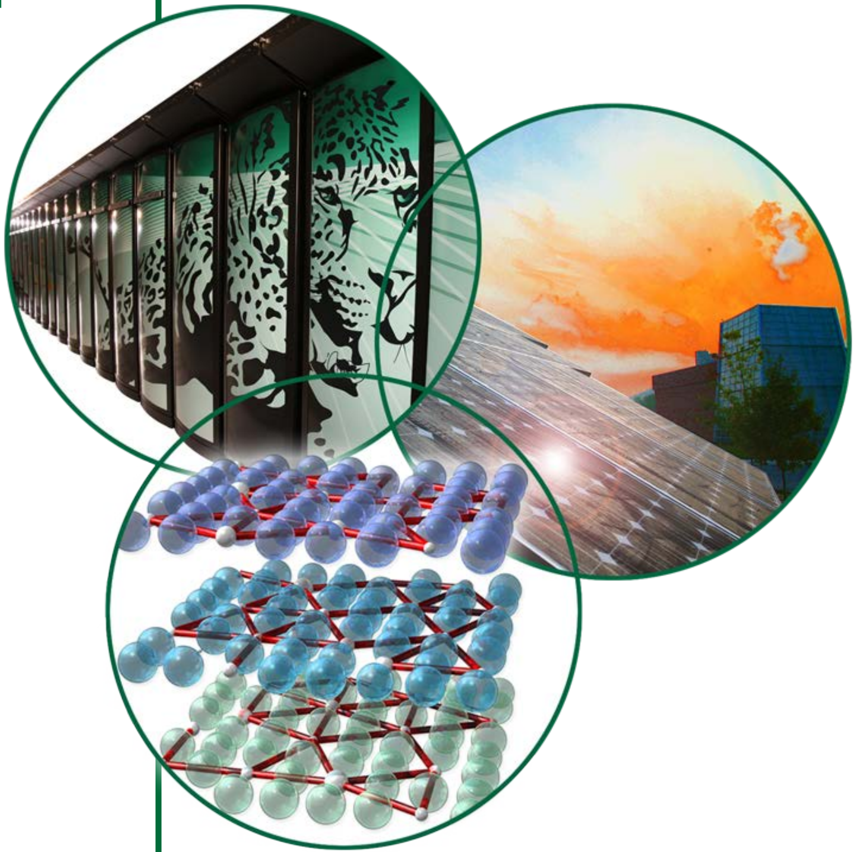
Emerging Manufacturing Technologies and Their Impact on Fluid Power



Lonnie J. Love (lovelj@ornl.gov)

Automation, Robotics and Manufacturing (ARM) Group

U.S. DEPARTMENT OF ENERGY

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

What is additive manufacturing

Where does hydraulics fit in? Freeform Fluidics

- Blending fluidic actuation (hydraulic and pneumatic) with additive manufacturing
  - Enables the rapid manufacture of lighter, inexpensive, customizable systems

E-beam approach: Hydraulic hand (DOE)

- Additive processes enable integrated pump, fluid passages and pistons into a structure with mesh for weight reduction
- Titanium hand made using E-beam fusion (operating pressure 3000 psi)

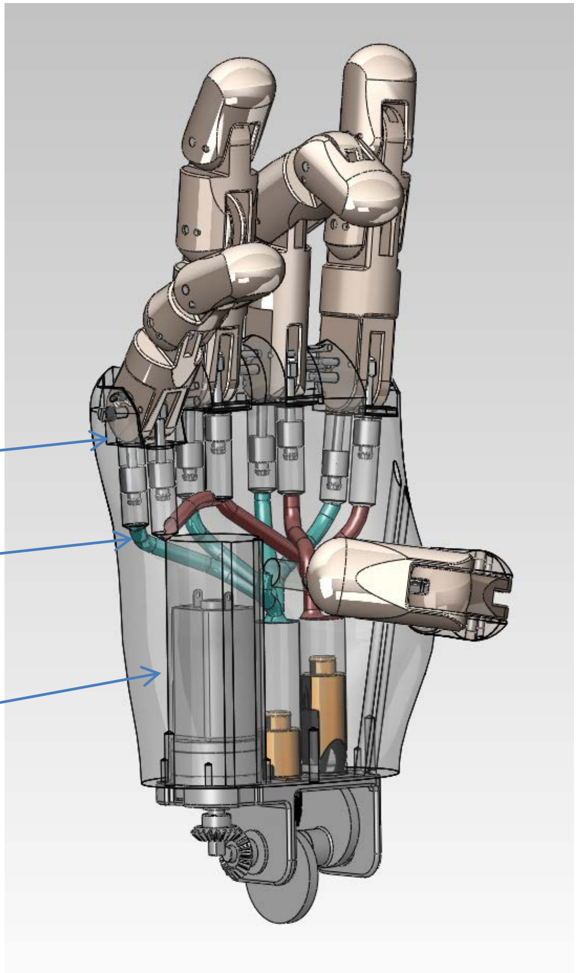
Solid palm weighing 857 grams.

