INL/MIS-23-72777-Revision-0

Powder Metallurgy Hot Isostatic Pressing of 316H Stainless Steel

June 2023

Changing the World's Energy Future

Tate Patterson

Idaho National Laboratory

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Idaho Falls, Idaho 83415

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U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Powder Metallurgy – Hot Isostatic Pressing of 316H Stainless Steel

ASME Code Case Development in Support of Microreactors

Joint ART Materials/AMMT Program Review

DOE Headquarters, Germantown, MD

June 5-8, 2023

Tate Patterson

Idaho National Laboratory

Fiscal Year 2023 Work Package

- AT-23IN0804094 – Structural Materials

Team

- Tate Patterson (INL)
- Ryann Bass (now at US NRC)
- Richard Wright (Structural Alloys, LLC)
- Sam Sham (INL)

Background

- **Powder metallurgy hot isostatic pressing (PM-HIP) is a manufacturing technique to produce metallic components by consolidating metal powder**
  - Minimizes additional fabrication steps
  - Eliminates directional grains and solidification structures

UK - Nuclear Advanced Manufacturing Research Center (NAMRC) System

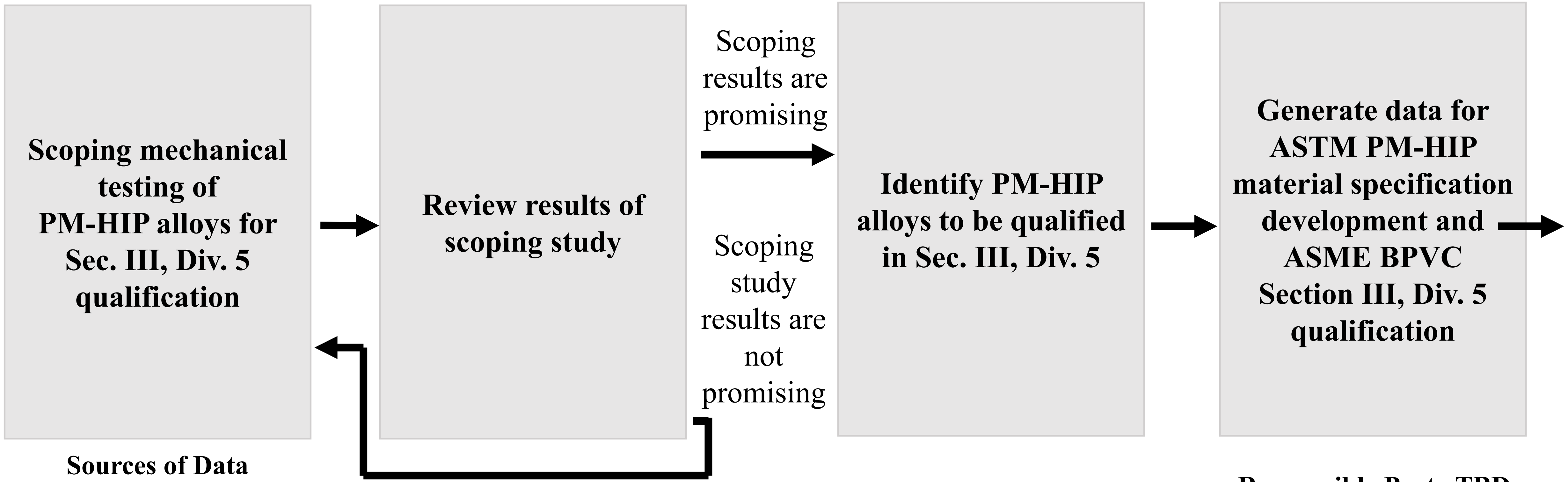
MTC Powder Solutions

PM-HIP Adoption for Microreactors

PM-HIP can benefit microreactor construction to optimize designs, reduce construction time, reduce waste, and improve component/material availability

- **Goals**
  - Demonstrate high temperature mechanical properties of PM-HIP materials compared to wrought materials
  - First address PM-HIP 316H stainless steel to support multiple advanced reactors
  - Develop specifications and acceptance criteria for PM-HIP components

PM-HIP Div. 5 Code Cases Roadmap



Sources of Data
INL, EPRI, UKNAMRC

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

Task Group (TG) on Div. 5 AM Components

TG on Div. 5 AM Components

Responsible Party TBD

Suggested Approach
Round robin discussed in Footnote 1.

Footnote: "A Systematic Study of the Material Performance of Hot Isostatically Pressed Type 316L Stainless Steel Powder for the Civil Nuclear Sector" by Kyffin, Gandy, and Burdett.

PM-HIP Div. 5 Code Cases 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

Three options compared to wrought material:

1) Use the same design rules (shortest)

2) Use a knockdown factor

3) Develop different design rules (longest)

→

Ballot code case permitting PM-HIP for low temperature Sec. III, Div. 5 applications

→

Ballot code case permitting PM-HIP for elevated temperature Sec. III, Div. 5 applications

