SAND2016-10882PE

Exceptional service in the national interest

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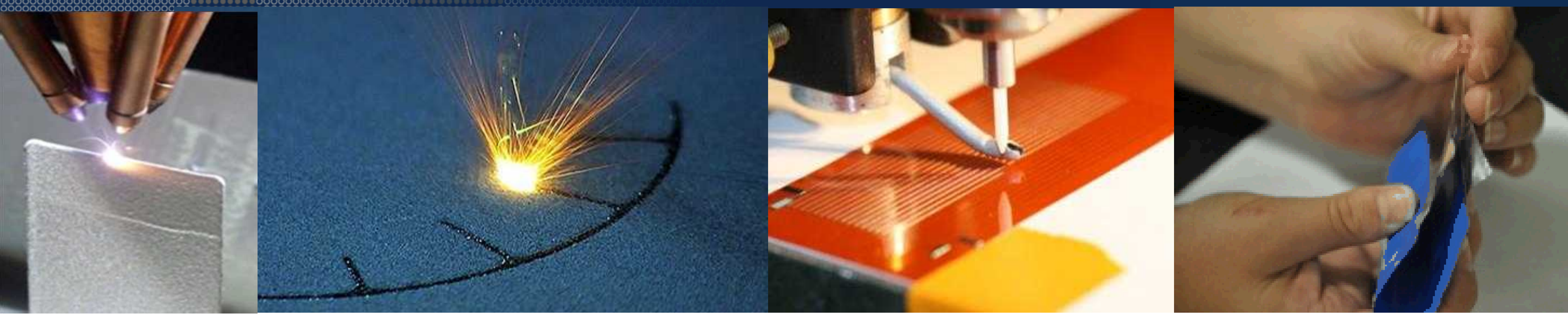

Additive Manufacturing at Sandia

Mark F. Smith
Materials Science & Engineering Center

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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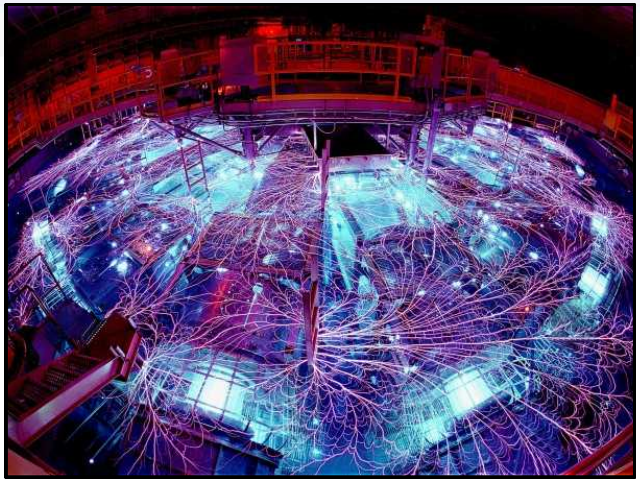
Sandia is a National Security Science and Engineering Laboratory

Weapon Drop Test



Energy R&D

Threat Test

- Historical mission -- non-nuclear components in nuclear weapons and nuclear weapon security
- Today, broader mission in science & engineering for U.S. national security

> *"We work on technologies at a scientific lab, but we must emphasize that science is not an end. The end is solving problems for the nation. Science is perhaps the best tool to achieve that end."*
> C. Paul Robinson, SNL President 1995-2005

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Materials Science at Sandia

Materials Science Objective: Materials R&D conducted at Sandia will enable mission delivery now and in the future and advance the frontiers of science and engineering.

Three Major Areas of Materials R&D

- *Materials Engineering Support*
  - Problem solving, program support
  - Application of existing expertise
  - Point solutions
- *Materials & Process Advanced Development*
  - Advanced & exploratory materials & process development
  - Production process development & technology transfer
  - Understanding the margins
- *Fundamental Materials & Process Science*
  - Develop/integrate theoretical insights, computational simulation tools, and experiments to provide foundational, predictive understanding
  - Develop innovative new materials and process technologies
  - Created advanced materials analysis & process diagnostics tools

Center for Integrated Nano Technologies
Adv. Materials & Processes Lab
Ion Beam Lab
Advanced Materials Lab
Processing & Environmental Tech. Lab
Integrated Materials Research Lab
Thermal Spray Research Lab

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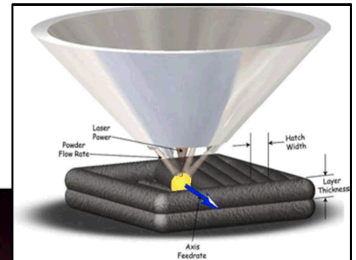
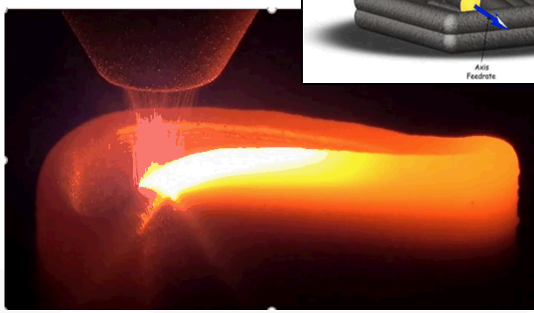
30+ Years of AM Technology Development and Commercialization

FastCast *
Development Housing

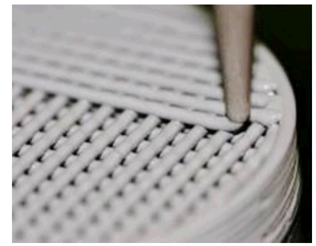
Laser Engineered Net Shaping *
LENS®

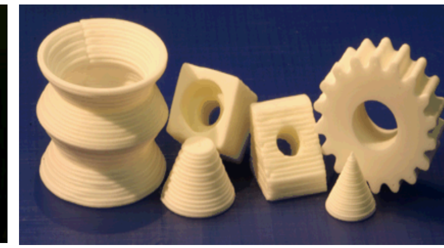


LENS Blade



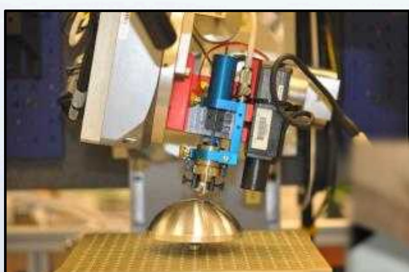
RoboCast *
Ceramic Parts





Energetic Materials

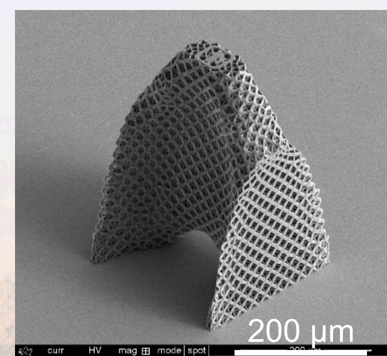
Direct Write
Conformal Electronics



Printed Battery

Spray Forming
Rocket Nozzle

Micro-Nano Scale AM
Lattice Structure



* = Licensed/Commercialized Sandia AM technologies
Underline = Current Capability/Activity

