OAK RIDGE National Laboratory

Additive Manufacturing of High Gamma Prime Alloys

Sebastien Dryepondt, Mike Kirka, Patxi Fernandez-Zelaia, Kinga A. Unocic & Yousub Lee

ORNL project FEAA125

Crosscutting Review Meeting

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U.S. DEPARTMENT OF ENERGY

Project Objectives

- **Optimize additive manufacturing (AM) fabrication processes for:**

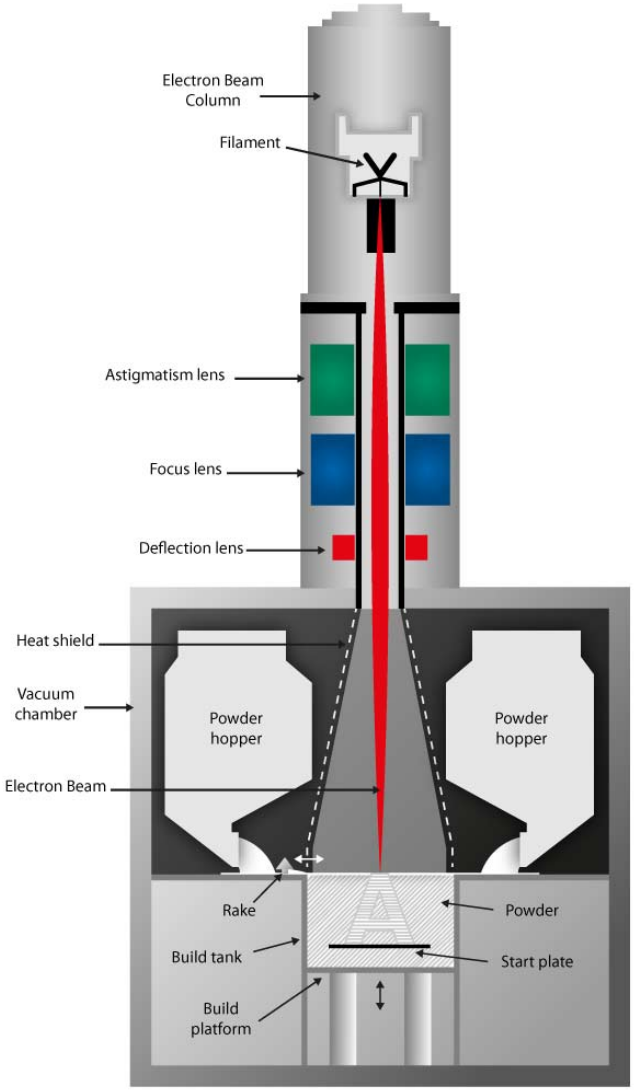
- Chromia forming 282: (57Ni-20Cr-10Co-8.5Mo-2.1Ti-1.5Al)

- Alumina forming Nimonic 105 (Ni-20Co-5Mo-15Cr-4.5Al-1Ti)

- **Improving understanding of the process-microstructure-property relationships**
- **Generate data (Tensile, Fatigue, Creep, Oxidation) relevant for FE applications**
- **Compare two AM techniques, electron beam melting (EBM) and selective laser melting (SLM).**
- **Effect of annealing on microstructure and mechanical properties**
- **Collaboration with other 282 related programs such as A-USC**

Fabrication of Haynes 282™ by EBM and SLM

Ebeam (Arcam S12)



EOS 250 machine

Three rods, 13mm in diameter, 100mm in height, courtesy of Siemens

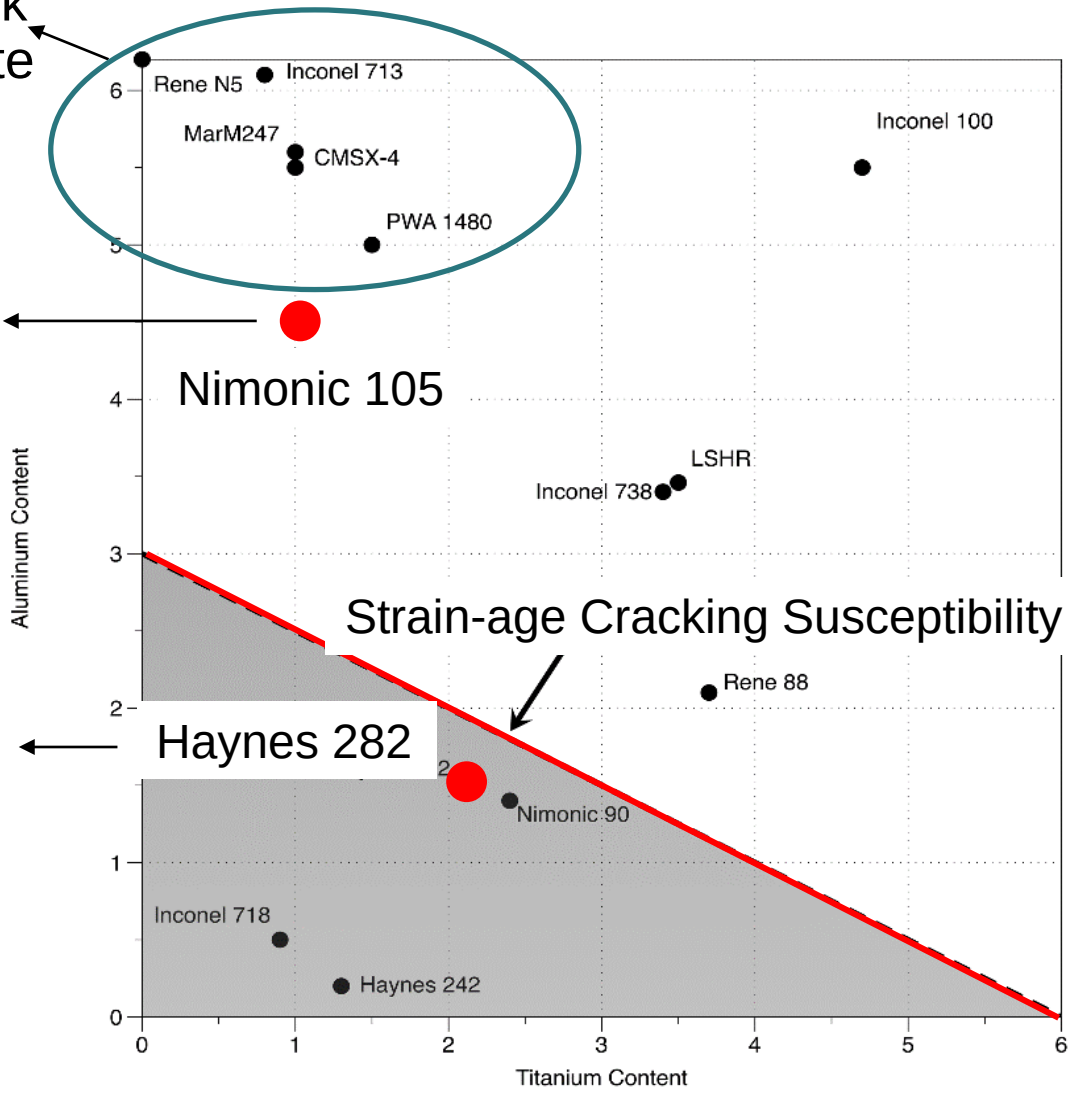
Alloy 282 Shows Unique Combination of High Strength and Fabricability

Extensive processing work funded by AMO to fabricate crack-free blades

More challenging but easier than many other high γ /γ' alloys

Easier to process due to "low" Al and Ti content

γ' volume fraction in Haynes 282 is ~20%. Great balance between fabricability and strength



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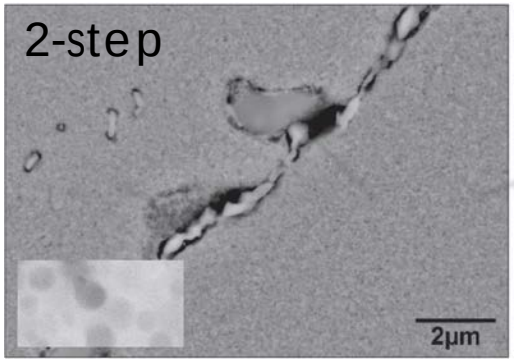
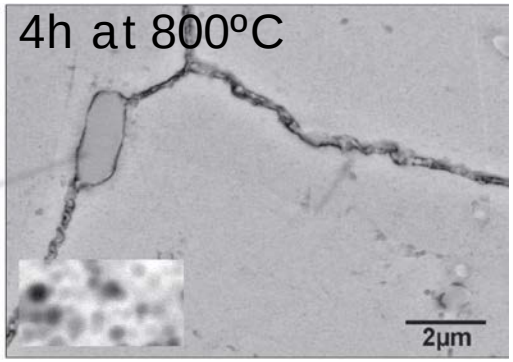
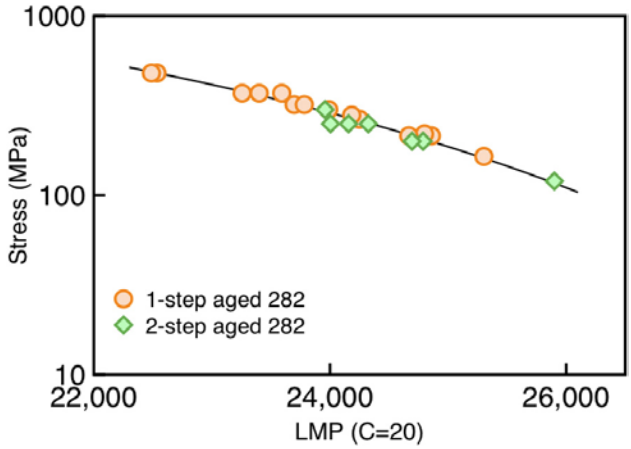
282 Creep Strength Depends on the γ' Precipitates Stability. Ductility Related to Precipitates at GB?

- Haynes recommended heat treatment (HT): Solution annealing at 1121 to 1149ºC and two-step aging 2h at 1010ºC + 8h at 788ºC
- First aging treatment for $M_{23}C_6$ Carbide formation at GB (L.M. Pike Superalloy 2008)
- Second aging treatment for optimum γ' precipitate size: is ~20-30nm
- Recent work has shown that 1-step 4h 800ºC heat treatment led to similar microstructure and creep properties
- Best heat treatment for AM 282?

