Microstructure and Properties of Hastelloy X Fabricated by Additive Manufacturing

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Crosscutting Research Review Meeting

ORNL project FEAA119

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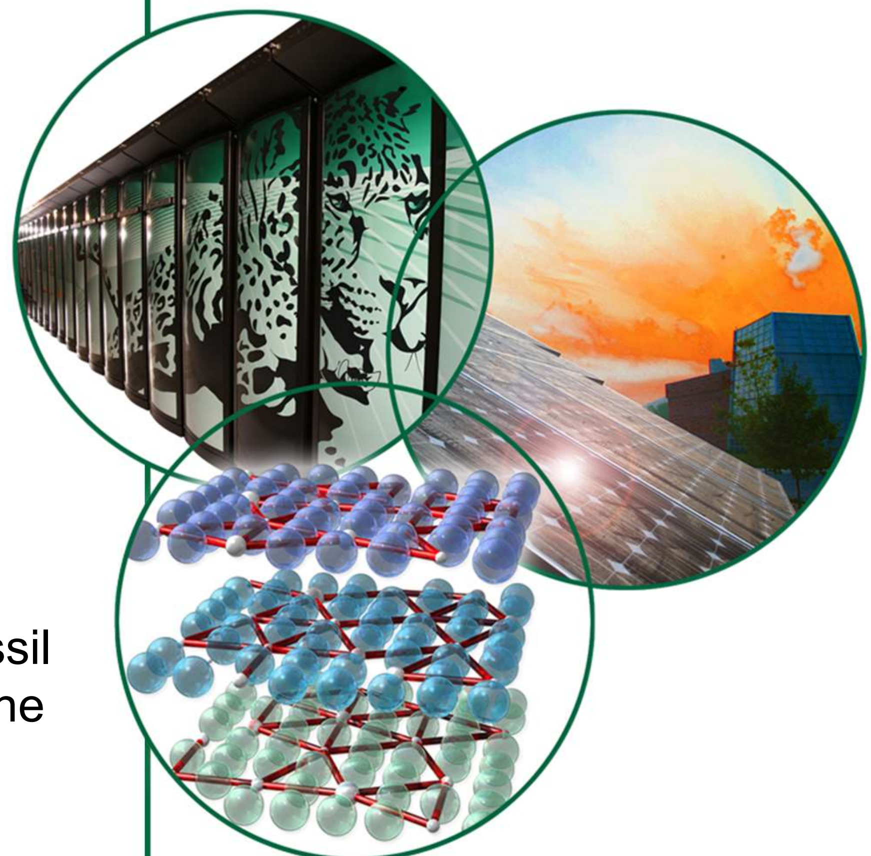

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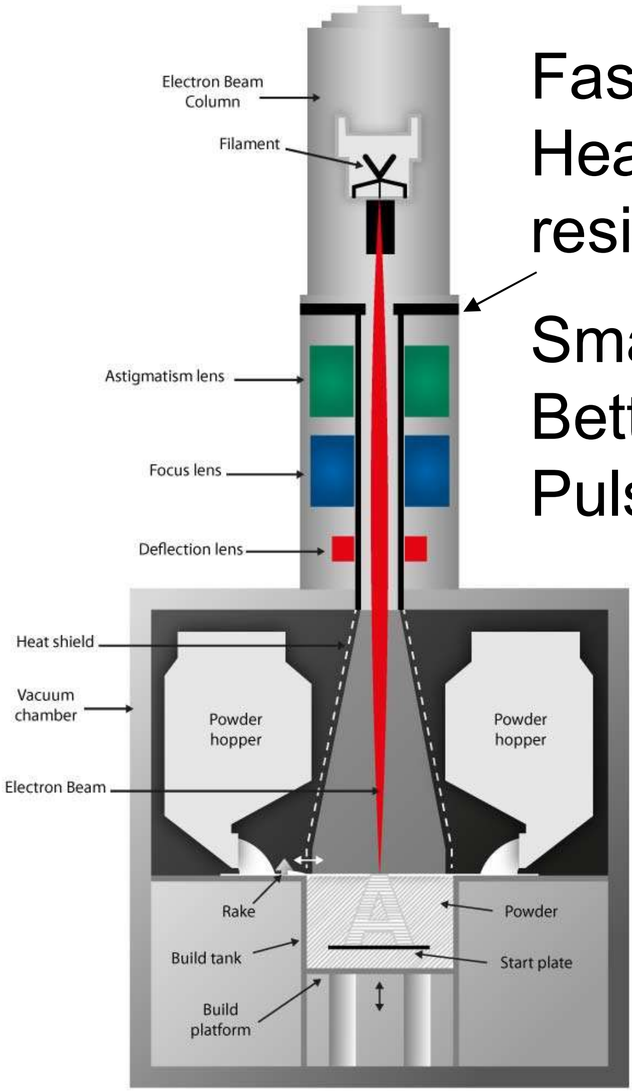
Project Objectives

- **Optimize additive manufacturing (AM) fabrication processes for solution strengthened Hastelloy X (HX, Ni-22Cr-19Fe-9Mo) gas turbine components (Fuel injector, Combustor)**
- **Generate data (Tensile, Fatigue, Creep, Oxidation) relevant for FE applications for Hastelloy alloy**
- **Properties requirement depends on component and application (prototyping, production and repair)**
- **Compare three AM techniques, electron beam melting (EBM) and selective laser melting (SLM) and laser metal depostion (LMD)**
- **Effect of annealing or HIP'ing on microstructure and mechanical properties**
- **Effect of different EBM precursor powders on mechanical and oxidation behaviors**

HX Made by EBM 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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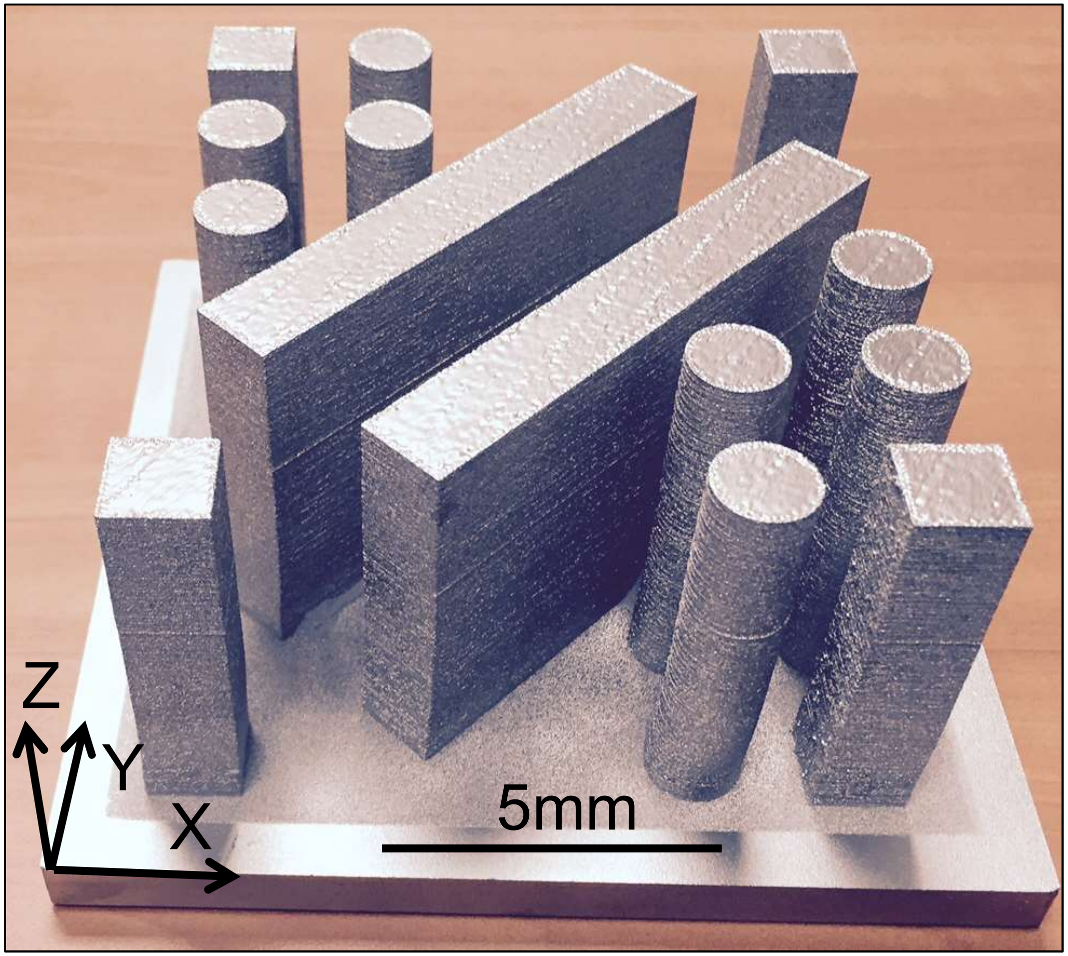
Small SLM HX Cube for Parameter Optimization Based on Microstructure

- Spot time
- Spacing
- Energy
- Optimization based on previous experience with Ni-based alloys
- typical duration ~2 weeks

Fabrication of 20-30 EBM and SLM Specimens For Tensile, Creep, Fatigue and Oxidation Testing



- Study the effect of property anisotropy

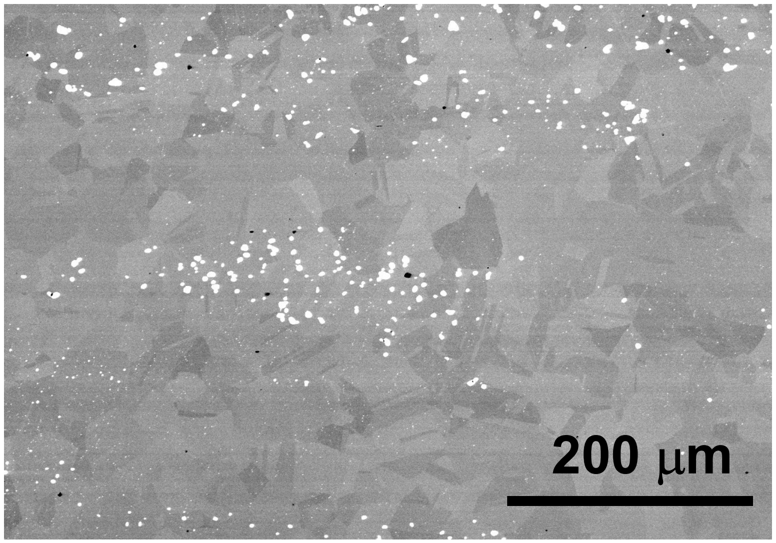
Similar Composition For EBM, SLM and Wrought HX Except for Si &Mn

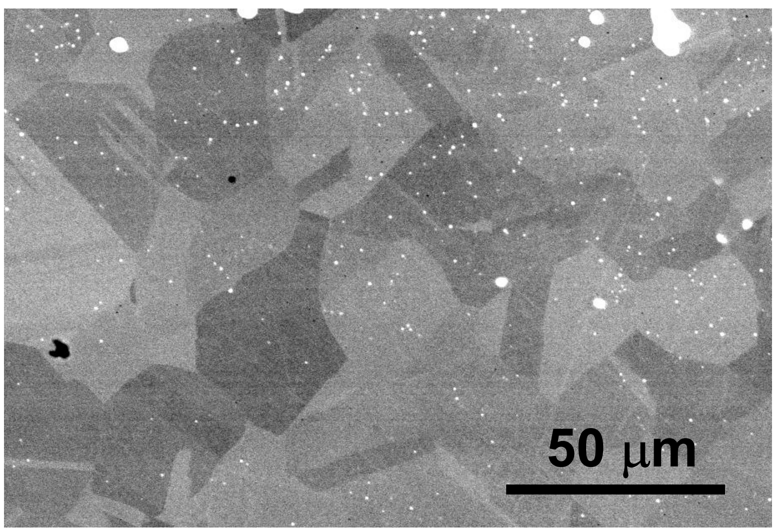
Hastelloy X (Ni-22Cr-19Fe-9Mo)

	Ni	Cr	Fe	Mo	Co	Mn	Si	W	C
EBM Alloy	Bal.	21.38	18.55	9.05	1.55	0.01	0.05	0.64	0.078
EBM(Si,Mn) Alloy	Bal.	21.43	18.87	9	1.56	0.67	0.71	0.65	0.048
SLM Powder	Bal.	21.47	18.83	8.96	1.51	0.01	0.16	0.63	0.07
SLM-Opt Powder	Bal.	21.72	18.51	8.87	1.51	0.01	0.06	0.6	0.08
Wrought	Bal.	22.06	17.86	9.53	1.8	0.65	0.31	0.6	0.067

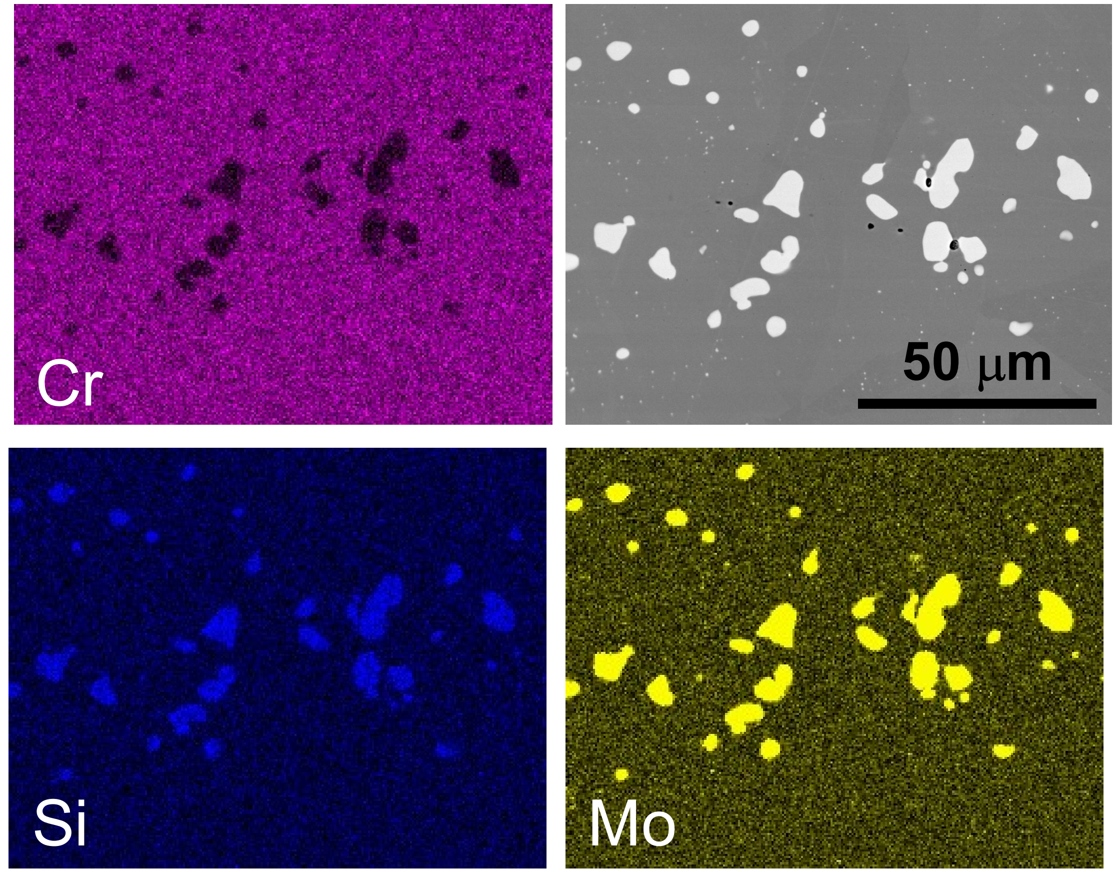
- Alloy composition consistent with EBM powder composition
- High concentration of Mn and Si in EBM(Si,Mn) and wrought HX. Specification: Mn and Si <1%

