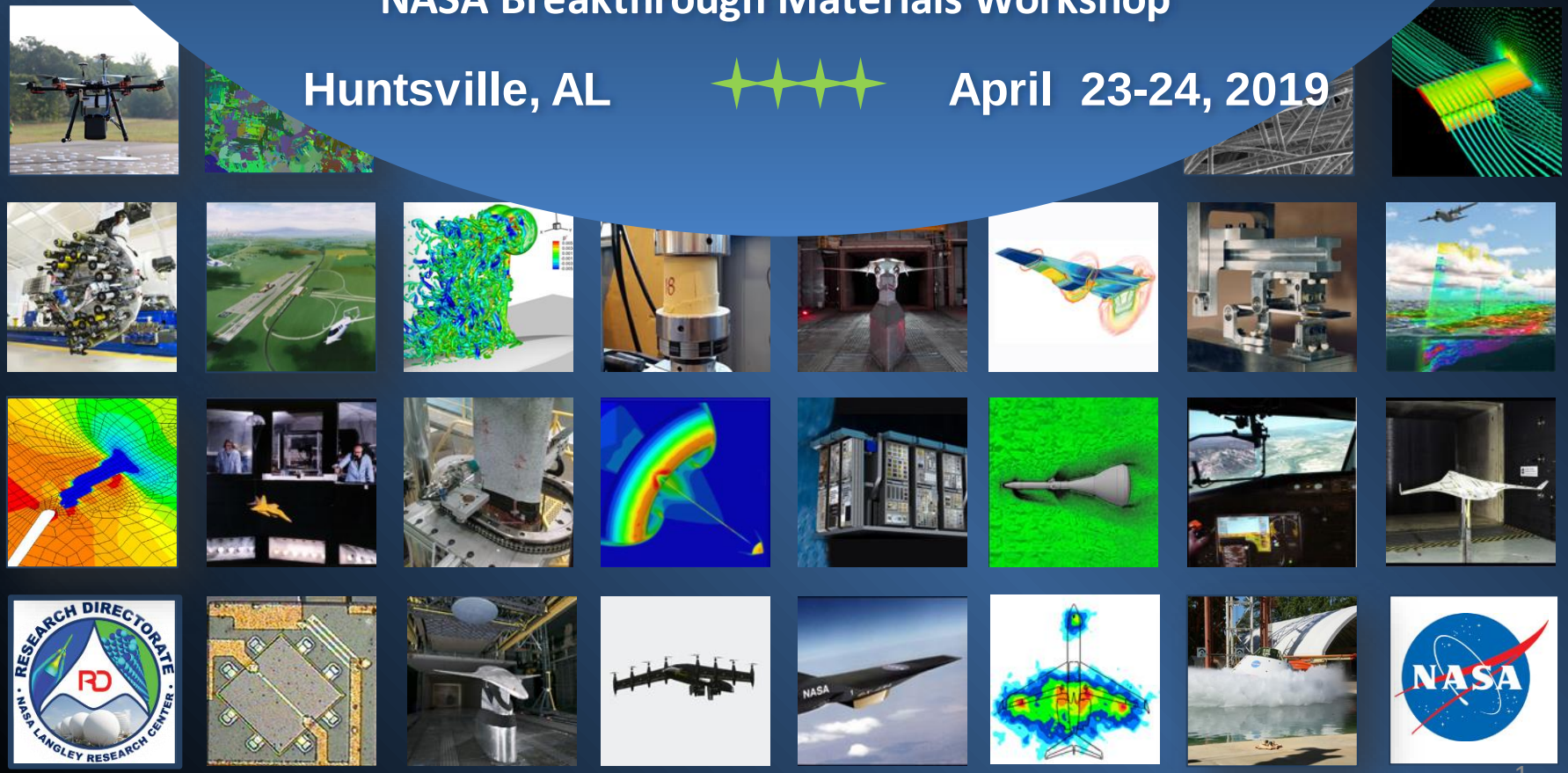
Recent Advances in Materials and Methods for Aerospace Applications at NASA Langley Research Center

Jonathan Ransom
Deputy Director for Structures and Materials

NASA Breakthrough Materials Workshop

Huntsville, AL ✦✦✦ April 23-24, 2019



Materials and Methods for Rapid Manufacturing for Commercial and Urban Aviation Workshop



Objective: To assess the state of technology of rapid/advanced manufacturing, identify technology gaps, develop whitepaper/roadmap identifying industry needs and insertion points to meet project needs, and to propose investment needs for NASA

Held: November 14-15, 2018, Tysons Corner Marriott, Tysons Corner, VA

Sponsored by: NASA Aeronautics Research Mission Directorate, Dr. John Cavolowsky, Program Director

Hosted by: NASA Langley Aeronautics Research Directorate, George Finelli, Director

Planning Committee: Jonathan Ransom (General Chair), Michelle Ferebee (General Co-Chair), Ed Glaessgen (Technical Program Chair), Brian Jensen (Technical Program Chair), Andrea McAlister (Logistics Coordinator)

Inter-Center Planning Team POCs: Sean Swei (ARC), Tim Risch (AFRC), James Zakrajsek (GRC), Joyce Dever (GRC)

Attendance: 122 participants including materials and manufacturing professionals, original equipment manufacturers, material suppliers, researchers, government, academia

Observations

High Level Observations

- Future aircraft will be heterogeneous - combination of metals and composites manufactured using a myriad of approaches
- Rate improvement from current advanced tools while using current materials limited to 2X or less improvement. New materials and processes required to meet 5X current production rate goals
- Must bridge gap between the research community and industry design and development practices
- Maintaining NASA relevance requires ability to address OEM concerns and FAA cert. requirements

Representative General Observations

- Future production rates require improvements and streamlined relationships in aircraft design, materials, certification and manufacturing methodologies
  - Design, certification and manufacturing inseparable and have to be considered as a unit
- The commercial and urban aviation markets have similar challenges. While rate of production and manufacturing approach is different, neither market can sacrifice structural performance with faster production rates
- The materials and methods identified for rapid manufacturing broadly applicable to both commercial and urban aviation markets. However, specific materials and manufacturing needs for urban aviation evolving as these vehicles continue to be defined whereas needs are well known for commercial aviation market.
- Rapid manufacturing-related technology development required as National asset; however, manufacturing approaches and forms will evolve significantly during next 20 years
  - NASA should invest in advanced materials and foundational methods (experimental and simulation) that are broadly applicable
  - Focus on providing well-validated modeling tools to community

Investment Areas – Where NASA should Contribute

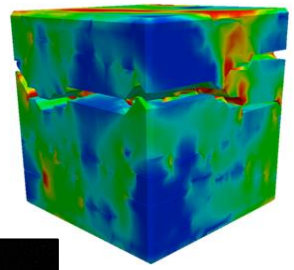
- **Design:**
  - Develop capabilities for application-specific design and optimization of materials and structures for rapid manufacturing incorporating inspectability, manufacturability, certification requirements
  - Develop concepts for closer integration of the manufacturing process with structural and material design
  - Design and analyze unitized and bonded structural concepts.
- **Materials, Processing & Manufacturing:**
  - Metals: Evaluate the potential efficacy of the broad range of emerging advanced metallic manufacturing technologies;
  - Thermosets: Develop fast curing resins tailored for out-of-autoclave (OOA) processes including automated fiber placement (AFP) w/vacuum bag only (VBO) curing and resin infusion with VBO curing.
  - Thermoplastics: Develop in situ consolidation of continuous carbon fiber thermoplastic matrix resins.
  - Develop high throughput, rapid surface treatment process
  - Down select for further material development based on an industry-responsive business case
  - Process Modeling and Simulation: Develop robust computational models that can be used to predict defects and material properties for varying process parameters.
  - In-Process Monitoring/NDE: Develop advanced in situ and real-time nondestructive inspection and monitoring of material state.

Investment Areas – Where NASA <u>should</u> Contribute Cont'd

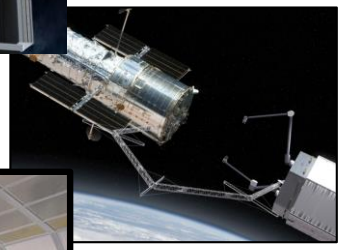
- **<u>Certification:</u>**
  - Develop capabilities to support certification of rapid manufacturing-produced components optimized for rapid manufacturing methods.
  - Understand process-microstructure-performance relationships over the entire design space; quantify uncertainties
  - Develop advanced test methodology for lower cost/rapid certification of new materials/processing methods and model development validation.
  - Transition high-fidelity simulation and characterization outcomes to engineering capabilities
  - Develop new capabilities for in-process inspection to reduce post-build testing; employ computational models for effective NDE and its certification
- **<u>Cross-cutting Technologies:</u>** Develop a comprehensive physics-based/machine learning-informed computational framework (digital thread) for materials, processing, performance and life.

Advanced Materials and Structural Systems

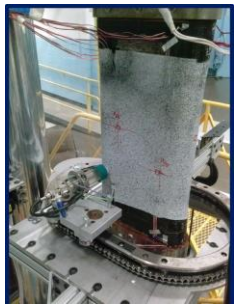
Mission Statement: We innovate new materials and structural concepts that enable future aviation & space exploration, and develop the foundational technologies essential for manufacturing, design, validation & sustainment.







