Microstructure and Properties of Ni-based Components Fabricated by Additive Manufacturing

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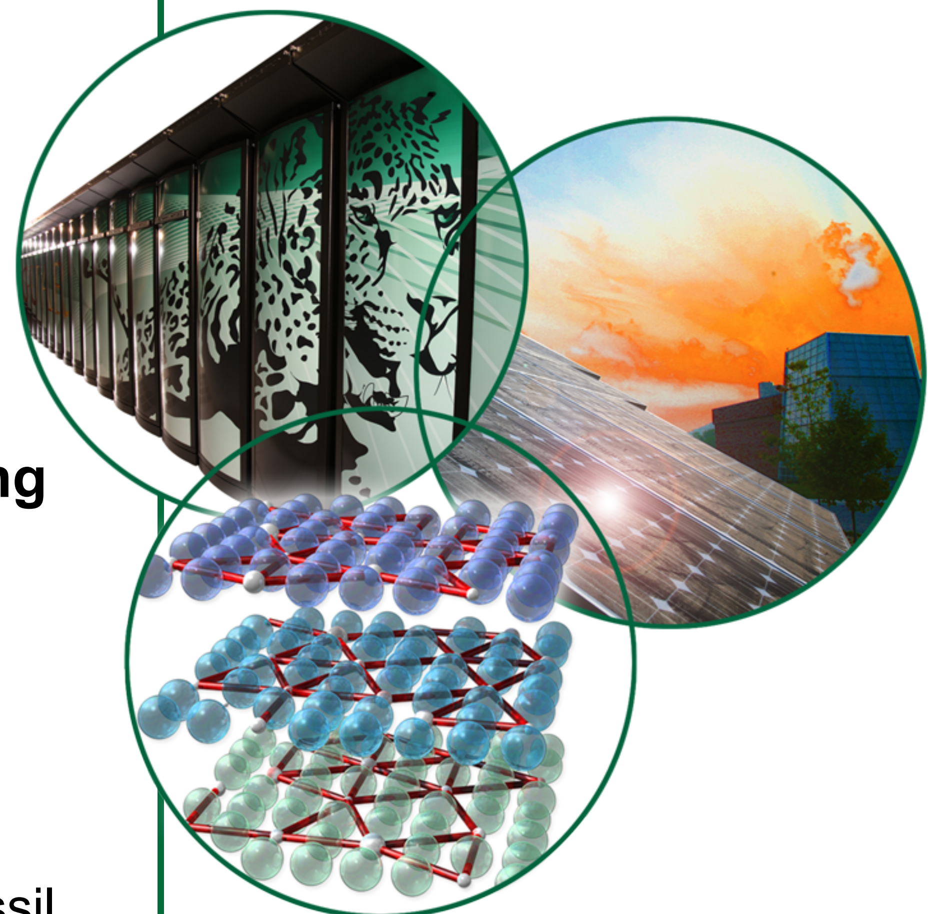

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Projects Goals & Objectives

- **Optimize additive manufacturing (AM) fabrication processes for Ni-based gas turbine components**
- **Three main AM techniques, electron beam melting (EBeam), laser metal deposition (LMD) and selective laser melting (SLM) will be assessed**
- **Generate long term data relevant for FE applications for Hastelloy (HX, Ni-22Cr-18Fe-9Mo) alloy**
- Fabricate rods of HX by EBM and LMD and assess the effect of Hip'ing and/or annealing on the alloy microstructure ***in progress***
- Determine the tensile properties of EBM, SLM and LMD alloys from room to 900ºC ***in progress***
- Perform or initiate at least three creep tests and three fatigue tests on specimens fabricated by two different AM processes **in progress**
- Complete comparison of EBM, LMD and SLM AM approaches ***in progress***

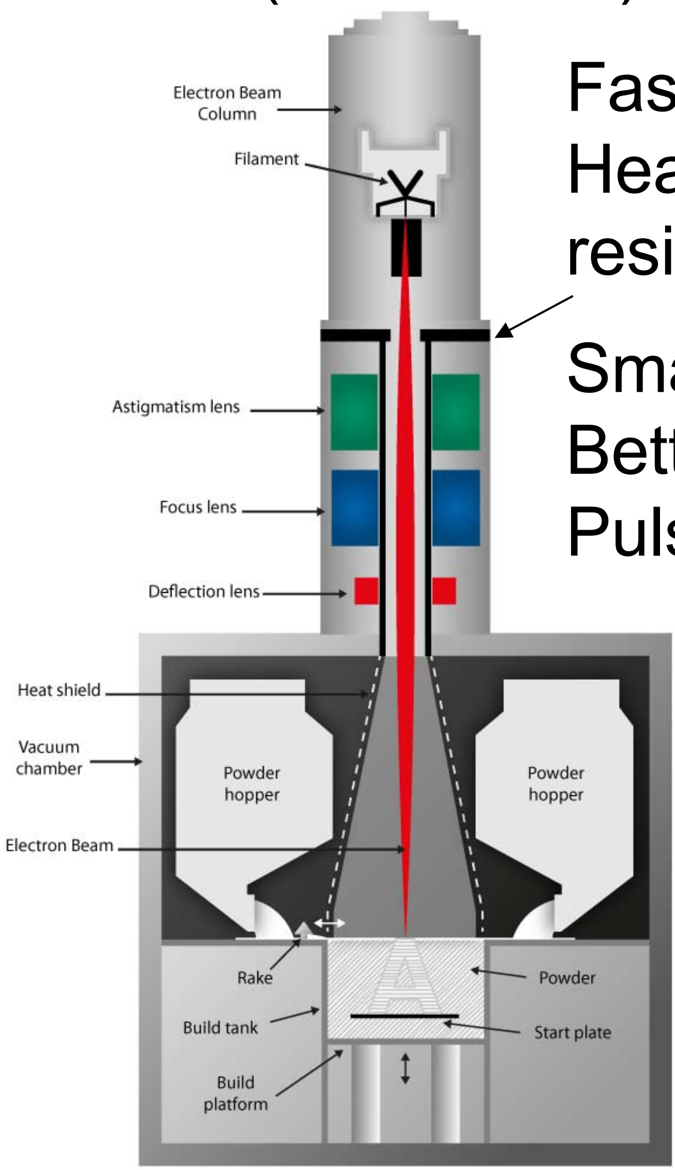
Outline

- Fabrication of electron beam melting (EBeam) and selective laser melting (SLM) specimens
- As Fab Ebeam and SLM microstructure and tensile properties (Building direction)
- As Fab Ebeam fatigue and creep properties
- Effect of HIP’ing on microstructure and tensile properties
- Effect of different Ebeam precursor powders on mechanical and oxidation behaviors

Mechanical Properties of HX Made by Ebeam and SLM

Ebeam (Arcam S12)

Laser (Renishaw AM250)



Faster

Heated bed = lower residual stress

Smaller beam size

Better resolution

Pulsed laser beam

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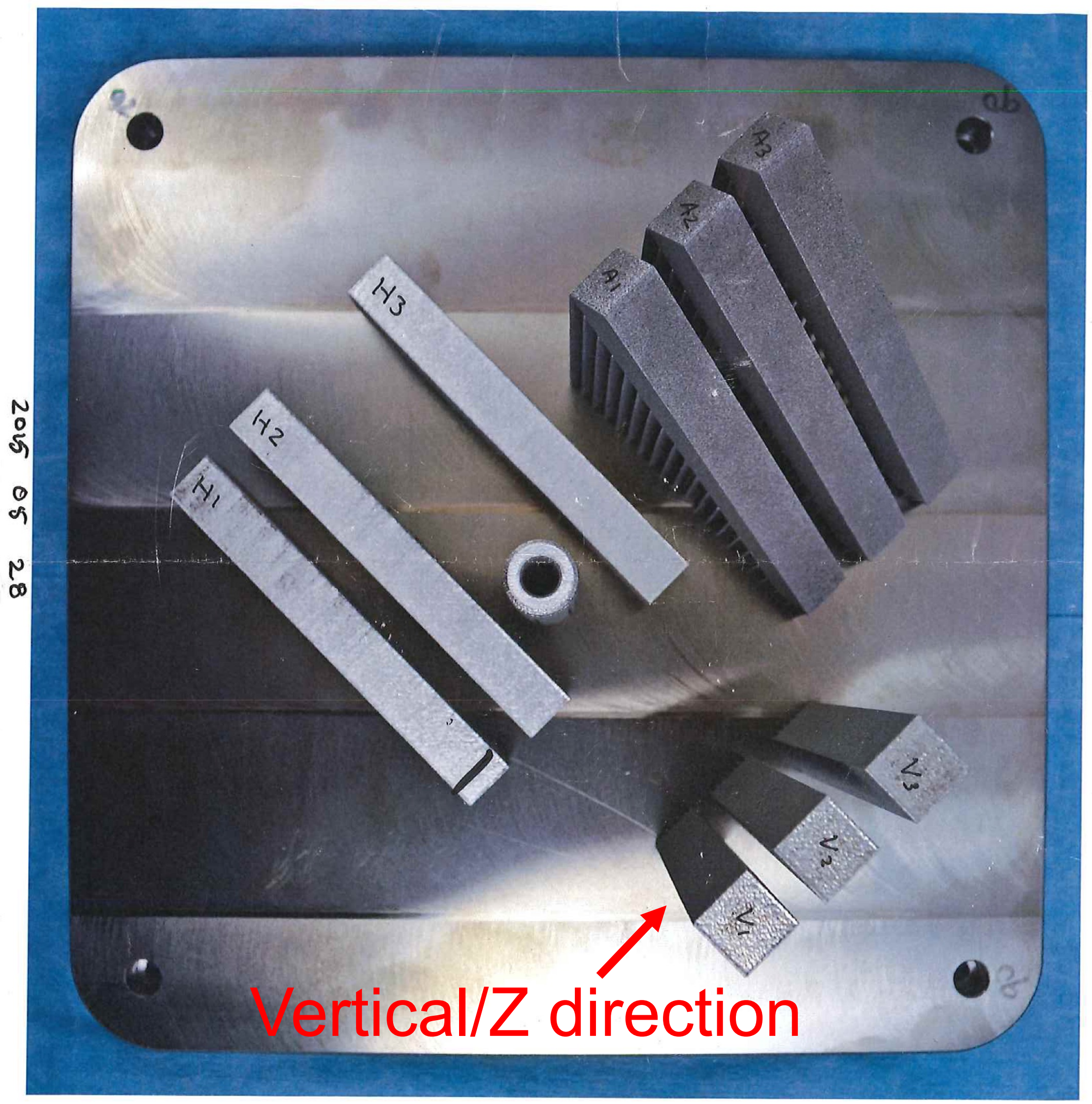
ORNL SLM Builds For Microstructure and Tensile Characterization



- Build made with leftover powder from AMO project
- Characterization of the microstructure and tensile properties in 3 directions
- Presentation on vertical specimens
- Study the effect of annealing and Hip'ing

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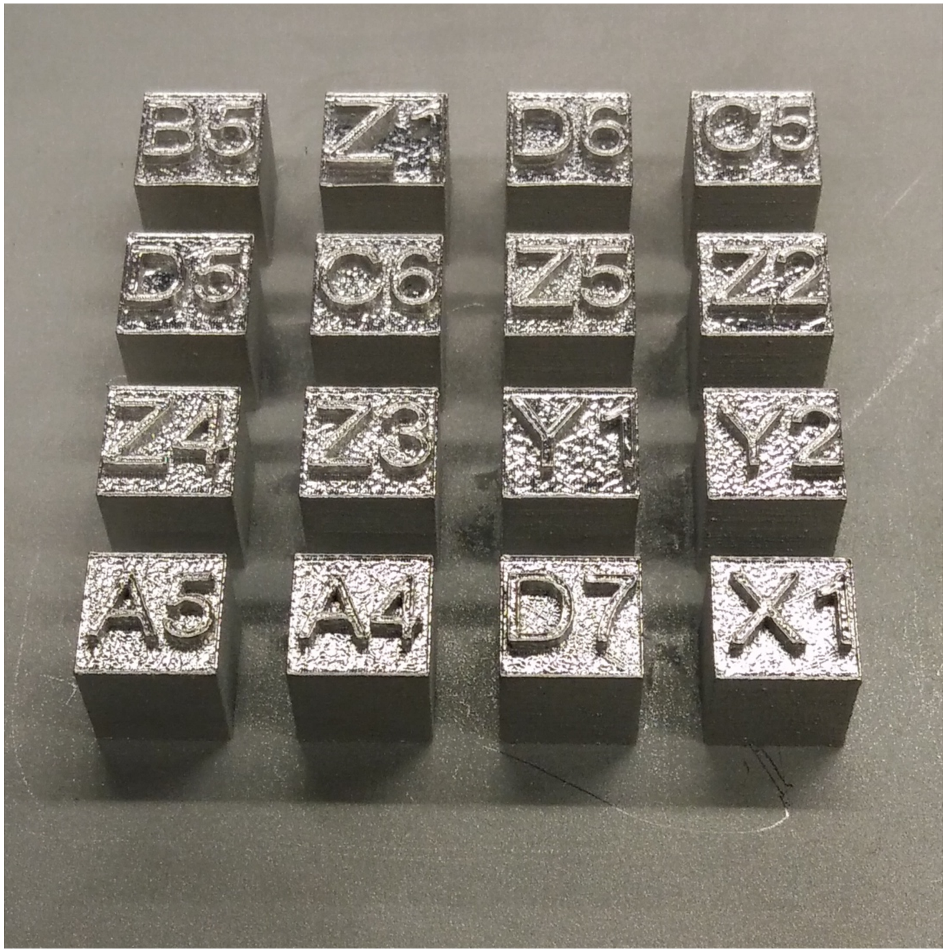
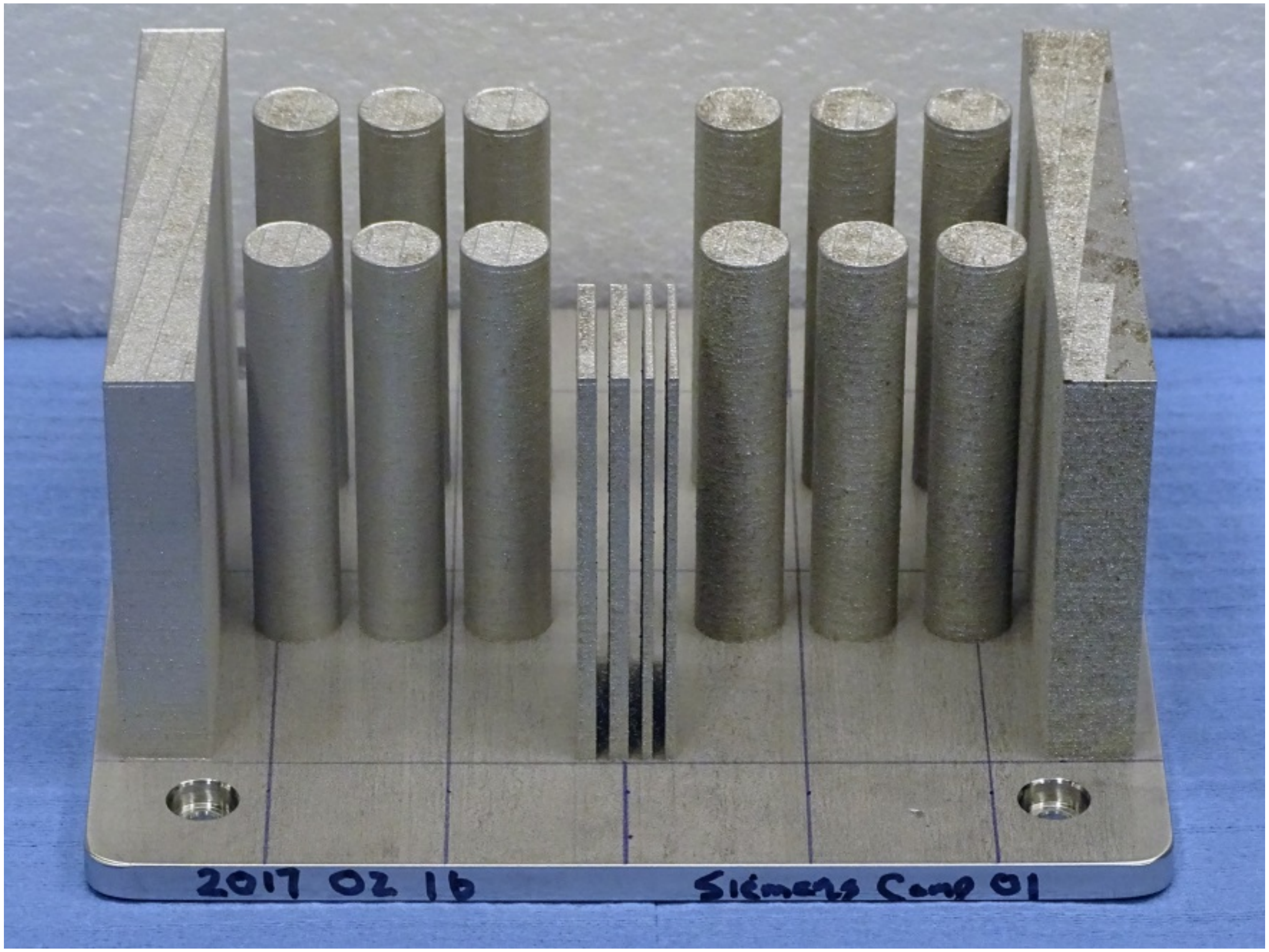
Small SLM HX Cube for Parameter Optimization



