Science-based Additive Manufacturing for NNSA Missions

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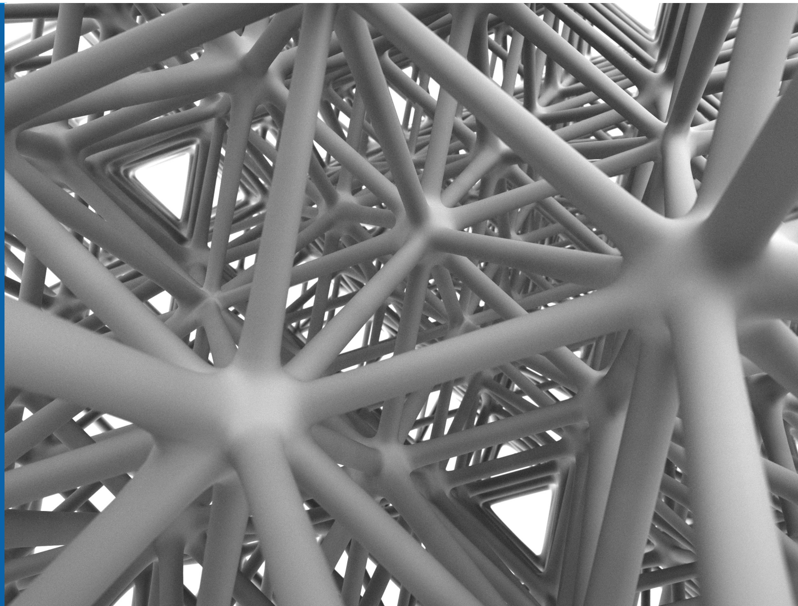

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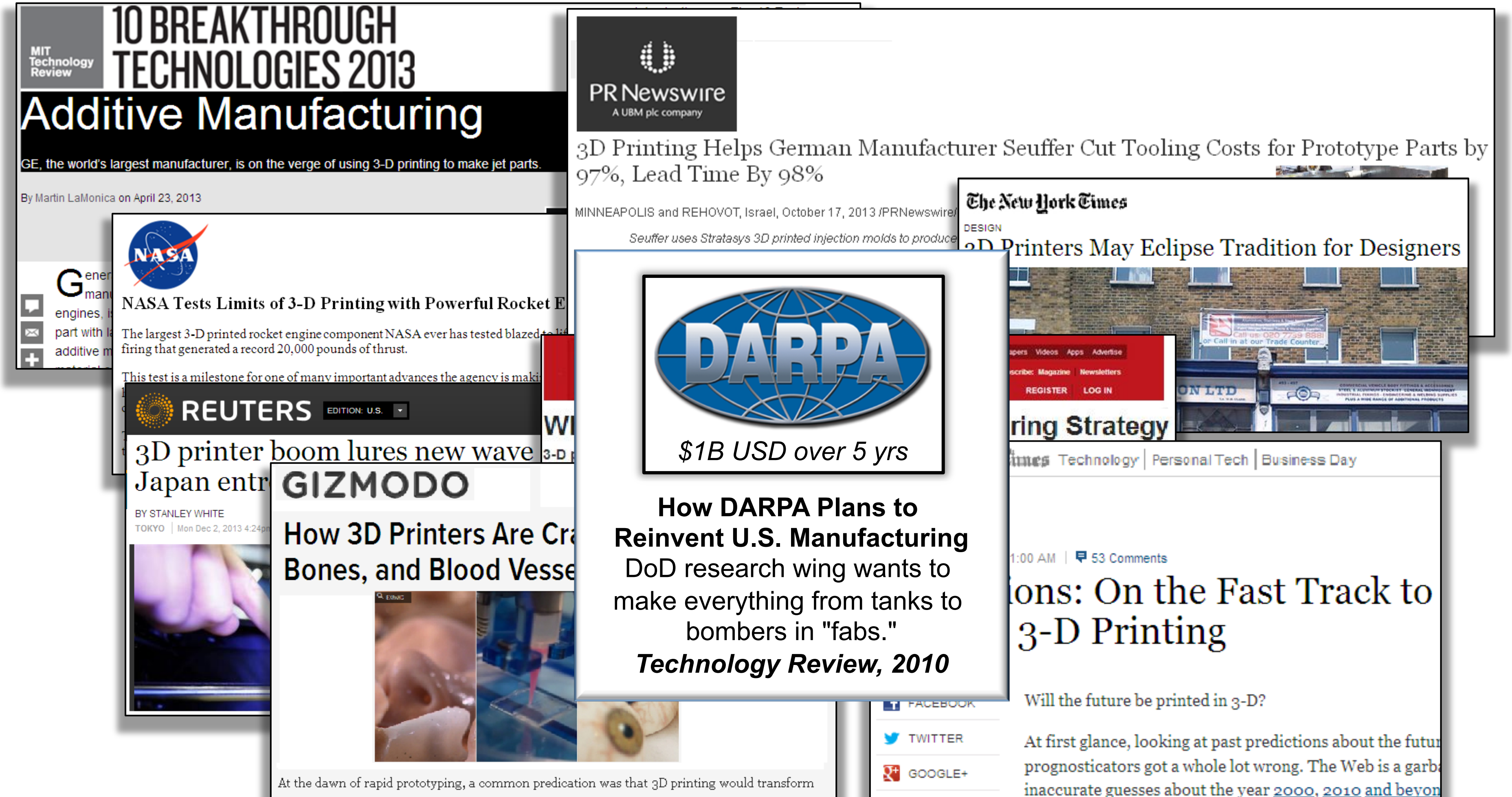
Additive Manufacturing (AM) = manufacturing layer by layer from a digital file

Movie provided by EOS

Additive Manufacturing is revolutionizing customized, tailored manufacturing



Advancing 21st century manufacturing technologies is integral to US national security

On a global scale, industry and foreign governments are positioning themselves to exploit additive manufacturing

Aircraft Bracket Optimized with Additive Design and Manufacturing Processes[1]

Primary Processing
(15.9 MJ/kg)

Atomization
(14.8 MJ/kg)

