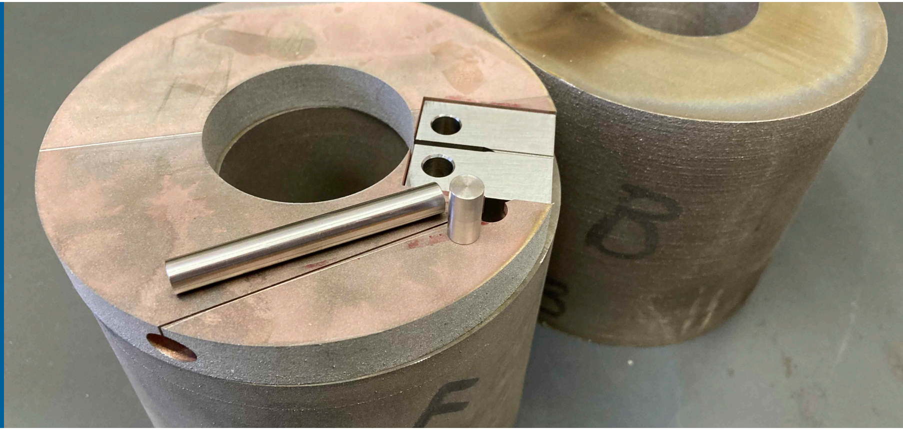
PERFORMANCE OF LASER ADDITIVELY MANUFACTURED SS316L IN LWR-RELEVANT ENVIRONMENTS



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2023 NRC Workshop on Advanced Manufacturing Technologies for Nuclear Applications
Oct. 24-26, 2023, NRC Headquarters, Rockville MD

PRESENTATION TOPICS

- Introduce new US DOE LWRS program at ANL “Performance Evaluation of Additive Manufacturing Materials for Light Water Reactor Sustainability”

- Present preliminary results
  - Preliminary Stress Corrosion Cracking (SCC) Crack Growth Rate (CGR) Evaluations
  - Preliminary Fatigue Evaluations

- Embedded watermarks in AM components

PERFORMANCE EVALUATION OF ADDITIVE MANUFACTURING MATERIALS FOR LIGHT WATER REACTOR SUSTAINABILITY

Objective:

Facilitate the adoption of Additively Manufactured (AM) technologies by the nuclear industry to fabricate replacement parts faster and cheaper, thus, facilitating the extended operation of the existing LWR fleet

Tasks:

Task 1: Support the regulatory acceptance of EPRI-led ASME code case (Record # 20-254) by conducting the additional stress corrosion cracking (SCC) and environmentally-assisted fatigue (EAF) testing

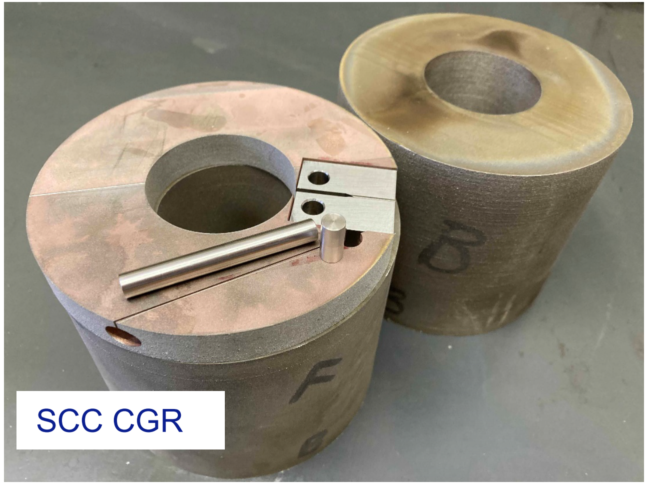
Task 2: Understand and quantify the effect of AM surface on fatigue and SCC crack initiation (CI) in LWR environment

Task 3: Evaluate the applicability of ANL-proposed F_{en} model to AM-produced alloys as well as long term operation

PERFORMANCE EVALUATION OF ADDITIVE MANUFACTURING MATERIALS FOR LIGHT WATER REACTOR SUSTAINABILITY

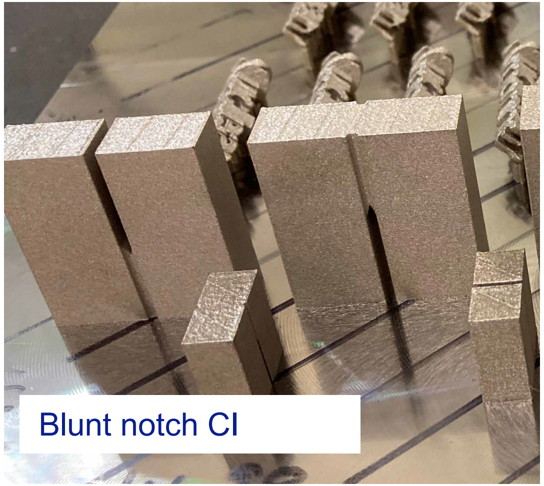
FY24 Key activities to be initiated

- EAF and SCC testing of AM materials to support the regulatory acceptance of EPRI-led ASME code case (Record # 20-254) submitted in Section III, Division 1 – Subsection NB/NC/ND, Class 1, 2 and 3 Components.
- Testing to understand and quantify the effects of porosity and AM surface finishing on the fatigue and SCC crack initiation in LWR environment.
- Evaluation of the applicability of ANL-proposed Fen model to AM-produced alloys as well as long term operation.