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Example Applications

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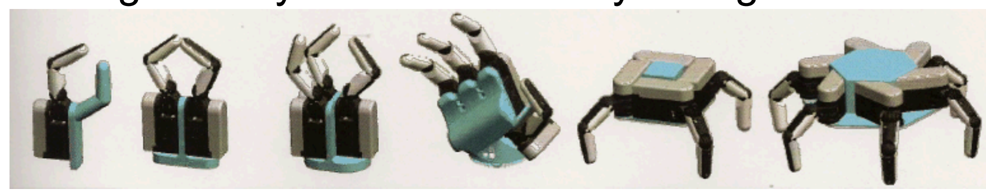
Sandia Hand – AM Enabled Innovative Design and Cost Reduction

(~<u>50% of hand built with AM</u>)

- Developed for bomb disablement
- Enabled rapid design iterations
- Cost $10k vs. ~$250k
- “Glove” controller
- Current version includes “touch” sensors

Fingers or other tools (e.g., drills) can be quickly magnetically attached in many configurations



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BaD_X Anthrax Diagnostics Tool

- Microfluidic platform for bacterial detection
- Self-contained, credit card-sized "Laboratory in a Pocket"
- 3D printed cap
  - Specialized geometry
  - Low cost, quick turnaround

3D Printed Cap/Seal

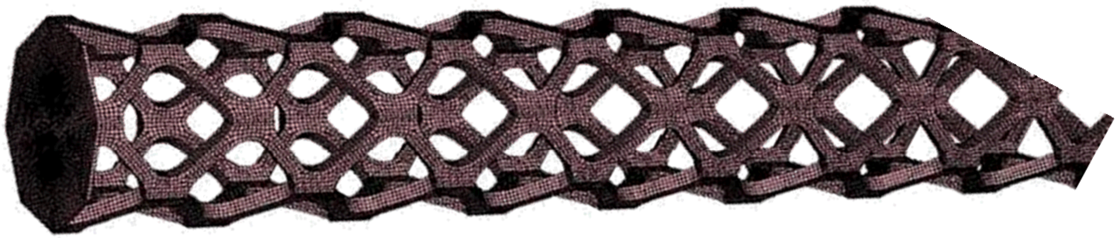
† Edwards *et al*. *Biomicrofluidics* **2011**, *5*, 044115.

Design/Analysis Tools

Analysis-Driven Design Optimization

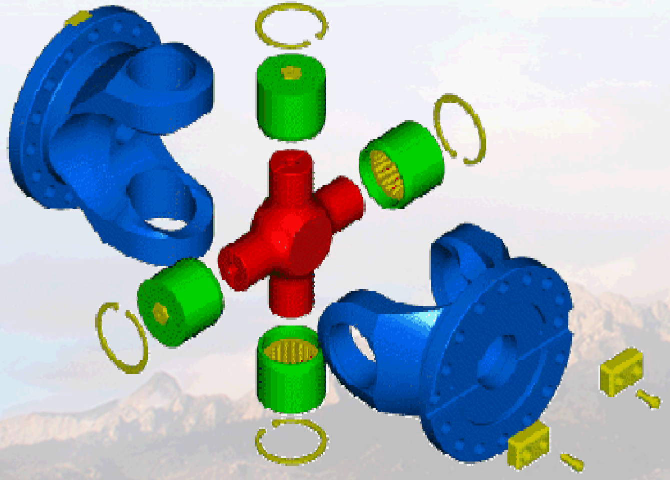
We combined Topological Optimization (TO) with eXtended Finite Element Modeling (X-FEM) & LENS® to optimize selected properties, e.g., strength/weight ratio

"Titanium Cholla" LDRD -- Minimum Weight, Maximum Strength, Rapidly Manufactured!



With AM it is faster and cheaper to build this optimized shaft than a solid shaft!

Core of a dead Cholla cactus (optimized designs often resemble natural structures -- bio-mimicry)



"Loxosphere" Universal Joint printed as a single integrated assembly –fewer parts, no assembly, no frictional wear!

