NAVAL NUCLEAR LABORATORY | Technology

Fatigue and Mechanical Properties of Laser Powder Bed Fusion 316L Stainless Steel

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Naval Nuclear Laboratory – Schenectady, NY

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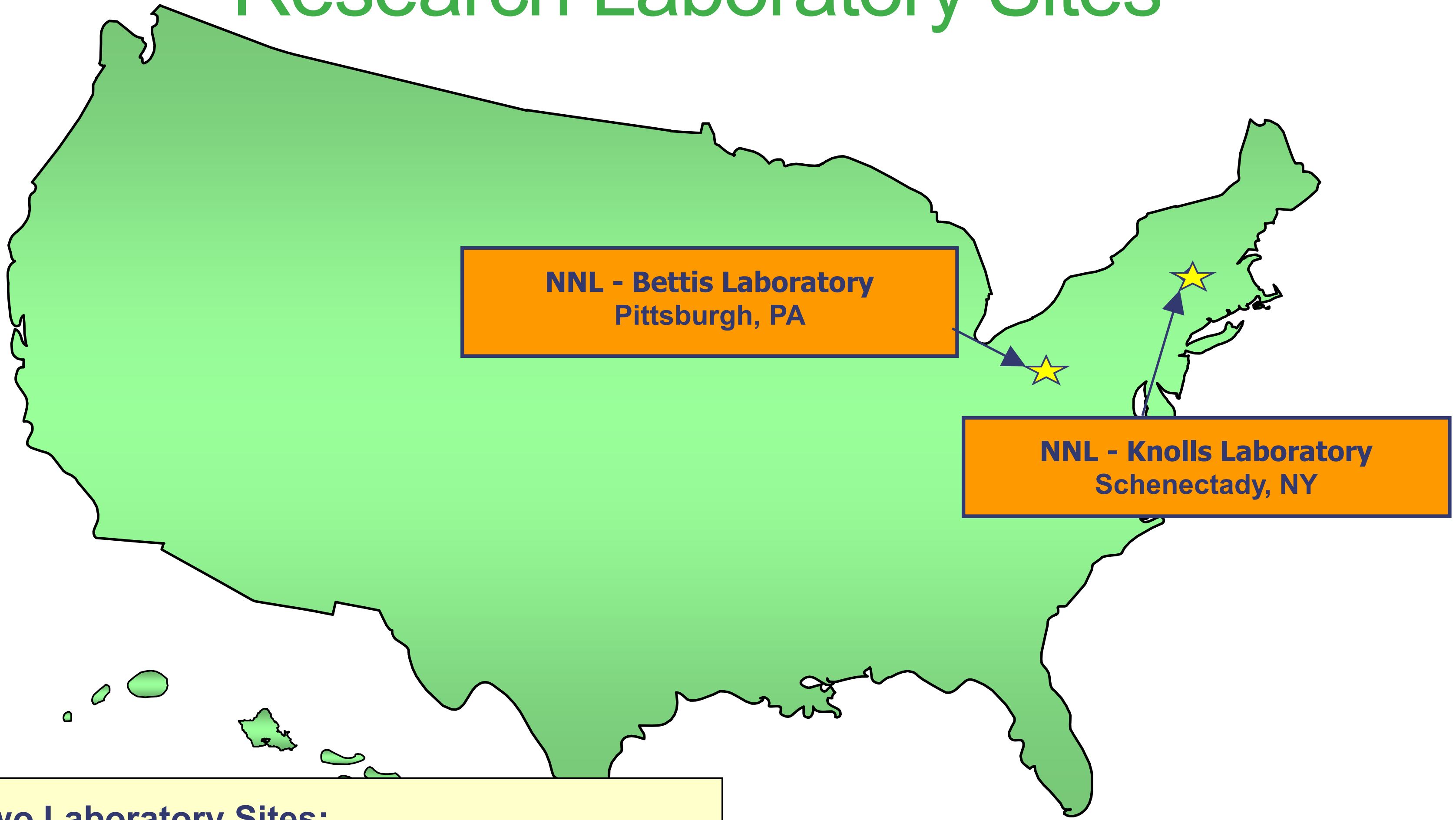
Naval Nuclear Propulsion Program:
A History of Success

Over 80 Nuclear-Powered Ships

Over 167 Million Miles Safely Steamed

Naval Nuclear Laboratory (NNL) Research Laboratory Sites



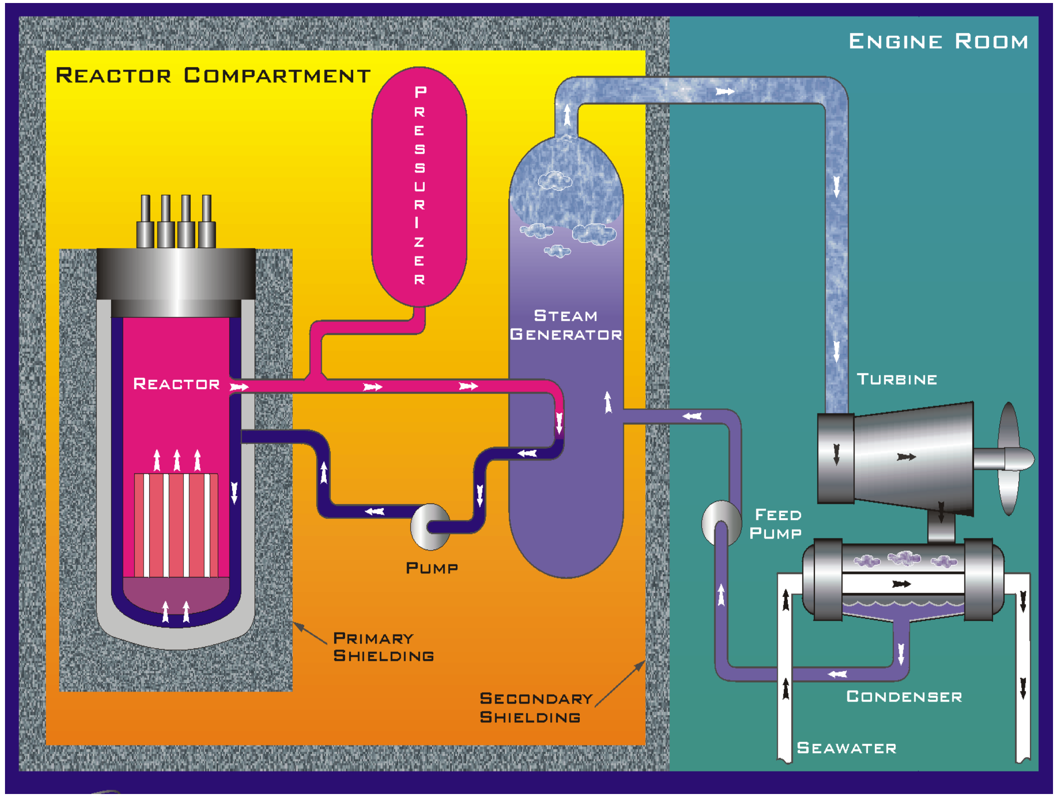
Two Laboratory Sites:

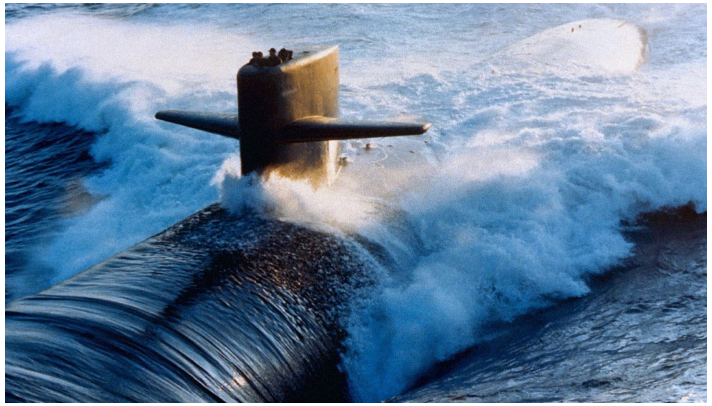
- **Headquarters for NNL Operations**
- **Centers for Design and Engineering**
- **Laboratory, Testing and Experimental Facilities**
- **Operated by FMP**

Naval Nuclear Laboratory Expertise

NNPP Reactor and Propulsion Plant Designs, Equipment, and Support Require Expertise In:

- Acoustics
- Materials Science
- Reactor Engineering
- Instrumentation & Control





- Power Electronics and Distribution
- Experimental Engineering
- Scientific Computations
- Information Technology

NNL Interests in Metal Additive Manufacturing (AM)

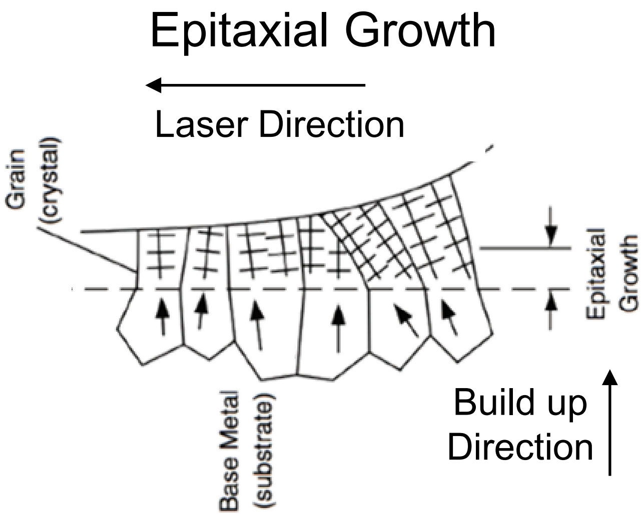
- **The capabilities of metal AM processes have spurred changes to fabrication methods in industries such as aerospace and medical**
  - *More modest changes to date in other areas such as the nuclear industry*

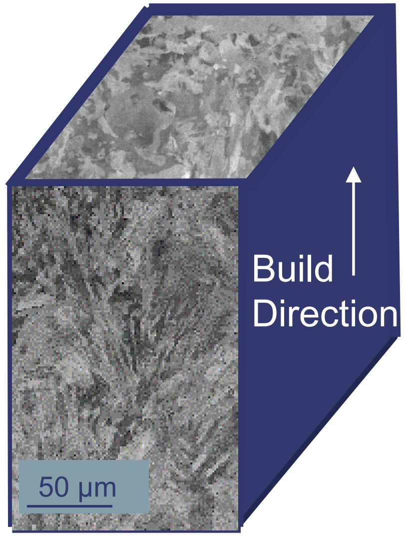
- **Prospective benefits include manufacturing and performance gains**
  - *Delivery time, hard-to-source parts, part consolidation, improved design*
  - *Tooling, rapid prototyping, repairs, hard-to-fabricate parts, tailored design*

Materials of interest include 316L SS and Alloy 625
Components of interest include valves and pump hardware

Laser Powder Bed Fusion (L-PBF)

- L-PBF 316L contains long grains and crystallographic texture in the build direction due to epitaxial growth across layers





Build Parameters and Chemistry for 316L Build

Naval Nuclear Laboratory (NNL) Build
20 µm layer
EOS M290
Hot Isostatic Press (HIP)
Porosity – Witness cylinder <0.05%

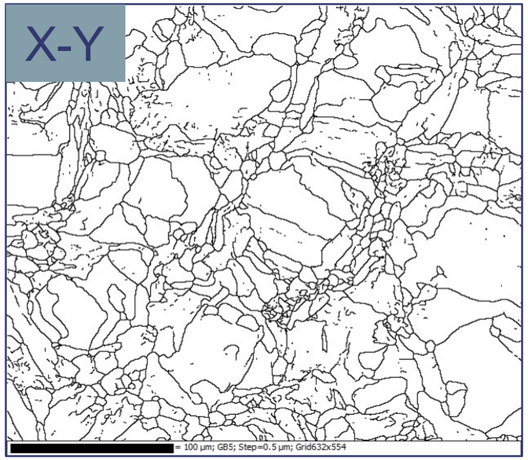
External Vendor (EV) Build
40 µm layer
EOS M290
Hot Isostatic Press (HIP)
Porosity – Witness cylinder <0.03%

	ASTM F3184	ASTM A182	EV As-Built	NNL As-Built	Bar Stock
Iron	Balance	Balance	Balance	Balance	Balance
Chromium	16.0 – 18.0	16.0 – 18.0	17.88 - 17.92	17.64 - 17.98	16.68
Nickel	10.0 – 14.0	10.0 – 15.0	12.95-12.99	13.15 - 13.40	10.62
Carbon	0.030, max.	0.030, max.	0.013	0.015 - 0.017	0.018
Copper	–	–	0.02	0.03	0.36
Manganese	2.00, max.	2.00, max.	1.22	0.84 - 0.87	1.38
Molybdenum	2.00 – 3.00	2.00 - 3.00	2.37	2.38 - 2.43	2.05
Nitrogen	–	0.10, max.	0.083 - 0.084	0.090 - 0.091	0.045
Oxygen	–	–	0.014 - 0.015	0.020 - 0.026	--
Phosphorus	0.045, max.	0.045, max.	0.009	0.005 - 0.007	0.026
Sulfur	0.030, max.	0.030, max.	0.004 - 0.005	0.004 - 0.005	0.0285
Silicon	1.00, max.	1.00, max.	0.78 - 0.80	0.70 - 0.72	0.28
Cobalt	–	–	0.02	0.03	0.28
Boron	–	–	<0.005	<0.005	--
Tantalum	–	–	<0.01	<0.01	--