Meshed palm weighing 178 grams

Pistons integrated into structure

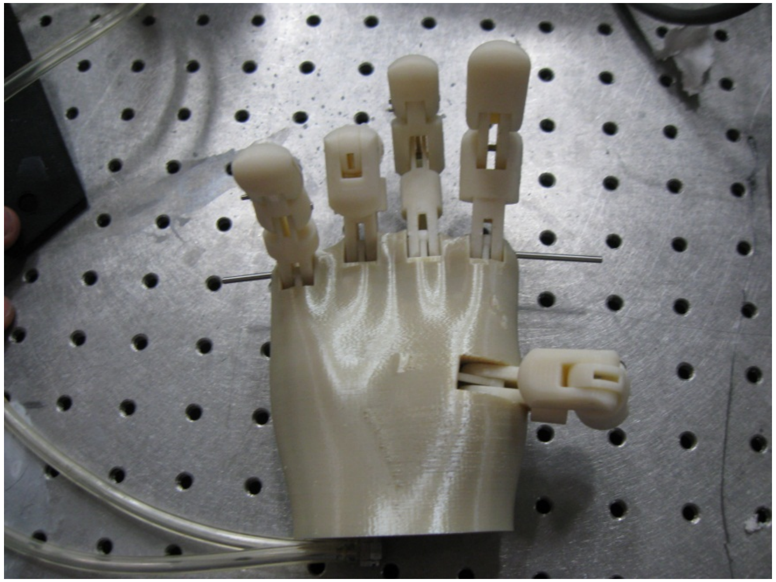
Curved fluid passages

Integrated motor and pump

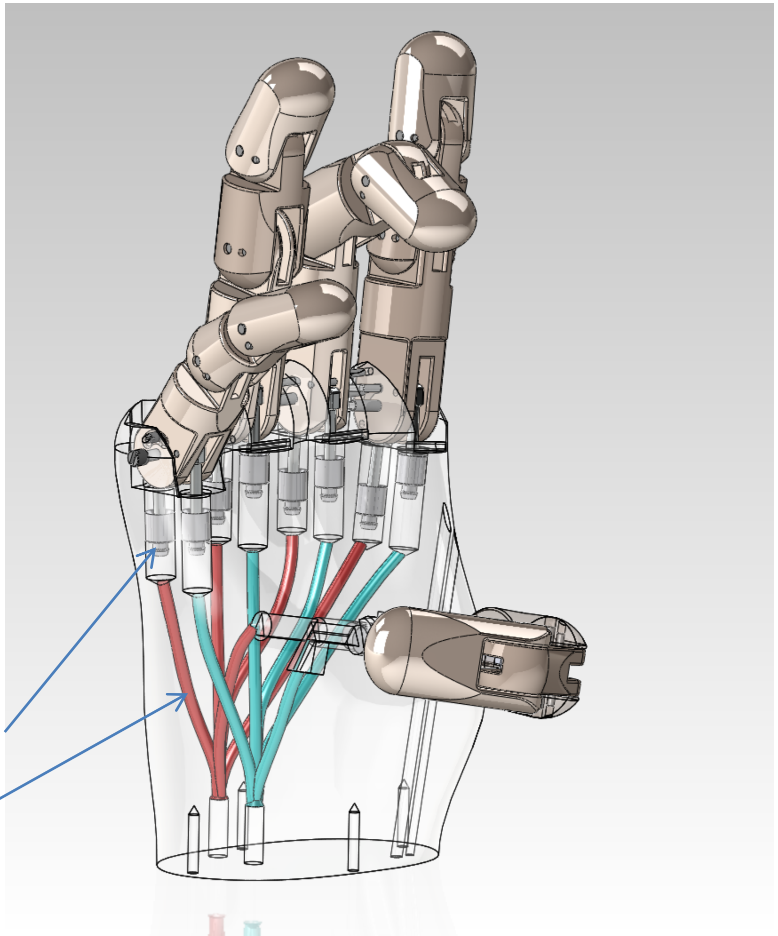


Fused Deposition Modeling: Pneumatic hand

- Developing polymer pneumatic hand with actuator bores and air routed directly into the structure.



Working polymer pneumatic hand made by additive manufacturing (operating pressure is 100 psi)

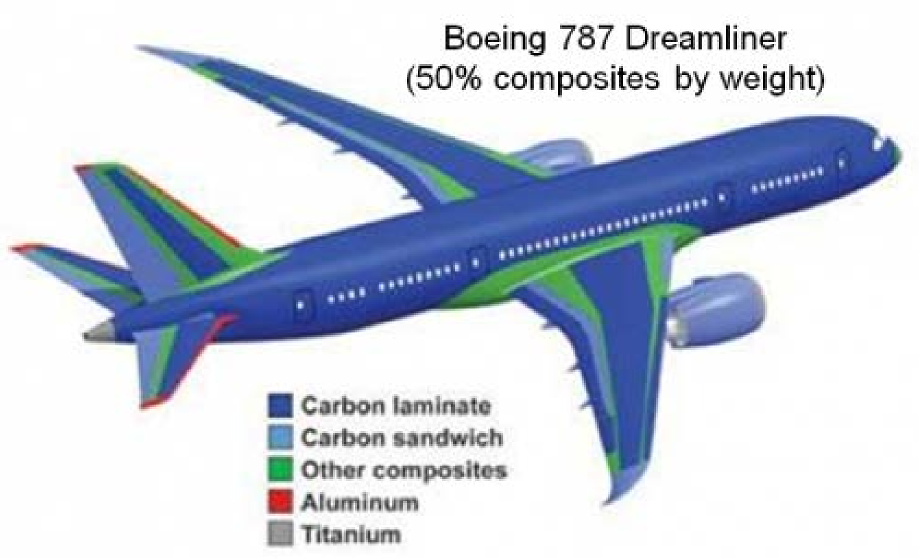


Pistons integrated into structure

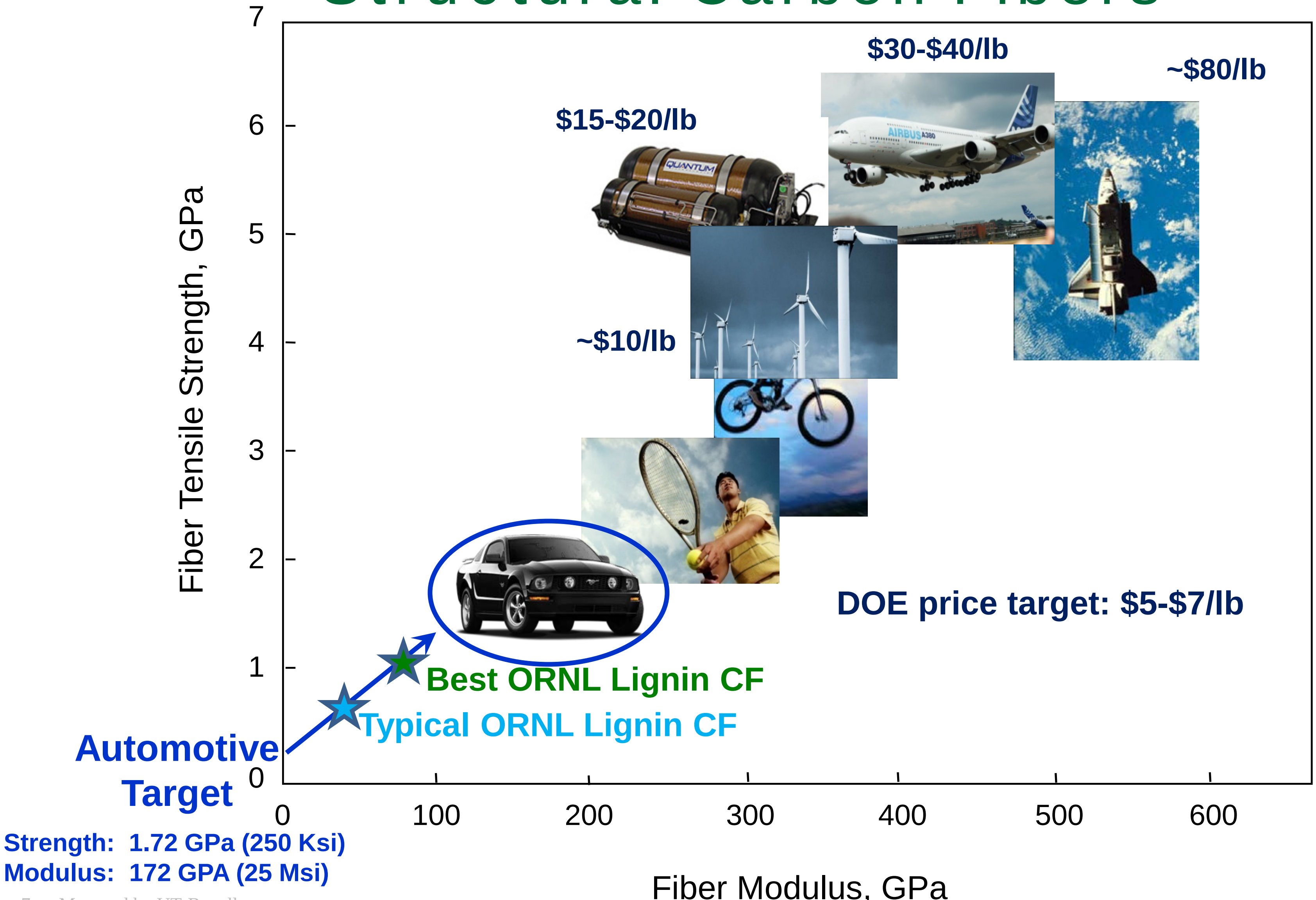
Curved air passages

Carbon Fiber: Is it just for aerospace?

