Integrated Computational Materials Engineering and In-Situ Process Monitoring for Rapid Qualification of LPB-AM Nuclear Components

ELECTRIC POWER RESEARCH INSTITUTE

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DOE AMM Technical Review Webinar

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THE UNIVERSITY of TENNESSEE UT KNOXVILLE

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE U.S. DEPARTMENT OF ENERGY

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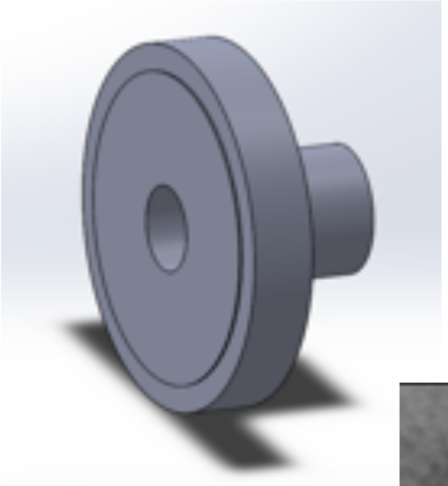
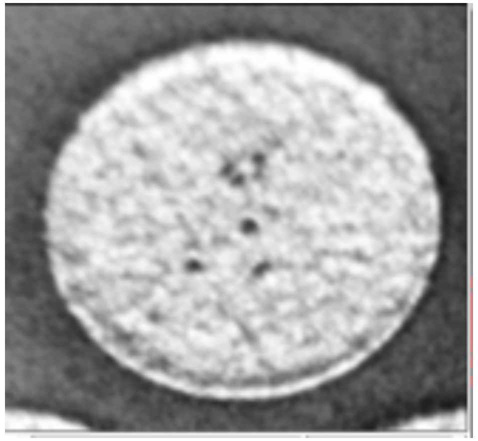
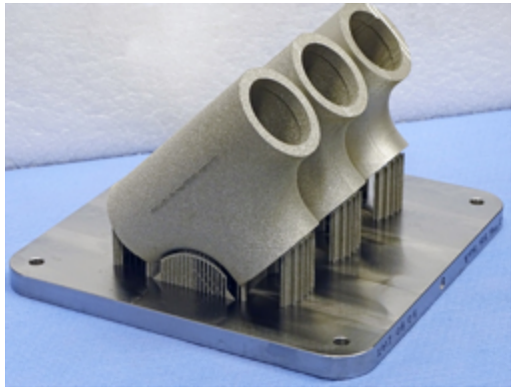
Project Motivation

- **Opportunity**
  - Potential to deploy additive manufacturing (AM) methods to produce reactor internal components
  - Unique capability to generate complex geometries rapidly with improved performance
  - Reduce the cost and time to market
- **Challenge**
  - Two parts made by the same AM equipment may not be the same
  - The same part made on different AM equipment may not have the same properties
- **Goal**
  - Rapid qualification of AM parts
  - ASME Data Package & Code Case



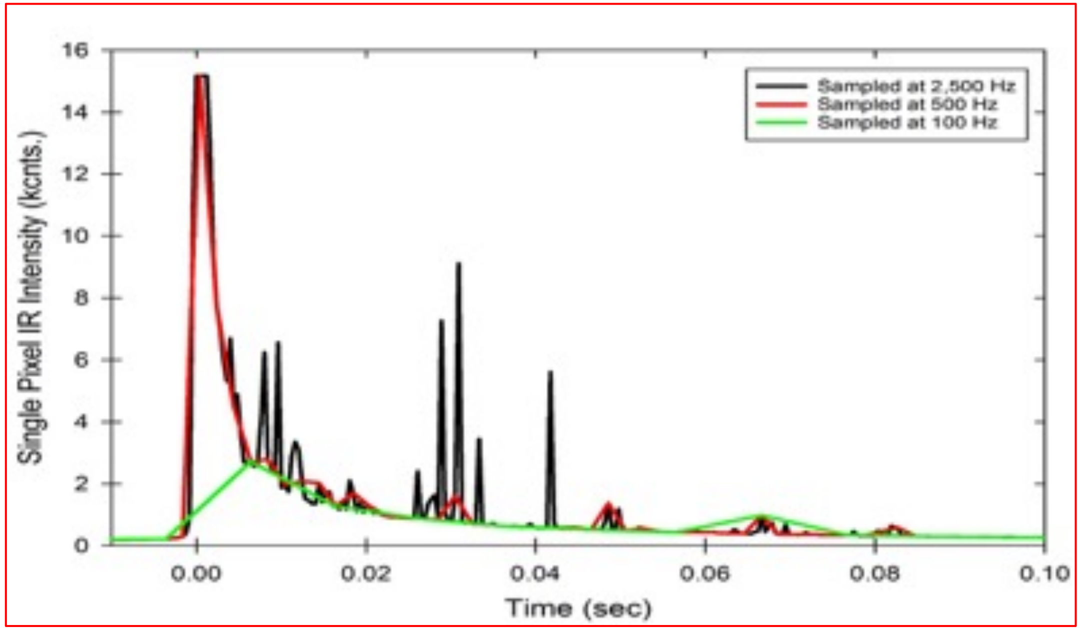




Review and Summary of Past Work

- **Infrared in-situ data**
  - Study conducted at very high sampling rate
  - Large sampling error and noise make it very challenging to determine small defect pore locations
  - Too much data (high sampling rates required
  - Conclusion: optical in-situ data more practical for a large build, promising in detecting porosity

- **Led to the focus on optical in-situ data, but we needed more data**
  - Tensile Bar build containing "twin" samples with engineered porosity: one to be HIP/SA, one as-built
  - XCT used to verify accuracy of optical data

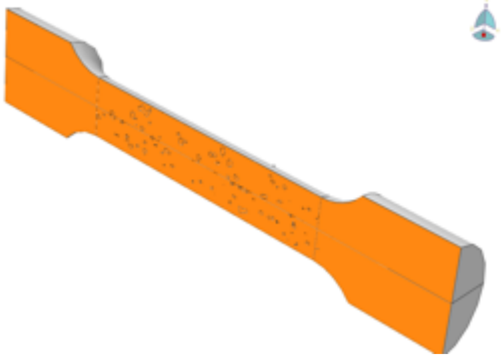


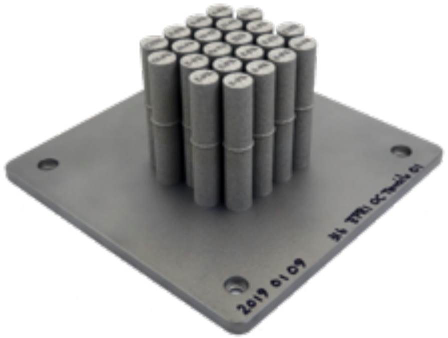
IR example from high rate experiment showing large difference in sampling rates

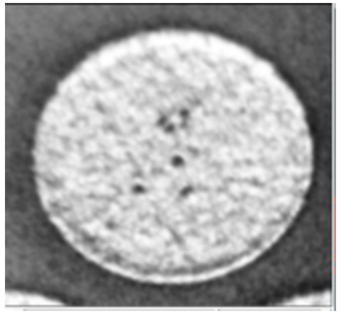
Optical In-situ Monitoring

- **Challenge**
  - Very dense (>99%) 316L builds still often include porosity [1]
  - Need more information accuracy of optical in-situ data pore detection

- **Questions**
  - Does HIP/SA fully close pores?
  - Do pores reopen or have lasting effects on tensile properties even after HIP/SA?
  - If we design to specific part mechanical behavior (i.e. elastic deformation), do we need HIP/SA?
  - Can optical in-situ data reliably capture porosity?



