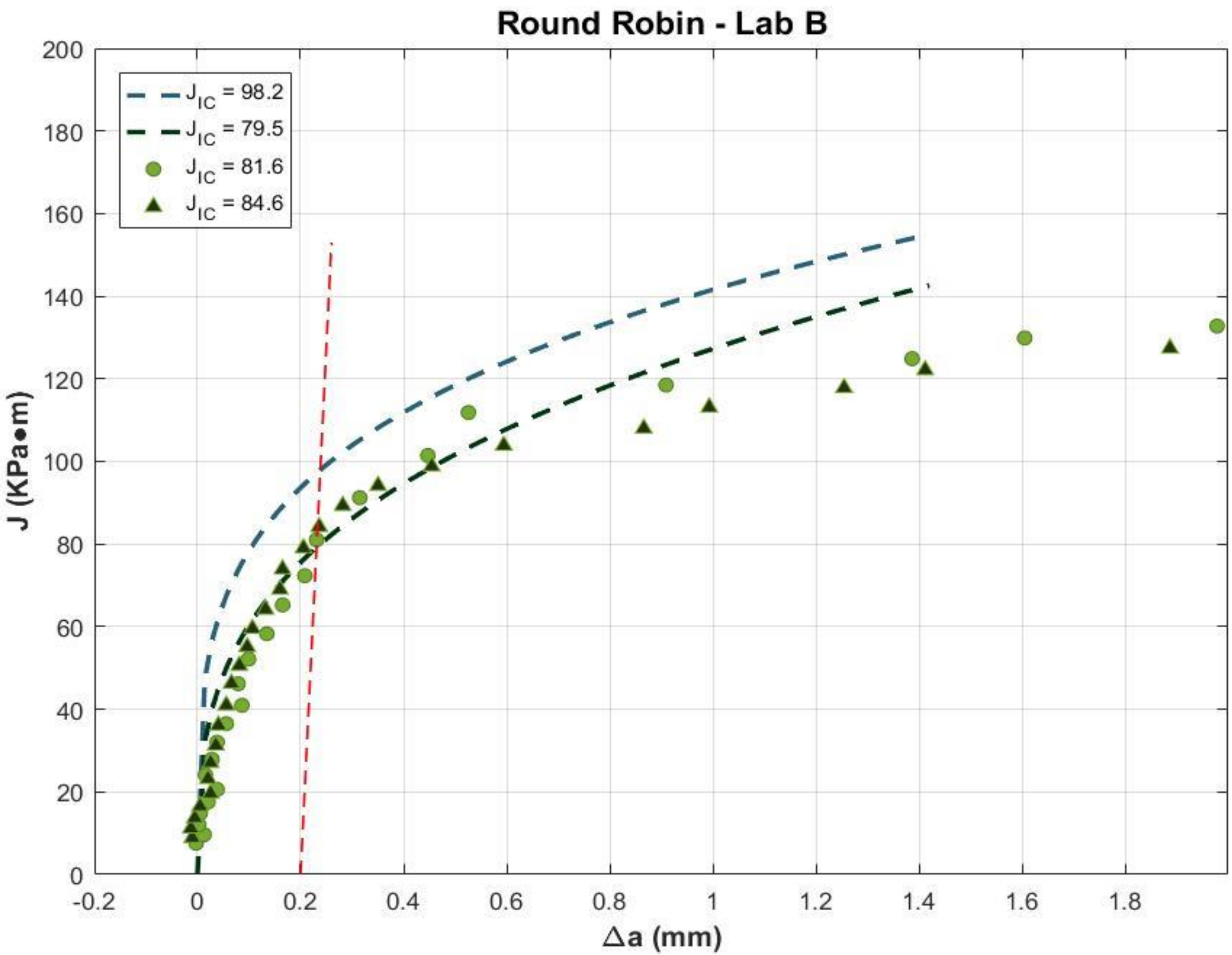


- Fits are power law regression line specified in ASTM E1820.
- Fits of highest and lowest value obtained from M1 machine for reference.

