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

Award Number: DE-NE0008521

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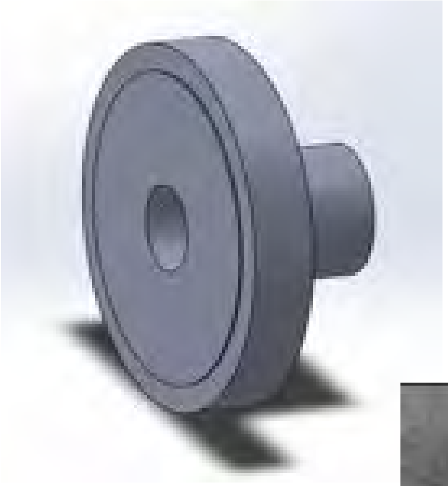
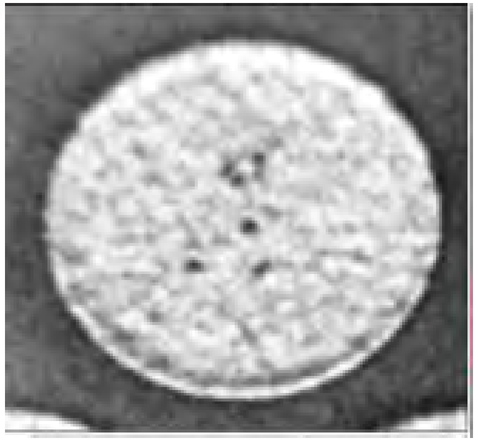
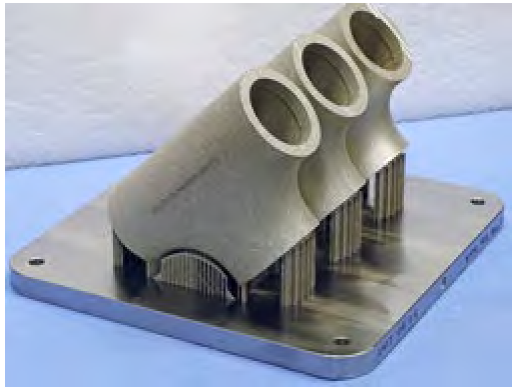
Project Motivation

- **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
- **Objectives**
  - Rapid qualification of AM parts
  - ASME Data Package & Code Case

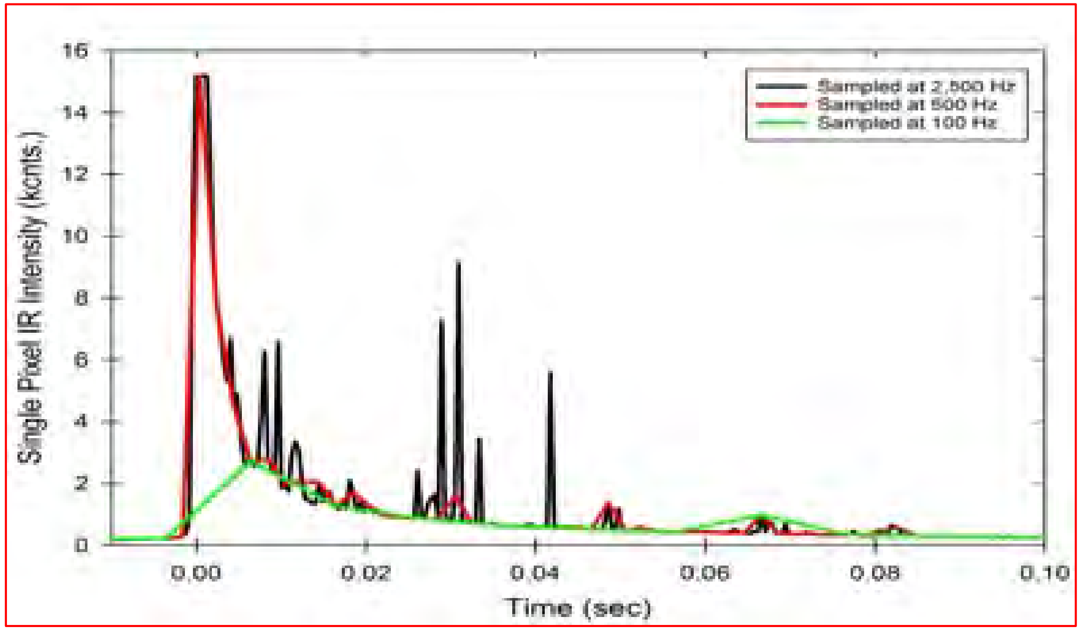






Review and Summary of Past Work

- **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

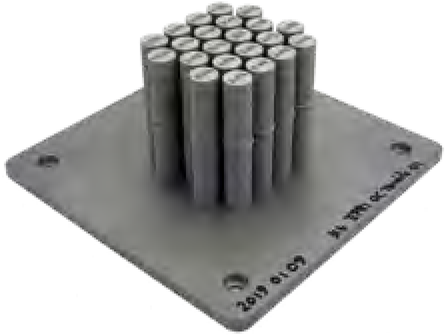


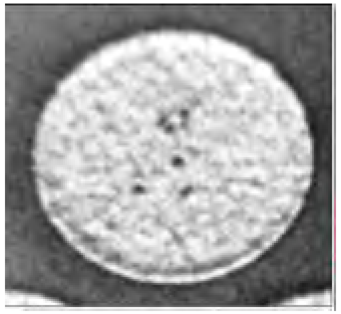
IR example from high rate experiment showing large difference in sampling rates

- **Led to the focus on optical in-situ data**

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?

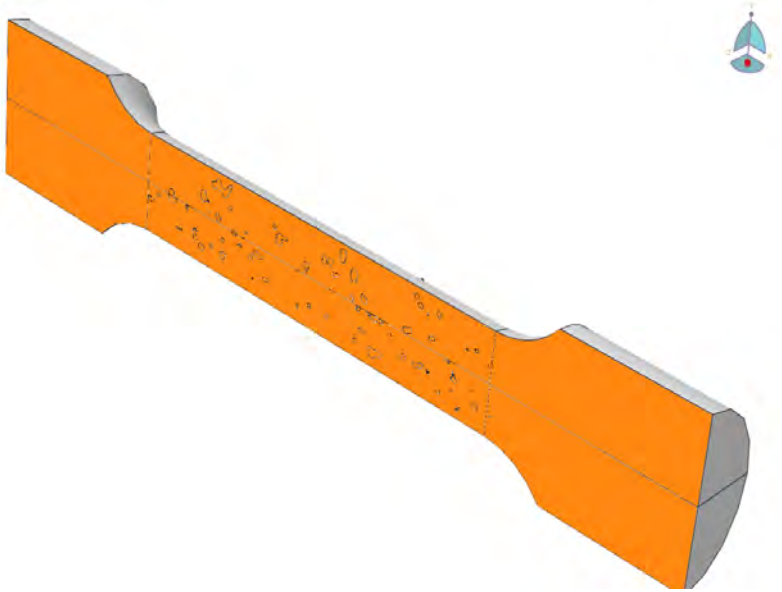




[1] Kamath, C., El-dasher, B., Gallegos, G.F. et al. “Density of Additively-manufactured, 316L SS parts using laser powder-bed fusion at powers up to 400 W,” Int J Adv Manuf Technol (2014) 74: 65. https://doi.org/10.1007/s00170-014-5954-9 [2]

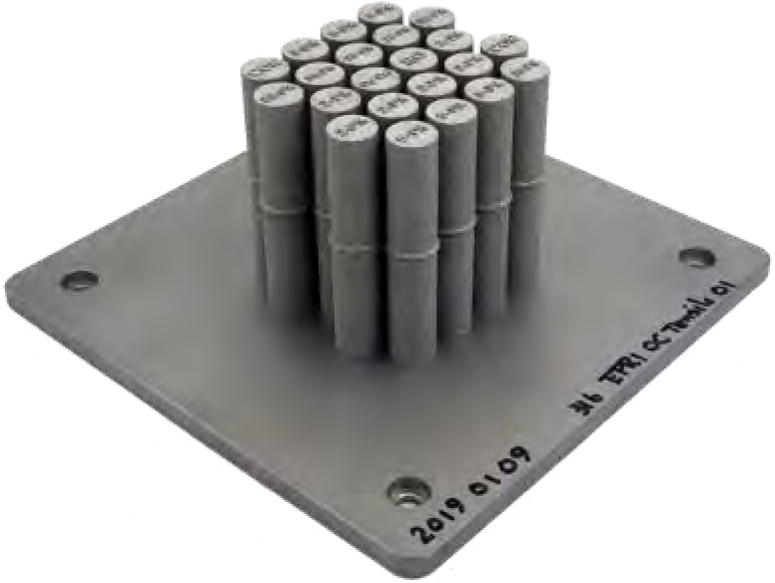
Tensile Bars Generated via AM with Engineered Porosity

- 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

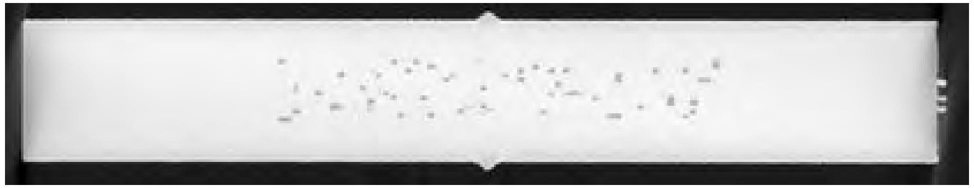
Test Conditions:

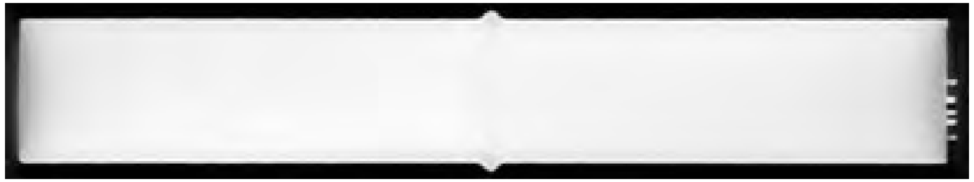
- Room Temperature
- Strain rate: 0.005 in/in/min through 0.2% Yield, then 0.063 in/in/min until failure
- Nominal gauge dimensions: 0.25in dia. x 1.35 in length