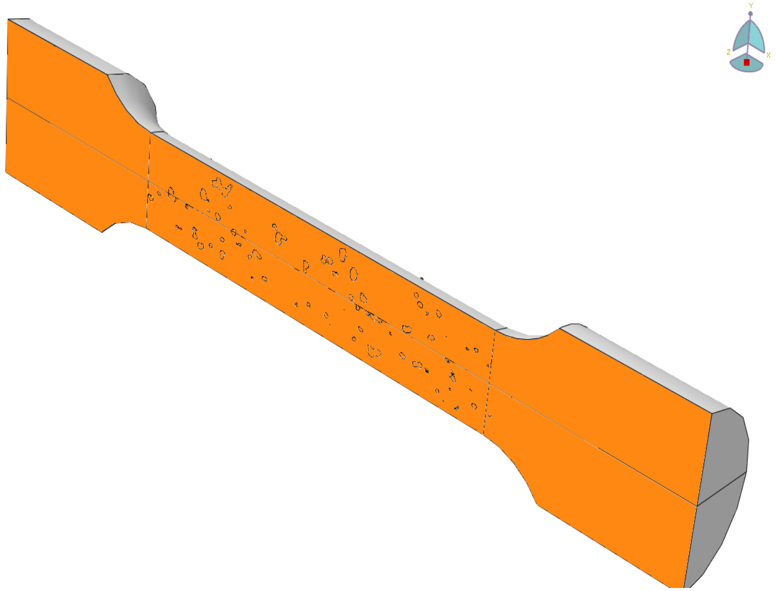




[1] Kamath, C., El-dasher, B., Gallegos, G.F. et al. “Density of Additively-manufactured, 316L SS parts using laser powder-bed fusion at powers up to 400 W,” Int J Adv Manuf Technol (2014) 74: 65. https://doi.org/10.1007/s00170-014-5954-9 [2]

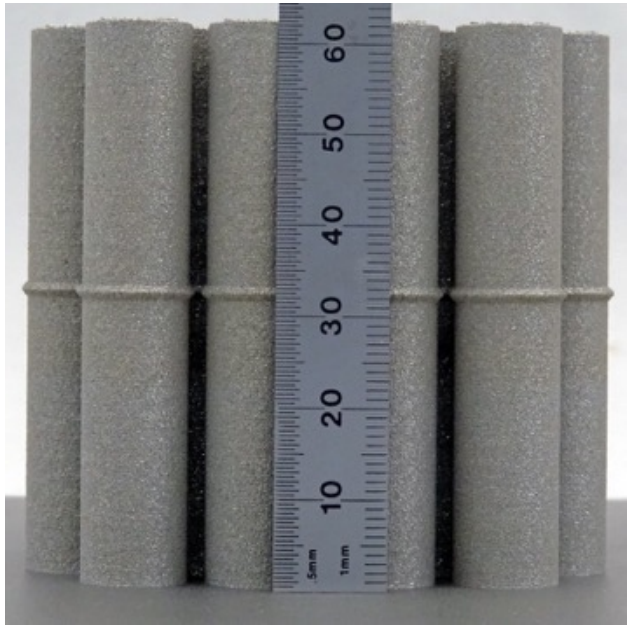
Tensile Bars Generated via AM with Engineered Porosity

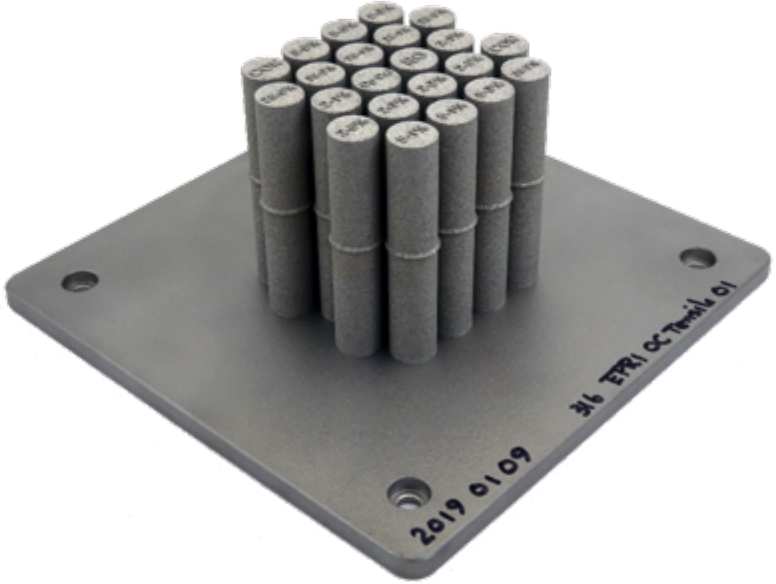
- 316L tensile bars containing randomized engineered porosity
  - 3 Pore sizes: 200, 350, and 500 µm
  - 3 Pore amounts: 1%, 3%, and 5% volume
- 2 bars of each combination were built
  - 1 to HIP/SA
  - 1 to remain as-built
- 2 Control bars with NO porosity were built, as well as an optical calibration bar
- Porosity was engineered to specific sizes and volume percentages, but randomized throughout gauge section
  - No pores were within 0.2 mm of the surface of the tensile bars



Engineered porosity tensile bars

Design	Label	# of bars	Defect size	Vol. % Density
200µm-1%	2-1%	2	200 µm	1
200µm-3%	2-3%	2	200 µm	3
200µm-5%	2-5%	2	200 µm	5
350µm-1%	35-1%	2	350 µm	1
350µm-3%	35-3%	2	350 µm	3
350µm-5%	35-5%	2	350 µm	5
500µm-1%	5-1%	2	500 µm	1
500µm-3%	5-3%	2	500 µm	3
500µm-5%	5-5%	2	500 µm	5
Optical Cal.	Op Cal	1	NA	NA
Rube Gberg	RG	1	NA	NA
Control	CON	2	NA	~0





Tensile testing was performed to ASTM E8 (16) Standards

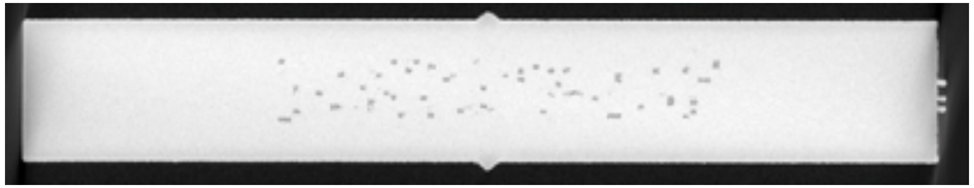
Test Conditions:

- Room Temperature
- Strain rate: 0.005 in/in/min through 0.2% Yield, then 0.063 in/in/min until failure
- Nominal gauge dimensions: 0.25 in dia x 1.35 in elg

Specimen ID	Test No.	Mod. (Msi)	U.T.S. (ksi)	0.2% Y.S. (ksi)	Elong. (%)(a)	RA (%)
2-1% HIP	T-234437	25.9	83.5	39.7	66	64
2-1% NO HIP	T-234438	21.9	85.0	59.0	44	43
2-3% HIP	T-234439	25.8	83.5	40.0	66	64
2-3% NO HIP	T-234440	24.0	77.0	55.0	25	34
2-5% HIP	T-234441	28.3	83.5	39.4	65	60
2-5% NO HIP	T-234442	22.1	74.5	54.0	22	24
5-1% HIP	T-234443	22.5	83.5	39.7	66	61
5-1% NO HIP	T-234444	21.7	81.5	58.0	30	38
5-3% HIP	T-234445	31.9	83.5	39.8	64	59
5-3% NO HIP	T-234446	21.2	78.5	55.5	27	36
5-5% CT-HIP-CT	T-234447	24.0	83.0	39.0	64	58
5-5% NO HIP	T-234448	31.0	74.5	53.0	23	34
35-1% HIP	T-234449	24.3	83.5	40.4	67	66
35-1% NO HIP	T-234450	21.8	83.0	58.0	38	35
35-3% HIP	T-234451	28.7	83.5	39.4	64	53
35-3% NO HIP	T-234452	24.3	77.0	55.5	23	34
35-5% HIP	T-234453	25.4	83.0	38.9	65	62
35-5% NO HIP	T-234454	22.8	76.0	54.0	24	33
CON HIP	T-234455	30.7	83.0	40.7	67	72
CON NO HIP	T-234456	29.9	85.5	58.5	51	50
RG NO HIP	T-234457	30.0	81.5	39.5	48	45
OP-CAL CT-HIP-CT	T-234458	21.5	79.5	58.0	23	43

500µm porosity bar: a closer look

- 500µm-5% was XCT scanned, HIP/SA, then XCT again before tensile testing
  - XCT appears to confirm pore closure post HIP/SA
- Results suggest closing of porosity for all cases
  - Also reflected in the mechanical testing data



