Manufacturing Demonstration Facility

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Advanced Manufacturing Office
Peer Review
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2016 PROJECT PEER REVIEW
U.S. DEPARTMENT OF ENERGY
ADVANCED MANUFACTURING OFFICE

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

OAK RIDGE National Laboratory

Today, ORNL is a leading science and energy laboratory

- $1.5B budget
- 4,600 employees
- $750M modernization investment
- Nation's largest materials research portfolio
- 3,200 research guests annually
- Nation's most diverse energy portfolio
- Forefront scientific computing facilities
- World's most intense neutron source
- World-class research reactor
- 1,845 journal articles published in CY15
- Managing billion-dollar US ITER project
- 198 invention disclosures in FY15
- 66 patents issued in FY15

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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

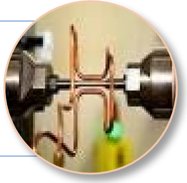
- Cooperative research to develop and demonstrate advanced manufacturing to industry in energy related fields

Education and Training

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

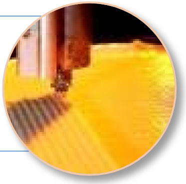
Neutron scattering: SNS and HFIR

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



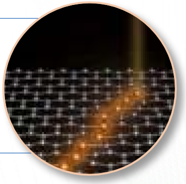
Advanced Materials

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



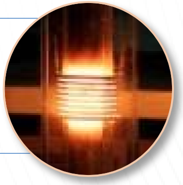
Leadership-class computing: Titan

- Nation's most powerful open science supercomputer



Advanced Manufacturing

- Novel materials
- Advanced processing



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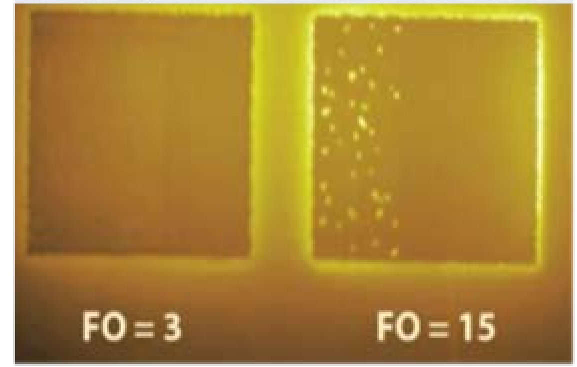
AM is an exciting, high-potential technology that is in the embryonic stage of development

Warping in Conventional Materials


Columnar Grain Growth



Porosity Due to Focus Offset Values

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.

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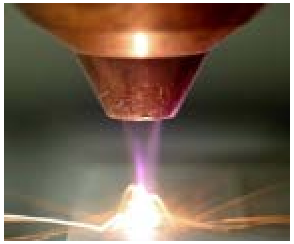
MDF Strategic Plan 2016-2021

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

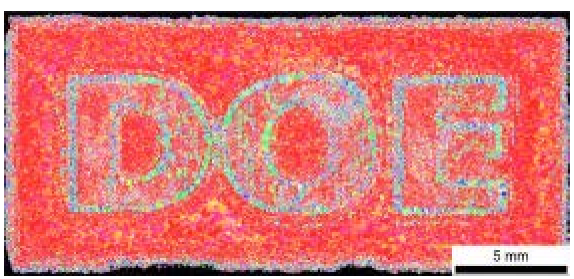
- Most materials used in AM were designed for conventional processes. However, AM enables development of new materials with highly tailored, superior performance.

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



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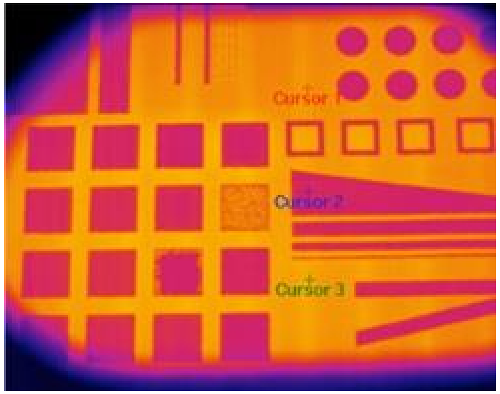
Qualification and Certification of AM Components for Intended End Use

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.

