



The Elevated-Temperature Cyclic Properties of Powder Metallurgy-Hot Isostatic Pressed 316H and 316L Stainless Steel

October 2023

Changing the World's Energy Future

Richard N. Wright, Ting-Leung Sham, Ryann Elizabeth Bass



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**Idaho National Laboratory
Idaho Falls, Idaho 83415**

<http://www.inl.gov>

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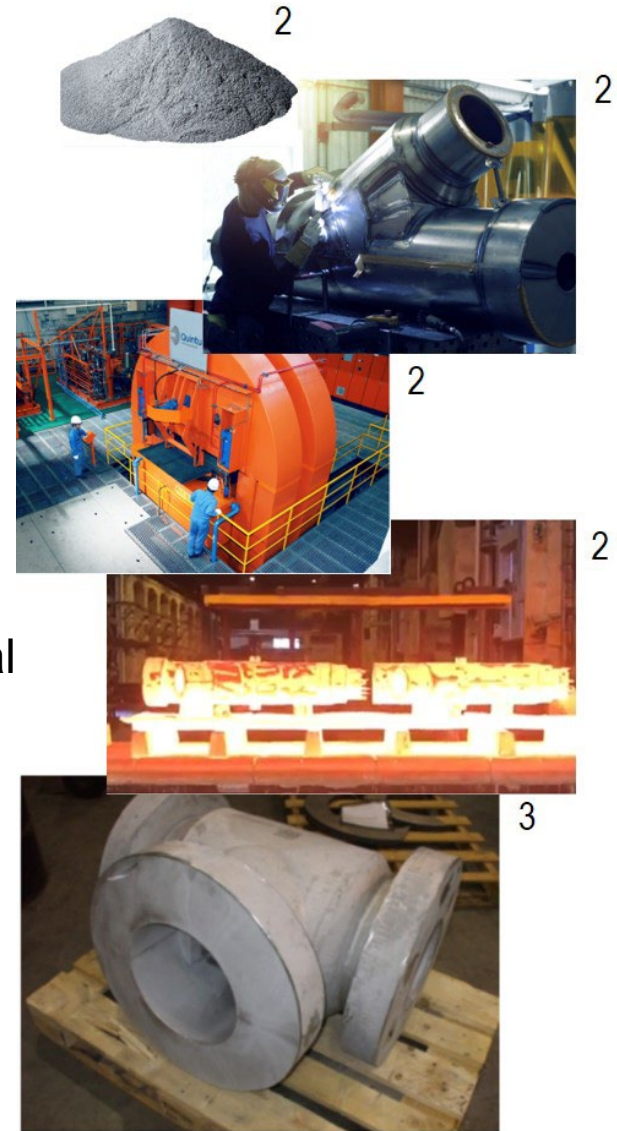
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Ryann E. Bass and Sam Sham
Idaho National Laboratory (INL)
Richard Wright
Structural Alloys, LLC

October 12, 2022

Process and Advantages

- PM HIP is a mature advanced manufacturing method that is used by many non-nuclear industries to fabricate structural components¹
 - Elimination of inspectability issues and concerns
 - Production of homogenous microstructures
 - Enabling components using near-net shape (NNS) technologies
 - Enabling new alloys systems & targeted chemistries
 - Enhancing weldability through stringent “tramp” element controls
 - Alternate supply route for long-lead time components
 - Elimination of re-work or repair of large cast components
 - Production of smaller, individual heats (lots) of material as opposed to several ton heats in near-net shape form or as ingots
- PM HIP attributes are also attractive for fabricating reactor components
 - **Particularly timely for microreactors due to smaller component size**



¹ From background file for RC 11-1826 associated with Code Case N-834

² MTC Powder Solutions AB. (downloaded 2021, June 27). Technology. <https://mtcpowdersolutions.com/technology>

³ Gandy, D., Siefert, J., Lherbier, L., & Novotnak, D. (2014, April). PM-HIP Research for pressure retaining applications within the electric power industry (SMR2014-3305). In ASME 2014 Small Modular Reactors Symposium. American Society of Mechanical Engineers Digital Collection.

CRITERIA FOR PRESSURE RETAINING METALLIC COMPONENTS USING ADDITIVE MANUFACTURING

- BPTCS/BNCS Special Committee on Use of Additive Manufacturing for Pressure Retaining Equipment
- This document provides the specific criteria completed by the Special Committee which addresses the AM Powder Bed Fusion Process.
- This additive manufacturing criteria document addresses the subjects listed below. It presents the criteria for each area followed by commentary for the section. The complete criteria are provided at the end of the report.
- Additive Manufacturing Specification
 - Materials
 - Thermal Treatment
 - Powder Requirements
 - Additive Manufacturing Design Requirements
 - Additive Manufacturing Procedure
 - Additive Manufacturing Procedure Qualification
 - Qualification Testing of Additive Manufactured Components
 - Production Builds
 - Chemistry Testing
 - Mechanical Property Testing
 - Metallographic Evaluation

Components Fabricated by PM HIP Relevant to Microreactors

1



Valve Body

316L Stainless Steel
780 kg (1,716 lbs)

2



Steam Plenum Access Port

A508
544 kg (1,200 lbs)
(still in HIP canister)

3



Upper Head

A508 Class 1, Grade 3
1,650 kg (3,650 lbs)
1,270 mm (50 inches) diameter

¹ Gandy, D., Siefert, J., Lherbier, L., & Novotnak, D. (2014, April). PM-HIP Research for pressure retaining applications within the electric power industry (SMR2014-3305). In ASME 2014 Small Modular Reactors Symposium. American Society of Mechanical Engineers Digital Collection.

² Gandy, D. W., Stover, C., Bridger, K., Lawler, S., Cusworth, M., Samarov, V., & Barre, C. (2019). Small Modular Reactor Vessel Manufacture/Fabrication Using PM-HIP and Electron Beam Welding Technologies. Hot Isostatic Pressing: HIP'17, 10, 224.

³ Gandy, D. (2020, May). Powder Metallurgy- HIP for SMRs and Advanced Reactors. Presented to the American Society of Mechanical Engineers Boiler and Pressure Vessel Code Task Group on Division 5 Advanced Manufactured Components.

Section III, Division 1 Applications - Code Case N-834

For Section III, Division 1 Subsection NB, Class 1, **316L** components fabricated by PM HIP, the wrought design methodology shall be used if the following requirements are met:

- **Conform to ASTM A988/A988M-11: Standard Specification for Hot Isostatically-Pressed Stainless Steel Flanges, Fittings, valves, and Parts for High Temperature Service**
- **Fabrication requirements:**
 - The maximum allowable powder particle size shall be 0.5 mm or less
 - Following atomization, powders shall be stored under a positive nitrogen or argon atmosphere
 - All surfaces exposed to process fluids shall be removed
- **Post-fabrication requirements:**
 - Density measurements and microstructural examination shall be performed in accordance with ASTM A988 paras. 8.1.1 and 8.1.2
 - 8.1.1: Measured density greater than 99% of the density typical of the wrought grade of the same heat-treated condition
 - 8.1.2: Microstructure shall be reasonably uniform and free of voids, laps, cracks, and porosity at 20-50x, 100-200x, and 1,000-2,000x
 - Meet minimum requirements for tensile strength, yield strength, elongation, and reduction of area
 - Chemical composition analysis of the final blend powder and component
 - Intergranular corrosion tests shall be performed in accordance with ASTM A262 Practice E
 - Ultrasonic examination over 100% its entire volume