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500µm-5%	5-5%	2	500 µm	5
Optical Cal.	Op Cal	1	NA	NA
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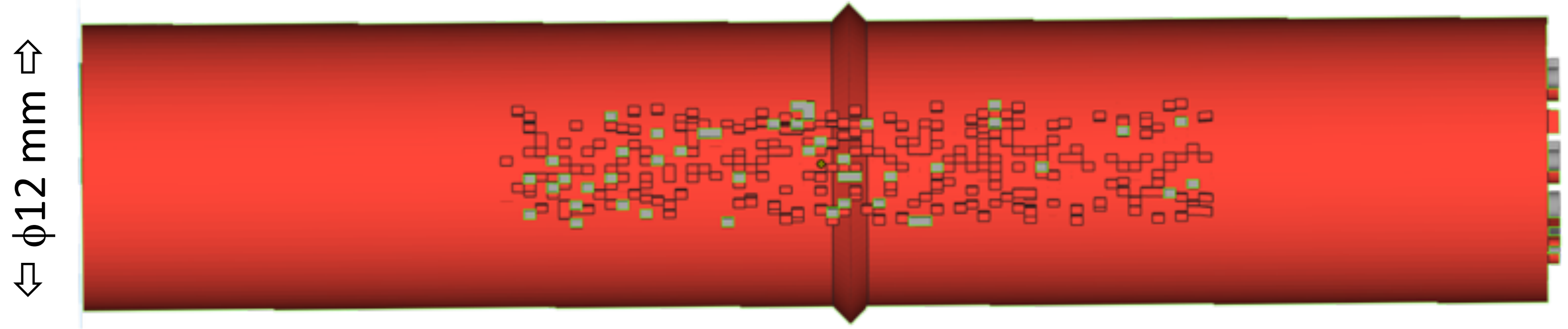
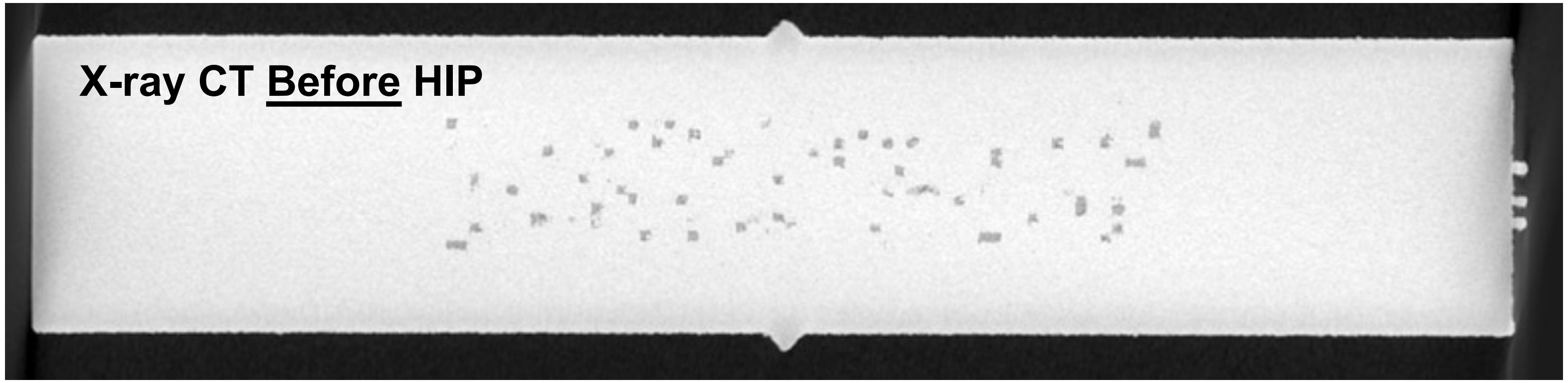
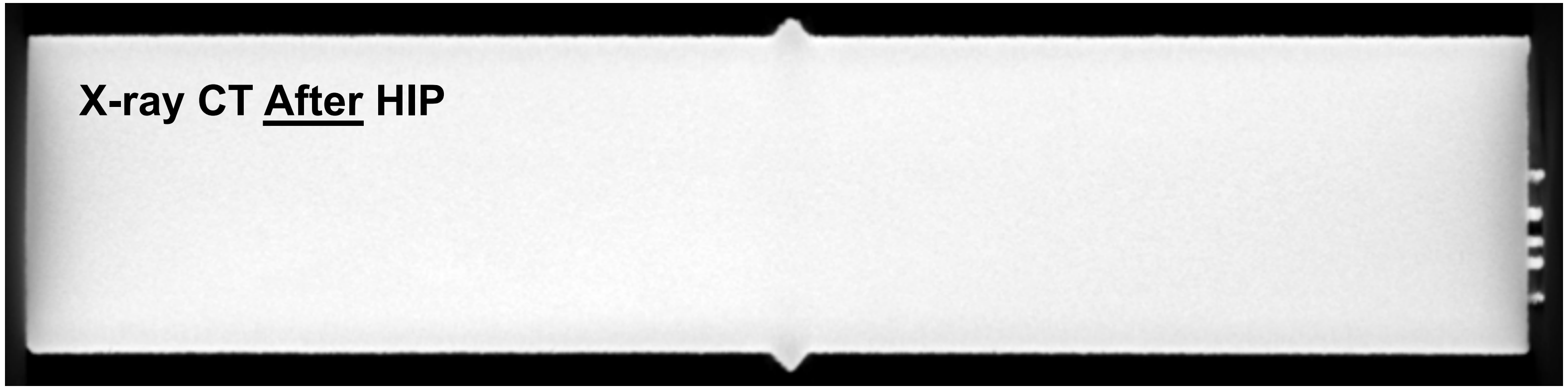
Control	CON	2	NA	~0