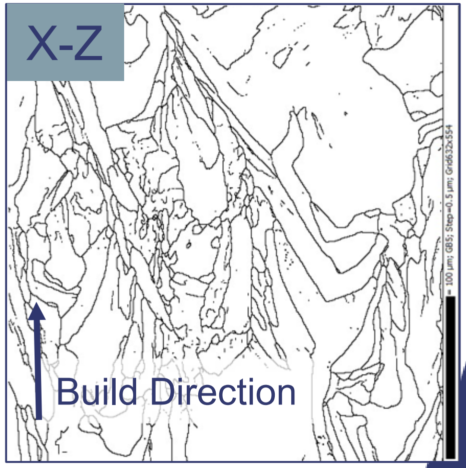
Microstructure

- Similar grain size and structure between builds
- Precipitate size and locations (primarily along grain boundaries) similar between builds
- Texture was stronger in the NNL build

Grain Sizing



Grain Size 19.5 μm
Aspect Ratio 3.4

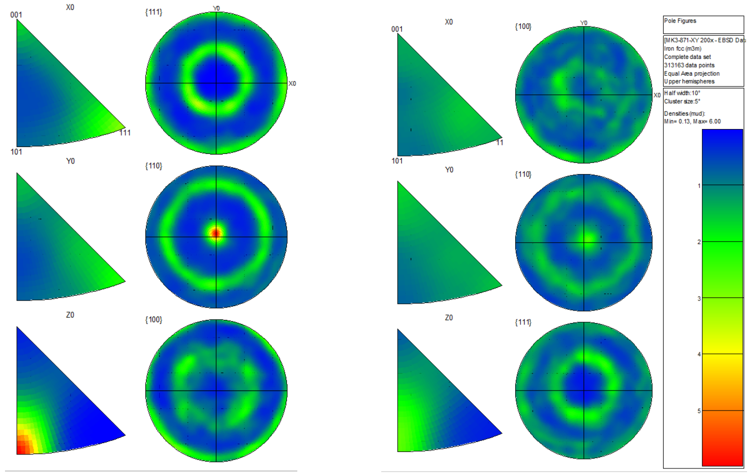