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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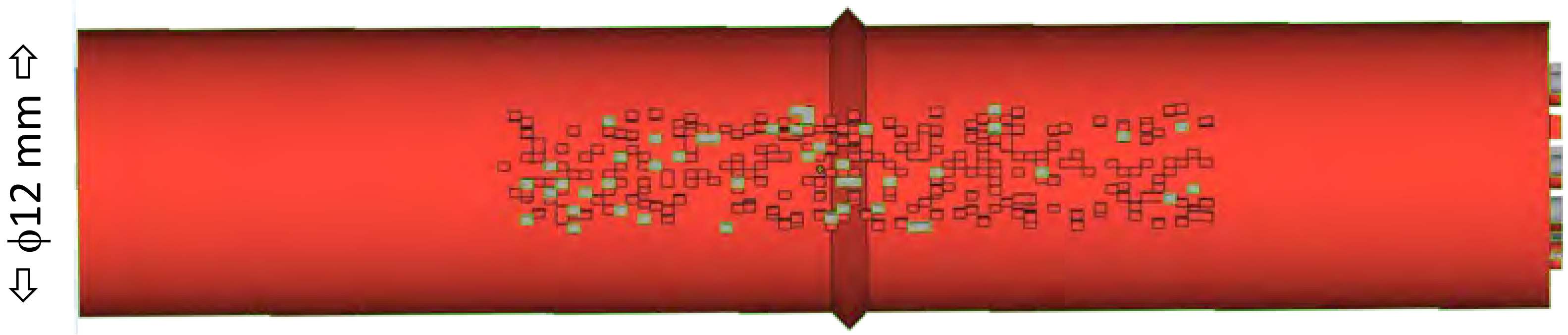
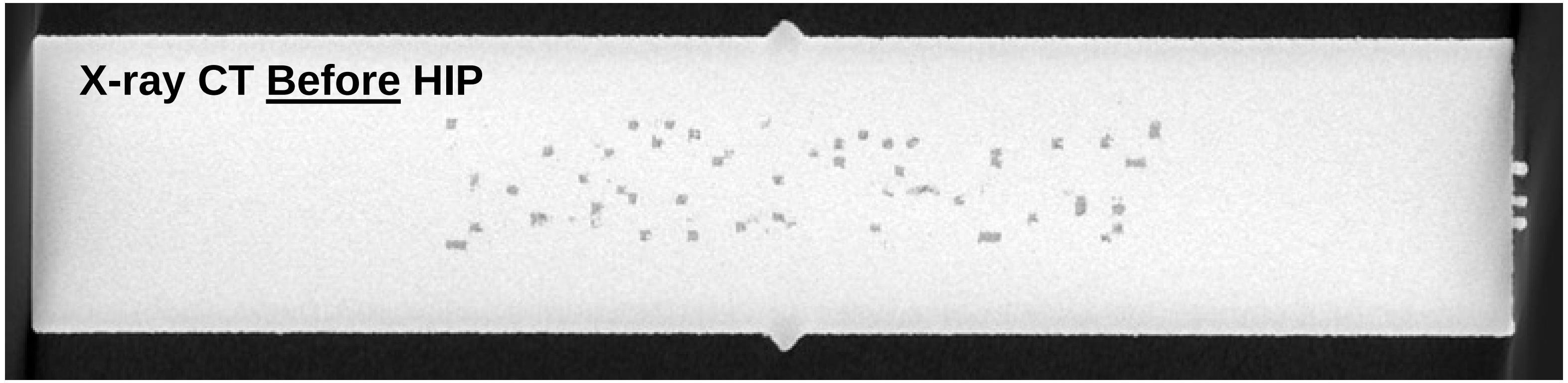
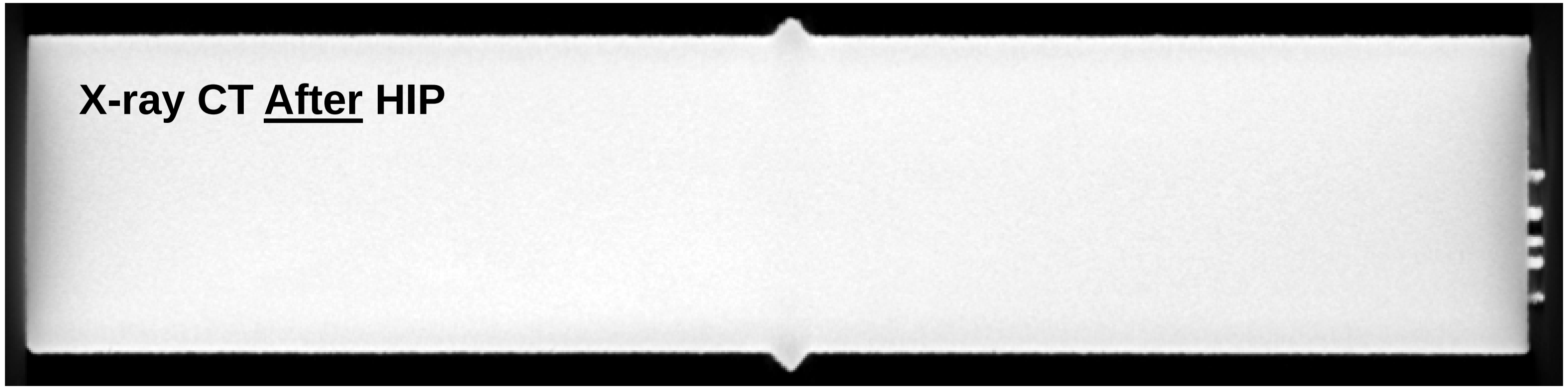
350µm-3%	35-3%	2	350 µm	3
350µm-5%	35-5%	2	350 µm	5
500µm-1%	5-1%	2	500 µm	1
500µm-3%	5-3%	2	500 µm	3
500µm-5%	5-5%	2	500 µm	5
Optical Cal.	Op Cal	1	NA	NA
Rube Gberg	RG	1	NA	NA
Control	CON	2	NA	~0