Conventional Machining - Buy-to-Fly Ratio 8:1

Mill Product (slab, billet, etc.) → Secondary Processing (8.72 kg) → Machined Product → Final Processing → Finished Part

Used: 0.2MJ

1.09 kg

Additive Manufacturing - Buy-to-Fly Ratio 1.5:1

Powder → (0.57 kg) → Electron Beam Melting (EBM) → Final Processing (0.38 kg) → Finished Part

Used: 0.08 MJ

0.38 kg

By 2020, GE will have 100,000 additively manufactured parts in jets engines.[2]

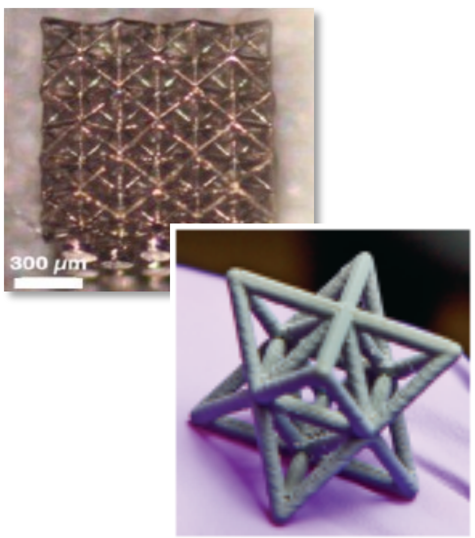
Industry believes additive manufacturing has a compelling cost benefit.
Additive uses less material, less energy, reduces waste, reduces manufacturing footprint AND produces parts with improved performance

1-MFI and LIGHTEnUP Team, GE, 2013, 2-Christine Furstoss, Technical Director, GE, 2013

AM can enable bespoke structures and components

Ultralight, Ultrastiff Mechanical Metamaterials

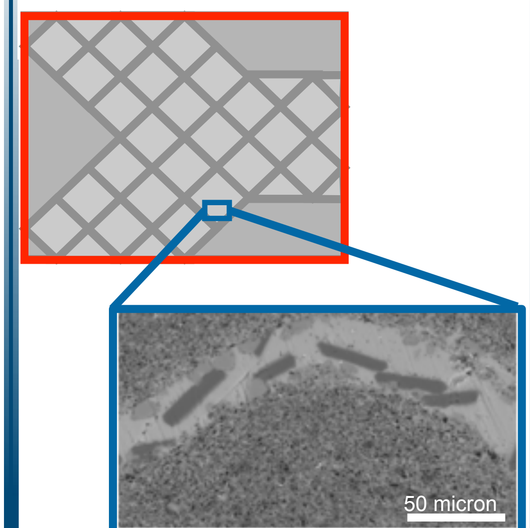
- Fabricated micro-architected materials that maintain constant stiffness per unit mass density across three orders of magnitude in density



Zheng et al., “Ultralight, Ultrastiff Mechanical Metamaterials,” Science, online June 2014.

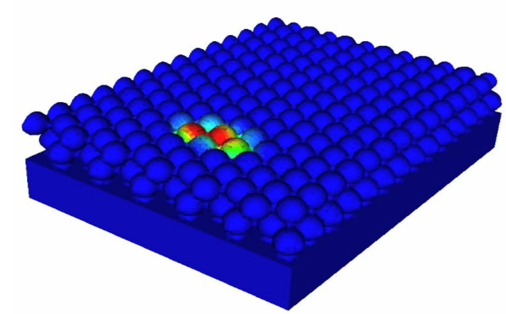
High-strength ceramic armor

- Microarchitected ceramic material fabricated with electrophoretic deposition
- Precision deposition method, unique feedstock enable high dynamic strength



First 3D simulation of melt-solidification in powder metal AM

- Multi-physics simulation includes: thermal, shrinkage, surface tension, gravity, convection, powder packing
- Advances understanding of AM process to improve quality AM metals – homogeneous, denser, less defects



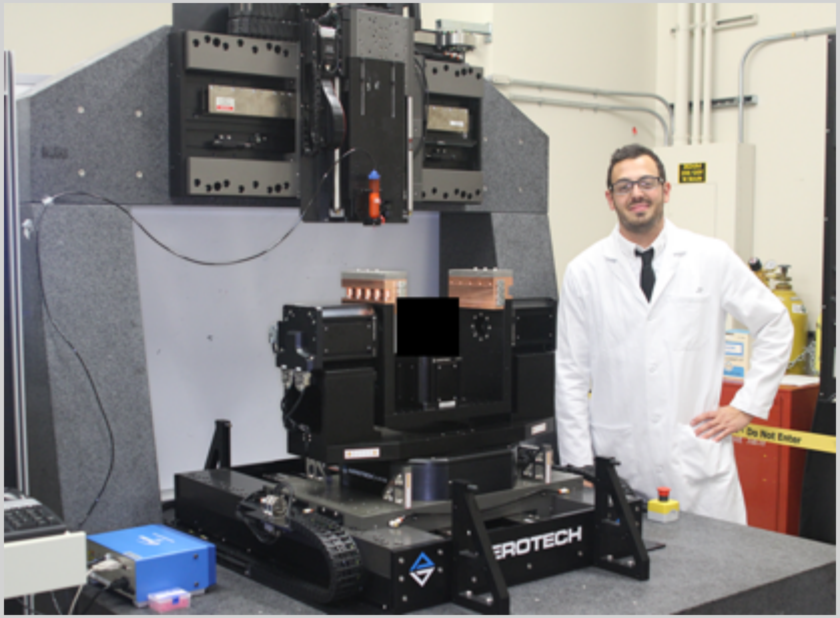
Khairallah, S.A., Anderson, A., 2014. Mesoscopic Simulation Model of Selective Laser Melting of Stainless Steel Powder. Journal of Materials Processing Technology, (in press).