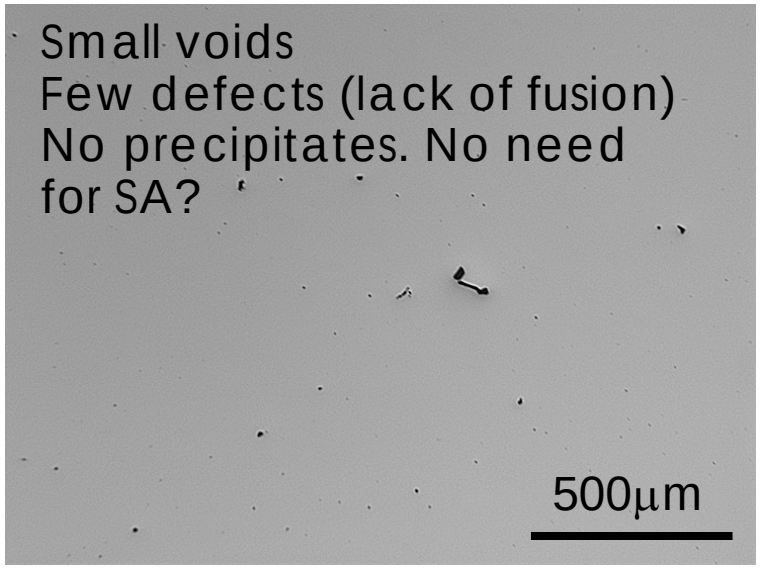


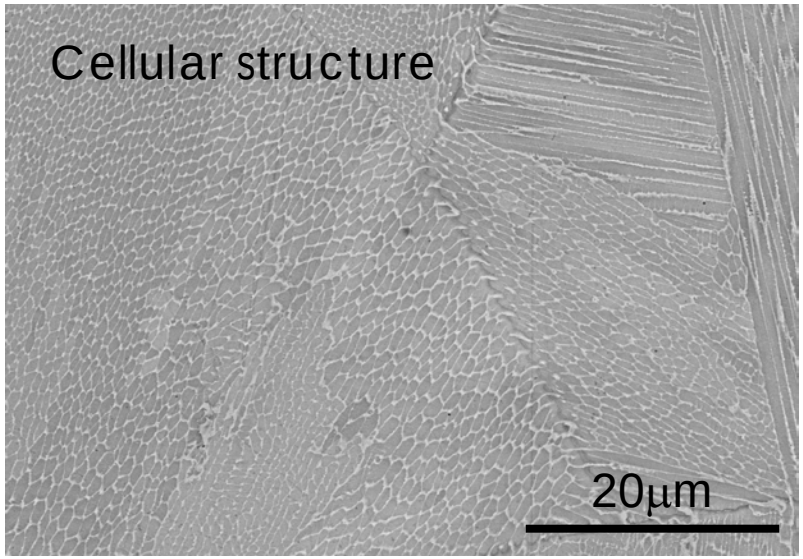


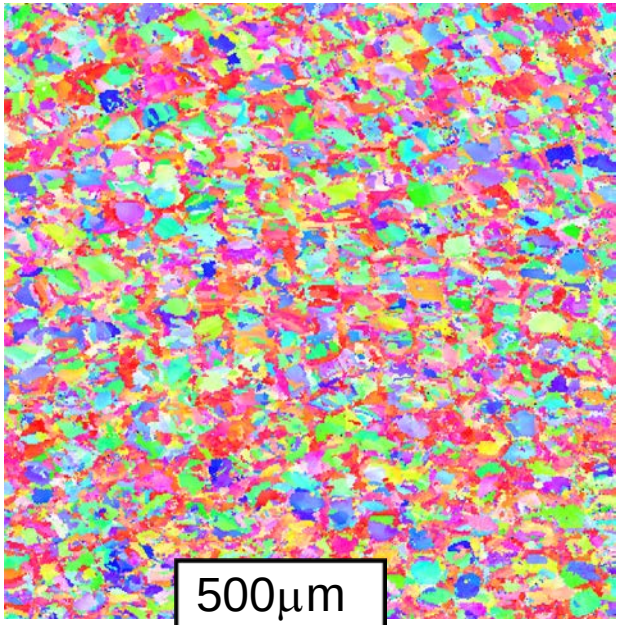


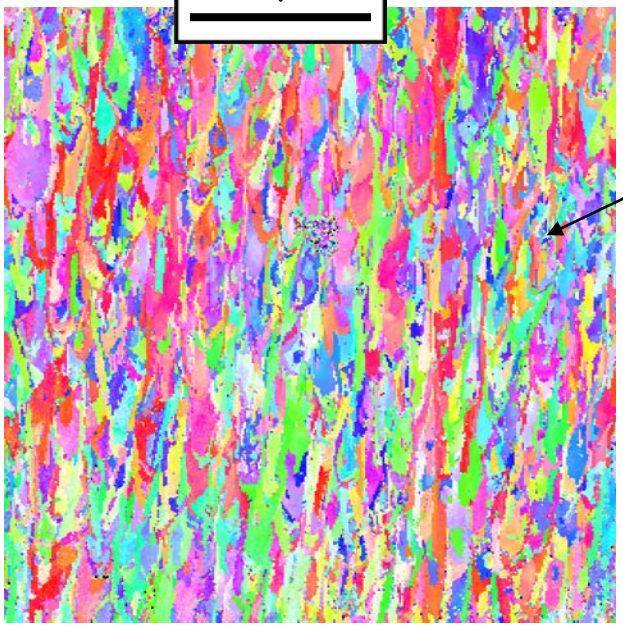
Unocic et al. Scripta Met 2019

No Significant Texture For the As-Fab SLM 282

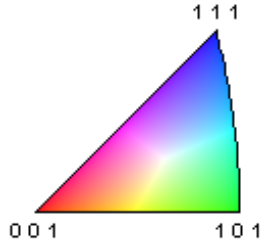








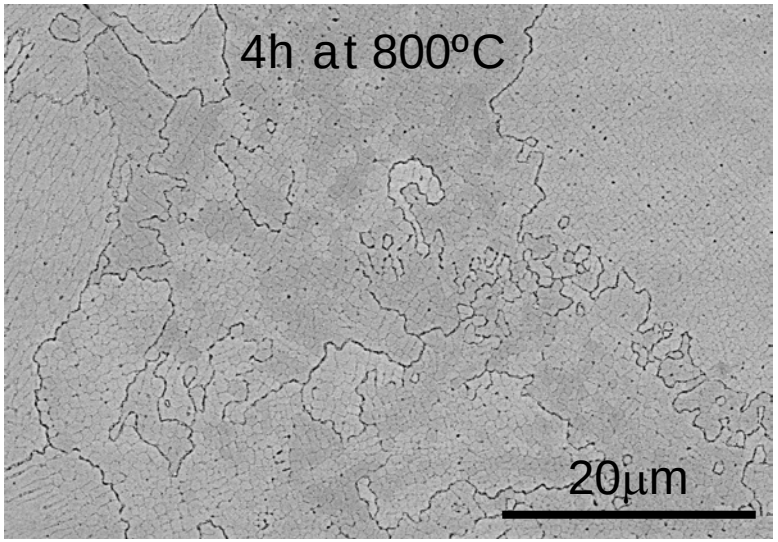
Transverse

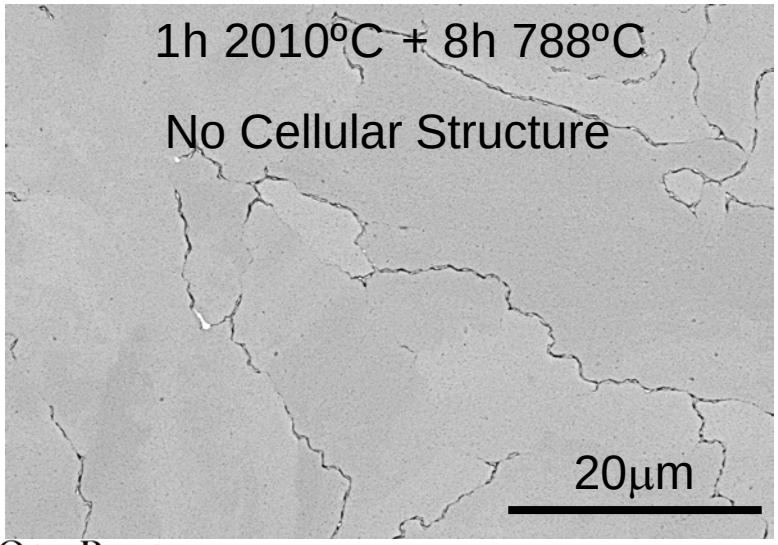


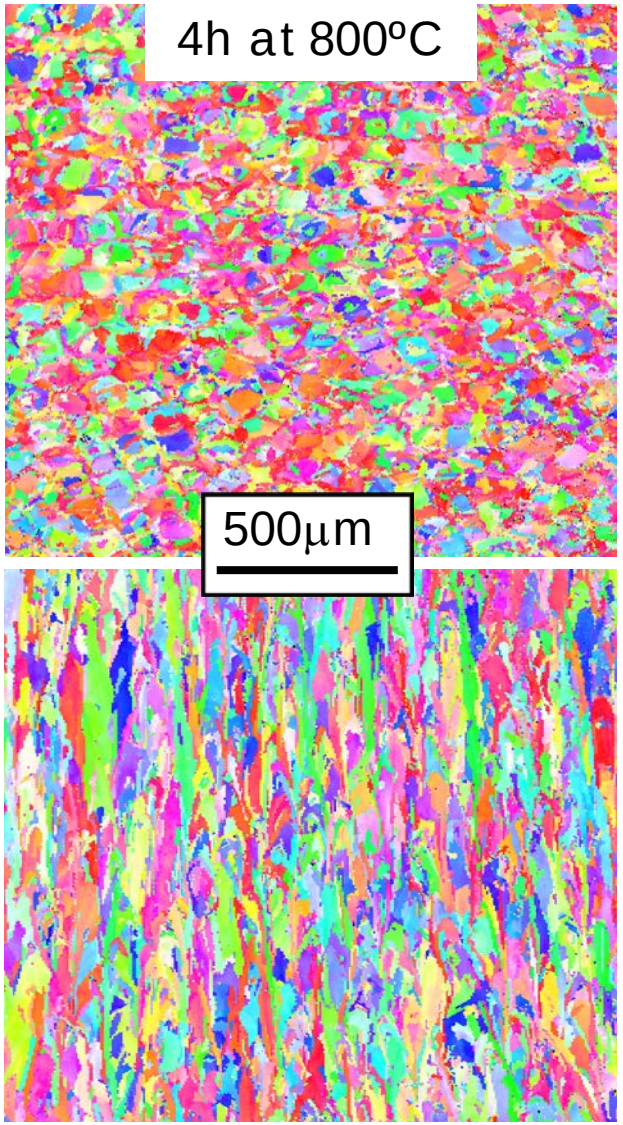
Elongated grains

Longitudinal

Aged SLM 282: Similar microstructure except for Discontinuous Carbides at Some GB







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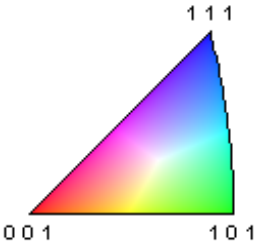