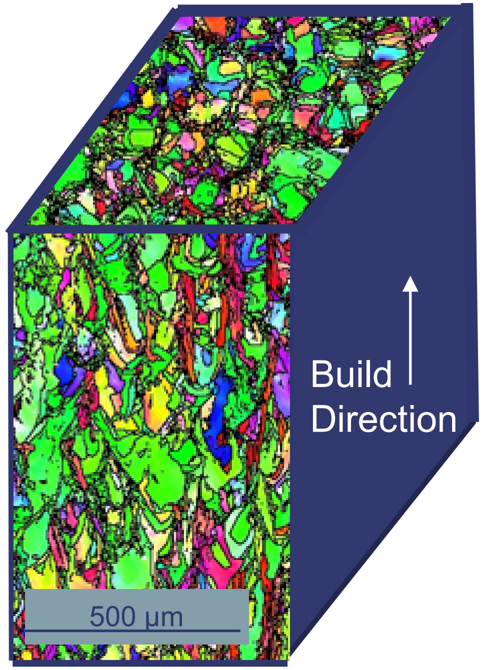
Grain Size 25 μm
Aspect Ratio 3.4

Texture

NNL

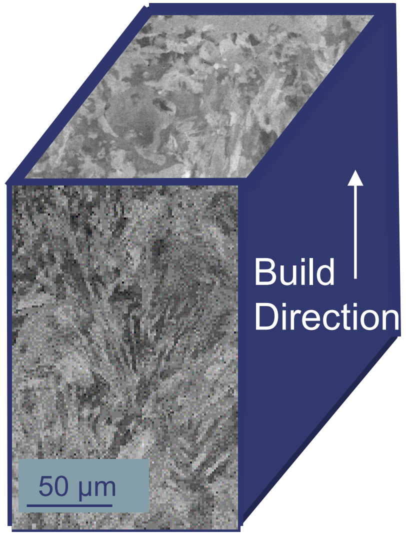
EV

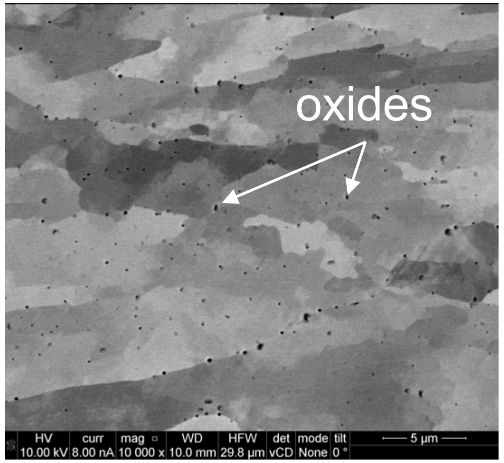




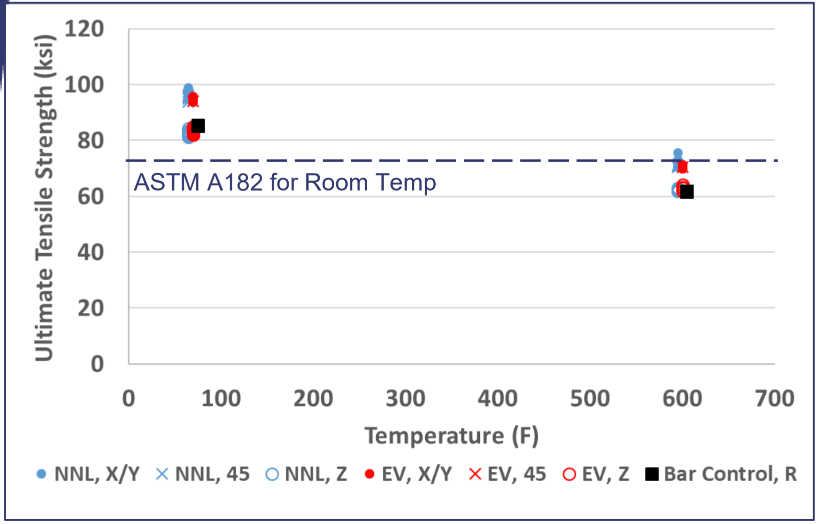
IPF-Z

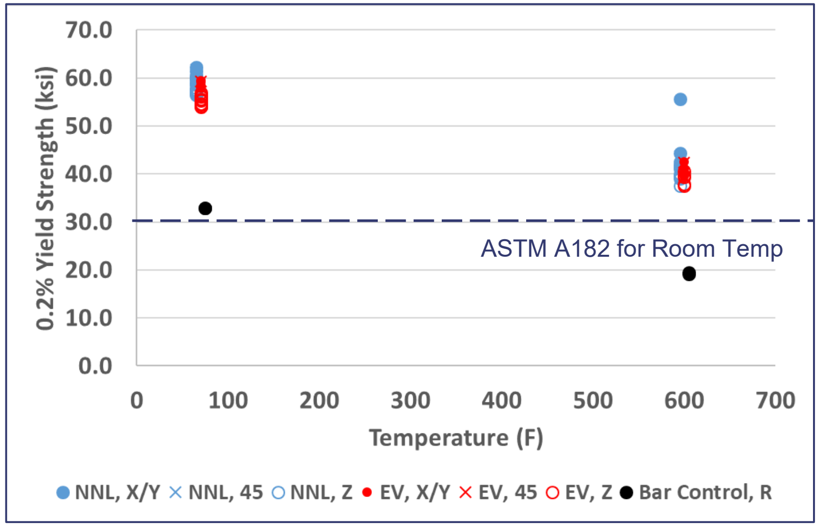
Microstructure

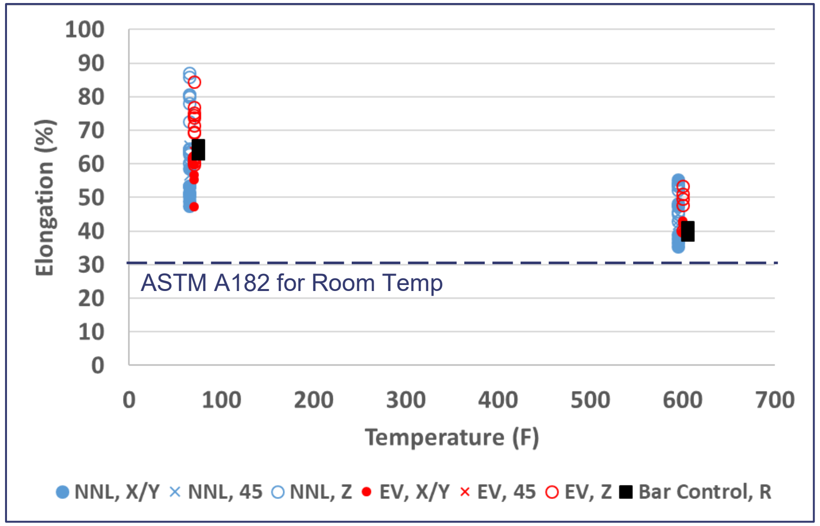


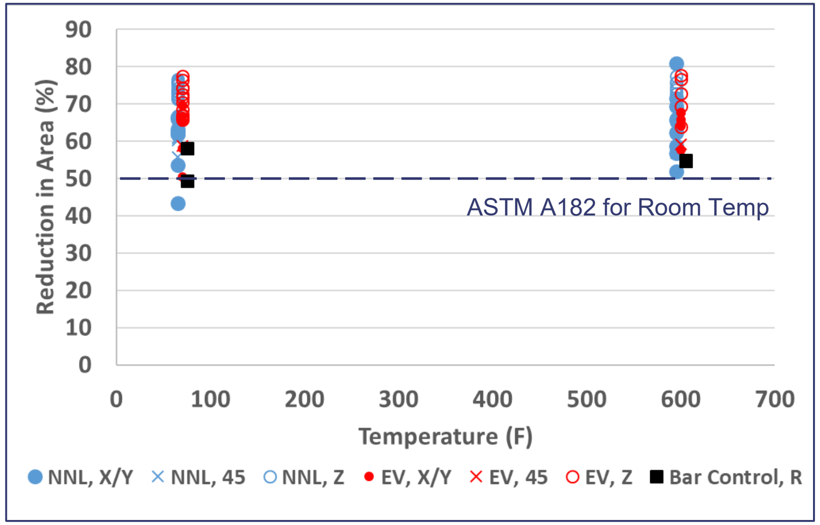