Responsible Party TBD

TG on Div. 5 AM Components

TG on Div. 5 AM Components

Responsible Party TBD

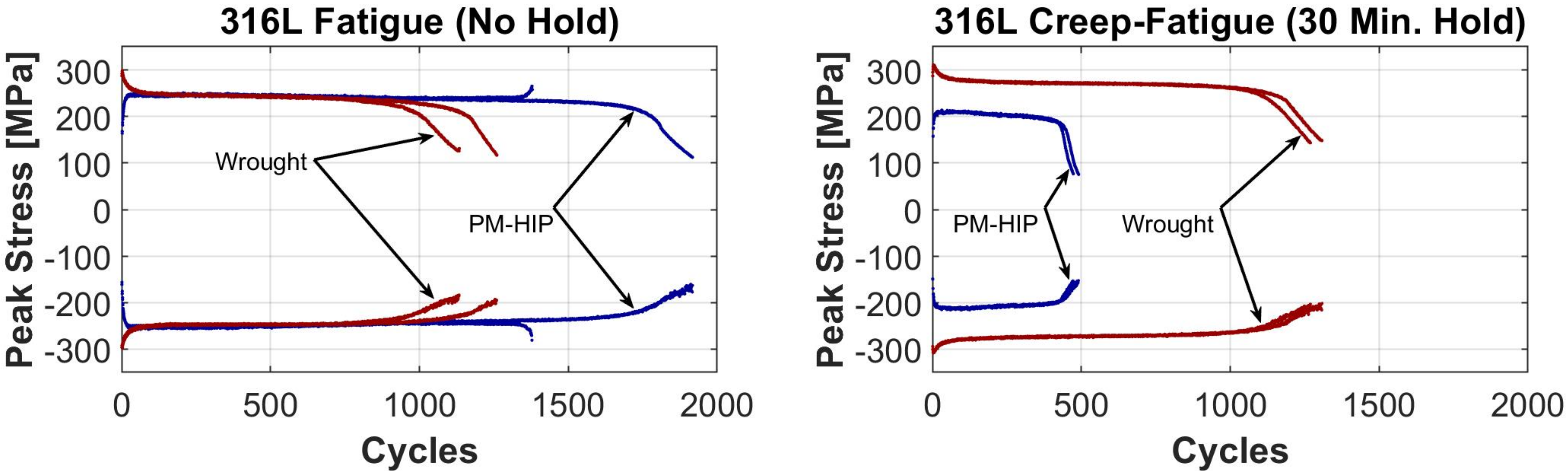
Major Milestones

- **Complete development of PM-HIP 316H code cases for the American Society of Mechanical Engineers (ASME) Section III, Division 5, Class A applications by 2025**
  - **Low temperature PM-HIP 316H code case (up to 371°C)**
  - **High temperature PM-HIP 316H code case (371°C<T<816°C)**

Prior Results – 316L

- Fatigue and creep-fatigue at 650°C

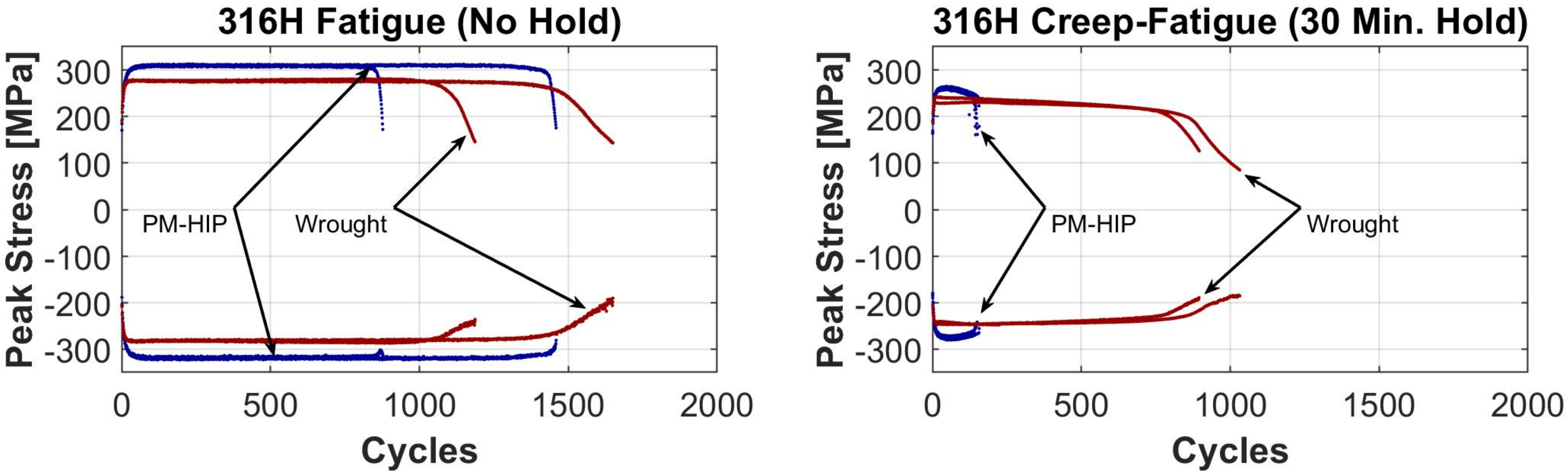
$$650°\mathrm{C},\ \Delta\varepsilon = 1\%,\ \ R = -1,\ \ \dot{\varepsilon} = 0.001\ s^{-1}$$



Prior Results – 316H

- **Fatigue and creep-fatigue at 650°C**

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



Properties and Process Optimization

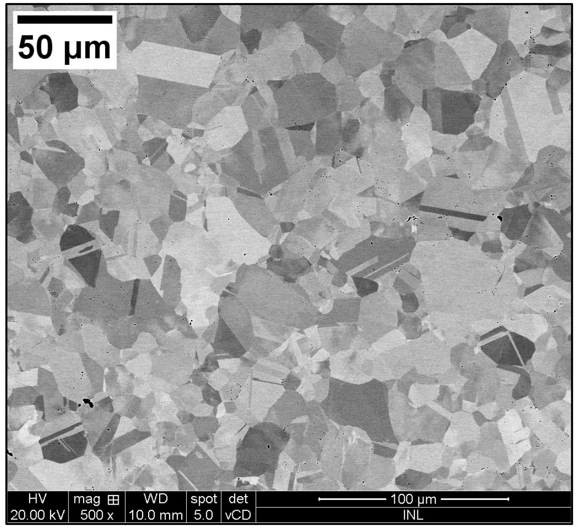
Why are fatigue and creep-fatigue results showing inferior performance compared to wrought 316 stainless steel?