Data Package Supporting Code Case N-834

- Chemical composition
- Grain size measurements
- Hardness measurements
- Drawings and images
- Microstructure
- Density
- Inclusion content
- Toughness
- Tensile properties (70–1000°F [21–538°C])
- Yield stress-strain curves
- Weldment properties
- Fatigue properties
- Corrosion results

300C Tests

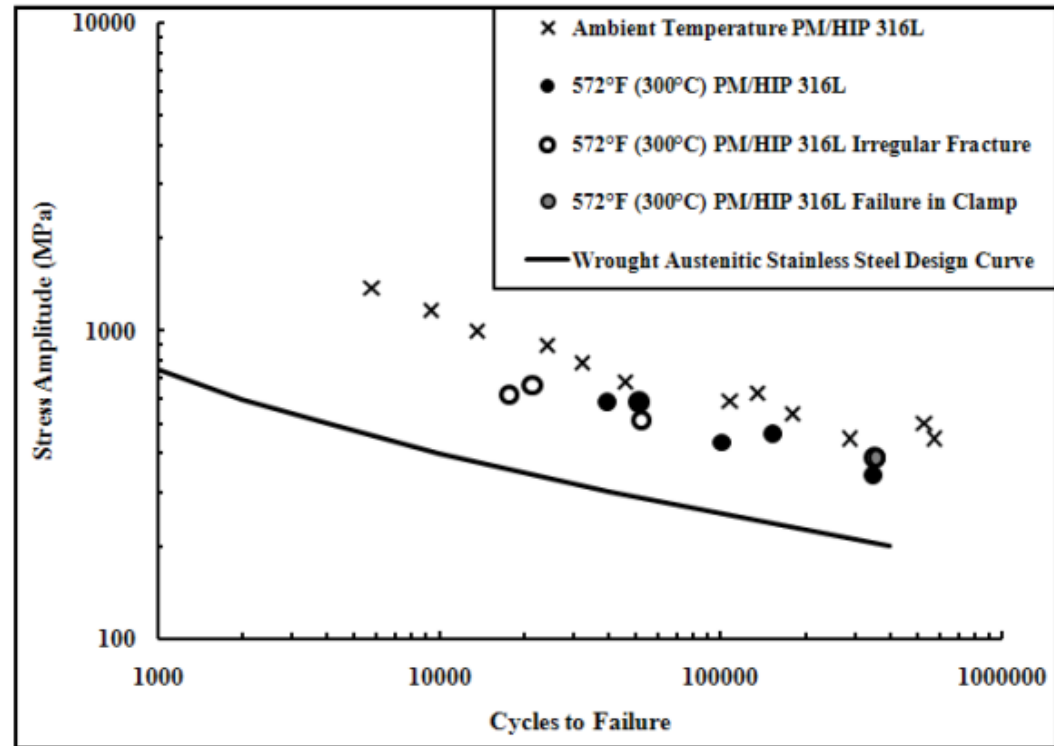


Figure 26
Stress Amplitude vs. Cycles to Failure for Heat 33836-01A

ASME Section III, Rules for Construction of Nuclear Facility Components - Division 5, High Temperature Reactors

Many of the proposed applications for advanced manufactured materials and components are for service in the time dependent material property range

- **ASME Section III Division 5 Scope**

- Division 5 rules govern the construction of vessels, storage tanks, piping, pumps, valves, supports, core support structures and nonmetallic core components for use in high temperature reactor systems and their supporting systems
 - Construction, as used here, is an all-inclusive term that includes material, design, fabrication, installation, examination, testing, overpressure protection, inspection, stamping, and certification
 - High temperature reactors include gas-cooled reactors, liquid metal reactors and molten salt reactors (liquid or solid fuel)

ASME Code Qualification of a New Material or Process

- **Division 5, Appendix HBB-Y, “Guidelines for Design Data Needs for New Materials”**
 - Recently exercised these rules through DOE ART base program on the Alloy 617 Code Case in support of HTGR/VHTR applications

Required testing to introduce a new structural material into Section III, Division 5, or a Division 5 Code Case

- | | |
|---|---|
| <ul style="list-style-type: none">• HBB-Y-2100 Requirement For Time-independent Data• HBB-Y-2110 Data Requirement for Tensile Reduction Factors for Aging• HBB-Y-2200 Requirement for Time-Dependent Data• HBB-Y-2300 Data Requirement for Weldments• HBB-Y-3100 Data Requirement for Isochronous Stress-Strain Curves• HBB-Y-3200 Data Requirement for Relaxation Strength• HBB-Y-3300 Data Requirement for Creep-Fatigue• HBB-Y-3400 Data Requirement for Creep-Fatigue of Weldments | <ul style="list-style-type: none">• HBB-Y-3500 Data Requirement for Cyclic Stress-Strain Curves• HBB-Y-3600 Data Requirement for Inelastic Constitutive Model• HBB-Y-3700 Data requirement for Huddleston multiaxial failure criterion• HBB-Y-3800 Data Requirement for Time-Temperature Limits for External Pressure Charts• HBB-Y-4100 Data Requirement for Cold Forming Limits• Validation of Elastic-Perfectly Plastic (EPP) Simplified Design Methods for the new alloy |
|---|---|

Approach to PM HIP technology adoption proposed in DOE Microreactor Program

Goals of the Microreactor Program PM HIP R&D

- Demonstrate that the elevated-temperature mechanical properties required by structural design of microreactors are comparable to, or better than, those from wrought products.
 - Through a combination of microstructural characterization and targeted elevated-temperature mechanical properties testing to reduce demonstration timeline.
- Develop specifications and acceptance criteria for PM HIP components based on allowable materials characteristics instead of solely by testing of witness specimens.
 - Providing assurance that the PM HIP components accepted for reactor construction will perform as designed throughout the design lifetime.
 - Important for the adoption of the PM HIP technology for high temperature reactor construction.

Examples of microreactor applications

- Reactor vessel, nozzle, reactor head, valve body, pump impeller, etc.

R&D Progress To Date

Procured 316H SS PM HIP bar

Chemistry , in wt.%

	C	Si	Mn	P	S	Cr	Ni	Mo	Al	Ti	N
Bar	0.040	0.17	0.21	0.002	0.003	16.44	11.95	2.48	0.007	0.005	0.147
Min	0.04					16.0	10.0	2.00			0.05
Max	0.1	0.75	2.00	0.045	0.030	18.0	14.0	3.00	0.03	0.04	

