SAND2015-6653C

Modeling the Mechanical Behavior of Additively Manufactured 304L Stainless Steel

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2: Los Alamos National Laboratories

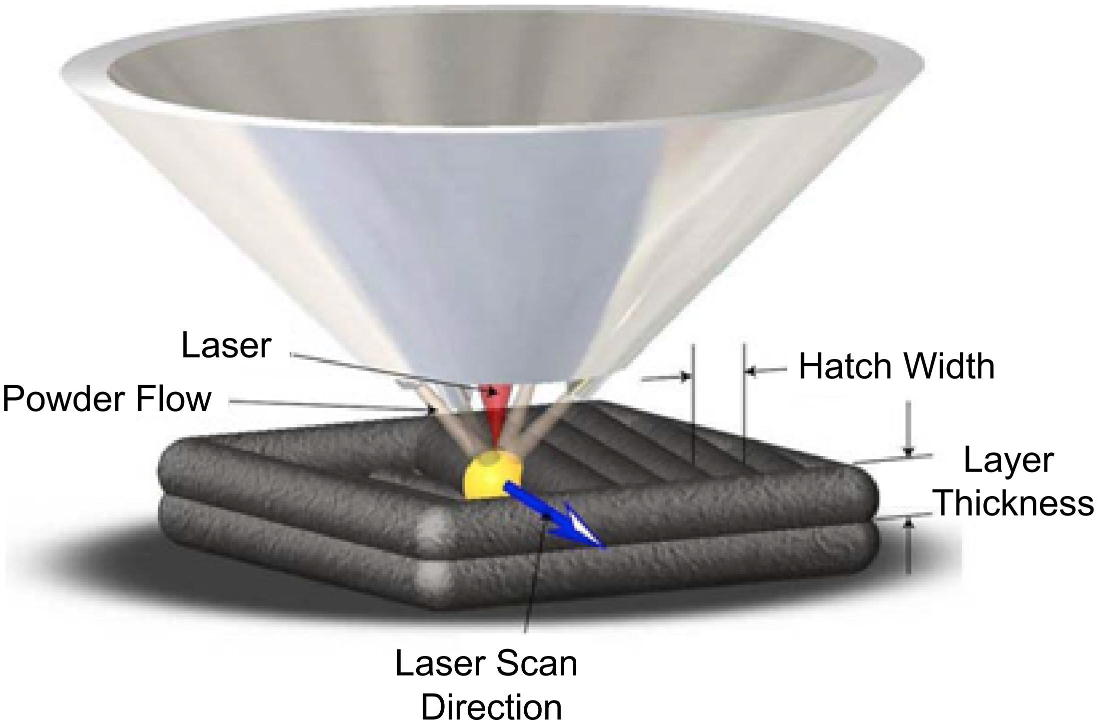
3: Pennsylvania State University

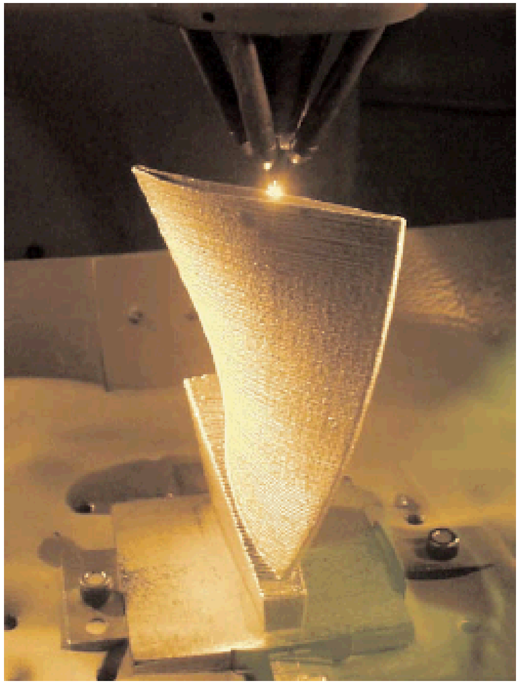
Outline

- Introduction
- Experimental Characterization
- Simulations
  - Model Construction
  - Preliminary Results

INTRODUCTION

Laser Engineered Net Shaping (LENS™)

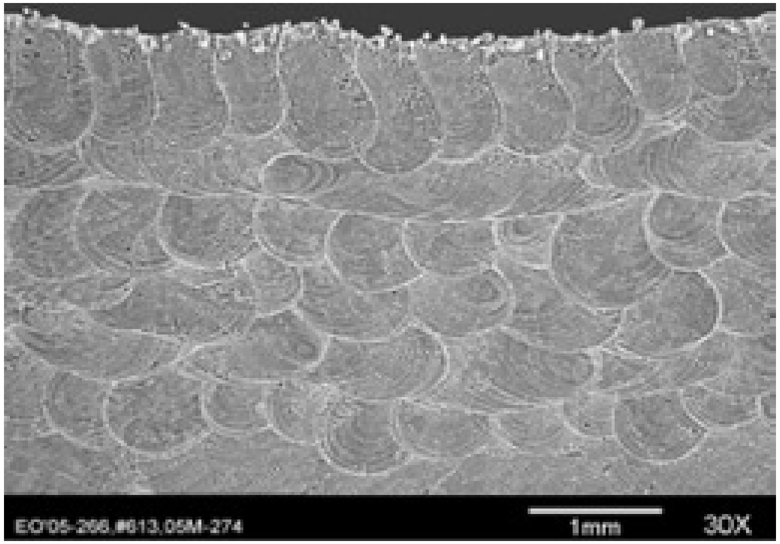




- Pros
  - Complex part geometries
  - Rapid design to production
- Cons
  - Speed
  - Finishing required
  - Open scientific questions

Fundamental Questions

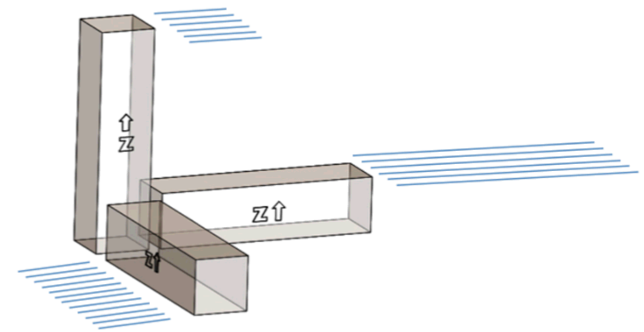
- How does the mechanical response of a LENS material compare to that of a wrought material.
  - What role does the exotic microstructure play?
  - Variability?

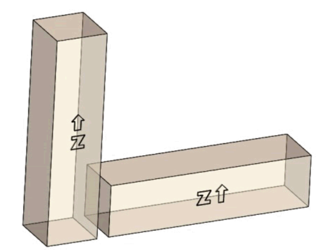


- How do we predict the response?
  - What level of sophistication do we need in our simulations?
  - Loss of ‘scale separation’?

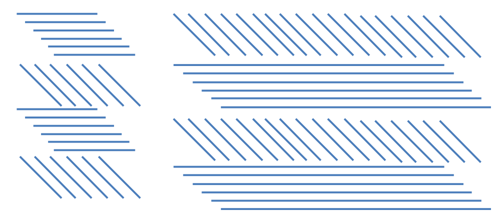
Parameter Sensitivities

- 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

Parameter Sensitivities

- Laser power
  - 3.8 kW, 2 kW, 0.5 kW
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  - X vs. Y vs. Z
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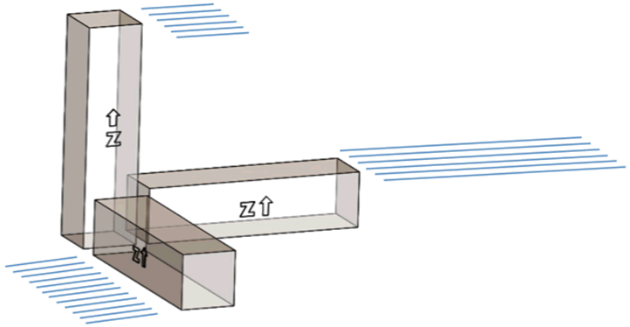
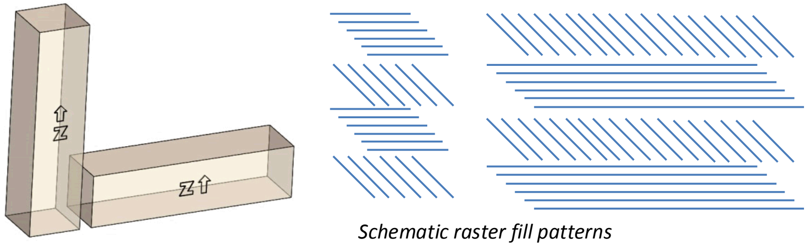
  - 10^{-5} s^{-1}, 10^{-3} s^{-1}, to 10^{9} s^{-1}
- Temperature
  - 20 ^{o}C to 300 ^{o}C





Schematic raster fill patterns

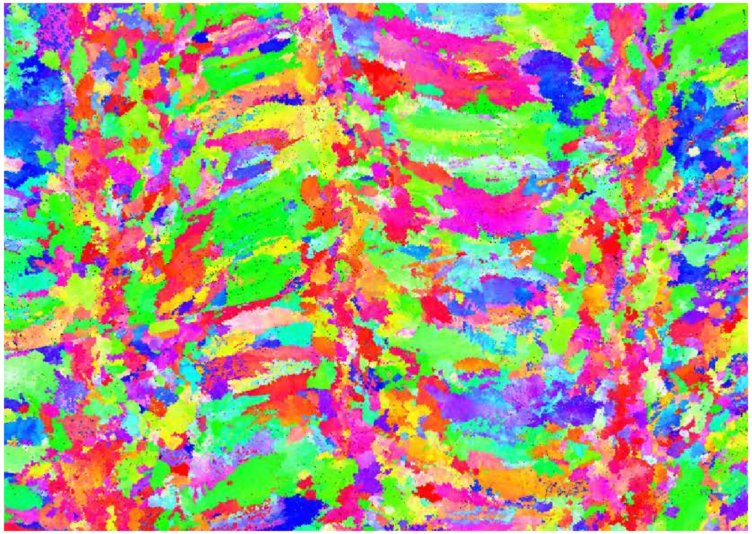
Sample Geometry

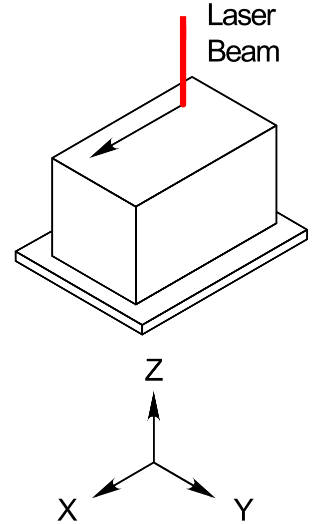
EXPERIMENTS

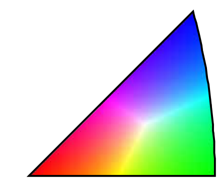
LENS Microstructure Orthographic Projections

Sandia National Laboratories

Z-Plane (Z-direction)

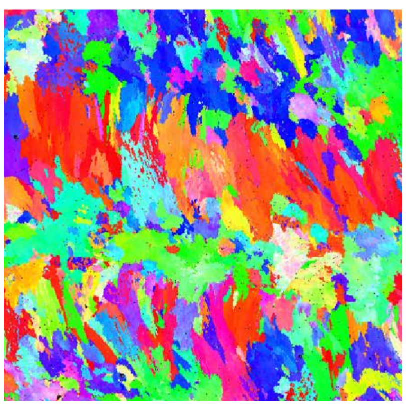






X-Plane (X-direction)

