Powder Metallurgy – Hot Isostatic Pressing of 316H Stainless Steel in Support of Microreactors

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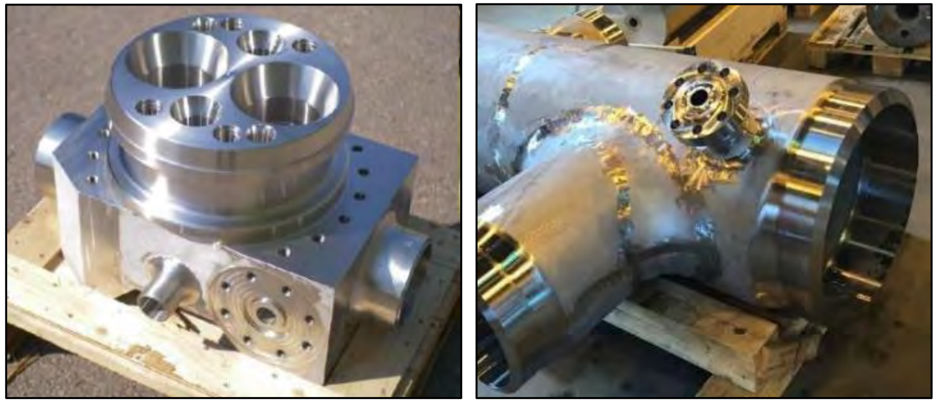
Tate Patterson
Welding Engineer, Idaho National Laboratory

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

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

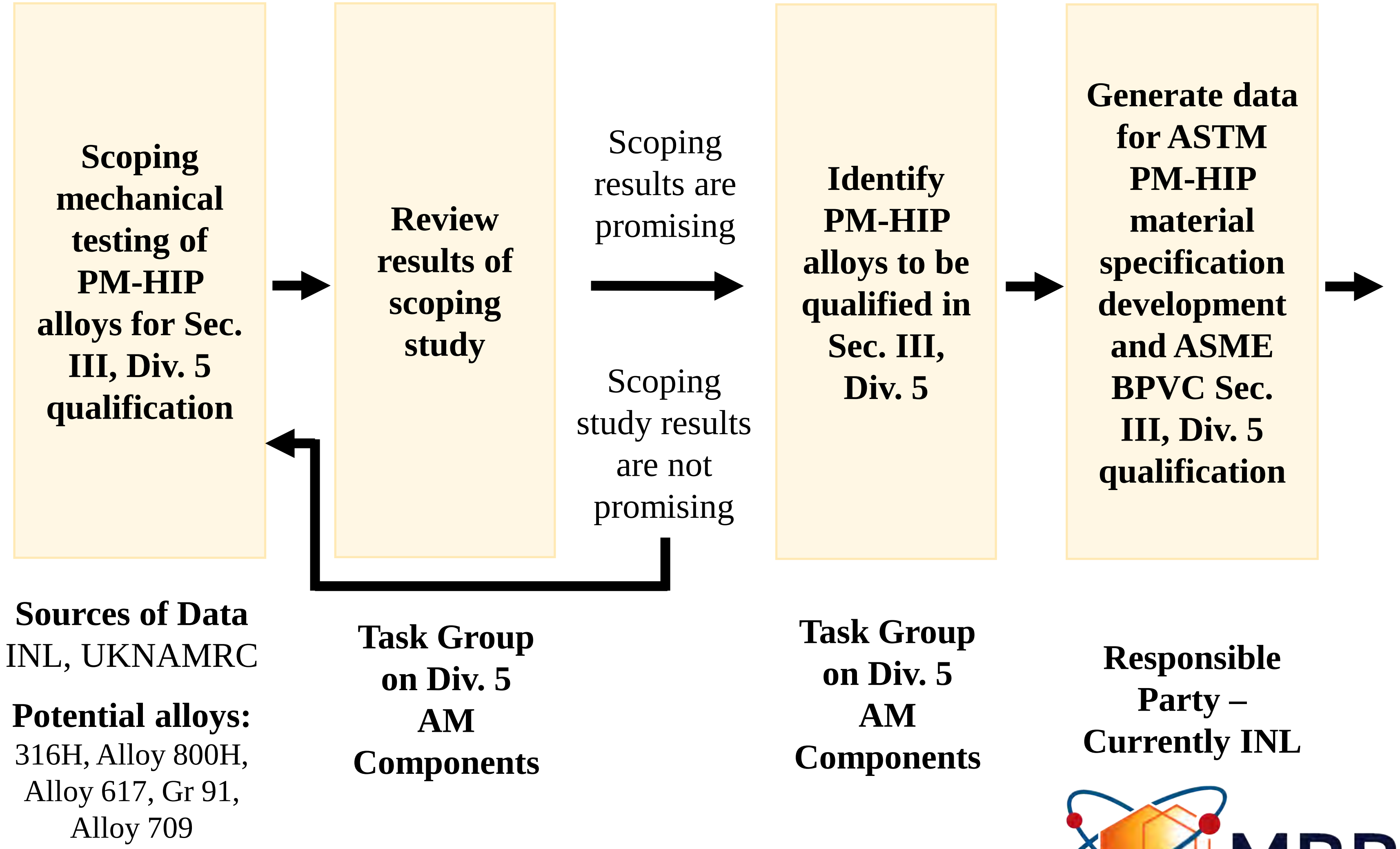
Goals

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

MARVEL Primary Coolant Test Apparatus Components

MRP Microreactor Program

PM-HIP Div. 5 Code Case Roadmap



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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 <u>low temperature</u> Sec. III, Div. 5 applications

→

Ballot code case for <u>elevated temperature</u> Sec. III, Div. 5 applications

Responsible Party – Currently INL

Task Group on Div. 5 AM Components

Task Group on Div. 5 AM Components

Responsible Party TBD

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Materials – PM-HIP 316H SS

Powder Compositions (wt%)													D50 (µm)
	C	Ni	Cr	Mo	Ti	Al	Si	Mn	S	P	N	O	
316H Billet 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	56
316H Billet 2	0.050	12.0	17.0	2.53	<0.003	<0.01	0.20	0.21	0.003	0.004	0.101	0.0120	52