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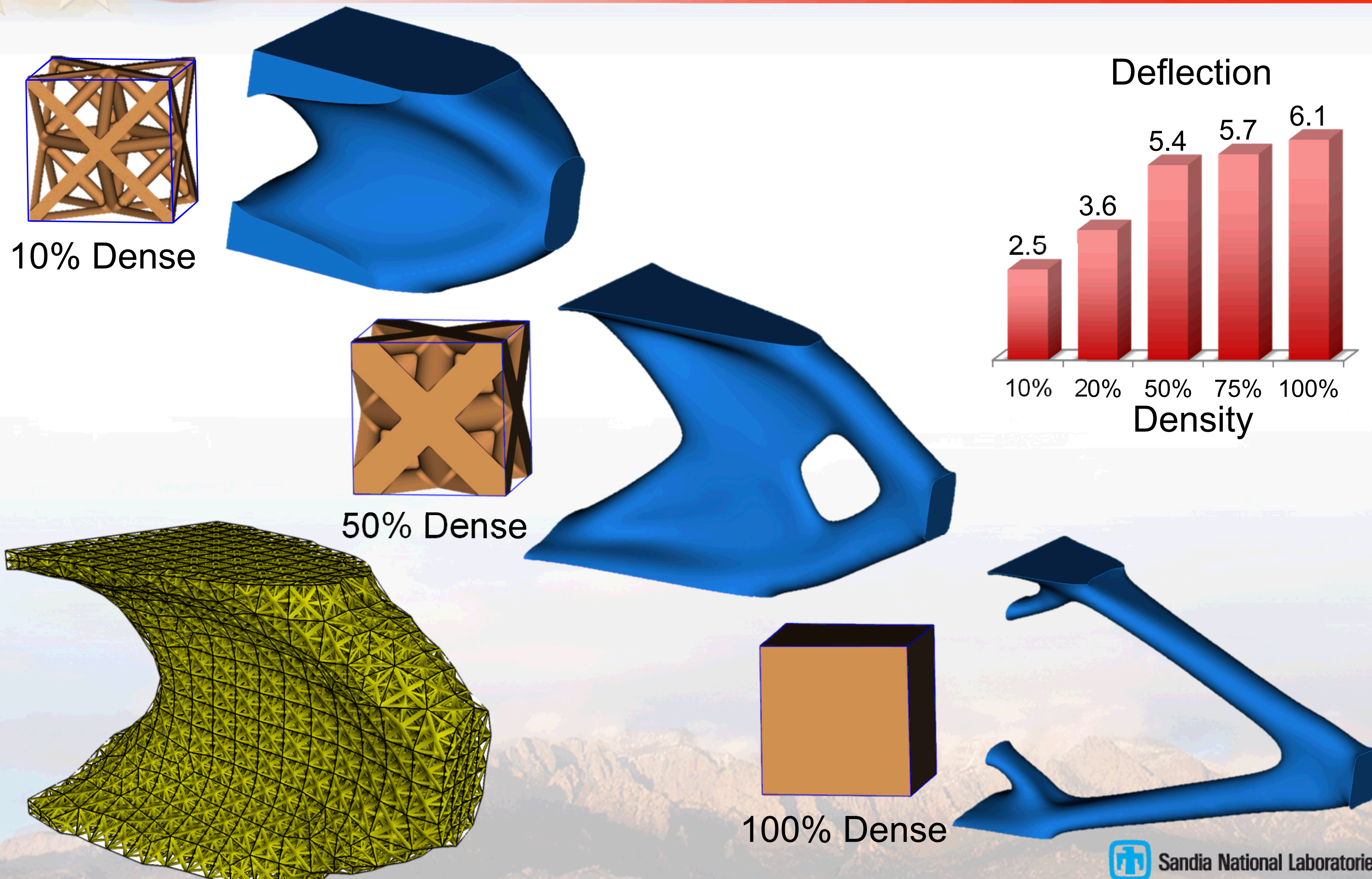
AM Lattice Structures Optimize Stiffness vs. Weight



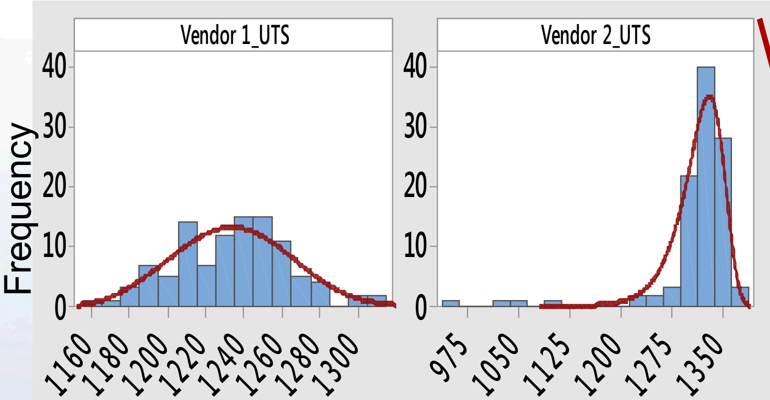
Materials Assurance

Residual Stress, Materials Properties, and Variability are Important Issues

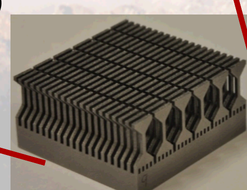
AM Is Still an Evolving/Emerging Technology

- Residual Stress is a Significant Issue
- Little Available Materials Property/Performance Data (no standards)
- Large Variability in Process and Materials
- Both Experimental & Modeling R&D in-progress

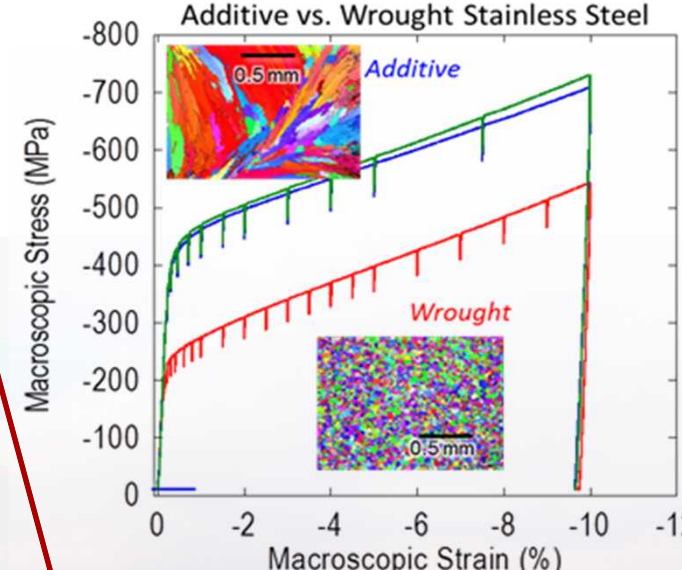
Large Variability in AM Materials Properties



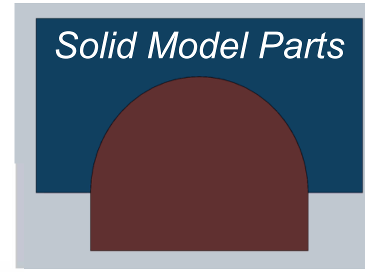
Ultimate Tensile Strength 17-4 PH (MPa)
(Typical wrought H900 ~ 1450 MPa)

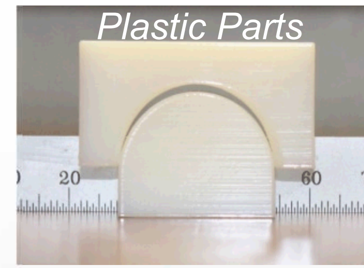


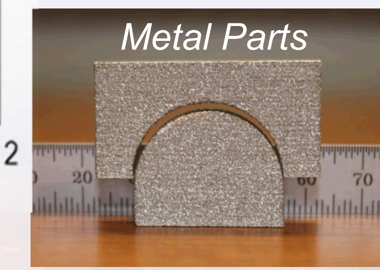
Mechanical Response of Additive vs. Wrought Stainless Steel



AM Metals are Unlike Cast or Wrought Metals







Residual Stress Causes Parts to "Move"

