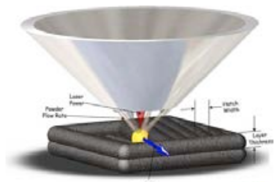

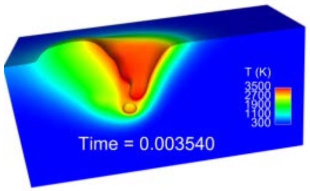


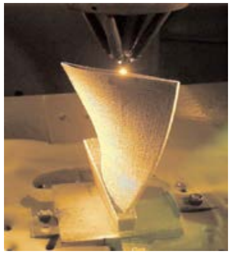

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*Exceptional service in the national interest*

SAND2014-20200C

# Characterizing and Predicting the Multiscale Mechanical Response of Additively Manufactured Materials across a Wide Spectrum of Loading Conditions

H. Eliot Fang
Manager, Solid Mechanics Department
Sandia National Laboratories

AmeriMech Symposium: Material Property Identification
December 10-12, 2014

U.S. DEPARTMENT OF ENERGY    NNSA National Nuclear Security Administration

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# Additive Manufacturing (AM) is viewed as a transformative technology at Sandia

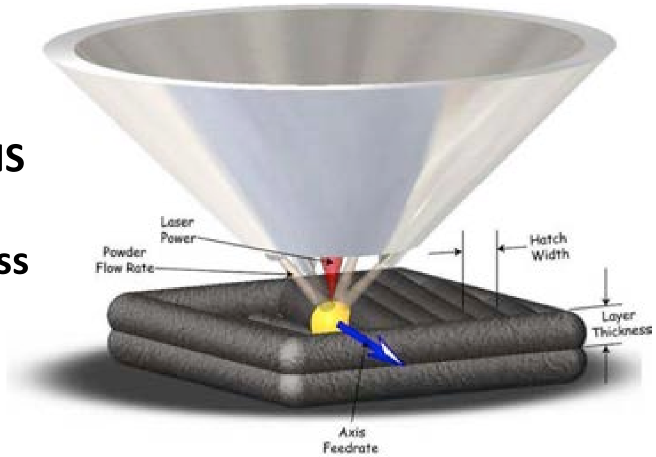
- Some Benefits of AM:
  - Complex structure – components may be built that are not possible using conventional methods.
  - Rapid design to production with reduced cost – items are fabricated as soon as the digital model is produced.

- Sandia has a differentiating need to predict materials property and reliability for high-consequence applications.
  - Characterizing AM materials and predicting reliability of AM products are challenges.
  - Must create a framework for characterizing and predicting property of AM materials for timely mission impact.

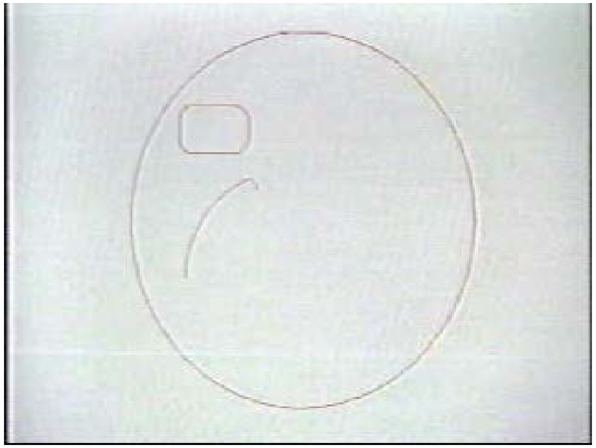
# Laser Engineered Net Shape (LENS$^{TM}$)

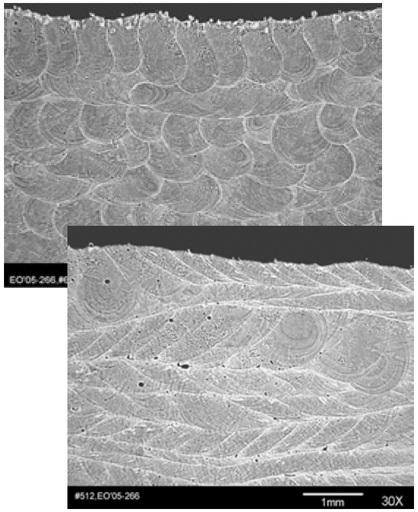
***A Sandia developed and commercialized process***

**Schematic of LENS laser-based deposition process**




**LENS Depositing complex shape (from David Gill, Sandia)**






**LENS mesostructure**

- <u>Transformative</u> technology
- LENS "hatch" structure results in a complex mesoscale structure.
- Classical assumption of scale-separation may no longer be applicable.

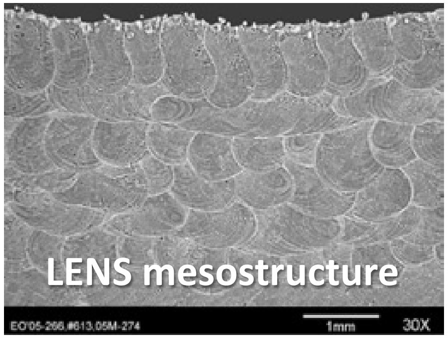
**Hybrid LENS product**

# Fundamental Science Questions

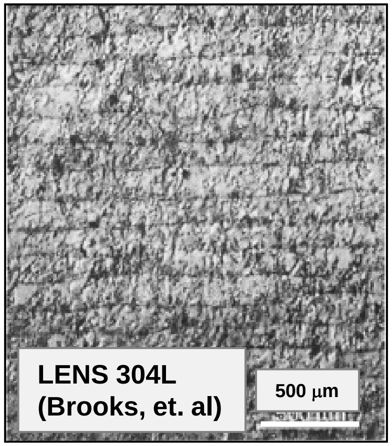
- What is material variability and how is it manifested at the macroscale for additively-manufactured structures? (Uncertainty Quantification)

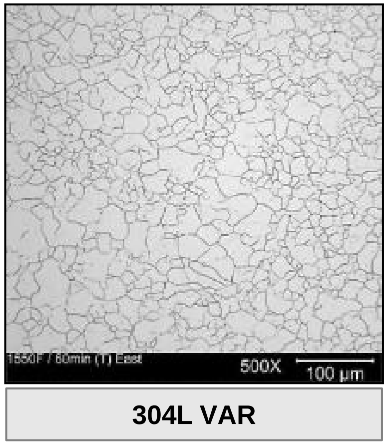
- With the loss of 'scale separation', homogenization theory may be inaccurate. How do we model additively-manufactured structures?

