2017 DOE Advanced Manufacturing Office Review Presentation

Manufacturing Demonstration Facility

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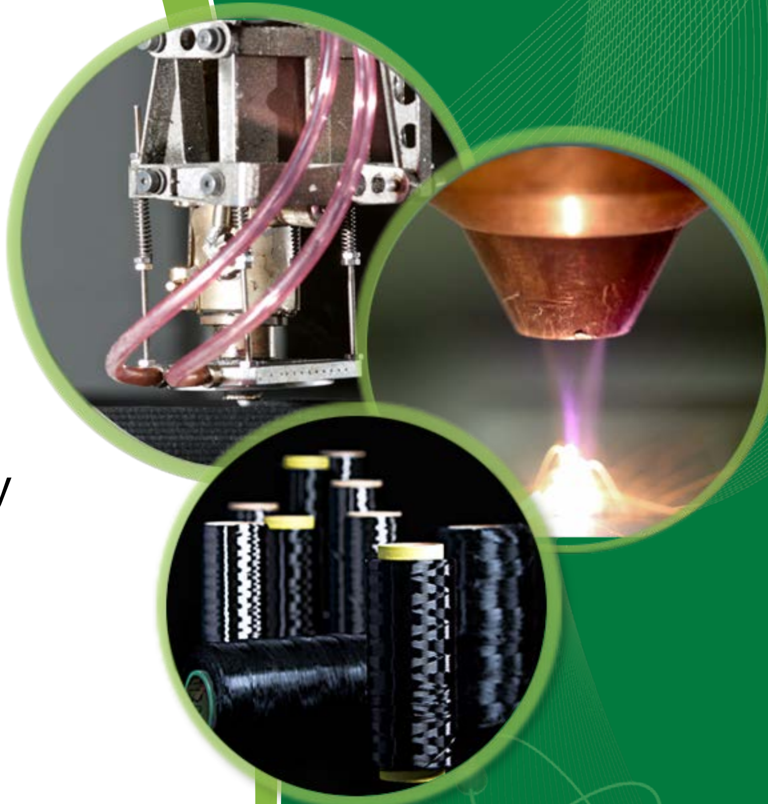

Project ID #

ORNL is managed by UT-Battelle
for the US Department of Energy

OAK RIDGE National Laboratory

Overview

Ever Growing Partnerships: Integrating the AM Supply Chain

Timeline and Budget

- Start Date: October 2011
- FY16 DOE Funding: $16M
- FY17 DOE Planned Funding: $16M
- Industry Meeting DOE with ~1:1 Cost Match
- Total DOE Funds Received to Date: $56M Over 5 Years

Barriers*

- Barriers to commercialization of additive manufacturing include process control, tolerances, surface finishes, processing speed, scalability, materials compatibility, modeling, validation, and demonstration

- **Technical Targets**
  - **Target 6.1:** Demonstrate AM components whose physical properties and cost/value outperform selected conventionally produced parts by 20%.
  - **Target 6.2:** Develop rapid qualification methodologies that reduce certification cost to 25% of the total component cost.
  - **Target 6.3:** Develop next-generation AM systems that deliver consistently reliable parts with predictable properties to six standard deviations ("six-sigma") for specific applications.

Partners

- **168 Industry Partners** to date
- >17,000 Visitors, **>2,500 Companies**
- **9 Other DOE Laboratories**
- **5 Other Federal Agencies**
- Membership and Participation in >**3 of the Manufacturing USA** Institutes

*Source: the Advanced Manufacturing Office Multi-Year Program Plan

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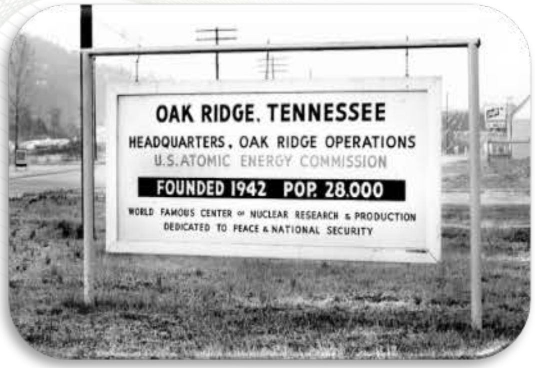
Technical Merit/Innovation

The Manufacturing Demonstration Facility at Oak Ridge National Laboratory



1942: Oak Ridge National Laboratory

- Manhattan Project, “Secret City”
- Over 70 Years Performing Research in Energy and National Security Challenges
- Multidisciplinary teams transforming fundamental research into new technologies and applications.

