Thinking Beyond Today: Comprehending the Potential of Additive Manufacturing Processes, Materials and Properties

MDF
Manufacturing Demonstration Facility

Ryan Dehoff

Manufacturing Demonstration Facility Technical Lead: Metal AM

July 11, 2013

Arlington, VA

NSF Workshop on Frontiers of Additive Manufacturing Research and Education

U.S. DEPARTMENT OF ENERGY | Advanced Manufacturing

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

We are focusing ORNL resources to support manufacturing initiative

- **Manufacturing and materials R&D to:**
  - Reduce the energy intensity of U.S. industry
  - Support development of new products
  - Strengthen our nation's competitiveness and economic vitality
- **Leveraging ORNL's distinctive core capabilities**
  - Advanced materials
  - Advanced characterization
  - Neutron scattering
  - High-performance computing

U.S. DEPARTMENT OF ENERGY | Advanced Manufacturing

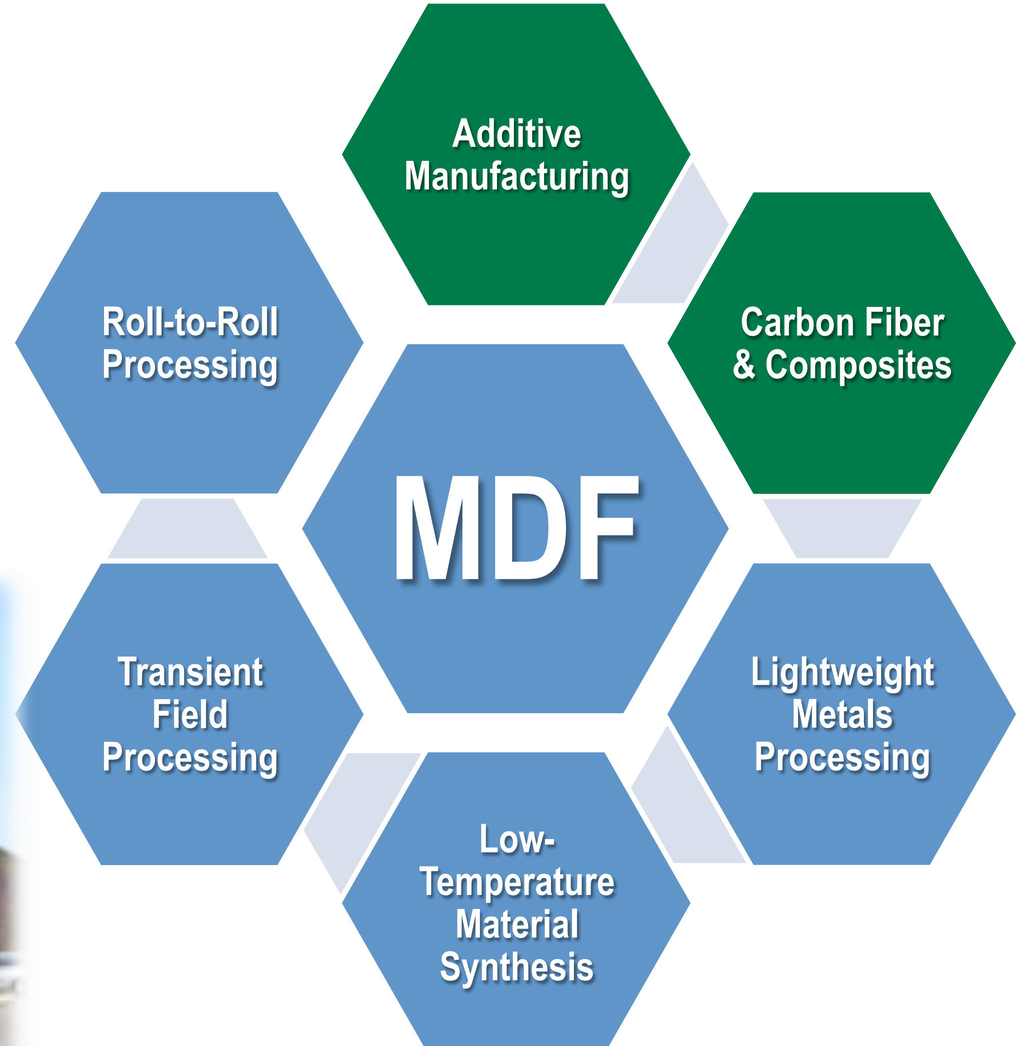
***Manufacturing Demonstration Facility (MDF)*: a multidisciplinary DOE-funded facility dedicated to enabling demonstration of next-generation materials and manufacturing technologies for advancing the US industrial economy**

www.ornl.gov/manufacturing

ORNL's MDF is primarily focused in two key areas– *additive manufacturing and carbon fiber & composites*

Several ancillary technical areas have been incorporated in the MDF as appropriate to the overall mission of the program

U.S. DEPARTMENT OF ENERGY | Advanced Manufacturing



MDF Focus Efforts in AM:

Leveraging key resources at ORNL to accelerate technology implementation

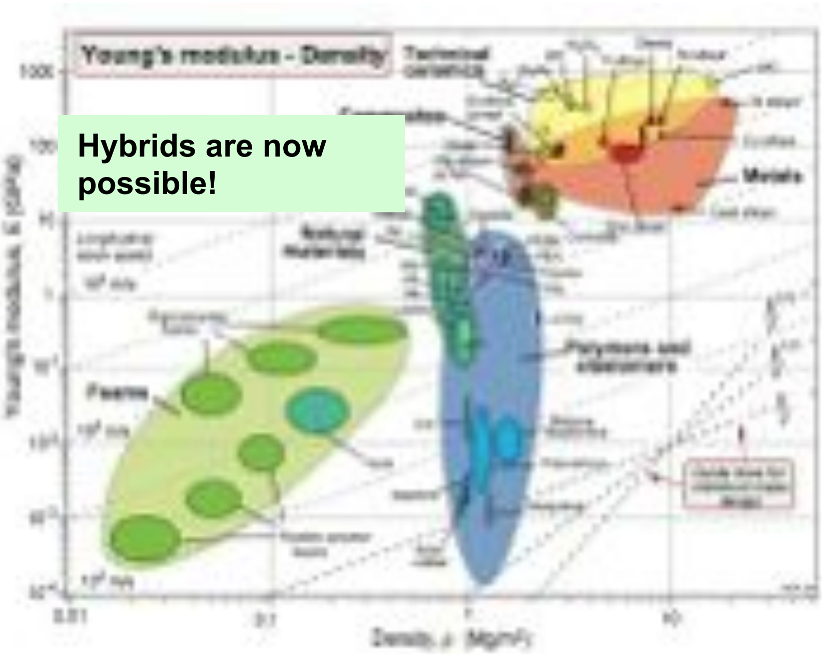
- **Developing advanced materials**
  – Titanium alloys, Ni superalloys, stainless and ultra high-strength steels
  – High-strength, carbon-reinforced polymers
- **Implementing advanced controls**
  – In-situ feedback and control for rapid certification and quality control
- **Exploring next-generation systems to overcome technology barriers for manufacturing**
  – Bigger, Faster, Cheaper
  – Integrating materials, equipment and component suppliers with end users to develop and evolve the supply chain

Additive Manufacturing Processes

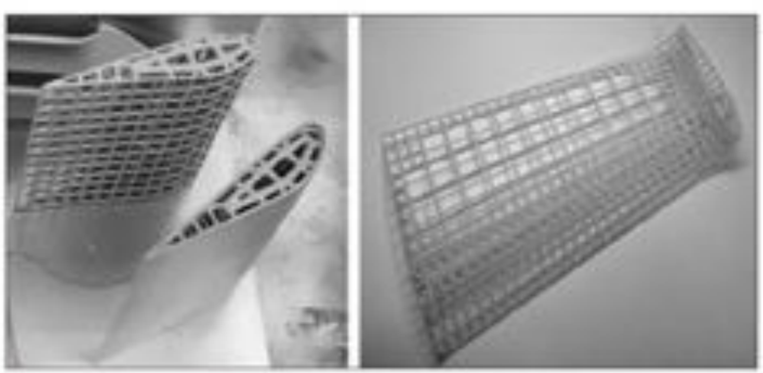
Process	Applications		
	Polymers	*Metals*	*Other*
Binder Jetting	✓	✓	✓ *
Directed Energy Deposition		✓	
Material Extrusion	✓		
Materials Jetting	✓		
Powder Bed Fusion	✓	✓	
Sheet Lamination	✓	✓	
Vat Photopolymerization	✓		

** ceramics, sand for metal casting*

Additive Manufacturing Offers New Frontier for Research



Hybrids are now possible!



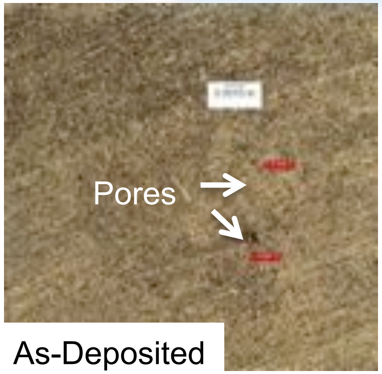
- *Airbus A380 Nacelle Hinge Bracket*
- *Weight Reduction by 64%*
  - *918 grams to 326 grams*

Altair- EADS Innovation Works

Application
Aerospace: Direct Parts

Titanium Brackets

- Bleed Air Leak Detect (BALD) Brackets
  - Buy to Fly Ratio of 33:1
- Fabricated BALD Brackets Using Arcam EBM, followed by HIP, and finished machined
  - Met ASTM standards for Tensile Properties
  - Decrease By to Fly Ratio Down to ~ 1.5:1
  - Decreased Cost by Over 50% with Additive Manufacturing



As-Deposited

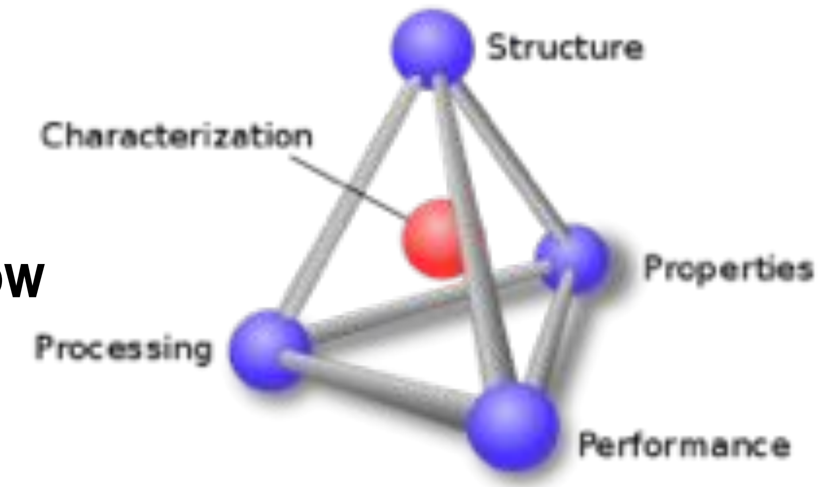

As-HIPED

Property	Minimum Value		Maximum Value	
Ultimate Tensile Strength, (ksi, MPa)	132	910	152	1,048
Elongation, %	12		22	
Over 60 Tensile Specimens Tested Within a Matrix of Processing Conditions				