- Do the complex mesostructures in additively manufactured parts give rise to mechanistic transitions between quasistatic (10-4 s-1) loading and shock regimes (109 s-1)? If so, how?




The assumption of 'scale separation' has been the foundation of structural mechanics since Cauchy developed continuum mechanics (150 years ago).



# Multiple pieces must be integrated

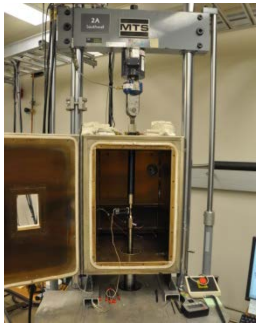
- Incorporate material variability across scales
- Probabilistic design predictions
- Incorporate materials physics in UQ
- Holistic Design and Fabrication

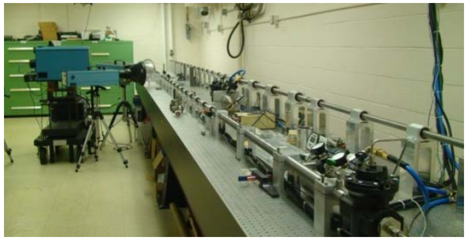
- Characterization & Testing
- Process Modeling
- Microstructural Models
- Design for Lifecycle
- Mechanistic Understanding


- Ready in weeks to months
- Rapid characterization
- Intelligent experimentation
- Enables iterative optimization

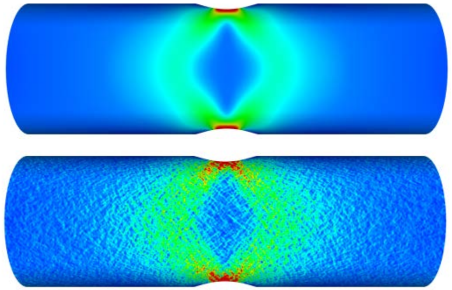
# Our Approach

1. Fabricate test material and structures by Additive Manufacturing (LENS) and characterize their microstructures.
2. Experimentally characterize mechanical response across 15-decades of strain rates (from quasi-static to Hopkinson-bar to plate-impact).
3. Use homogenization theory to populate conventional macroscale viscoplastic constitutive models.
4. Characterize LENS microstructure as a function of deposition history.
5. Develop Direct Numerical simulation (DNS) of test samples and validation specimens/structures.
6. Compare and contrast conventional material modeling approach to DNS.



**Hopkinson Bar**



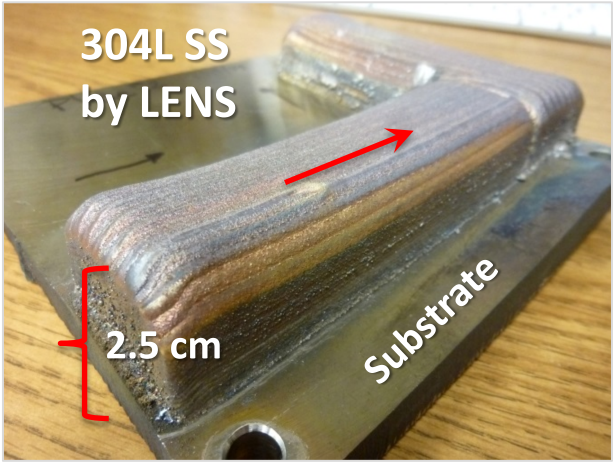
**Homogenized vs DNS**

# Accomplishments To Date

- LENS process was established at Penn State University and 304L stainless steel bars for mechanical test have been made.
  - High power LENS process – 3.8 KW
  - Low power LENS process – 0.5KW

- Wrought and LENS (high power) materials comparison
  - Initial microstrutural characterization – grain size, texture, phase
  - Quasistatic mechanical testing
  - Hopkinson high rate testing
  - Elastic properties – acoustic

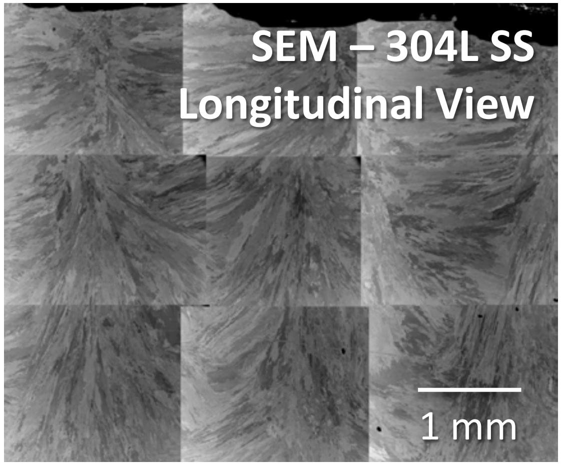
- Solid mechanics DNS
  - LENS microstructure model developed
  - Mechanics simulations ongoing

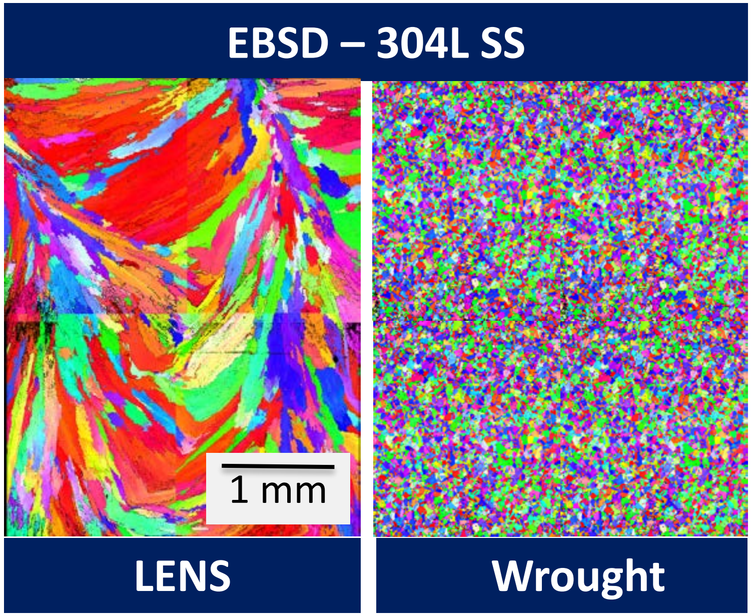


# Microstructural Characterization

- LENS 304L SS (3.8 kW) is/has
  - austenite
  - relatively large grain structure
  - complex refined microstructure
  - small amount of retained ferrite
- Wrought 304L SS is/has
  - austenite
  - small grain structure
  - equiaxed grain structure
  - small amount of retained ferrite

