Manufacturing Demonstration Facility

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This presentation does not contain any proprietary, confidential, or otherwise restricted information.
Today, ORNL is a leading science and energy laboratory
The Manufacturing Demonstration Facility at Oak Ridge National Laboratory

Core Research and Development
- R&D in materials, systems, and computational applications to develop broad applications 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
AM is an exciting, high-potential technology that is in the embryonic stage of development.

**Challenges with additive manufacturing technologies and deployment include**

**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

*Most companies do not have the background and resources required to mature the technologies or commercialize additive manufactured components.*
MDF Strategic Plan 2016-2021

MDF Mission

Develop and mature additive manufacturing and composite technologies for clean energy applications.

MDF Vision

A competitive America using additive and composite processes in mainstream manufacturing industries to achieve carbon neutrality and energy independence.

Goals

1) Improved Performance Characteristics of AM Components

2) Qualification and Certification of AM Components for Intended End Use

3) AM Systems Optimized to Achieve Mainstream Manufacturing Application

4) Comprehensive Understanding of AM Process Capabilities and Limits
Improved Performance Characteristics of AM Components

Background and Motivation
• Most materials used in AM were designed for conventional processes. However, AM enables development of new materials with highly tailored, superior performance.

Objectives
• Materials designed for AM that improve the performance of components for energy applications and lightweight vehicles.

Challenges & Mitigations
1) Microstructure Engineering through Precise Process Control and Monitoring
2) New Metallic Alloys And Polymers Designed for AM
3) Spatially Graded & Hybrid Materials
4) Understanding the Role of Feedstock
Qualification and Certification of AM Components for Intended End Use

Background and Motivation

• Although AM has demonstrated complex geometries capable of high performance, few AM components are currently manufactured and used due to the challenges and costs in certification.

Objectives

• Framework of in-situ NDE, new post characterization techniques, and data analytics in order to detect defect formations and heterogeneity.

Challenges & Mitigations

1) In-Situ Process Monitoring
2) Filters and Correlative Data Analysis
3) Machine Learning and Uncertainty Quantification
4) Integration and Deployment of Rapid Qualification tools
AM Systems Optimized to Achieve Mainstream Manufacturing Application

Background and Motivation

- AM systems are limited by the costs of materials, rates of fabrication, reliability of processes, integration with other processes and limitations in layer-by-layer deposition.

Objectives

- Next generation systems explore controls, hardware, feedstock condition, and software to develop new machines with high deposition rates, large build volumes, and improved properties.

Challenges & Mitigations

1) Reliability
2) Next Generation Machines (e.g., out of plane)
3) Expansion of Process Systems: New Materials
4) Large-Scale Metal Systems
Advanced Characterization Techniques and Modeling for Understanding of AM

Background and Motivation
• Additive manufacturing technologies typically result in non-homogeneous microstructures and non-uniform material properties. Capabilities must be developed that can rapidly expand the methods in which we capture, analyze, and use information about the material.

Objectives
• Develop new characterization technologies capable of rapidly extracting information at both new rate and length scales and develop advanced ICME approaches to advance the understanding of AM.

Challenges & Mitigations
1) Development, Implementation, and Validation of AM Specific Workflow
2) Crystallographic & 3-D Tomographic Information
3) Physics Based Simulations
4) In-Situ NDE and Post Processing Metrology Techniques
High Temperature Metals AM

Increased Performance, Processing Challenges

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.
HPC Modeling to Determine Process Parameters for Controlled Texture in AM Components

**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.
Developing Data Analytics Framework for Additive Manufacturing

- **Obstacle:** Spatial-temporal changes in process parameters and complexity in parts make qualification of additive components costly and difficult.
- **Solution:** Develop computational framework to analyze and visualize data from in-situ sensors in order to qualify and certify 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.
Big Area Additive Manufacturing (BAAM)

• **Obstacle:** Most additive processes are slow (1-4 in³/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
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.
ORNL’s digitally manufactured, high temperature thermoplastic molds withstood industrial autoclave cycles for the first time ever!