Before HIP/SA, engineered defects are visible; then closed after HIP



Solid model showing imbedded porosity

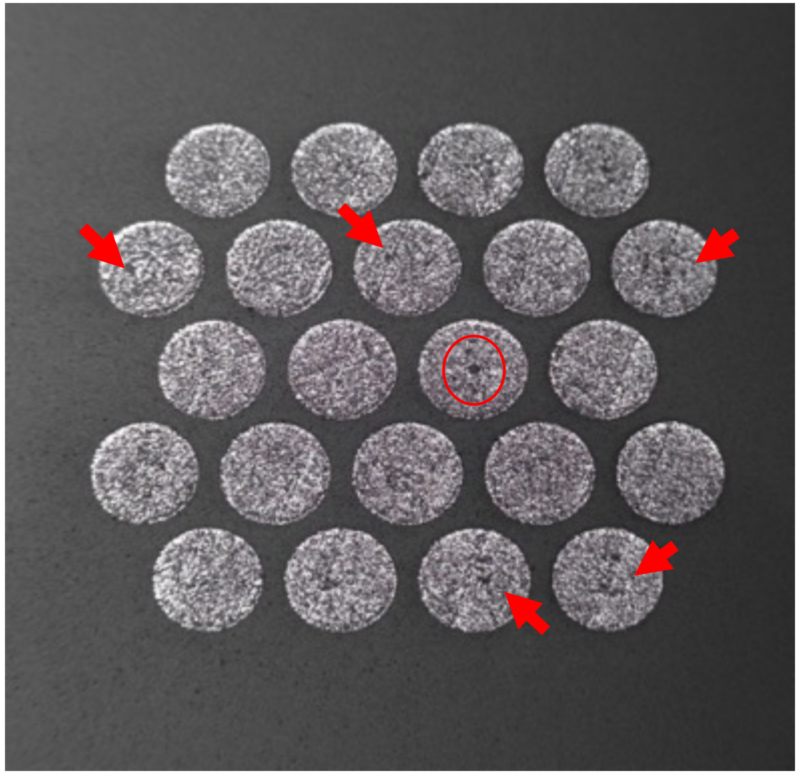


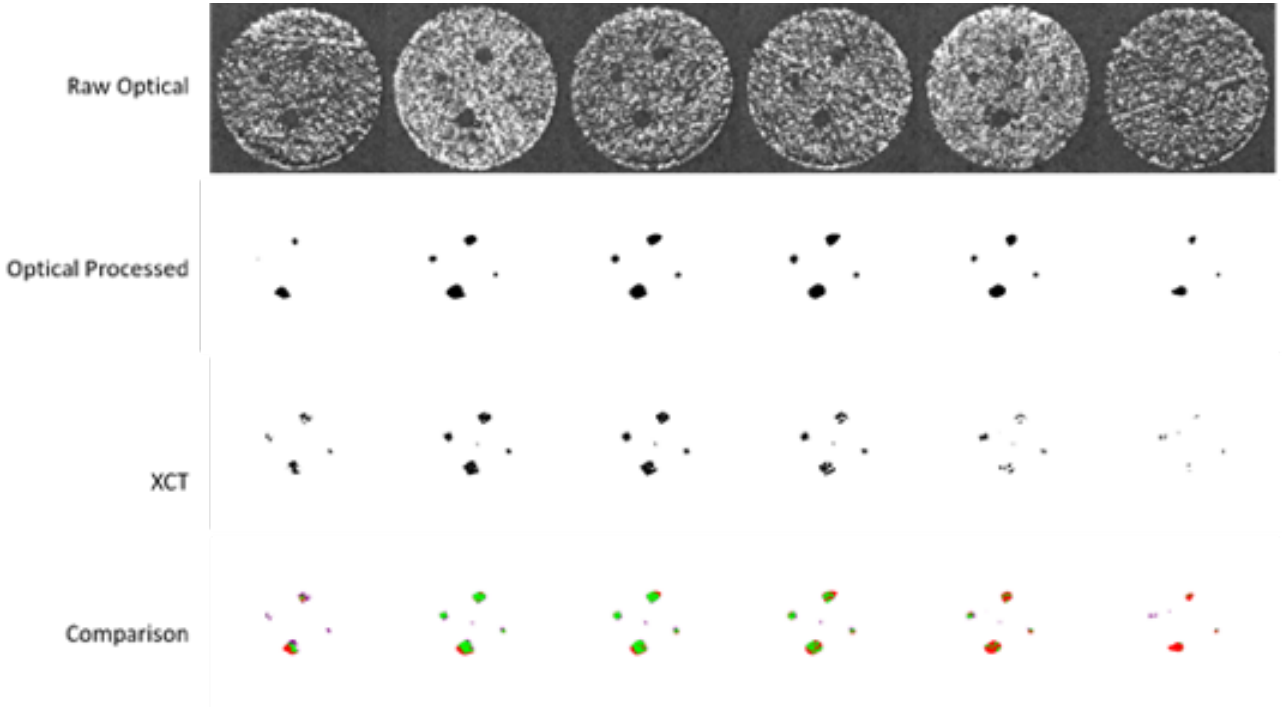


Note: X-ray CT resolution ~40 μm

Pores are visible initially in optical in-situ data

Part for Layer 634



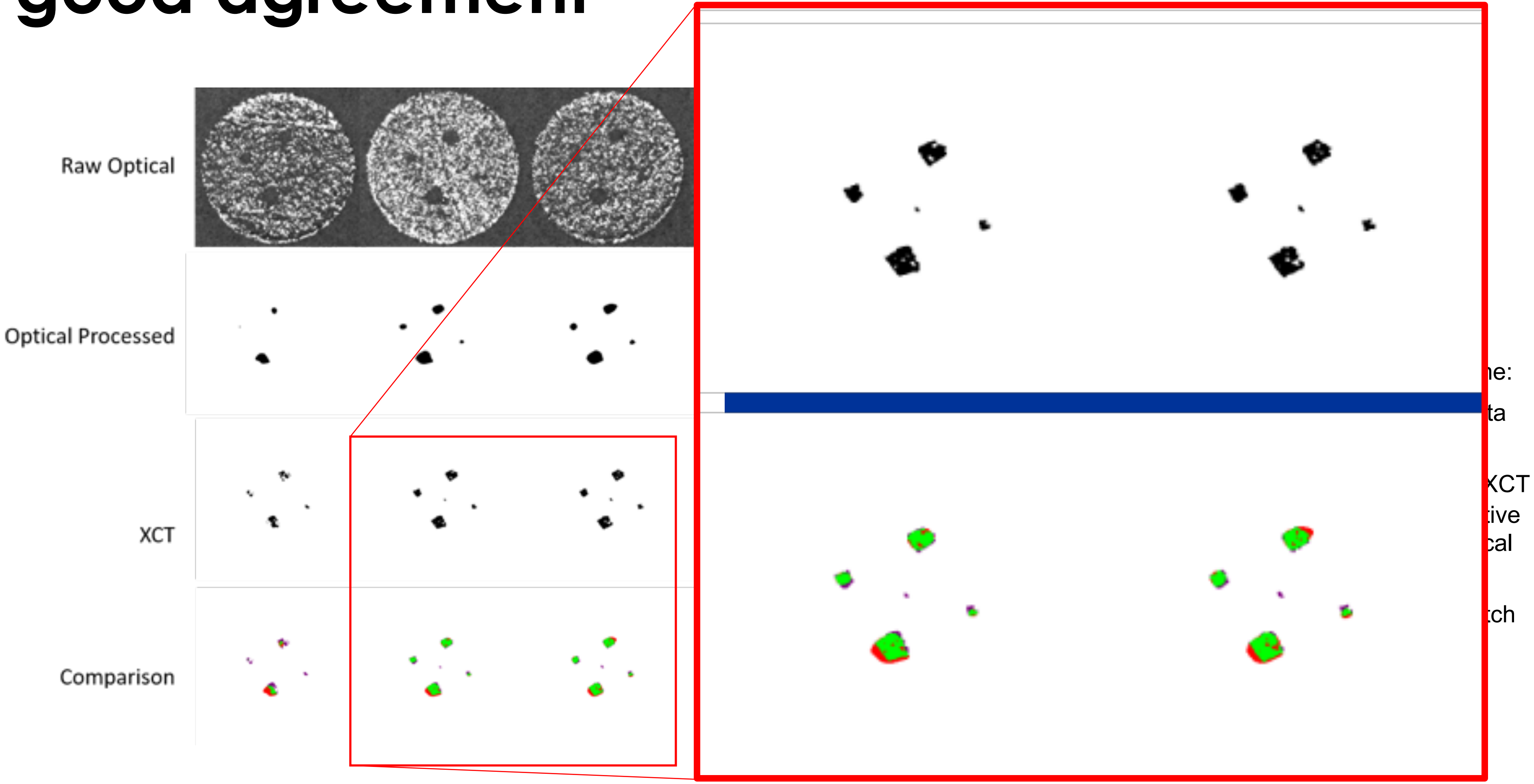


Green: Part and XCT Data Match

Red: Part Does not Match XCT (likely caused by consecutive layer re-melting after optical image)

Purple: XCT does not match part

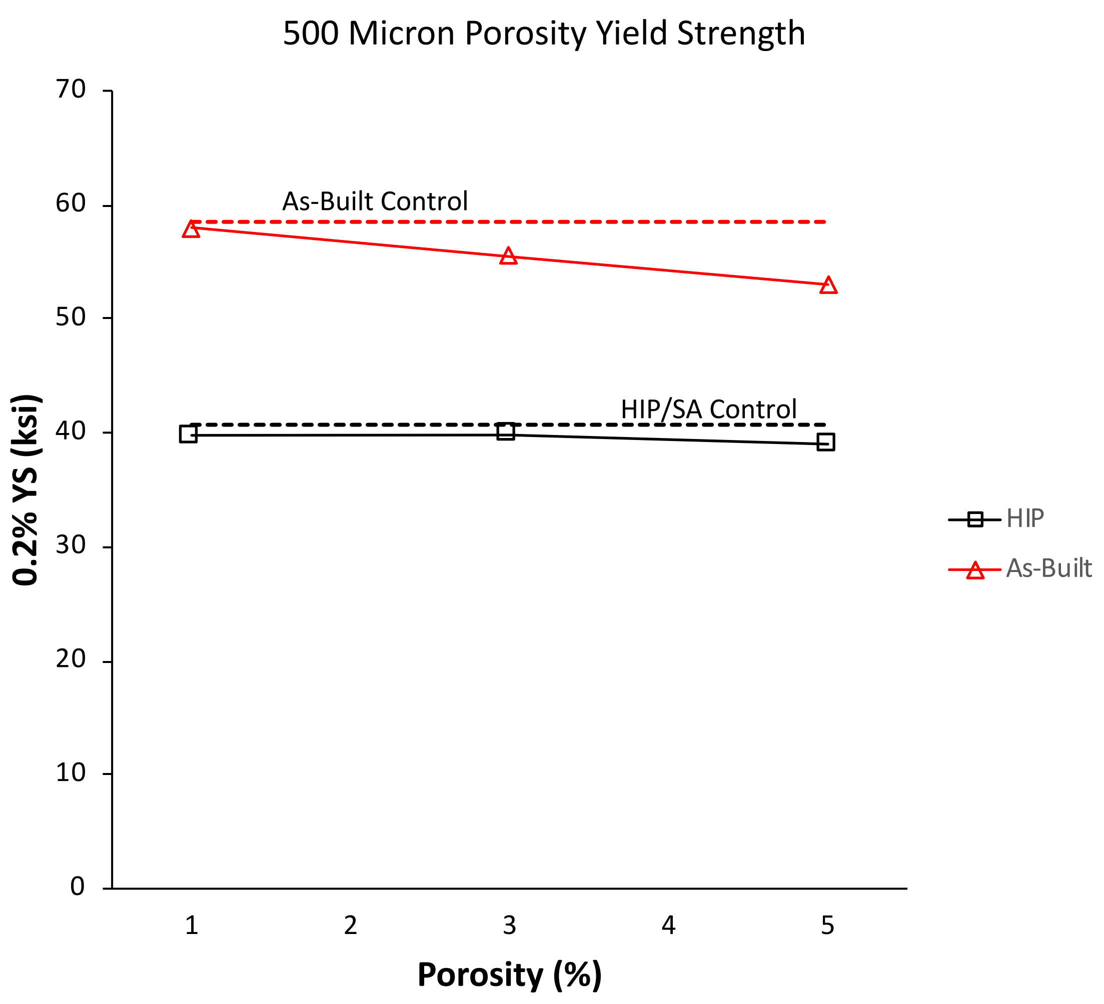
Comparing Optical and XCT data shows good agreement



- Optical data porosity is almost always larger than XCT, likely due to remelting that occurs after image is taken

Tensile test results suggest that HIP/SA closes pores and minimizes their affect on tensile properties

In each case, the HIP/SA bars achieved closer properties to the control (no porosity) bar, while the as-built bars diverged from the control bar with increasing porosity amounts