2017: The Manufacturing Demonstration Facility

Core Research and Development

Leveraging ORNL’s Science Capabilities to Solve Challenges in 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.

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Technical Merit and Innovation

Advanced Manufacturing: High Potential, Early-Stage Technology

Challenges:

Materials

- Costly Material Feedstocks
- Limited Materials
- No AM Developed Materials
- Required Materials Specifications & Practices

Process Limits

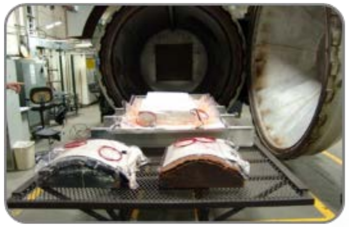
- Limited Sensor Employment
- No Closed Loop Control
- Slow Processing
- Limitations in Build Volumes
- Post-Processing Required

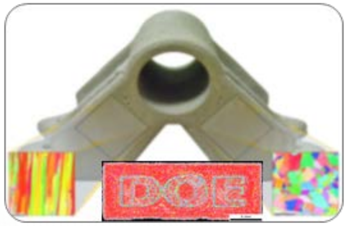
Reliability

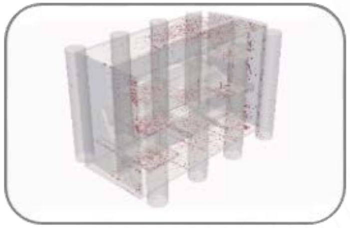
- High Variability
- Lack of Understanding On How Local Microstructure Impacts Properties
- Warping
- Anisotropic Properties

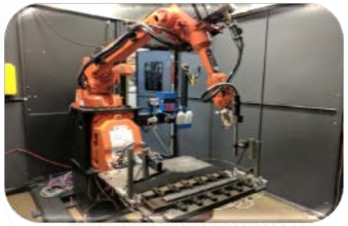
Goals:

- Improved Performance Characteristics of AM Components
- Qualification and Certification of AM Components for Intended End Use
- AM Systems Optimized to Achieve Mainstream Manufacturing Application
- Comprehensive Understanding of AM Process Capabilities and Limits









Technical Merit and Innovation

Leveraging the Laboratory's Signature Strengths

Addressing Challenges in Materials, System & Controls, Characterization, Modeling & Data Analytics for Additive Manufacturing

Neutron scattering: SNS and HFIR
- World's most intense pulsed neutron beams
- World's highest flux reactor-based neutron source

Leadership-class computing: Titan
- Nation's most powerful
  open science supercomputer

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

Advanced manufacturing
- Novel materials
- Advanced processing

- *5 Year Strategic Plan Developed in Collaboration with DOE*
  - *Annual Review of Existing Projects and Proposed Work Plan*
  - *2 Day Annual Peer Review with Committee Selected by DOE*

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Energy and Market Impacts

Enhancing the Clean Energy Economy

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

Innovation

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

Lower Energy Consumption

Big Area Additive Manufacturing Cincinnati Inc. (BAAM-CI) operates at only **1.17 kWh/kg** is less than electron beam, forging, injection molding, and conventional FDM .

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**

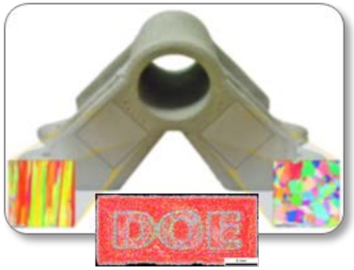
Light-weighting

DOE Study showed the total energy saving per part for a Airbus bracket would be 66 Mbtus over the lifetime of the component from a 65% reduction in weight enabled by additive manufacturing.