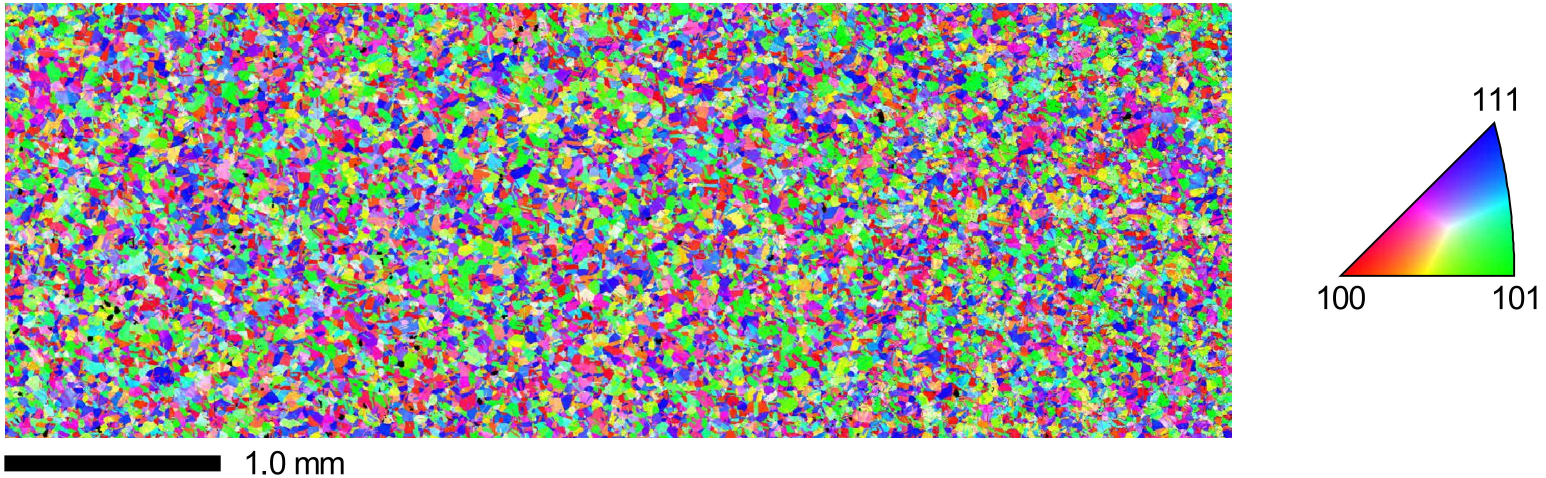
Y-Plane (Y-direction)



1.0 mm

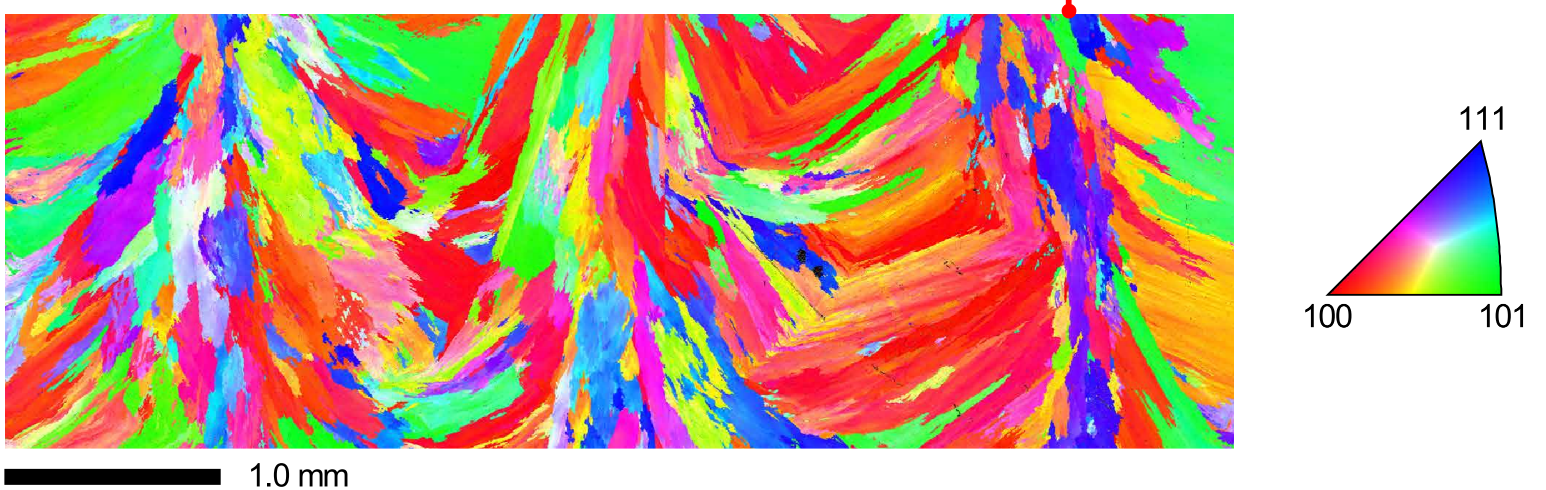
Wrought vs. LENS Microstructure

Wrought



Laser Beam

3.8 kW LENS



Base Material

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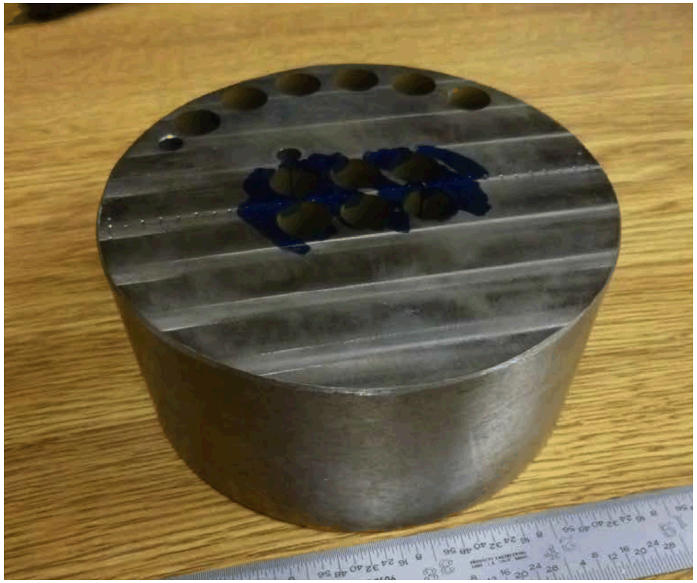
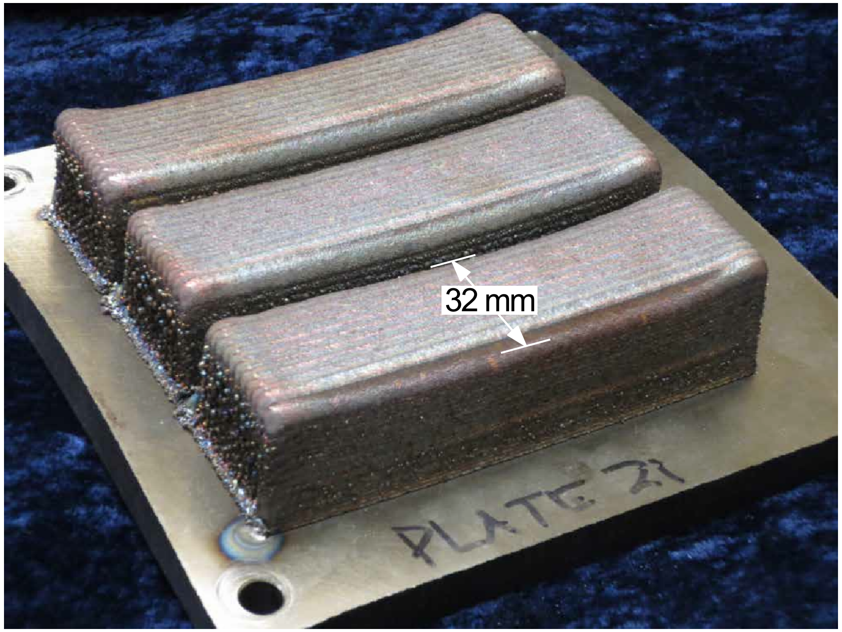
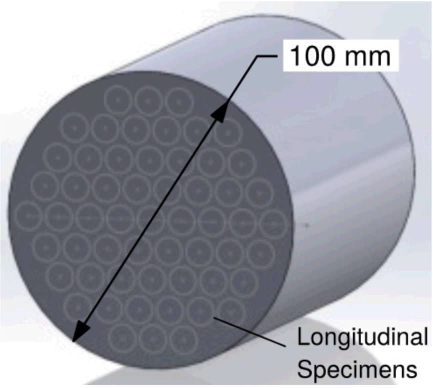
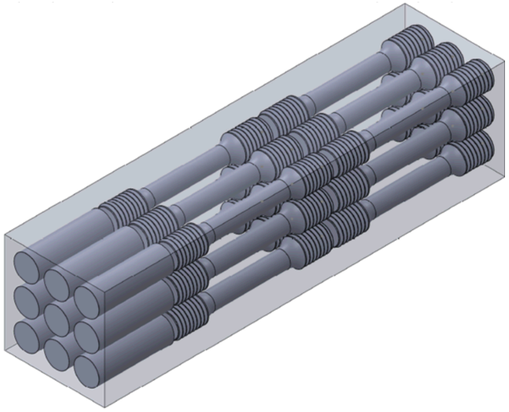
Wrought Bar

LENS Bars ("Twinkies")

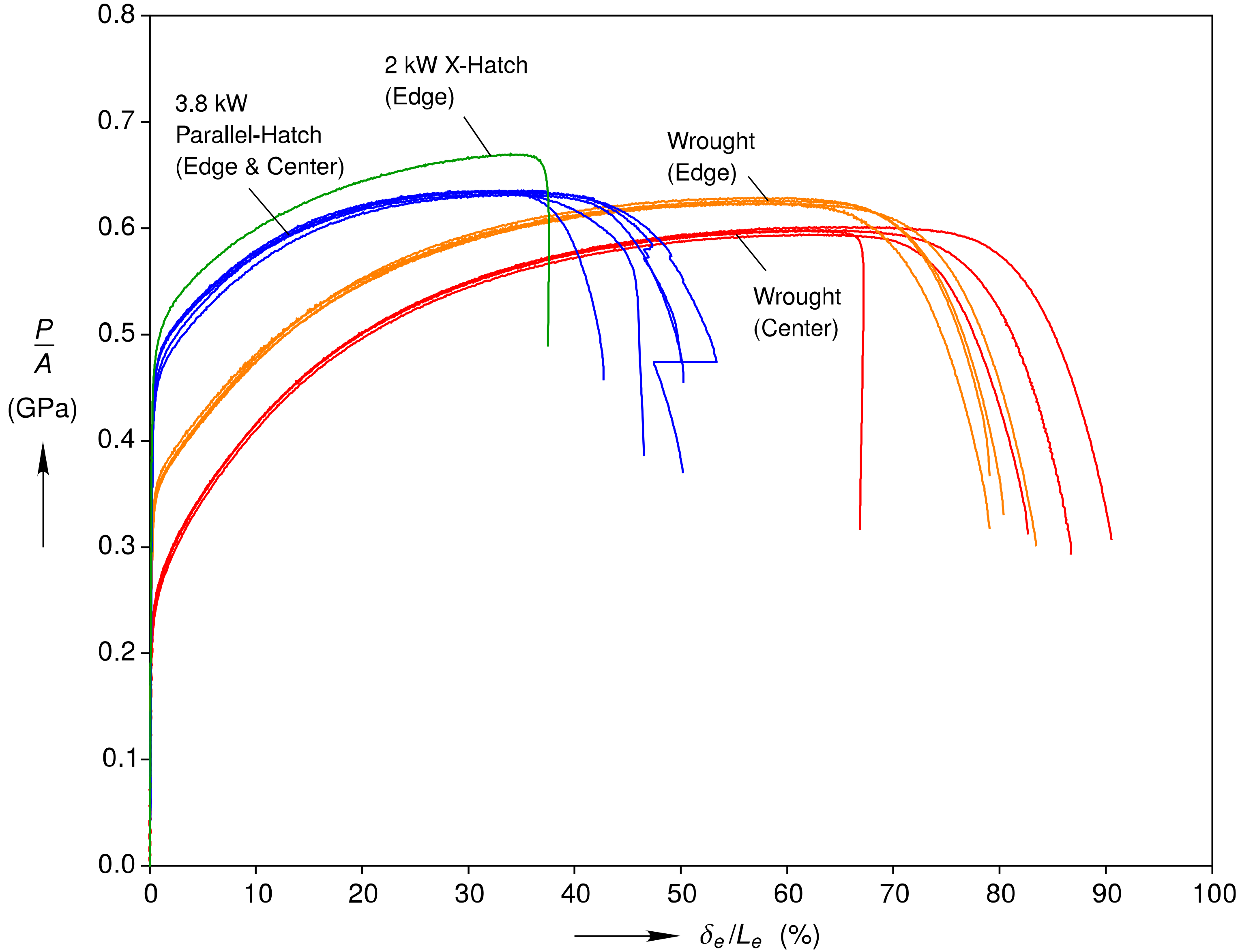






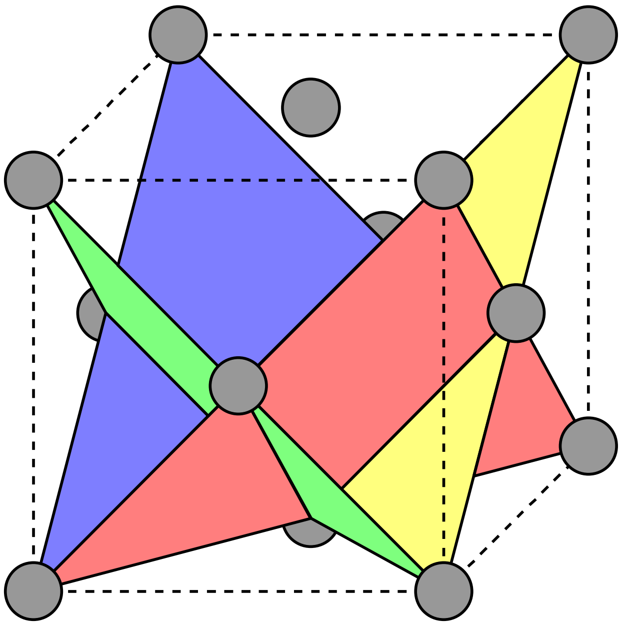


Tensile Tests



SIMULATIONS

Crystal Plasticity Model



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

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

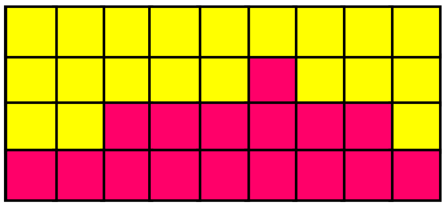
$$\gamma = \sum_{\alpha}^{N} |\gamma^\alpha| \qquad \text{(sum over slip systems)}$$

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

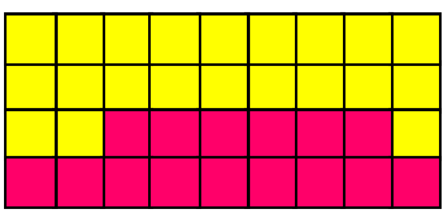
Matous, K. and Maniatty, A., Finite element formulation for modeling large deformations in elasto-viscoplastic polycrystals. *Int. J. Numerical Methods in Engineering*. 2004; **60**:2313-2333.

