SAND2015-5097C

Mechanical Behavior of Additively Manufactured 304L Stainless Steel

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Outline

- Background
- Experiments
  - Microstructural Characterization
  - Tensile Test Results
- Simulations
  - Model Construction
  - Preliminary Results

Laser Engineered Net Shaping (LENS™)

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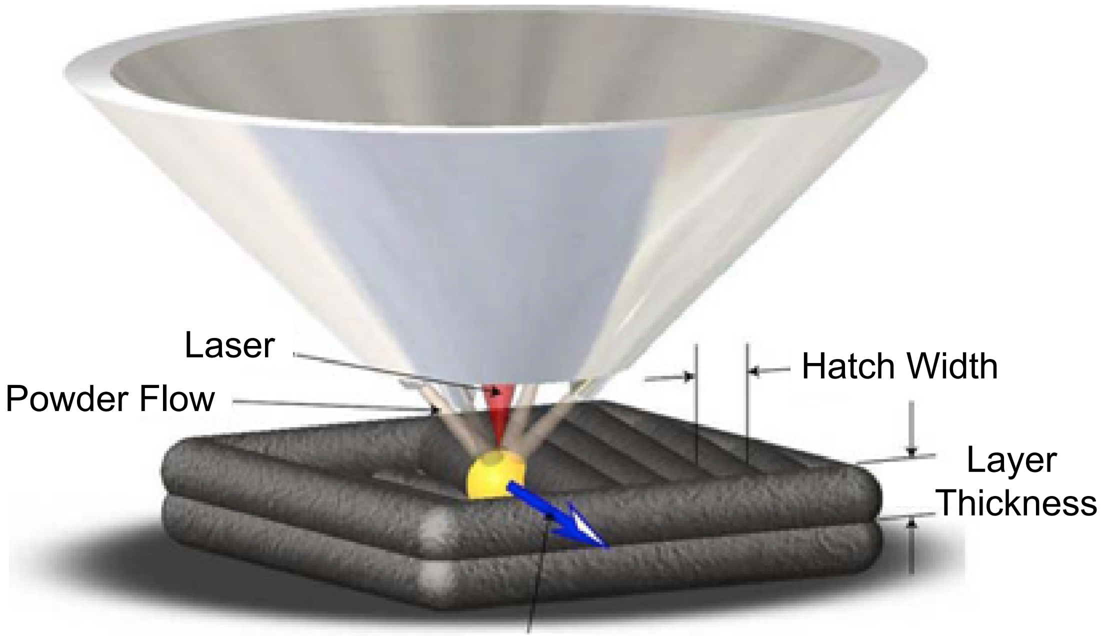
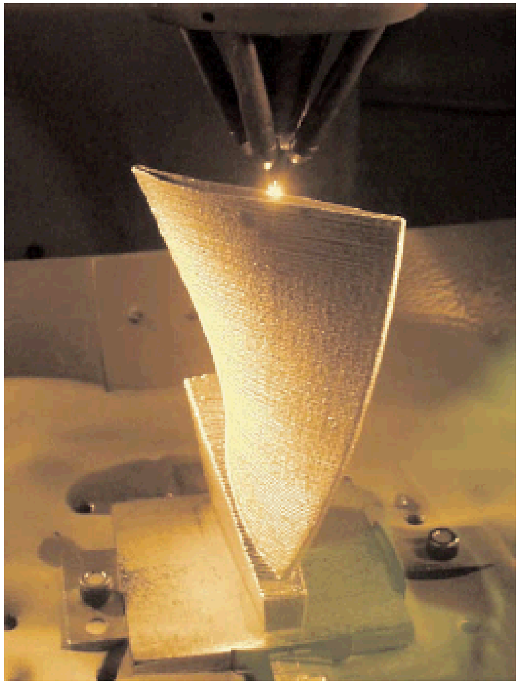
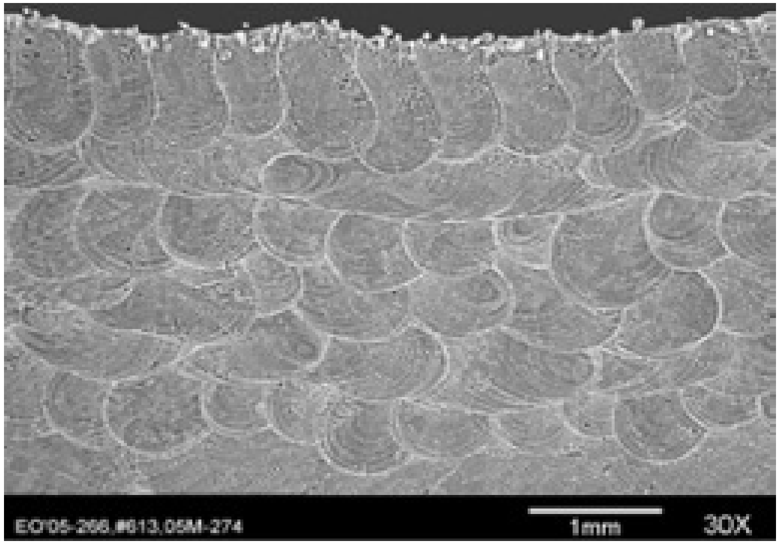




- Pros
  - Rapid design to production
  - Complex part geometries
- Cons
  - Speed
  - Finishing required
  - Open scientific questions

Fundamental Questions

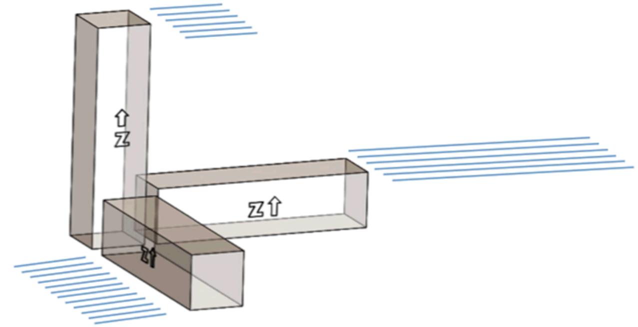
- How does the mechanical response of a LENS material compare to that of a wrought material.
  - What role does the exotic microstructure play?
  - Variability?

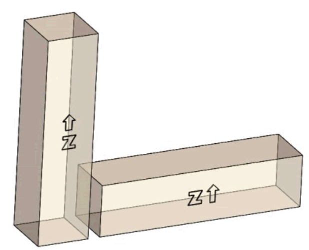


- How do we predict the response?
  - What level of sophistication do we need in our simulations?
  - Loss of ‘scale separation’?

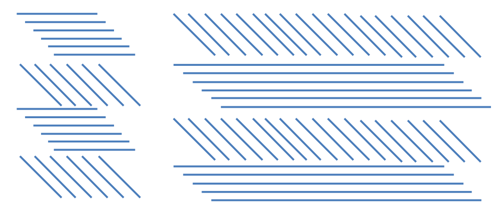
Parameter Sensitivities

- Laser power
  - 3.8 kW, 2 kW, 0.5 kW
- Parallel Hatch vs. Cross Hatch
- As-Deposited vs. Annealed
- Anisotropy
  - X vs. Y vs. Z
- Center vs. Edge
- Strain Rate
  - 10^{-5} s^{-1} to 10^{9} s^{-1}
- Temperature
  - 20 ^{o}C to 300 ^{o}C





Sample Geometry

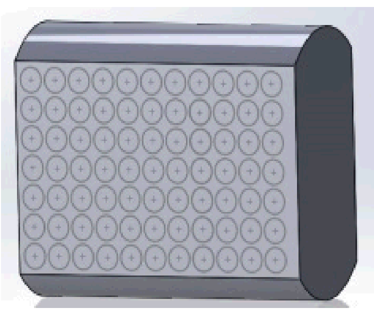


Schematic raster fill patterns

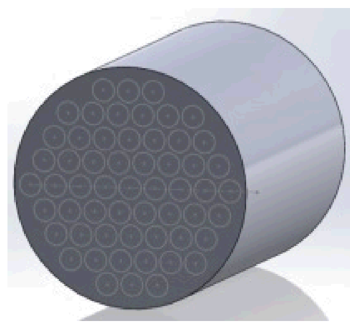
EXPERIMENTS

Base Material

Wrought Bar

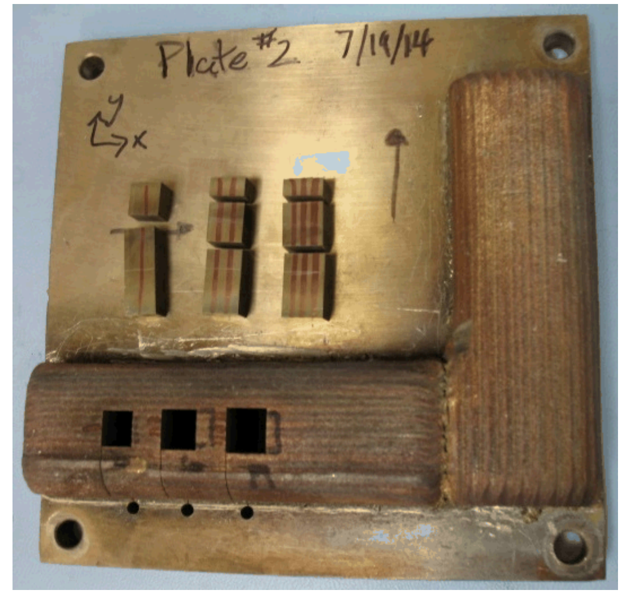


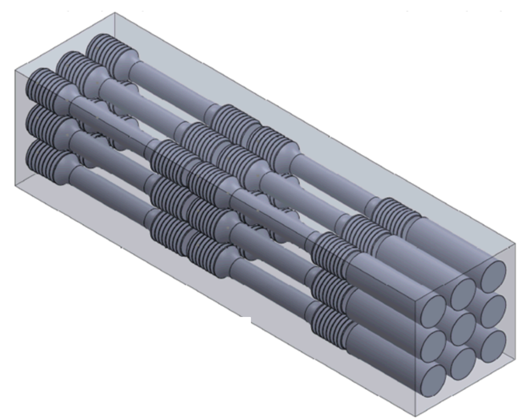
Transverse



Longitudinal

LENS Bars ("Twinkies")