- Why Carbon Fiber?
  - High strength (600-1000 ksi), high stiffness (30-85 Msi), low density (1.8 g/cc)
  - But expensive ($10-$40/lb), non isotropic behavior (can be good, can be bad)
- Boeing 787 is made of approximately 50% CF, is 20% more efficient than similarly sized planes, eliminating 1500 aluminum sheets and 50,000 fasteners
- Dominant industries are aerospace, defense, wind turbine blades, pressure vessels



Costs and Properties of Structural Carbon Fibers



Science to Application

Dow and Ford partner with ORNL to scale up low-cost carbon fiber

- Dow and Ford team up to bring low-cost, high-volume carbon fiber composites to next-generation vehicles
  - Reducing weight of new cars and trucks by up to 750 lbs by the end of the decade
  - Foundational work at ORNL on low-cost precursors key to automotive applications
  - DOE and state of Michigan fund $13.5M research agreement to develop lower cost carbon fiber production process using polyolefin in place of conventional polyacrylonitrile (PAN) as feedstock
  - Novel process could reduce production cost by 20%
  - High-volume commercial launch anticipated outcome

Biomass for Biofuels and Carbon Fiber
Enabling both to be economically viable?

- Oil refinery profitability is in making fuel AND other products from input material
- Virtually all input crude is turned into value-added product
- To be economically viable, a bio-refinery will have to operate in much the same manner

Cellulose and hemicellulose

Chemical building blocks: Plastics, industrial additives, biomedical applications

Biofuels

BESC
BioEnergy Science Center

Lignin

Reduction in finished carbon fiber production cost: ~30–40%

Melt spinner

Carbon fiber production line

Conversion cost: 30% of conventional

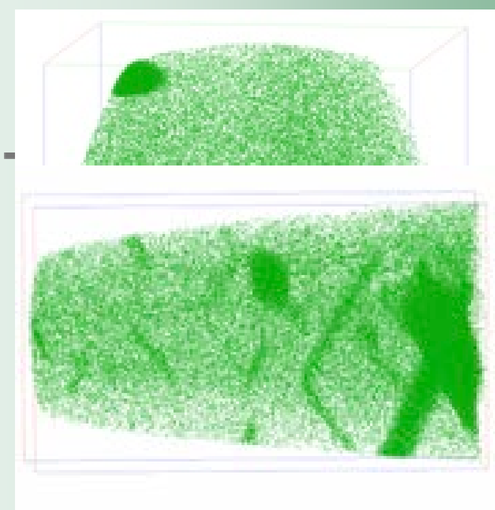
P4 Preforming

Lignin and innovative processing: ~50% less than PAN and conventional processing

Rapid Infrared Heating Technology: From Lab Discovery to Commercialization.

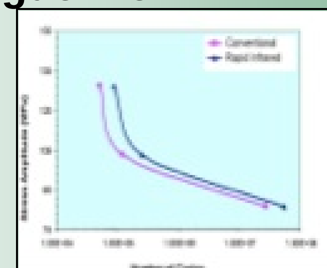
Basic Science
(NSF & DOE OS)

Atom probe results showing finer distribution of nano-size Al_2CuMg precipitates in infrared heated forgings:



Applied R&D
(EERE Industrial Technologies and DOE Fossil Energy)

Finer precipitate distribution improves fatigue life:



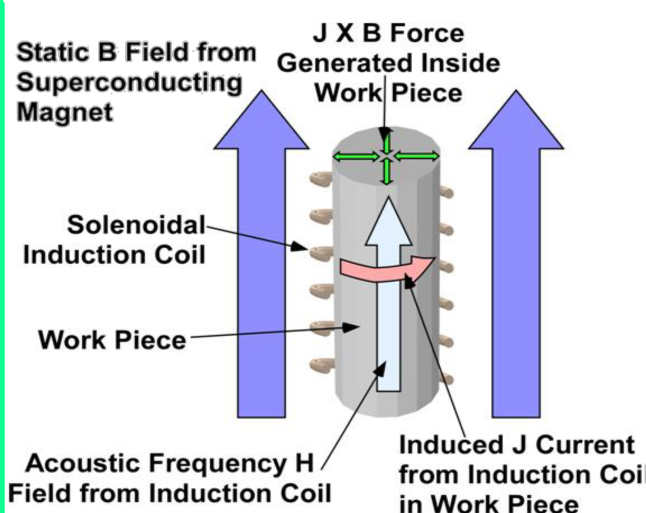
IR Preheating of Aluminum Billets

Manufacturing & Commercialization

- ✓ 2.5 hours with conventional preheat down to 18 minutes
- ✓ Decrease in cost by order of magnitude
- ✓ 4x increase in throughput
- ✓ 72% savings in energy
- ✓ >2 million impellers in diesel engines

Magnetic Field Processing to Achieve Wrought Like Properties In Castings

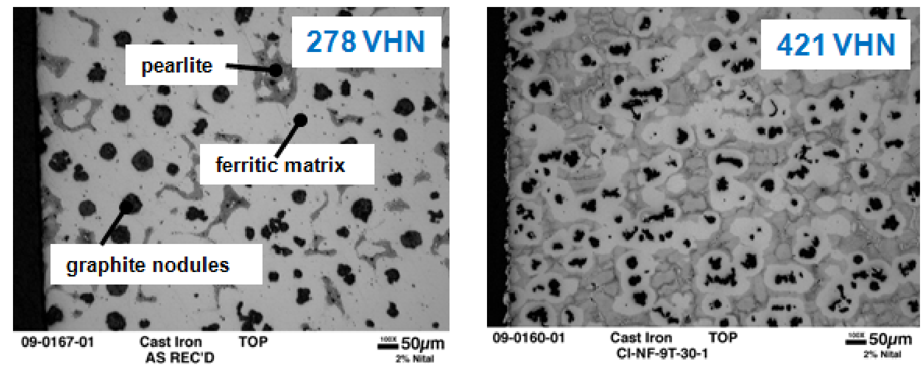
Electro Magnetic Acoustic Transmission (EMAT)



Wrought-Like Properties in Cast Iron

As-received Cast Iron

Cast Iron solidified under 9T (51% increase in VHN)

