Structural Material

Powder Metallurgy – Hot Isostatic Pressing of Steels in Support of Microreactors

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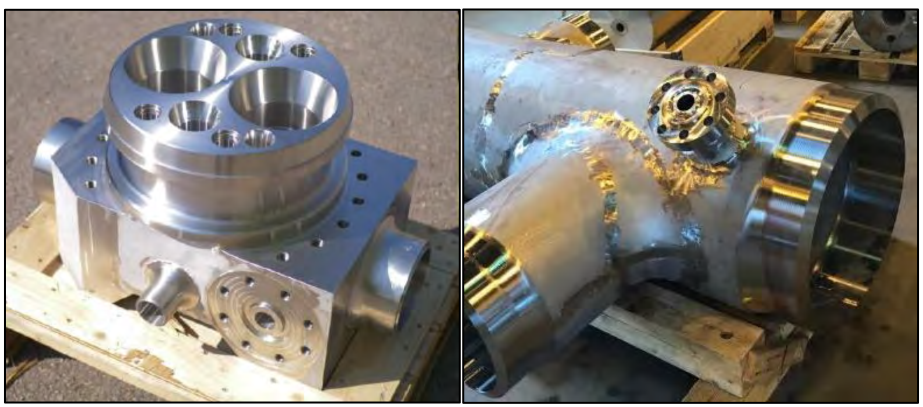
Background

- Powder metallurgy hot isostatic pressing (PM-HIP) is a manufacturing method that produces components by consolidating metal powder
  - Minimizes additional fabrication steps
  - Eliminates solidification structures
  - Eliminates directional grain elongation caused by rolling or forging


MTC Powder Solutions

UK - Nuclear Advanced Manufacturing Research Center (UK-NAMRC) System

MRP Microreactor Program

PM-HIP Adoption for Microreactors

- PM-HIP may benefit structural components for microreactors (i.e., core barrels, primary coolant loops, etc.) by reducing construction time, reducing waste, and improving component availability

Goals

- Demonstrate high temperature mechanical properties of PM-HIP compared to wrought materials for Sec. III Div. 5 structural alloys
- Address PM-HIP 316 stainless steels to support multiple advanced reactors
- Develop specifications and acceptance criteria for PM-HIP components
  - Low temperature code case (up to 371°C)
  - High temperature code case (371°C<T<816°C)

MARVEL Microreactor Components

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PM-HIP Div. 5 Code Case Roadmap

Scoping mechanical testing of PM-HIP alloys for Sec. III, Div. 5 qualification

→

Review results of scoping study

Scoping results are promising →

Scoping study results are not promising (returns to scoping mechanical testing)

Identify PM-HIP alloys to be qualified in Sec. III, Div. 5

→

Generate data for ASTM PM-HIP material specification development and ASME BPVC Section III, Div. 5 qualification

→

Sources of Data
INL, UKNAMRC

Potential alloys:
316H, Alloy 800H, Alloy 617, Gr 91, Alloy 709

Task Group on Div. 5 AM Components

Task Group on Div. 5 AM Components

Responsible Party TBD

PM-HIP Div. 5 Code Case Roadmap

Submit data package to ASTM for alloy(s) to be added to ASTM PM-HIP

(Note: This step is not required for Gr. 91)

→

Determine ASME BPVC qualification approach

1) Use the same design rules (shortest)

2) Use a knockdown factor

3) Develop different design rules (longest)

→

Ballot code case for low temperature Sec. III, Div. 5 applications

→

Ballot code case for elevated temperature Sec. III, Div. 5 applications

Responsible Party TBD

Task Group on Div. 5 AM Components

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Responsible Party TBD

Materials – 316 SS

Powder Compositions (wt%)												
	C	Ni	Cr	Mo	Ti	Al	Si	Mn	S	P	N	O
316H Billet 1[1]	0.055	11.8	16.3	2.51	0.01	0.01	0.18	0.22	0.01	0.003	0.140	0.0167*
316H UK-NAMRC[2]	0.05	11.9	17.1	2.52	<0.01	0.01	0.17	0.18	0.002	0.004	0.076	0.0093*
316L UK-NAMRC[2]	0.015	11.9	17.7	2.44	0.003	0.006	0.83	1.88	0.008	0.008	0.060	0.0117**

Consolidated Product Chemical Compositions (wt%)												
	C	Ni	Cr	Mo	Ti	Al	Si	Mn	S	P	N	O
316H Billet 1[1]	0.040	12.0	16.4	2.48	0.005	0.007	0.17	0.21	0.003	0.002	0.147	0.020
316H UK-NAMRC[2]	0.040	11.8	17.3	2.53	<0.01	<0.01	0.17	0.18	<0.003	<0.005	0.069	0.015
316L Billet 1[3]	0.012	11.5	17.4	2.22	0.006	<0.002	0.65	0.58	0.009	0.011	0.049	0.020
SA 240 S31609 (316H)	0.04-0.10	10.0-14.0	16.0-18.0	2.00-3.00	-	-	1.00	2.00	0.030	0.045	-	-
ASME III Div. 5 (>595°C)	≥0.04	10.0-14.0	16.0-18.0	2.00-3.00	0.04	0.03	1.00	2.00	0.030	0.045	≥0.05	-

[1]Solution heat treated at 1050°C for 2 hours 16 minutes followed by water quenching
[2] Solution heat treated at 1050°C for 4 hours followed by water quenching
[3] Solution heat treated at 1055°C for 4 hours followed by water quenching
*Measurement from full powder fraction (500 µm)
**Measurement sieved to 63 µm

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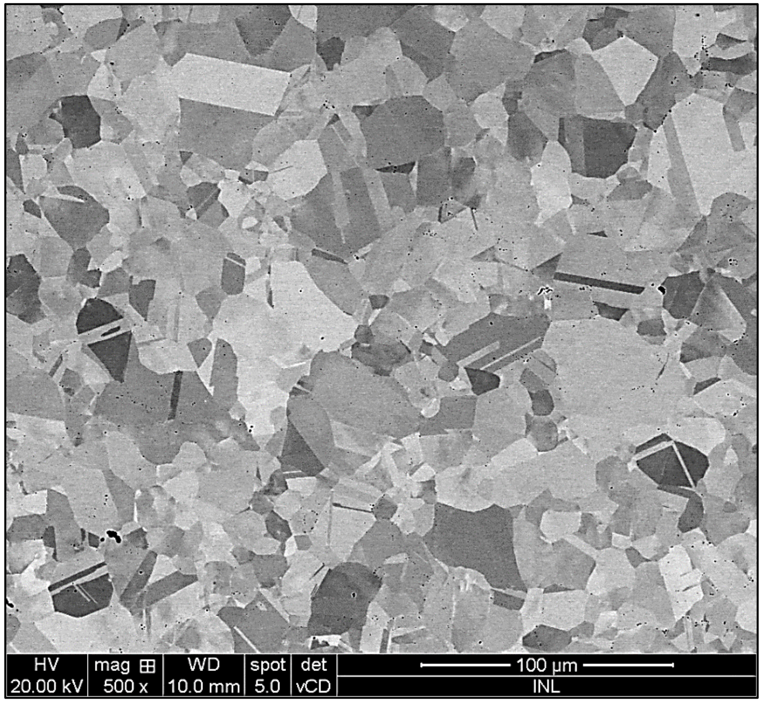
Results – 316 SS Microstructure