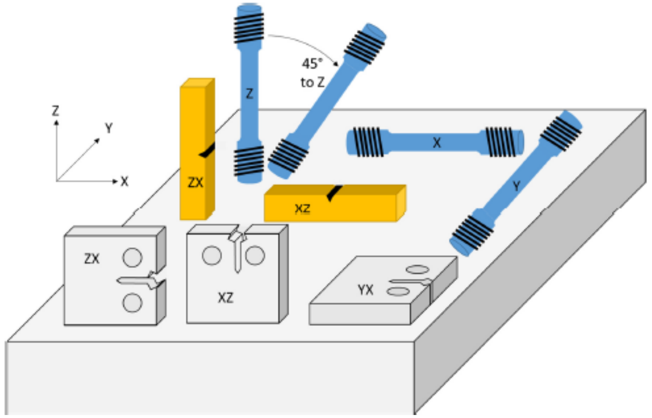
Tensile Testing



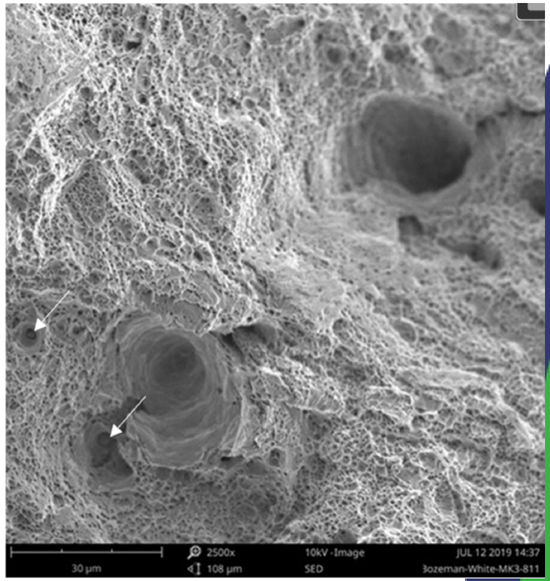








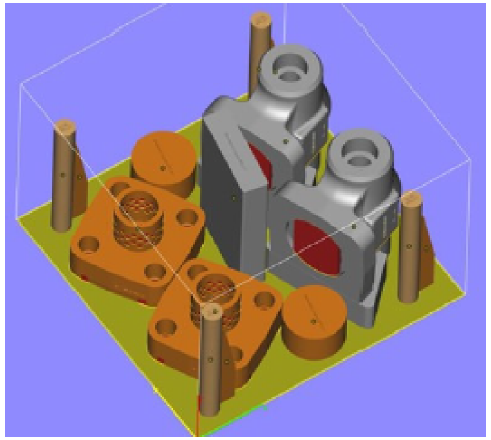
Specimen Orientations

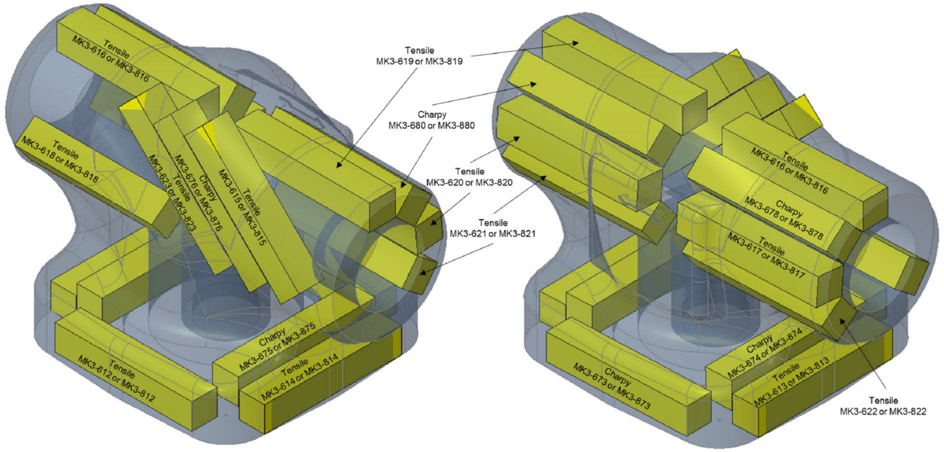


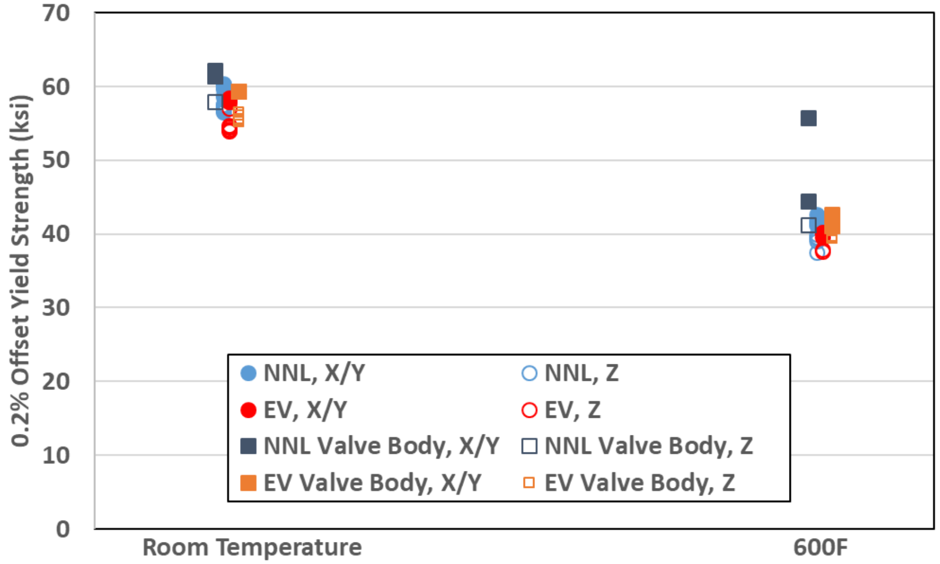
Fractography

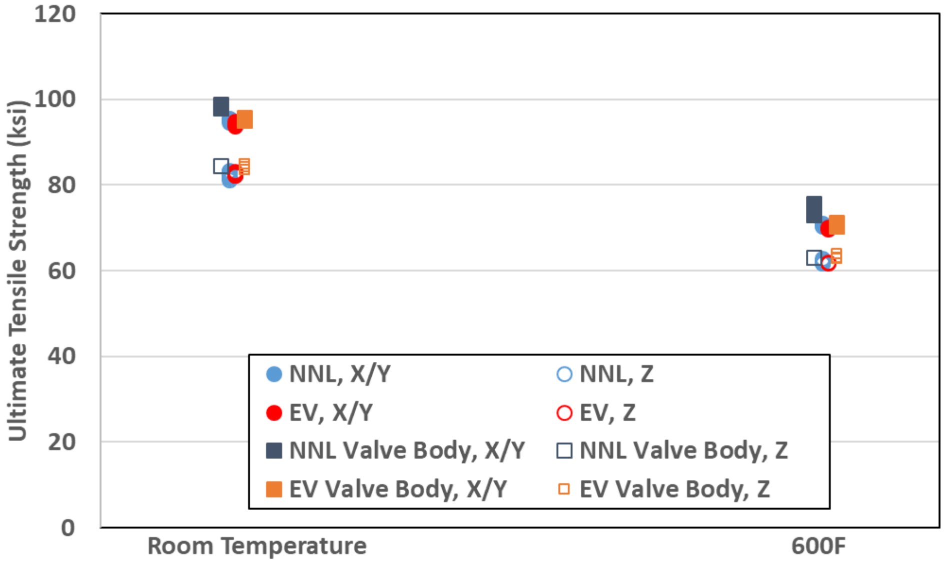
Tensile Testing