Consolidated Product Chemical Compositions (wt%)												
	C	Ni	Cr	Mo	Ti	Al	Si	Mn	S	P	N	O
316H Billet 1[1]	0.040	11.95	16.44	2.48	0.005	0.007	0.17	0.21	0.003	0.005	0.147	0.0200
316H Billet 2A[2]	0.043	12.06	17.13	2.54	<0.003	0.003	0.18	0.19	0.003	0.004	0.090	0.0156
316H Billet 2B[2]	0.043	12.01	17.05	2.53	<0.003	0.005	0.19	0.19	0.003	0.004	0.088	0.0149

Code/Standard Composition Requirements for Wrought 316H (wt%)												
	C	Ni	Cr	Mo	Ti	Al	Si	Mn	S	P	N	O
ASTM 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 Sec. 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

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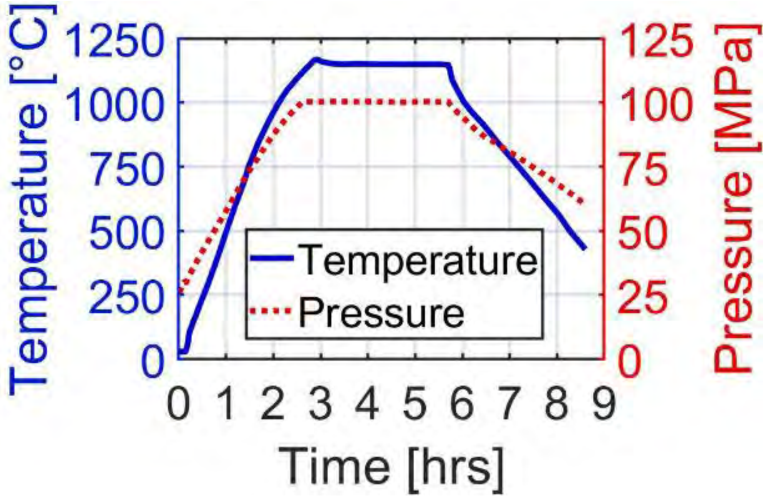
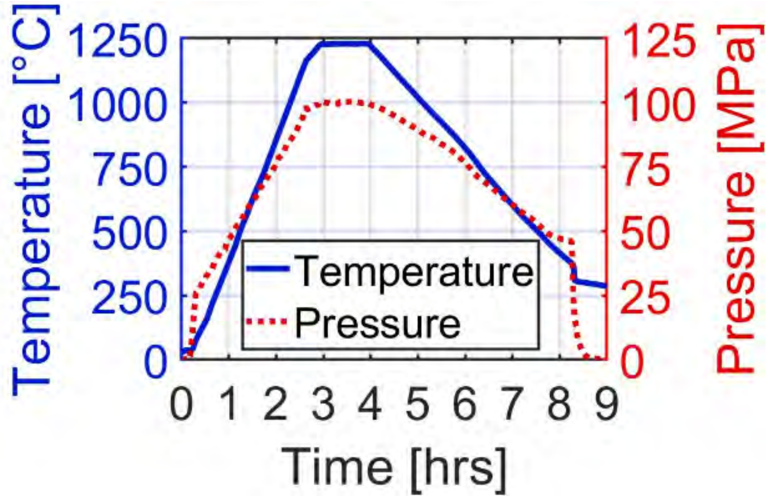
Process Parameters

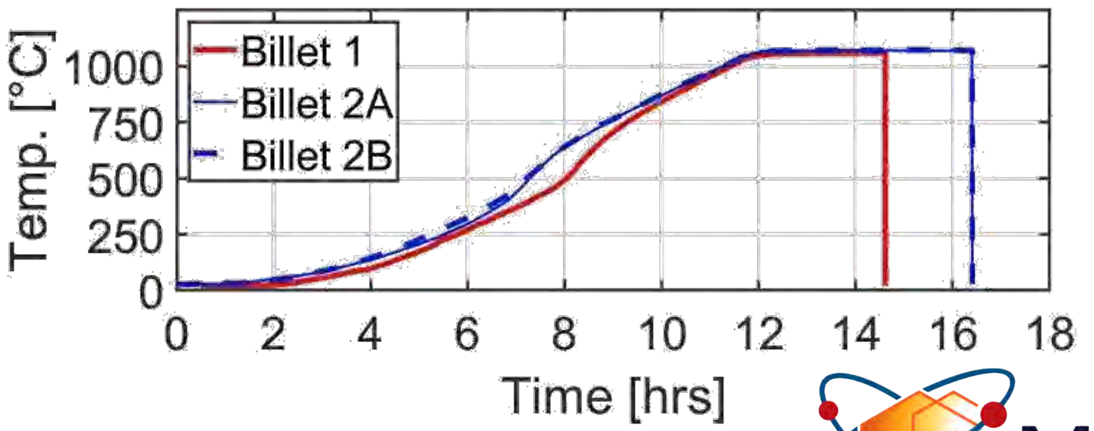
Billets 1/2A



Billet 2B



Heat Treatment (Sec. III, Div. 5)