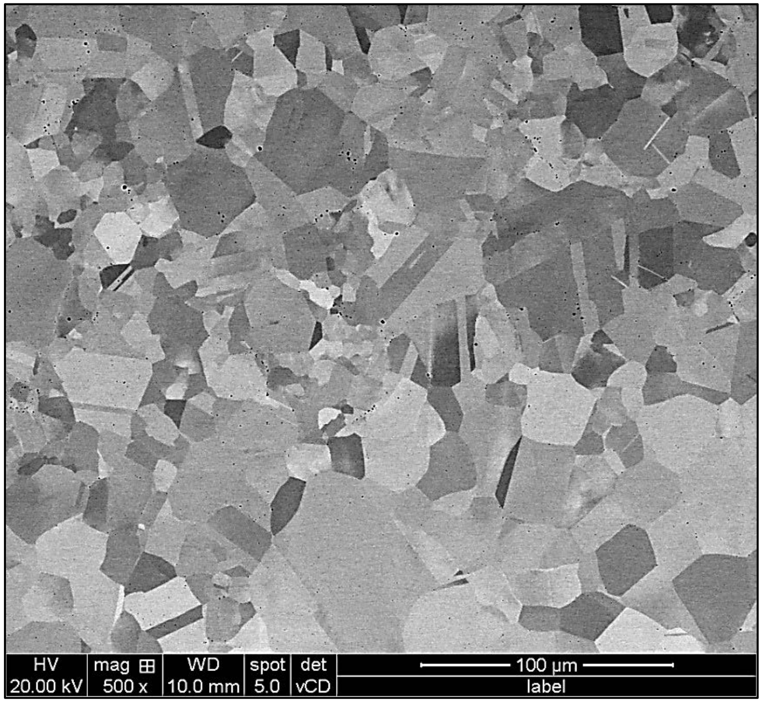
316H – Billet 1



d_{avg} = 35 µm

$HV_{0.3}$= 224

316H – UK-NAMRC



d_{avg} = 47 µm

$HV_{0.3}$ = 194

*SA240: ASTM No. 7 (d = 31.8 µm) or coarser

*Sec. II Part A: ≤ 200 HV

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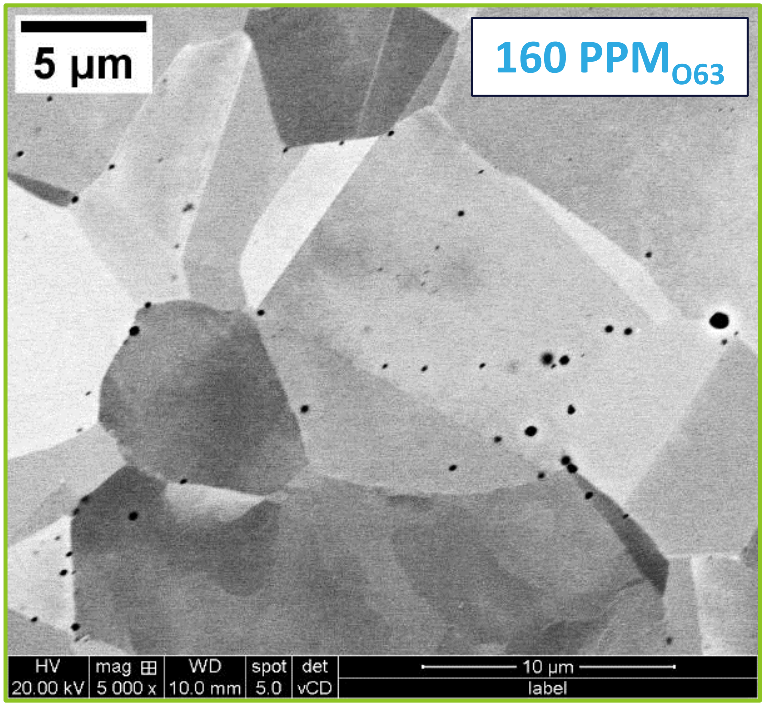
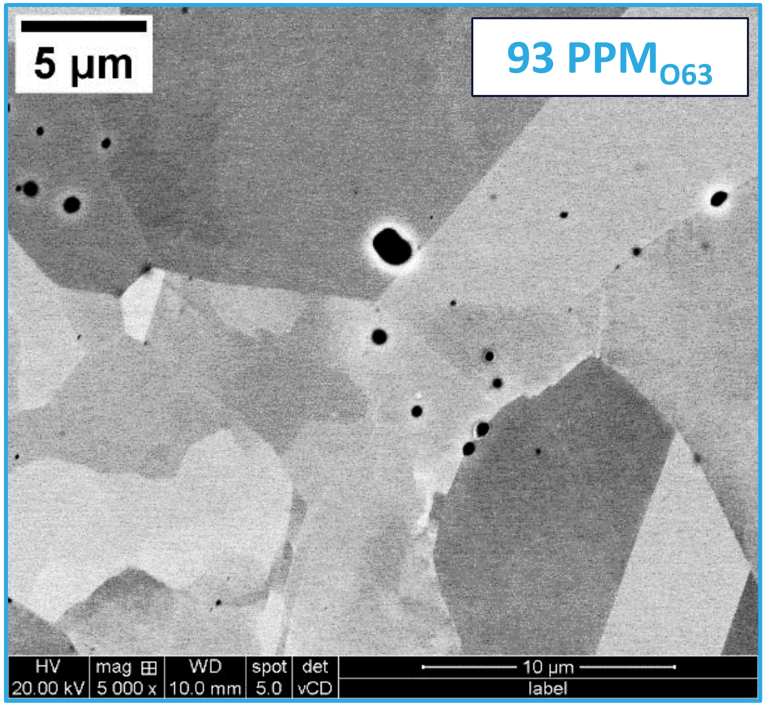
Results – 316 SS Oxide Analysis

