Microstructure and Properties of Hastelloy X Fabricated by Additive Manufacturing

Sebastien Dryepondt, Mike Kirka,
Patxi Fernandez-Zelaia & Fred List

ORNL project FEAA119

Crosscutting Review Meeting

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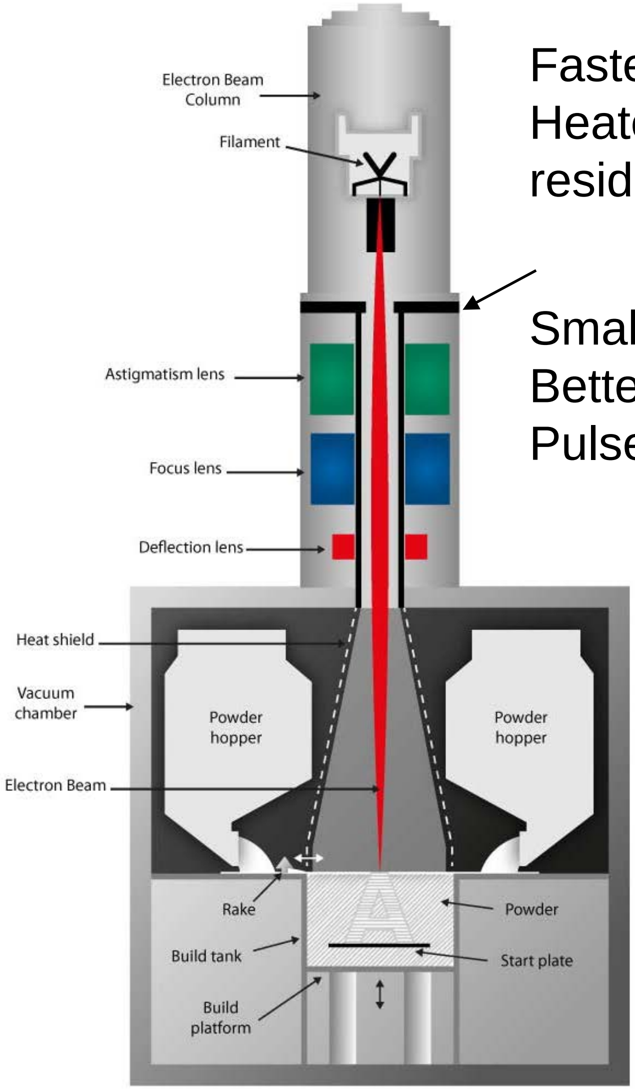
Project Objectives

- Optimize additive manufacturing (AM) fabrication processes for solution strengthened Hastelloy X (HX, Ni-22Cr-19Fe-9Mo) gas turbine components (Fuel injector, Combustor)
- Effect of annealing / HIP'ing on microstructure and mechanical properties of parts fabricated by Selective Laser (SLM) and Electron Beam Melting (EBM)
- Generate data for AM Hastelloy alloy (Tensile, Fatigue, Creep, Oxidation) relevant for Fossil Energy (FE) applications
- Compare properties along and perpendicular to the build direction

HX Made by EBM and SLM

Ebeam (Arcam S12)



Faster
Heated bed = lower residual stress

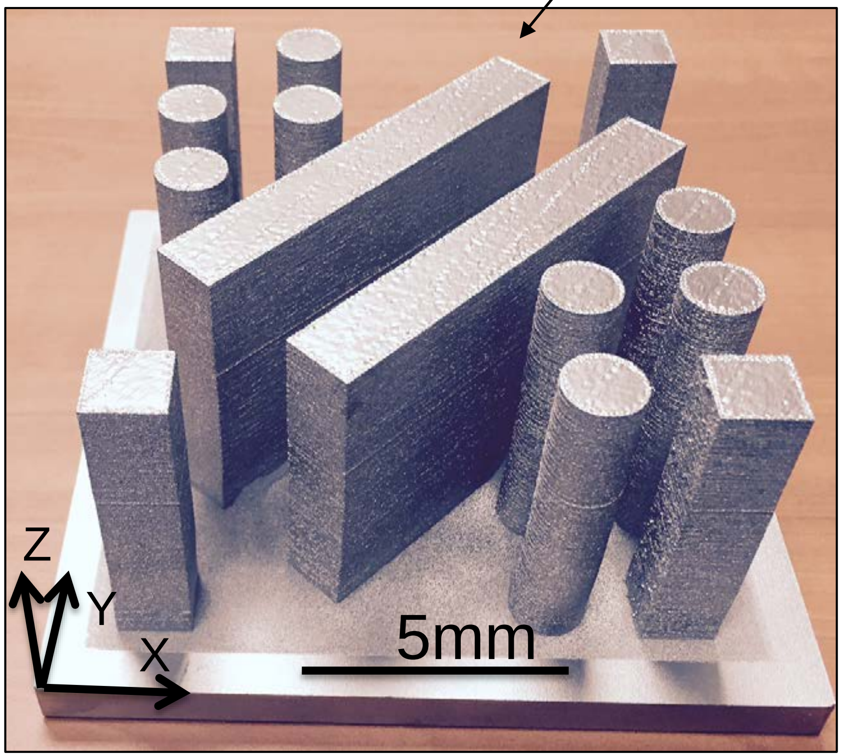
Laser (Renishaw AM250)

Smaller beam size
Better resolution
Pulsed laser beam

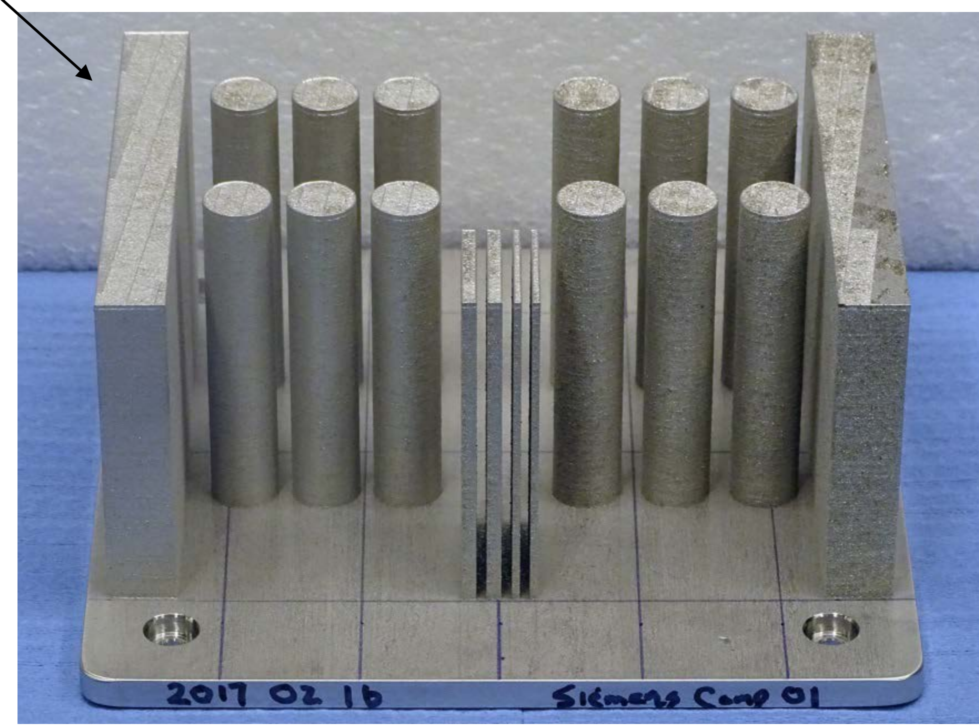
Fabrication of EBM and SLM Rods & Plates For Tensile, Creep, Fatigue and Oxidation Testing

Specimen machining perpendicular to the build direction

Arcam S12



Renishaw AM250



Initial specimen surface removed by machining

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

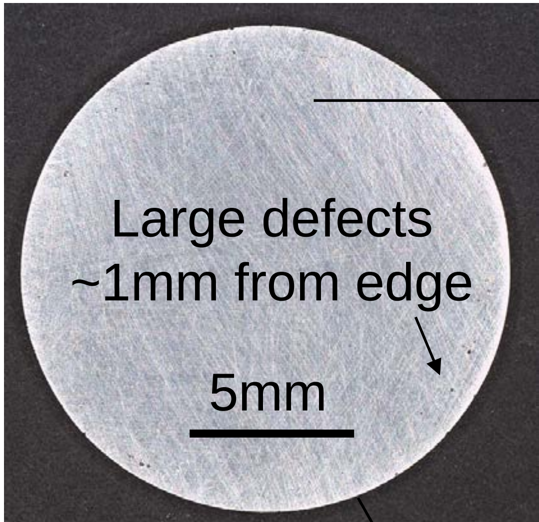
Hastelloy X (Ni-22Cr-19Fe-9Mo)

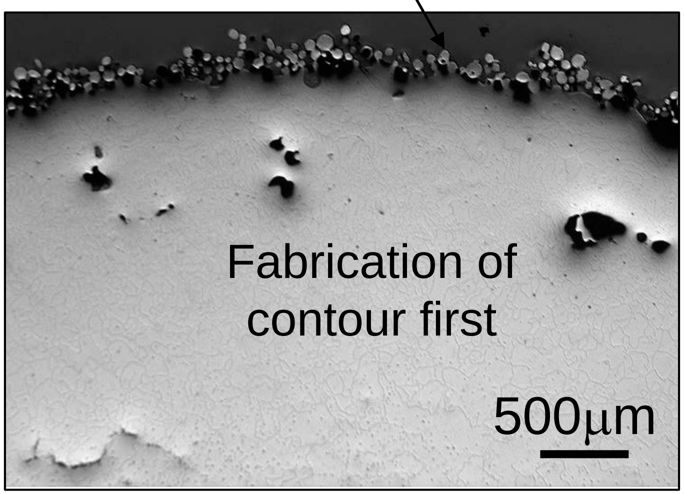
	Ni	Cr	Fe	Mo	Co	Mn	Si	W	C
EBM Alloy	Bal.	21.38	18.55	9.05	1.55	0.01	0.05	0.64	0.078
EBM(Si,Mn) Alloy	Bal.	21.43	18.87	9	1.56	0.67	0.71	0.65	0.048
SLM-1 Powder	Bal.	21.47	18.83	8.96	1.51	0.01	0.16	0.63	0.07
SLM-2 Powder	Bal.	21.72	18.51	8.87	1.51	0.01	0.06	0.6	0.08
Wrought	Bal.	22.06	17.86	9.53	1.8	0.65	0.31	0.6	0.067

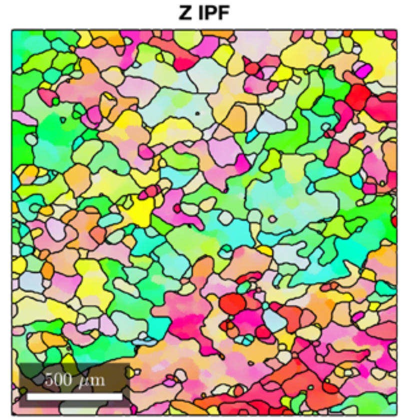
- Alloy composition consistent with EBM powder composition
- High concentration of Mn and Si in EBM(Si,Mn) and wrought HX
- Specification: Mn and Si <1%