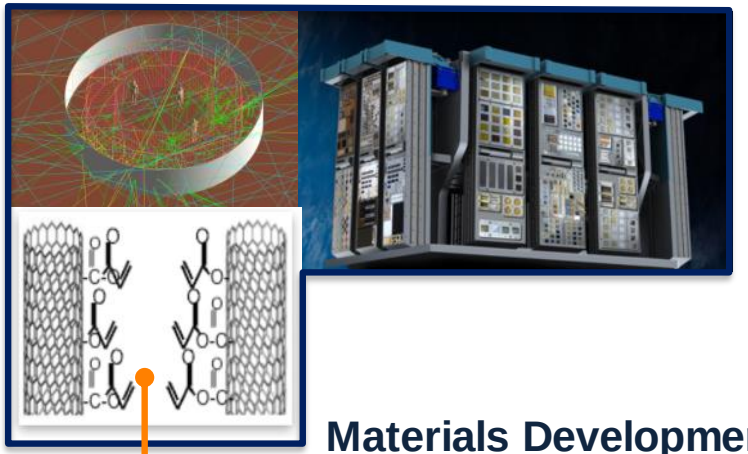




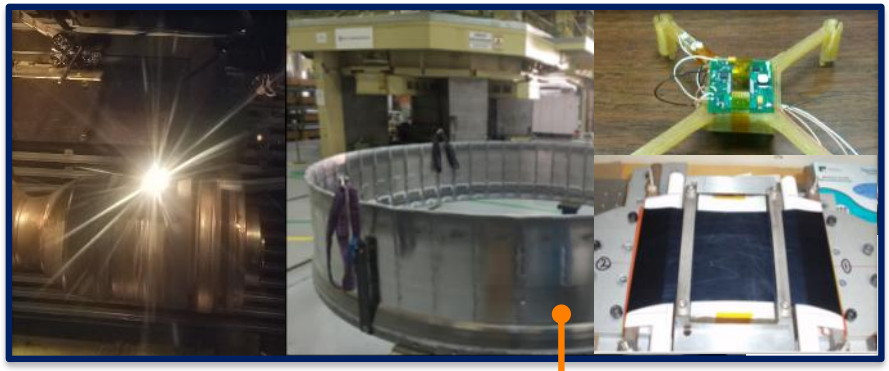
Technology Areas

- Materials
- Structures
- Mechanisms/Manipulators
- Advanced Manufacturing Technology
- Flight Qualified Structures
- Advanced NDE and SHM Technology

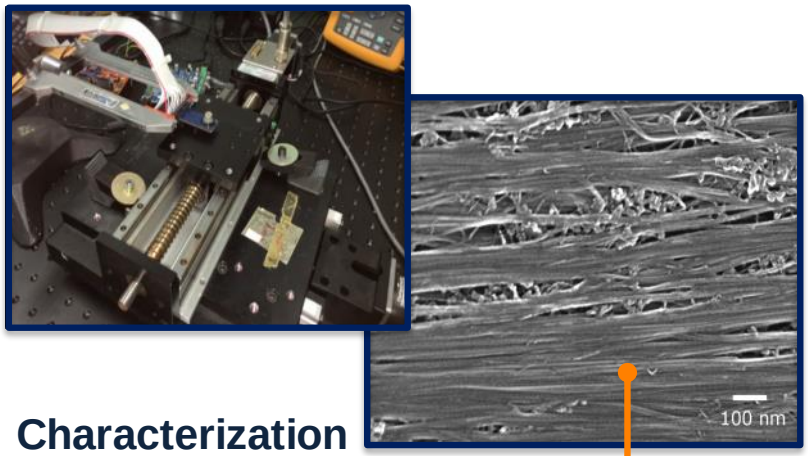
Advanced Materials and Processing Capabilities



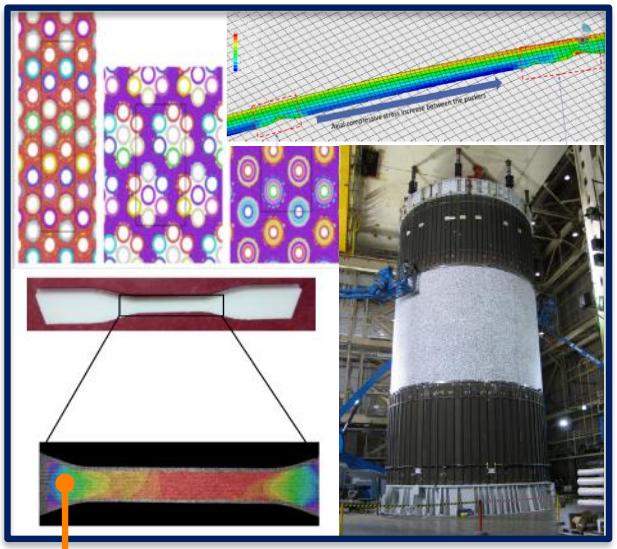
Materials Development



Process Development



Characterization

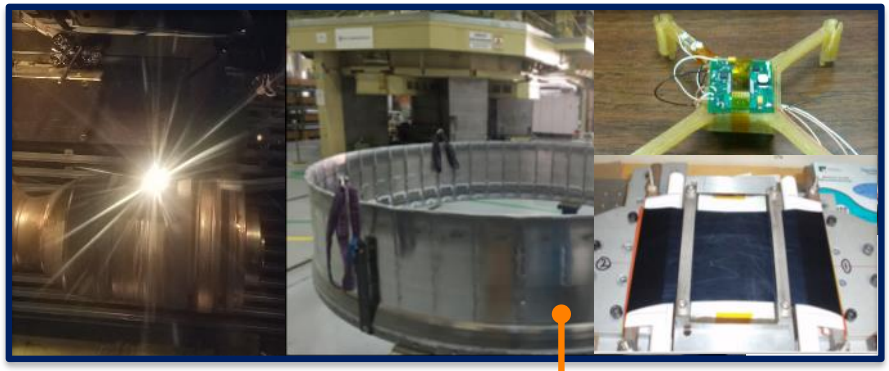


Modeling and Simulation

Advanced Materials and Processing Capabilities



Materials Development



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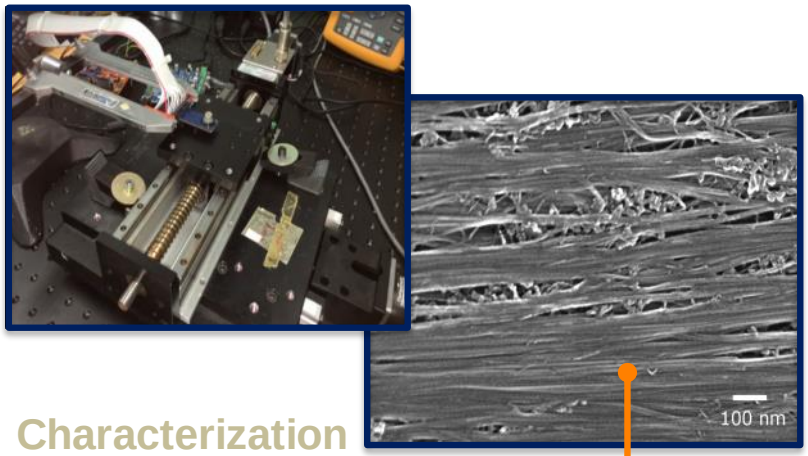

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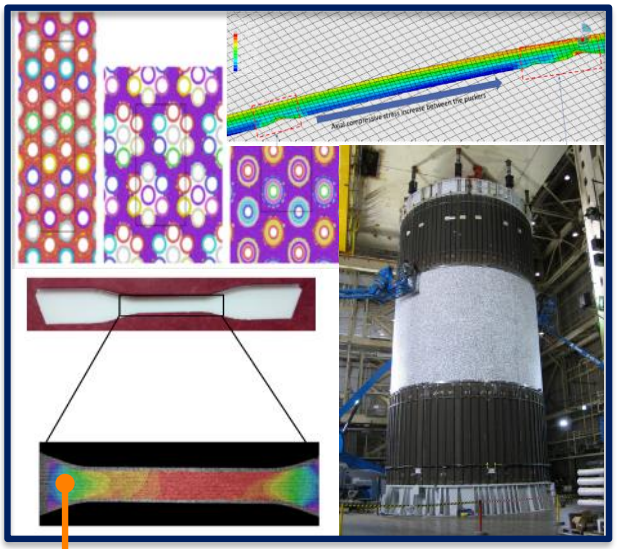
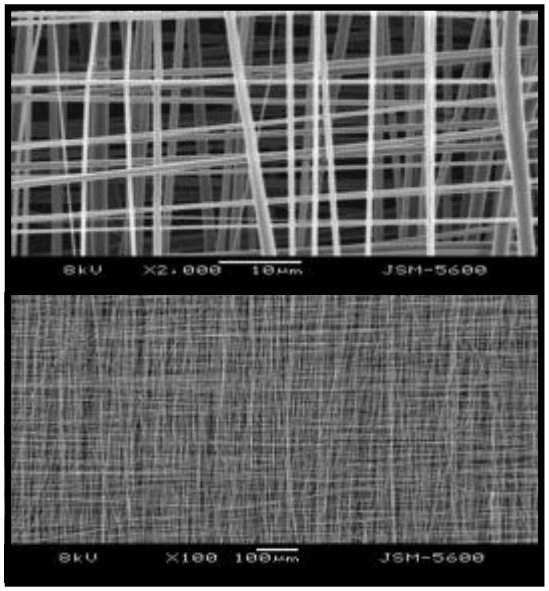


Modeling and Simulation

Positioning Ourselves for the Future

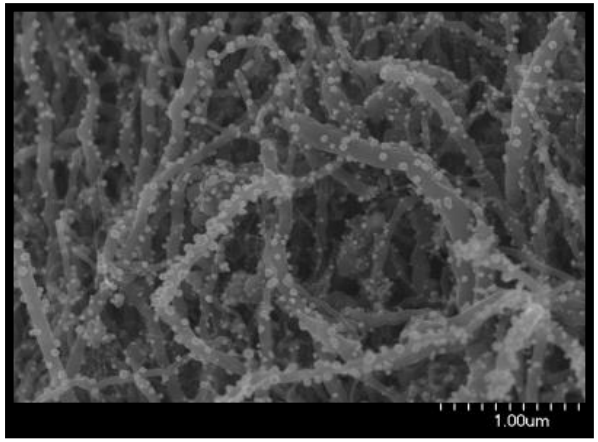
Emerging Technologies – Beyond Carbon Nanotubes