SCC CGR

Fatigue, EAF



Blunt notch CI

PRELIMINARY RESULTS

- Preliminary Stress Corrosion Cracking (SCC) Crack Growth Rate (CGR) Evaluations
- Preliminary Fatigue Evaluations

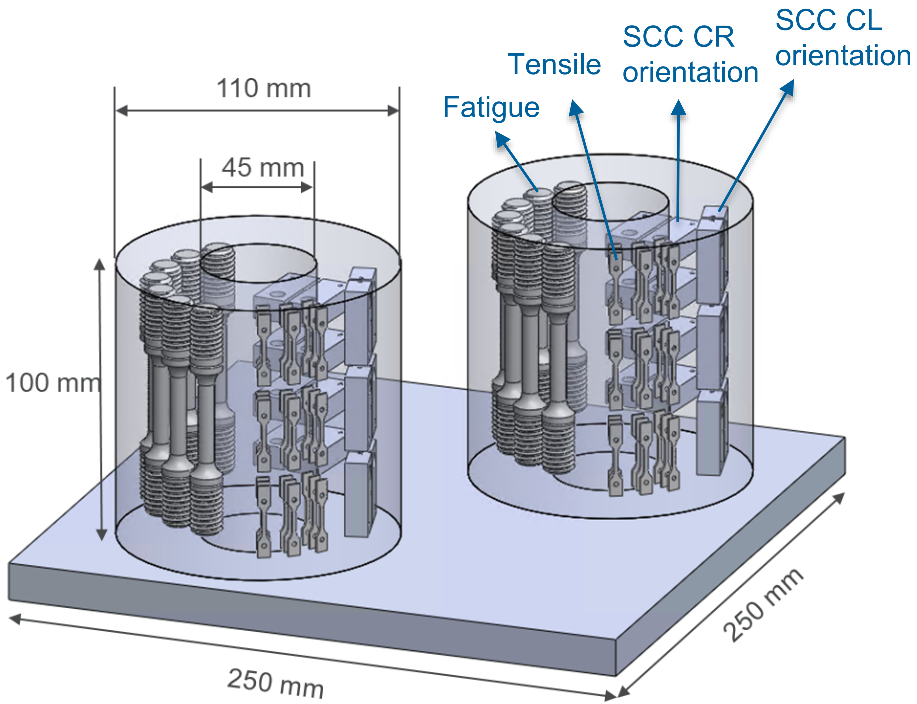
Objective

- Evaluate the “performance” of AM 316L SS in a light water reactor (LWR) – relevant environments, and compare with the response of the conventionally-produced alloy

Approach

- Build a component-like part using laser powder bed fusion (LPBF)
- Conduct microstructural investigation (with a focus on porosity)
- Conduct mechanical testing <u>on the as-printed</u> alloy with a focus on “performance testing” – SCC CGR and fatigue, and compare with the behavior of the conventionally-produced alloys

AM 316L TUBES



- AM 316L SS tubes – surrogates for component-like structures - were produced at Argonne with the Renishaw AM400 LPBF system