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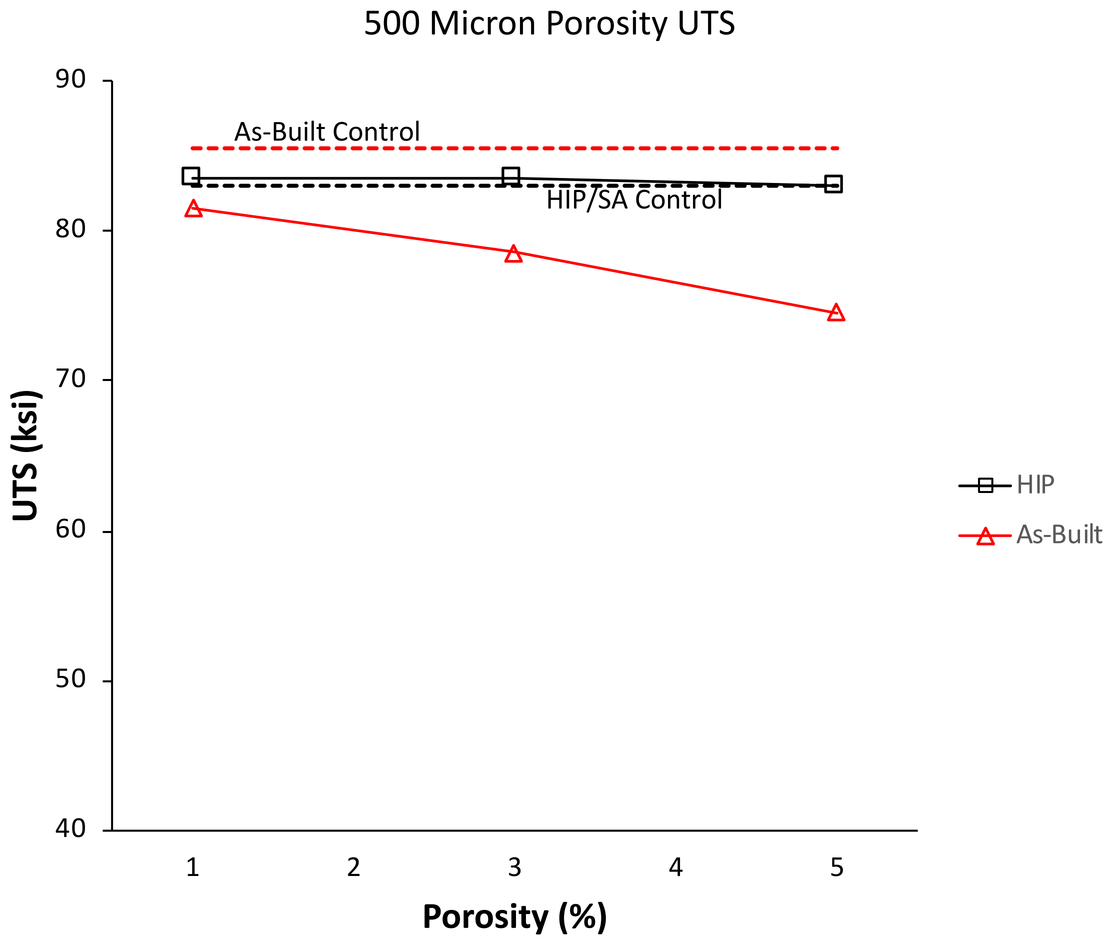
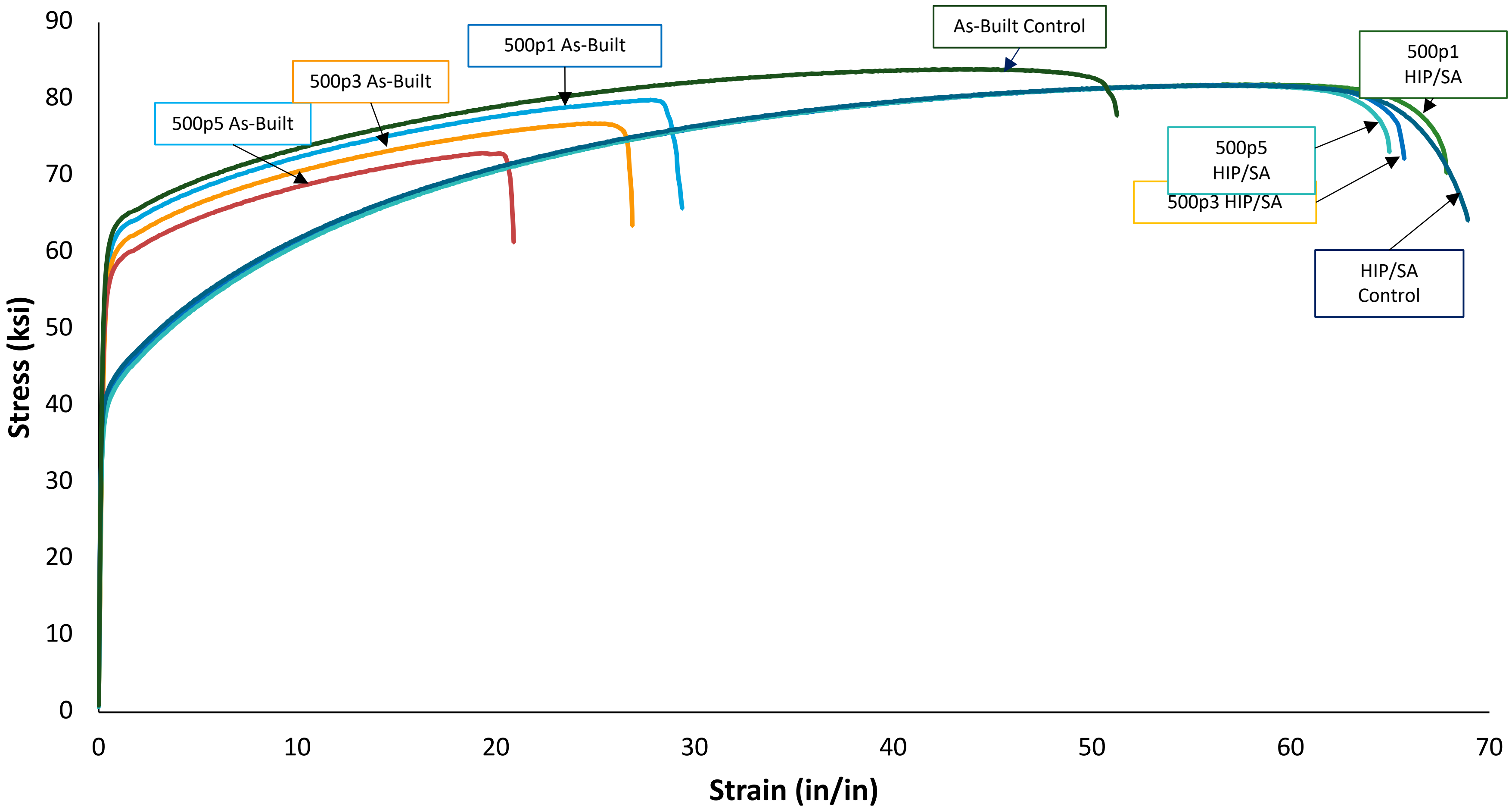
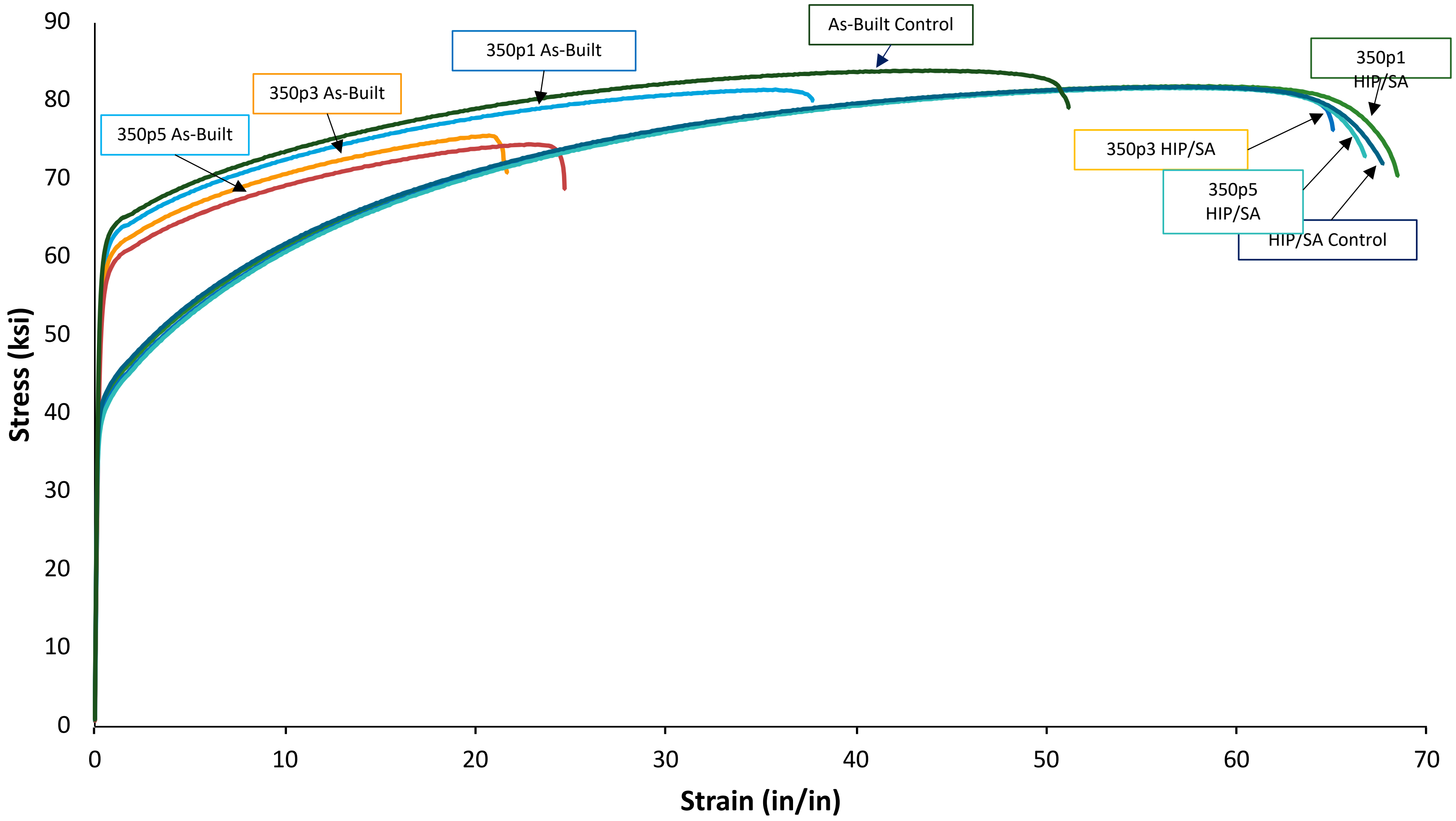