Longitudinal

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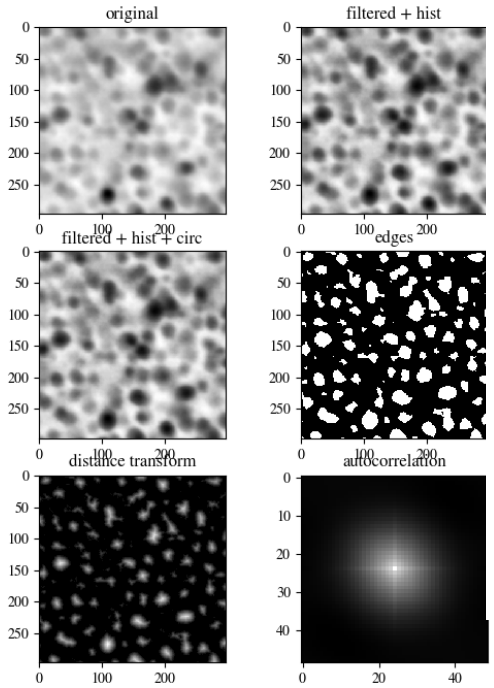
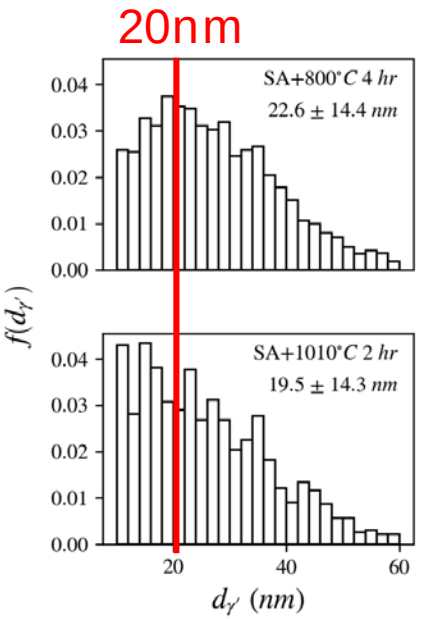
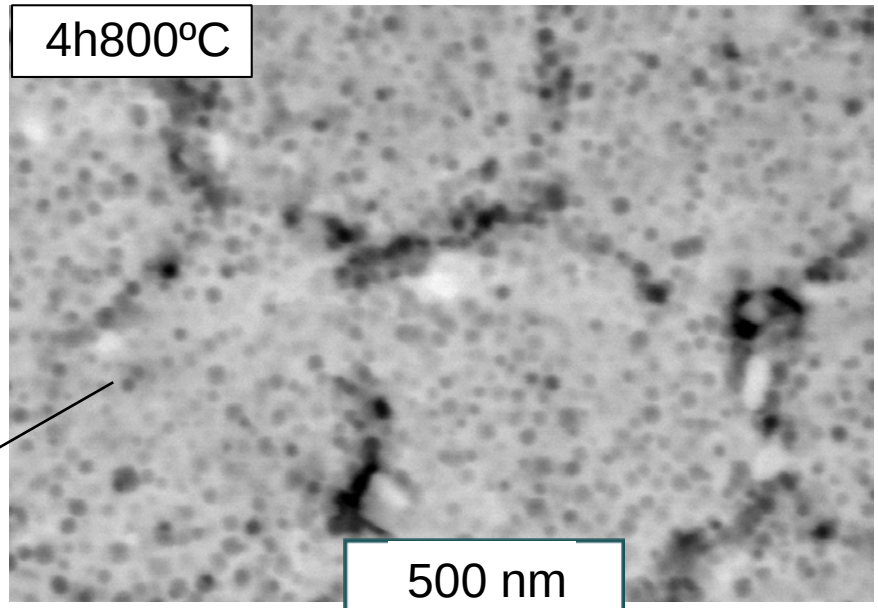
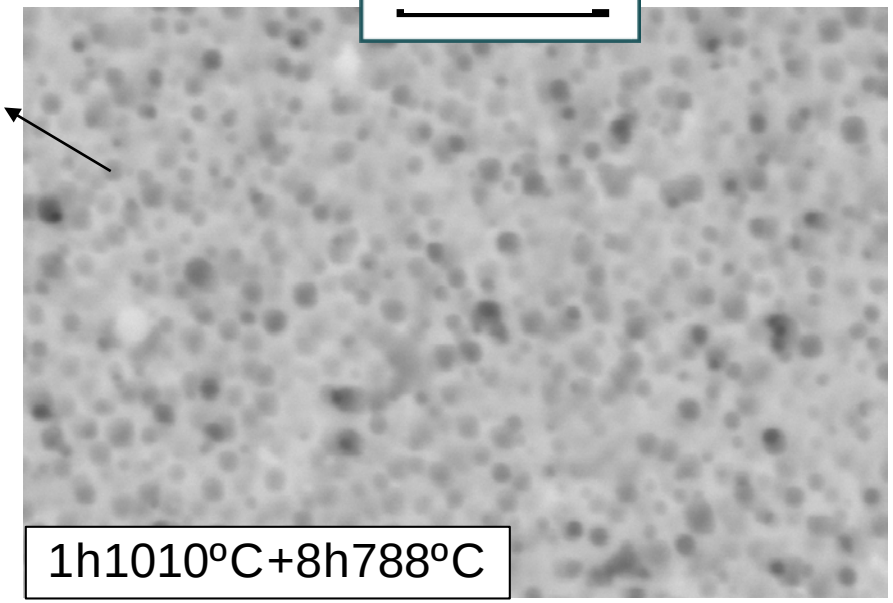
SLM 282: γ' ~20nm in size after 1h1010ºC + 8h788ºC or 4h800ºC

γ' prime size determine by image analysis









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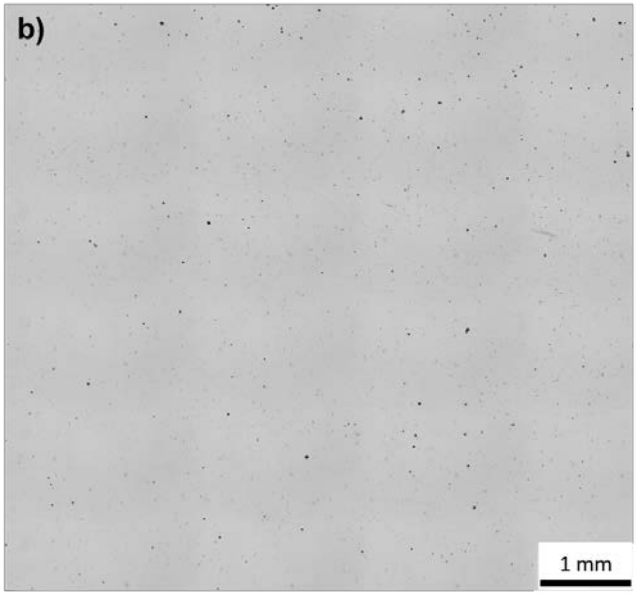
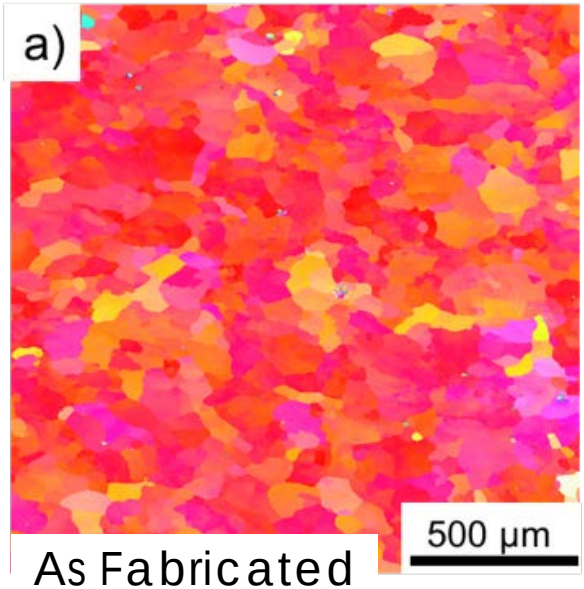
EBM 282: Fabrication of Cubes for Process Optimization and Larger/Longer Builds For Mechanical Testing

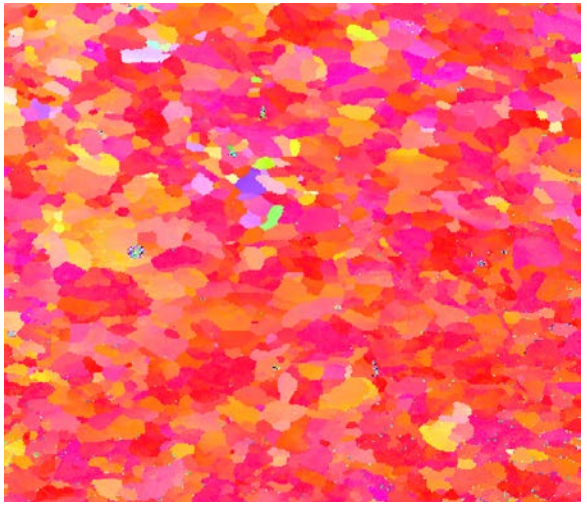


- **Density from 97.9% to a high of 99.5% depending on build parameters**
- **Tensile/creep specimens were machined along and perpendicular the build direction**

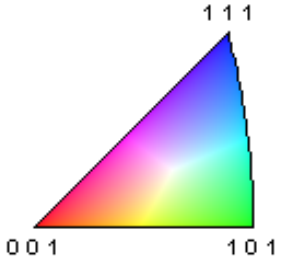
EBM 282: Significant Texture in the As Fabricated & Annealed Conditions