In FY14, NNSA launched an initiative to demonstrate efficient manufacturing of stockpile components with AM

- Proceed with AM technologies to reap near-term benefits
- Mature most promising technologies to produce other stockpile components & improve understanding of higher risk opportunities
- Build on Stockpile Stewardship capabilities & expertise to develop accelerated certification of AM components (science-based approach)

By FY17, this will be a ~$100M initiative

LLNL/KCP demonstrate dramatic improvements in manufacturing stockpile cushions/pads



Production footprint 10,000 ft^2 → 100's ft^2

Development time 2 yrs → 3 months

Production time 40 days → 4 days

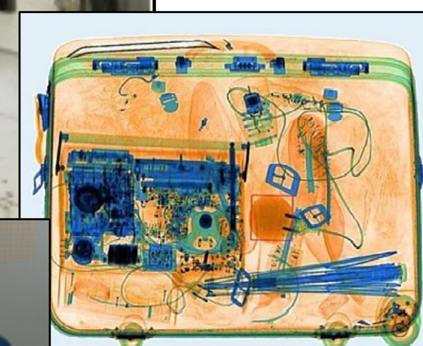
Tailored material properties

85% reduction in cost

National security threats could increase as AM devices become ubiquitous & terrorists learn to exploit them

Could terrorists manufacture ordinary-looking objects from HE, which then might be smuggled through security screening portals?

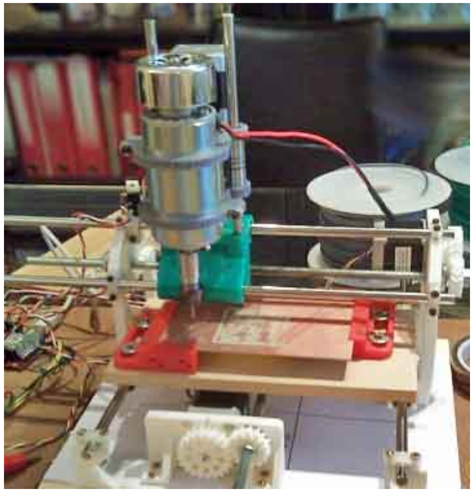
NNSA AM R&D coupled to high explosive testing & security screening could provide valuable insights



Readily available commercial AM supply chain & digital files will give national security competitors new tools

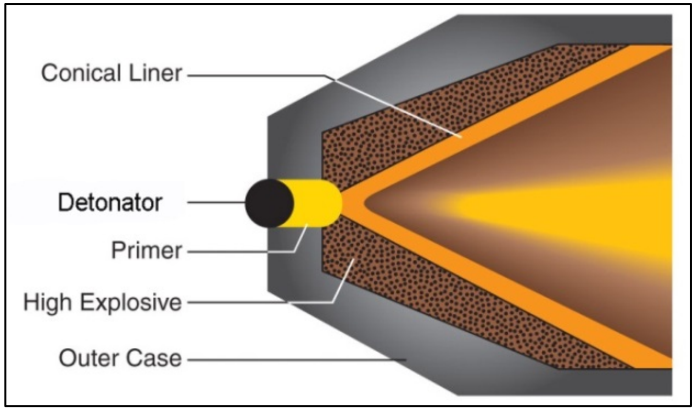
***Much like DoD is thinking about forward deploying AM*,**

a digital print file together with an AM machine and feedstock materials could be powerful tools for geographically dispersed terrorists



3D-printed circuit boards

UAV components

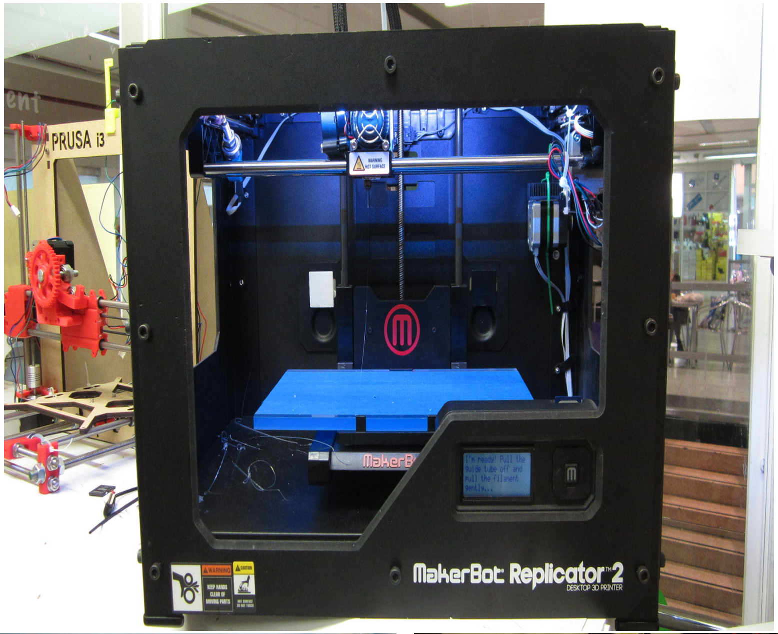


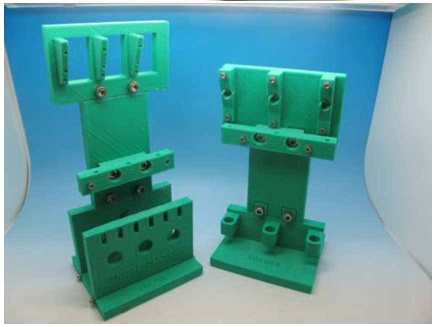
Shaped charges for breaching tanks and buildings

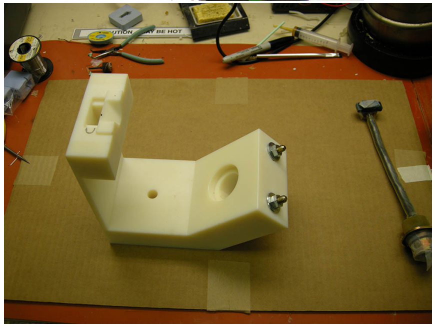
We need to understand the art of the possible

Commercial plastic AM is already making a difference in NNSA mission space

- At KCP, $4M savings in development from three $2500 MakerBots in FY13
- Plastic additive prototypes used instead of costly metal ones
- Build intricate parts without the constraint of machining
- Inexpensive way to get staff thinking about how to design with 3D capability







