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Title: Capturing the Complexity of Additively Manufactured Microstructures

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Capturing the Complexity of Additively Manufactured Microstructures

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ASC/AM speaker series

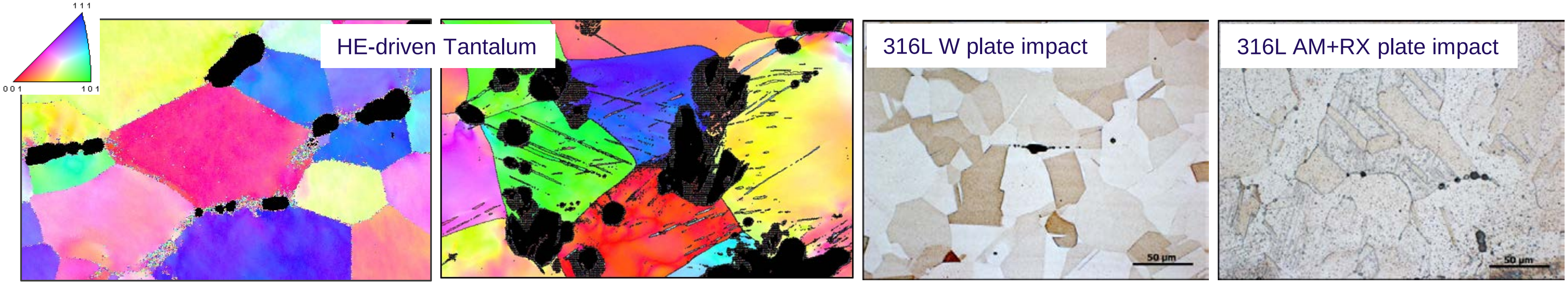
Outline

- **Role of microstructure characterization**
- **Characterization path for 316L SS**
- **Preliminary work on 304L SS**

The Microstructure-Performance Relation

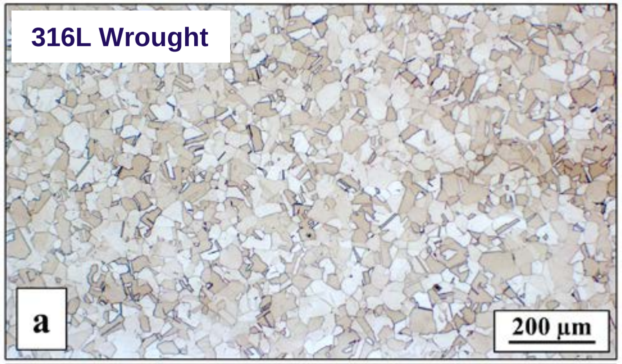
- **The underlying mechanisms and kinetics controlling damage nucleation and growth as a function of material microstructure and loading path are not well understood.**

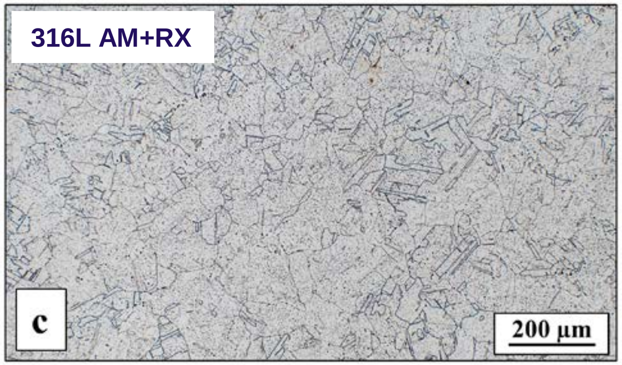
- **Experiments indicate that structural features such as grain boundaries, grain size distribution, grain morphology, crystallographic texture are all factors that influence mechanical behavior.**



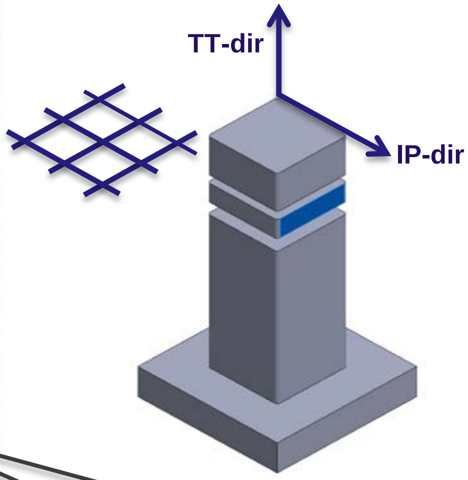
- **Additively manufactured materials impose a new level of microstructural complexity:**
  - ❑ The build pattern in addition to the polycrystalline microstructure within that pattern.
  - ❑ Potential for significant residual stresses