- Minimal difference in properties between witness coupon and body specimens

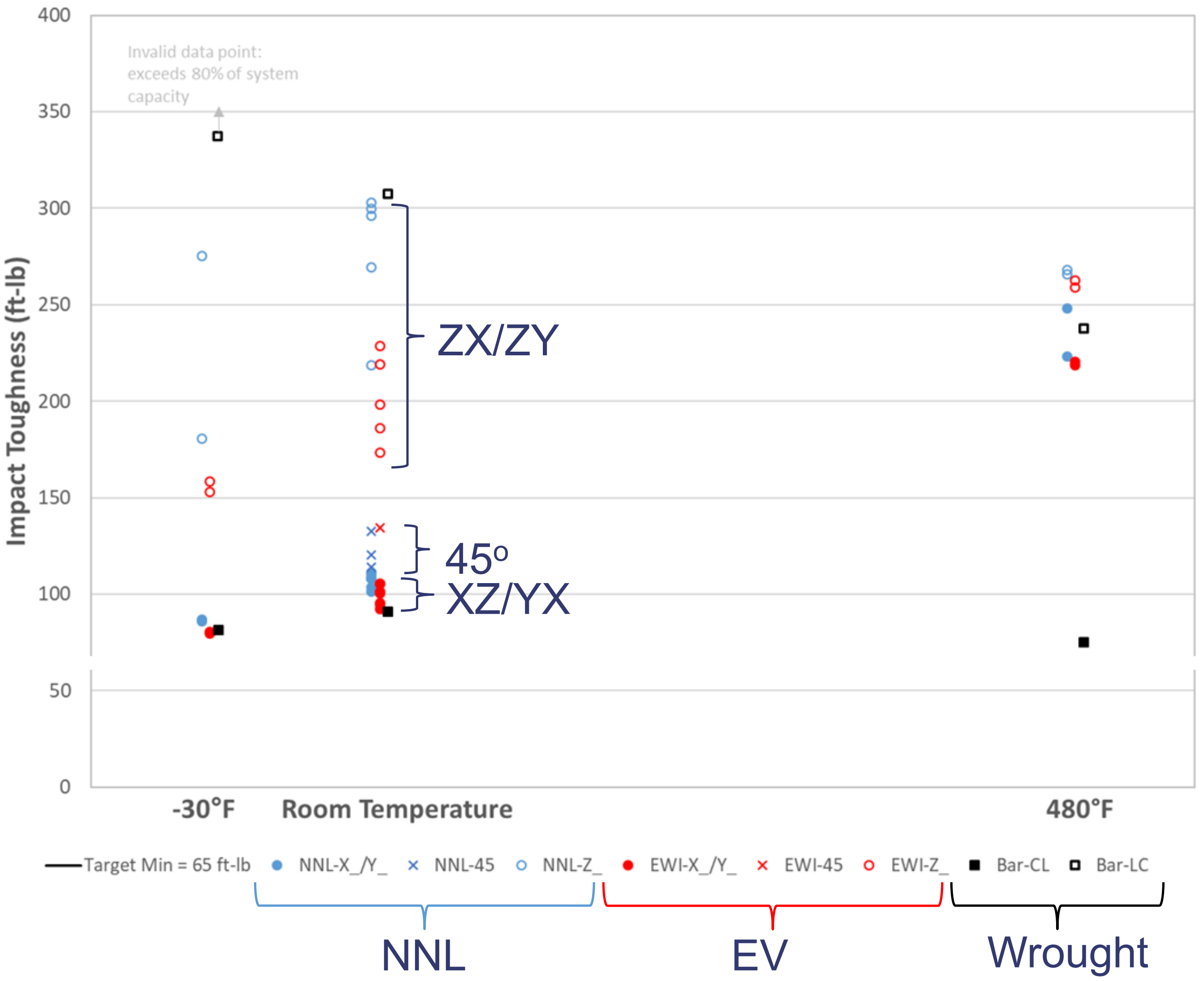


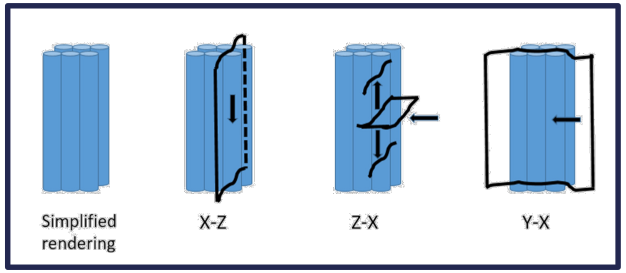


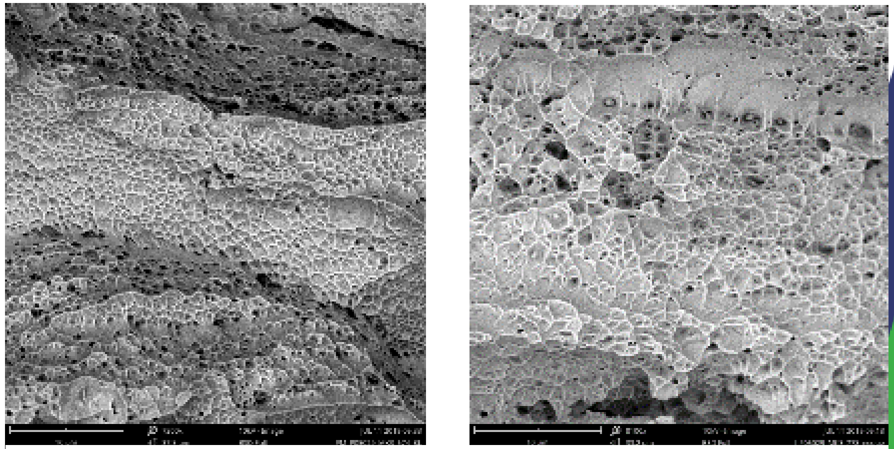




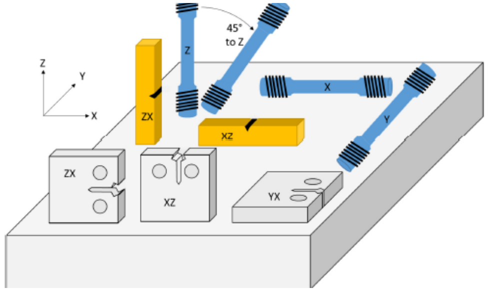
Charpy Impact Toughness





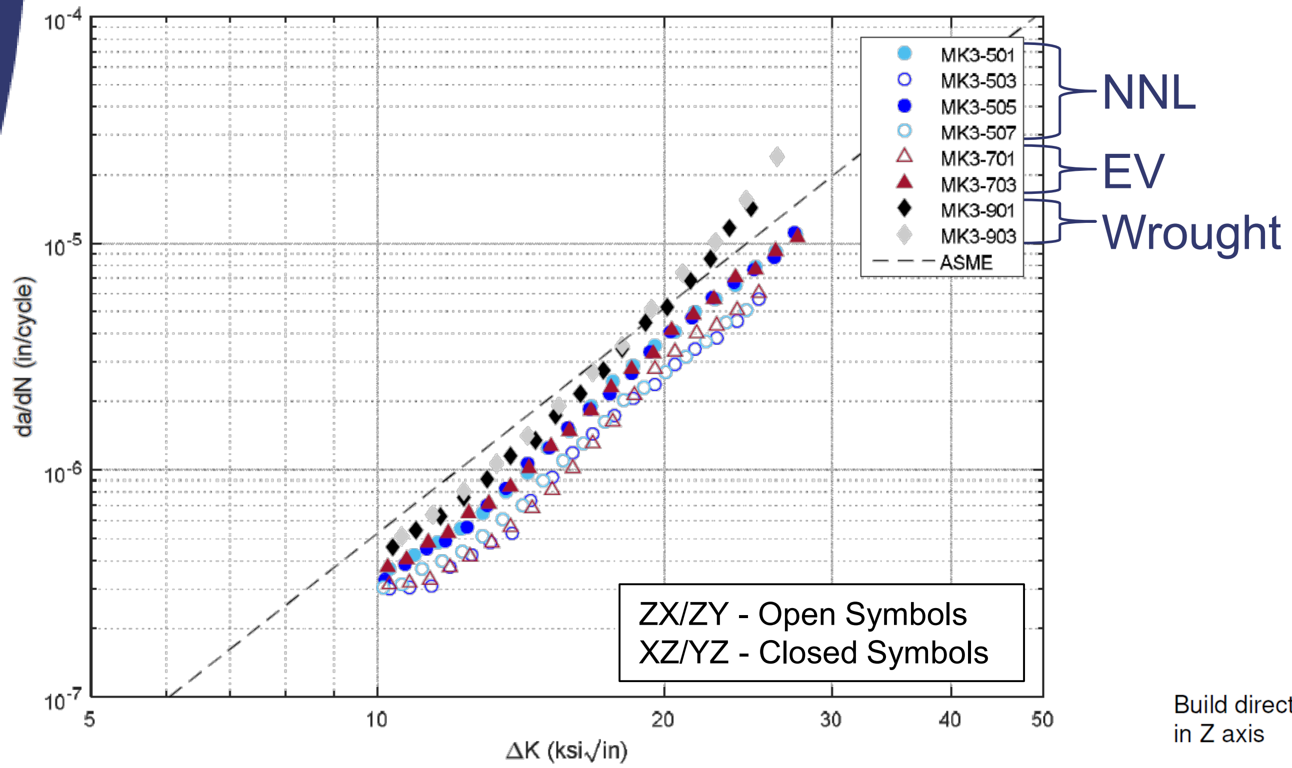


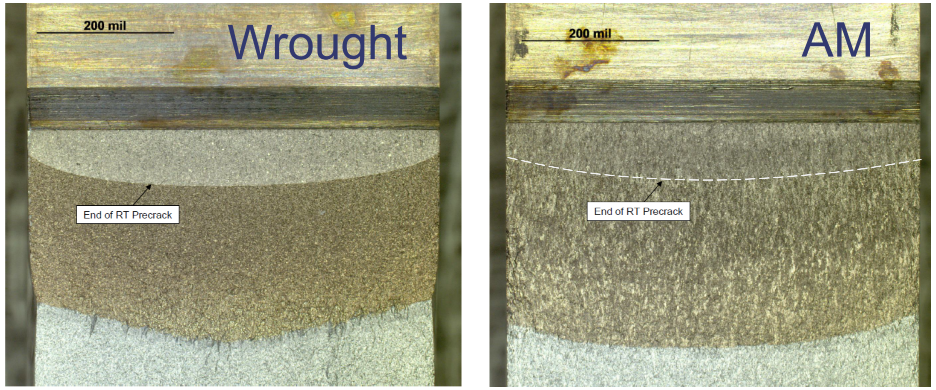