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



Solid model showing imbedded porosity

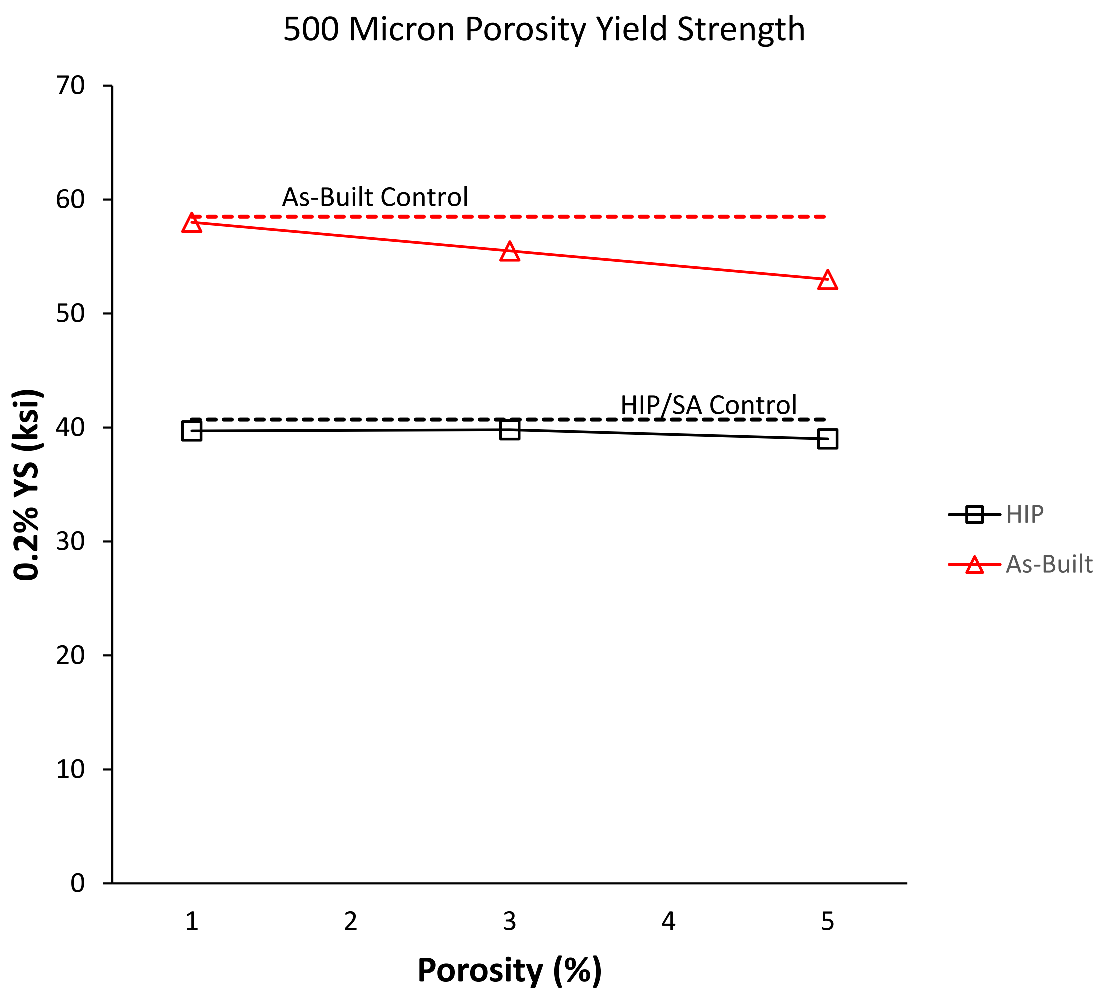




Note: X-ray CT resolution ~40 µm

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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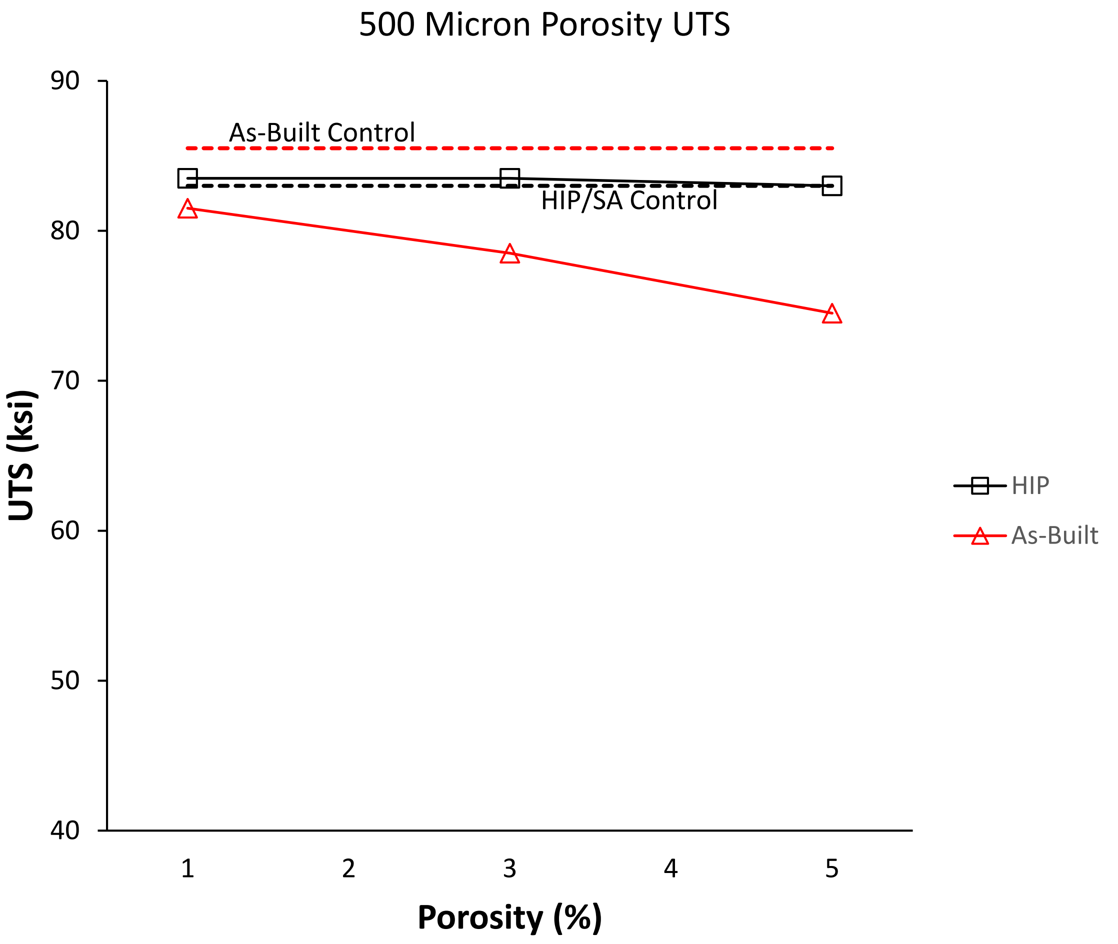
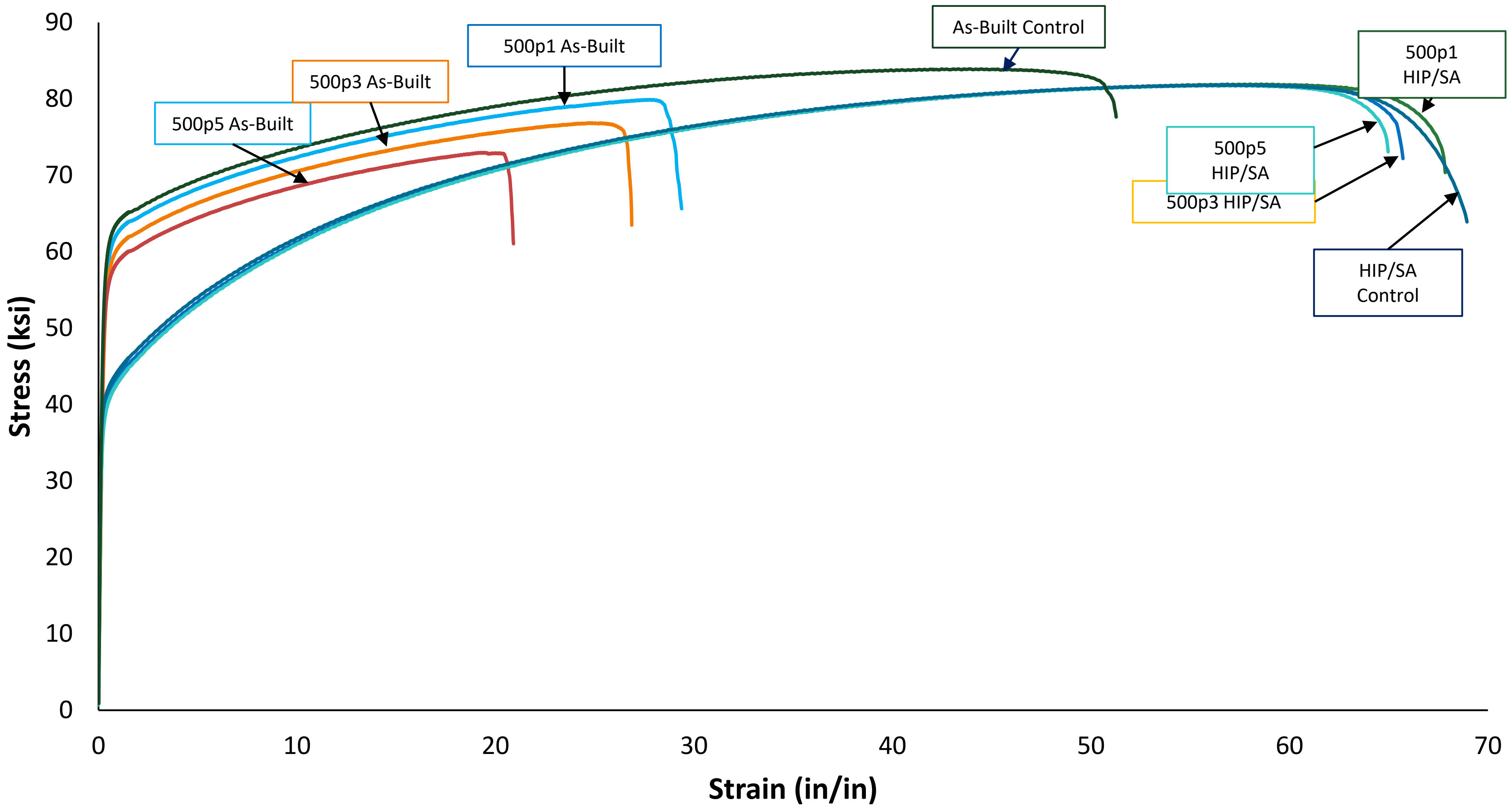
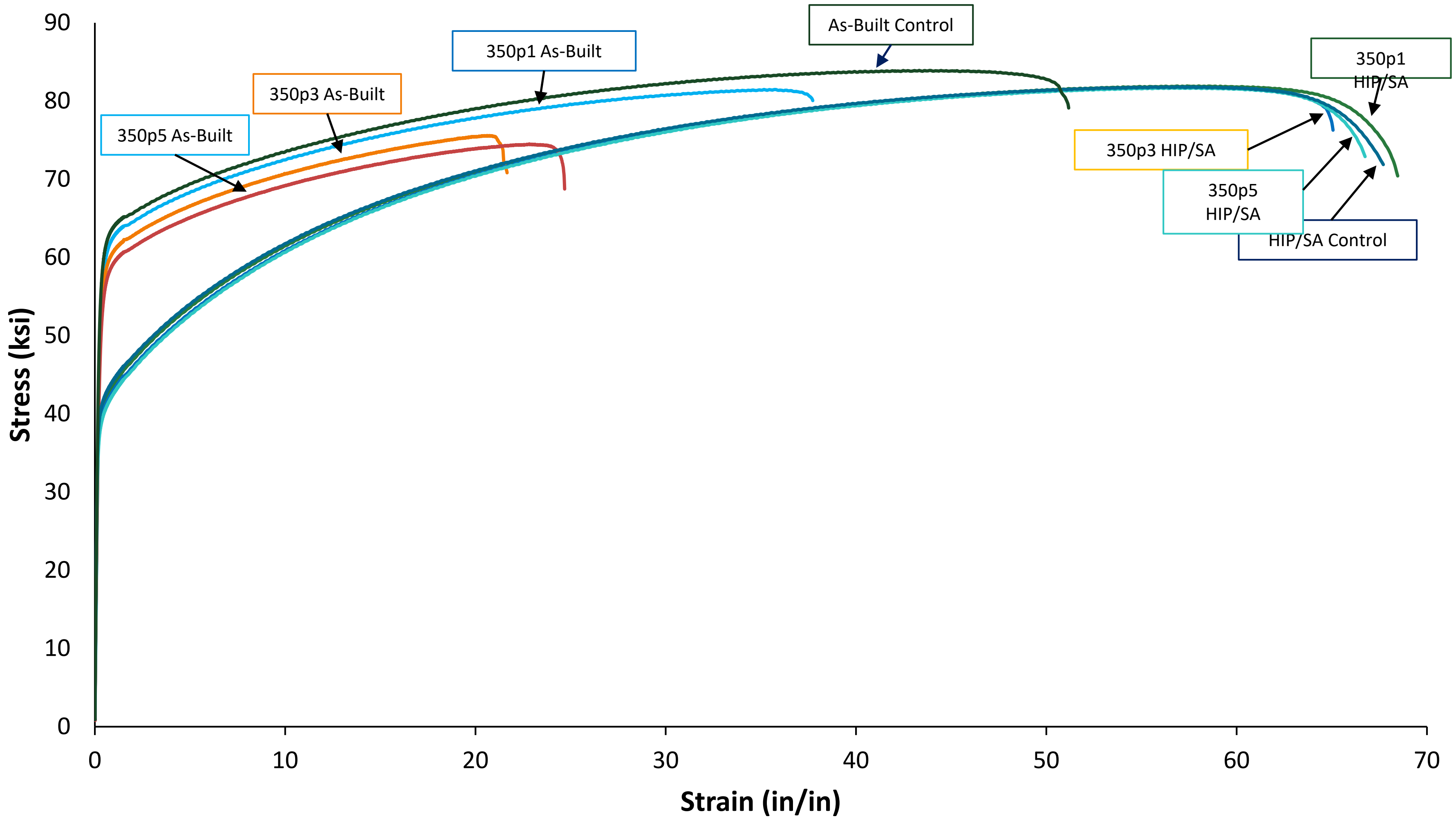


Stress-strain curves for the HIP/SA bars at all porosity values for the 500µm samples achieved similar results as the control sample. This suggests that pores were closed.



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



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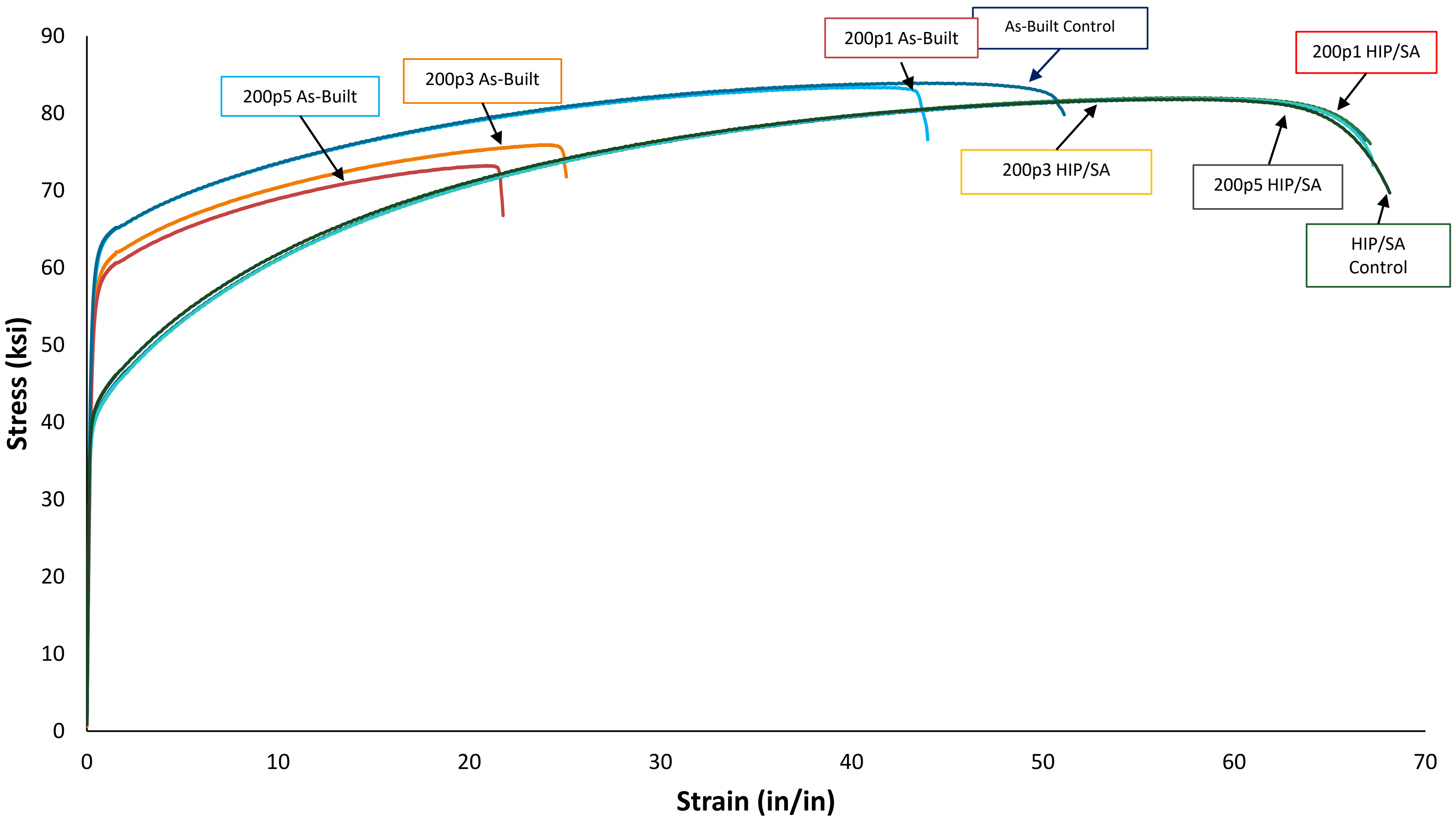
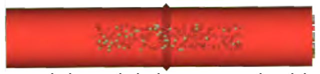
In the 200µm samples, we see the "best case" porosity sample (200µm-1%) stress-strain curve some closest to matching the control