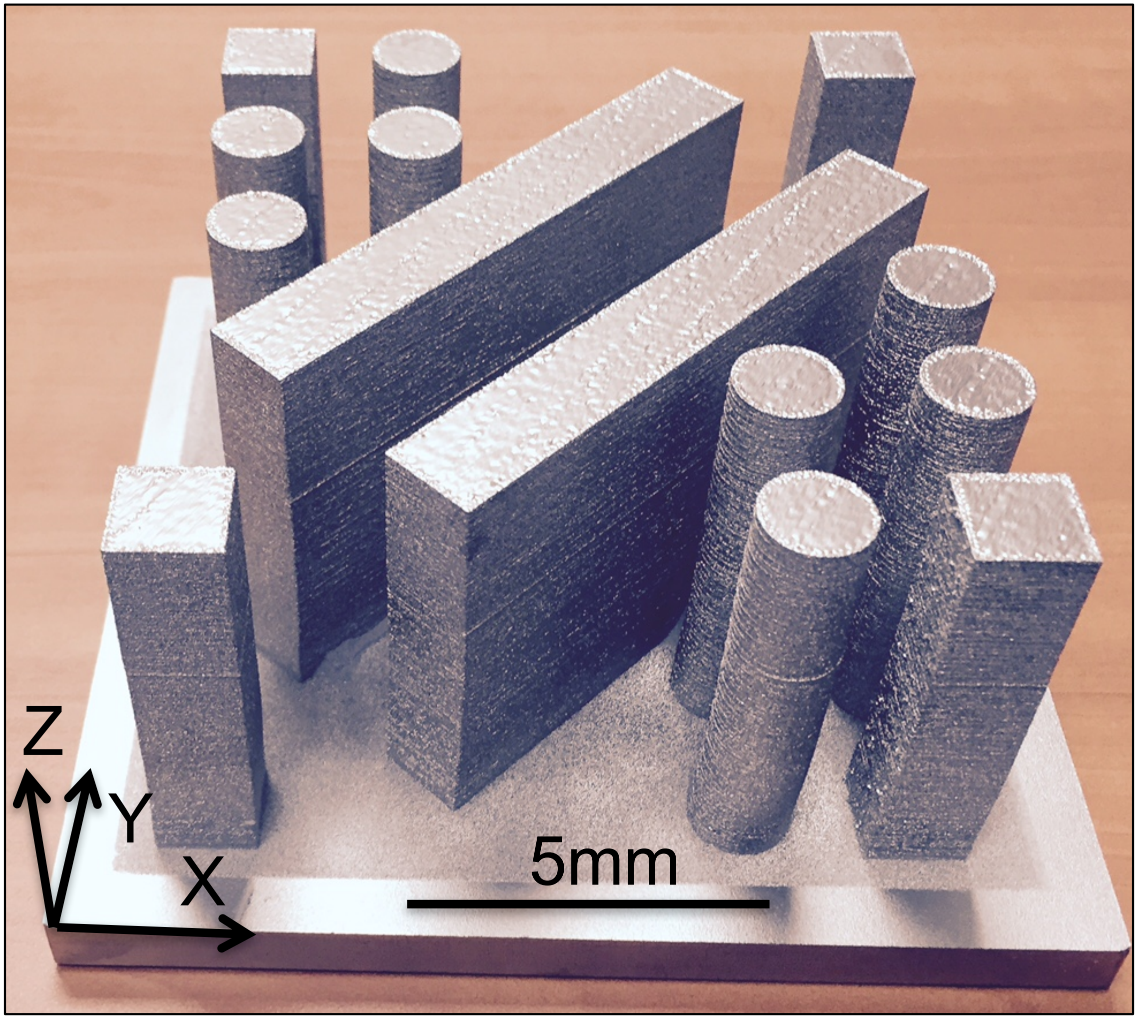
- Spot time
- Spacing
- Energy

New SLM Build For Extensive HX Characterization



- 35h, ~2000 layers 65mm tall
- Rectangular blocks to study properties anisotropy
- Thin wall effect

Fabrication of 20-30 Ebeam Specimen For Tensile, Creep and Fatigue Testing



- 27h, 1240 layers, ~65mm
- Small builds first to optimize parameters based on 718 work
- Study the effect of post annealing and Hip'ing

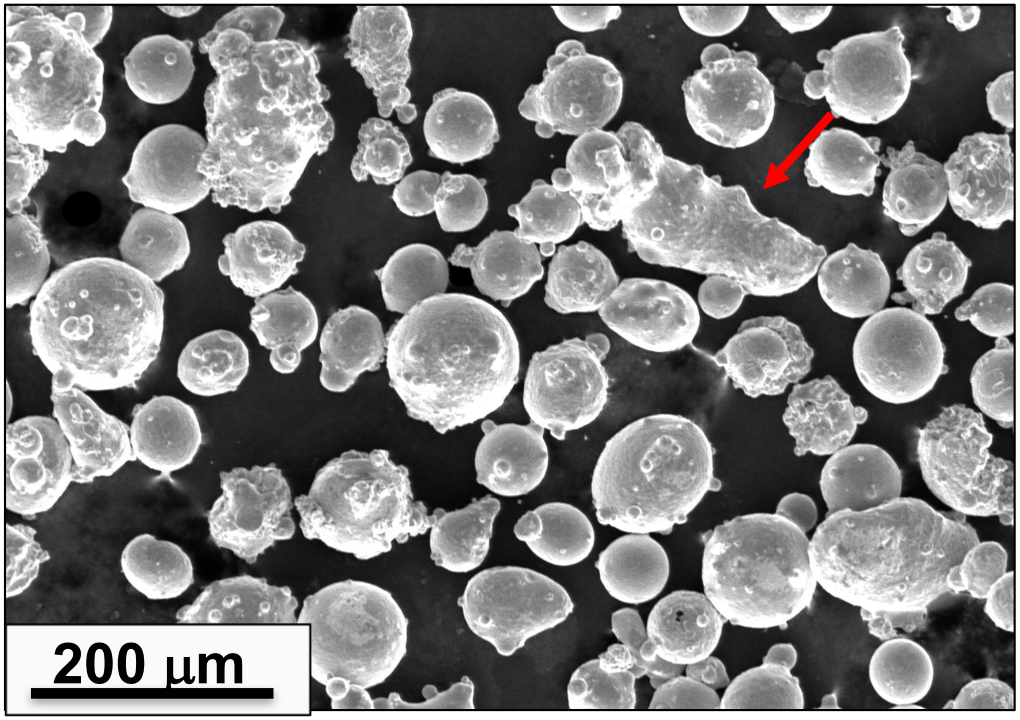
Very Similar Gas Atomized Powder Composition For Ebeam & SLM

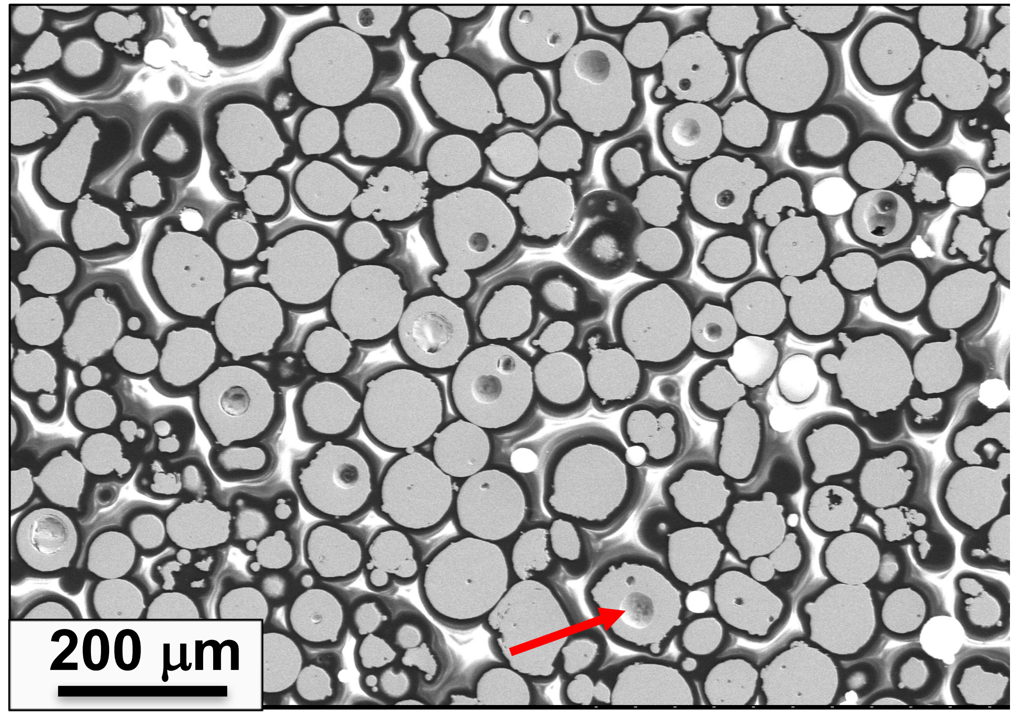
AM	Particle Size
SLM	size < 44μm
Ebeam	44μm < size < 125μm

AM	Ni	Cr	Fe	Mo	Co	Mn	Si	W	C
Ebeam Powder	Bal.	21.76	18.43	8.91	1.51	0.07	0.08	0.6	0.08
Ebeam Alloy	Bal.	21.38	18.55	9.05	1.55	0.01	0.05	0.64	0.078
SLM powder	Bal.	21.47	18.83	8.96	1.51	0.01	0.16	0.63	0.07
Wrought	Bal.	22.06	17.86	9.53	1.8	0.65	0.31	0.6	0.067

Low level of Mn and Si content in comparison with wrought
Specification: Mn and Si <1%
Alloy composition consistent with Ebeam powder composition

EBeam Powder Morphology Typical of Gas Atomized Powder



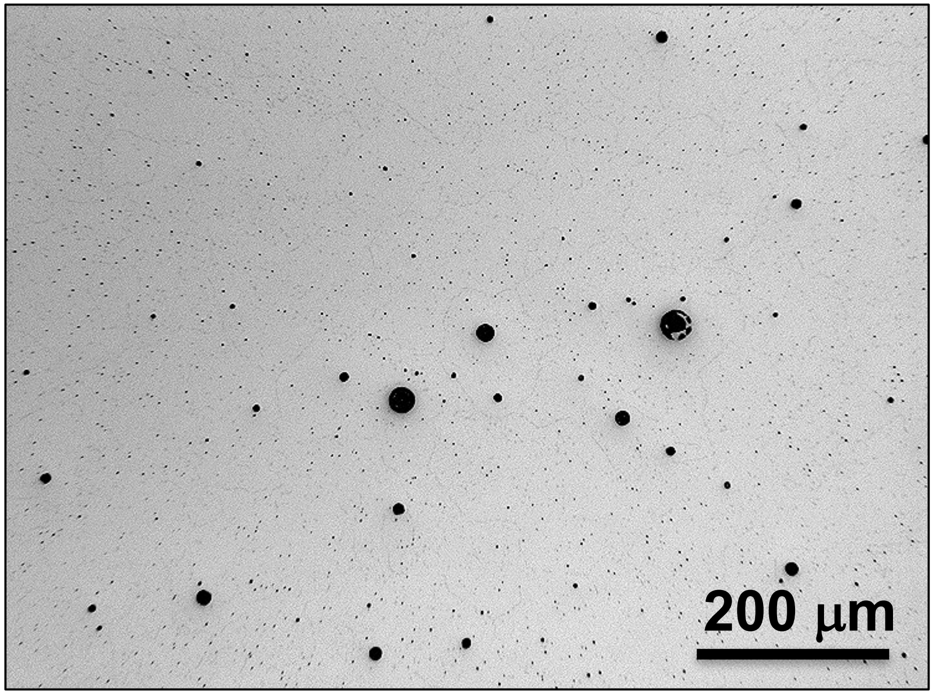


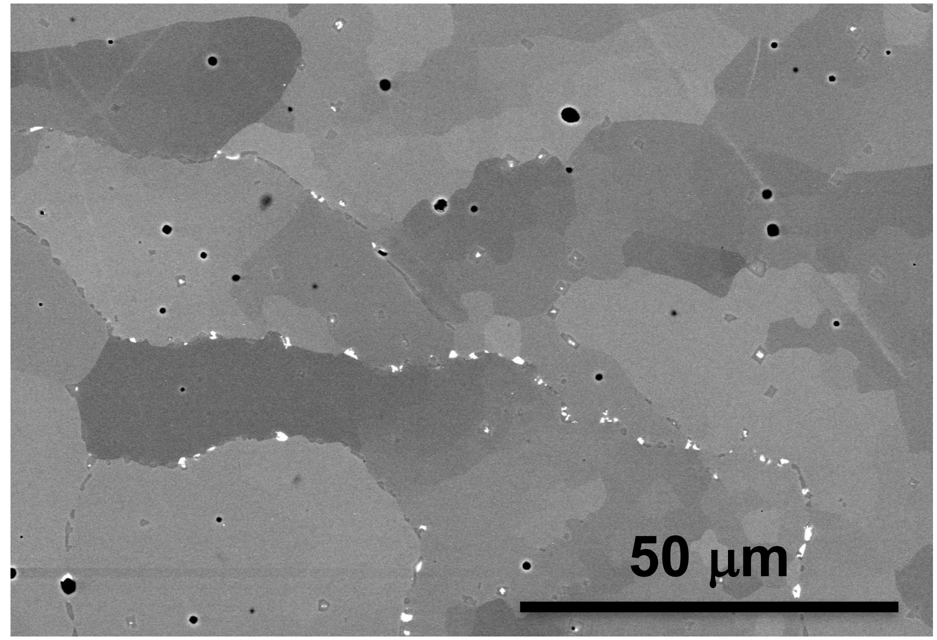
Most powder particles contain large numbers of satellite particles