BUILD PARAMETERS

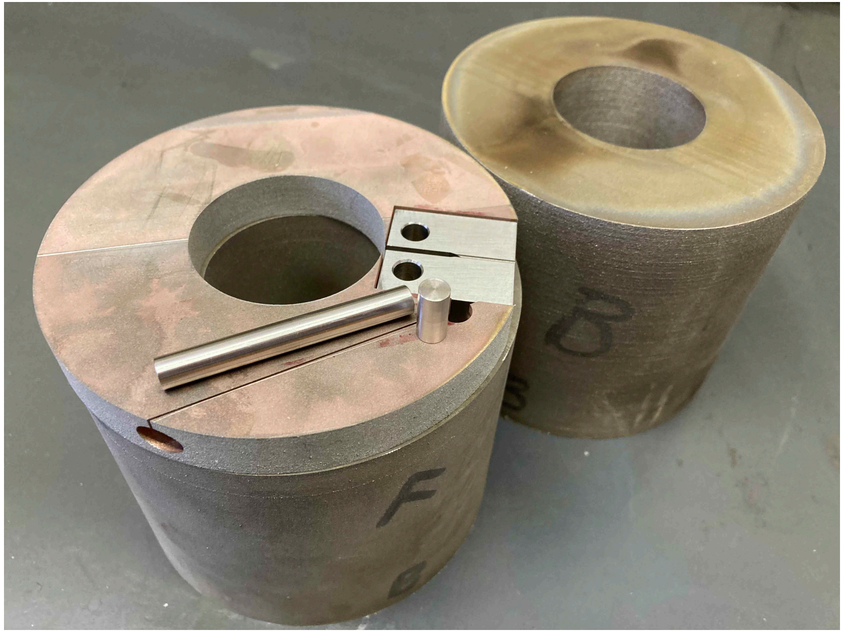
Parameter	Value
Laser Power	195 W
Layer Thickness	50 µm
Melting Method	Stripe (5mm)
Rotation	67 degrees
Exposure Time	80 µs
Point Distance	60 µm
Effective Velocity	0.75 m/s
Hatch Spacing	110 µm
Energy Density	53.33 J/mm^3
Recoater Blade	Rubber
Atomization Gas	Argon
Build Chamber Atmosphere	Argon
Equipment Type	Renishaw AM400

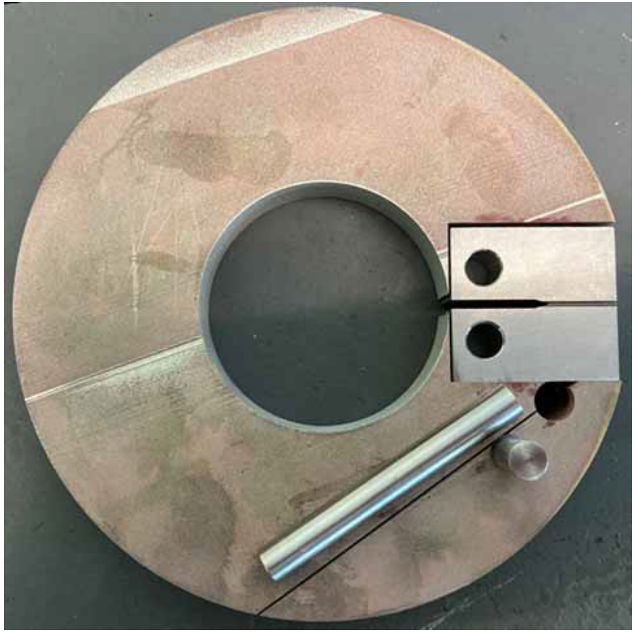
- AM 316L SS tubes were produced at Argonne with a Renishaw AM400 LPBF system

Composition of powder

Element	Mass (%)
Iron	Balance
Chromium	16.00 to 18.00
Nickel	10.00 to 14.00
Molybdenum	2.00 to 3.00
Manganese	≤ 2.00
Silicon	≤ 1.00
Nitrogen	≤ 0.10
Oxygen	≤ 0.10
Phosphorus	≤ 0.045
Carbon	≤ 0.03
Sulphur	≤ 0.03

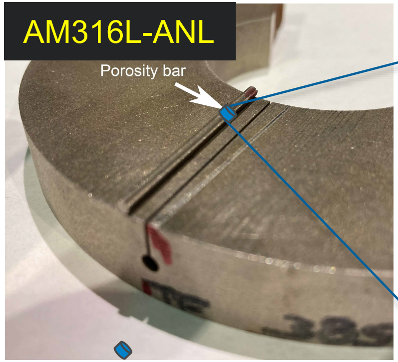
AM 316L SS TUBES



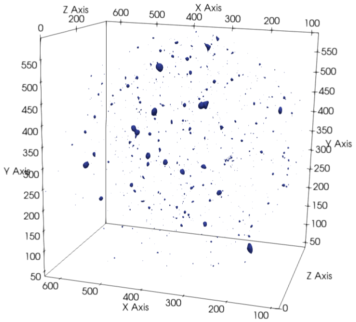


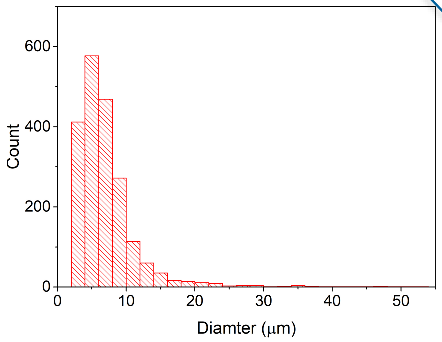
- Compact tension (CT) samples for crack growth testing (CR orientation) and rod samples for synchrotron X-ray tomography measurement were machined from the as-built part
- Porosity is evaluated at the same location as the test plane in the CT specimen