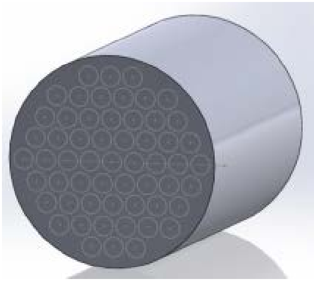
Additional characterization is in progress (composition, density, elastic properties).

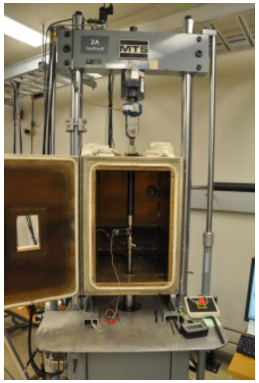


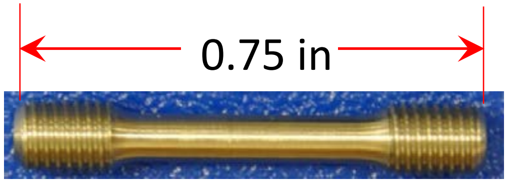



# Quasistatic Mechanical Tests

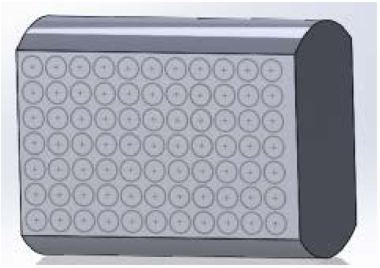
Transverse



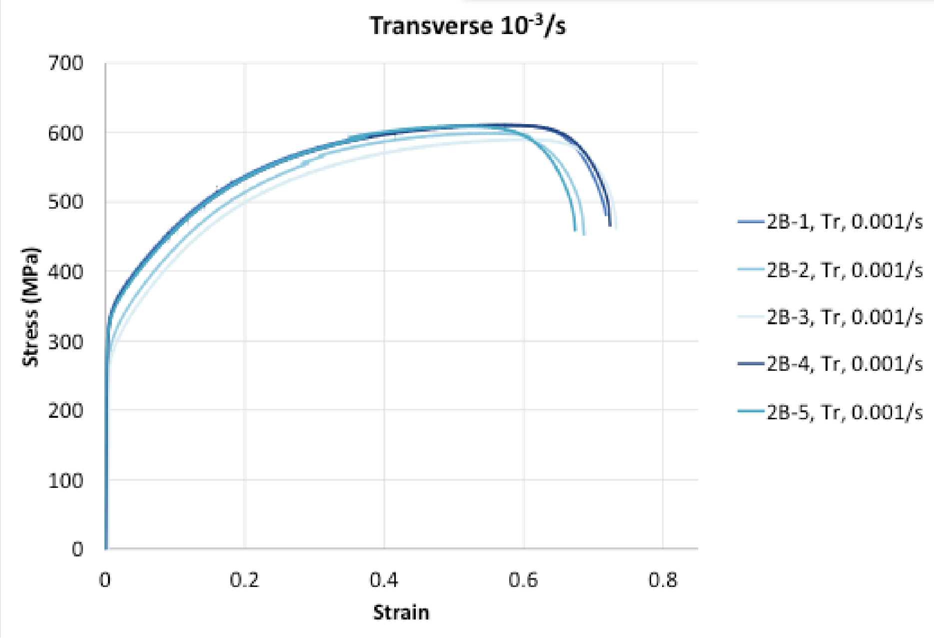


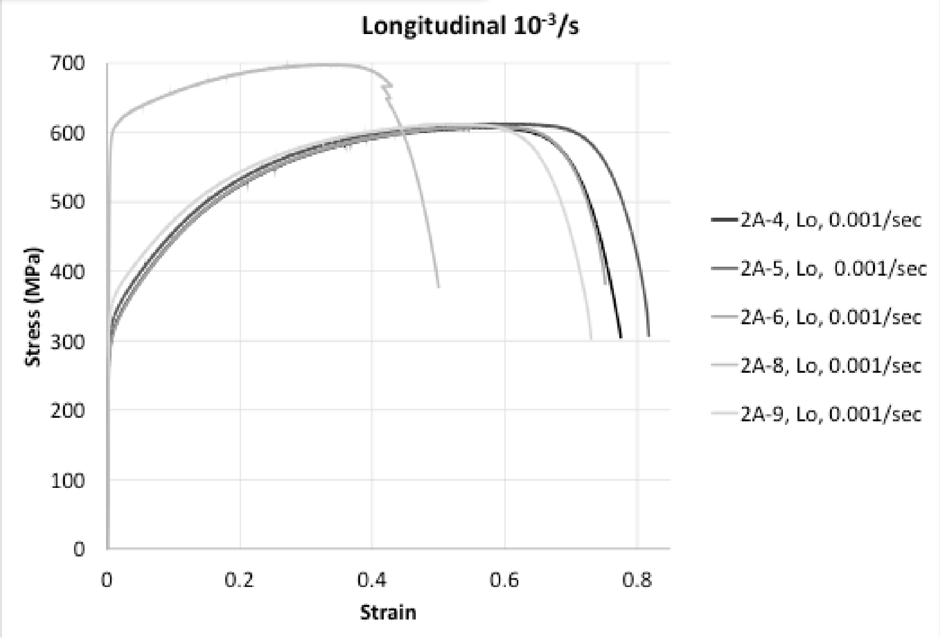