Source: *Department of Energy, Quadrennial Technology Review 2015, Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing, Additive Manufacturing, pgs. 4-6*

Objectives and Approach

4 Goals for Enabling Additive Manufacturing

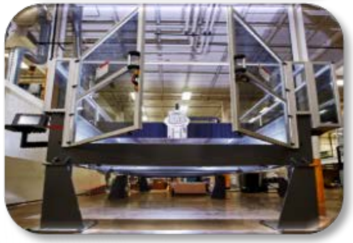


Enhancing Additive Manufactured Components Performance Through Materials Development

- Microstructure Engineering through Precise Process Control and Monitoring
- New Metallic Alloys And Polymers Designed for AM
- Spatially Graded & Hybrid Materials
- Understanding the Role of Feedstock

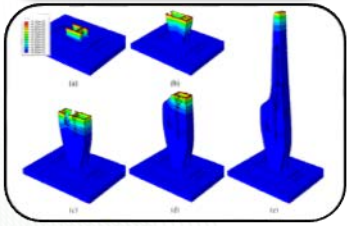
Developing New Methodologies for Certifying Additive Components for Use

- In-Situ Process Monitoring
- Filters and Correlative Data Analysis
- Machine Learning and Uncertainty Quantification
- Integration and Deployment of Rapid Qualification tools



Develop new machines with increased deposition rates, build volumes, and mechanical properties

- Increased Reliability through Better Controls, Hardware, Feedstock and Software
- Next Generation Machines with Capability to Deposit Out of Plane



Develop characterization and Integrated Computational Materials Engineering (ICME) capabilities to advance the understanding of AM.

- Physics Based Simulations
- In-Situ Non Destructive Evaluation and Post Processing Metrology Techniques
- Crystallographic & 3-D Tomographic Information

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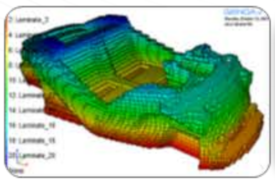
New Equipment

Accomplishments and Progress

*Developing reliable, large-scale additive processes that are **bigger, faster, and cheaper***

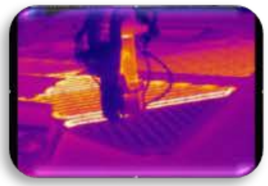
- ✓ Cincinnati System 8’x20’x6’ build volume
- ✓ Ingersoll system up to 100’ x 80’ x 60’
- ✓ Up to 100 lbs/hr (or 1,000 ci/hr)
- ✓ Pelletized feed replaces filament reducing cost up to 50%

Model



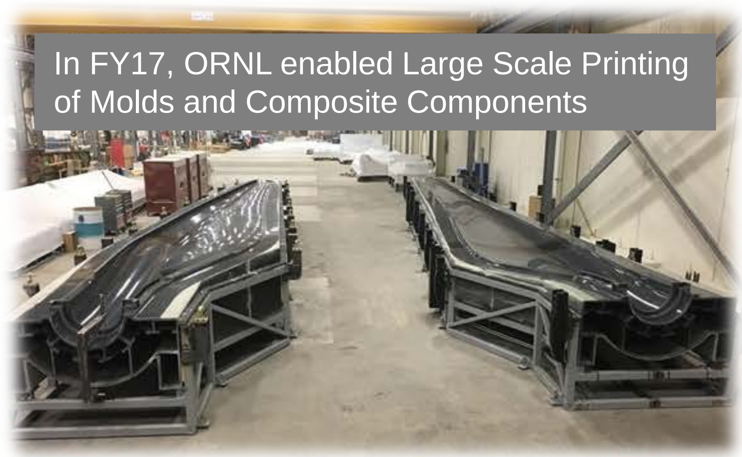
Make

Measure



FY17 System Research Activities

- Baseline Performance Metrics: standard test articles to quantify overhangs, gaps, surface finish, accuracy,
- High speed, high resolution, high performance deposition: hardware and software that enables fine surface finish with course infill
- Five axis deposition: hardware and software to enable out of plane AM.