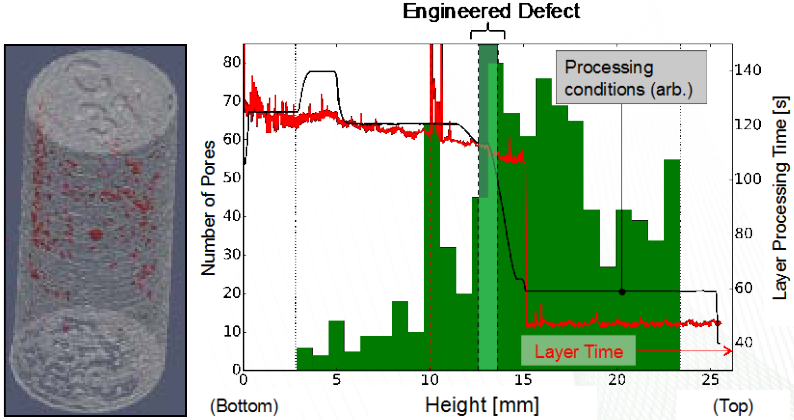
Objectives

- 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



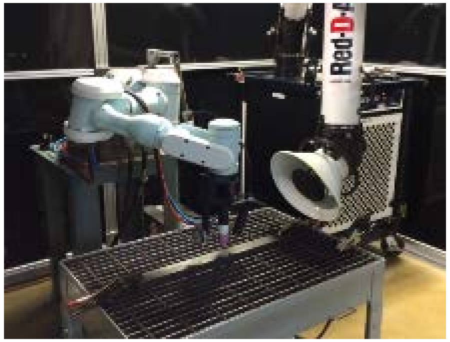
AM Systems Optimized to Achieve Mainstream Manufacturing Application

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

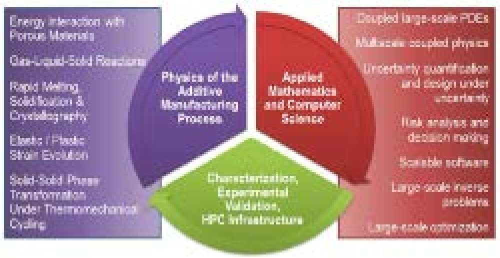
- Additive manufacturing technologies typically result in non-homogeneous microstructures and non-uniform material properties. Capabilities must be developed that can rapidly expand the methods in which we capture, analyze, and use information about the material.

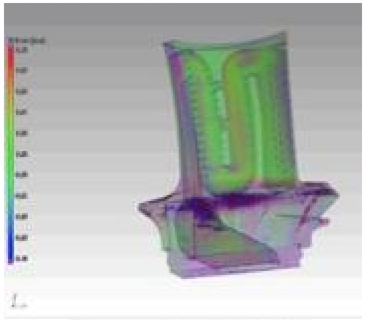
Objectives

- 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





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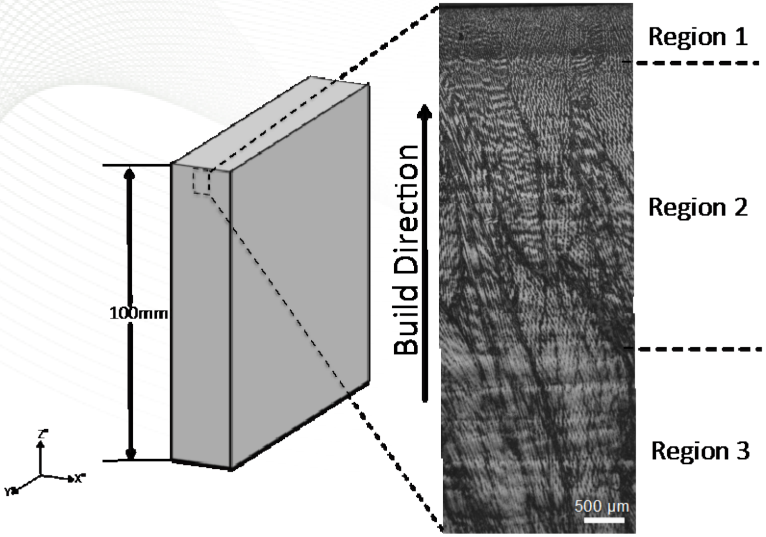
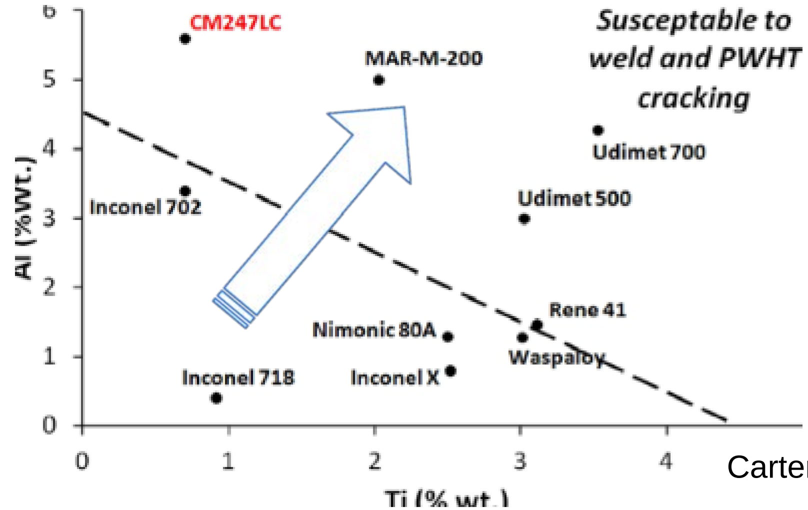
High Temperature Metals AM