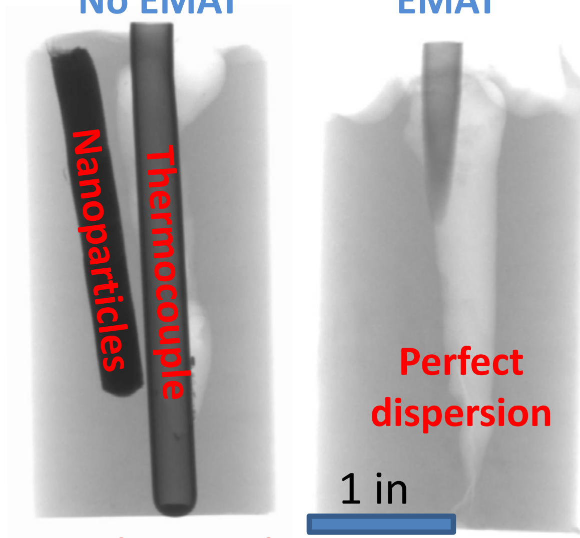


Dissolution of graphite nodules as a result of Non-contact Electro-Magnetic Accoustic Transmission

- Magnetic Field Processing Can
  - Change phase equilibrium
  - Kinetics
  - Crystal alignment or second particle/phase orientation
  - Stress state

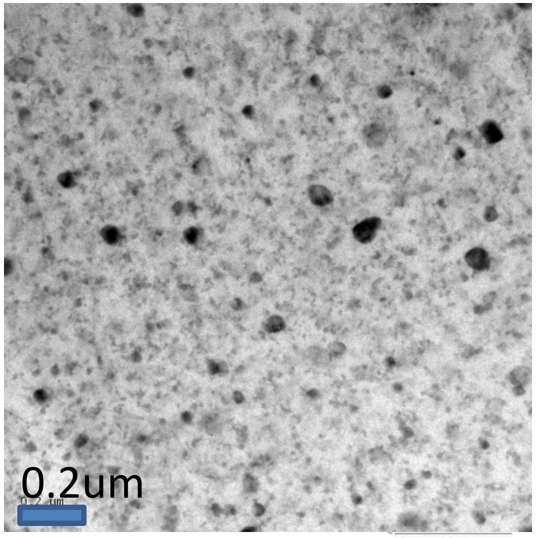
No EMAT

EMAT



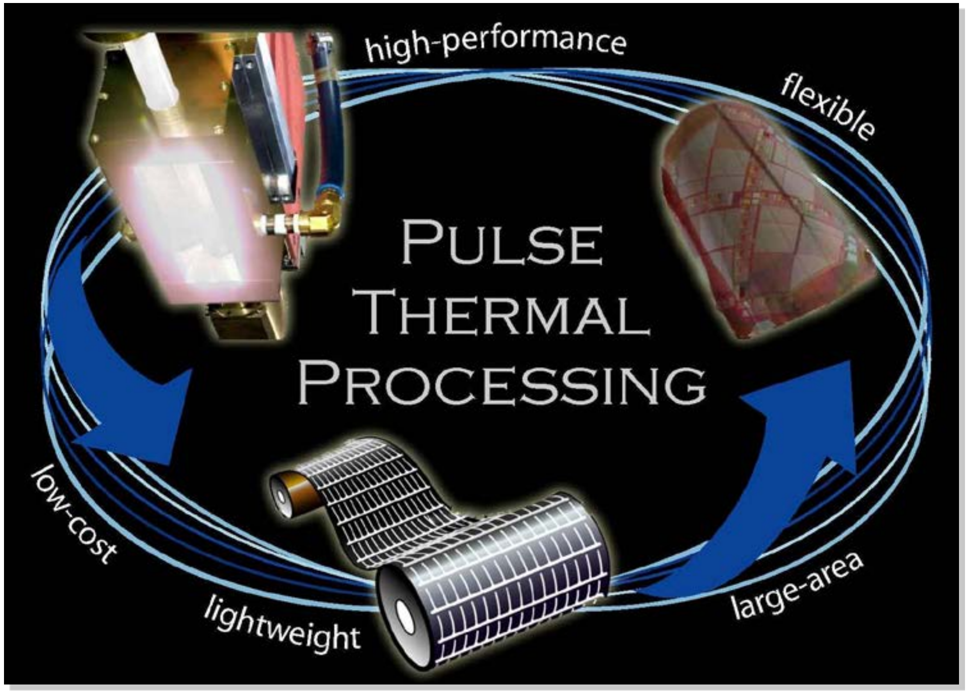
Not dispersed

Uniform Mg nanocomposites



Pulse Thermal Processing

Plasma Arc Lamp



Flexible Displays

Crystallize a-Si thin film transistors for backplane

Increase electron mobility by 10x

Thin Film Batteries

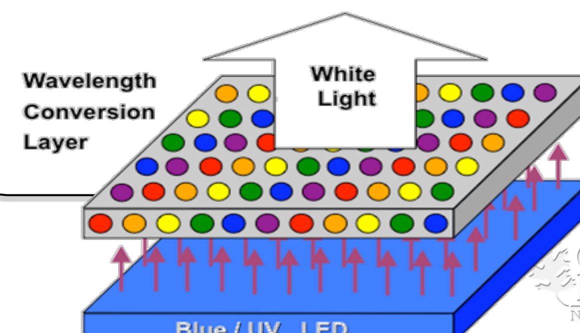
Increase storage capacity by controlling grain growth and orientation

Decrease $LiCo_2O$ cathode resistance by 10x

Solid State Lighting

PTP anneals nanostructure to reduce defects and increase efficiency

Increase luminescence by 300%



Thin Film Photovoltaics

Crystallize a-Si on Metal Foil

Texture CIGS Nanocrystals on Polymer Substrate

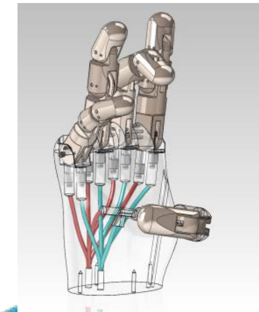
Increase efficiency by 50%

Merging Printed Electronics and Additive Manufacturing

- Achieve high performance on low-cost, low temperature substrate
- Joining of dissimilar material classes (e.g., metal to ceramic)
- Enable multifunctional systems
  - Structure
  - Actuation
  - Energy Generation
  - Energy Storage
  - Display
  - Communication
  - Sensors

Substrate Integration

Integrated 3-D Systems

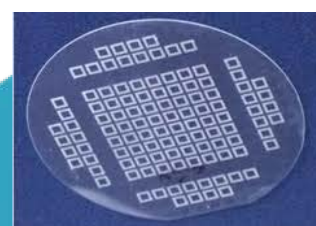


Functional 3-D Printing

Plastic: Low-cost Electronics

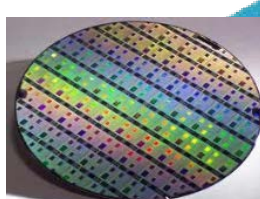
T<200°C

Glass: Transparent Electronics



T<600°C

Si: CMOS



T<1000°C

The future of manufacturing:
STEM - High School Robotics Teams

FIRST Robotics Competition

- Founded by Dean Kamen (Segway inventor): For Inspiration and Recognition of Science and Technology
- Goal: Inspiring youth to be science and technology leaders