LENS Microstructure: Orthographic Projections

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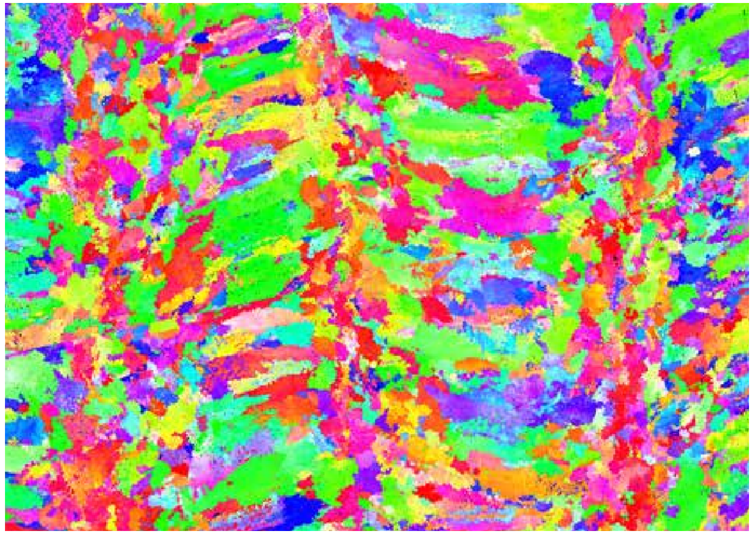
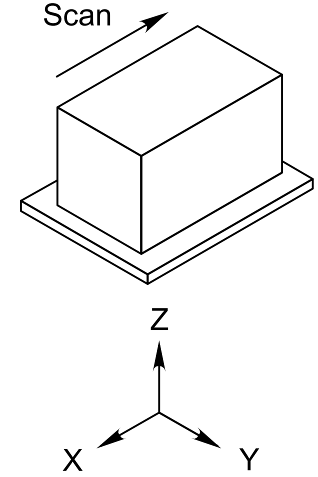
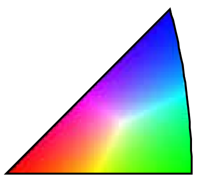
Z-Plane (Z-direction)



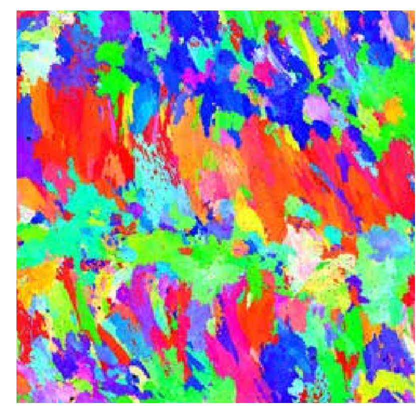




X-Plane (X-direction)

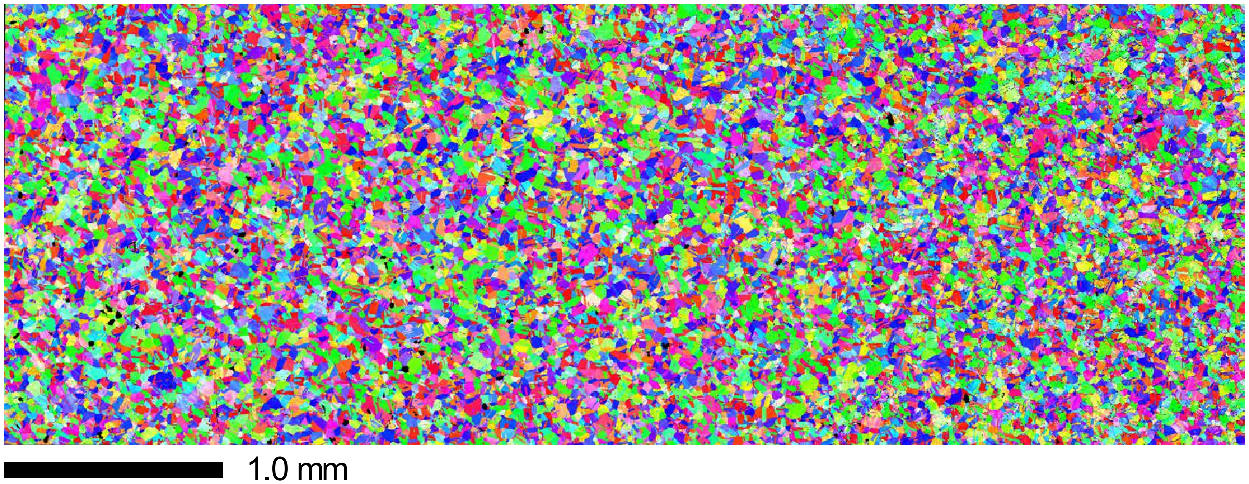
1.0 mm

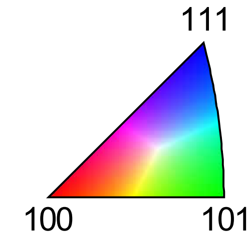
Y-Plane (Y-direction)



