Additive Manufacturing: Manufacturing Demonstration Facility

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The Manufacturing Demonstration Facility
at Oak Ridge National Laboratory

Core Research and Development

- R&D in materials, systems, and computational applications to develop broad of additive manufacturing

Industry Collaborations

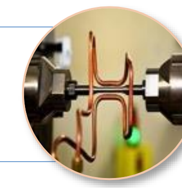
- Cooperative research to develop and demonstrate advanced manufacturing to industry in energy related fields

Education and Training

- Internships, academic collaborations, workshops, training programs, and course curriculum for universities and community colleges.

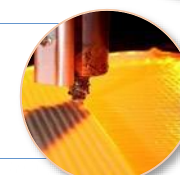
Neutron scattering: SNS and HFIR

- World's most intense pulsed neutron beams
- World's highest flux reactor-based neutron source



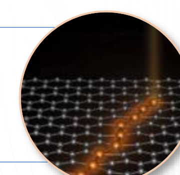
Advanced Materials

- DOE lead lab for basic to applied materials R&D
- Technology transfer: Billion dollar impacts



Leadership-class computing: Titan

- Nation's most powerful open science supercomputer



Advanced Manufacturing

- Novel materials
- Advanced processing

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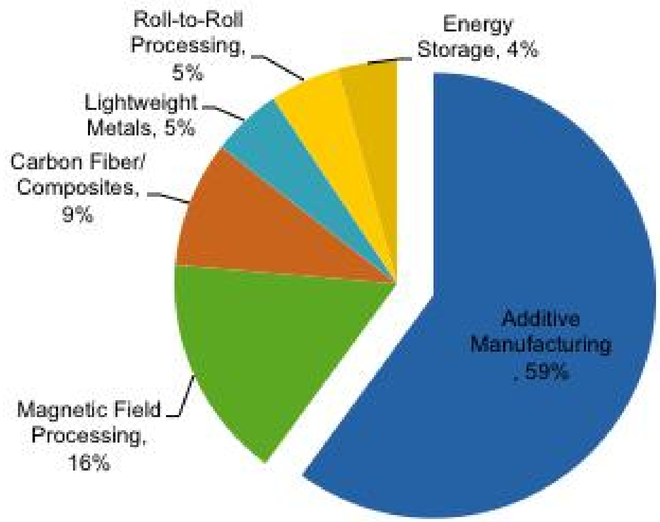
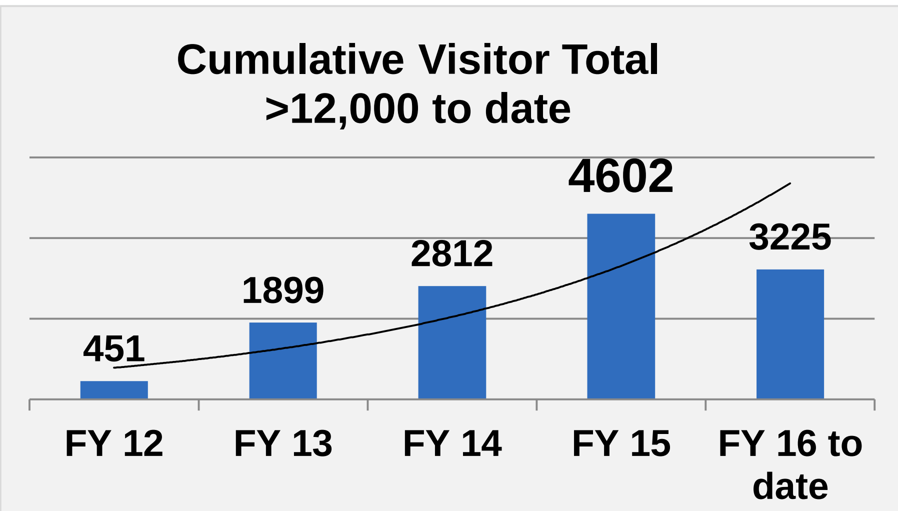
MDF Quick Stats

102 projects and counting

Company Size

- **56 small, medium**
- **34 large**





Quick Facts

- **>100 active or completed projects across 24+ industry sectors**
- **Approaching 50 completed projects with 10 going into phase 2**
- **Over 100 publications this year**
- **More than 12,000 visitors**

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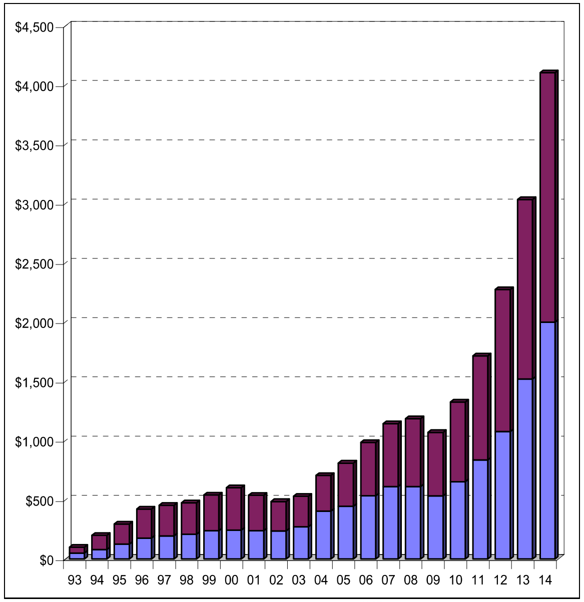
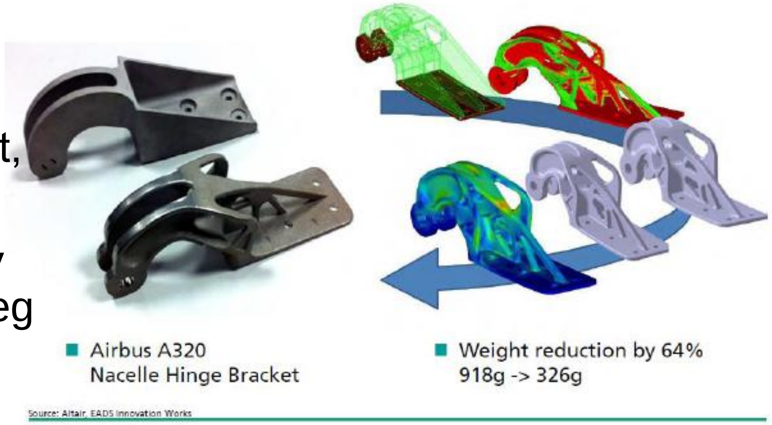
Additive Manufacturing is an Enabling Technologies for the 21st Century