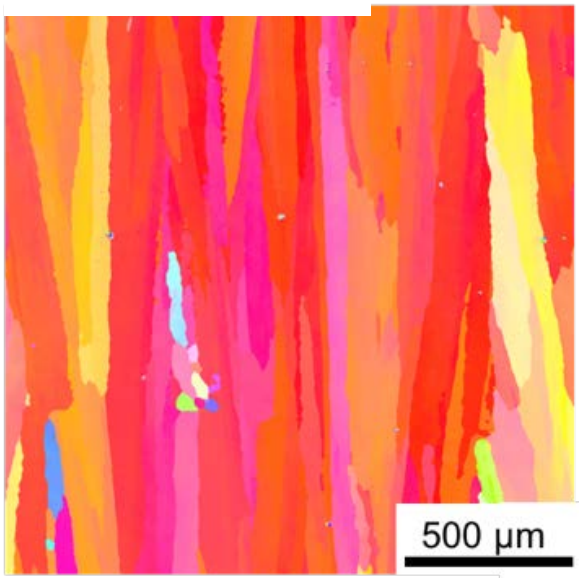


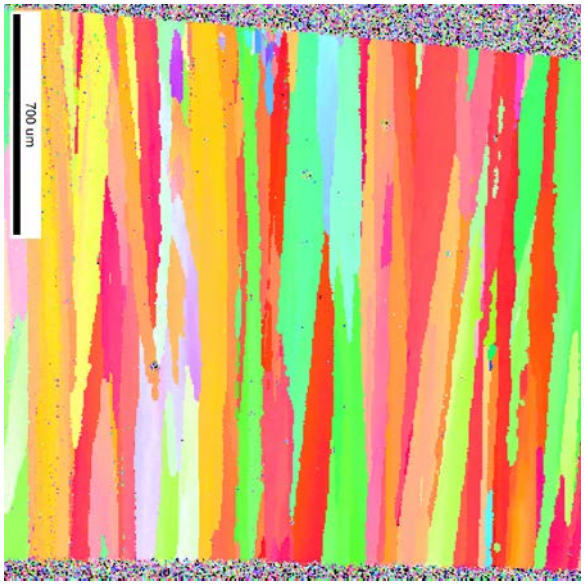
As Fabricated



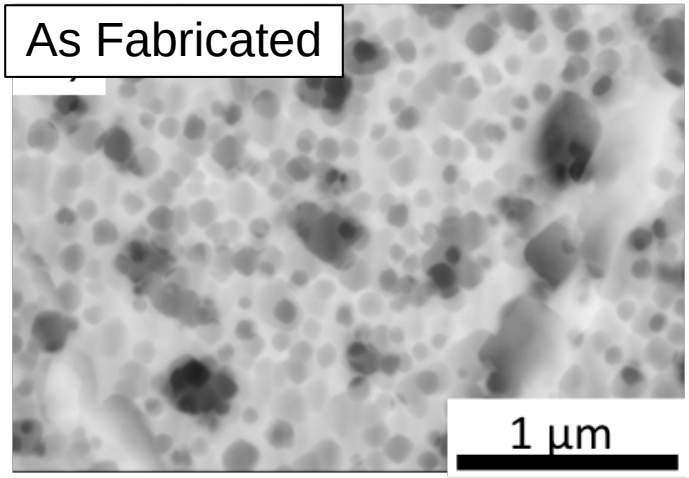
10min 1135ºC (SA)+4h at 800ºC

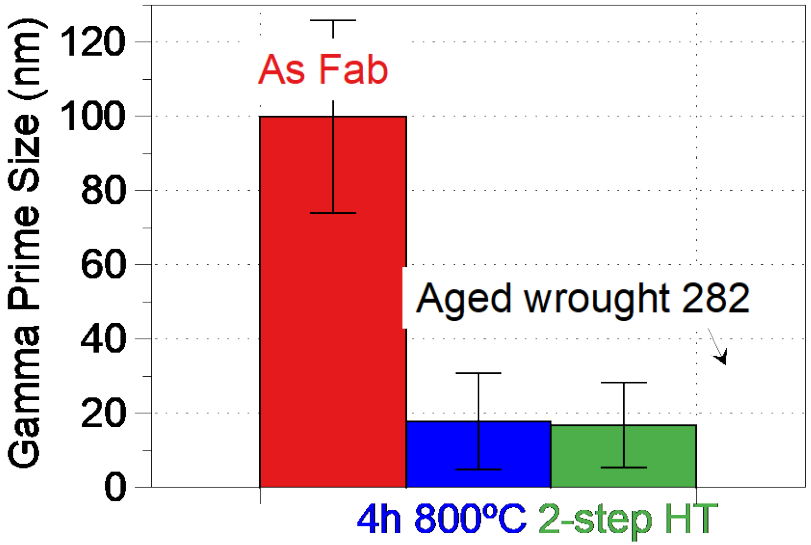


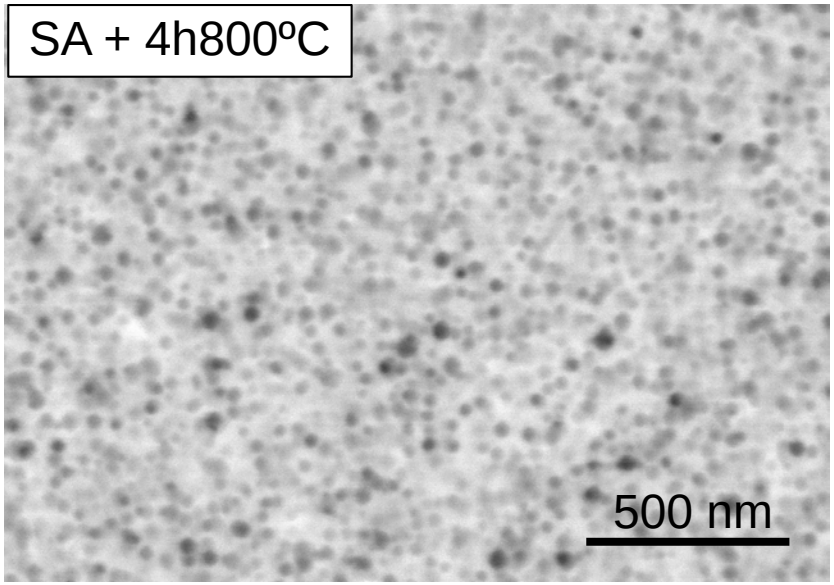


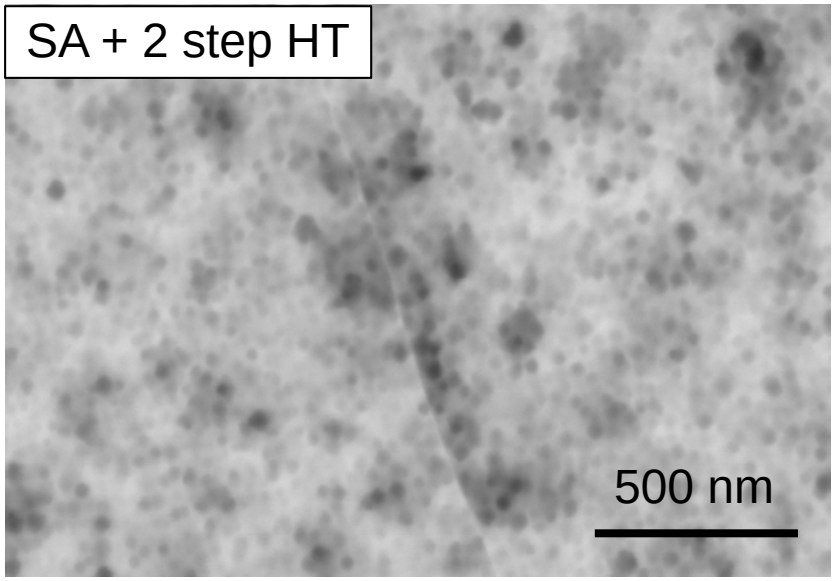


~100nm γ' Precipitates For As Built EBM 282
~20nm After 4h800ºC or 1h1010ºC+8h788ºC



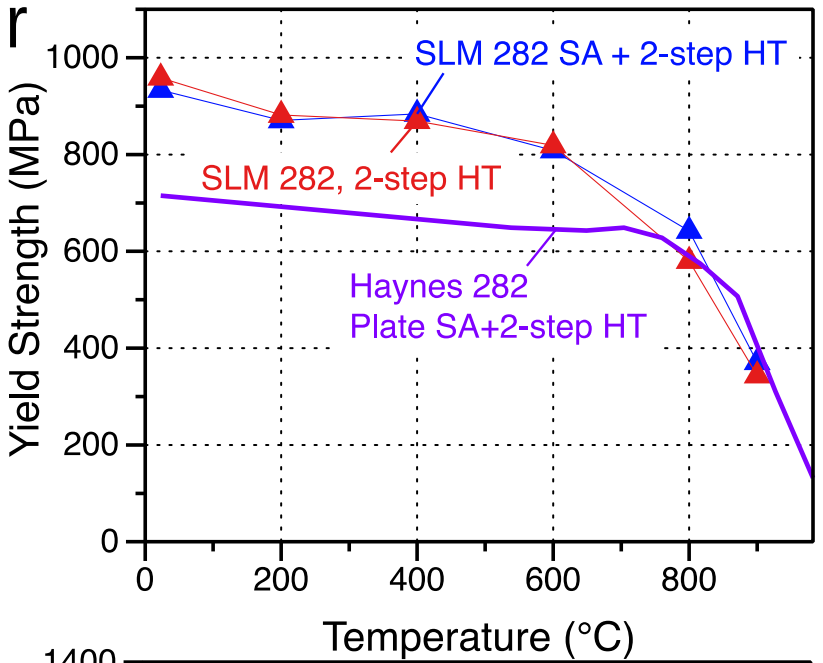


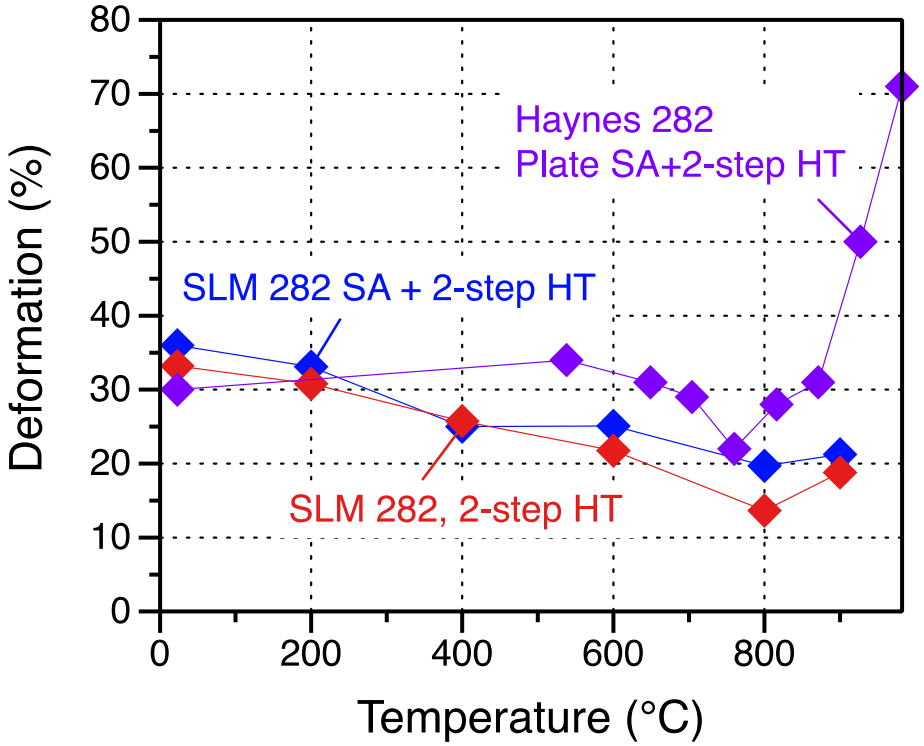


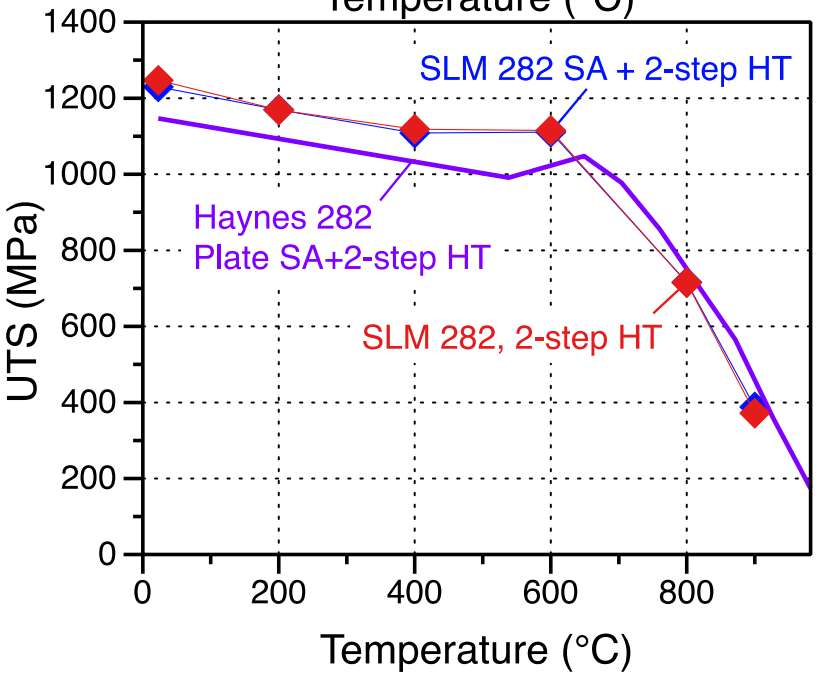


High Strength at T<600ºC for SLM 282 after two-step HT

- **No effect of SA on SLM 282 tensile properties**
- **Acceptable but slightly lower ductility compared to wrought 282**







