OPPORTUNITIES AND CHALLENGES IN RAPID FLEXIBLE MANUFACTURING

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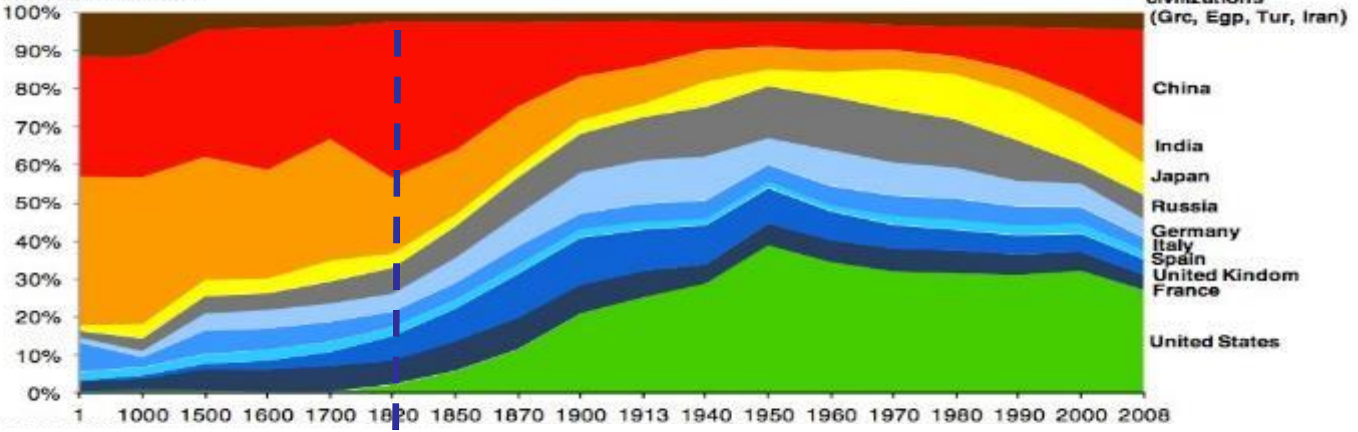
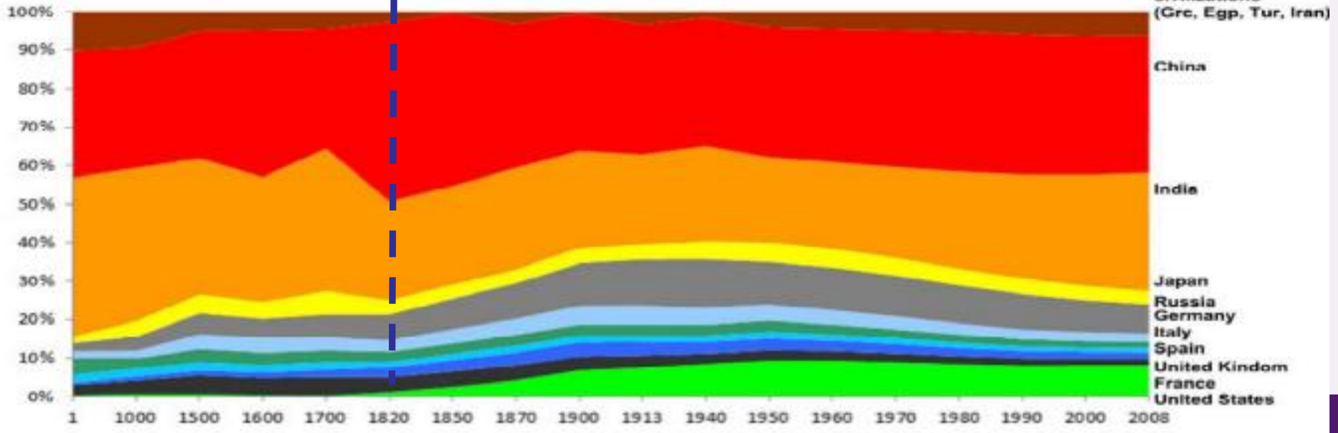
MAUFACTURING & POPULATION

Economic history – Share of world GDP



Population history – Share of world population



Source: "*Historical Statistics of the World Economy:1-2008 AD*", Angus Maddison

MAUFACTURING TREND

TYPE OF MANUFACTURING

DISTRIBUTED	***CONCENTRATED***	***DISTRIBUTED ???***
1800 AD	***2000 AD***	***2100 AD***
Self-reliance	***Reliance on others***	***Self-reliance ???***

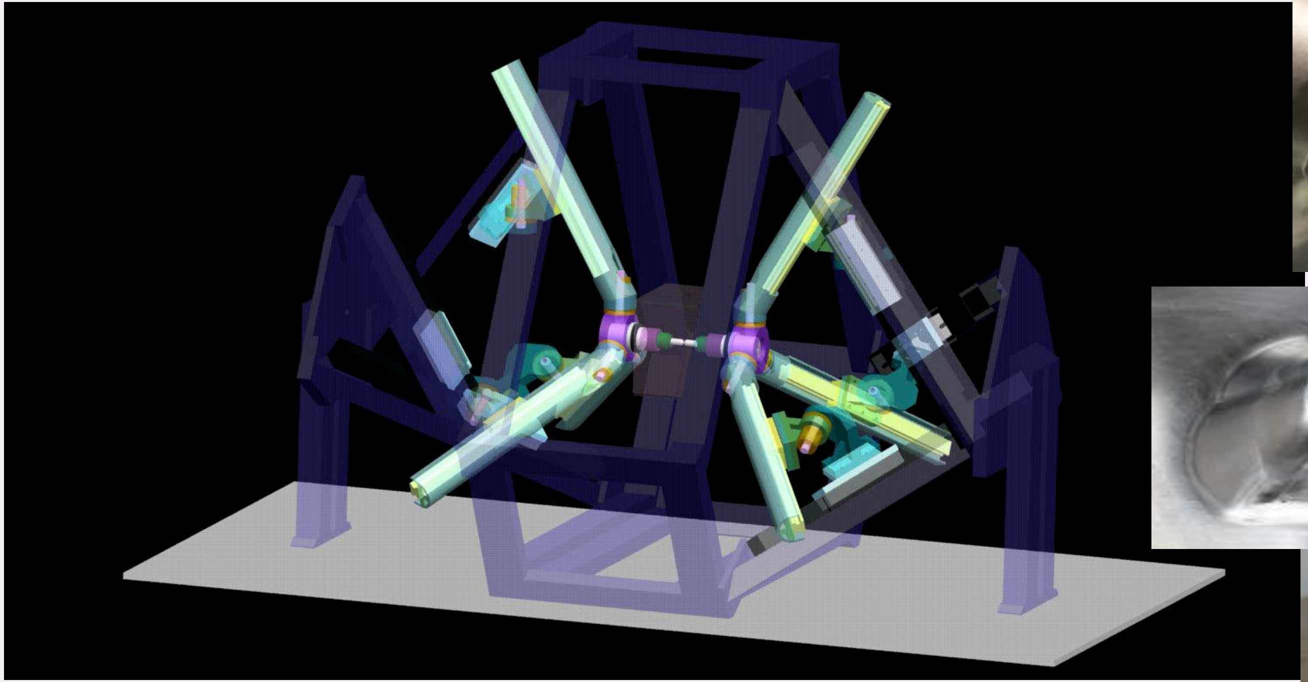
CURRENT FORCES NOW AT WORK

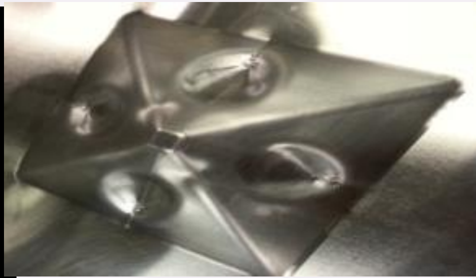
- Globalization
- Cyber Infrastructure
- Technological Advances
- Mass Customization / Personalization
- Emergence of Point-of-use Technologies

→ Rapid Flexible Manufacturing

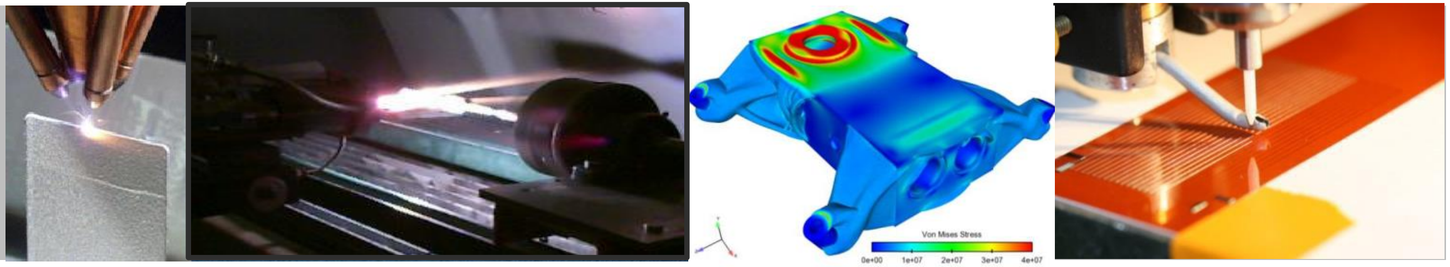
DEFORMABLE PROCESS

Dieless Tri-Pyramid Robots for Rapid Forming





ADDITIVE PROCESSES



Predictive Theory and Computational Approaches for Additive Manufacturing

Justine Johannes

Engineering Sciences Director , Sandia National Laboratories

Contributors: Mark Smith, Tony Geller, Arthur Brown, Mario Martinez, Joe Bishop, Ben Reedlunn, David Adams, Jay Carroll, Mike Maguire, Bo Song, Jack Wise, Brad Boyce,

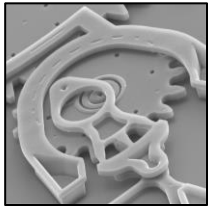
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP

30+ yrs of Sandia Additive Manufacturing Technology Development & Commercialization