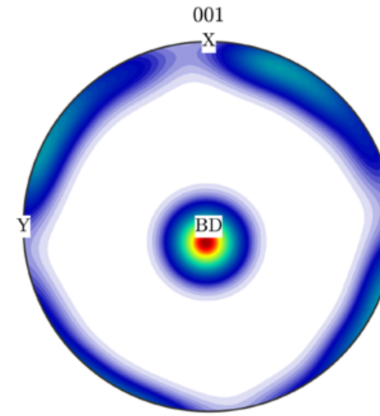
EBM: Textured & Elongated Grains

Perpendicular to build direction

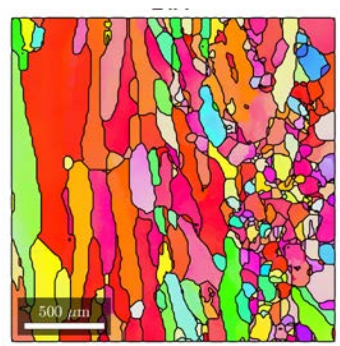




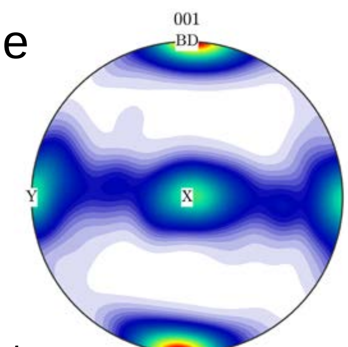




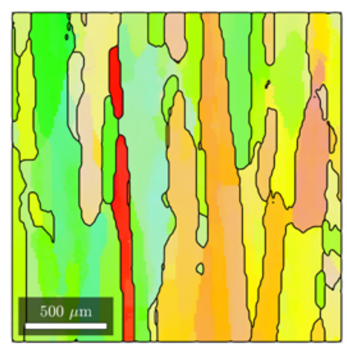
Along the build direction

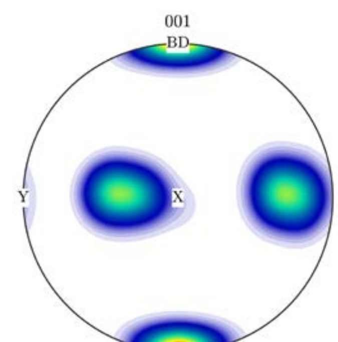


Edge



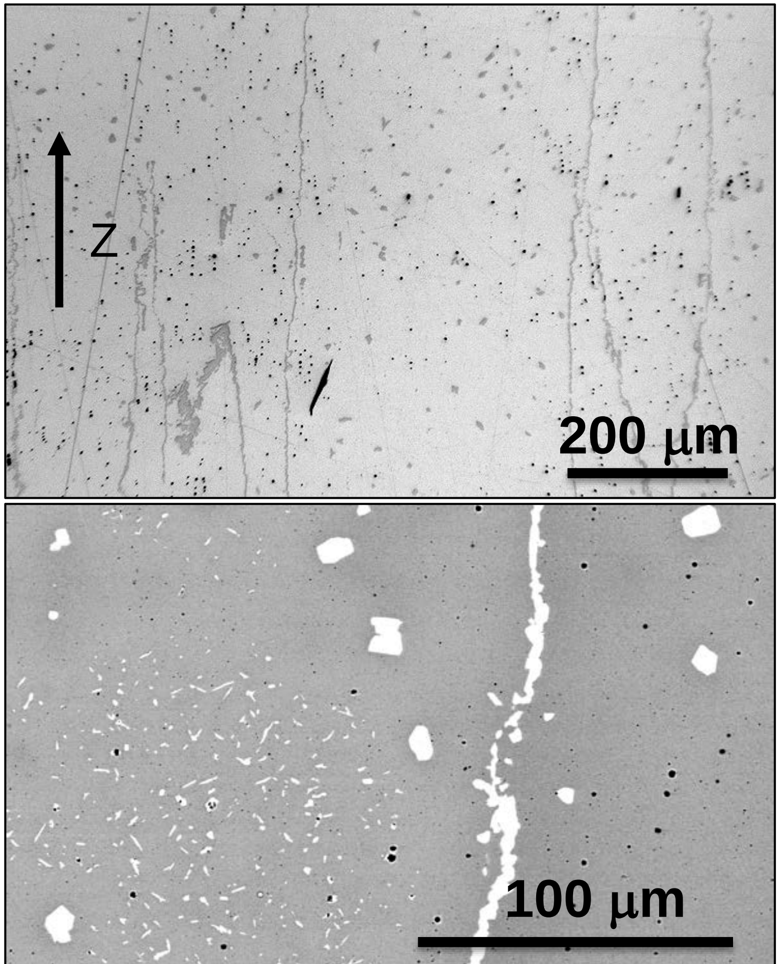
Center



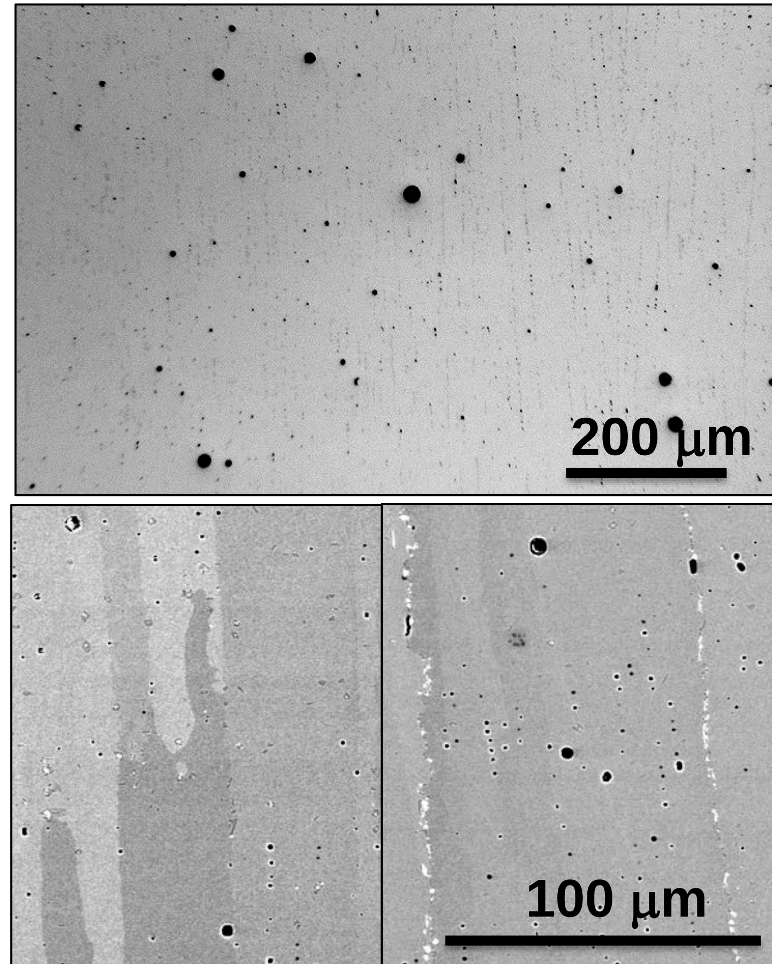


Elongated Grain Along the Build Direction & Greater Number of Precipitates for EBM(Si,Mn)

EBM(Si,Mn) = Larger grains
(Mo,Si)-rich Carbides

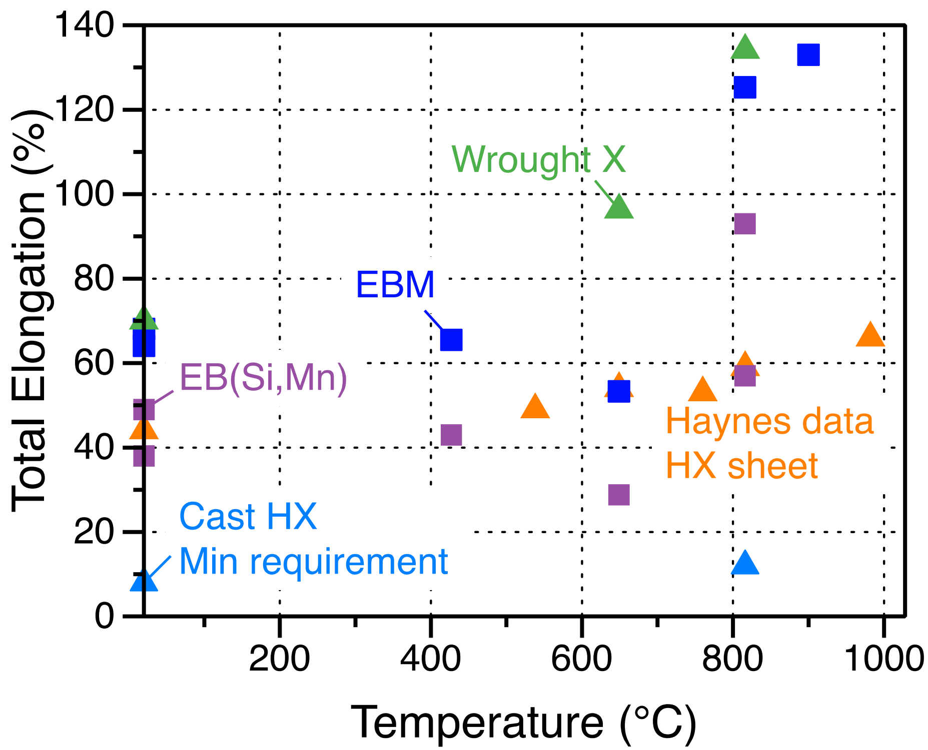


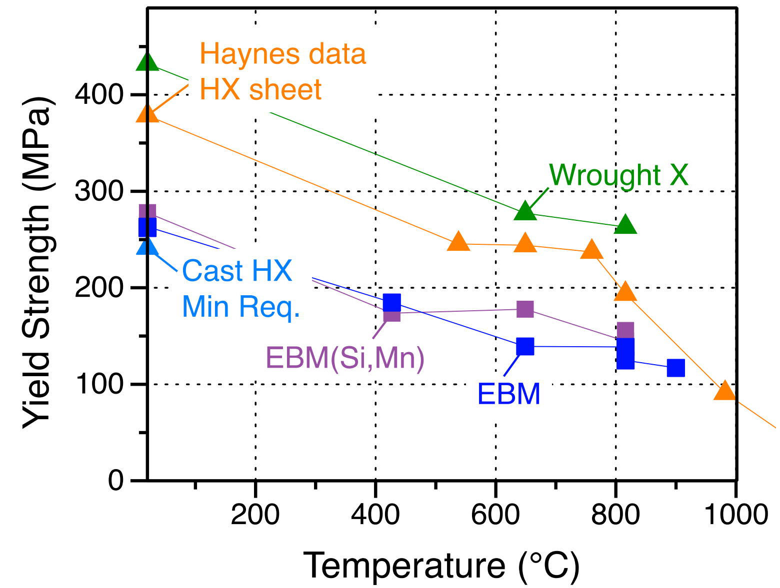
EBM = Larger voids
Mo and (Cr,Mo)-rich carbides

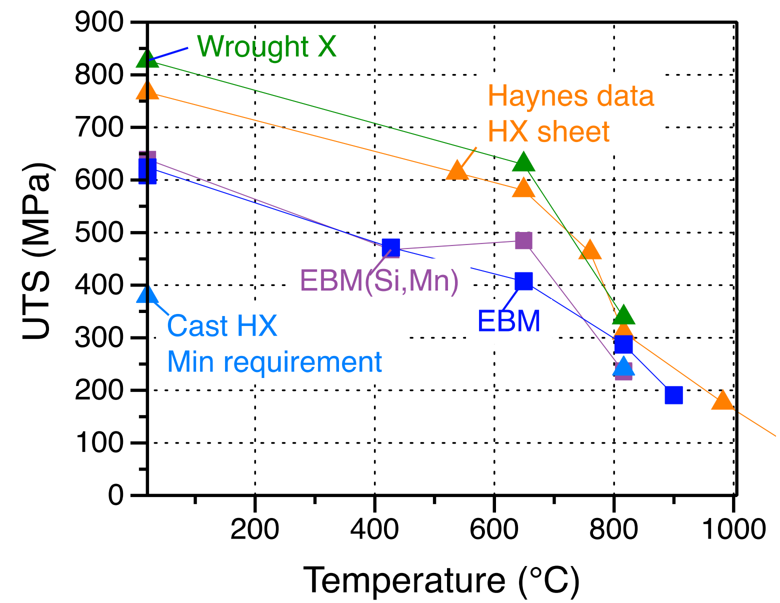


Both EBM & EBM(Si,Mn) HX Alloys Exhibit Good Ductility Along BD But Lower Strength < 800ºC