Consistent with data from ARCAM

Changing the Paradigm on Advanced Manufacturing
Interview with Leo Christodoulou

- ***Information Content:*** **Principle value of a component is not in the design or the material its made from, but what you know about it, the information content.**
- **Information content is key for putting a part in service due to risk and regulation.**
  - **Conventional processes have established information contents which drives utilization**
- **Not economically viable to certify advanced processes using conventional methods. Need advanced modeling.**

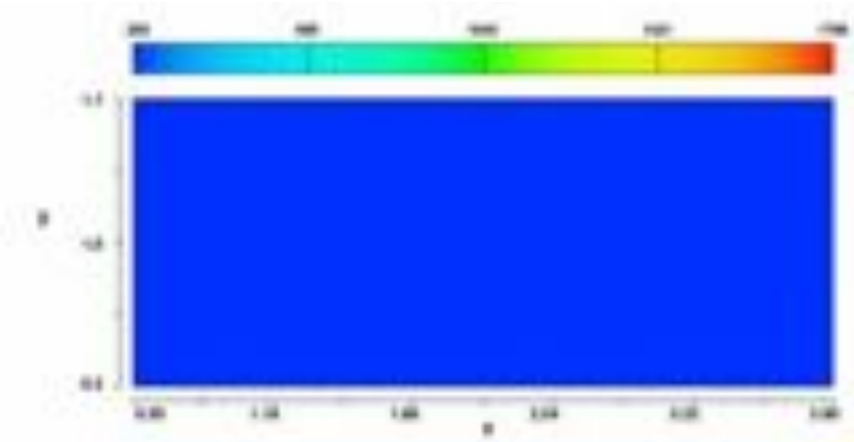


May 7, 2012

What Scientific Challenges:

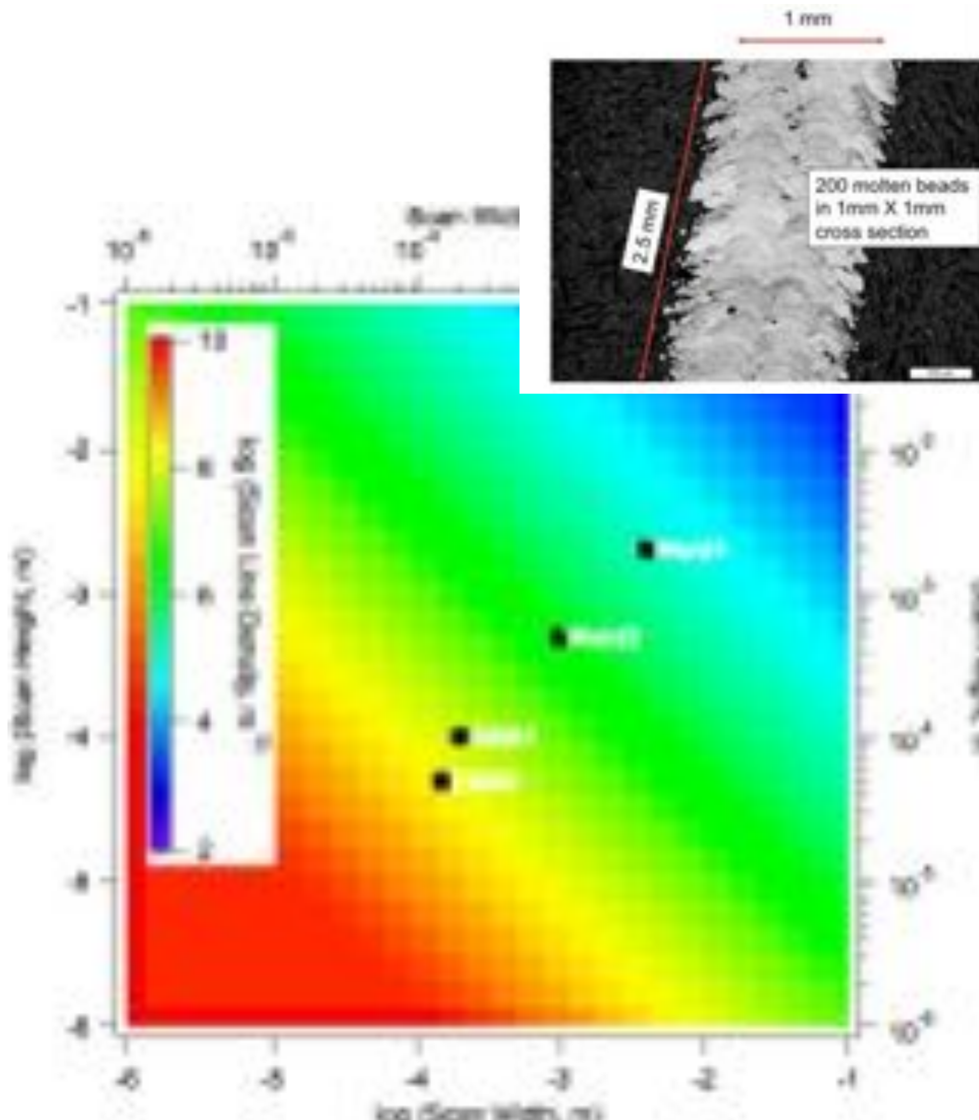
- Thermal Conditions
  - Coupling of Energy Source with Feed Stock
  - Wide Range of $\delta T/\delta x$ & $\delta T/\delta t$ ➔Microstructural & Residual Stress Gradients
- Microstructural Heterogeneity
  - Solidification – Crystal Orientation ➔ Anisotropy
  - Solid-State Phase Transformations ➔ Heterogeneous Microstructure
- Mechanical Heterogeneity
  - Due to different precipitation kinetics ➔Residual Stress
  - Locked in Residual Stresses ➔ Pre-existing Cracks
  - Fatigue Properties ➔ Inferior to Traditional Manufacturing
  - Unreliable mechanical properties ➔Need for Secondary Process
- ***All of these are process, material, AND part specific!***

Modeling of AM is Challenging and Computationally Intensive: But Needed!



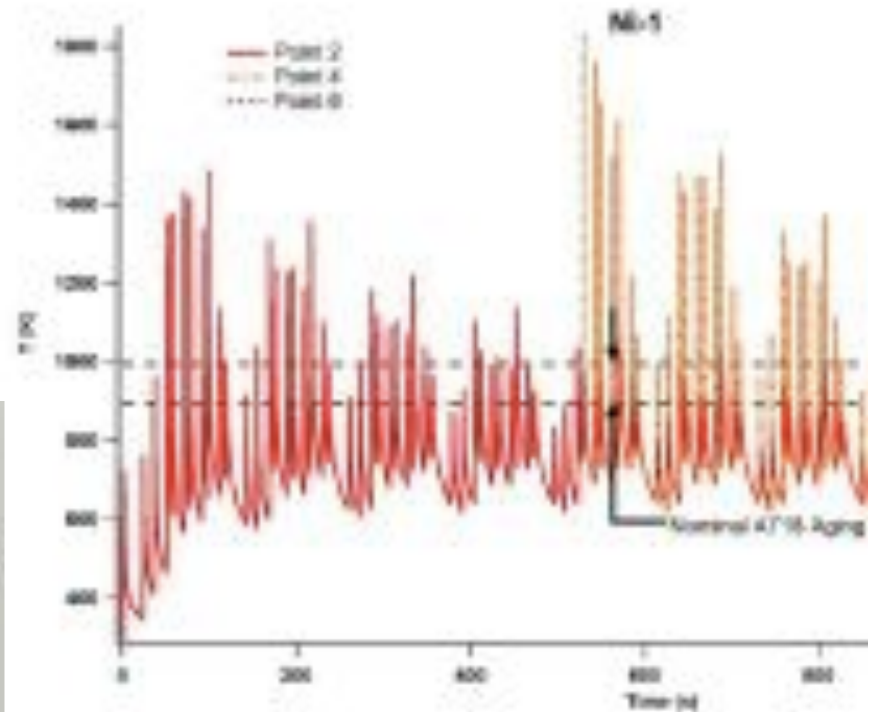
3-mm weld pool motion simulation takes more than 48 hours in a high-end computer using a commercial fluid dynamics software!

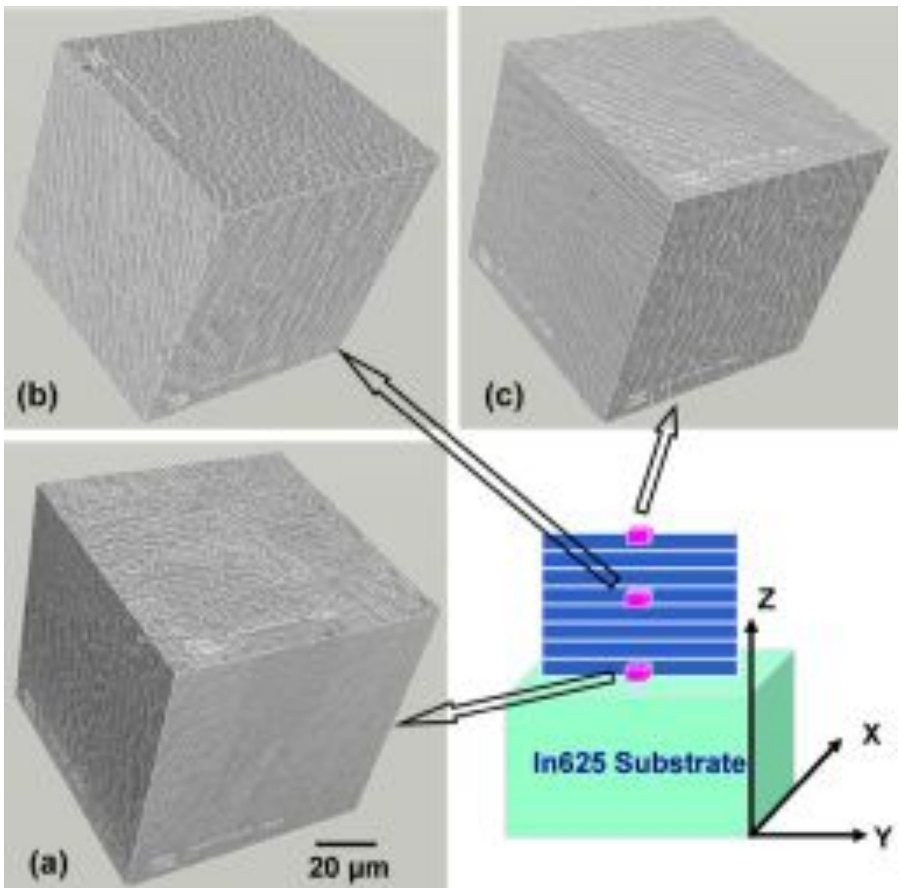
Pervasive AM modeling efforts will Rapidly increase process knowledge