Longitudinal

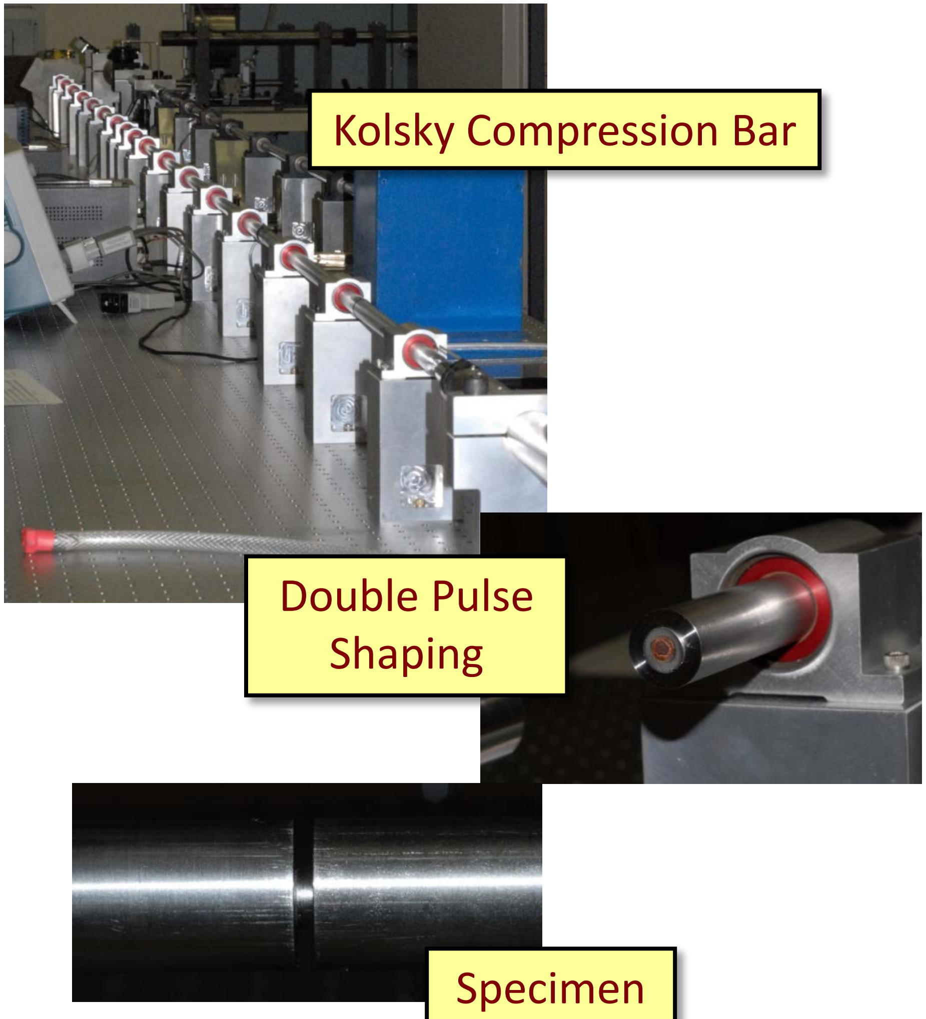


**Stress-Strain Curves – Wrought 304L SS**

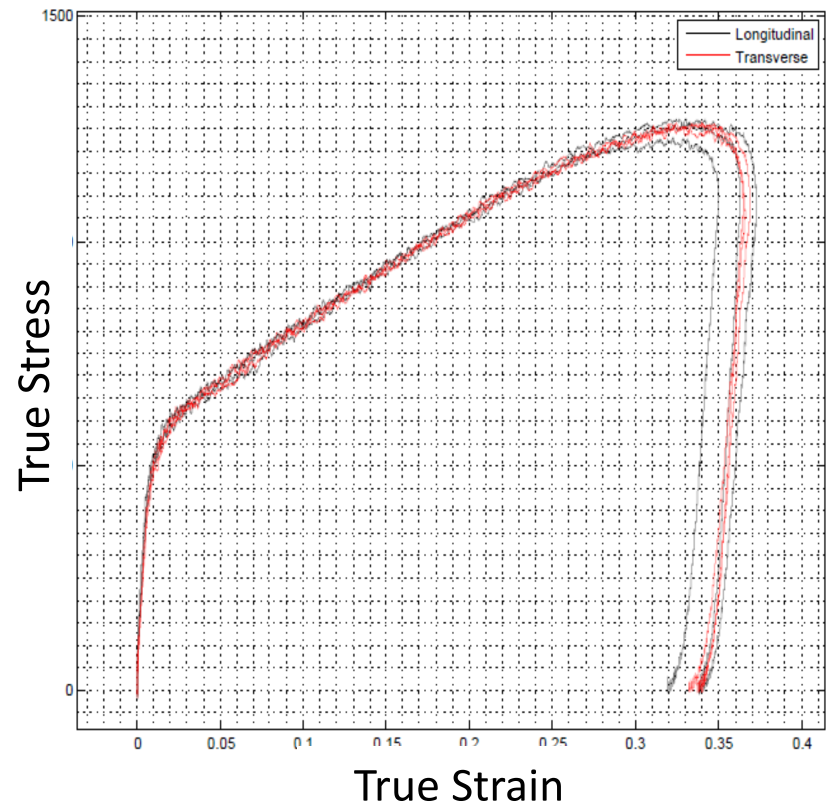


# Dynamic Compression Tests

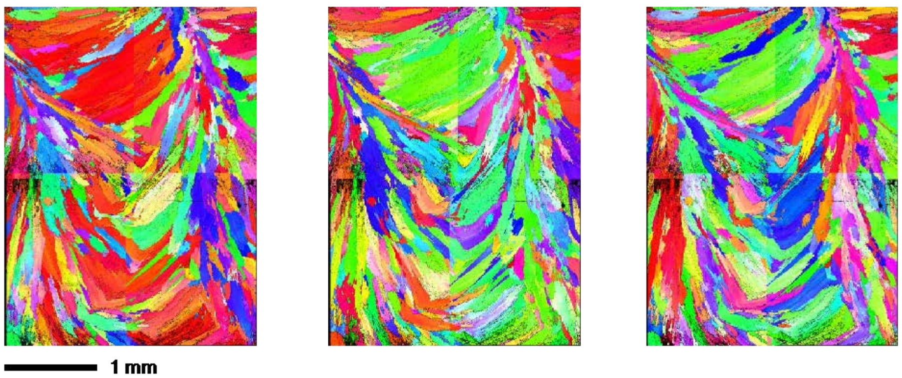



**Stress-Strain Curves on Wrought 304L SS at 2500 $s^{-1}$**

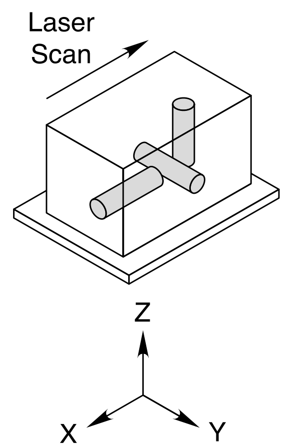


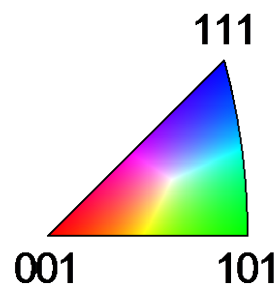