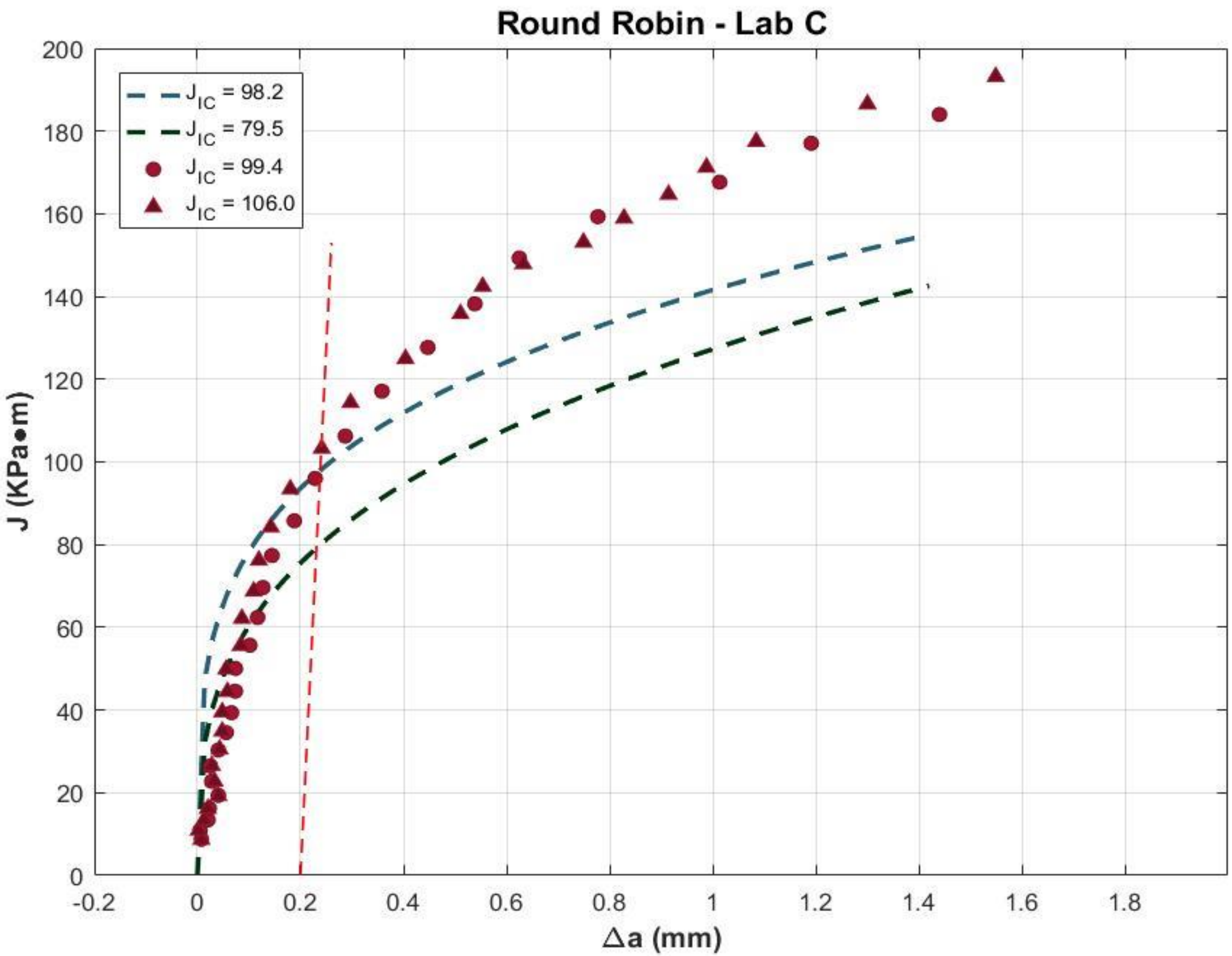
Fracture Toughness of SLM Alloy 718: MSFC Results