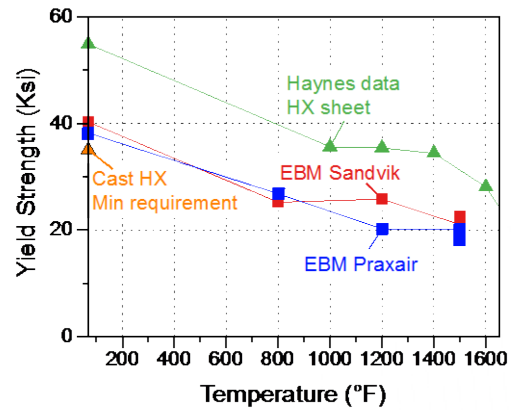
Increased Performance, Processing Challenges

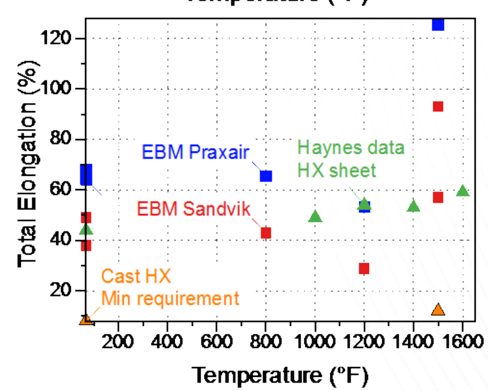




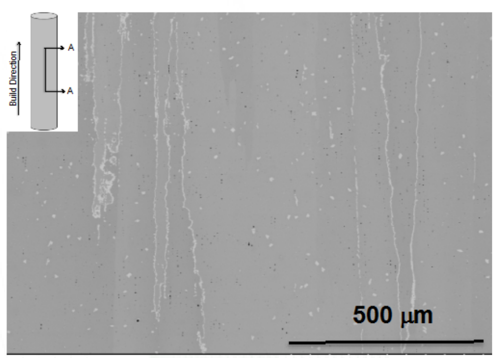
Carter (2012)

- **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.