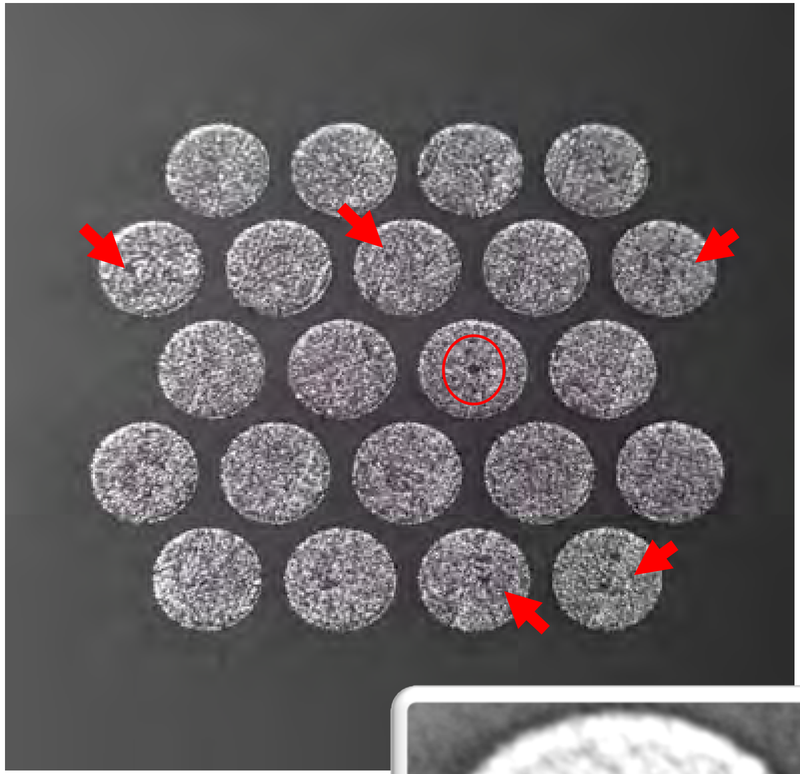


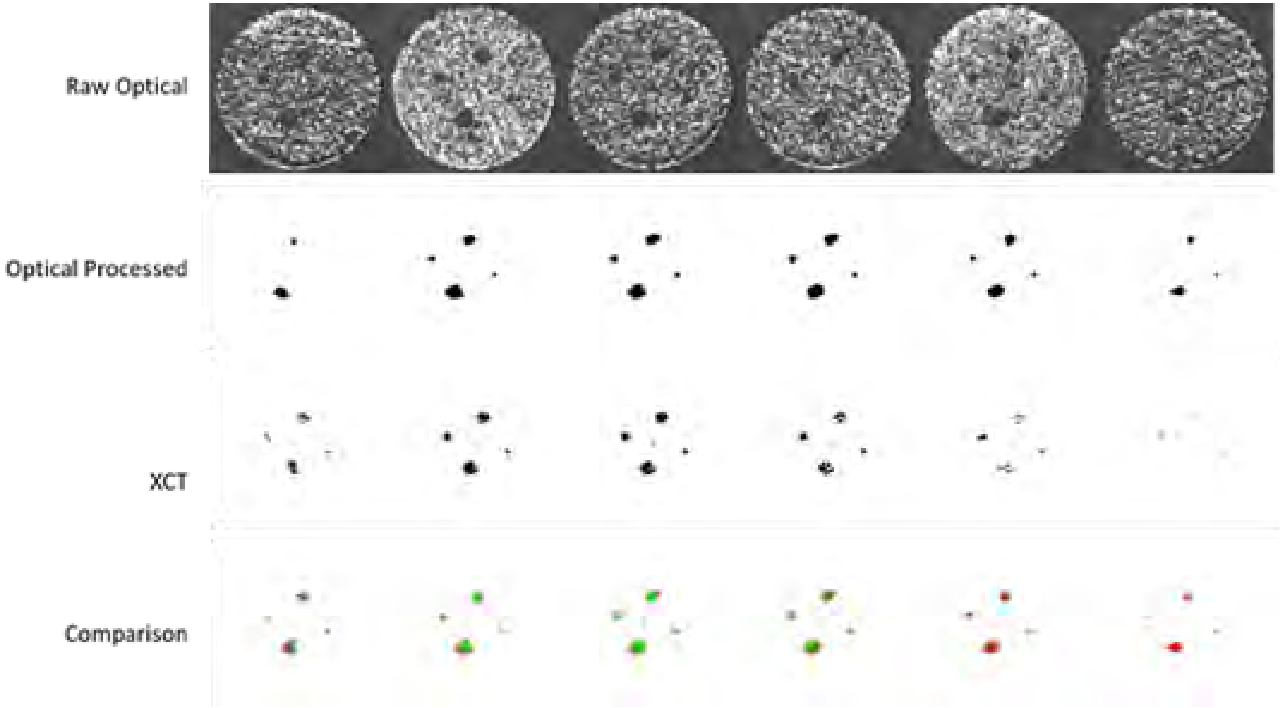
Pores are visible initially in optical in-situ data



Solid model showing imbedded porosity

Part for Layer 634



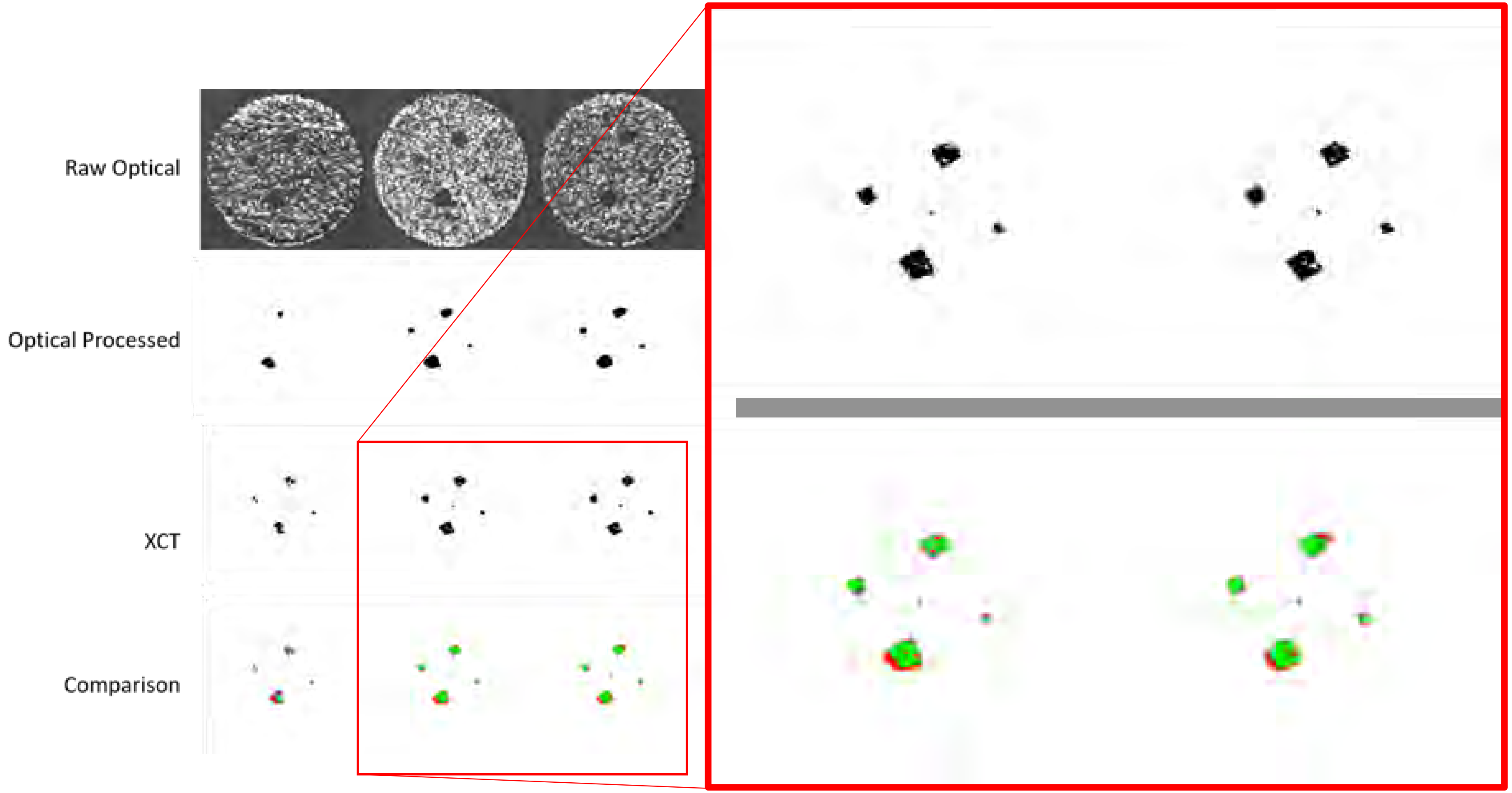


Green: Part and XCT Data Match

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



Comparison Color Scheme:

Green: Part and XCT Data Match

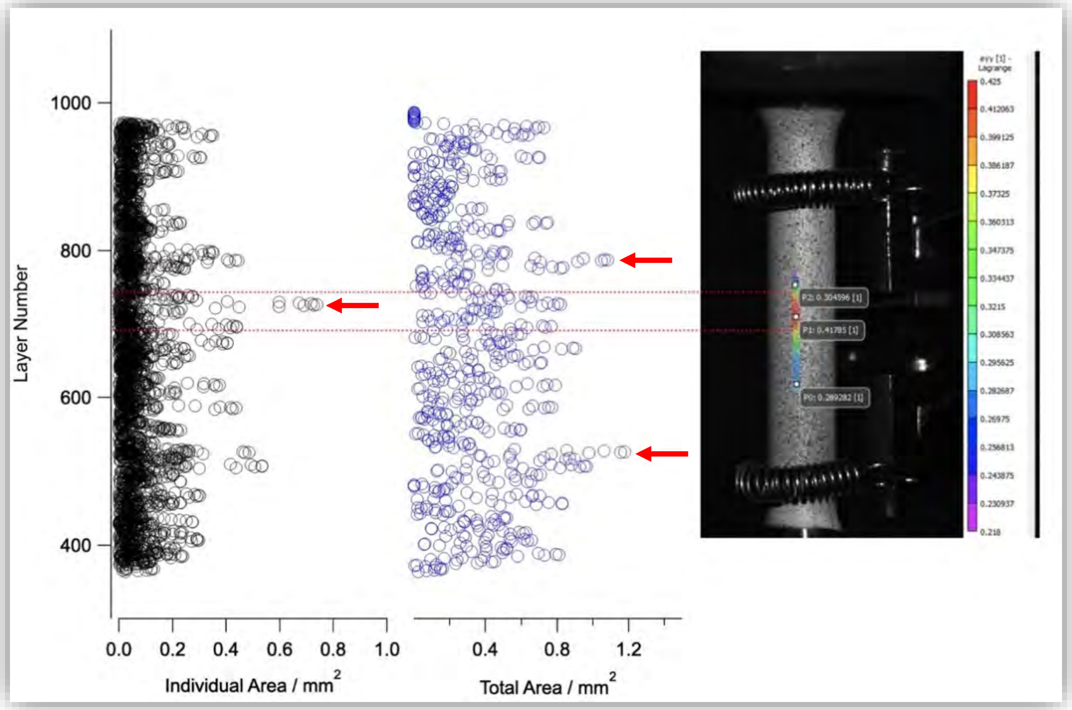
Red: Part Does not Match XCT (likely caused by consecutive layer re-melting after optical image)

Purple: XCT does not match part

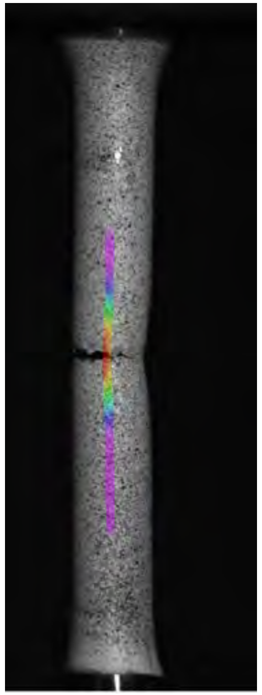
Optical data porosity is almost always larger than XCT, likely due to re-melting that occurs after image is taken

Integrated Computational Materials Engineering (ICME)

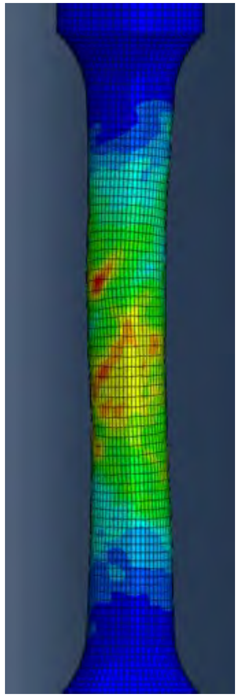
- GOAL: Create an FEA model using optical porosity data to determine if it fails in the same location as the physical tensile sample.
- Digital Image Correlation used to record strain during tensile testing
- Location of Failure was NOT always at the location of most porosity in a single layer
  - Instead showed a correlation with aggregation of large porosities



As-Built



FEA Model



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Summary

- Defect detection: optical in-situ data
  - 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 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
- 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 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

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ASME Data Package and Code Case Development

316L Laser Powder Bed Fusion (LPBF)

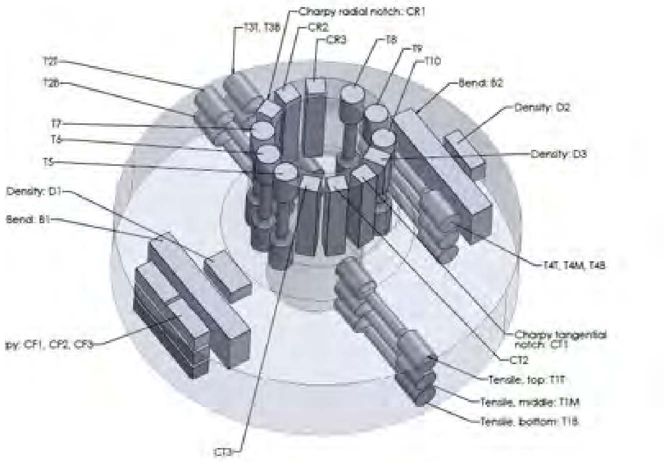
AM Qualification for Nuclear Applications
--ASME Data Package Development