# Preliminary Texture Study

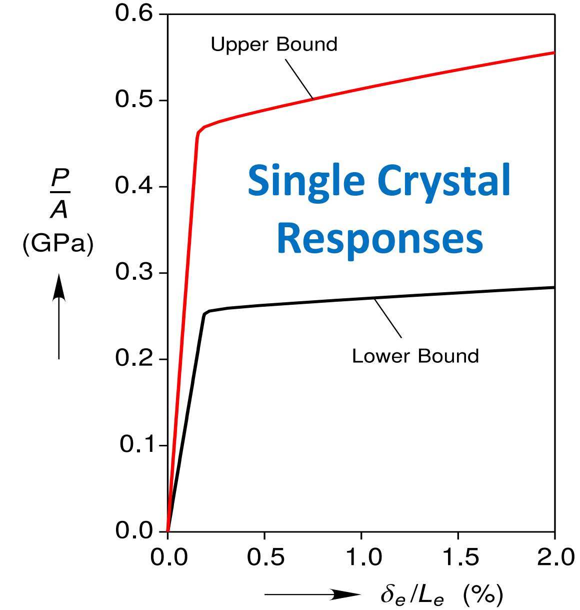
## EBSD Orientation Maps

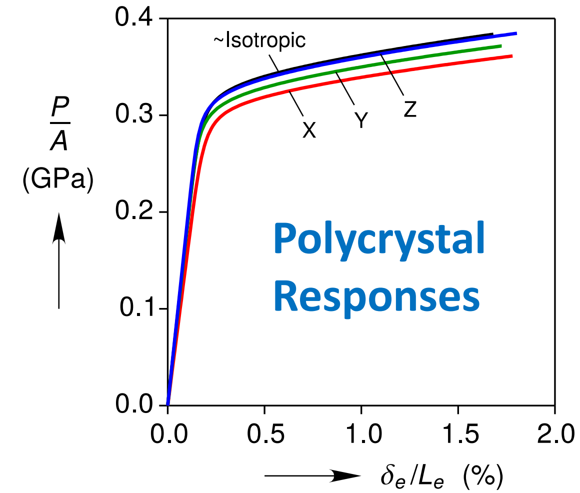



## Tensile Specimens

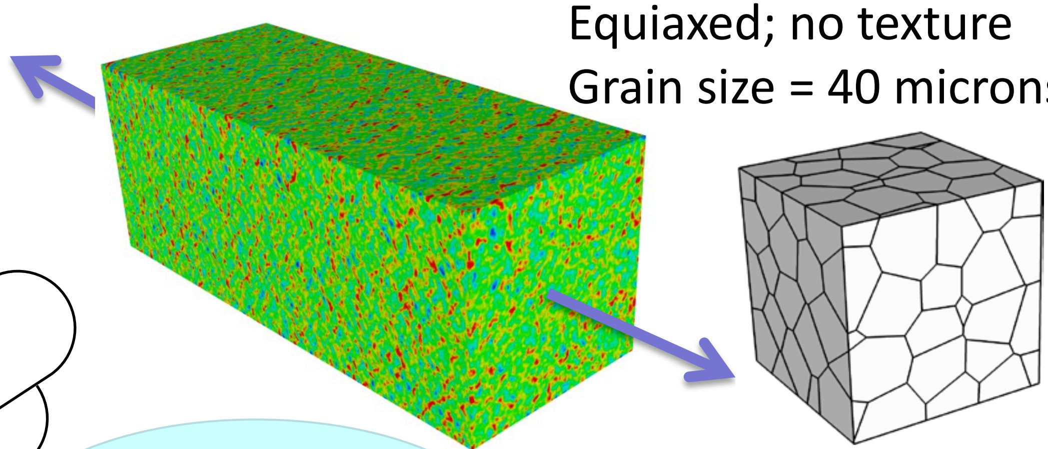



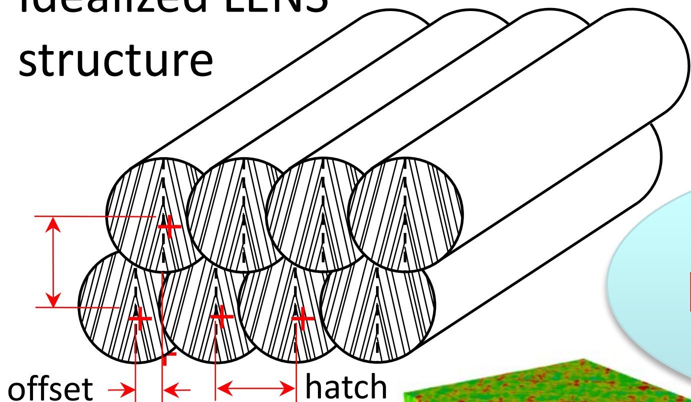



# DNS of Idealized LENS Microstructures

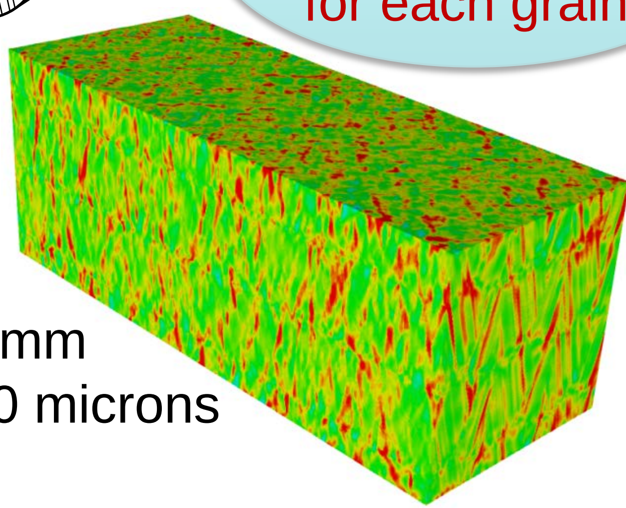
Equiaxed; no texture
Grain size = 40 microns