316H – Billet 1



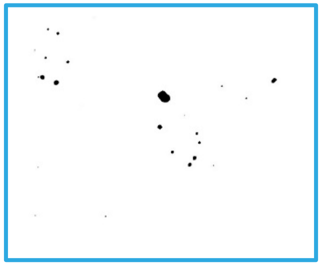
Oxide Area Fraction = 0.15%

316H – UK-NAMRC



Oxide Area Fraction = 0.37%

Image Thresholds



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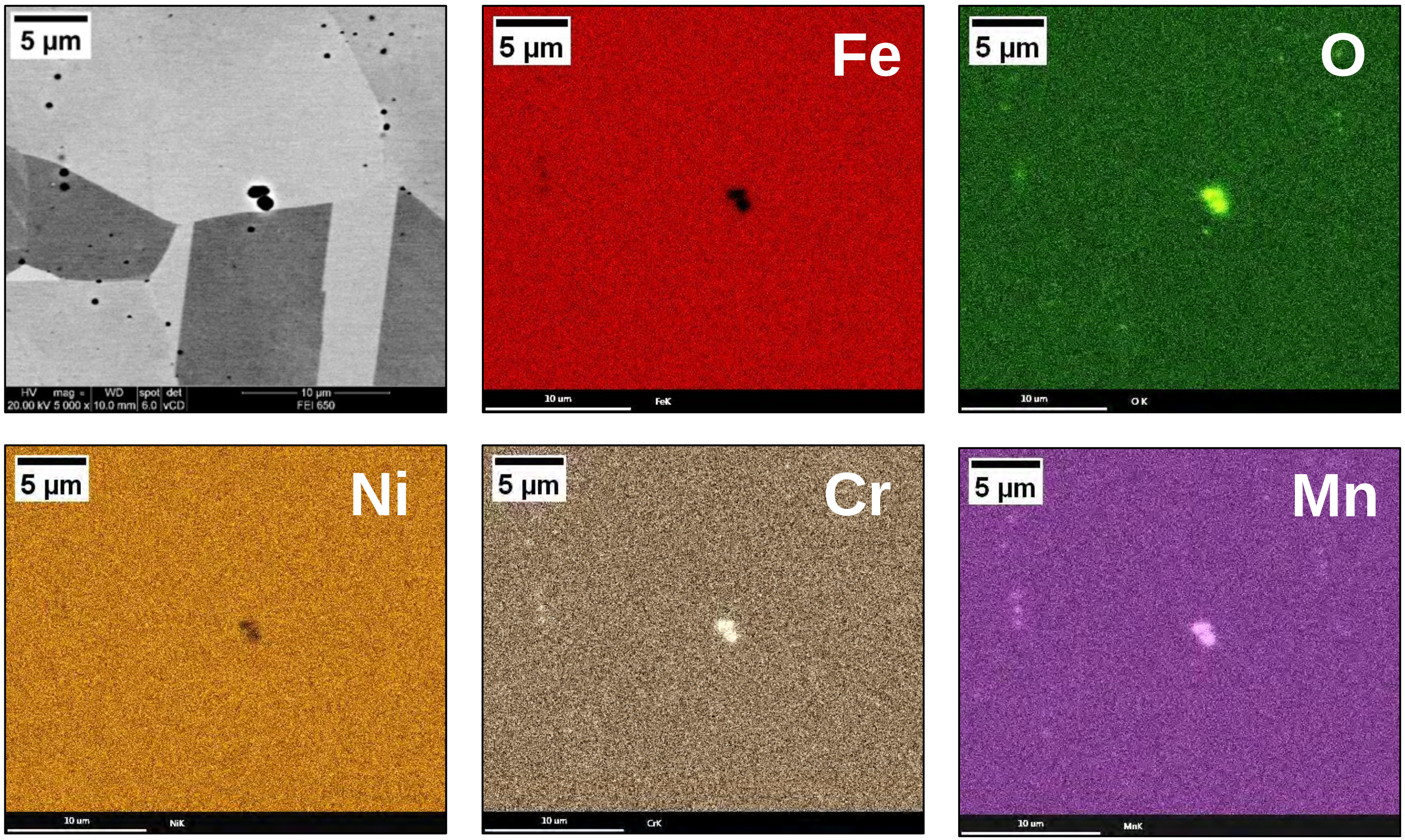
Results – 316 SS Oxide Analysis

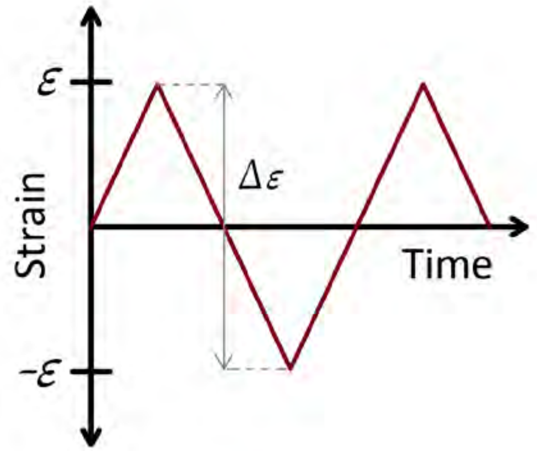
- Qualitative EDS Analysis – UKNAMRC 316H



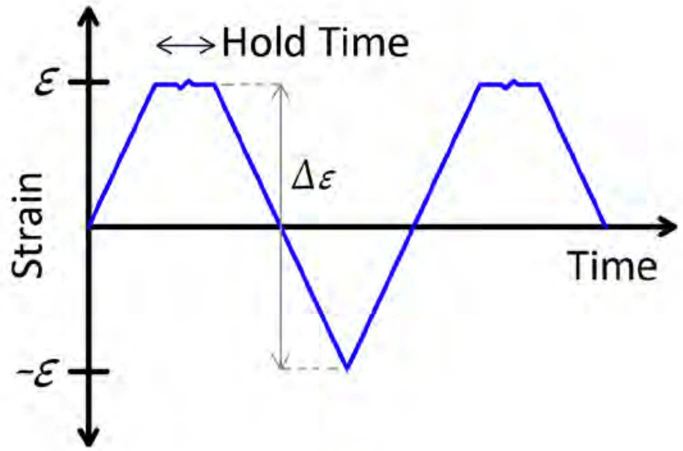
Procedures – Fatigue Testing

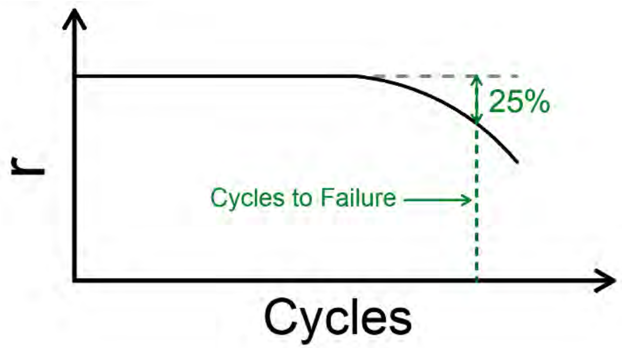
$$650°C,\ \Delta\varepsilon = 1\%,\ \ R = -1,\ \ \dot{\varepsilon} = 0.001\, s^{-1}$$

Low cycle fatigue (LCF)