In FY17, ORNL enabled Large Scale Printing of Molds and Composite Components

2015 R&D 100 WINNER

Cincy Magazine's MANNY AWARDS 2016 Winner Biggest Breakthrough

JEC WINNER OF 2016 INNOVATION AWARD

sme

ASM INTERNATIONAL

CAMX Combined Strength Award Winner – 2015

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Materials Development

Accomplishments and Progress

Developed new classes of materials for large-scale polymer additive manufacturing

AM of Tooling

- Over one-third of U.S. tool, die, and mold establishments have gone out of business. Source: 2012 Congressional Report
- AM provides opportunity to fabricate tools at greatly reduced times and costs
- Develop materials to be used in AM with the required performance for applications

Lightly Loaded and End Use Primary Structures via Additive

- Development of materials systems suitable for end use
- Address fundamental challenges posed by layered AM technologies
- Evaluate materials that could be used in hybrid manufacturing methodologies (additive and conventional composite techniques) to improve design, performance, and fabrication time.

FY17 Research Activities

- Room Temperature and High Temperature Tooling for Transportation Applications (Composites Trim Tool for Aircraft, Autoclave Tools, Compression Molding for Automobiles)
- Bio-Derived Sustainable Composites and Low Density Polymers for Primary Structures

Developed high temperature materials, bio-derived materials, thermosets, foams, and magneto-sensitive materials for tooling and end use structures

ACE Awards for Composites Excellence
2016 Materials and Process Innovation Award Winner

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Accomplishments and Progress

Large-Scale Metal AM System for Steel

Characterization and ICME

New Machines

ORNL is developing large-scale systems for metal deposition with the following capability:

Modeling of the process and Component Performance

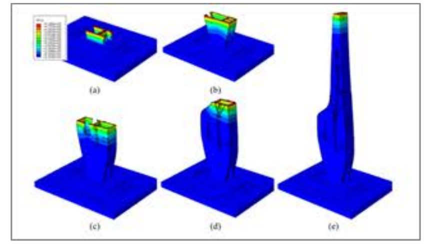
- System design: energy source, manipulator kinematics
- Process refinement: Sensor selection, controls
- Part design: Geometry, predicted stress and distortion

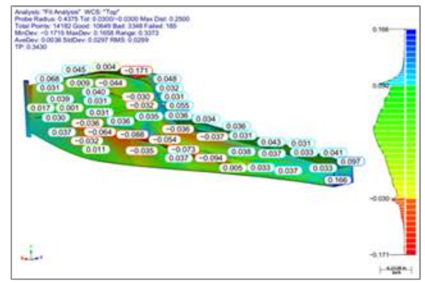
Development of Systems

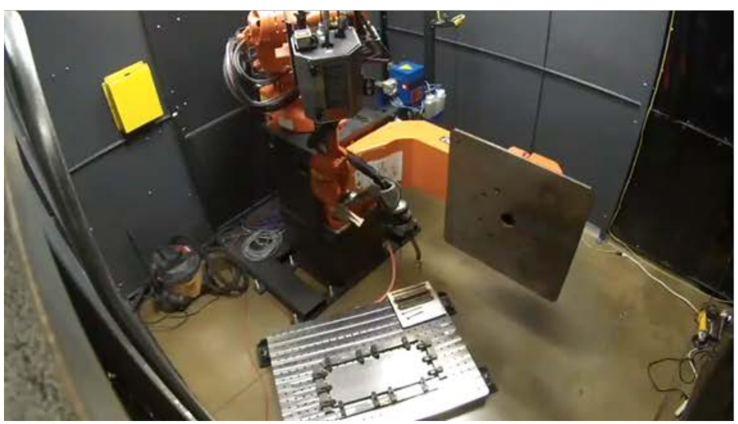
- Prototype systems: Different materials, applications…
- Material: Synthesize material for AM
- Parts: Geometry, predicted stress and distortion