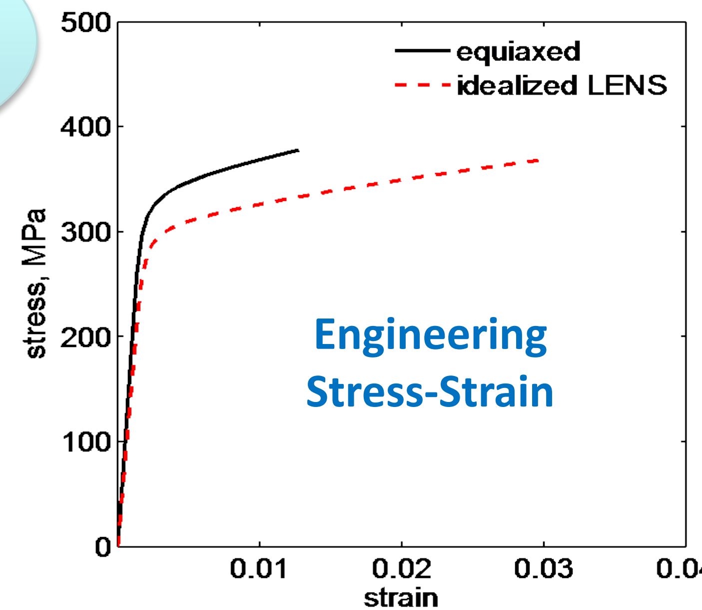
Idealized LENS structure




Using crystal plasticity model for each grain.

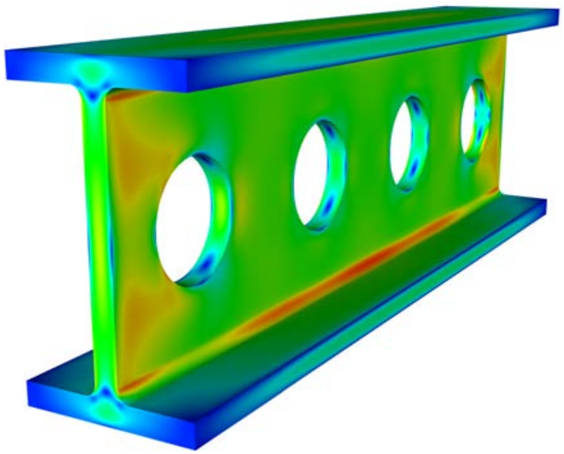


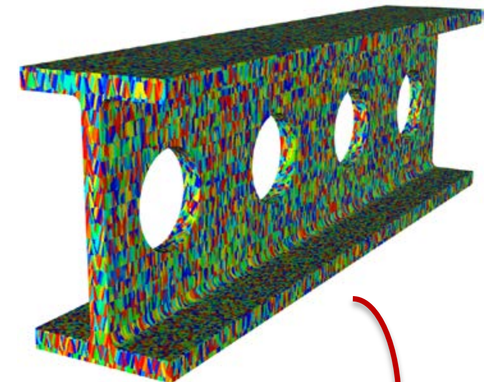
Bead size = 1 mm
Grain size = 40 microns