Creep-fatigue (CF) 30 min. Hold

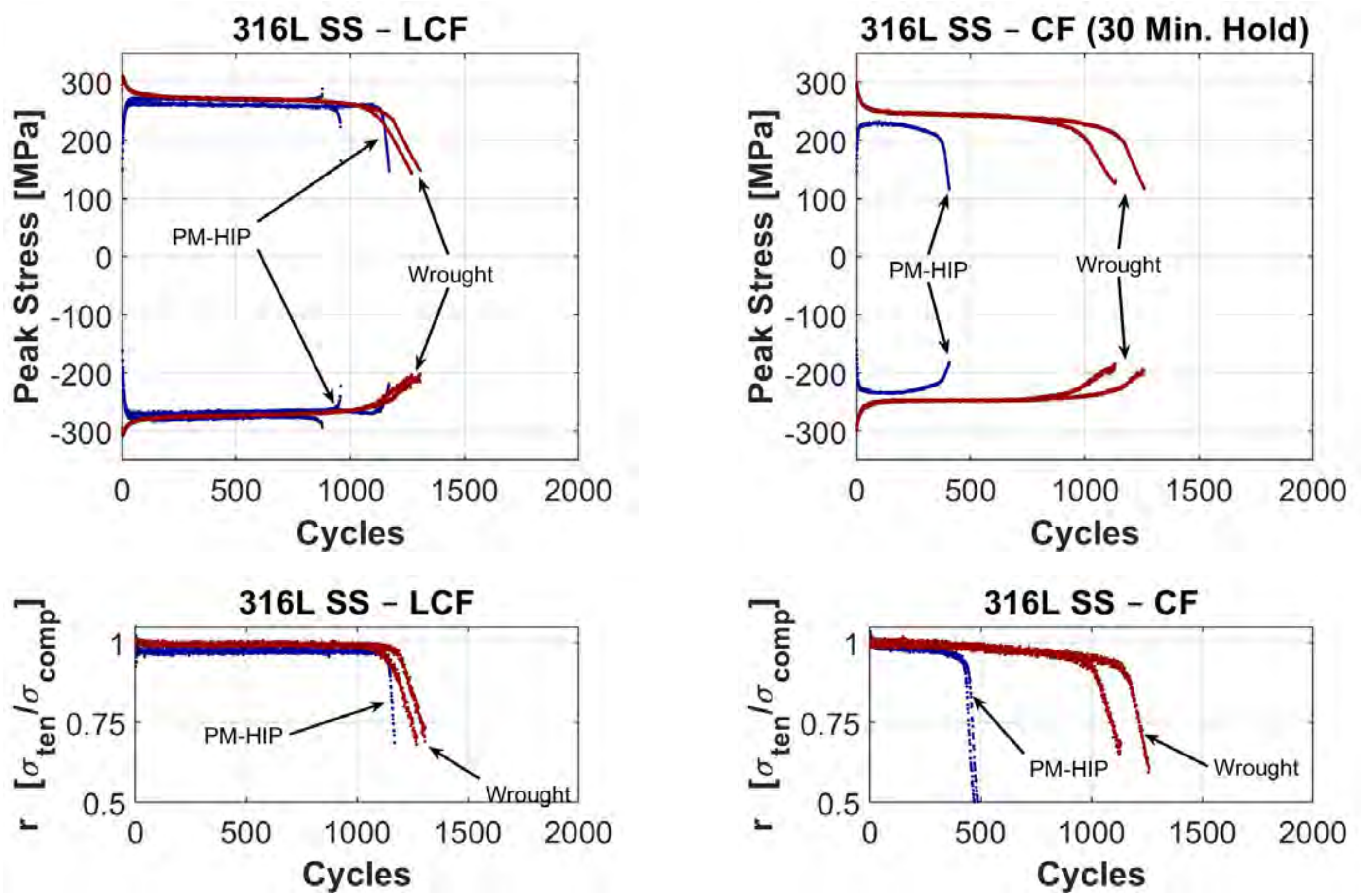




$$r = \left|\frac{\sigma_{tensile}}{\sigma_{compression}}\right|$$

Results – 316L Billet 1

- $650°C, \; \Delta\varepsilon = 1\%, \; R = -1, \; \dot{\varepsilon} = 0.001\, s^{-1}$