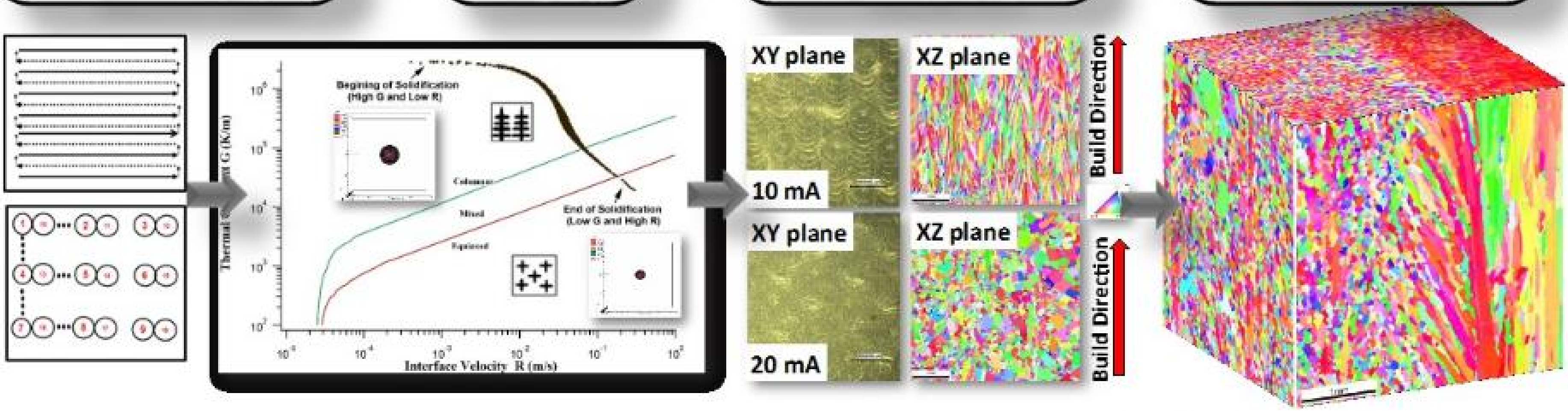


Electron Beam Powder Bed Deposited Inconel X

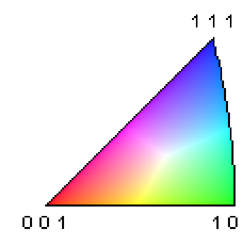


HPC Modeling to Determine Process Parameters for Controlled Texture in AM Components

PROCESS PARAMETERS CONTROL SOLIDIFICATION IN ELECTRON BEAM ADDITIVE MANUFACTURING → DESIGN NOVEL MELT SCAN STRATEGY → HIGH PERFORMANCE COMPUTING TO UNDERSTAND SOLIDIFICATION BEHAVIOR AS FUNCTION PARAMETERS → NUMERICALLY OPTIMIZE THE PROCESS FOR SITE SPECIFIC CRYSTALLOGRAPHIC TEXTURE CONTROL IN ACTUAL PARTS



- **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.



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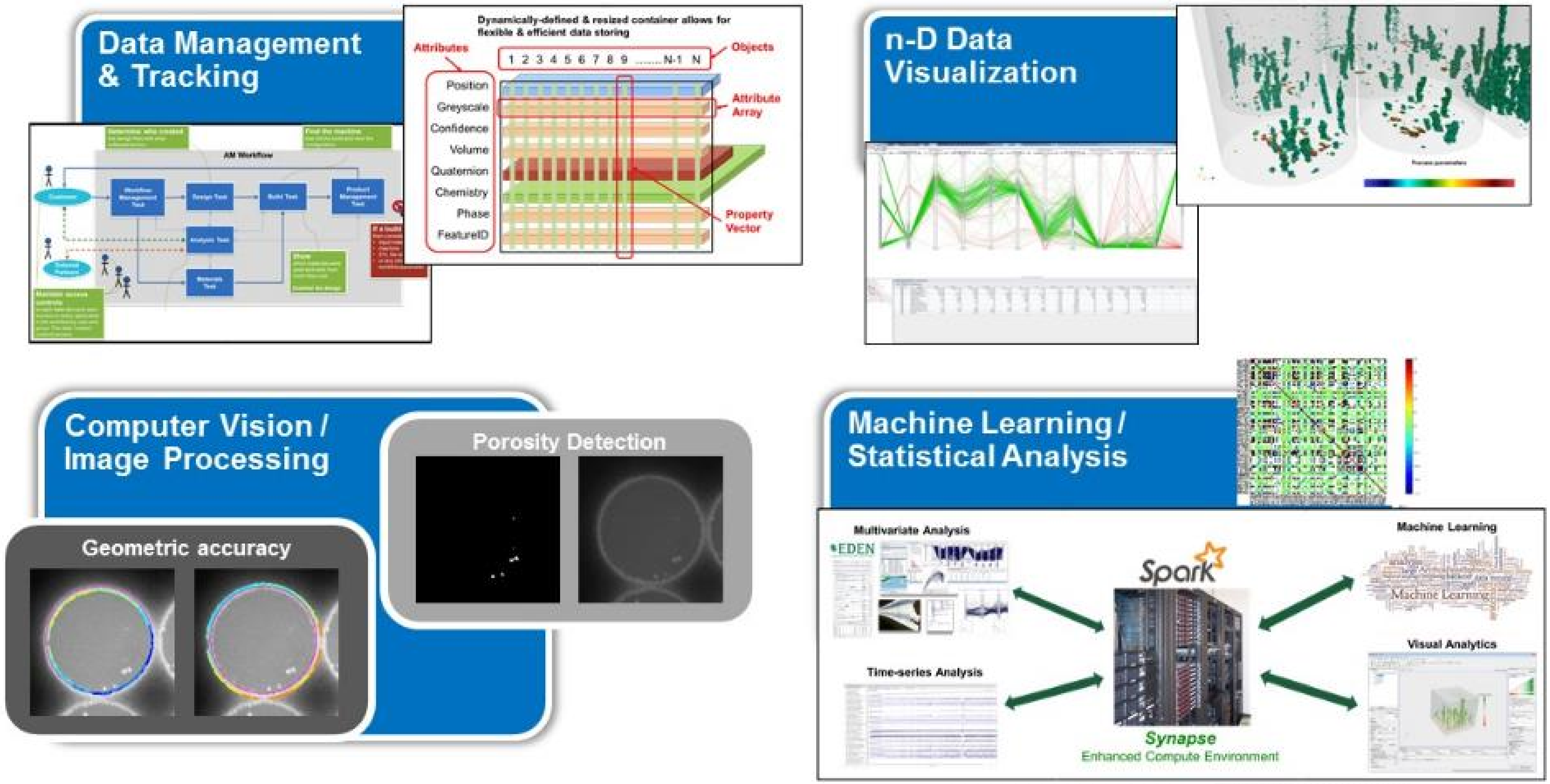
Developing Data Analytics Framework for Additive Manufacturing