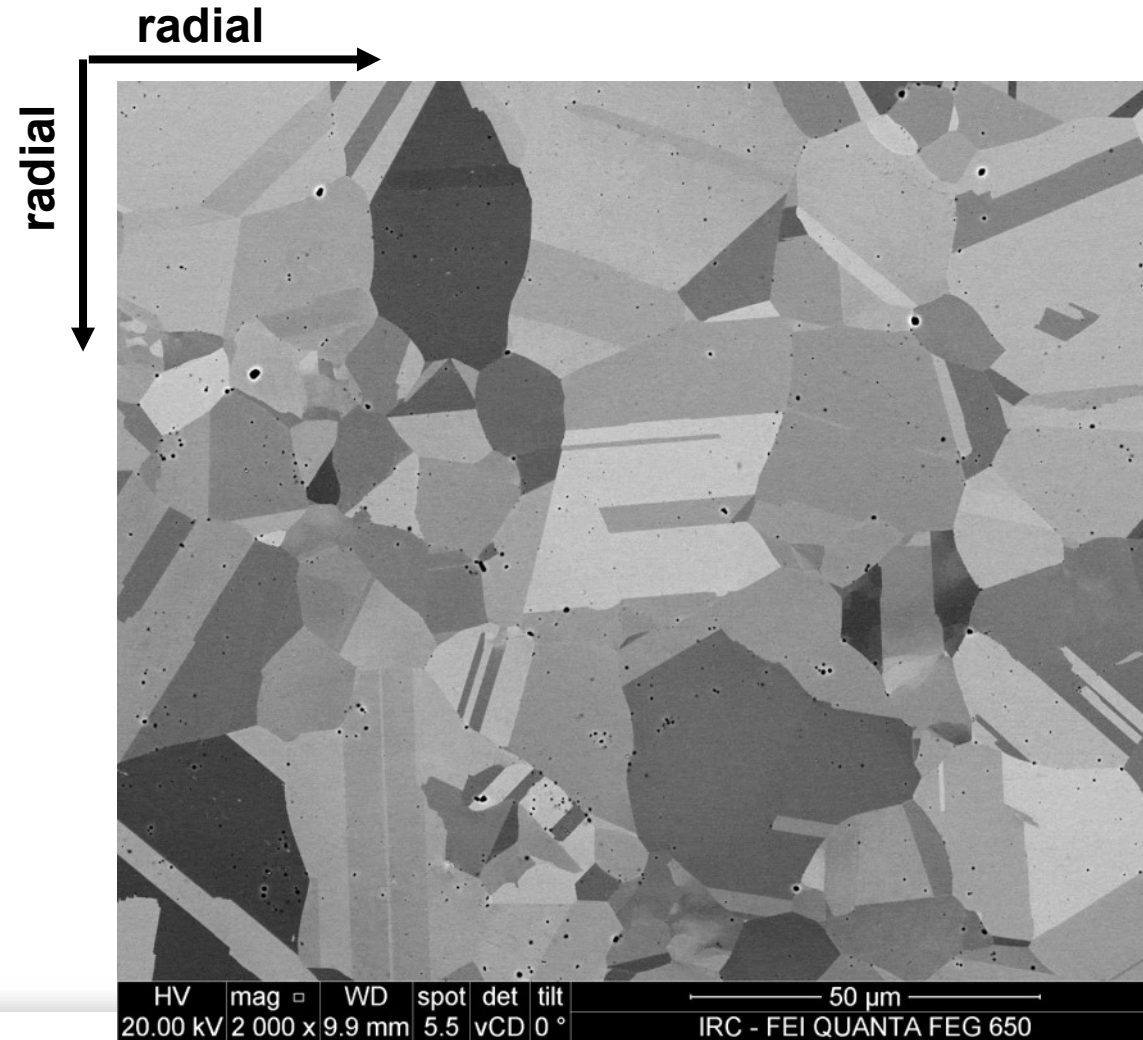
	B	Co	Cu	Nb	Ta	V	Fe	O	Ta+Co
Bar	0.0003	0.011	0.012	< 0.005	0.006	< 0.005	68.47	0.0202	0.017

Mechanical and microstructural properties

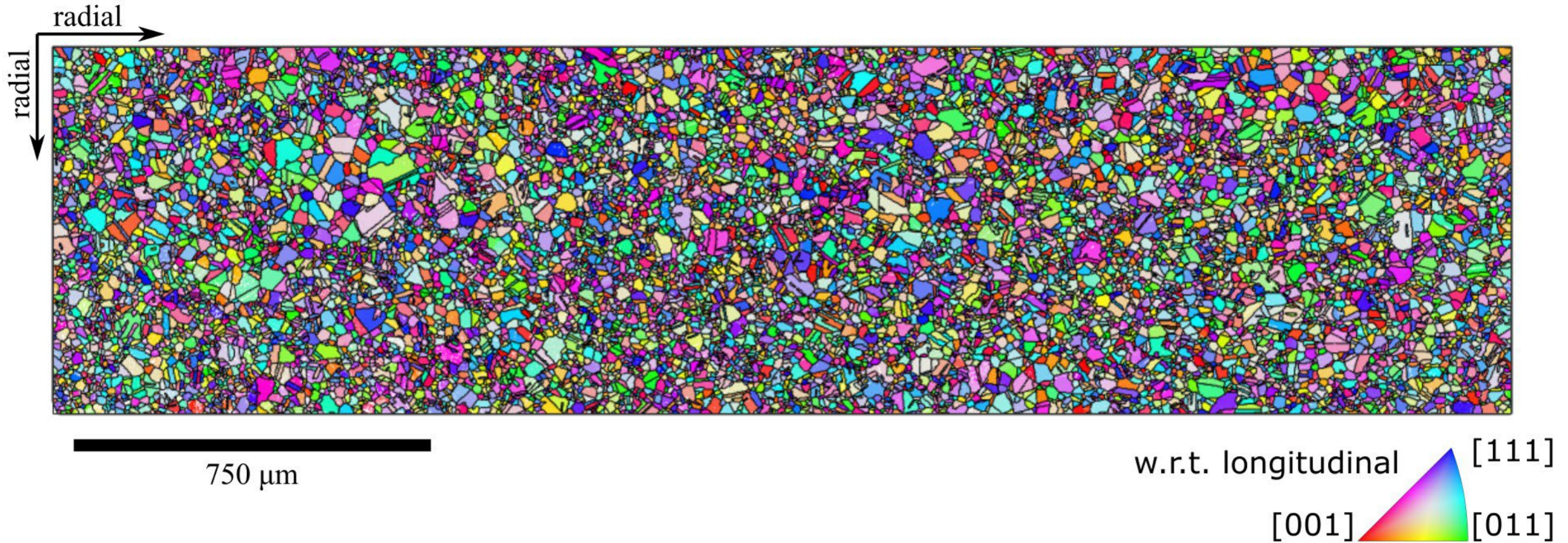
	Tensile Strength MPa	Yield Strength MPa	Elongation %	Hardness HRB	Grain size
Bar	671	370	50	89	7
Requirement	≥ 515	≥ 207	40	≤ 95	≤ 7