Sandia National Laboratories

*FastCast**
Development

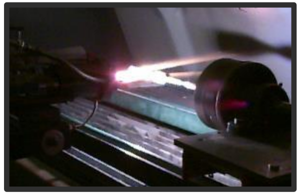
*MEMS SUMMIT™ **
Micro gear assembly



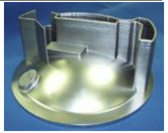
Sandia Hand
50% AM built

LIGA
"Hurricane" spring

Spray Forming
Rocket nozzle

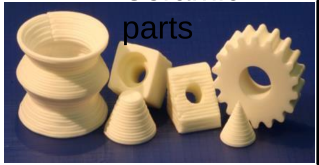


*LENS®**
Stainless housing



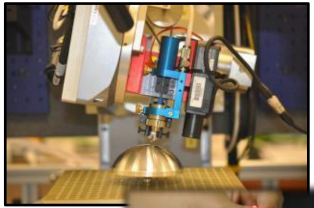
*RoboCast**

Ceramic parts



Energetic

Direct Write
Conformal electronics



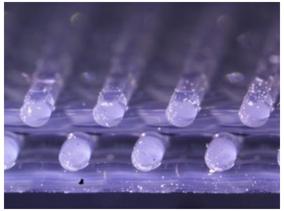
Printed battery

* Licensed/Commercialized Sandia AM technologies

Current Capability/Activity

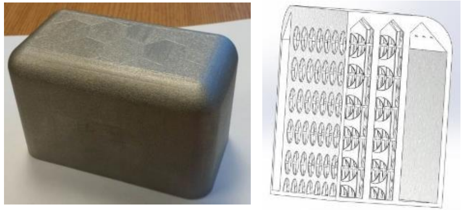
Drivers for AM for National Security Applications

- Potential Cost/Schedule/Design/Risk Benefits
- Optimize for Performance, Not Machinability
  - Revolutionary new design possibilities
  - Engineering analysis driven designs
- Engineered Materials
  - Multi-material and graded material parts
  - Future potential for microstructural control?



pad side view

Sandia Mass Mock



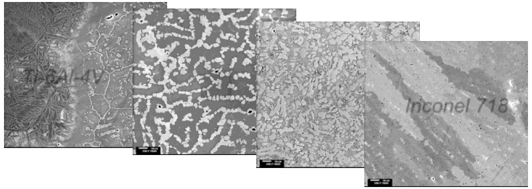
Easily customize weight, center of gravity, moment of inertia

GE Additive Manufacturing Design Competition

Original Design 4.5 lb.

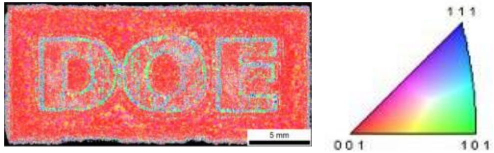
AM Design 0.7 lb.
- 84% wt. reduction
- Successful load tests

Sandia LENS® Functionally Graded Materials



Inconel 718

AM Inconel 718 Crystallographic Orientation Control Demo'd at ORNL



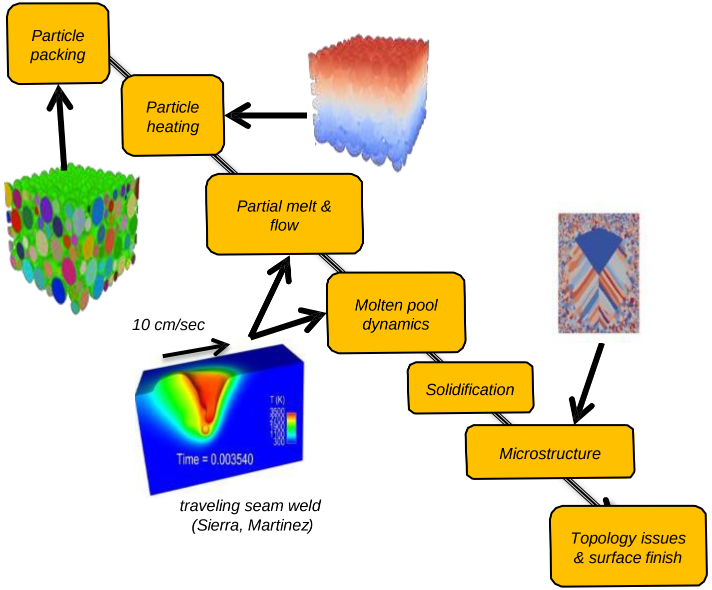
"We can now control local material properties, which will change the future of how we engineer metallic components," R. Dehoff

Enabling Design through Computational Simulation

Process → Microstructure → Properties → Performance Relationships

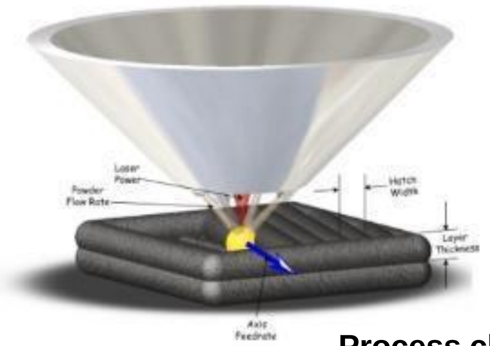
Key Advancements Needed

- Improved fundamental understanding of AM process to macroscale properties
- Predict response from knowledge and control of microscale process
- Constitutive model advancement
- Predict response from stochastic process knowledge leading to quantified performance uncertainty
- Topology optimization driven by advance computational approached, coupled with in-situ metrology, to modernize design



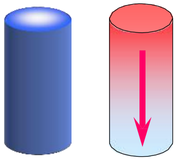
Predictive tools and approaches opportunity for innovation

Exemplar of Materials and Computational Challenges



Lens Process

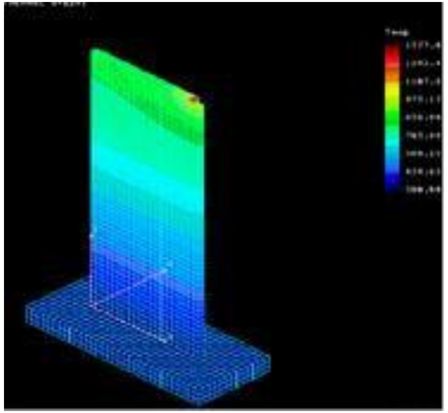
- Fully dense metal
- Good mechanical properties
- Graded materials
- Add to exiting parts

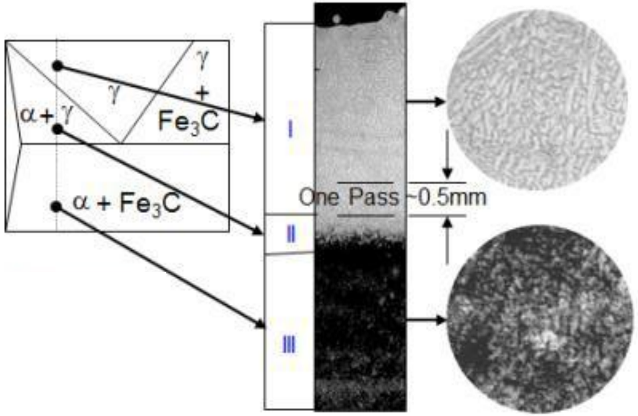


Uni-directional Solidification

- Built narrow "wires" to achieve 1-D heat flow to simplify & understand solidification front
- Simplified comparison with model predictions

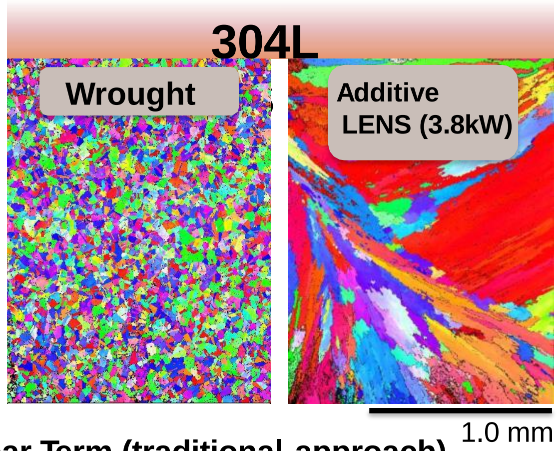
Process characterization/modeling

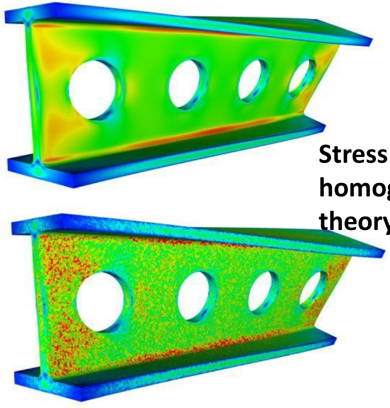




Part heats up during the build & heat flow changes -- so microstructure & properties in the top (I), middle (II), & base (III) may differ

AM Materials Are Unlike Conventional Mat’ls





Stress field using homogenization theory

Near Term (traditional approach)

- Property measurements
- Microstructure/defect analyses
- H_2 compatibility/permeability
- Statistical variability analyses
- Effects of post treatments
- …

Future State (predictive modeling w QMU)

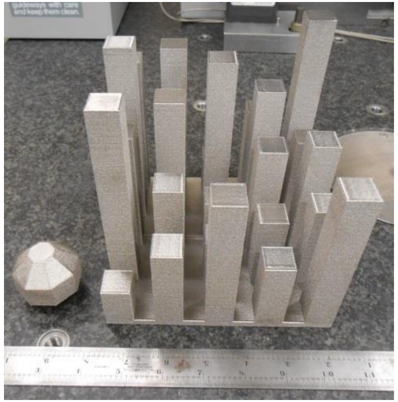
- Establish microstructure-properties-performance relationships
- Multi-scale modeling/validation
    - Poly-crystal plasticity models
    - Direct numerical simulation
    - …

Engineered Materials Reliability (EMR) Research Opportunity: *Develop a framework for understanding how material variability impacts the reliability of engineered products through the use of multi-scale computational and experimental approaches that account for variability across length scales and provide probabilistic predictions of product performance.*

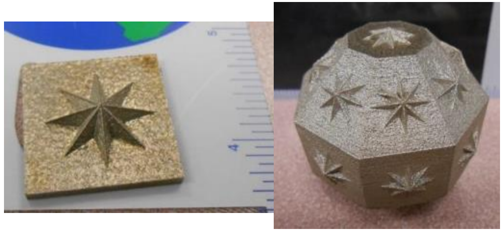
Metrology for AM Is Also A Key Challenge

Sandia National Laboratories

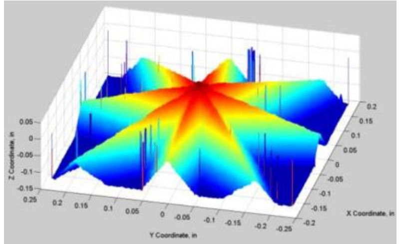
- Family of artifacts designed, 3D printed, & measured
  - Opportunity to develop better AM metrology artifacts
- Unique challenges for process/equip. characterization
  - Tolerance/Surface Finish/Properties vary with machine, material, print orientation, support structures, post-processing,…)