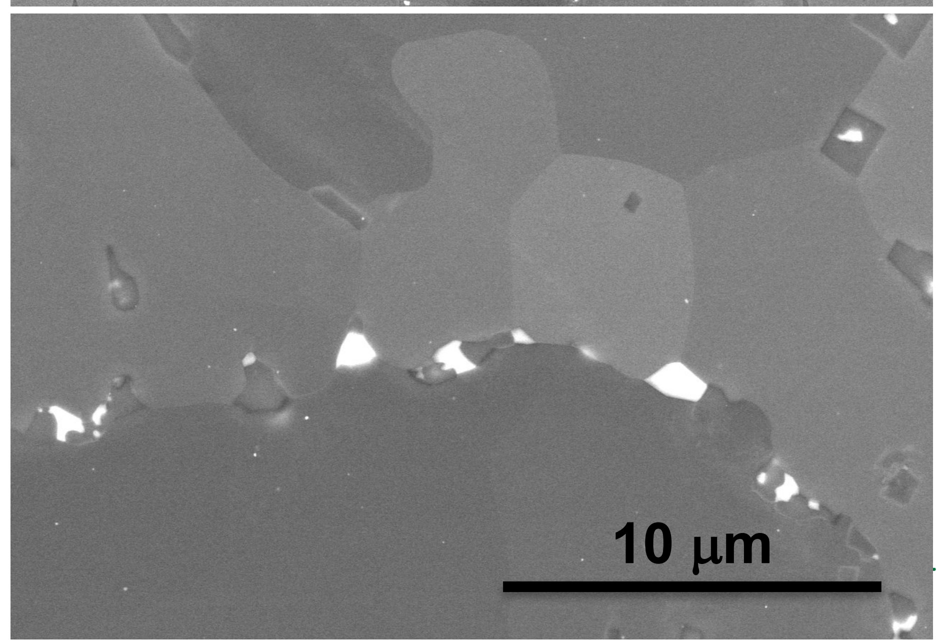
Irregularly shaped particles

Entrapped gas lead in the powder

Ebeam: Porosity from Powder Porosity + Precipitates along some GB

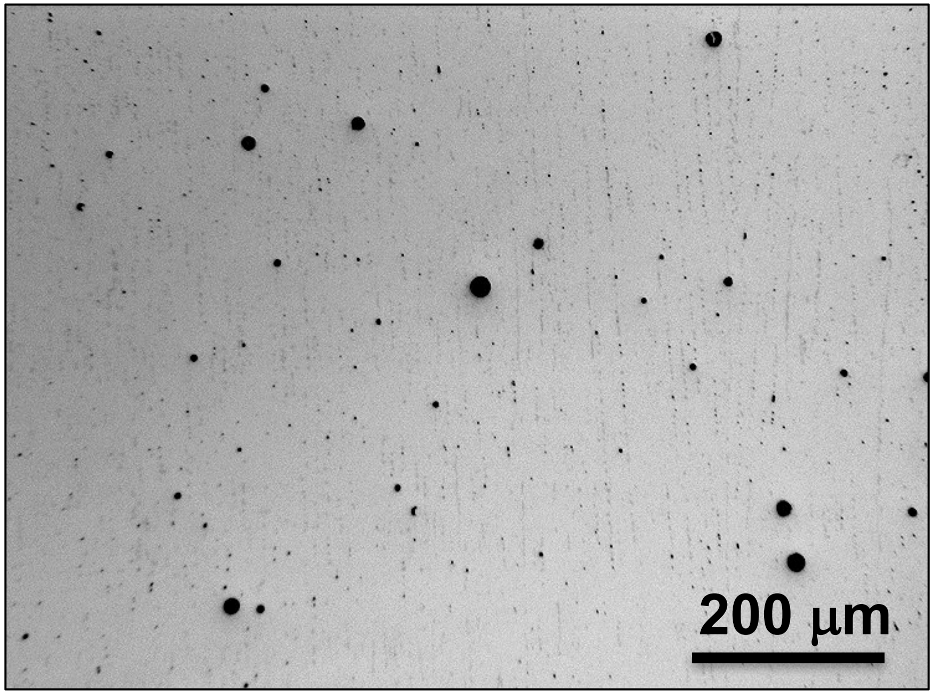


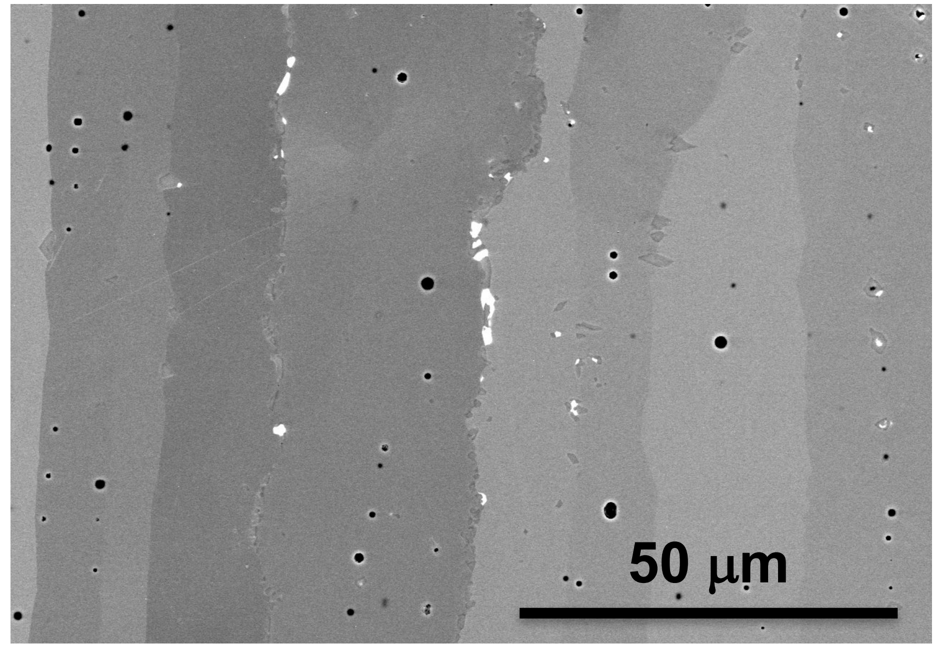


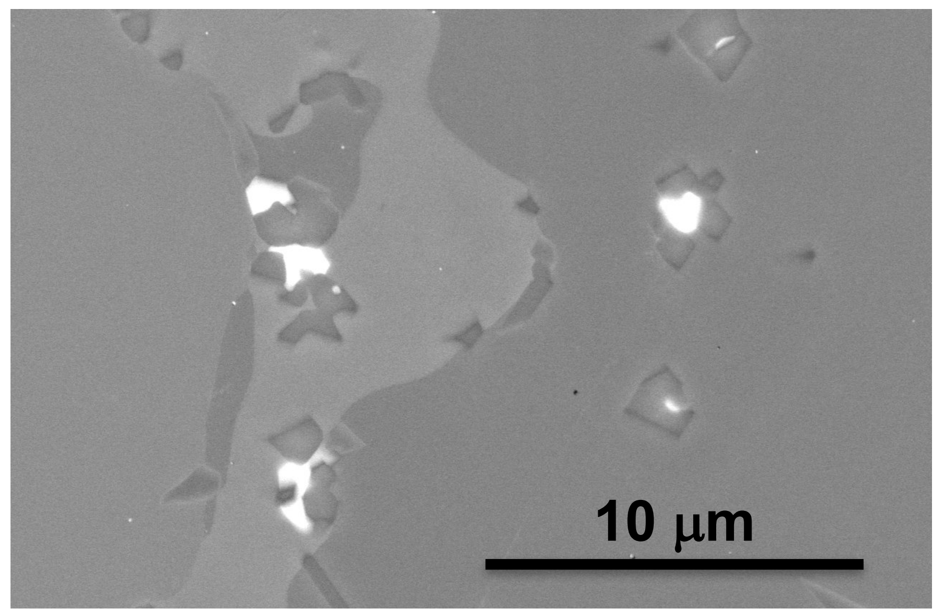


Transverse direction

Ebeam: Elongated Grain Structure Along The Build Direction

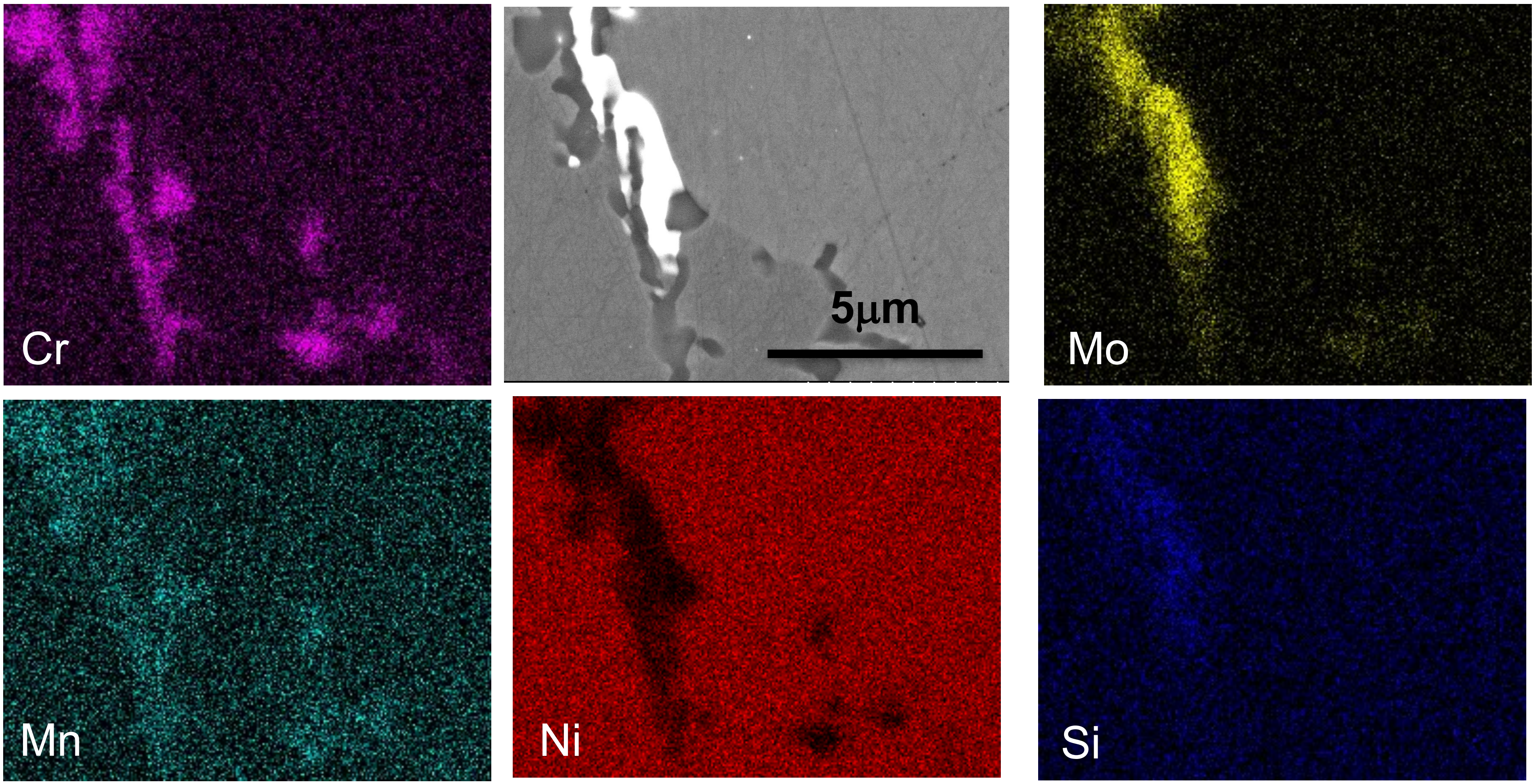




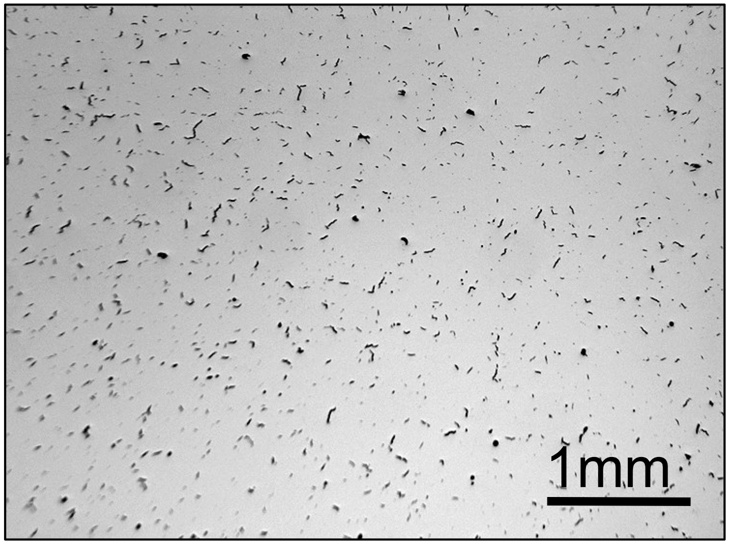