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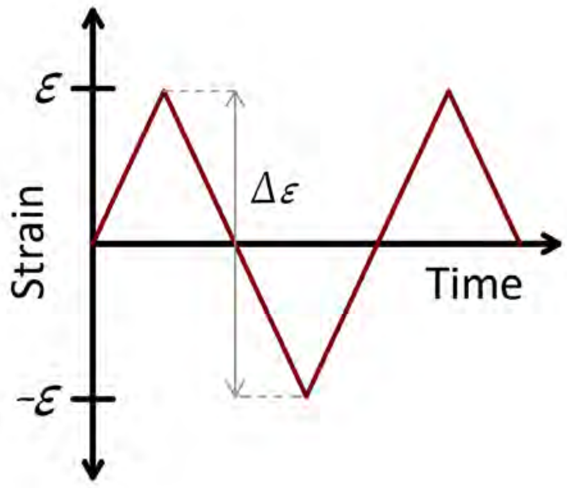
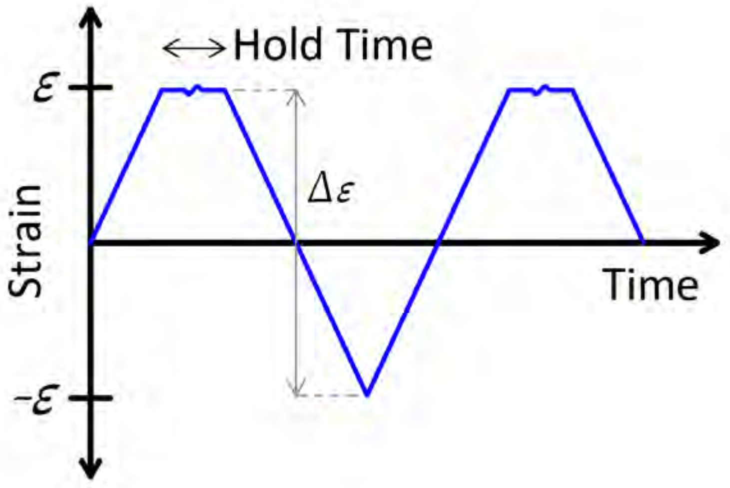
Mechanical Testing Procedures

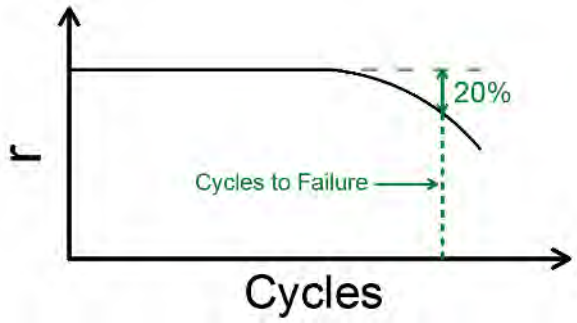
Low cycle fatigue (LCF)



Creep-fatigue (CF)