Courtesy of Dr. S Babu

Resulting Microstructure of Directed Energy Deposition Correlates to Process Parameters, Scan Strategy and location





Dinda et. Al., 2009

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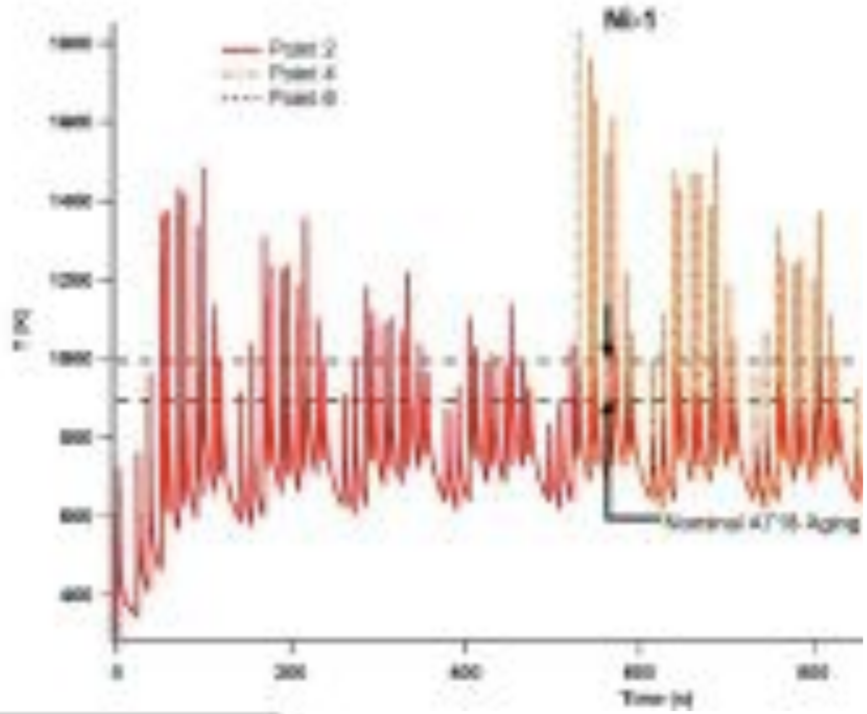
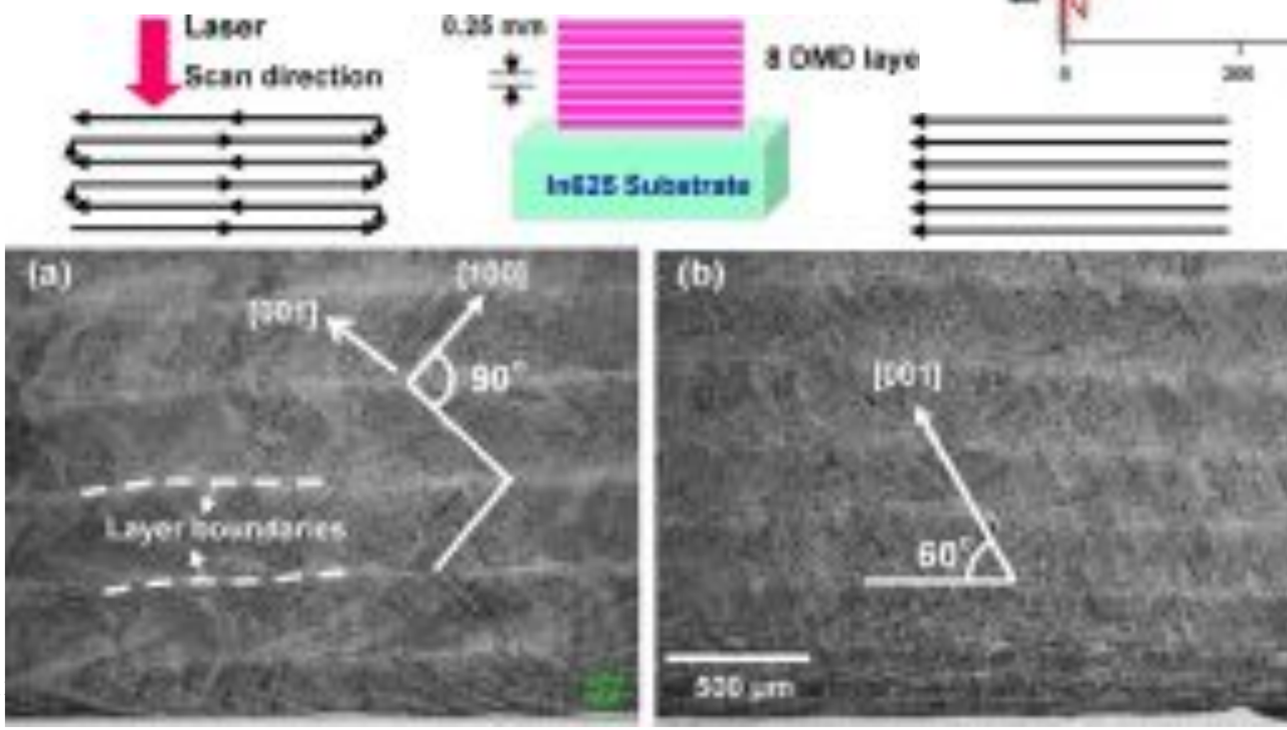
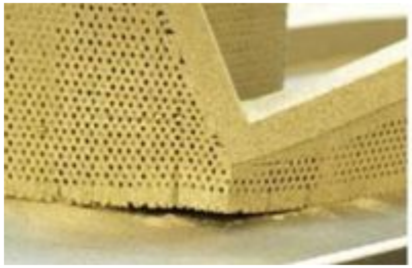


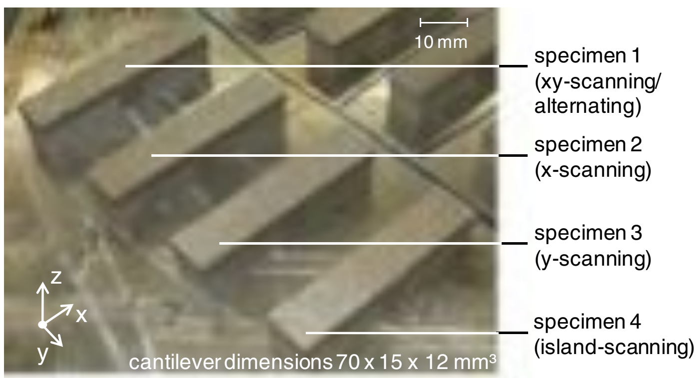


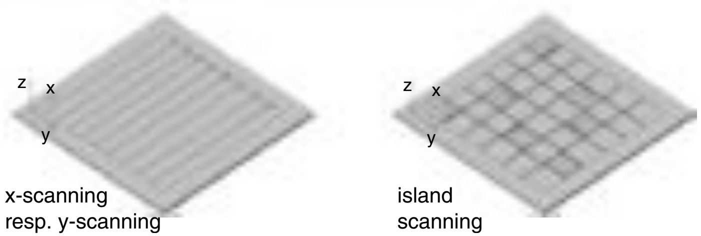
Dinda et. Al., 2009

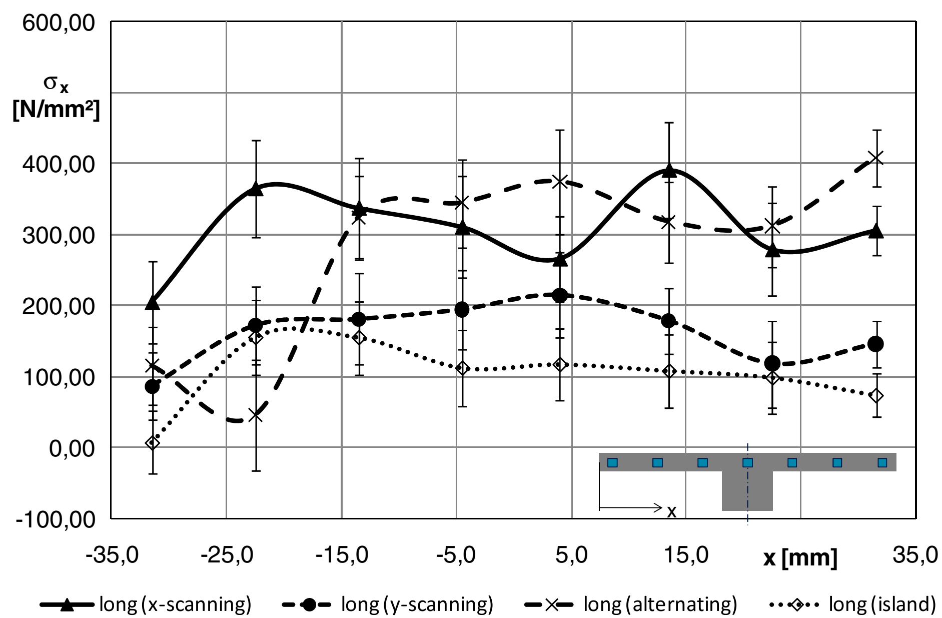
Residual Stress is a Significant Challenge in AM:

- **Dependent on Composition, Process, Energy Source, Energy intensity, Scan strategy**







Longitudinal Stresses in Horizontal Direction

Zaeh and Branner, 2009

Enabling Additive Manufacturing (AM) of Turbine Blades

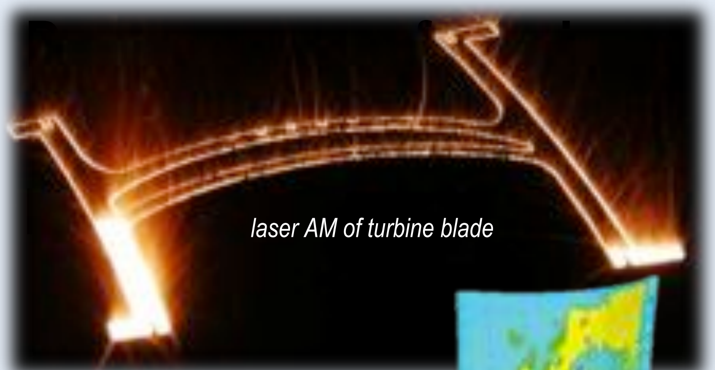
- Optimized internal cooling structures are desired for maximum efficiency
- AM can produce geometries not possible with conventional processes

turbine blade

MORRIS TECHNOLOGIES
Precision. Innovation. Expertise.