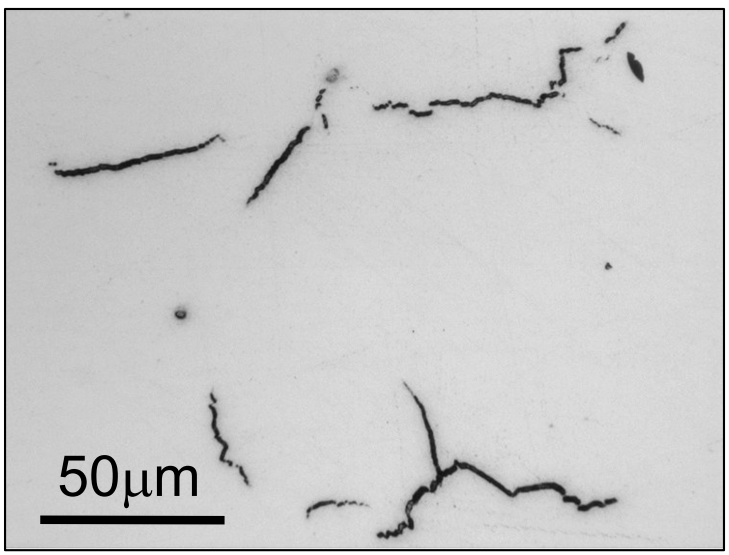
Build direction Z

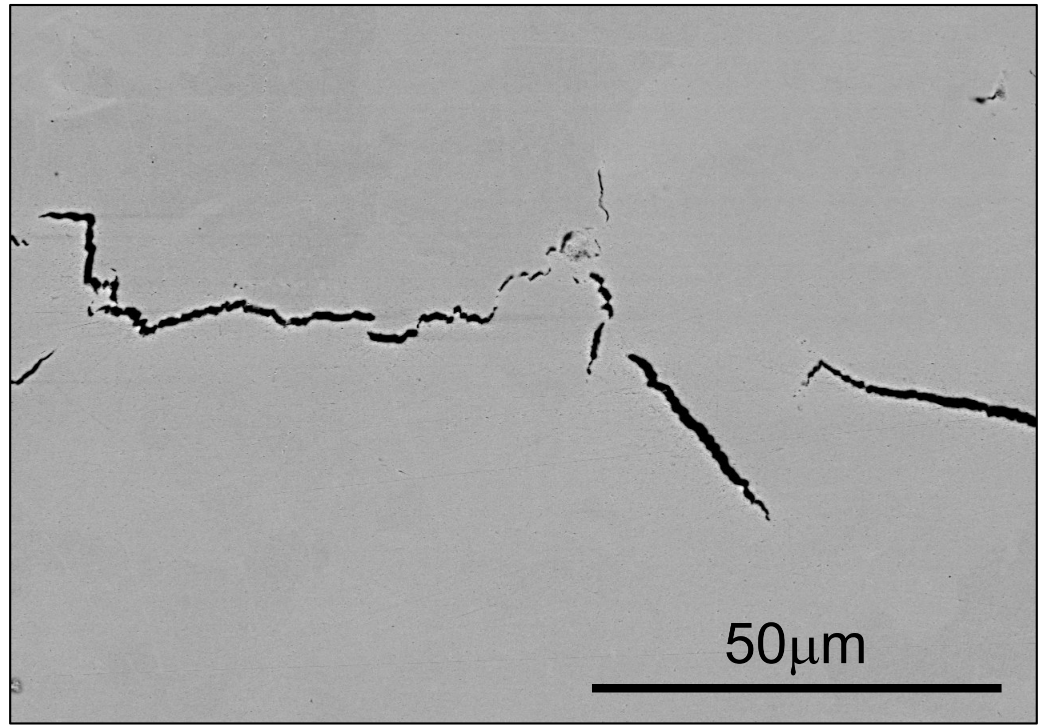
Cr or Mo-rich Carbides with Slight Mn and Si enrichment



SLM: Local Delamination/Lack of Melting

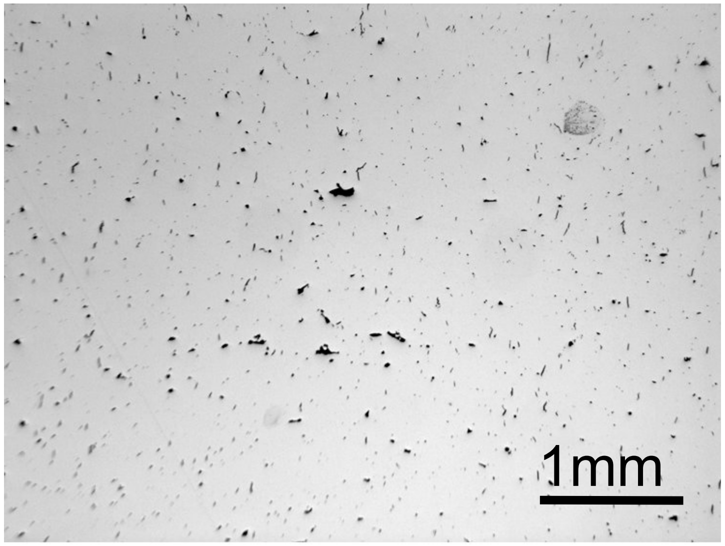


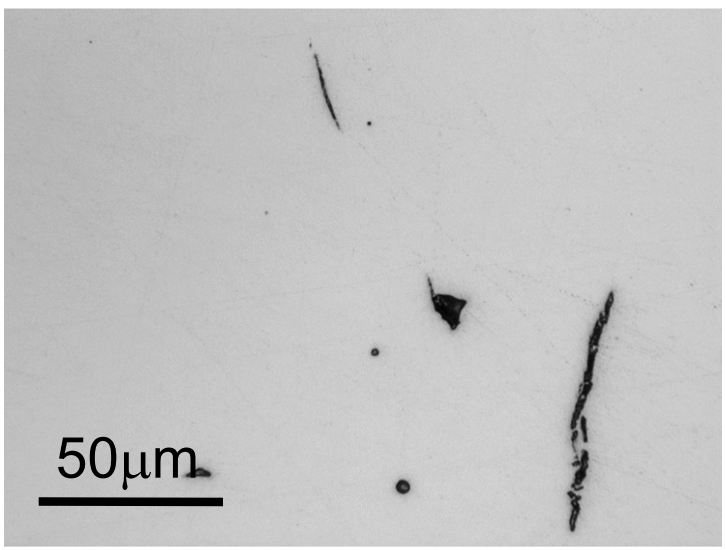


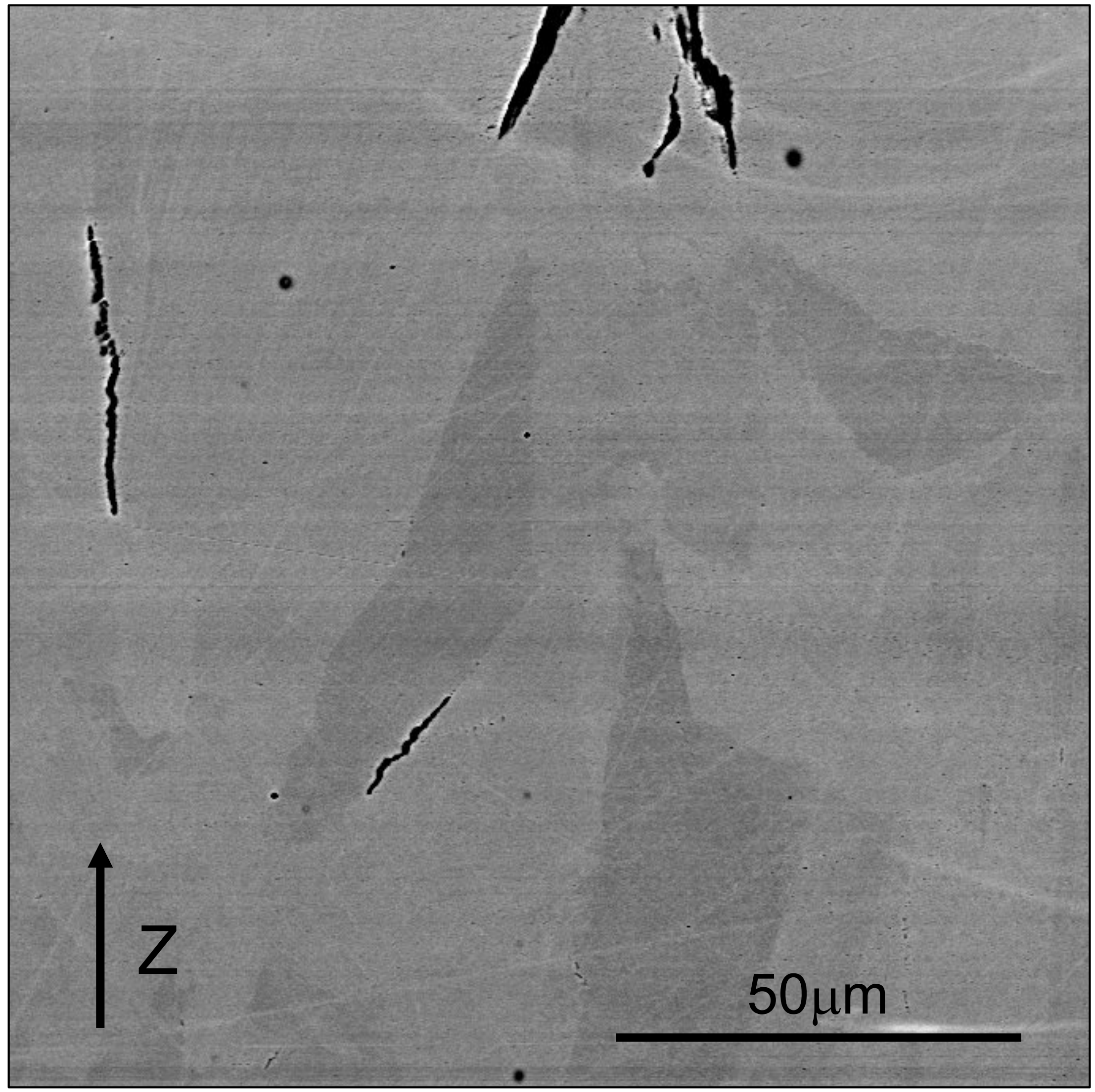


Transverse direction

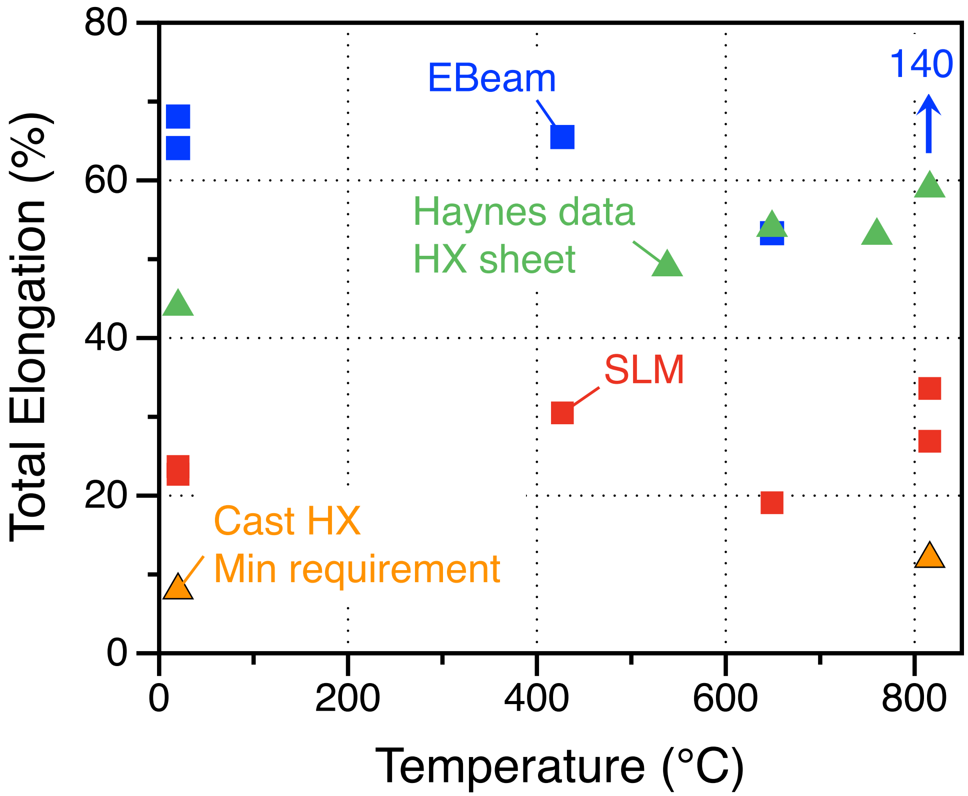
SLM: More Complex As Fab Microstructure + Elongated Grains?