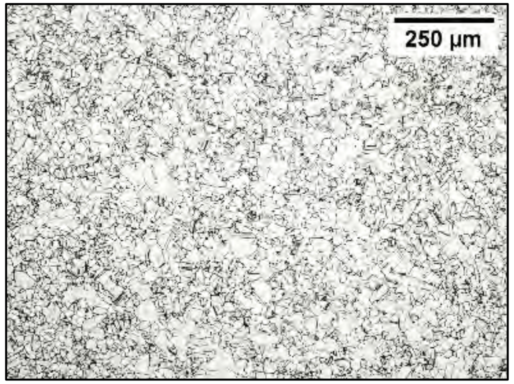
Failure Criteria

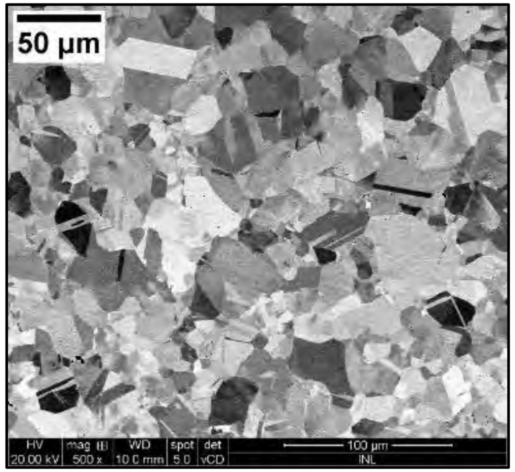


$$r = \left| \frac{\sigma_{tensile}}{\sigma_{compression}} \right|$$

Results – PM-HIP 316H Microstructure

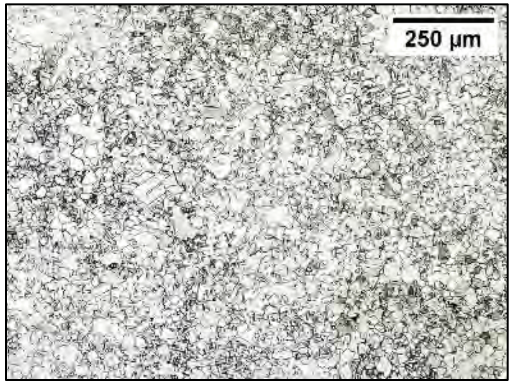
Billet 1

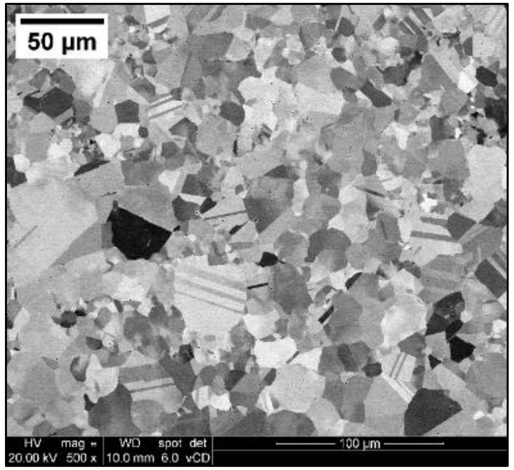




ASTM No. = 7
BHN = 180

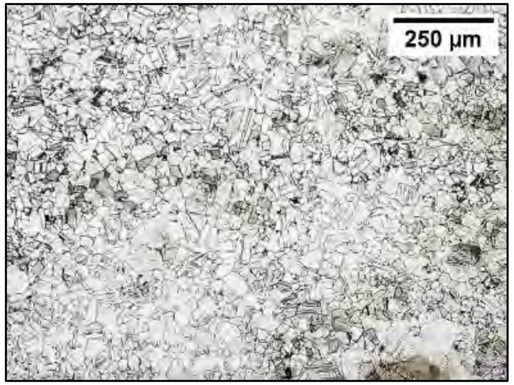
Billet 2A

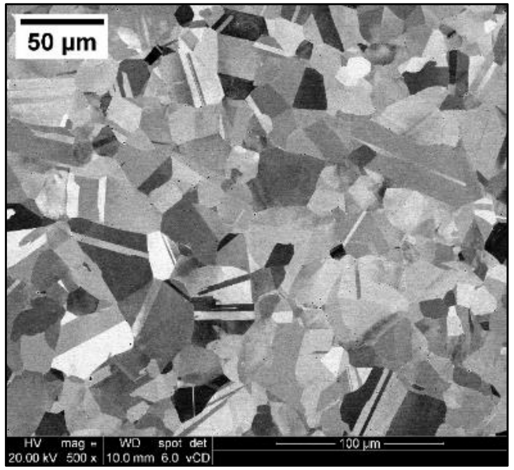




ASTM No. = 8
BHN = 176

Billet 2B





ASTM No. = 7
BHN = 167

*SA240 (Wrought 316): ASTM No. 7 (d = 31.8 µm) or coarser
*ASME Sec. II Part A (Wrought 316): ≤ 200 HV

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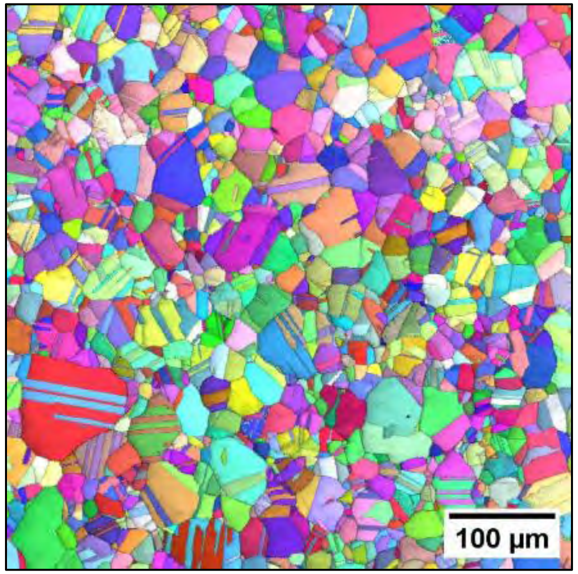
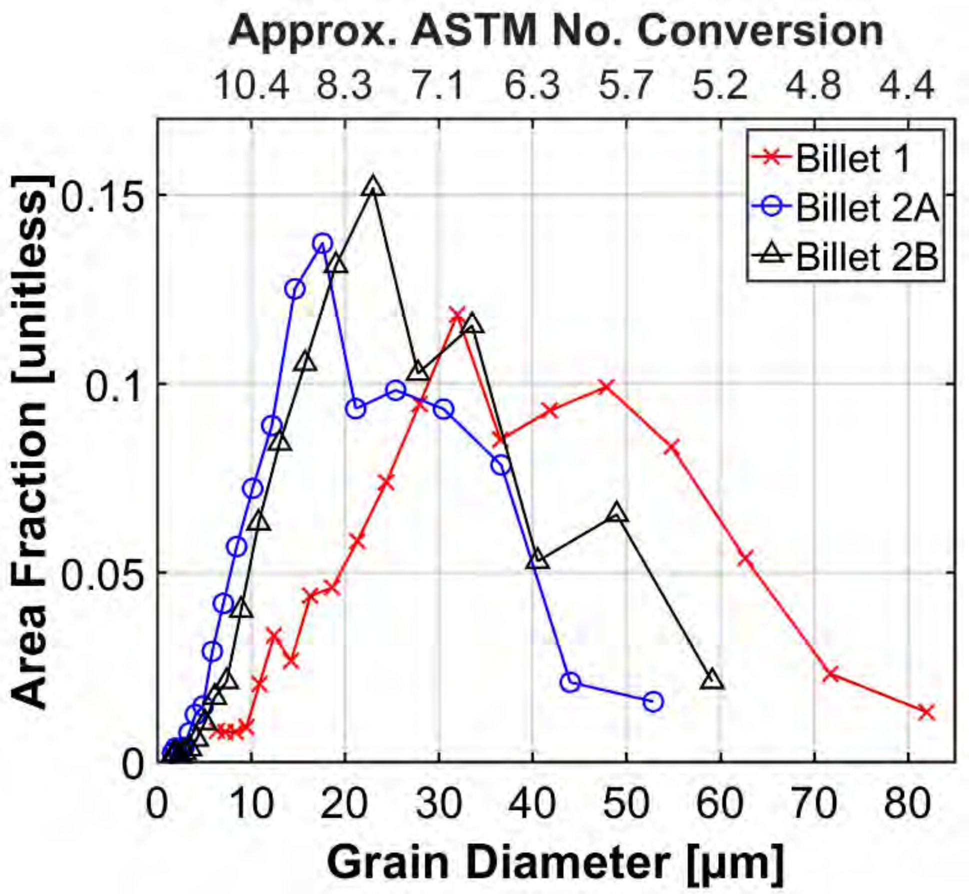
Results – PM-HIP 316H Microstructure