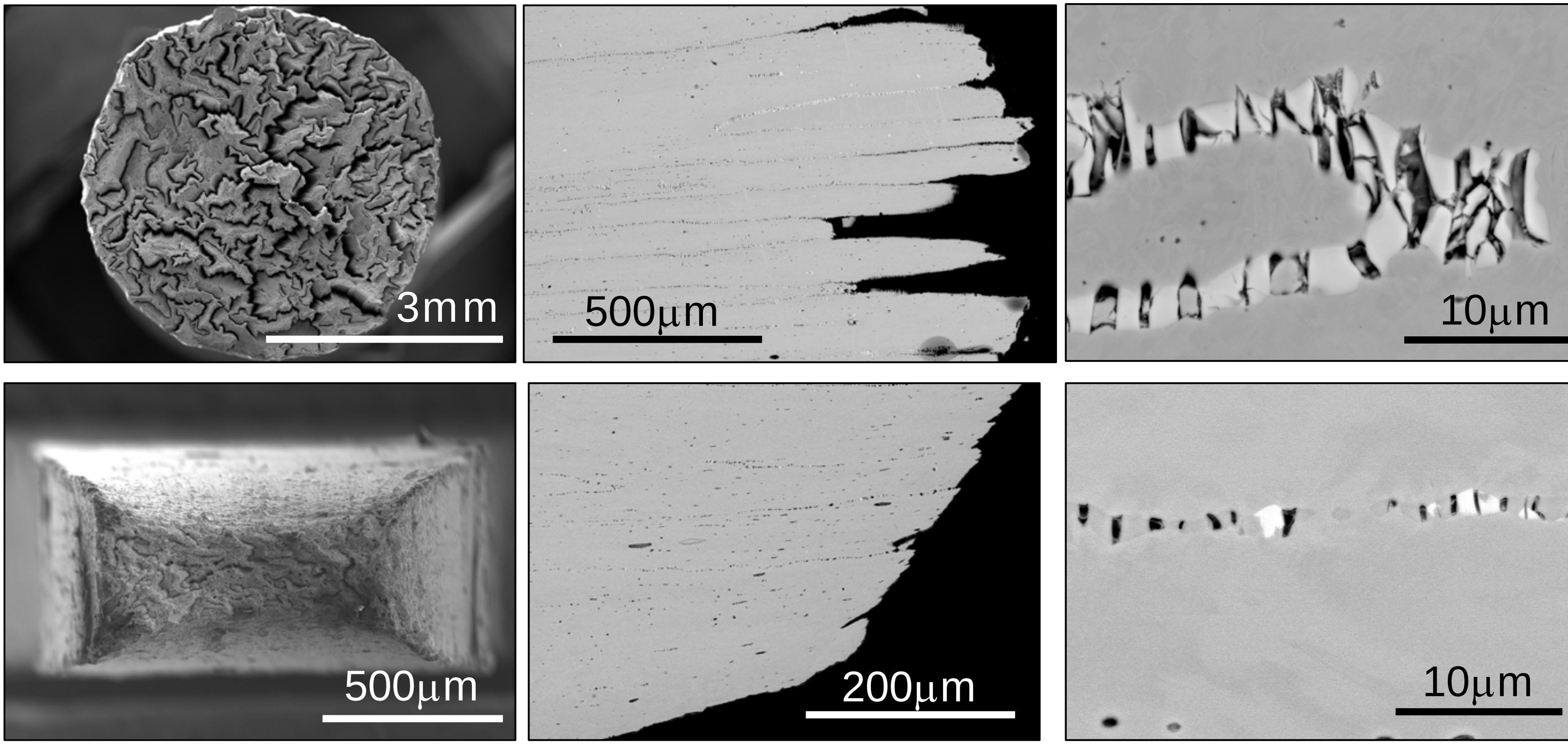
Meet cast HX AMS requirement



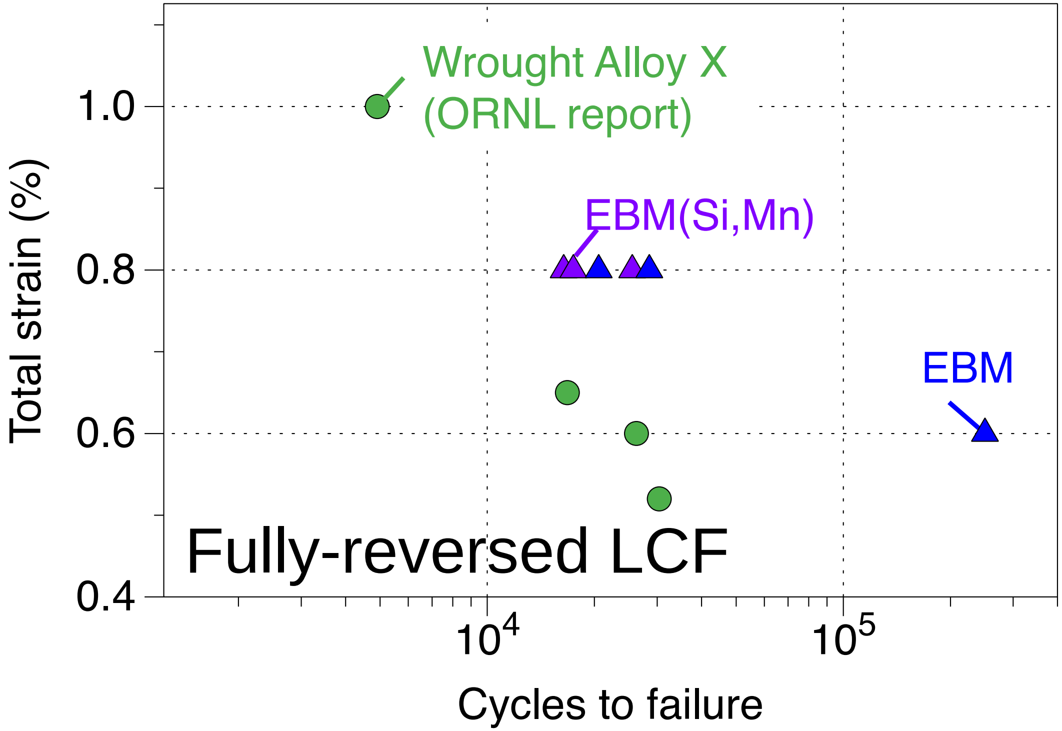


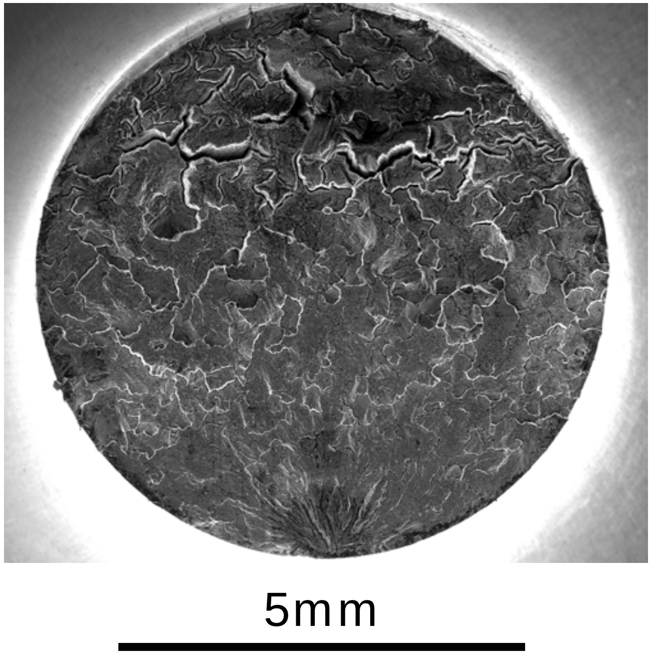


Lower Strength for EBM & EBM(Si,Mn) HX Alloys Due to Elongated Grains+ Weak Grain Boundary Interface



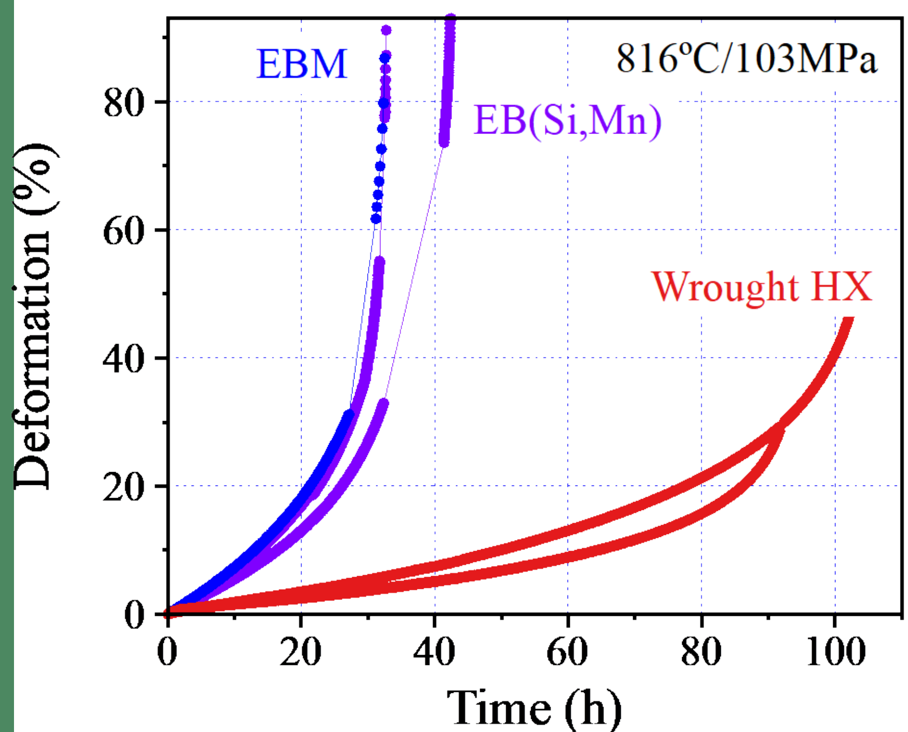
EBM & EBM(Si,Mn): Good Low-Cycle Fatigue Properties at 800ºF/425ºC Along the Build Direction