- **Need to better understand how the composition and microstructure influence PM-HIP mechanical properties**
  - **Overall oxygen concentration**
    - Prior data has shown that >130 ppm oxygen content in PM-HIP SS may be deleterious to elevated temperature properties
  - **Oxide size and distribution**
  - **Grain size and grain size distribution**

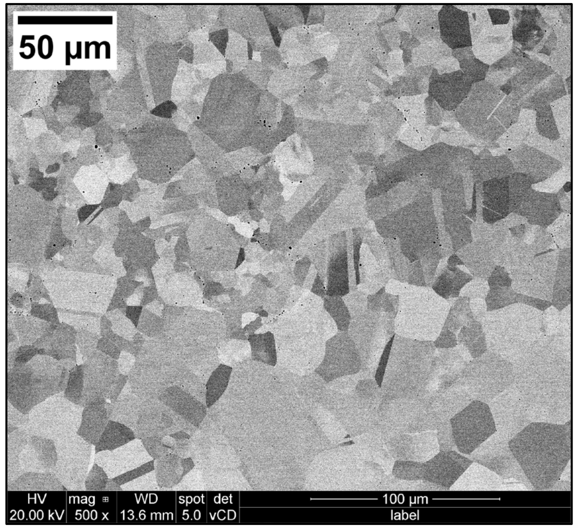
Current Material Investigation

Consolidated Product Chemical Compositions (wt%)											Hardness ($HV_{0.3}$)
	Ni	Cr	Mo	C	Si	Mn	S	P	O	N	
316H – MTC Heat 1	12.0	16.2	2.53	0.05	0.17	0.21	0.01	0.003	0.0190	0.141	**224**
316H – UK-NAMRC	11.8	17.3	2.53	0.04	0.17	0.18	<0.003	<0.005	0.015	0.069	**194**
316L – UK-NAMRC	11.9	17.7	2.44	0.015	0.83	1.88	0.008	0.008	0.0117	0.06	**173**