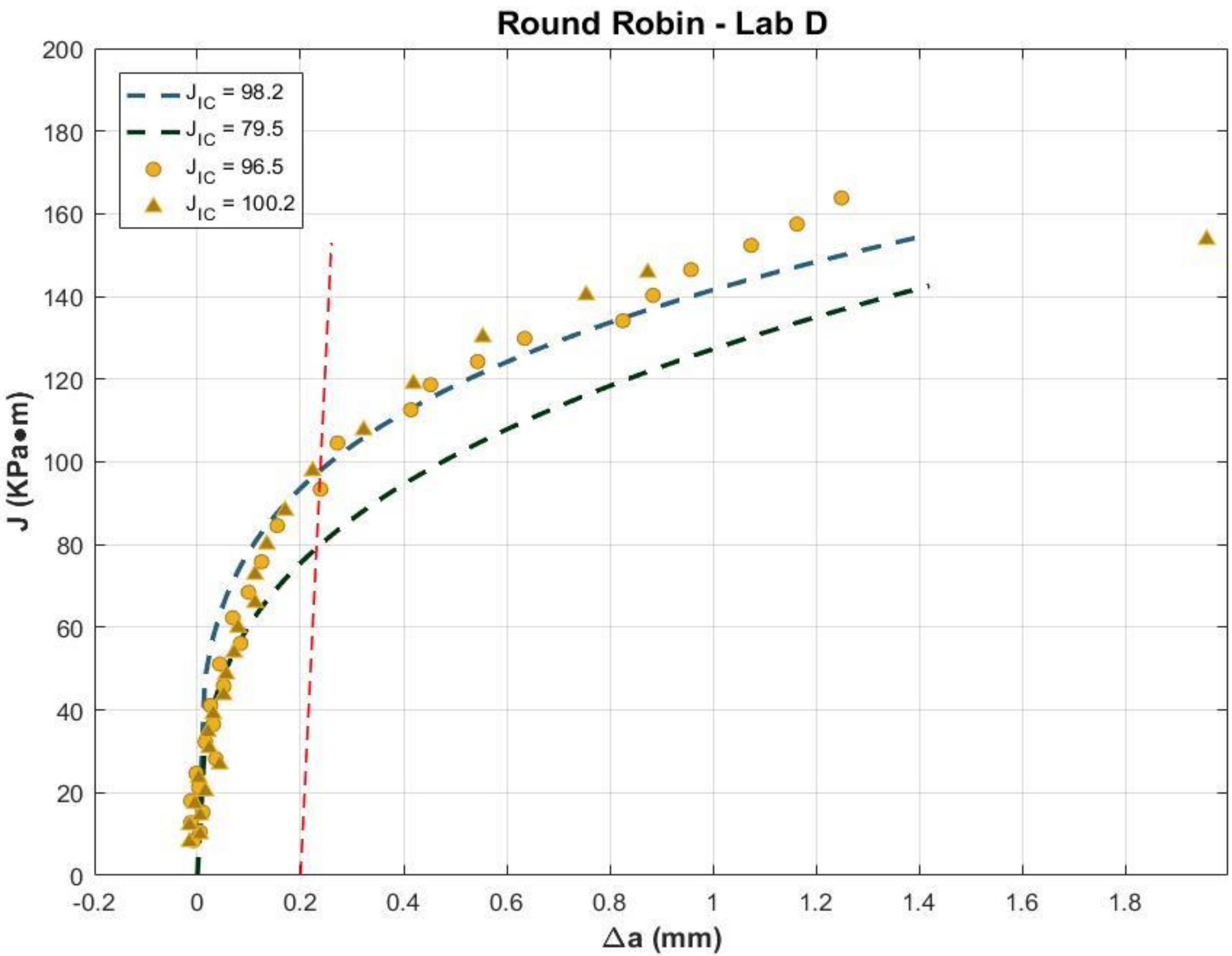
Fracture Toughness of SLM Alloy 718: Lab B Results