2011–2012 teams now at work

- Opened ORNL MDF to work with 8 area high schools
    - Over 50 mentors and teachers
    - Over 200 students
    - Over $200K in industrial support (Stratasys, DOE, NFPA, Bimba,Festo)
- 2012 Smoky Mountains Regional Competition
    - Hardin Valley Academy
      Engineering Excellence Award (first completely AM Robot!)
    - Oak Ridge High School
      Top Rookie All Star Award & Nationals Contender
    - Webb High School
      Woodie Flowers Finalist Award
    - Knoxville Catholic High School and Seymour High School
      Ranked in the Top 5

Discussion

Lonnie Love

lovelj@ornl.gov

(865)576-4630

Emerging Trends in Manufacturing and the potential for new U.S. fluid power products

- Additive manufacturing
  - Blending hydraulics, pneumatics, electronics… into one process
  - New materials and processes will enable high value, low manufactured cost products
- Low-cost carbon fiber
  - Lignin-based precursors has the potential to make CF a commodity material for actuators, accumulators, structure…
- External Field Processing
  - Magnetic fields enabling wrought like mechanical properties in cast parts such as pumps, vanes, pistons…
  - Radiant heating significantly reduces preheat, increase throughput and improve mechanical properties

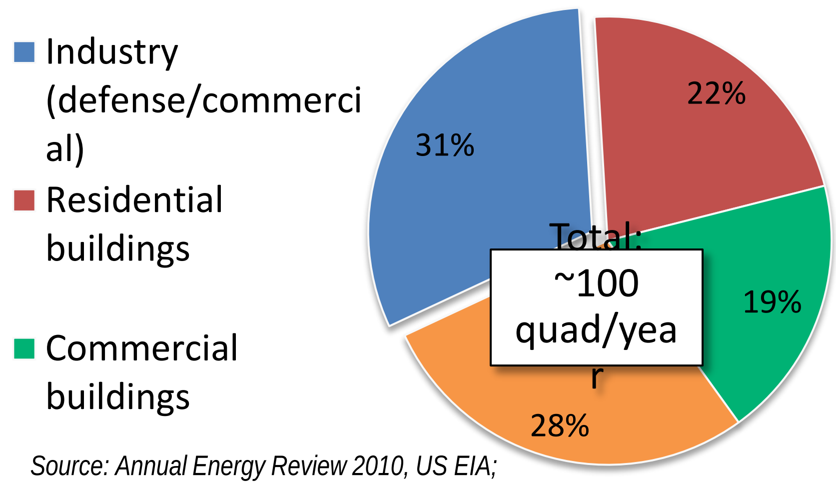
Transient Field Processing

- Traditional manufacturing is “beat” and “heat”.
- Processing capabilities of materials for enhanced properties and reduced processing cost/energy include:
  - Magnetic field, radiant (laser, plasma lamps, infrared lamps), ultrasonic, induction, and microwave processing
- Working with industry, ORNL has developed six superconducting thermomagnetic processing facilities.
- Thermal magnetic field processing (TMP) enables
  - Major improvements in performance
  - Unique microstructures due to impacts on phase equilibria and phase transformation kinetics

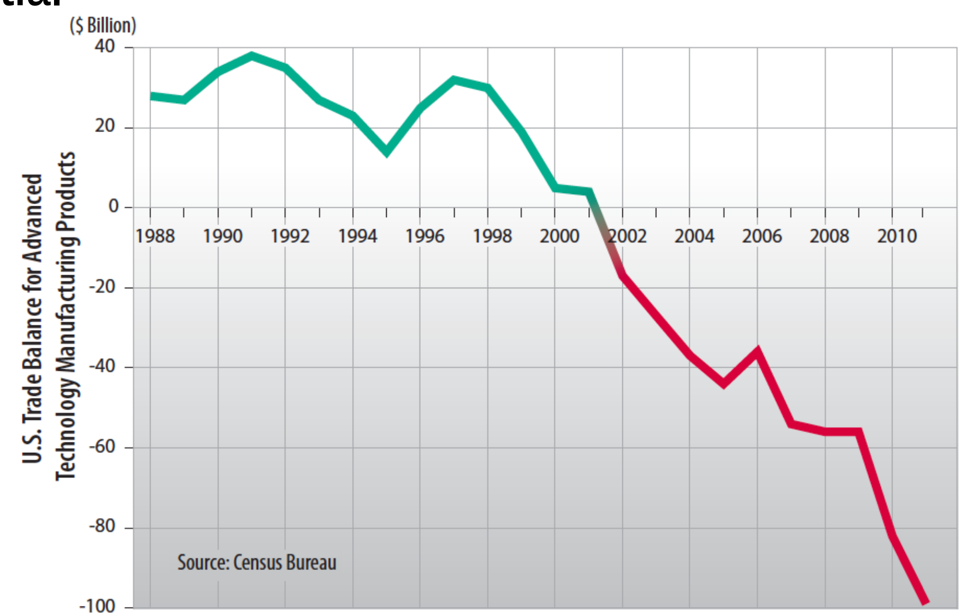
U.S. manufacturing

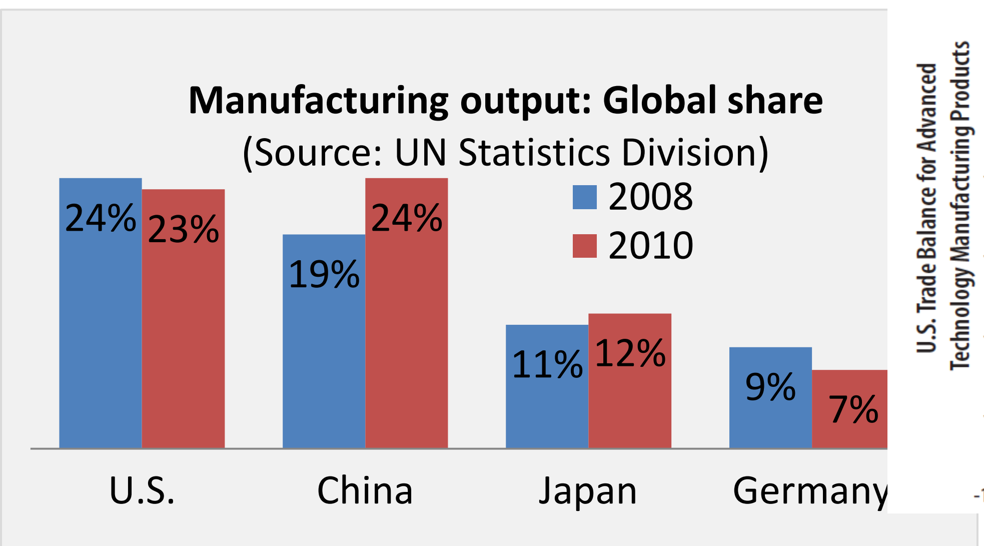
- Manufacturing is a major component of the U.S. economy
  - 12 million jobs (60% of U.S. engineering and science jobs)
  - 11% of GDP ($1.5 trillion)
  - 57% of U.S. exports
- U.S. innovation remains strong, but trends are moving in the wrong direction
- Following is an overview of emerging high value manufacturing that have the potential to impact the fluid power industry