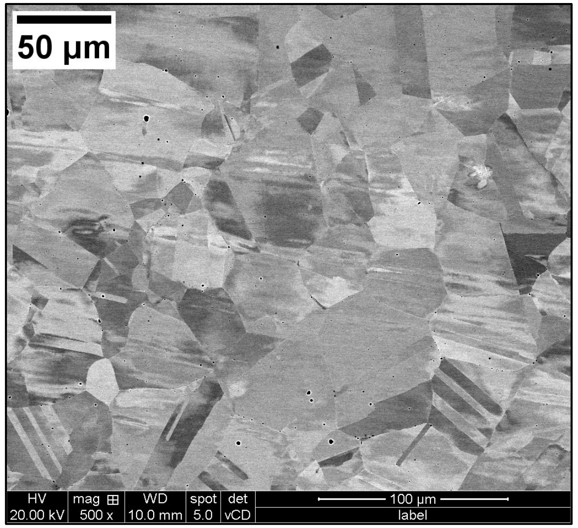
316H – MTC Heat 1



316H – UK-NAMRC

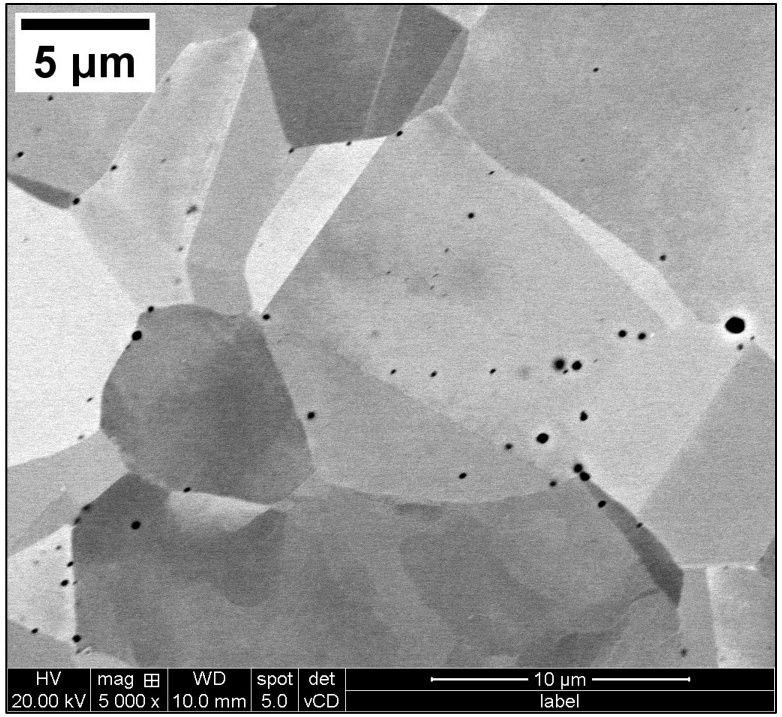


316L – UK-NAMRC



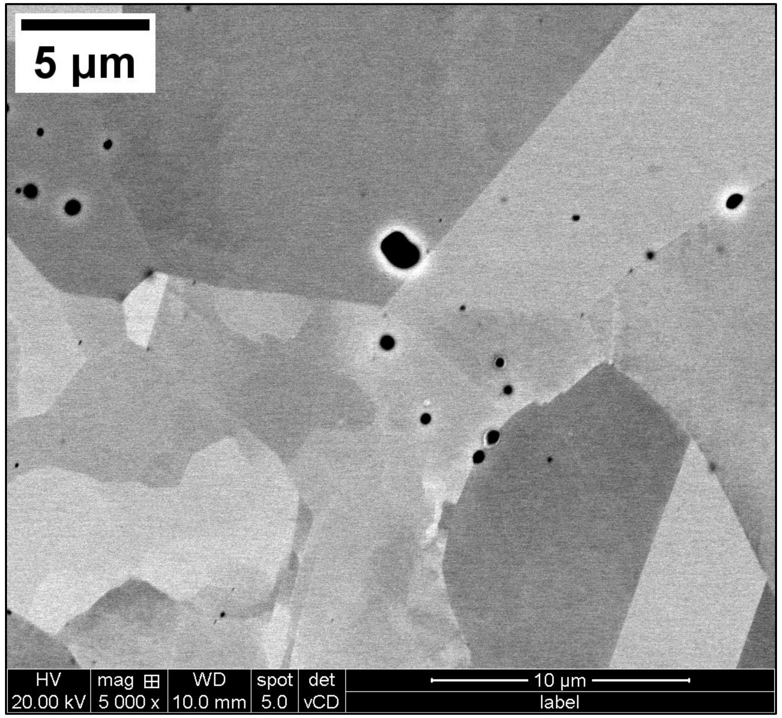
Results – Oxide Analysis

316H – MTC Heat 1



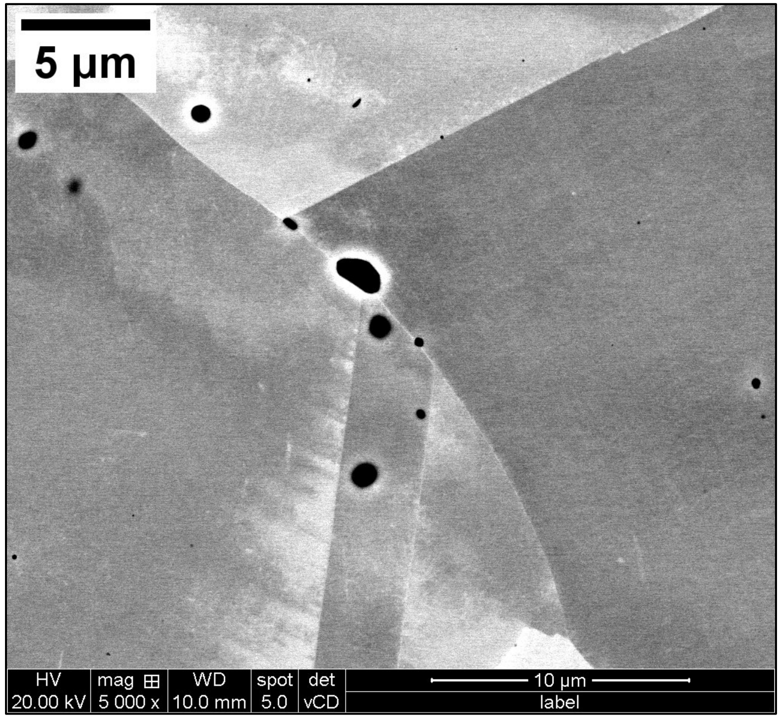
Oxide Area Fraction = 0.10%

316H – UK-NAMRC



Oxide Area Fraction = 0.18%

316L – UK-NAMRC

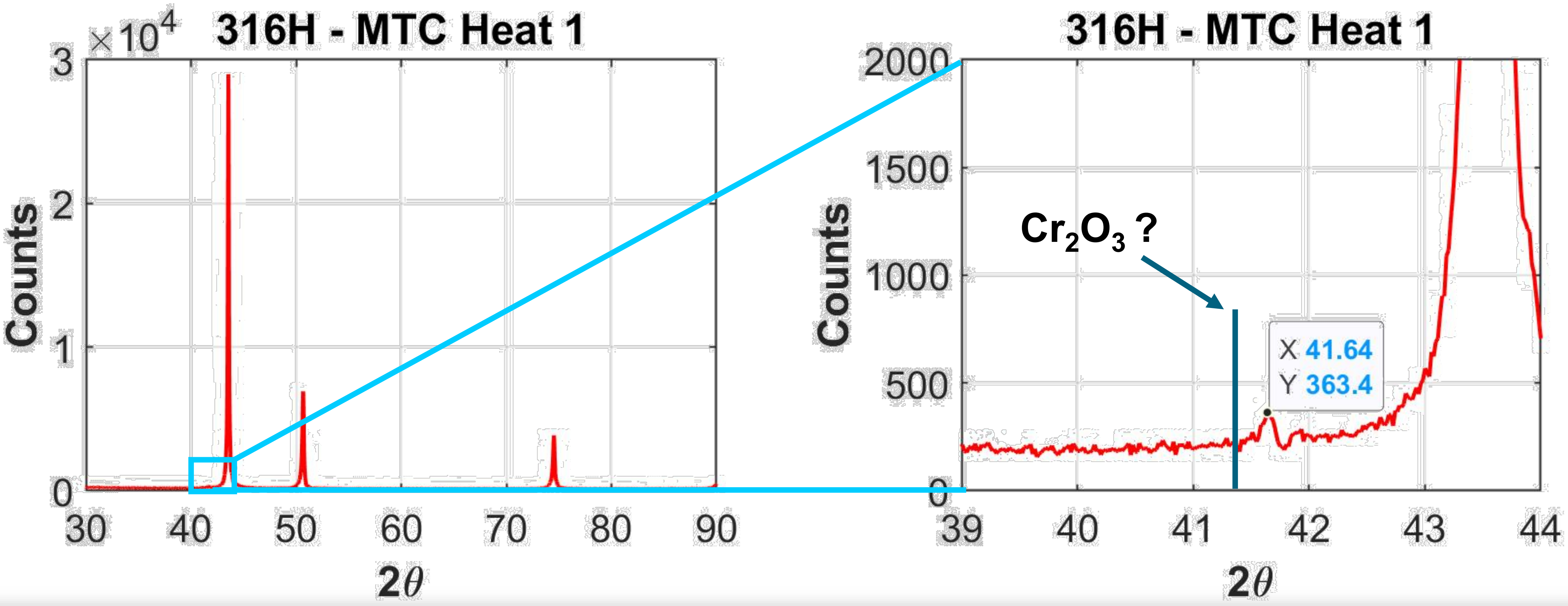


Oxide Area Fraction = 0.18%

*Fraction averages are from five random images at an original magnification of 2500X captured at a 10 µm working distance