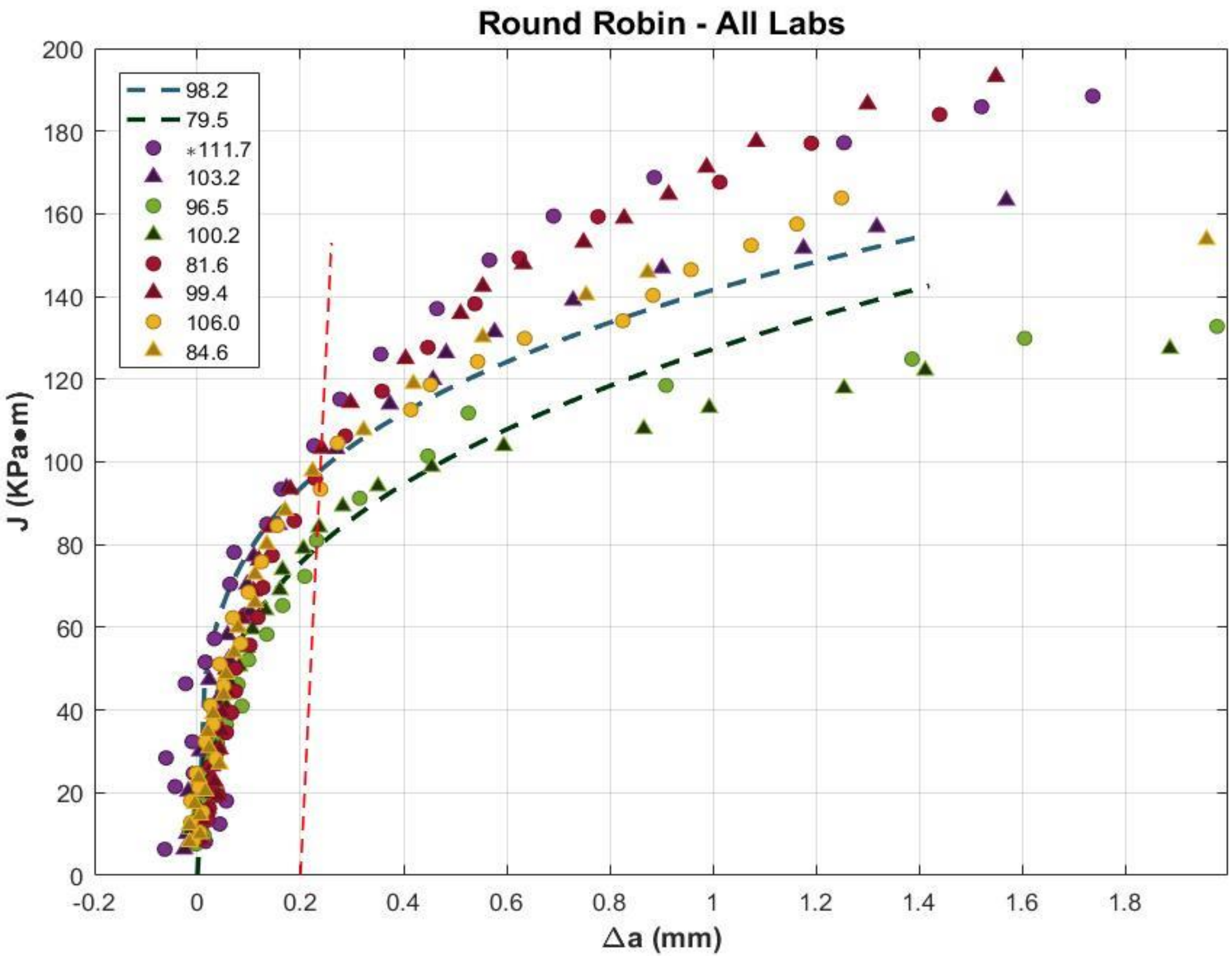
Fracture Toughness of SLM Alloy 718: Lab C Results



Fracture Toughness of SLM Alloy 718: Lab D Results



Fracture Toughness of SLM Alloy 718: All Results



Summary of Observations

Tensile

- Reduced elongation is good indicator of poor quality build.