- **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.

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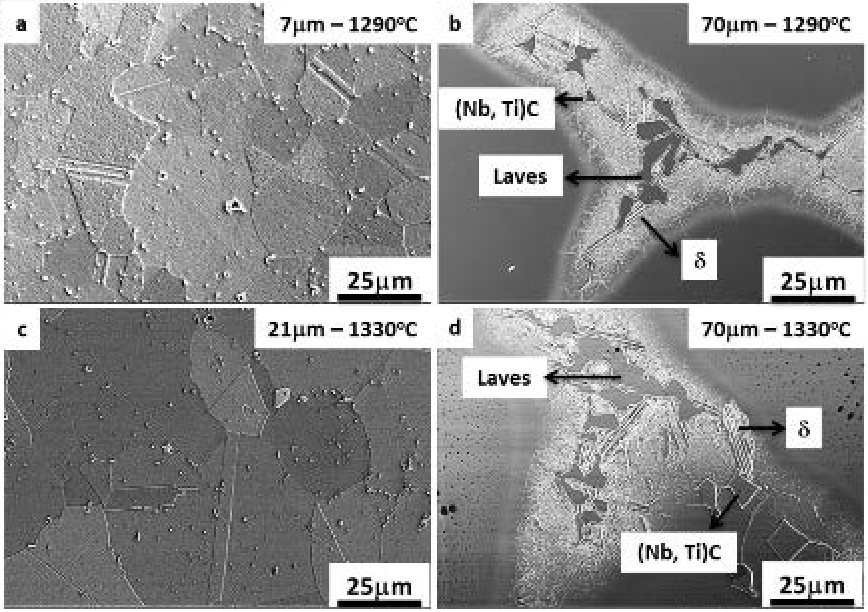
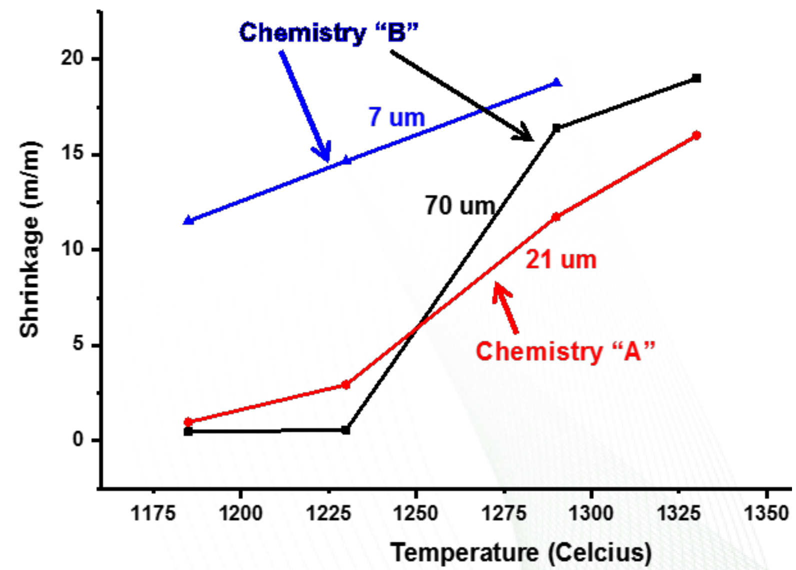
Fully Dense Inconel 718 Binder Jet Components