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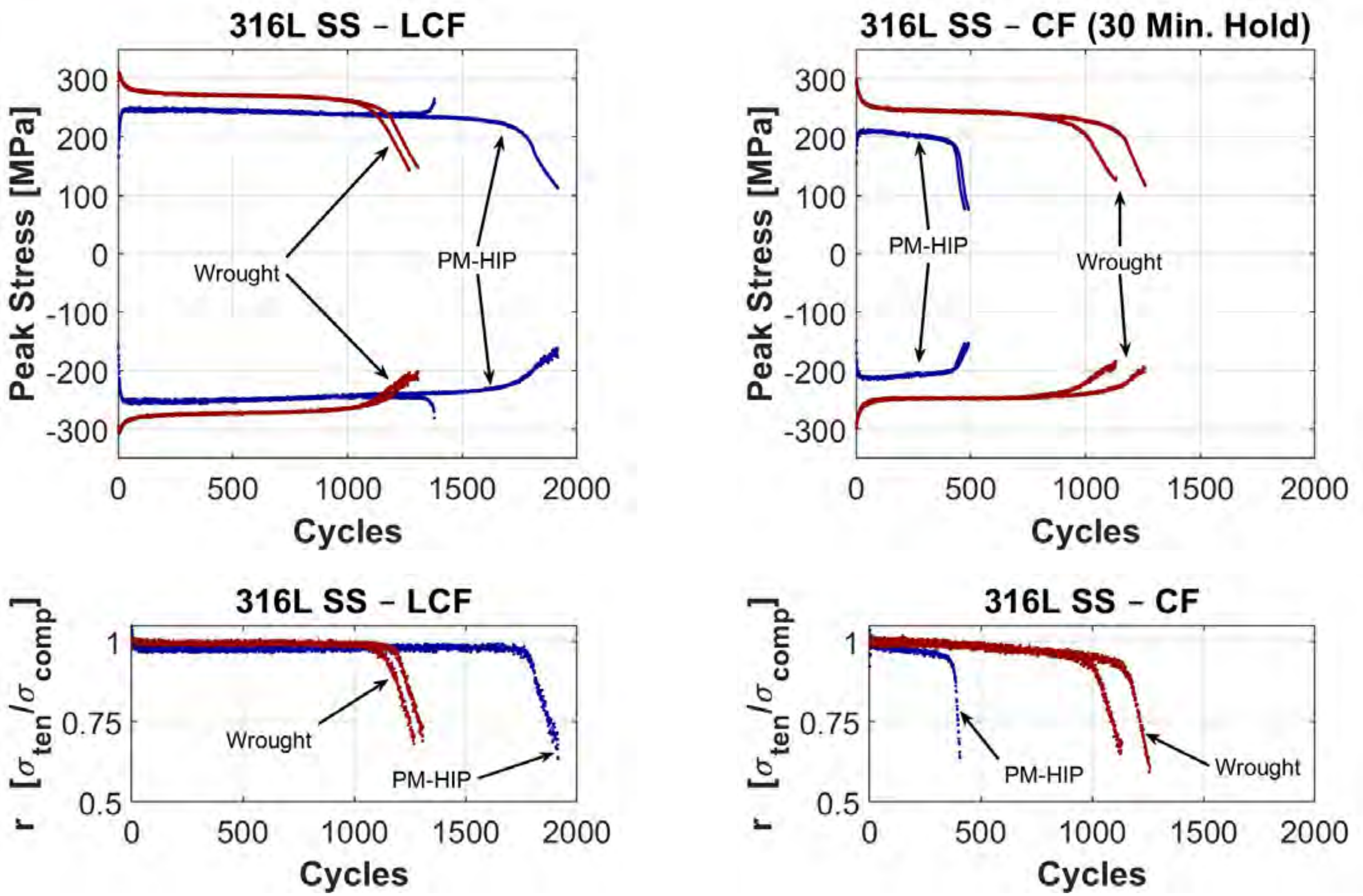
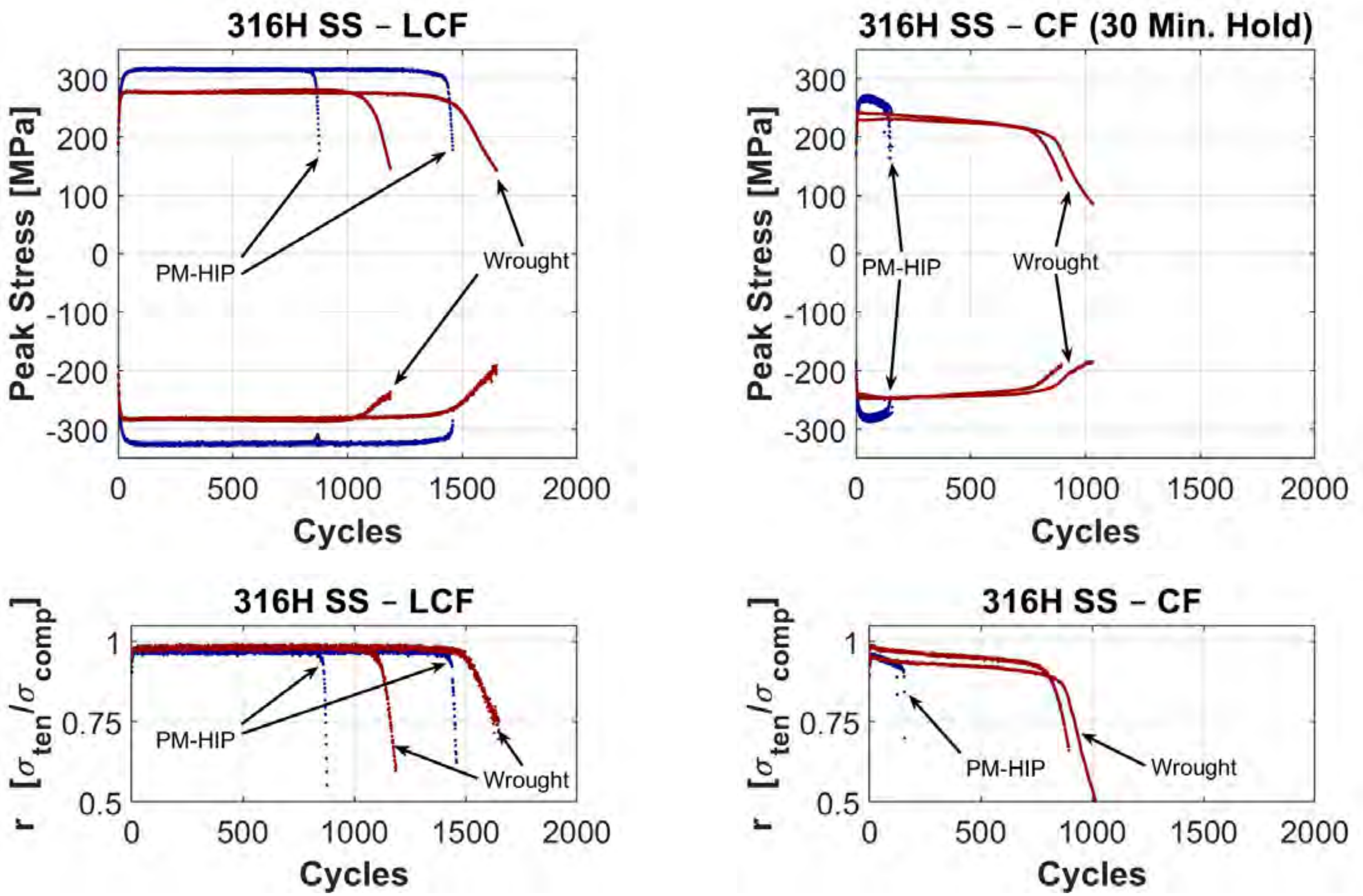
Results – 316L UK-NAMRC

- $650°C, \ \Delta\varepsilon = 1\%, \ \ R = -1, \ \ \dot{\varepsilon} = 0.001 \ s^{-1}$



Results – 316H Billet 1

- $650°C, \ \Delta\varepsilon = 1\%, \ \ R = -1, \ \ \dot{\varepsilon} = 0.001\, s^{-1}$