Fatigue

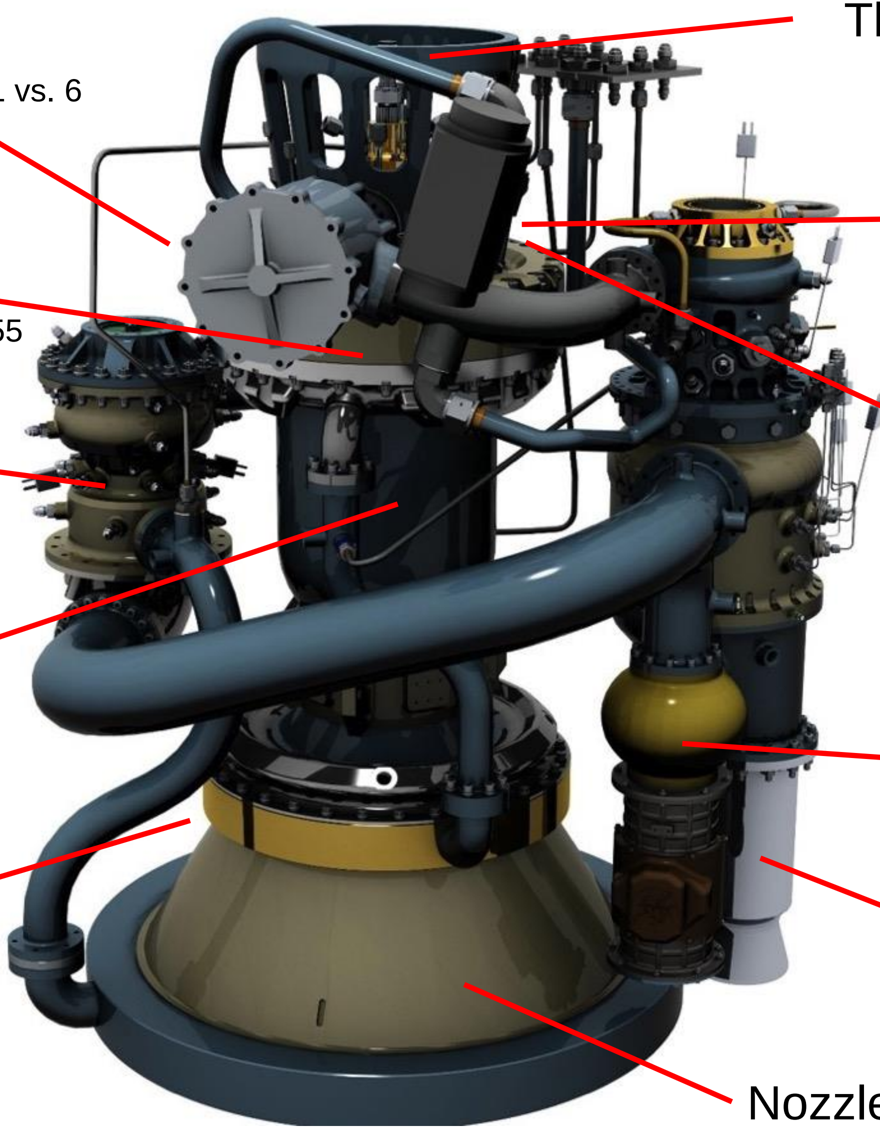
- Surface finish effects were stronger than build orientation influence.
- Surface finish effects dominated internal defects for a defective build.
- Surface finish effects appear to more strongly influence HCF than LCF.
- Mostly consistent da/dN data across 4 laboratories.