- **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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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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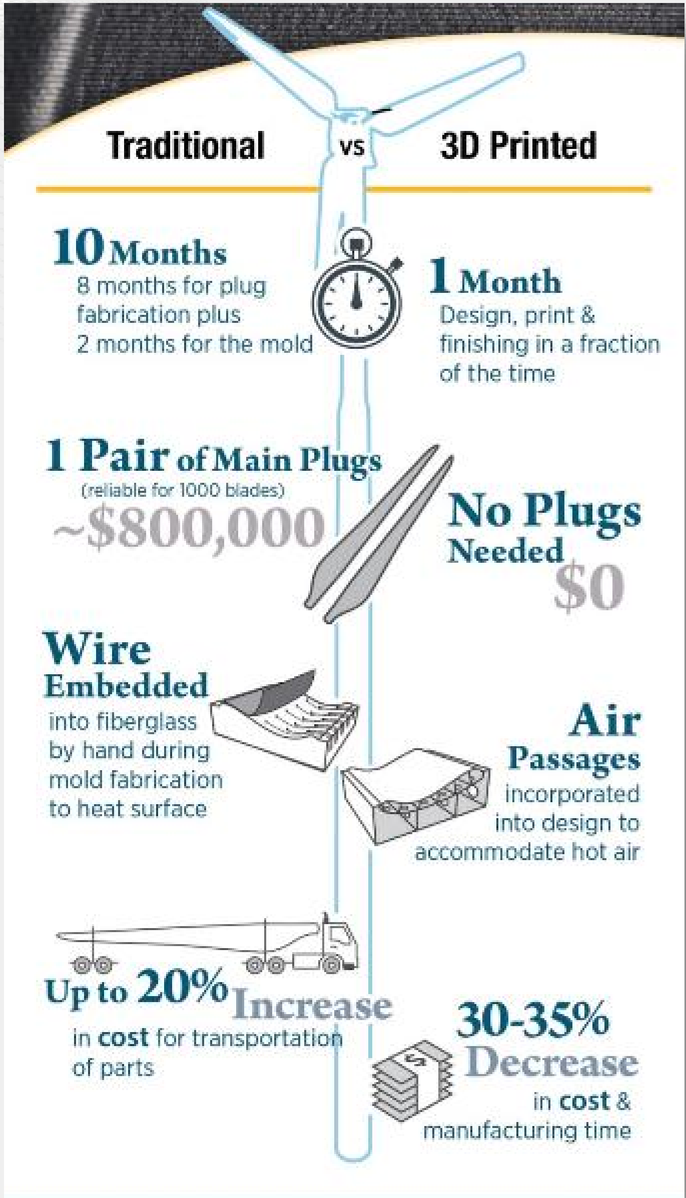
Innovation in the Design and Manufacturing of Wind Power



- **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**

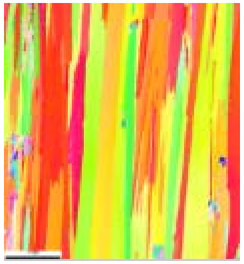
This was the **1st successful trial of 100% digitally manufactured tools in autoclave cure cycles**

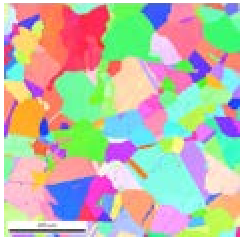
- **Obstacle:** Die and tool companies decreased by 37% in less than a decade. Tooling is expensive and can take large lead times.
- **Solution:** ORNL is evaluating additive manufactured tools for use in autoclaves for composite fabrication.

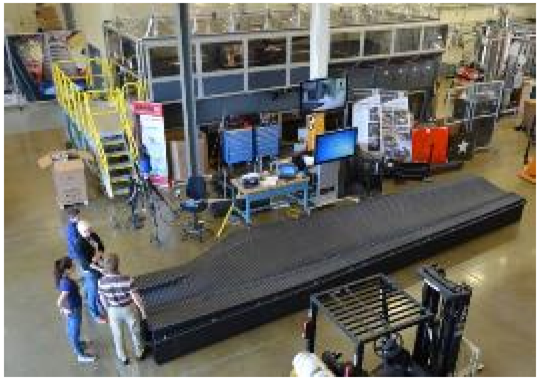
TruDesign · TECHMER PM · Ford · BOEING · CINCINNATI · NAVAIR · BASF · OAK RIDGE National Laboratory

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







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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'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

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.