POROSITY



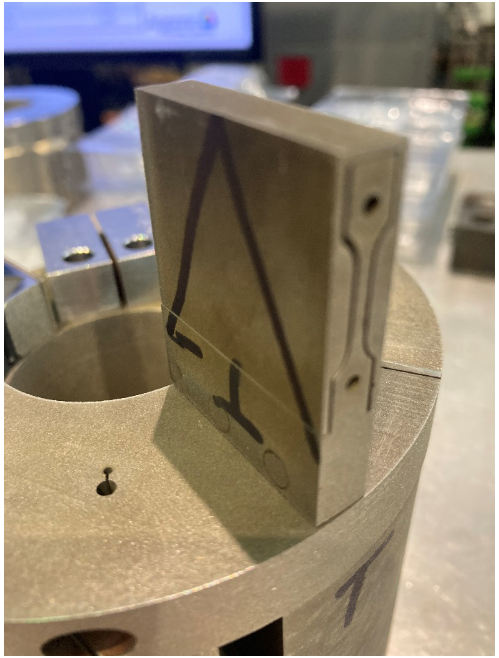
1.8 mm (D) × 1.2 mm (T) (a 3.05-mm^3 volume)

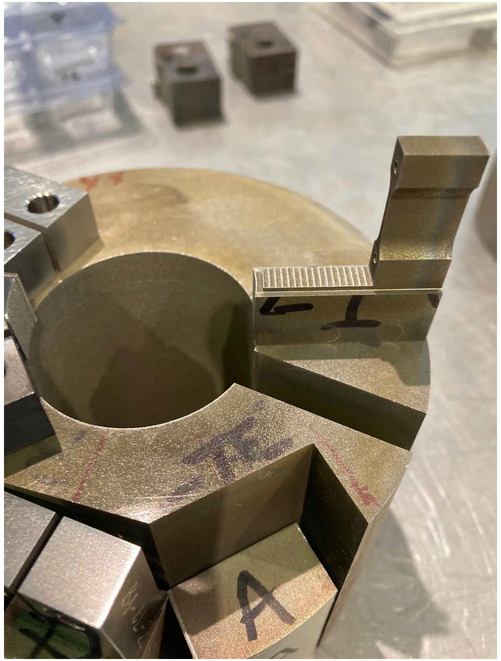


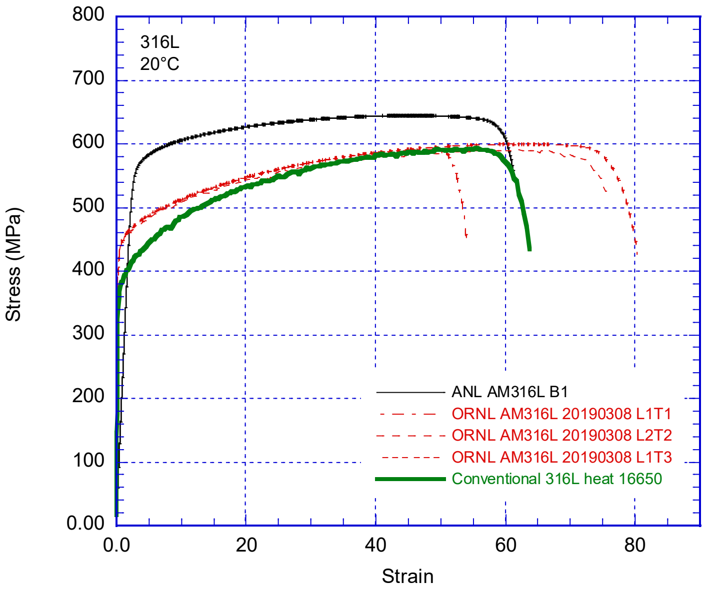


- Porosity measured by X-ray CT: **0.06%**
- Average pore size: **7.2 μm** (with 3 μm detection limit)

AM 316L TENSILE PROPERTIES







- Tensile properties comparable to those of conventional alloy and those of ORNL AM 316L plate (ANL and ORNL use different 3D printers)
- YS 517 MPa, UTS 644 MPa, UEL 43%

SCC CRACK GROWTH TESTING

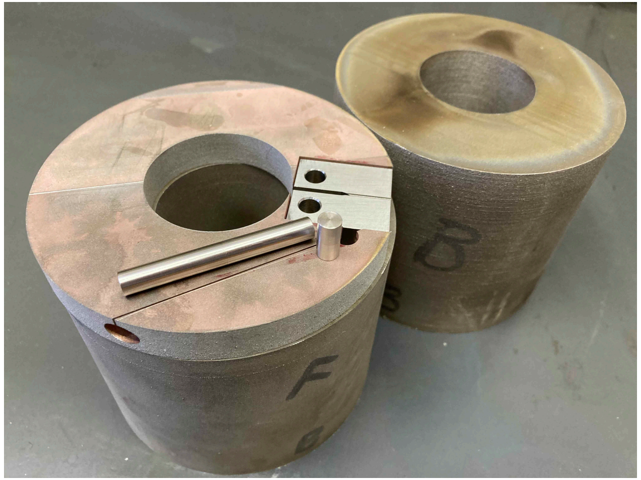
Crack growth rate (CGR) testing was conducted using one of the several dedicated systems at Argonne