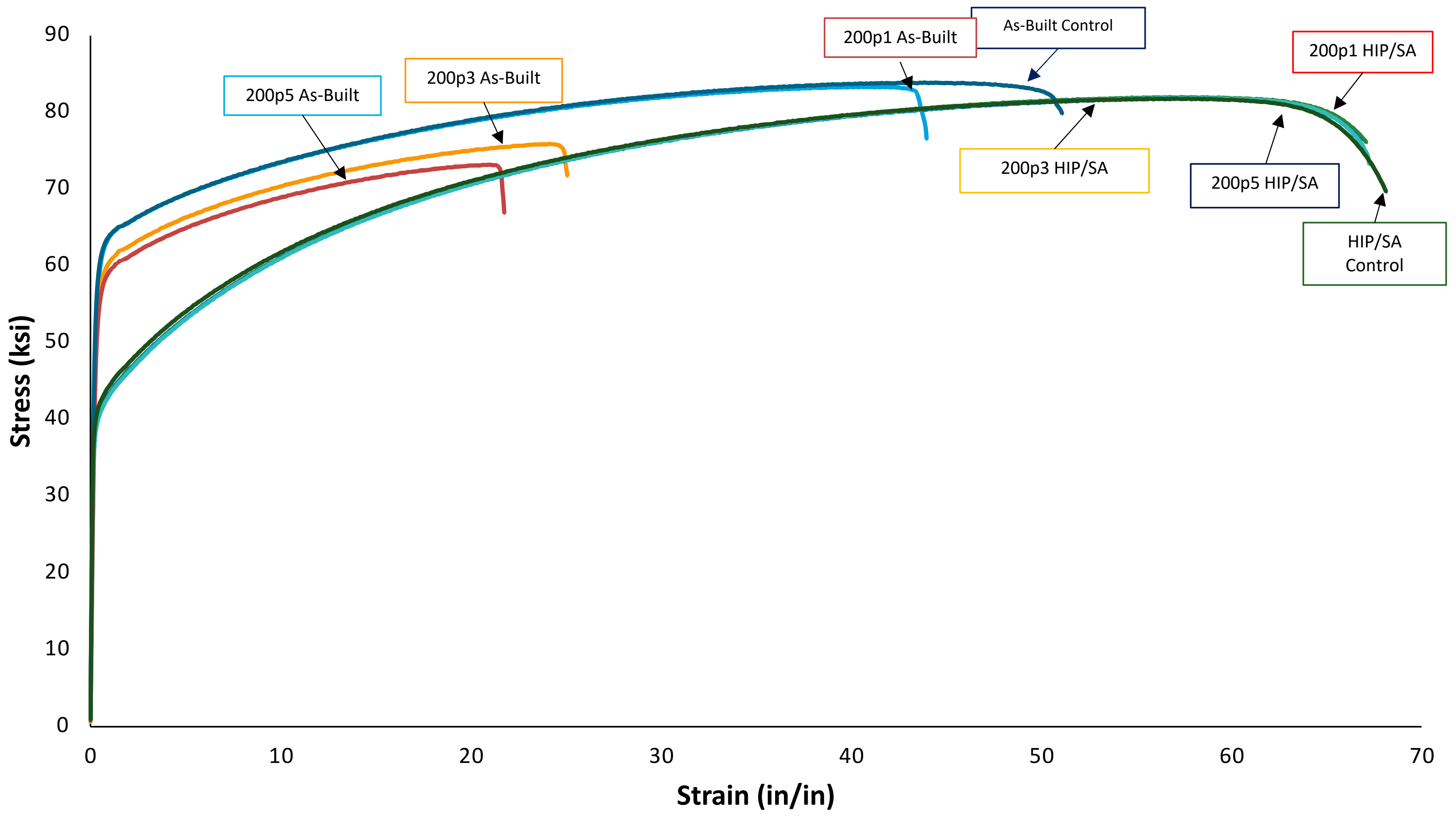
Stress-strain curves for the HIP/SA bars at all porosity values for the 500μm samples achieved similar results as the control sample. This suggests that pores were closed.



This trend is again observed in the 350µm porosity samples, while we again see the as-built samples decrease from the control with increasing porosity amounts



In the 200µm samples, we see the "best case" porosity sample (200µm-1%) stress-strain curve some closest to matching the control



Summary—Optical In-situ Monitoring

- **Defect Detection**
  - Optical in-situ data is able to accurately detect the size and location of engineered pores, with the exception of overestimation due to remelting
  - Optical in-situ data can also detect non-engineered porosity
- **Part Qualification**
  - Even in exaggerated pore sizes and amounts, HIP/SA closed porosity with little to no residual effects on tensile properties
  - Reopening seems to be occurring, but tensile mechanical properties do not suffer significantly despite this
- **Part Certification**
  - Optical data may be useful in predicting failure and mechanical properties, more work is needed to find correlation between data and performance/failure

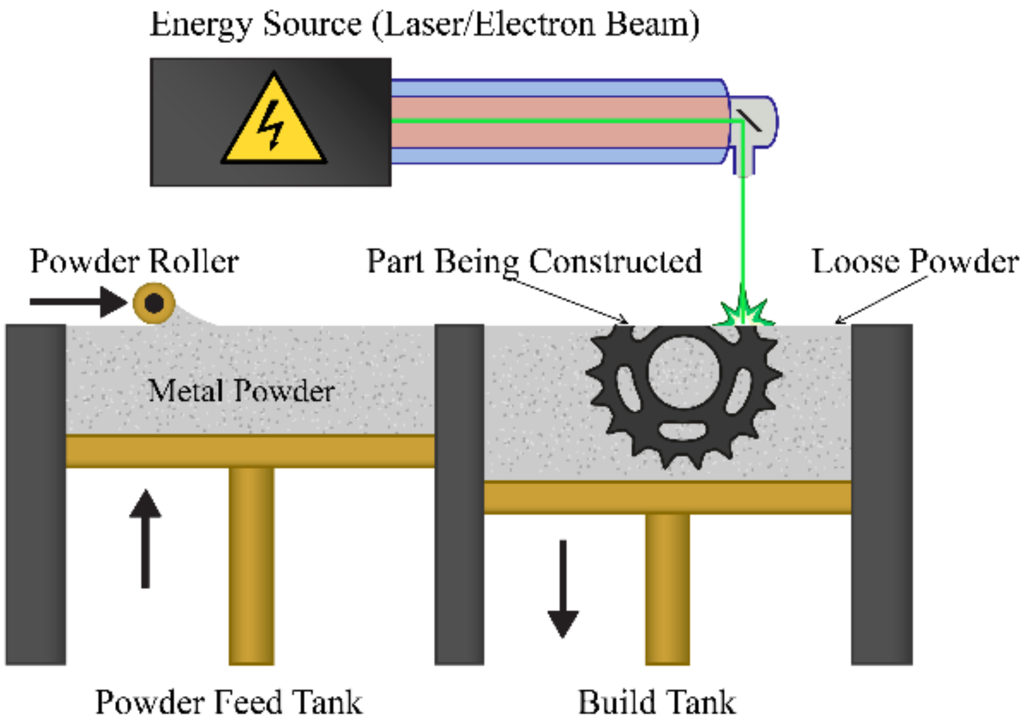
Limitations and Comments

- **Defect detection: optical in-situ data**
  - Overestimation due to remelting is not currently quantifiable
  - Data processing is highly manual, calibrated to each individual system
- **Part Qualification**
  - Tensile test was the only test performed on engineered porosity bars, no Charpy or hardness
  - Only one sample of each type
  - HIP and SA done together, never separately. No experimental data for influence of each process individually
- **Part Certification**
  - More work needed in correlating optical data to mechanical properties