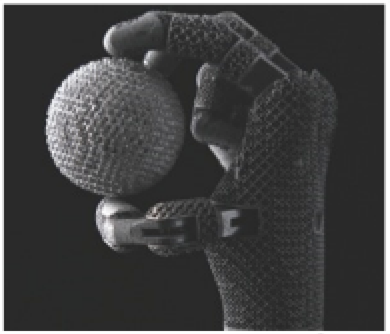
Carbon Fiber and Composites

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

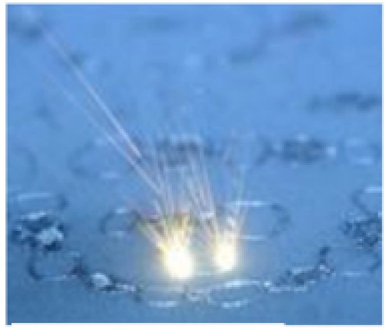
Supporting Industry and R&D with a Wide Range of AM Capabilities

Electron Beam Melting



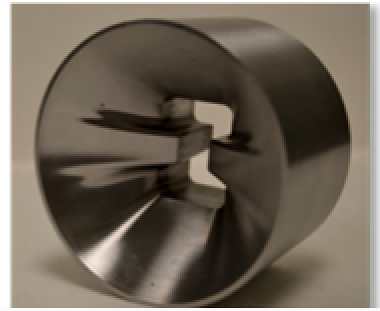
CAD TO METAL®
Arcam AB®

Laser Sintering



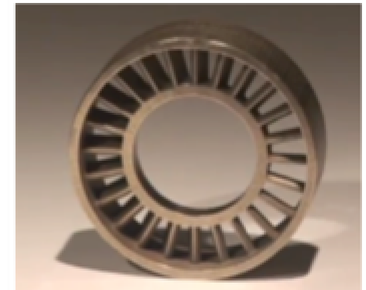
RENISHAW
CONCEPTLASER
hofmann innovation group
SLM SOLUTIONS

Laser Blown Powder Deposition



POM
DM3D

Binder Jetting



ExOne™
DIGITAL PART MATERIALIZATION

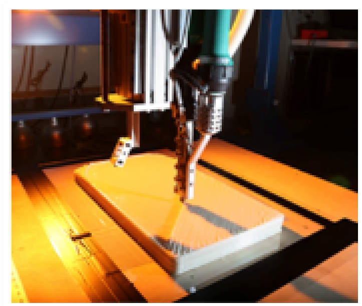
Fused Deposition Modeling

Stratasys
FOR A 3D WORLD™
AFINIA
Solidoodle
MakerBot
Cubify

Multi-head Photopolymer

OBJET
Stratasys
FOR A 3D WORLD™

Large-Scale Polymer Deposition



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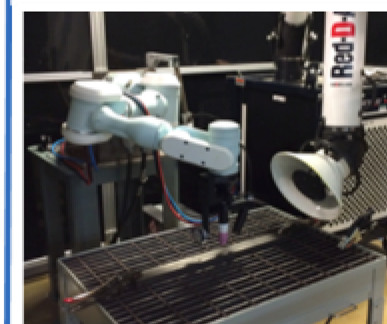
Future Systems



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Ever Growing Partnerships: Integrating the AM Supply Chain

Materials Suppliers

- TechmerPM Polymer Modifiers
- ATI
- nanocomp Technologies, Inc.
- American Process
- Imerys
- FMC Technologies
- Metal Powder Products
- Erasteel
- Stratasys
- PolyOne
- Sandvik
- TLS Technik Spezialpulver
- Carpenter
- sabic
- Timet
- Cristal
- Chomarat
- Raymor Industries Inc.
- AvCarb
- Continental Structural Plastics
- Alcoa

Equipment Suppliers

- Arcam AB (CAD to Metal)
- Fabrisonic
- ExOne
- Stratasys
- Cincinnati Incorporated
- Impossible Objects
- Ajax Tocco
- DM3D
- Quintus Technologies
- POM
- ECM Technologies
- MakerBot
- Grid Logic
- Renishaw
- HotEnd Works
- Solidoodle
- Afinia
- Magnum Venus Products (MVP)
- Objet
- Cubify
- AO Applied Optimization

End Users

- Local Motors
- Cummins
- PPG
- S-RAM Dynamics
- Lockheed Martin
- EPRI Electric Power Research Institute
- Solar Turbines (A Caterpillar Company)
- Faurecia
- GE
- Hendrickson
- Brayton Energy LLC
- Eaton
- Whirlpool Corporation
- United Technologies Research Center
- Praxair
- Arnold Magnetic Technologies
- Piedmont Propulsion Systems, LLC
- Honeywell
- Aerovalve
- Radio Systems Corporation
- Composite Application Group
- Planetary Systems Corporation
- Northrop Grumman
- CK Technologies
- Boeing

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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An Example of Core R&D Leading to Industry Growth

Arcam EBM
Measurable Outcomes for U.S.