As-received microstructure



As-received microstructure



Elevated-temperature cyclic properties

316H SS

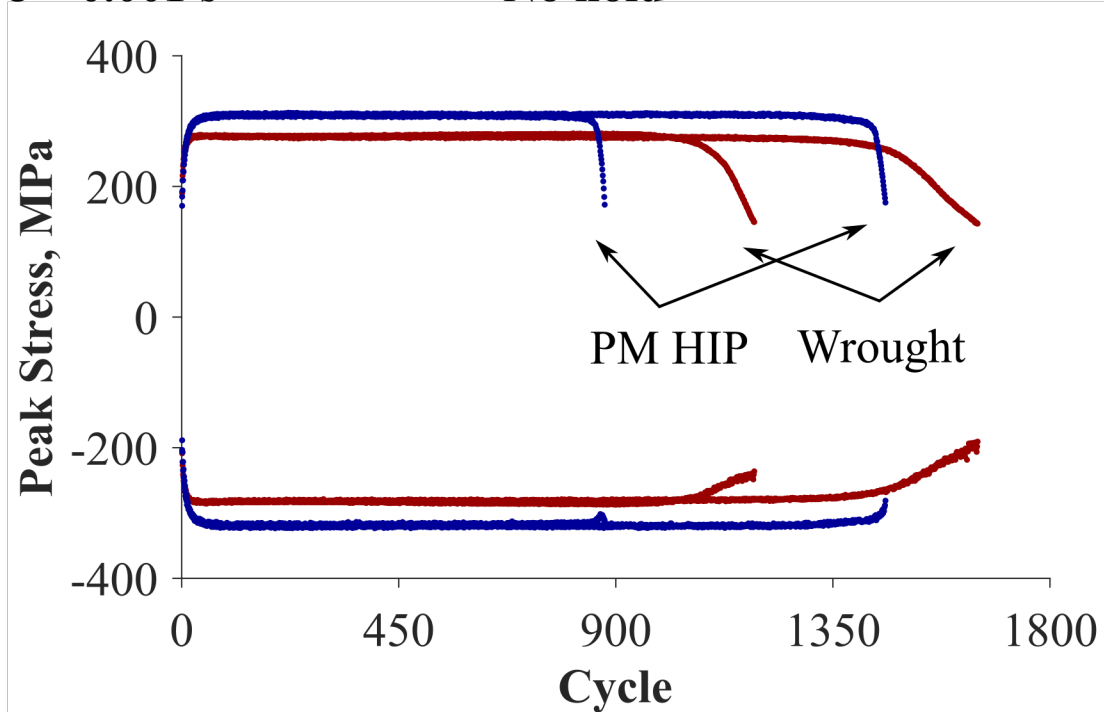
$T = 650^{\circ}\text{C}$

$\Delta\varepsilon = 1\%$

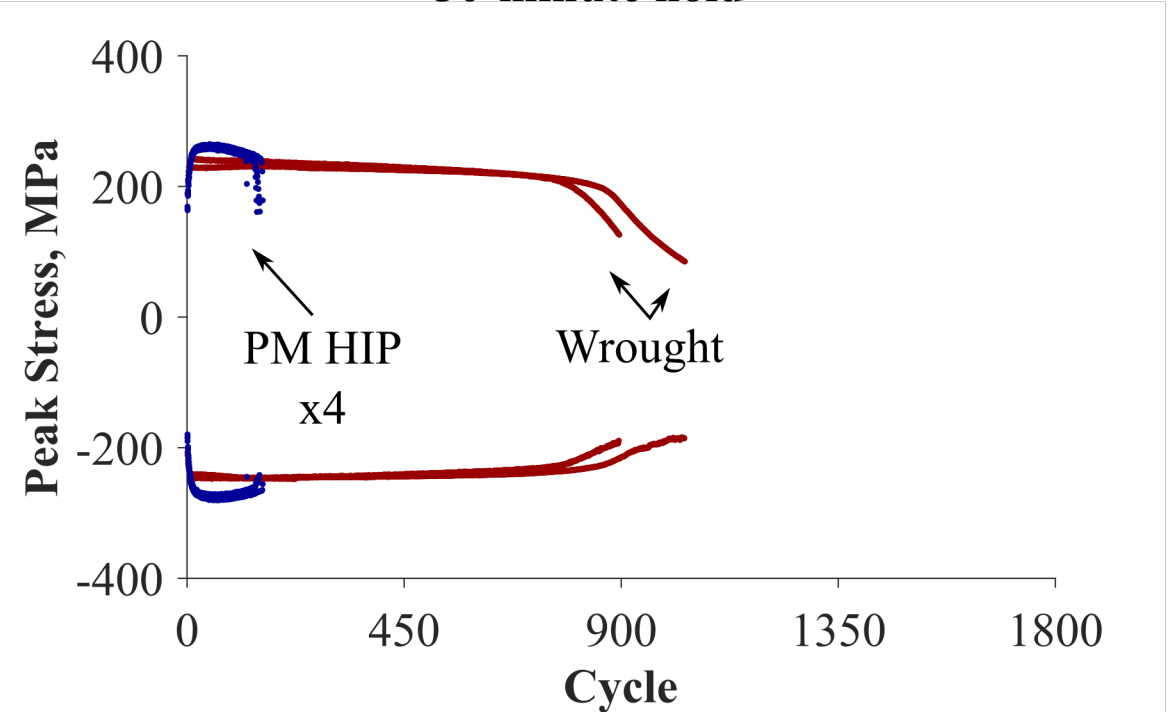
$R = -1$