ASME Data Package and Code Case Development

AM Qualification for Nuclear Applications
--ASME Data Package Development

- DOE Project: **DE-NE0008521**
- EPRI lead
- Five organizations involved
  - Rolls-Royce
  - Westinghouse
  - ORNL MDF
  - Auburn University
  - Oerlikon
- Laser Powder Bed-AM
- 316L SS



Laser Powder Bed-AM (*courtesy of 3DEO*)

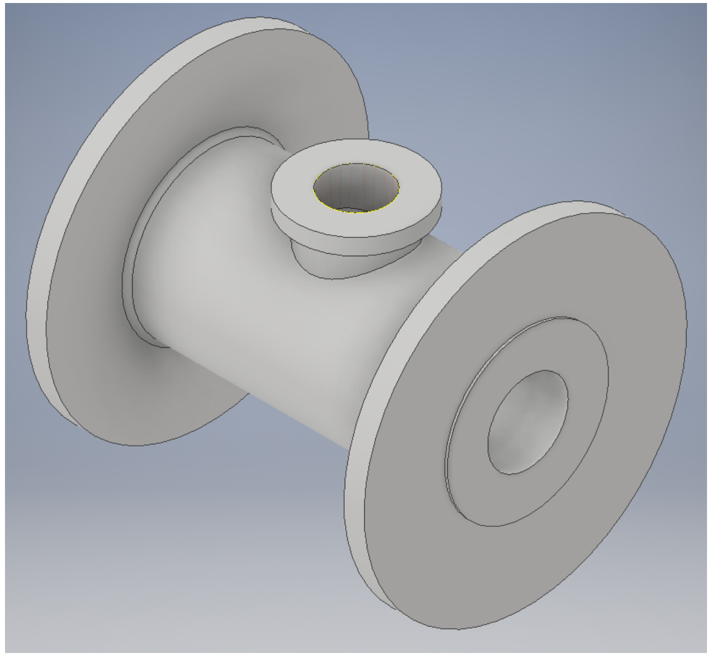
AM Qualification for Nuclear Applications
--ASME Data Package Development

- 2 Types of machines
  - EOS, Renishaw
- 5 sets of processing parameters
- 5 different 316L powder heats
- 3 different components (next slide)
- Components are >8-inches in diameter and ~0.5-inch thick
- Different build environments
  - argon and nitrogen
- Vertical control/witness samples included
- Parameter data sheet recorded for each build