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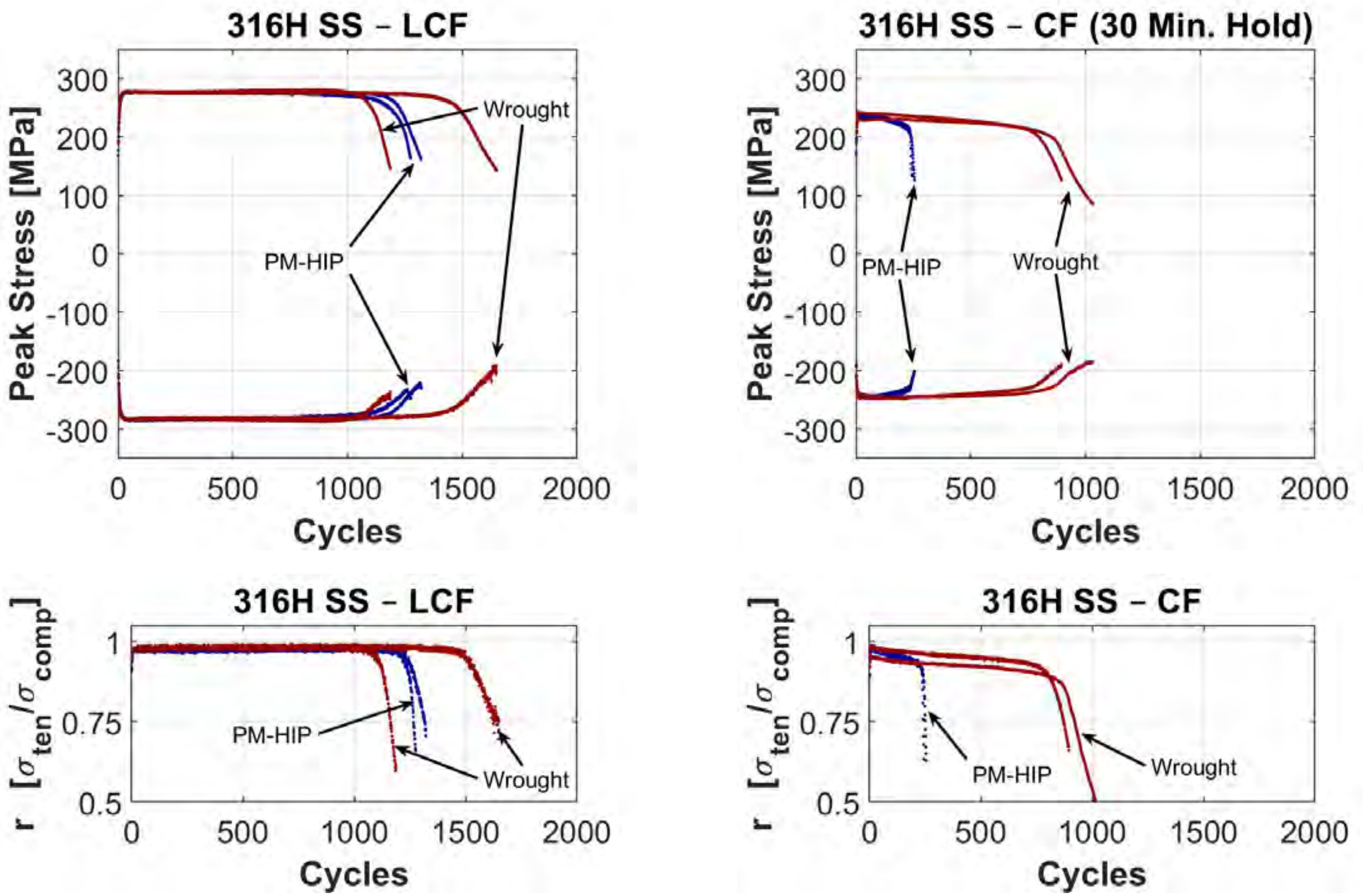
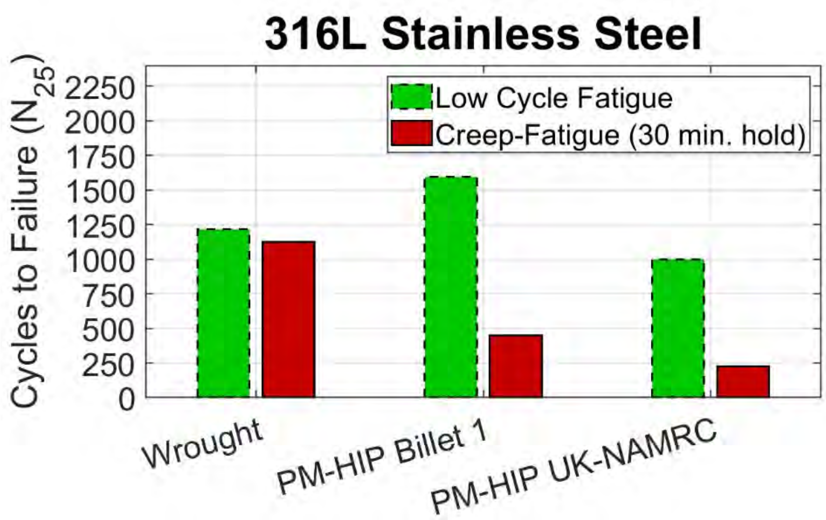
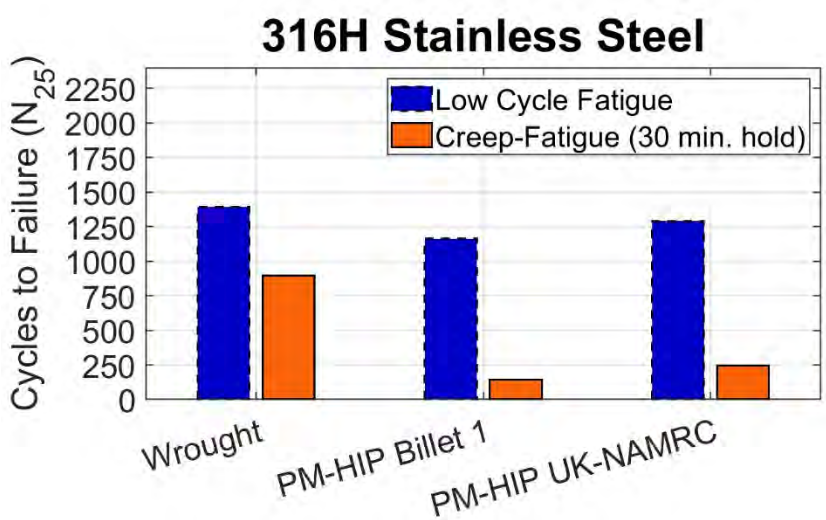
Results – 316H UK-NAMRC

- $650°C, \ \Delta\varepsilon = 1\%, \ \ R = -1, \ \ \dot{\varepsilon} = 0.001 \, s^{-1}$