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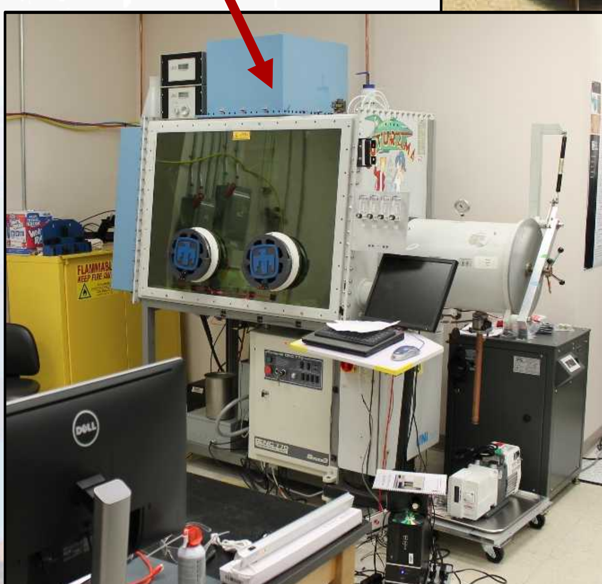
Sandia Metal/Multi-Material AM Process R&D Laboratory

3D Systems ProX 200 Laser Metal Powder Bed Machine

Aspex Explorer SEM-based powder particle analyzer

Next Generation Custom Built Hybrid LENS™ System



Haas VF2 mill-turn machine will be Modified for Multi-Material hybrid AM, including LENS™

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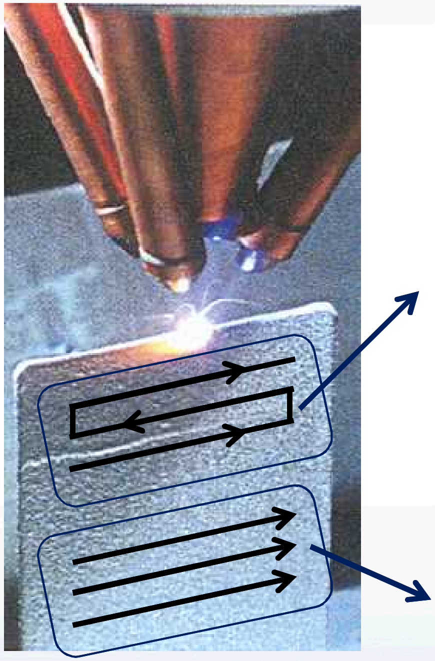
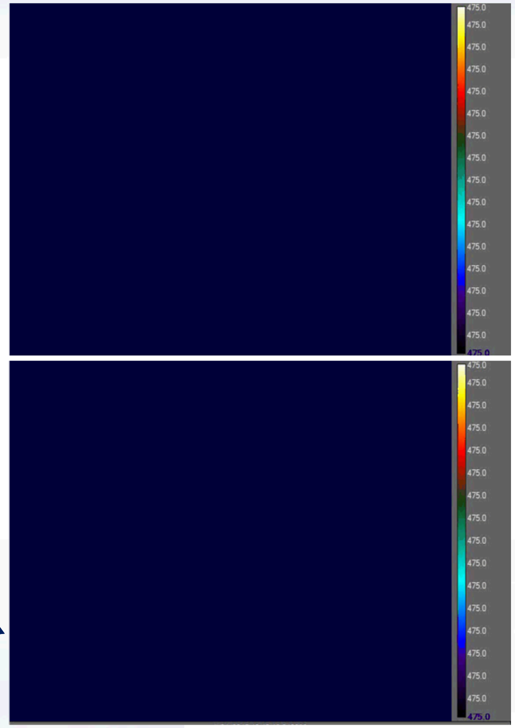
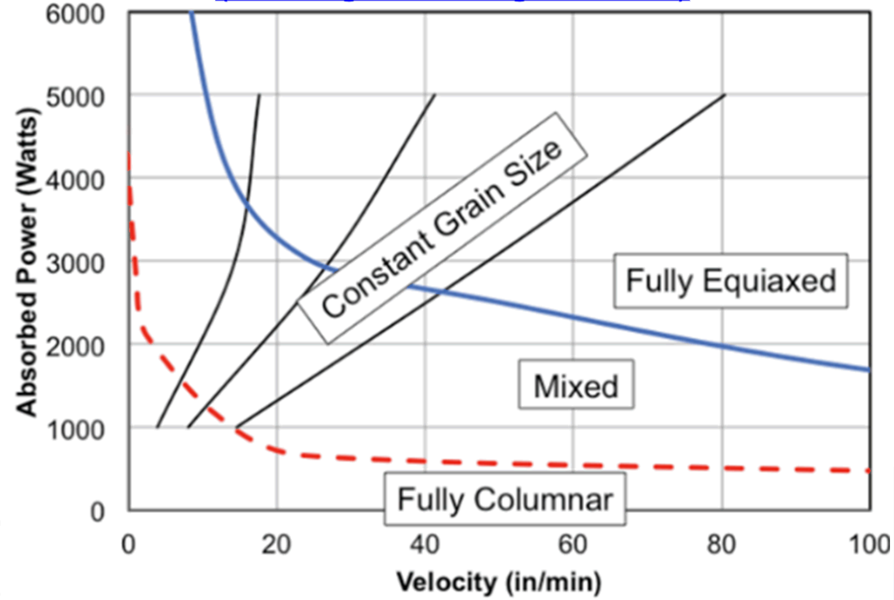
Working to Understand LENS™ Processing-Microstructure Relationships



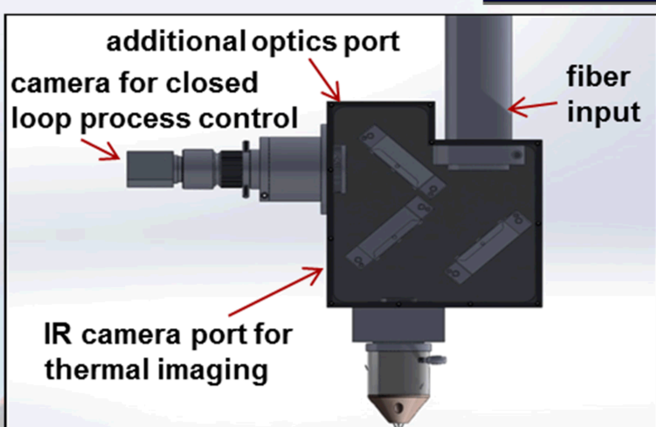


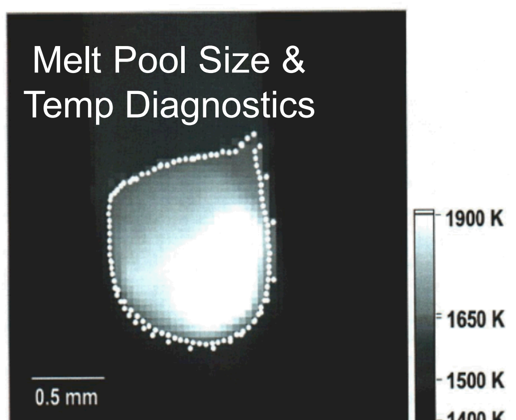
Processing-Microstructure Relationships

(teaming w Carnegie Mellon)