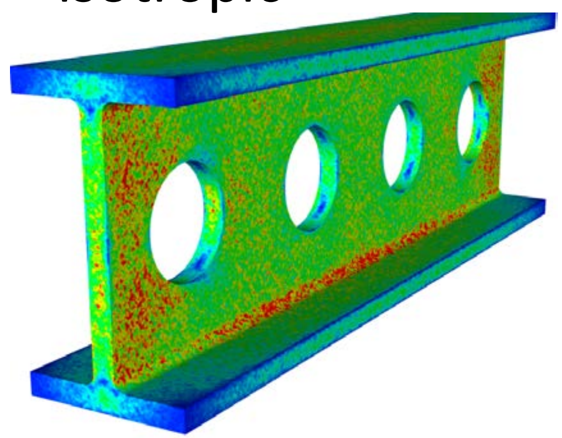
# Macroscopic Stress Field

Homogeneous; isotropic

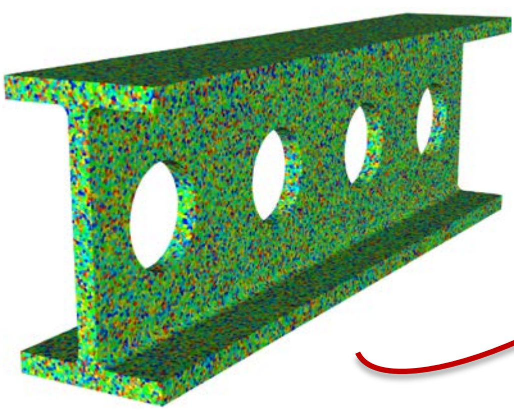


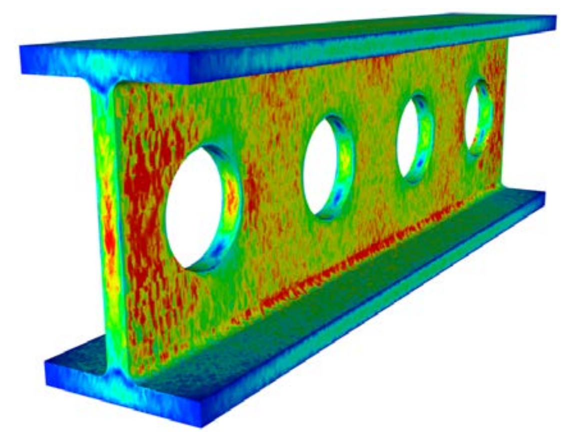


Equiaxed; no texture; isotropic



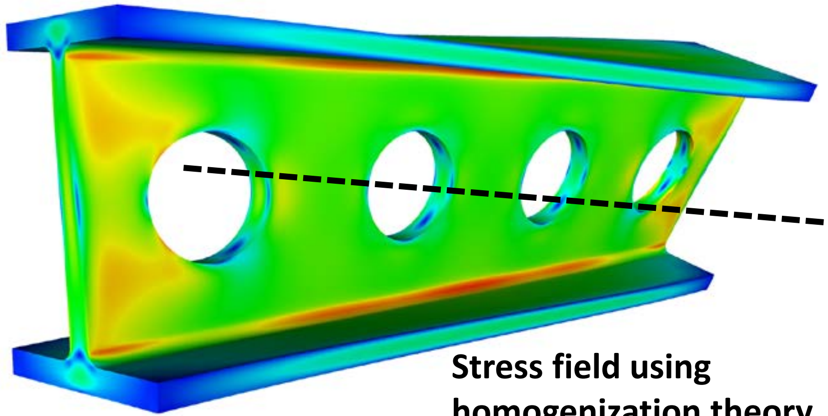
Idealized LENS





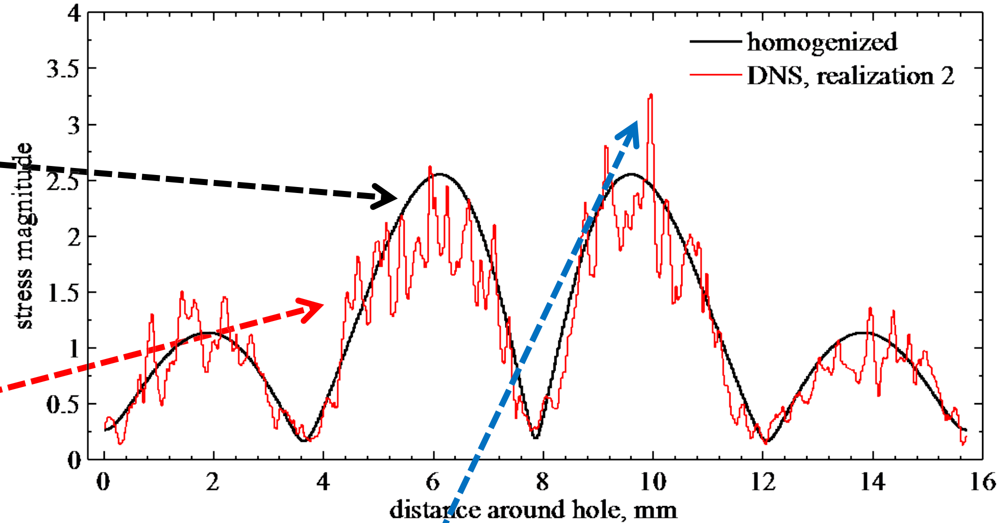
# Homogenization may filter physics necessary to predict failure



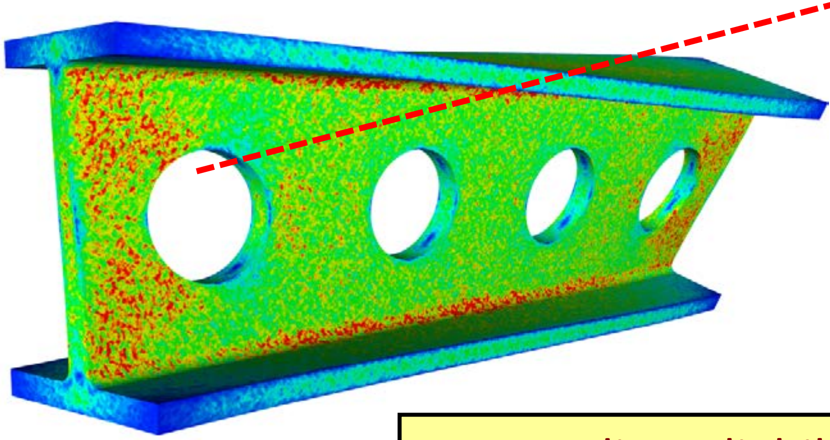


Stress field using homogenization theory

**"Enriched physics"**




**The stress field resulting from homogenization theory can miss potential fracture initiation locations.**



**Stress field using Direct Numerical Simulation**

To predict reliability with true Uncertainty Quantification, we must locally enrich physics by incorporating the microstructure.

# Summary

- Additive Manufacturing is a potentially transformative technology.
- Sandia has a differentiating need to predict property and reliability of materials for high-consequence applications.
- To predict material property and reliability with true Uncertainty Quantification, we must locally enrich physics by incorporating the microstructure.
- We are developing integrated experimental and modeling capabilities for characterizing and predicting property and reliability of new materials.
- The current work will be the first application of Direct Numerical Simulation in Solid Mechanics.
  - Understand the response of LENS microstructures compared to wrought.
  - Use idealized microstructures until process modeling is available.
  - Texture measurement through EBSD.

# Future work – integration of Sandia process and performance simulation tools

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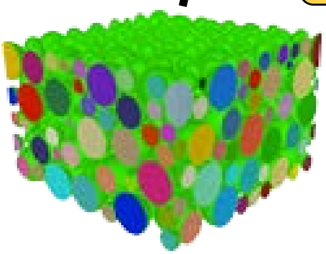
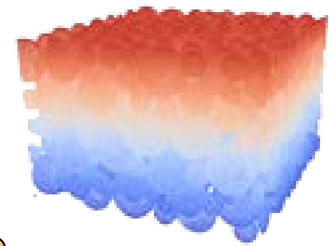
***Particle packing***