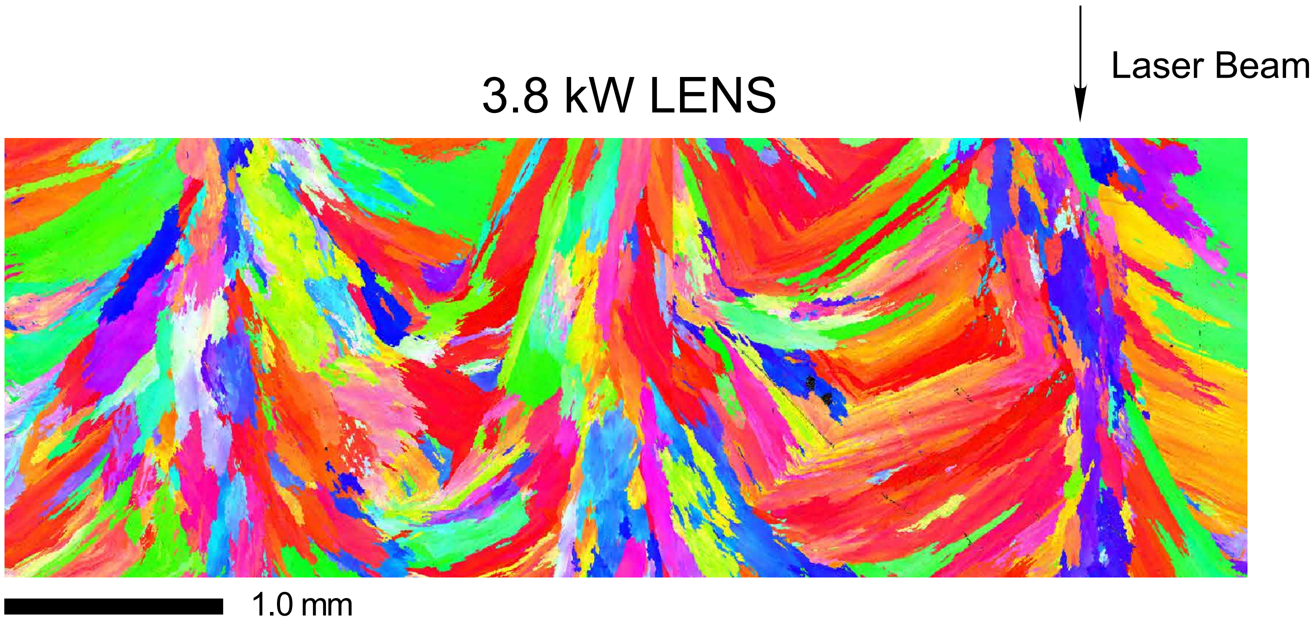
Wrought vs. LENS Microstructure

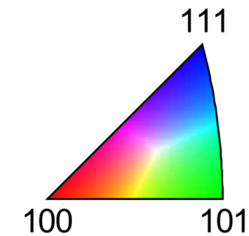
Wrought



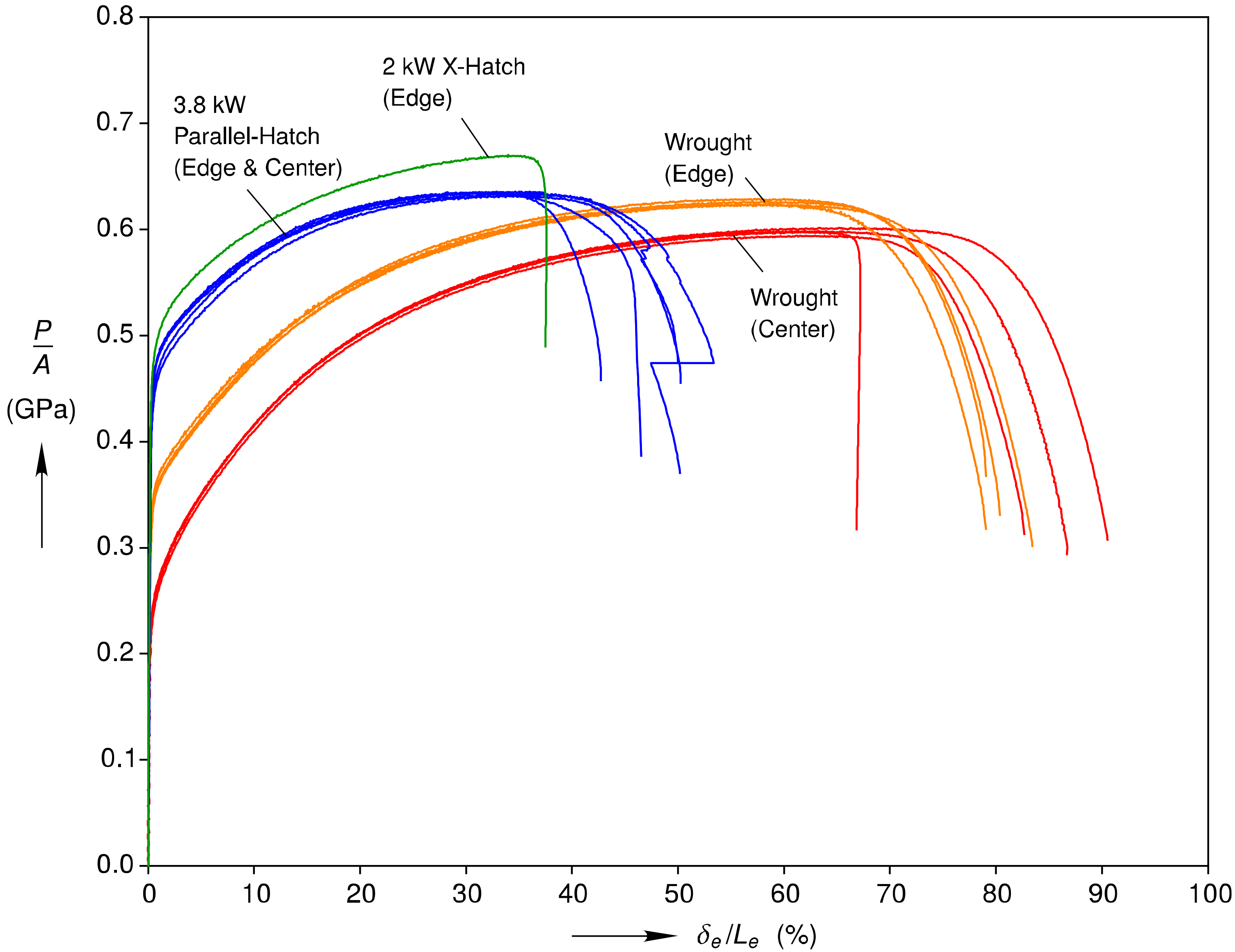


3.8 kW LENS

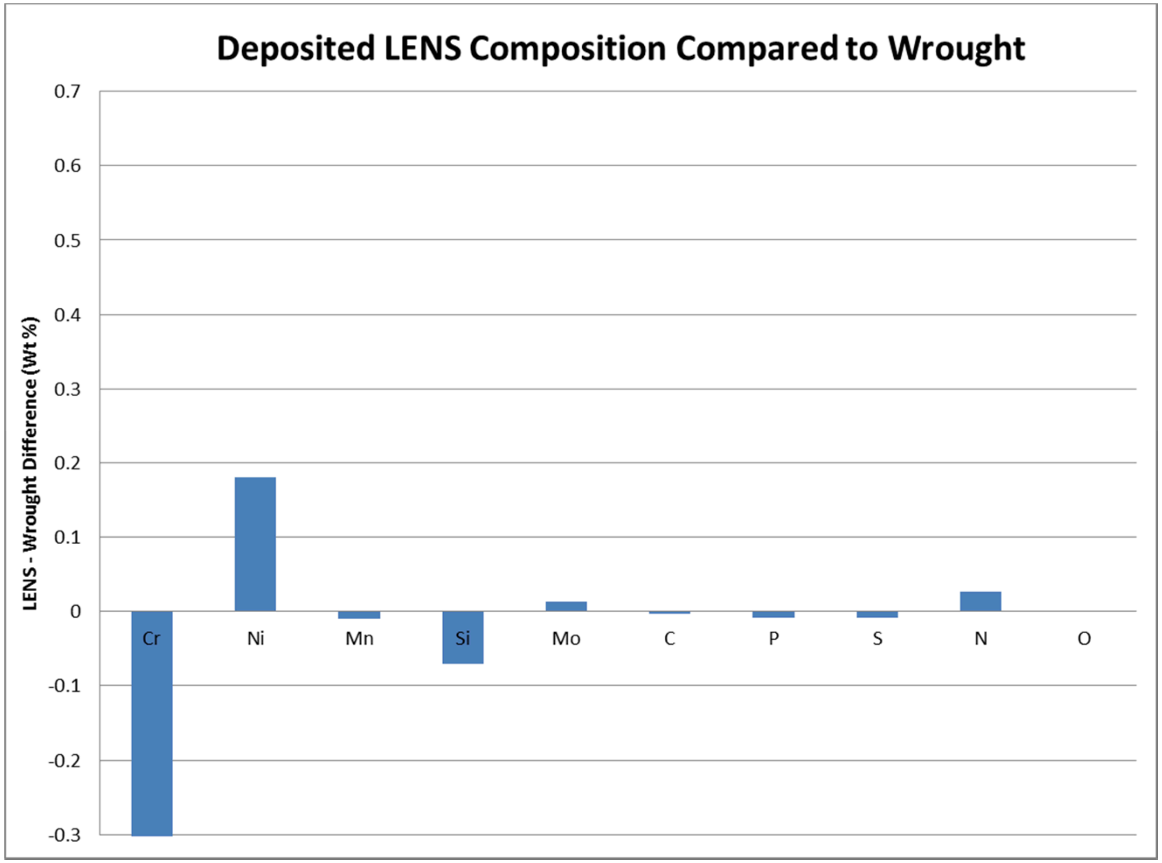




Tensile Tests

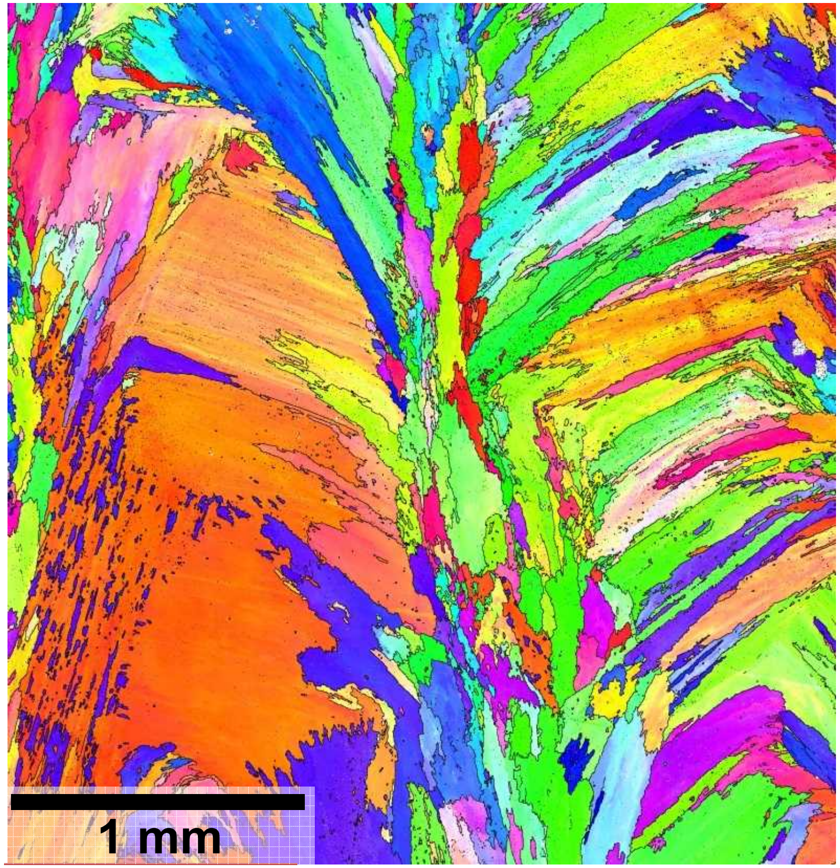


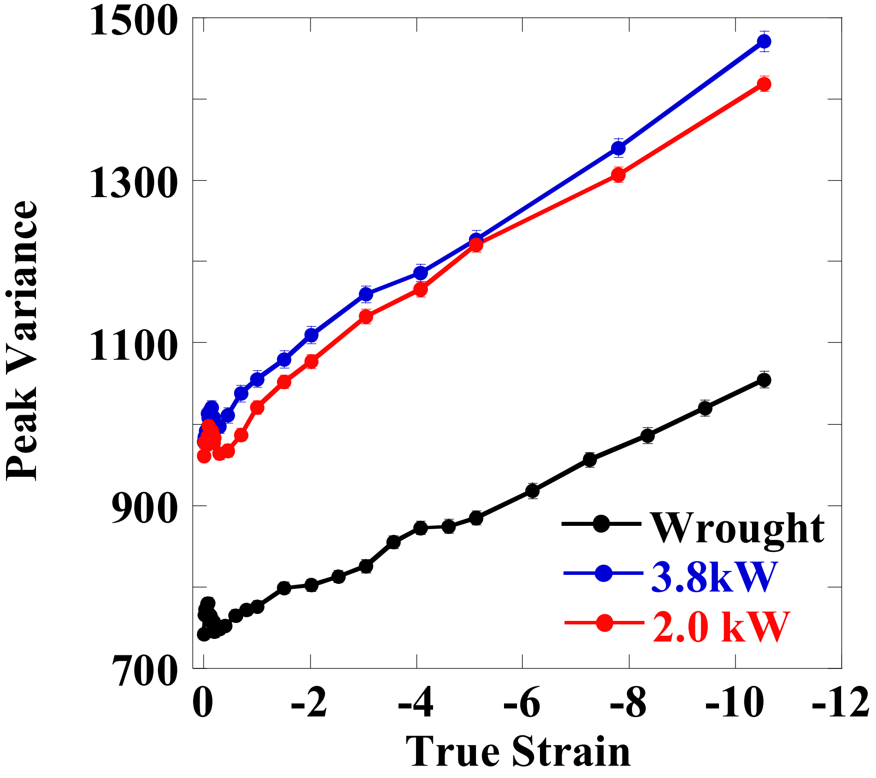
Composition Differences



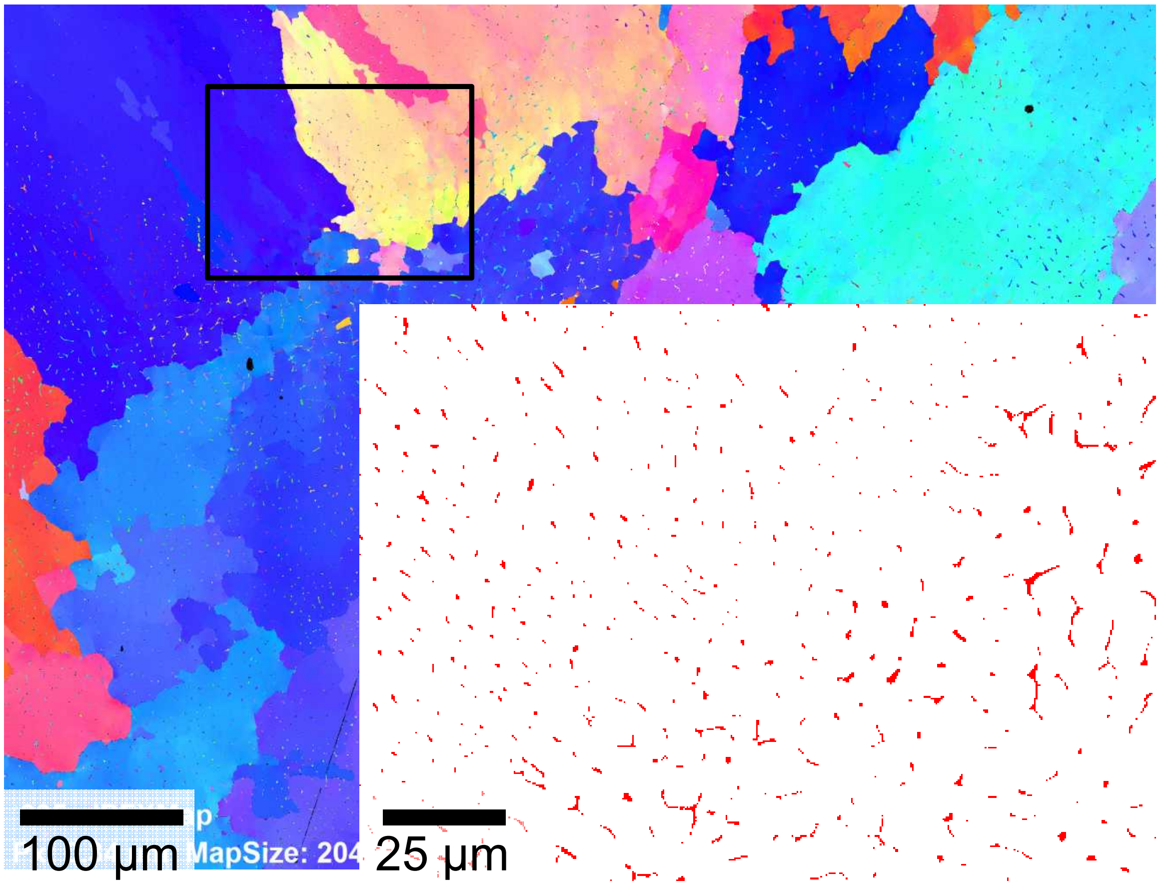
	Fe	**Cr**	**Ni**	Mn	Si	Mo	N	Co	P	S	C	O
Wrought	bal (68.2)	**19.5**	**10.1**	1.5	0.58	0.027	0.049	0.029	0.015	0.015	0.013	0
LENS Deposited	bal (68.8)	**18.8**	**10.28**	1.49	0.51	0.04	0.075	0	0.007	0.007	0.01	0.023