$\dot{\varepsilon} = 0.001 \text{ s}^{-1}$

No hold



30-minute hold



Comparison with PM HIP 316L SS

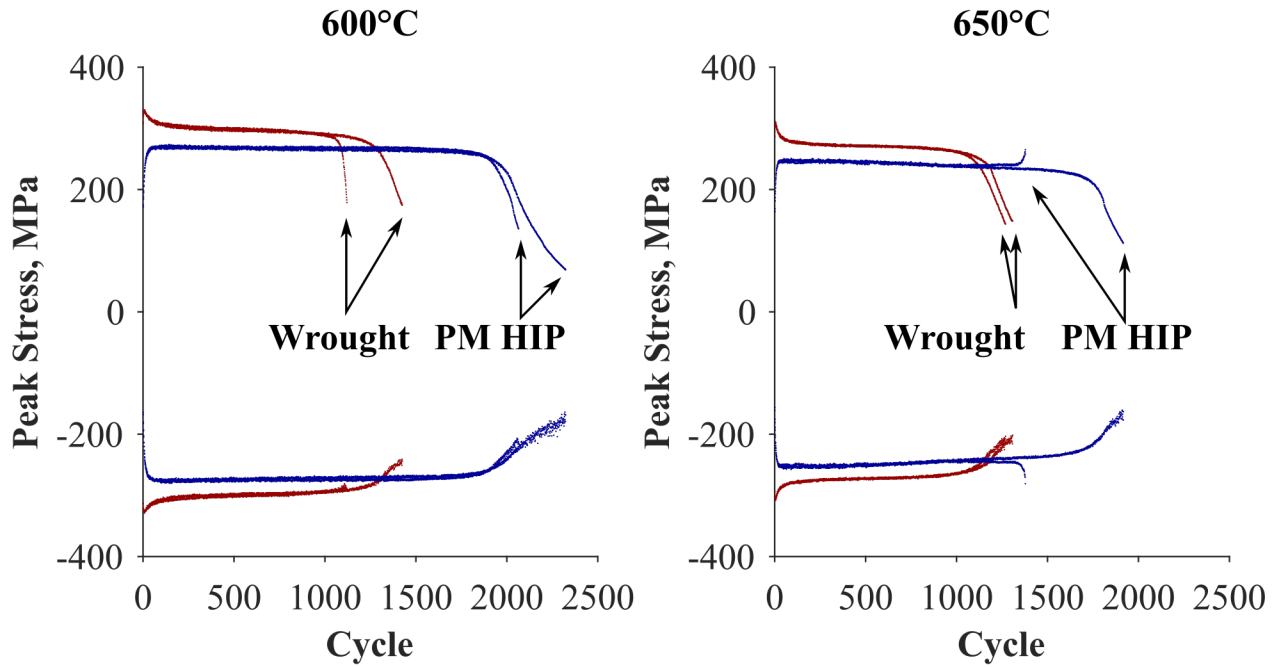
316L SS

$\Delta\varepsilon = 1\%$

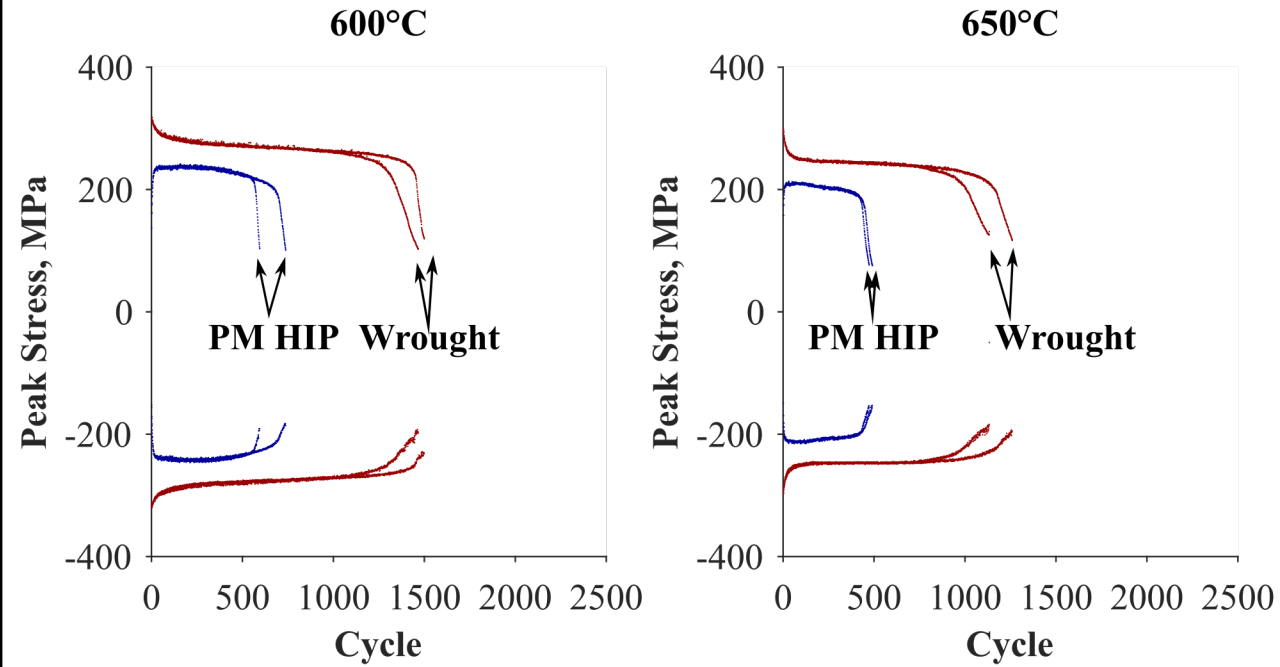
$R = -1$