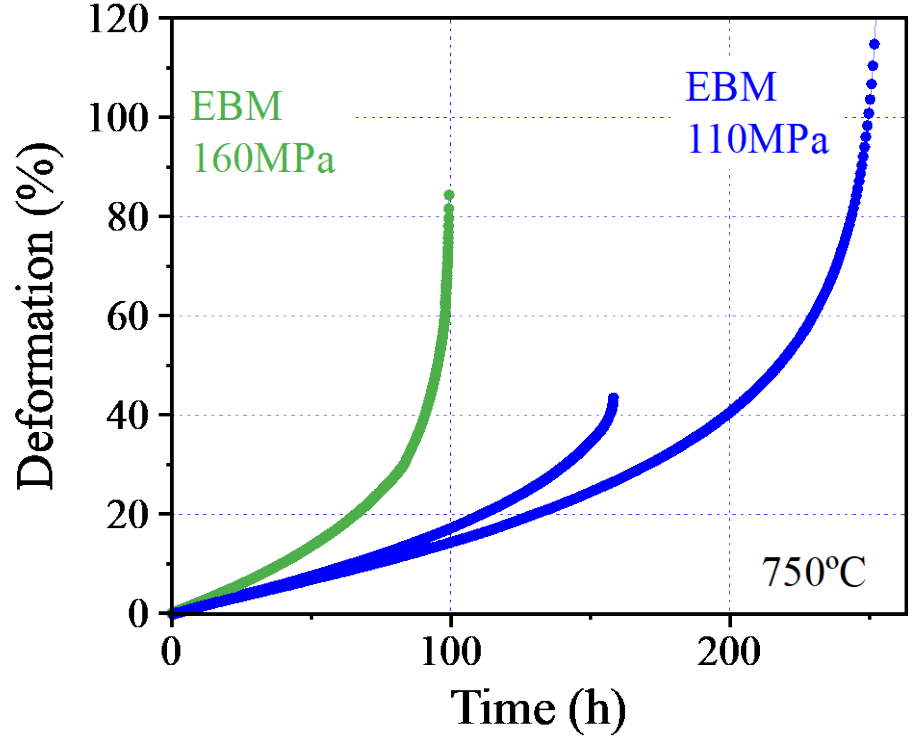




- Crack initiation at interface, not defects

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

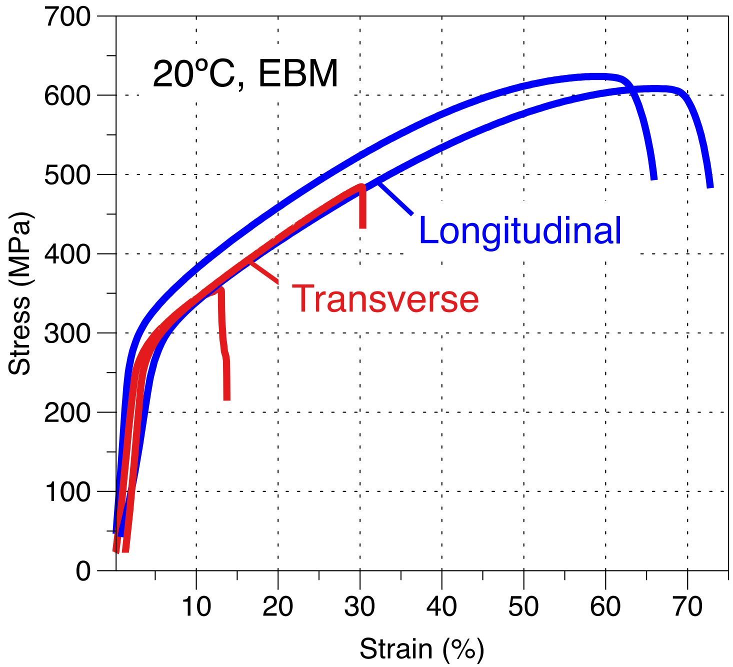


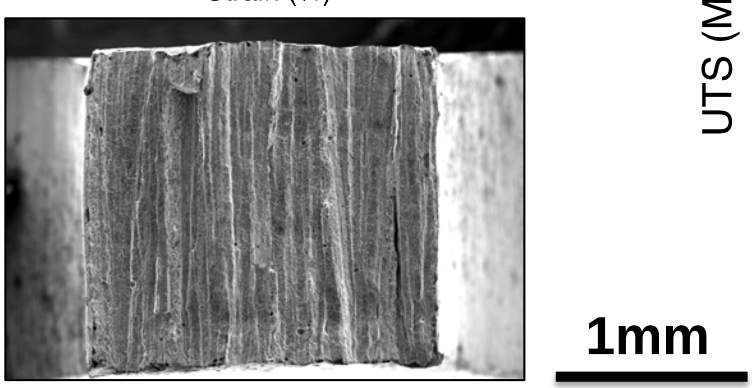


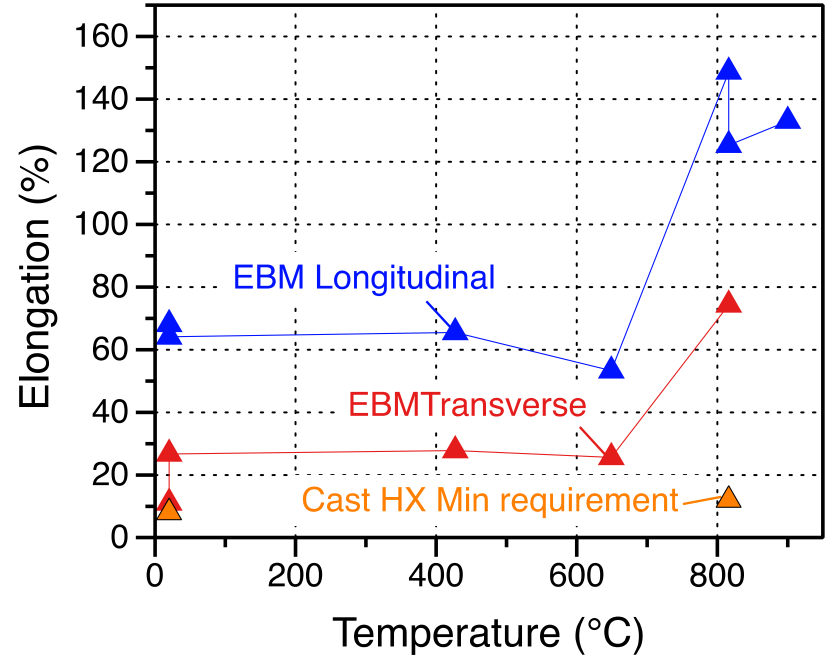
Wrought expected lifetime:

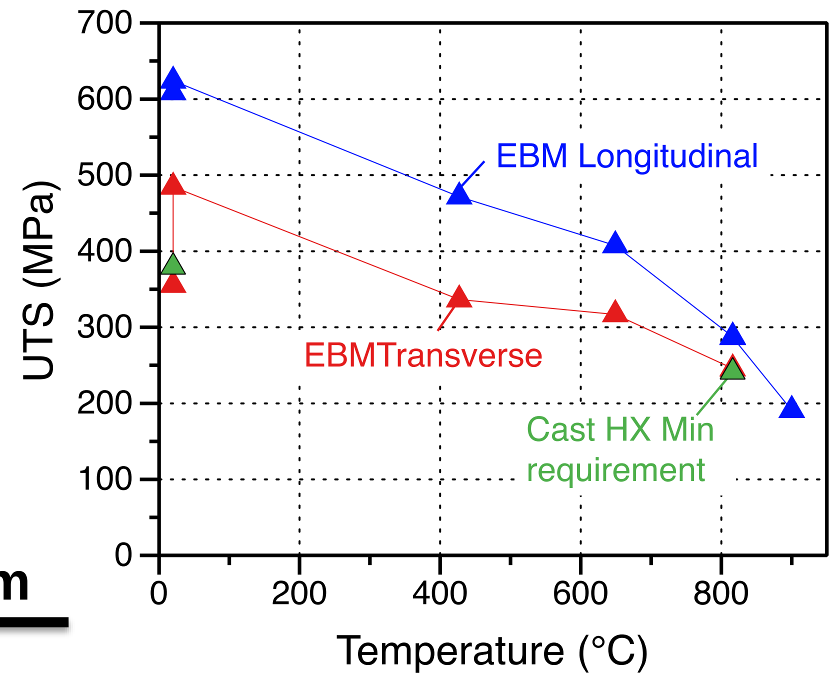
- 160MPa: 100h
- 110MPa: 1000h

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



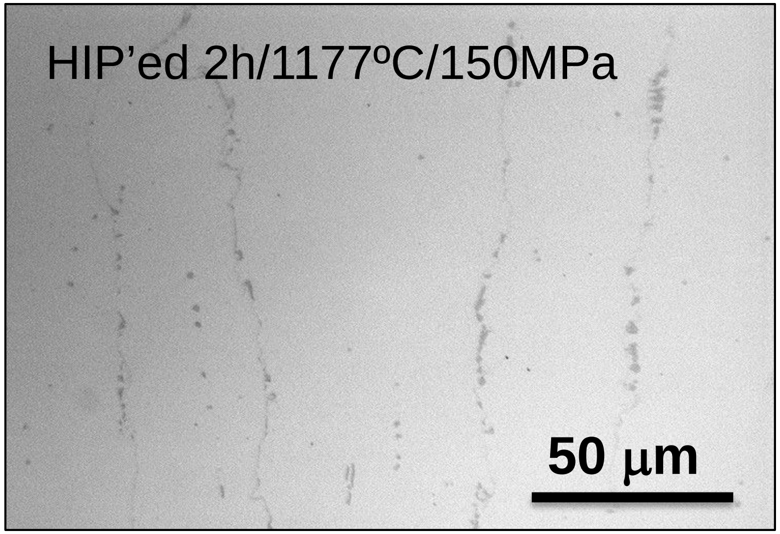


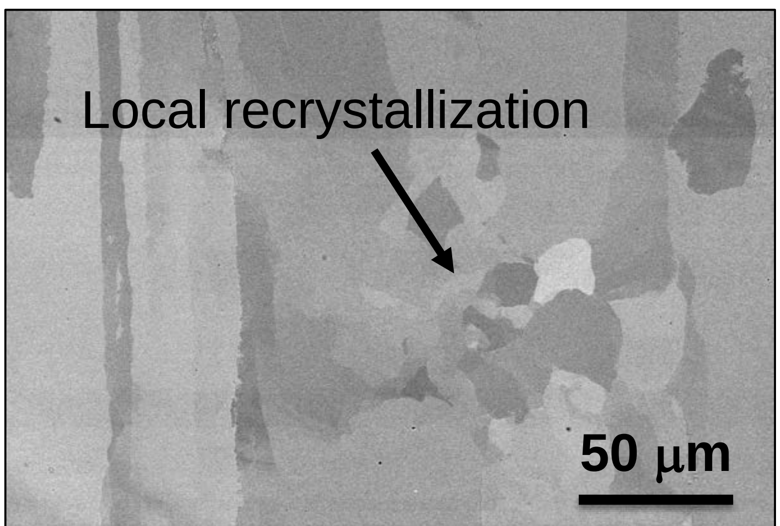




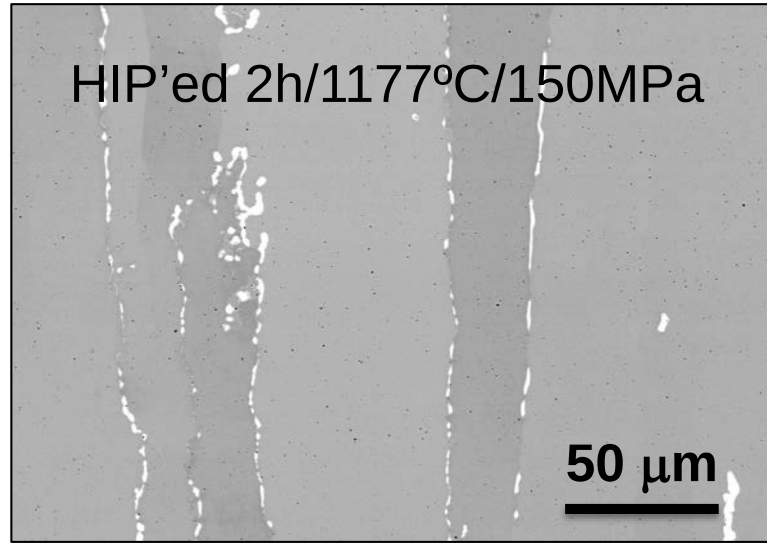
HIP’ing at 1177ºC/2h/150MPa, “Fast Cooling”

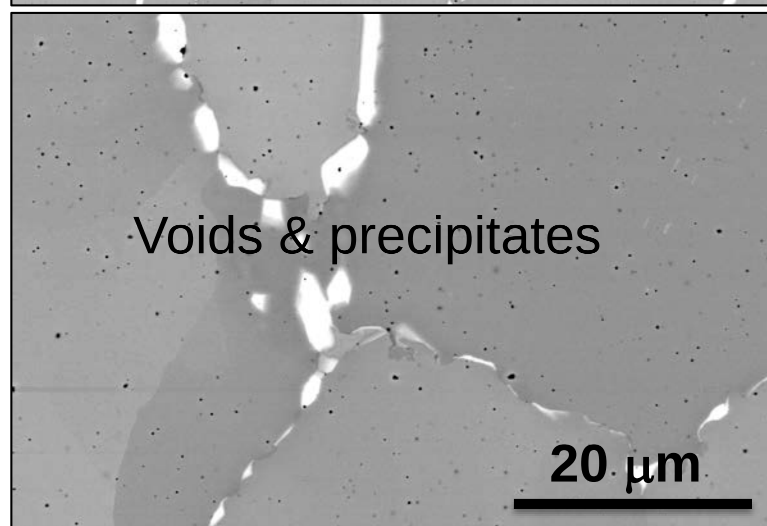
EBM Fully dense, Fewer precipitates



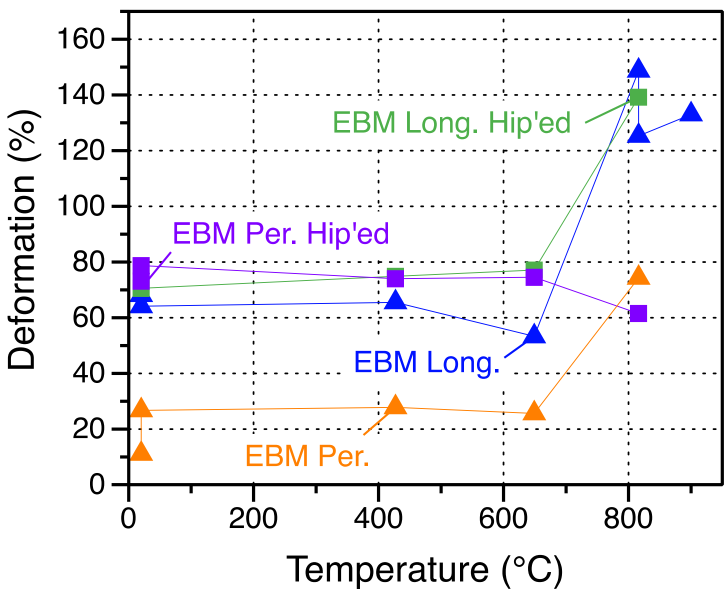


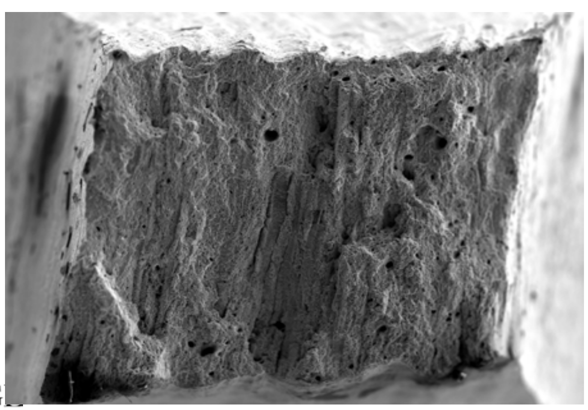
EBM(Si,Mn) Micro voids+precipitates at GB