Wrought HX: Random Distribution of (Mo,Si) Precipitates

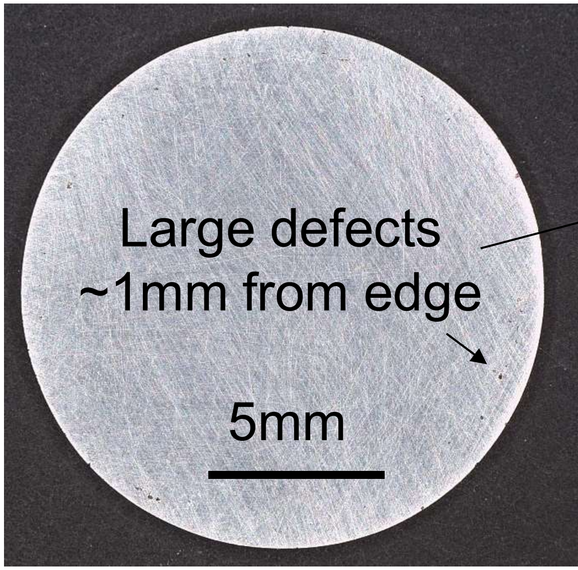


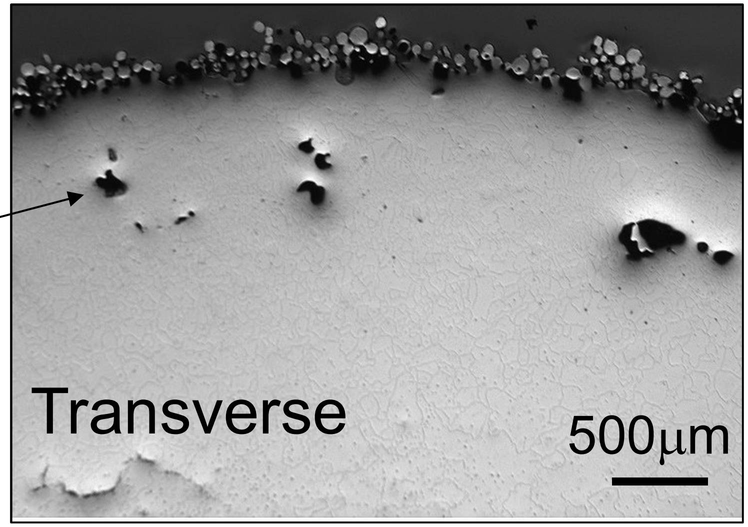


~50μm equiaxed grains

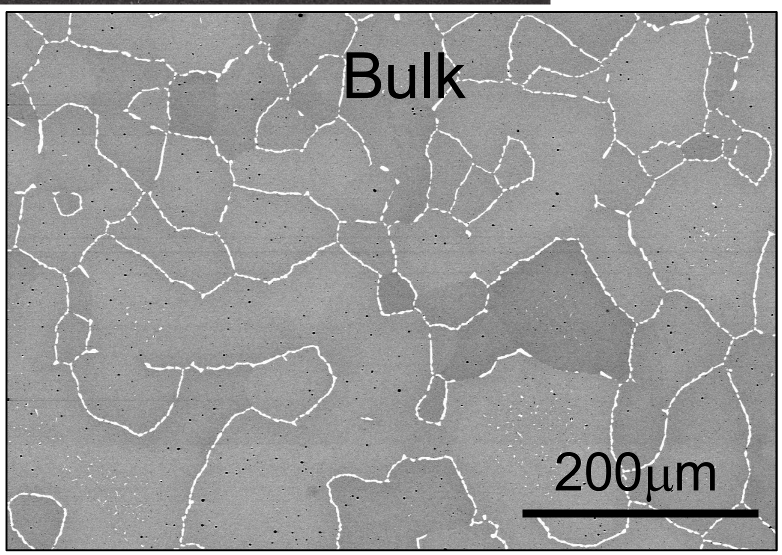


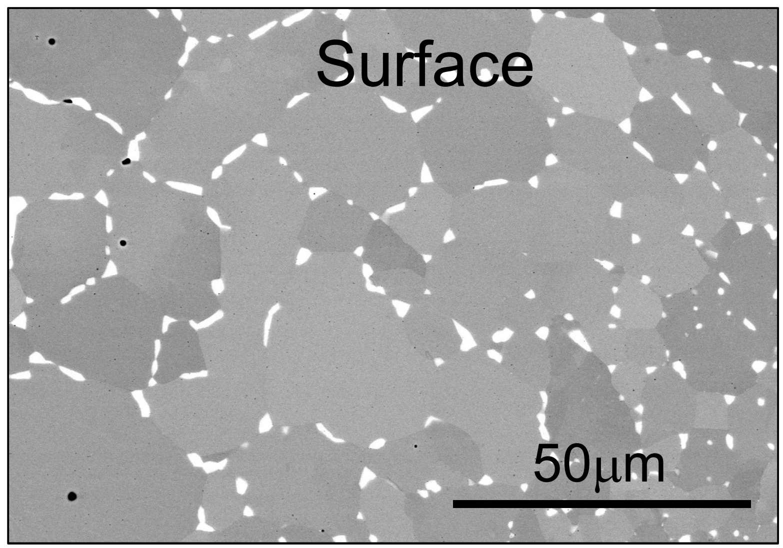
EBM: Larger Grains at the Center vs Surface





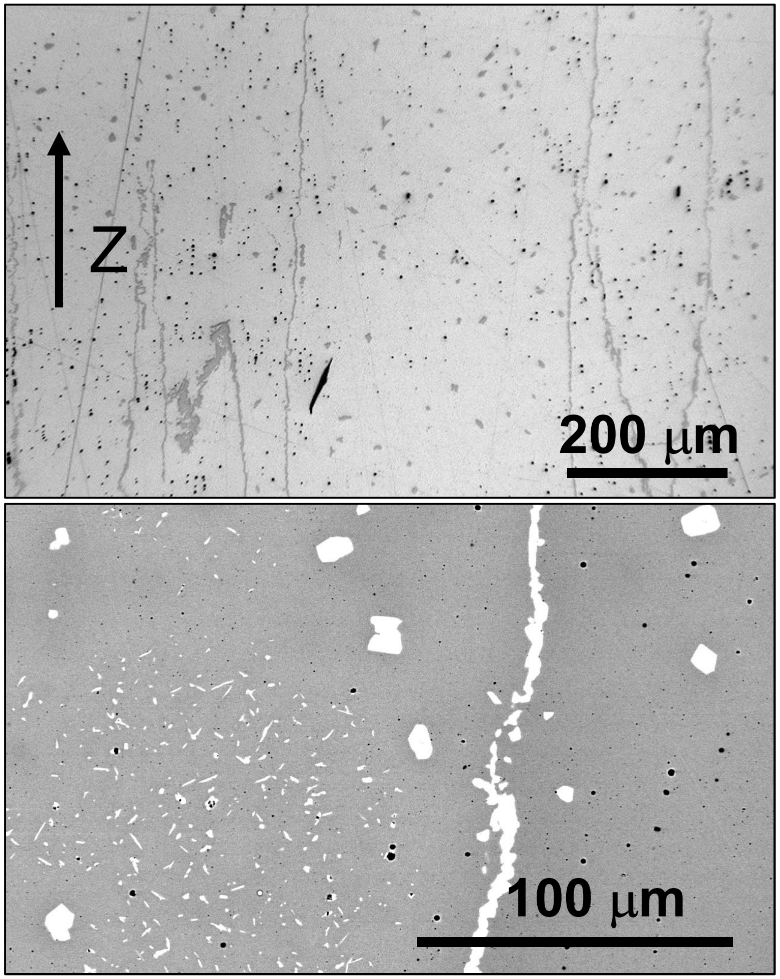
Fabrication of contour first



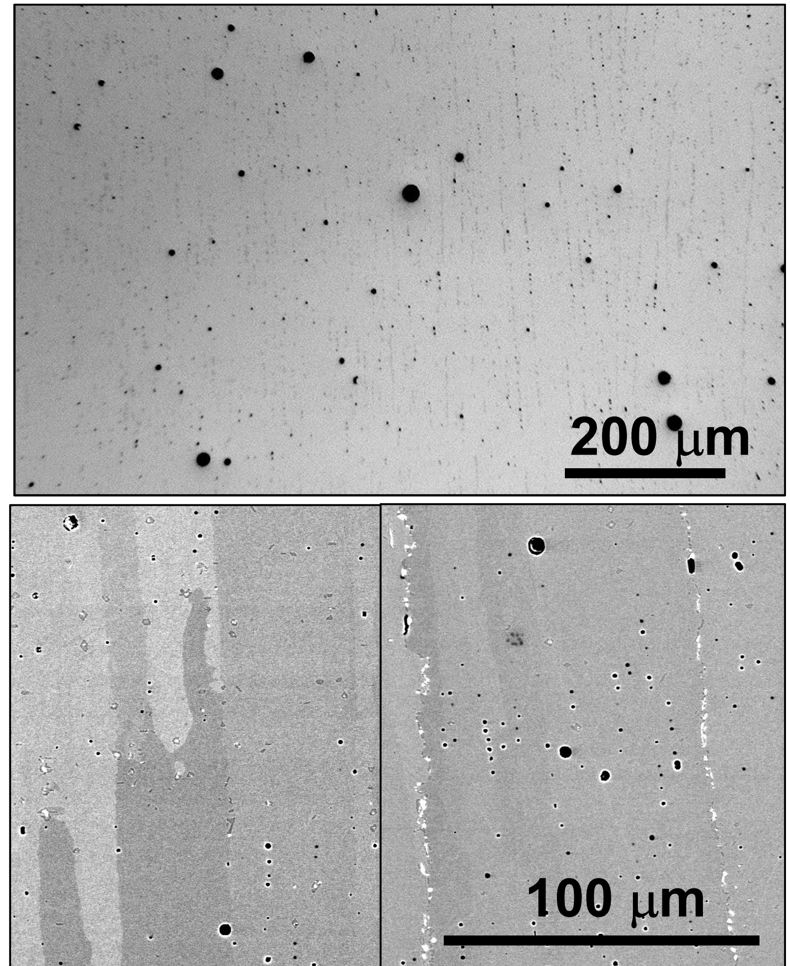


Elongated Grain Along Z Direction More Precipitates for EBM(Si,Mn)

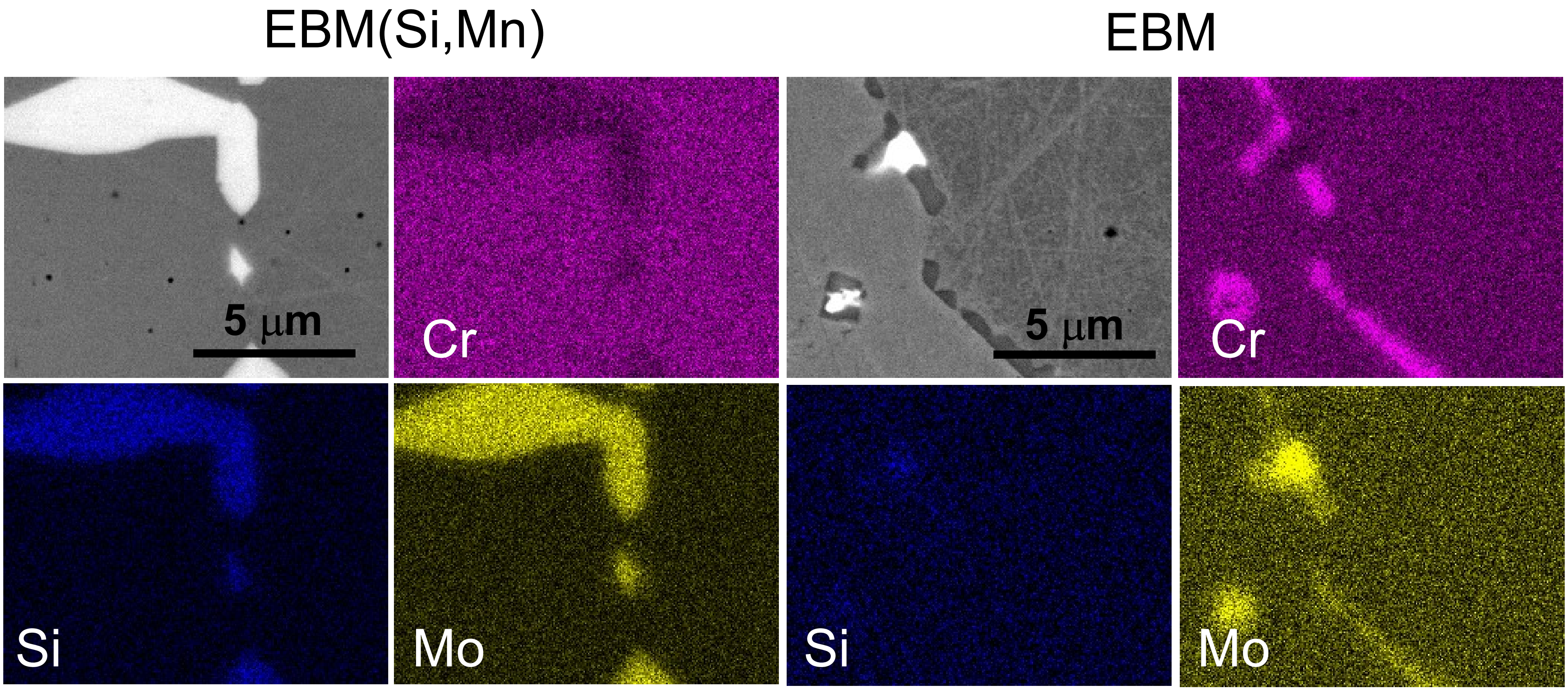
EBM(Si,Mn) = Larger grains



EBM = Larger voids

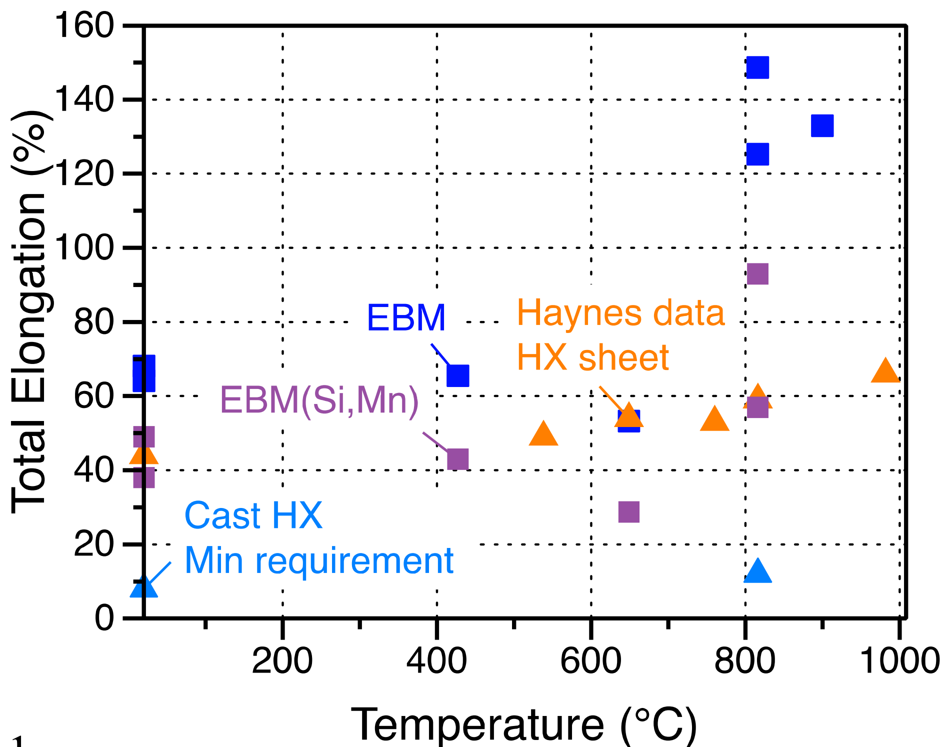


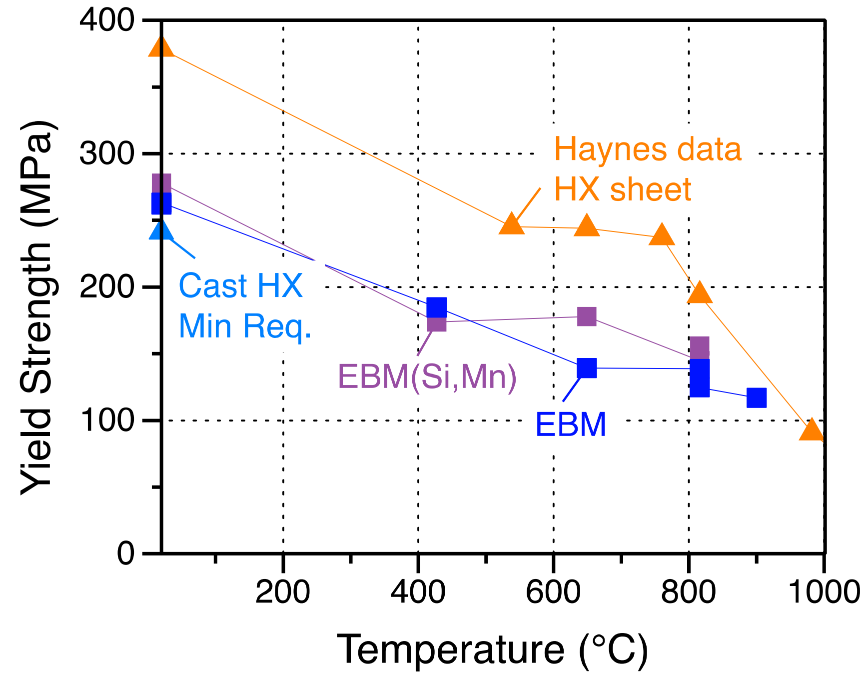
EBM(Si,Mn): Many (Mo,Si)-rich Carbides EBM: Few (Mo,Cr)-&(Mo,Si)-rich Carbides at GB