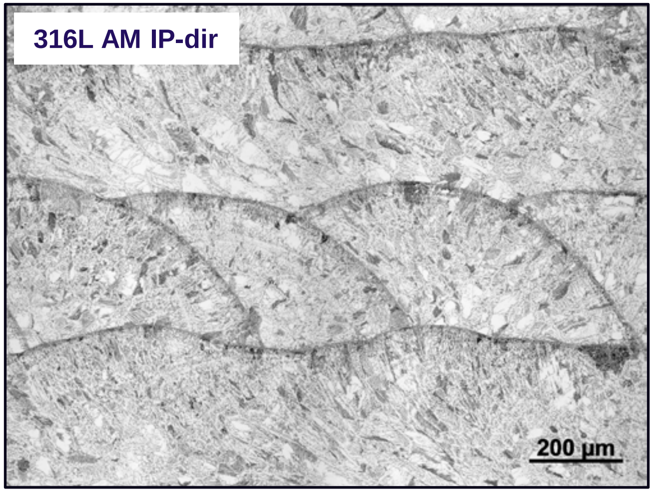
Microstructural Differences in 316L SS

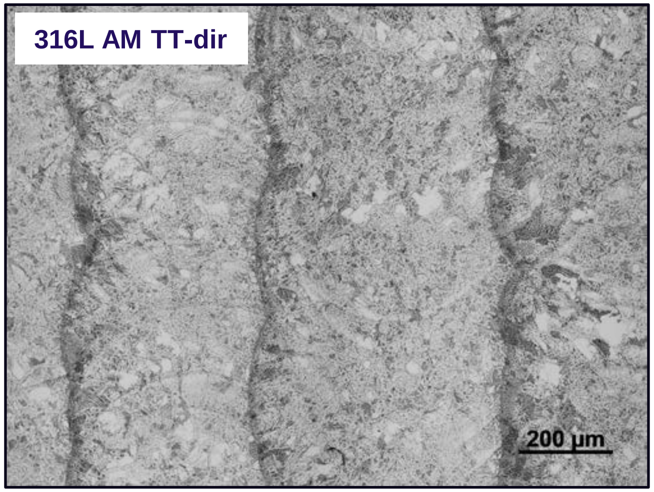




LANL LENS-built 316L

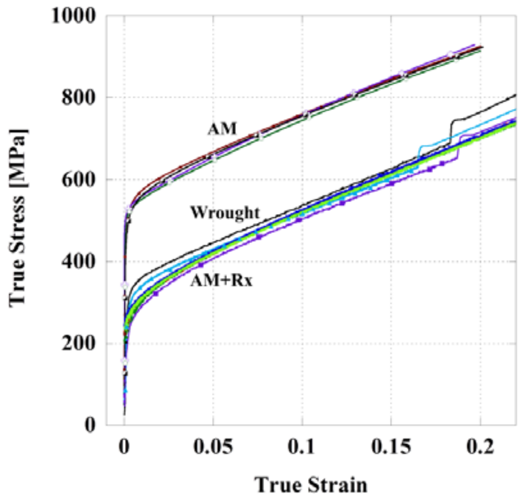




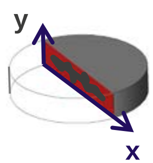


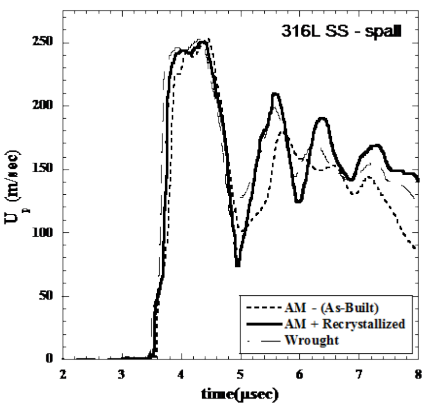
AM material exhibits consistently finer microstructure and directional anisotropy determined by building pattern

Material Response to Loading (316L SS)



Quasi-static compression tests





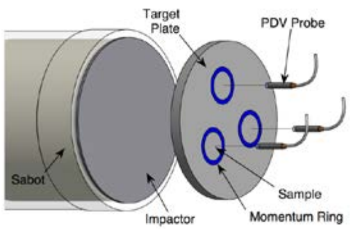
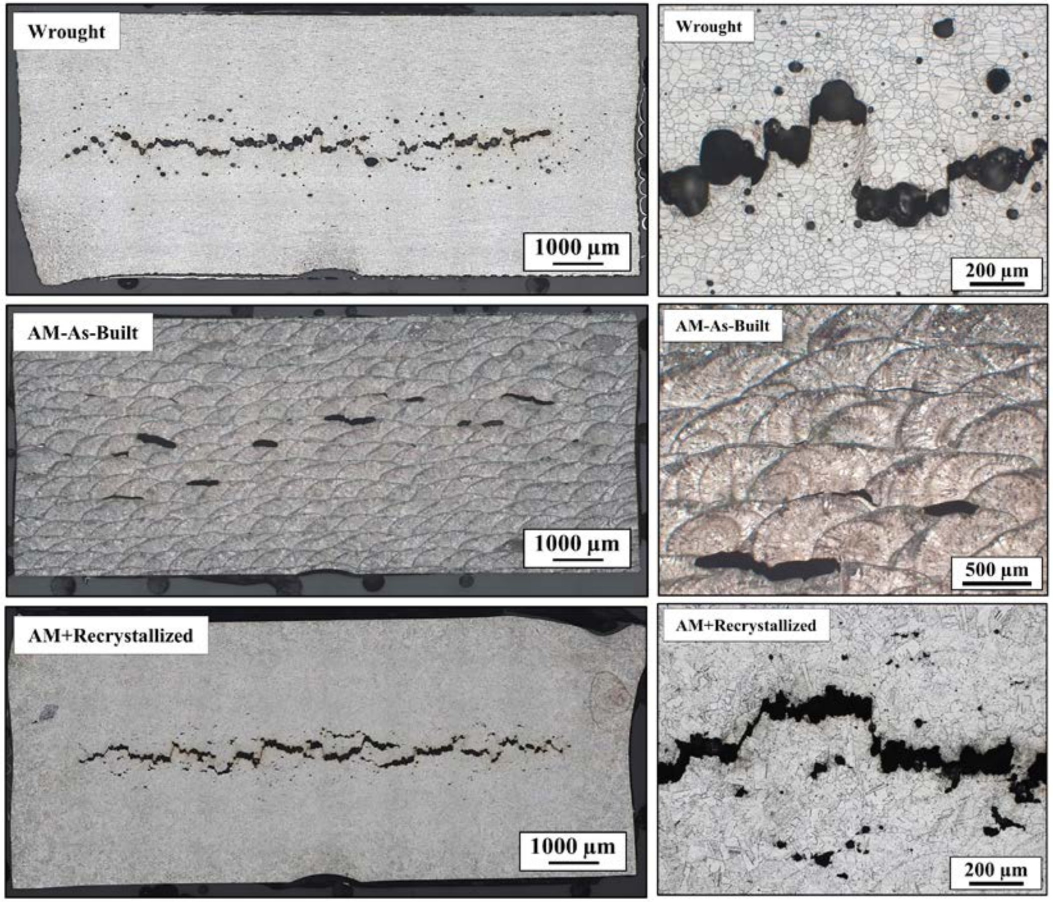


Plate impact triple-shot experiment 250m/s (80mm gas gun, MST-8)

G.T. Gray III, V. Livescu, P.A. Rigg, C.P. Trujillo, C.M. Cady, S.R. Chen, J.S. Carpenter, T.J. Lienert, and S. Fensin,, EPJ Web of Conferences, 94 (2015) 02006.

Shock damage distribution in cross-section



Mechanisms of damage nucleation are strongly dependent on material processing and resulting microstructure.