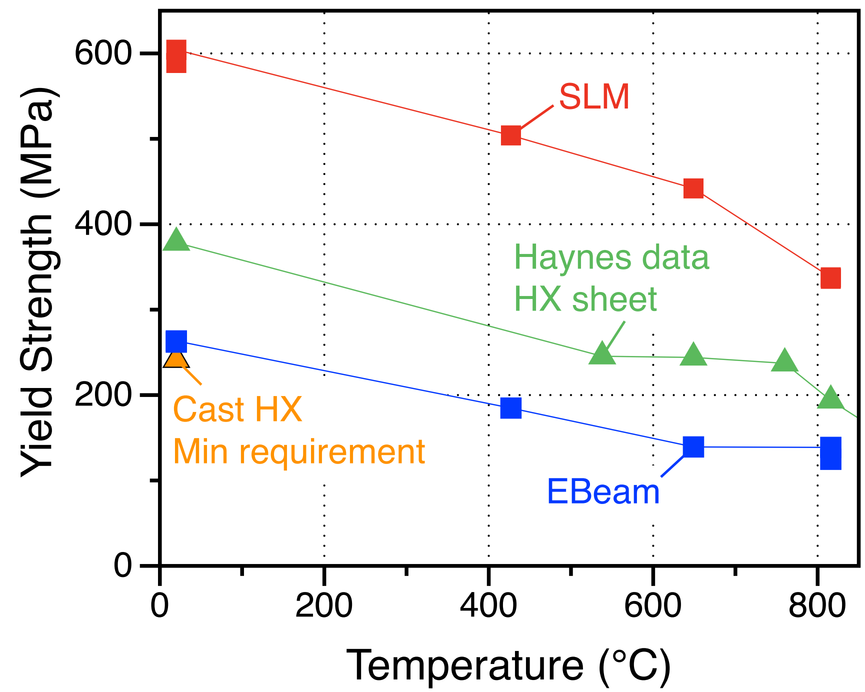


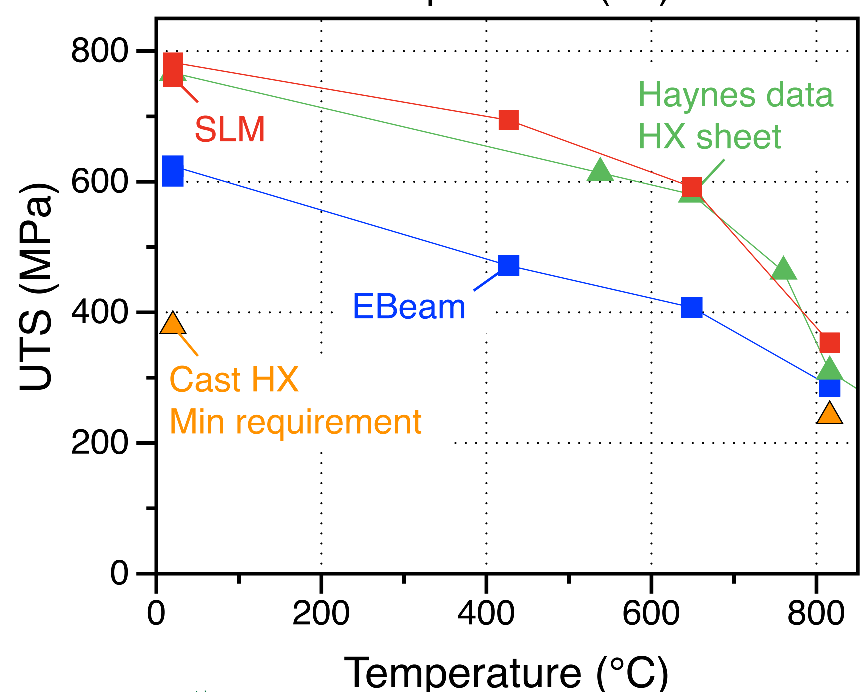


SLM HX Exhibits Superior Strength but Lower Ductility

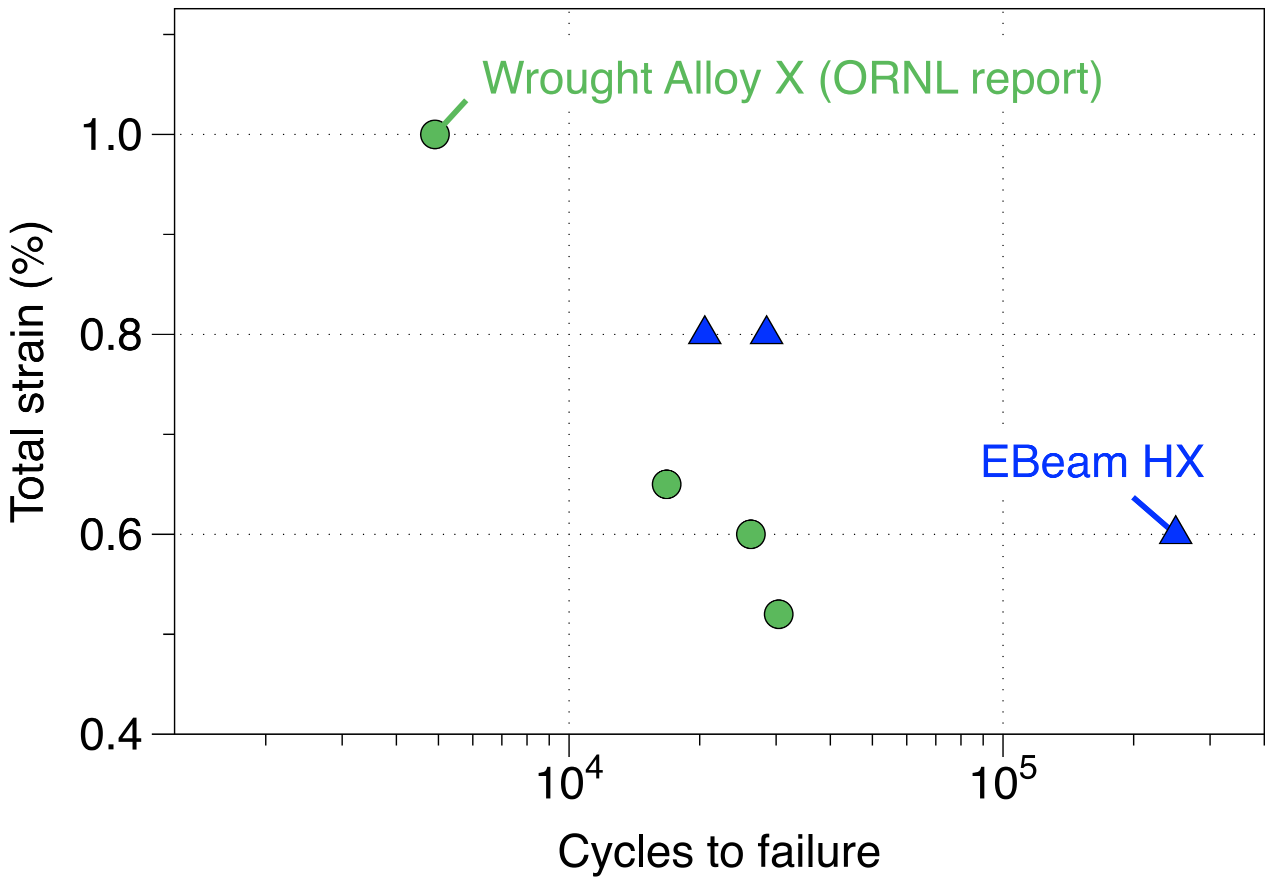


Meet cast HX requirement





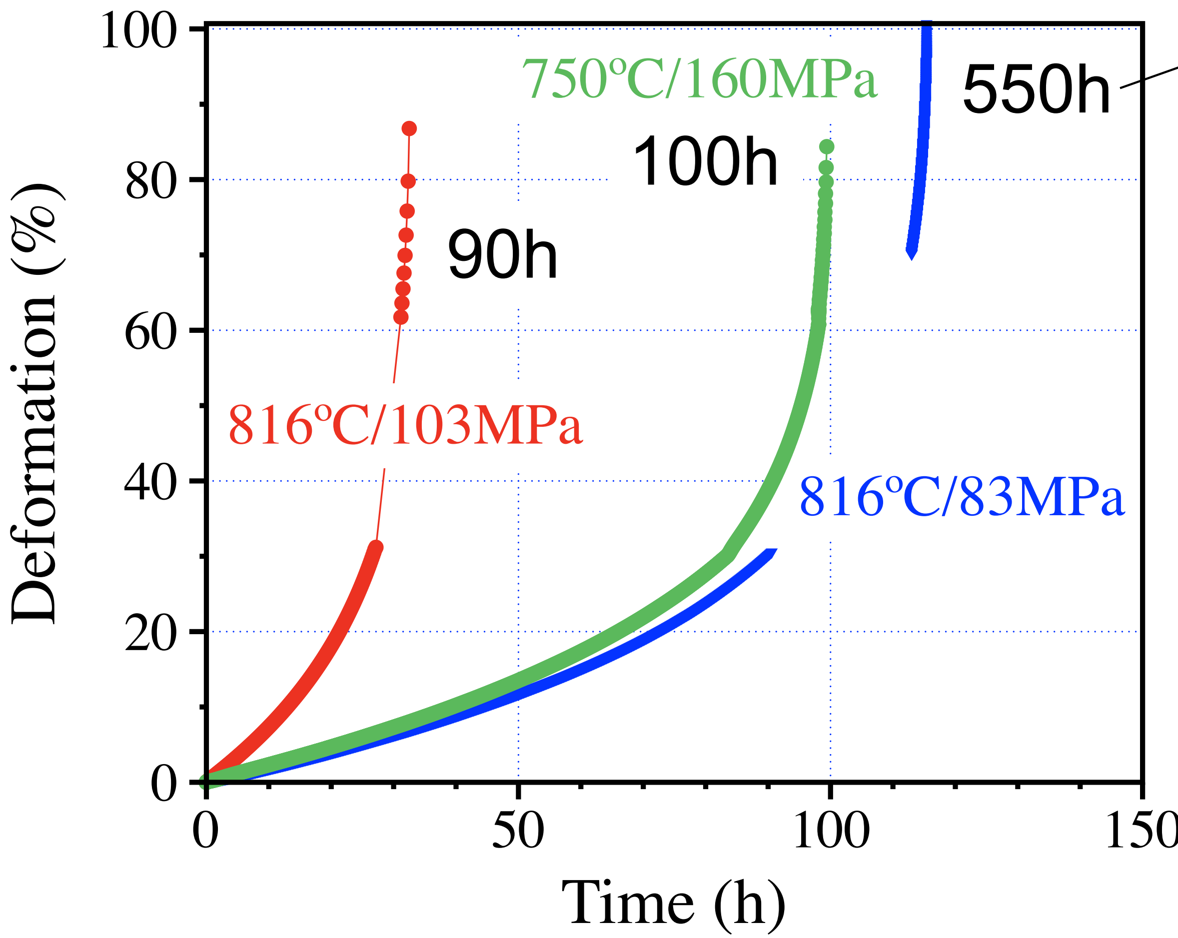
Ebeam: Good Low Cycle Fatigue Properties at 800ºF/425ºC



- Fully-reversed LCF
- Consistent with excellent alloy ductility

Ongoing extensive LCF characterization at Siemens

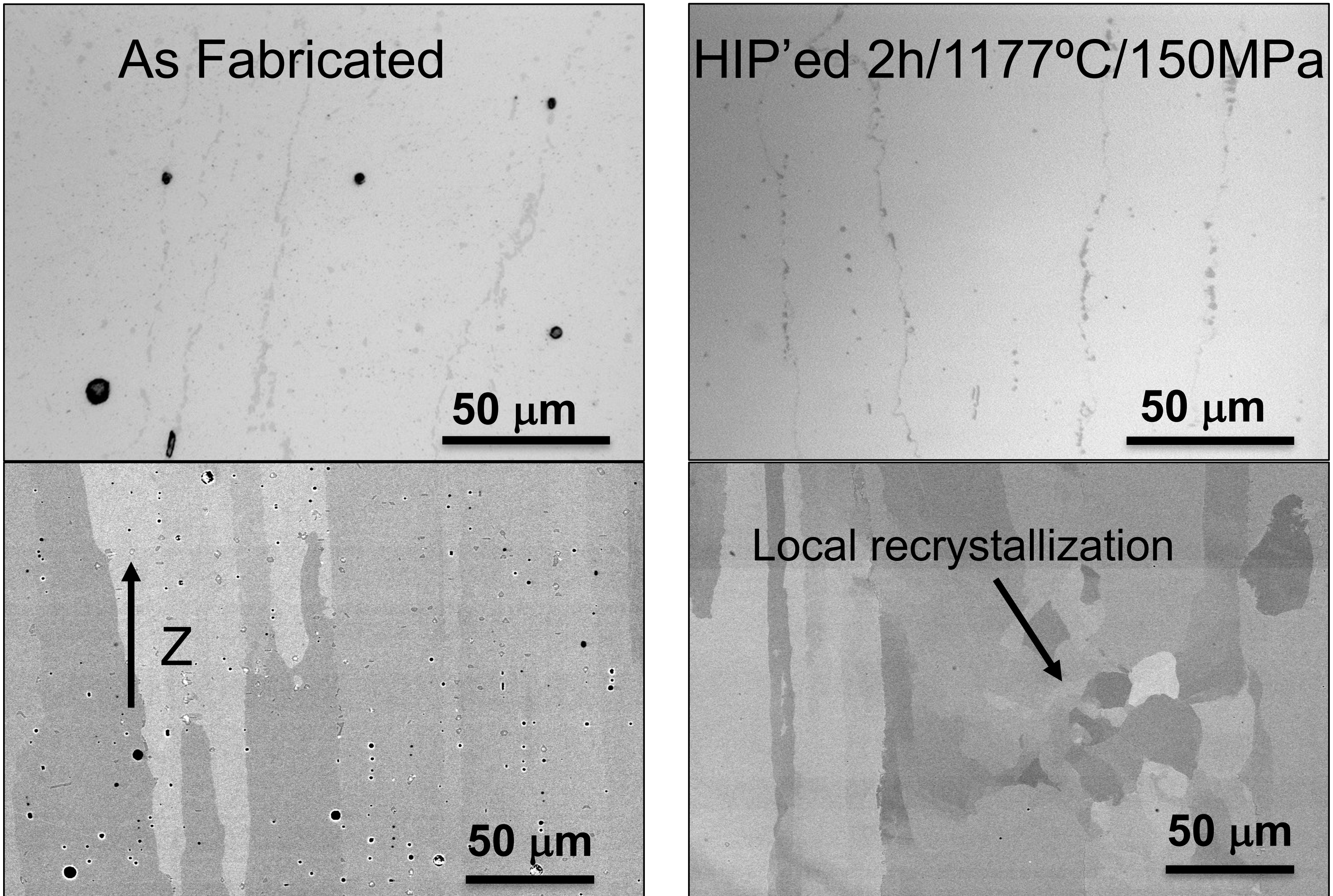
Ebeam: Low Creep Properties at 816ºC Better Creep Strength at Lower Temp?



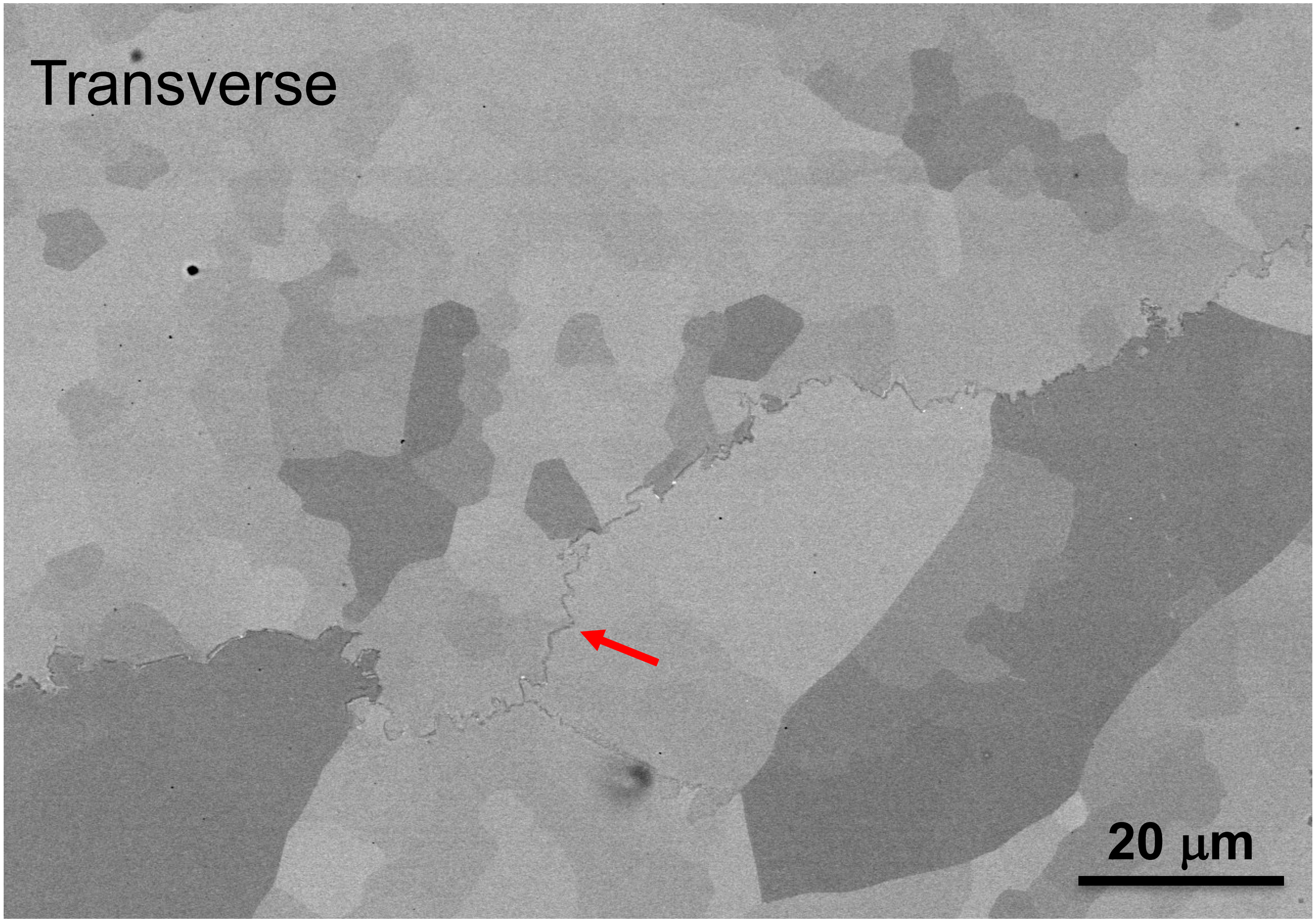
Expected lifetime for Haynes HX plate

- Very high deformation at rupture
- HIP'ing to remove cracks and improve creep properties?
- Extensive creep testing at Siemens