Methodologies for Measuring

- Part distortion during manufacturing: Adaptive control
- Residual stress to validate models: HIFR, SNS







FY17 Research Activities

- Integration of System and Slicing Software
- Thermal Models to Predict Part Distortion
- Process Controls to Maintain Geometry

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Wire Arc Melt and Laser Wire Technologies

Accomplishments and Progress

Improve performance and reliability for widespread adoption of binder-jet AM

Materials Development

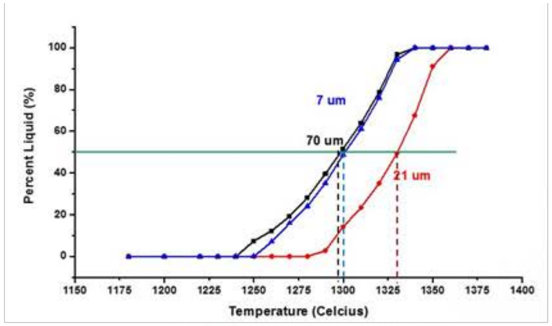
Characterization and ICME

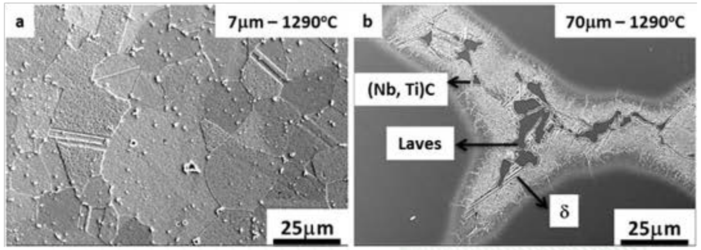
Enhanced Process Modeling
- Understanding effects of powder morphology and size distribution on processing
- Prediction of distortion and shrinkage during densification

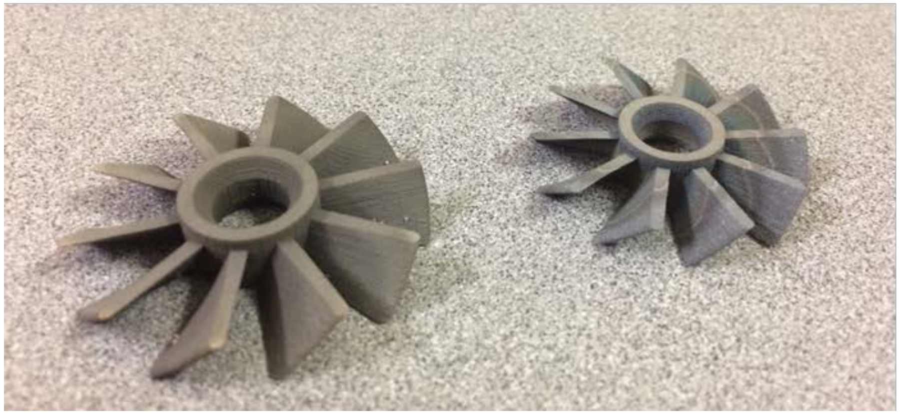
Materials Development
- Fully dense monolithic alloys designed for the AM process
- Hybrid structures not possible though conventional processing
- New binder development for ease of use, reliability, and compatibility with specific alloys

FY17 Research Activities

- Creation of fully-dense H13 tool steel equivalent materials
- Investigation of powder chemistry on liquid phase sintering approaches for full density
- Model development on distortion prediction during consolidation







Fully Dense Single Alloy Materials

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Accomplishments and Progress