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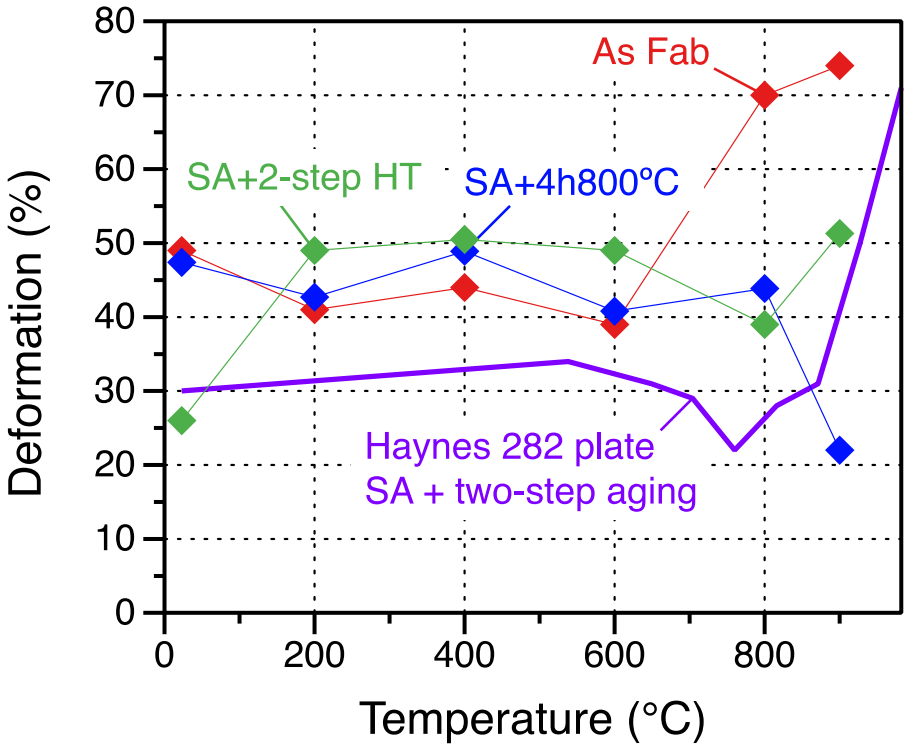
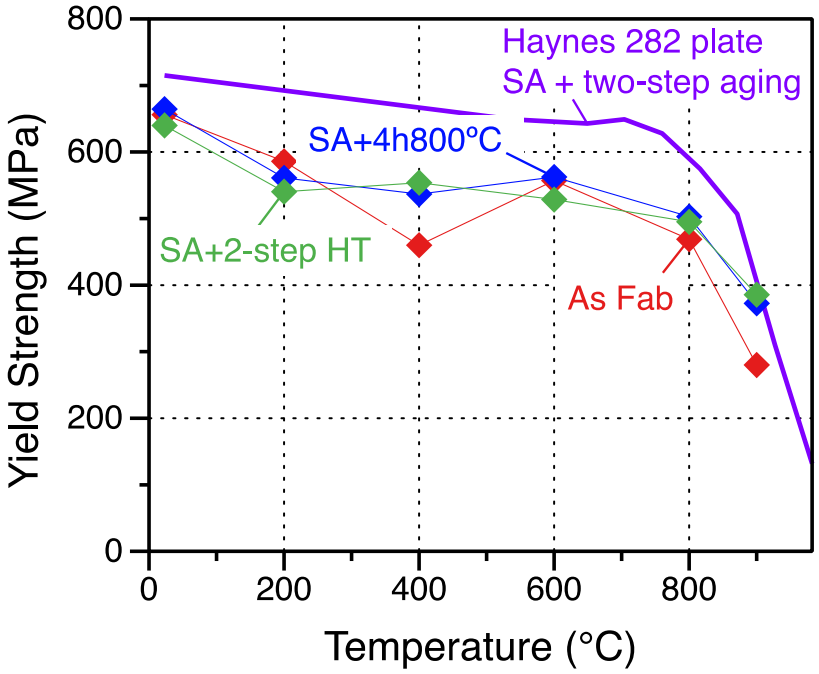
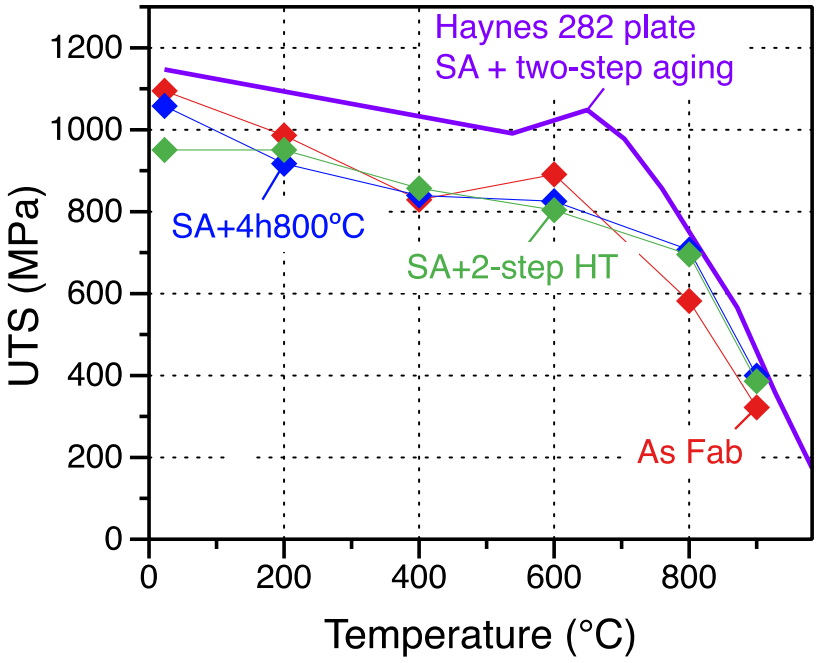
Good Ductility, Slightly Lower Strength for EBM 282

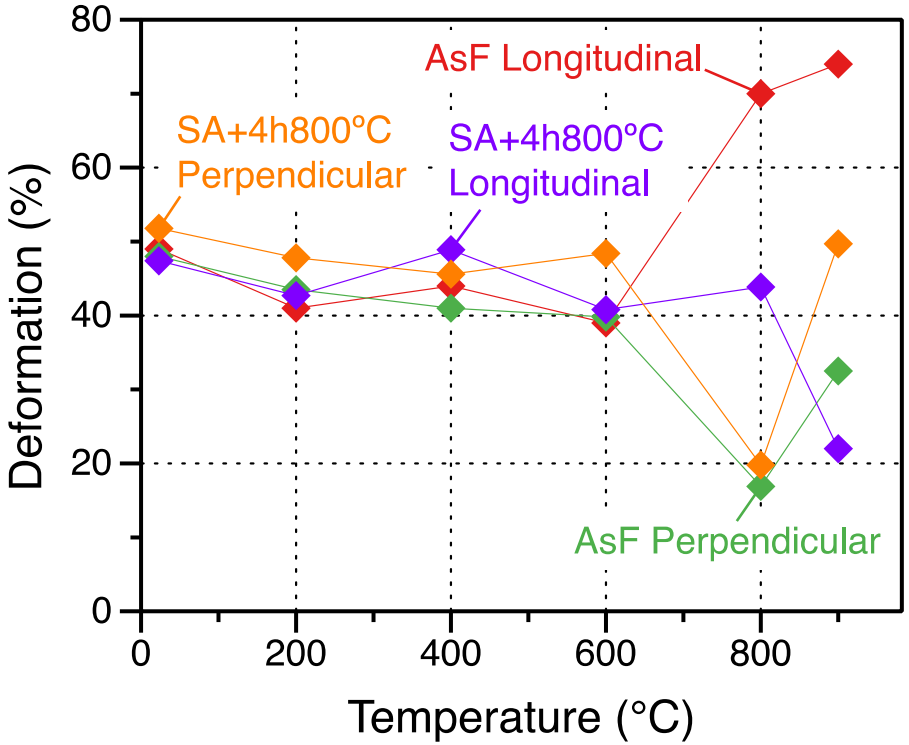
Slight increase of strength and decrease of ductility at high temp after annealing