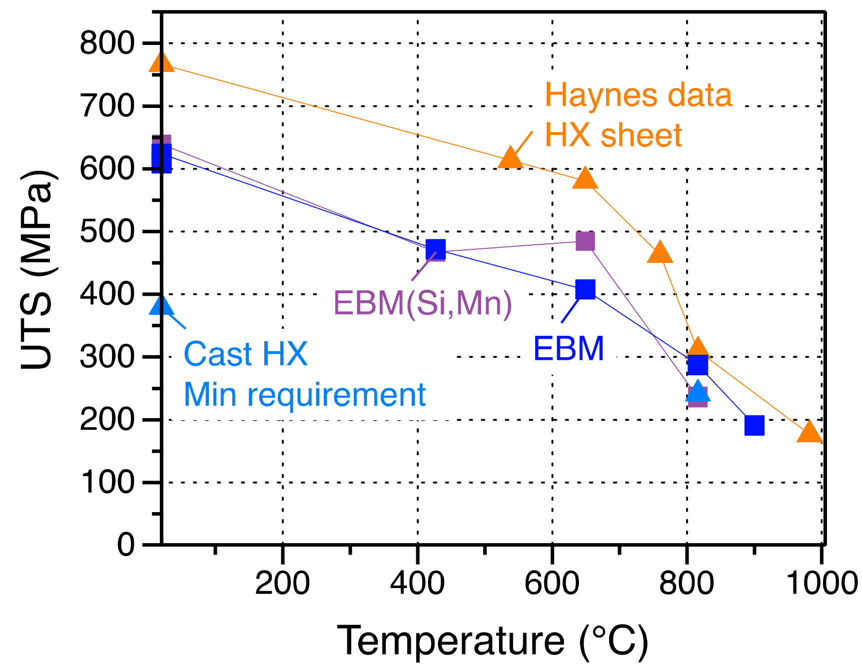


Both EBM & EBM(Si,Mn) HX Alloys Exhibit Good Ductility But Lower Strength < 800ºC

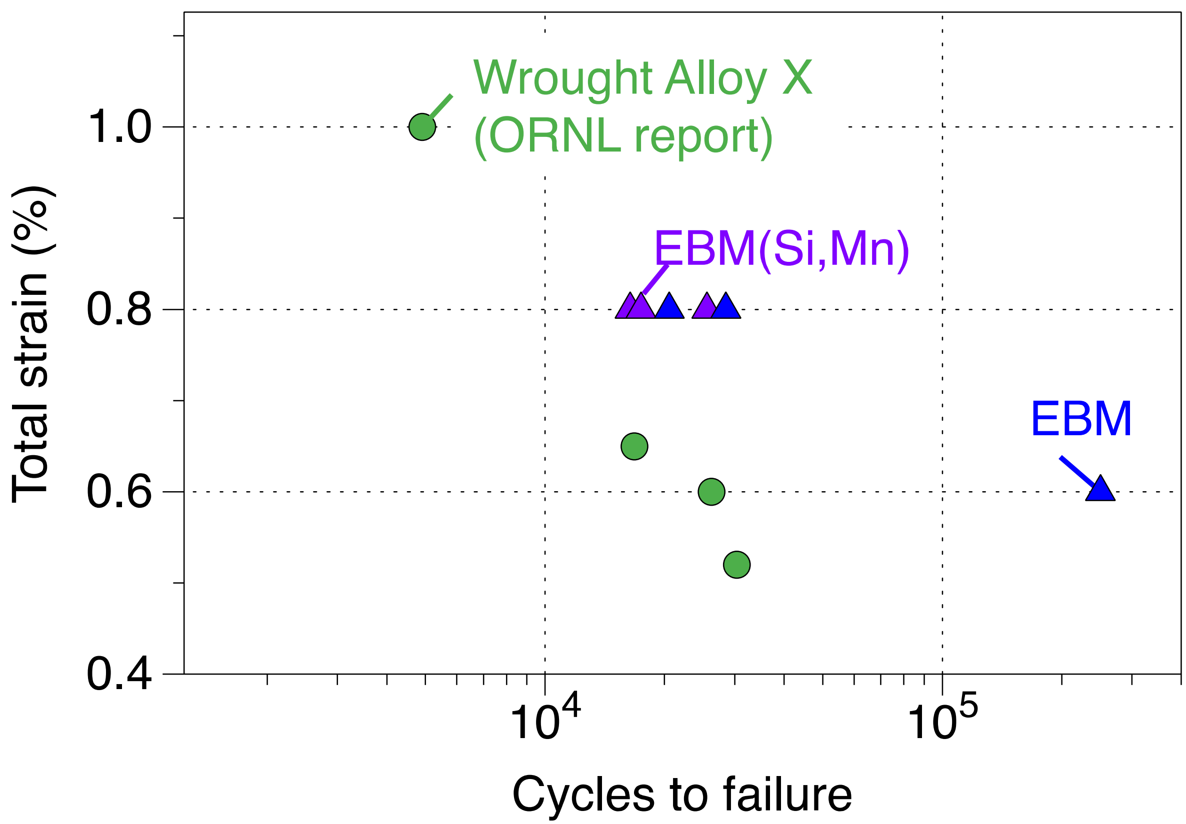
Meet cast HX AMS requirement







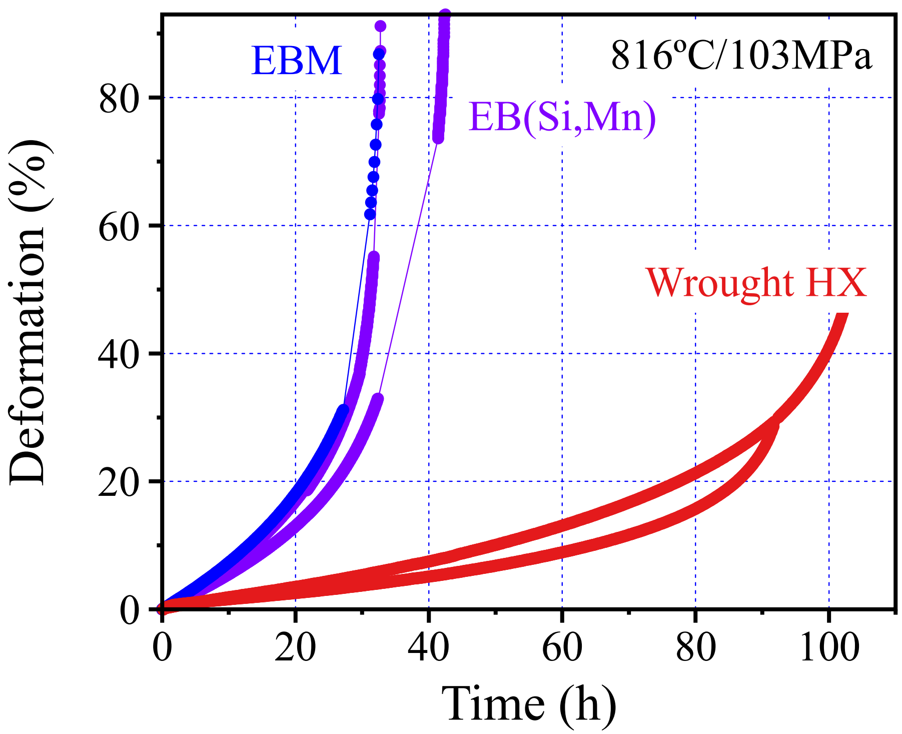
EBM & EBM(Si,Mn): Good Low-Cycle Fatigue Properties at 800ºF/425ºC

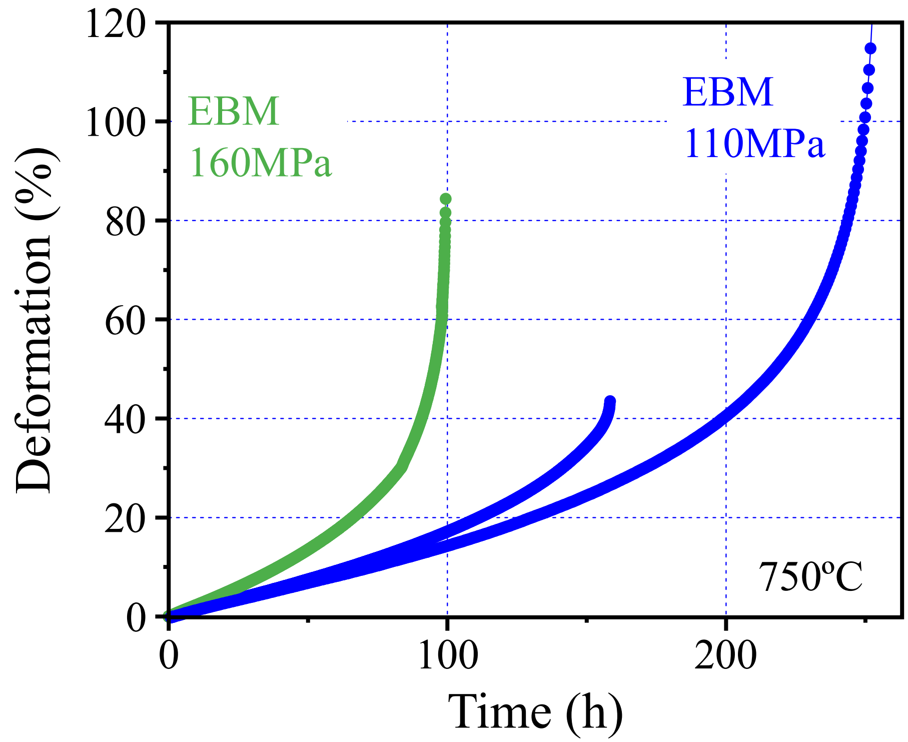


- Fully-reversed LCF
- Consistent with excellent HX EBM alloys ductility
- Similar results at other temperatures