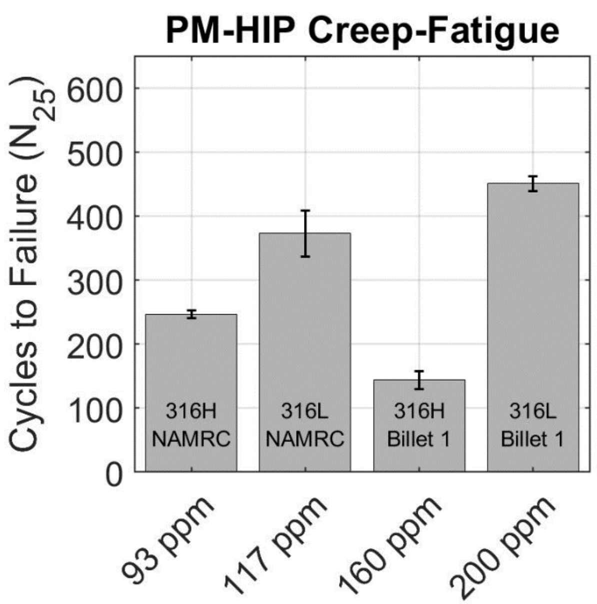


Results – Wrought vs. PM-HIP





Oxygen Comparison for <u>PM-HIP Materials</u>



*Note: excludes other compositional and grain size influence

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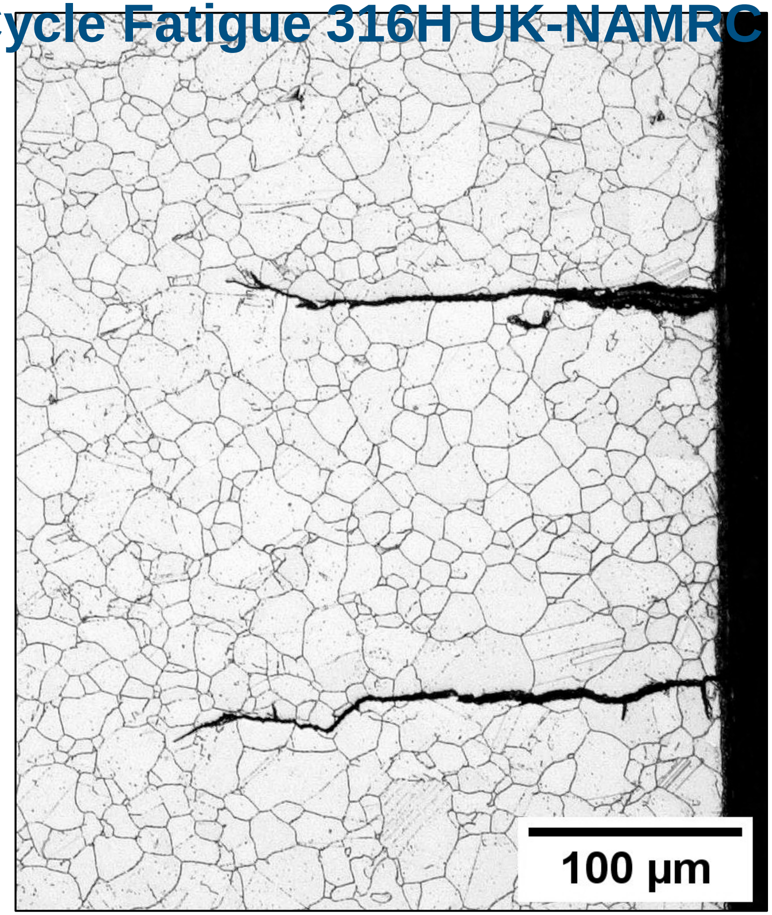
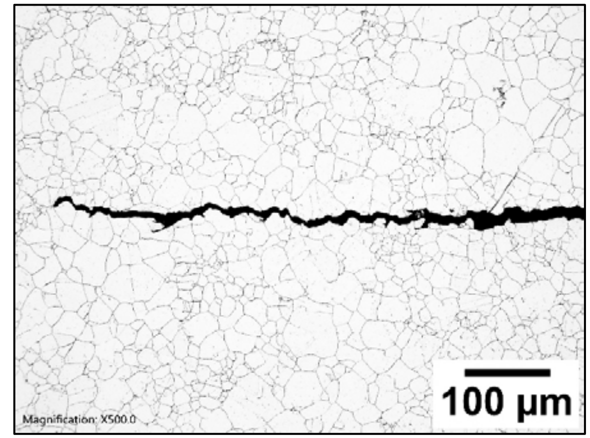
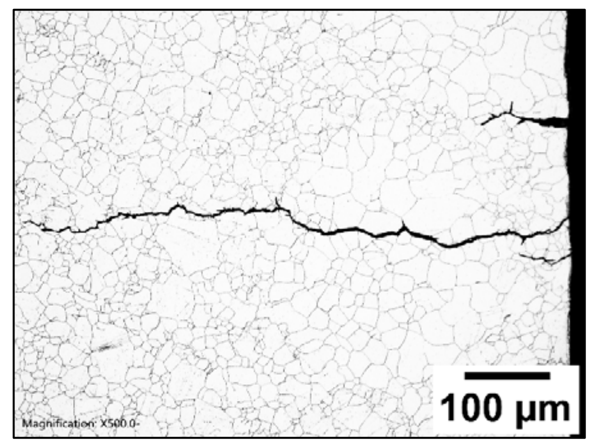
Results – Crack Morphologies

- Low Cycle Fatigue 316H UK-NAMRC







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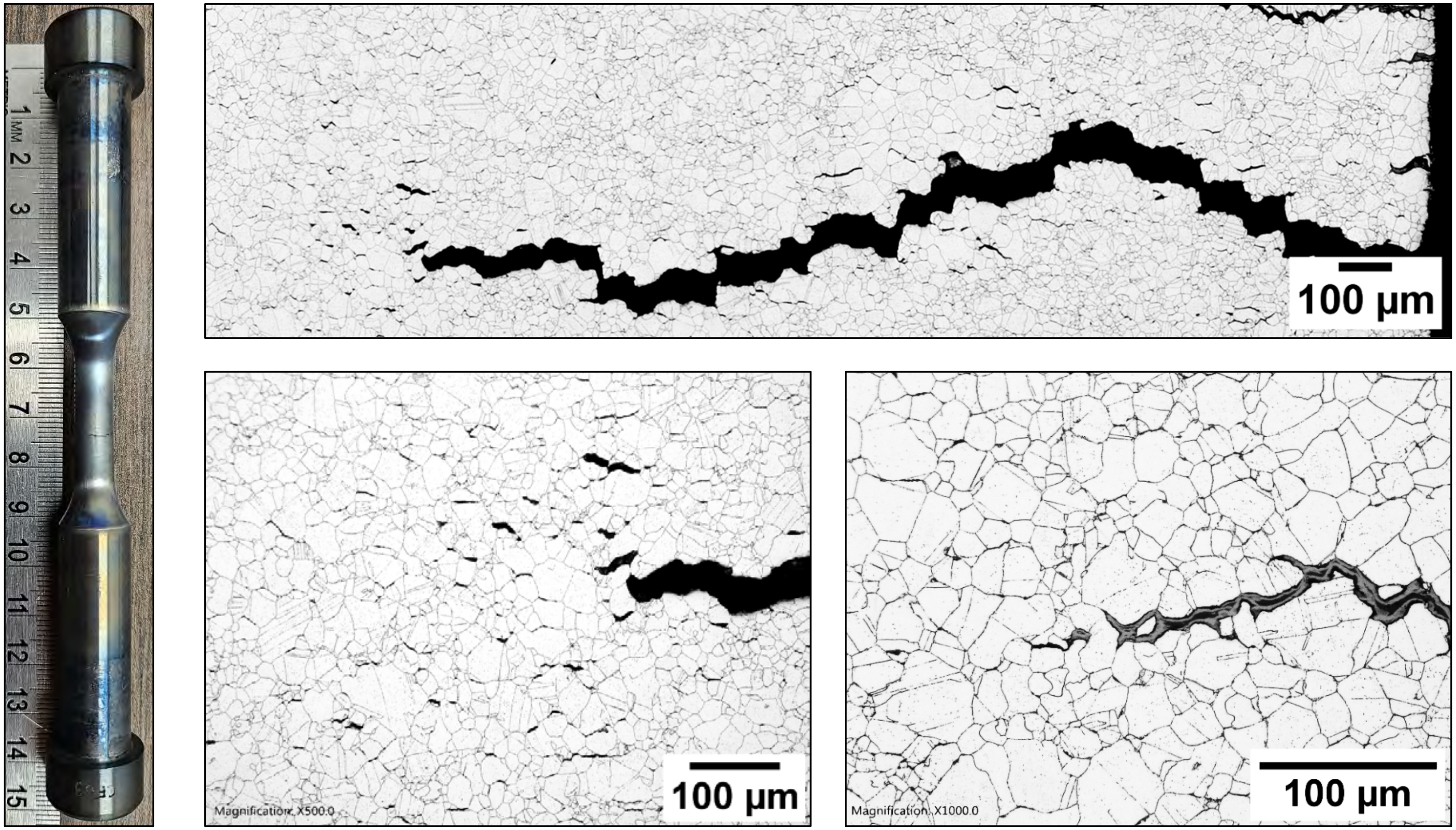
Results – Crack Morphologies