- 3 different LPBF machine models
  - EOS M280, EOS M290, Renishaw 250
- 4 different vendors/suppliers
- 4 sets of processing parameters
- 4 different 316L powder heats
- 3 different components (next slide)
- Different build environments --argon and nitrogen
- Components are >8-inches in diameter and ~0.5-inch thick
- Two conditions: HIP and SA; SA only
- Vertical control/witness samples included
- Parameter data sheet recorded for each build

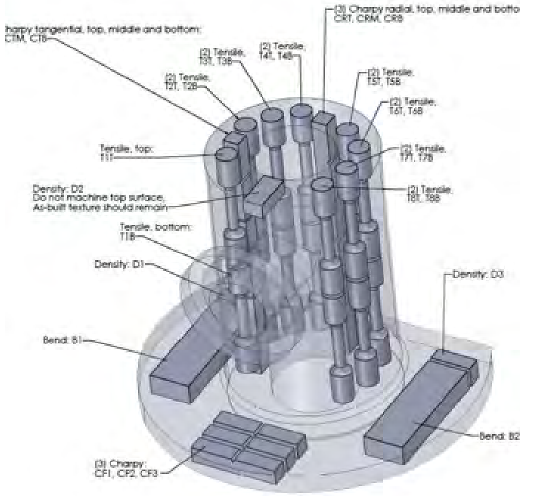
Renishaw AM 250 System

Courtesy: ORNL/Renishaw

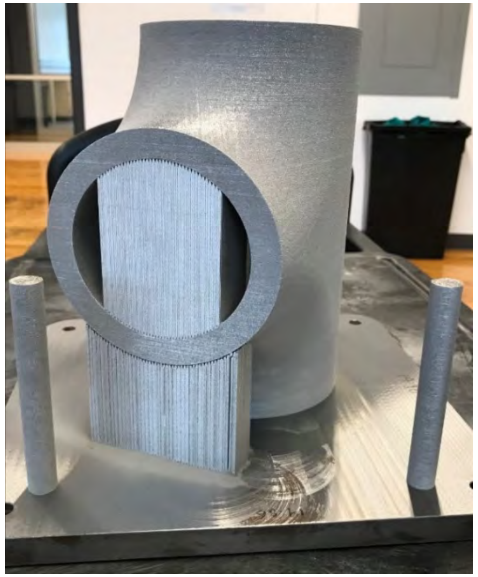
ASME Data Package Development

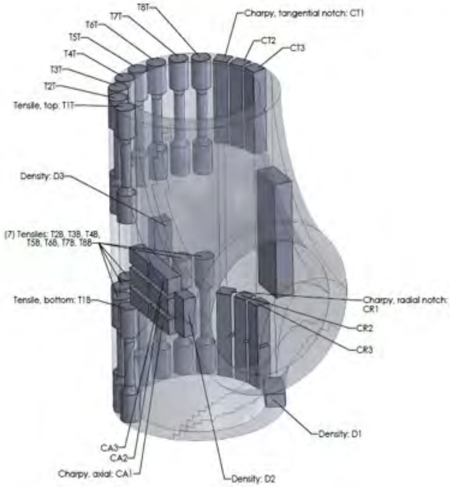


8.5” Ø x 1.5” thick x 2” bore
(216mm Ø x 38mm thick x 51mm bore)



8” Ø x 2” bore x 4” OD x ½” thick
(203mm Ø x 51mm bore x 102mm OD x 13mm thick)

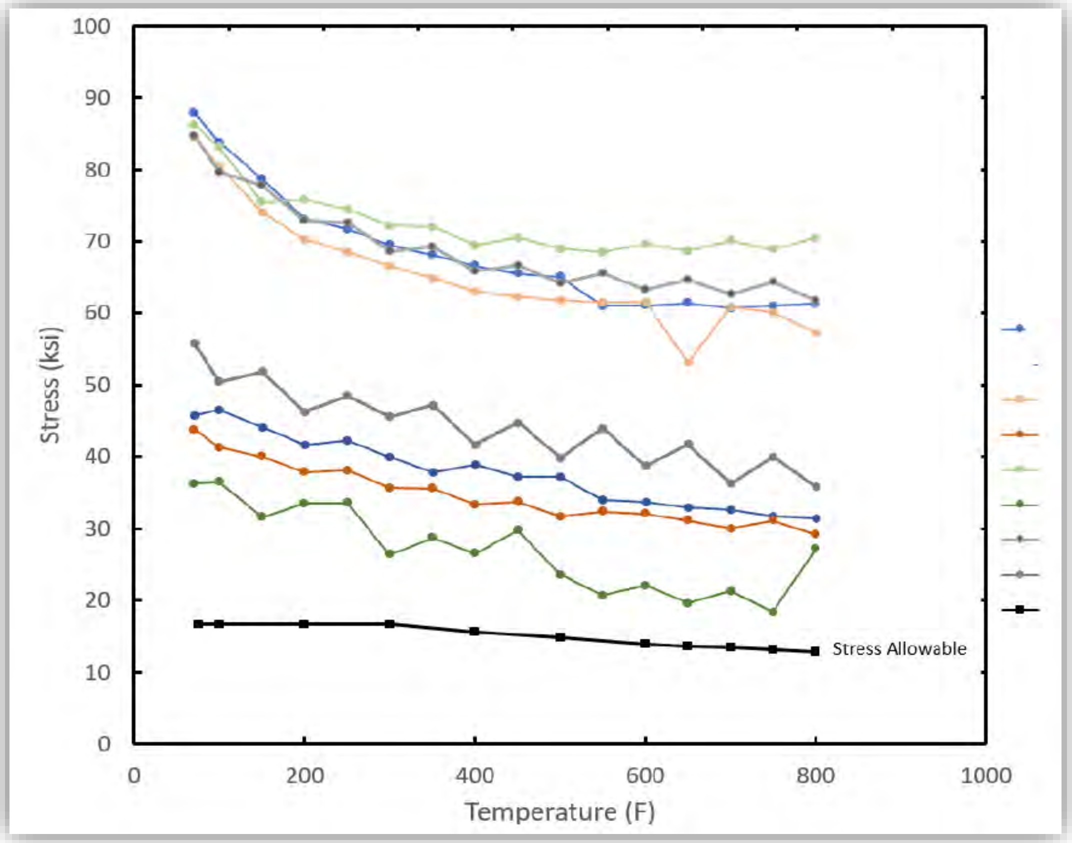




4-1/8” wide x 8-1/4” tall
(105mm wide x 210mm tall)

Summary of Data Package Contents

- Data package with mechanical and microstructural results:
  - Chemical analysis (both powder post printing)
  - Microstructure analysis
    - Microstructure – multiple magnifications
    - Grain size
    - Density
    - Inclusion content
  - Inspection data
  - Process parameter data sheets
  - Heat Treatment data
  - Hardness
  - Tensile (yield to 800°F and UTS)
    - including elongation and reduction in area
  - Toughness (Charpy testing)
  - Side Bends
  - Fatigue Data
  - Weld data



Draft ASME Section III Code Case for AM 316L using LPBF

- Summary of Code Case Contents
  - Design stress intensity values and maximum allowable stresses
  - Heat Treatment
  - Powder to ASTM F3184
  - Essential LPBF build variables (*proposed*)
    - Layer thickness
    - Laser power
    - Focus settings
    - Beam diameter
    - Effective velocity
    - Scan strategy
    - Stripe width
    - Hatch spacing
    - Shielding gas composition and flow
  - Witness samples and test specimen requirements
  - Examination techniques
  - Pressure testing requirements
  - Neutron dose limits

Code Case Record No: 20-254

Record 20-254

DRAFT Code Case XXXX
Austenitic Stainless Steel (UNS S31603)
Section III, Division 1 – Subsection NB/NC/ND, Class 1, 2 and 3 Components

Inquiry: May UNS S31603 that meets the specification requirements of ASTM F3184-16 for additively manufactured stainless steel products produced using the laser powder bed fusion process, then hot isostatic pressed and solution annealed, be used for Section III, Division 1--Subsection NB/NC/ND, Class 1, 2 and 3 components construction?

Reply: It is the opinion of the Committee that UNS S31603 conforming to ASTM F3184-16 for additively manufactured stainless steel products produced using laser powder bed fusion, then hot isostatic pressed and solution annealed, may be used for Section III, Division 1 – Subsection NB/NC/ND, Class 1, 2 and 3 components construction provided the following additional requirements are met:

2.0 Chemical Composition Requirements

Table 2-1. Chemical Composition of S31603 (316L) Manufactured Components

Element	C*	Mn*	P*	S*	Si*	Cr	Ni	Mo	Fe
	0.030	2.00	0.045	0.030	1.0	16.0-18.0	10.0-14.0	2.0-3.0	Bal

**maximum*

2.1 Tensile Requirements

The minimum tensile requirements per ASTM F3184-16 are shown below:

Table 2-2. Minimum Tensile Requirements

TABLE 3 Minimum Tensile Requirements[A]

Room Temperature Condition	Tensile Strength, MPa (ksi), X and Y Directions	Tensile Strength, MPa (ksi), Z Direction	Yield Strength at 0.2% Offset, MPa (ksi), X and Y Directions	Yield Strength at 0.2% Offset, MPa (ksi), Z Direction	Elongation in 50 mm (2 in.) or 4D, (%), X and Y Directions	Elongation in 50 mm (2 in.) or 4D, (%), Z Direction	Reduction of Area, %, X and Y Directions	Reduction of Area, %, Z Direction
A - Stress Relieved[B]	515 (75)	515 (75)	205 (30)	205 (30)	30	30	40	40
A - Solution Annealed	515 (75)	515 (75)	205 (30)	205 (30)	30	30	30	30
B	515 (75)	515 (75)	205 (30)	205 (30)	30	30	30	30
C	515 (75)	515 (75)	205 (30)	205 (30)	30	30	30	30
E	no requirement	no requirement	no requirement	no requirement	no requirement	no requirement	no requirement	no requirement

[A] A gauge length corresponding to ISO 6892 may be used when agreed upon by the component supplier and purchaser.
[B] Mechanical properties conform to Specification A479/A479M.

2.2 Heat Treatment Requirements

The minimum heat treatment requirements per ASTM F3184-16 are shown below:

Process components under inert atmosphere at not less than 100MPa (14.5ksi) within the range of 1120 to 1163°C (2050 to 2125°F); hold at the selected temperature within 614°C (625°F) for 60 min and cool under inert atmosphere to below 427°C (800°F), or to parameters agreed upon by the component supplier and purchaser.

NOTE 10—Proper heat treatment of Condition C components may be necessary to enhance corrosion and environmental cracking resistance. When specified by the purchaser, the component supplier shall test the material in its final condition in accordance with Supplementary Requirement S16.

2.3 Hardness Requirement

Not applicable under ASTM F3184-16.

3.0 COMPONENT BUILD AM PARAMETERS

Table 3-1. Component Build Parameters Used by Each Manufacturer

Parameter	Westinghouse Build	Auburn University Build	Rolls-Royce Build	Oerlikon Build
Laser Power:	214W	200W	195W	265
Layer Thickness:	40 microns	50 microns	20microns	40
Melting Method:	Stripe, (12mm)	Stripe, (8mm)	Stripe, (5mm)	Stripe (7mm)
Rotation:	47 degrees	67 degrees	67 degrees	67 degrees
Exposure Time:	N/A	80 us	N/A	N/A
Point Distance:	N/A	60 microns	N/A	N/A
Effective Velocity:	0.928 m/s	0.75 m/s	1.083 m/s	1.15 m/s
Hatch Spacing:	100 microns	100 microns	90 microns	100 microns
Energy Density (J/mm3)	57.65	53.33	100.03	57.61
Recoater Blade Type	Hard (Steel)	Silicon Rubber	High speed steel	Silicone Rubber
Atomized Powder Gas Type	Argon	Argon	Nitrogen	Argon
Build Chamber Gas Type	Argon	Argon	Nitrogen	Argon
Equipment Type	**EOS M290**	**Renishaw AM250**	**EOS M280**	**EOS M290**

The actual components are shown in Section 5.5 of this Data Package.