SLM testing coming soon

EBM& EBM(Si,Mn) = Lower Creep Strength at 750 and 816ºC but High Ductility

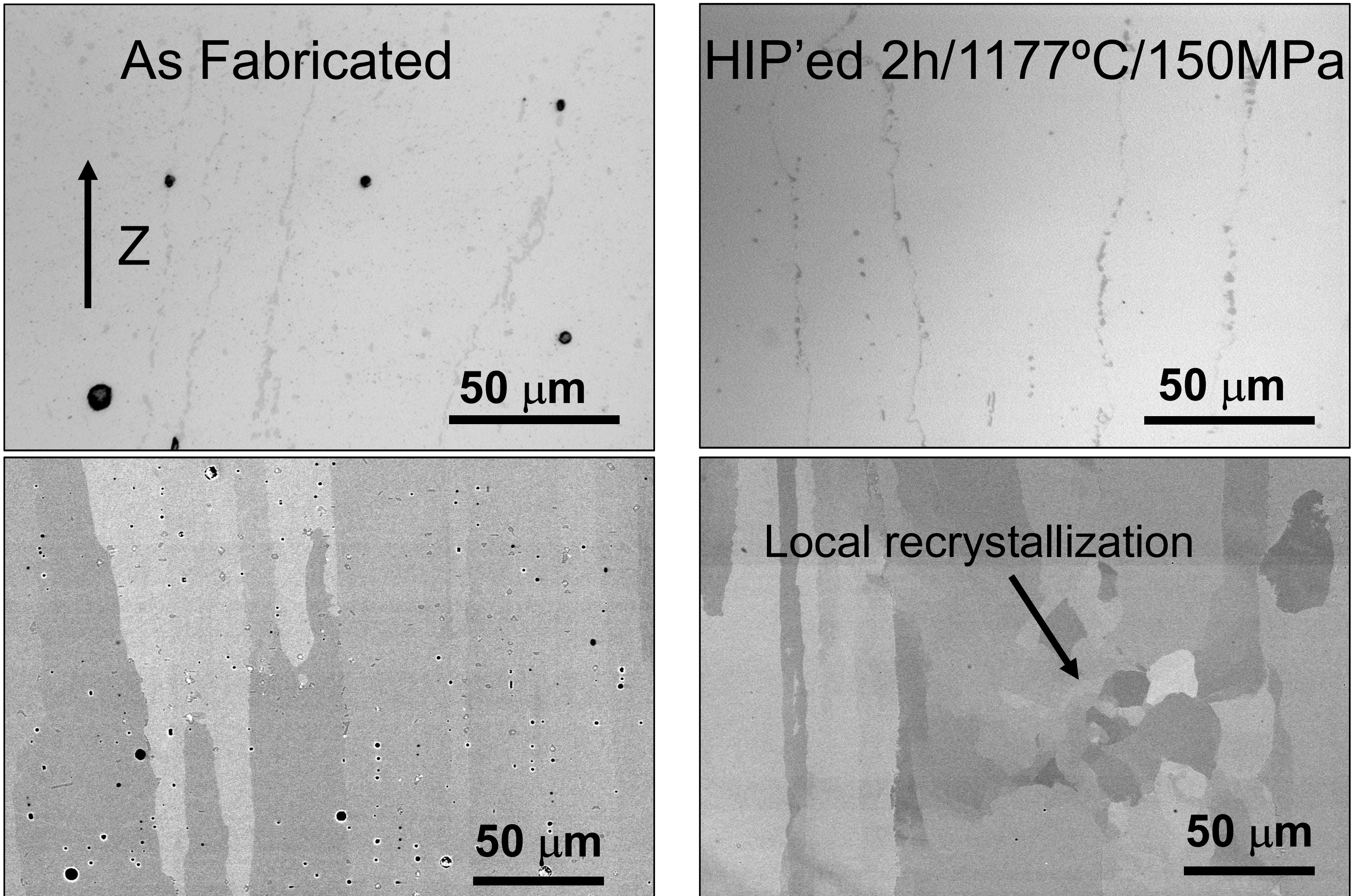




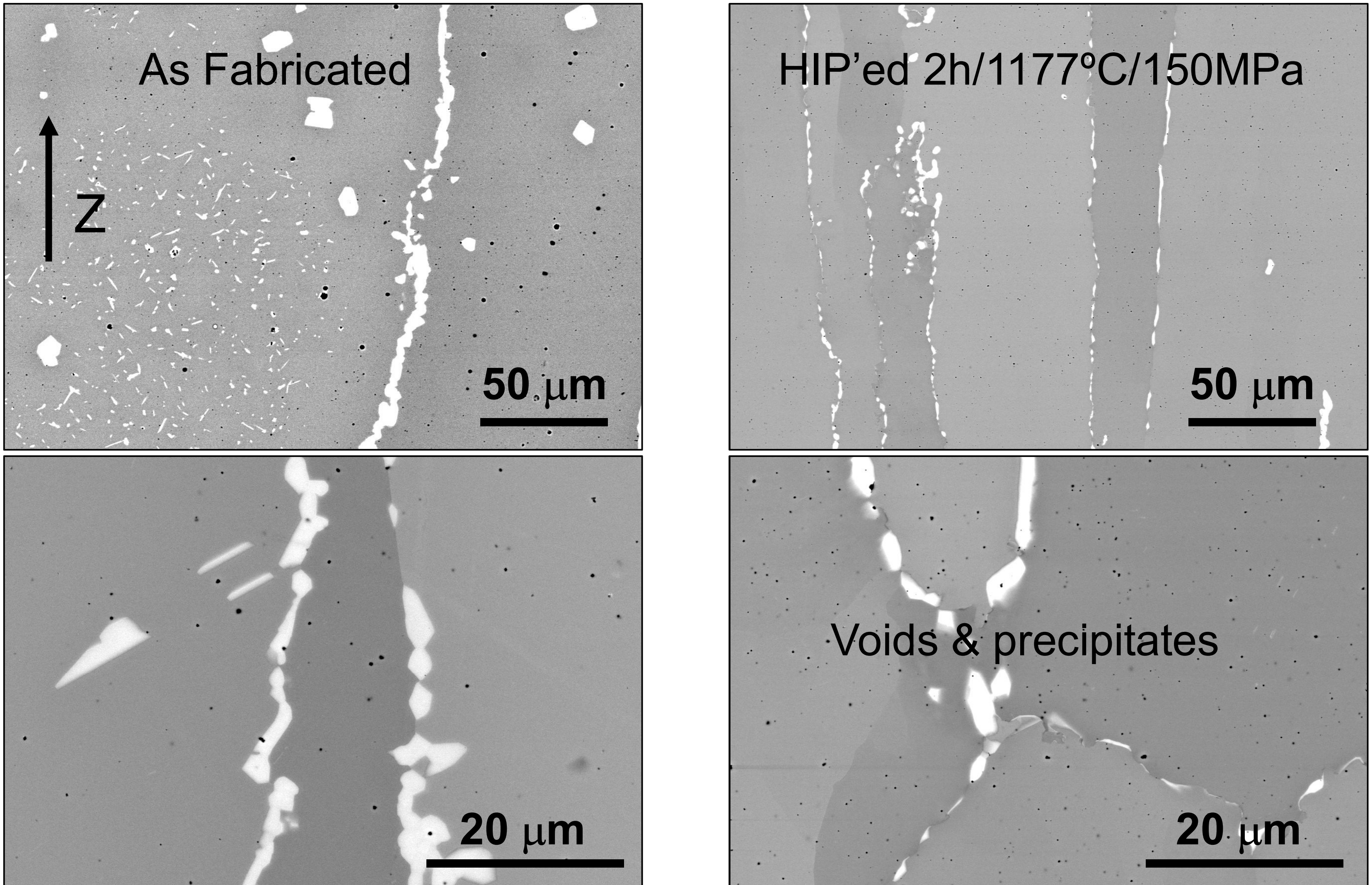
Wrought expected lifetime:

- 160MPa: 100h
- 110MPa: 1000h

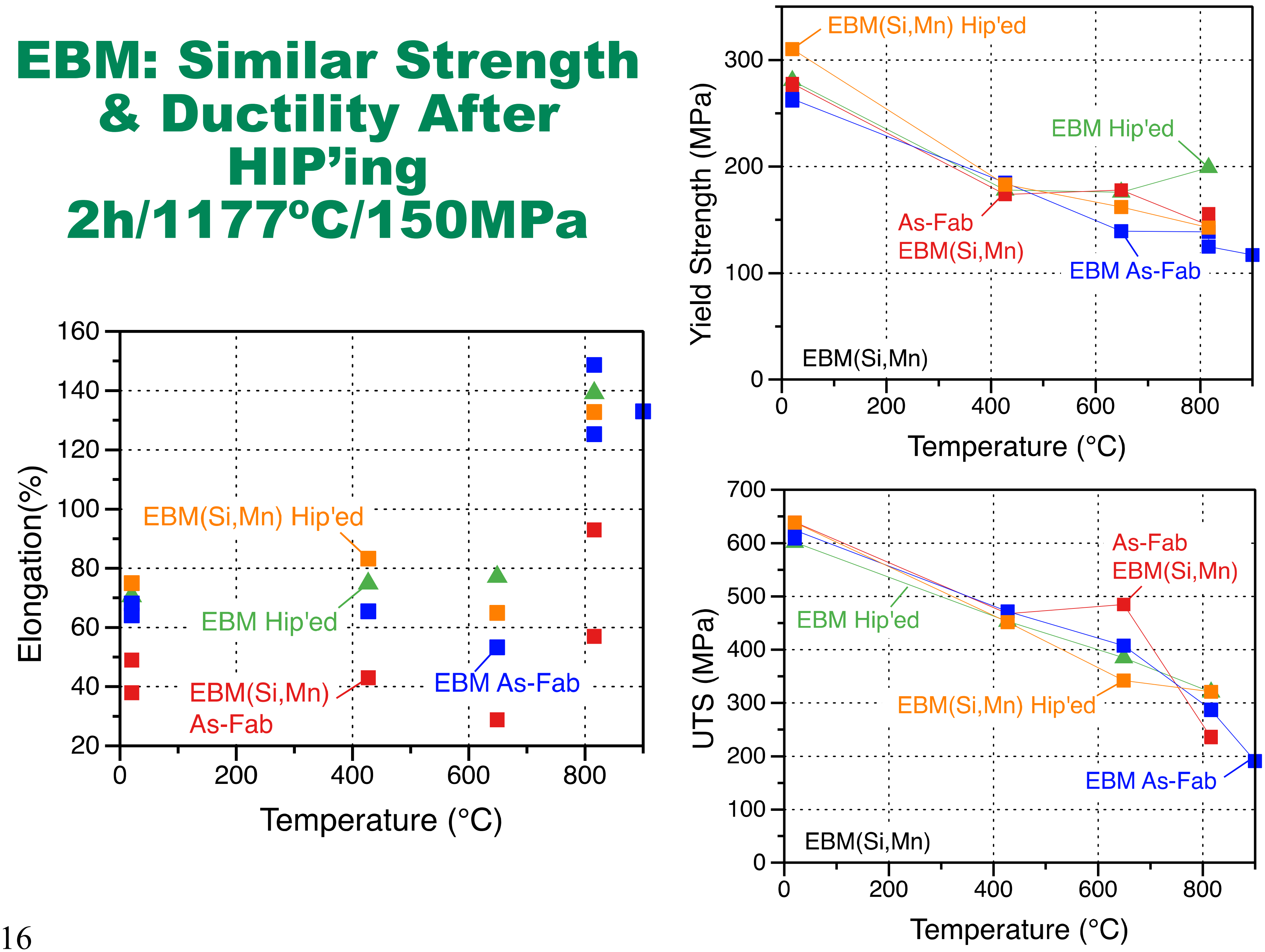
EBM: Fully Dense Material after HIP'ing at 1177ºC/2h/150MPa, "Fast Cooling"



EBM(Si,Mn): Micro voids still present after HIP'ing + Precipitates at GB only

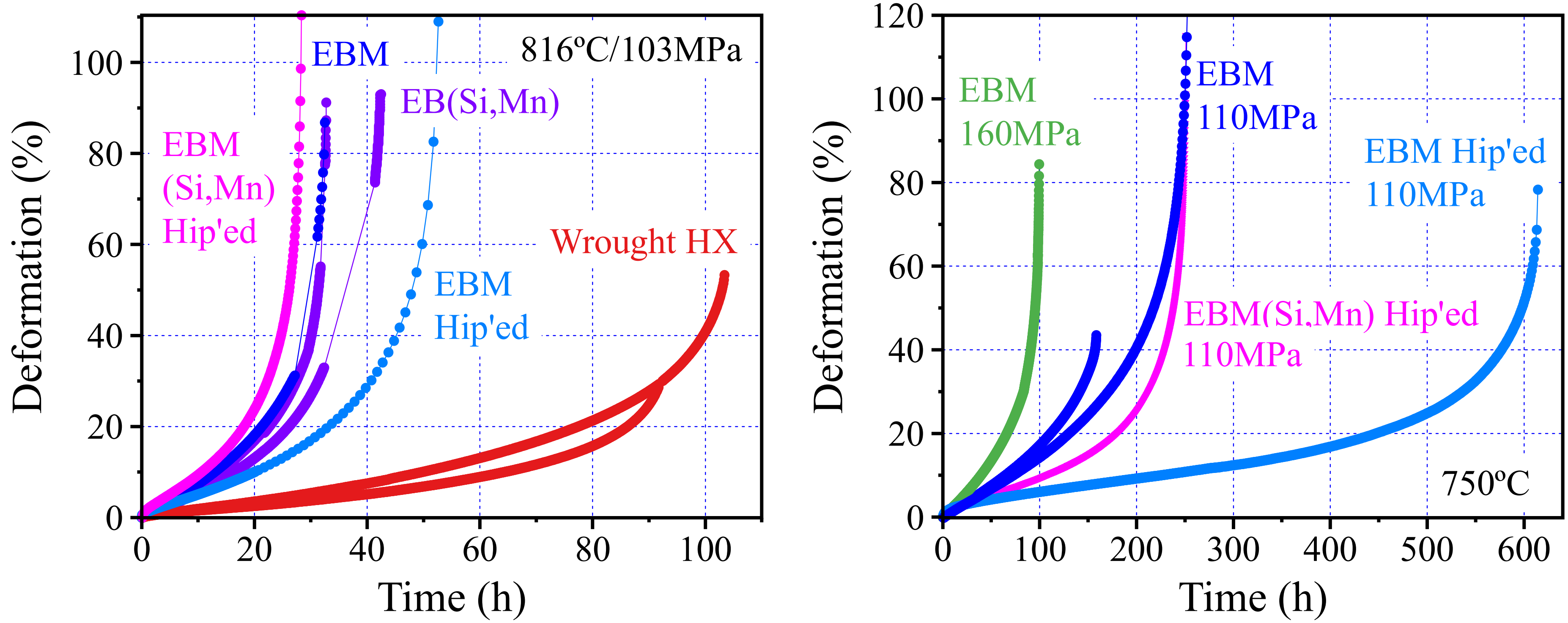


EBM: Similar Strength & Ductility After HIP'ing 2h/1177ºC/150MPa



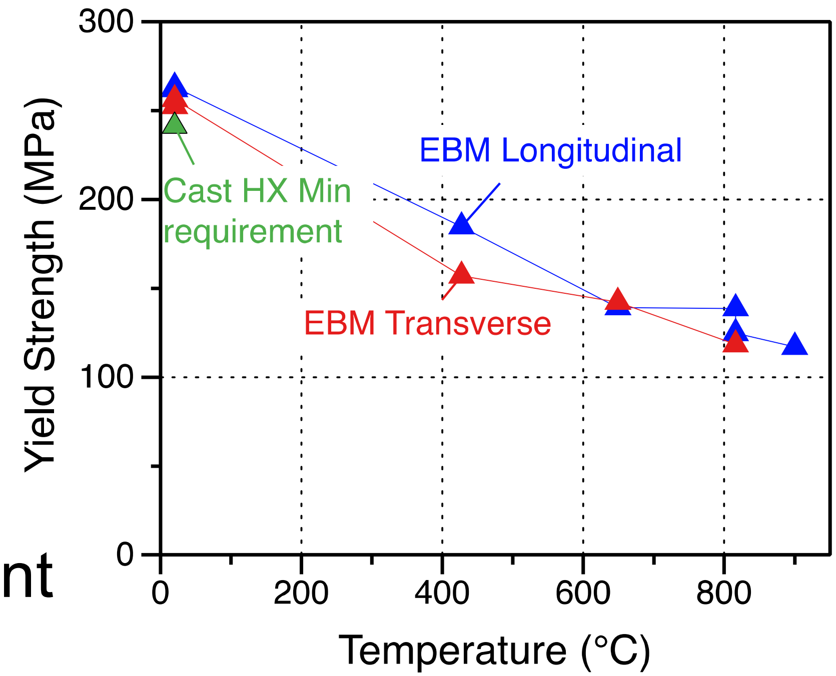
EBM& EBM(Si,Mn) = Lower Creep Strength but high ductility

Significant improvement after HIP'ing for EBM alloy at 750ºC

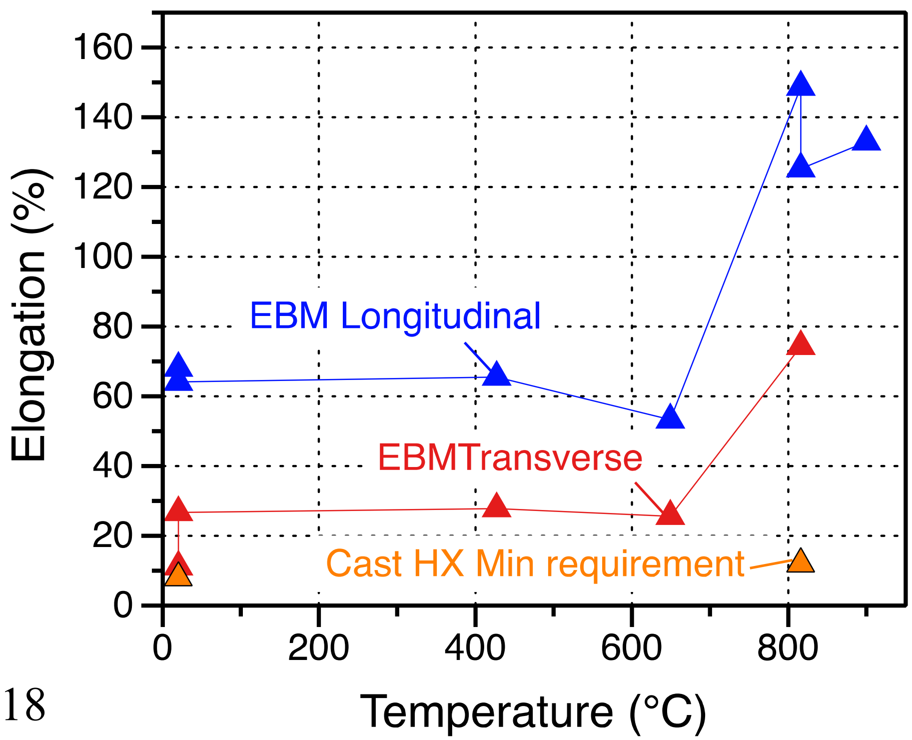


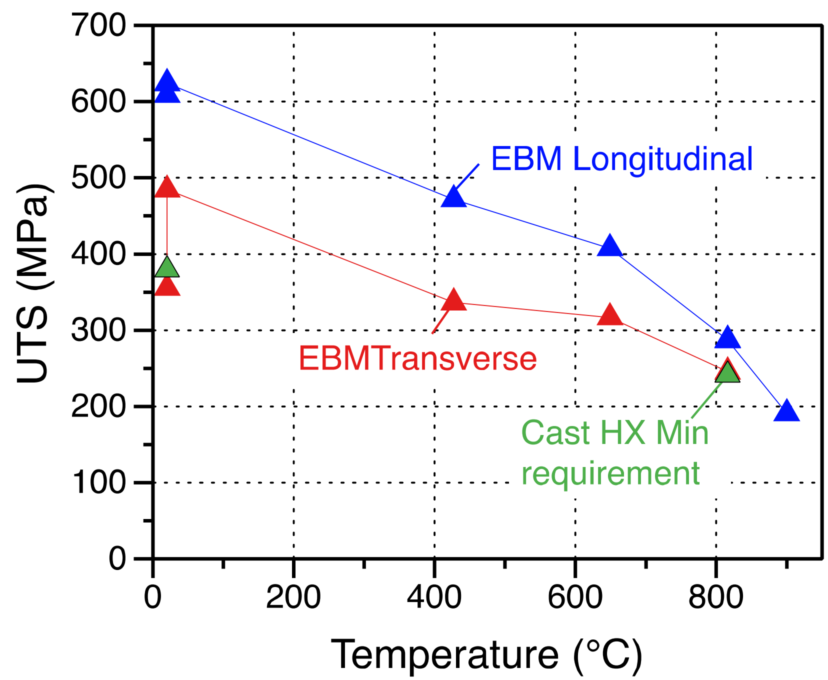
Wrought expected lifetime:
- 160MPa: 100h
- 110MPa: 1000h