Indicators of Dislocation Density





Ferrite / Martensite

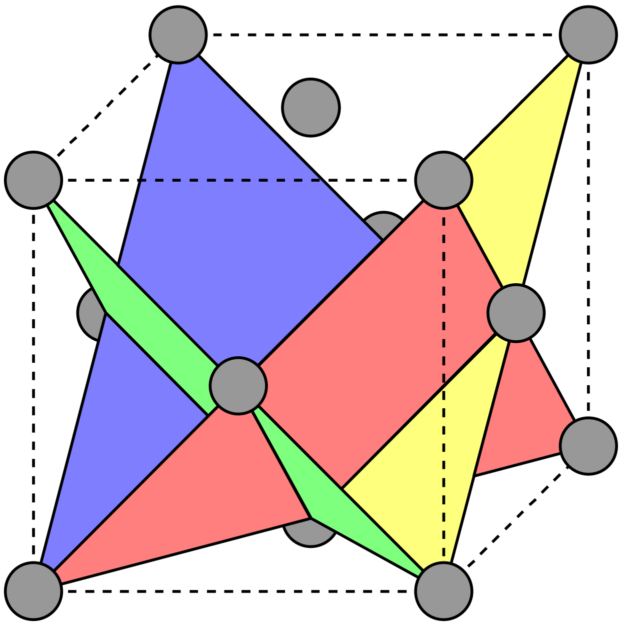


- Initial BCC phase: 1.2% for Wrought and 2.3% for LENS (ferrite scope and XRD)
- Small ferrite islands
  - Avg size = 0.5 µm
  - Avg spacing = 5 µm

white = austenite
black/red = ferrite

SIMULATIONS

Crystal Plasticity Model



$$\tau^{\alpha} = \boldsymbol{n}^{\alpha} \cdot \boldsymbol{\sigma} \cdot \boldsymbol{m}^{\alpha}$$

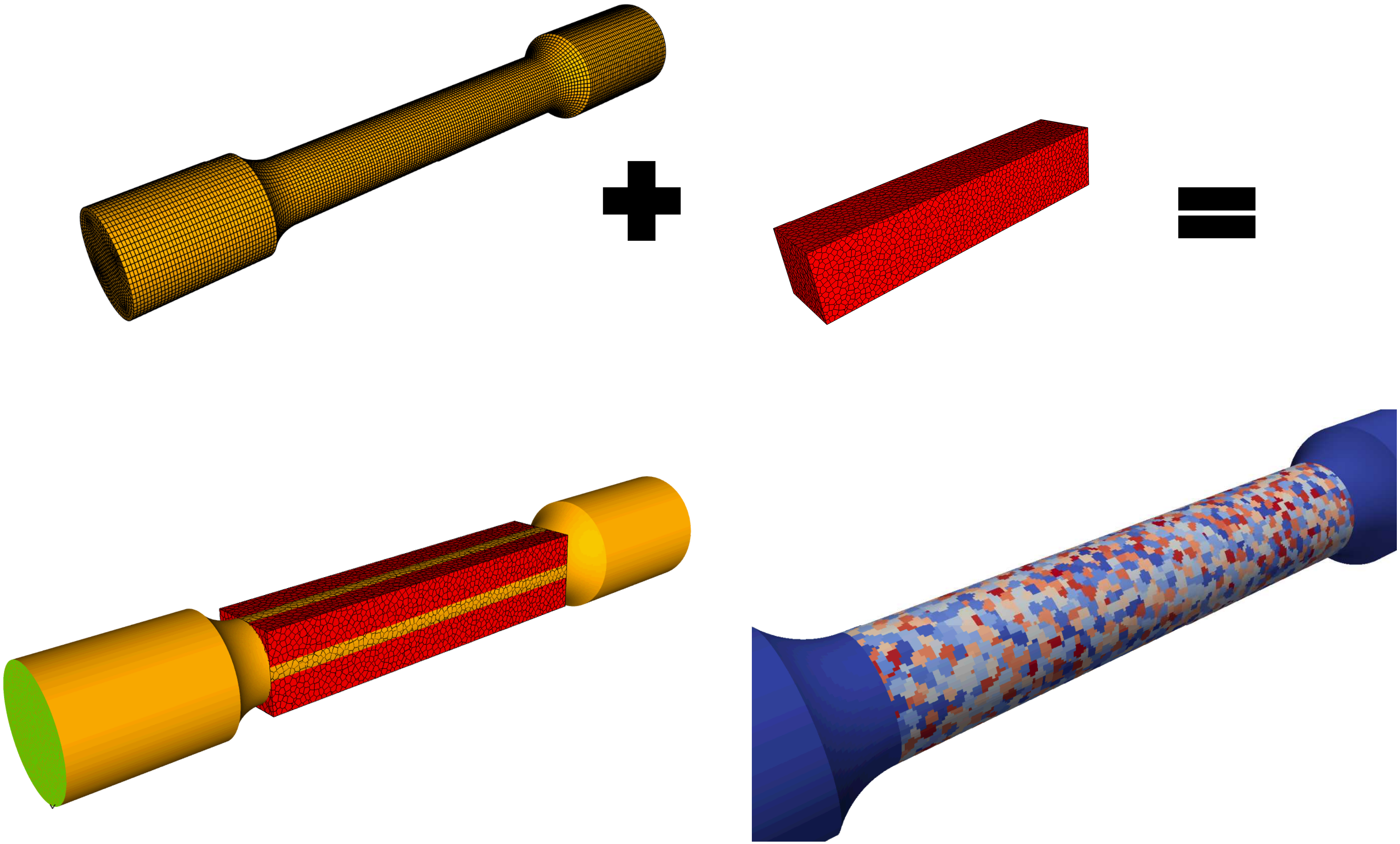
$$\dot{\gamma}^{\alpha} = \dot{\gamma}_0 \left(\frac{\tau^{\alpha}}{g} \right)^{1/m} \operatorname{sign}(\tau^{\alpha})$$