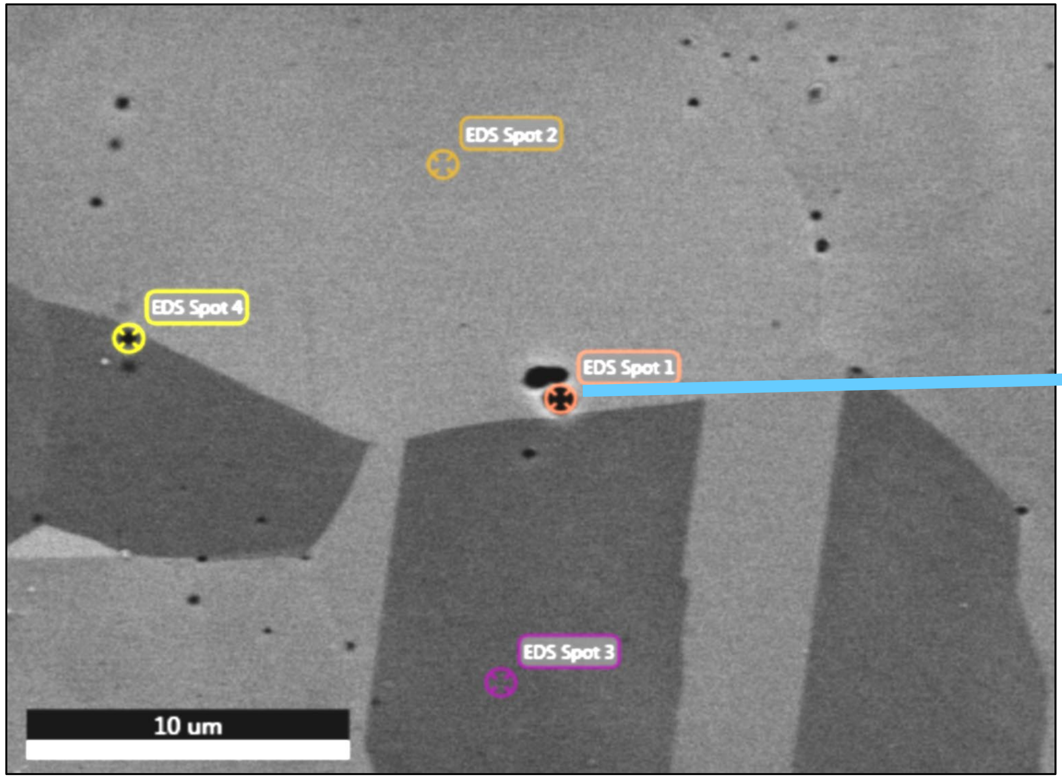
Results – Oxide Analysis

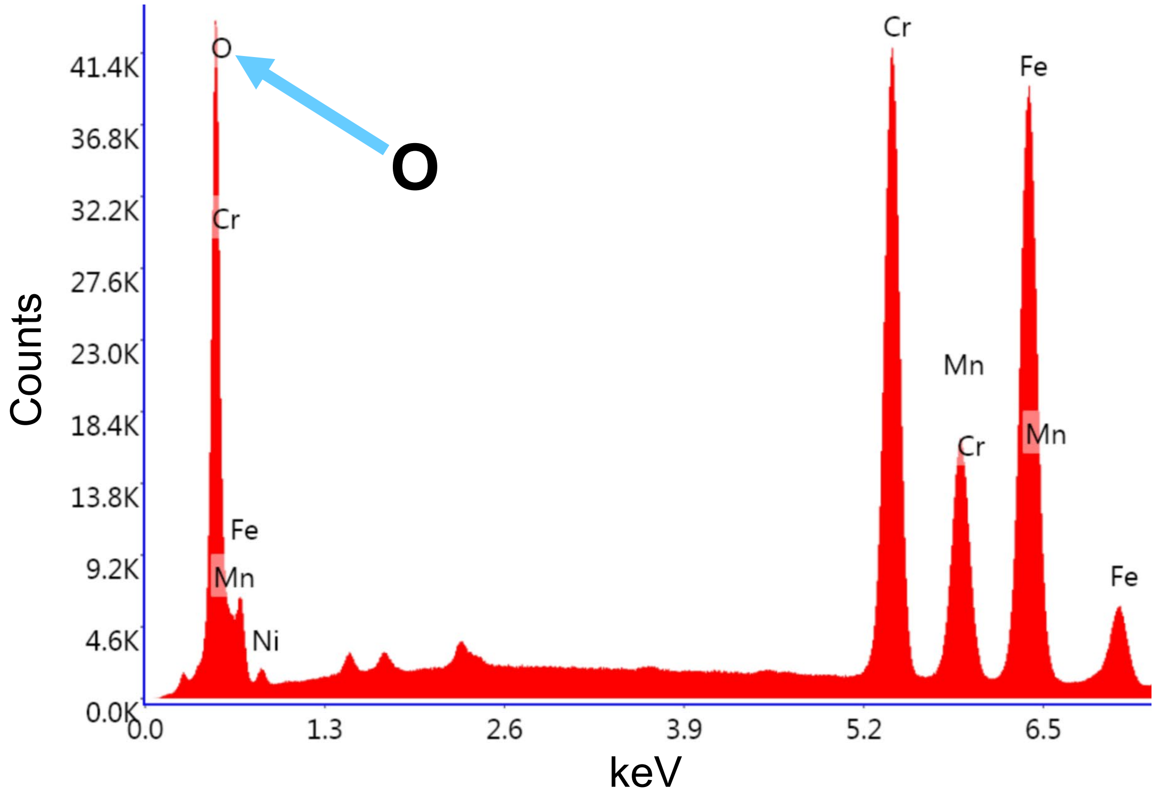
- X-ray Diffraction Data



Results – Oxide Analysis

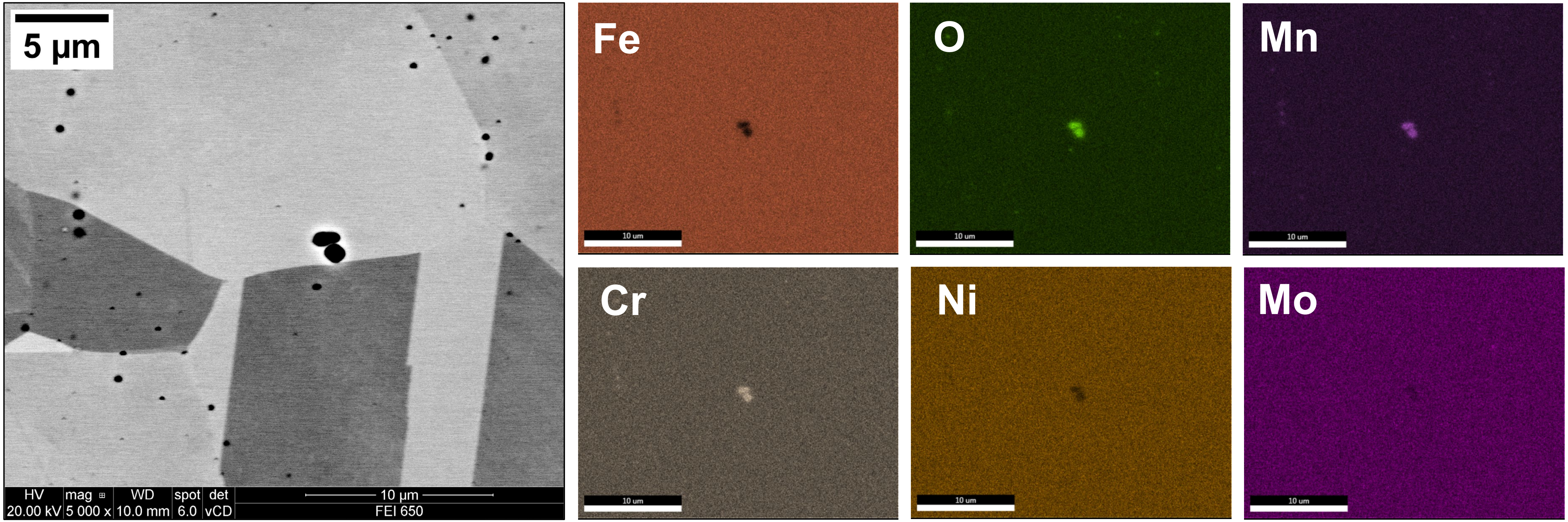
- **Are the precipitates oxides?**





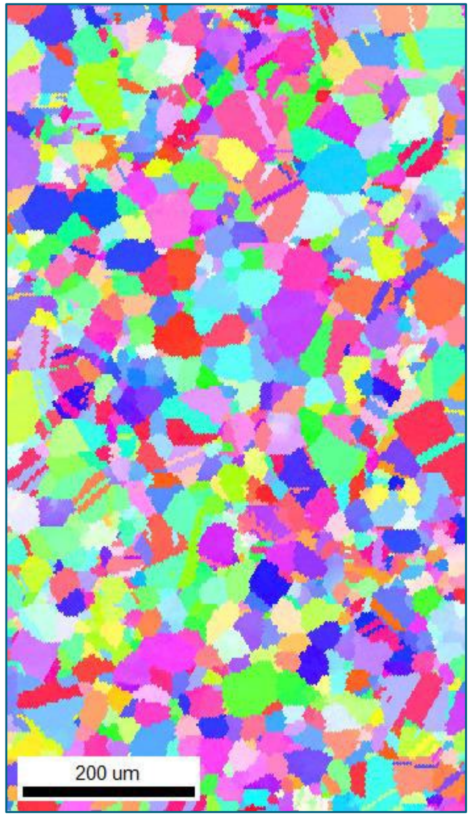
Results – Oxide Analysis

- EDS Analysis (Qualitative) – UKNAMRC 316H



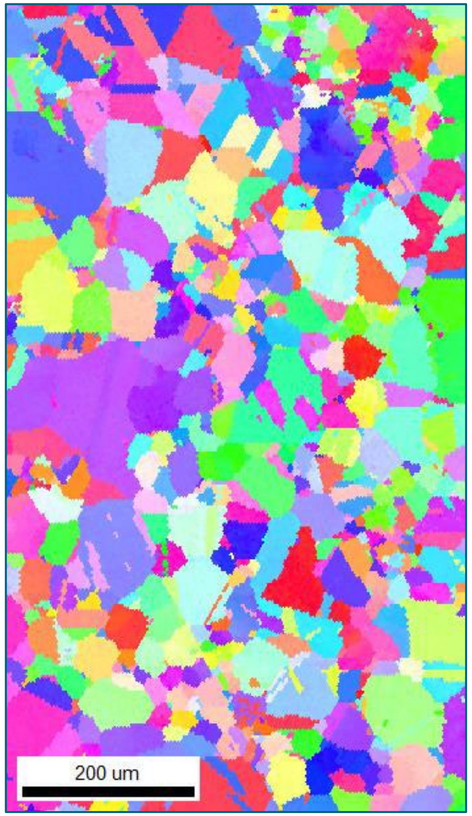
Results – Grain Size

316H MTC Heat 1



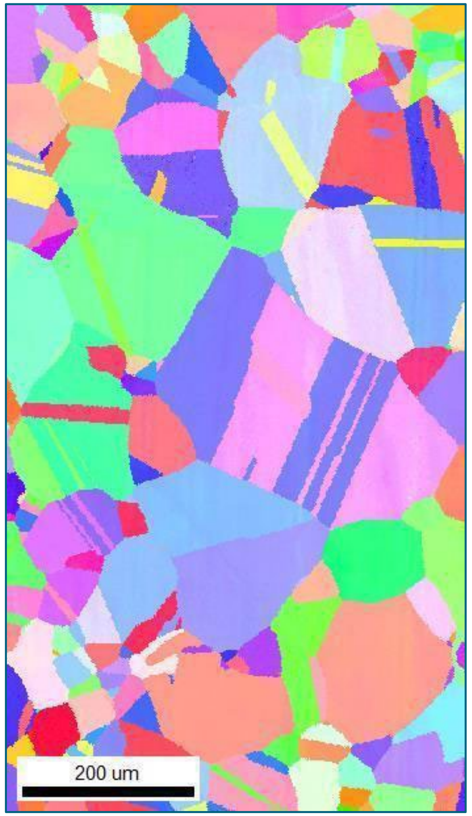
d_{avg}= 35 μm

316H UK-NAMRC

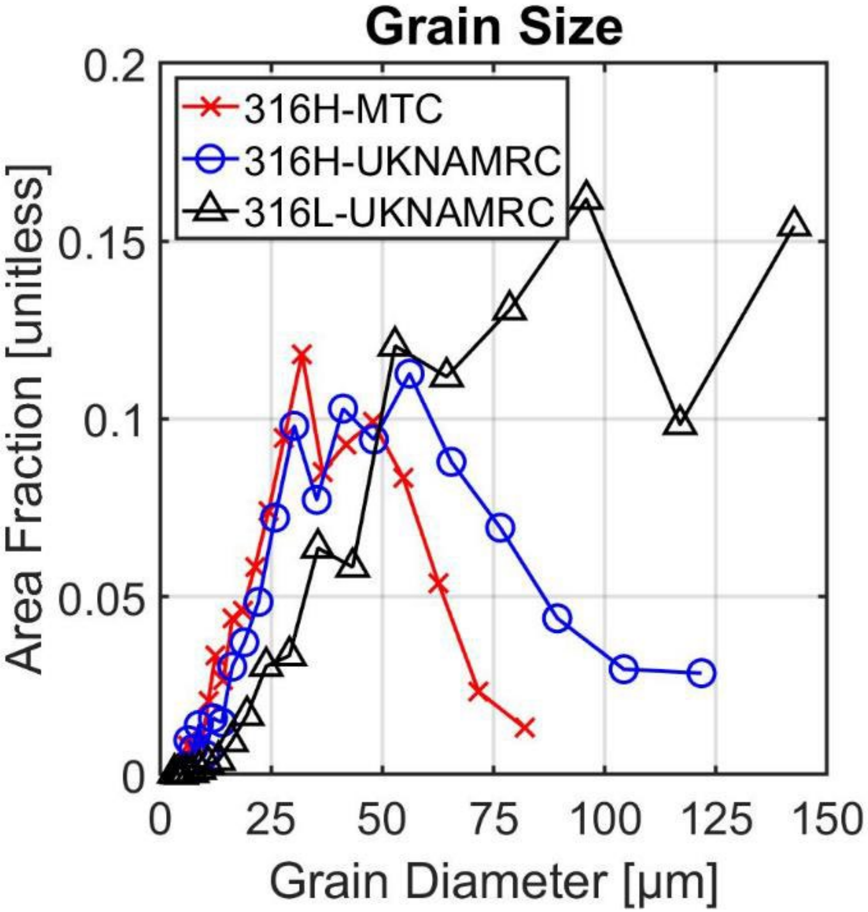


d_{avg}= 47 μm

316L UK-NAMRC

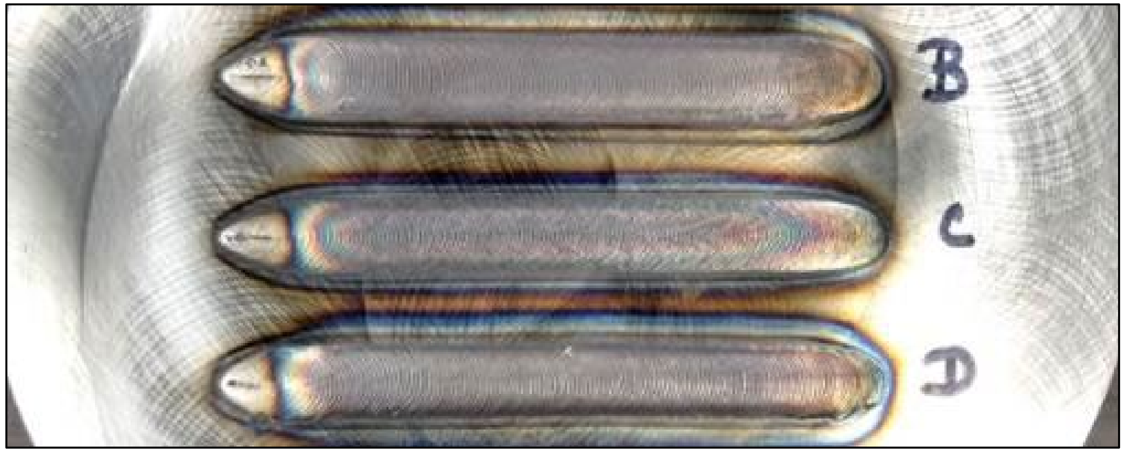