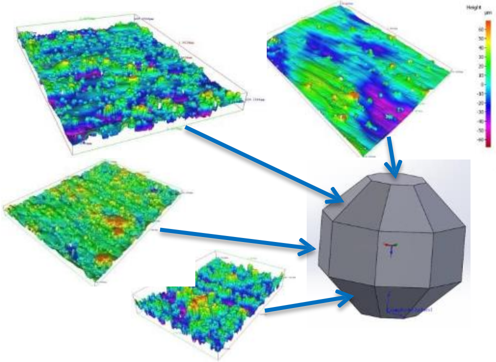


Ti-6Al-4V polyhedron & "Manhattan" artifacts for MPE (maximum permissible error)

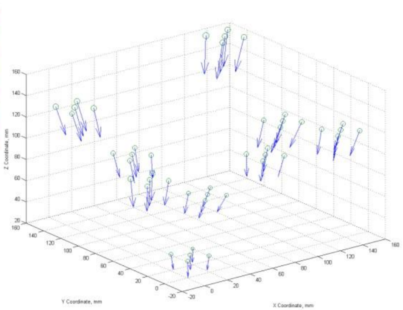


Siemens star geometries for resolution evaluation





17-4PH polyhedron texture anisotropy map

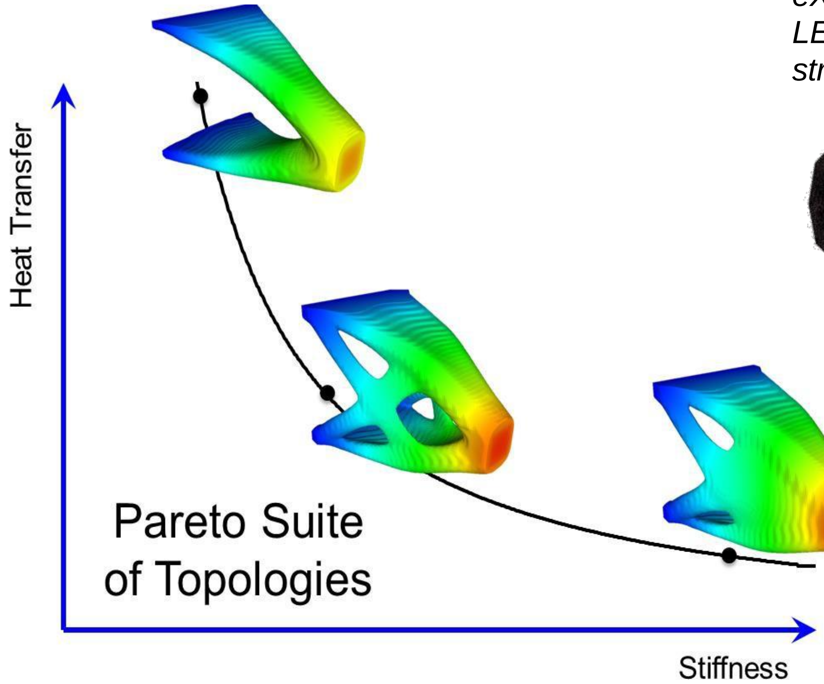


Ti "Manhattan" error map

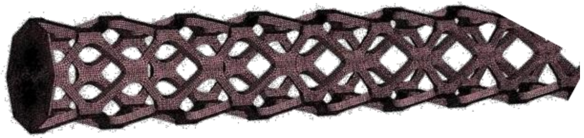
Analysis-Driven Design Optimization

Critical to Advance Fundamental Understanding along with Computational Approaches

AM Design Via Functionality Prioritization

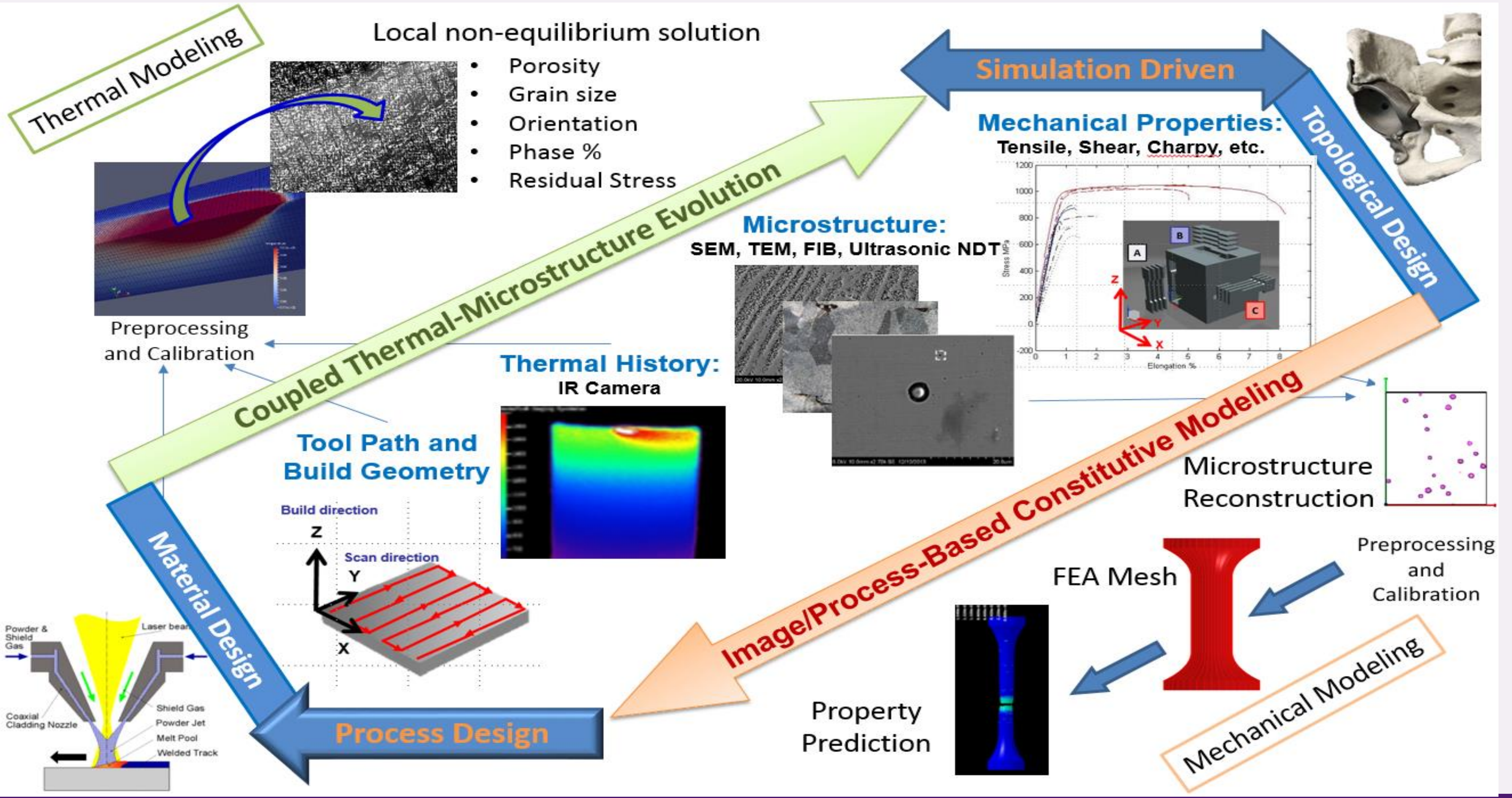


We combined Topological Optimization (TO) with eXtended Finite Element Modeling (X-FEM) & LENS® to optimize selected properties, e.g., strength/weight ratio.

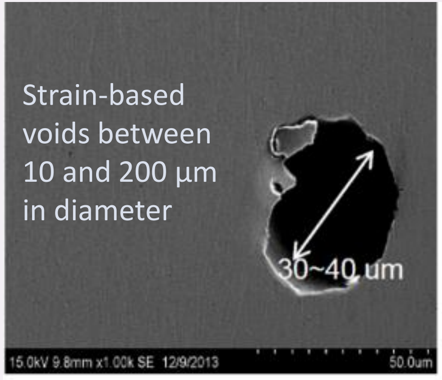


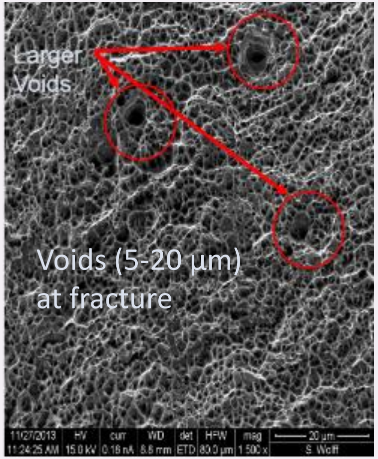
Core of a dead Cholla cactus. It is interesting that optimized designs often resemble natural structures (bio-mimicry).

INTEGRATION



Stainless Steel 316L (LENS)