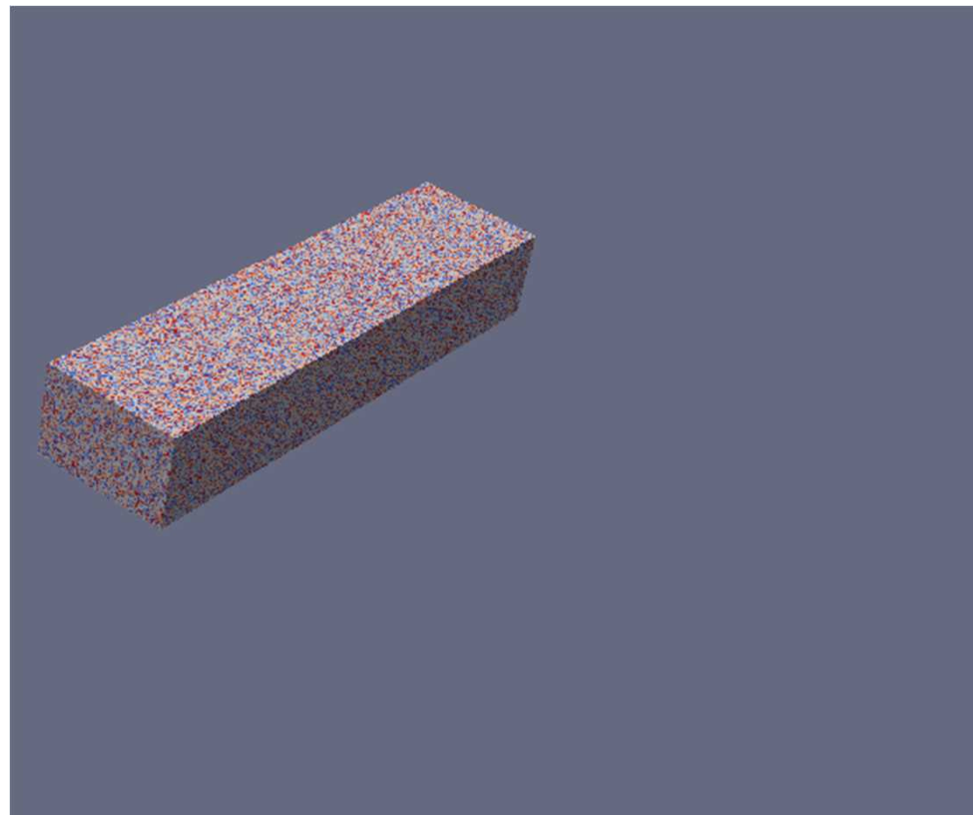
Synthetic Microstructure Generation

Potts grain growth model with a moving heat source



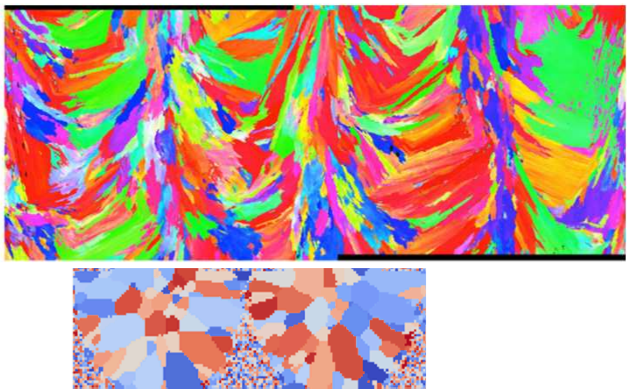
$$P = \begin{cases} 1 & for \quad E \le 0 \\ \exp\left(\frac{-\Delta E}{kT}\right) & for \quad E > 0 \end{cases}$$