$\dot{\varepsilon} = 0.001 \text{ s}^{-1}$

No hold



30-minute hold

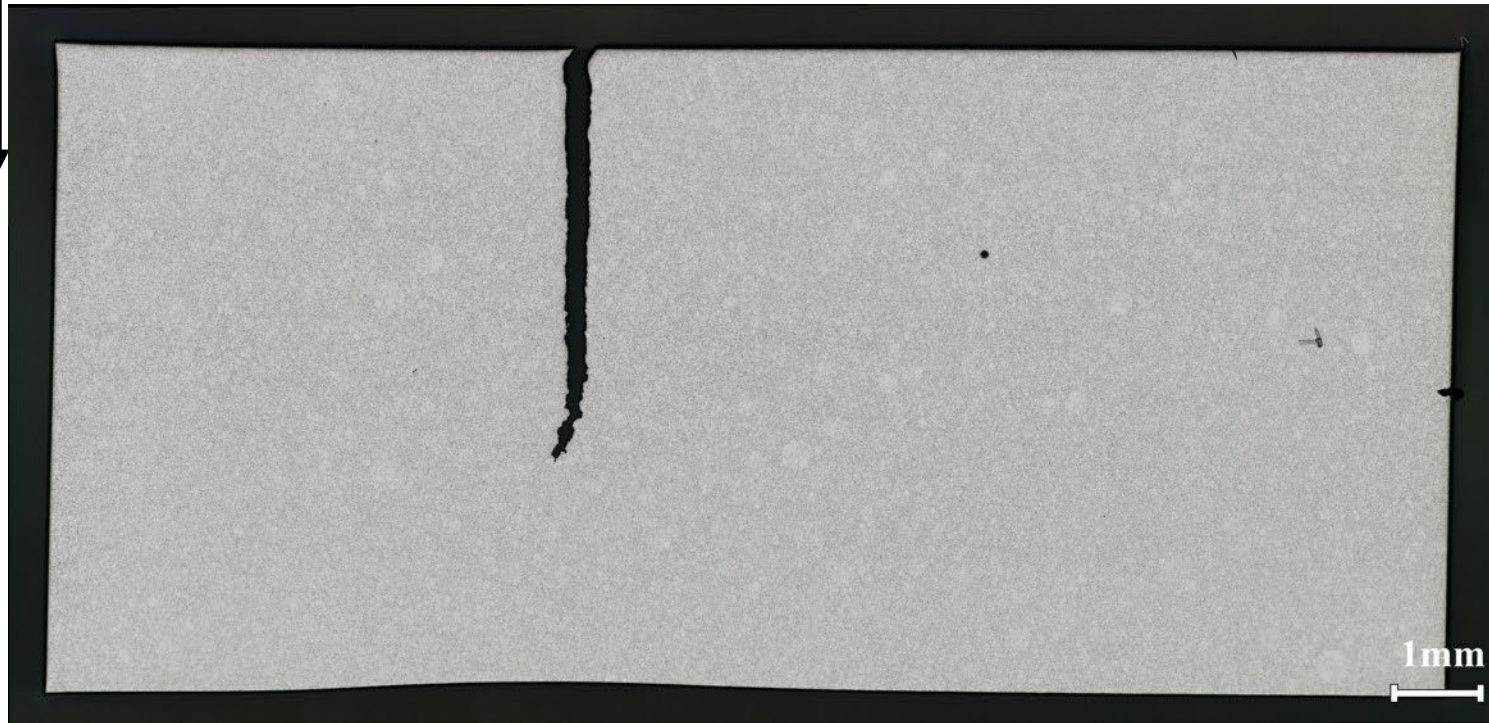


Identification of unallowable materials characteristics

Fatigue

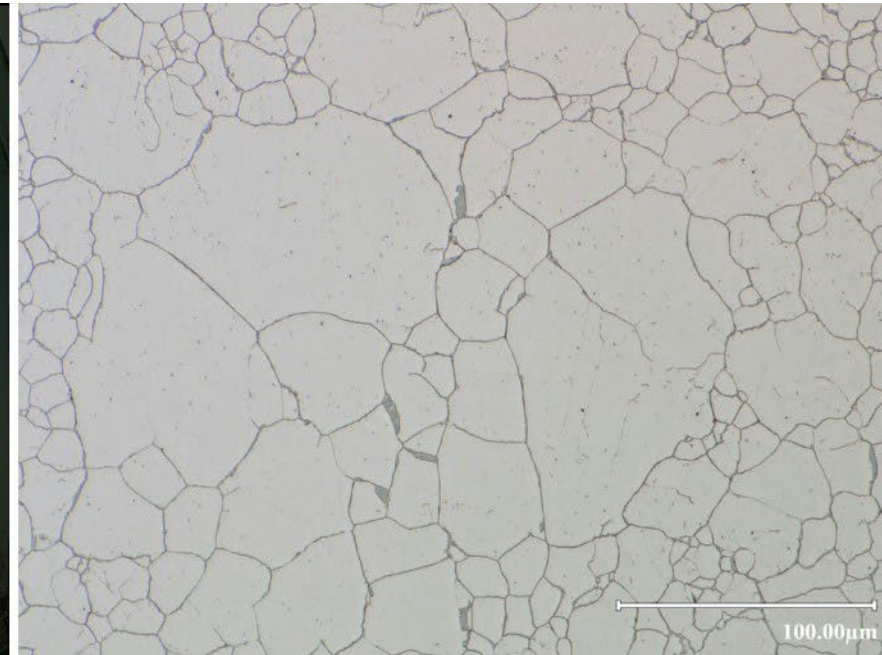
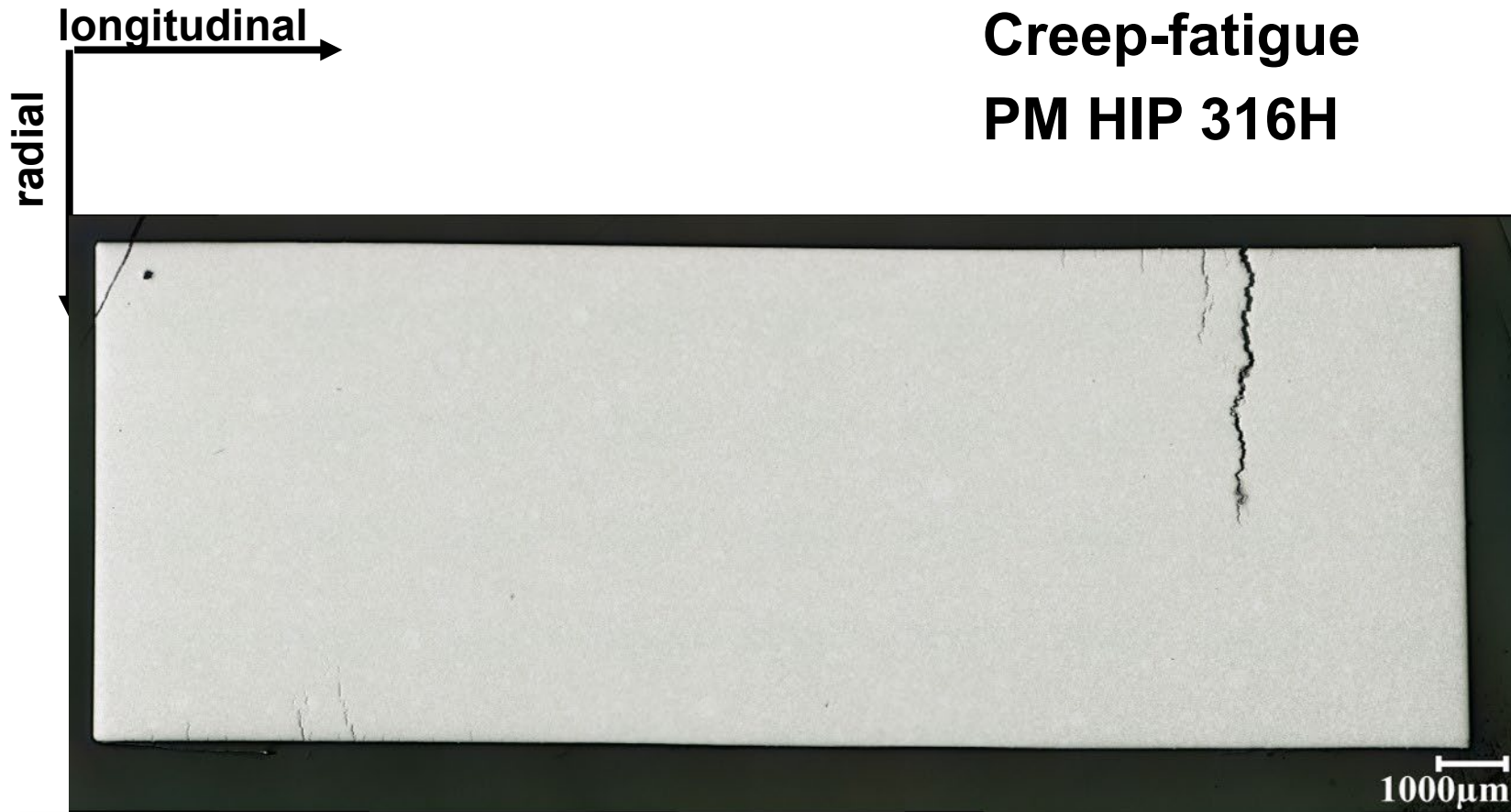
PM HIP 316H