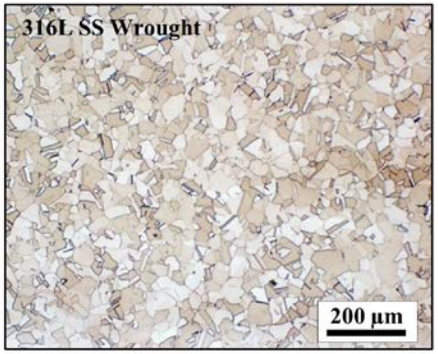
Suspects for Differences in Material Behavior

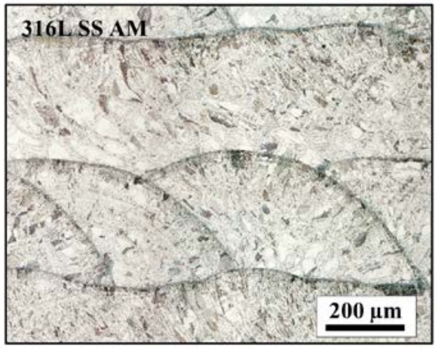
- **GRAIN SIZE**
  - ❑ **Plastic flow resistance of a material generally increases with decreasing grain size**
  - ❑ **Grain size of the additive materials is a factor of 4 smaller than either of the other two materials.**
- **HIGH STARTING DEFECT POPULATION (dislocations)**
- **CHEMICAL INHOMOGENEITY (from solidification)**
- **GRAIN BOUNDARY CHARACTER (could affect damage nucleation)**

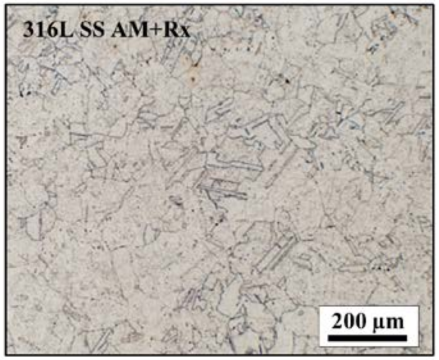
All of these microstructural quantities influence dislocation motion and determine their response to deformation.

Microstructure Characterization (Process-Performance-Prediction)

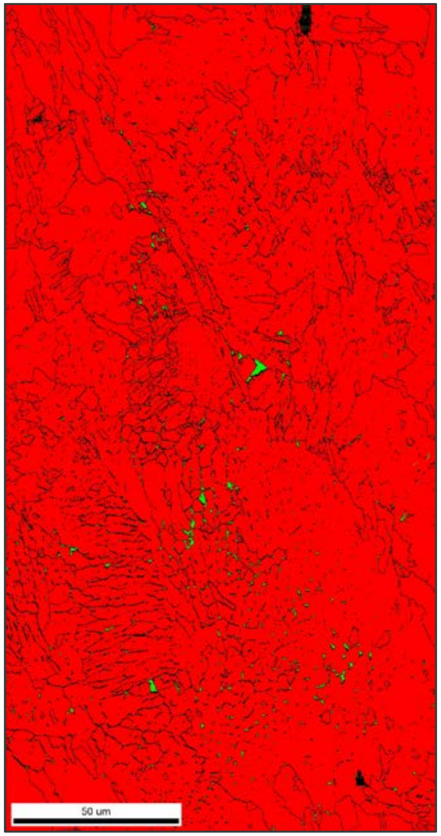
Grain Morphology/Crystallographic Texture (directional material properties)