$$\gamma = \sum_{\alpha}^{N} |\gamma^{\alpha}| \qquad \text{(sum over slip systems)}$$

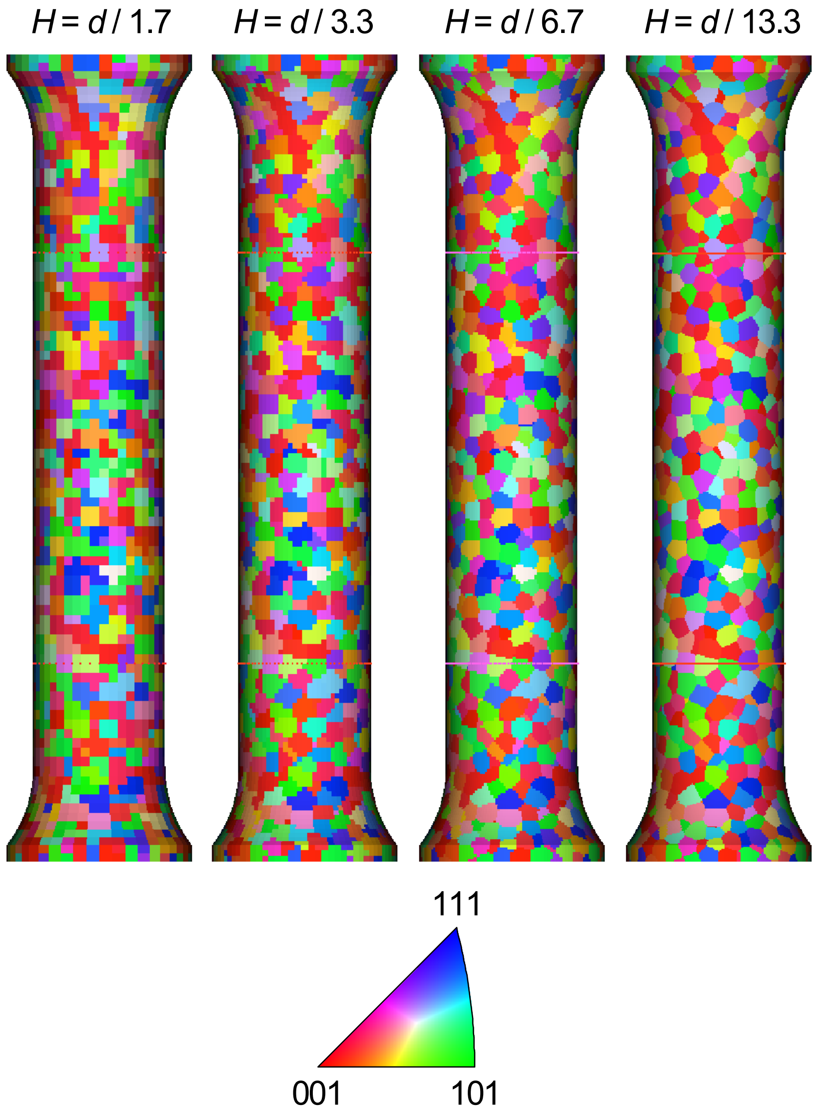
$$g = g_0 + (g_{s0} - g_0) \left[1 - \exp\left(-\frac{G_0\, \gamma}{g_{s0} - g_0} \right) \right]$$

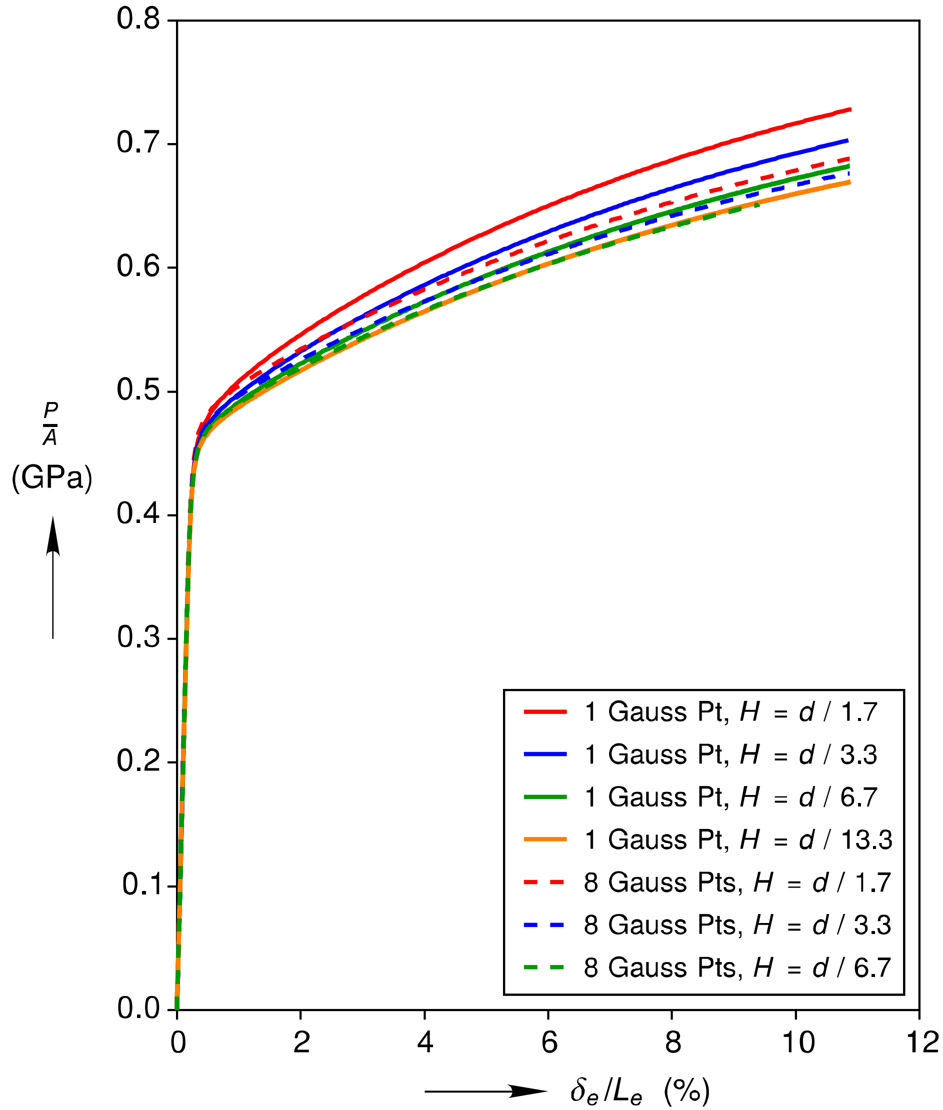
Matous, K. and Maniatty, A., Finite element formulation for modeling large deformations in elasto-viscoplastic polycrystals. *Int. J. Numerical Methods in Engineering*. 2004; **60**:2313-2333.