J. Gockel et al. / Additive Manufacturing 1–4 (2014) 119–126





Control melt pool size & temperature to create desired microstructure and reduce variability

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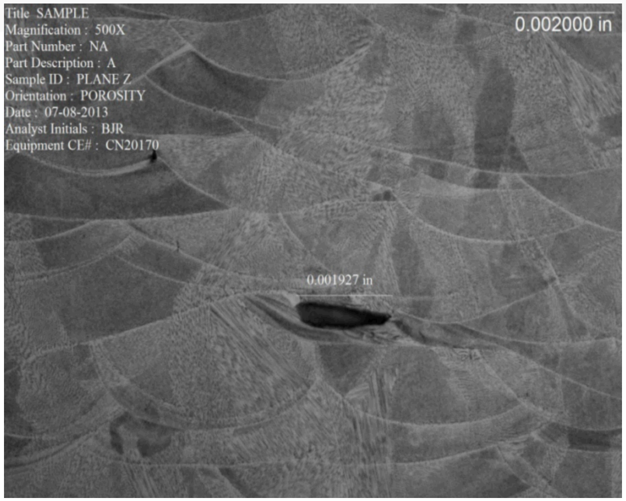
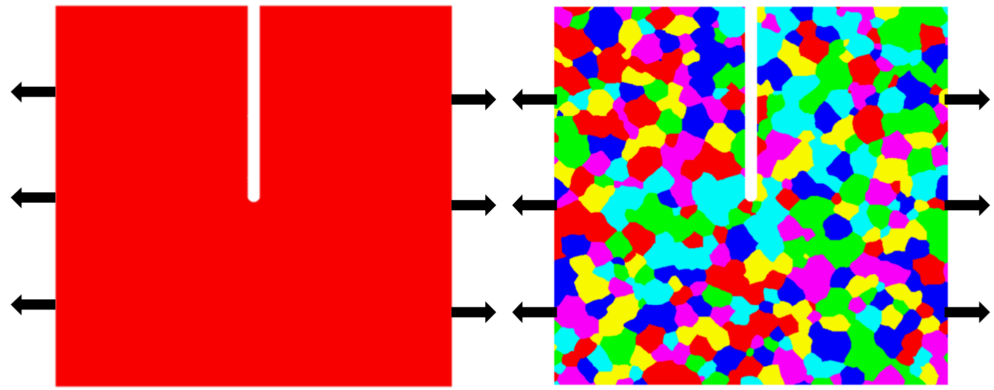
Modeling Microstructure & Behavior

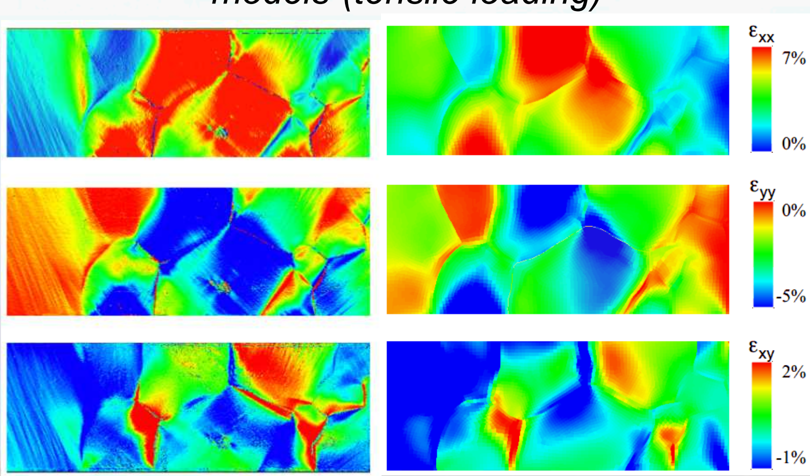


Ta single crystal [100] orientation

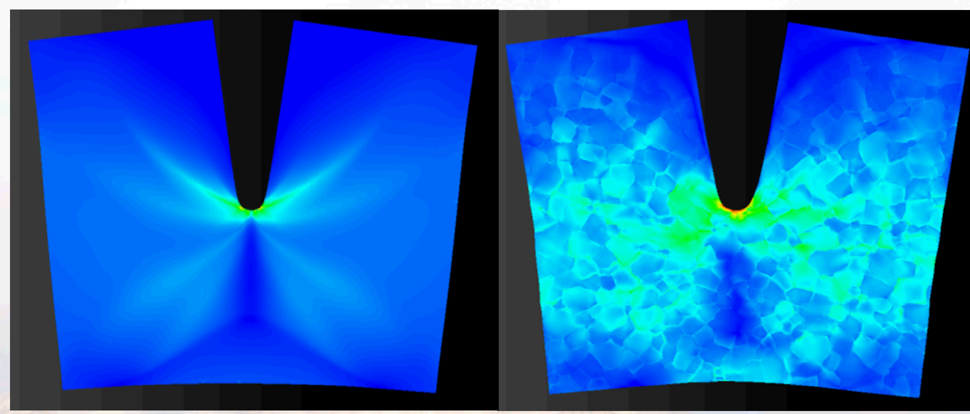
Ta polycrystal 482 grains



Oligocrystal experiments vs. crystal plasticity models (tensile loading)