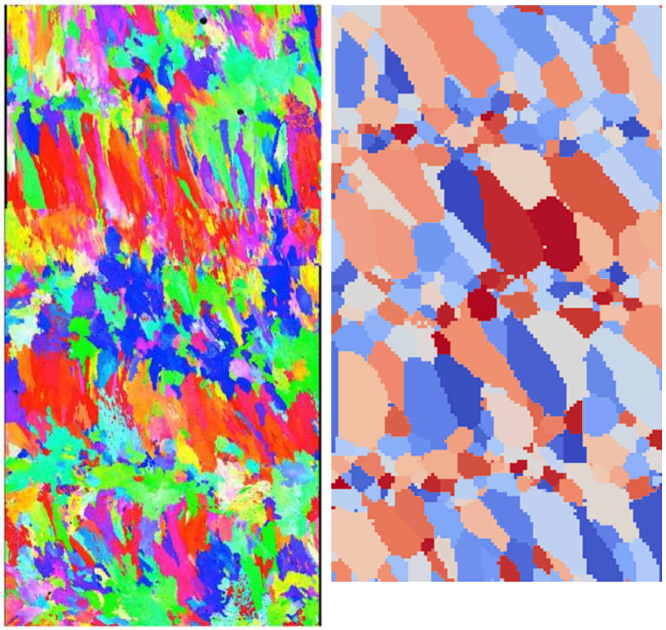


Synthetic Microstructure Generation

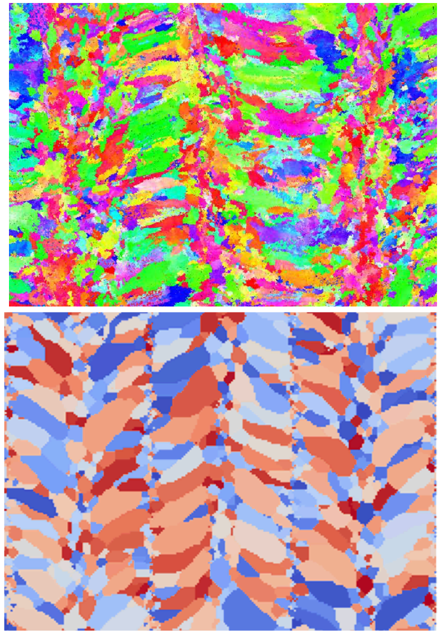
X-Plane



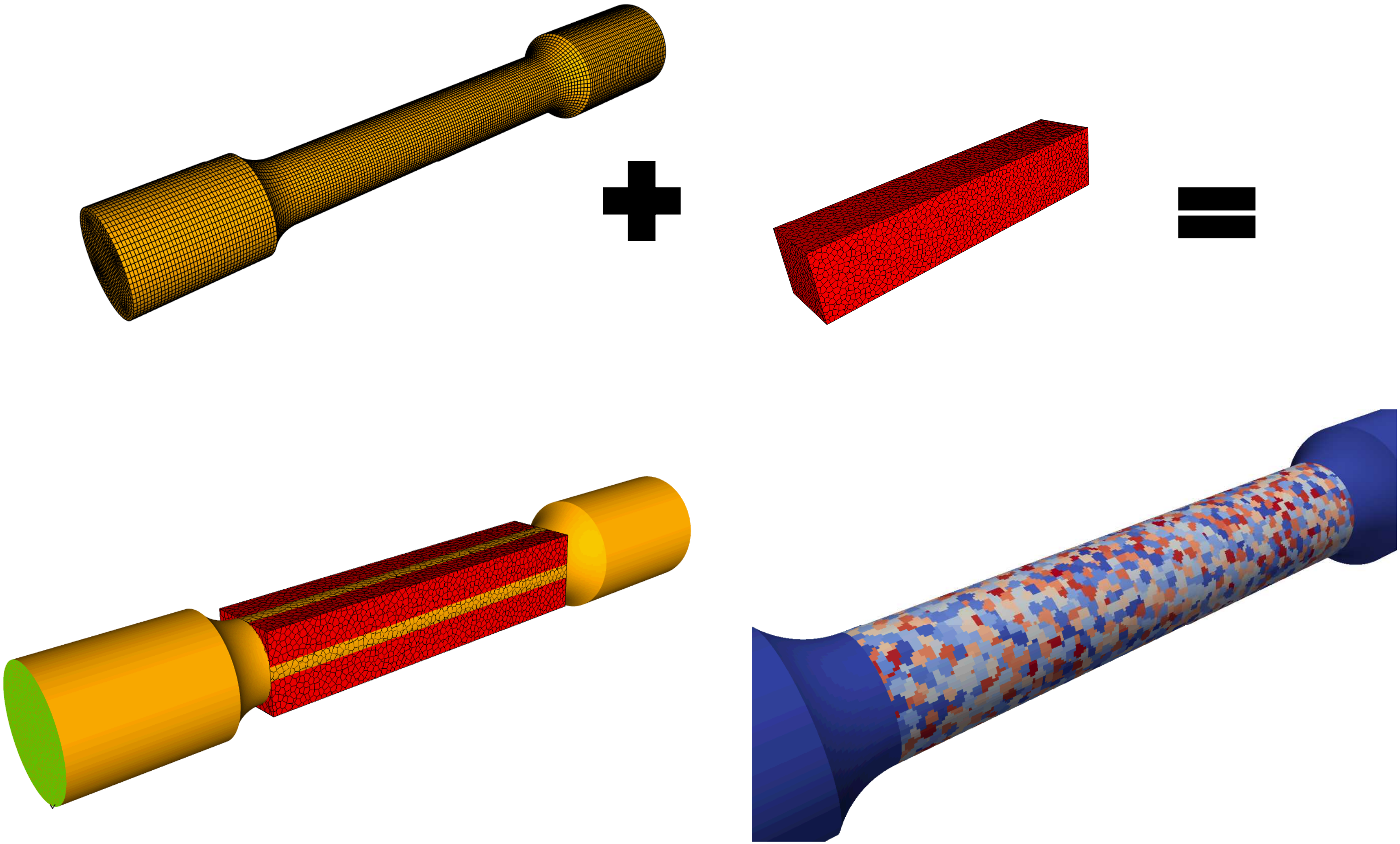
Y-Plane



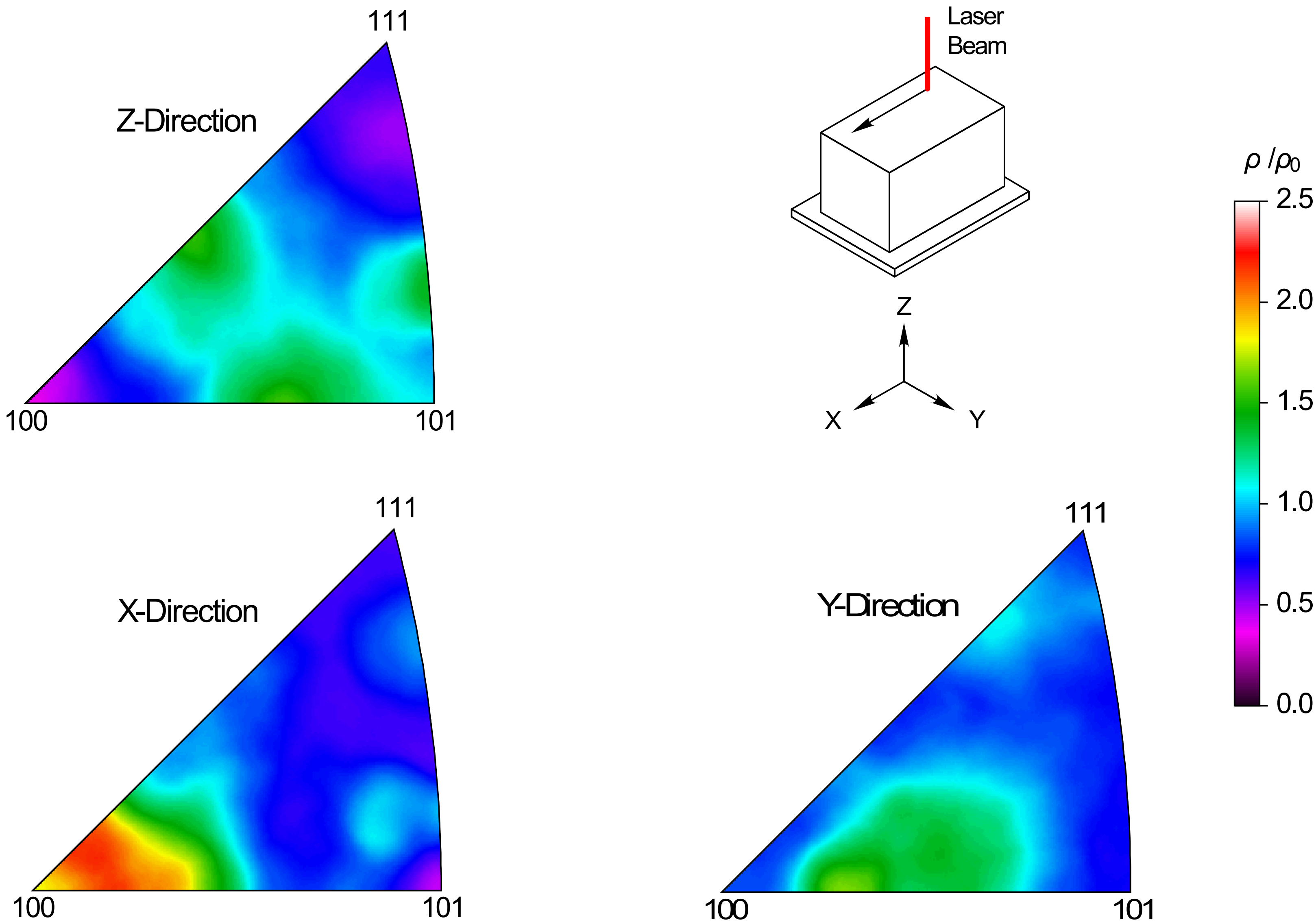
Z-Plane



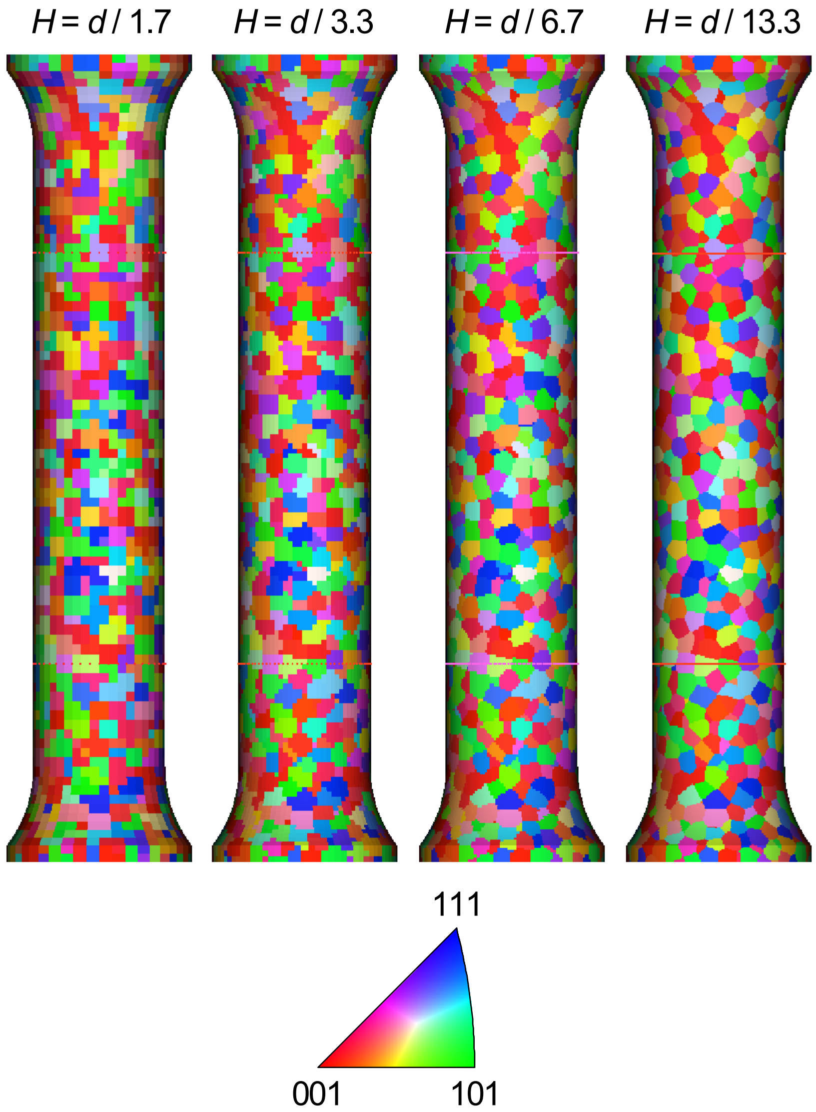
Voronoi Overlay on a Hexahedral Mesh