Secondary Electron Microscopy (SEM) images of lowest energy fracture surfaces



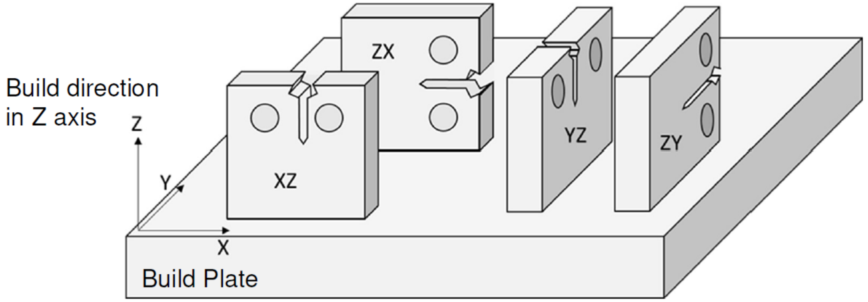
Testing according to ASTM E23-16b

480°F Air Fatigue Crack Growth Testing



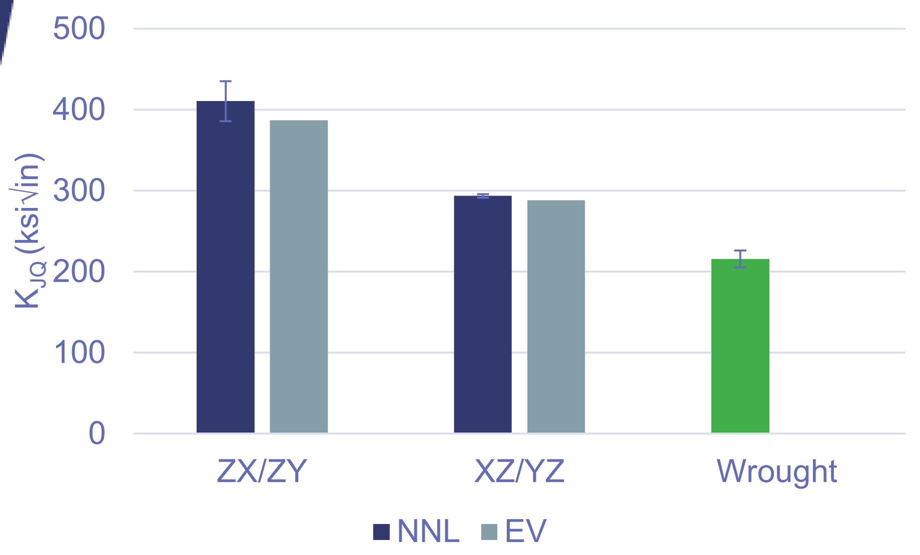


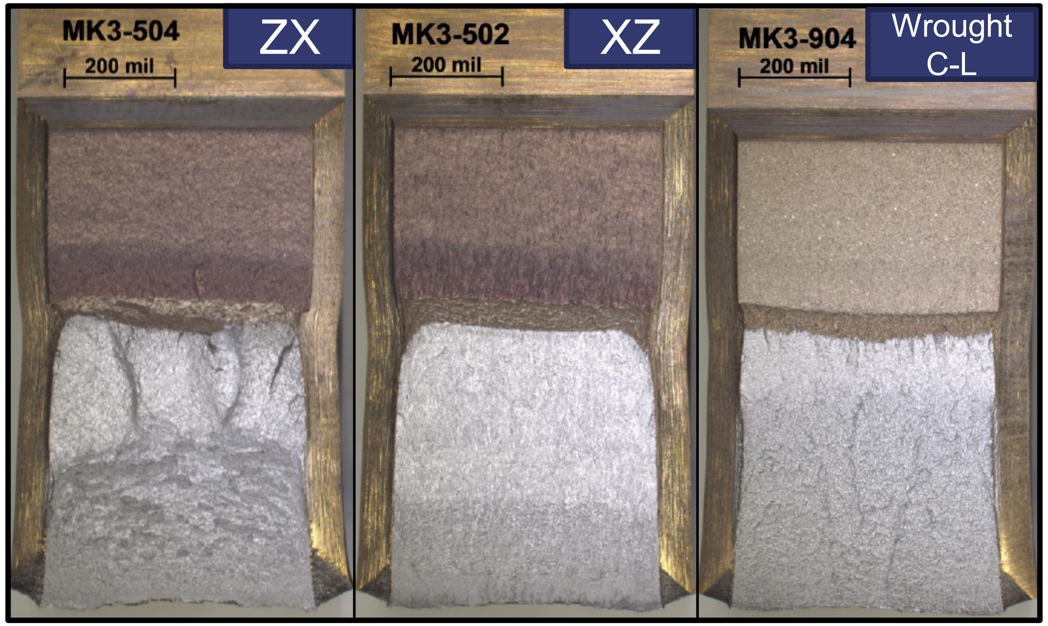
Heat tint more difficult to see in AM material