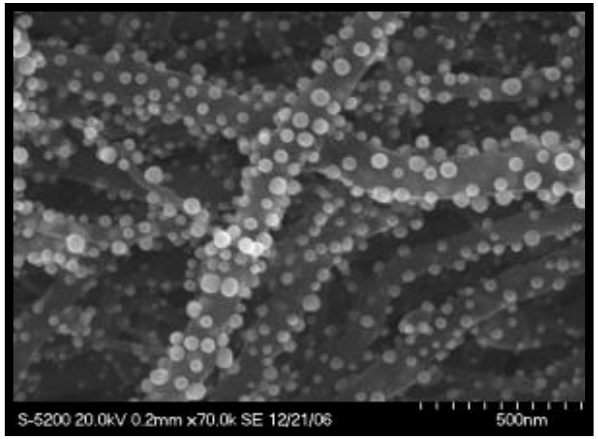
Aligned Electrospun Fabric



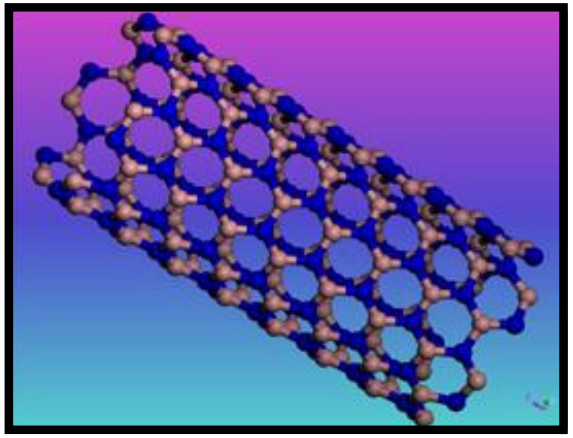
PGA 30 Layer mat: top image at 2000x; bottom image at 25x

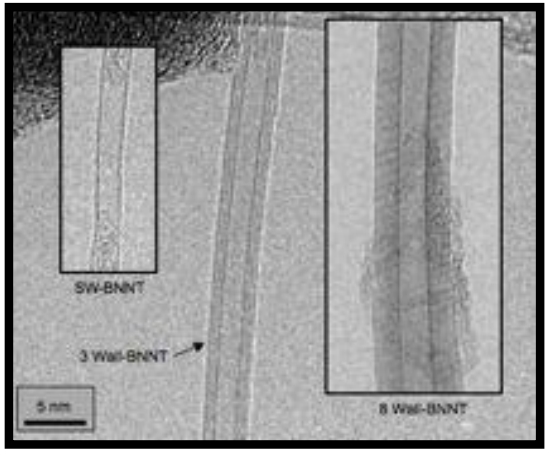
Metal Decorated Nanotubes





Boron Nitride Nanotubes





Holey Graphene Materials for Energy Storage

Objective

- **To fully exploit the potential of holey graphene materials and their derivatives for high performance energy storage and conversion applications that meet future NASA and national needs.**

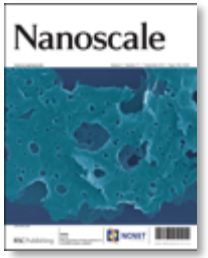
Why It Matters

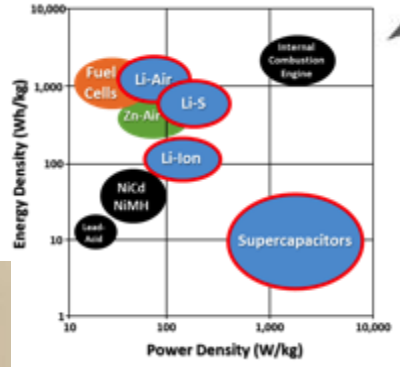
- Holey graphene has unique combination of properties (such as conductivity, porosity, surface area, chemistry, processibility) that make it a top electrode platform choice for a variety of next-generation energy applications.

Recent Accomplishments

- Demonstrated scalable preparation of holey graphene and structure-property relationship in electrochemical energy storage [1-5].
- Demonstrated the potentials of holey graphene electrodes in supercapacitors [4,5] and lithium ion batteries that are lightweight and of ultrahigh volumetric performance [6].

(1) U.S. Patent 9,2242,861; (2) Patent filed; (3) *Nanoscale* **2012**, *4*, 6908; (4) *ACS Nano* **2014**, *8*, 8255; (5) *Adv. Func. Mater.* **2015**, *25*, 2920; (6) *Small* **2015**, *11*, 6179.











Holey graphene can be made into ultra-lightweight and highly compact electrodes that have high accessible active surface area with effective through-electrode molecular storage and transport, thus enabling superior performance in various types of electrochemical energy storage mechanisms.

Clients

- NASA Langley
- NASA-ARMD

Participants

- NIA – Yi Lin, Jae-Woo Kim
- NASA LaRC – John Connell
- U. Maryland – Liangbing Hu
- Case Western Reserve U. – Liming Dai

Materials International Space Station Experiment – Flight Facility (MISSE-FF)

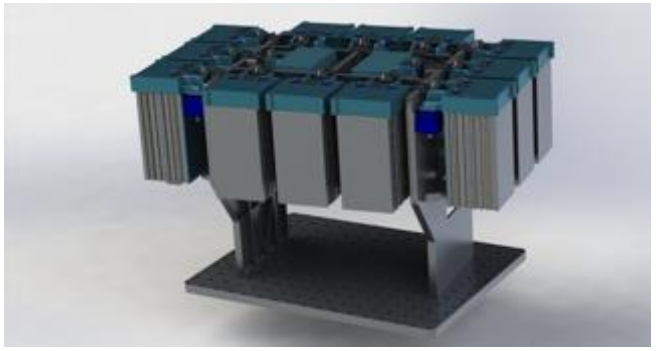
HISTORY

- NASA Langley's MISSE & MISSE-X Programs directly led to MISSE-FF

FEATURES

- To be launched in 2017
- Permanent facility on outside of International Space Station (ISS)
- For testing materials and devices in the space environment
- Passive and active experiments
- Power and communications from ISS for active experiments
- Ram, wake, zenith, and nadir orientations
- On-orbit photographs
- Modular experiment containers to be robotically deployed/retrieved
- Temperature and contamination monitoring
- Long-duration space exposures
- Affordable, easy access to space
- 40% allocation for NASA
- 60% allocation for non-NASA
- http://www.alphaspace.com/





Materials International Space Station Experiment – Flight Facility (MISSE-FF), in open and closed positions. *Images with permission from Alpha Space Test & Research Alliance, LLC.*

MISSE

MISSE Missions:

- Experiments on orbit for MISSE-9 and MISSE-10
- Experiments manifested for MISSE-11 and MISSE-12
- Experiments proposed for MISSE-13

MISSE Experiments:

- Radiation shielding materials
- Radiation resistant materials
- Atomic oxygen resistant materials
- Candidate Mars Ice Home materials
- Mars regolith simulant materials
- Bulk metallic glass (BMG)
- Advanced composites

SBIR Subtopic on MISSE Experiments:

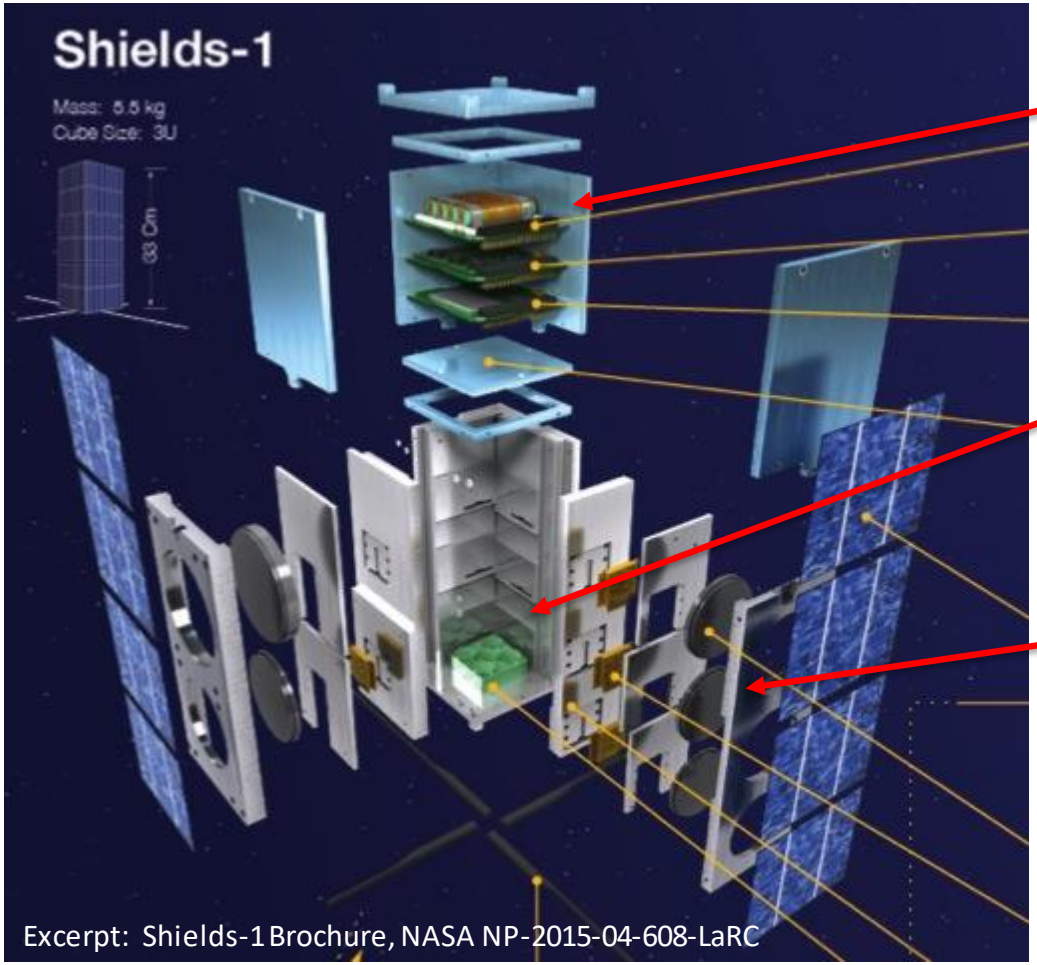
- One Phase II contract
- Three Phase I contracts



Kim de Groh (GRC) and Sheila Thibeault (LaRC) hold two of the three MISSE-9 flight decks they integrated on August 3, 2017 at Alpha Space in Houston, Texas.