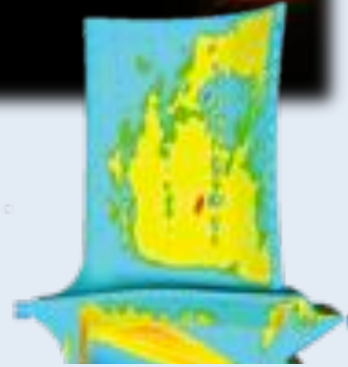
Headquartered in Cincinnati, OH

- *~20 DLMS Machines*
- *18-yrs experience in laser deposition*
- *Recently acquired by General Electric*



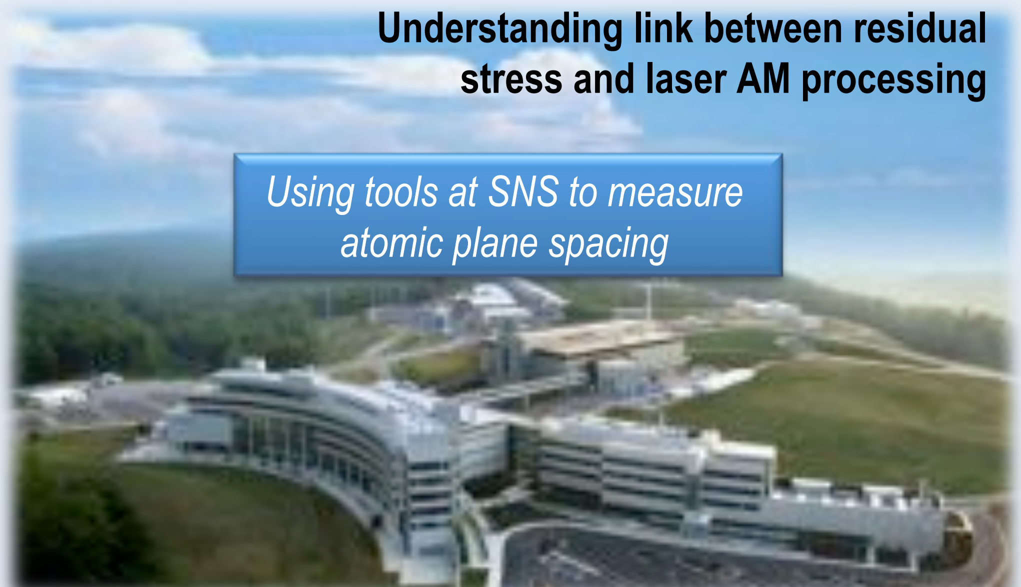
laser AM of turbine blade

Laser AM creates large residual stress leading to distortion



Profilometry map illustrating distortion

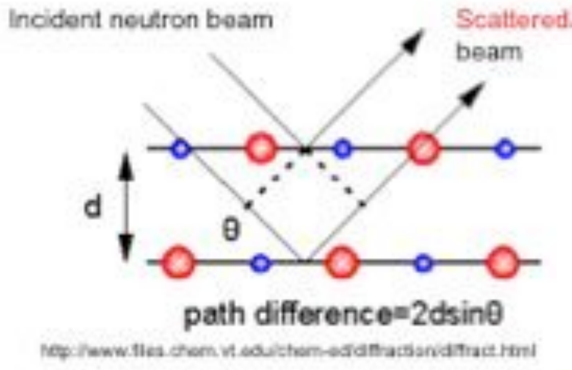
Critical to widespread adoption of technology

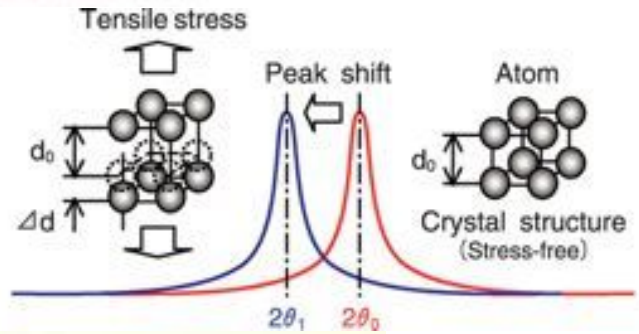


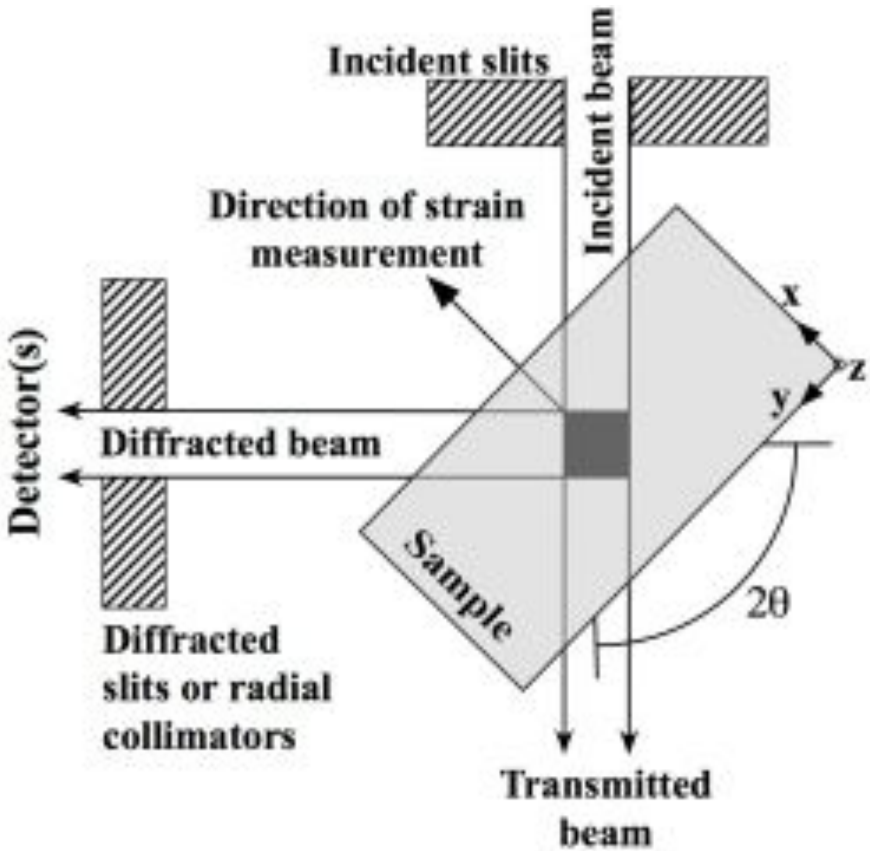
Understanding link between residual stress and laser AM processing

Using tools at SNS to measure atomic plane spacing

Neutron Diffraction for Residual Stress of DLMS Turbine Blade:

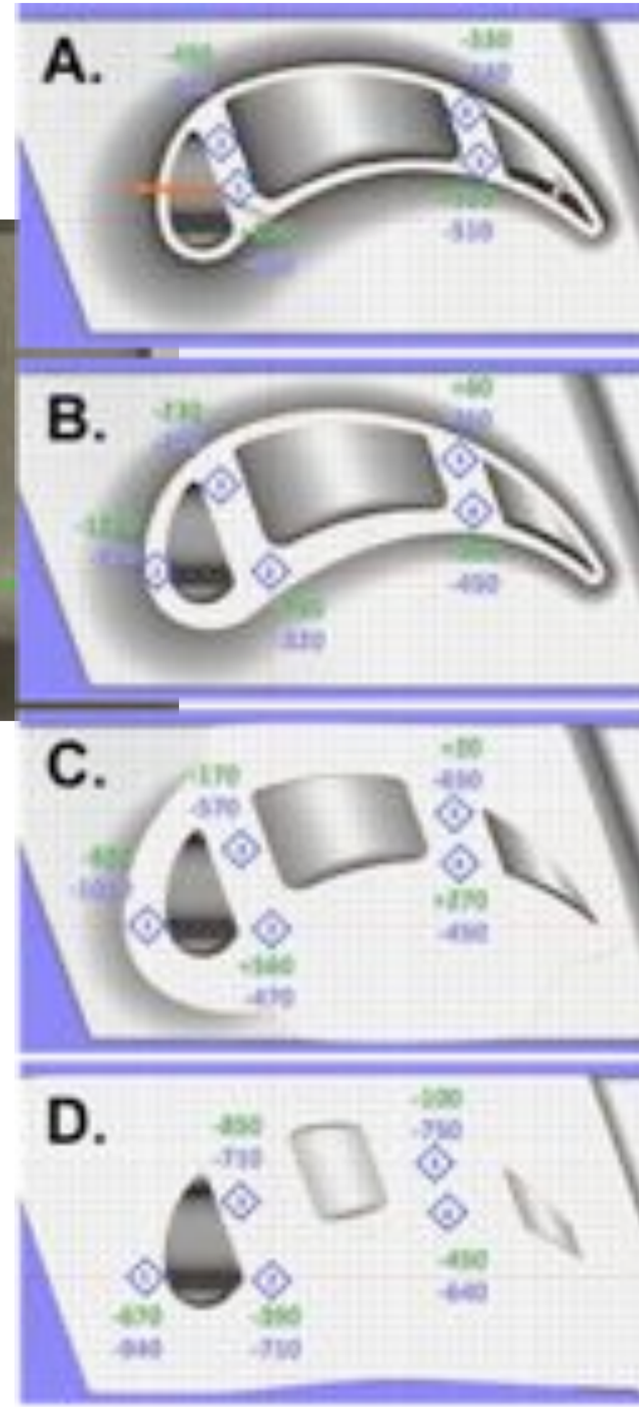






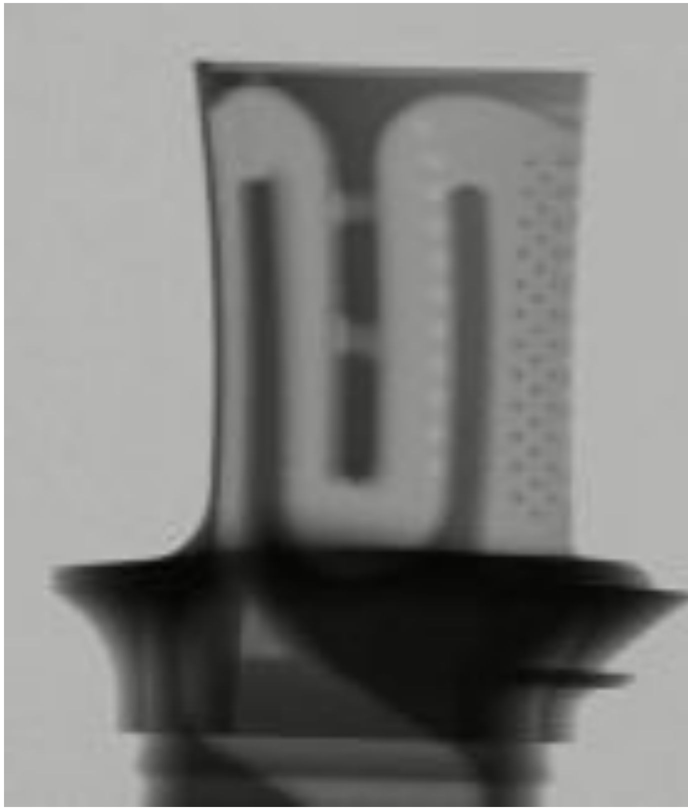
Measurement of Lattice Spacing in Turbine Blade