- "AM is the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing technologies, such as traditional machining" – ASTM F42
- Geometric complexity is unlimited, but materials behavior is not understood.
- Significant developments in technology and materials are required
  - "… in our lifetime, at least 50% of the engine will be made by additive manufacturing." Dave Abbott, GE Aviation
  - 1,400 parts could be made by AM for one military program if the right materials were available. Greg Stein, Northrop Grumman

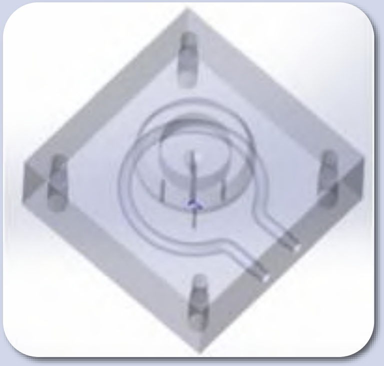


Source: Wohlers Associates, Inc.



Additive Manufacturing's Role in Enhancing the Clean Energy Economy

- ✓ Innovation
- ✓ Part Consolidation
- ✓ Lower Energy Consumption
- ✓ Less Waste
- ✓ Reduced Time to Market
- ✓ Light-weighting
- ✓ Agility of Operations



Reduced Time to Market

Cummins low-cost, hybrid mold for injection molding demonstrated the ability to lower costs for manufacturing injection molds by **60%.**

DOE-AMO, R. Dehoff

Light-weighting

3D Printed Shelby Cobra printed on the BAAM illustrates the most **energy efficient** way to produce a car.

DOE-AMO, L. Love

Agility of Manufacturing Operations

BAAM 3D printed mold for composite hood was fabricated in **<2 days** and used **<$2,500** in materials.

DOE-AMO, L. Love

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Additive Manufacturing Processes

Process	Applications		
	Polymers	*Metals*	*Other*
Binder Jetting	✓	✓	✓ *
Directed Energy Deposition		✓	
Material Extrusion	✓		
Materials Jetting	✓		
Powder Bed Fusion	✓	✓	
Sheet Lamination	✓	✓	
Vat Photopolymerization	✓		

** ceramics, sand for metal casting*

Big Area Additive Manufacturing (BAAM)

- **Obstacle:** Most additive processes are slow (1-4 in^3/hr), use higher cost feedstocks, and have small build chambers.
- **Solution:** ORNL has worked with equipment manufacturers and the supply chain to develop large scale additive processes that are bigger, faster, cheaper, and increase the materials used.

- **Large Scale Printers**
  - Cincinnati System 8’x20’x6’ build volume
- **Fast Deposition Rates**
  - Up to 100 lbs/hr (or 1,000 ci/hr)
- **Cheaper Feedstocks: Pellet-to-Part**
  - Pelletized feed replaces filament with up to 50x reduction in material cost
- **Better Materials**
  - Higher temperature materials
  - Bio-derived materials
  - Composites Hybrids