Renishaw AM 250 System

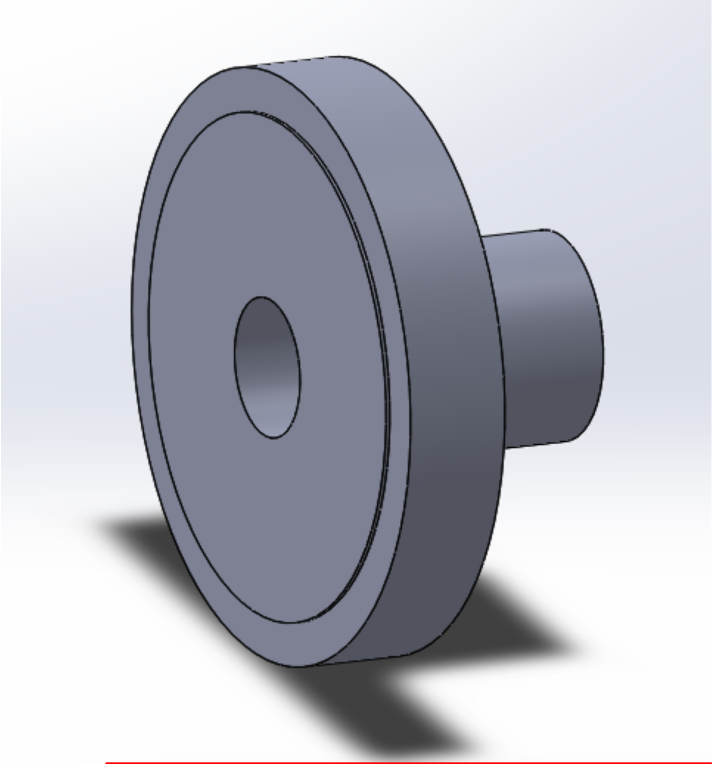
Courtesy: ORNL/Renishaw

AM Qualification for Nuclear Applications
--ASME Data Package Development



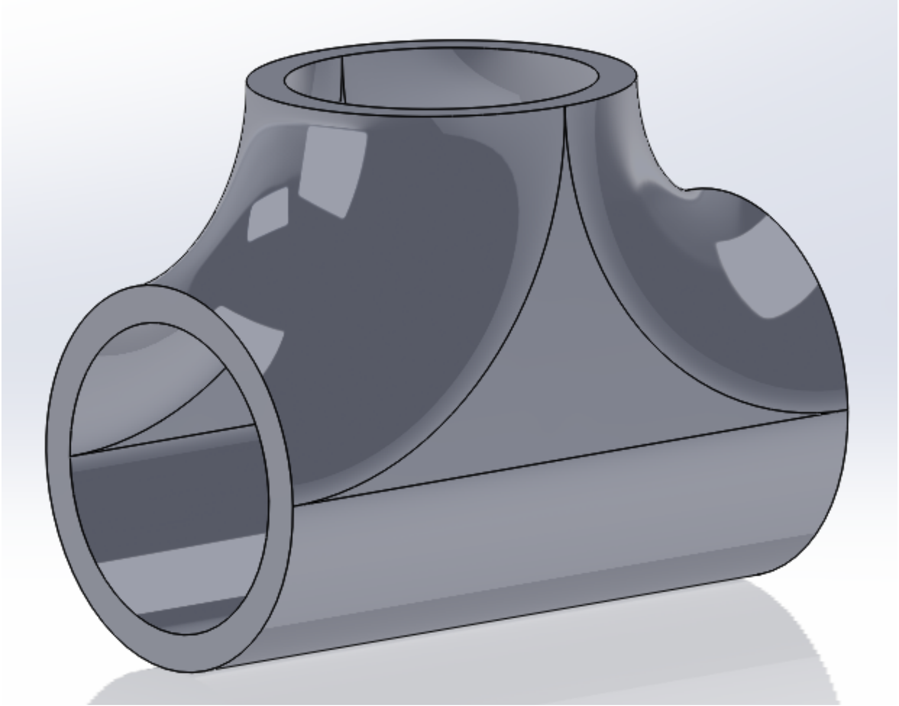
Class 300 Forged Gate Valve Body

8”Ø x 2”bore x 4”OD x ½”T



Ring Flange End Connection

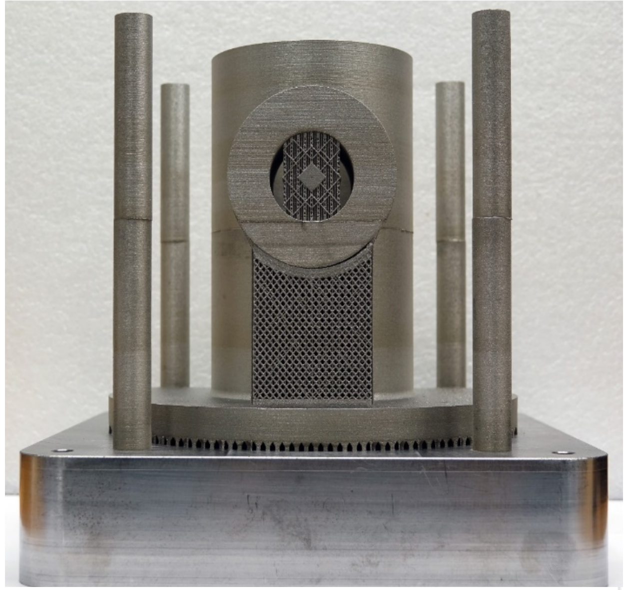
8.5”Ø x 1.5”T x 2” bore

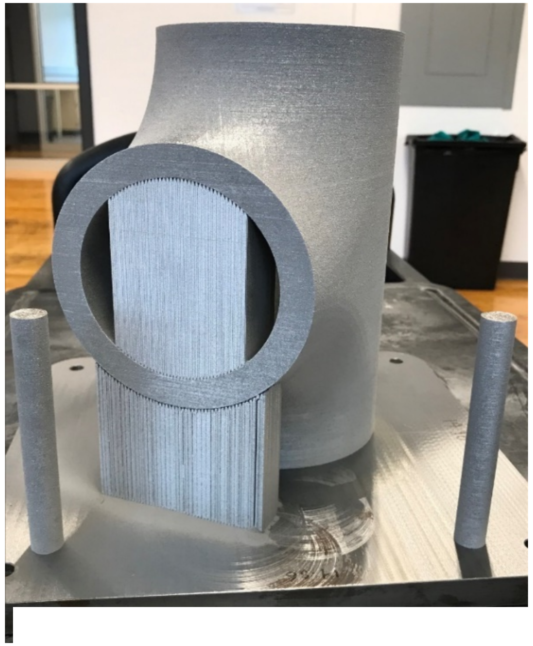


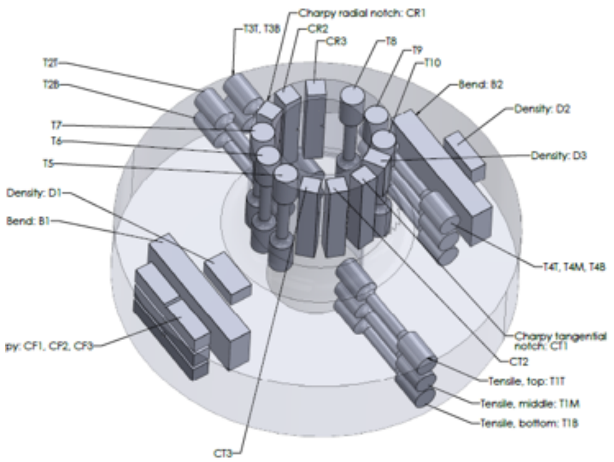
Straight Pipe Tee

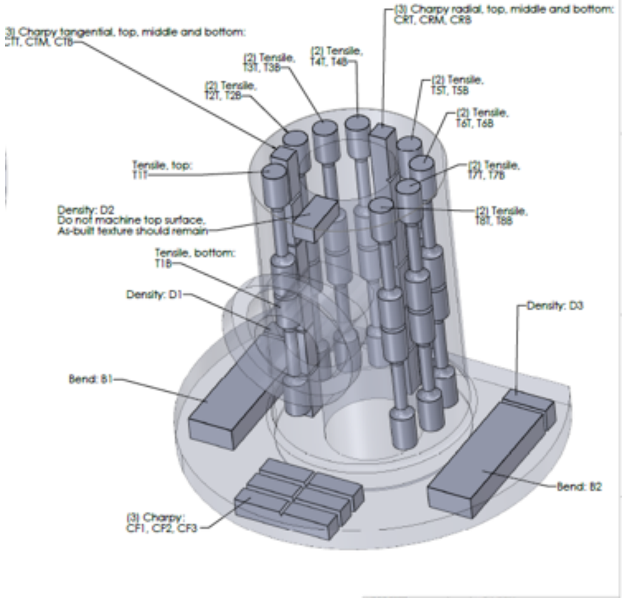
8-1/4”W x 4-1/8”T

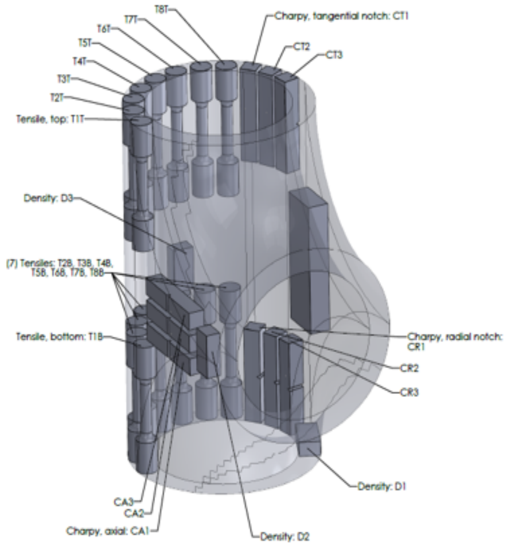
ASME Data Package Development











AM Qualification for Nuclear Applications
--ASME Data Package Development

General

- To ASTM F3184-16 Requirements
- Component Build--Process Information (Parameter Data Sheets for each Build)
- Photographs of the final component
- Drawings of components
- Geometric inspection of final component
- Chemical analysis – powder and final component
- Hot Isostatic Pressing parameters
- Heat treatment – solution anneal parameters
- Inspection data captured--Digital RT/UT

Microstructural Information

- Microstructure – multiple magnifications
- Grain size
- Density
- Inclusion content

AM Qualification for Nuclear Applications
--ASME Data Package Development

<u>Mechanical Information</u>

- Provide ASME requirements for wrought 316L
- Hardness mapping
- Tensile to 800F (50F increments)
  - Include stress/strain curves
- Tensile (RT) for 3 vertical build control samples
- Charpy impact toughness
- Side bends
- Fatigue (one component only)
- Plan to meet ASME stress allowable values

ASME Code Case Development

- To be modeled after Code Case N-834 (PM-HIP of 316L SS).
- Plan toward BPV-III application.
- Case N-XXXX – ????
- DRAFT Inquiry: *May ASTM F3184-16 (UNS 31603) be used for Section III, Division 1, Subsection NB, Class 1 Construction?*
- Plan to submit in February 2020

CASES OF ASME BOILER AND PRESSURE VESSEL CODE

CASE
N-834

Approval Date: October 22, 2013

Code Cases will remain available for use until annulled by the applicable Standards Committee.

Case N-834
ASTM A988/A988M-11 UNS S31603, Subsection NB, Class 1 Components
Section III, Division 1

Inquiry: May ASTM A988/A988M-11 UNS S31603 be used for Section III, Division 1, Subsection NB, Class 1 Components construction?

Reply: It is the opinion of the Committee that, ASTM A988/A988M-11 UNS S31603 may be used for Section III, Division 1, Subsection NB, Class 1 Components in construction provided the following additional requirements are met:

(a) For purposes of welding procedure and performance qualification, this material shall be considered P-No. 8.

(b) The design stress intensity values and the maximum allowable stress values, fatigue design curves, tensile strength and yield strength values, thermal expansion and other properties shall be the same as for SA-240 UNS S31603.

(c) The maximum allowable powder particle size shall be 0.020 in. (0.5 mm) or less.

(d) Following atomization, powders shall be stored under a positive nitrogen or argon atmosphere.

(e) An 8 in. (200 mm) or longer protrusion (extension) shall be added to one end of each item that equals or exceeds the thickest section of that item. The protrusion shall be removed upon completion of isostatic pressing and heat treatment of the item and shall be used for micro structural characterization, density measurements, chemical testing, mechanical testing, and intergranular corrosion testing as required below:

(1) Density measurements and microstructural examination shall be performed at the midsection of coupons removed from the protrusion in accordance with ASTM A988/A988M-11 paras. 8.1.1 and 8.1.2.

(2) In addition to a chemical composition analysis of the final blend powder, an analysis of a sample from each component shall be required.

(3) Intergranular corrosion tests shall be performed using test coupons removed from the protrusion in accordance with ASTM A262 Practice E.

(4) Mechanical property tests, including tension tests and hardness tests, shall be performed using test coupons removed from the protrusion in accordance with ASTM A988/A988M-11, Section 9, Mechanical Properties.

(f) The material shall be examined using the ultrasonic examination method in accordance with NB-2540 over 100% of its entire volume using both straight and angle beam methods. Items that are produced in the form of tubular products shall be examined in accordance with NB-2550.

(g) The material shall not be used for components where the neutron irradiation fluence levels will exceed 1×10^{17} n/cm^2 (E > 1 Mev) within the design life of the component.

(h) Following final hot isostatic-pressing, all surfaces exposed to the process fluid shall be removed by machining or grinding to a depth of 0.008 in. (0.2 mm) or greater. Final accessible surfaces shall be examined by the liquid penetrant method in accordance with NB-2576.

(i) All other requirements of NB-2000 for austenitic materials shall apply.

(j) This Case number shall be marked on the material and listed on the Certified Material Test Report and on the Component Data Report.

The Committee's function is to establish rules of safety, relating only to pressure integrity, governing the construction of boilers, pressure vessels, transport tanks and nuclear components, and inservice inspection for pressure integrity of nuclear components and transport tanks, and to interpret these rules when questions arise regarding their intent. This Code does not address other safety issues relating to the construction of boilers, pressure vessels, transport tanks and nuclear components, and the inservice inspection of nuclear components and transport tanks. The user of the Code should refer to other pertinent codes, standards, laws, regulations or other relevant documents.

1 *(N-834)* NC – SUPP. 3

ELECTRIC POWER RESEARCH INSTITUTE

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