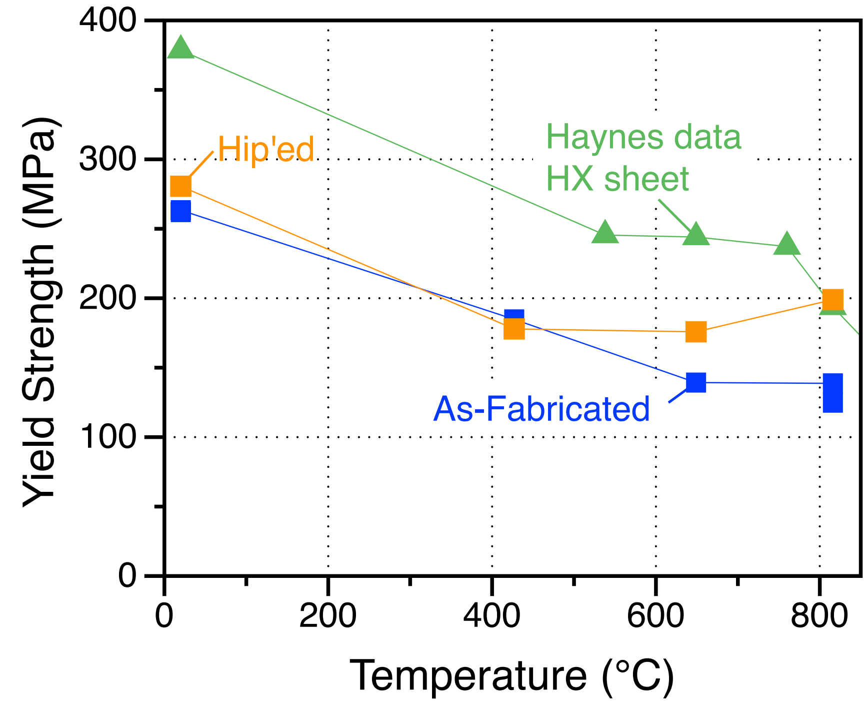
Ebeam: Fully Dense Material after HIP'ing at 1177ºC/2h/150MPa

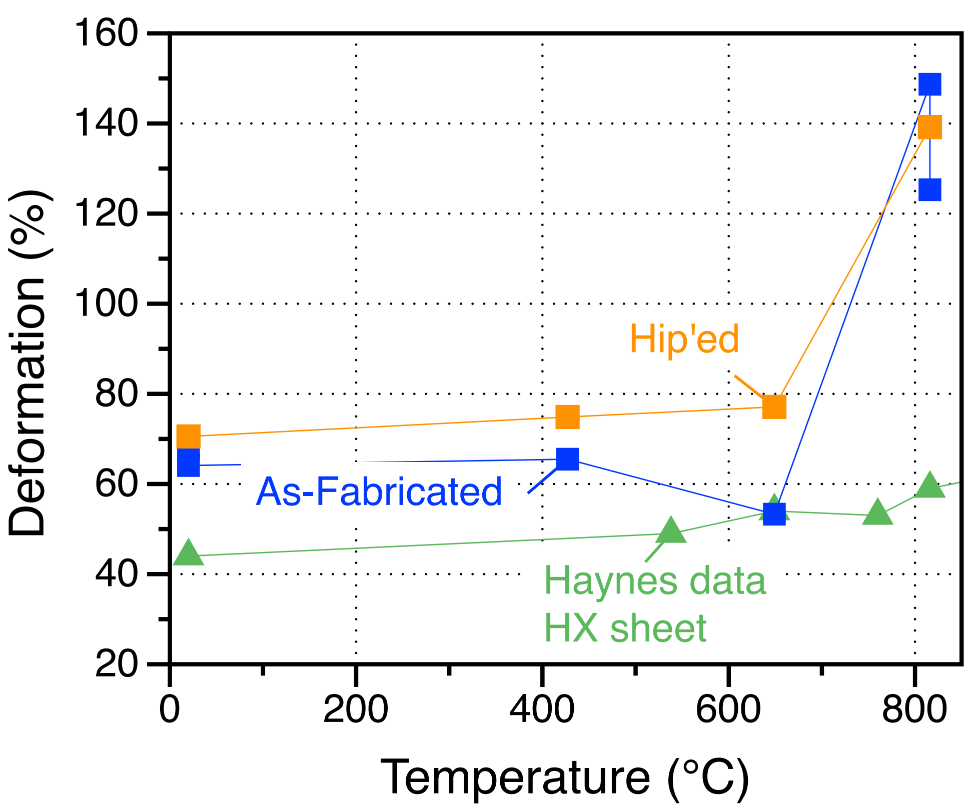


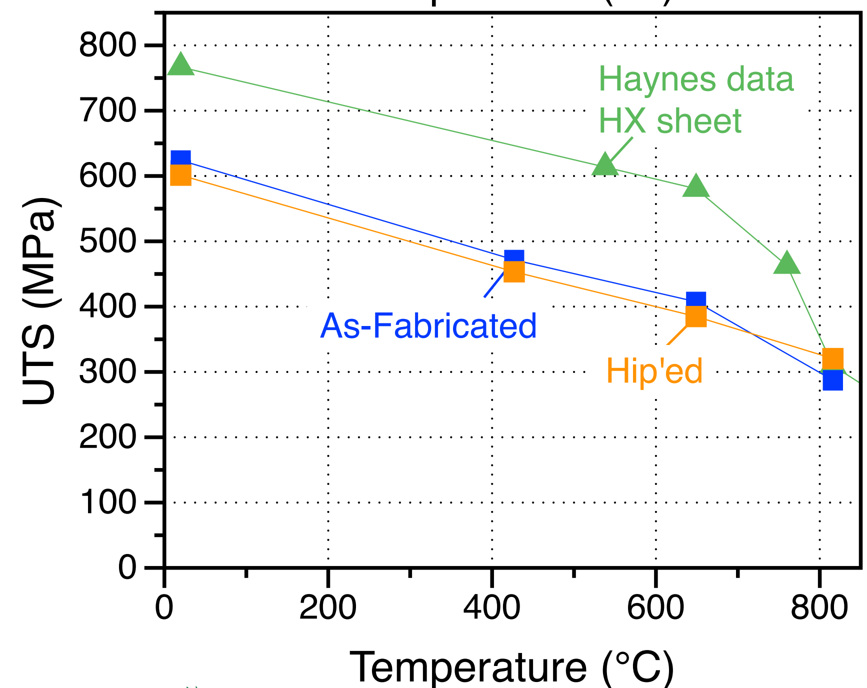
HIP'ed Ebeam: Increasing Number of Small Grains + Precipitates Along Few Grain Boundaries



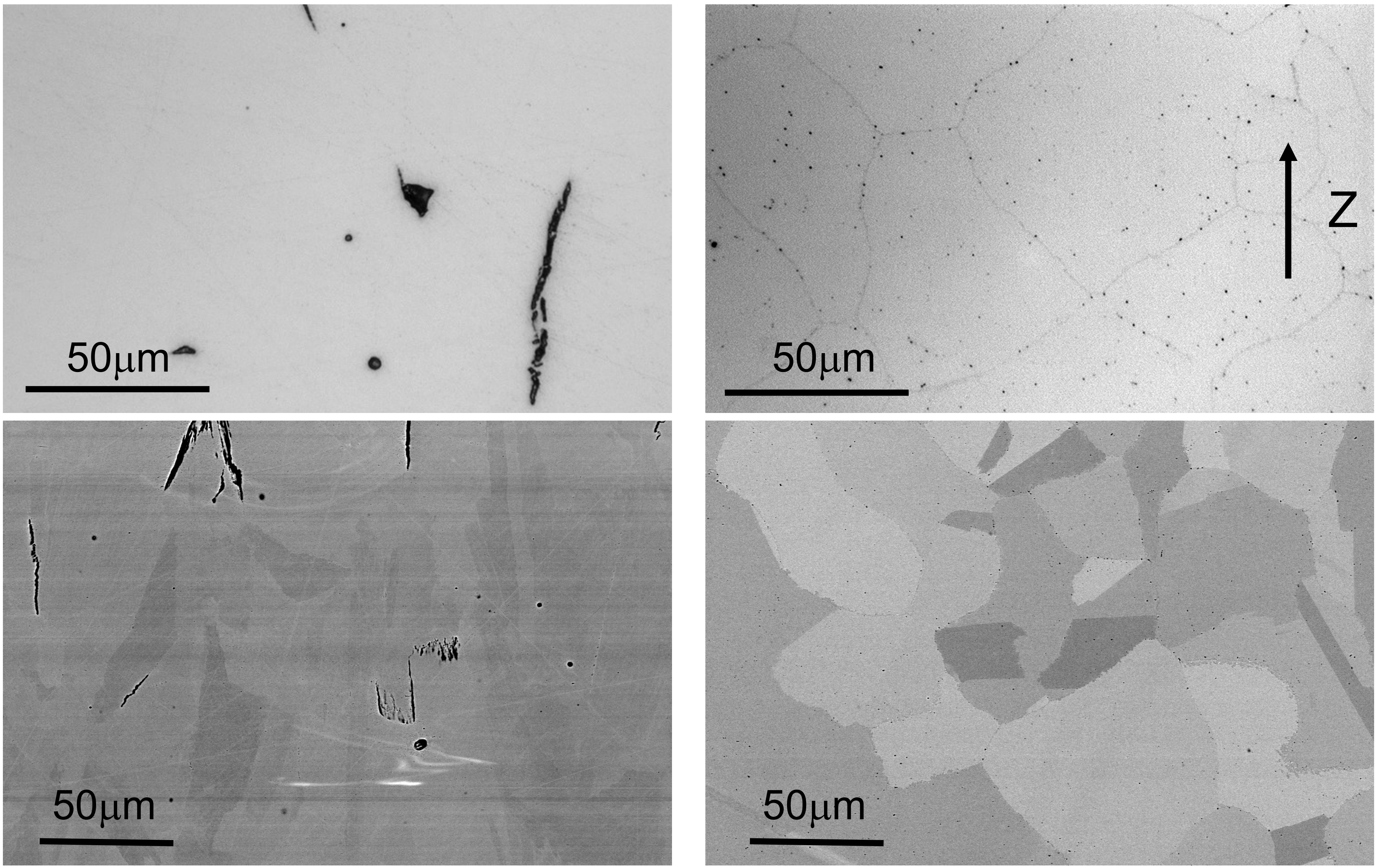
Ebeam: Similar Strength & Ductility After HIP'ing 2h/1177°C/150MPa



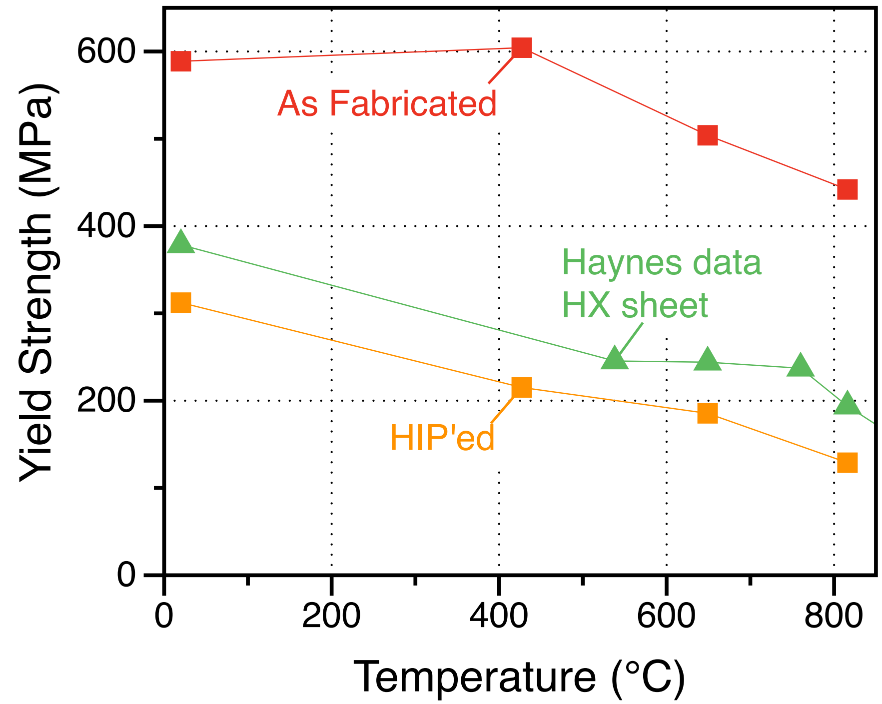




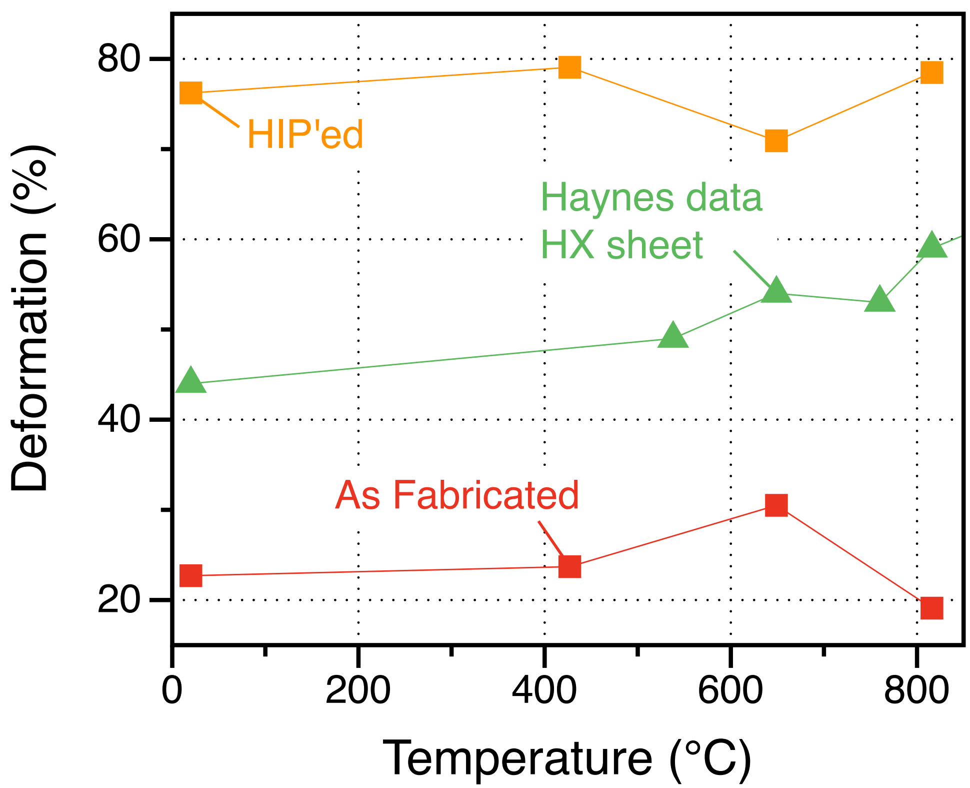
SLM: Fully Dense Material After HIP'ing at 1177ºC/2h/150MPa+Recrystallization