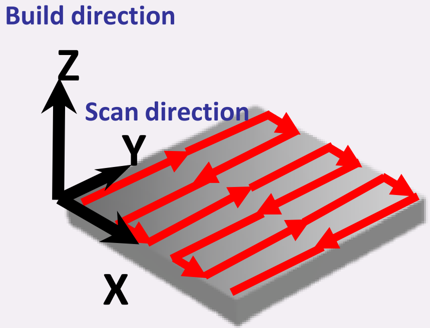


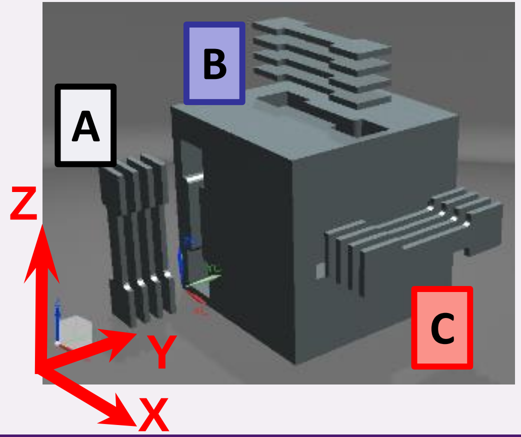


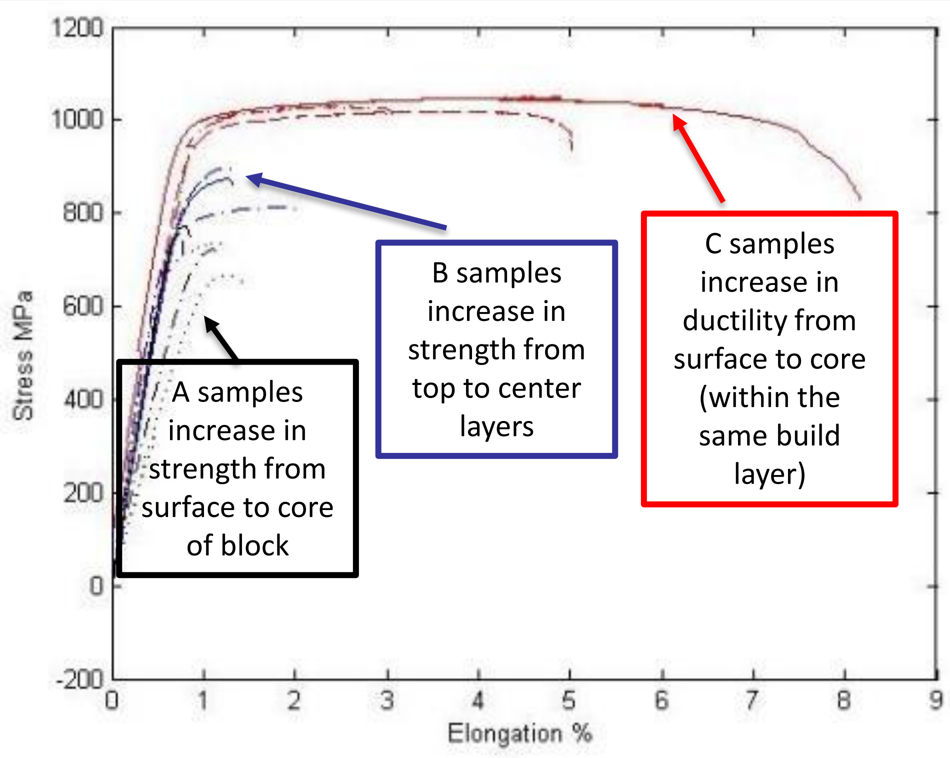
- Strain-based voids due to lack of fusion of powders
- Stress-based oxides due to the entrapped gas
- Fracture surfaces reveal coalesced large voids and increased average concentration of oxygen

NON-UIFORMITY

Ti-6Al-4V Mechanical Testing

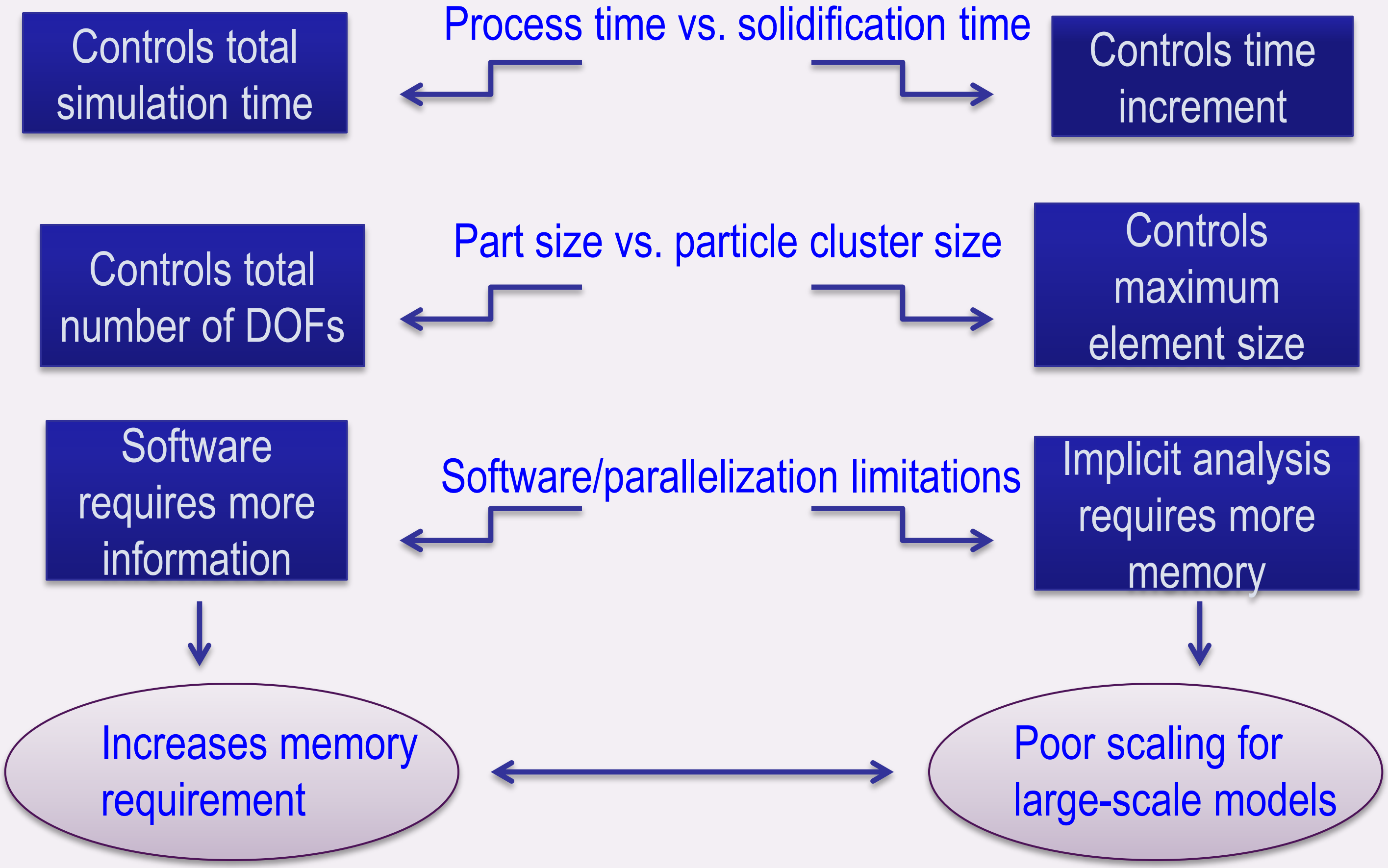






Wolff et al., RAPID 2015
ampl.mech.northwestern.edu

HPC CHALLENGES

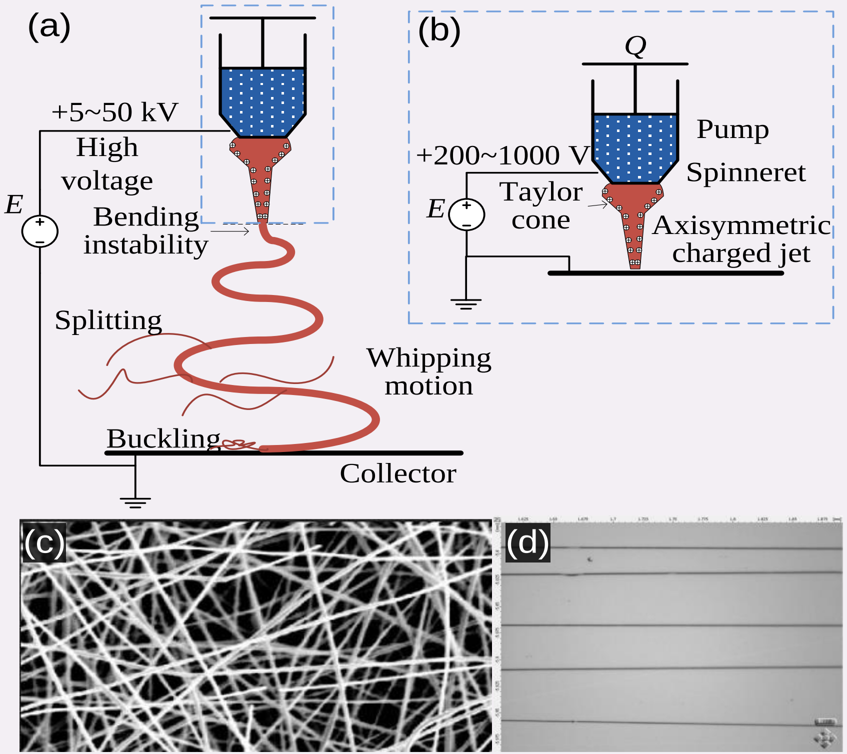


Comparison w/ Abaqus Solution

Quantity of Interest		Abaqus	In-House Code
Peak Temp (℃)	Min	1126	1150
	Max	1433	1384
	Diff	307	234
	Avg	1280	1267
Temperature Resolution (℃)		110	5
Solution Steps		301	5556
Computation Time (s)		39.0	2.08

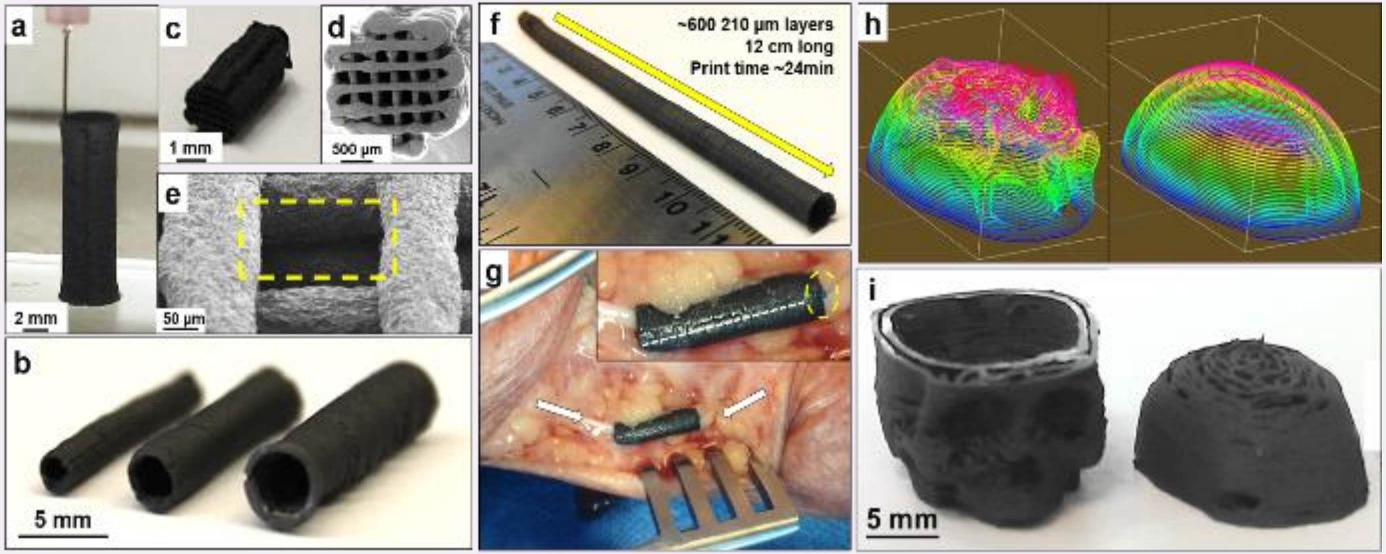
Smith, J., Liu, W.K., and Cao, J.