Experimental Results *Simulations*



(a) Von Mises stress distributions: single crystal vs. polycrystal

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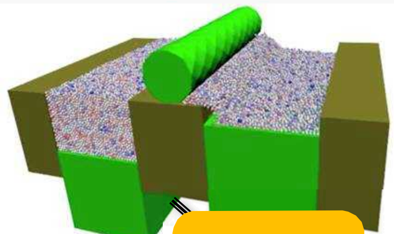
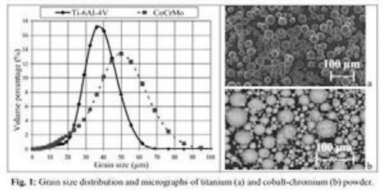
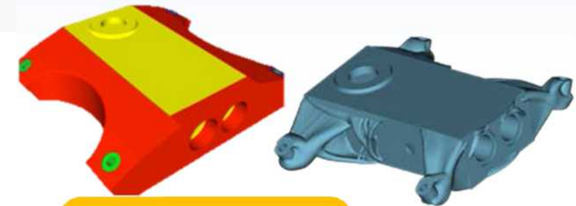
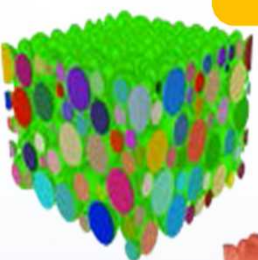
Ultimate Vision is to Understand/Control Process → Microstructure → Properties → Performance



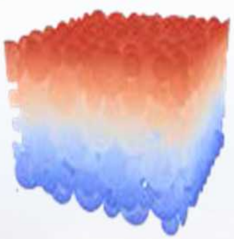




Particle packing

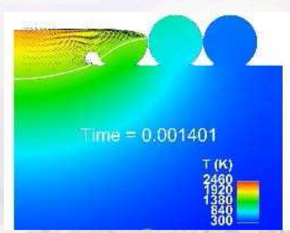


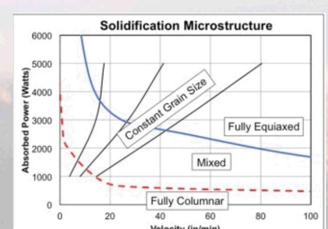
Heat Transfer



Partial melt & flow

Molten pool dynamics





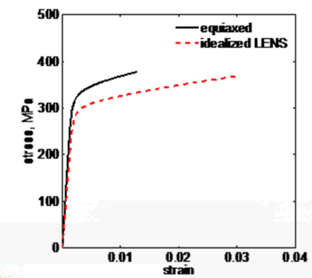
Solidification

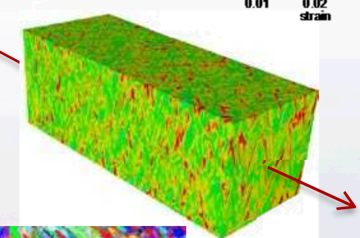
Microstructure

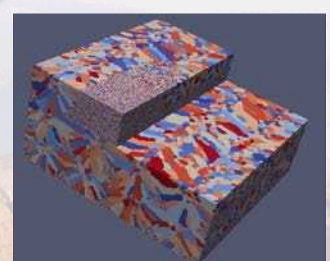
Property-Performance

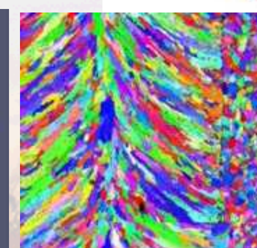
Topology Design

- Process control
- Materials characterization
- Interfaces
- GRANTA database



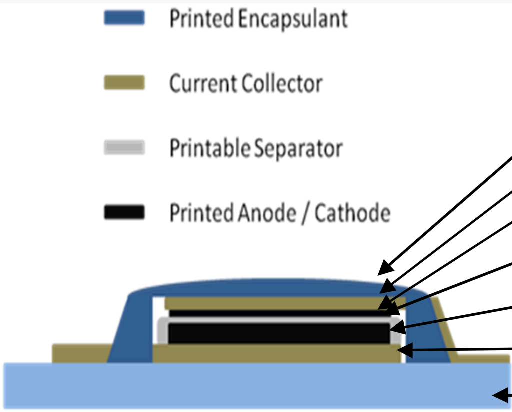






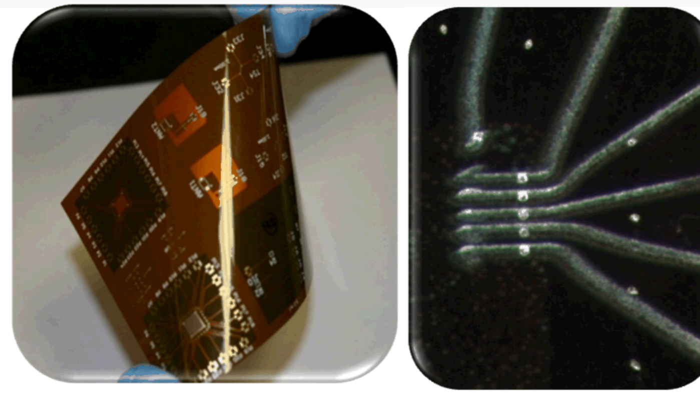
Multi-Material AM

Sandia has Strong Capabilities/Expertise In Printed Electronics

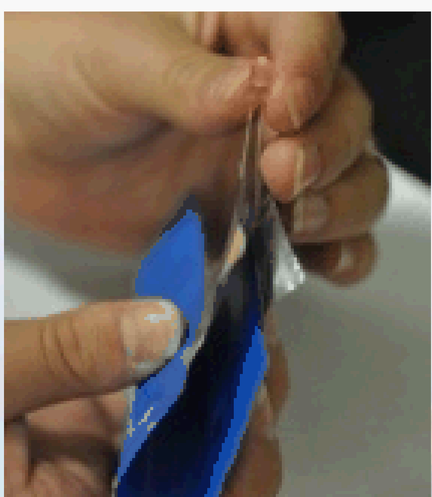


Printed flexible battery

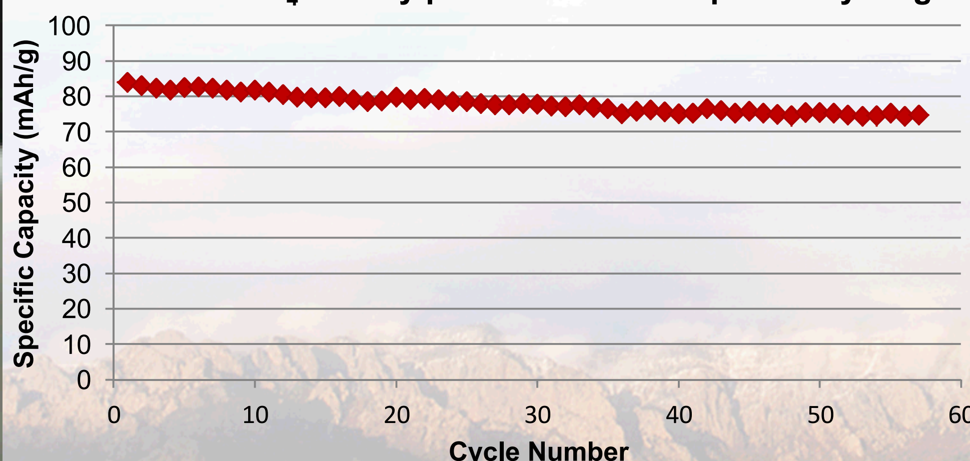
Encapsulant (DW UV-curable epoxy)
Current collector (DW carbon ink)
Anode (DW graphite/carbon)
Separator (DW mesoporous polymers)
Cathode (DW $LiFePO_4$)
Current collector (DW copper ink)
Substrate (polyimide)