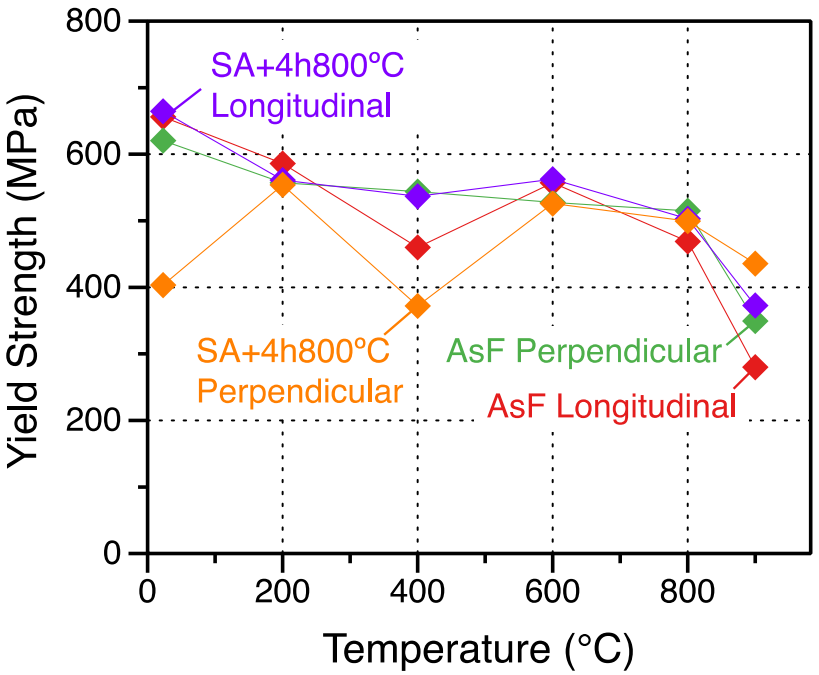


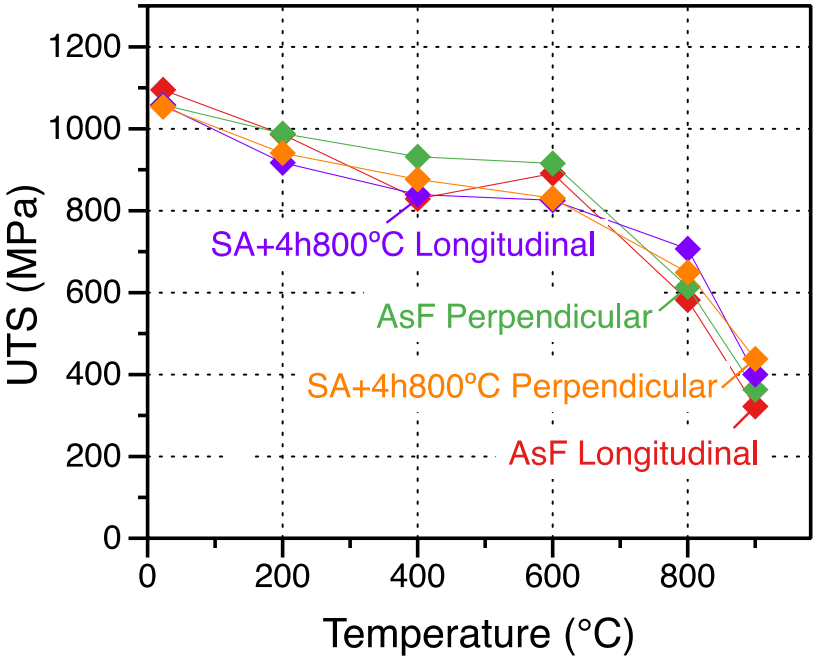




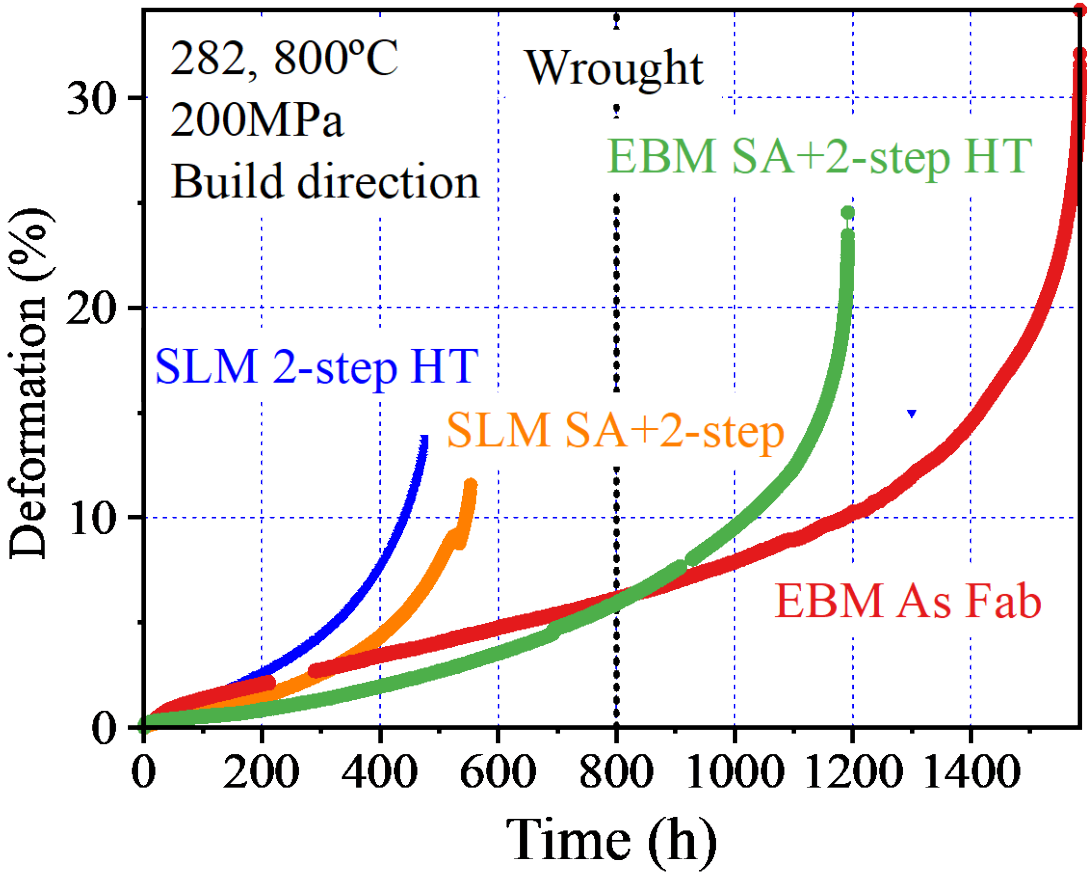
Similar Tensile Properties Along & Perpendicular to the Build Direction For EBM282



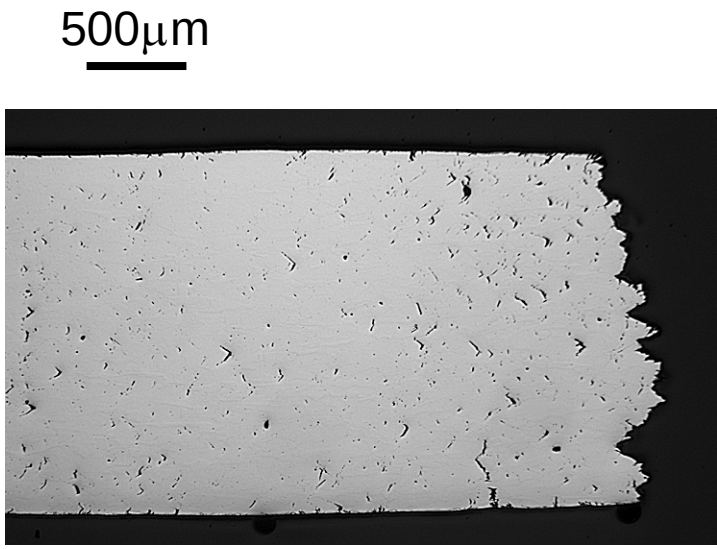




Great Creep Strength for EBM282 in the As Fabricated & Annealed Conditions Acceptable Creep Properties for SLM282

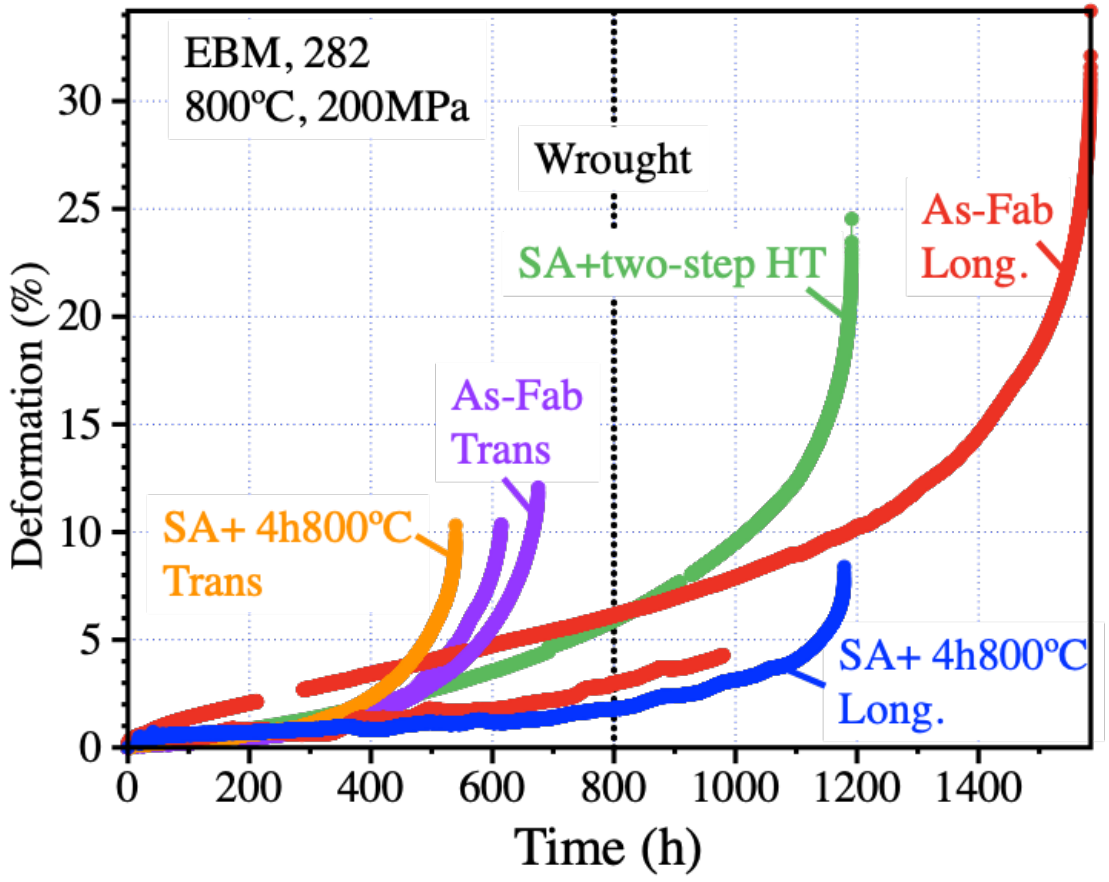


Sub size 1" dog bone specimens



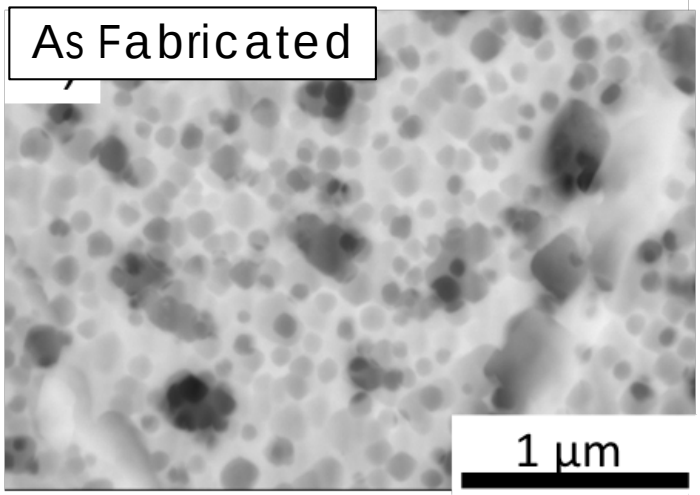
Siemens will conduct tensile creep fatigue tests on annealed SLM 282.