Industry: 31% of total U.S. energy consumption



Source: Annual Energy Review 2010, US EIA; U.S. Bureau of Labor Statistics, 2011 data





Science to Application

Enabling AM of Turbine Blades

- **Optimized internal cooling structures are desired for maximum efficiency**
- **AM can produce geometries not possible with conventional processes**
- **Decrease manufacturing costs while maximizing performance**

urbine blade

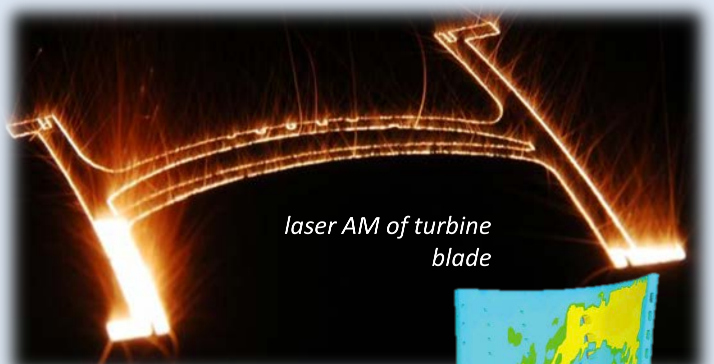
Reconstructed image using neutron tomography

MORRIS TECHNOLOGIES

Precision. Innovation. Expertise.

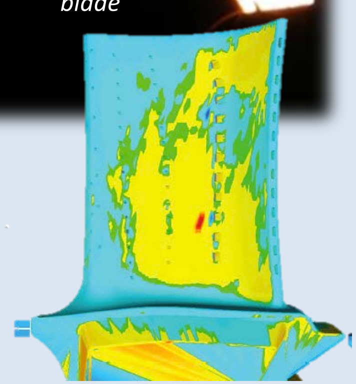
Headquartered in Cincinnati, OH

- ***Largest number of AM machines worldwide***
- ***18-yrs experience in laser deposition***
- ***Works with every major aerospace company in US***



laser AM of turbine blade

Laser AM creates large residual stress leading to distortion



Profilometry map illustrating distortion

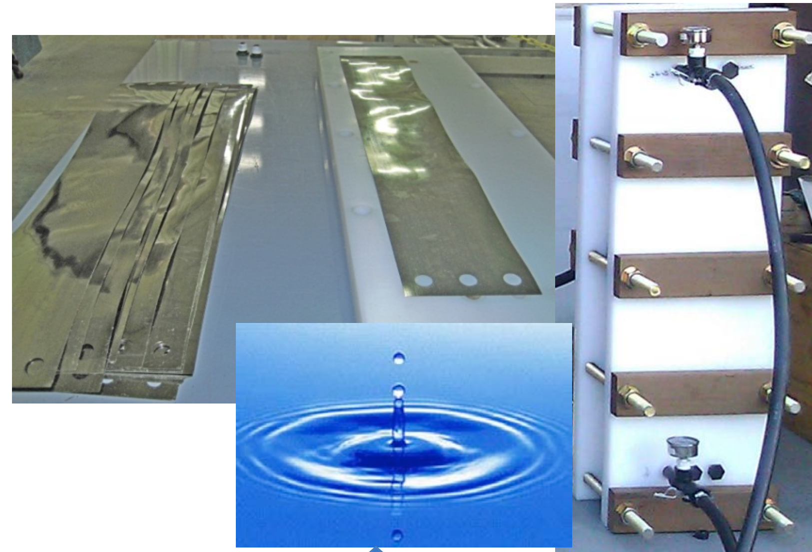
Critical to widespread adoption of technology

Understanding link between residual stress and additive manufacturing

Utilizing neutron science to impact industry

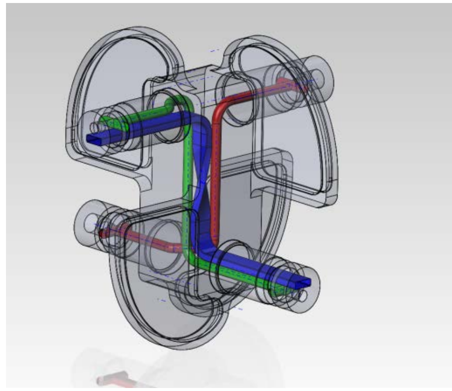
Affordable Titanium from the Consolidation of New Ti Powders

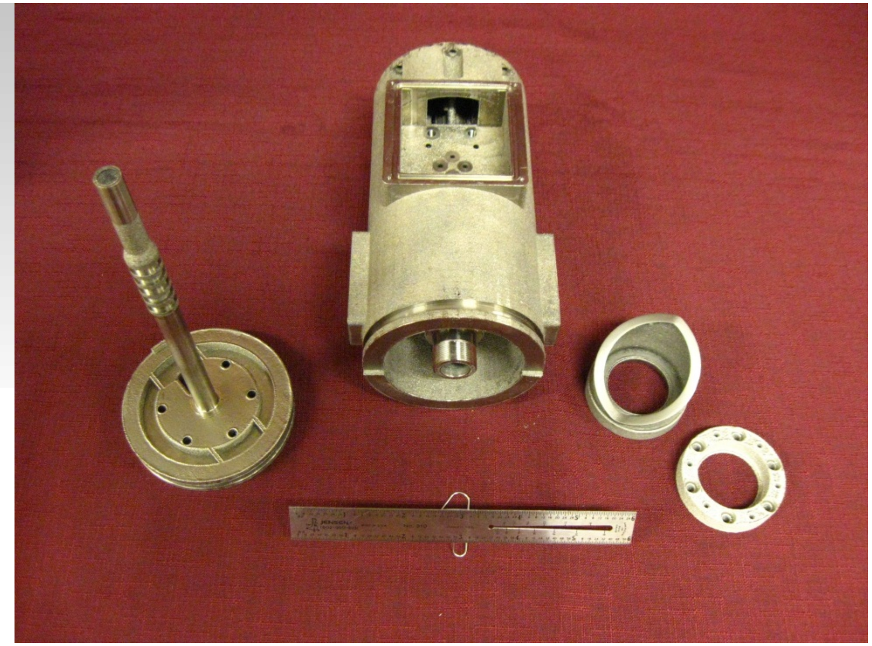
- **Titanium 9th Most Abundant Element (0.6% of Earth's Crust)**
  - **95 to 97% of Refined TiO_2 Used in Pigments, Chemicals, Etc.**
  - **Cost & Use of Ti Not Reflective of Its Abundance**
- **Aircraft Industry Currently Accounts for 78% of the US Ti Milled Product (GSDS)**
- **Aircraft Industry Purchases 8 to 11 Pounds for Every 1 Pound that Flys [e.g., F-22: Buy 110,239 lbs per jet fighter to yield 10,043 fly-away]**
- **New Reduction Technologies Produce Powder**
- **Powder Metallurgy or Additive Manufacturing Used to Consolidate New Powders Could Enable Paradigm Shift for Titanium**
  - **Increase Yields (10% → 90%)**
  - **Lower Cost (e.g., 50% for thin sheet and aircraft bracket)**