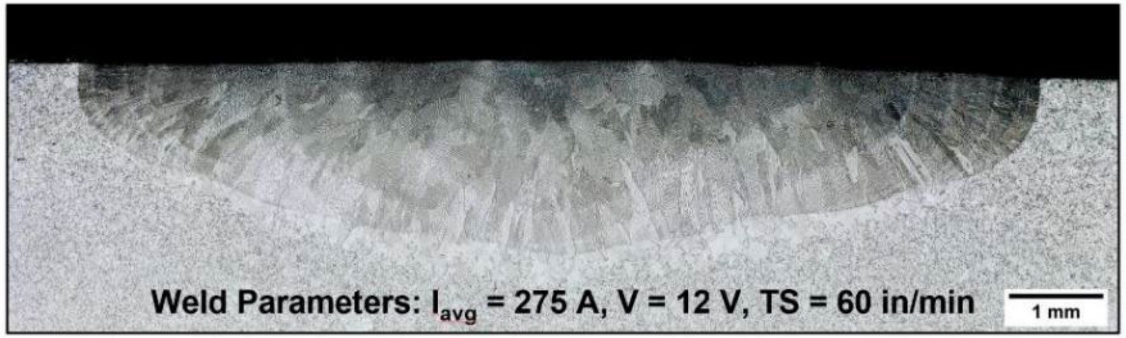
d_{avg} = 80 μm

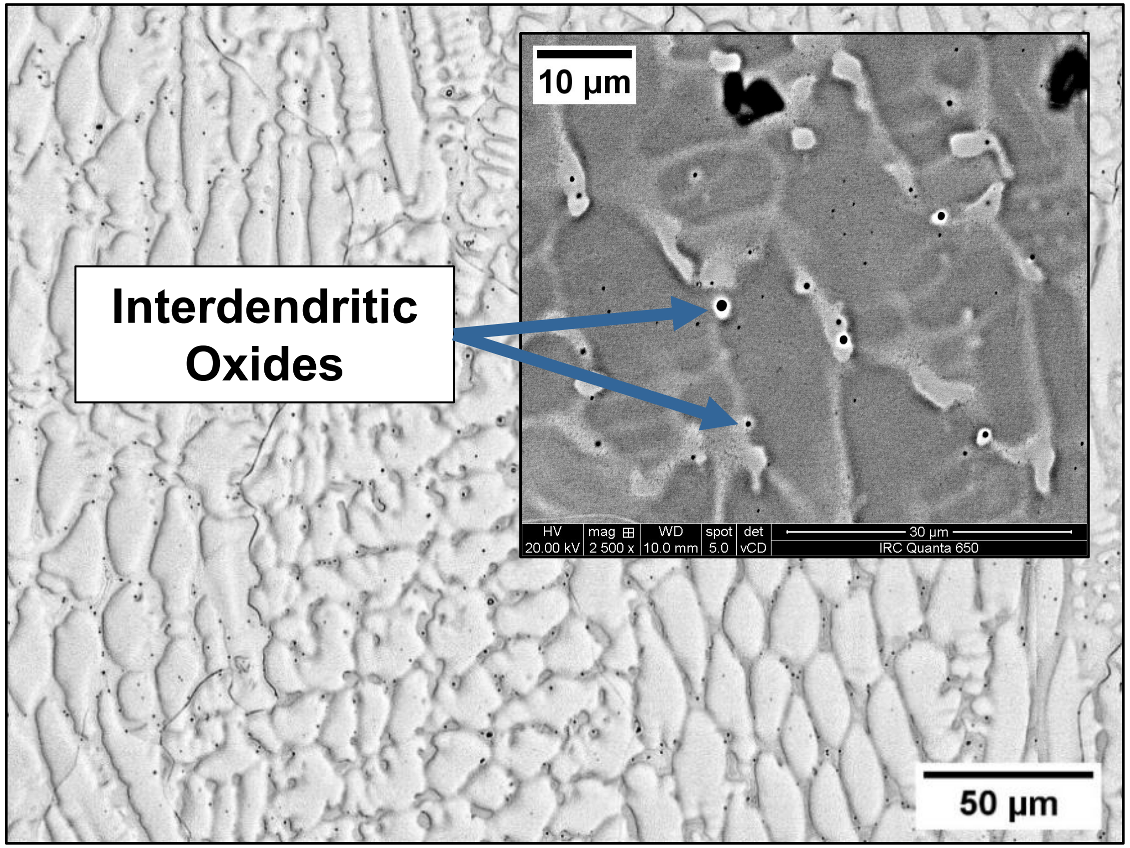


Results – Initial Weldability

- **Bead-on-plate welds on 316H – MTC Heat 1**







316H Procurement Status

- MTC Heat 2 was procured with an oxygen concentration in the powder of 120 ppm
- One-third of the powder was hot isostatically pressed and underwent a heat treatment identical to MTC Heat 1
- Another third is being heat treated at different conditions to try to influence the oxide size/distribution

Conclusions

- Initial evaluation of 316L and 316H stainless steel showed poor creep-fatigue performance compared to wrought materials