Electrospinning



Schematics illustration of
(a) far-field electrospinning
(b) Near-field electrowriting processes, which produce
(c) random [adapted from *Science*, **2004**], and
(d) aligned nanofibers [Xu et al. 2014, ICOMM]

Conductive Bioscaffolds

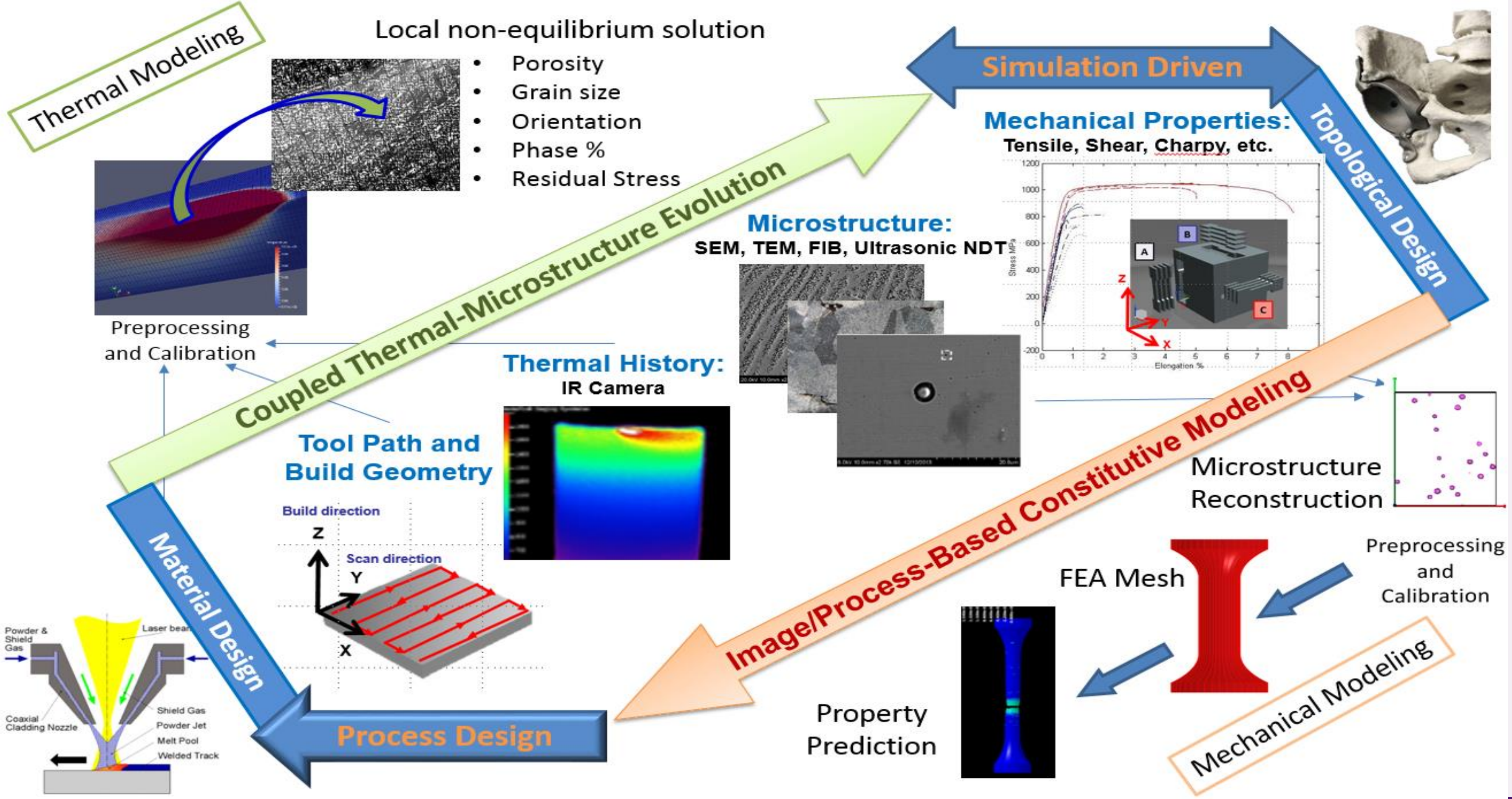


High-content (60 vol%) graphene inks can be 3D printed into self-supporting, electrically conductive, and mechanically resilient structures (e.g., implantable tubular nerve conduits)

Hersam & Shah
ACS Nano, in press, 2015

What can the computational mechanics community contribute for additive manufacturing (rapid flexible manufacturing, distributed manufacturing)?

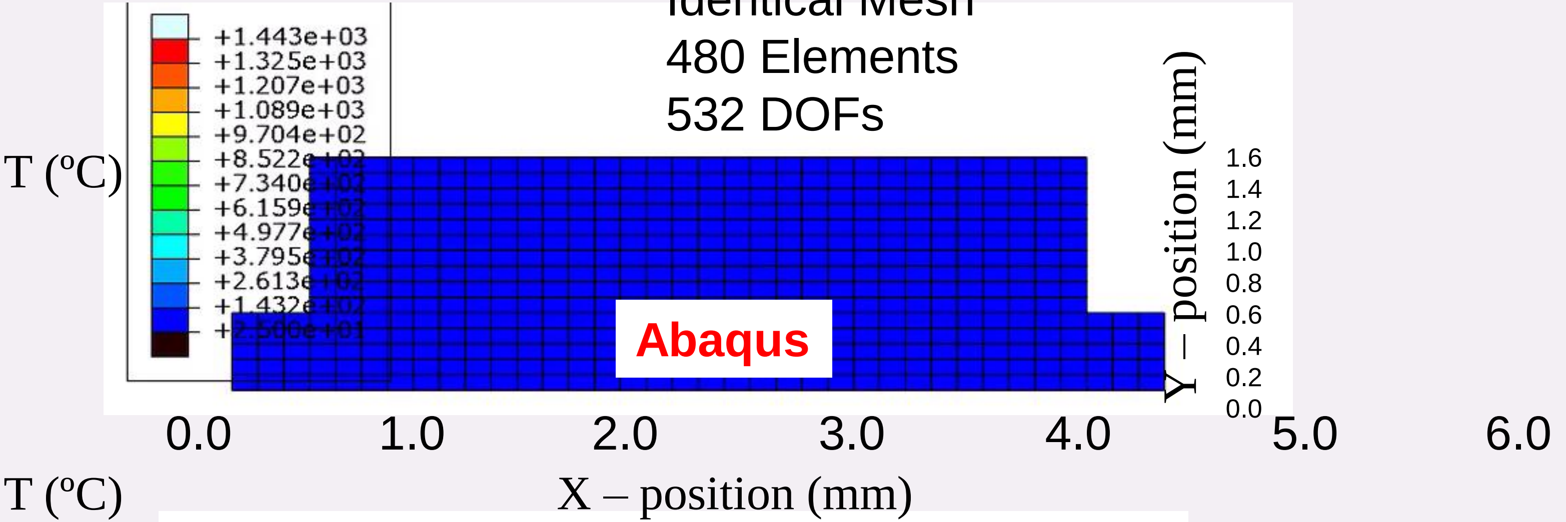
INTEGRATION

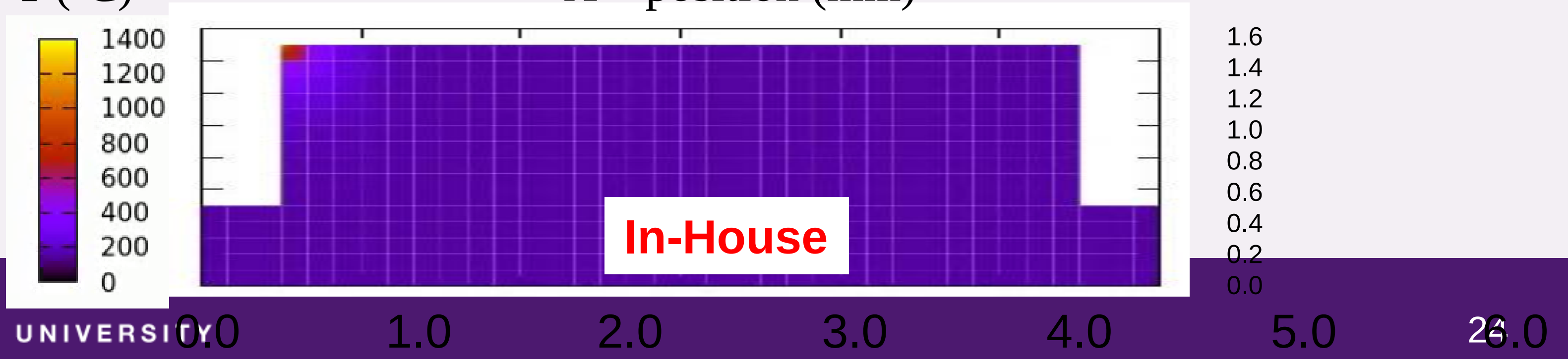


Backup Slides

AM Verification

Identical Mesh
480 Elements
532 DOFs



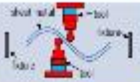


DSIF - Flexible Forming

LOW VOLUME SHEET METAL PRODUCTION

AEROSPACE PRODUCTION

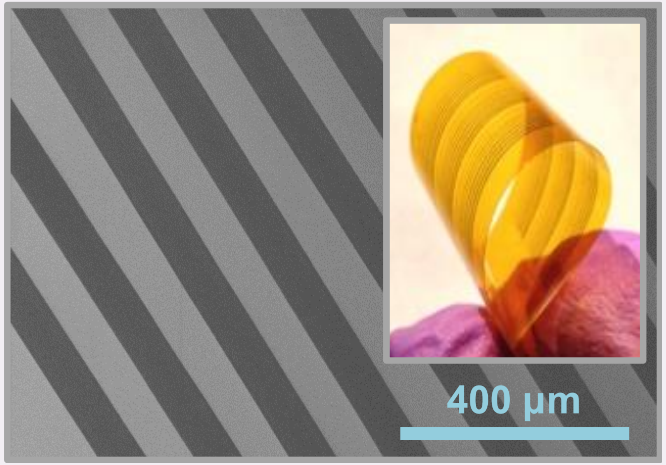
AUTOMOTIVE DESIGN & PROTOTYPING

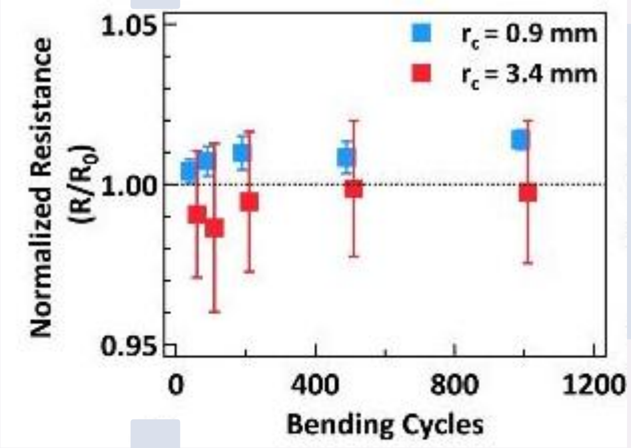
	TRADITIONAL PROCESSES	DSIF
		
TOOLING COST	$100K - $1M	NEGLIGIBLE
DESIGN TO PRODUCTION	8 – 15 WEEKS	< 1 WEEK
FACILITY SIZE & COMPLEXITY	HIGH	LOW
TOOLING STORAGE	REQUIRED	NONE
MATERIAL CHOICE	LIMITED	BROAD