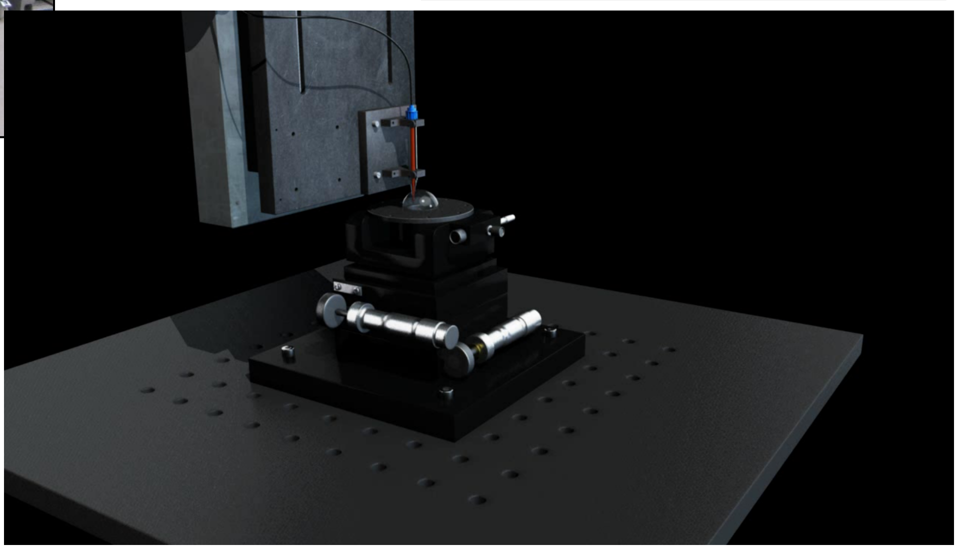
Kansas City Plant
National Security Asset

For NNSA, tailoring commercial AM technologies are equally important to newly invented AM processes

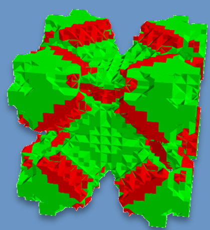
Laser Metal Powder Bed

Binder printer

Direct Ink Write

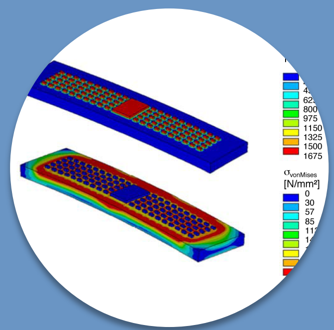


HPC modeling and simulation capabilities are being used to guide additive processing



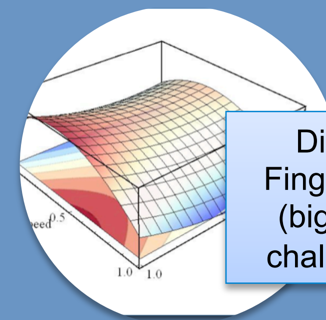
Product design tools

- Optimize macro-scale component shapes (e.g. light-weighting)
- Optimized micro- or macro-scale architectures to achieve new material properties



Process models

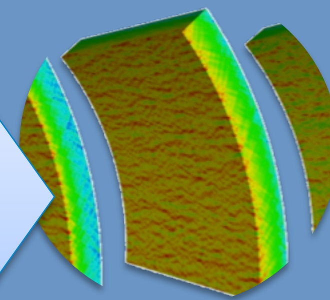
- Build a better understanding of the complex multi-physics process effecting builds
- Rapidly develop processing parameters



Digital Fingerprint (big data challenge)

Data mining & UQ pipeline

- Probe sensitivities
- Reveal critical parameters
- Quantify properties and uncertainties on a voxel by voxel basis
- Process hardening



Processing-properties-performance connection

- Link processing to properties and performance (including dynamic performance)
- Fully process aware material model