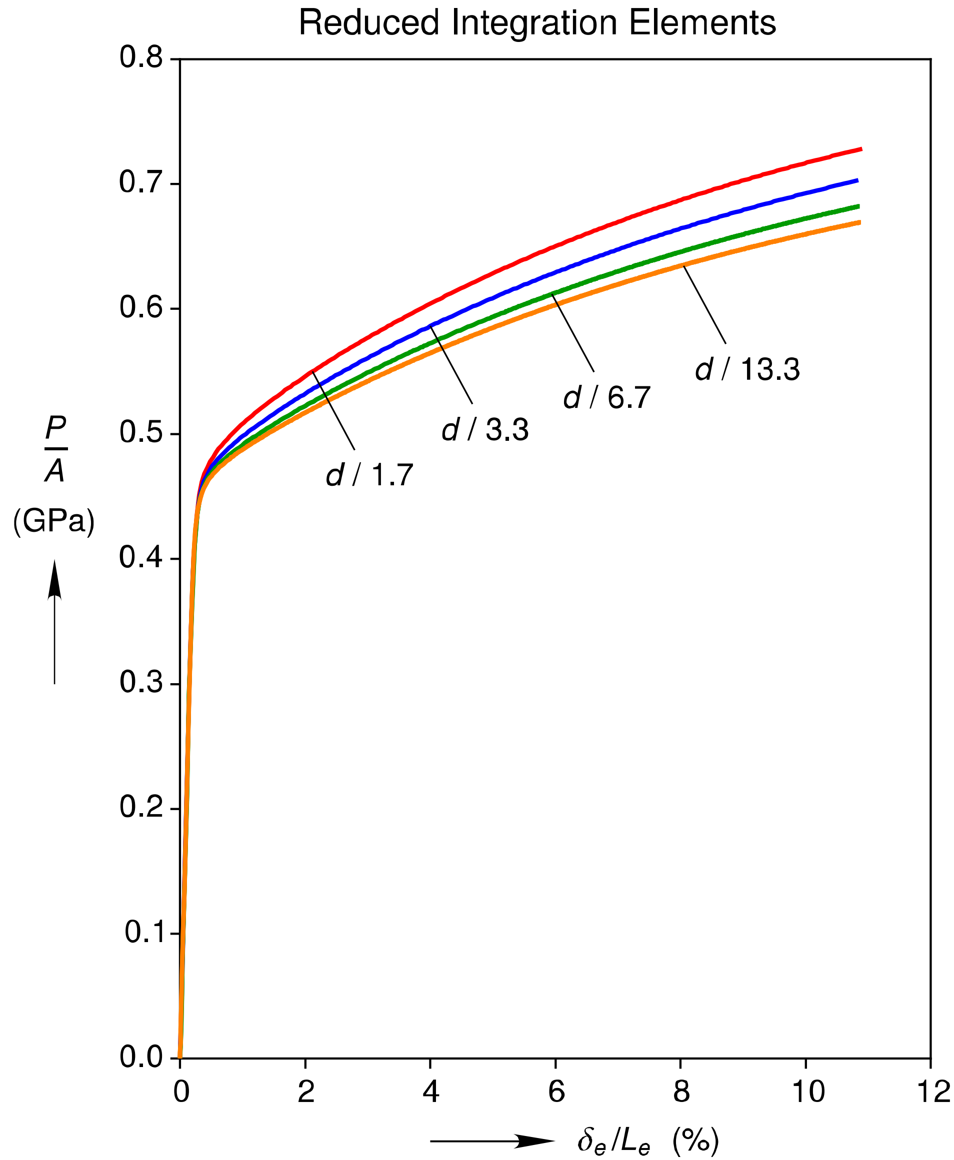


Inverse Pole Figures

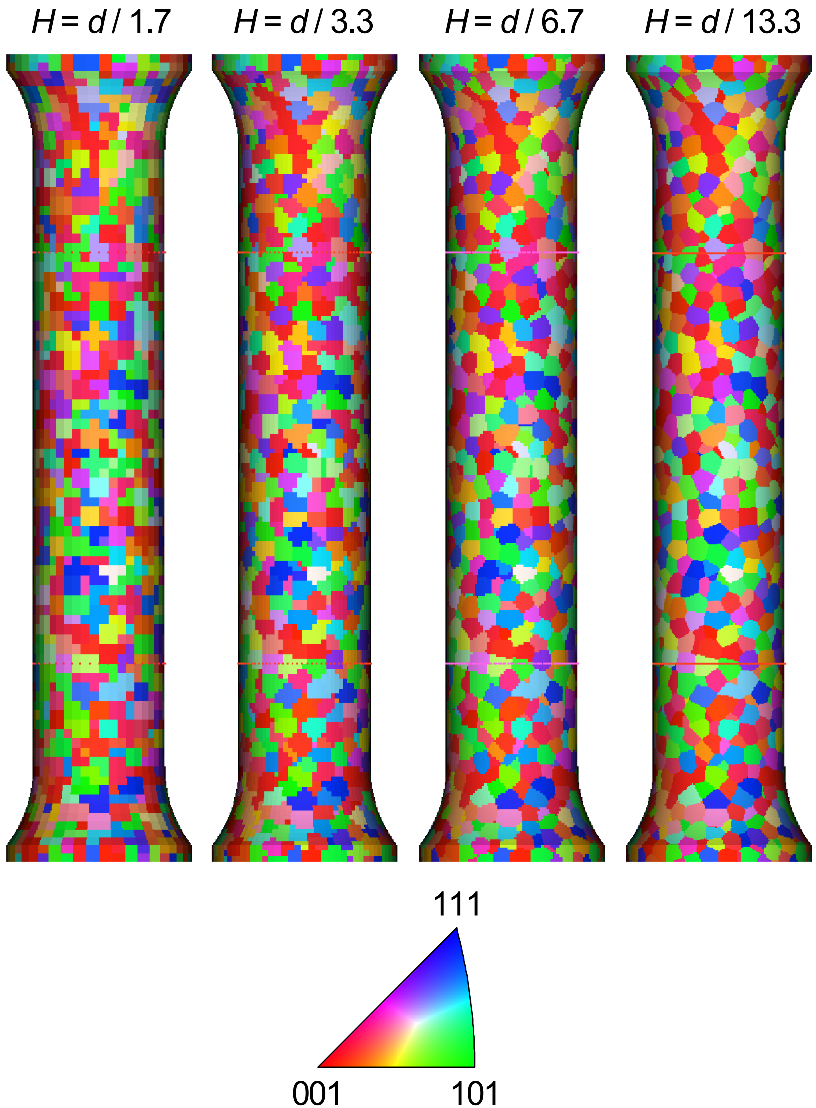


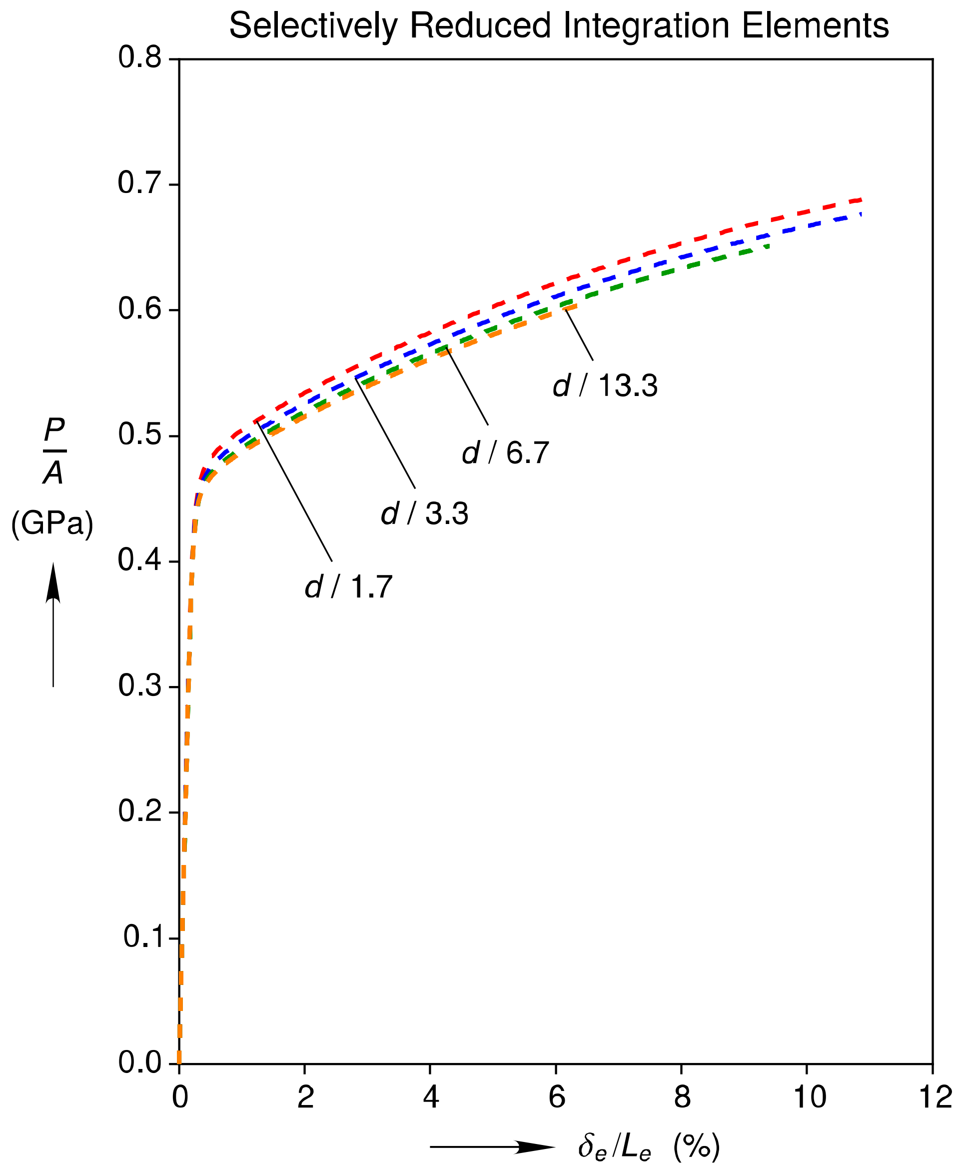
Mesh Convergence



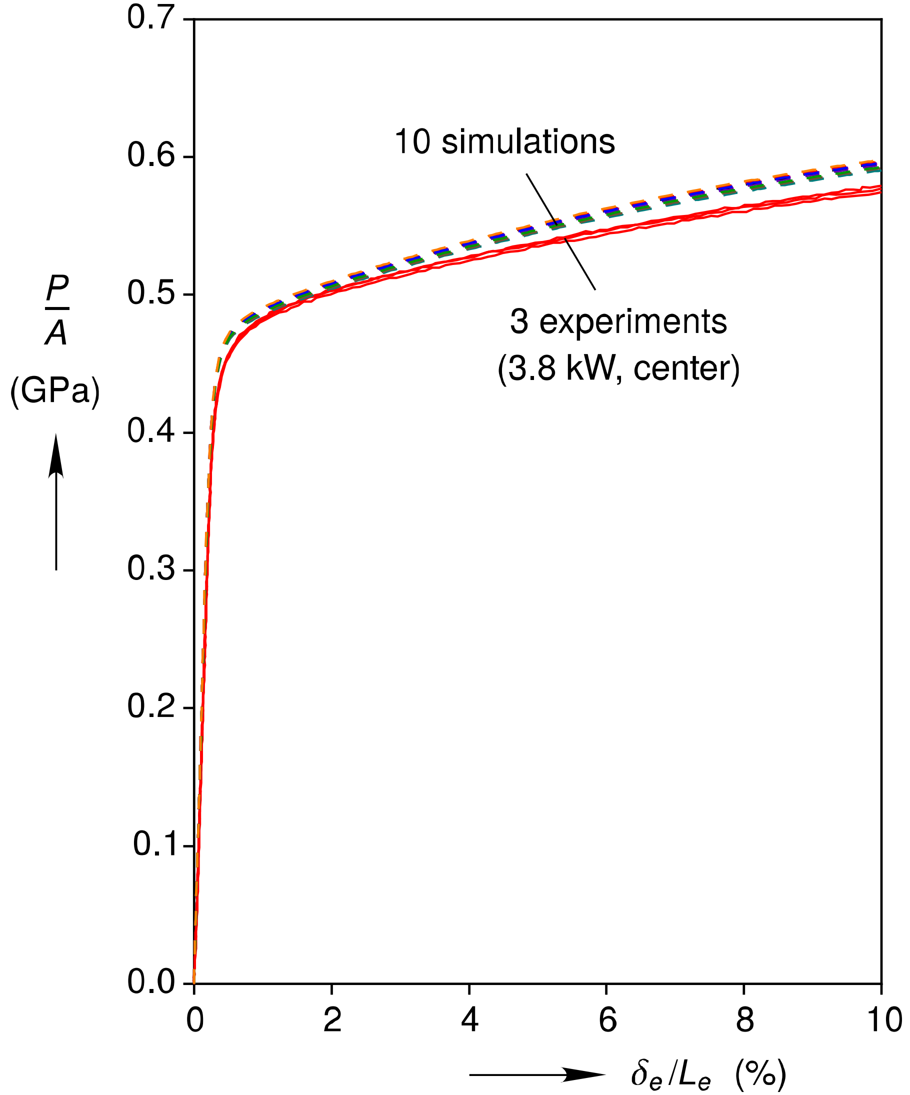


Mesh Convergence

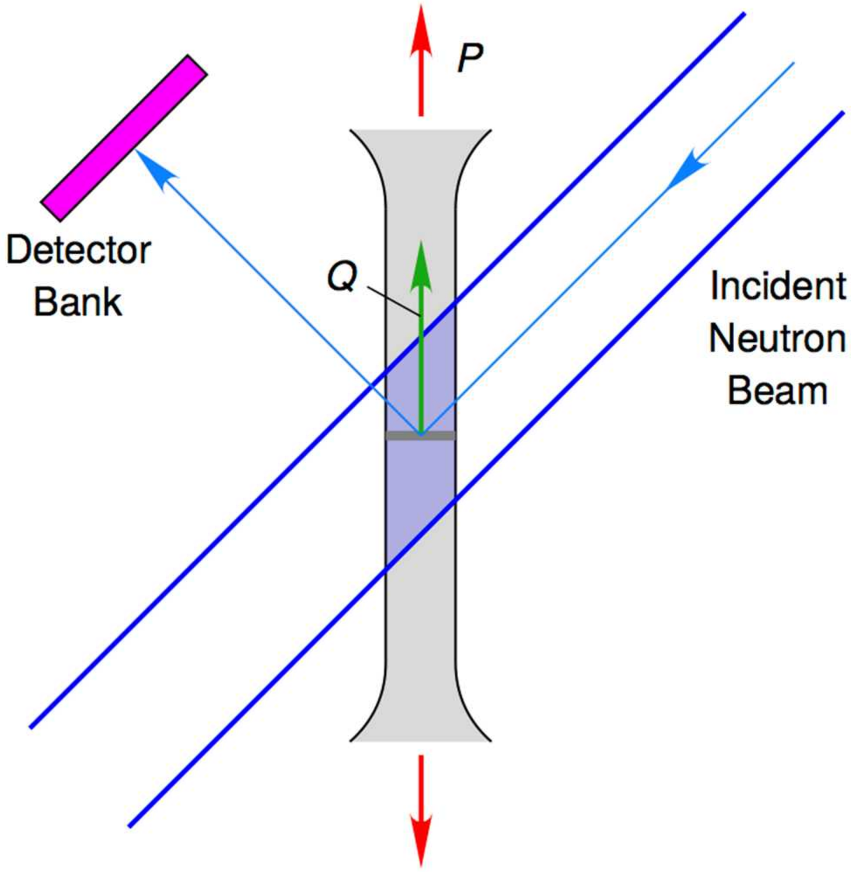




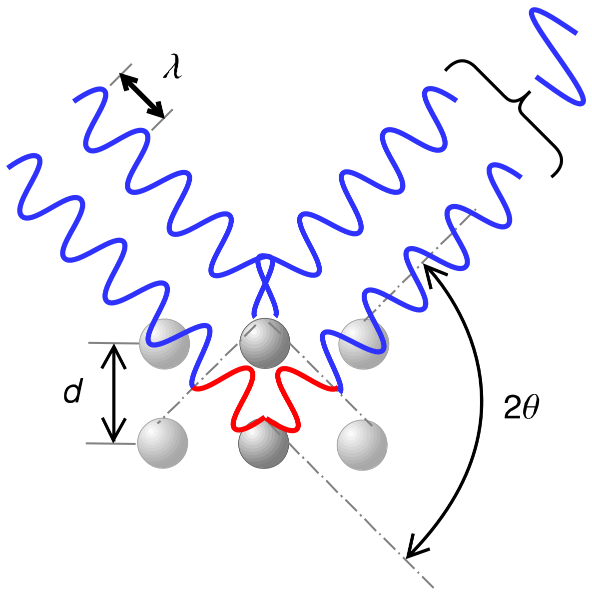