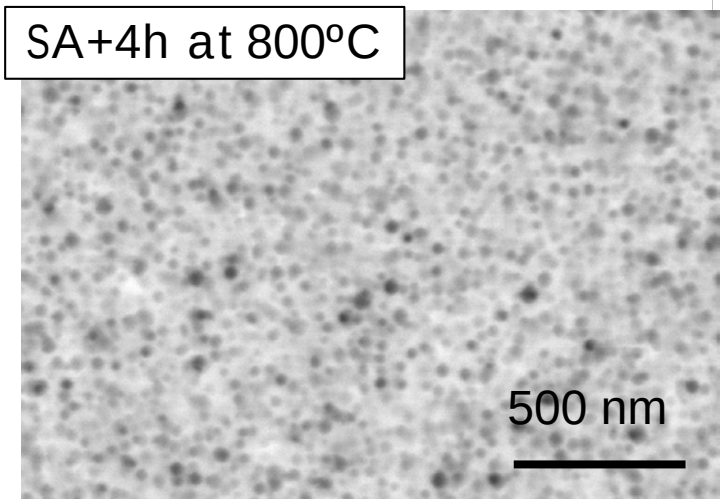
Significant Decrease of Creep Strength Perpendicular to the Build Direction But Still Close to Wrought Creep Strength

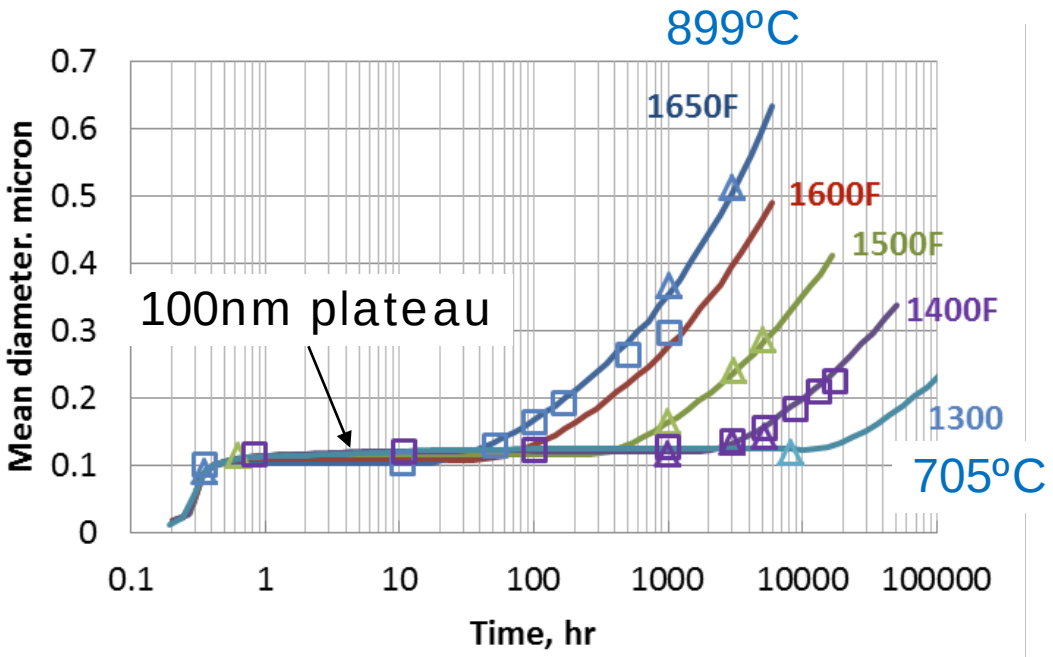


Decrease of creep ductility after 4h at 800ºC?

~100nm Gamma Prime Can Provide Good Creep Strength

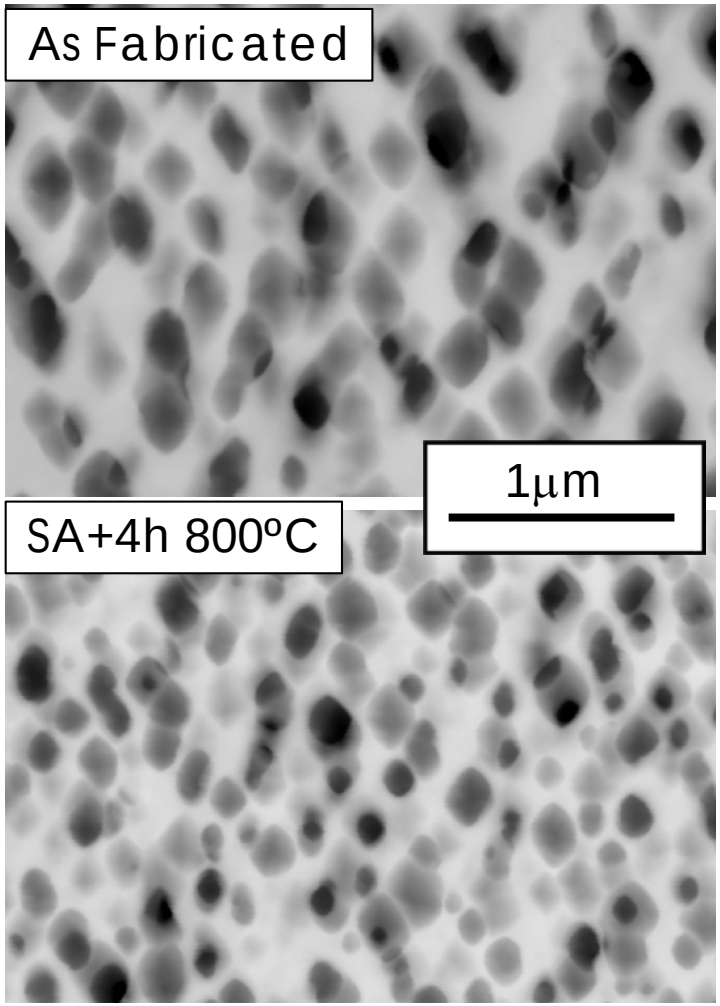


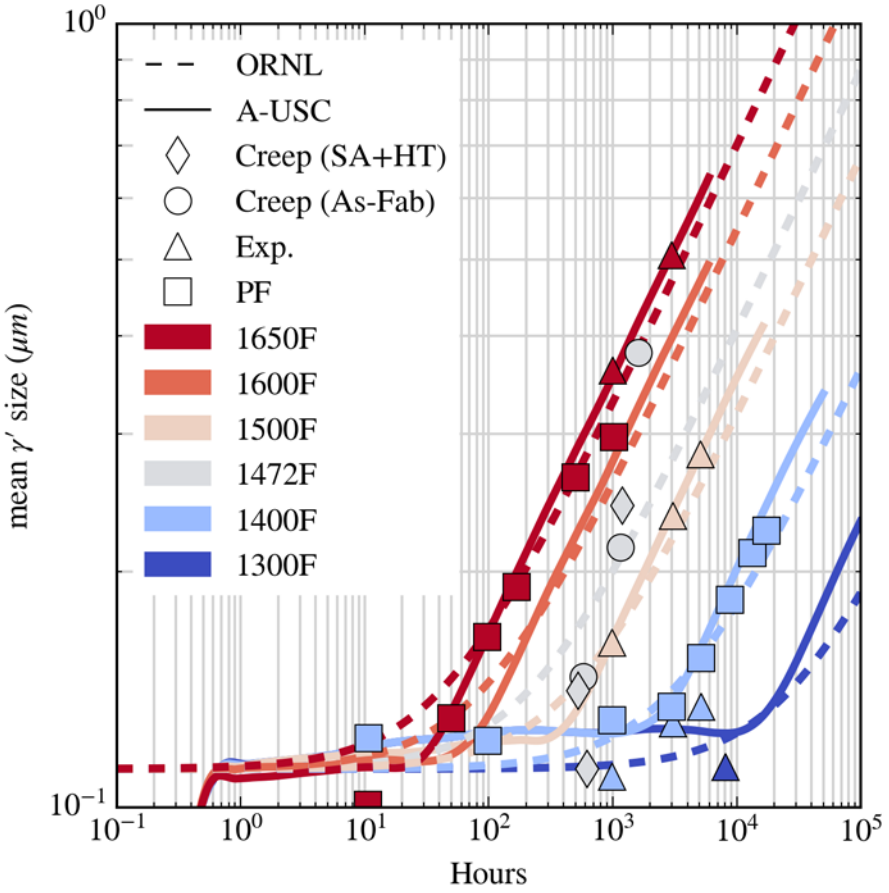




Predicted γ' sizes by precipitation model (curves) and by phase field model (squares) vs. experimental data (triangles)
C. Shen, GE report on Modeling Creep-Fatigue-Environment Interactions, DOE/NETL, DE-FE0005859

Significant Gamma Prime Coarsening During Creep Testing

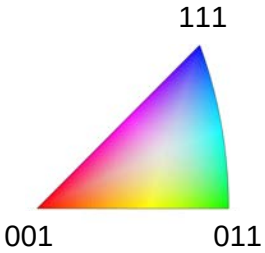




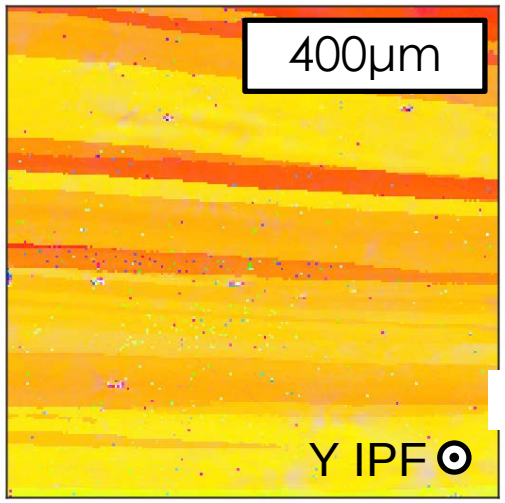
Coarsening according to a cubic rate law

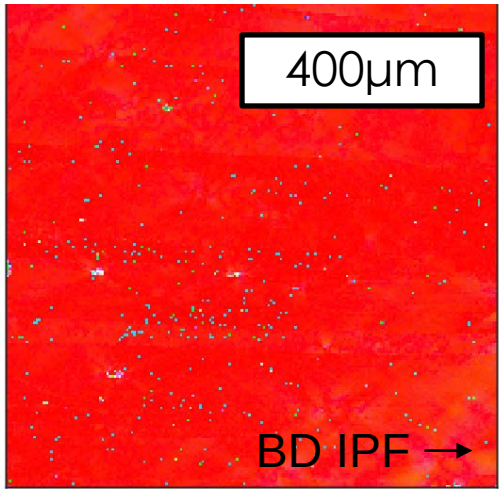
Need to refine image analysis method to sperate precipitates

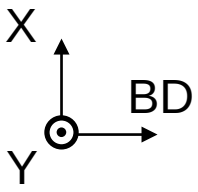
Higher Lifetime for As-Fabricated Specimens Along Build Direction Due to Extreme Texture