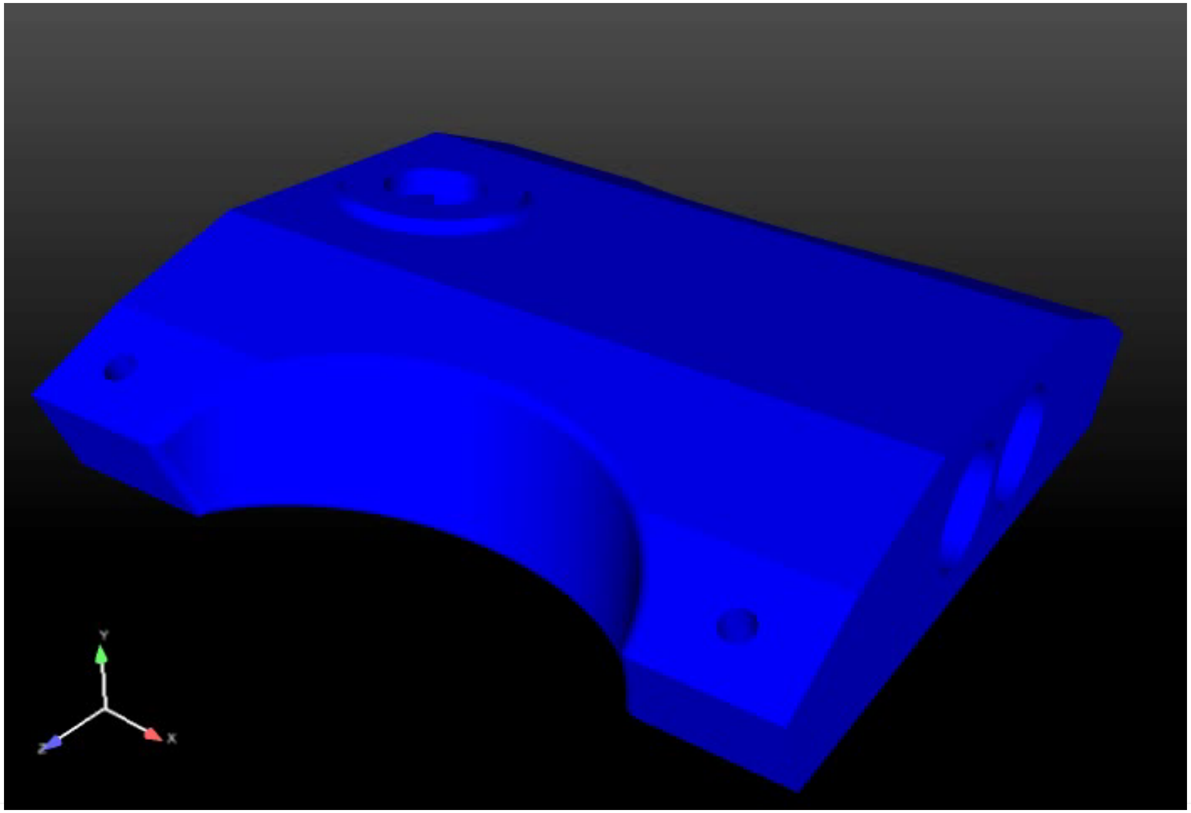
Validate through experimentation

Advanced simulation and modeling tools are crucial for accelerating qualification of additively manufactured parts

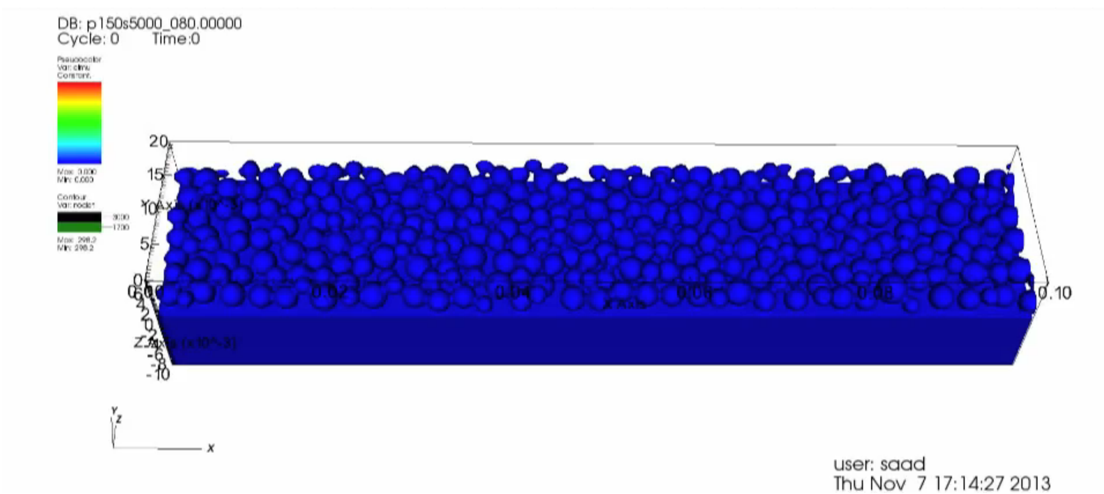
Adaptive topological optimization (ATO) + AM present solutions unavailable via traditional manufacturing

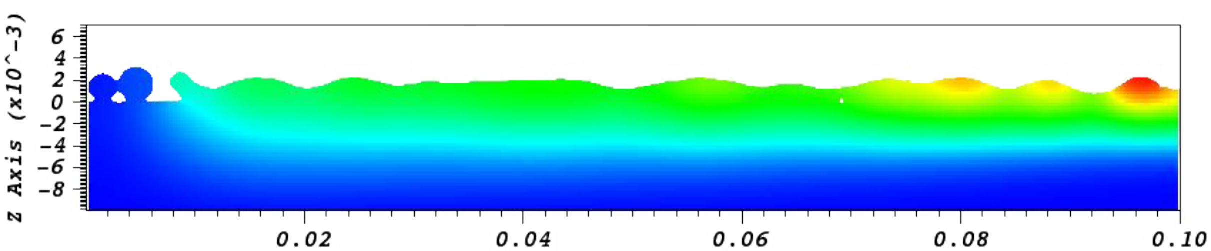
ATO

- Computational synthesis optimizes material use
- Constrained by performance requirements
- Requires parallel supercomputer processing
- Solutions resemble natural structures (bio-mimicry) and require AM fabrication



Laser powder bed metal AM processes are inherently dynamic





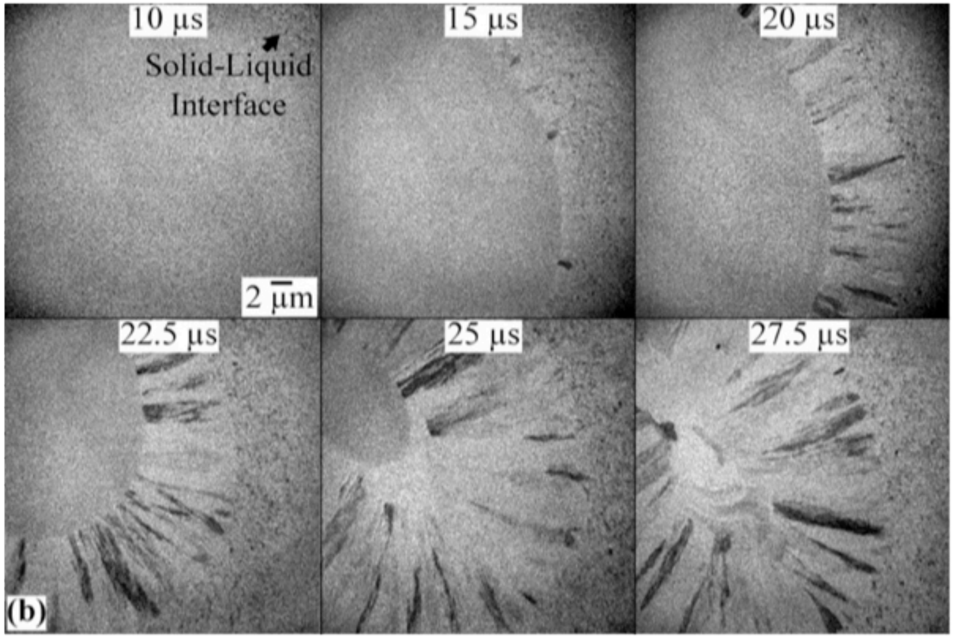
ALE-3D simulation of laser interaction with powder bed includes multi-physics effects of the rapid thermal excursions