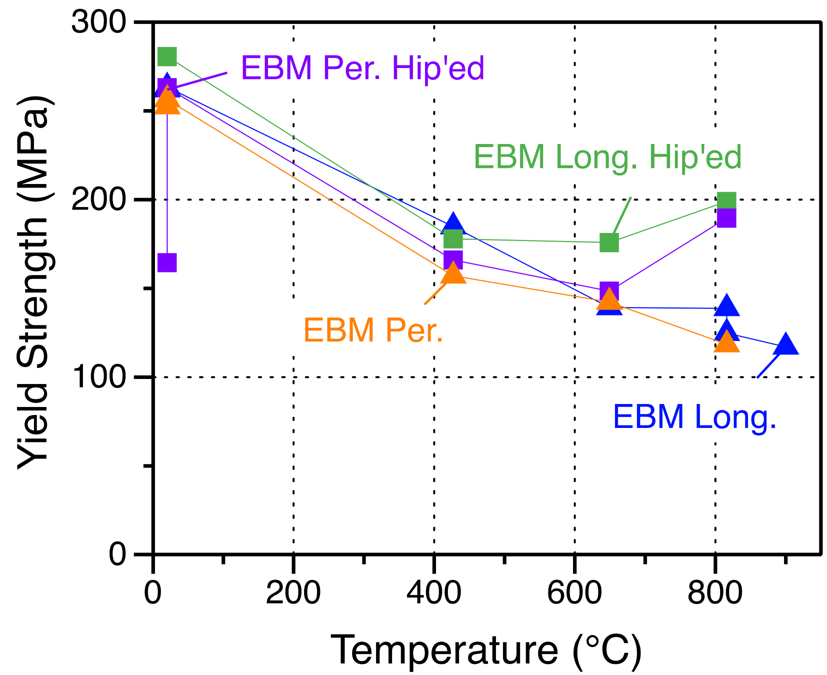


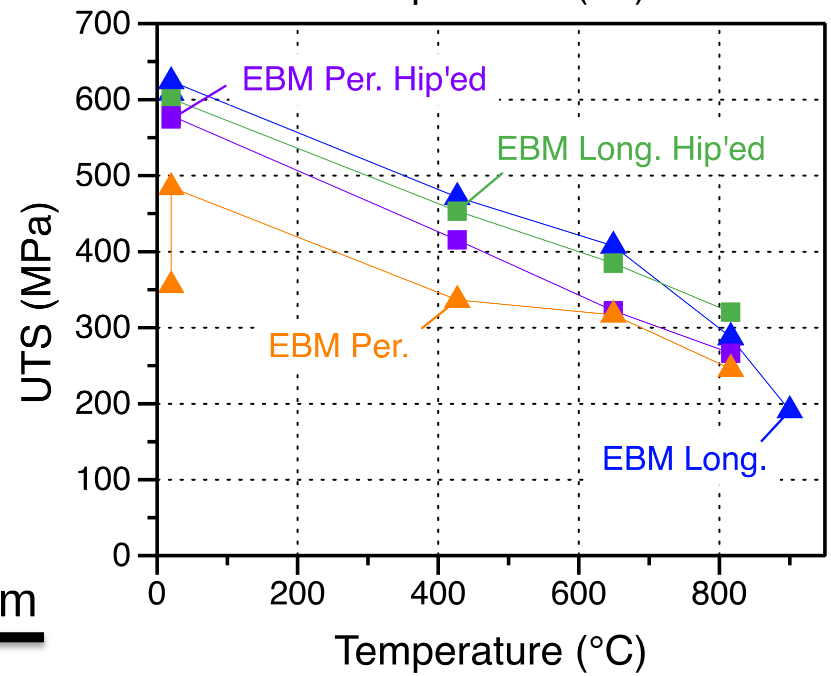


Significant Improvement of Tensile Properties after Hip'ing Perpendicular to theBD

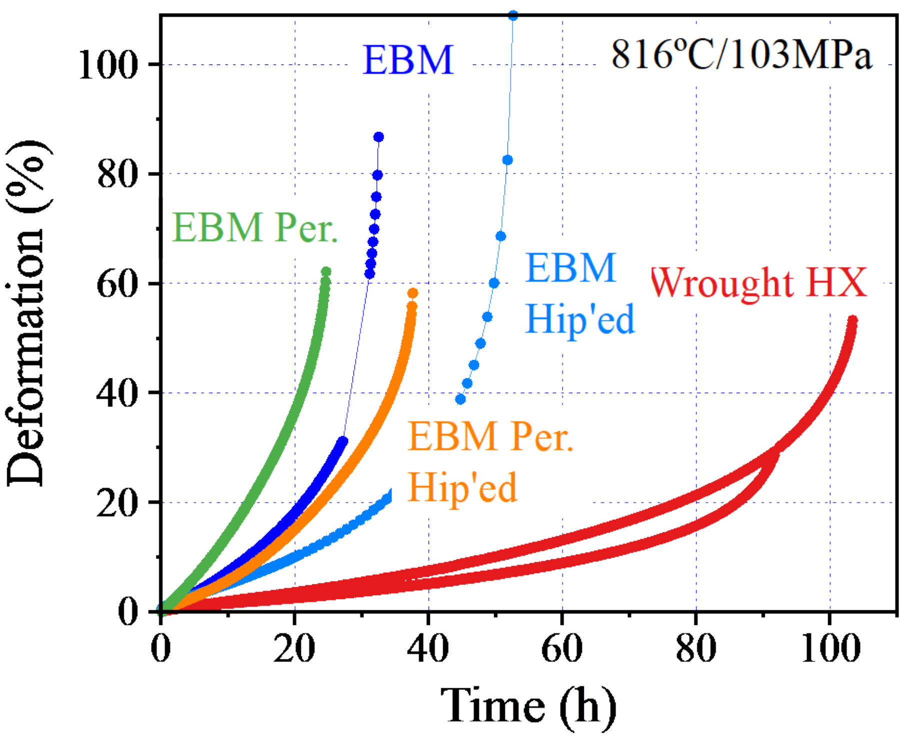


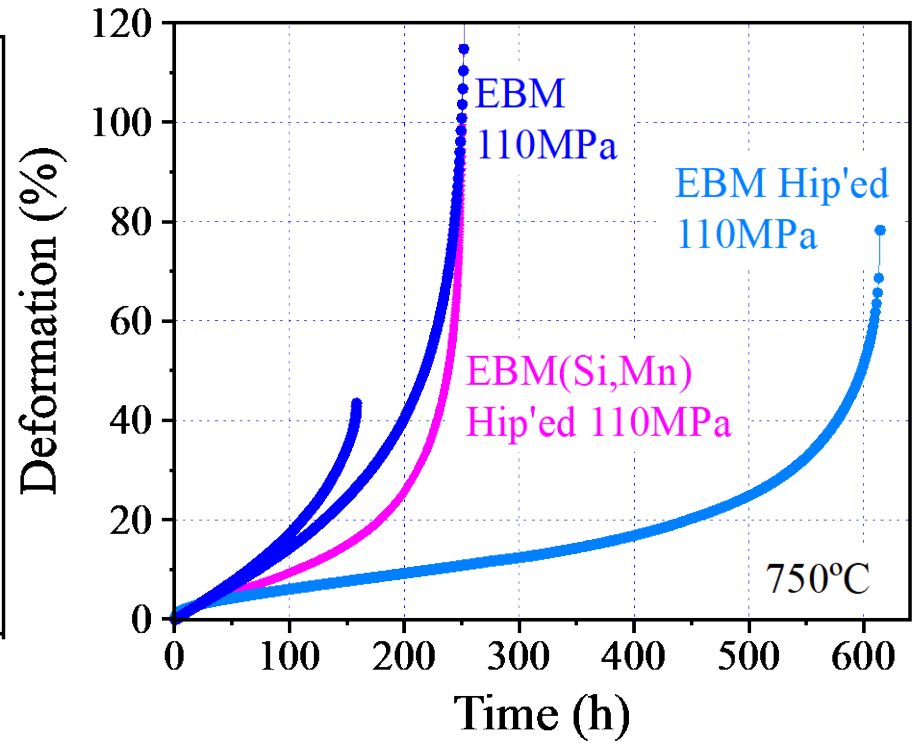






Improvement of the Creep Properties After Hip'ing for EBM but not for EBM(Si,Mn). Lower Creep Properties Perpendicular to the Build Direction

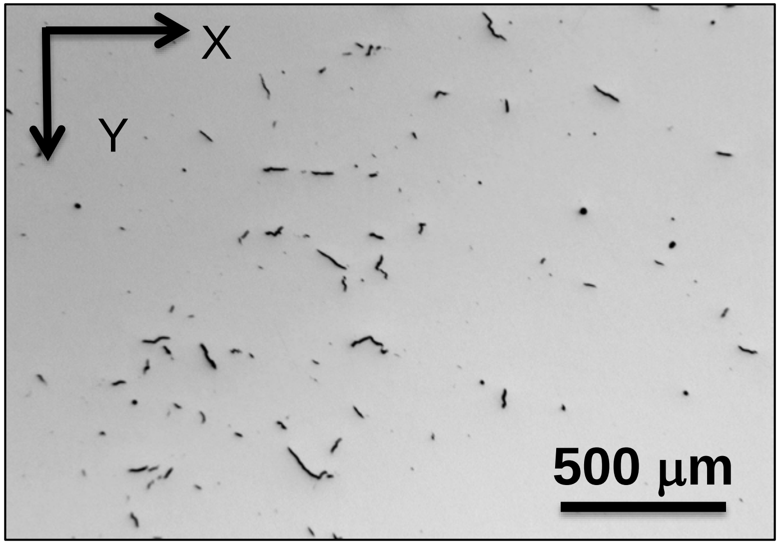


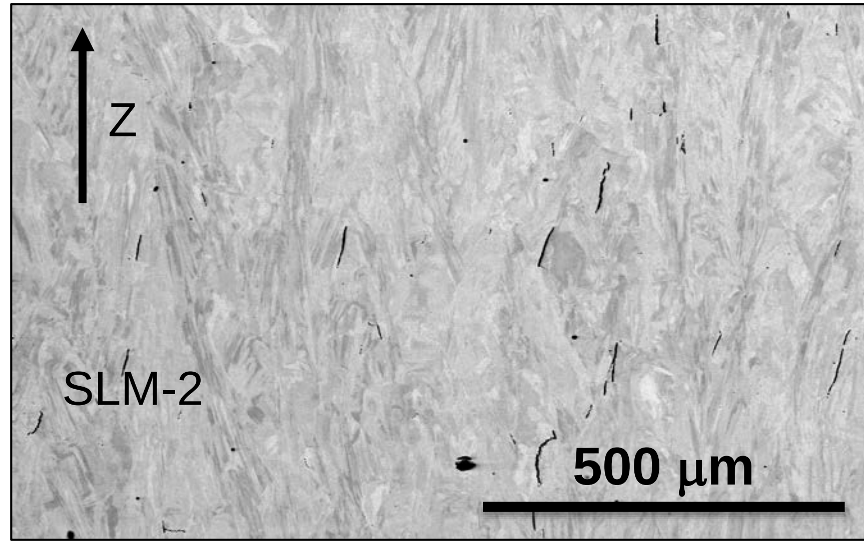


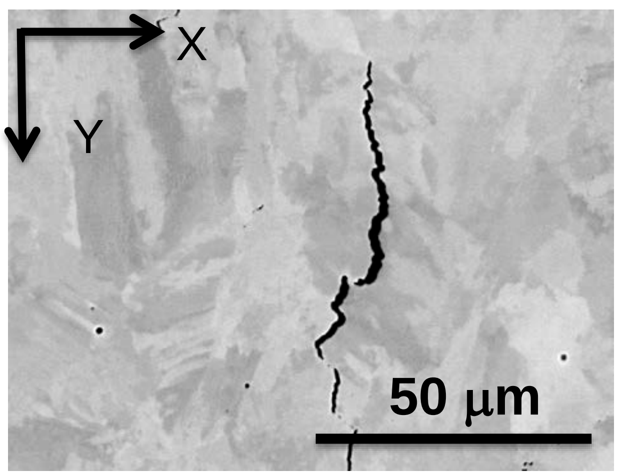
Wrought expected lifetime:

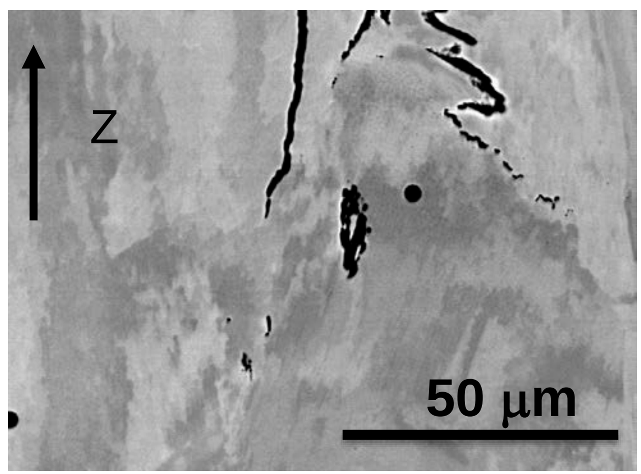
- 160MPa: 100h
- 110MPa: 1000h

SLM: Small Elongated Grains, No Precipitate, Hot Tearing Cracks



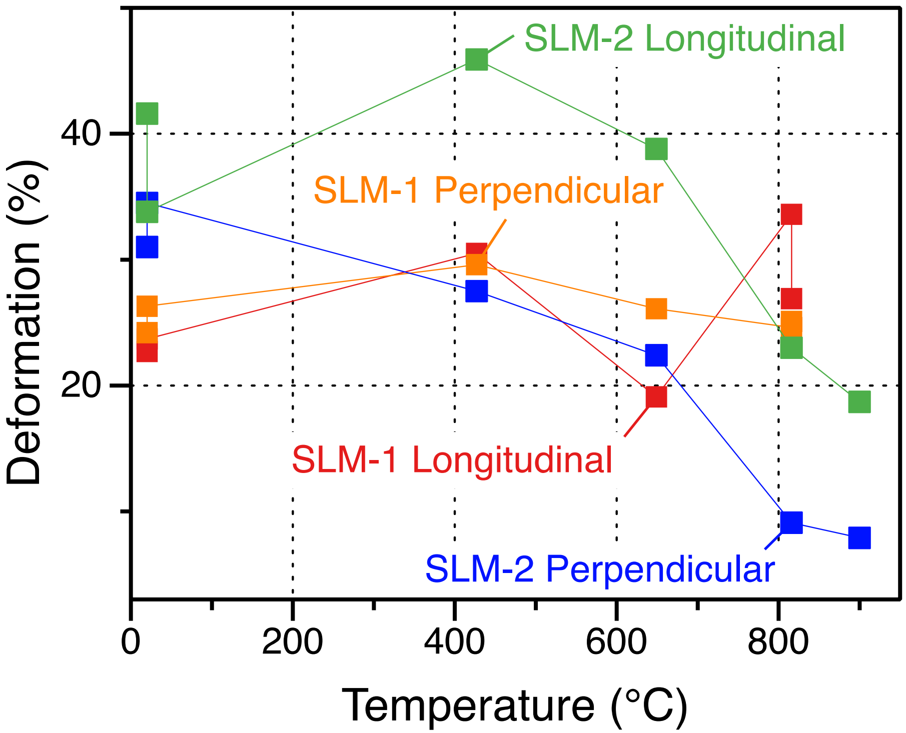


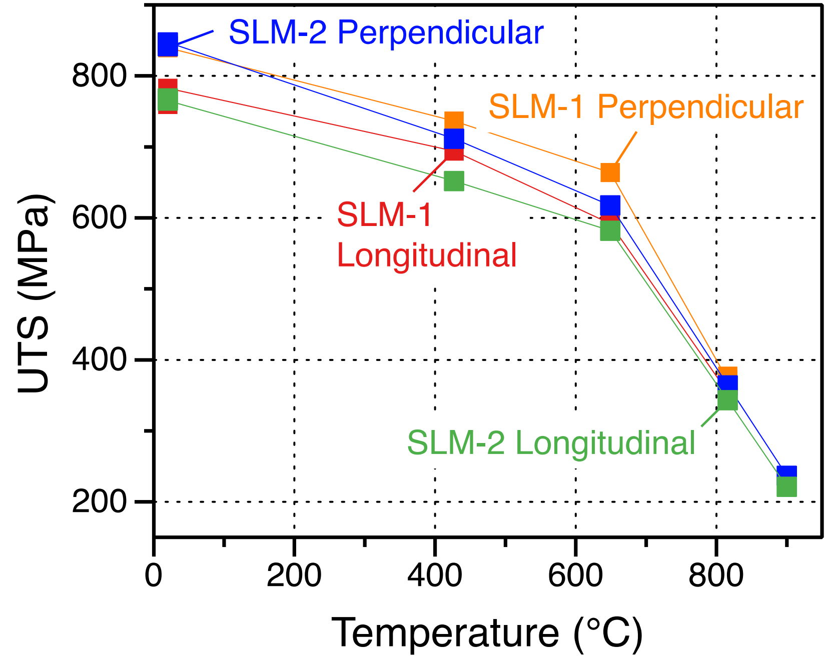


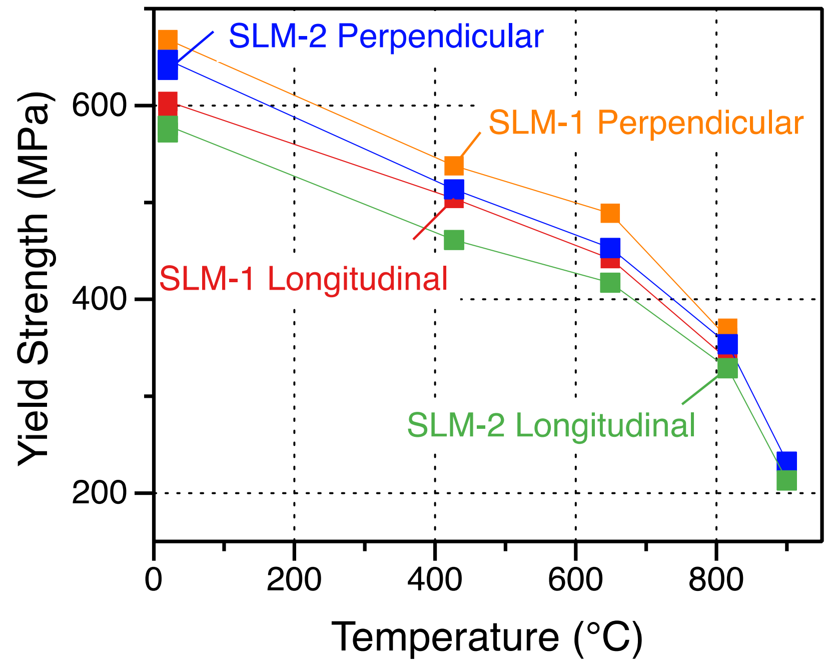


Typical of SLM microstructure
Could further optimize the SLM parameters

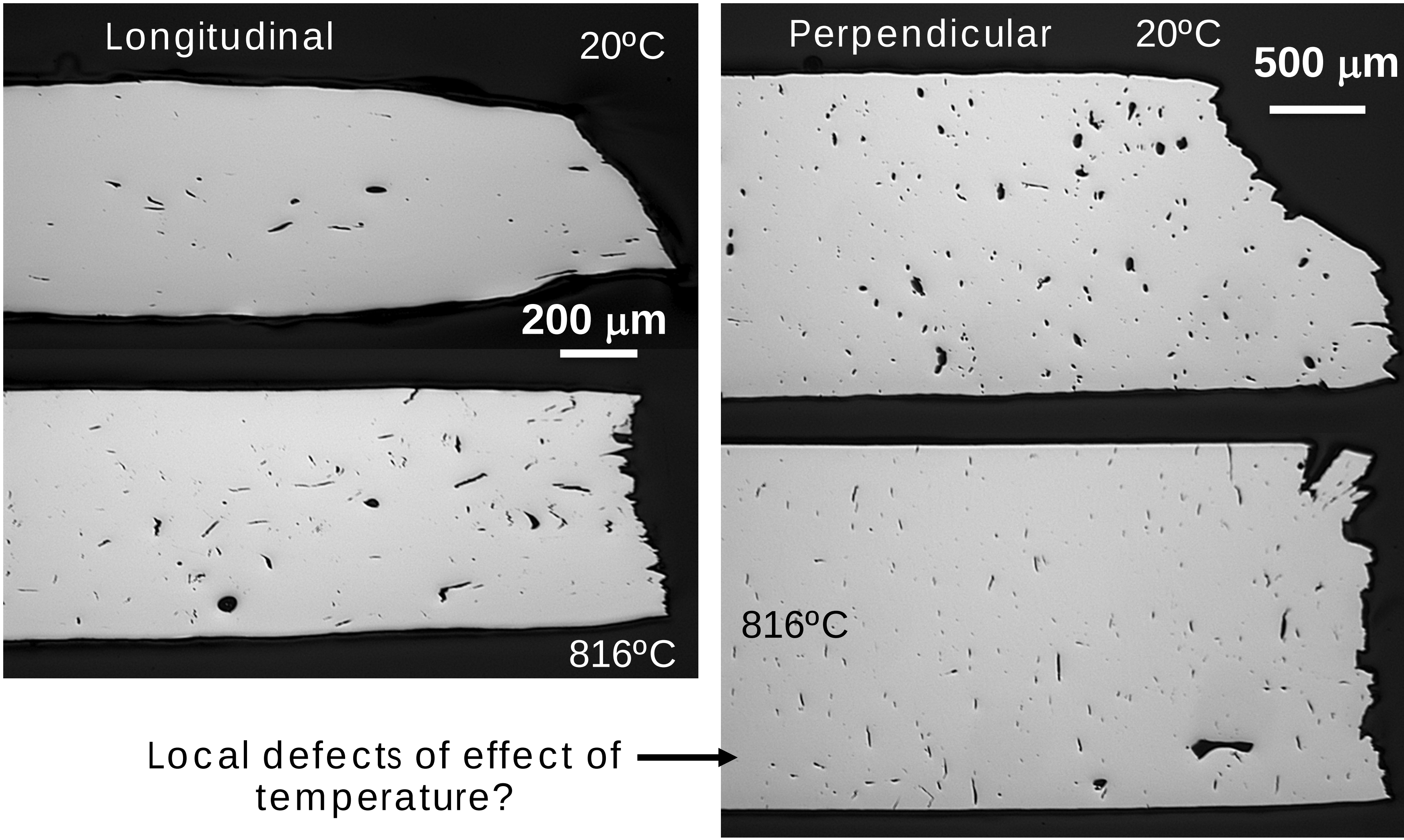
SLM HX Exhibits High Strength but Moderate to low Ductility, Above all at T>600°C for SLM-2