Calibration and Statistical Consistency



Neutron Diffraction



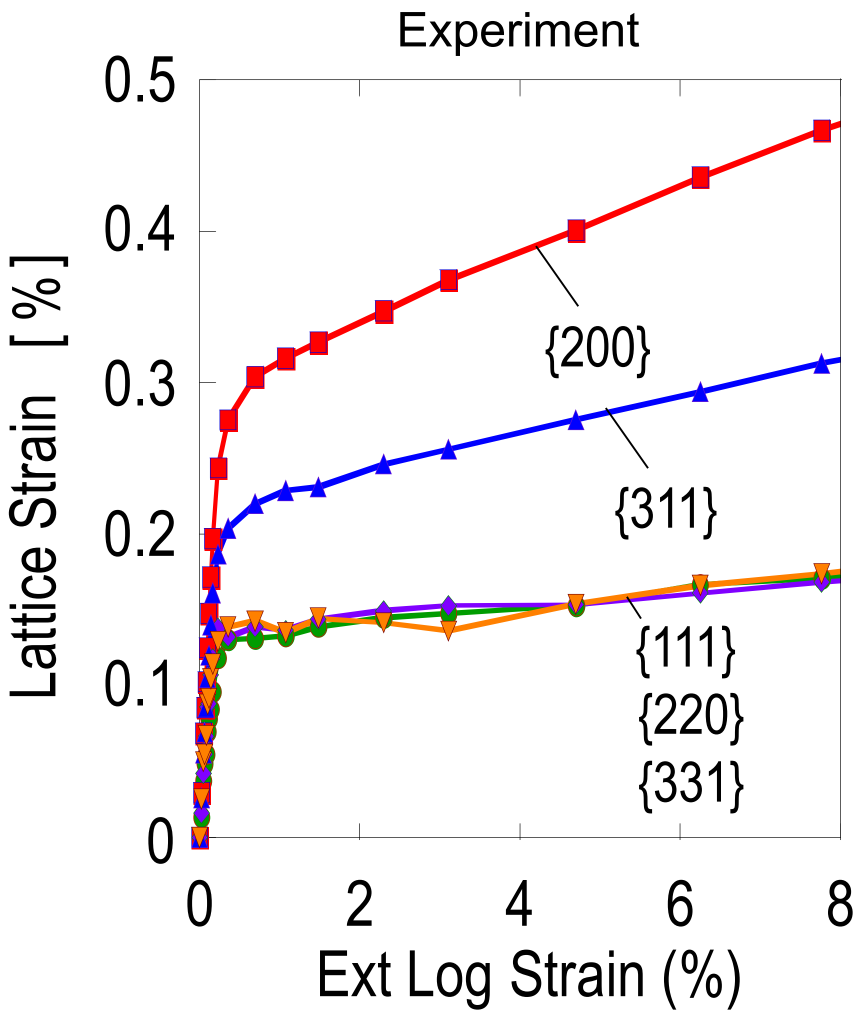
Bragg's Law

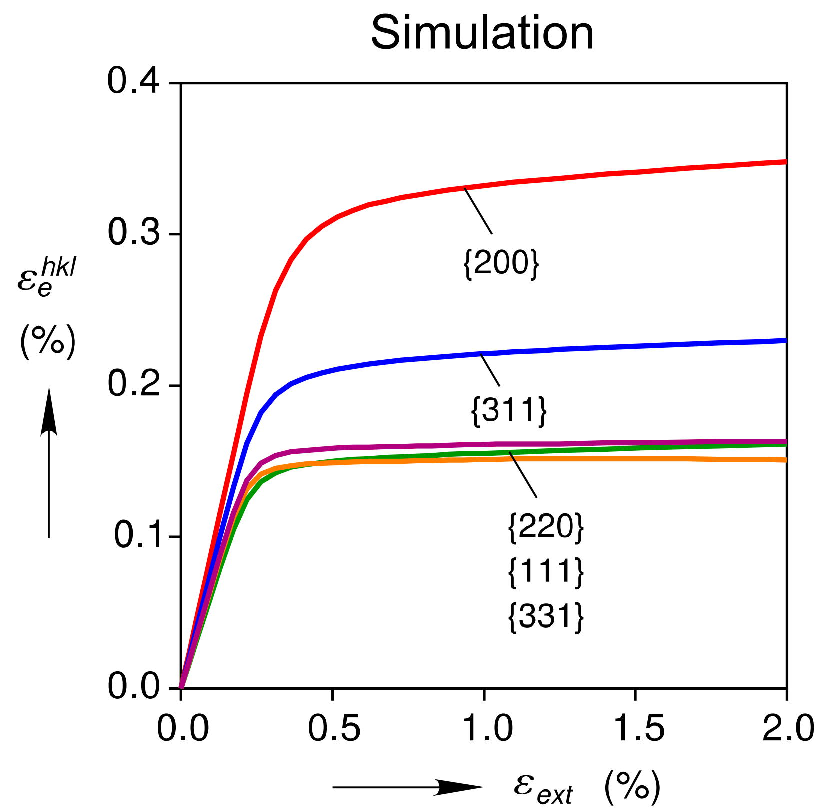


$$2\,d\sin\theta = n\,\lambda$$

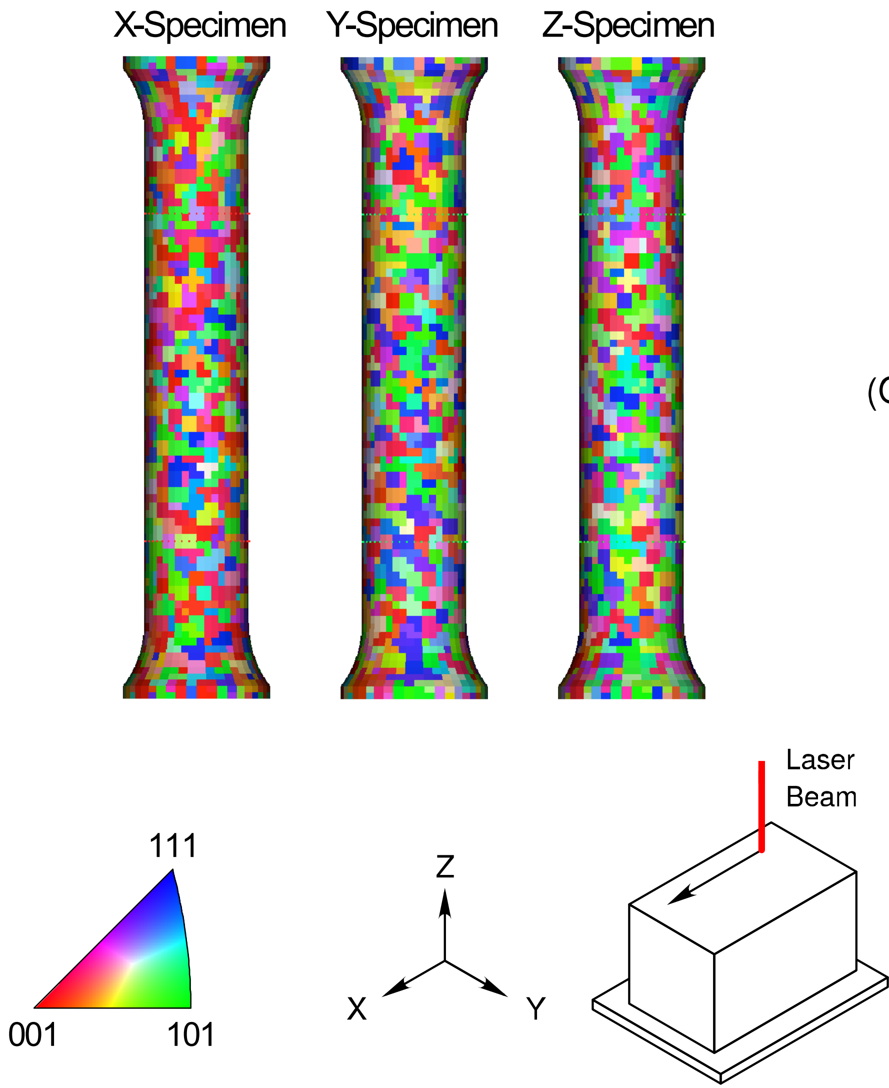
http://en.wikipedia.org/wiki/Bragg's_law (modified)