- Melt/freeze
- Phase transitions
- Compositional partitioning
- Turbulent flows
- Formation of porosity

Simulations point to Plateau-Rayleigh instabilities as the cause of surface roughness & balling

In-situ characterization tools are key to understanding solidification during AM processing

Dynamic Transmission Electron Microscopy (DTEM)



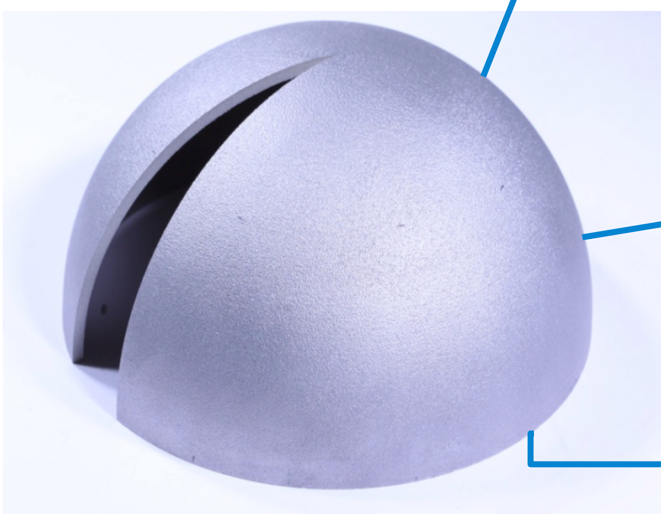
15-ns-exposure DTEM images recorded at multiple time delays after laser melting of an Al-7at.%Cu alloy

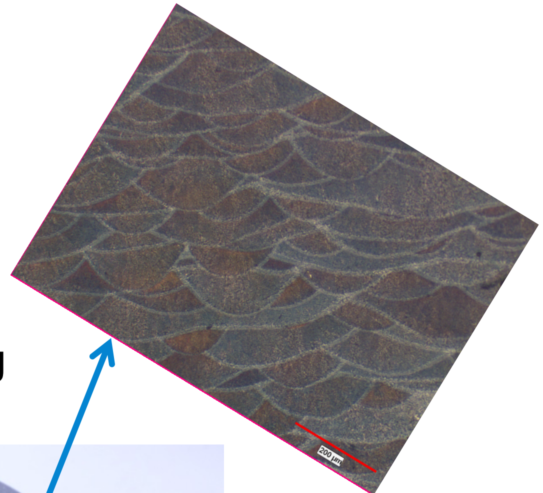
Microstructure depends critically on the composition and solidification rate of the melt pool – data crucial for predicting performance

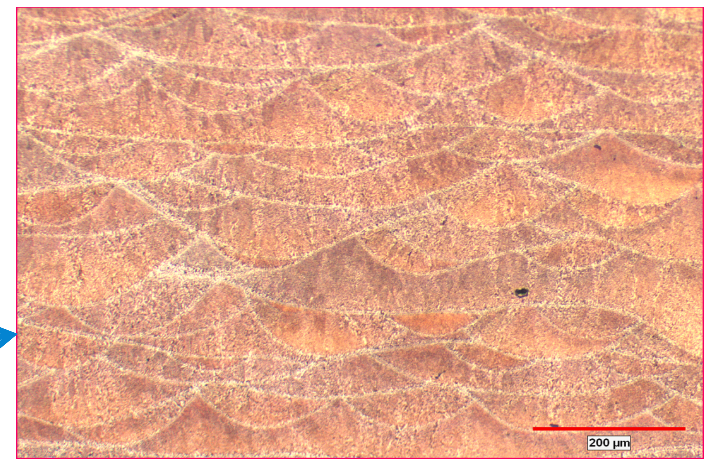
Understanding how AM microstructures effects material properties and performance is key to AM acceptance

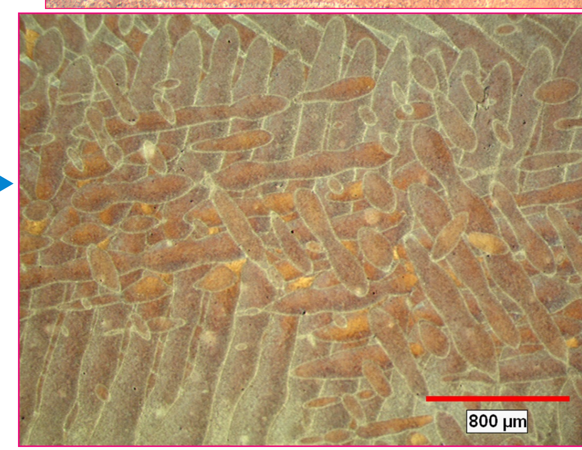
Growth Direction

Selective Laser Melting
AlSi10Mg Hemisphere



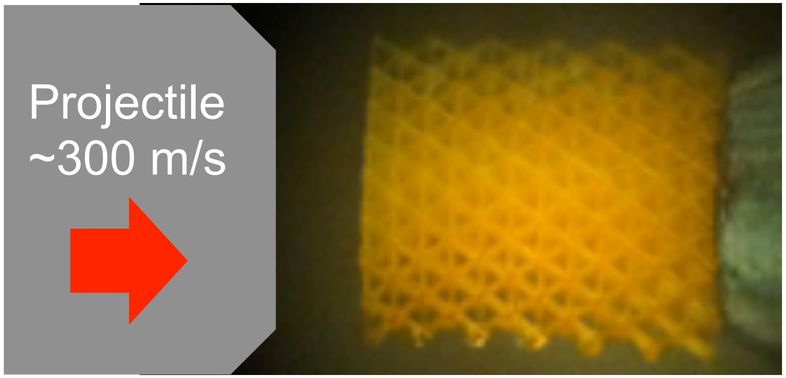


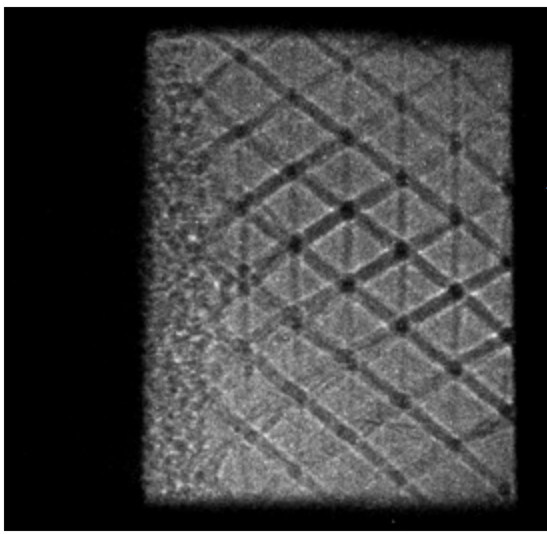




Oriented microstructure changes with position on the dome. How does this effect performance?