Next Launch: MISSE-11 is scheduled to launch on the Cygnus NG-11 spacecraft on the Antares 230 rocket on April 17, 2019 from Wallops Island, Virginia.

Space Durable Hardware Experiments

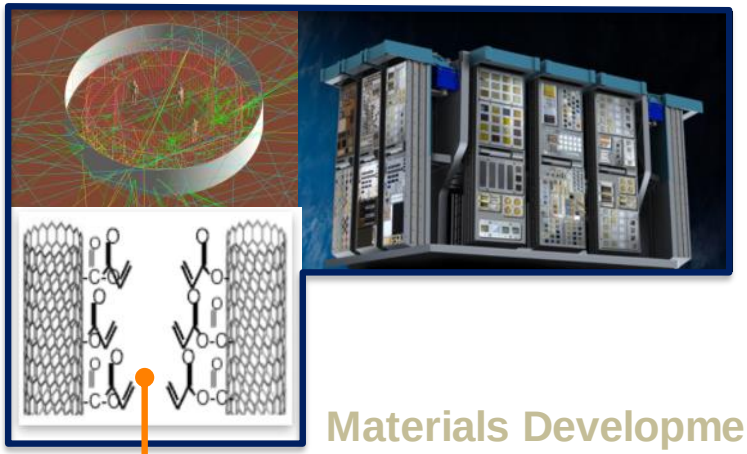


Excerpt: Shields-1 Brochure, NASA NP-2015-04-608-LaRC

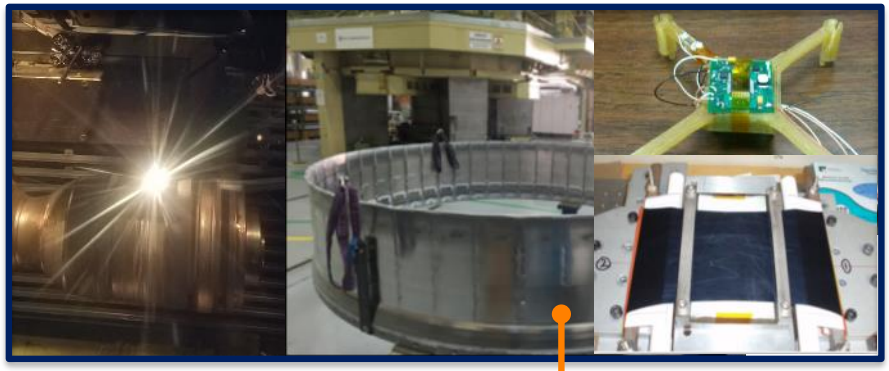
- **Vault Electronics**
  - To measure total ionizing dose (TID) over time and monitor system electronics performance.
- **Charge Dissipation Film Resistance**
  - Measure the resistance over time
- **Atomic Number (Z)-Grade Radiation Shielding**
  - To measure total ionizing dose of Z-grade radiation shielding and compare to baseline aluminum for at least 3 samples each.

Reference: D. Laurence Thomsen III, Wousik Kim, James W. Cutler, "Shields-1, A SmallSat Radiation Shielding Technology Demonstration", 29th Annual AIAA/USU Conference on Small Satellites, SSC15-XII-9, 8-13 August 2015, Logan, UT, p.1-7.

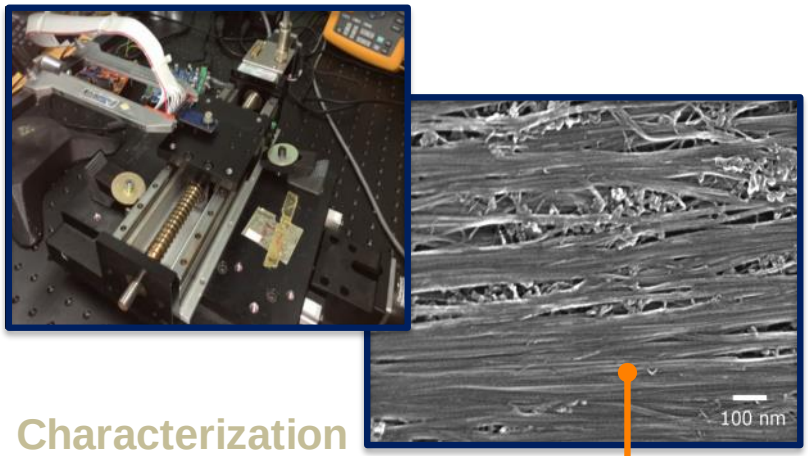
Advanced Materials and Processing Capabilities



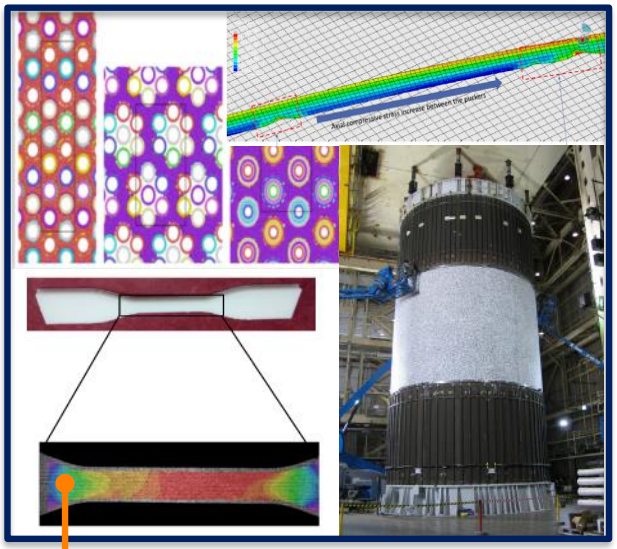
Materials Development



Process Development



Characterization



Modeling and Simulation

Technology Maturation of Integrally Stiffened Cylinder Process for Launch Vehicles

Al-Li Forming

Commercially produced steel clutch housing

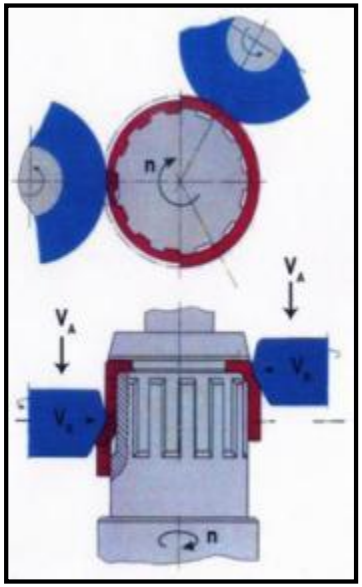


As-formed, No machining, ~ 8" (0.2m) dia.

Successful Forming of Al-Li 2195



As-formed, No machining, ~ 8" (0.2m) dia.

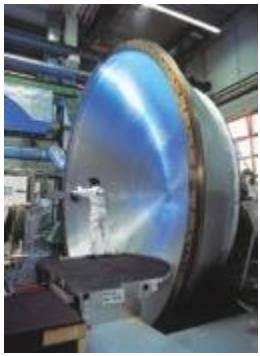


Spin/flow forming process for fabrication of integrally stiffened cylinders

Scale-up to 17" (0.4m) **dia.** for Sounding Rocket



Scale-up to 10' dia. for Cryogenic Tank Dome





ISC Forward Cylinder Launched October 2015 on Sounding Rocket

John.A.Wagner@nasa.gov

Marcia.S.Domack@nasa.gov

All images credit: NASA

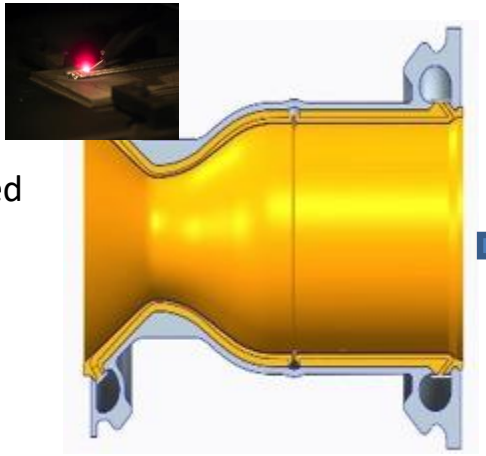
Electron Beam Freeform Fabrication (EBF^3) Functionally Graded Rocket Nozzle

Basics:

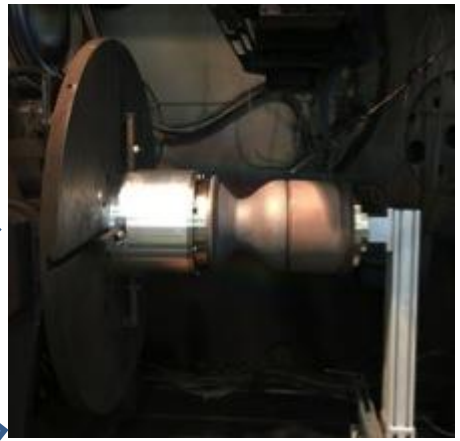
- **Additive manufacturing being investigated for next generation rocket engine components**
- Copper combustion chamber and nozzle produced via Selective Laser Melting (SLM)
- **Functionally graded** from copper to nickel for structural jacket and manifolds enabled using **Electron Beam Freeform Fabrication (EBF^3)**
- Additive Manufacturing refers to a process by which digital 3D design data is used to build up a component in layers by depositing material. The term "3D printing" is increasingly used as a synonym for Additive Manufacturing

Benefits:

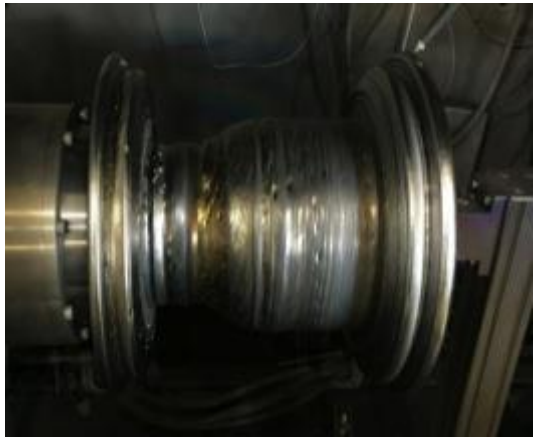
- **Reduce injector manufacture time** from months to weeks
- **Increased performance** through improved cooling with conformal passages enabled by additive manufacturing
- Potential to **reduce full scale injector cost** by nearly an order of magnitude (~90% reduction)



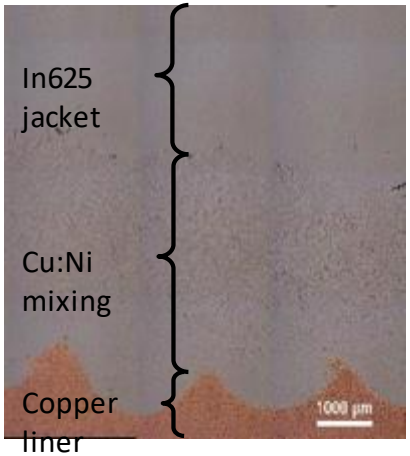
Schematic of Cu-Ni graded rocket nozzle



EB weld SLM Cu liner in LaRC EBF^3 chamber



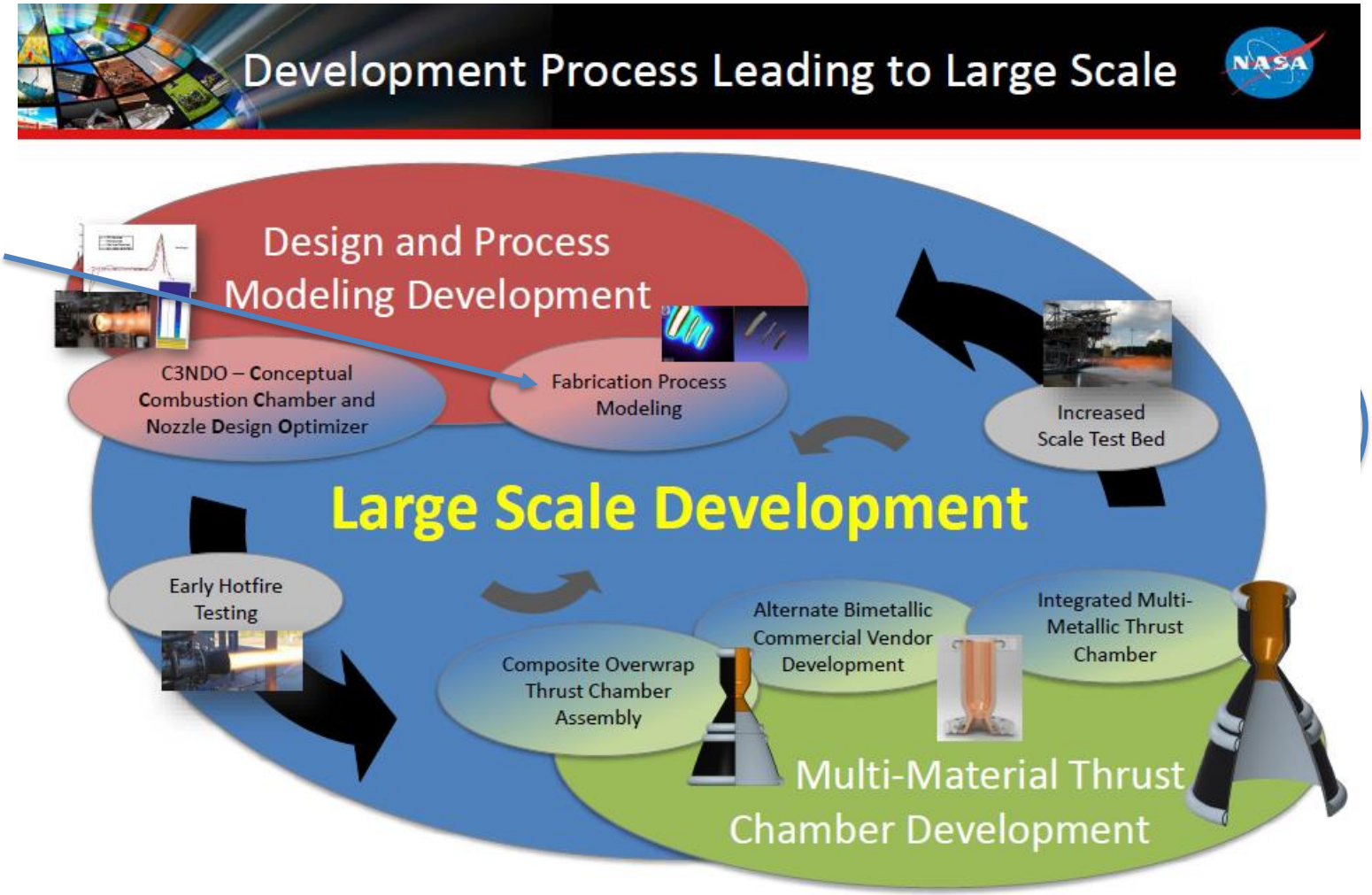
Structural Inconel 625 jacket EBF^3 deposited onto SLM Cu liner



Microstructure of graded interface

Rapid Analysis and Manufacturing Propulsion Technology (RAMPT) Project

Process modeling tools for metallic additive manufacturing to be developed by LaRC and ARC



Iterative process development, subscale testing and test bed hot fire testing to develop technologies feasibility, anchor data and reduce overall project risk

Rapid Analysis and Manufacturing Propulsion Technology (RAMPT)

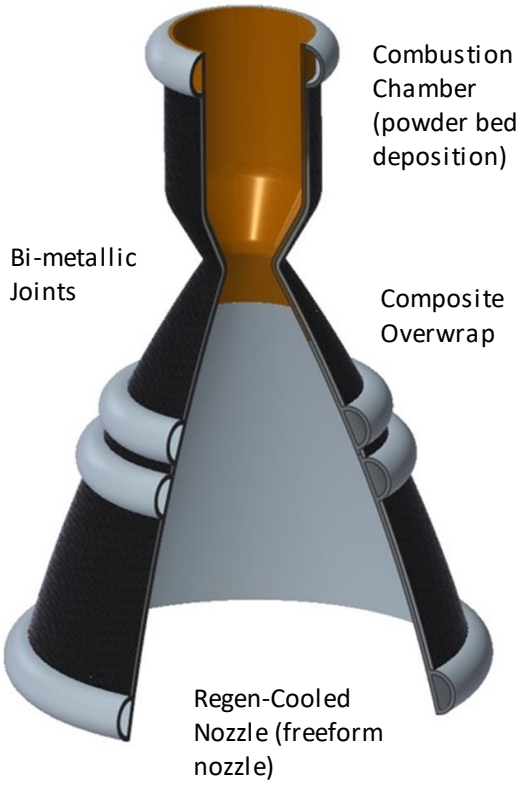
Objective: Develop and advance large scale freeform manufacturing and composite overwrap techniques required to enable reduced design and fabrication cycles, reduced cost, and improved performance for regeneratively-cooled components

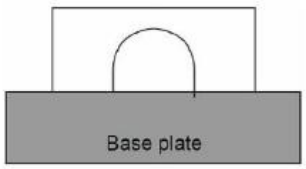
Approach: Large scale nozzle process development (MSFC, LaRC, GRC, ARC)

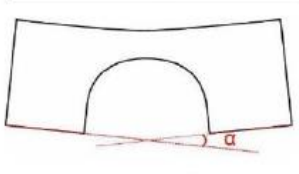
- Fabricate regeneratively-cooled nozzle >3 feet diameter
- Reduce design, analysis, and fabrication cycle through AM process models

Validation Data: SLM and blown powder distribution

- Process design, powder characterization
- Collect characterization data for melt pool dimensions, defects, chemistry
- Arch configuration and alligator specimen