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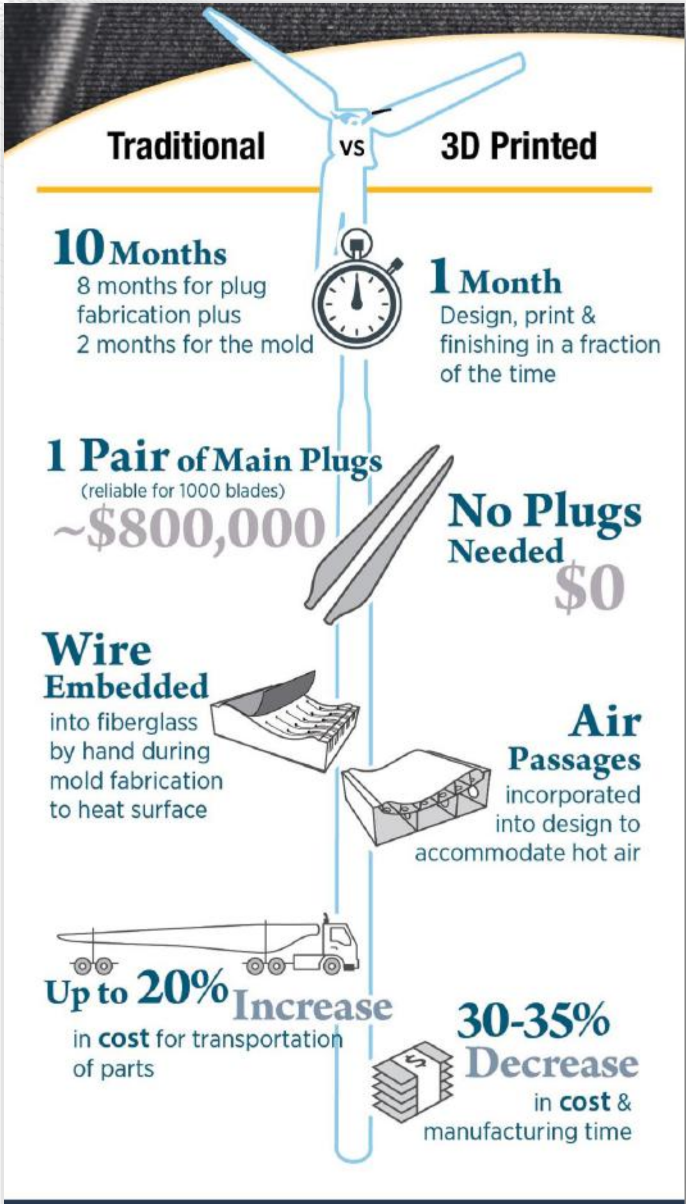
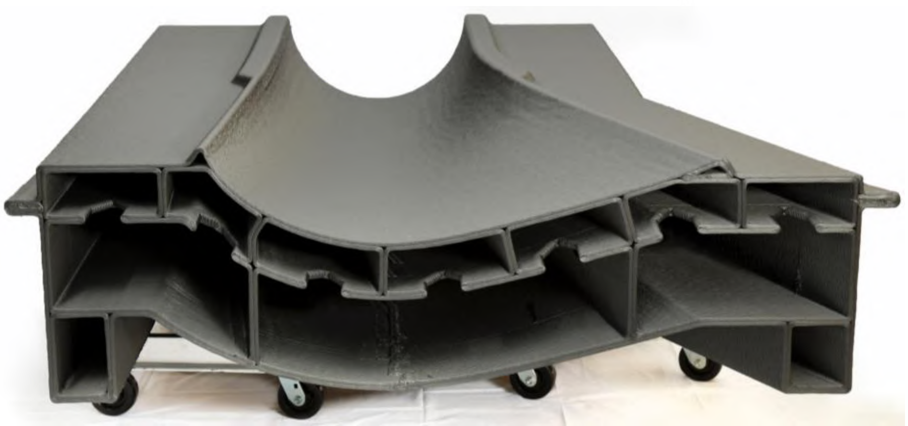
Innovation in the Design and Manufacturing of Wind Power



- **Obstacle:** Although wind energy is among the fastest growing clean energy technologies, there are still critical challenges in achieving our national clean energy goals
- **Solution:** By utilizing large-scale additive manufacturing, ORNL researchers were able to redesign the traditional mold, eliminating unnecessary parts and procedures. Creating unique opportunities in this traditionally time consuming process.



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Digitally Manufactured Molds Successfully Withstand Autoclave

ORNL's digitally **manufactured, high temperature thermoplastic** molds withstood industrial autoclave cycles for the first time ever!

November 2015:

Industry partners came to MDF to collaborate on tooling development effort.

6 new materials were successfully tested on the **BAAM-CI** during these trials

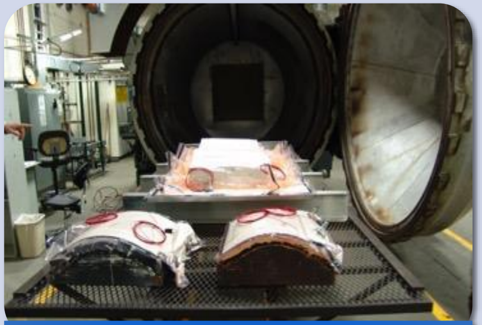
March 2016:

Over the course of three weeks, **4 tools** were fabricated using the 2 selected high temperature materials

Tools were **100% digitally manufactured**

No touch labor was involved

Each tool was printed in **1 hour** & machined in **4 hours as opposed to the normal 14 week lead time**



April 2016:

The 4 tools were taken to an industry partner's facility for testing.

The tools **withstood 2 autoclave cure cycles**

This was the **1st successful trial of 100% digitally manufactured tools in autoclave cure cycles**

- **Obstacle:** Die and tool companies decreased by 37% in less than a decade. Tooling is expensive and can take large lead times.
- **Solution:** ORNL is evaluating additive manufactured tools for use in autoclaves for composite fabrication.

TRUDESIGN · TECHMER PM POLYMER MODIFIERS · Ford · BOEING · CINCINNATI INCORPORATED · NAVAIR · BASF We create chemistry · OAK RIDGE National Laboratory

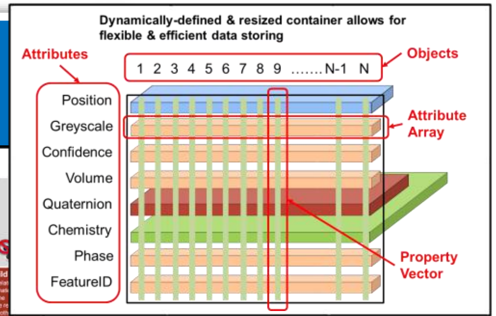
Powder Bed Technologies:

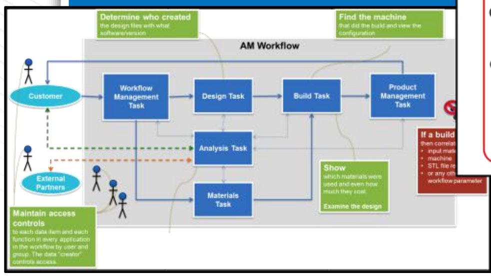
Electron Beam Melting

Laser Powder Bed

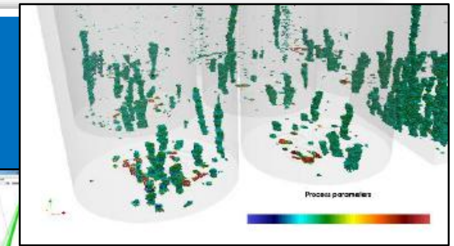
Certification and Qualification is Moving forward: Potential for data driven certification