Fracture

- Similar initiation toughness values; more variability in R curve shape (tearing modulus).

Propulsion Design and Development

Additive Manufacturing Demonstrator



Transforming Liquid Propulsion Systems DDT&E

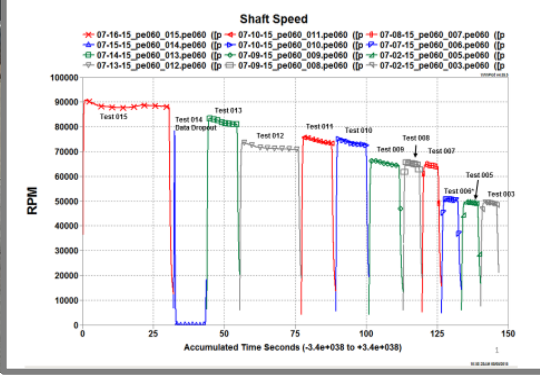
Advanced Manufacturing Demonstrator Test Stand

Fuel Turbopump Performance Test in Hydrogen

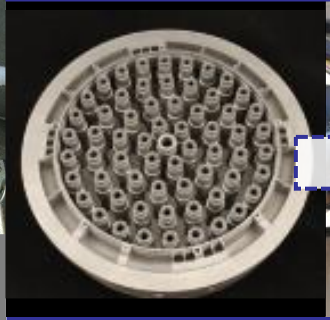
LCUSP MCC Liner

Main Fuel Valve Cryo Test

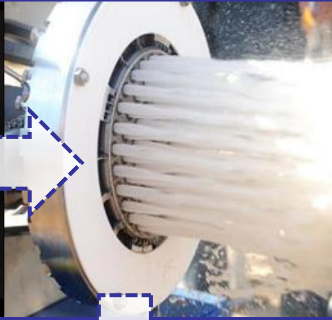
Test Data – Shaft Speed

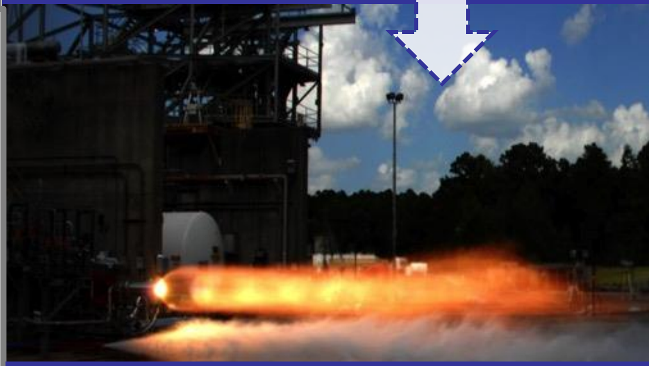


Fuel Scale Injector Swirl Elements



Full Scale Injector Water Flow



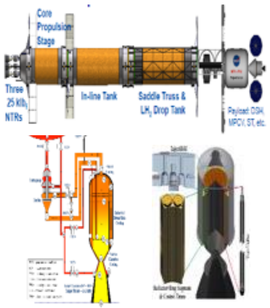


Sub-scale Injector Test

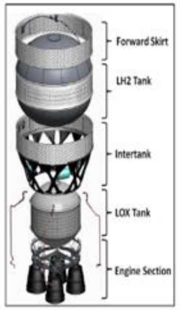
Advanced Manufacturing Demonstrator (AMD)

Investment directly benefits prototype engine development and indirectly enables and facilitates technology across multiple current and future activities for NASA and industry.