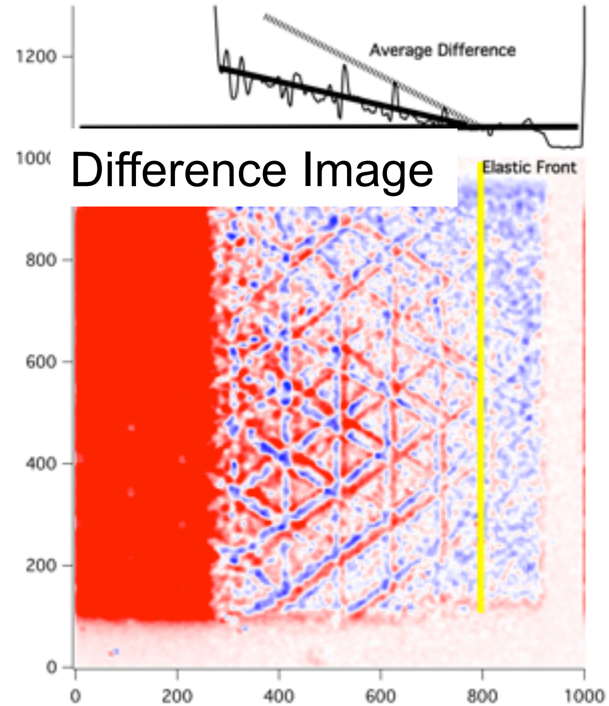
New experimental tools are giving new insights about dynamics of lattice structures





4-Frame Phase Contrast Imaging

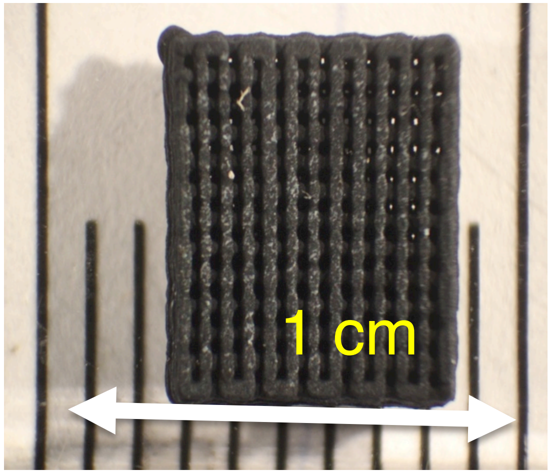
APS-DCS Data

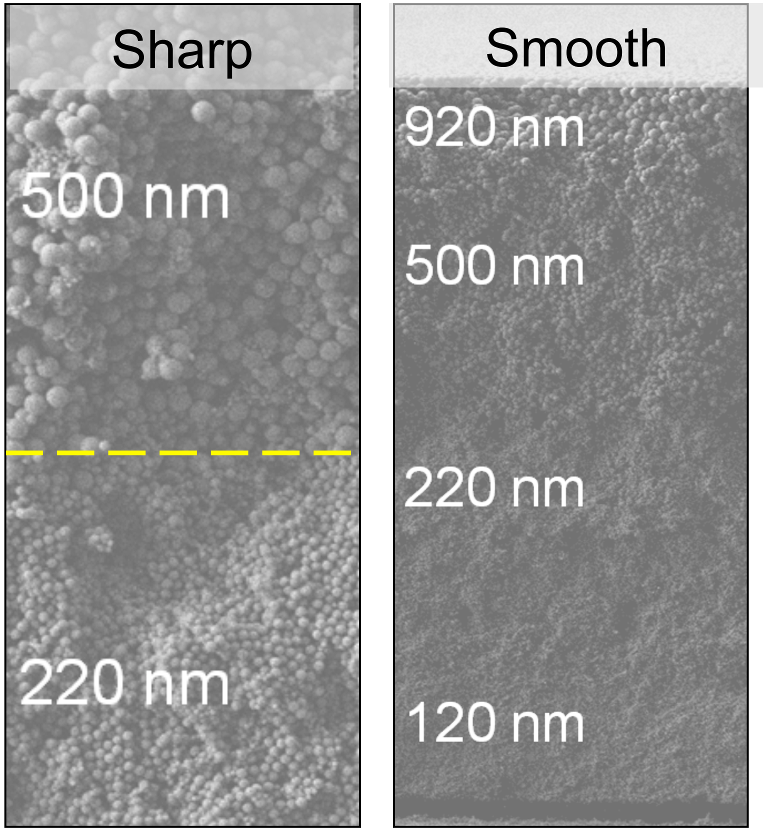


- **Strain rate dependency of the mechanical response of these dissipative structures is largely unknown**
- **Data reveals many features of the elastic & compaction wave fronts as well deformation mechanisms**