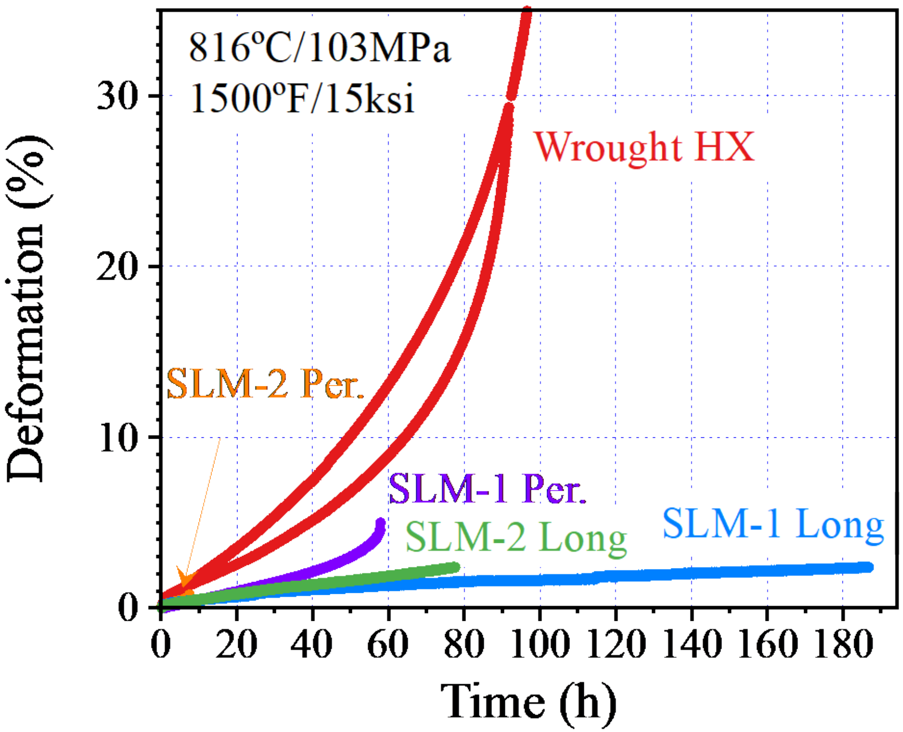


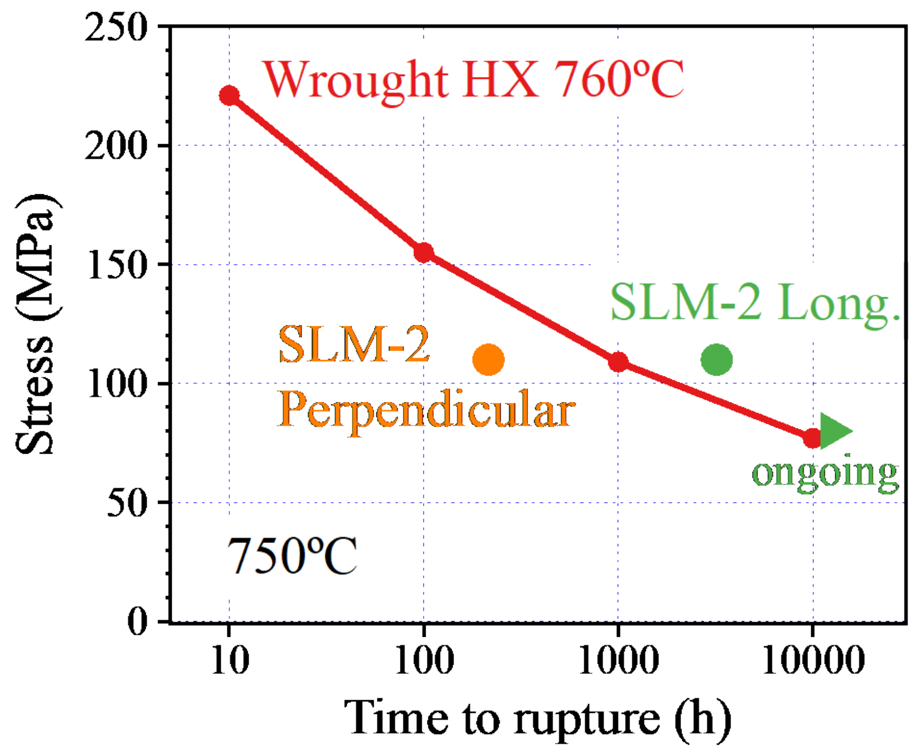
SLM2: Low Ductility Perpendicular to The Build Direction Due to The Presence of Cracks



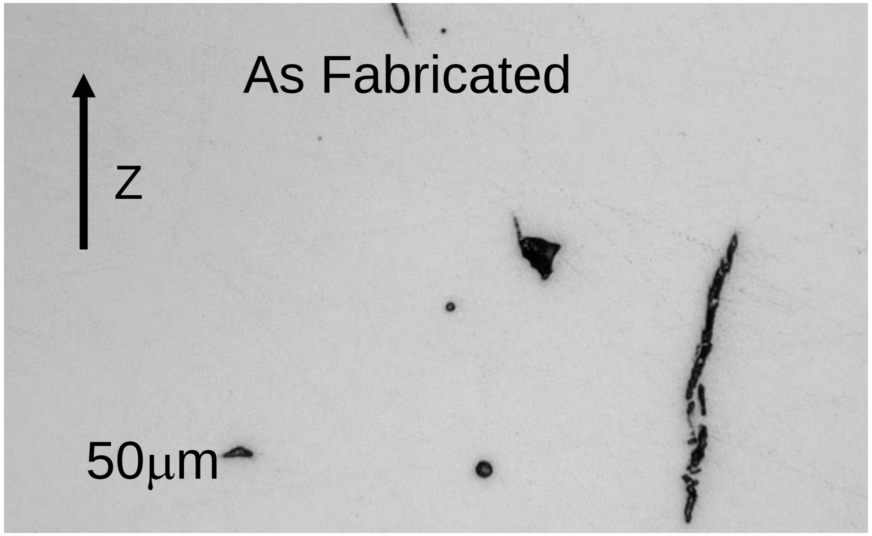
Local defects of effect of temperature?

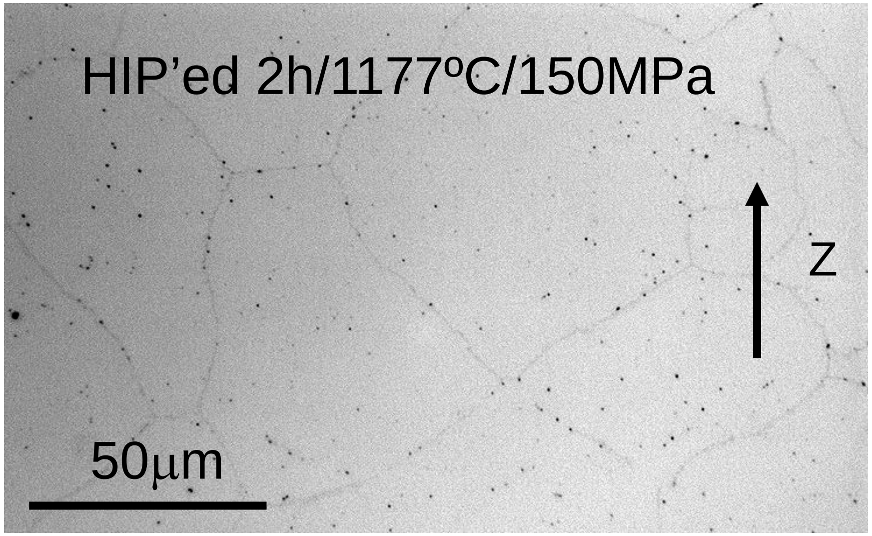
SLM: Very Low Creep Rate and Good Lifetime but Limited Ductility. Significant Decrease of Lifetime for SLM-2 Perpendicular to the Build Direction

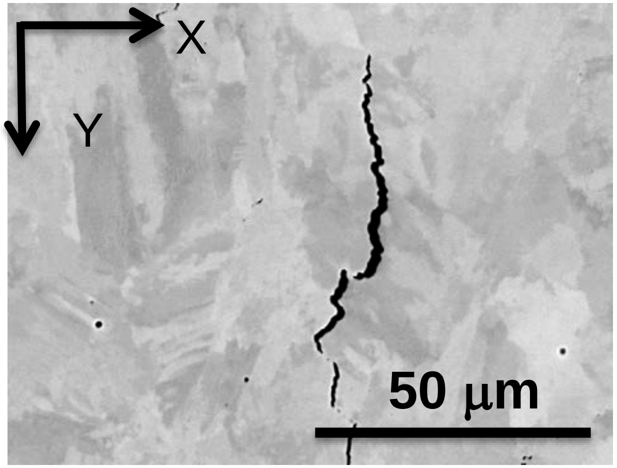


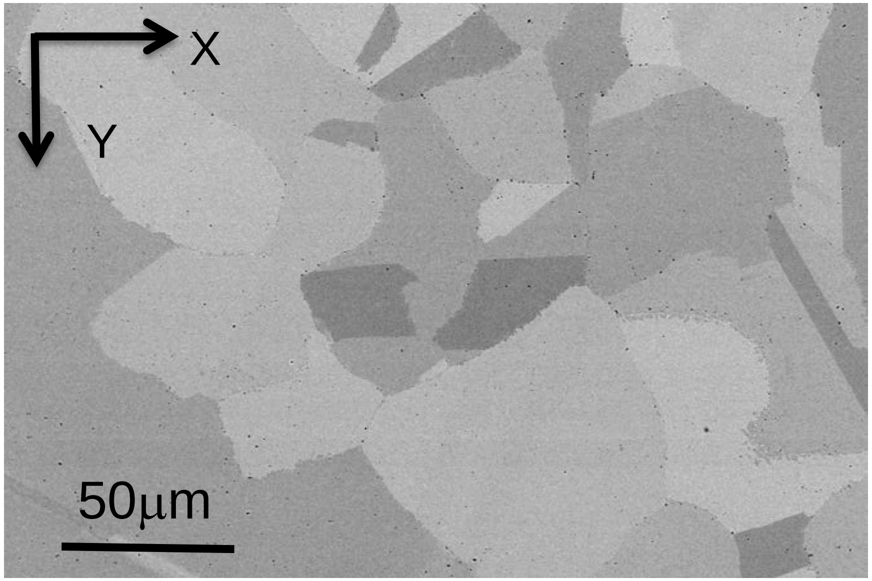


SLM-1: Fully Dense Material After HIP'ing at 1177ºC/2h/150MPa + Recrystallization