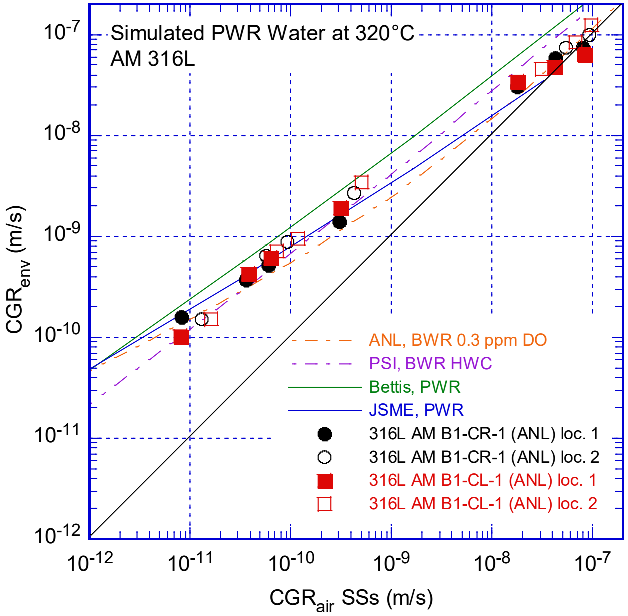
The test on the AM 316L specimen was conducted in primary water environment (HBO_3 and LiOH additions) at 320°C

The test followed a typical sequence for evaluating material performance in LWR environments:

1. Pre-cracking in water at high frequency (mechanical fatigue regime);
2. Transitioning to SCC (corrosion fatigue regime);
3. SCC growth under constant load.

CYCLIC AND SCC CGR RESPONSE OF AM 316L





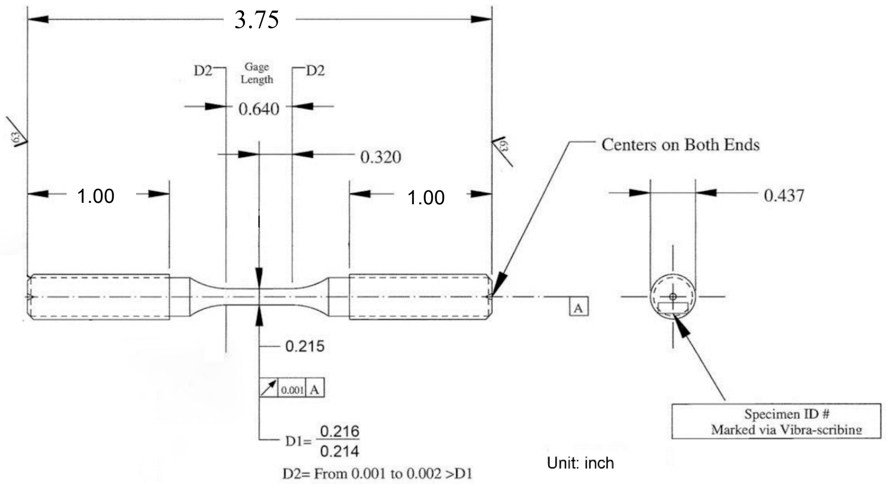
Both CR and CL orientations - results:

- Fatigue and corrosion fatigue CGR response (2 locations along the crack path) is similar to that of conventionally-produced alloy
- AM 316L was resistant to SCC (2 attempts at 2 locations)
- No effect of orientation

FATIGUE TESTING

ASTM standard cylindrical samples:

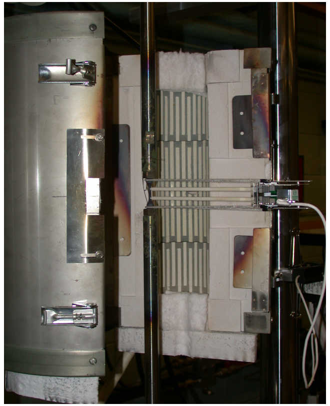
- As-built condition (no post-processing)
- Sample axis along the built direction
- Gauge diameter = 0.215”, Gauge length = 0.64”
- Polished gauge surface, Ra=0.2 μm