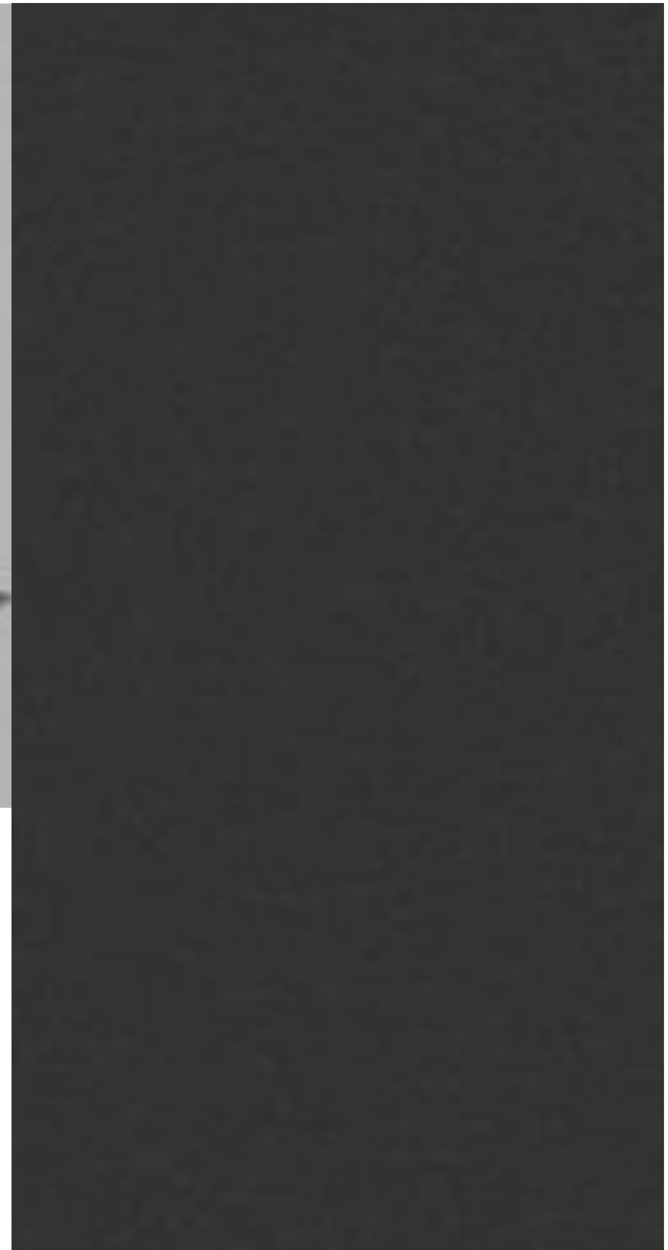
Laser Power	Machine	Condition
400	280	As-Built
400	280	Heat Treated
400	280	Stress Relieved
200	270	Heat Treated
200	270	Stress Relieved
200	270	As-Built

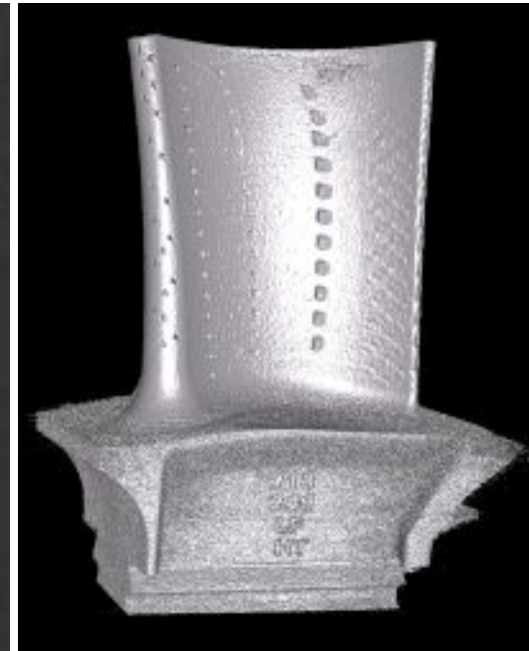


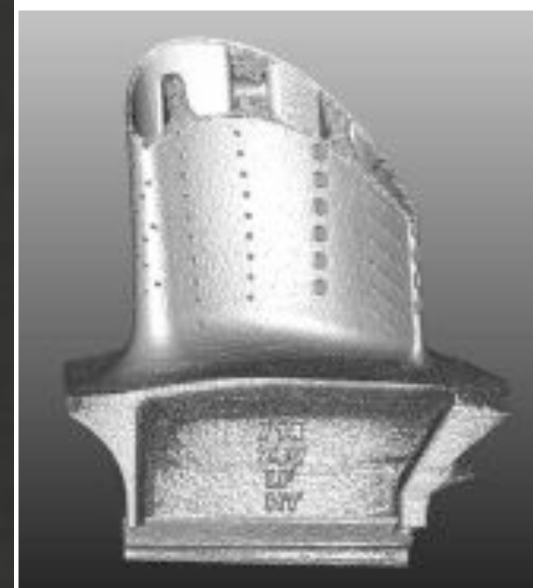
- Different geometry features result in different residual stress states (tensile vs. compressive)
- Stress relief unifies residual stress (compressive), but results in geometric distortion
- Understanding stresses induced by laser deposition is critical for improving part accuracy and performance during service

Neutron Imaging of DLMS Turbine Blade:





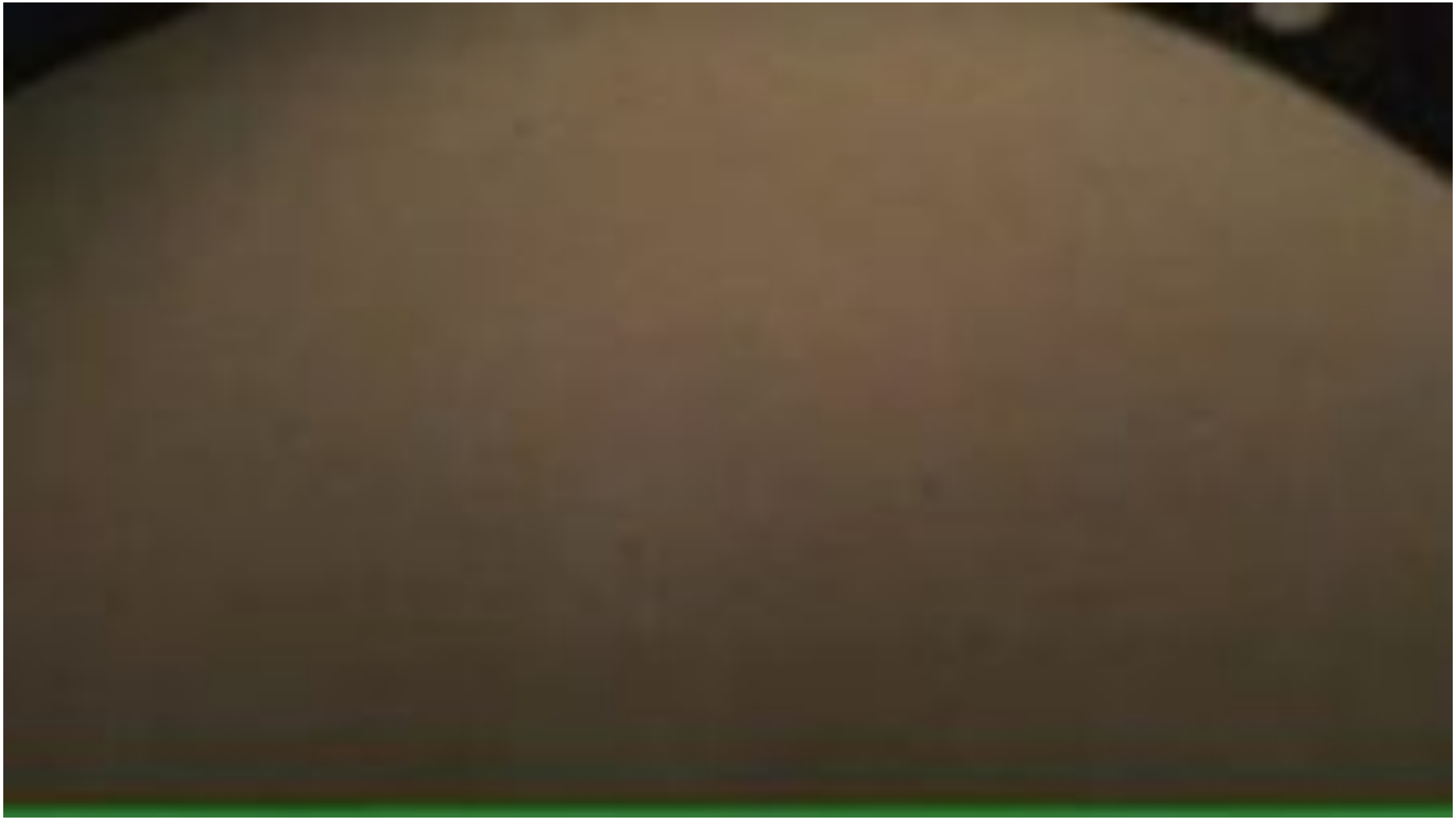




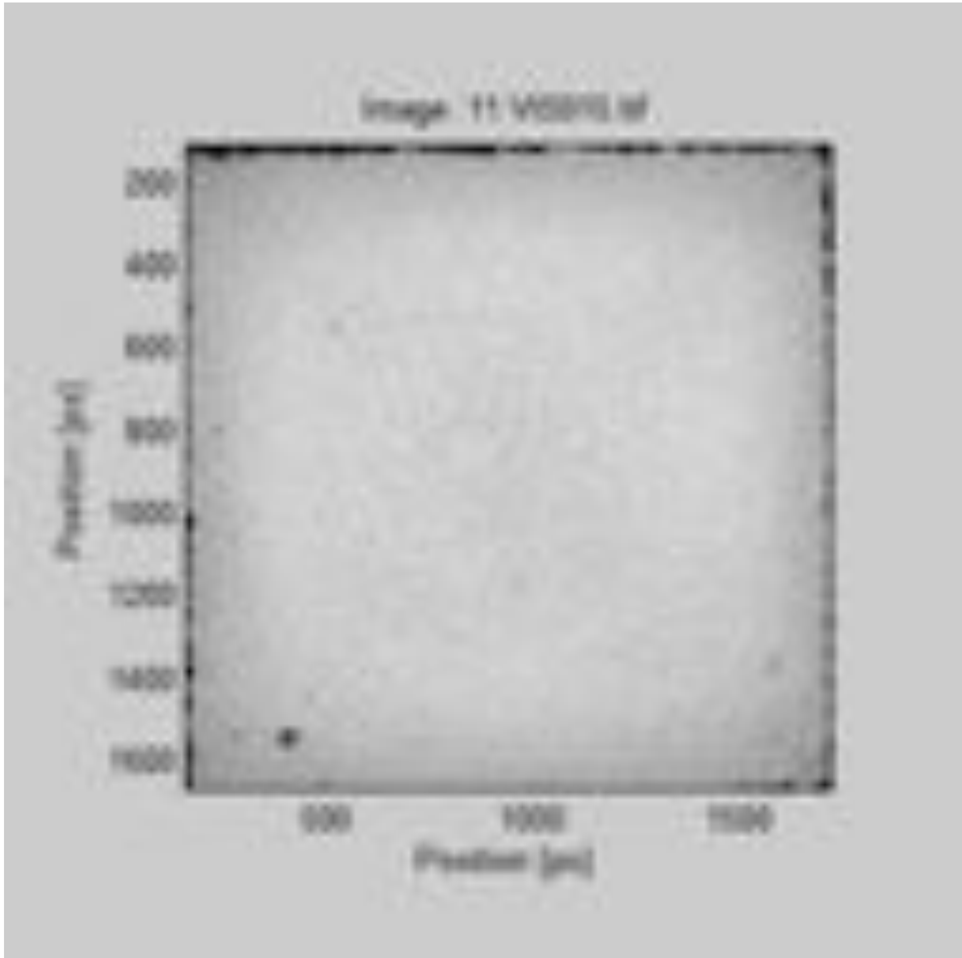
- 210 Images around 180 degree rotational axis
- Currently ~75 μm resolution at HFIR, VENUS is targeting 10 μm
- Developing methodology to perform stress mapping with tomography