EBM HX Alloys Decrease of UTS & Elongation in the Transverse Direction

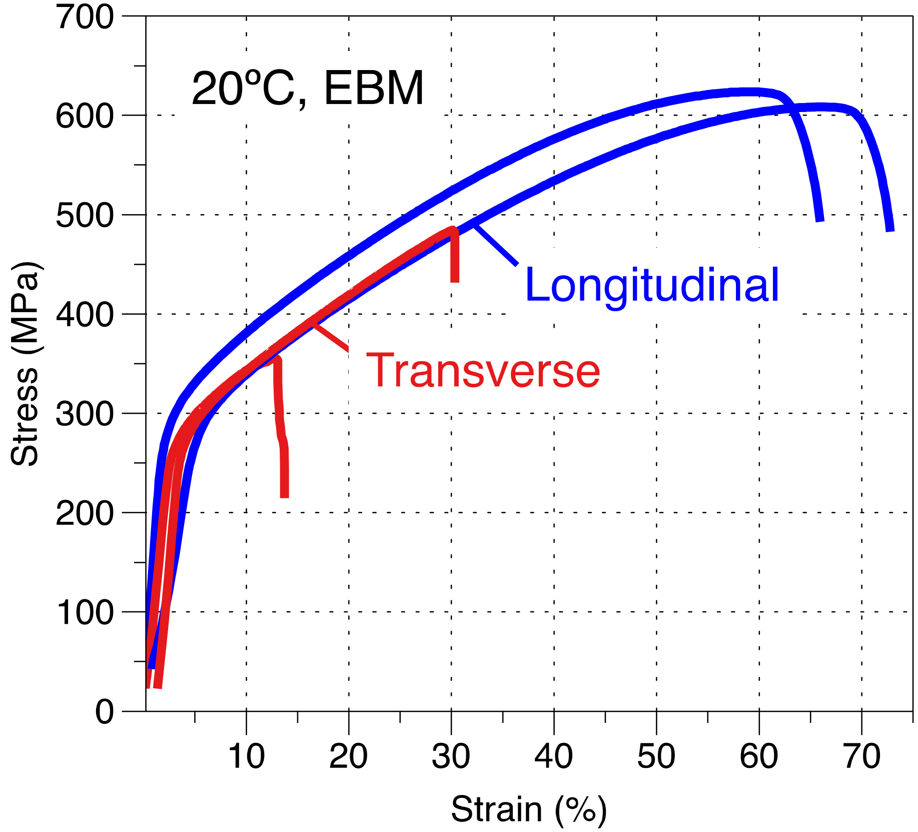


Close to cast HX AMS requirement





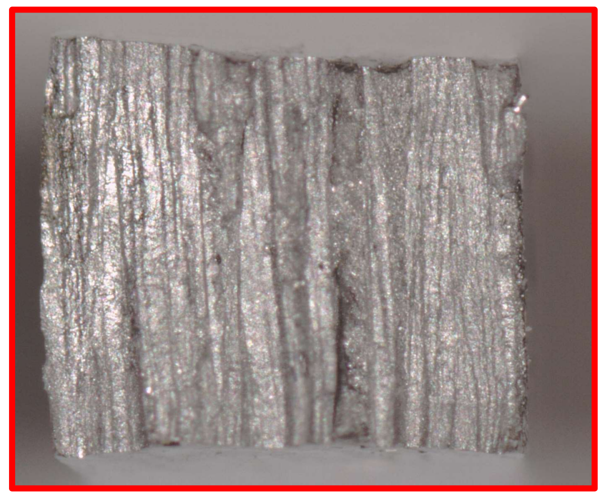
EBM HX Alloys Decrease of UTS and Elongation due to Microstructure Anisotropy



Longitudinal

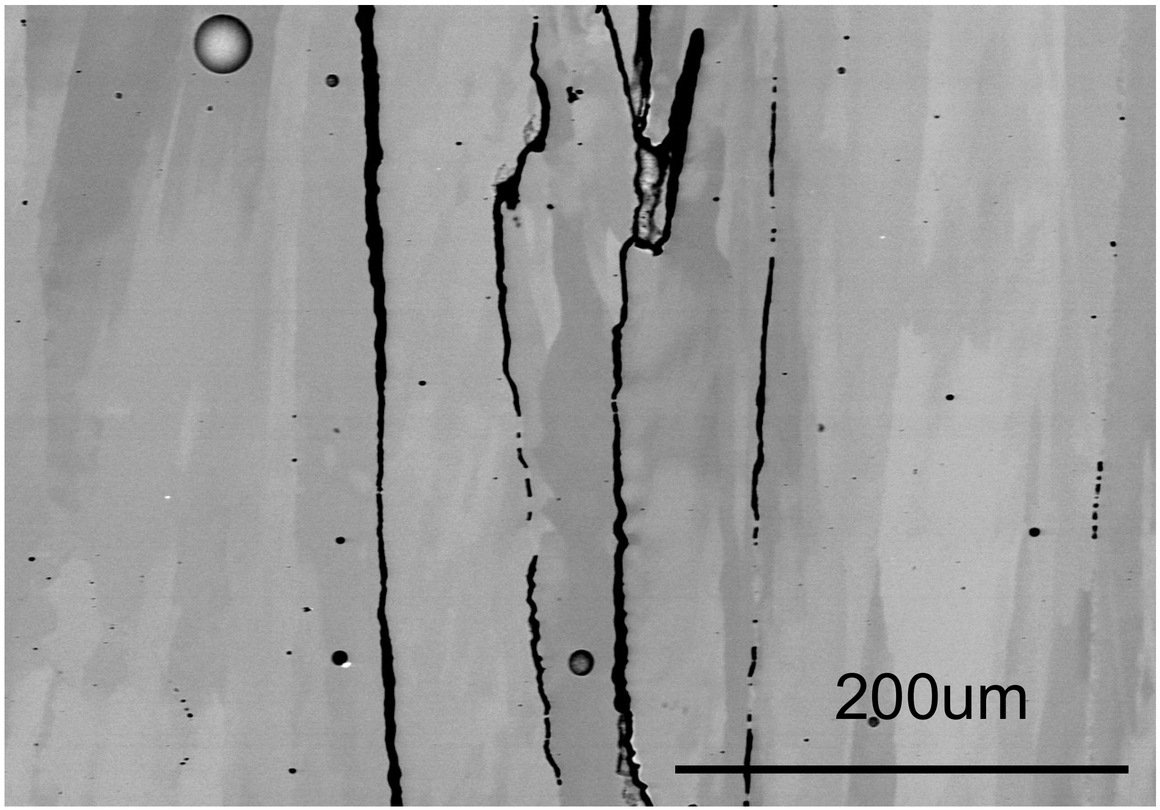
1mm

Transverse

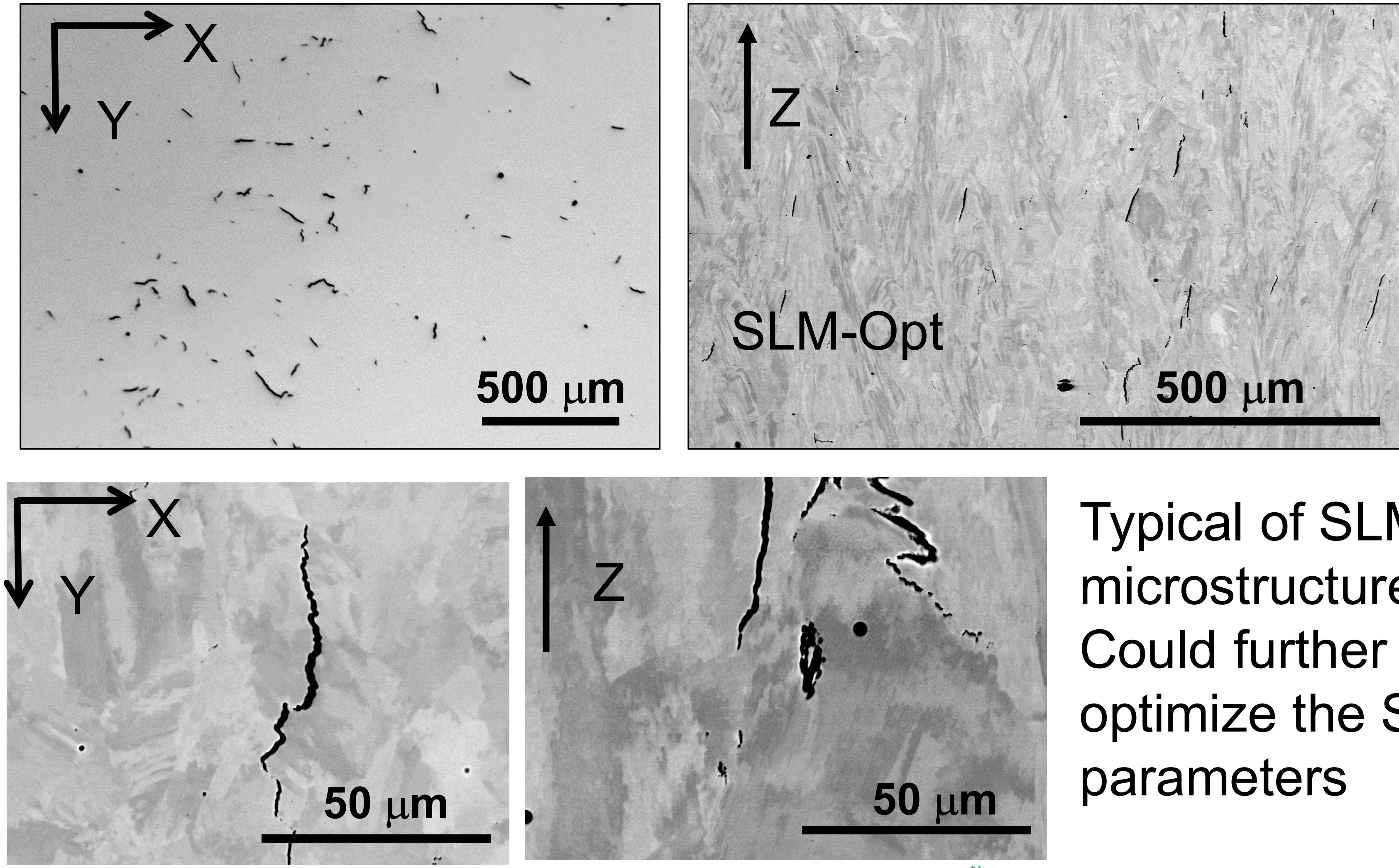


EBM HX Alloys: Need to Develop Build Parameters for a Given Composition?

Hot tearing observed for very low Si and Mn HX alloy
Opposite to what has been reported for SLM HX

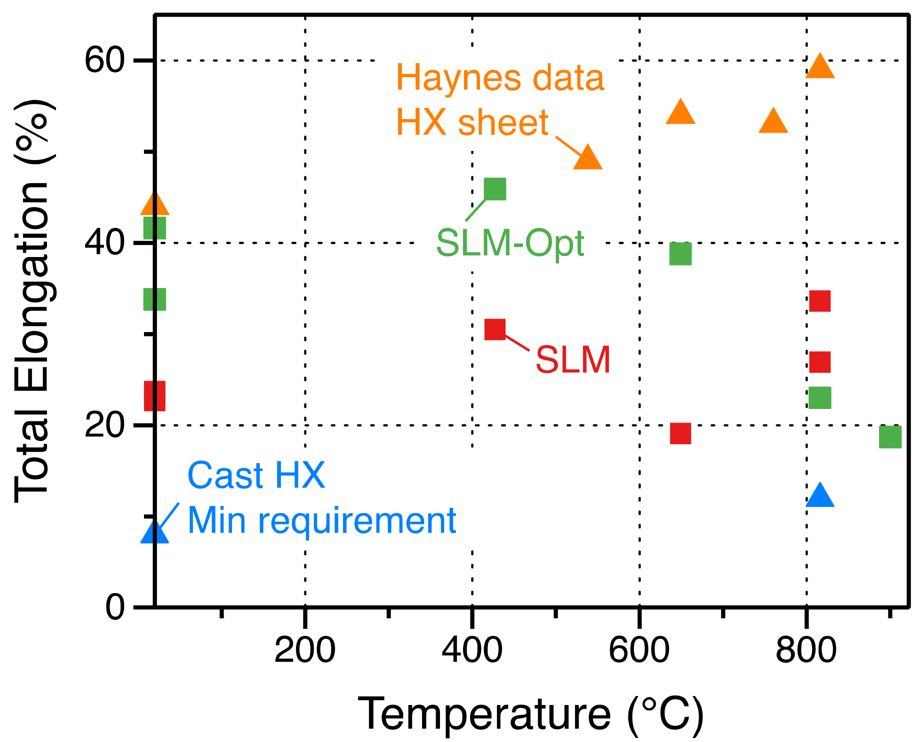


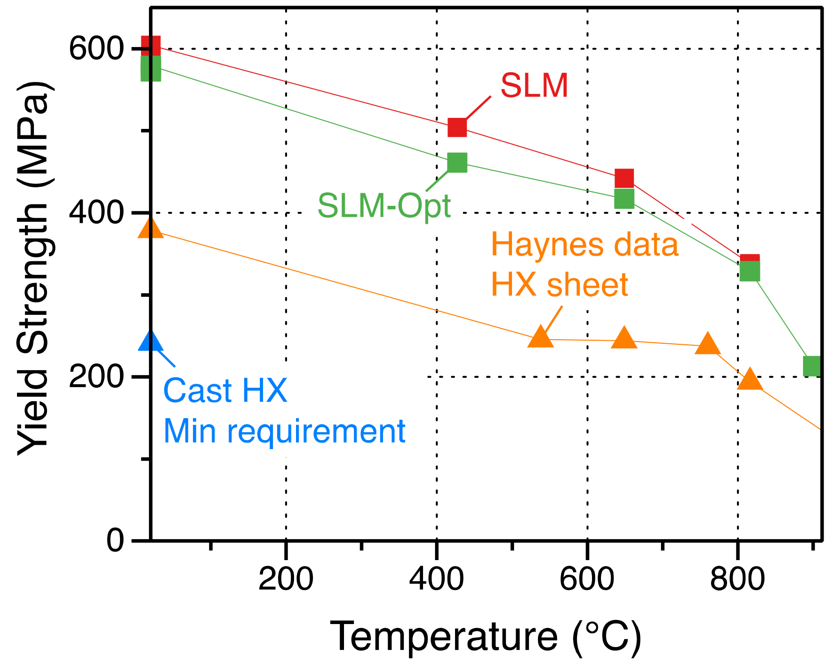
SLM-Opt: Small Grains, No Precipitate Hot Tearing Cracks