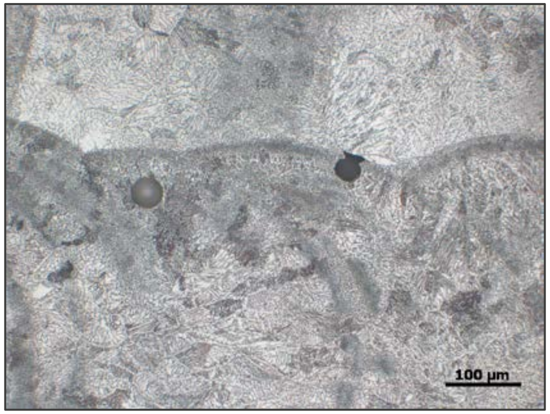


Phases/Chemistry Present



Phase	Fraction	Fraction
Austenite	0.976	0.976
Ferrite	0.024	0.024

Deposition Defects

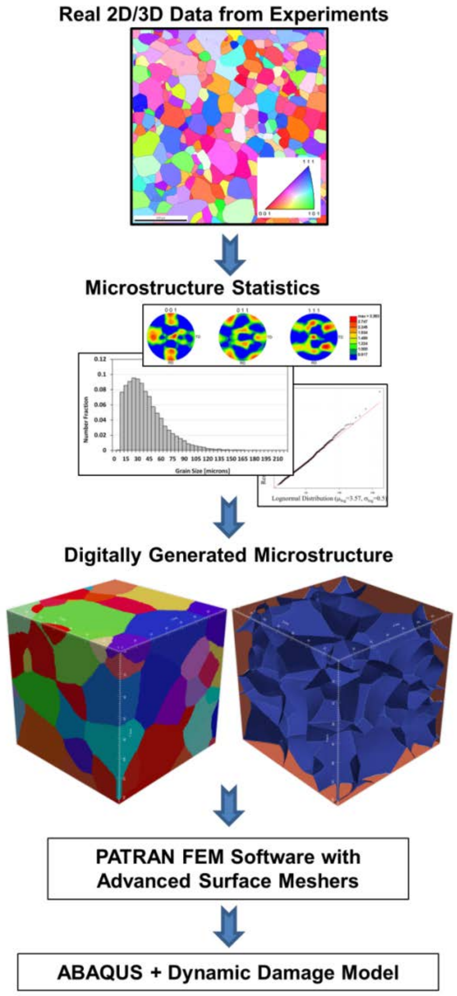


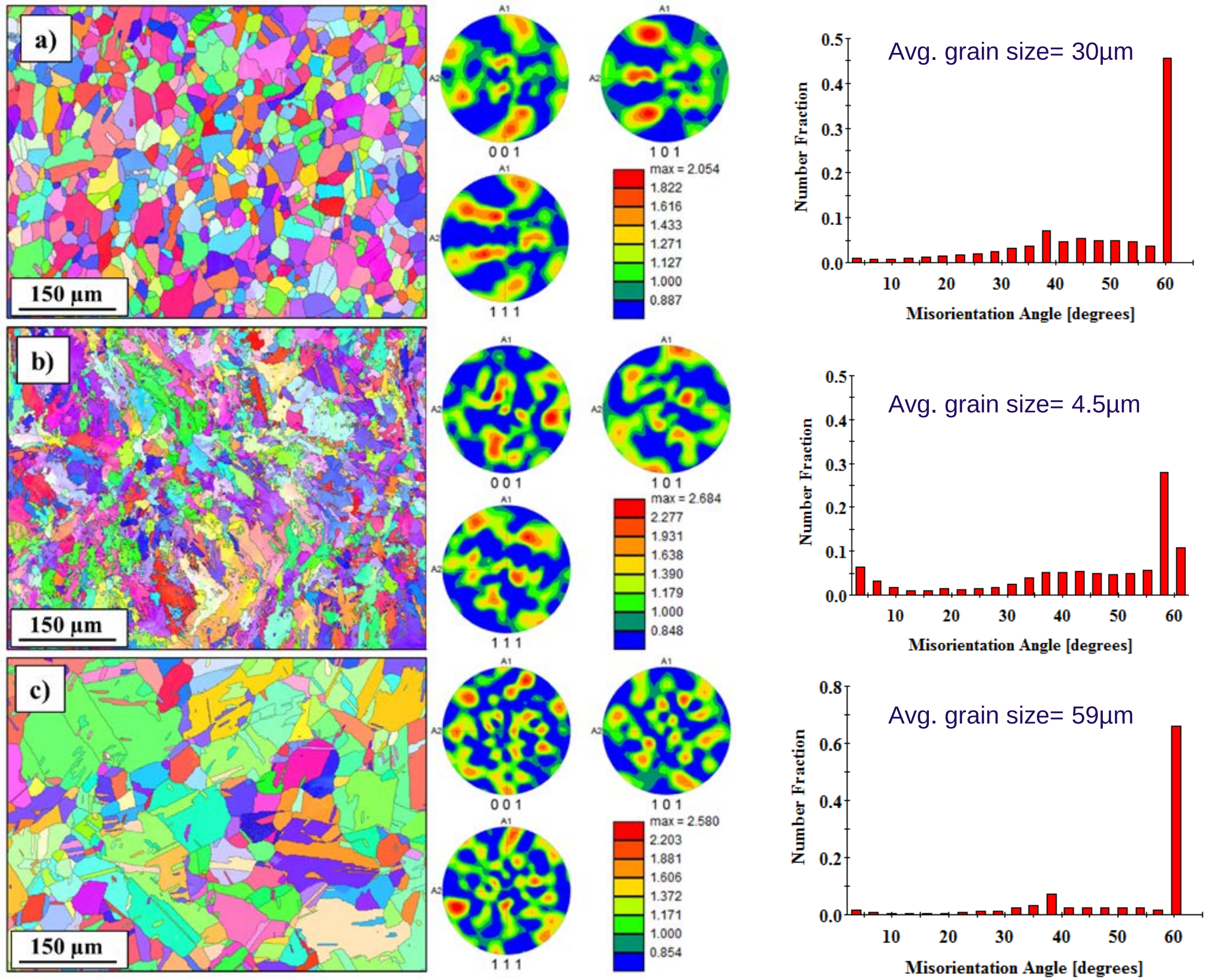
Identify important microstructure parameters for material performance

316L Process-Aware Modeling, Performance, and Prediction

- Explaining the significant difference in flow stress between wrought, additive, and heat-treated additive 316L materials
- Single and polycrystal modeling of the metallographically characterized 316L material as well as continued development of the single bead RVE system to assess magnitudes of internal stress developed during probably cooling scenarios for single phase cooling.
- Metallographic work on the 316L material has been completed (unless additional characterization questions arise from our modeling efforts)
- Learning about the new 304L material and populating a microstructure database in order to carry-on our polycrystal modeling of the materials.
- Critical linkages with other experimental work (like mechanical performance) also take place.