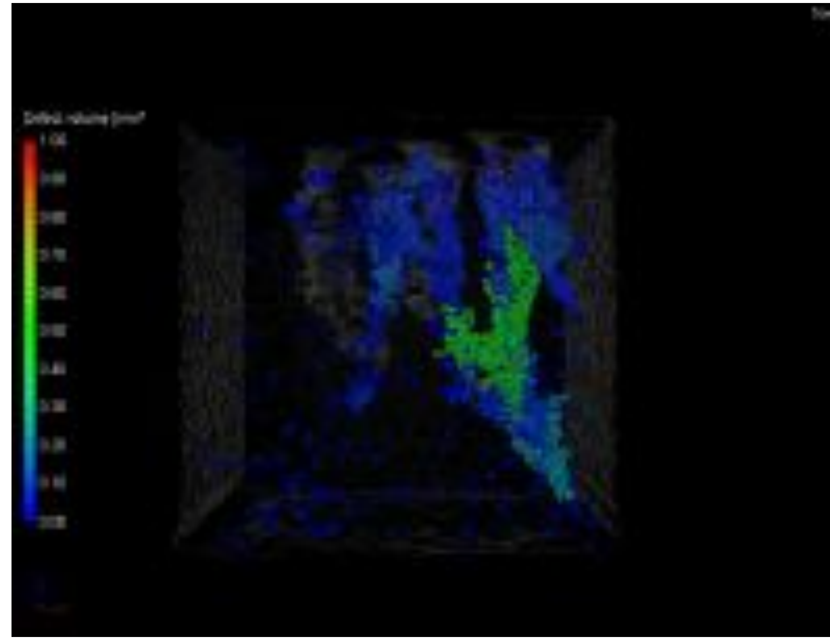
Powder Bed Fusion: Arcam EBM

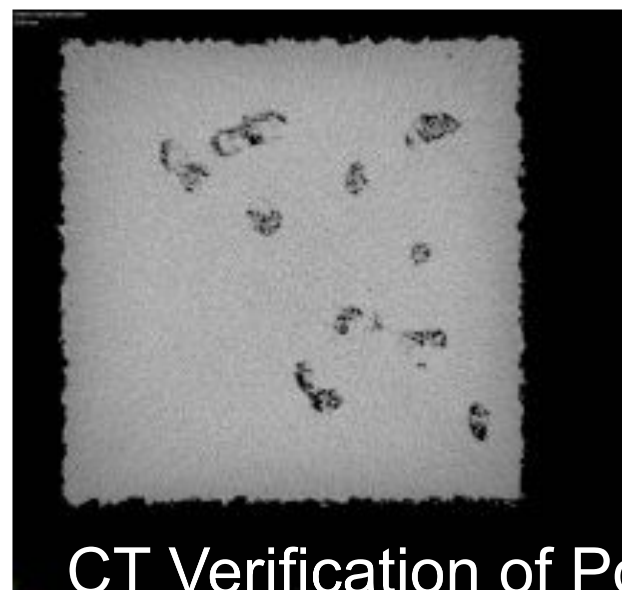
Single Layer Deposition:



Verification of Porosity In a 10 mm cube

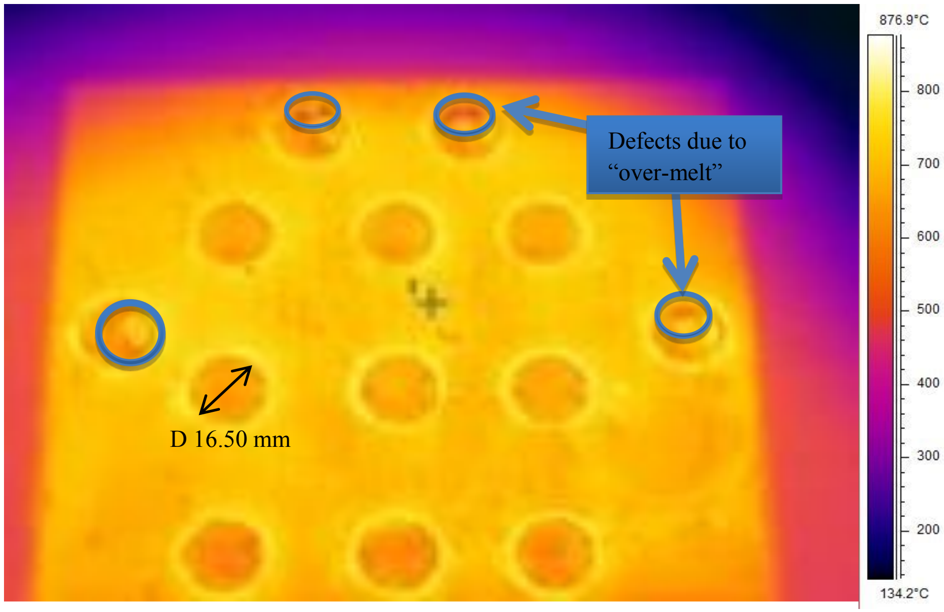


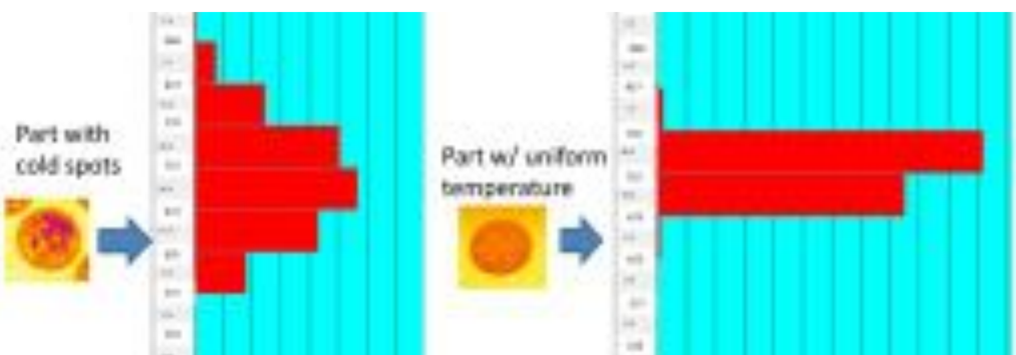


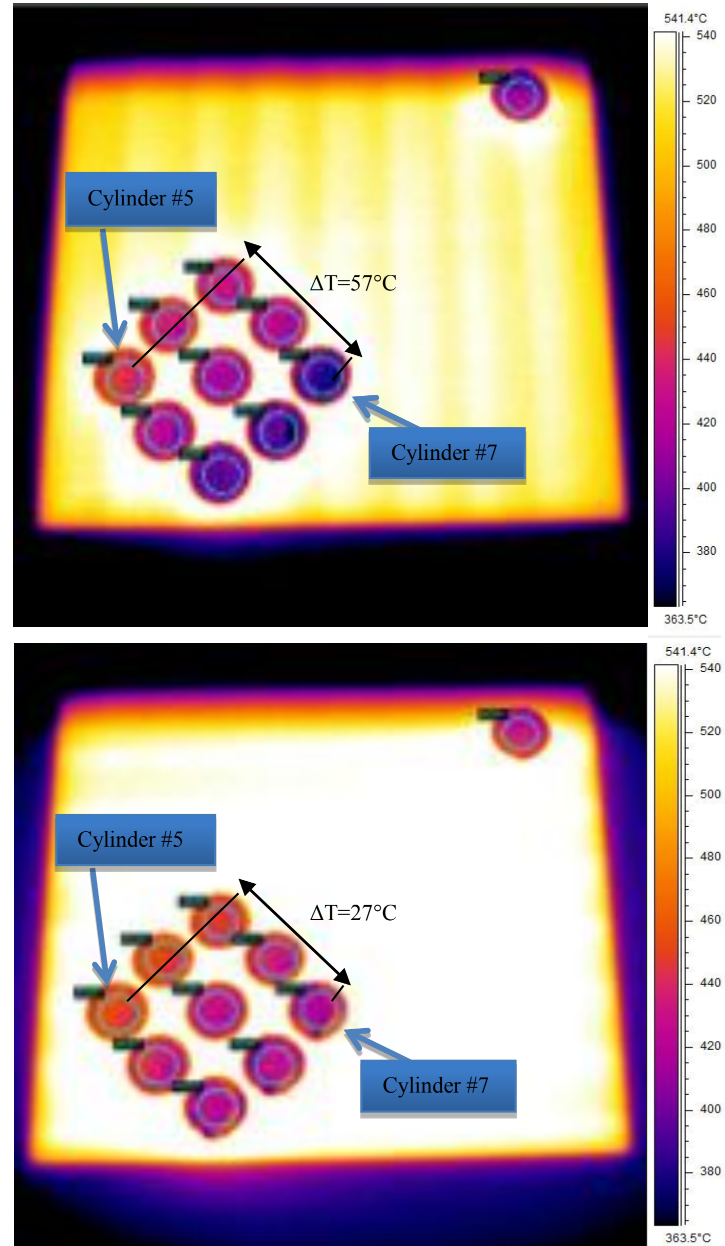


Energy verification by Infrared Thermography:

- **FLIR SC645 IR Camera, ~350 μm/ pixel**



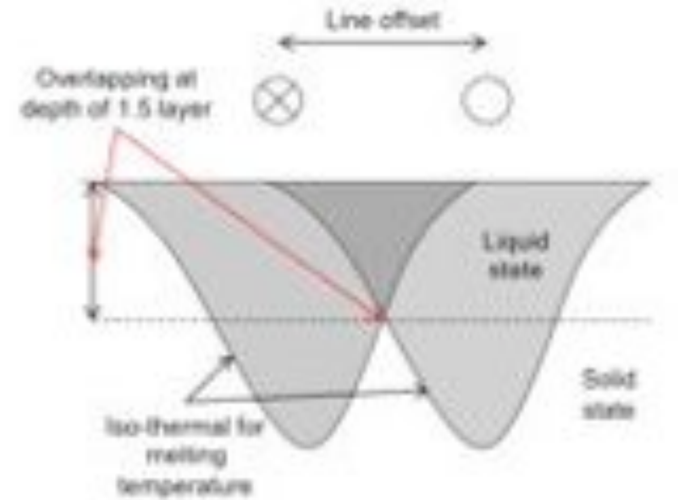


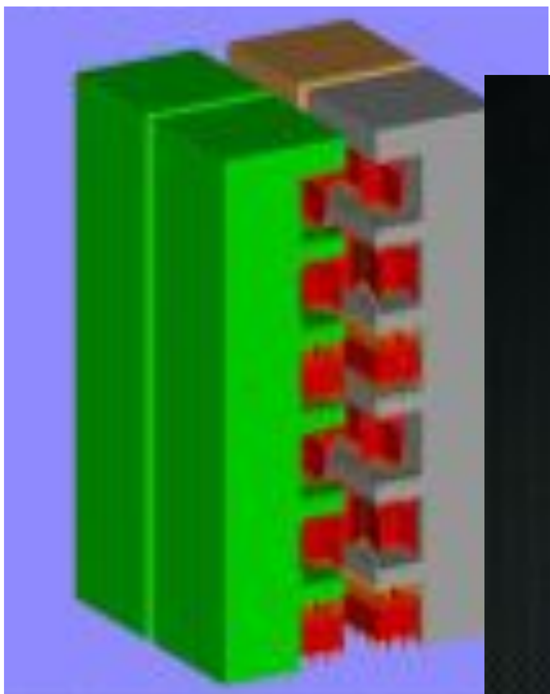


Rodriguez et. Al., 2012

High Speed Infrared Thermography During Melting Process:

- Examination of specific properties on melting process and quality
  - Focus Value, Support Structure, Current, Speed, etc.