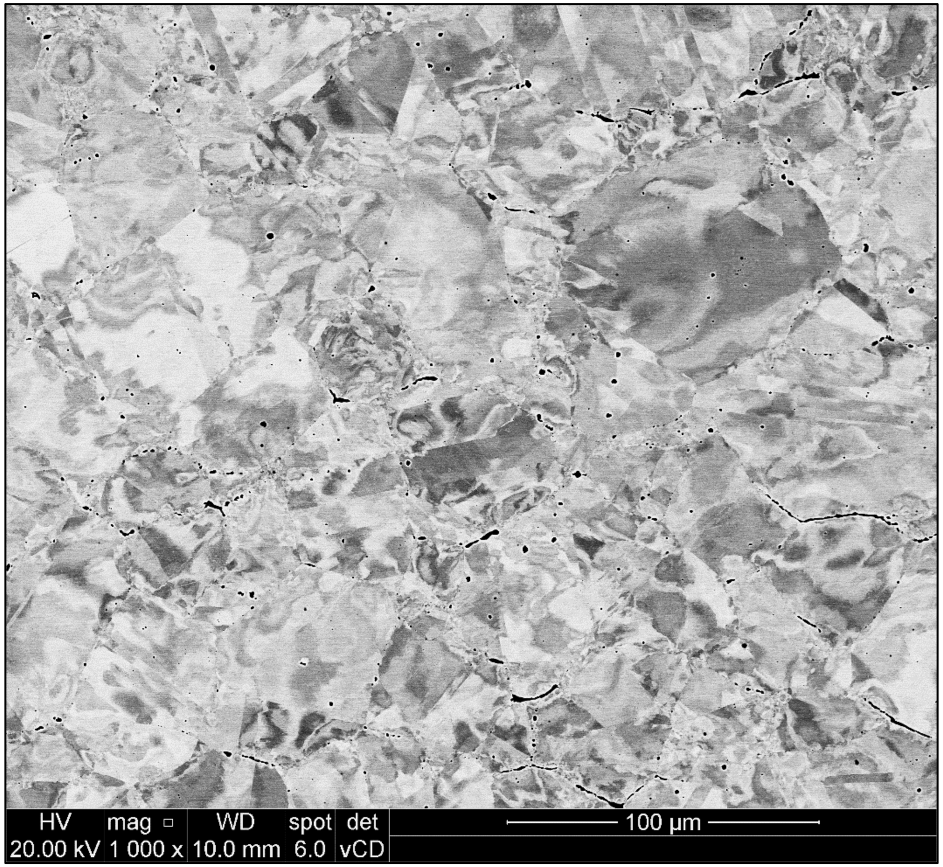
- Creep-Fatigue 316H UK-NAMRC



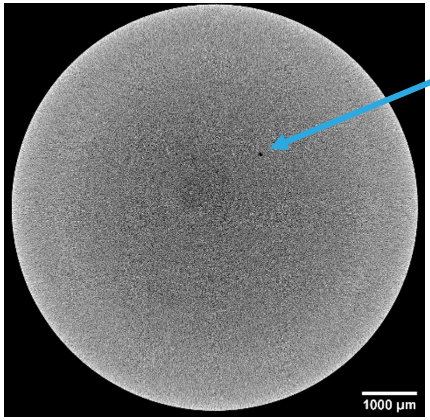
Results – Crack Morphologies

- **Creep-Fatigue 316H UK-NAMRC**

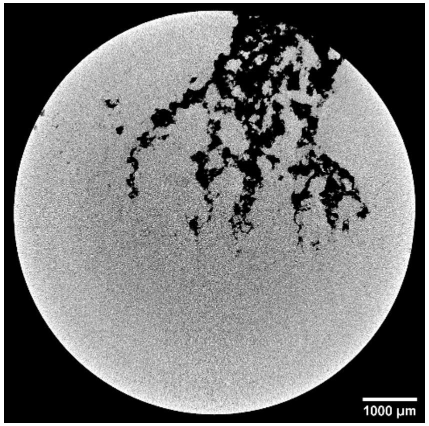
Backscatter Electron Image



X-Ray CT



Before Testing



After Testing

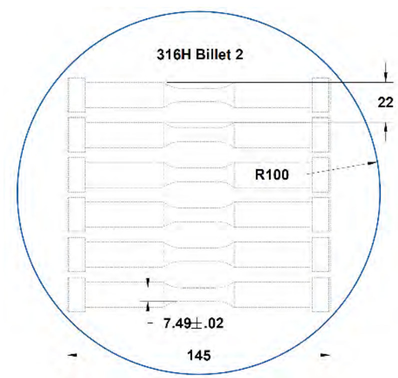
Conclusions

- PM-HIP 316 stainless steels continued to show reduced cycles to failure under creep-fatigue testing conditions compared to wrought 316 stainless steel
- Grain boundary oxides are likely resulting in reduced creep-fatigue resistance through crack nucleation and propagation
  - Microstructure showed grain boundary cavitation ahead of the main crack
- Low cycle fatigue specimens showed transgranular and intergranular crack propagation
- Creep-fatigue specimens only showed intergranular crack nucleation/propagation

Future Work

- Conduct elevated temperature mechanical testing on 316H with low oxygen and processed using different hot isostatic pressing conditions
  - One-third of the powder was hot isostatically pressed and underwent a heat treatment identical to MTC Billet 1
  - Another third is being heat treated at different conditions to try to influence the oxide size/distribution

Powder Composition (wt%)										
	Ni	Cr	Mo	C	Si	Mn	S	P	N	O
316H Billet 2	12.0	17.0	2.53	0.05	0.20	0.21	0.003	0.004	0.101	0.0120*



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