Voronoi Overlay on a Hexahedral Mesh

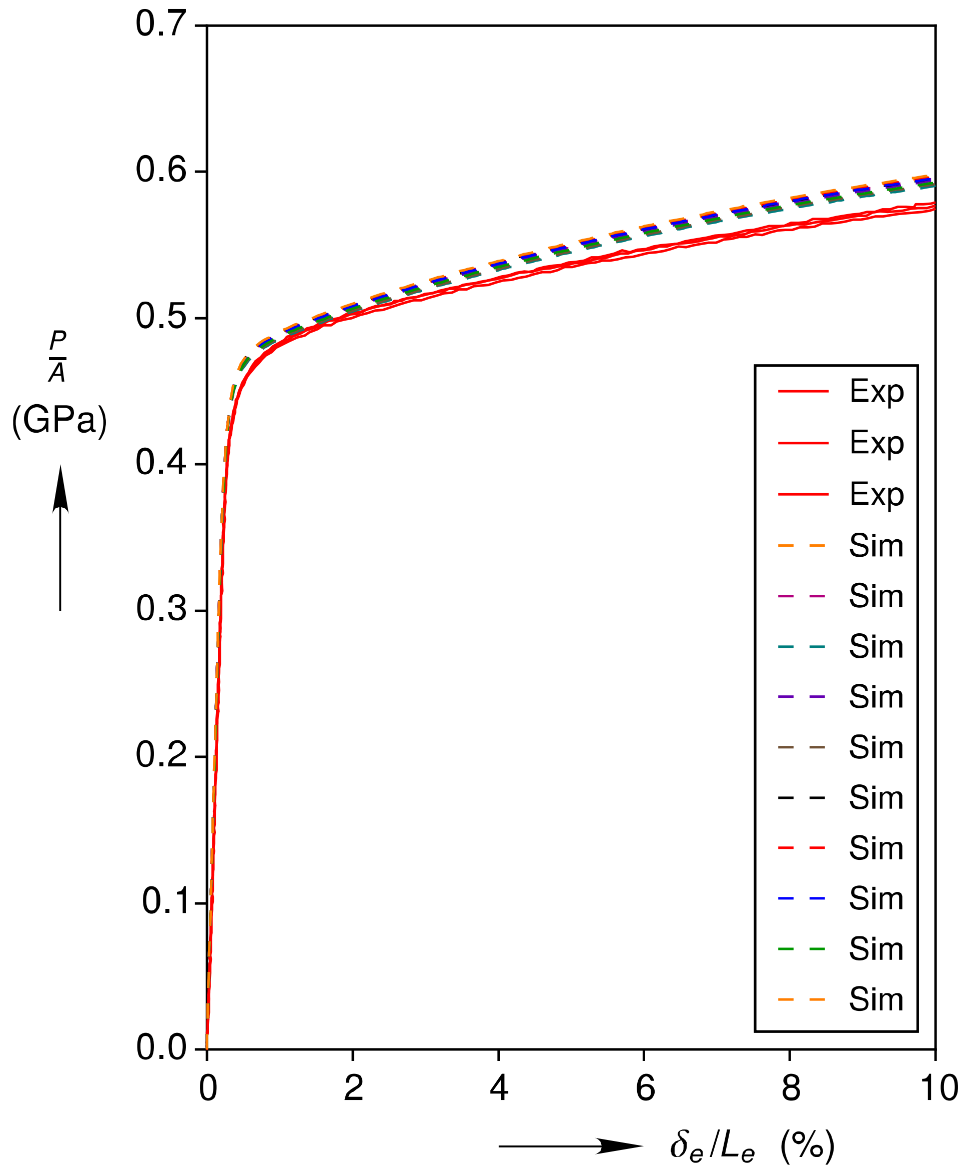


Mesh Convergence

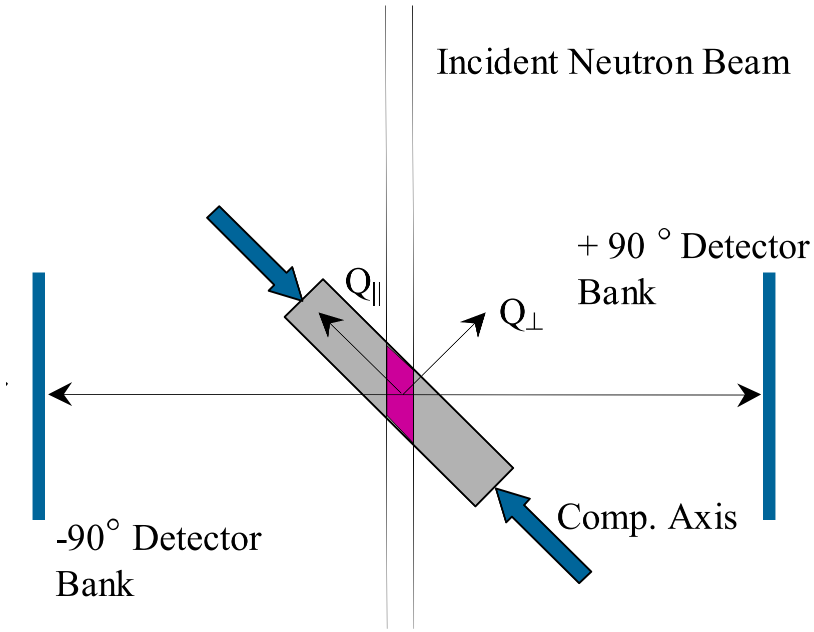




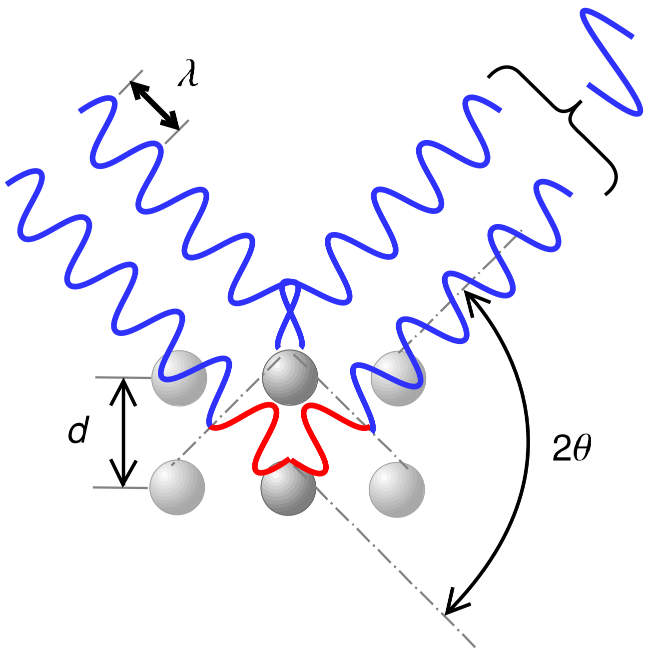
Calibration and Statistical Consistency