Inkjet Printable Graphene for Flexible Interconnects

Journal of Physical Chemistry Letters, **4**, 1347 (2013).

Available from Sigma-Aldrich: Catalog # 793663



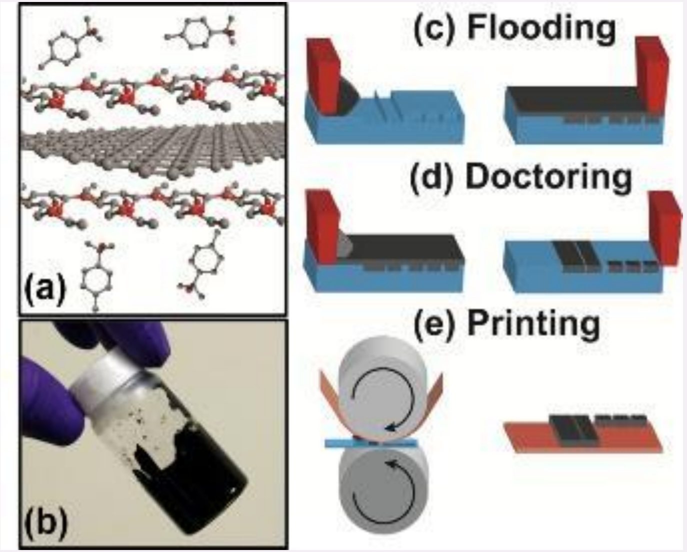


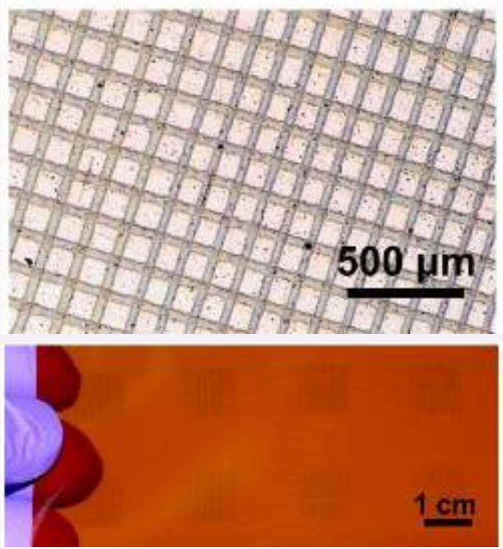
- **Inkjet printable graphene based on ethyl cellulose stabilizer in terpineol.**
- **Low resistivity of 4 mΩ-cm maintained following repeated flexing and even folding.**

Large-Area Gravure Printable Graphene

Advanced Materials, **26**, 4533 (2014).

Collaboration with Lorraine Francis and Dan Frisbie (Minnesota)



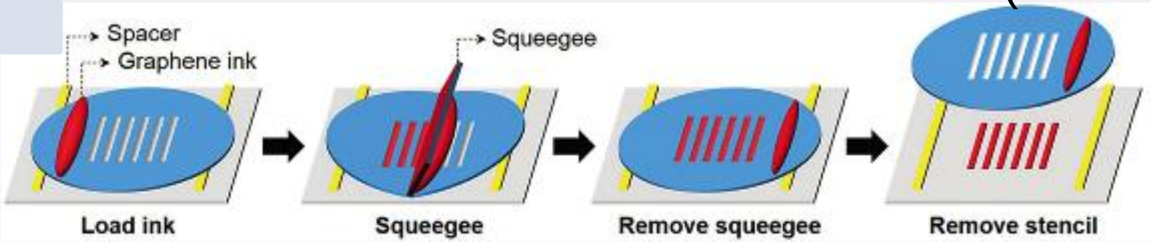


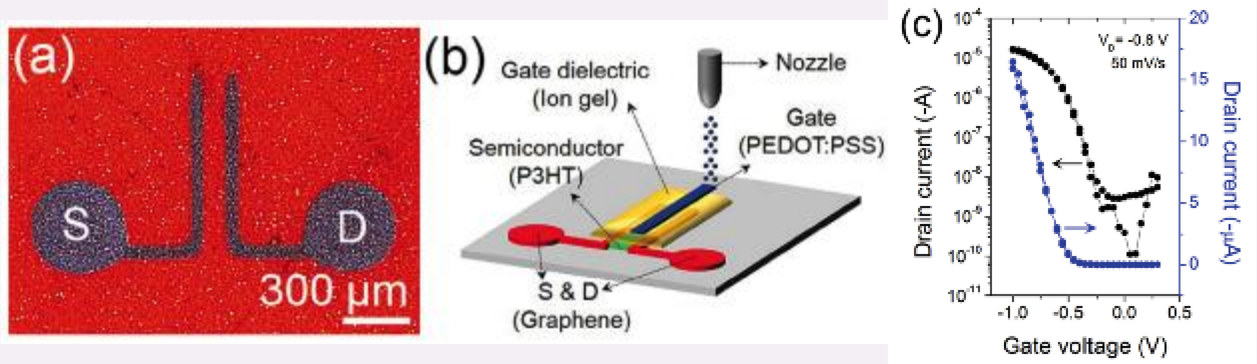
Ethyl cellulose stabilizer allows viscosity tuning over multiple orders of magnitude, enabling compatibility with a diverse range of printing methods

Screen Printable Graphene for Flexible Electronics

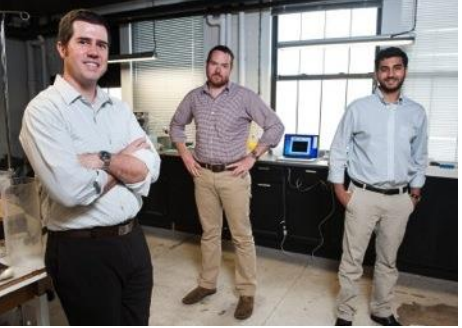
Advanced Materials, **27**, 109 (2015).

Collaboration with Lorraine Francis and Dan Frisbie (Minnesota)

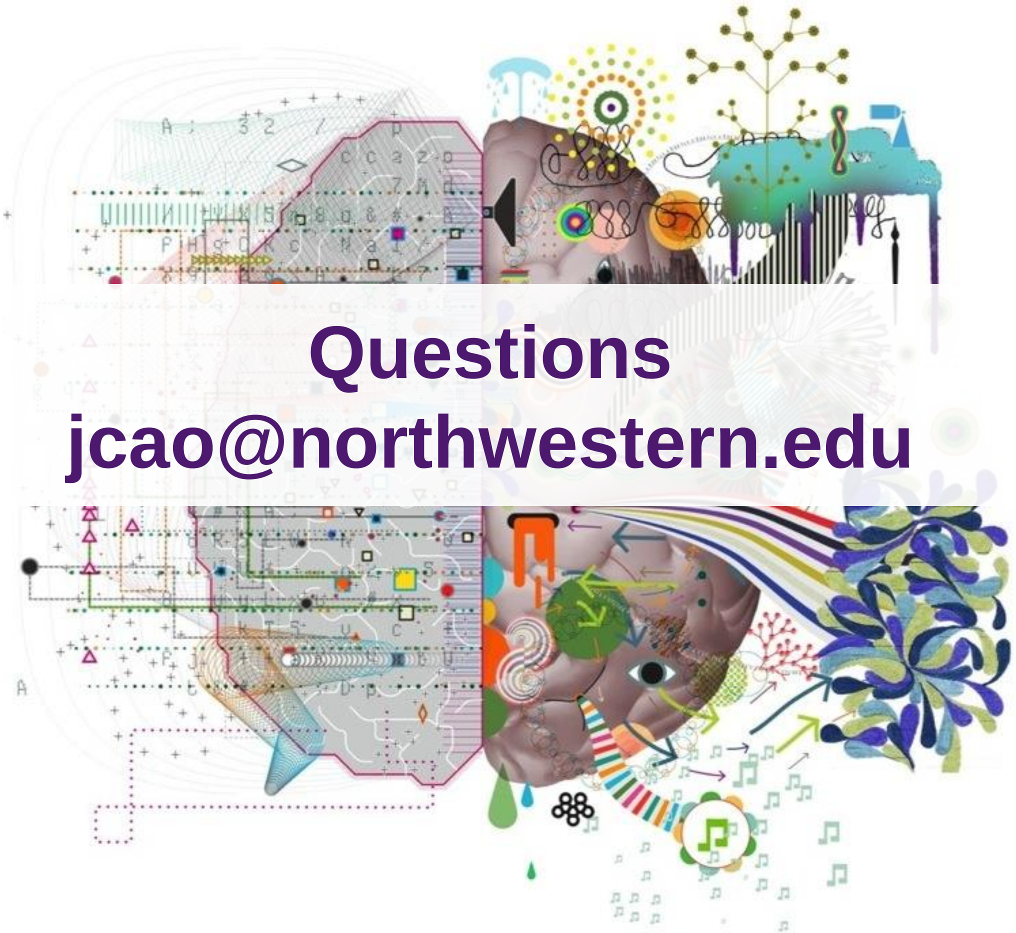




Screen printable graphene is compatible with other materials that are commonly employed in printed/flexible electronics