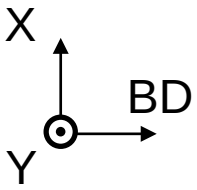


As-Fab Longitudinal specimens after rupture

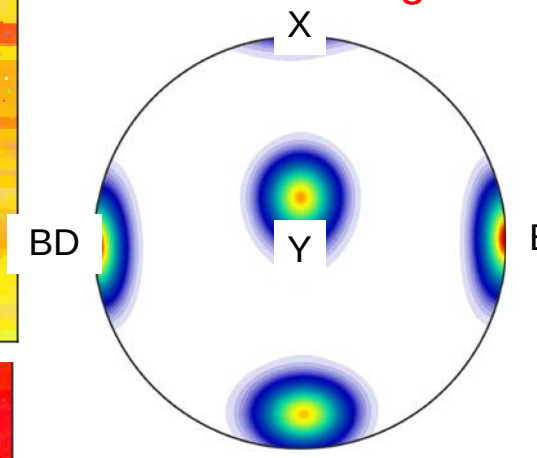




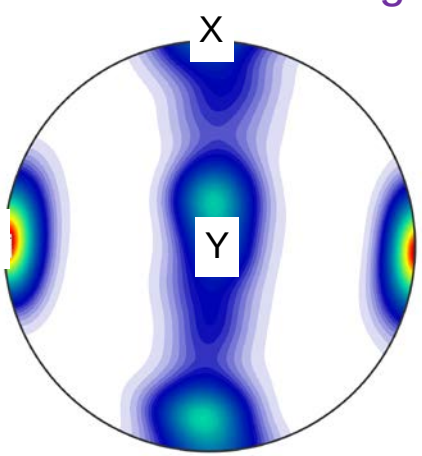




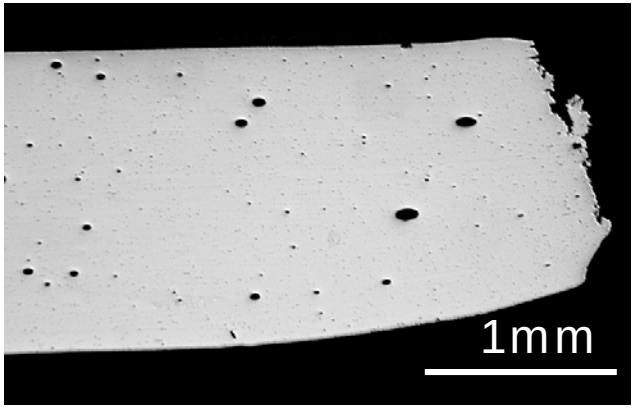
As-Fab Long.

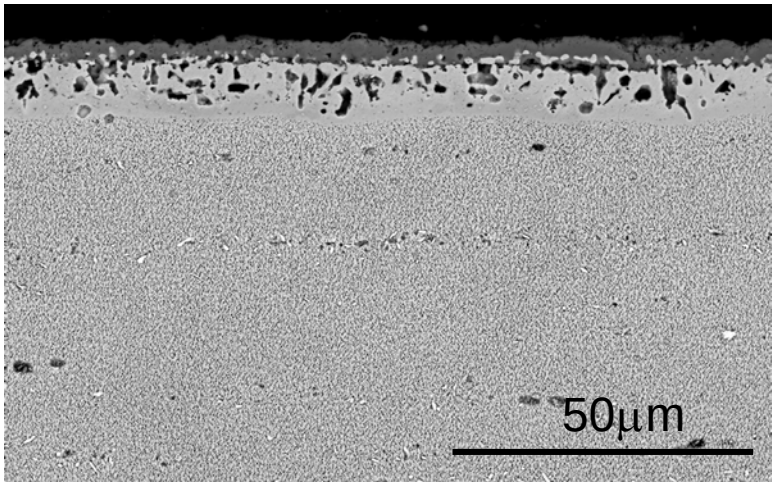


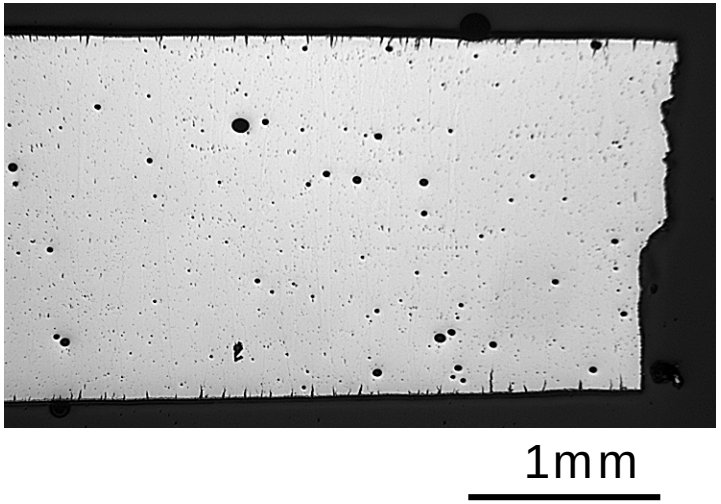
SA+4h800C Long.

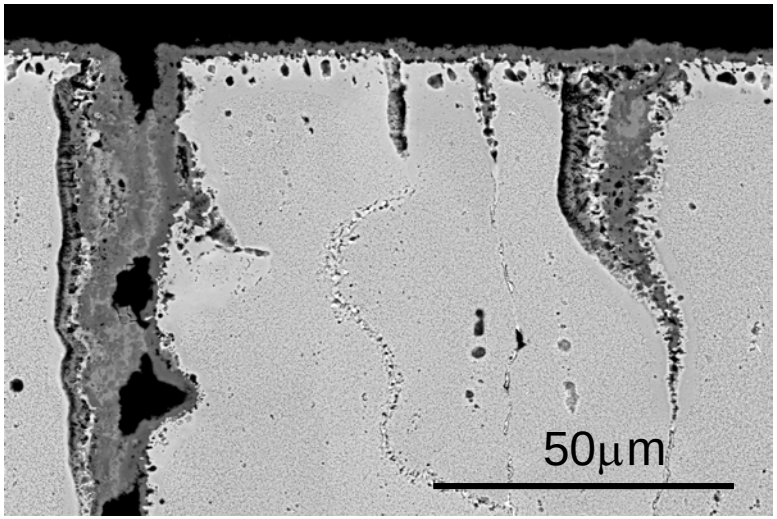


Anisotropic Creep Behavior Due to Elongated Grains & Failure at Grain Boundaries

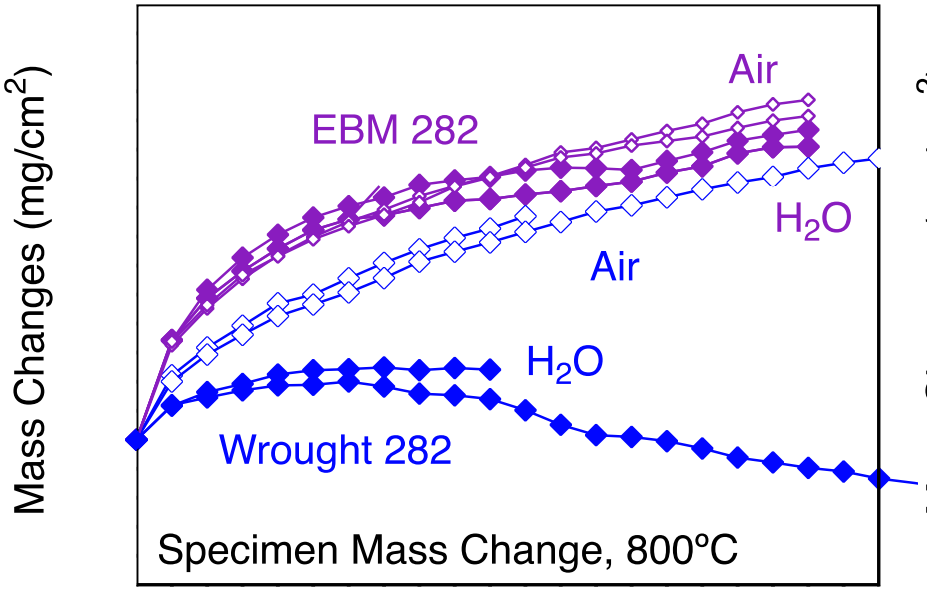


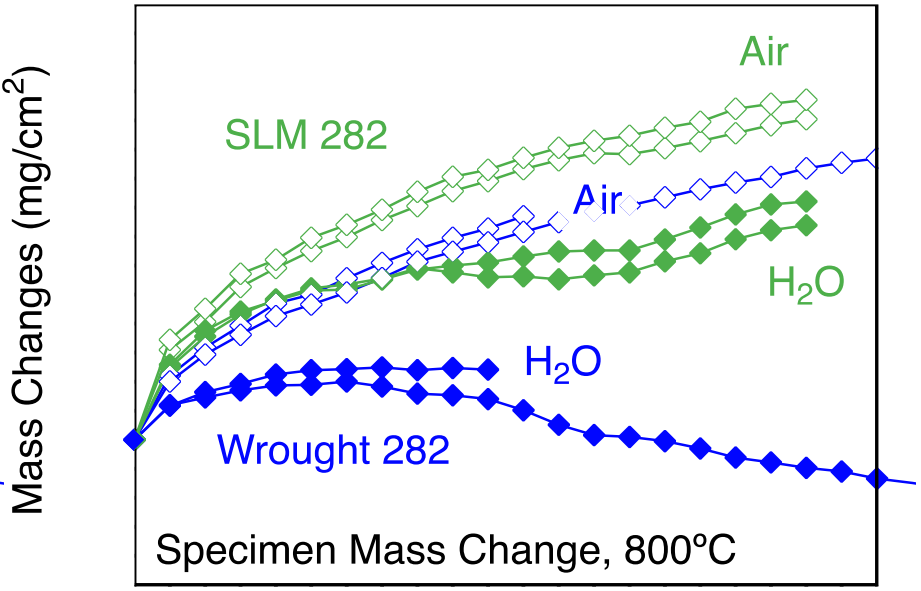






EBM282 and SLM282 Coupons Showed Good Oxidation Behavior at 800ºC. Limited Effect of H_2O

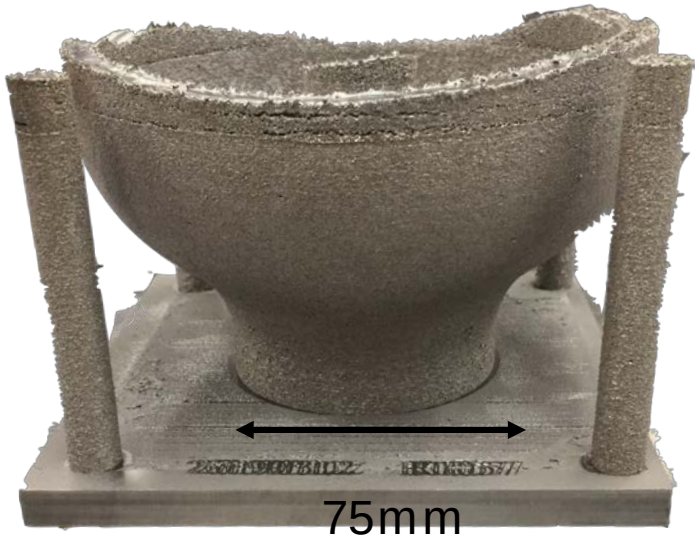




Fabrication of a 282 Concentric Reducer By EBM

DeBarbadillo et al. Epri conference, Fitting capability for A-USC

"Three successive cold reductions were required with intermediate annealing steps at 1121 °C "



Conclusion and Future Work

- Good creep properties for EBM282 alloy in the as fabricated and annealed conditions. Promising properties for annealed SLM 282
- Continue Generate relevant data for EBM and SLM 282 (oxidation fatigue, etc.)
- Demonstrate possibility to locally control the alloy grain structure and reduce properties anisotropy
- Modeling process-microstructure-properties-performance relationship