Neutron Diffraction



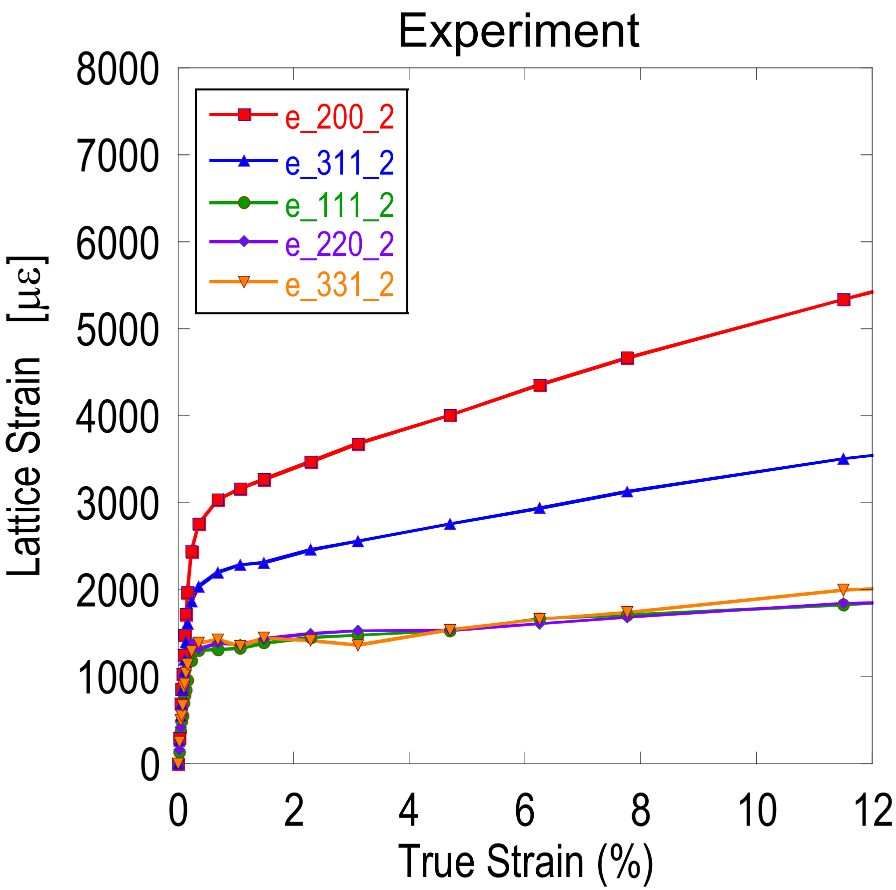
Bragg's Law

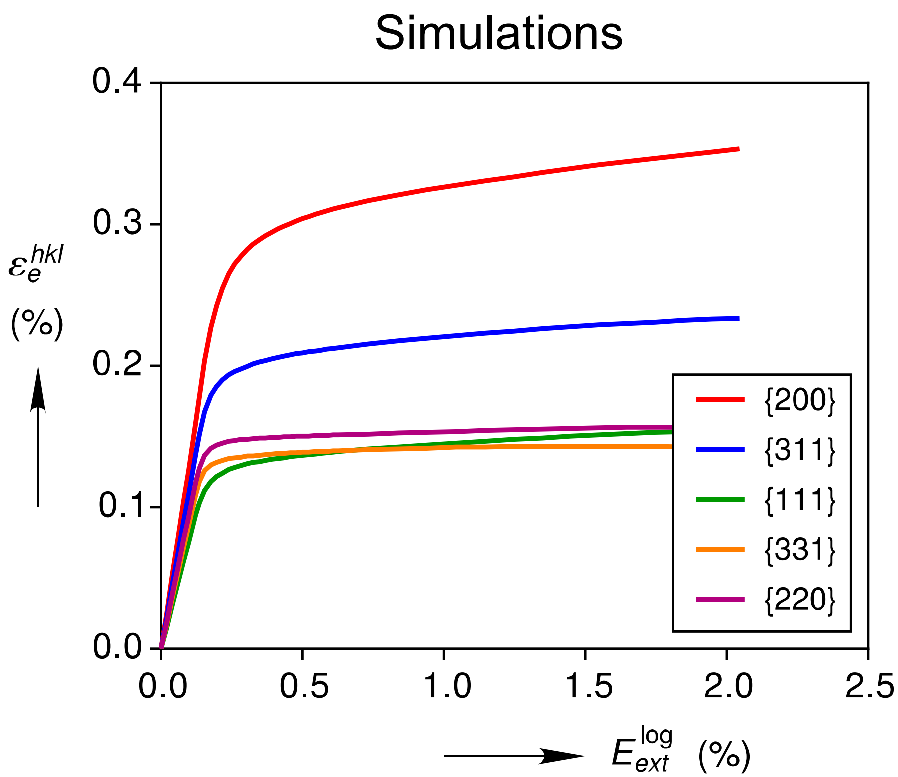


$$2\,d\sin\theta = n\,\lambda$$

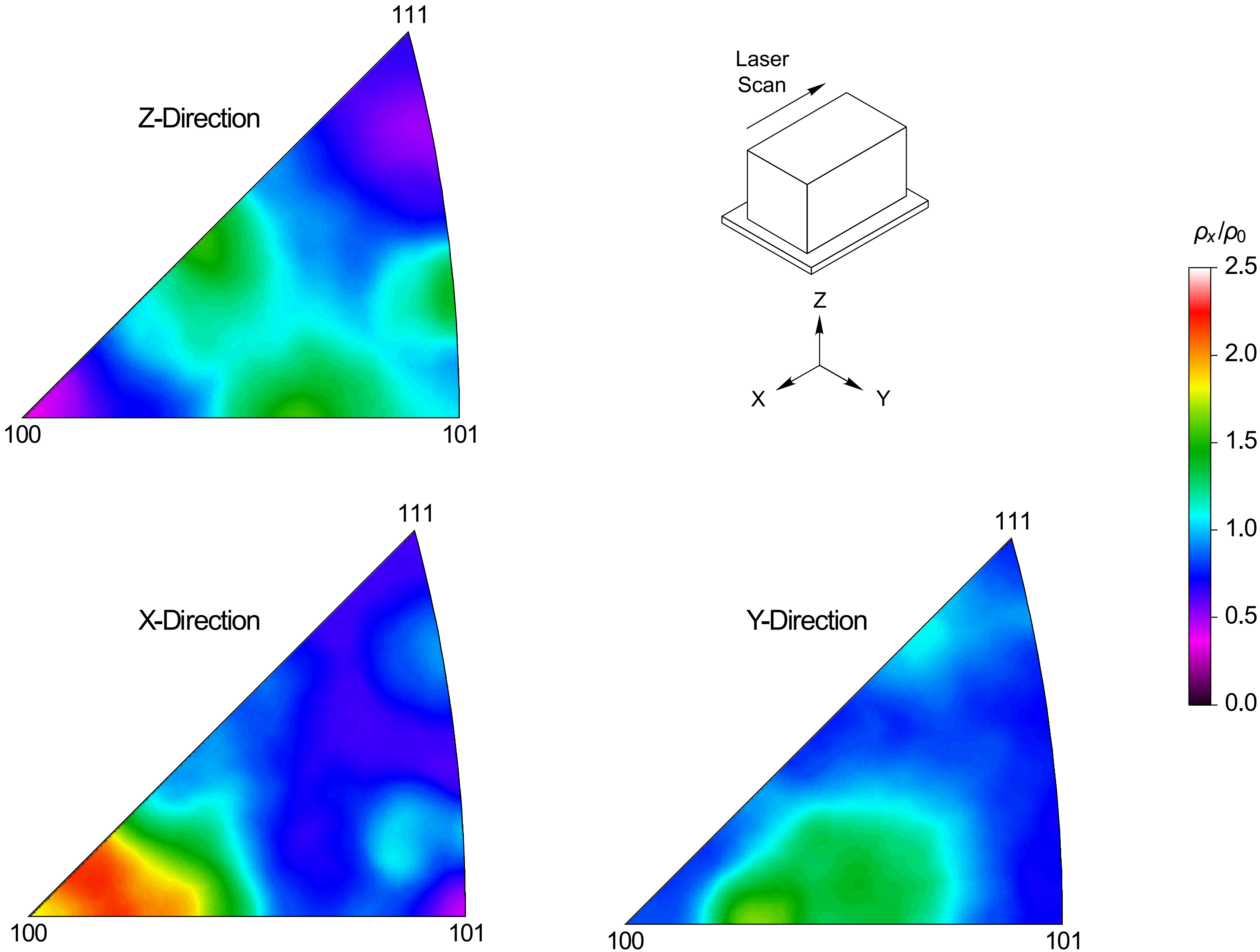
http://en.wikipedia.org/wiki/Bragg's_law (modified)