- It is currently unknown as the exact mechanism resulting in the reduced creep-fatigue properties
- Evidence of oxide size and distribution may be attributing to the reduced properties regardless of the overall oxygen concentration
- Oxides remained in the gas tungsten arc weld metal

Future Work

- Conduct elevated temperature mechanical testing on the MTC Heat 2 alloy and UK-NAMRC 316 alloys
- Determine if a lower overall oxygen content improves the creep-fatigue properties
- Compare oxide size and distribution at lower oxygen content

	Powder Chemical Composition (wt%)										D50 Powder Size (um)
	Ni	Cr	Mo	C	Si	Mn	S	P	O	N	
316H – MTC Heat 2	12.0	17.0	2.53	0.05	0.20	0.21	0.003	0.004	0.0120	0.1010	**52**
316H – UK-NAMRC	11.9	17.1	2.52	0.05	0.17	0.18	0.002	0.004	0.0064	0.0755	**100**
316L – UK-NAMRC	11.9	17.7	2.44	0.015	0.83	1.88	0.008	0.008	0.0117	0.06	-

FY23 Milestone

M3AT-23IN0804091, 9/15/2023

- Complete an initial evaluation of the elevated-temperature cyclic properties of optimized Alloy 316H fabricated by powder metallurgy hot isostatic pressing

M4AT-23IN0804093, 9/29/2023

- Provide status of procurement of several heats of PM-HIP 316H stainless steel with optimized processing

Thank you

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