AM methods can be used to manufacture gradient density granular composites

DIW Graphene Aerogel Composite with bimodal density distribution





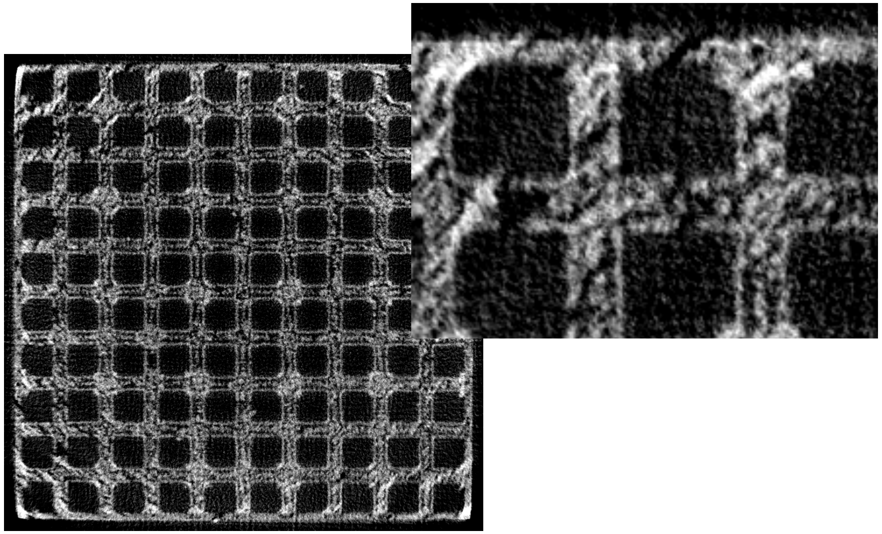
These targets can be used to test theories of shock response of heterogeneous composites

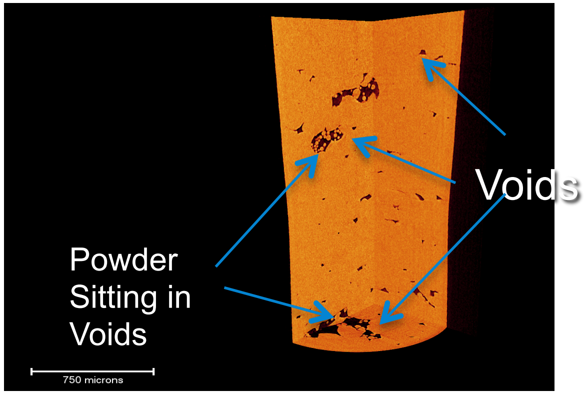
Performance certification requires us to invest in the science of AM

- How perfect does the manufacturing need to be and over what length scales?
- How best to measure, in real time?
- Can we correct during the build process?
- How do we deal with the data overload?

Rapid quantification of residual stresses is key

Synchrotron Radiation micro-Tomography of AM 316L





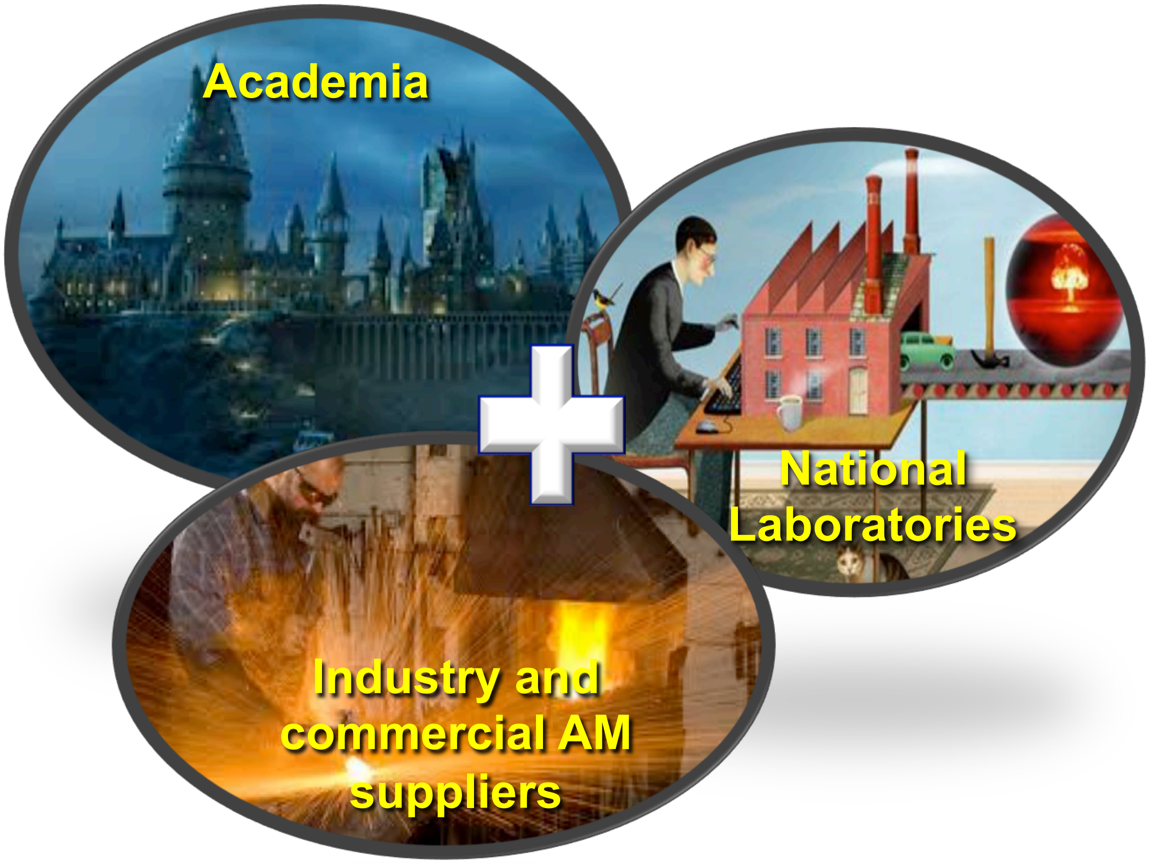
NNSA AM R&D differs from commercial AM R&D

Barriers Limit Application – R&D directions

- Material Types & Properties
- Part Accuracy & Surface Finish
- Fabrication Speed & Build Volume
- Lack of AM Standards
- **Exotic materials**
- **Process Understanding & Performance - Modeling**
- **Next Generation Processes**
- **Microarchitecture & "New" Material Properties – "Boutique Materials"**
- **Qualification & Certification**

NNSA specific research

There is significant R&D before us all



Partnerships and collaborations required. We want your help!