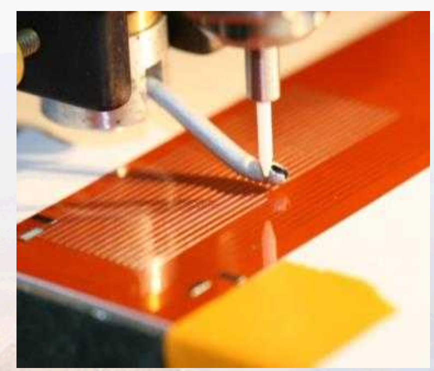


"Flexible Chips" with printed wirebonds



$LiFePO_4$ Battery performs well in repeated cycling





Aerosol jet printing to 10 μm

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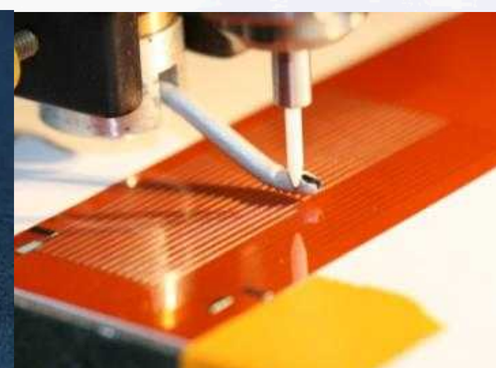
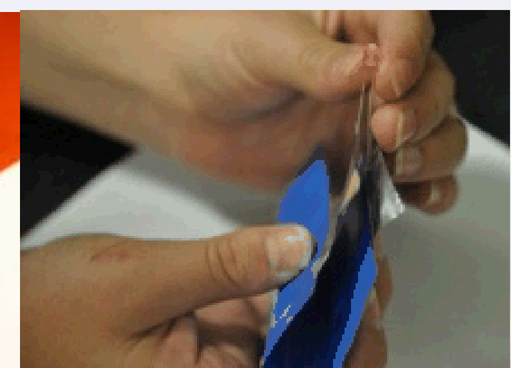
Summary

- Sandia has a rich history in AM technology development & commercialization
- Special interest in Design for AM, Materials Assurance, & Multi-Material AM
- Strong, uncommon, experimental and computational capabilities
- Strong interest in teaming with universities in areas of mutual interest

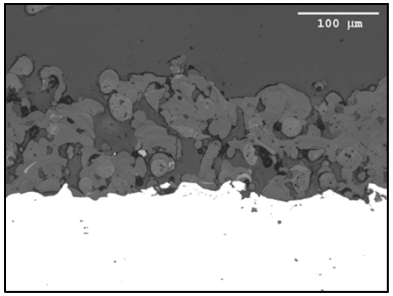


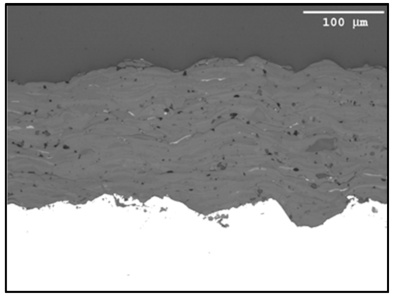
Backup Slides

Fundamental Process Understanding is Key to Controlling Variability

Same System, Same Feedstock,

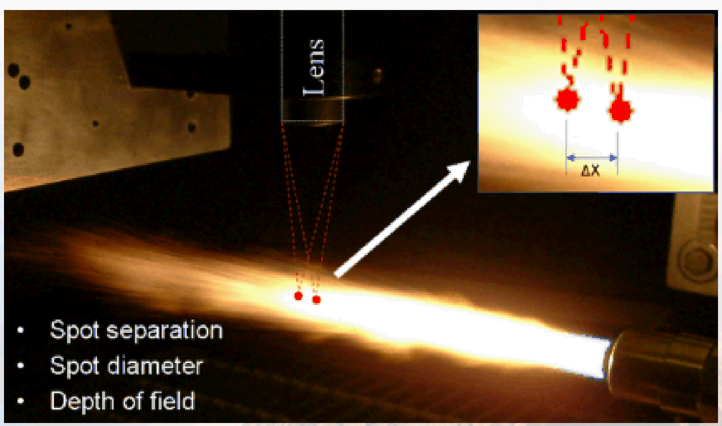


VS.