From Sheet to Netshape Components

Lightweight Underwater Robotics (ONR)





Barrel cam joint

Involute cam joint

Science to Application

Carbon Fiber Technology Facility (CFTF)

CFTF: **A DOE-funded facility for demonstrating advanced technology scalability and producing market-development volumes of prototypical carbon fiber**

Demonstrate low cost carbon fiber (LCCF) technology scalability with the last scaling step before full-scale commercial production

Produce quantities of LCCF for large-scale material and process evaluations and prototyping

Deploy a training system, in partnership with Roane State Community College, for developing the future carbon fiber workforce

CFTF is the bridge from R&D to deployment and commercialization

Manufacturing initiative development

2011

January: Plan to Win the Future by Investing in Advanced Manufacturing Technologies

May: DARPA BAA, Open Manufacturing

June: DOE FOA, Innovative Manufacturing Initiative

June: Launch of Advanced Manufacturing Partnership

2012

January: Blueprint to Support U.S. Manufacturing Jobs

Feb: DOE announces first Manufacturing Demonstration Facility at ORNL (AM/CF)

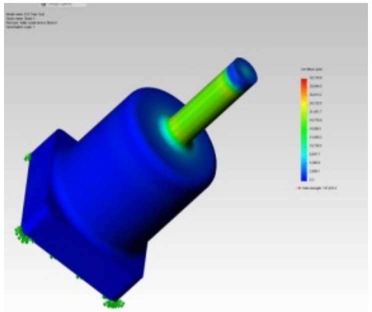
March: Announce National Network for Manufacturing Innovation (NMMI)

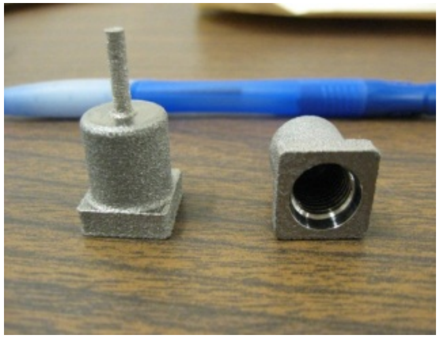
ORNL's vision:

Provide industry access to unique research facilities and expertise that reduce the risk and accelerate the development and deployment of next-generation materials and manufacturing technologies

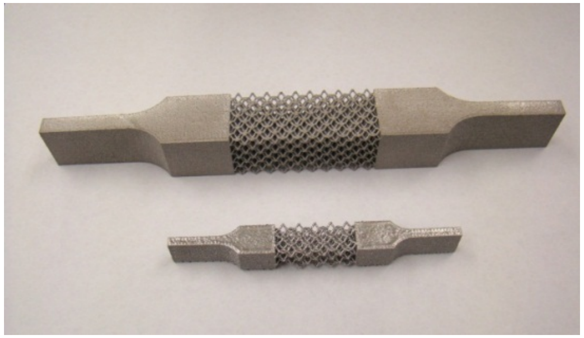
Mechanical considerations

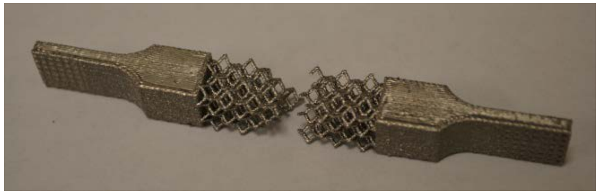
- Mechanical Strength
  - Hold to well over 6000 psi at 0.020” wall thickness on 0.125” tube





  - Wrought Mechanical properties, even for 0.015” AM mesh

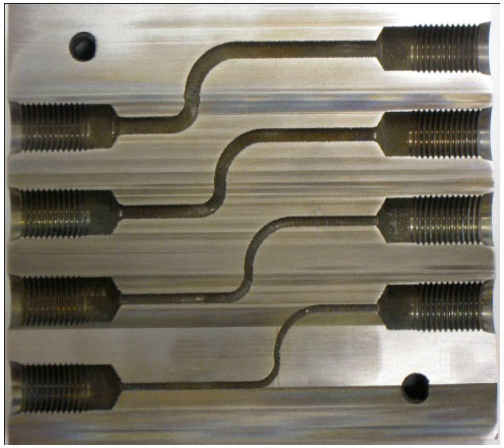


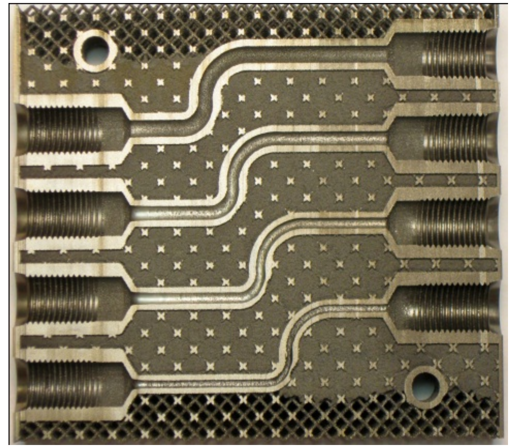


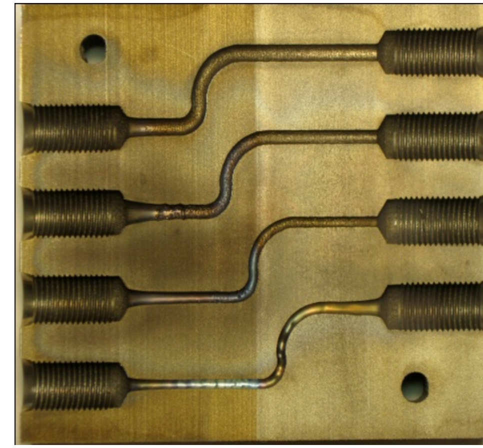
Oak Ridge National Laboratory

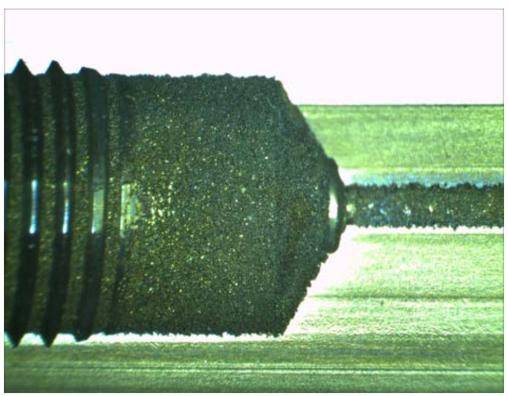
Hydraulic Consideration

- Removal of powder on blind holes with abrasive slurry

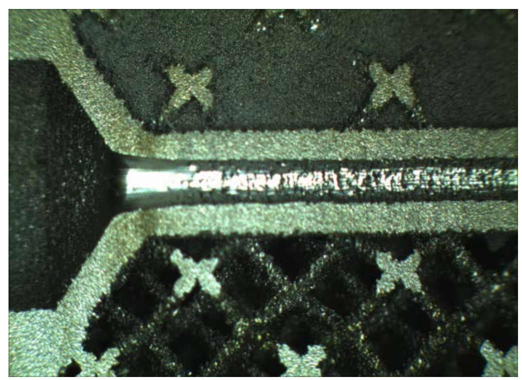








No finishing



Moderate finishing

Aggressive finishing

MDF – integration of cutting-edge manufacturing technologies

Additive Manufacturing

- Metal Powder Bed Consolidation
- Direct Metal Deposition
- Polymer Extrusion
- Ultrasonic Consolidation