Next-Generation ARCAM EBM A2XX

Machine Specifications:

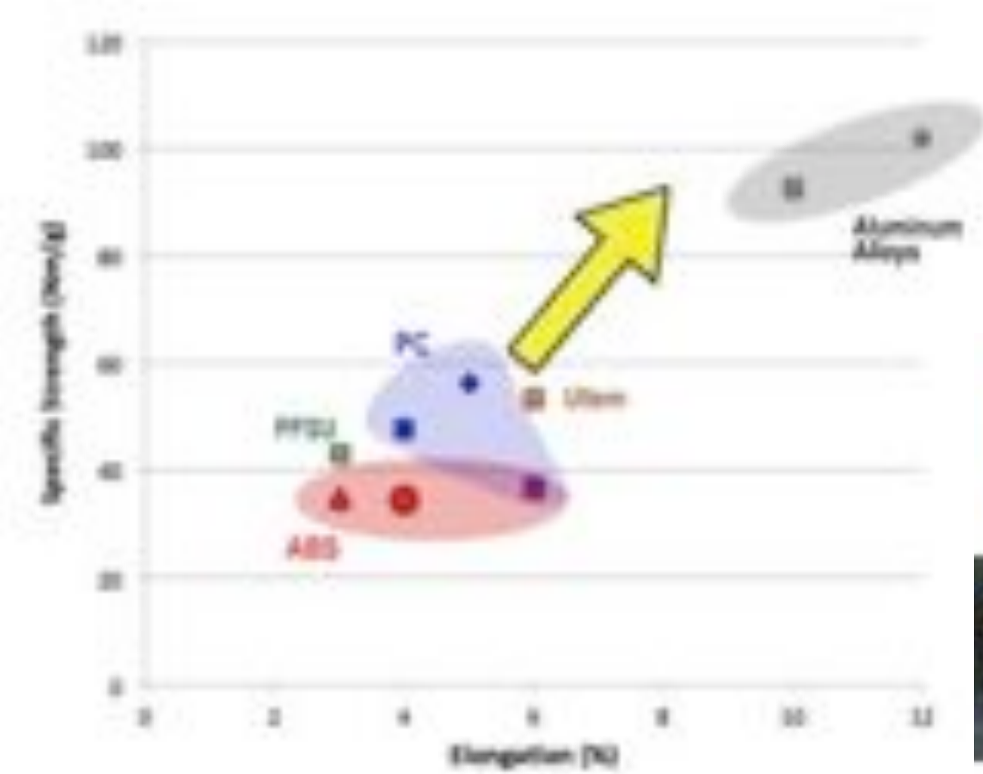
- Expand Build Envelope from 200mm x 200mm to Ø350mm x 380mm tall
- Build Rate for Ti-6Al-4V is ~80cm^3 per hour

Challenges:

- Similar Electron Column and Control Hardware
- Limited to specific geometries due to limited beam current

Fused Deposition Modeling:

- **Extrusion Thermoplastic Materials**
- **Known as a Rapid Prototyping Tool**
  - **Modeling**
  - **Visualization**
  - **Multi-Materials**



Example: Sheet Metal Tooling

Demonstrated Application of AM in Tool and Die

- **Large Tools**
  - 2.3m Long Hydro Form Tool
  - PC Material
  - Methods to join parts proven

Optimized Tool

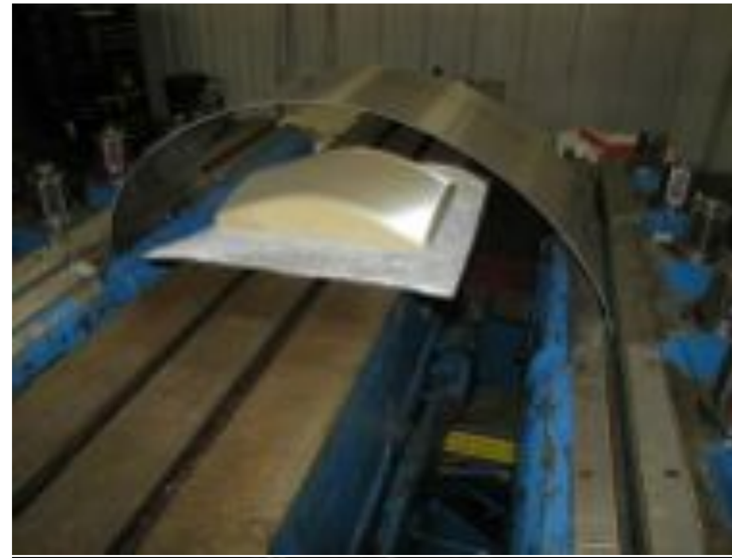
Optimized Tools

- Match FDM material to forming pressure
  - ABS max 20.7 MPa
  - PC max 55.2 MPa
  - ULTEM max 68.9 MPa
- Rubber Pad Tool optimized for cost and build time
  - ***~ $200US in material***
  - ***~ 8 hour build time***

Credit Bill Macy, NAMII

Example: Stretch Form Tooling
Emerging

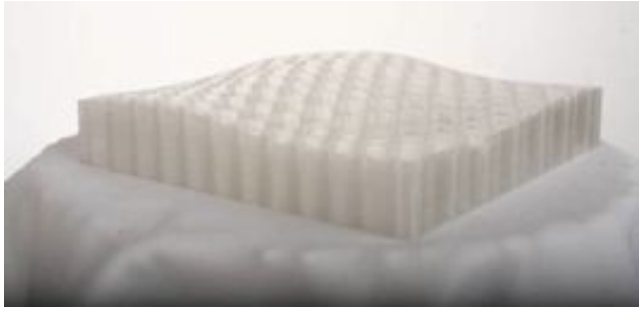
- Tool Details
  - Size 10” x 13” x 2.5”
  - 2” crown w/ multiple contours
  - Tool Material – ULTEM 9085
- Successfully Formed
  - Alloy 2024-0
  - Thickness 0.050” up to 0.100”
- Notes
  - Surface pressures are minimal
  - Tool can be optimized to minimize build times and cost
  - PC is a viable alternate material depending on alloy, thickness and tool build styles



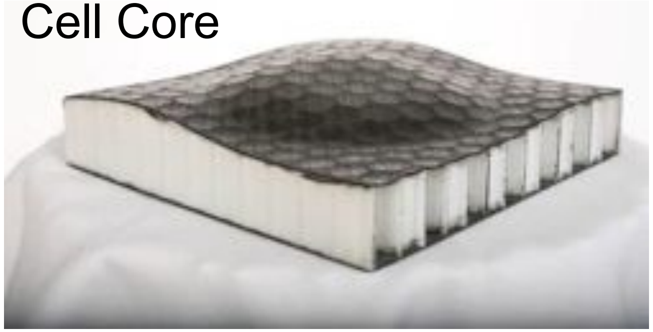
Credit Bill Macy, NAMII

Example: Laminated Net Shaped Core

Demonstrated Application



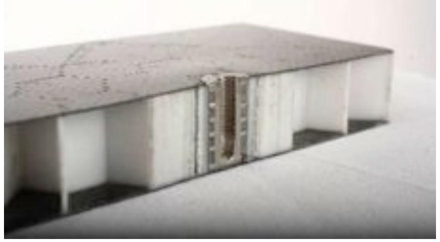
FDM Polycarbonate Hex Cell Core



3 plies of bi-directional weave epoxy matrix facing skins wet lay-up over core. Note dimple pattern.

Same construction using proprietary lay-up/curing method. Note smooth outer surface.

Courtesy of Aviradyne
US Patent No. 6,630,093



Sealed part edges

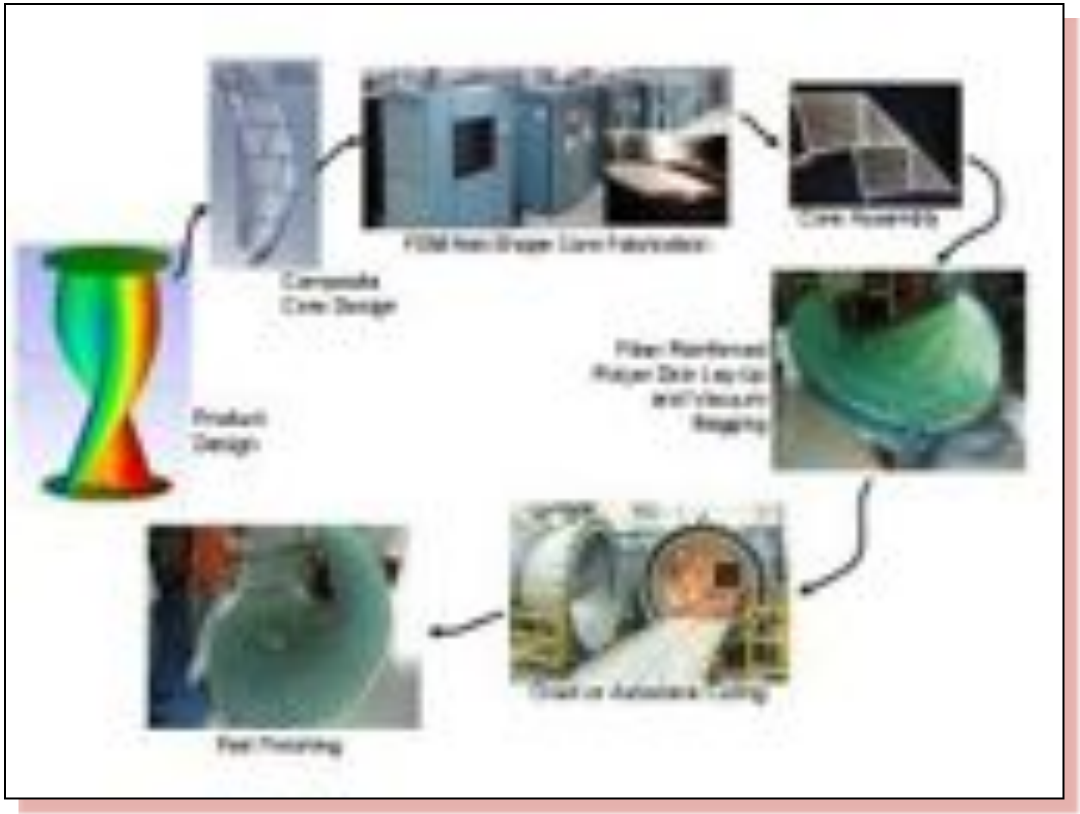
Proven insert methods

Credit Bill Macy, NAMII

Example: Large Net shape Cores
Demonstrated Application

Direct-Digital Advanced Composites (D-DAC®)

- Employs additive fabrication technology to produce "net-shaped" self-supporting polymer cores
- High specific strength sandwich composites
- Eliminates part specific composite tools
- Compatible with most fiber reinforcements and resin systems
- Compatible with most lay-up methods (wet, pre-preg, VARTM, fiber placement, filament winding, etc.)