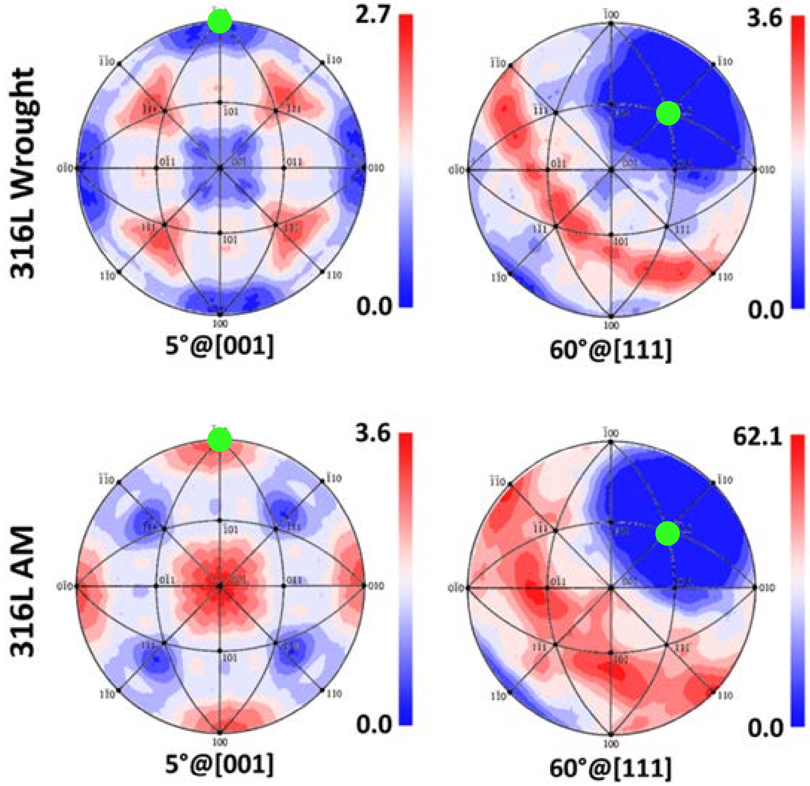
316L Metallographic Characterization

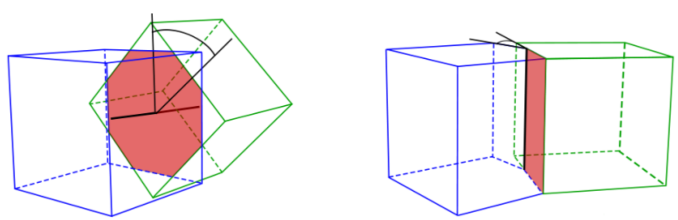




Different grain sizes, similar texture, different misorientation distribution

3D Distribution of Grain Boundary Planes





Twist Boundary

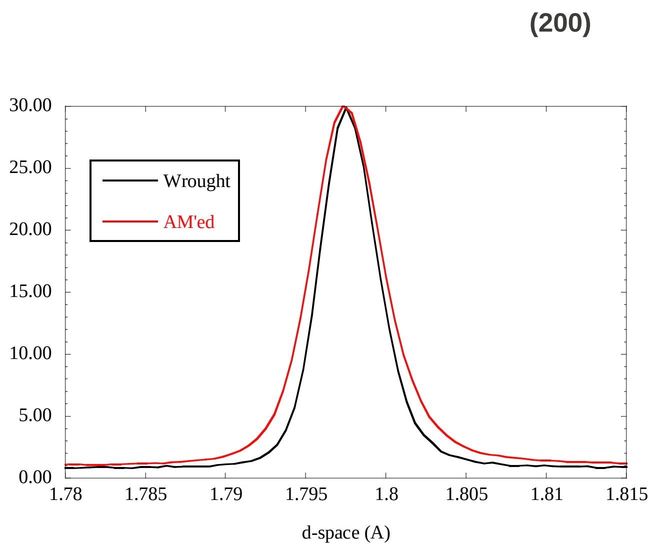
Tilt Boundary

- **Grain boundary types and energies determine the properties of a material.**
- **Stereological method applied to statistically significant EBSD data**
  - The distribution of the grain boundary planes can be plotted on a stereographic projection.
  - Boundaries with normals parallel to the misorientation axis are twist boundaries
- **Significant differences in distributions of grain boundary types can be a potential factor in the development of stresses and damage in these microstructures.**
- **At specific misorientations, the distribution of grain boundary planes exhibits dramatic differences.**

Veronica Livescu, et al., Proceedings of The Ninth Pacific Rim International Conference on Advanced Materials and Processing (PRICM9), 2016 – accepted

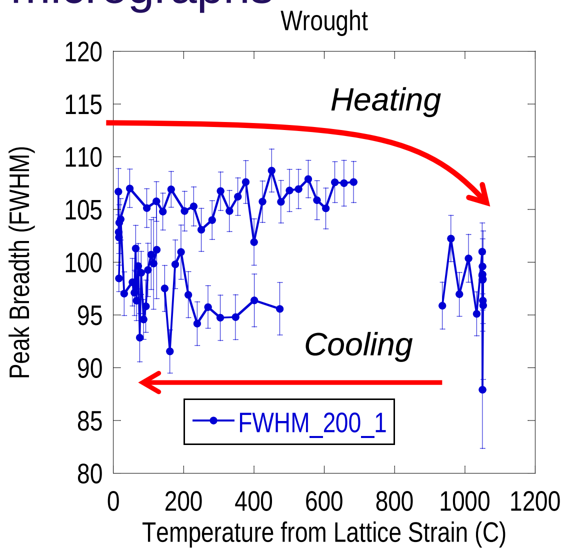
Neutron Diffraction on Wrought and AM 316L

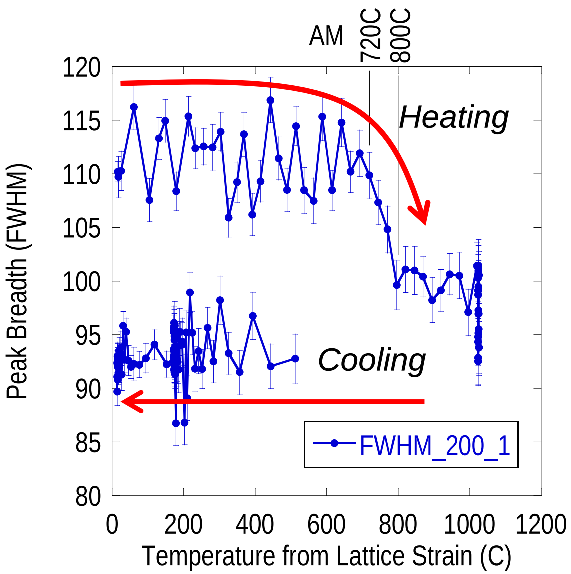
Diffraction line profile analysis performed both at RT and through a recrystallization treatment at 1060°C



- Strong *hkl* dependence of peak broadening is the signature of increased dislocation density.
- Able to quantify both the grain sub-cell size and the dislocation density from this data.
- Diffraction data indicates a combined effect of increased dislocation density and crystallite size
- Different lattice expansion in these materials is also indicative of slightly different chemistry consistent with the chemical coring observed in the optical micrographs

- **The peak from the AM material starts broader and decreases more (to a narrower final peak) than that from the wrought.**

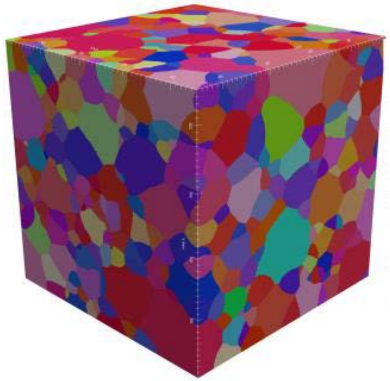




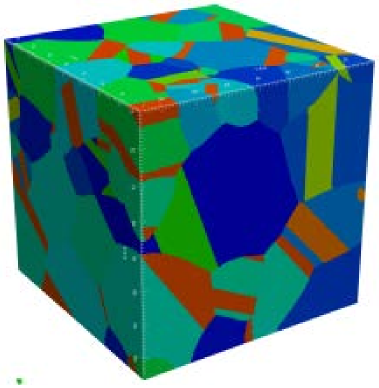
Microstructure Statistics for Model Development

- Develop material models
- Provide critical parameters for material response to loading
- Create a microstructure-aware predictive capability for all microstructures