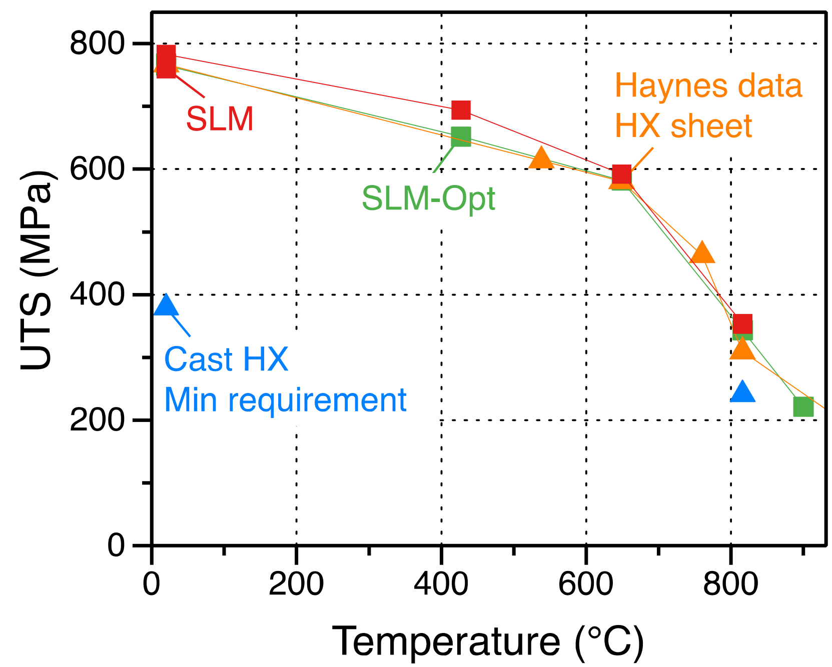


- Typical of SLM microstructure
- Could further optimize the SLM parameters

SLM HX Exhibits High Strength but Moderate Ductility

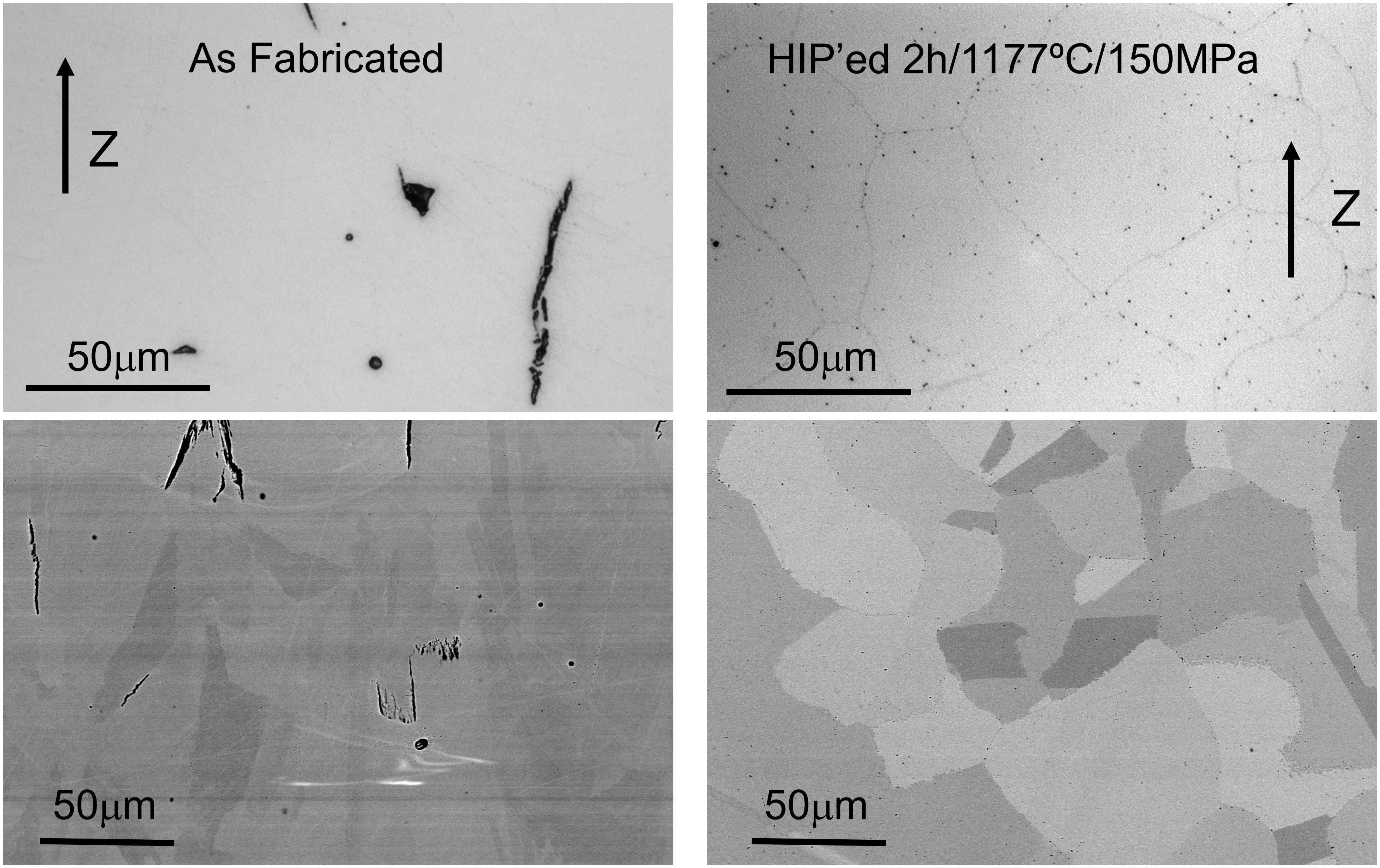






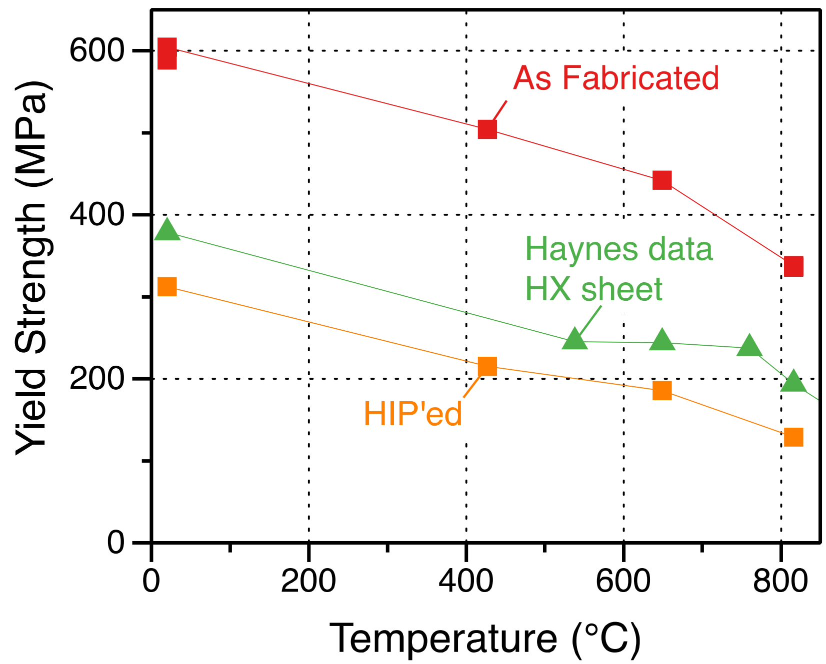
- High YS due to high residual stress
- Higher ductility for SLM-Opt

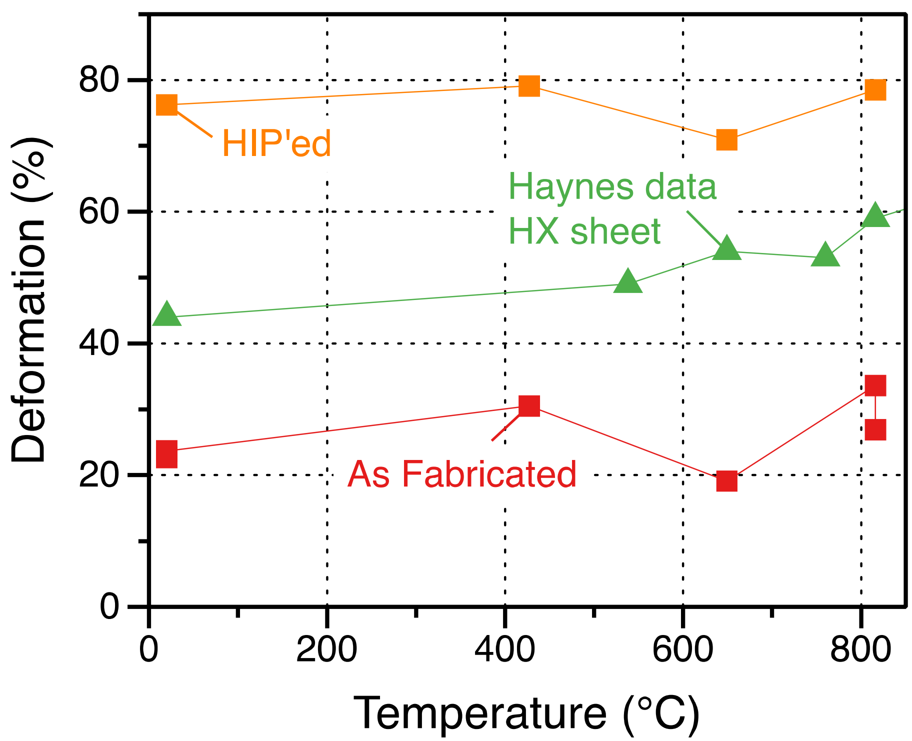
SLM: Fully Dense Material After HIP'ing at 1177ºC/2h/150MPa+Recrystallization

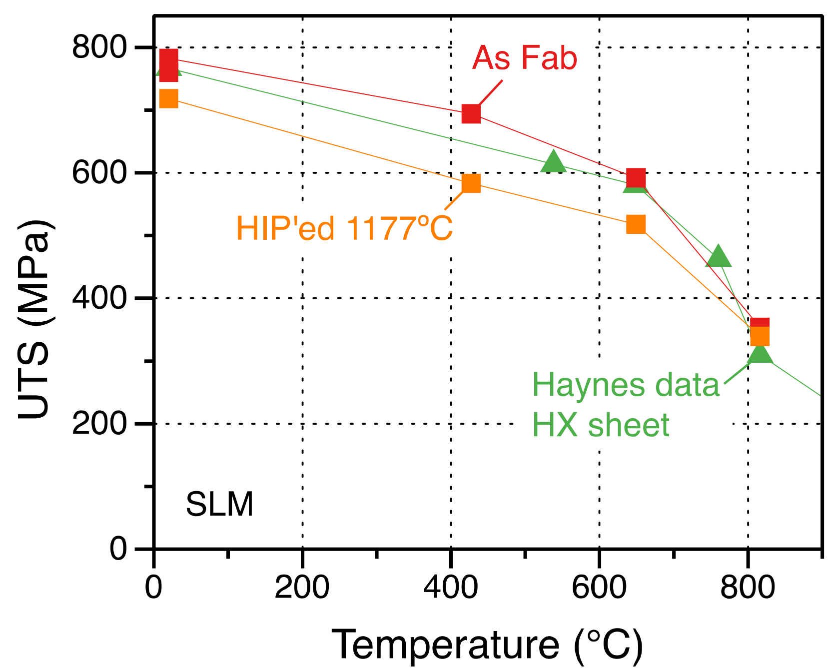


SLM: Increase of Ductility and Decrease of YS after HIP'ing 2h/1177ºC/150MPa

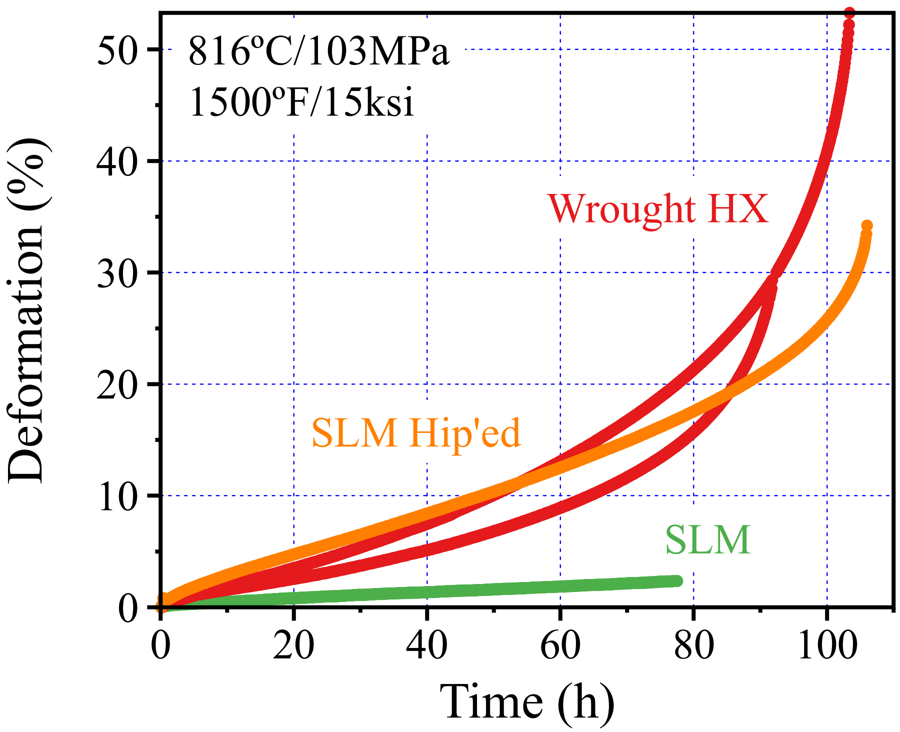
Release of Residual Stress + Microstructure evolution

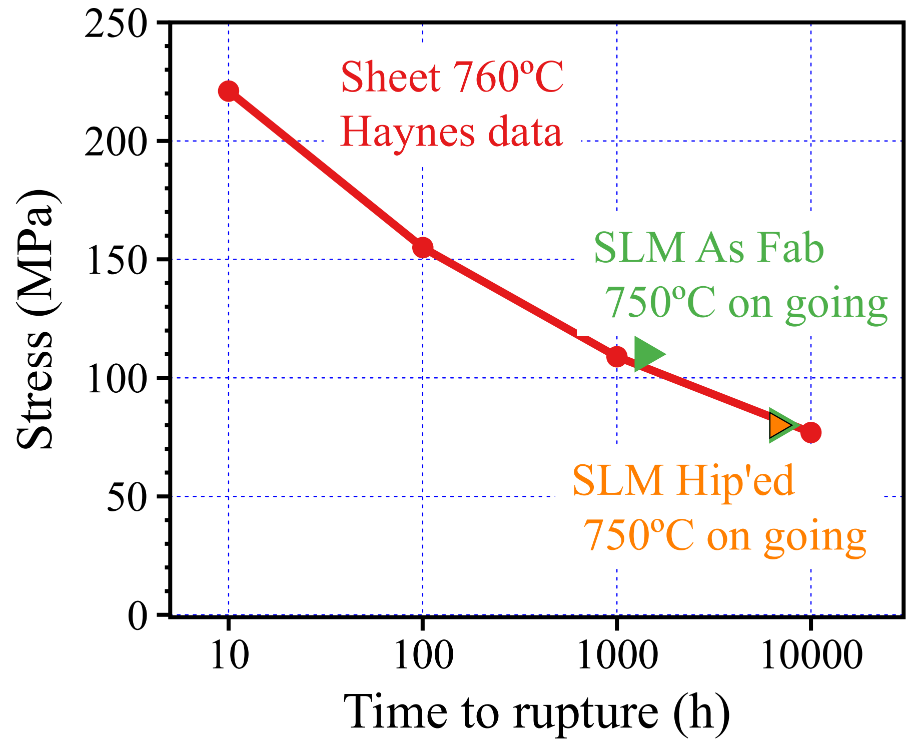






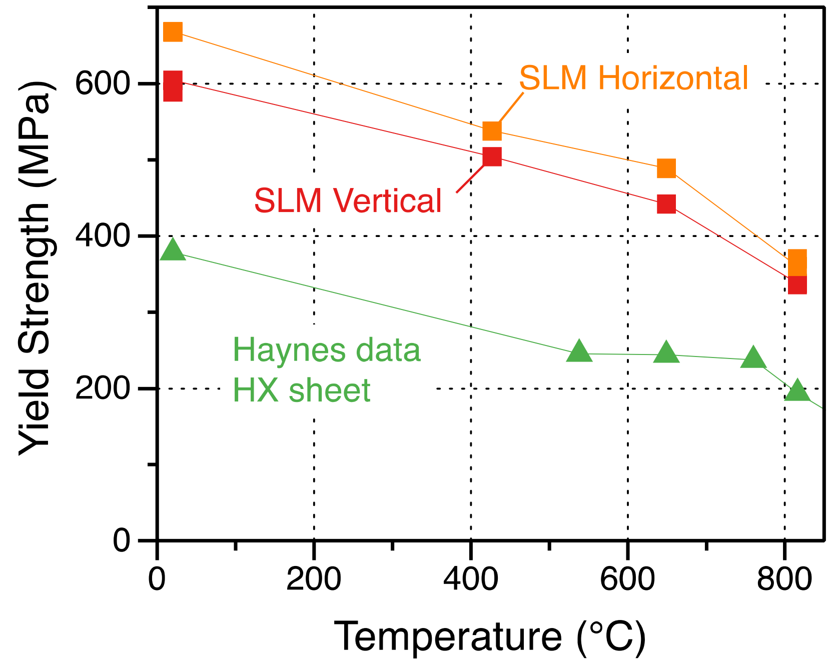
SLM: Very Good Creep Lifetime
Ductility improvement after Hip'ing