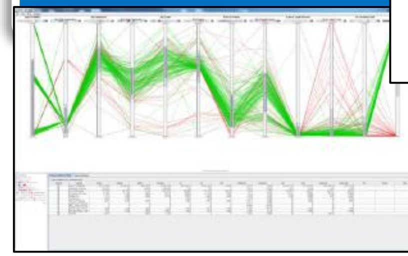
Data Management & Tracking





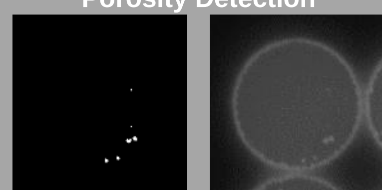
n-D Data Visualization



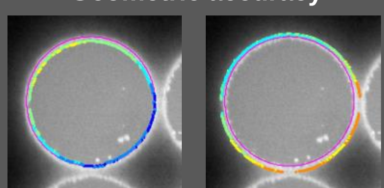


Computer Vision / Image Processing

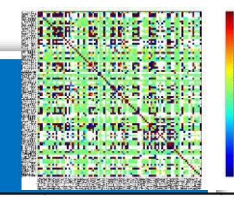
Porosity Detection

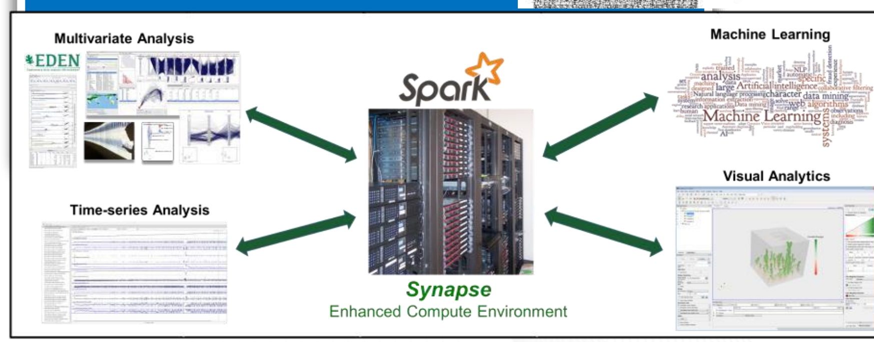


Geometric accuracy



Machine Learning / Statistical Analysis





- **Huge Quantities of Data:** may have more data than we know what to do with at this point.
- **Standards Organizations are moving forward:** ASTM, ASM, AWS, etc

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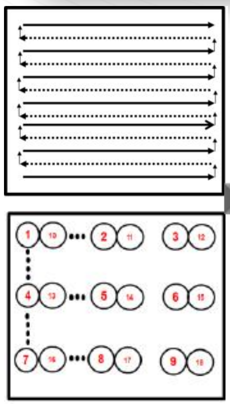
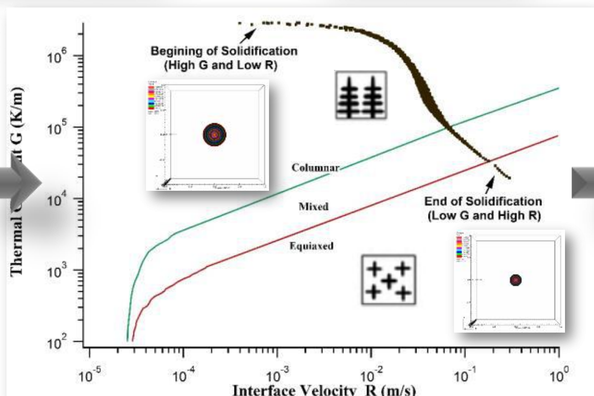
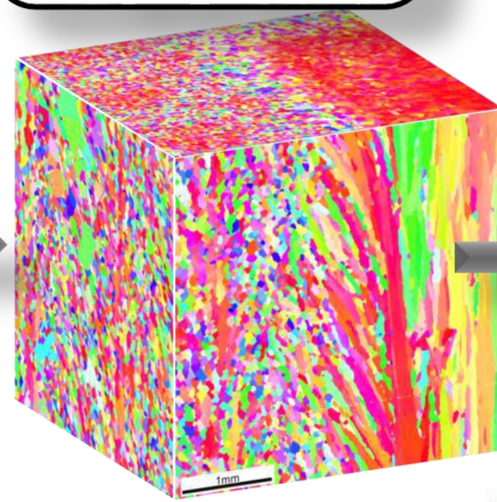
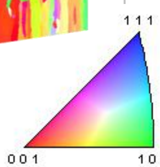
Microstructure and Material Properties can be Controlled at a Local Level

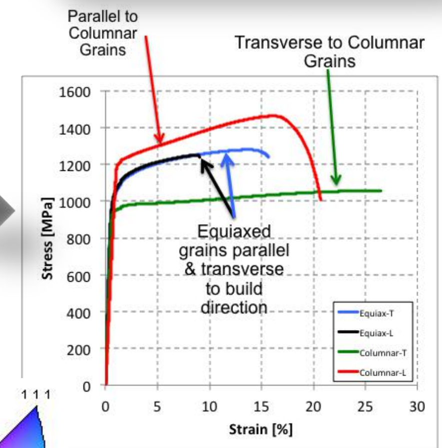
Process Parameters Control Solidification in Electron Beam Additive Manufacturing → **Design Novel Melt Scan Strategy** → **Numerically Optimize the Process For Site Specific Crystallographic Texture Control in Actual Parts** → **Demonstrate Local Property Control for Improved Performance**