High Temperature Materials for Energy Applications

Materials Development

New Methodologies for Certifying

Characterization and ICME

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

Multiscale modeling of Powder Bed processes

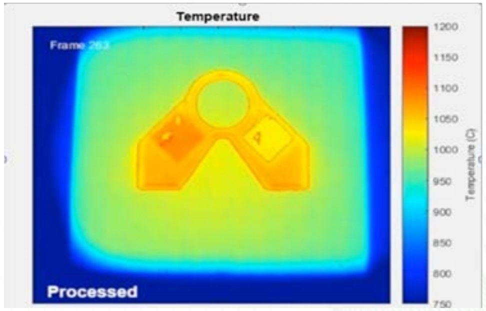
- High fidelity models for solidification, understanding residual stress and precipitation kinetics
- HPC and reduced order models to capture relevant physical phenomena over entire build

Materials deposition and testing

- Understand links between process parameters, microstructure and mechanical behavior
- Design AM specific alloy chemistries for improved properties
- Understanding links between transient thermal behavior and defect formation (porosity and cracking)

Fabrication and Certification of Components

- Manufacture defect free, complex geometry components
- Demonstrate a 3-5% efficiency improvement in land based gas turbines



FY17 Research Activities

- Successful deposition of high γ’ containing Ni-base Superalloys (MARM 247 and IN738)
- Increase high temperature yield strength by 50% compared to IN718

Electron Beam Melting of MARM 247

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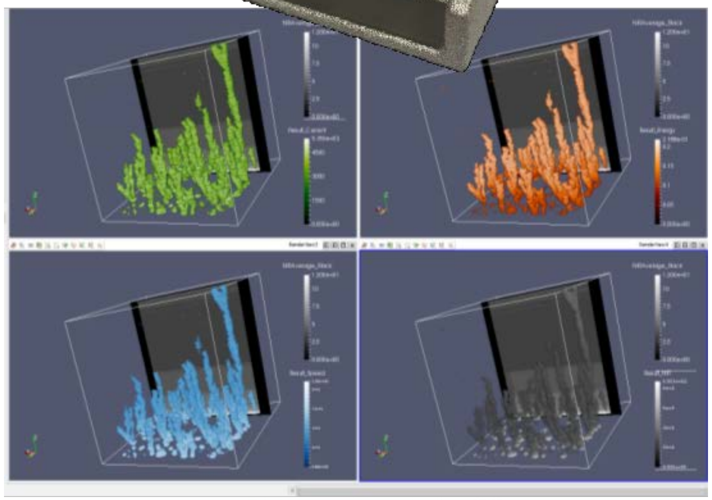
Accomplishments and Progress

Qualification Framework for Additive Components

Creation of a 3D data framework for Additive Manufacturing
- Utilizing DREAM3D in collaboration with AFRL
- Independent of size scale, material or deposition technology

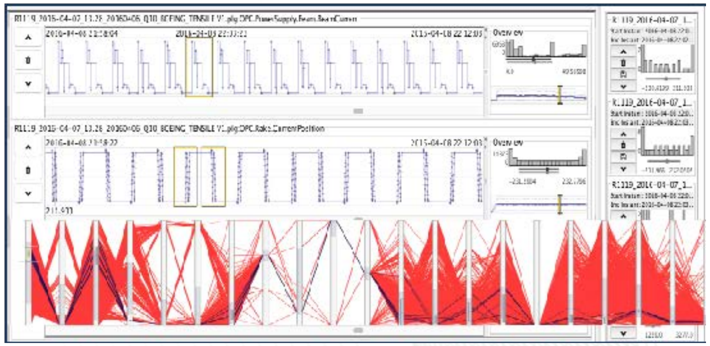
Software tool development
- Broad dissemination of tools to help users understand process variables which govern material quality
- Visualization and statistical correlation methodologies

Certification with Industry
- Novel data driven construct for certification of AM processes as opposed to individual parts: Built-certified components



FY17 Research Activities Include

- Deployment of data tools for powder bed technologies
- Release convolutional neural networks to industry for in-situ data processing
- Predict functionality of Ti-6Al-4V components fabricated by Electron Beam Melting



Transition Plan

This presentation does not contain any proprietary, confidential, or otherwise restricted information.