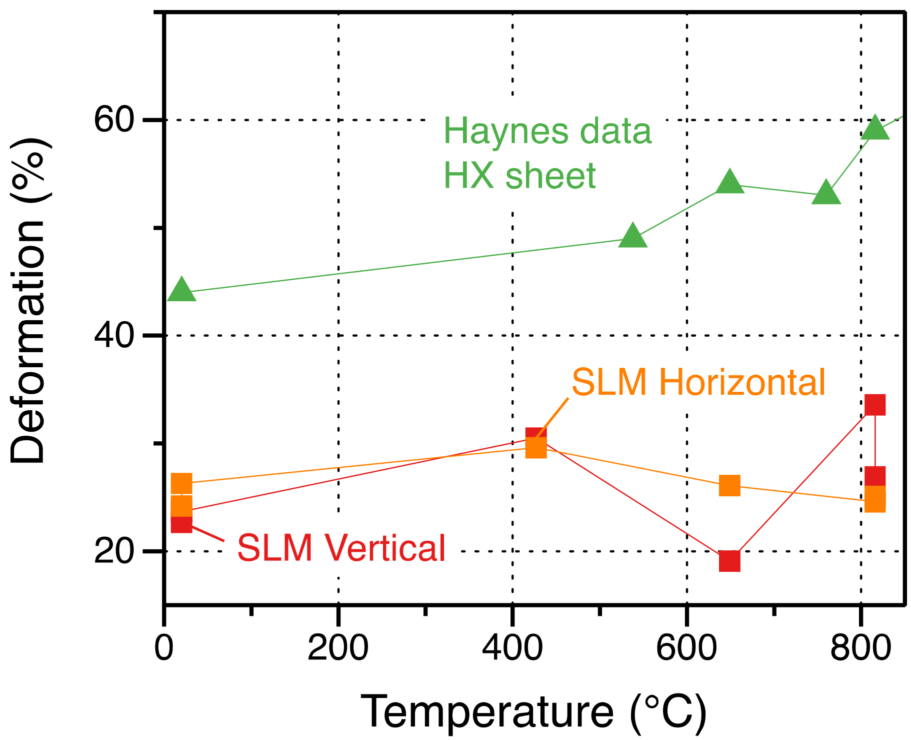


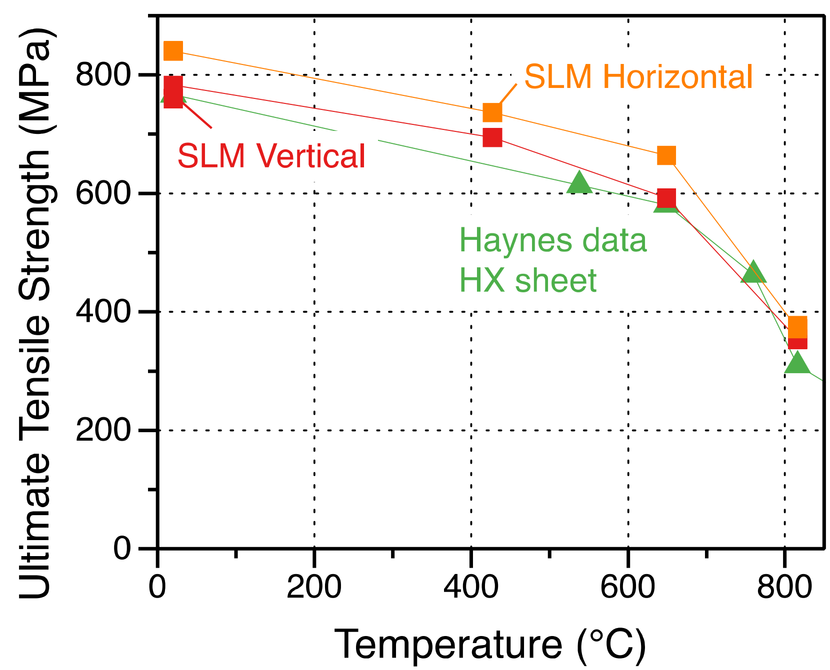


2 tests reached ~7,000h

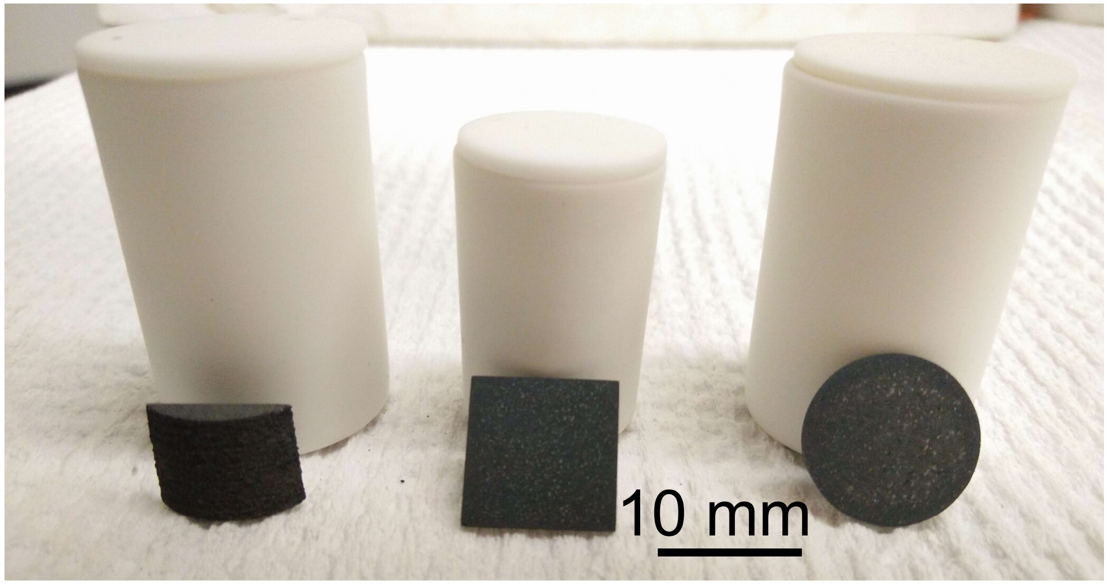
SLM HX Alloys Similar properties along and perpendicular the build direction





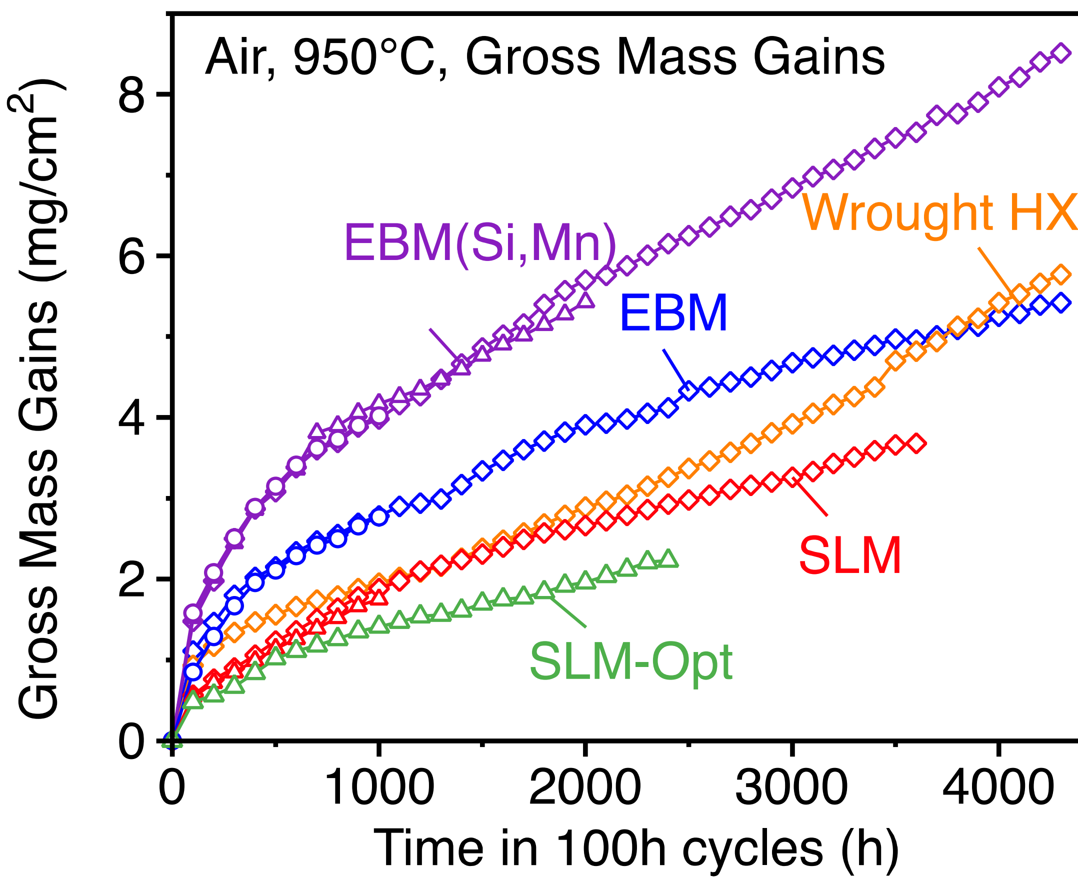


Cyclic Oxidation Testing of HX in Box Furnace at 950ºC, 100h Cycles

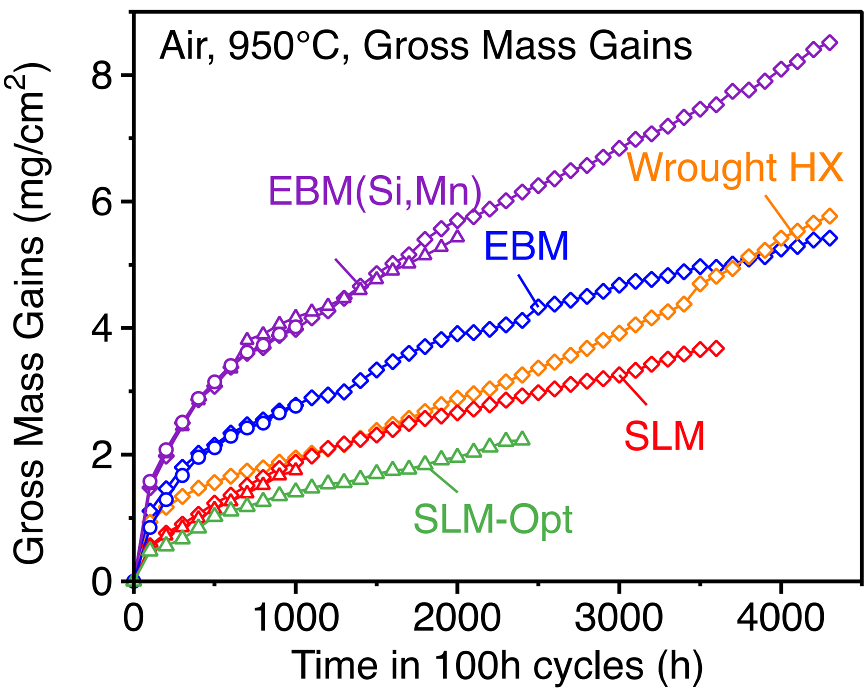


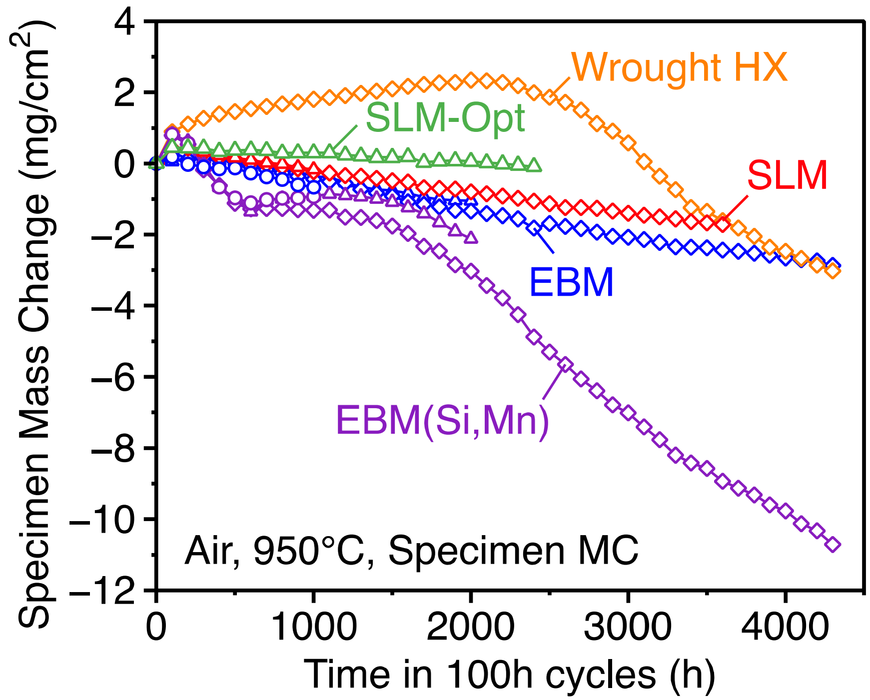
- 950ºC for fast assessment of long-term oxidation behavior
- As Fabricated AM coupons. **Polished** & not polished
- Crucible to generate both specimen and gross mass gains
- Gross mass gains = oxygen pickup ~ Metal (Cr) loss
- Surface imaging using Keyence 3D microscope

Faster Oxidation Rate for EBM(Si,Mn) Similar Rate for EBM and Wrought HX Lower GMG for SLM specimens

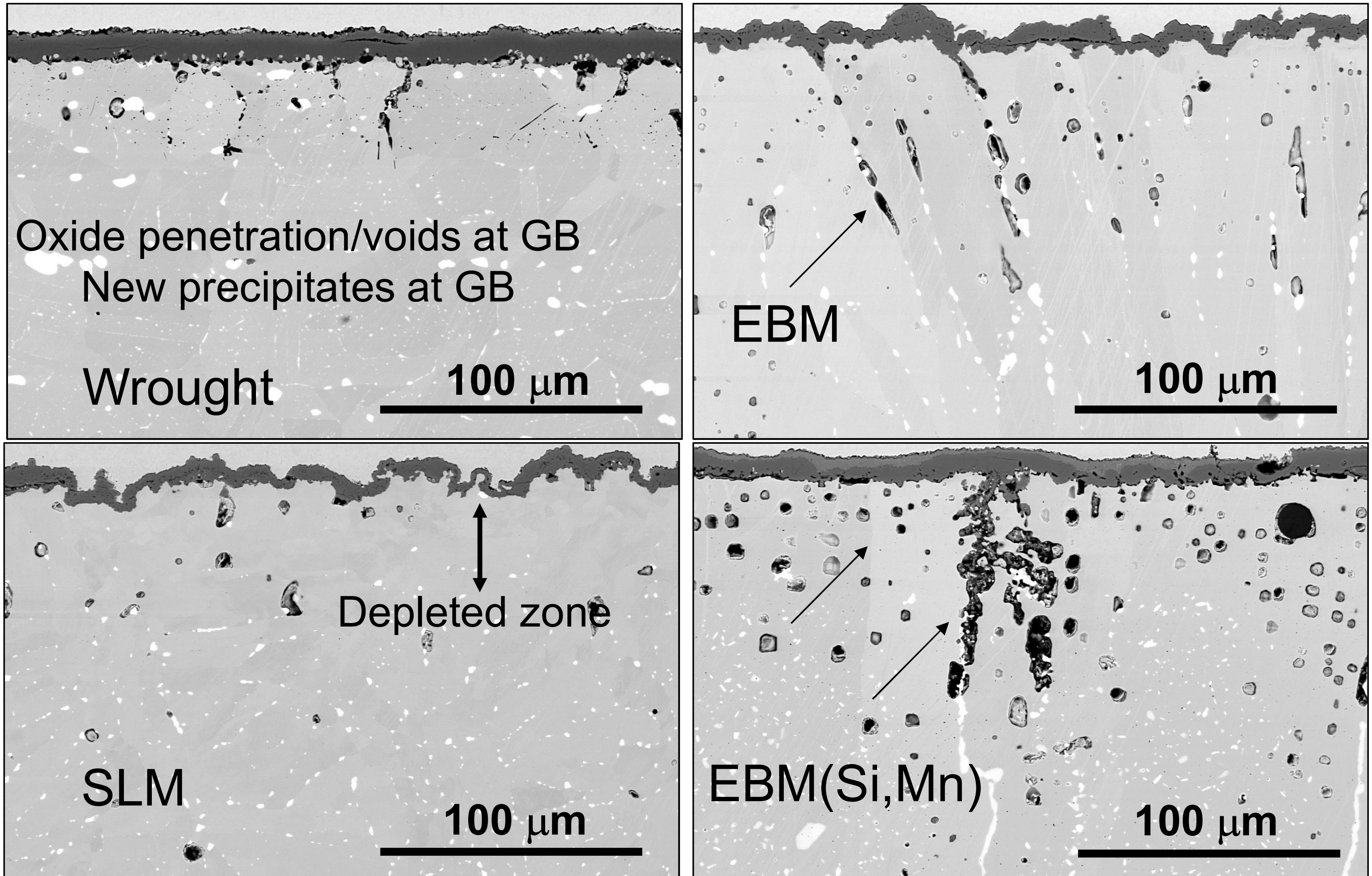


High Spallation for EBM(Si,Mn). Moderate Spallation for SLM & EBM. Increasing Spallation for Wrought HX