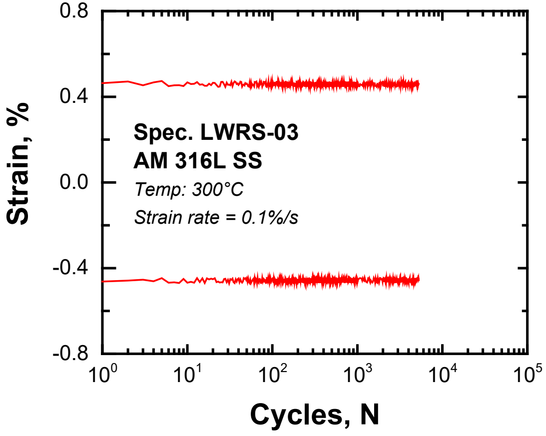


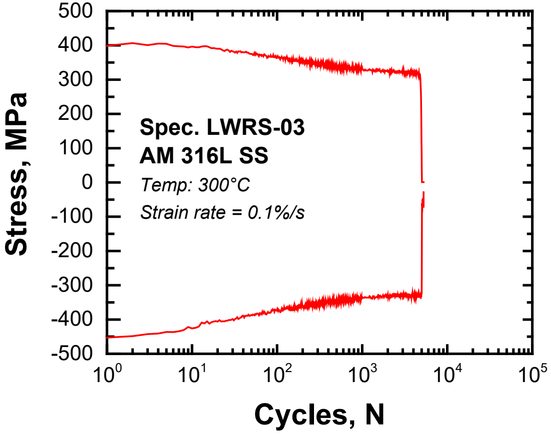
FATIGUE TESTING

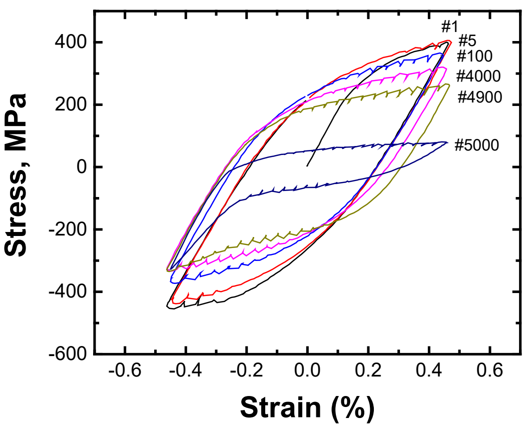
ASME design curves are based on strain-controlled fatigue tests

- Fully-reversed, strain-controlled tests
- In air, at 300°C
- Strain rate: 0.1%/s



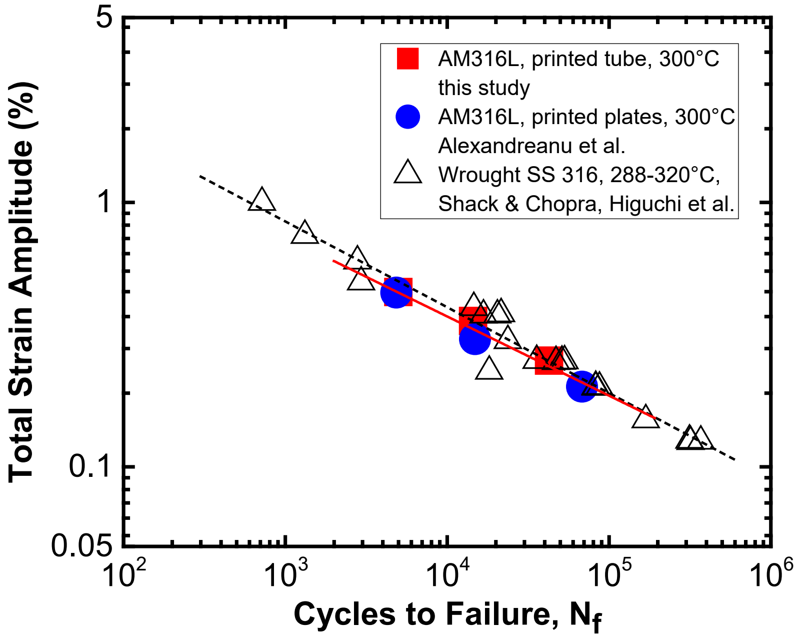






R = -1

STRAIN-LIFE RESULTS



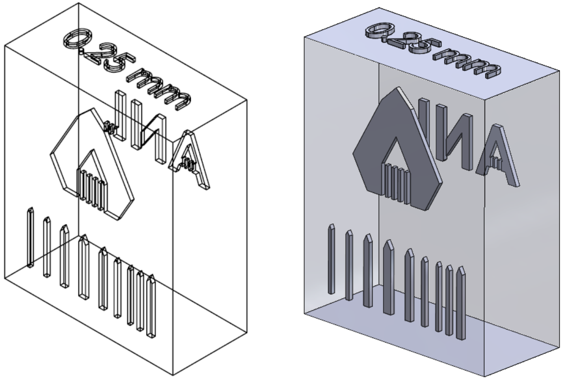
- Strain-life results from two AM prints are nearly identical
- The fatigue performance of AM316L is also similar to that of traditionally manufactured Type 316L SS.