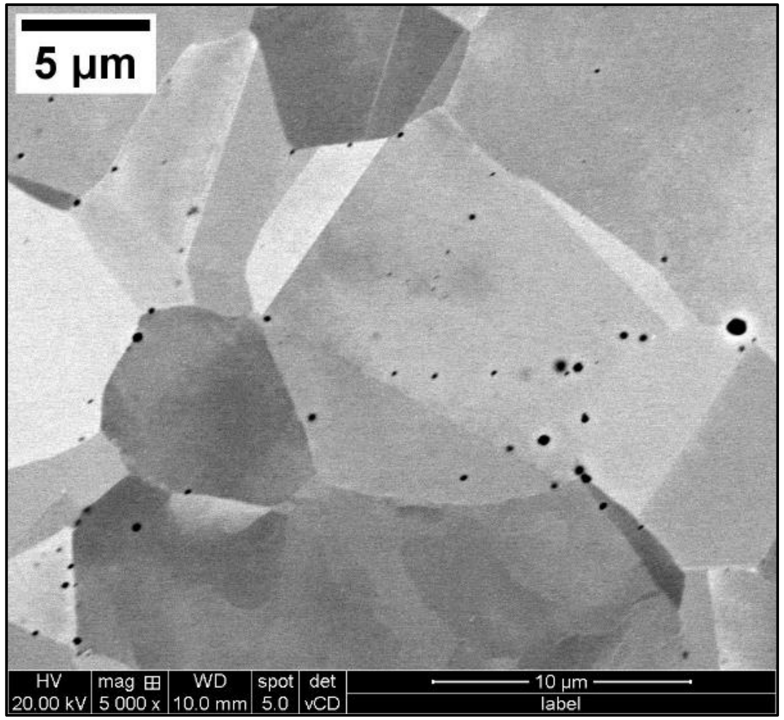
- Grain size analysis based on electron backscattered diffraction data (EBSD) and an ellipsoidal fit



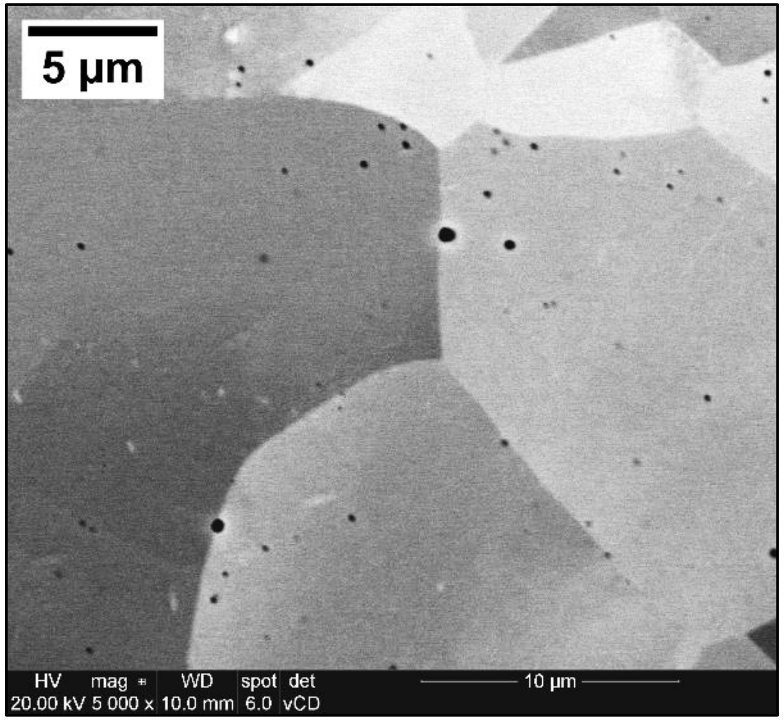


Results – PM-HIP 316H Microstructure

Billet 1



Billet 2A



- Particles exist in all PM-HIP 316 components procured regardless of the oxygen and/or nitrogen level

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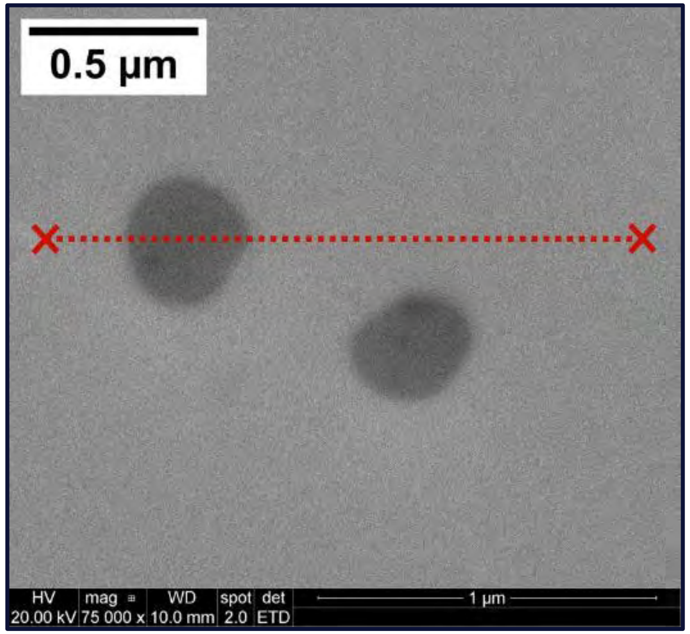
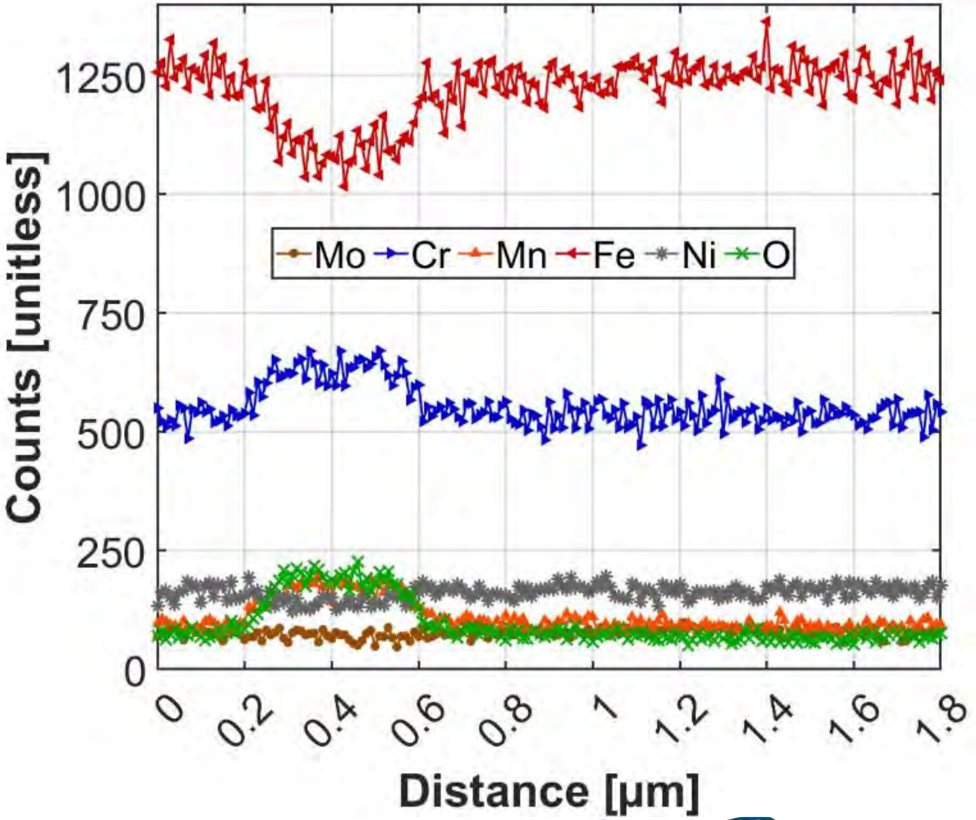
Results – PM-HIP 316H Microstructure