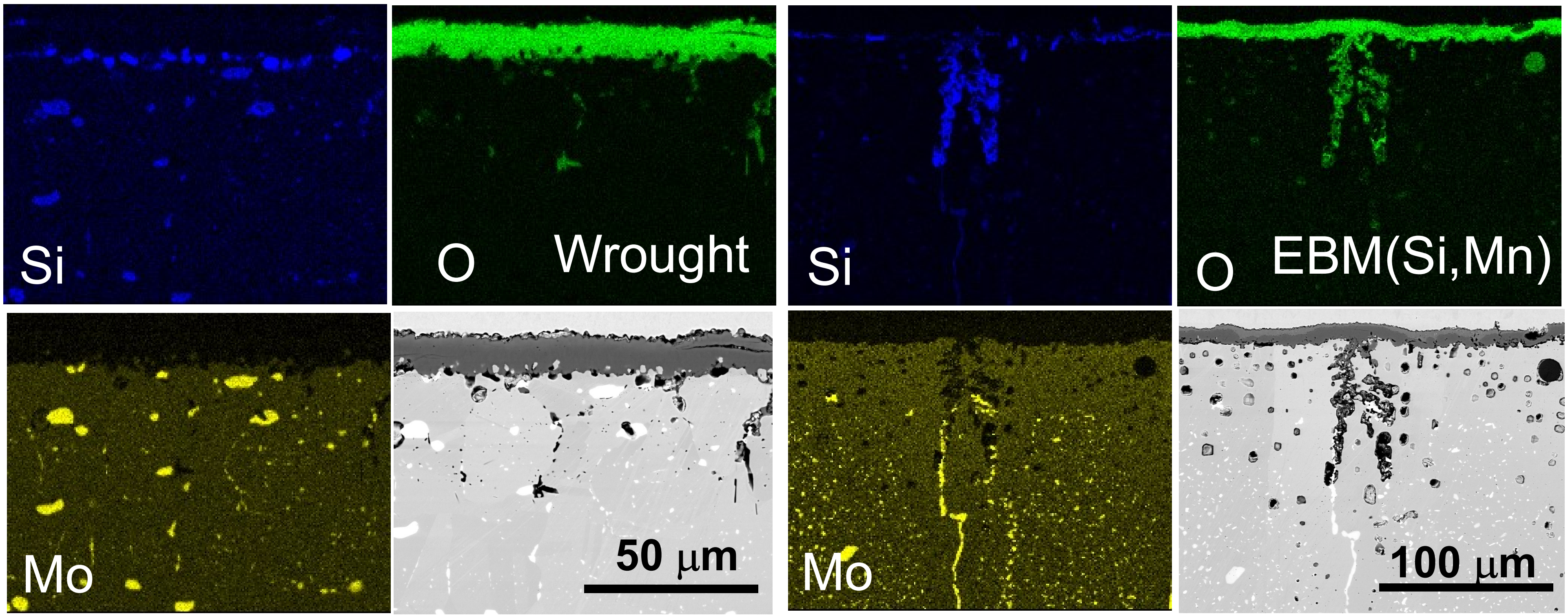




10x100h Cycles: Voids formation in the Grain and at GB for EBM HX

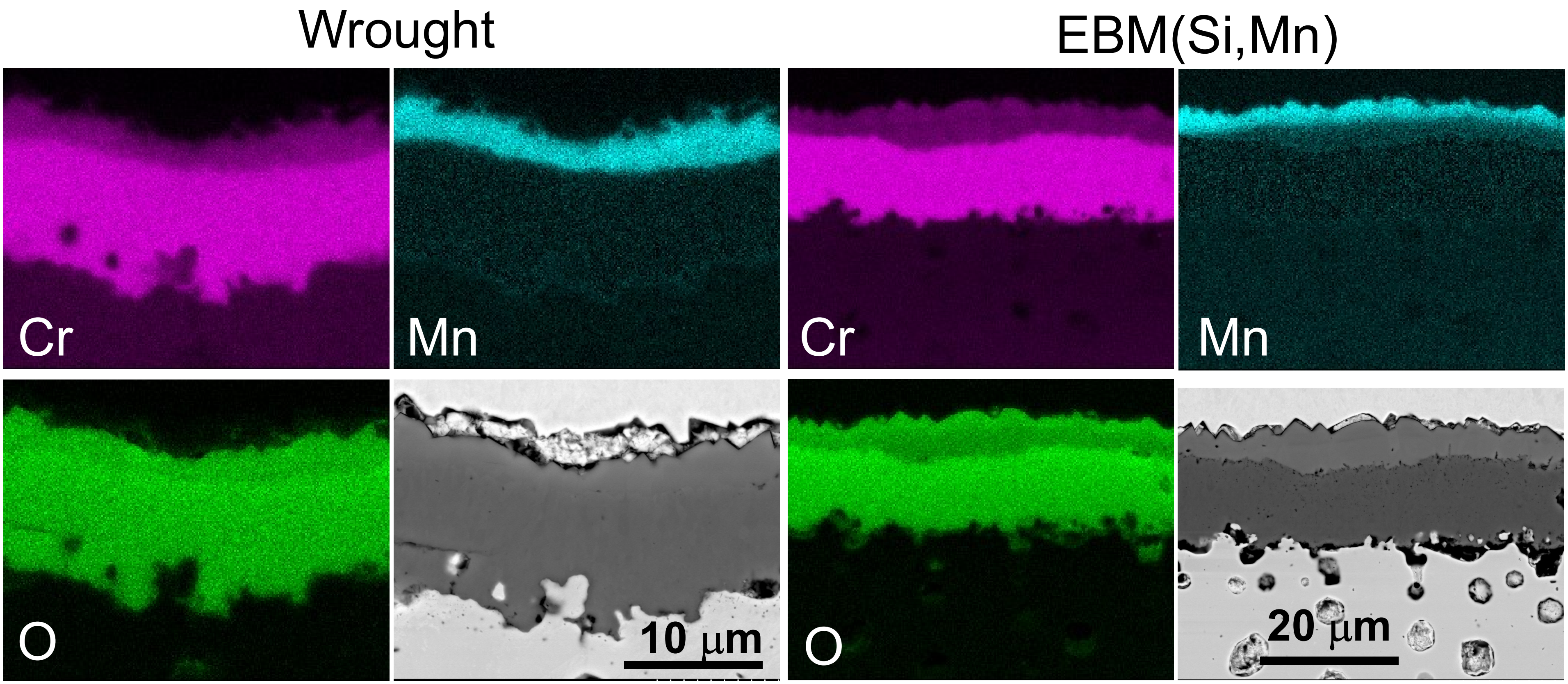


1000h, 950°C, Wrought and EBM(Si,Mn): Si segregation at Interface + Voids formation related to Mo evaporation

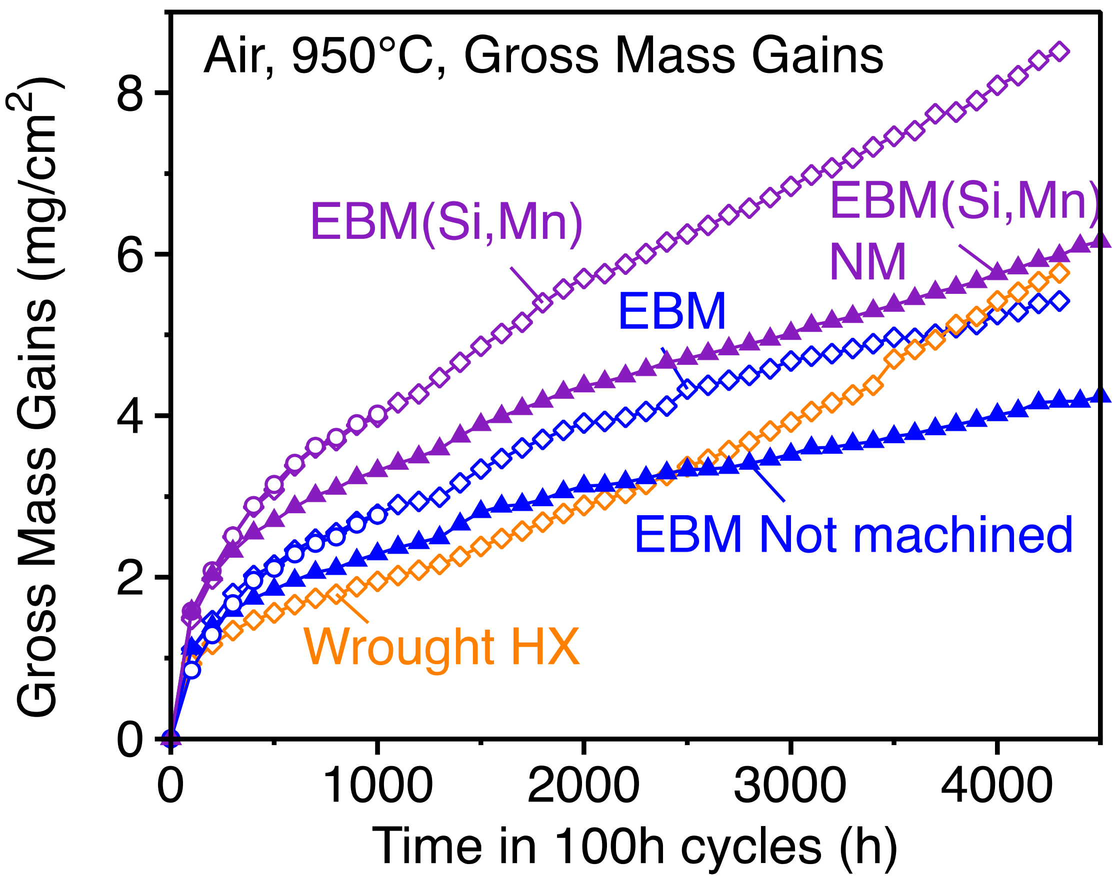


Cr-rich oxide + numerous voids at GB
Mo depleted zone for EBM(Si,Mn)

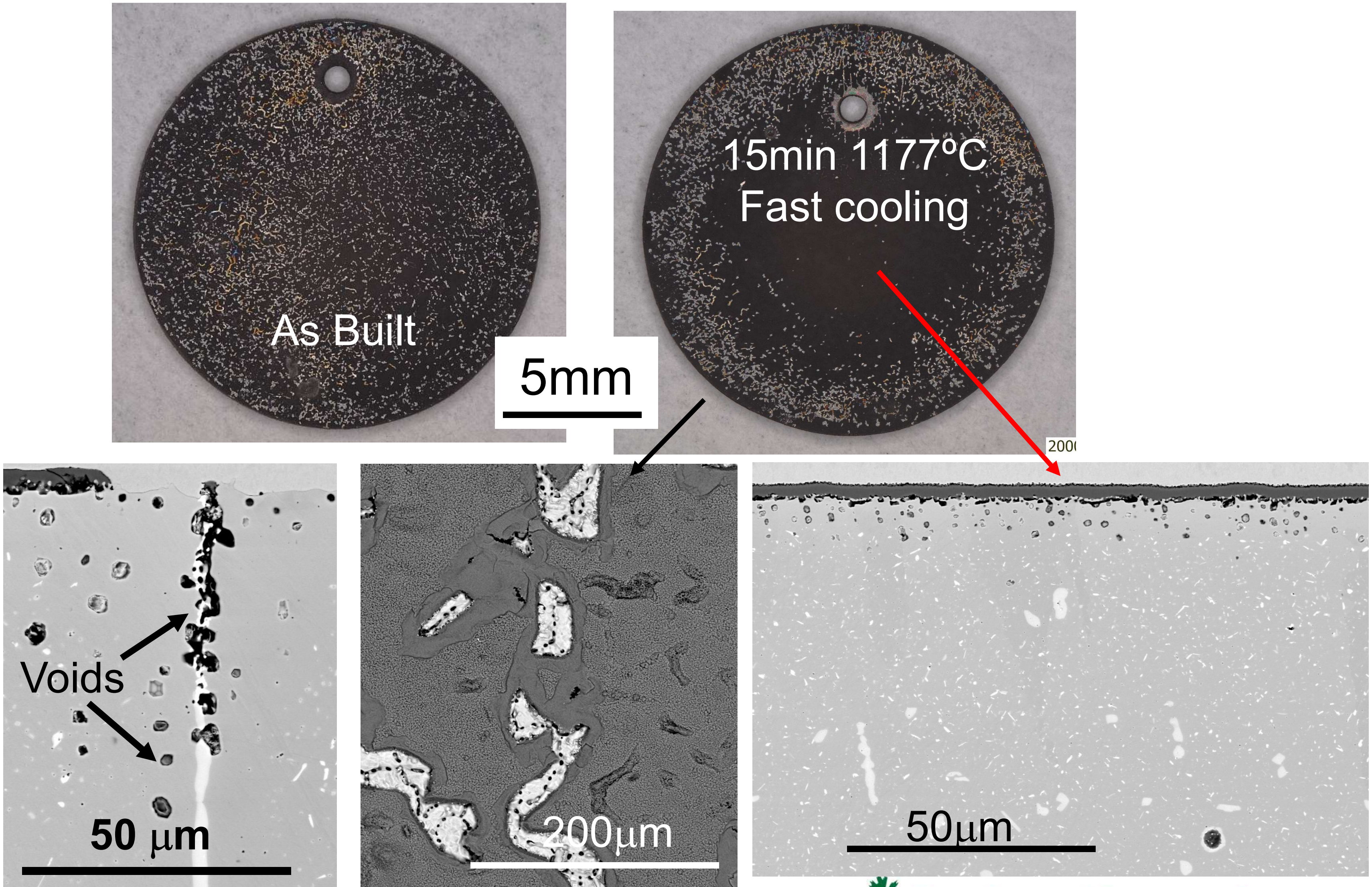
1000h, 950ºC, Wrought & EBM(Si,Mn): (Cr,Mn) and Cr-Rich Layers



Better Oxidation Behavior for the EBM Specimen not Fully Machined



Locally Less spallation after 15min 1177ºC Fast Cooling for EBM(Si,Mn)



Conclusion

- EBM HX shows good ductility and tensile strength superior to the cast HX requirement. Anisotropy might be an issue
- Good fatigue properties for the EBM HX but lower creep strength. Sufficient for some applications using cast HX?
- Hot tearing led to crack formation in SLM as observed by others. Could further optimize fabrication parameters and/or alloy composition
- SLM HX exhibited good tensile strength and acceptable ductility. Good creep strength but limited ductility. Great ductility improved after Hip'ing
- Great potential for improvement: chemistry, deposition parameters , post treatment…for properties superior to wrought HX?