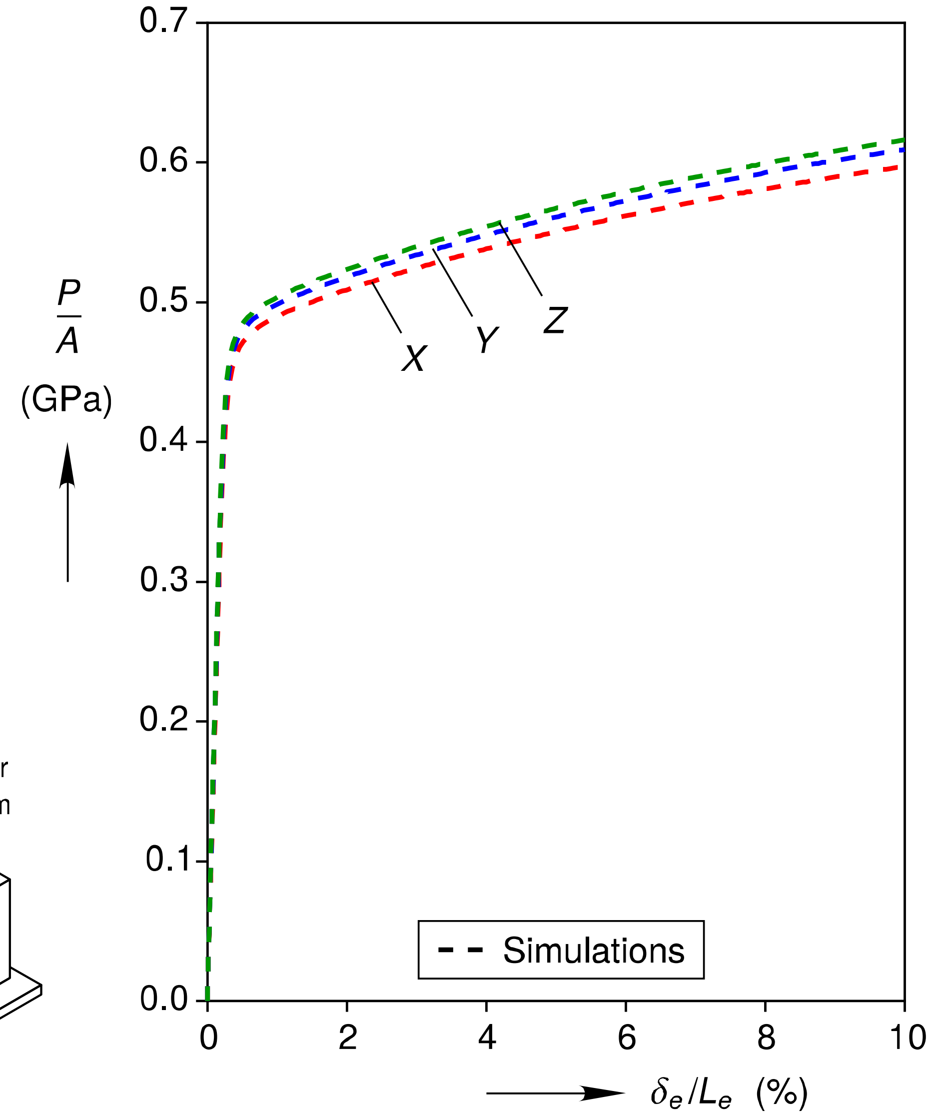
Lattice Strains



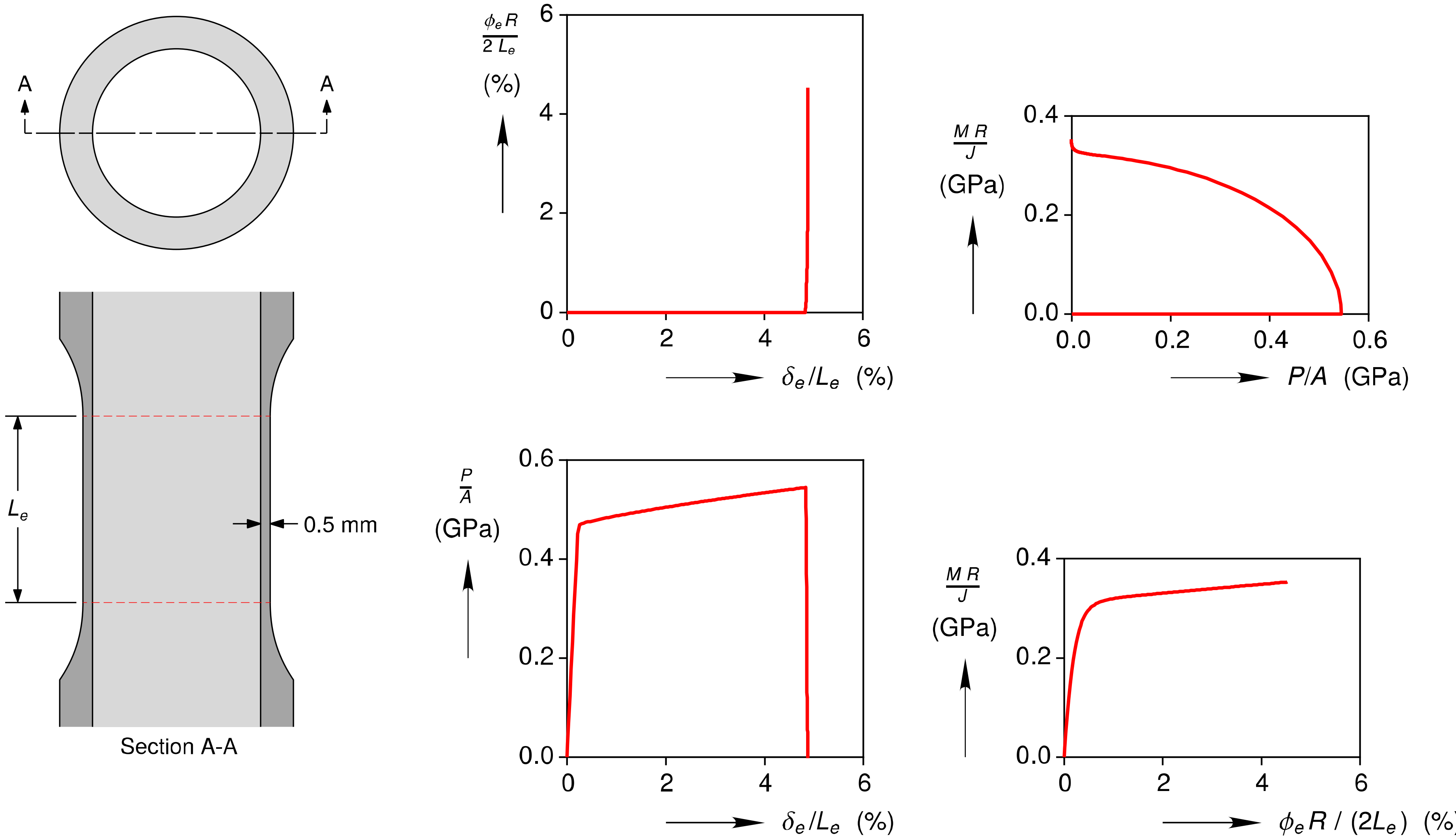


Anisotropy Predictions





Validation Simulations

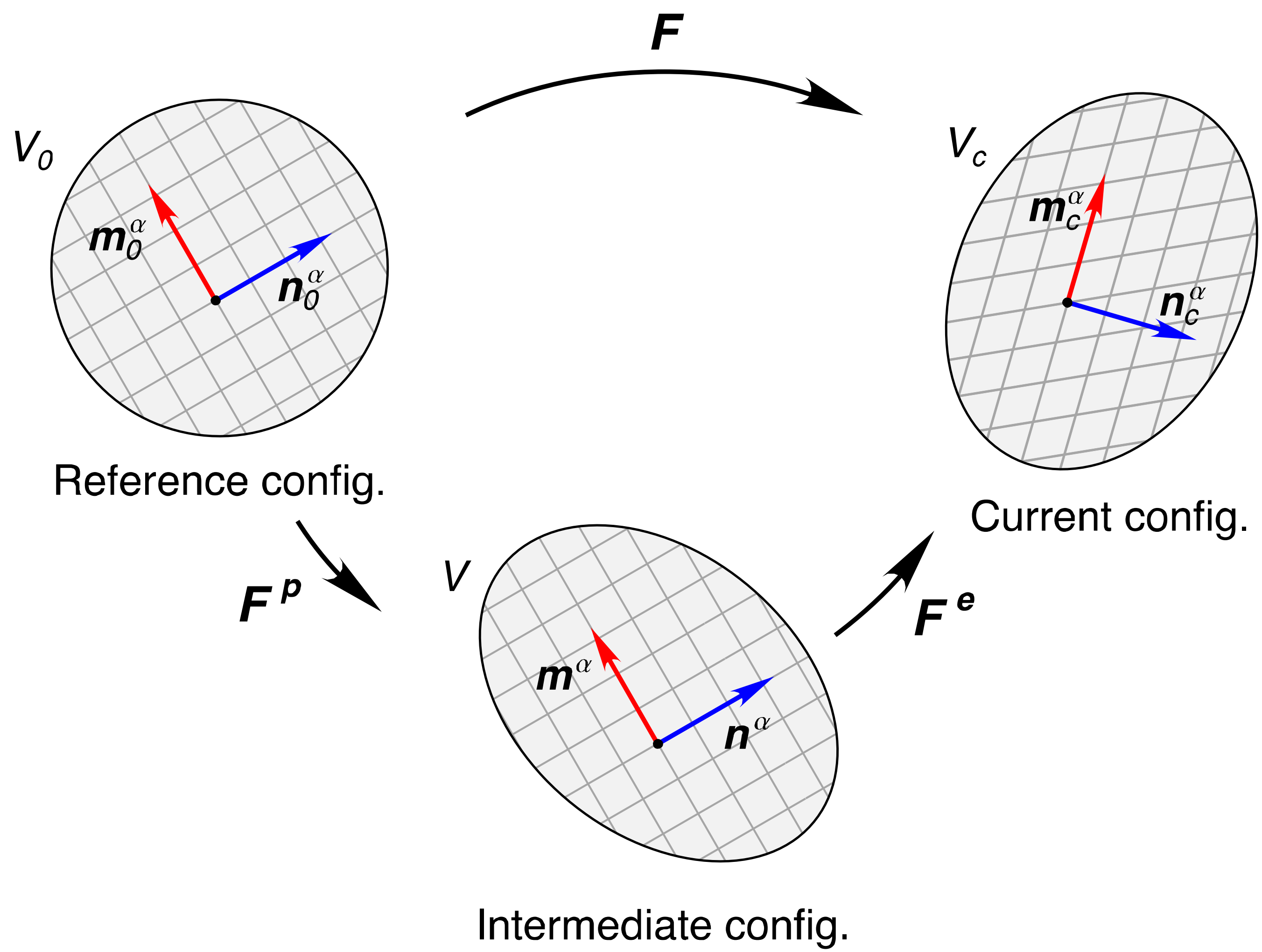


Summary

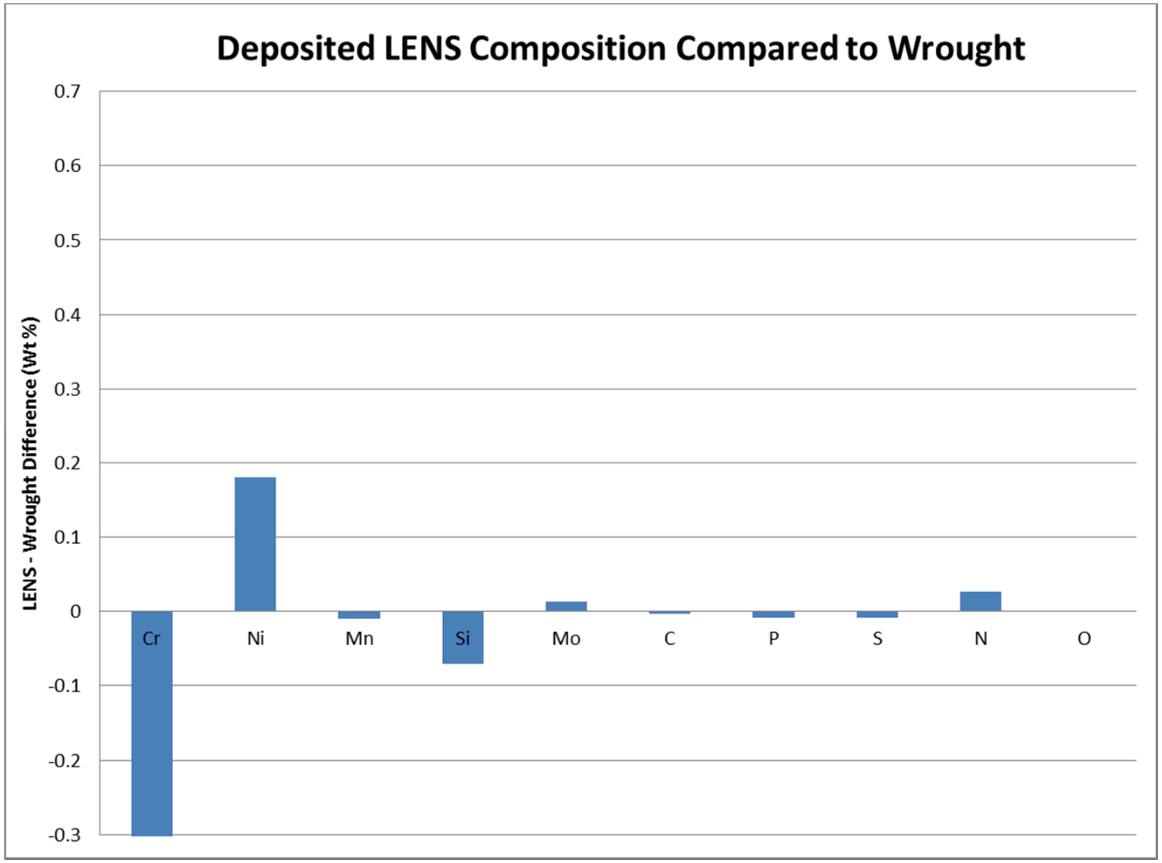
- Experiments
  - Additively manufactured 304L is 50-100% stronger and less ductile than comparable wrought 304L
- Simulations
  - Synthetic microstructures generated
  - Mesh convergence is difficult to obtain
  - Qualitatively validated the model against neutron diffraction measurements
  - Predicted mild anisotropy in yield and hardening

Questions?