Methane Lander

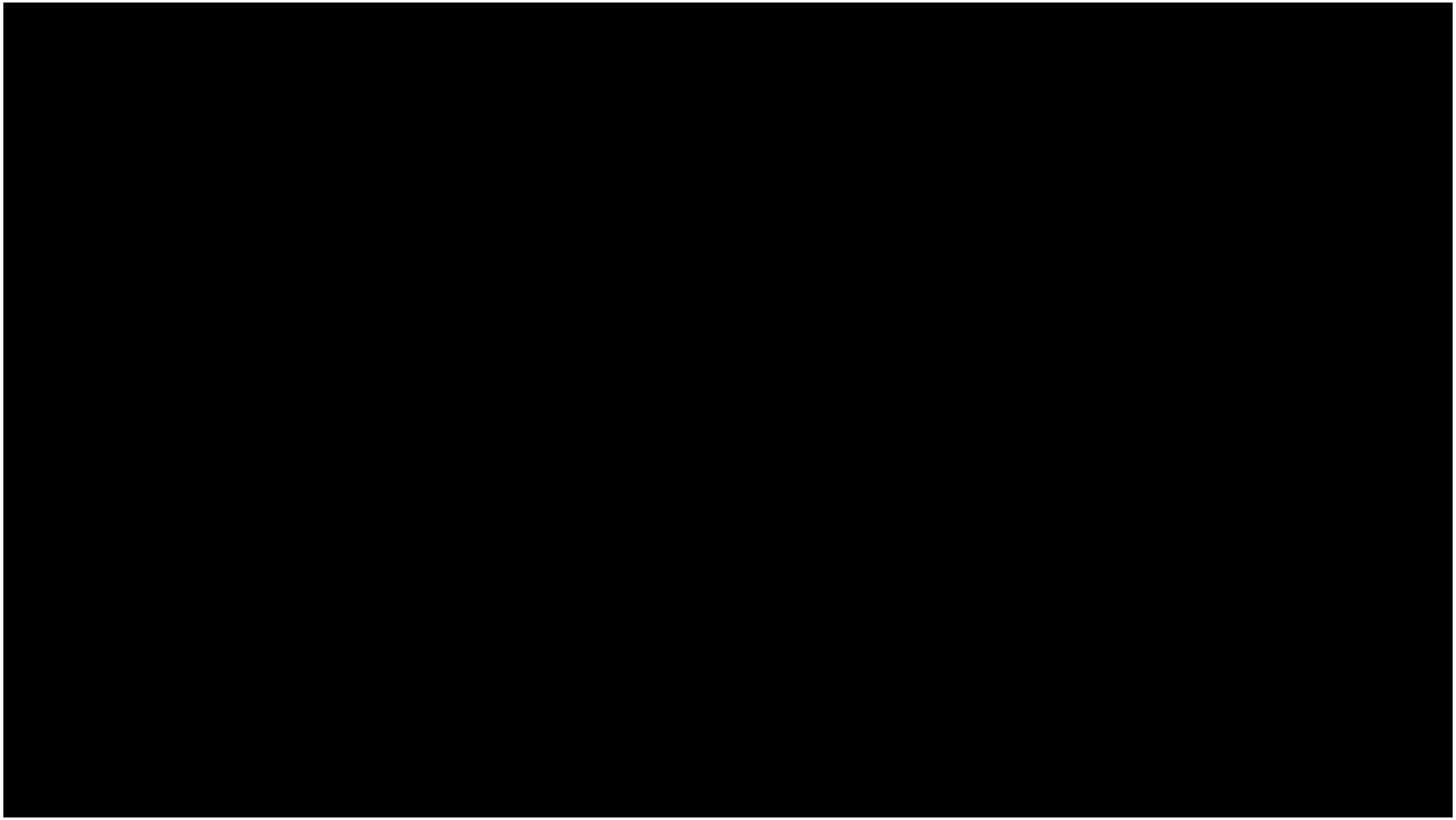


Nuclear Thermal Propulsion (NTP)



Exploration Upper Stage (EUS)

Breadboard Testing



Questions?