longitudinal
radial



Identification of unallowable materials characteristics

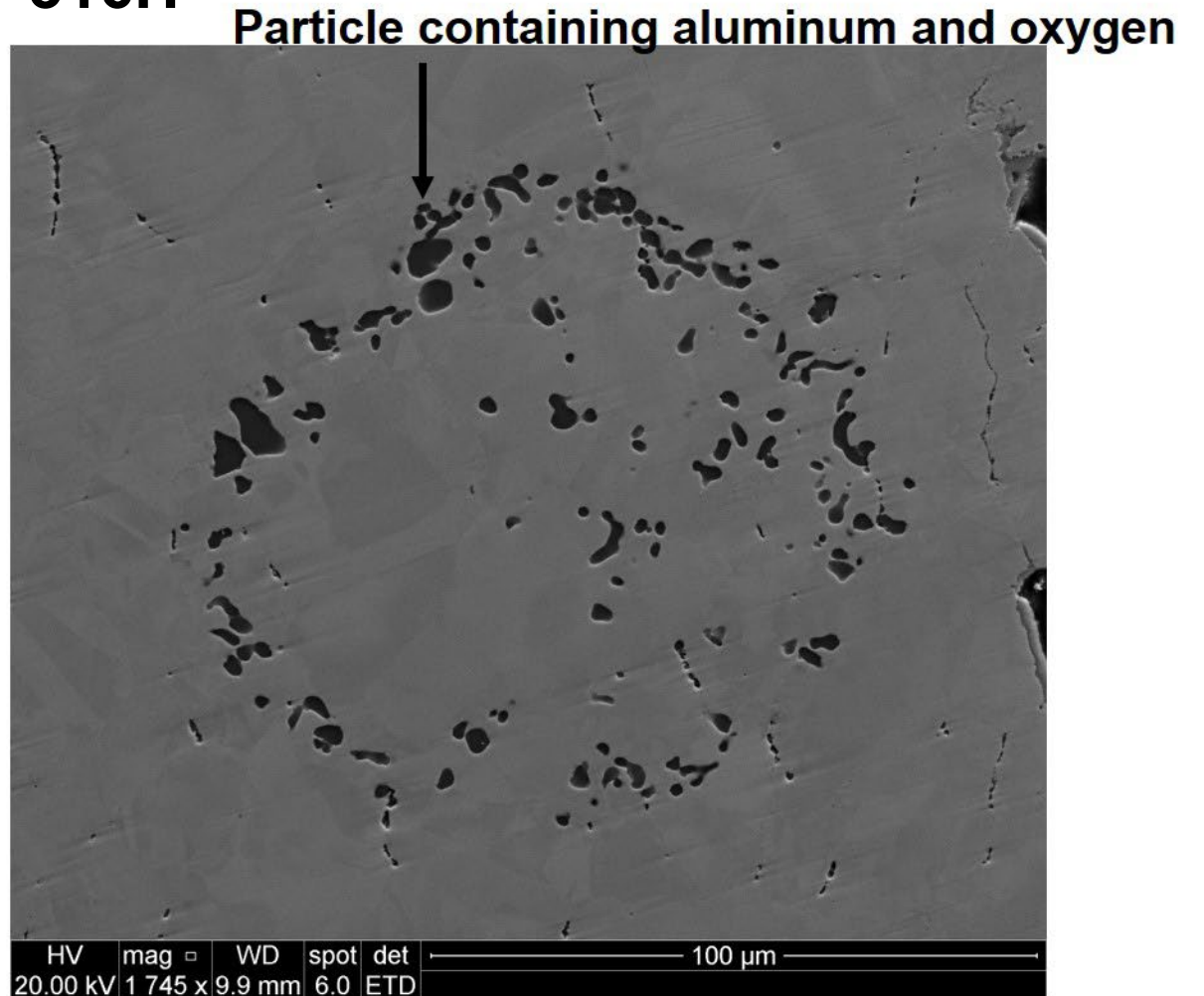
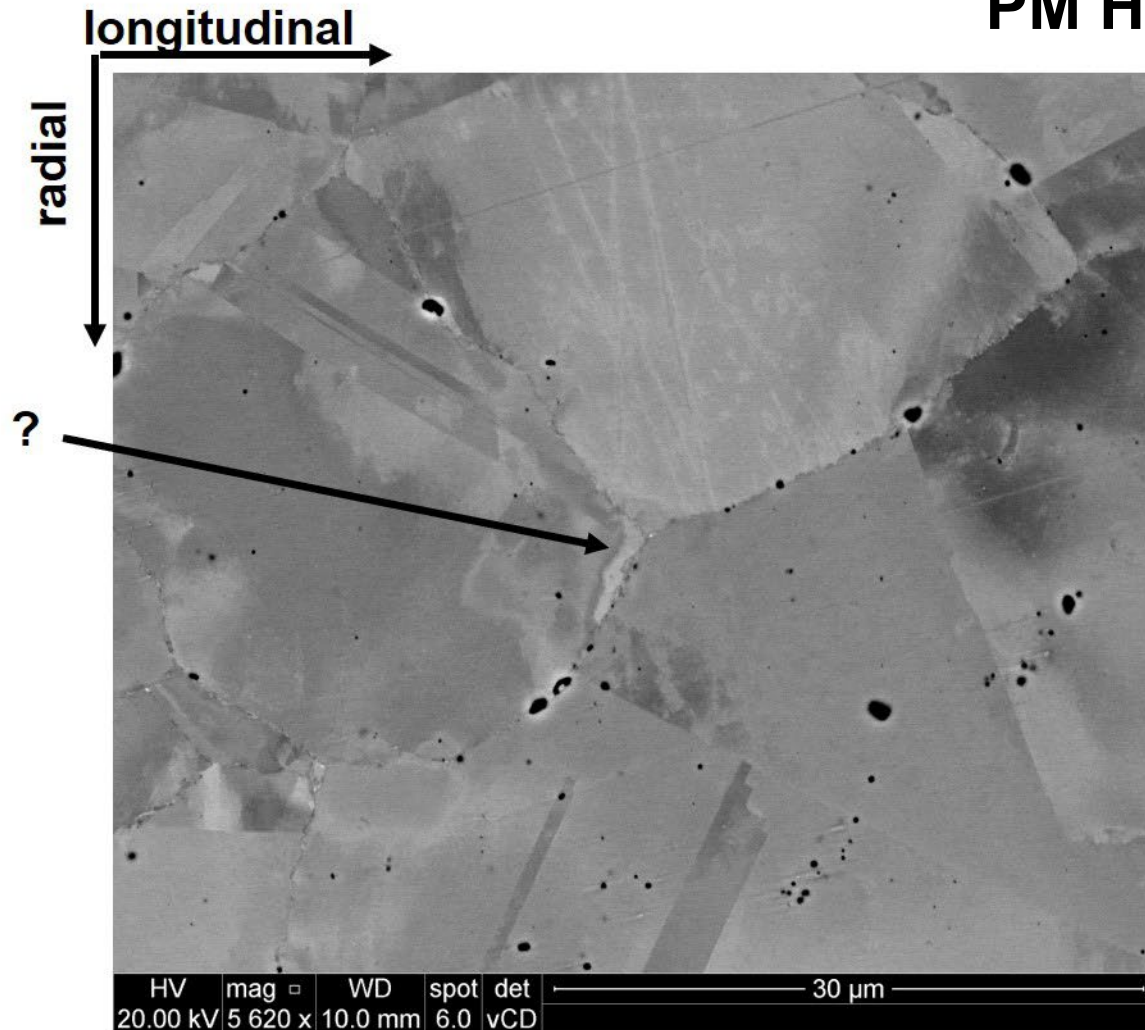
Creep-fatigue
PM HIP 316H