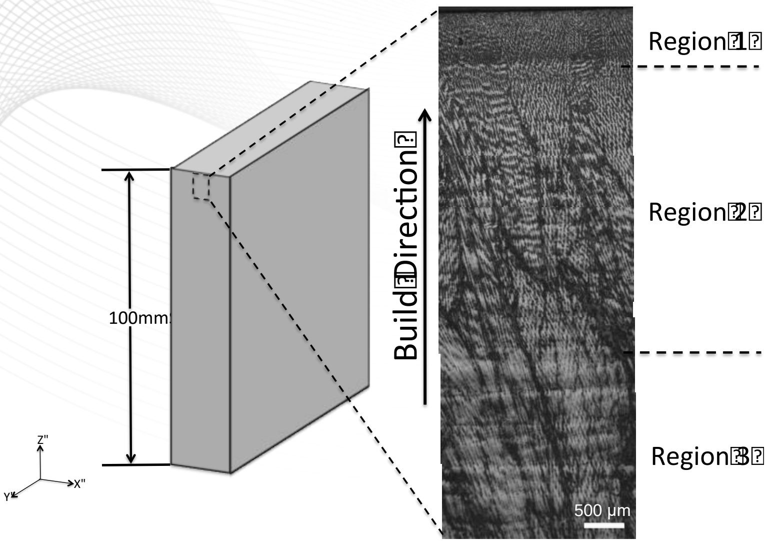


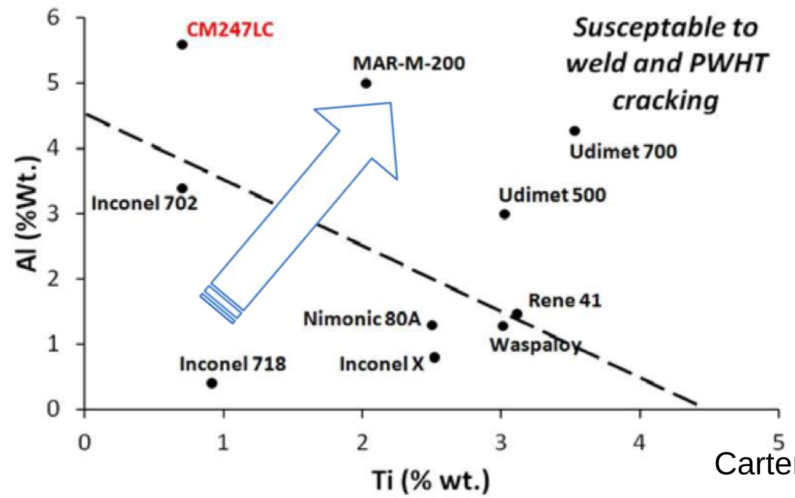


- **Obstacle:** We currently optimize process parameters for geometric control, not microstructure and properties.
- **Solution:** Combine HPC modeling with understanding of solidification behavior to change the microstructure and properties, with minimal trial and error optimization.

High Temperature Metals AM

Increased Performance, Processing Challenges

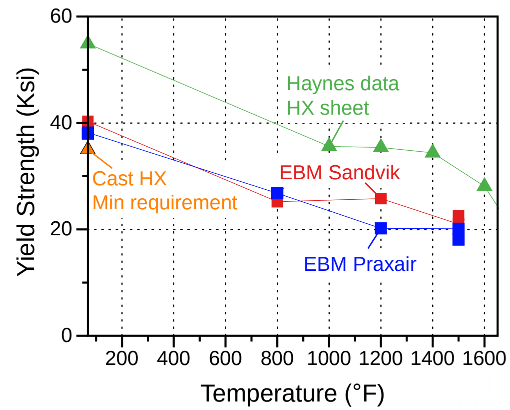


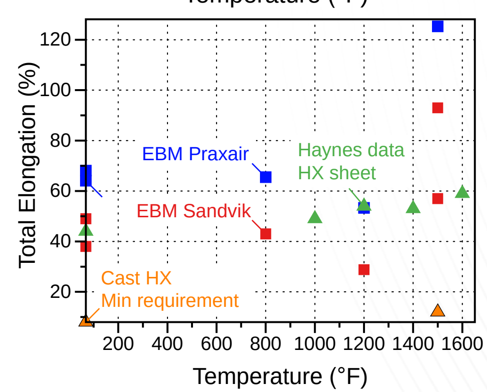


Carter (2012)

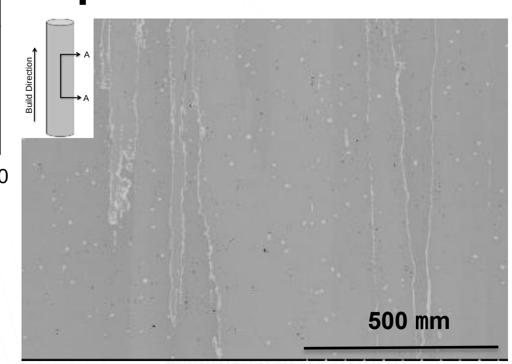
- **Obstacle:** Most high temperature alloys used today were not designed for additive manufacturing, resulting in detrimental precipitates and non-optimal properties.

- **Solution:** Selection and/or design of other alloys that could increase the operating temperatures and fully utilize complex geometries by additive processes.