- Qualitative composition analysis

Billet 2A





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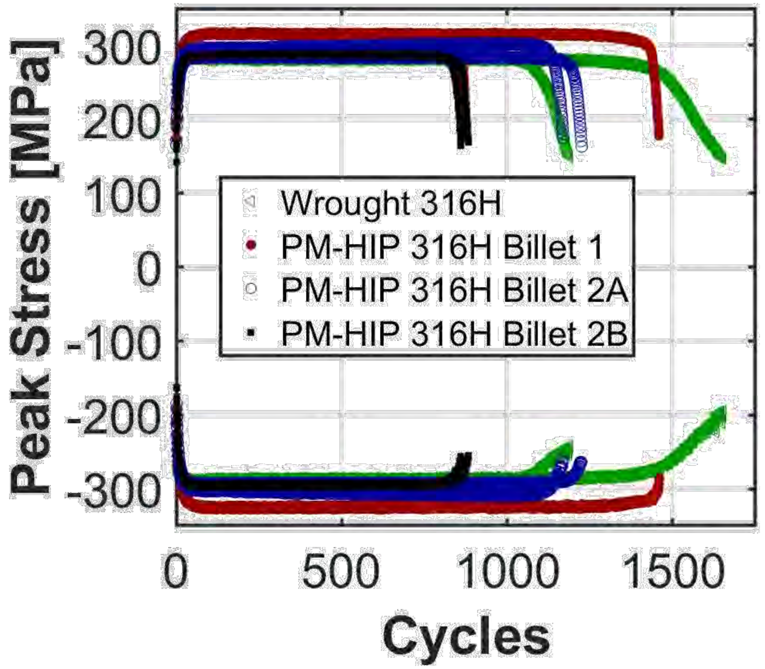
Results – Fatigue and Creep-Fatigue

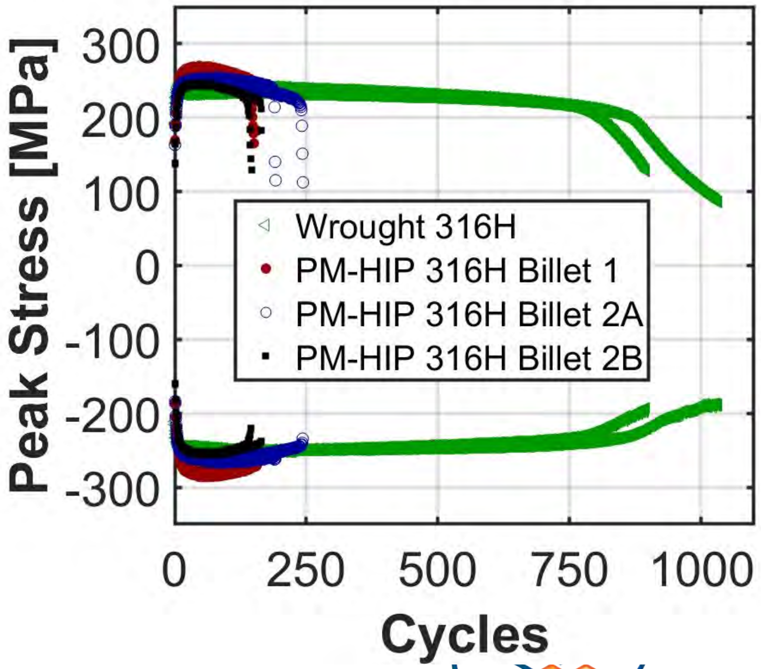
Low Cycle Fatigue

650°C
$\Delta\varepsilon$=1%, R=-1, $\Delta\dot{\varepsilon}$=0.001s^{-1}
No Hold



Creep-Fatigue

650°C
$\Delta\varepsilon$=1%, R=-1, $\Delta\dot{\varepsilon}$ =0.001s^{-1}
t_{hold}= 30 minutes