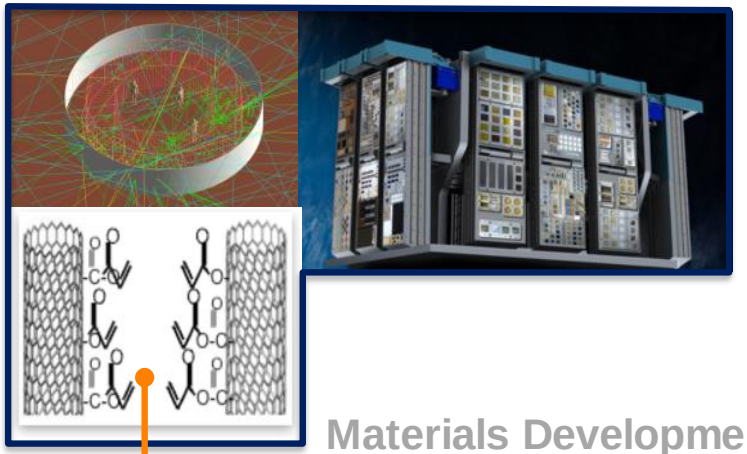




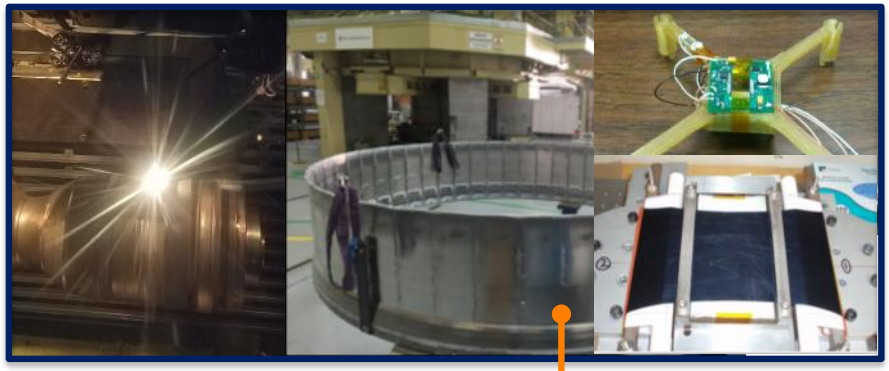




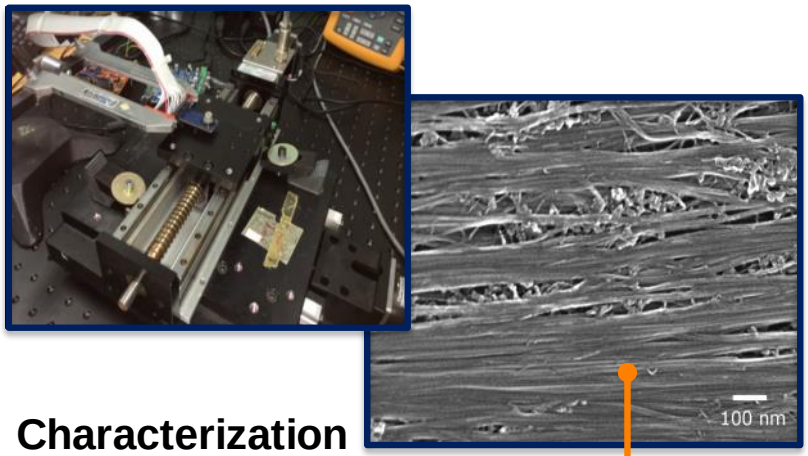
Advanced Materials and Processing Capabilities



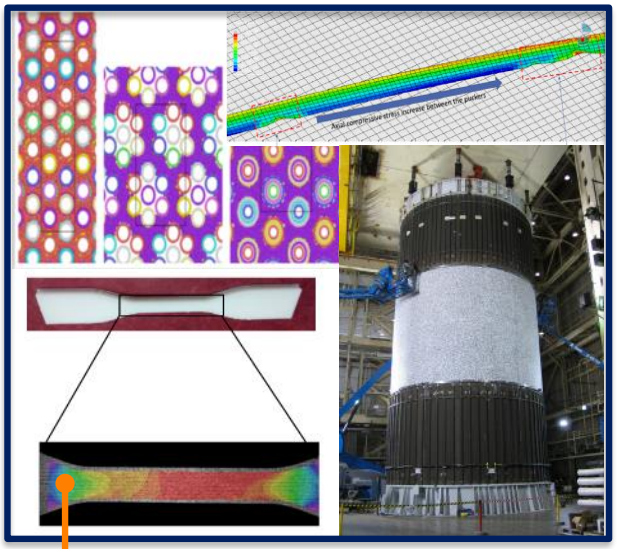
Materials Development



Process Development



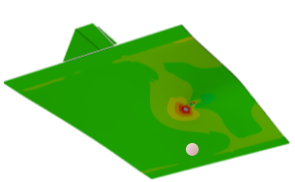
Characterization

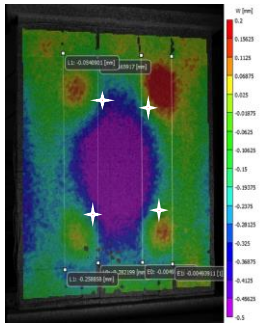


Modeling and Simulation

Advanced Composites Project

Technical Challenge:
Develop validated strength and life prediction tools with known accuracy for complex composite structures and standardized procedures for their reliable use.





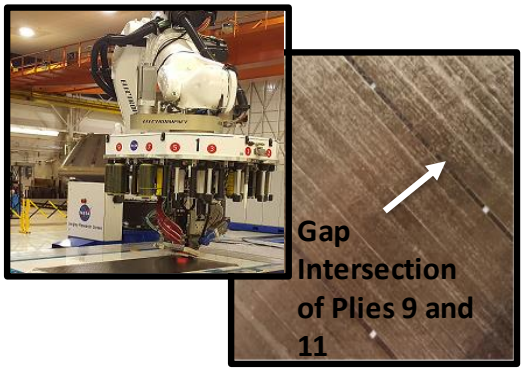
Objective:
- Develop high fidelity analysis tools able to predict reliably the strength and life of composite structures with damage or defects, and the failure of structures subject to high-energy impact events.

Technical Challenge:
Develop and demonstrate NDE systems and enabling technologies to fully inspect and rapidly disposition findings in complex composite structures.



Objective:
- Develop in situ quality control systems to monitor fabrication process
- Develop improved NDE systems that permit faster collection, characterization, and disposition of findings
- Develop and demonstrate NDE simulations that predict part inspectability and optimize the NDE process

Technical Challenge
Inability to predict and quantify the effects of random and shape induced in-process defects during automated fiber placement (AFP) on complex contour resulting in expensive rework or performance degradation of final component.

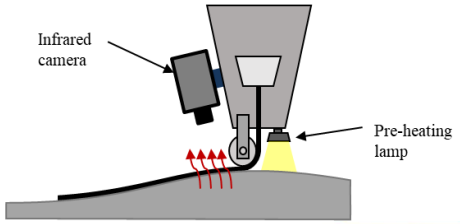


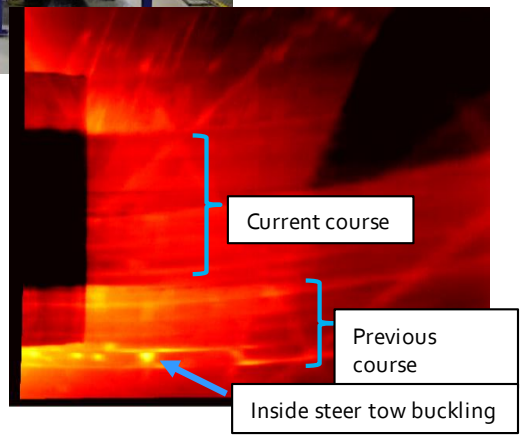
Objective:
- Develop a physics-based AFP process model based on a deep understanding of the AFP process and the effects of AFP defects on laminate quality and performance.

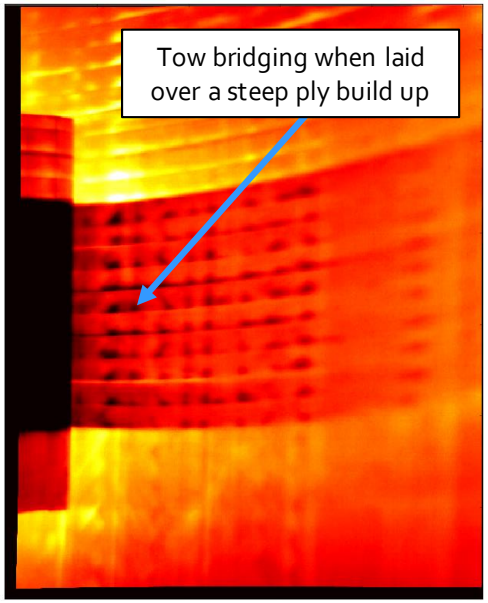
In situ NDE During AFP

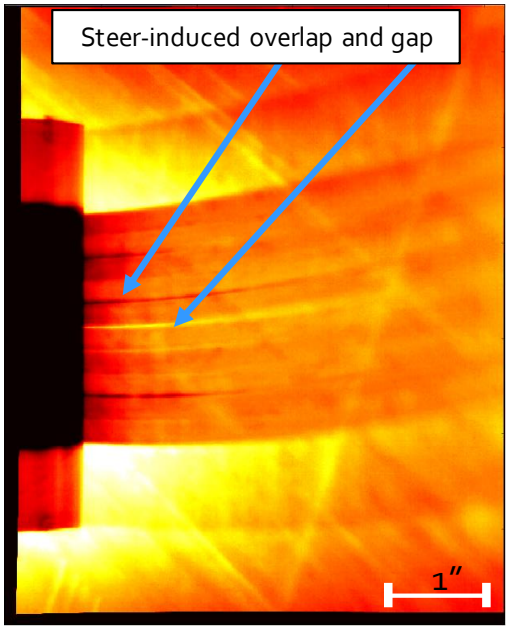
Multi-axis Automated Fiber Placement (AFP) Robot