Lattice Strains

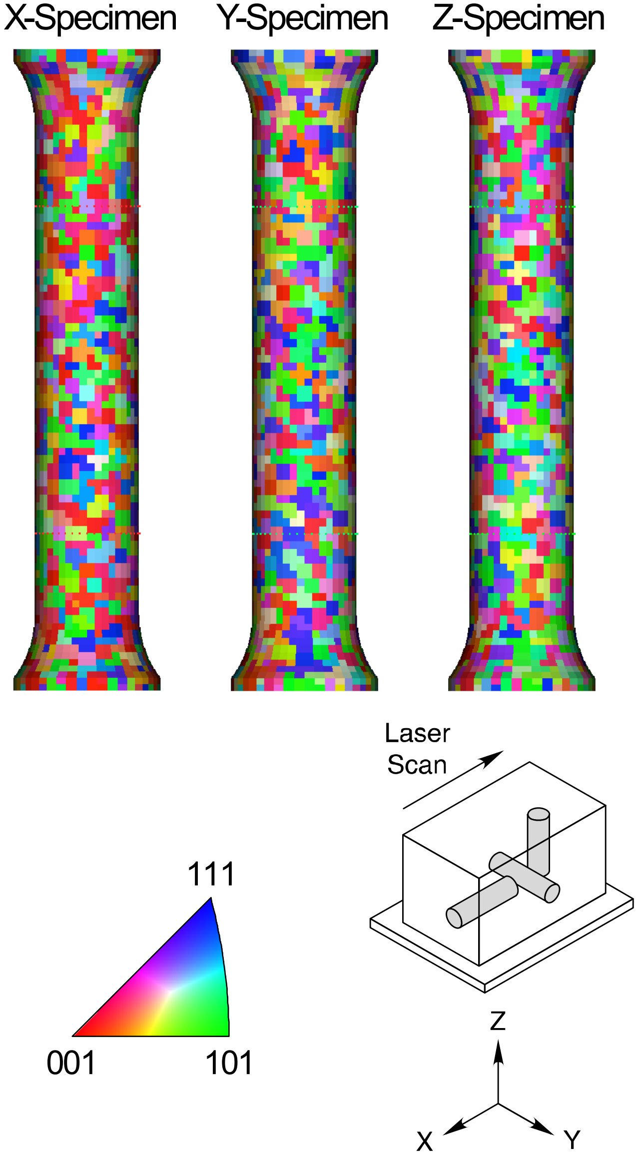


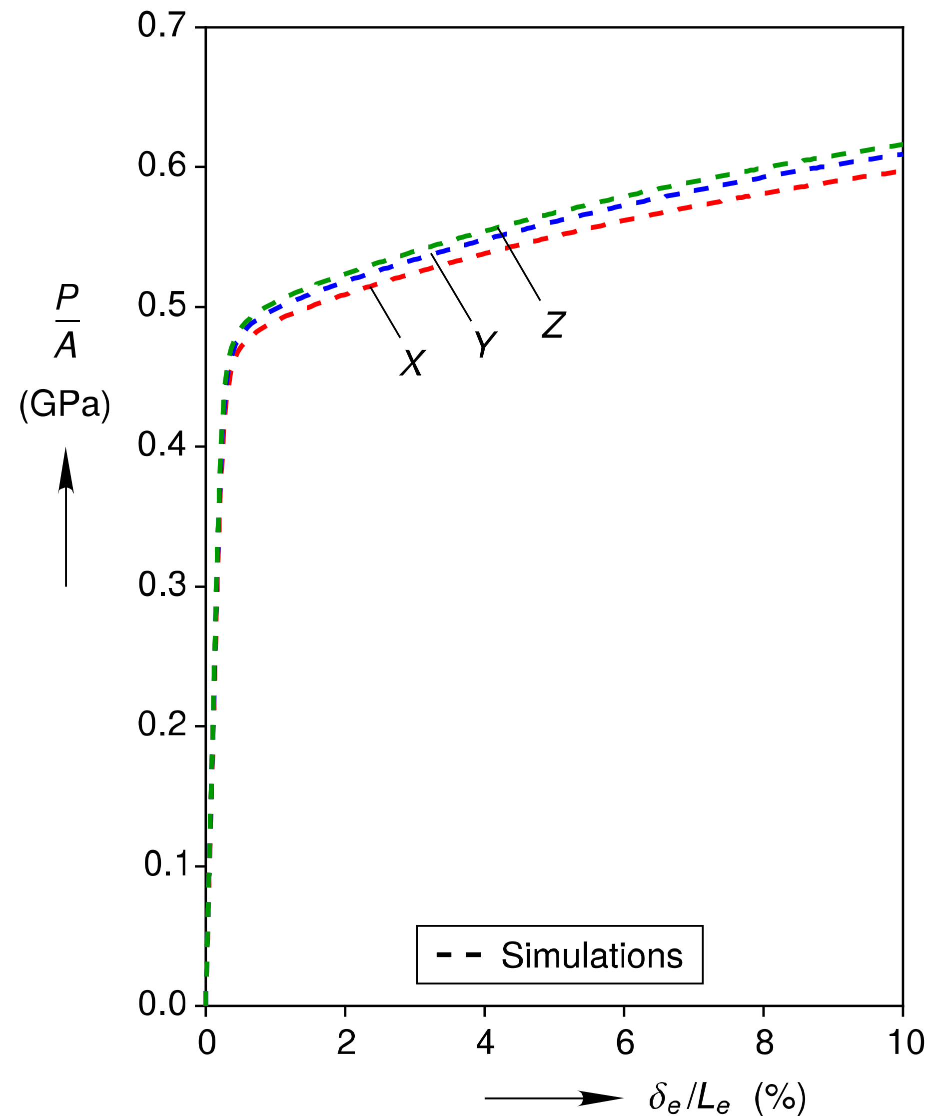


Inverse Pole Figures



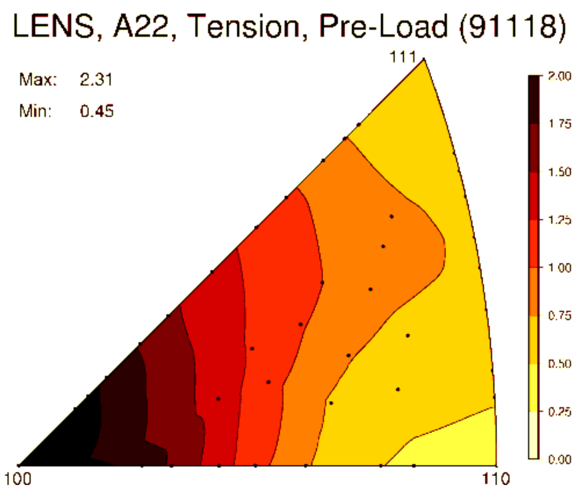
Anisotropy Predictions

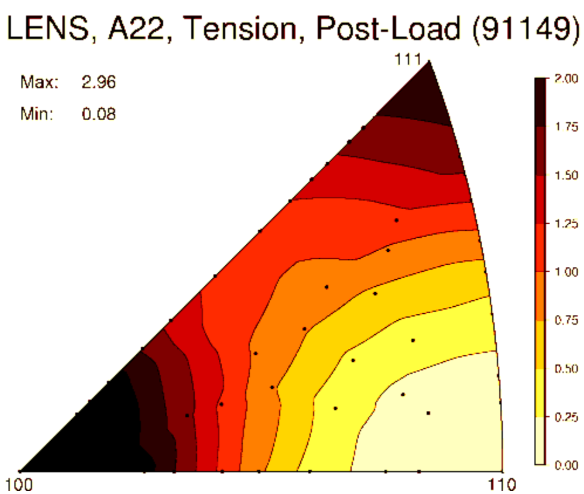




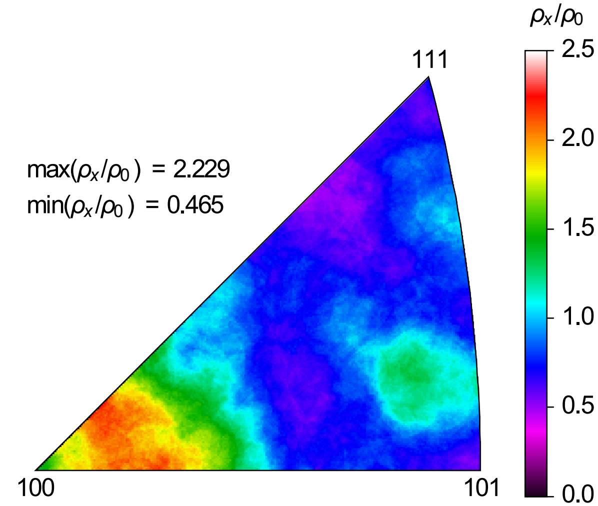
Deformation Induced Texture

Experiment





Simulations

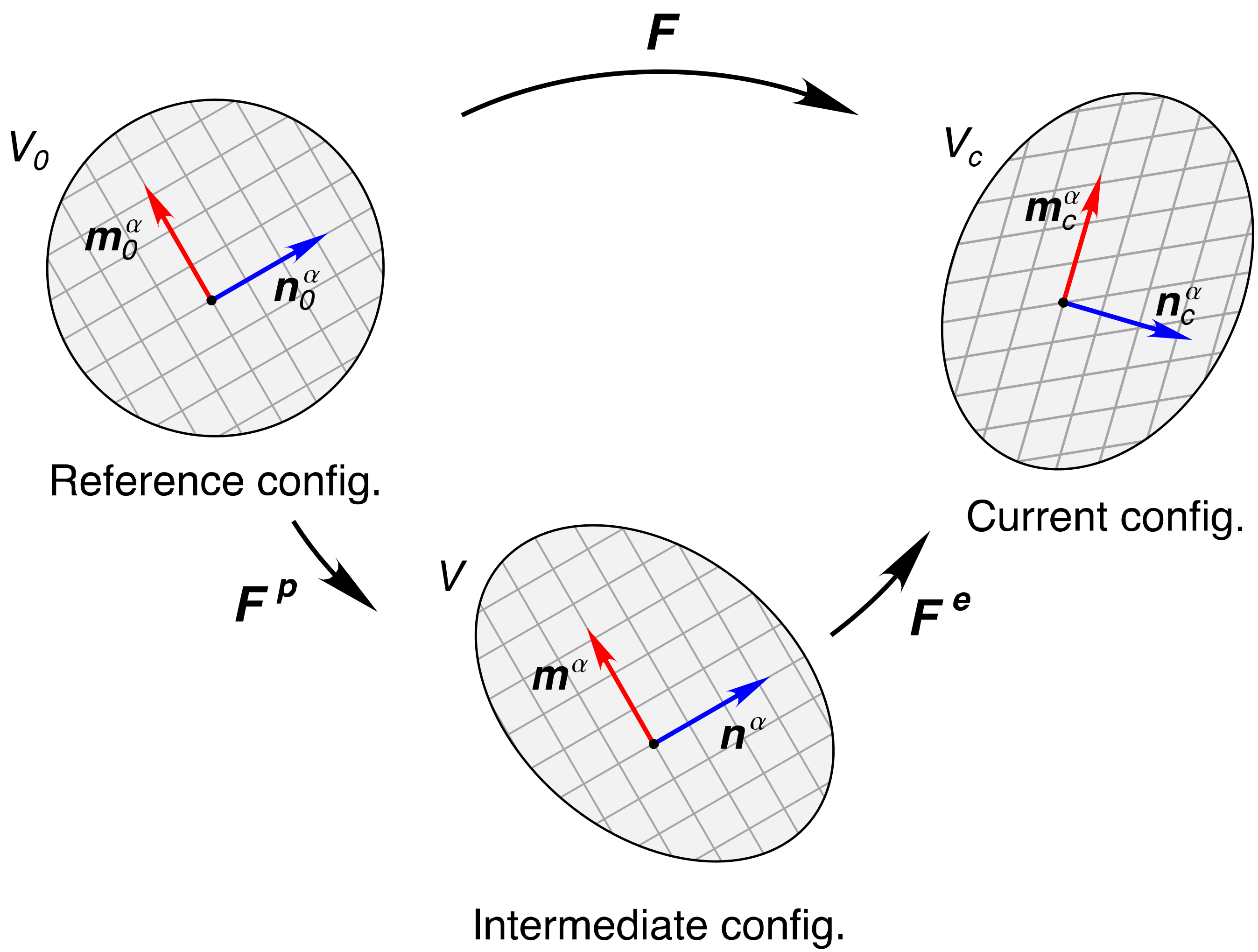


Summary

- Experiments
  - Exotic microstructures
  - Additively manufactured 304L is stronger and less ductile than comparable wrought 304L
- Crystal Plasticity Simulations
  - Mesh convergence is difficult to obtain
  - Partially validated the model against lattice strain measurements
  - Predicted mild anisotropy in yield and hardening

Questions?

Crystal Plasticity



Modeling Strategy

- Homogeneous Plasticity Models
  - Isotropic, Von Mises
  - Anisotropic, Hill
- Crystal Plasticity Finite Element Models
  - Textured microstructure with equiaxed grains of uniform size
  - Textured microstructure with approximate grain morphology
- Other material models?