Results – Div. 5 Creep-Fatigue

- **ASME BPVC Section III Division 5 High Temperature Reactors**

HBB-2800 FATIGUE ACCEPTANCE TEST

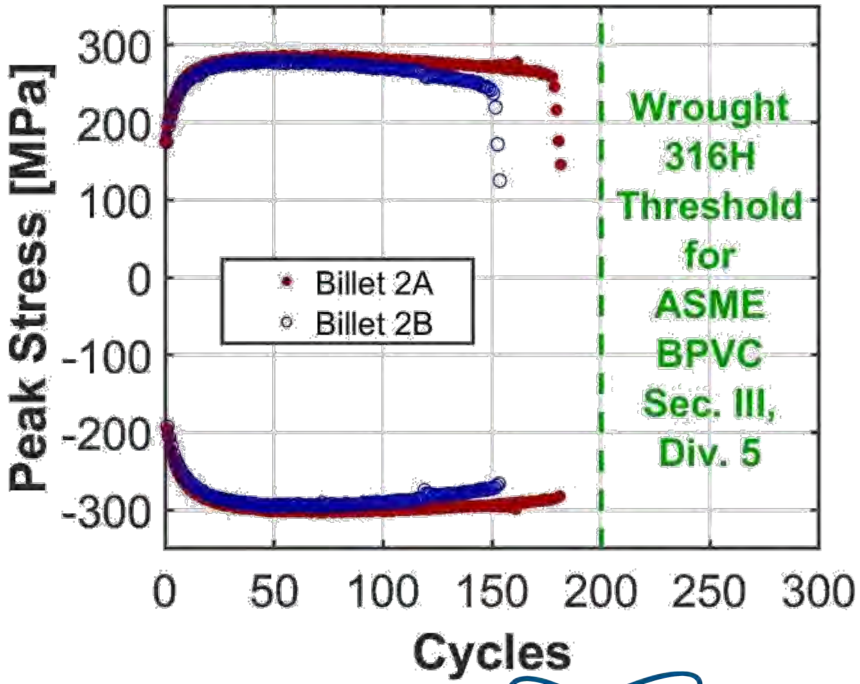
(a) For 304 and 316 austenitic stainless steel components intended for service where conditions for Levels A, B, and C do not satisfy the limits of HBB-T-1324(a) and HBB-T-1324(b), a uniaxial fatigue acceptance test of each lot of material shall be performed.

(b) The fatigue test shall be performed in air at 1,100°F (595°C) at an axial strain range of 1.0% with a 1-hr hold period at the maximum positive strain point in each cycle. Test-specimen location and orientation shall be in accordance with the general guidance of SA-370, paras. 6.1.1 and 6.1.2 and the applicable product specifications. Testing shall be conducted in accordance with ASTM Standard E 606. The test shall exceed 200 cycles without fracture or a 20% drop in the load range.

(c) Failure to meet this requirement shall be cause for rejection of the lot for use in Class A elevated temperature components.

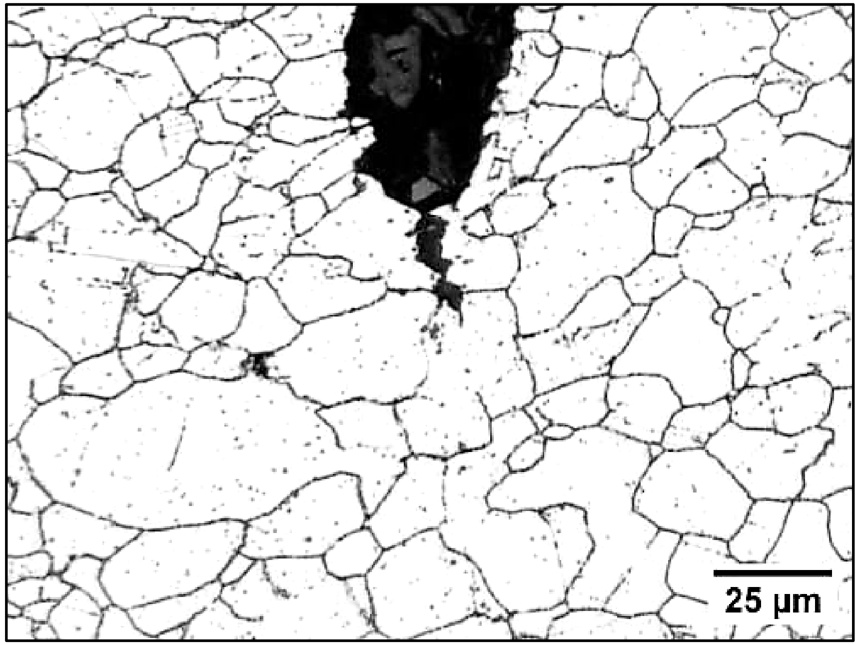
(d) The definition of "lot" shall be obtained from the material specification. Where more than one definition is provided by the specification, the definition used to establish the tensile properties shall govern. Either the Material Organization or N-Type Certificate Holder may perform the lot qualification test.

595°C,
$\Delta\varepsilon$=1%, R=-1, $\Delta\varepsilon$=0.001s^{-1}
t_{hold}= 60 minutes