Unallowable materials characteristics

Creep-fatigue

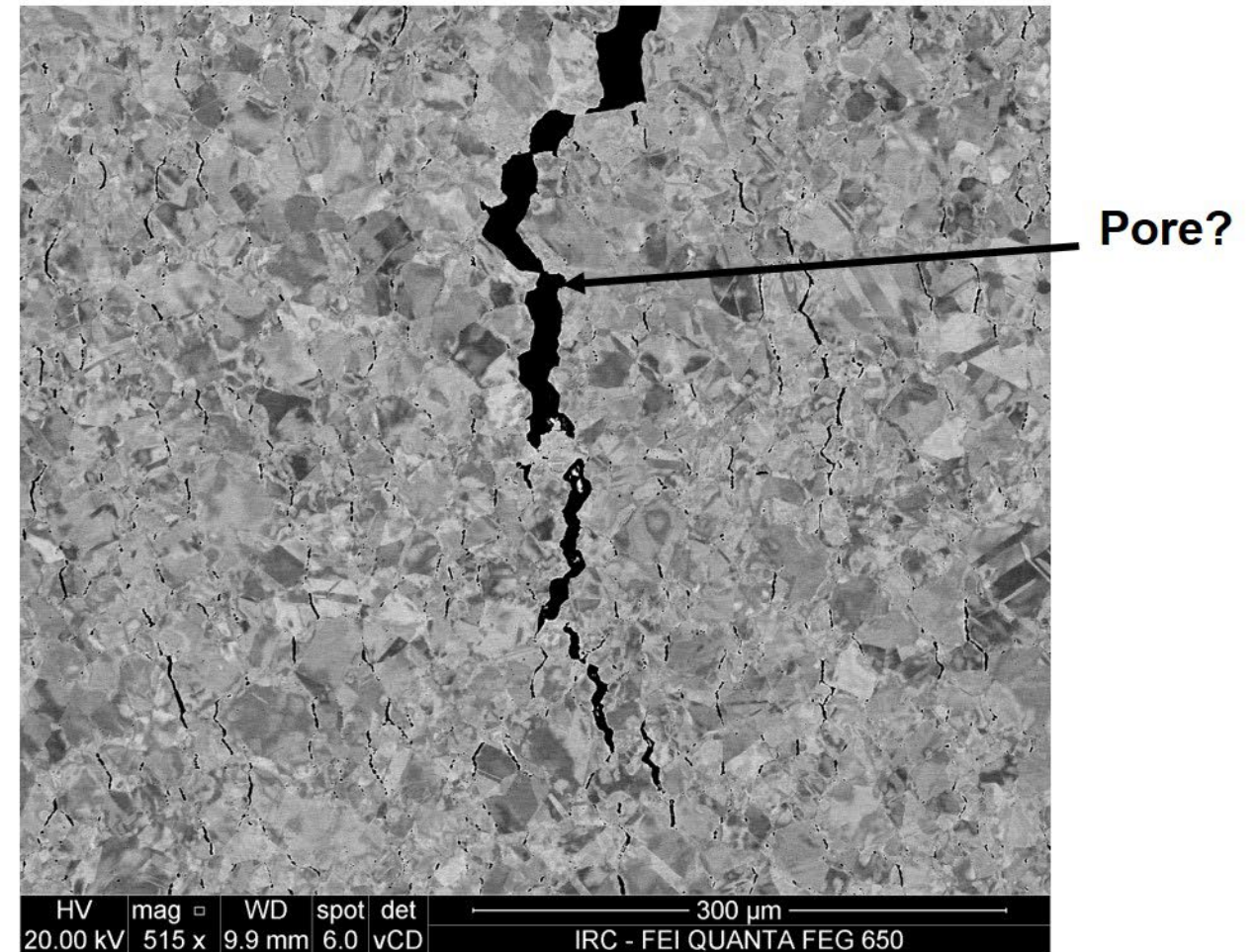
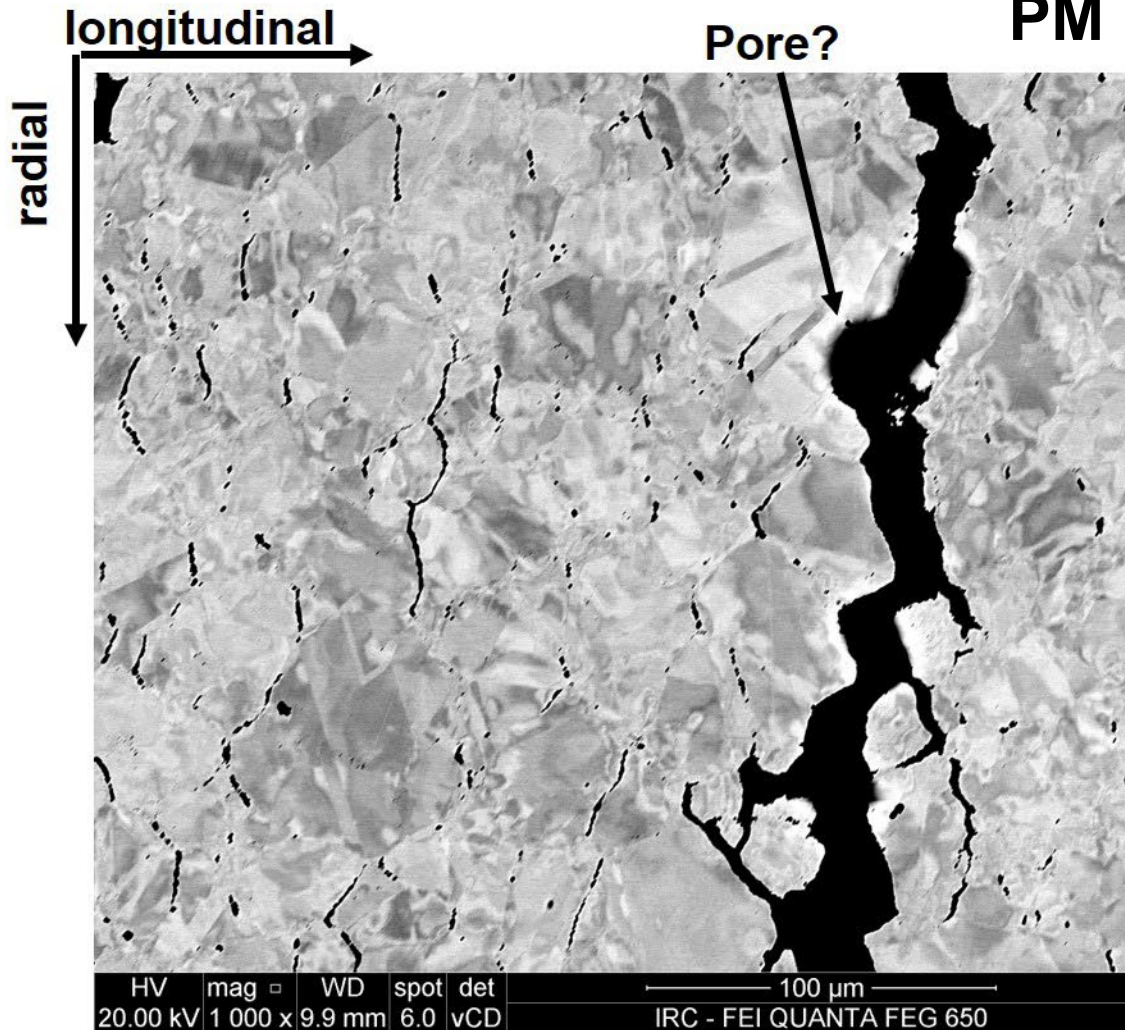
PM HIP 316H



Unallowable materials characteristics

Creep-fatigue

PM HIP 316H



Summary

- The PM HIP 316H SS bar exceeded the minimum room-temperature tensile property requirements.
- The elevated-temperature creep-fatigue properties of the PM HIP 316H SS bar are reduced compared to the wrought material.
- Room-temperature tensile data from witness specimens are not representative of, and do not predict, creep-fatigue properties.
- The mechanisms responsible for the observed behavior need to be identified.
- Current PM HIP practices are not able to fabricate elevated-temperature nuclear components that have similar or more superior creep-fatigue properties compared with components fabricated from traditional wrought product.

Summary

- PM HIP is a mature technology that offers many advantages that are attractive to the microreactor industry.
- The elevated-temperature creep-fatigue properties of the PM HIP 316H SS bar that has been characterized are reduced compared to the wrought material.
- Work will be carried out in FY-22 to identify the mechanisms responsible for the reduced creep-fatigue properties.
- Confirmatory testing of optimized material will be conducted to demonstrate long-term PM HIP properties comparable to wrought-product form.
- The lessons learned for PM HIP 316H SS will be applied to the procurement and confirmatory testing of PM HIP Alloy 800H.

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