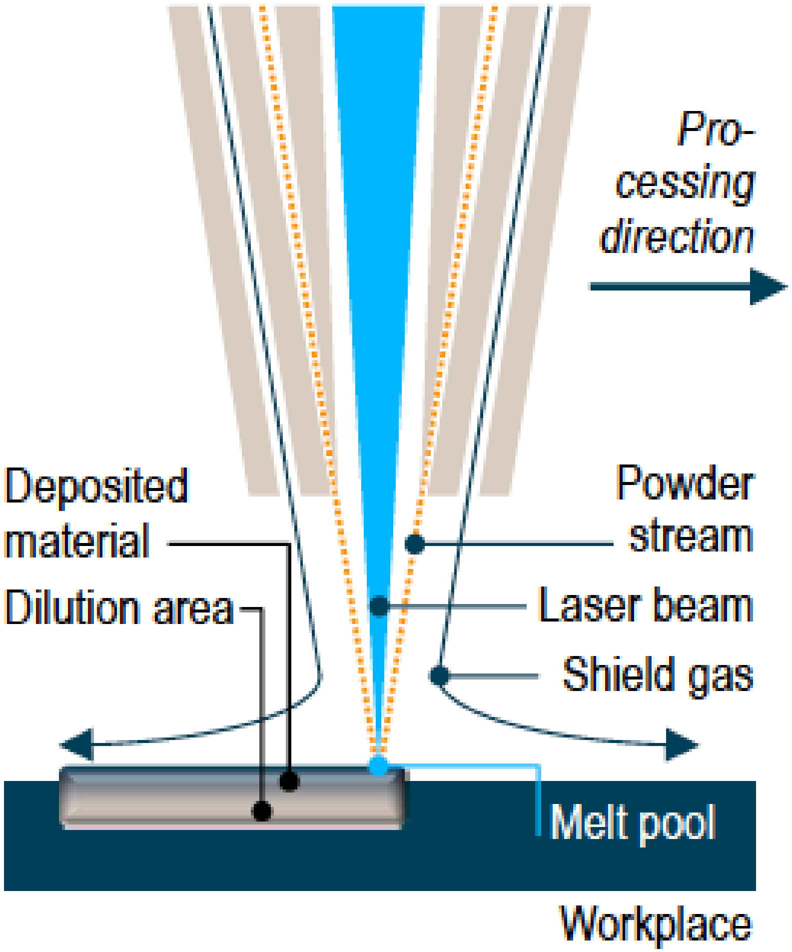


Electron Beam Powder Bed Deposited Inconel X



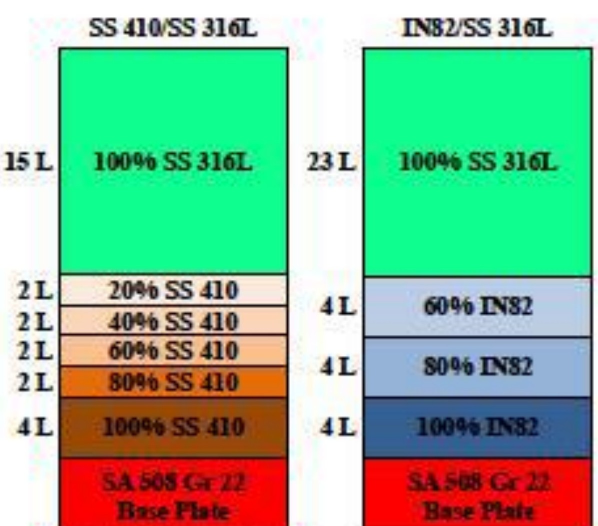
Directed Energy Technologies:

- Good for repair, large structures with high fidelity
- Slow and expensive

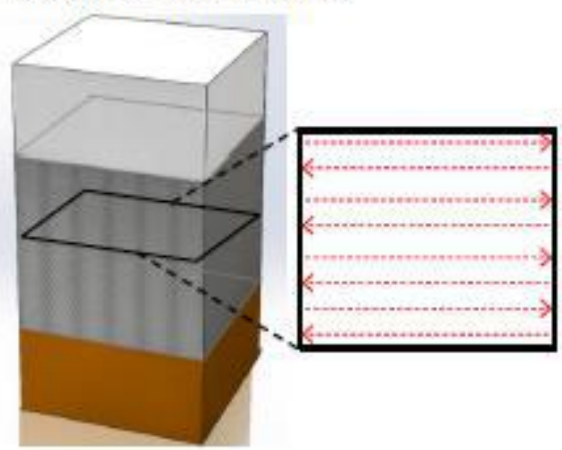


Graded transition joints are fabricated using a co-axial powder blown laser DMD process

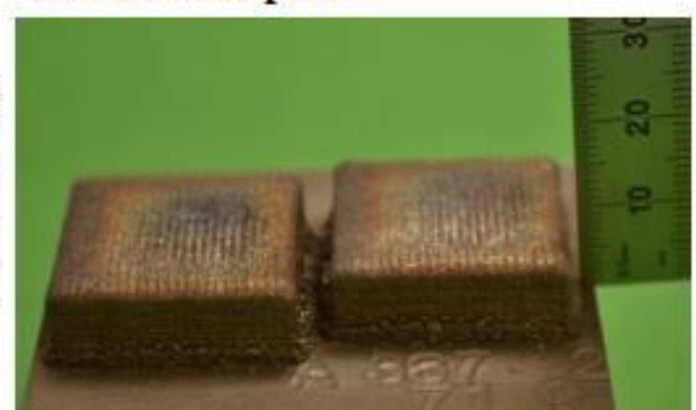
- Transition joints were fabricated using the following parameters
  - Travel speed: 600mm/min
  - Step over: 0.5mm
  - Power: 400W
  - Powder feed rate: 5g/min
- Preheat maintained at 300ºC using a hot plate



A line raster pattern was used for the builds.