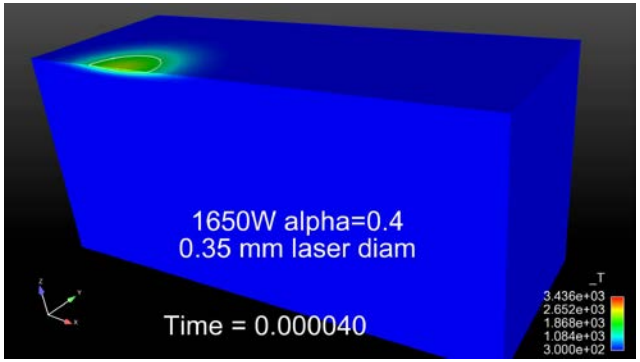
***Particle heating***



***Partial melt & flow***

***Molten pool dynamics***

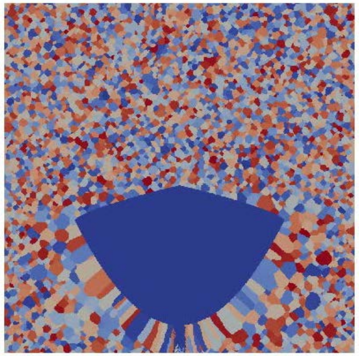
*Traveling seam weld*




*(M. Martinez, SNL)*

***Solidification***

*Microstruction evolution*



*(V. Tikare, SNL)*

***Microstructure***

***Topology & surface finish***

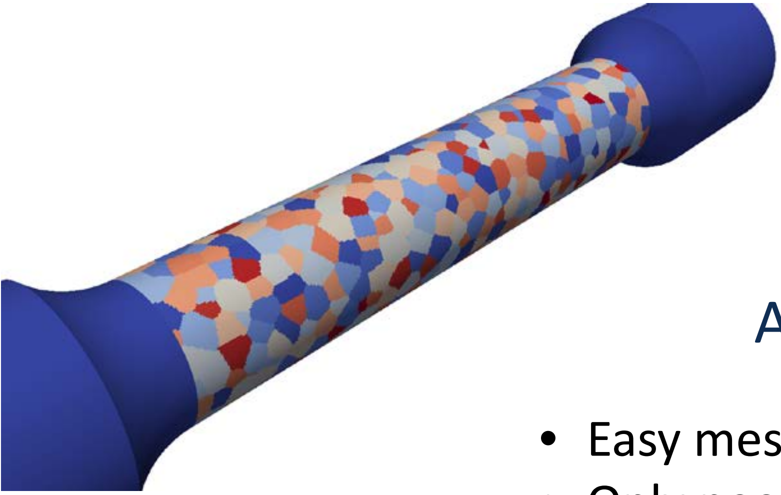
***Performance & reliability***

# Back up


17

# Direct Numerical Simulation in Solid Mechanics (DNS)

- Use voxelation approach to mesh grains
- Use macroscale hexahedral mesh as “overlay” grid
- Use idealized microstructure and texture (until process modeling is available)

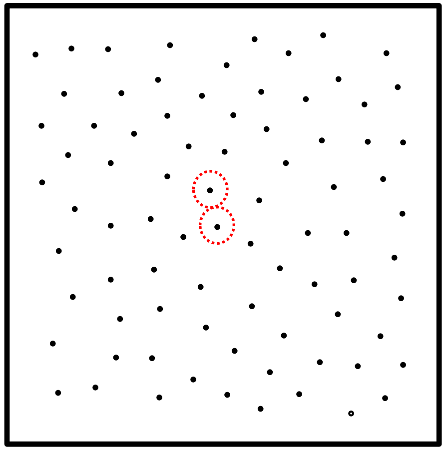


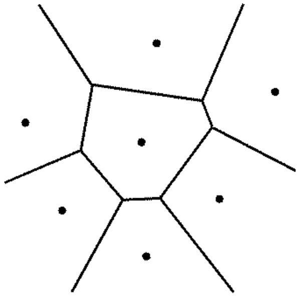
## Advantage of voxelation approach

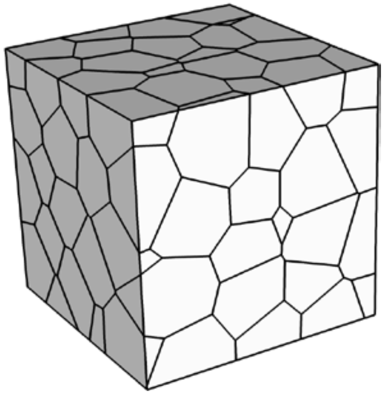
- Easy meshing of microstructure
- Only need implicit representation of microstructure
- Can robustly generate many microstructural realizations
- Robust under large deformation

# Voronoi Microstructure for Equiaxed Grain Structure









## Maximal Poisson Sampling

- constraint on min. dist.
- seed until 'max' packing
- Ebeida/Mitchell Algorithm (1400)

# RPI Crystal Plasticity Model

Sandia National Laboratories

Dave Littlewood (SNL)

plastic velocity gradient: $$L^p = \sum_{\alpha=1}^{N} \dot{\gamma}^\alpha P^\alpha$$ (sum over slip systems)

Schmid tensor: $$P^\alpha = m^\alpha \otimes n^\alpha$$

slip system slip rates: $$\dot{\gamma}^\alpha = \dot{\gamma}_o \frac{\tau^\alpha}{g^\alpha} \left| \frac{\tau^\alpha}{g^\alpha} \right|^{1/m-1}$$

slip system hardening: $$g = g_o + (g_{so} - g_o) \left[ 1 - \exp\left( - \frac{G_o}{g_{so} - g_o} \gamma \right) \right]$$

$$\gamma = \sum_{s=1}^{N} |\gamma^s|$$

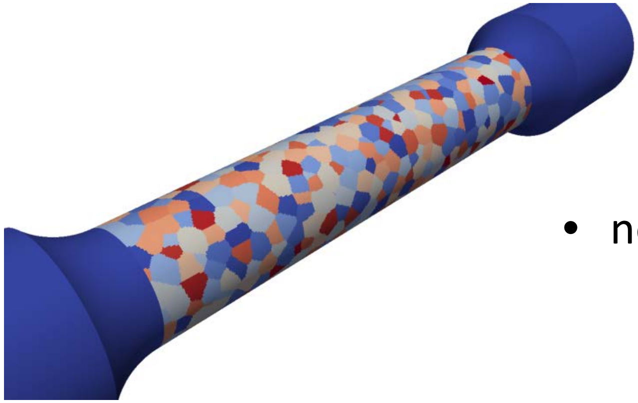
# 304L Single Crystal Elasticity Constants

(Ledbetter, 1984)

single crystal elastic constants (cubic symmetry)

$$C_{11} = 204.6 \ \ \text{GPa}$$
$$C_{12} = 137.7 \ \ \text{GPa}$$
$$C_{44} = 126.2 \ \ \text{GPa}$$

anisotropy ratio, $$A = \frac{2C_{12}}{C_{11} - C_{44}} = 3.5$$



- need to define texture as well