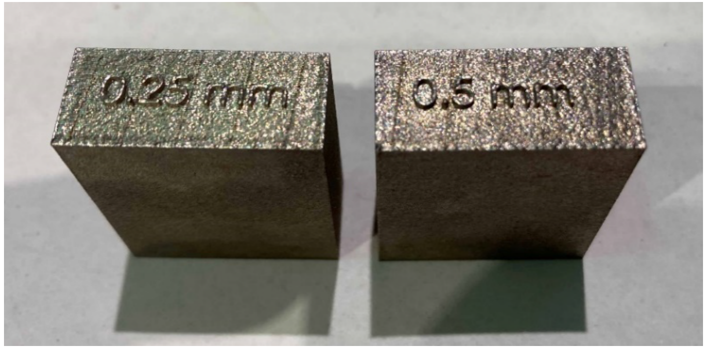
- Porosity at the level of <0.2% does not seem to affect fatigue life in air

EMBEDDED WATERMARKS

Objective: create an embedded watermark in a 3D printed structure to uniquely identify/certify/authenticate a part, e.g. “certified” for use

- Collaboration with NDE group (Dr. Alex Heifetz)



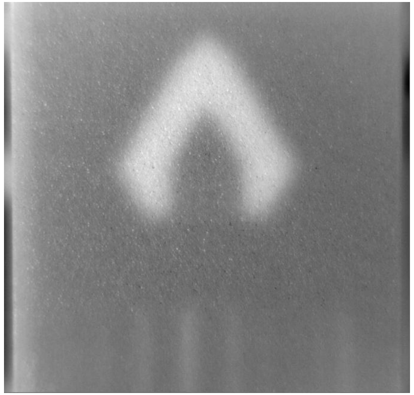


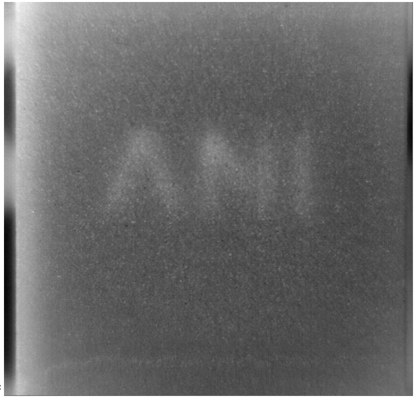
- Blocks with embedded features (ANL logo, bar code) were printed at two depths (0.25 mm, 0.5 mm) underneath the surface
- Detection was via Pulsed Infrared Thermography (PIT) and associated ML-software. Setup is portable and analysis is 6 sec/image

EMBEDDED WATERMARKS

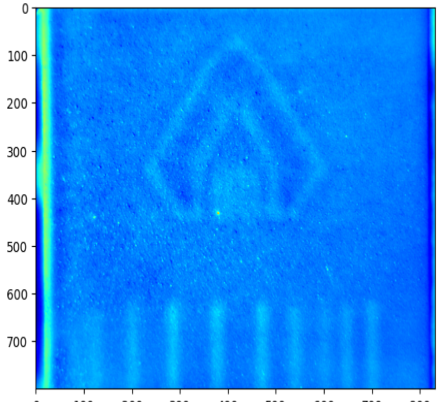
Depth-0.25 mm

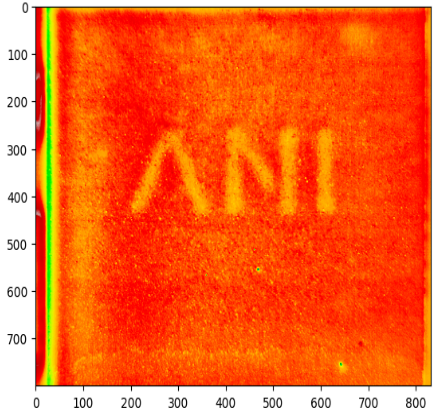
Observed Thermogram after Pulse



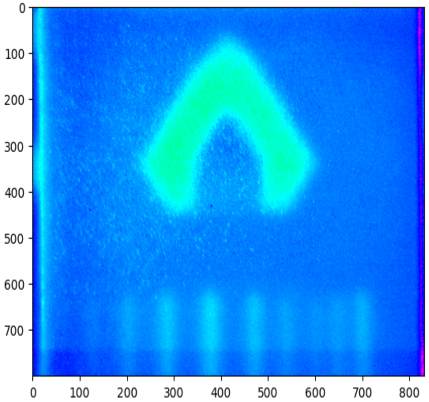


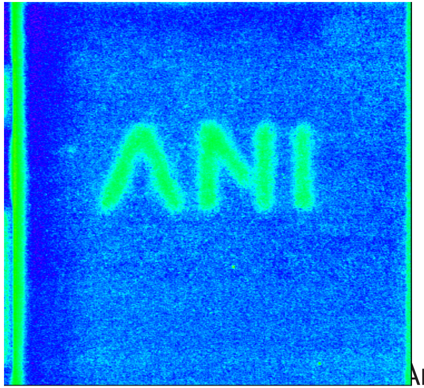
Self Learning Calibrated Online STBSS Reconstruction