Chemical Composition of 316L SS Powder

Element	S31603 (316L) Spec	Auburn	Westinghouse	Oerlikon	Rolls Royce
C	0.030 max	0.023	0.012	0.02	0.02
Mn	2.00 max	0.88	1.24	0.41	0.01
P	0.045 max	0.008	<0.005	0.014	<0.01
S	0.030 max	0.004	0.004	<0.010	0.014
Si	1.00 max	0.70	0.47	0.38	0.56
Ni	10.0-14.0	12.7	12.02	12.43	12.78
Cr	16.0-18.0	17.7	17.02	17.28	17.23
Mo	2.0-3.0	2.29	2.50	2.33	2.51
N	0.10 max	0.10	0.01	0.08	0.07
Cu	NS	0.04	0.01	0.08	NA
Fe	NS	Bal	Bal	Bal	Bal
O	NS	NR	0.04	0.04	0.034
Powder Manufacturer	---	LPW	Praxair	Oerlikon Metco	LSN Diffusion
Powder Lot/Batch No.	---	UK83448	22	471705	55999
Powder Product Name	---	LPW-316-AAAV	TruForm 316-3	MetcoAdd 316L-A	F-316LNRR-ALMD
AM Equipment	---	**Renishaw 250**	**EOS M290**	**EOS M290**	**EOS M280**

Chemical Composition of 316L SS Manufactured Components

Element	S31603 (316L) Spec	Auburn	Westinghouse	Oerlikon	Rolls Royce
C	0.030 max	0.023	0.012	0.017	0.017
Mn	2.00 max	0.89	1.14	0.34	0.02
P	0.045 max	0.012	0.004	0.01	0.002
S	0.030 max	0.005	0.003	0.004	0.012
Si	1.00 max	0.77	0.44	0.38	0.64
Ni	10.0-14.0	12.8	11.83	12.82	12.57
Cr	16.0-18.0	17.82	16.96	17.66	17.04
Mo	2.0-3.0	2.26	2.64	2.38	2.52
N	0.10 max	0.0885	0.0099	0.0568	0.089
Cu	NS	0.03	0.01	0.04	<0.01
Fe	NS	Bal	Bal	Bal	Bal
O	NS	0.0214	0.0334	0.0568	0.030

4.0 HEAT TREATMENT OF COMPONENT BUILDS

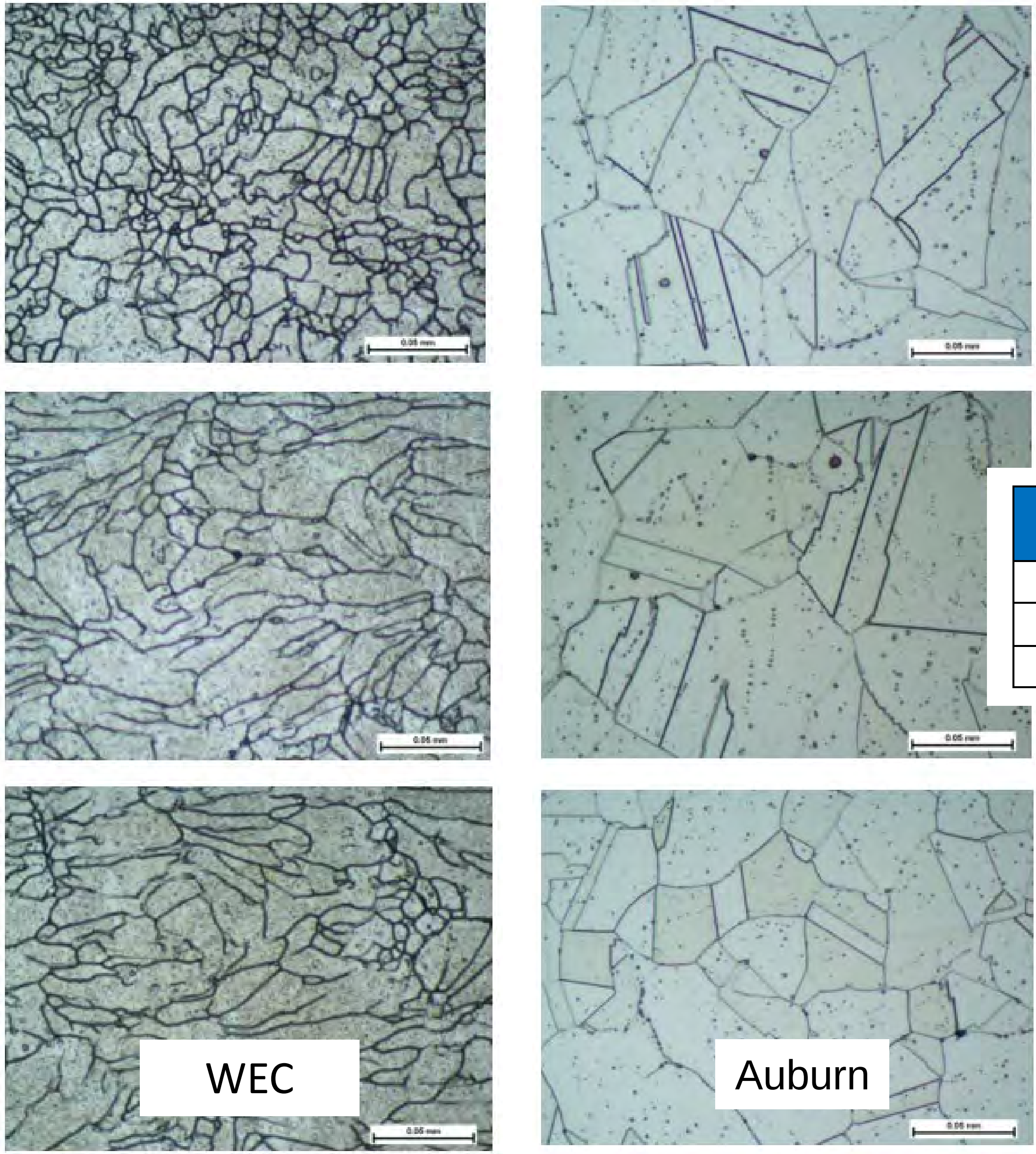
4.1 Hot Isostatic Pressing and Solution Anneal Parameters

Two of the component builds (Westinghouse and Auburn U.) were hot isostatically pressed (HIP'ed) at 2050F (1120C) for 2 hours in an argon environment, then cooled to room temperature. Following HIP, the component builds were solution heat treated for 2 hours at 2050F and quenched in water.

4.2 Solution Anneal Parameters

Two additional component builds (Oerlikon and the second Westinghouse build) were solution annealed only (no HIP applied) at 2050F (1120C) for 2 hours in an argon environment and quenched in water.

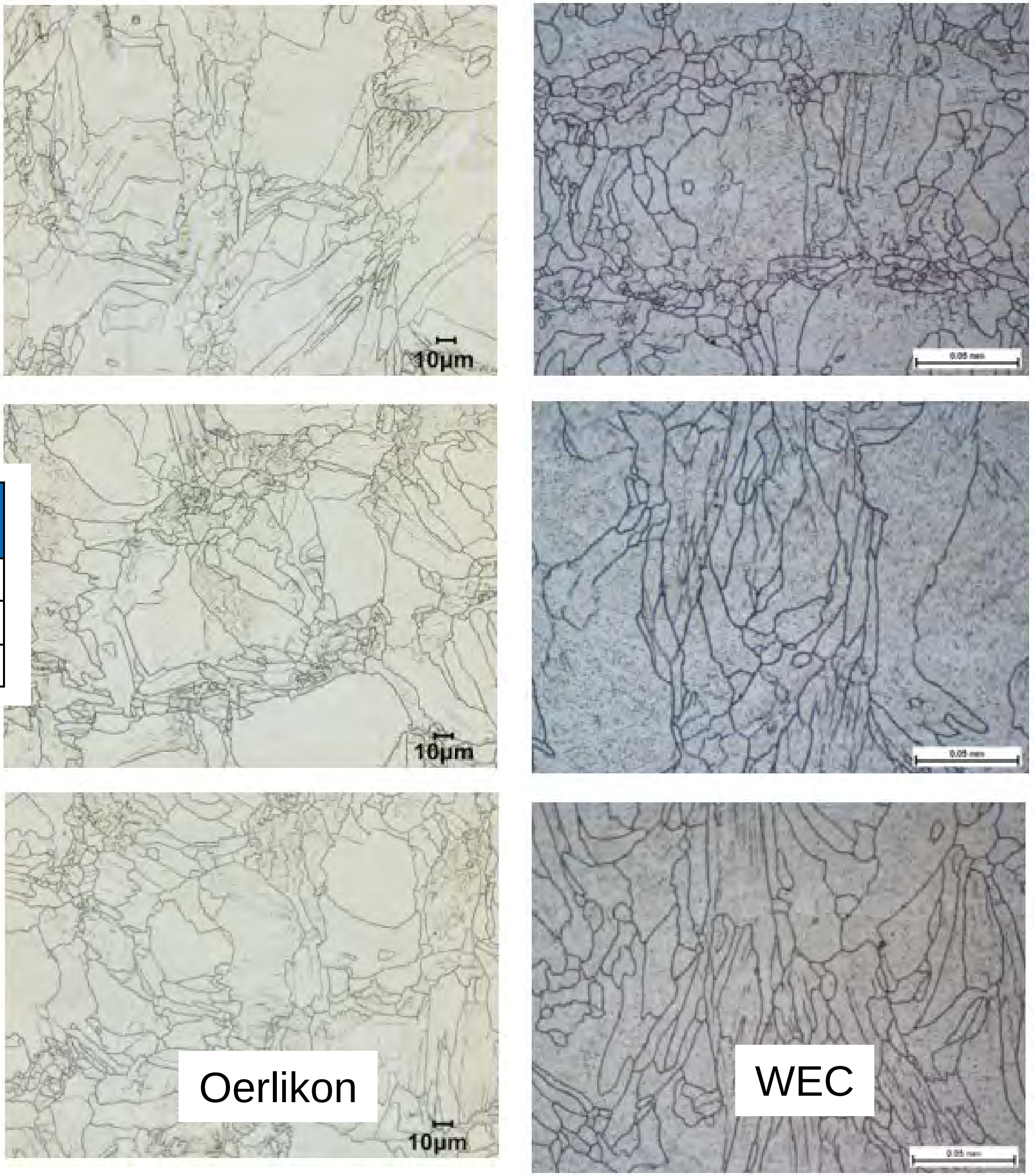
HIP & Solution Annealed



Part	Grain Size
WEC	8
Auburn	4
Oerlikon	6.5

500X

Solution Annealed only



Charpy Impact Results – HIP & Solution Anneal

Table 5.7a. Westinghouse – Ring Flange Charpy Toughness Results					
Sample ID	Test Log Number	Test Temp. (F)	Energy ft-lbs	Mils Lat Exp	% Shear
CF1	294KXH	73	107	81	100
CF2	295KXH	73	111	83	100
CF3	296KXH	73	110	79	100
	Average		**109**	**81**	**100**
CT1	297KXH	73	168	66	100
CT2	298KXH	73	158	73	100
CT3	299KXH	73	172	74	100
	Average		**166**	**71**	**100**
CR1	300KXH	73	183	75	100
CR2	301KXH	73	177	70	100
CR3	302KXH	73	167	77	100
	Average		**176**	**74**	**100**

Table 5.7b. Auburn – Pipe Tee Charpy Toughness Results					
Sample ID	Test Log Number	Test Temp. (F)	Energy ft-lbs	Mils Lat Exp	% Shear
CT1	046LNH	73	113.9	75	100
CT2	047LNH	73	122.8	75	100
CT3	048LNH	73	125.6	78	100
	Average		**120.8**	**76**	**100**
CR1	049LNH	73	136.9	78	100
CR2	050LNH	73	136.5	77	100
CR3	051LNH	73	153	78	100
	Average		**142.1**	**77.7**	**100**
CA1	043LNH	73	123.8	79	100
CA2	044LNH	73	119.7	73	100
CA3	045LNH	73	112.8	76	100
	Average		**118.8**	**76.0**	**100**