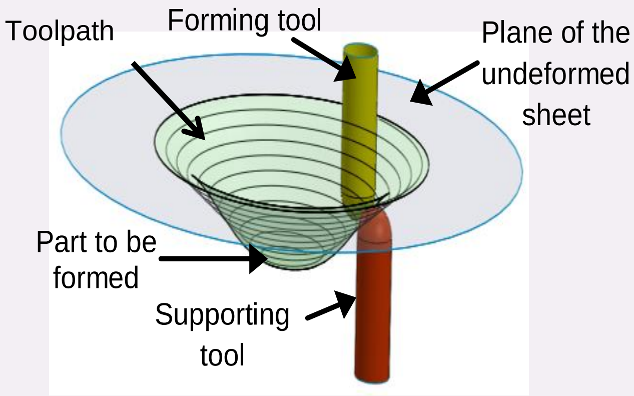
Questions

jcao@northwestern.edu





Double Sided Incremental Forming: DSIF



- DSIF uses two tools, one on each side, of a peripherally clamped sheet metal to locally deform the sheet along a predefined toolpath

- The sum total of the local deformations adds up to result in a final formed part

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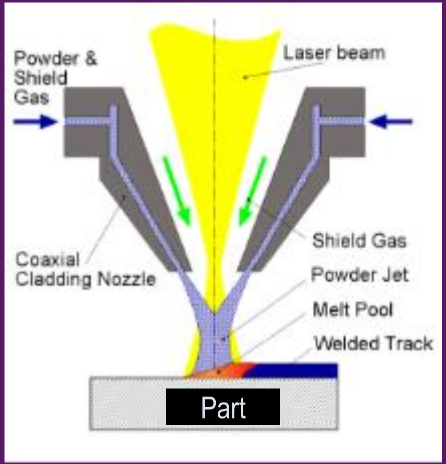


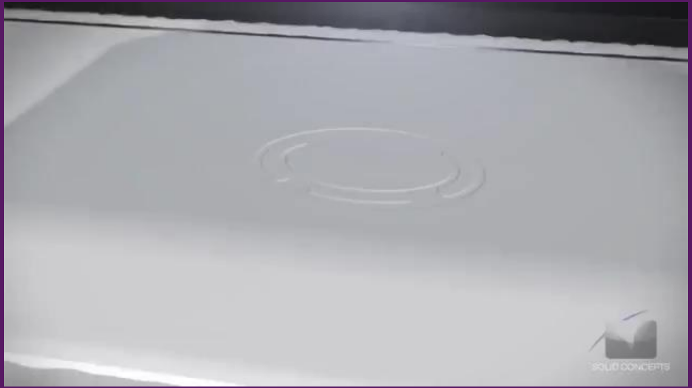
Advantages

- Build fully dense shapes
- Closed-loop, four-axis control
- Customizable process parameters for speed, accuracy and property control
- Wide variety of materials, composite deposition

Disadvantages

- Poor resolution and surface roughness
- Long build times
- High laser power required

Powder Bed



Advantages

- Repeatable process control
- Build complex shapes

Disadvantages

- Expensive and time-consuming post-processing
- Long pre-heat and cool-down cycles
- Contamination of previous molten layer by environment
- Supports required to prevent warping
- Uneven deposition and balling due to gradients in surface tension on powders

3

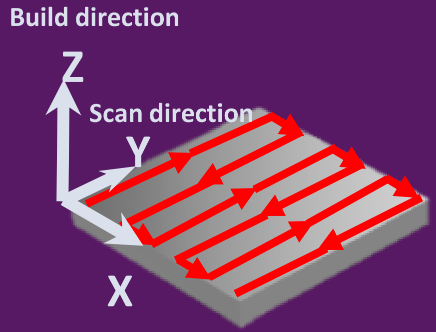
Ti-6Al-4V Porosity and Mechanical Properties

Specimen	Laser Power (W)	Laser Beam Diameter (mm)	Hatch spacing (mm)	Layer Thickness (mm)	Elastic Modules (GPa)	Ultimate Tensile Strength (MPa)	Elongation at Break (%)	Bulk Porosity %
ASM Grade 5 Ti-6Al-4V, annealed [1]	-	-	-	-	114	950	15	-
Best reported study [2]	2000	4.0	2.29	0.89	-	1087	10	-
Set A (avg)	800	1.8	1.25	0.95	116	725	0.9	2.2
Set B (avg)					109	820	1.7	2.7
Set C (avg)					144	1015	6.0	2.0

- Increased mechanical strength in the C orientation
- No heat treatment or additional post-processing done on the LENS cube
- hot isotatic pressed (HIP-ed) component testing is ongoing

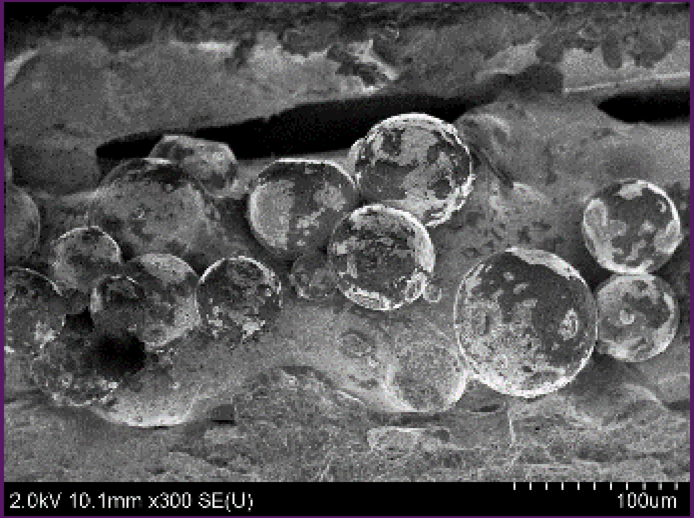
[1]Boyer, R., et al. (1994), Material Properties Handbook: Titanium Alloys, *ASM International.*
[2] Carroll, B. E., et al. (2015), *Acta Materialia*, 87, 309-320.

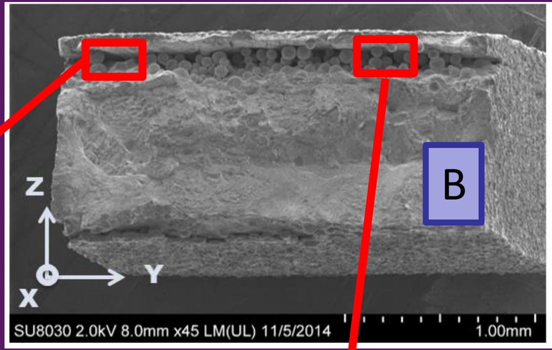
LENS Surface Finish



- Resolution is usually not better than 0.25 mm and surface roughness more than than 25 microns
- Cannot produce as complex of structures as powder bed fusion processes such as selective laser sintering (SLS)

Ti-6Al-4V Fractography

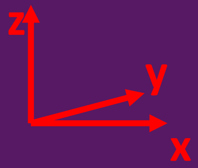




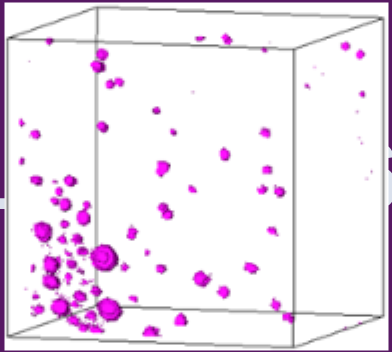
Areas of unmelted powders (45-150 µm) also show higher oxide concentrations – these can be avoided by optimizing the relationships between hatch spacing, layer thickness, laser power and scan speed

$$E_d = \frac{P}{v \cdot d}\left[\frac{J}{mm^2}\right]$$

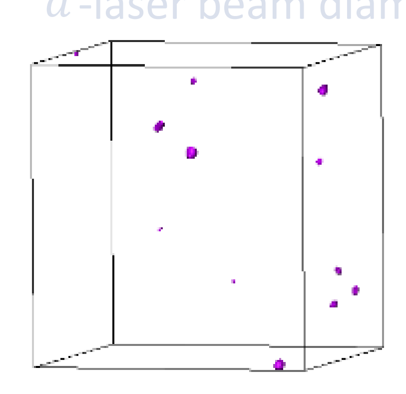
P -laser power (W)
v -scan speed (mm/s)
d -laser beam diameter (mm)



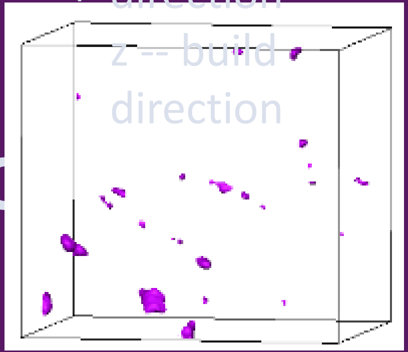
y -- scan direction
z -- build direction



E_d: 20 J/mm^2

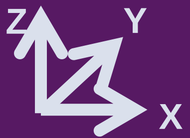


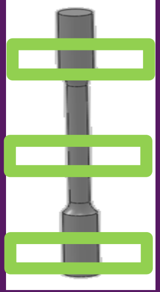
E_d : 40 J/mm^2



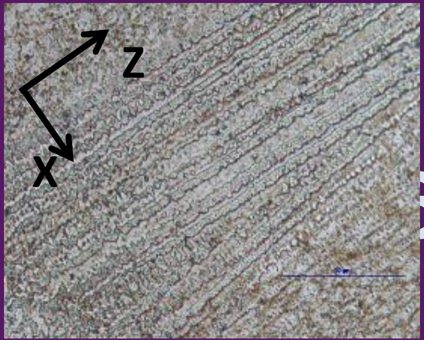
E_d : 50 J/mm^2

- Focused Ion Beam (FIB) takes 2D thin slices to create 3D tomography images and captures micro-pores about a micron or less in diameter
- Micro-pores coalesce to failure; images are provided to mechanical models to simulate uniaxial tensile tests

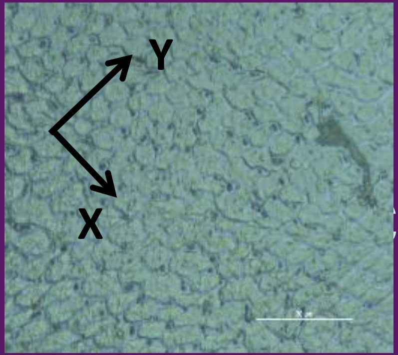




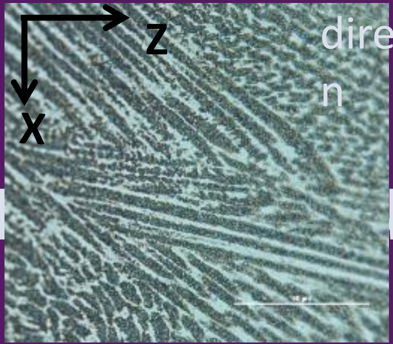
y -- scan directio n
z -- build directio n