**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.
Additional highlights

- Low cost, energy source for AM
- Full consolidation of Inconel 718 with Binder Jet
- Printing with bio-derived materials
- High temperature composite tooling
- Wind turbine blade mold
- New Binder Jet casting materials
- 3D printed two magneto sensitive materials
- New visualization and analysis tools for electron beam powder bed
  - heading toward certification/qualification
- Demonstrated six new Nickel based alloys for Electron Beam
- Test printed 8 new metal powders
- Demonstrated columnar and equiaxed material in a single component for improved performance
- Release of in-situ process monitoring algorithms to US-based industry
- Test printed 22 new polymer materials including 7 bio-based composites
- Injection mold tooling at 60% cost reduction with 25% improvement in production rate
- High efficiency and high temperature fuel injectors
- Printed a house and vehicles
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%.

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

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

**DOE-AMO, 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**
Technical Collaborations Program
The MDF Model

**Explore**
- Opportunity for industry to discover and apply new manufacturing technologies

**Engage**
- Work with MDF staff to develop scope of work

**Execute**
- Simplified on-line application
- Phase 1 $40K, Phase 2 $200K
- 1:1 Cost Match
- Non-Negotiable CRADA
- ~90-day cycle time from review to a signed agreement

**Additive Manufacturing**
Drawing on its close ties with industry and world-leading capabilities in materials development, characterization, and processing, ORNL is creating an unmatched environment for breakthroughs in both metal and polymer additive manufacturing, or 3D printing.

**Carbon Fiber and Composites**
New manufacturing processes for low-cost precursor development technologies hold the key to reducing carbon fiber cost for energy applications. Similarly, innovative performance-focused materials and processes can potentially drive significant performance improvements for national security applications.

www.ornl.gov/manufacturing
Supporting Industry and R&D with a Wide Range of AM Capabilities

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<th>Electron Beam Melting</th>
<th>Laser Sintering</th>
<th>Laser Blown Powder Deposition</th>
<th>Binder Jetting</th>
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<tr>
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<td>Multi-head Photopolymer</td>
<td>Large-Scale Polymer Deposition</td>
<td>Future Systems</td>
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<td><img src="MakerBot.png" alt="Image" /></td>
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**Supporting Companies**

- Arcam AB
- ConceptLaser
- DM3D
- ExOne
- Oak Ridge National Laboratory
- MakerBot
- AFINIA
- OBJET
- Cubify
- Stratasys
- Cincinnati
- Cosine
Ever Growing Partnerships: Integrating the AM Supply Chain
MDF Quick Stats

102 projects and counting

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

Company Size

• 56 small, medium
• 34 large

Cumulative Visitor Total

>12,000 to date

FY 12 | FY 13 | FY 14 | FY 15 | FY 16 to date
---|---|---|---|---
451 | 1899 | 2812 | 4602 | 3225
An Example of Core R&D Leading to Industry Growth

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.

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

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.

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.

Inauguration of Woburn, MA Office
• CEO Relocates to US
• 50% Arcam employees now in North America
• Recent acquisition of DiSanto and AP&C
• Dramatic expansion of installed EBM systems at aerospace, NNSA and medical device companies

"With the MDF and your help, we have been able to reach world leading research as well as a lot of potential customer”

...“strong development has to a great extent been possible due to your firm [MDF]”...
Setting the Pace for Large-Scale Polymers
24 Months of Innovation

Dec 2013
ORNL, Local Motors sign CRADA to produce the world's first production 3D printed vehicle

Feb 2014
ORNL, Cincinnati sign CRADA to develop commercial large-scale additive manufacturing (BAAM) system

Sept 2014
• Strati car printed live at IMTS Show on BAAM system
• Cincinnati Inc. sells first BAAM beta system

Jan 2015
Cincinnati delivers next-generation BAAM system to MDF
Shelby Cobra goes global

May 2015
Local Motors breaks ground on Knoxville micro-factory co-locates with MDF

Sept 2015
• Additive Manufactured Integrated Energy (AMIE)
• 3D Printed House and Utility Vehicle
• Off the Grid: Integration of Natural Gas and Solar