Crystal Plasticity

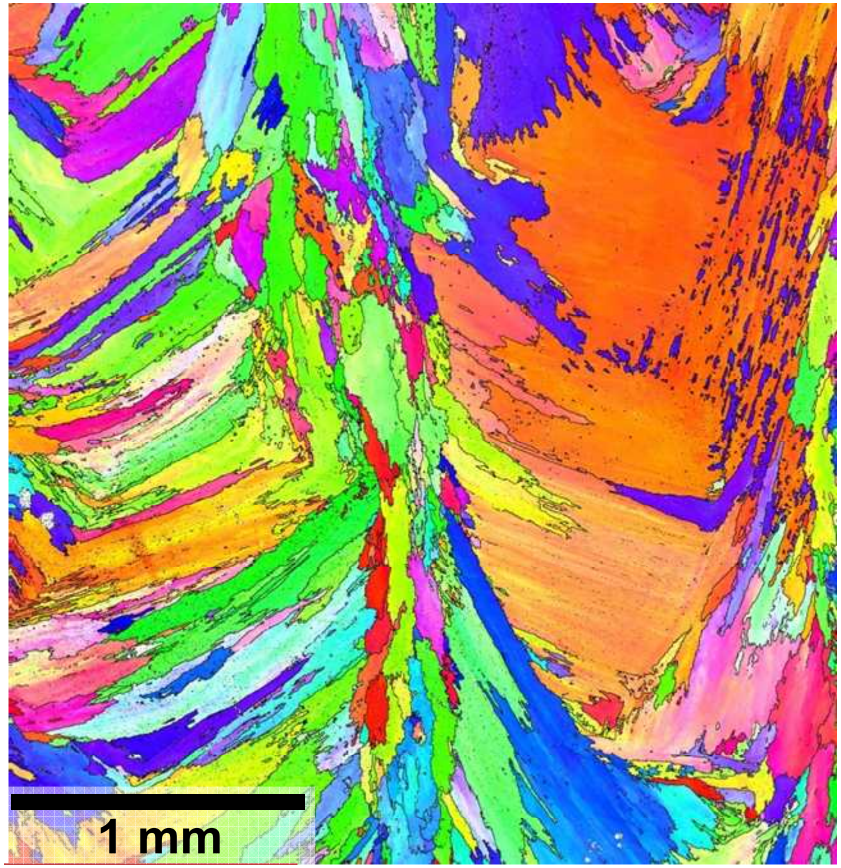


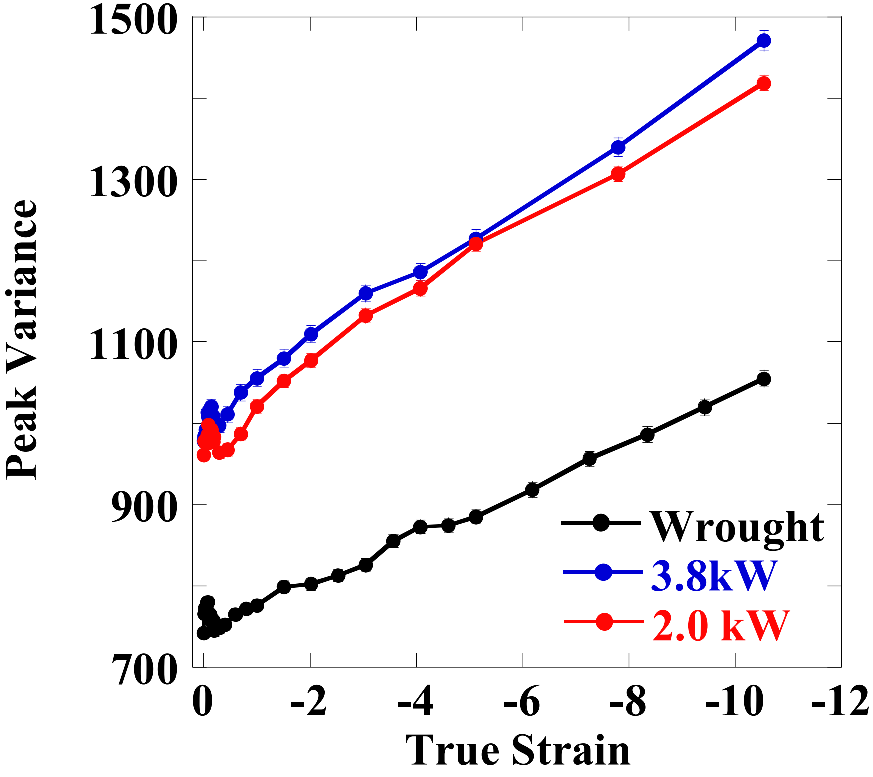
Composition Differences



	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

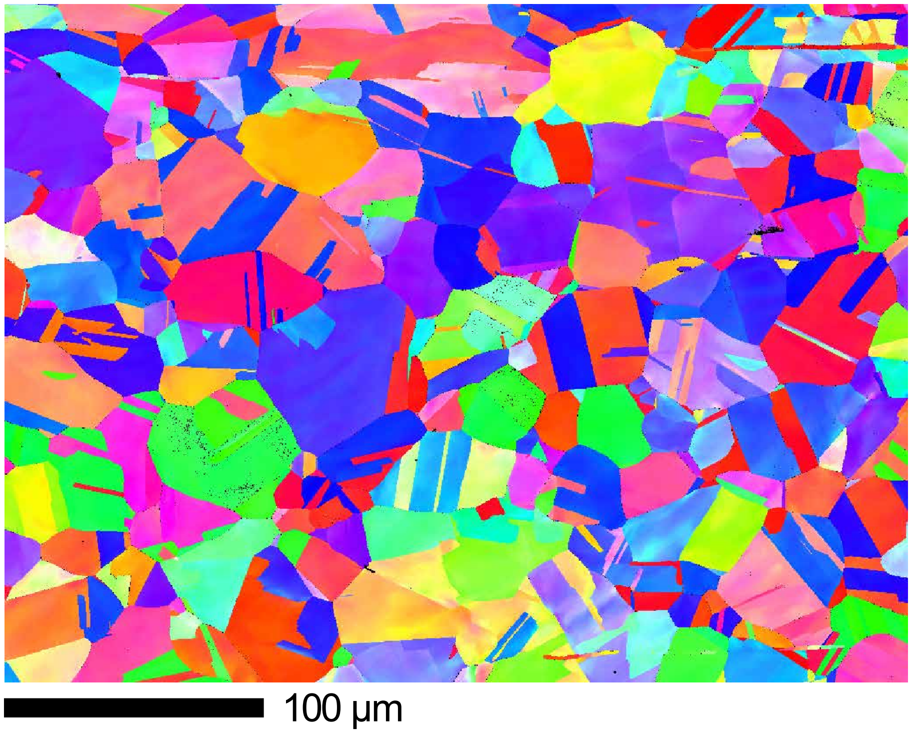
Indicators of Dislocation Density



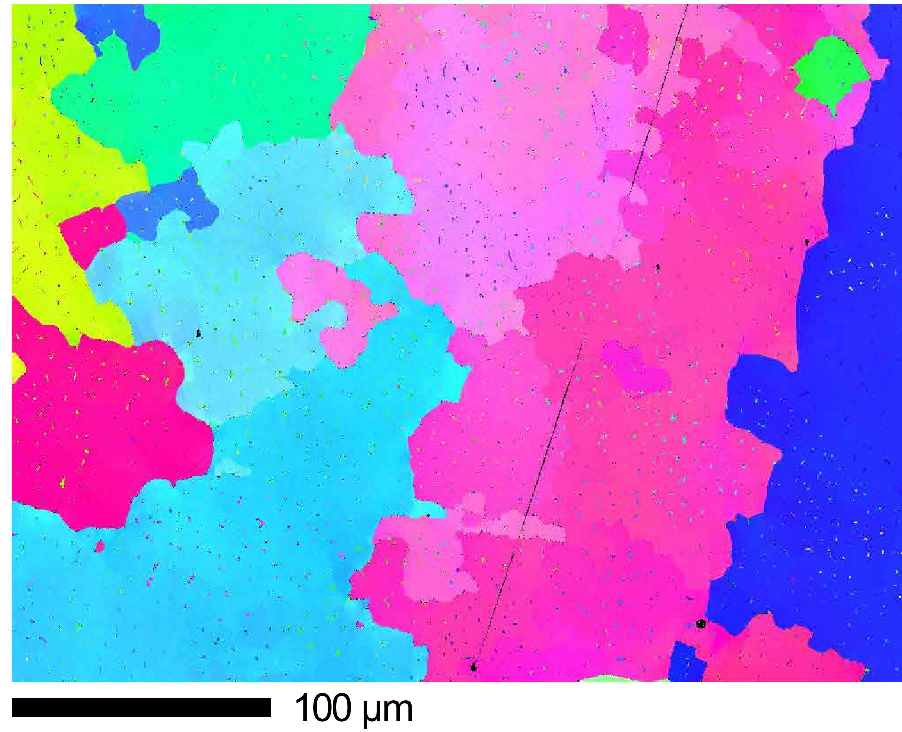


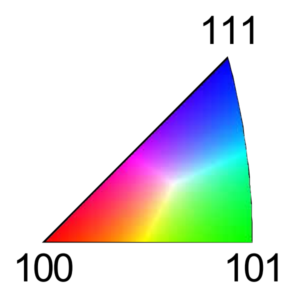
Ferrite / Martensite

Wrought
1.2 % Ferrite/Martensite (Ferrite Scope)



LENS 2 kW
2.3 % Ferrite/Martensite (Ferrite Scope)





Ferrite / Martensite

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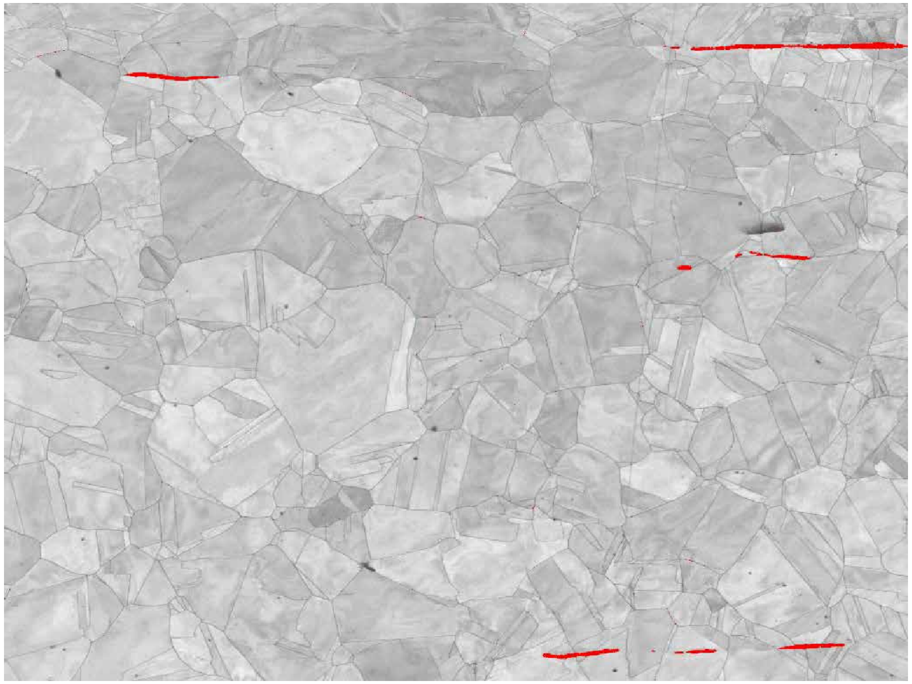
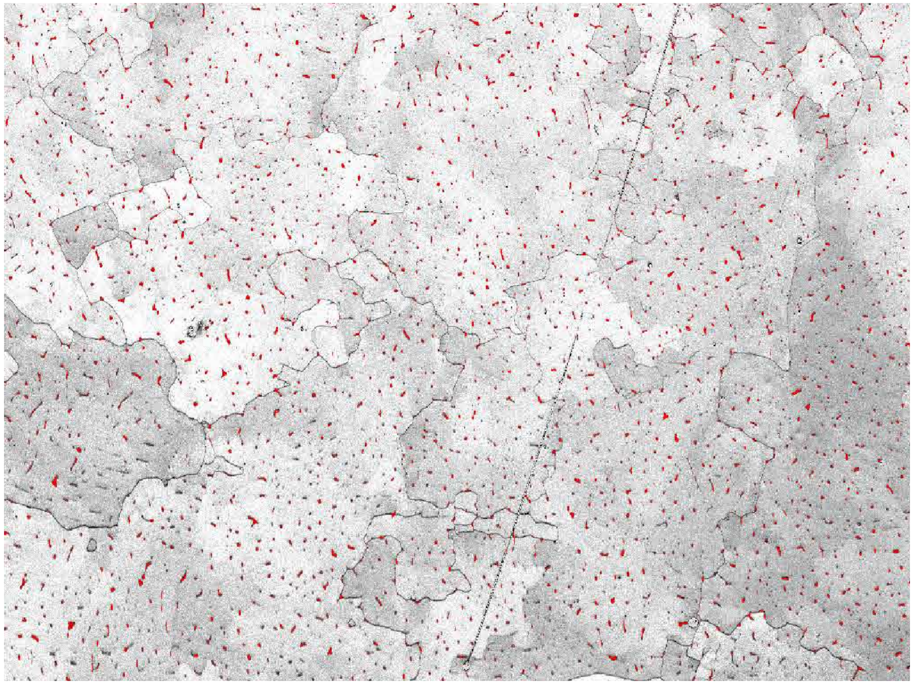


100 µm

LENS 2 kW
2.3 % Ferrite/Martensite (Ferrite Scope)



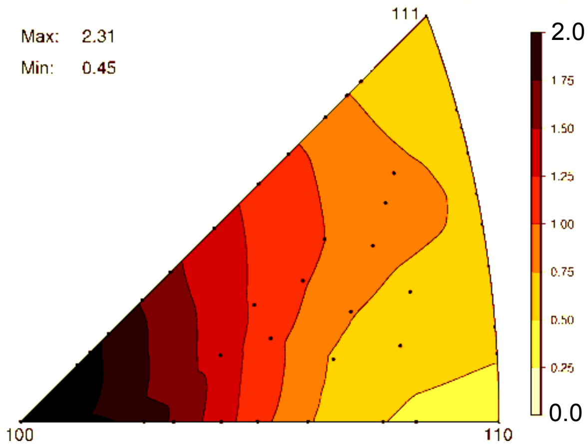
100 µm

Gray = Austenite, Red = Ferrite

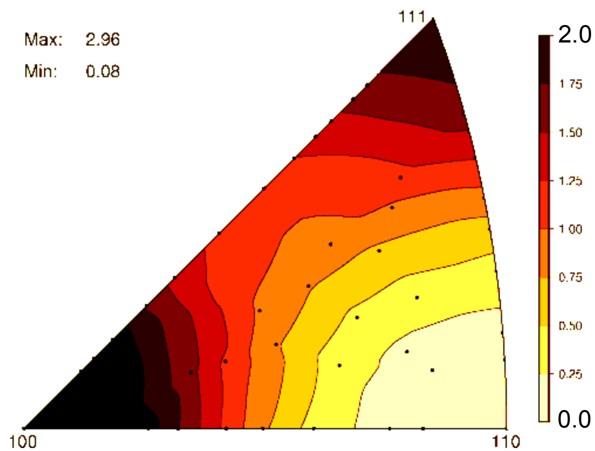
Deformation Induced Texture

Experiment

0 % Strain

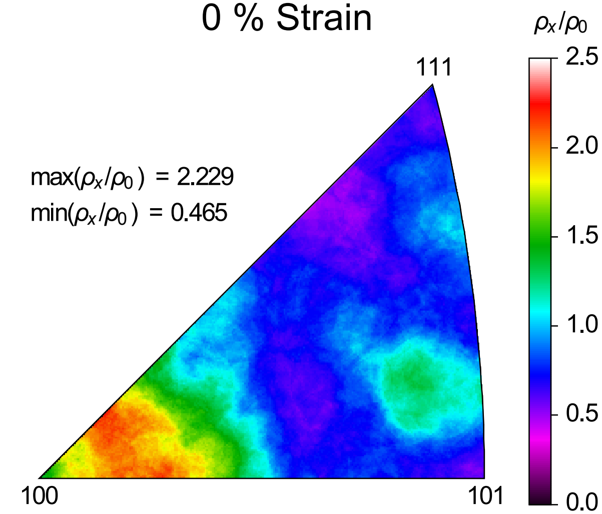


32 % Strain

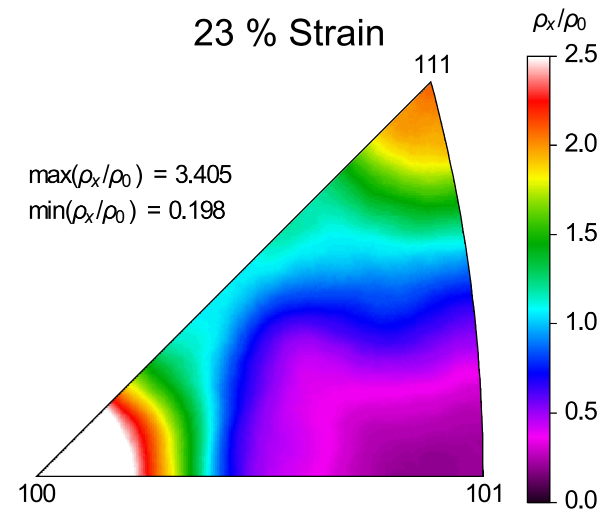


Simulations

0 % Strain



23 % Strain



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?