Courtesy of Aviradyne
US Patent No. 6,630,093

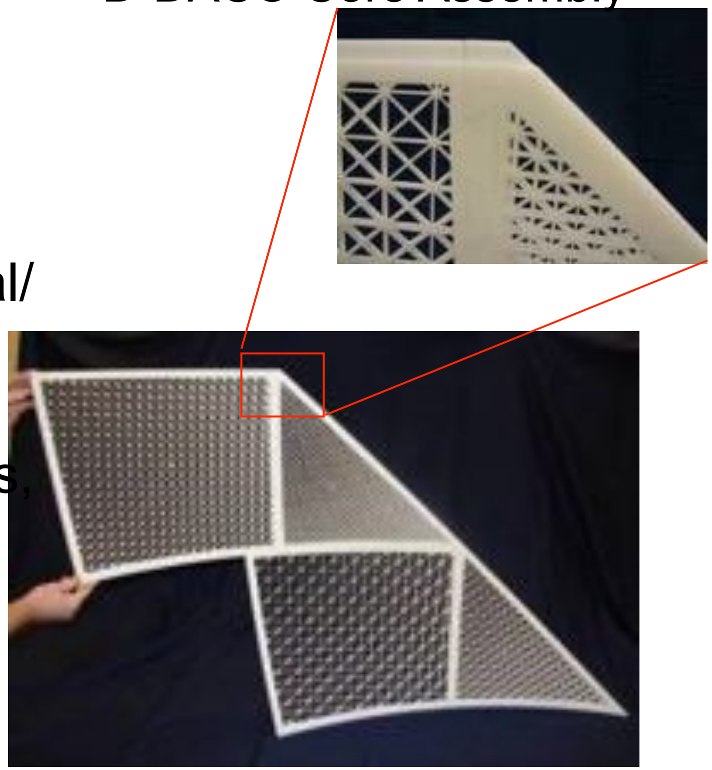
Credit Bill Macy, NAMII

Example: Large Net shape Cores

Demonstrated Application

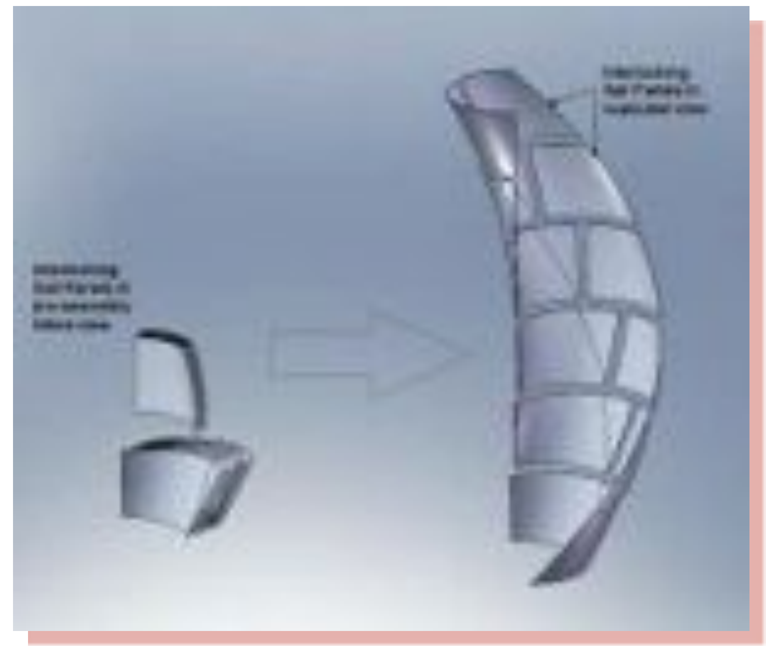
Note: AM is limited to small parts and very low deposition rates

D-DAC® Core Assembly



Joining Techniques: Adhesive Bonding, Metal/ Polymer Fasteners, Snap-Fit Joints, Traditional Mechanical Joining Methods, etc.

Composite Panel Assembly



Proprietary Modular Savonius Wind Sail Assembly Design Using D-DAC® Interlocking Composite Sandwich Panels

Courtesy of Aviradyne
US Patent No. 6,630,093

Credit Bill Macy, NAMII

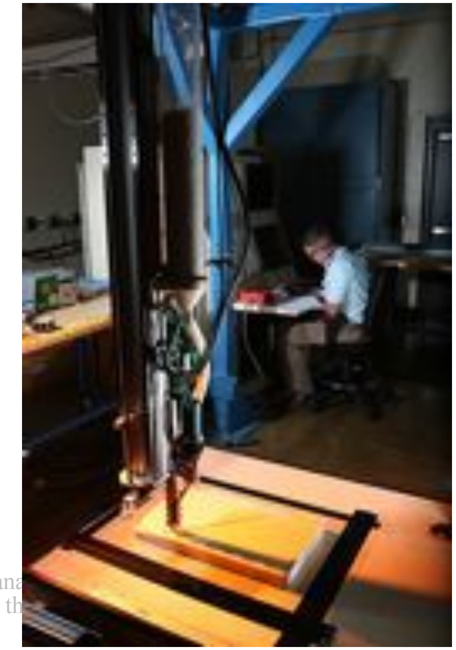
Large Scale Additive Manufacturing

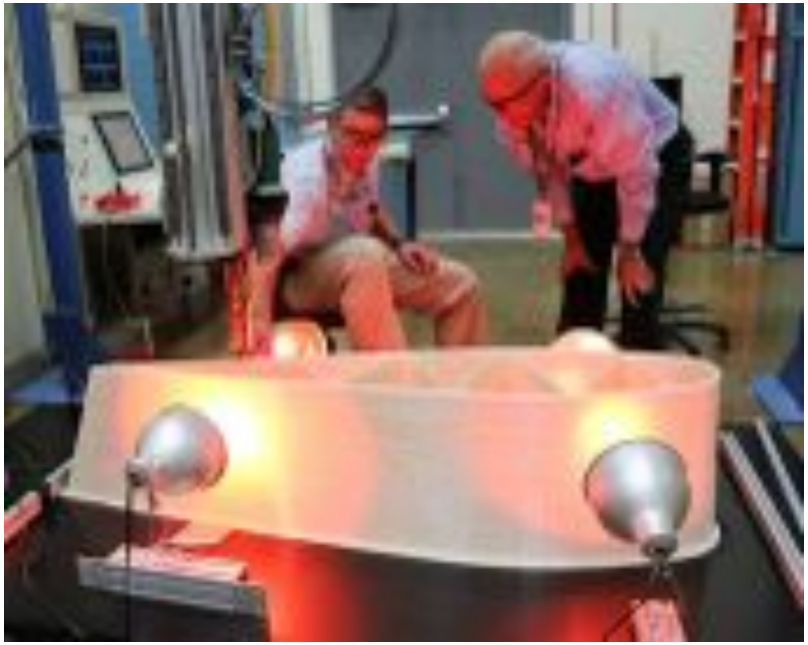
- ***All of the previous examples demonstrated***
  - **Feasibility of using additive components for tool and die**
  - **The present limitation in part size**
    - **To make large tools requires joining many small parts together**
- ***Just making a larger additive manufacturing system isn't the solution***
  - **Deposition rate of present technology is 1 to 5 ci/hr. A 6' X 3' X 2' tool would take 518 days to manufacture**
- ***Need new materials and deposition methodologies that can enable quantum jump in deposition rate and size***

Vision: Large Scale, High Deposition Rate Additive/Subtractive Machining Centers

Leveraging existing infrastructure

- Lockheed Martin recently located their large scale AM system at ORNL MDF
  - Powder feed and mix, extrusion system and robotic deployment
  - Interest is to have ORNL jump start materials/process development
- Objective is to get "out of the oven" to enable:
  - *Unbounded part size*
  - *Integration of subtractive processes for part finish*
  - *Integration of robotic pick and place for system integration on parts*





Goals and Challenges

- Goals
  - Unbounded part size
    - Present technology limited to 3’ x 2’ x 3’ parts
    - *Many tools and dies are many meters long*
  - >100 X increase in build rate
    - A solid 3’ x 2’ x 3’ part with 0.010” layer thickness *(1 ci/hr) would take over a year to manufacture*!
    - *A 5 ci/minute build rate would make the same part in under 5 days*
- Challenges
  - Material properties & performance
    - Investigate impact filled materials (glass and carbon fiber) have on mechanical properties, residual stress, geometric stability
      - Strength, ductility, toughness, geometric accuracy, etc.
  - Deposition in open environment
    - Layer to layer processing for cross-linking, z-strength
    - Alternative processes (induction melting) for finer flow control
  - Coordination of processing of materials (extrusion), processing of layers (accelerate cross-linking) and finishing (subtractive processes)
    - Coordinate flow control with motion control
    - Layer to layer processing
    - Integrated post processing for surface finish

Science, Technology, Engineering & Mathematics (STEM)

The future of additive manufacturing: high school robotics teams

FIRST Robotics Competition	2011–2012 teams

• Founded by Dean Kamen (Segway inventor): For Inspiration and Recognition of Science and Technology
• Goal: Inspiring youth to be science and technology leaders
	• ORNL mentor: Lonnie Love
	• 8 area high schools
	• 2012 Smoky Mountains Regional Competition
	    • **Hardin Valley Academy** *Engineering Excellence Award*
	    • **Oak Ridge High School** *Top Rookie All Star Award & Nationals Contender*
	    • **Webb High School** *Woodie Flowers Finalist Award*
	    • **Knoxville Catholic High Scho** and **Seymour High School** *Ranked in the Top 5*

Science, Technology, Engineering & Mathematics (STEM)
ORNL helps kick off 2013 FIRST

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Questions

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