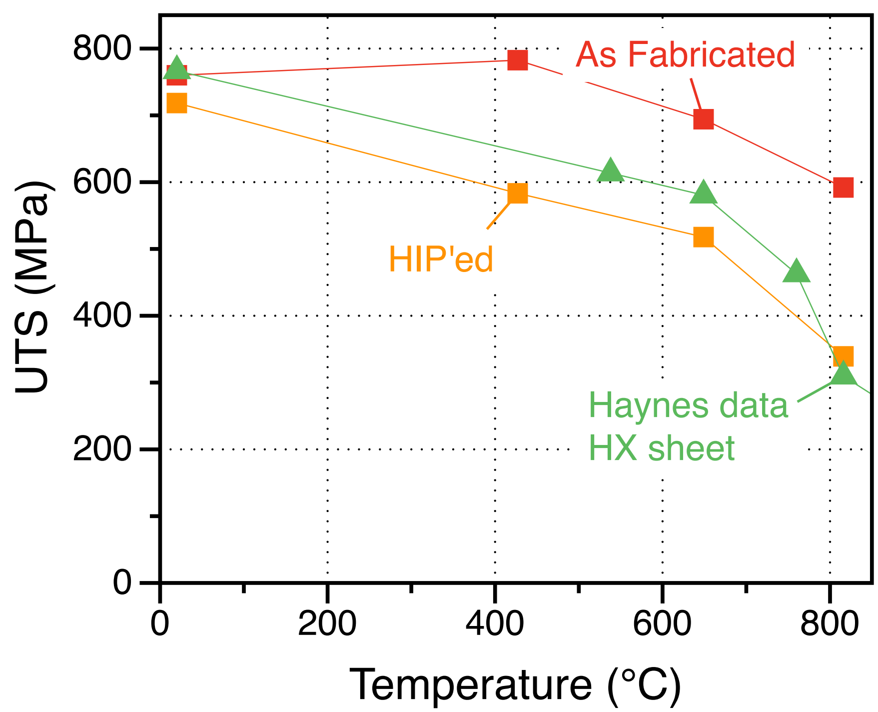


SLM: Increase of Ductility & Decrease of YS after HIP'ing 2h/1177°C/150MPa



Release of Residual Stress + Microstructure evolution



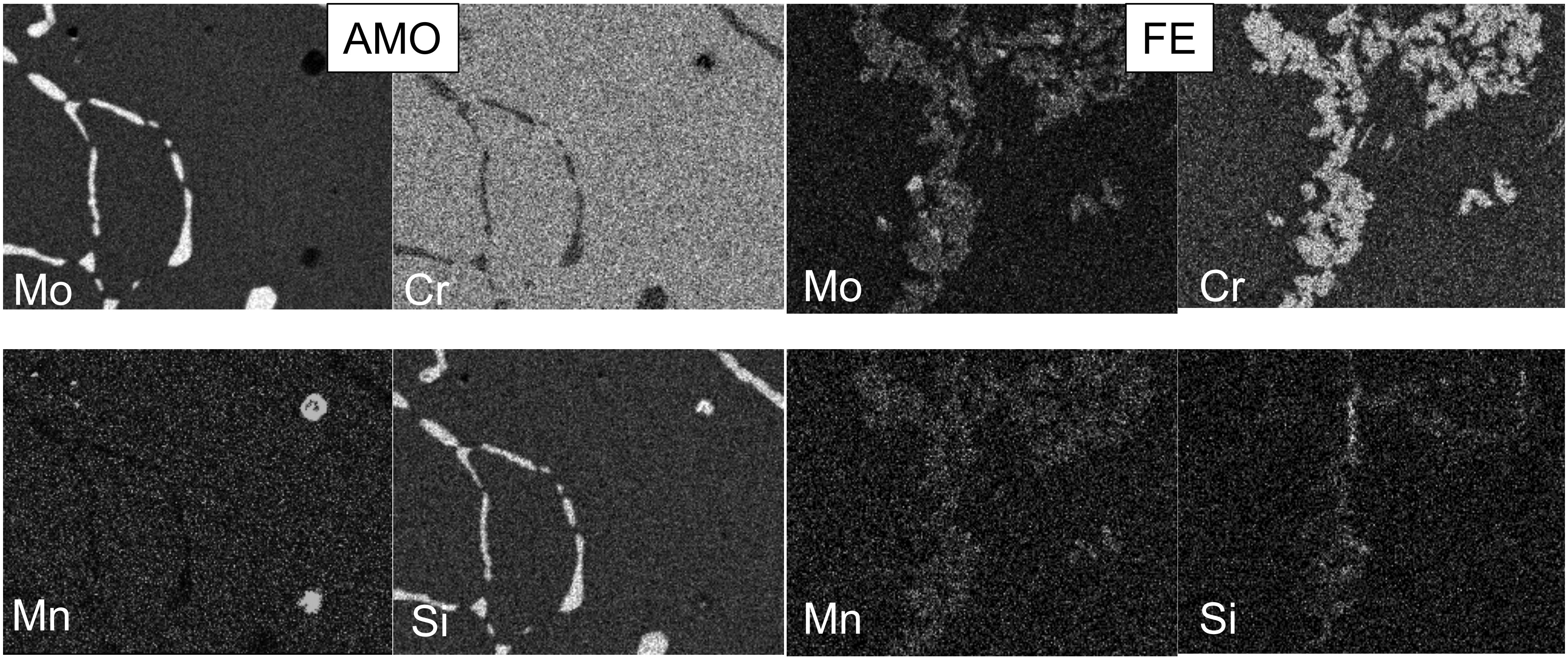


Ebeam Builds Fabricated with High Si (AMO) and Low Si (FE) HX Powders

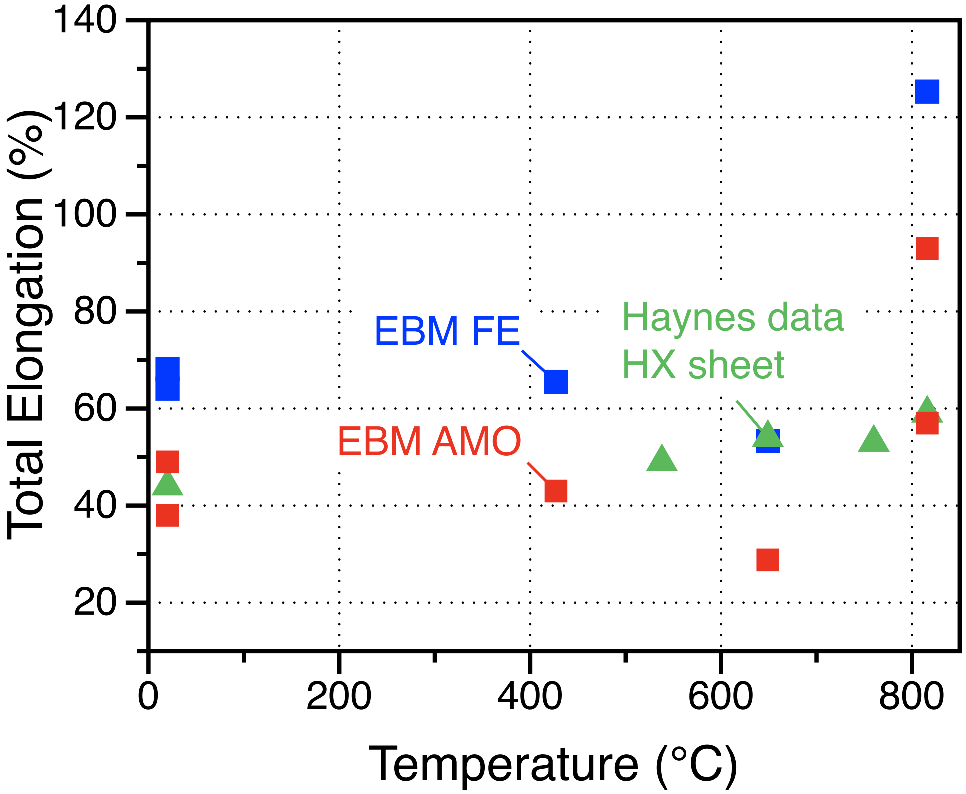
AM	Ni	Cr	Fe	Mo	Co	Mn	Si	W	C
Powder FE	Bal.	21.76	18.43	8.91	1.51	0.07	0.08	0.6	0.08
Alloy FE	Bal.	21.38	18.55	9.05	1.55	0.01	0.05	0.64	0.078
Powder AMO	Bal.	21.7	18.7	9	1.56	0.93	0.86	0.66	0.06
Alloy AMO	Bal.	21.43	18.87	9	1.56	0.67	0.71	0.65	0.048
Wrought	Bal.	22.06	17.86	9.53	1.8	0.65	0.31	0.6	0.067

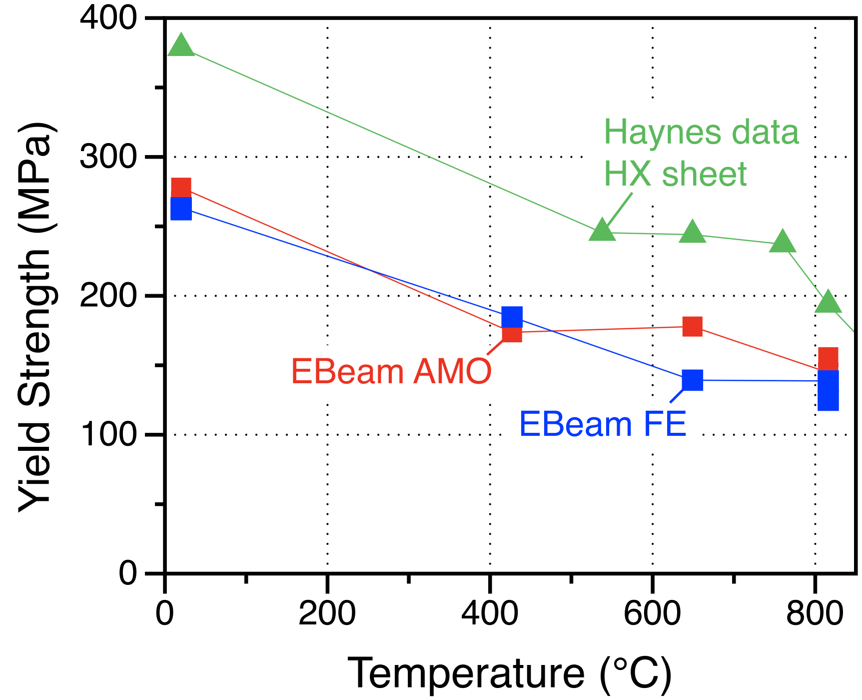
HX specification: Mn and Si < 1 wt%

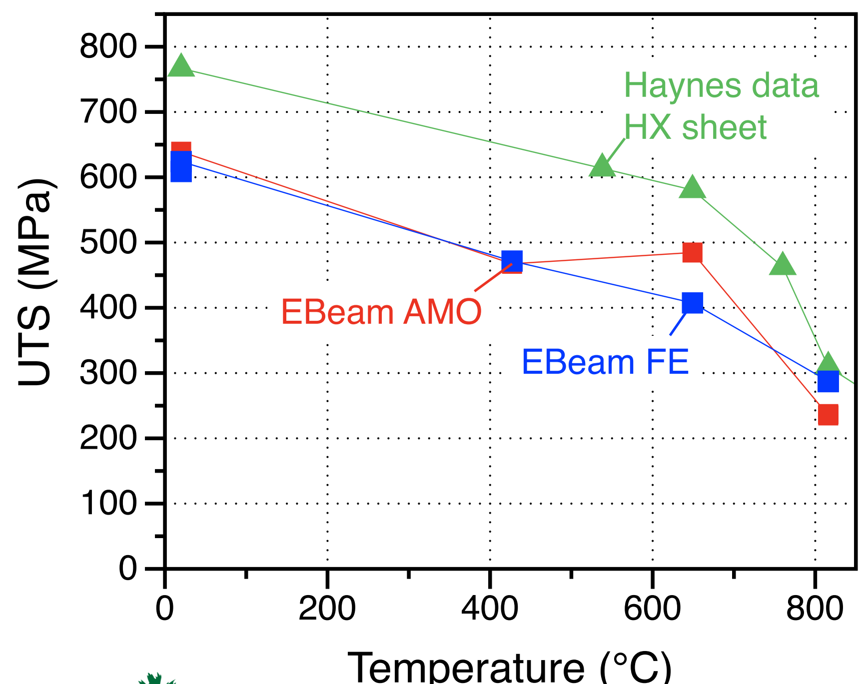
Significant Impact of Powder Chemical Composition on Microstructure