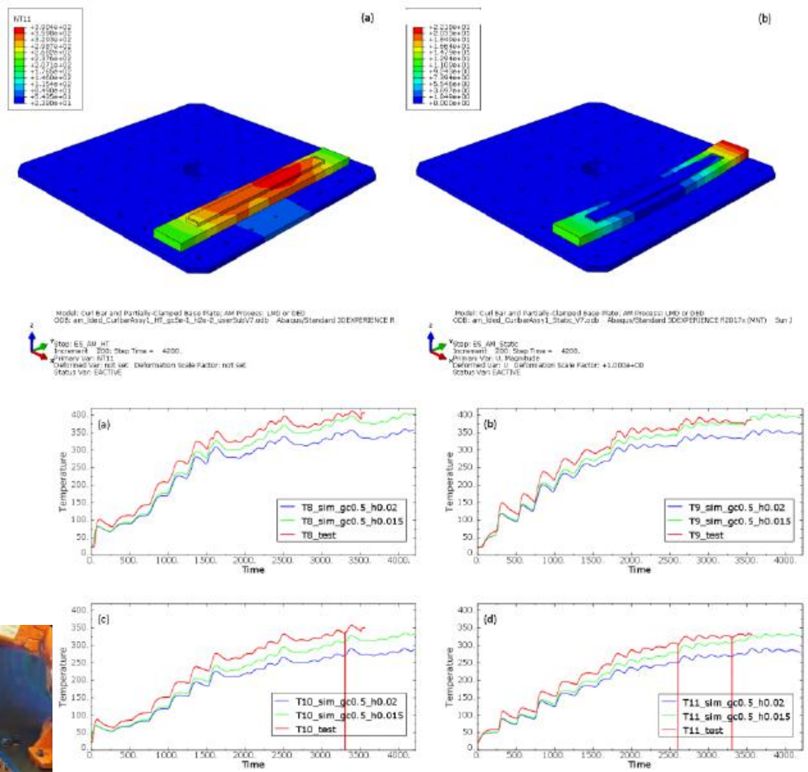


Example builds are shown below; deposited on a SA 508 Gr. 22 ferritic base plate.



Wolf Robotics CRADA

- Robotic MIG arc welding
  - Named Best New Technology at 2016 FABTECH
- Using process modeling and simulation for
  - System design
  - Development of design rules
  - Toolpath generation (thermal based CAD to part)
  - Have manufactured a 400 lb, 7 ft tall steel part
- Demonstrate system at CONEXPO



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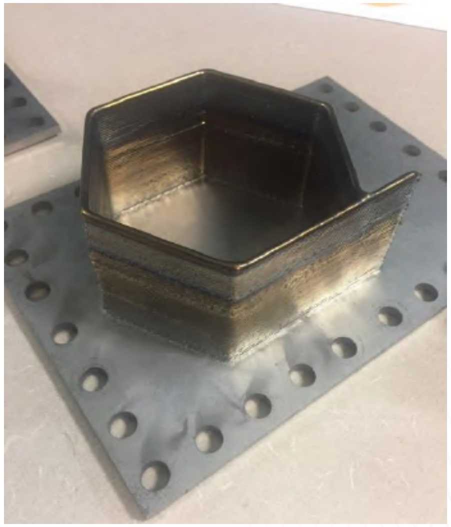
CONEXPO

- Largest construction exhibition in Las Vegas
- Demonstrating multiple technologies
  - Polymer BAAM for CAB
  - Concept Laser for heat exchanger
  - Wolf metal BAAM for stick

ORNL GKN Cooperative R&D:

- Hybrid technologies
  - Experimenting with numerous laser power sources
    - 4 kW Coax wire feed
    - 20 kW side wire feed
    - Two 25 kW laser powder feed (coax, side feed)
  - Developing processing parameters and CAD to part toolpaths
  - Printing titanium test articles for properties
  - Target is 5 ft long printed wing rib by Dec. 2017



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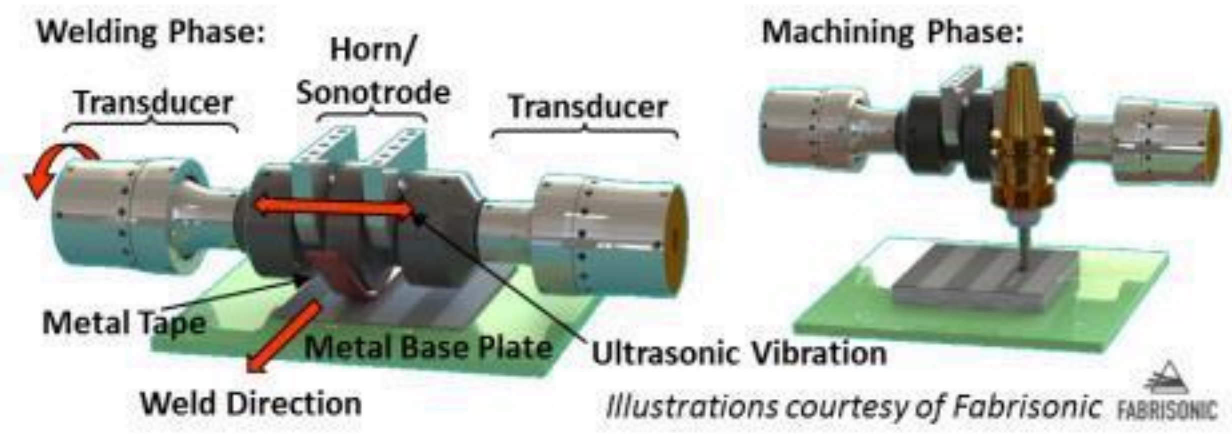
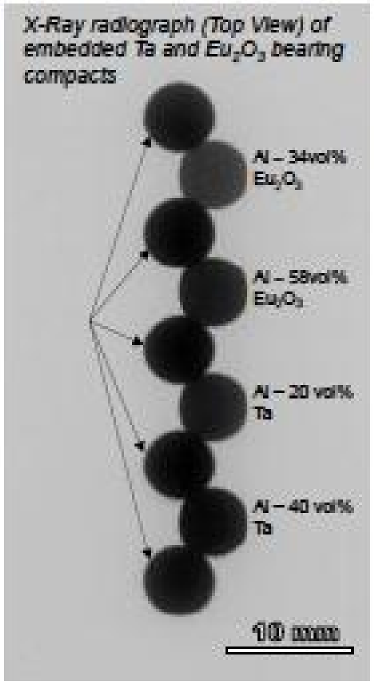
Demonstration of Ultrasonic AM for Part Production in Nuclear Reactors – ORNL LDRD