Media Mentions for Jan 2015-current
• 726 articles
• >300,000 YouTube views
• 239 social media
• >50 broadcasts
• Most viewed video in ORNL history

National and International coverage!
Industry Fellows: Engaging Industry and National Labs

- David Dietrich (Boeing)
- Jonaaron Jones (Boeing)
- Frank Medina (Carnegie Mellon)
- Roger England (Cummings)
- James Earle (Local Motors)
- David Riha (Local Motors)
- Kurtis Hodge (Local Motors)
- Sid Palas (Lockheed Martin)
- Sergey Mironets (United Technologies)
- John O'Connell (Cosine)
- Zeke Sudbury (Cincinnati)
- Bradley Jared (Sandia National Laboratories)
- Eddie Schwalbach (Air Force)
- Kelly Thompson (Air Force)
- Lance Hall (AMRDEC)
- Omar Abdelaziz (NASA)
STEM
Science, Technology, Engineering & Mathematics

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

DOE-AMO enabled
- 400 desktop printers 2014 FIRST Robotics
- Partnering with America Makes
- Initiated the Robotics Internship Program this year

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.

FY15-16 Activities
Developing Continued Research with Students Throughout the Year

- High School: **3 high school students**
- Undergraduate: **22 Undergraduates** that are working with us throughout the year.
- Graduate: **19 Graduate students** throughout the year.
- IUCRC and other activities: Ohio State, WPI, and 2 More Students at the University of Tennessee
- Post Doctoral: **14 post docs that are full time at the MDF**
- In Addition: Industrial visiting researchers
Strategic Investment in Advanced Manufacturing R&D:

2013
Dr. Suresh Babu
Mechanical, Aerospace & Biomedical Eng. (Ohio State)
light weight metals additive manufacturing

2014
Dr. Art Ragauskas
Chem. Biochem Eng. (Georgia Tech)
biopolymers and carbon fiber

2015
Dr. Uday Vaidya
Mechanical, Aerospace & Biomedical Eng. (UAB)
composites manufacturing

2015
Dr. Chad Duty
Mechanical, Aerospace & Biomedical Eng. (Virginia Tech)
composites 3D printing additive manufacturing

2015
Dr. Brett Compton
Mechanical, Aerospace & Biomedical Eng. (UCSB) hybrid materials
RAMP-UP
Research for Additive Manufacturing Program – University Partnerships

- 9 awards for university professors and student support from over 30 applications
- Aligned with MDF core research in additive manufacturing
- Internships at the MDF (Student and Faculty)

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<td>Baylor University</td>
<td>Douglas Smith</td>
<td>Predictive Engineering for Discrete Fiber Polymer Composites in Large Scale FDM Processes</td>
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<td>David Jack</td>
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<td>Georgia Tech</td>
<td>Tom Kurfess</td>
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<td>Penn State</td>
<td>Tarasankar DebRoy</td>
<td>Rapid Deposition Rate and Solidification Structure Control During Additive Manufacturing</td>
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<td>Tennessee Technological University</td>
<td>Holly Stretz</td>
<td>Improving Interfacial Strength of 3-D Printed ABS Weld Lines</td>
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<tr>
<td>The George Washington University</td>
<td>Saniya LeBlanc</td>
<td>Next Generation Energy Devices with Selective Laser Melting of Thermoelectric Materials</td>
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<td>The University of Tennessee</td>
<td>Mark Dadmum</td>
<td>Scalable Reactive Engineering Processes to Fabricate Robust Polymer Structures by FDM</td>
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<tr>
<td>University of California, Santa Barbara</td>
<td>Tresa Pollock</td>
<td>A New High-Resolution 3D Mesoscale Characterization Approach for Additively Manufactured Structures</td>
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<td>University of Southern California</td>
<td>Qiang Huang</td>
<td>Robust and Smart Control of Additive Manufacturing Processes for High Geometric Accuracy</td>
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<td>Virginia Tech</td>
<td>Scott Case</td>
<td>Models for Mechanical Performance of Composites Made Using Fused Filament Fabrication</td>
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