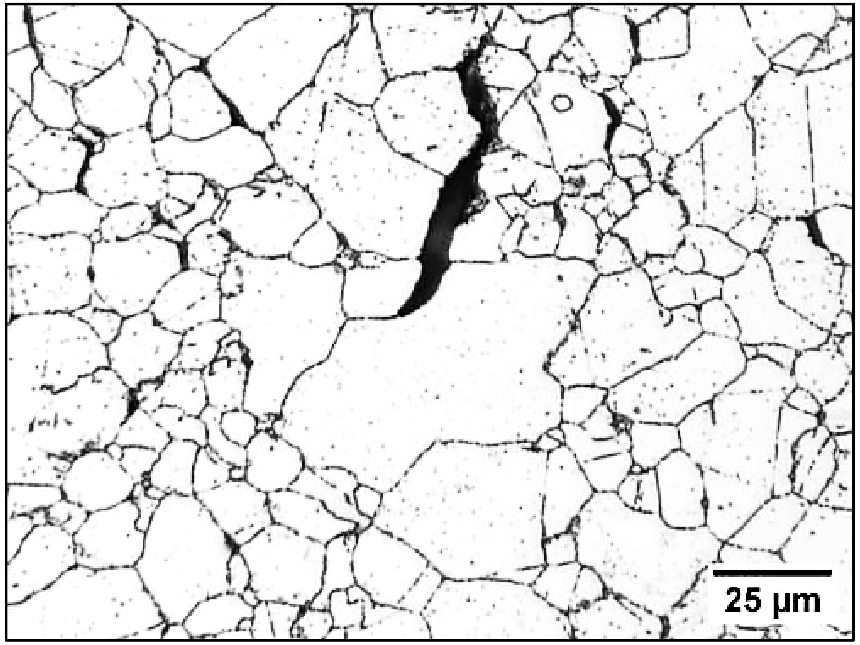
Results – Crack Propagation

Low Cycle Fatigue



*always intragranular crack propagation

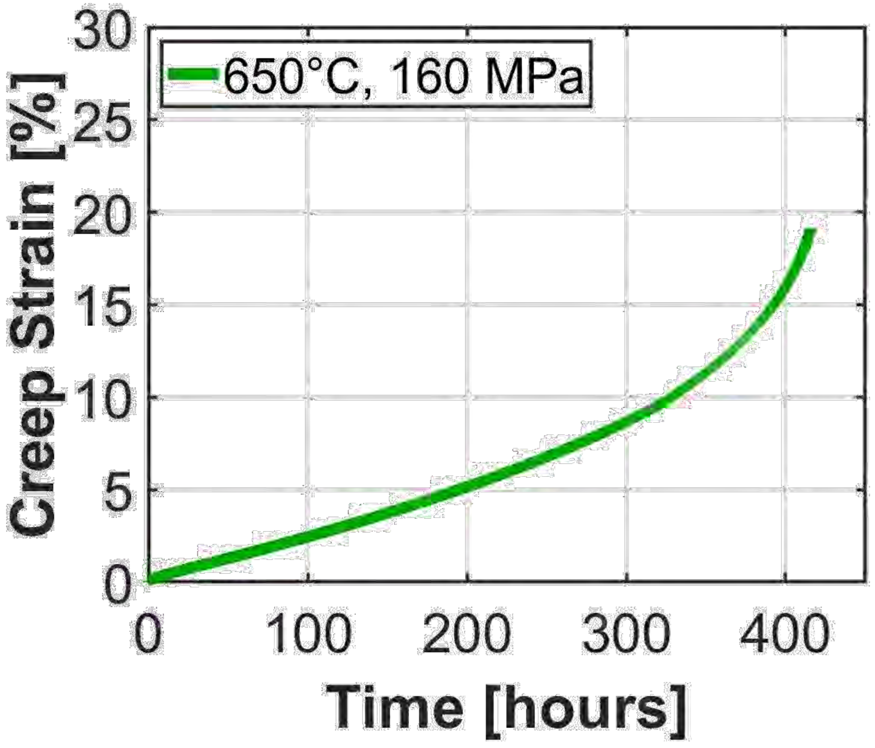
Creep-Fatigue

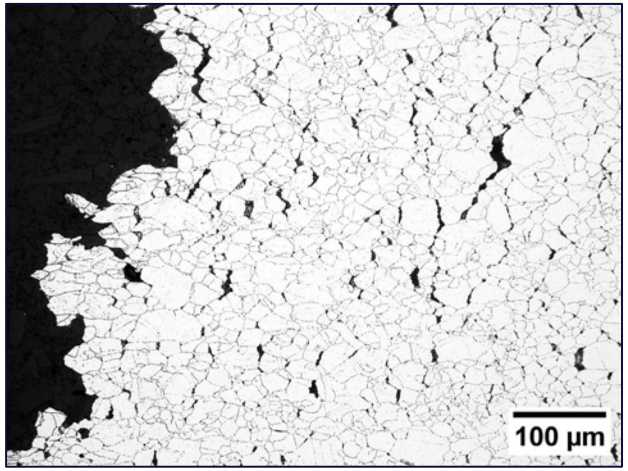


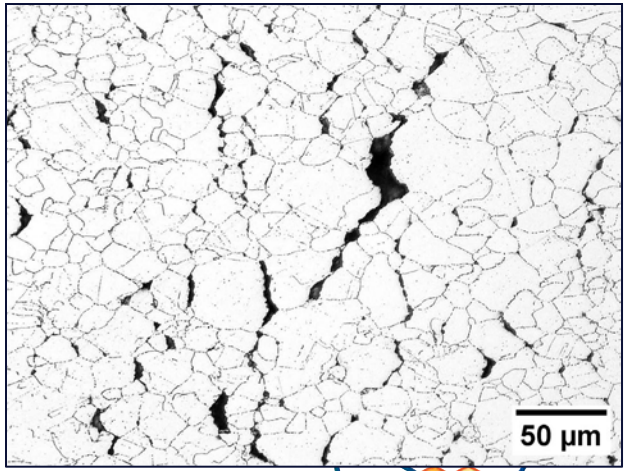
*always intergranular crack propagation

Results – Creep Testing

- One, completed creep test







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Conclusions

- PM-HIP 316H stainless steels under different processing conditions and/or lower oxygen concentration have shown no improvement in creep-fatigue properties
- Prior particle boundary oxides existed in the all the 316H powders procured
- Thes oxides are the most likely cause of reduced creep-fatigue resistance likely aiding in crack nucleation and propagation
- Low cycle fatigue specimens showed only intragranular crack propagation
- Creep-fatigue specimens showed only intergranular crack nucleation/propagation

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Future Work

- Conduct at least four creep tests with the Billet 2 powder chemistry
- Work to introduce the PM-HIP 316H composition into the American Society for Testing of Materials (ASTM) A988/A988M “Specification for Hot Isostatically-Pressed Stainless Steel Flanges, Fittings, Valves, and Parts for High Temperature Service”
  - This is needed to introduce PM-HIP 316H into ASME BPVC Section III Division 5
- Perform scoping, creep-fatigue tests on specimens heat-treated near 1200°C to increase the grain size

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