- **Research Highlight:**
  - ORNL's Manufacturing Demonstration Facility (MDF) has manufactured control rods for HFIR (High Flux Isotope Reactor) using ultrasonic additive manufacturing (AM).
- **R&D Highlights:**
  - The control rods are used for absorbing neutrons in order to shut the reactor down, and are currently made from an aluminum matrix and various oxides.
  - Manufacturing the rods with these materials is a time-consuming process filled with 18 steps and multiple supply-chain issues.
  - Manufacturing the control rods using ultrasonic AM reduces the fabrication process to only 3 steps and enables all parts to be manufactured in the same location, reducing supply-chain obstacles.
- **Results:**
  - MDF researchers have demonstrated the proof-of-concept which is that ultrasonic AM is an efficient way to fabricate HFIR control rods.



Completed HFIR control plate

Questions?


BAAM CI
CONTRIBUTORS
TECHMER
INNOVATION
INNOVATION
FRAGILE
Yale

Additive Manufacturing's Role in Enhancing the Clean Energy Economy Cont.

Innovation

ORNL's 80 kW Inverter module (Left) has **~3.1x** the power density of a Nissan LEAF (Right)

Vehicle Technologies, B. Ozpineci

Part Consolidation

Underwater Robotic Arm with **7 degrees of freedom** is **neutrally buoyant**. By utilizing AM fabrication number of individual components was reduced from **250 to 49**, and weight of each arm from **80 lbs. to 20 lbs.**

ONR, L. Love

Lower Energy Consumption

(BAAM-CI) operates at only **1.17 kWh/kg** is below electron beam, forging, injection molding, and FDM .

DOE-AMO, L. Love

Less Waste

Titanium bracket for aircraft. reduced buy-to-fly ratio (ratio of material weight purchased vs. final component) from **33:1 to < 2:1**

DOE-AMO, B. Peter

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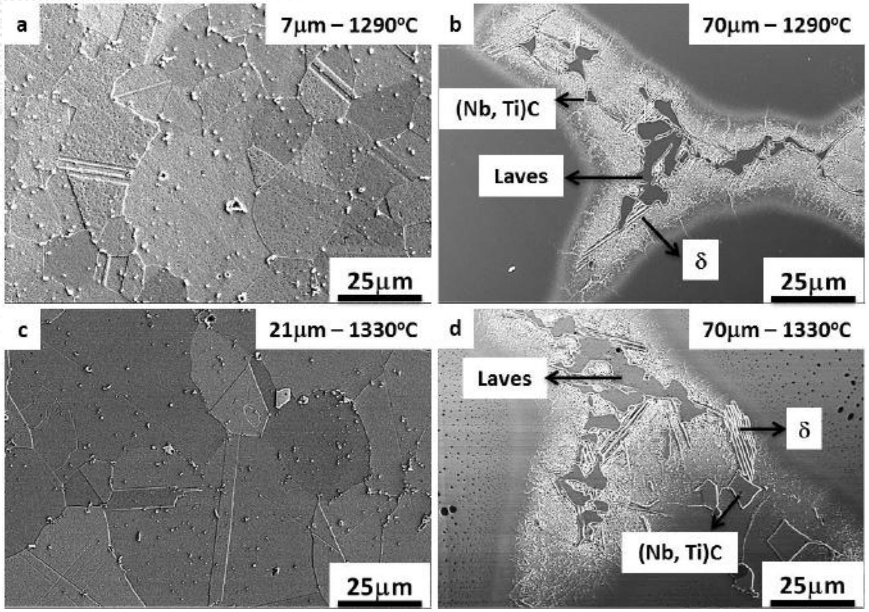
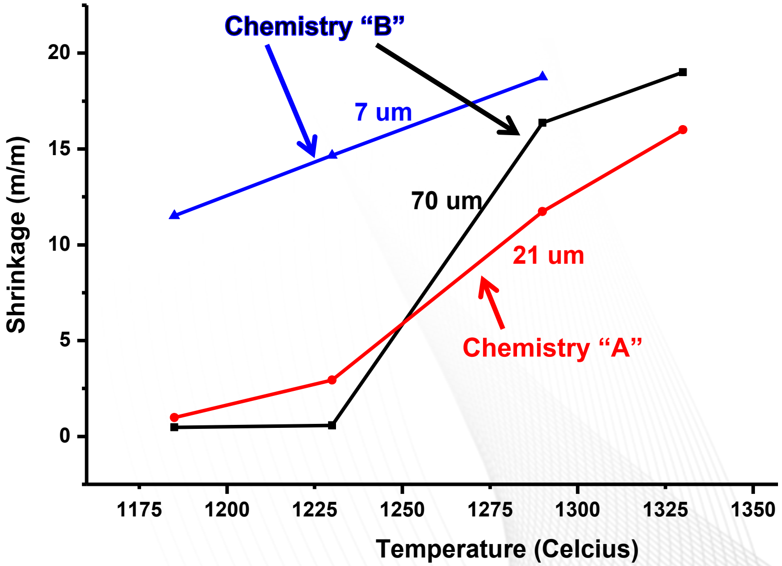
Fully Dense Inconel 718 Binder Jet Components



- **Obstacle:** Difficult to get fully dense components with only applying temperature (no pressure) due to sluggish diffusion kinetics.
- **Solution:** Develop process methodologies based on supersolidus liquid phase sintering to control consolidation and shape.

Change in Linear Shrinkage – Increases with the formation of liquid phase



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