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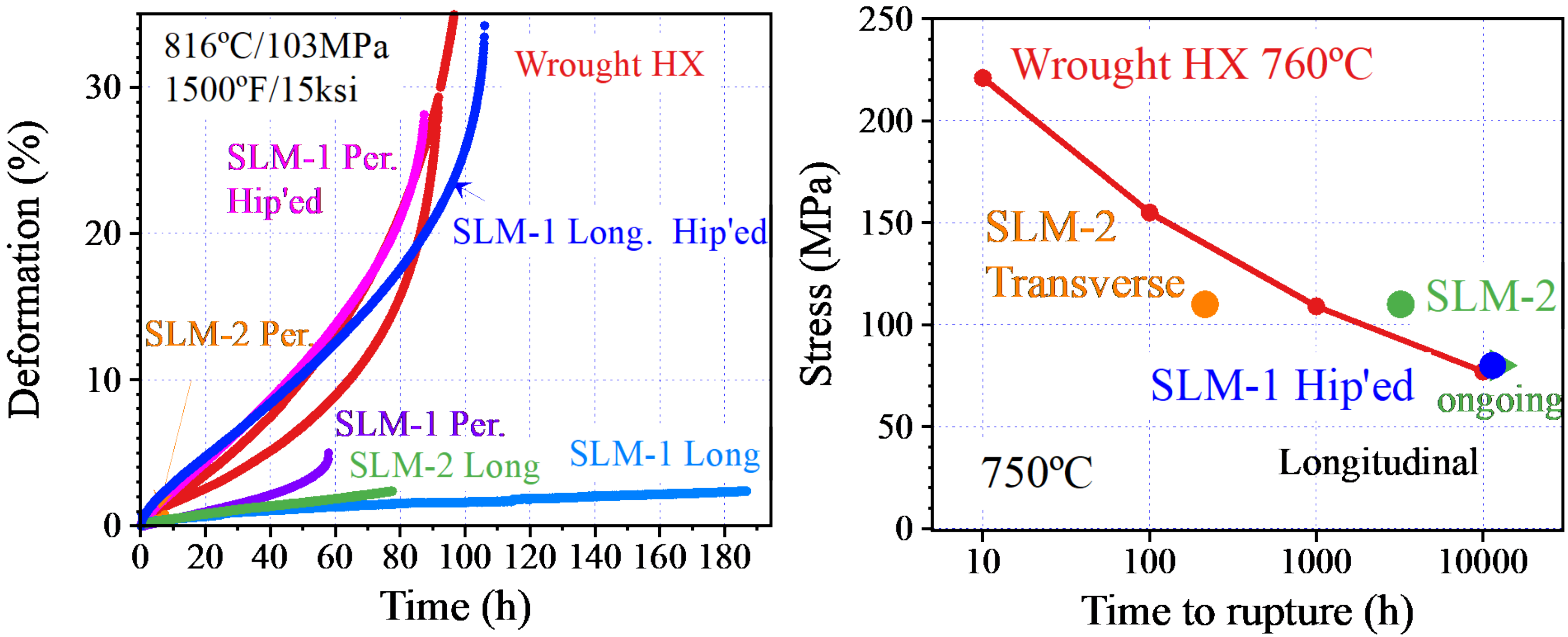
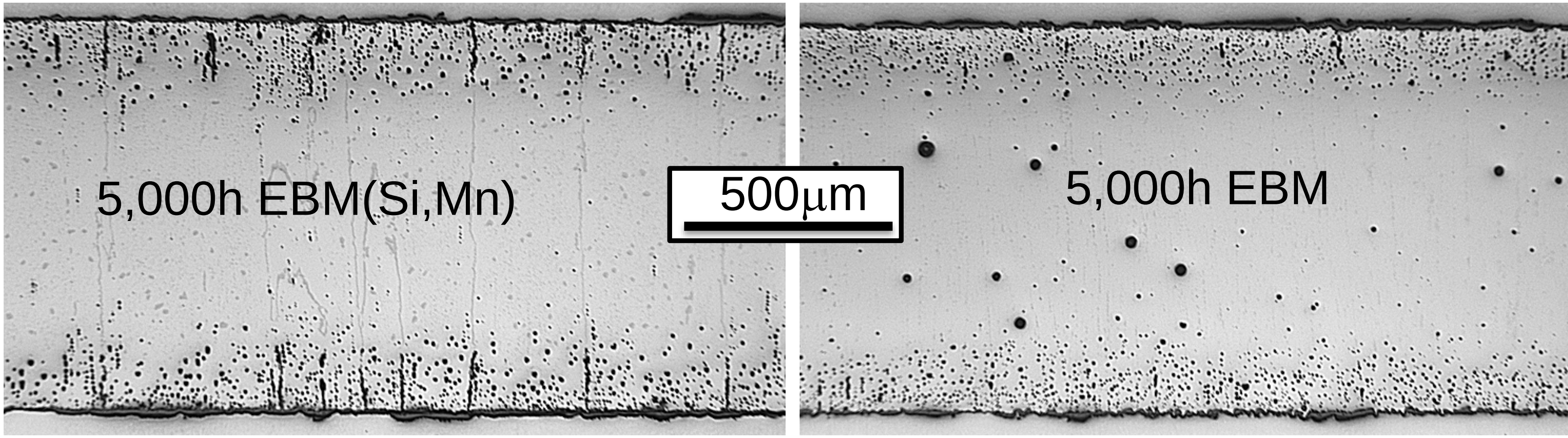
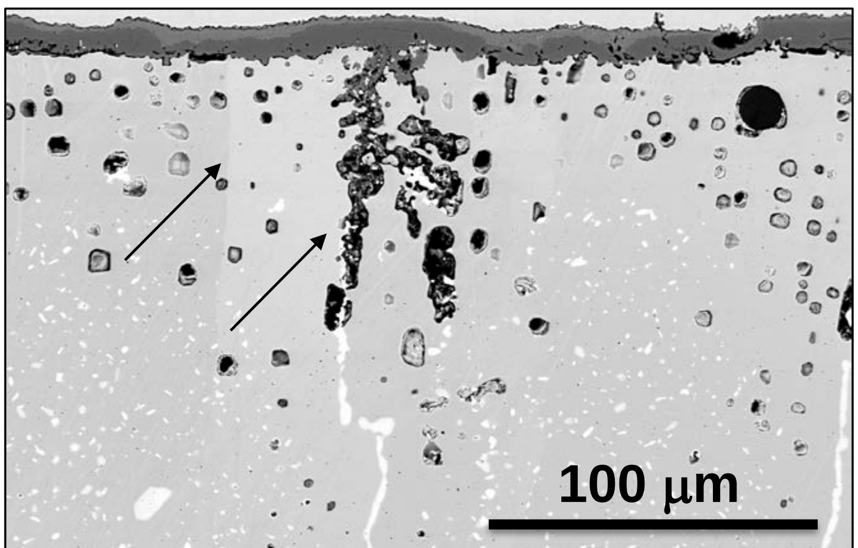
SLM: Fully Dense Material After HIP'ing at 1177ºC/2h/150MPa+Recrystallization



Significant Void Formation in EBM & EBM(Si,Mn) Alloys Related to Mo-rich Precipitates

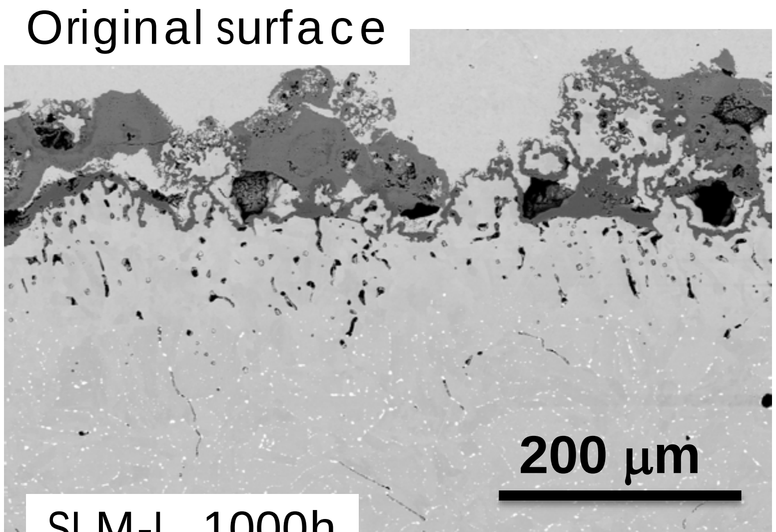


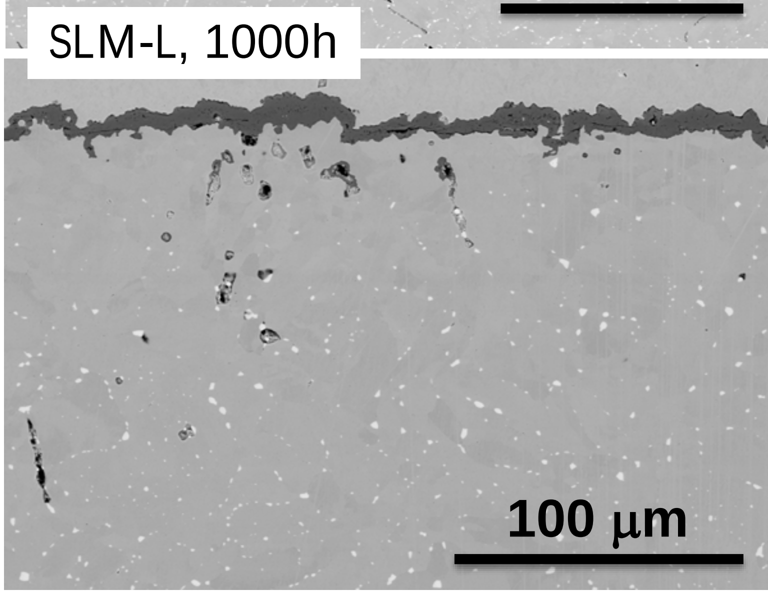


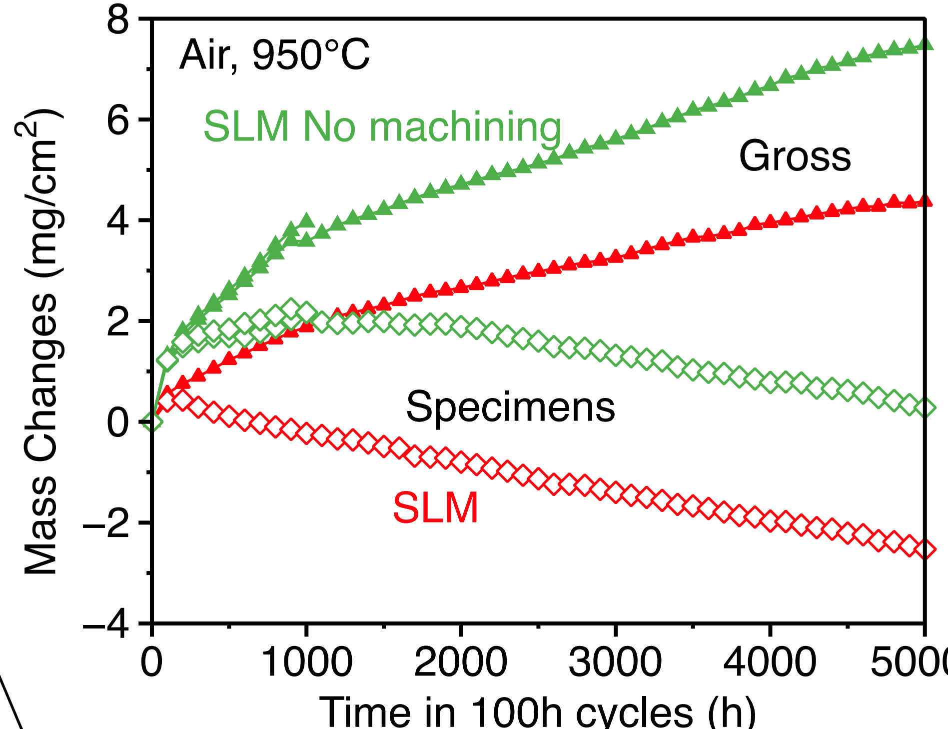
1000h, EBM(Si,Mn)

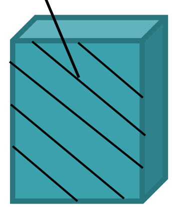
- Cr consumption leads to gradient of Cr concentration at the surface and destabilization of carbides
- Void formation is directly related to carbide disappearance

SLM: Very good oxidation behavior. Thicker Scale For The As-Fab Surface





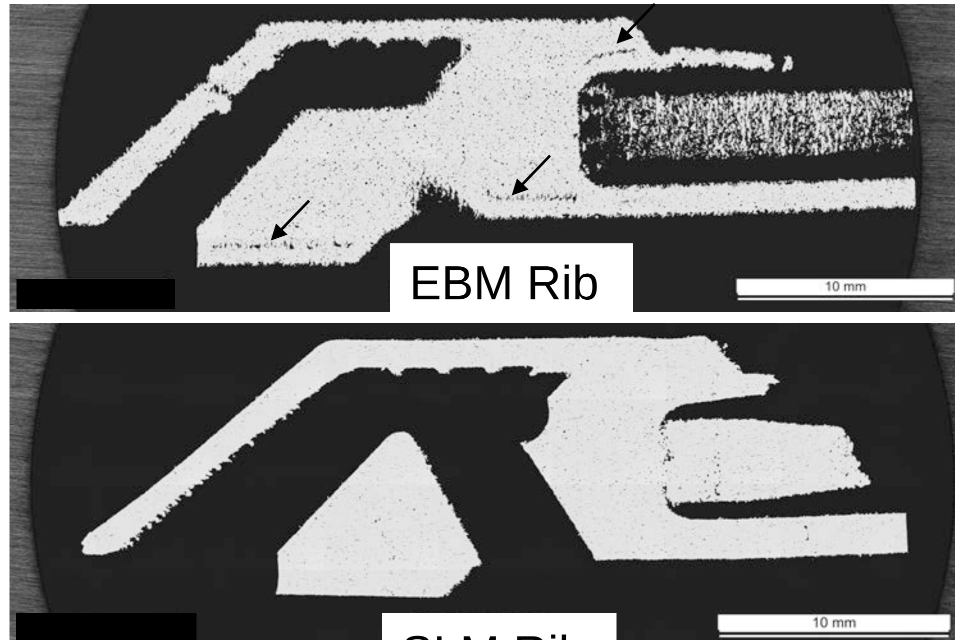




- Higher Mass Gains Only For the first 1000h & related to higher roughness
- Surface roughness could be optimized

Fabrication and Characterization of Hastelloy X EBM and SLM Components

Fuel injector



Determination of optimum print strategies

Conclusion

- EBM HX shows great ductility, acceptable tensile strength, great LCF performance but limited creep strength
- Low EBM tensile properties perpendicular to the BD can be improved by HIP'ing. Hip'ing can also improve creep resistance
- SLM HX exhibited good tensile and creep strength but limited ductility along the B.D. Low Creep strength & ductility perpendicular to the BD.
- HIP'ing of SLM HX removed hot tearing Cracks & led to recrystallization
- Hip'ing resulted in isotropic creep behavior for SLM HX similar to wrought HX