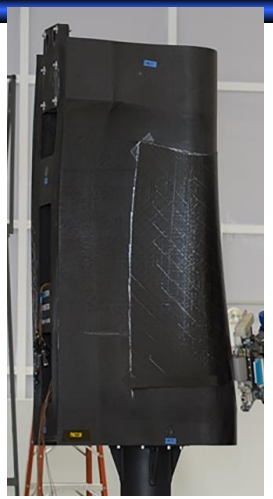








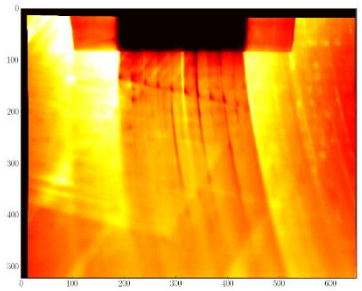
In situ NDE During AFP



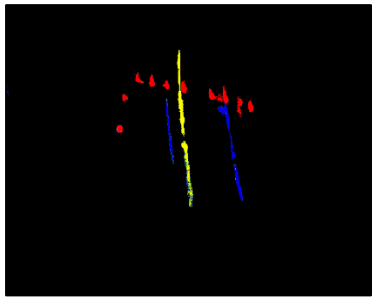
AFP Manufacturing Challenge
Current Process Time: 19% Layup vs. 42% Inspection
Goal Process Time: 76% Layup vs. 8% Inspection

System Capabilities

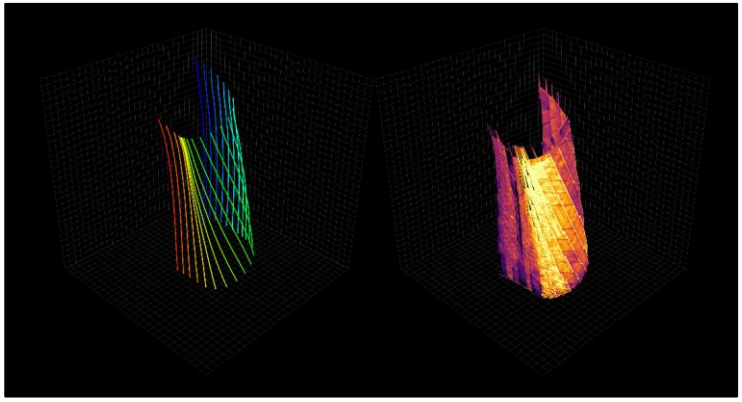
- Real time inspection with immediate defect reporting to operator
- Artificial intelligence algorithms quickly pass pristine data and only highlights discontinuities
- High accuracy/precision of inspection for better risk assessment
- Quantitative measurement of parameters that affect build quality
- Moving toward real time control of the manufacturing process



Temperature



Automatic Feature Recognition



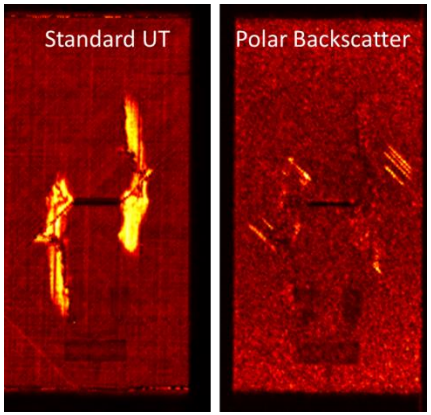
Temperature Data Mapped Layer by Layer

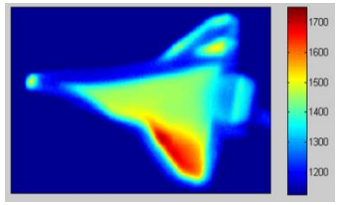
General Technical Capabilities and Instrumentation

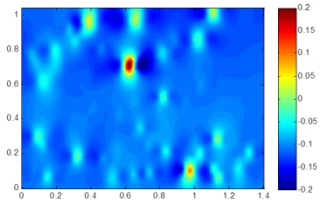
- **Materials Synthesis**
  - Chemical (small molecule)
  - Polymer (macromolecule)
  - Metallic Alloys
- **Materials Processing**
  - Prepreg and Composite (any resin/fiber)
  - Solution film casting/melt extrusion
  - Vac Press, VARTM, Autoclave, ATP
  - Plasma Spray
  - EBF3
  - Bonding/Joining
  - Heat treatment Vac. Furnaces
  - Sputtering/PVD
- **Mechanical**
  - Electromagnetic/servo-hydraulic load-frames (Liq. He to 3000F to 10-7T)
  - Small Ball-screw frames w/ E-Chambers
  - Pin-on-disk Tribometer w/ furnace
  - Tabor Abrader
- **Analytical**
  - Microscopy: SEM/TEM/HR-SEM Xe^{+}-PFIB: SEMs – Variable Pressure Lg chamber (w/ EDX, WDS, μ-probe, load frame, EBSD/AFM tips, EELS, SIMS)
  - Thermal Analysis: DSC, TGA, TGA-MS,DMA, TMA, Laser Flash, Heat Flow, Rheometers
  - Spectroscopy: NMR, IR, near-IR, UV-Vis, RAMAN, /XRD, Elipseometer, XPS, Auger
  - Chromatography: GPC, GC-MS
  - Surface Analysis: Droplet and Insertion instruments for surface tension, Optical profilometer, SPM, Nitrogen Absorption
  - Optical Microscopy: Confocal, Fluorescence, Metallograph, X-Polarized

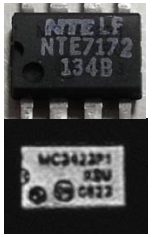
NDE Research Capabilities

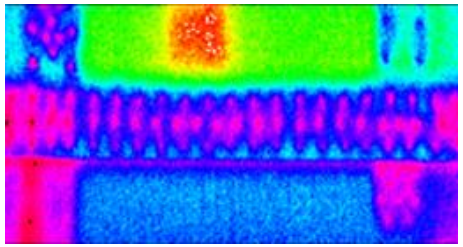
- Thermal Imaging
  - Flash, step, scanning, passive, vibro, etc.
- Ultrasonic
  - Immersion, nonimmersion, air coupled, etc.
  - Phased-Array Ultrasound
  - Nonlinear Ultrasound
- Electromagnetics (Eddy Current)
- Digital Radiography
- Computed X-Ray Tomography
  - Microfocus to <5µm resolution
- Backscatter x-ray
- Photo & Thermal Elasticity
- Scanning Electron Microscopy
- Shearography
  - Vacuum, Thermal & Acoustic Stress
- Terahertz Imaging
- Raman Spectroscopy