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

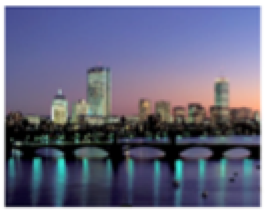
June 2014

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.*

Jan 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**

March 2016



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*

Technical Collaborations:

Solar Turbines
A Caterpillar Company

S-RAM DYNAMICS

Planetary Systems Corporation

PRAXAIR

ECM Technologies

Quintus Technologies

CAD TO METAL® arcam
Arcam AB®

"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]"…

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Setting the Pace for Large-Scale Polymers

24 Months of Innovation

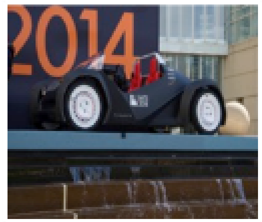
Dec 2013

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

Media Mentions
for Jan 2015-current

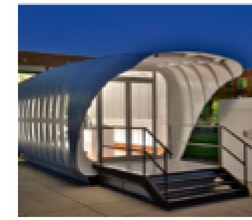
- 726 articles
- >300,000 YouTube views
- 239 social media
- >50 broadcasts
- Most viewed video in ORNL history

National and International coverage!

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

BAAM CI
BIG AREA ADDITIVE MANUFACTURING

LOCAL MOTORS

OAK RIDGE National Laboratory

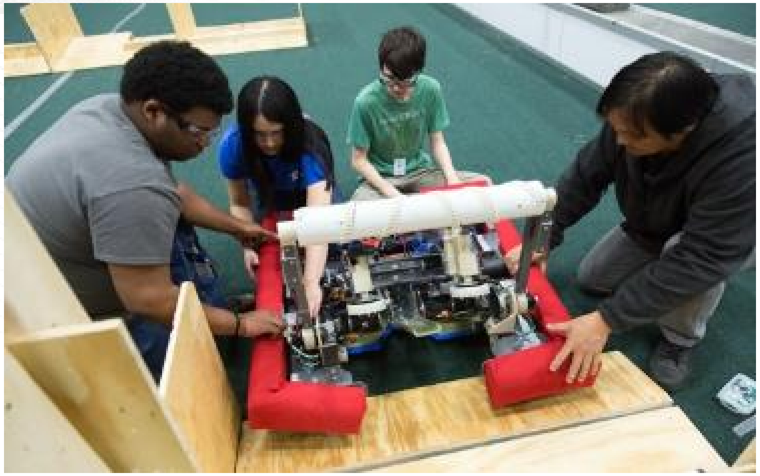
Industry Fellows: Engaging Industry and National Labs

- David Dietrich — BOEING
- Jonaaron Jones — BOEING
- Frank Medina — CAD TO METAL / Arcam AB
- Roger England — Cummins
- 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
- Kelly Thompson
- Lance Hall — AMRDEC
- Omar Abdelaziz — NASA

FY15-16 Activities

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.

FLL FIRST LEGO League

FRC FIRST Robotics Competition

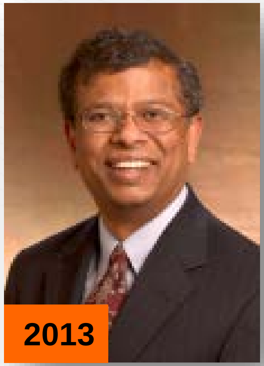
Oak Ridge National Laboratory

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

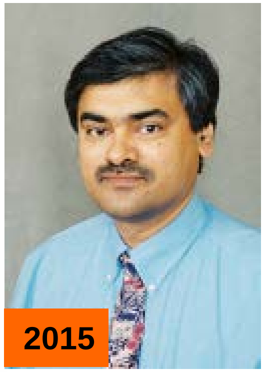
OAK RIDGE National Laboratory

Strategic Investment in Advanced Manufacturing R&D:



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

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



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

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

Dr. Brett Compton
Mechanical, Aerospace & Biomedical Eng.(UCSB) *hybrid materials*

THE UNIVERSITY OF TENNESSEE KNOXVILLE

OAK RIDGE National Laboratory

RAMP-UP

Research for Additive Manufacturing Program – University Partnerships

Initiated 2016

- **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)**

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


BAAM
INNOVATION
INNOVATION
FRAGILE
Yale