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Transition Plan

Core R&D Leading to Industry Growth

On-Shoring of a Powder Bed Technology

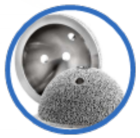
•*Acquisition of Majority Shares by GE*

•HQ moved to Boston

•*Over 8 Technical Collaborations*

July 2012

ORNL, Arcam sign CRADA *to improve process reliability, develop in-situ process monitoring and closed loop control, expand materials systems, increase deposition rate, and increase build volume of the Electron Beam Melting (EBM) technology*



Feb 2013

Arcam and DiSanto Technology sign Strategic Alliance *to accelerate market adoption and penetration of commercially manufactured, finished EBM-based implants and components.*

February 2014

ORNL, Cincinnati sign CRADA *to develop commercial large-scale additive manufacturing (BAAM) system*

June 2014

Arcam launches Nickel Base Superalloy process for 3D printing *The Inconel process is "initially" available for its A2X platform. Arcam's A2X is highly suited for processing high temperature materials and is used for aerospace applications.*

September 2014

Strati car printed live at IMTS Show *on BAAM system,* Cincinnati Inc. sells first BAAM beta system

January 2015

In collaboration with Oak Ridge National Laboratory, **Honeywell became the first company** to use electron beam melting (EBM) to produce an **aerospace component from Inconel 718**

January 2015

Cincinnati delivers next-generation BAAM system to MDF

Shelby Cobra goes global

September 2015

Additive Manufactured Integrated Energy (AMIE), 3D Printed House and Utility Vehicle forOff the Grid: Integration of Natural Gas and Solar

March 2016

Inauguration of Woburn, MA Office

- *CEO Relocates to US*
- *50% Arcam employees in North America*
- *Acquisition of DiSanto and AP&C*
- *Dramatic expansion of installed EBM systems*

September 2016

ORNL receives GUINNESS World Record award for Boeing 777x trim tool, the largest single 3D printed component, now being used on Boeing production floor

November 2016

"GE to buy SLM, Arcam for $1.4billion in 3D printing push" -CNBC

- *GE offered 5.86 billion crowns or $685M for the purchase of ARCAM*
- *GE holds >73% of Arcam shares in November*

January 2017

TPI uses 3D printed mold to fabricate wind turbine blade for the 1st time

Creation of an Industry

•13 Units Sold

•*Over 7 AM Equipment Manufacturers Using/Evaluating Technology*

•*Over 25 Technical Collaborations*

•*10s to 100s of End Users Evaluating the Technology*

•*New Materials Suppliers*

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Transition Plan

Birth of a Large Scale Polymer Industry

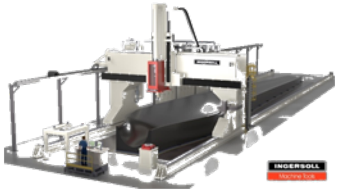
- ***Cincinnati Inc*** has sold 13 BAAM machines (licensed technology)
  - Purchased startup out of MIT to introduce SAAM (Small Area Additive Manufacturing)
  - Aerospace (Lockheed, Textron), Automotive (Local Motors), Material providers (Sabic), Academia (UTEP – America Makes), NIAR (aero), AES (tooling), TSN (auto)
- ***Cosine Additive*** startup initiated after seeing the BAAM at IMTS
- ***Wolf Robotics*** developed a robotic polymer BAAM
- ***Ingersoll Machine Tool*** is developing a very large BAAM (WHAM)
- ***Thermwood*** is manufacturing Large Scale Additive Manufacturing (LSAM)
- ***Strangepresse*** is manufacturing extruders for BAAM (license)