Charpy Impact Results – Solution Anneal only

Table 5.7c. Oerlikon – Valve Body (Solution Annealed only - No HIP) Charpy Toughness Results

Sample ID	Test Log Number	Test Temp. (F)	Energy ft-lbs	Mils Lat Exp	% Shear
CF1	046LNH	73	114	86	62
CF2	047LNH	73	113	85	62
CF3	048LNH	73	119	80	60
	Average		**115**	**84**	**61**
CTT	049LNH	73	207	83	89
CTM	050LNH	73	197	82	89
CTB	051LNH	73	143	81	92
	Average		**182**	**82**	**90**
CRT	043LNH	73	200	76	100
CRM	044LNH	73	159	81	90
CRB	045LNH	73	128	80	84
	Average		**162**	**79**	**91**

Table 5.7d. Westinghouse – 2nd Ring Flange (Solution Annealed only - No HIP) Charpy Toughness Results

Sample ID	Test Log Number	Test Temp. (F)	Energy ft-lbs	Mils Lat Exp	% Shear
CF1	474QNH	73	87	76	100
CF2	475QNH	73	88	87	100
CF3	476QNH	73	86	70	100
	Average		**87**	**78**	**100**
CT1	477QNH	73	123	79	100
CT2	478QNH	73	119	84	100
CT3	479QNH	73	113	58	100
	Average		**118**	**74**	**100**
CR1	480QNH	73	119	79	100
CR2	481QNH	73	115	90	100
CR3	482QNH	73	109	83	100
	Average		**114**	**84**	**100**

Tensile Properties – HIP & Solution Anneal -- Westinghouse

Sample ID	Temp. (°F)	Temp. (°C)	UTS (ksi)	UTS (MPa)	YS (ksi)	YS (MPa)	Elong. in 4D (%)	ROA (%)
T1T	70	21.1	87.8	605.4	45.8	315.8	72.7	78
T1M	100	37.8	83.8	577.8	46.5	320.6	69.9	76.5
T1B	150	65.6	78.7	542.6	44.1	304.1	61.7	78.5
T2T	200	93.3	73.1	504.0	41.7	287.5	48.7	77
T2M	250	121.1	71.7	494.4	42.3	291.6	47.0	74.5
T2B	300	148.9	69.5	479.2	40.0	275.8	44.7	76.5
T3T	350	176.7	68.1	469.5	37.9	261.3	43.2	76.5
T3B	400	204.4	66.6	459.2	38.9	268.2	40.6	73
T4T	450	232.2	65.5	451.6	37.2	256.5	39.1	73
T4B	500	260.0	65.1	448.8	37.3	257.2	37.2	73.5
T5	550	287.8	61.0	420.6	34.1	235.1	44.1	76
T6	600	315.6	61.1	421.3	33.7	232.4	44.9	73
T7	650	343.3	61.4	423.3	32.9	226.8	47.9	72
T8	700	371.1	60.7	418.5	32.6	224.8	44.6	72.5
T9	750	398.9	61.0	420.6	31.7	218.6	47.2	74.5
T10	800	426.7	61.3	422.6	31.4	216.5	48.5	69.5
Witness Samples								
T11 (HIP)	70	21.1	84.2	580.5	43.7	301.3	86.1	73
T12 (HIP)	70	21.1	84.1	579.8	44.7	308.2	87.3	79
T13 (AB)	70	21.1	87.3	601.9	63.0	434.4	76.0	78
T14 (AB)	70	21.1	87.3	601.9	62.9	433.7	76.5	78

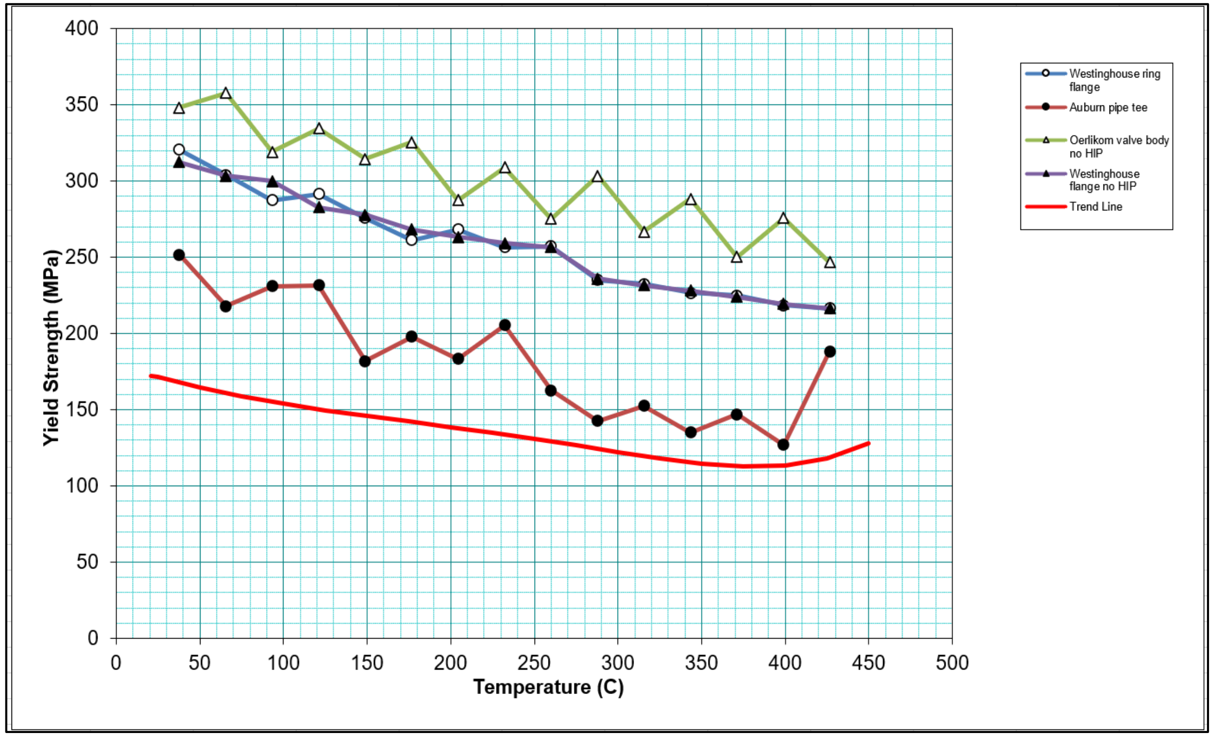
Note: 0.252 diameter coupons per ASTM E21-17

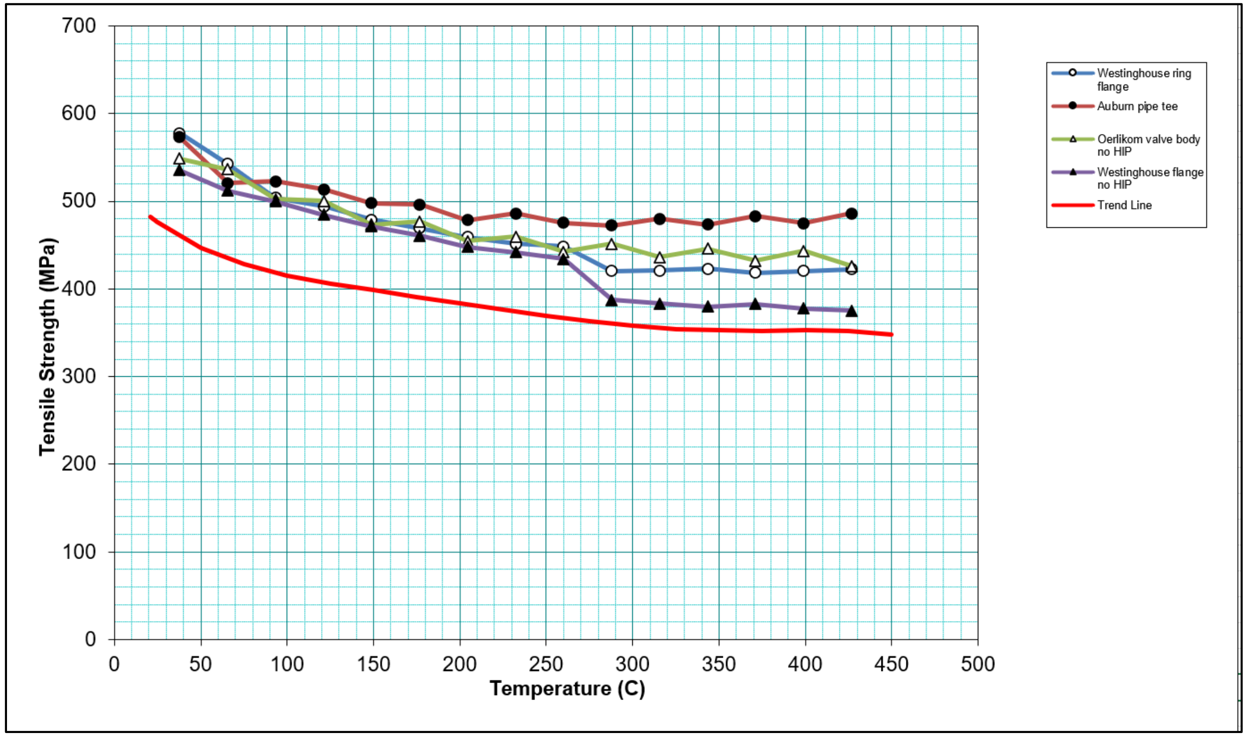
Tensile Properties – Solution Anneal only -- Westinghouse

Sample ID	Temp. (°F)	Temp. (°C)	UTS (ksi)	UTS (MPa)	YS (ksi)	YS (MPa)	Elong. in 4D (%)	ROA (%)
T1T	70	21.1	81.6	562.6	46.7	322.0	58	67
T1M	100	37.8	77.7	535.7	45.3	312.3	53	67.5
T1B	150	65.6	74.3	512.3	44	303.4	46	70.5
T2T	200	93.3	72.5	499.9	43.5	299.9	43	68
T2M	250	121.1	70.3	484.7	41	282.7	40	72
T2B	300	148.9	68.4	471.6	40.3	277.9	40	71
T3T	350	176.7	66.8	460.6	38.9	268.2	38	71.5
T3B	400	204.4	65	448.2	38.2	263.4	36	73
T4T	450	232.2	64.1	442.0	37.6	259.2	35	68
T4B	500	260.0	63	434.4	37.2	256.5	35	70.5
T5	550	287.8	56.2	387.5	34.2	235.8	41	71
T6	600	315.6	55.6	383.3	33.6	231.7	41	72.5
T7	650	343.3	55.1	379.9	33.1	228.2	41	70.5
T8	700	371.1	55.5	382.7	32.5	224.1	45	68.5
T9	750	398.9	54.8	377.8	31.8	219.3	43	65
T10	800	426.7	54.4	375.1	31.4	216.5	43	69
Witness Samples								
T11 (HIP)	70	21.1	74.7	515.0	44.5	306.8	45	37
T12 (HIP)	70	21.1	75.5	520.6	44.3	305.4	72	69