Model-ready digital representations of real materials



Digitally generated tantalum microstructure



Digitally generated 316L wrought microstructure

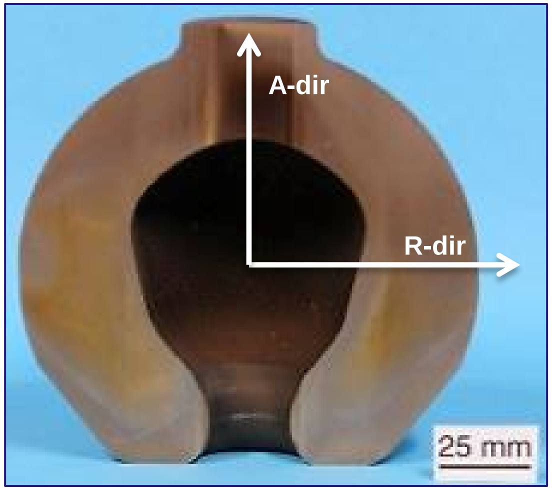
First cut topology for 316L AM

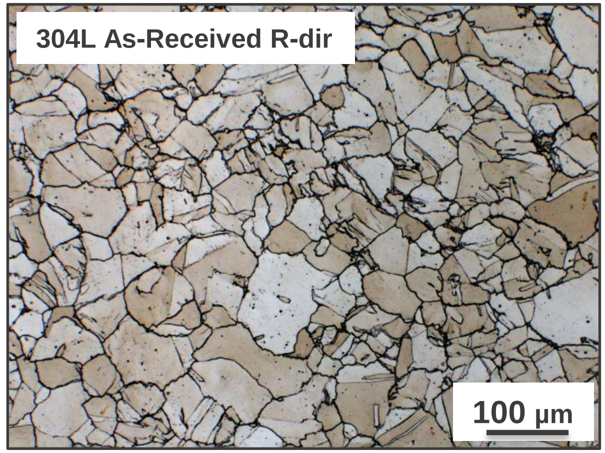
Mesh by Tim Helton

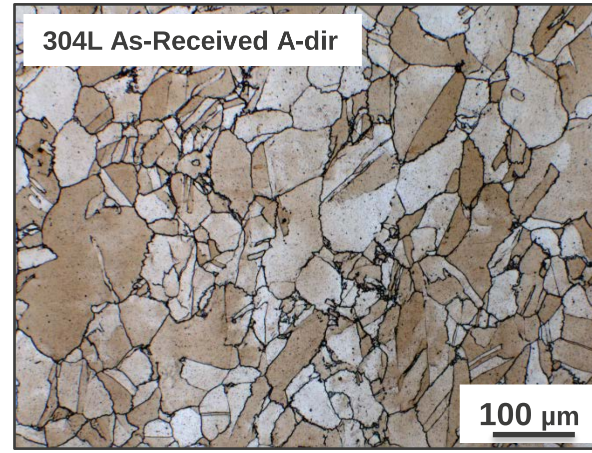
dream3D software

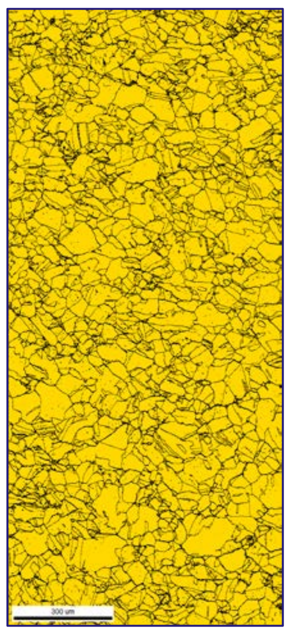
Veronica Livescu, Curt A. Bronkhorst, John F. Bingert, Proceedings of the 2nd International Congress on 3D Materials Science (2014), pp. 53-58.

304L As-Forged

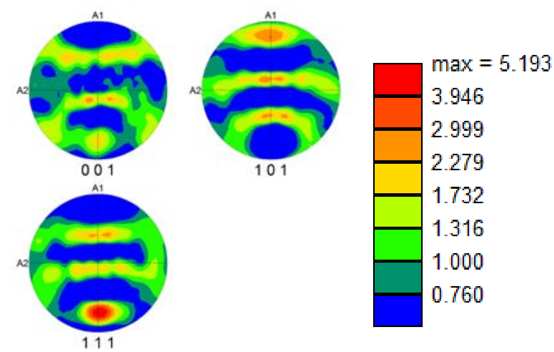






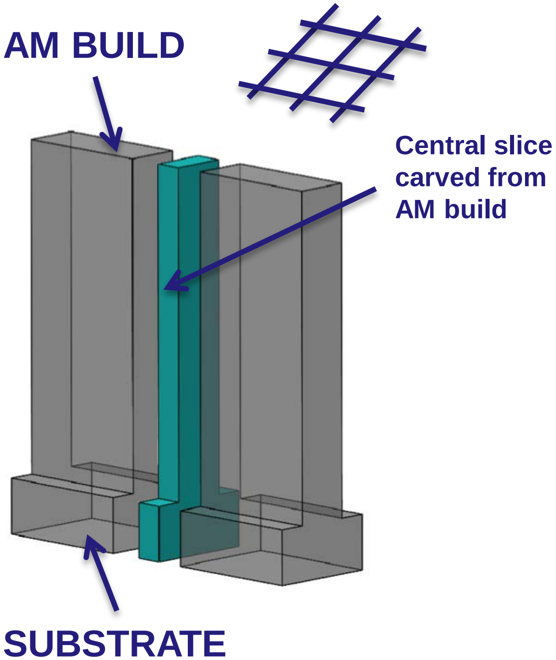


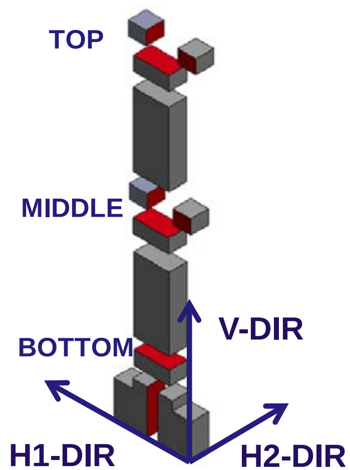
Phase	Fraction
Austenite	0.970
Ferrite	0.030

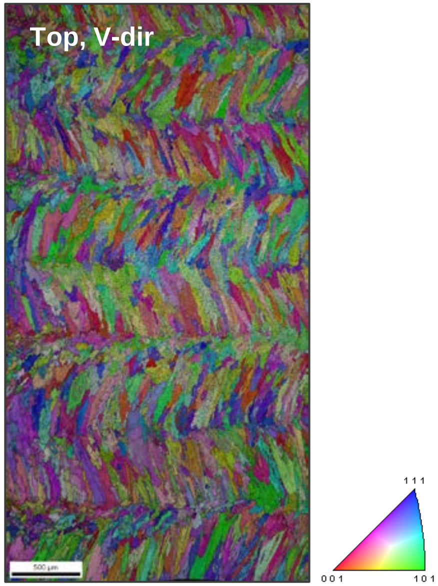


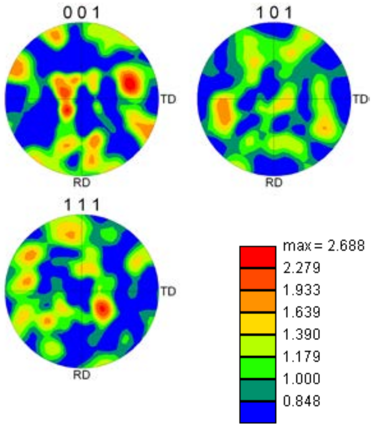
- Moderate Texture
- Very fine dispersion of ferrite
- Signs of work in the microstructure