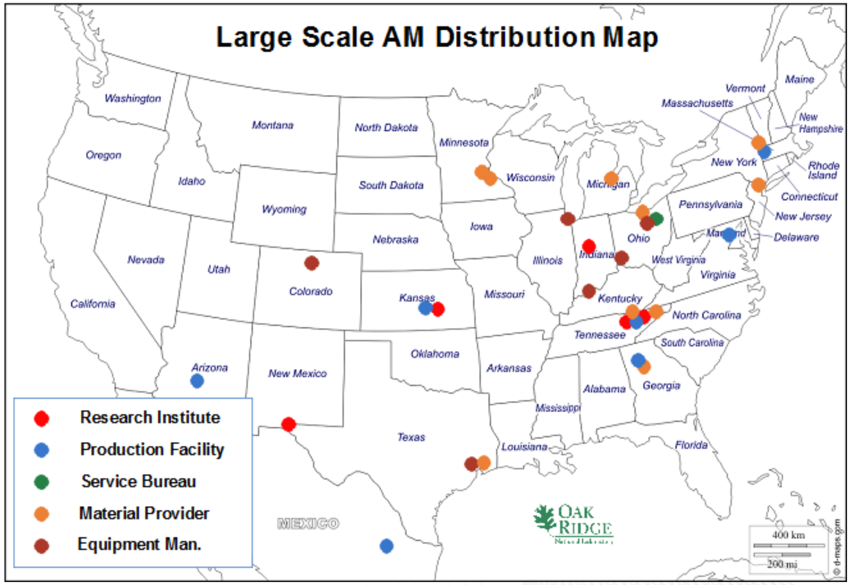

Wolf BAAM


Thermwood LSAM


Strangepresse extruders


CI BAAM


Ingersoll WHAM



Materials

Equipment

End Users

Transition Plan

Technical Collaborations Program

Explore	Engage	Execute
• Opportunity for industry to discover and apply new manufacturing technologies	• Work with MDF staff to develop scope of work	• Phase 1 $40K, Phase 2 $200K • 1:1 Cost Match • Non-Negotiable CRADA • ~90-day cycle time from review to a signed agreement

Company Size

- **57 small/medium**
- **52 large**

Quick Facts

- >100 active or completed projects across 7 technologies
- >60 completed projects
- >75 publications this year
- >17,000 visitors

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STEM

Post Docs and Technician Interns

109 students Summer 2016

- 80 Students Summer of 2015
- 50 Students Summer of 2014
- Teams of 5 Take on Projects
- High School to Graduate Students
- Projects Include Prosthetics, Robotic Design, Software for AM, Efficient Propeller Design, etc.

2016 FIRST Robotics

- >750 students engaged, 26 teams FRC
- Over 5 Years of Mentorship
- 3 High Schools Use MDF on Nightly Basis, 50 to 200 Students FRC
- Most Recent Trends in Manufacturing

Governor's Chair in Advanced Manufacturing at The University of Tennessee

Dr. Suresh Babu
Mechanical, Aerospace & Biomedical Eng. (Ohio State) light weight metals *additive manufacturing*

Dr. Uday Vaidya
Mechanical, Aerospace & Biomedical Eng. (UAB) *composites manufacturing*

THE UNIVERSITY OF TENNESSEE KNOXVILLE

- Undergraduate and Graduate Students Performing Research in Advanced Manufacturing (~40 Students)
- IUCRC (the Ohio State University, the University of Tennessee, etc.)

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Summary Slide

Objective

- Enhancing additive manufactured components performance through materials development
- Developing new methodologies for certifying additive components for use
- Develop new machines with increased deposition rates, build volumes, and mechanical properties
- Develop characterization and Integrated Computational Materials Engineering (ICME) capabilities to advance the understanding of AM

Accomplishments

- Enabled a large-scale polymer additive manufacturing industry
- Development of multiple polymers for additive manufacturing of tooling and primary structures
- Developed commercial large scale metal additive manufacturing system for steel structures
- Development of high temperature nickel superalloys in electron beam melting
- Qualification framework for additive components
- Fully dense nickel alloy binder jet components and initiated models to predict distortion during sintering

- **Transition**
- New markets in AM materials, equipment, and end users from MDF technology developments
- Over 17,000 visitors and 2,600 companies to the MDF (>6,200 visitors last year)
- 109 Technical Collaborations (29 CRADAs initiated last year)
- >75 publications and 50 reports last year
- 29 patent applications with 12 technologies licensed