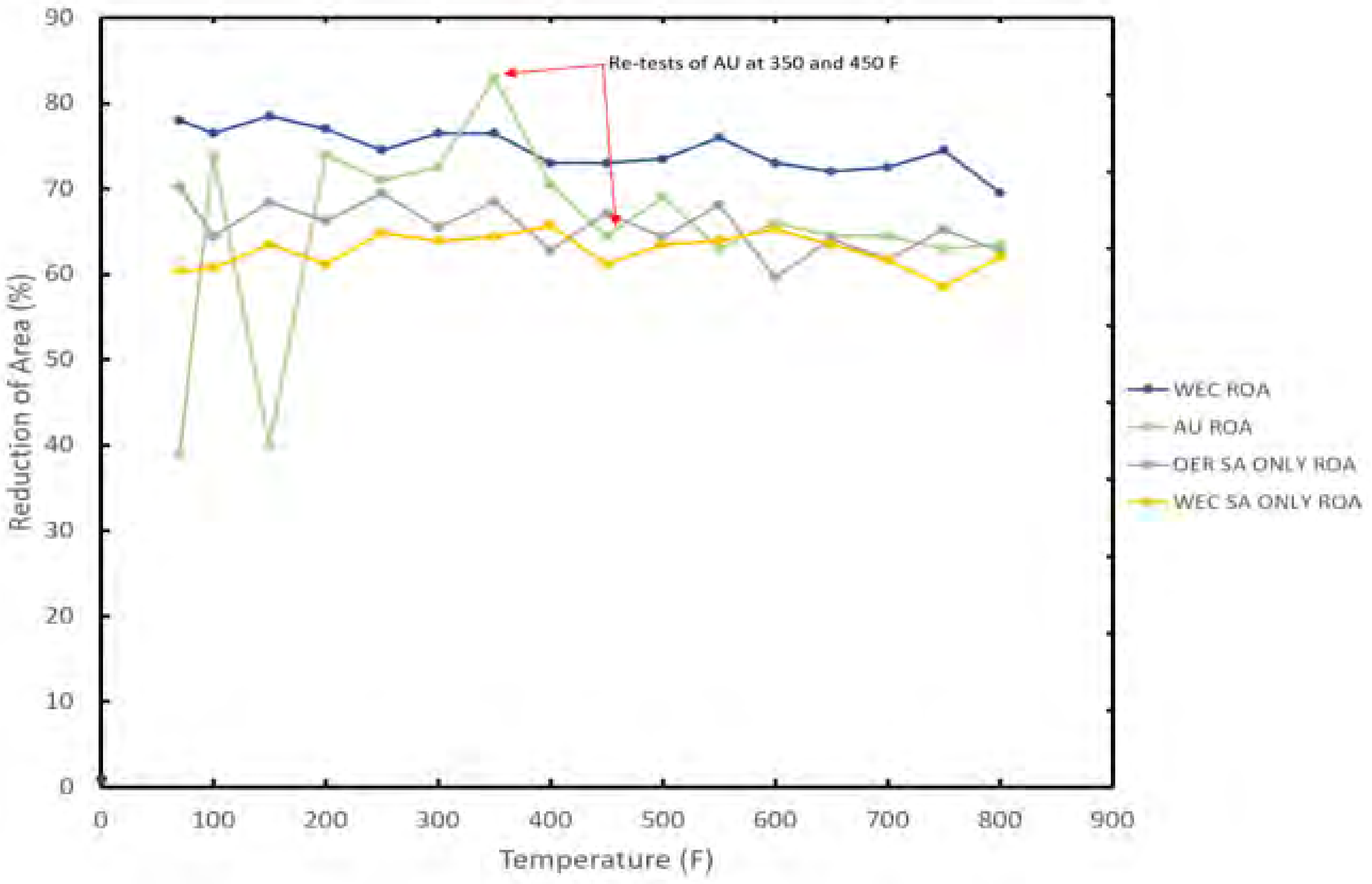
Note: 0.252 diameter coupons per ASTM E21-17

Yield and Tensile Strength as a Function of Temperature

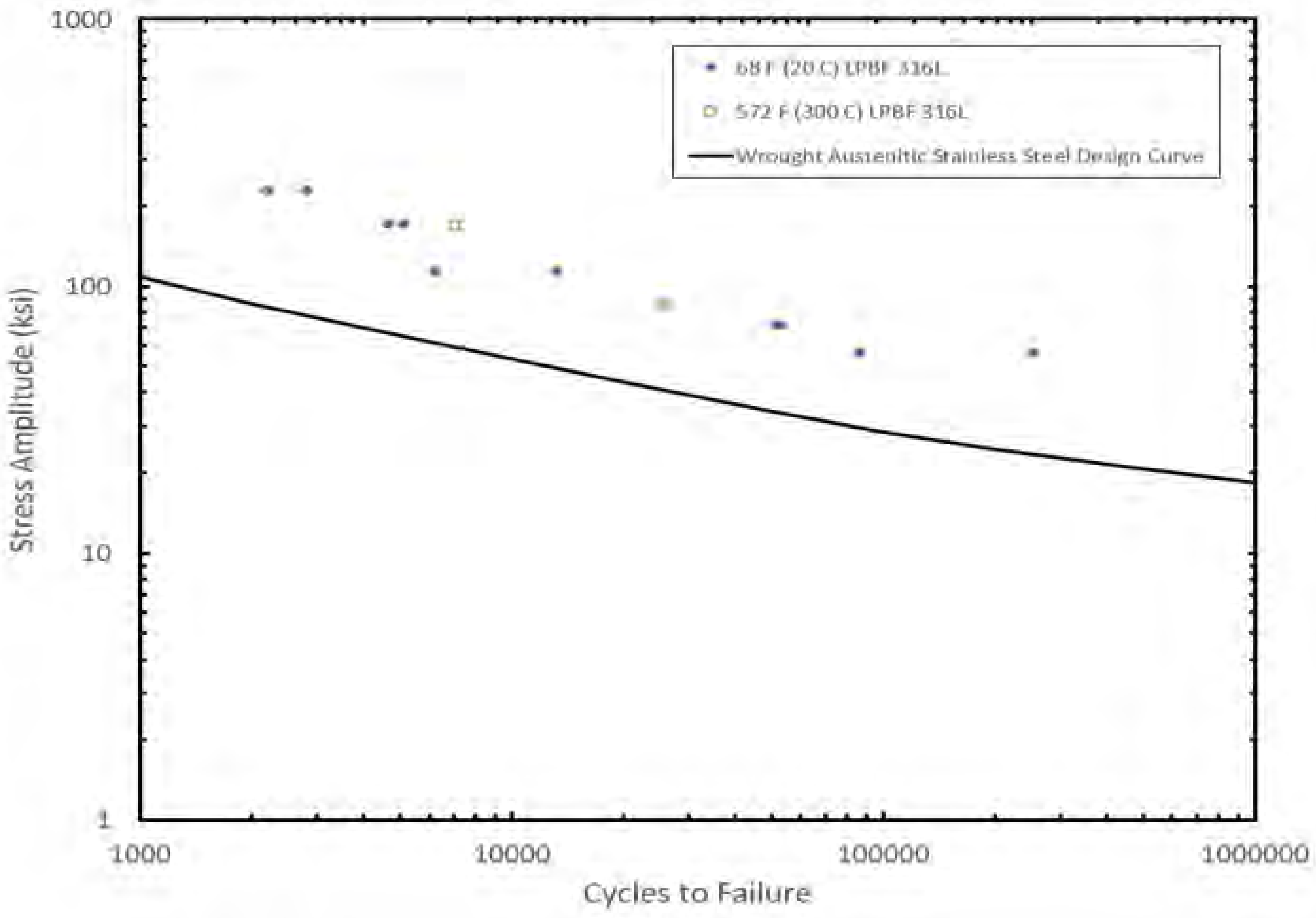




Reduction of Area as a Function of Temperature



Fatigue Data—HIP and Solution Anneal -- Rolls Royce component build



Extra -- Fatigue Data

Table 7-1. Fatigue Data for Rolls Royce Tee

Sample ID	Temp. (°F)	Temp. (°C)	Stress Amplitude (ksi)	Stress Amplitude (MPa)	Total Strain Amplitude (%)	Cycles to Failure
1	68	20	226.4	1561	0.8	2202
2	68	20	226.4	1561	0.8	2821
3	68	20	169.8	1171	0.6	5160
4	68	20	169.8	1171	0.6	4693
5	68	20	113.2	780	0.4	6229
6	68	20	113.2	780	0.4	13227
7	68	20	56.6	390	0.2	254532
8	68	20	56.6	390	0.2	86286
9	68	20	70.8	488	0.25	51370
10	68	20	70.8	488	0.25	53154
11	572	300	84.9	585	0.3	26420
12	572	300	86.3	595	0.305	25536
13	572	300	169.8	1171	0.6	7000
14	572	300	169.8	1171	0.6	7000

Note: Per ASTM E606—19e1

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Record 20-254

DRAFT Code Case XXXX
Austenitic Stainless Steel (UNS S31603)
Section III, Division 1 – Subsection NB/NC/ND, Class 1, 2 and 3 Components

Inquiry: May UNS S31603 that meets the specification requirements of ASTM F3184-16 for additively manufactured stainless steel products produced using the laser powder bed fusion process, then hot isostatic pressed and solution annealed, be used for Section III, Division 1-- Subsection NB/NC/ND, Class 1, 2 and 3 components construction?

Reply: It is the opinion of the Committee that UNS S31603 conforming to ASTM F3184-16 for additively manufactured stainless steel products produced using laser powder bed fusion, then hot isostatic pressed and solution annealed, may be used for Section III, Division 1 – Subsection NB/NC/ND, Class 1, 2 and 3 components construction provided the following additional requirements are met:

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(a) For purposes of welding procedure and performance qualification, this material shall be considered P-number 8.

(b) The design stress intensity values and the maximum allowable stress values for the material shall be those given in Tables 1(1M) and 2(2M).

(c) Feedstock powder cert(s) associated to individual lots and/or powder blends will be provided for each production build. In addition to the Feedstock requirements in ASTM F3184-16 Section 7, the following requirements apply:

  a. Complete or partially used powder lots will be re-analyzed after 10 uses maximum, to ensure it conforms to the specified chemical composition, size distribution, shape, density and flow rate.

  b. The maximum allowable powder size is 100 microns or less.

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Westinghouse

Record 20-254

(d) Essential laser powder bed fusion build variables, captured within the manufacturing plan, shall include, at a minimum:

a. Layer thickness
b. Laser power
c. Pulse Characteristics
d. Pulsing
e. Focus Settings
f. Beam Diameter
g. Position of Beam Diameter Relative to Feedstock Layer
h. Energy density
i. Effective velocity
j. Scan strategy
k. Stripe width
l. Offset
m. Hatch spacing
n. Shielding gas composition and flow rate
o. Recoater blade type / material

(e) All production components and witness specimens produced by the laser powder bed fusion process shall be hot isostatic pressed per the requirements of ASTM F3184-16 section 13 (Condition C), and then solution annealed per the requirements of ASTM F3184-16 Section 12.2 (Condition B).

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(f) Witness specimens shall be constructed with each production build and tested after all thermal post-processing.
   a. One witness specimen from the first and final production builds, for each production run, shall be analyzed for chemical composition per the requirements of ASTM F3184-16 Section 9.
   b. A minimum of 4 tensile specimens (2 built in the Z orientation, 2 built in the X-Y orientation) will be built in the 2 locations of limiting material conditions, and tested per the requirements of ASTM F3184-16 Section 11.
      i. Locations of limiting material conditions shall be identified during machine and/or process qualification builds (supplemental requirement to ASTM F3184-16 Section 6.1.1 and Note 3)
   c. Hardness testing shall be completed on one witness specimen per the requirements of ASTM F3184-16 Supplemental Requirement S4.
   d. Microstructure examination shall be completed on one witness specimen.
      i. 100X and 500X micrographs will be supplied for the Z and X-Y build orientations.
      ii. Per ASTM F3184-16 Section 10, Specimen preparation shall be in accordance with ASTM Guide E3 and Practice E407.

(g) The material shall be examined using either the ultrasonic method or radiographic method per the Sub-article of NB/NC/ND-2500 applicable to the product form being produced.

(h) All production components shall be pressure tested per NB-6000 requirements.

(i) The material shall not be used for components where neutron dose will exceed $7x10^{20}$ n/cm^2 (E > 1 Mev) within the design life of the component.

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Westinghouse

Record 20-254

High values (Sect III)

For Metal Temperature Not Exceeding , °F	Stress Values, ksi
-20 to 100	16.7
200	16.7
300	16.7
400	16.7
500	16.7
600	15.6
650	15.1
700	14.7
750	14.7
800	14.7

Summary – ASME Code Case & Data Package

- Three different components, four builds performed
- >0.50-inch thick components (for testing)
- All builds provide acceptable microstructural and mechanical properties
- Good fatigue properties
- Stress Allowables developed
- Weldment data to be provided shortly

What's Next?

ASME Code Case balloting, comments & resolution support

Regulatory Approval – additional data required?

Project Impacts, Milestones, Deliverables

- Project Completed 6/30/3030
- ASME Section III Code Case & Data Package

  Code Case Record No: 20-254 *(submitted August 2020)*

- DOE-EPRI Technical Report

  OSIT.gov

  EPRI.com: 3002018273

- Conference Presentations:
  – ASME Boiler & Pressure Vessel Code Week Meetings (2020 Q1, Q2, Q3)

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