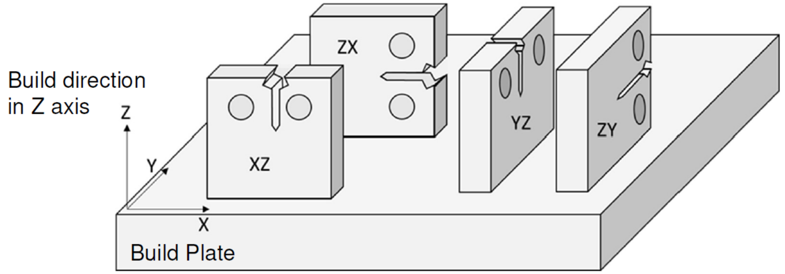


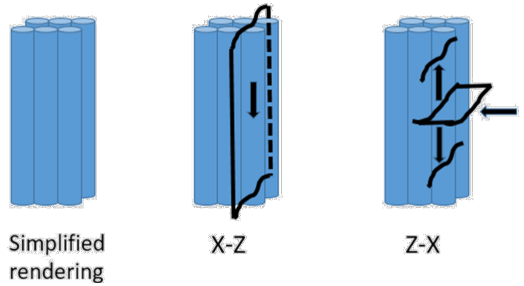
Testing according to ASTM E647-15$^{\varepsilon 1}$
Temperature: Precrack 70 °F air, Test 480 °F air
Stress Ratio: Precrack R = 0.1, Test R=0.3
Clip gage compliance method used
ASME Boiler and Pressure Code, Section XI, Article C-8410 for Austenitic Steels

Fracture Toughness









Testing according to ASTM E1820-17a
70F, air
Precrack to 0.55 a/W, 0.6T C(T) specimens
Partially side-grooved (10% total) prior to precrack and then further side-grooved prior to test (additional 10% total)

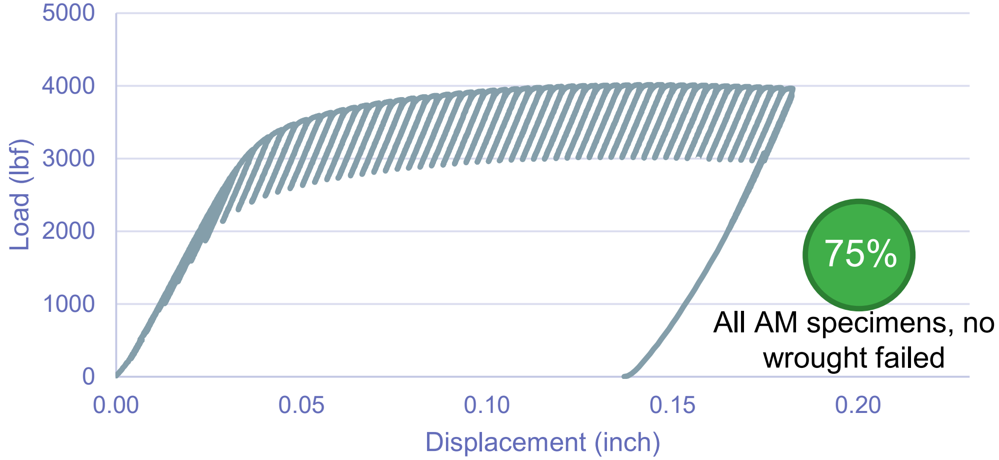
Fracture Toughness

E1820 Validity Criteria

- High toughness performance made it difficult to meet all validity requirements and therefore qualify K_Q as K_{Ic}.

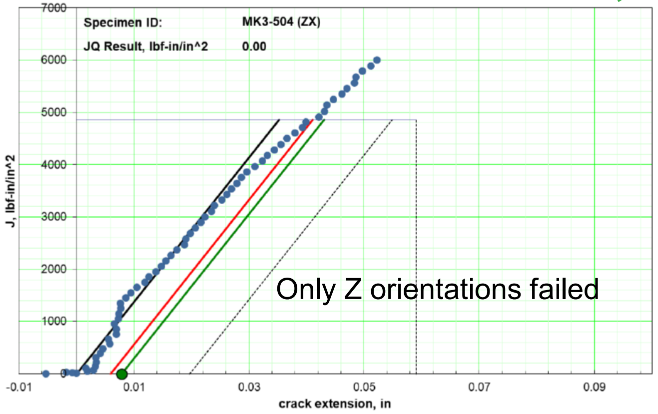
ASTM E1820 -17a: Section 9.1.5.2

Load-Disp Curve



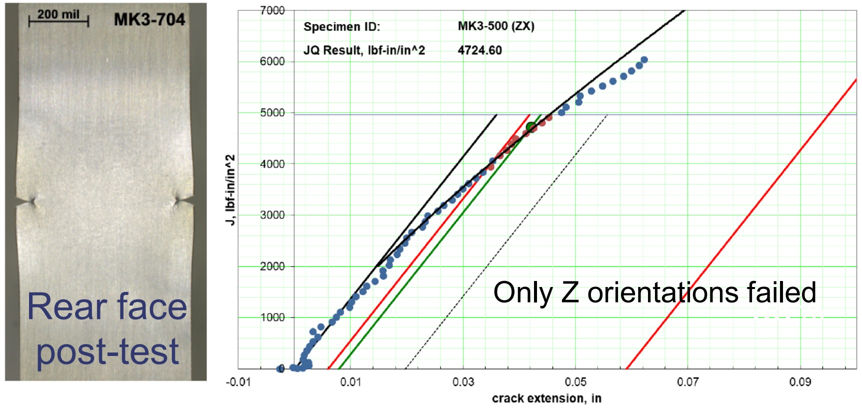
($\Delta a_{predicted}$) at the last unloading differed from physical crack extension (Δa_p) by more than $0.15\Delta a_p$ for crack extensions less than $0.2b_o$, and $0.03b_o$ thereafter.

ASTM E1820 -17a: Section A9.6.4, A9.6.6.6



Not enough qualified data points (Region A or B)

ASTM E1820 -17a: Section A8.3.1, A9.10.1, A9.10.2



Maximum J-integral capacity was exceeded, thickness and initial ligament < 10 J_Q/σ_Y

Summary

- Similar microstructure and properties were observed across vendors and when comparing test blocks to components
- Orientation effects caused by deposition process could be traced back to microstructural differences and texture in material
- Despite orientation effects, AM material performed as good as or better than wrought material
- Satisfactory performance of AM material gives confidence in qualification of methods for component fabrication and use of this material in applications