Carbon Fiber

- Precursor to Filament
- Filament to Carbon Fiber
- Carbon Fiber to Composite Material

Advanced Materials & Processing

- Lightweight Metals
- Roll-to-Roll
- Low-Temperature
- Transient Field

Automation & Controls

- Modeling & Simulation
- Sensing, Tracking & Measurement
- Communicating Wirelessly
- Systems Engineering

Manufacturing Demonstration Facility

Market

Technology Impacts:

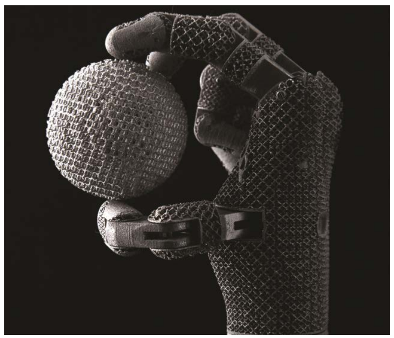
- Market Driven Adoption of New Materials and Processes
- Transformational & Cross-Cutting for Next-Generation Products

Thrust Area

Additive Manufacturing

Metal

Electron Beam Melting



- Developing in-situ characterization, feedback and control
- Precision melting of powder materials
- Processing of complex geometries not possible through machining

Ultrasonic Additive Manufacturing

- Simultaneous additive and subtractive process for manufacturing complex geometries
- Solid-state process allows embedding of optical fibers and sensors

Laser Metal Deposition

- Site-specific material addition
- Application of advanced coating materials for corrosion and wear resistance
- Repair of dies, punches, turbines, etc.

Polymer

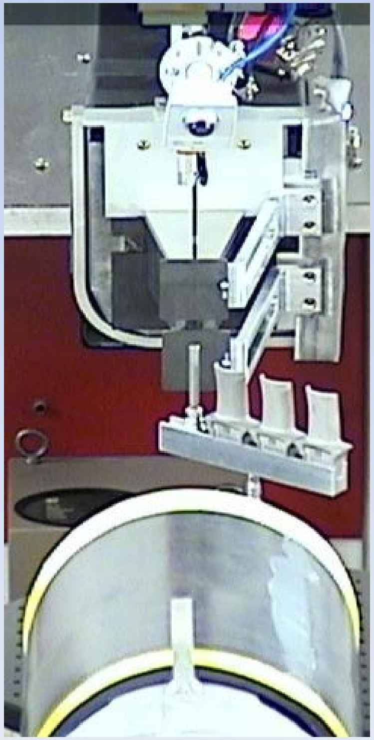
Fused Deposition Modeling

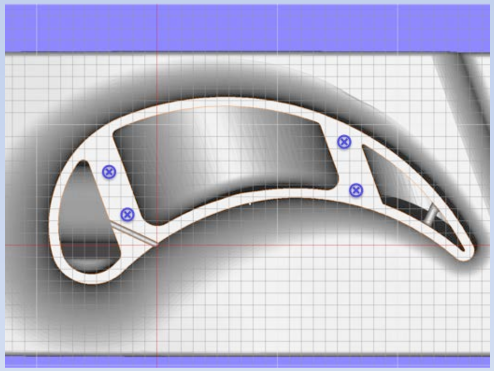
- Development of high-strength composite materials for industrial applications
- Precision deposition of thermoplastic materials

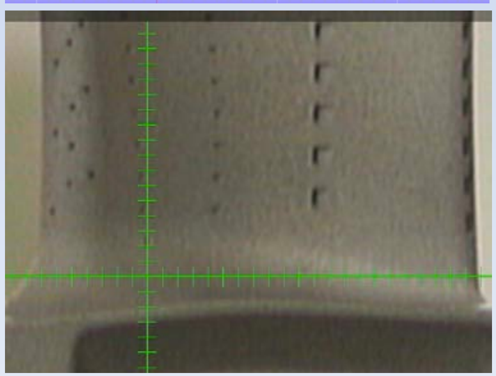
Working with AM equipment providers to develop high-performance materials, low-cost feedstocks, processing techniques and in-situ characterization and controls to enable broad dissemination of technologies

Science to Application

Neutron characterization of additive manufacturing





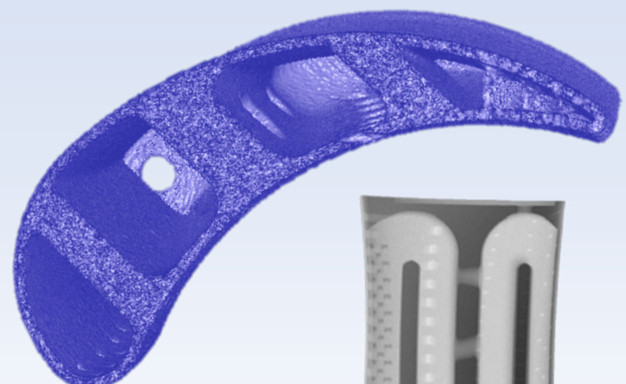


- Successful Inter planer spacing measurements on complex geometry
- Developing capabilities for residual stress mapping
- In-situ measurement during processing, HT, mechanical testing

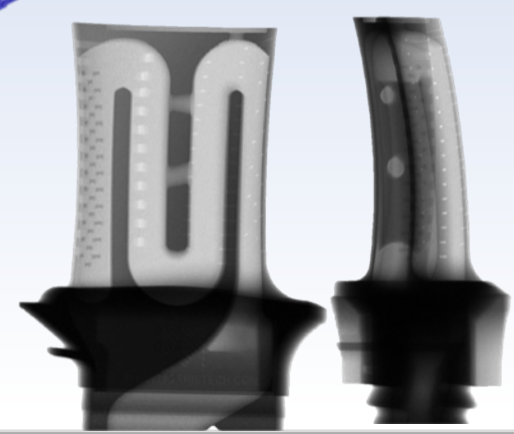
Residual Stress Measurements

Neutron Imaging and CT

- Neutrons offer higher contrast and better resolution than x-rays
- Resolution Capabilities
  - Currently at HFIR: 50 μm
  - Proposed VENUS: 1 μm
- Ability to study micro/macro cracking phenomena related to residual stress during processing



Reconstructed image using neutron tomography



ORNL was selected as DOE's Pilot Manufacturing Demonstration Facility (MDF)

- 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
- Main components
  - Programs with OEMs to ensure broad distribution of technology
  - User facility
- Leveraging ORNL's distinctive core capabilities
  - Neutron scattering
  - High-performance computing
  - Advanced materials
  - Advanced characterization

***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