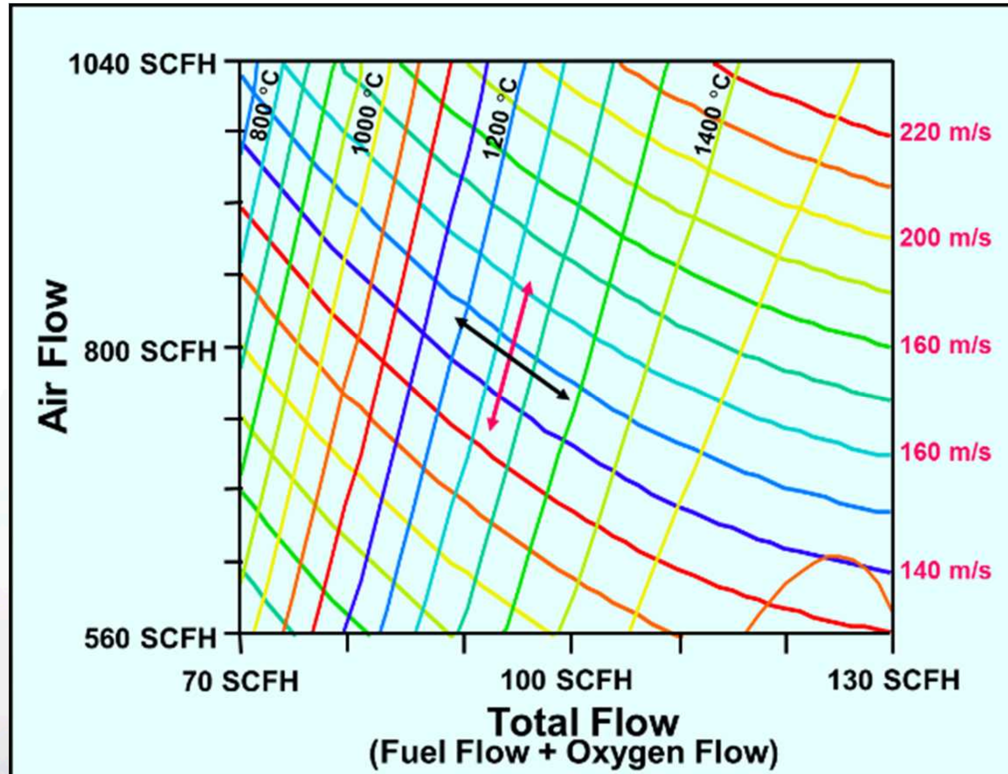
Very Different Results!

- Experimental/computational R&D used to develop processing-microstructure-properties relationships



Process Diagnostics/Monitoring

Fundamental process understanding enables closed-loop control based on droplet *temperature* and *velocity* to reduce *variability*

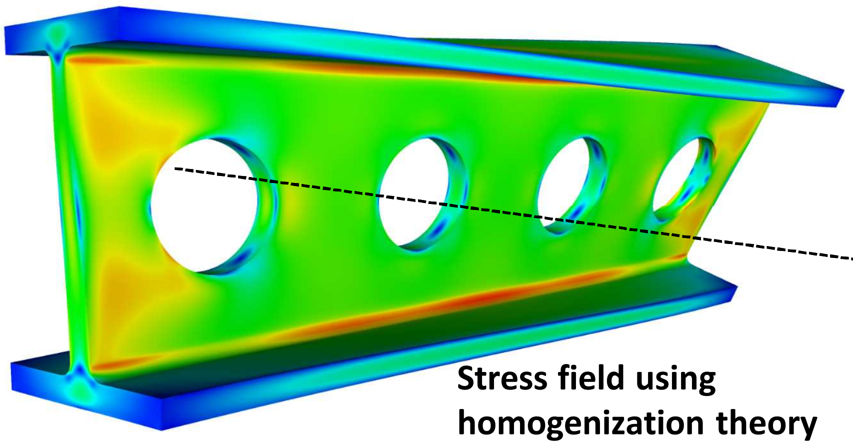


Response surface showing relationships between Process Inputs (Air Flow, Fuel Flow, Oxygen Flow) and Critical Outputs (droplet temperature, droplet velocity)

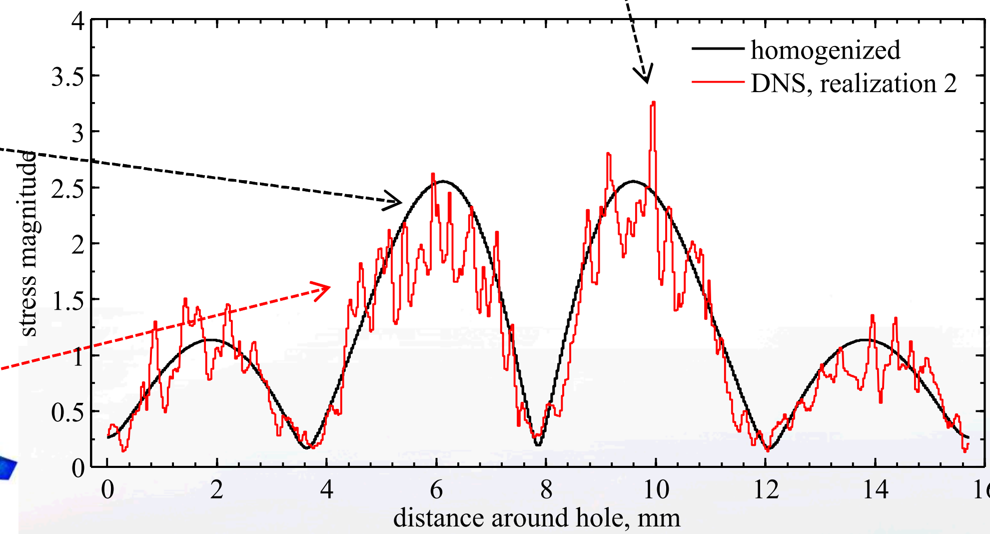
Microstructure Influences Variability & Failure

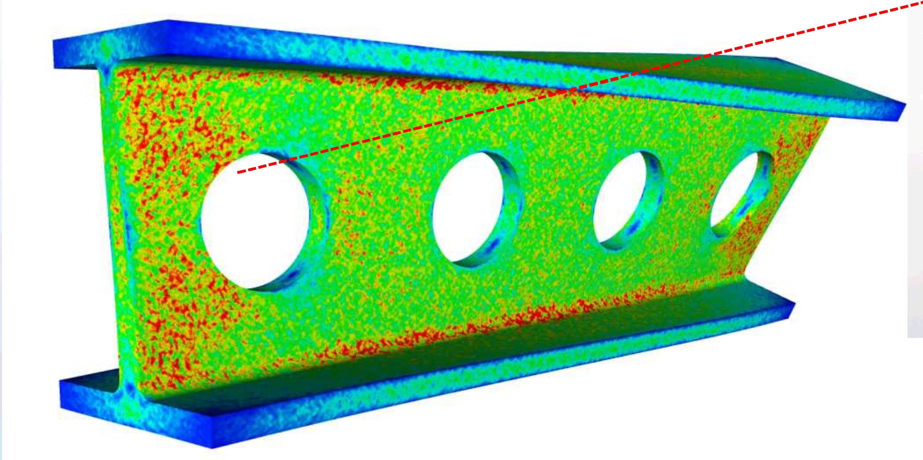
Homogenization theory misses local details - potential fracture initiation

"Enriched physics"



Stress field using homogenization theory





- Homogenization filters physics necessary to predict failure
- Microstructure influences peak stress

Stress field using Direct Numerical Simulation

J. E. Bishop

Sandia National Laboratories