304L AM LANL LENS V-build - Optical Microscopy

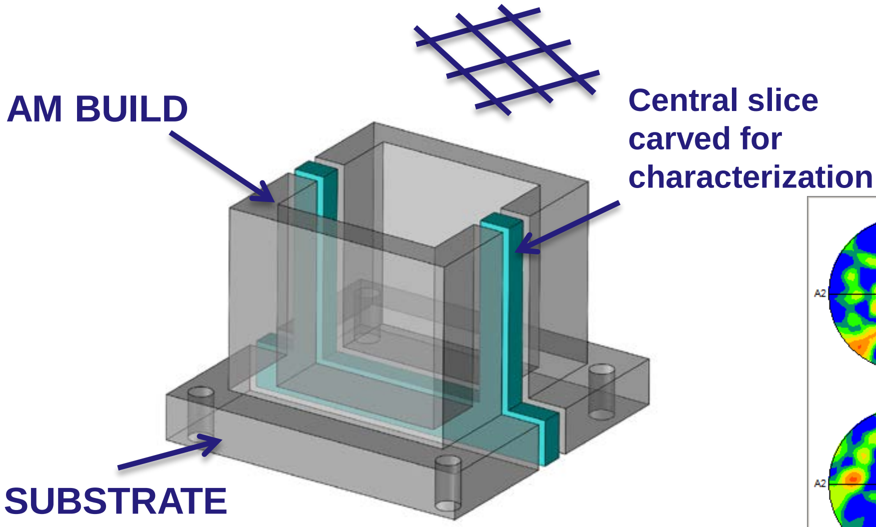


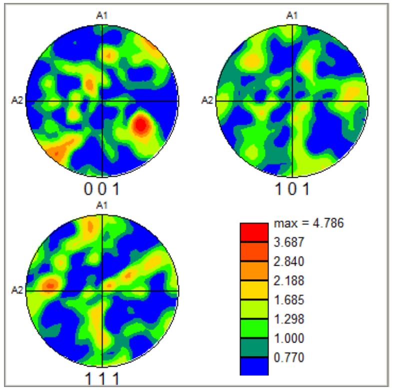


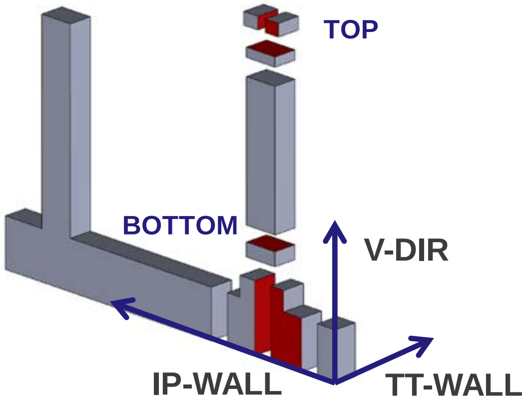


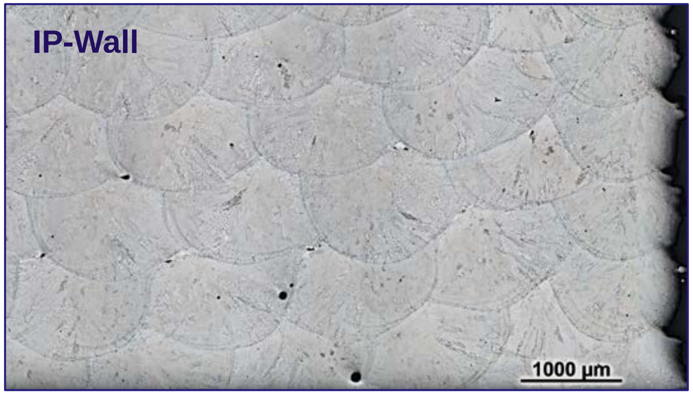


304L AM LANL LENS Box - Optical Microscopy





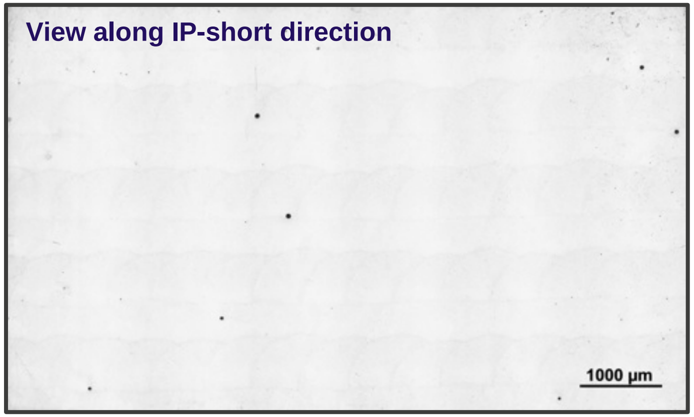


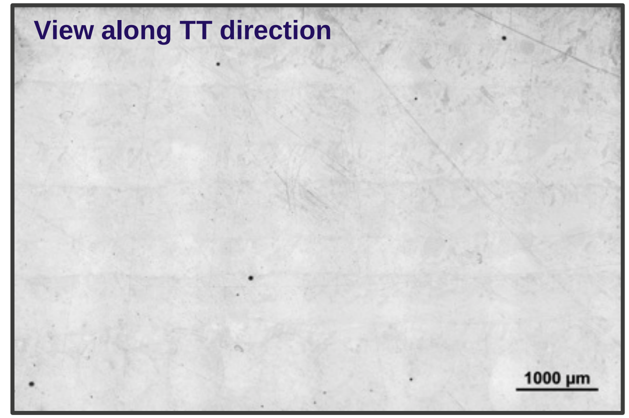


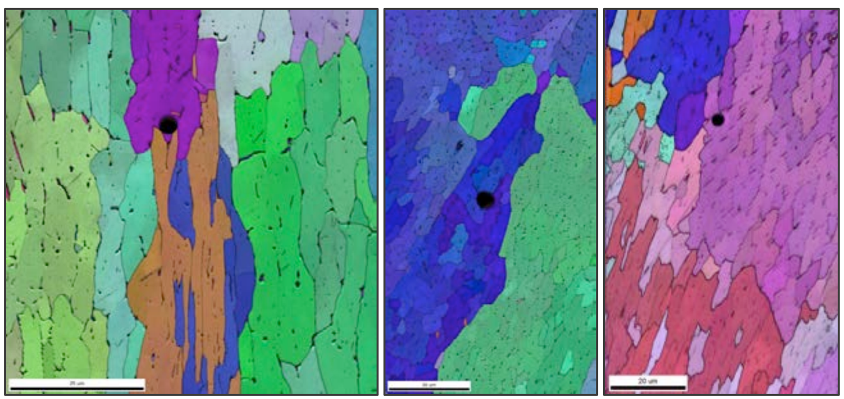
TT-Wall Bottom

304L AM LANL LENS – Defects vs. Powder

Occasional porosity, between 5 and 50μm diameter

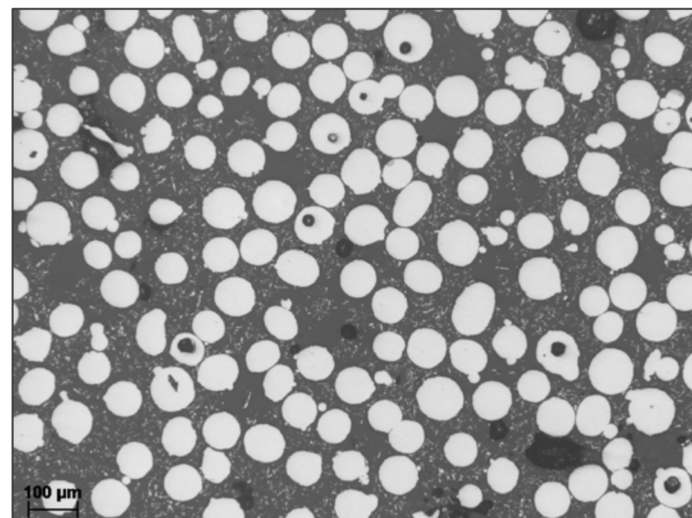






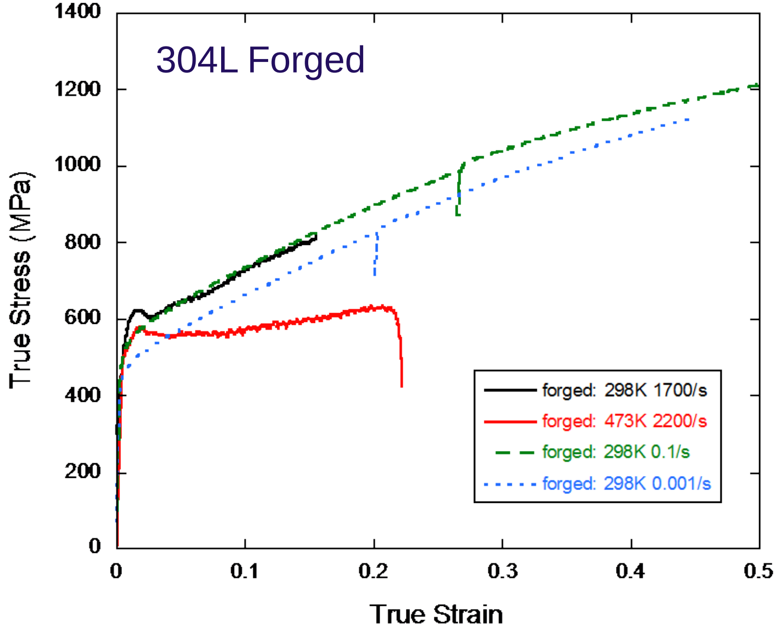
Voids are spherical and are NOT connected to high angle boundaries

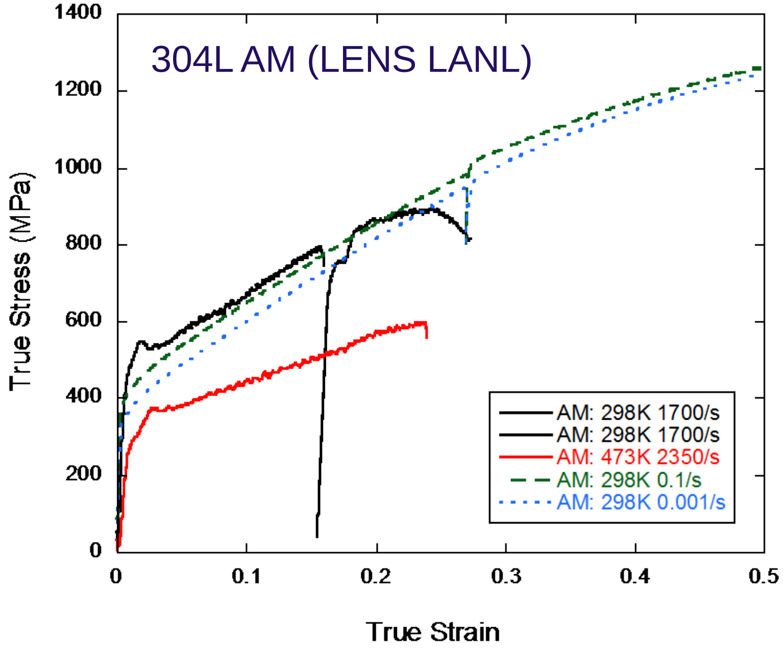
LENS Pedigreed 304L SS Powder

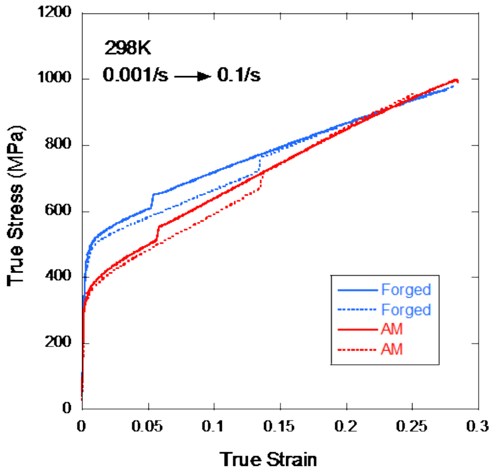


Picture by Ben Morrow

304L First Mechanical Tests







- **Different starting dislocation density**
- **Different hardening rate**

Summary

- **The Wrought, AM, and AM Heat-Treated materials are significantly different in both structure and mechanical behavior.**
- **Metallographic characterization – key to our ability to develop appropriate single crystal and microstructural models – including EBSD, serial sectioning, HEDM.**
- **316L mechanical testing and microstructure characterization is sufficient for now for pursuing the questions related to plastic flow stress differential and our study of AM materials.**
- **Neutron and x-ray diffraction - determine internal stress and structural state evolution of the stainless steel materials.**
- **304L – on-going evaluation of microstructures. A lot more work to be done!**