Bottom of a part, 50X magnification, (50µm scale bar)



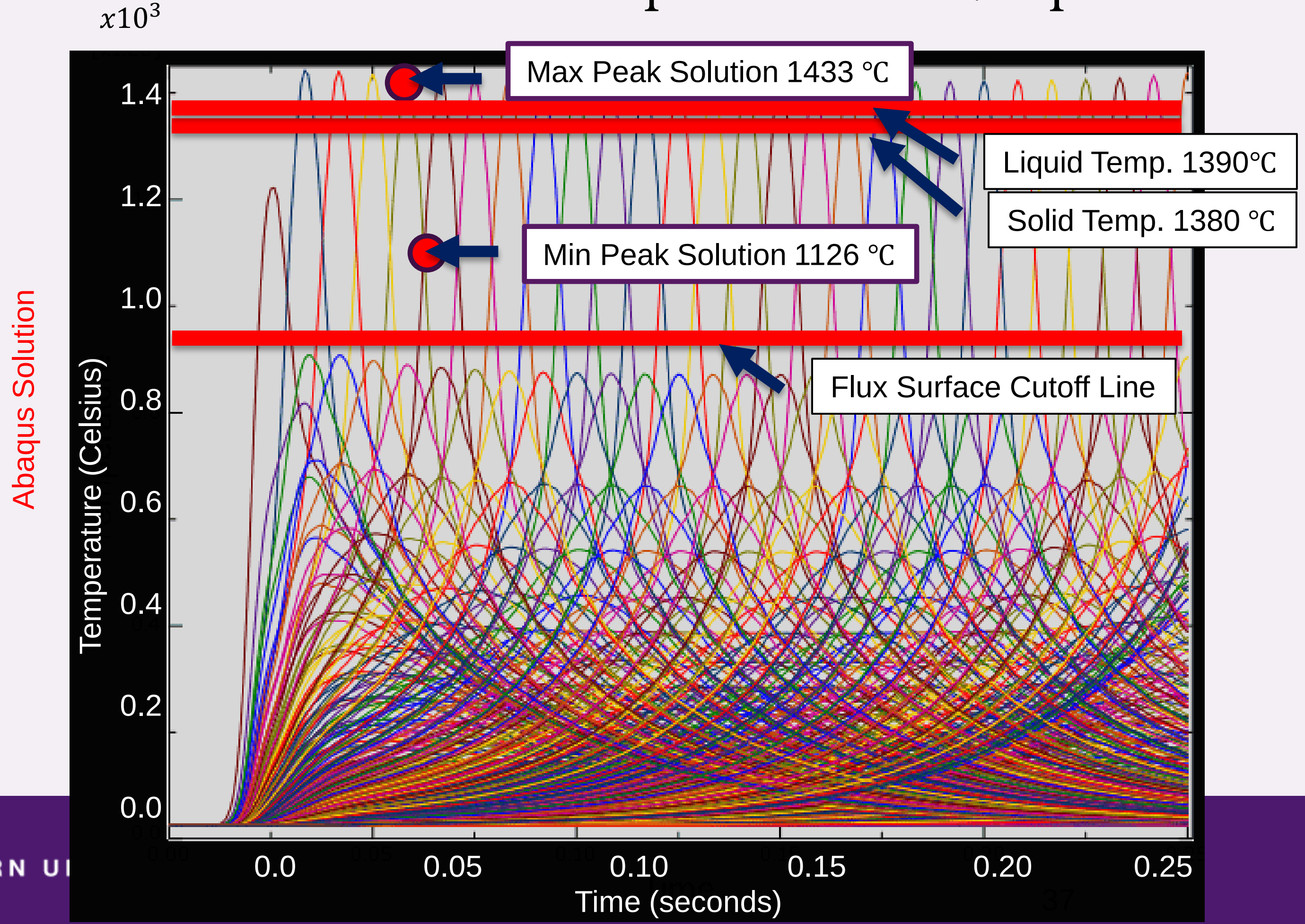
Center of a part, 100X magnification, (20µm scale bar)



Top of a part, 50X magnification, (50µm scale bar)

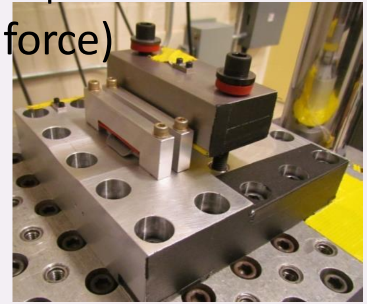
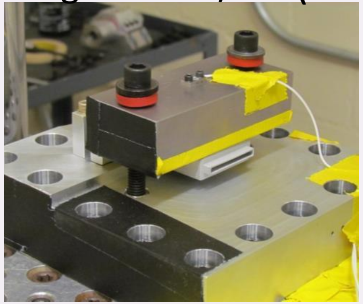
- More lamellar-like structures at bottom of the XZ plane due to high cooling rate (showing multiple layers)
- Cellular structures at the XY plane (showing a single layer) – showing low thermal gradient within a layer

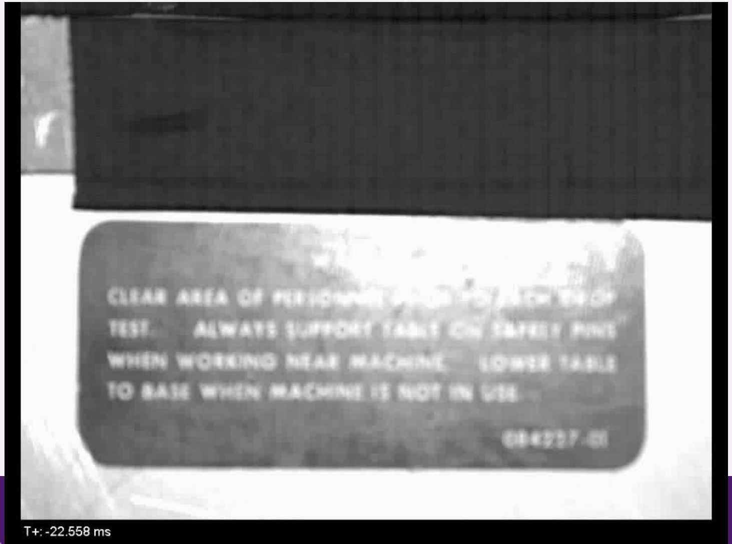
Comparison w/ Abaqus



Superior Impact Performance

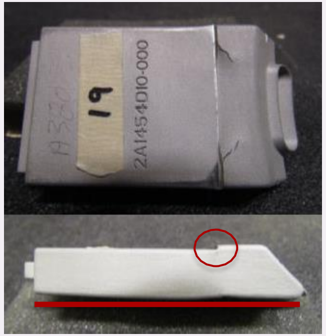
Impact Tests of 3 Al housings at 32 ft/sec (3500 lb. impact force)



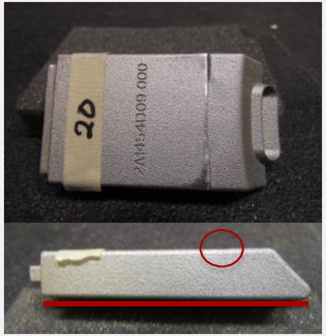
Cast, A380
1 pc, 38 g

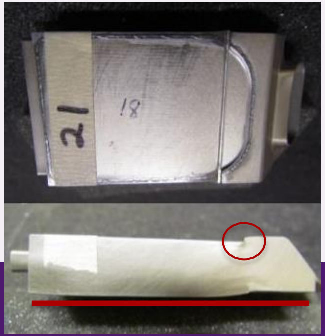
- cracked
- buckled



AM, AlSi10Mg
1 pc, 38 g

- slight indent
- still straight
- best result



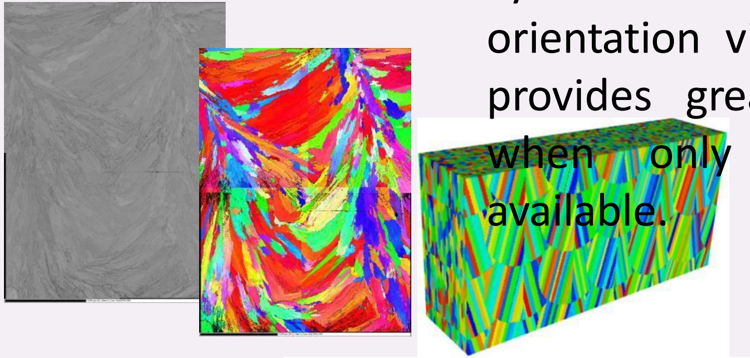


Machined

Modeling Microstructure & Behavior

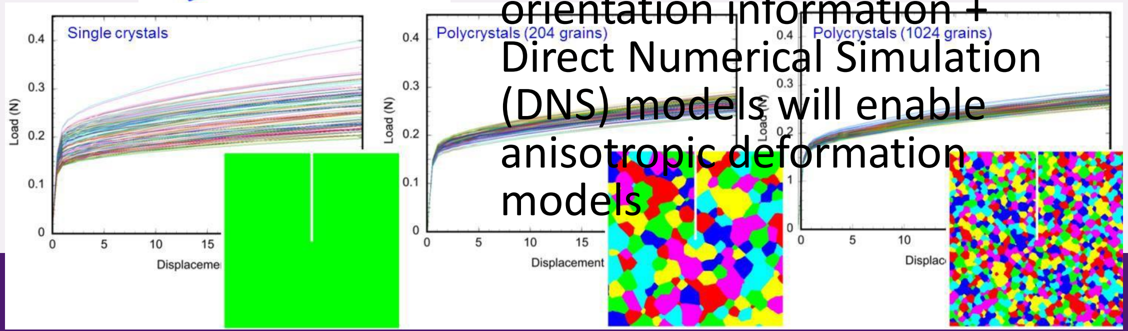
Goal: Incorporate material variability in a predictive and probabilistic manner to optimize performance and determine margins

Systematic sampling of grain structure and orientation via modeling and simulations provides greater confidence of margins when only limited experiments are available.



LENS® microstructure with orientation information + Direct Numerical Simulation (DNS) models will enable anisotropic deformation models

Grain size impacts the uncertainty margins of properties and performance.



Brad Boyce