Similar Properties for the High Si (AMO) & Low Si (FE) Alloys







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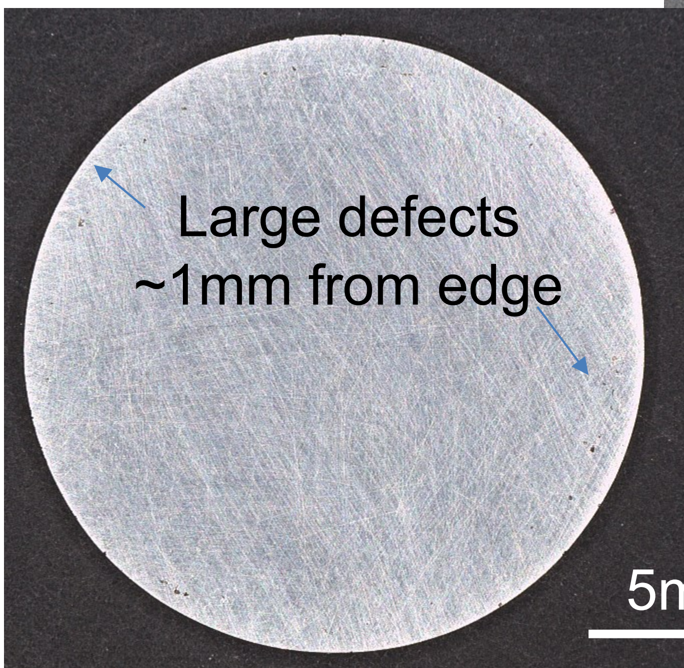
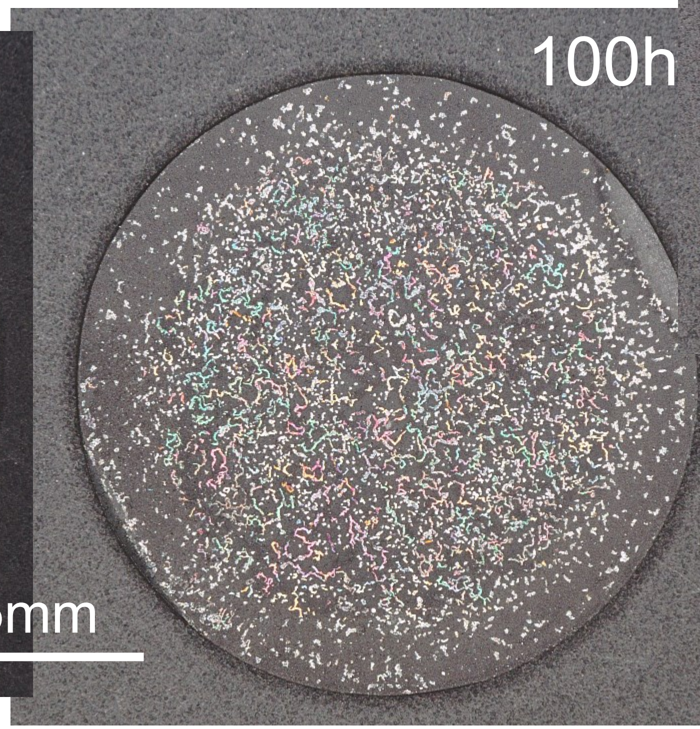
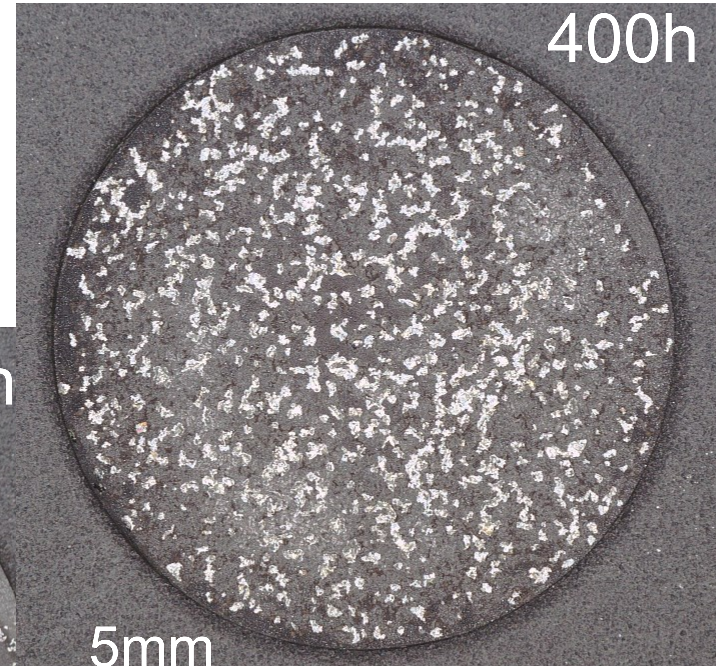
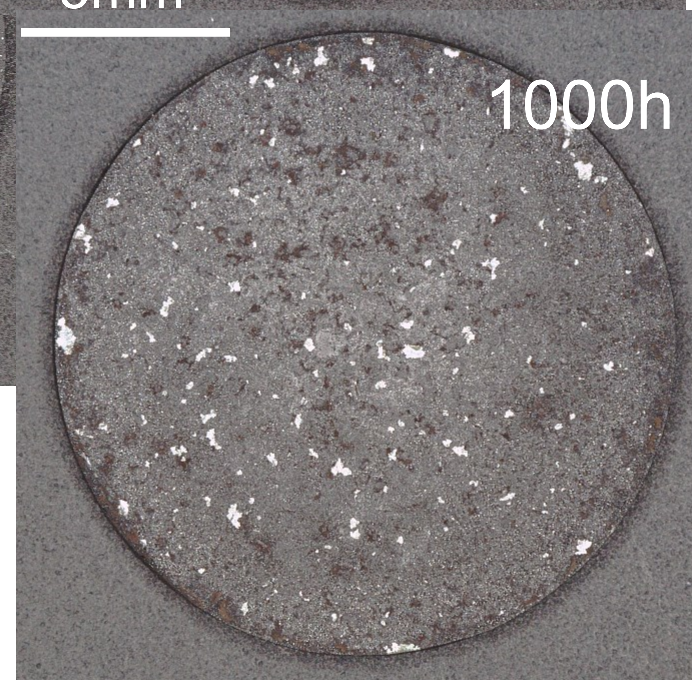
High Si HX-AMO Oxidation Coupons 100h Cycle, Air, 950ºC



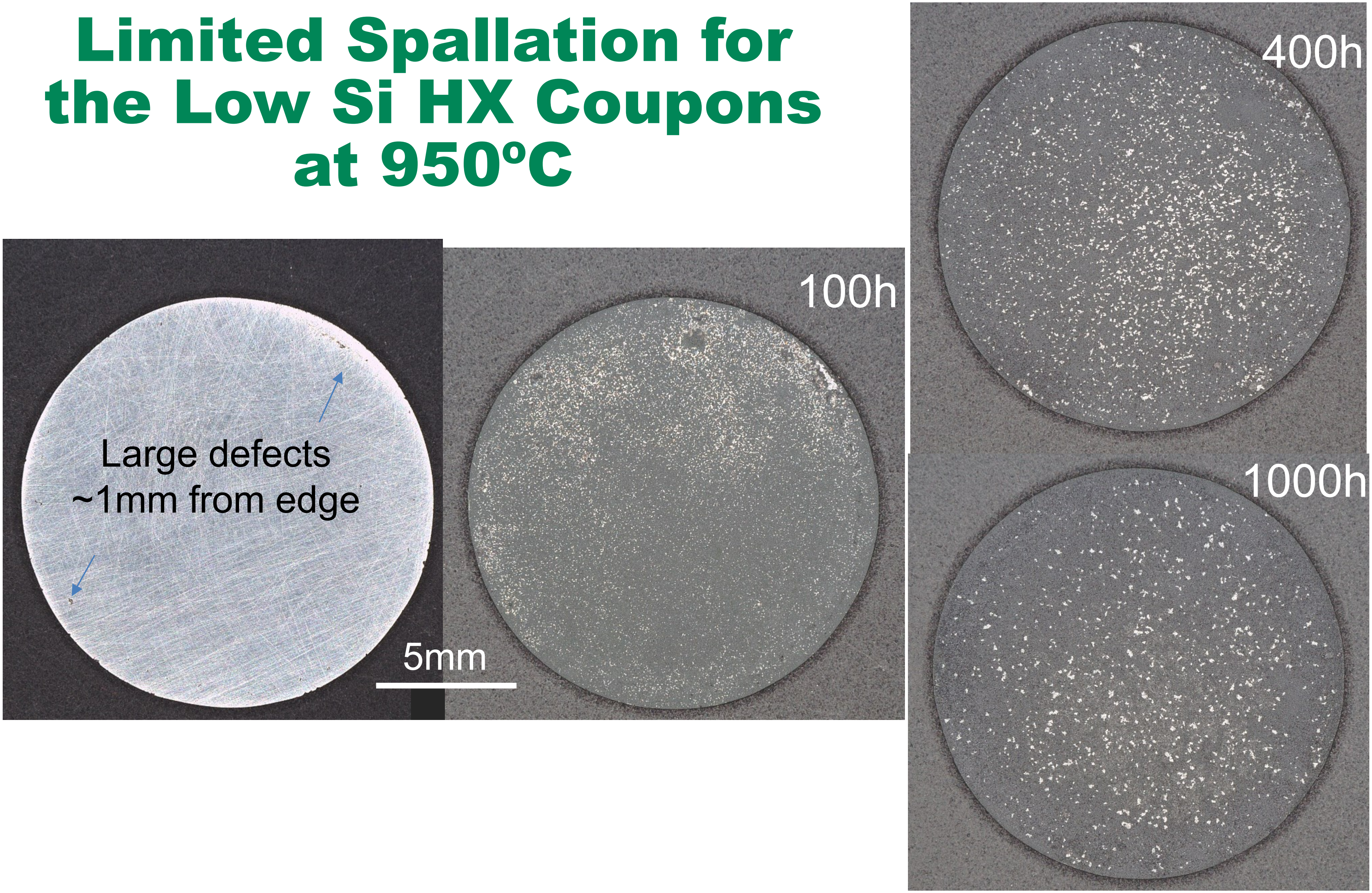






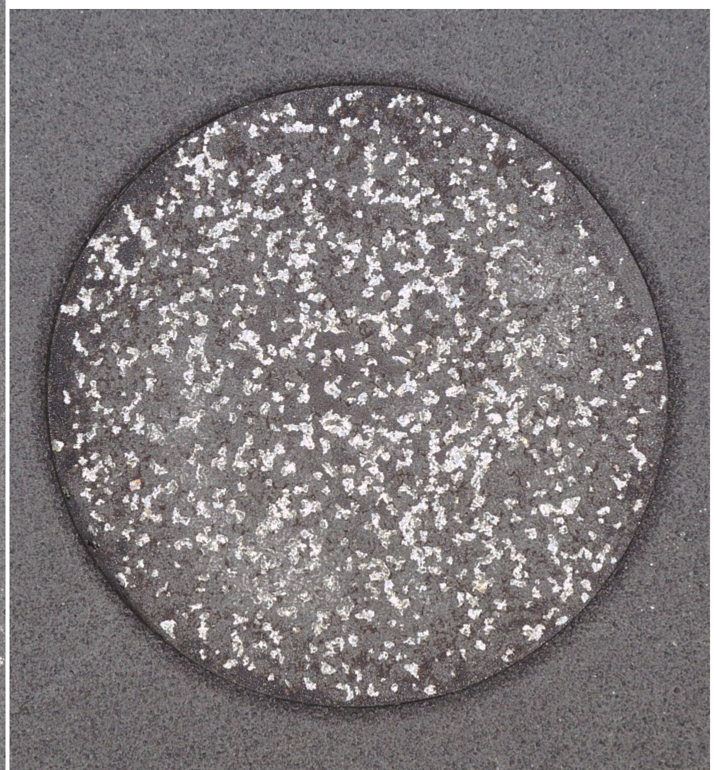
- High spallation rate likely related to High Si grain boundaries
- Less spallation at edges due to different microstructure?

Limited Spallation for the Low Si HX Coupons at 950ºC

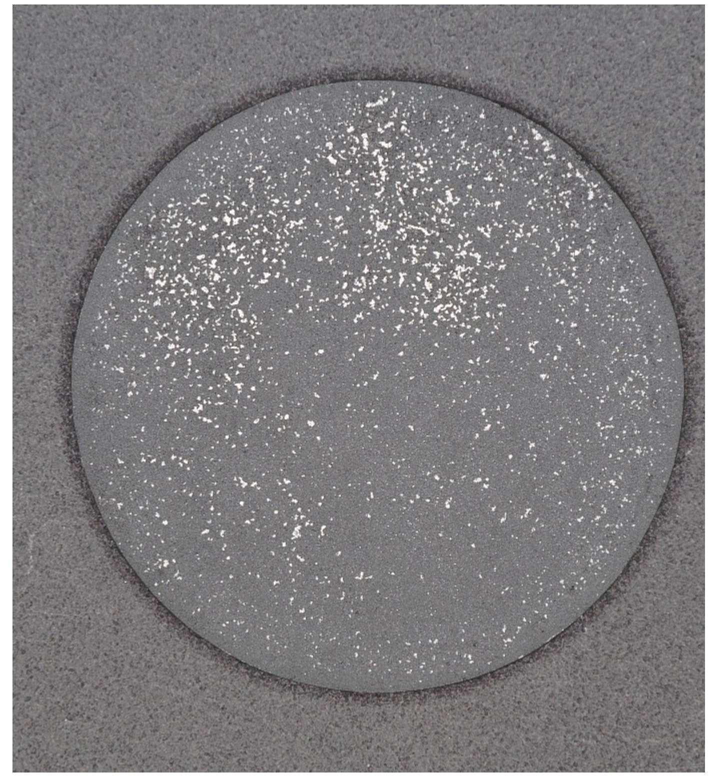


No spallation for wrought HX 4x100h at 950ºC

HX wrought

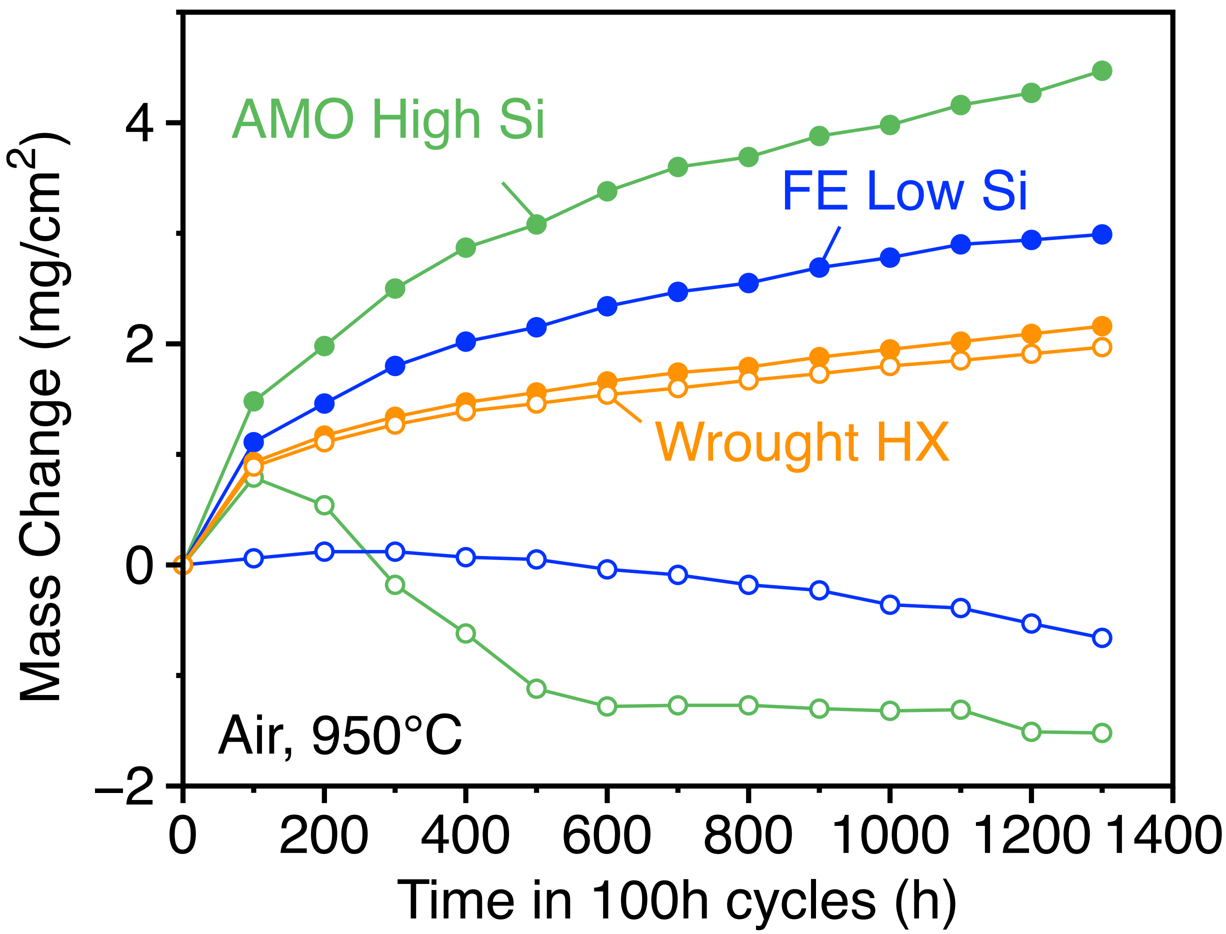


Ebeam High Si



Ebeam low Si

Significant Impact on Mass Changes Long Term Effect on Oxidation Behavior?



Gross Mass Gains (Oxygen pick up)

Specimen Mass Changes

Conclusion

- Ebeam HX shows good ductility and strength superior to the cast HX requirement
- No effect of HT and Hip’ing on Ebeam HX tensile properties
- SLM HX exhibited good tensile strength and acceptable ductility
- HT or Hip’ing increased the SLM HX ductility but reduced YS
- Good fatigue properties for the Ebeam HX but limited creep strength at 816ºC. Larger creep database will be generated + testing of Hip’ed HX alloy
- Significant spallation was observed for the High Si HX alloy Need to control Si content or new scanning strategies to improve oxidation at the surface