Thermal DefectsNet Reconstruction

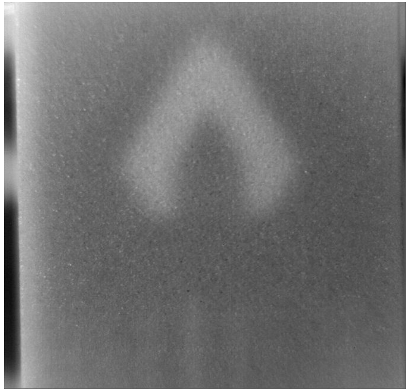


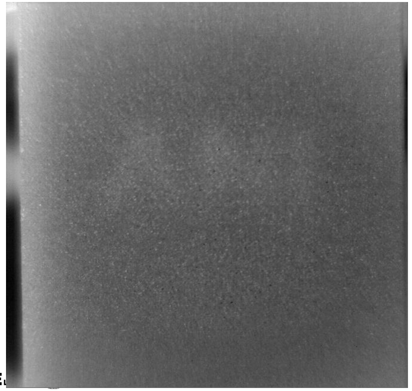


EMBEDDED WATERMARKS

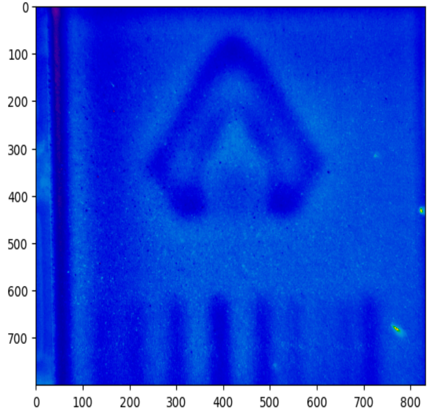
Depth-0.5 mm

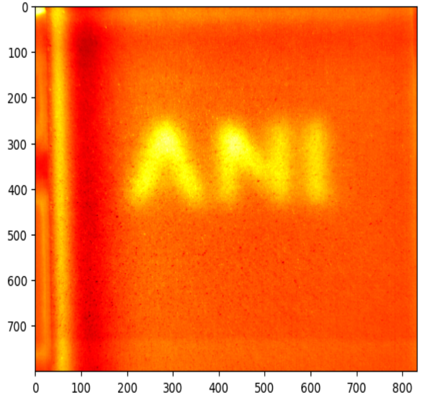
Observed Thermogram after Pulse



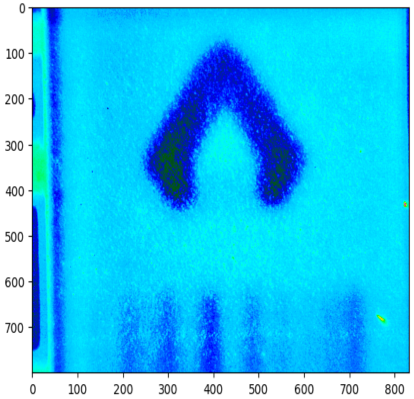


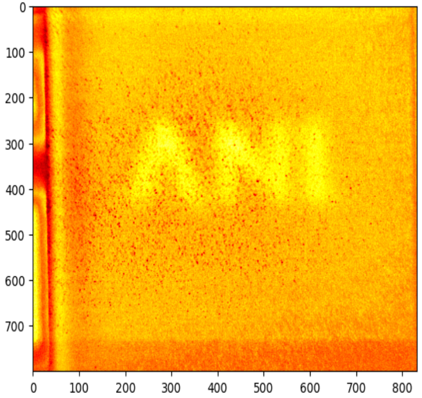
Self Learning Calibrated Online STBSS Reconstruction





Thermal DefectsNet Reconstruction





SUMMARY

- A new program to evaluate performance (SCC, EAF, CI) of AM materials was initiated at ANL under US DOE LWRS
- Preliminary (SCC, fatigue) results are encouraging

- Tubes – surrogates for components – were printed and evaluated in as-printed condition

- Microstructural investigations focused on porosity (measured by synchrotron X-ray tomography) and performance testing in LWR-relevant environment.

- Porosity was found to be small (0.06%), and the average pore size was 7.2 μm

- SCC CGR response of AM alloy is similar to that of conventionally-produced alloy

- Fatigue response in air of AM alloys seems similar to that of the conventional alloy. Further evaluation of environmental fatigue is needed

- Preliminary results with embedded watermarking of components are encouraging

ACKNOWLEDGEMENTS

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