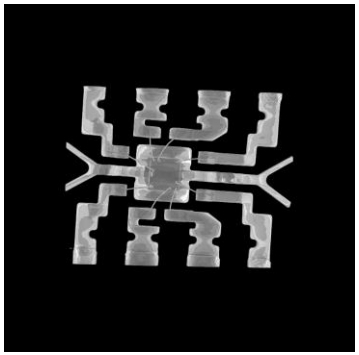


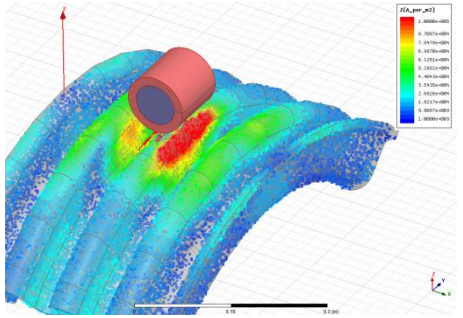






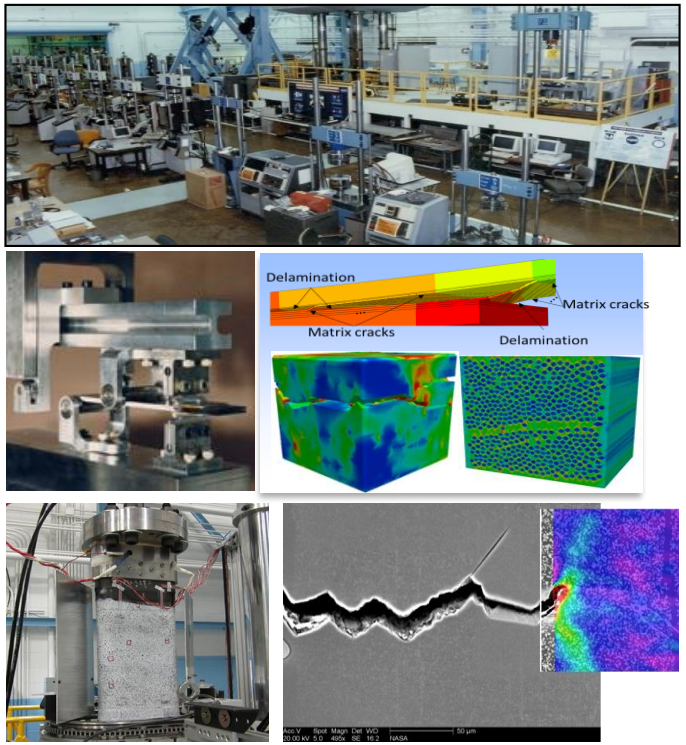




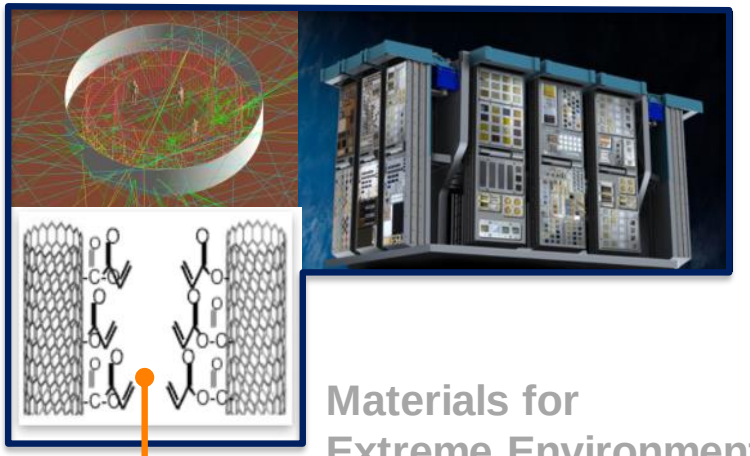


Durability and Damage Tolerance Tech Areas and Capabilities

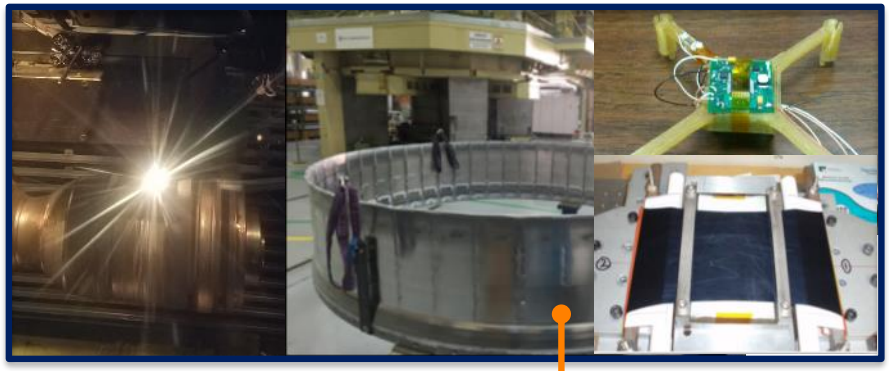
- **Damage Mechanics of Composite Materials**
  - Delamination / migration characterization
  - Develop / validate progressive failure analysis tools
  - Interfacial material properties
  - Durable composite materials
- **Damage Mechanics of Metallic Materials**
  - Develop multiscale approaches to model microstructure / damage evolution prediction (**Sc**alable **I**mplementation of **F**inite **E**lements by **N**ASA, ScIFEN)
  - Multiscale characterization of damage progression



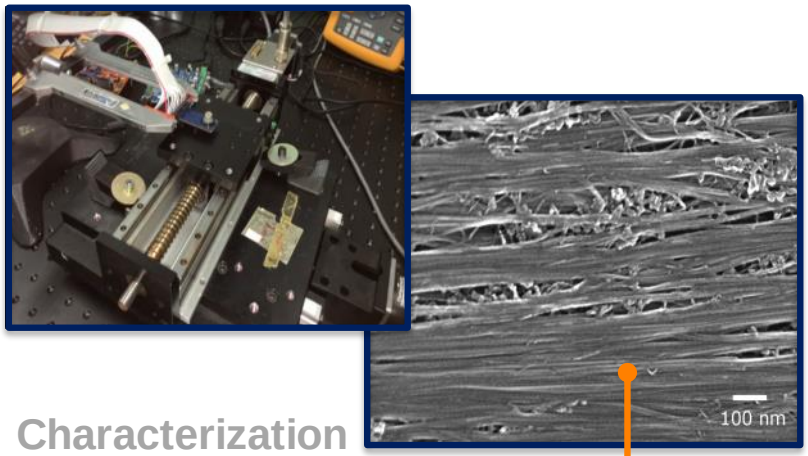
Advanced Materials and Processing Capabilities



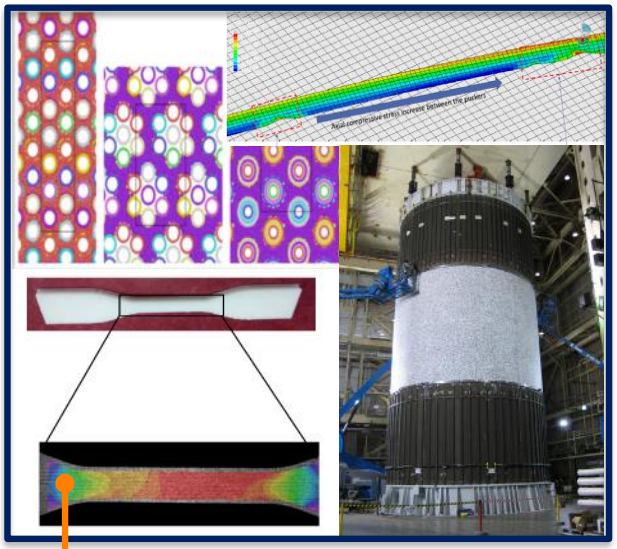
Materials for
Extreme Environments



Process Development



Characterization



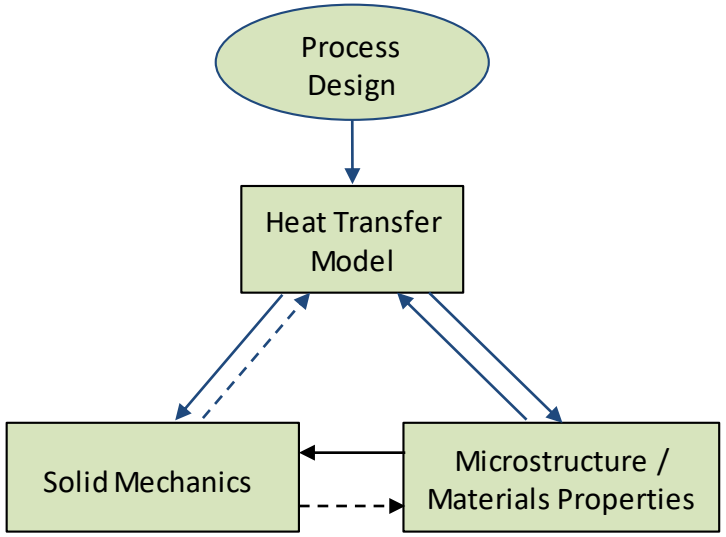
Modeling and Simulation

Overview

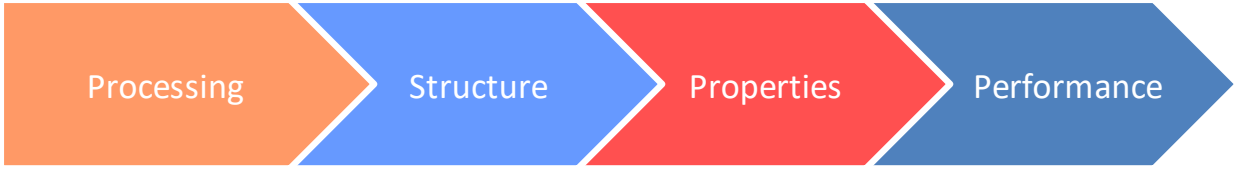
- **Physics-based modeling of the additive manufacturing (AM) process contributes to the following:**
  - **Process Design/Optimization**
  - **Defect formation/mitigation**
  - **Certification**
  - **Component Design**

- Heat transfer during the process drives the formation of the microstructure and residual stress

- Current focus is selective laser melting (SLM), electron beam freeform fabrication (EBF3), and blown powder deposition



Note: Dashed lines represent insignificant coupling which is generally ignored



Computational Modeling for Additive Manufacturing: Process to Microstructure

Problem

MSFC is using Concept Laser M2 and XLINE SLM additive manufacturing systems to build space flight prototypes and hardware. Parameters to produce consolidated material for the M2 machine are established, but material produced by the newer XLINE machine showed unacceptable lack of fusion defects and porosity.

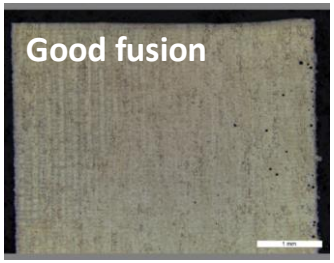
Goal

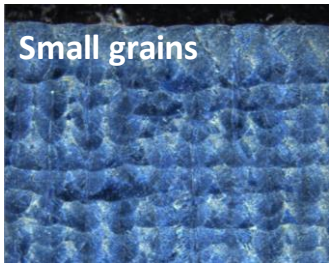
Use computational models to identify process parameters for ideal melt pool size to streamline parameter development for XLINE machine

Approach

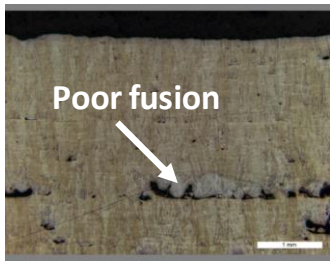
- Predict the scan speed for various XLINE power settings to produce a similar melt pool depth as the M2
- Use surface heat source developed from electrodynamics
- Verify results from experimental methods

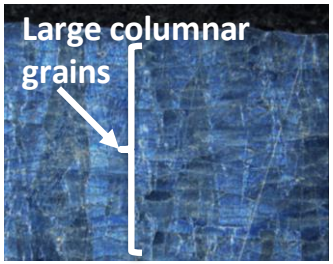
M2 Machine:
Power 180 W, Scan Speed 600 mm/s, Hatch 4 mm





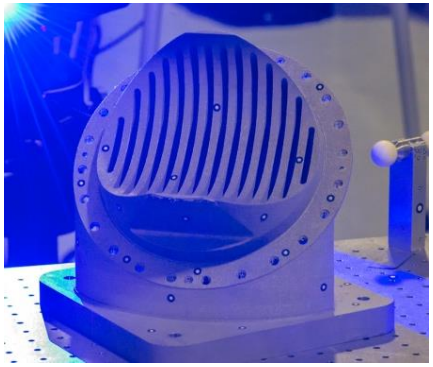
XLINE Machine:
Power 180 W, Scan Speed 600 mm/s, Hatch 4 mm



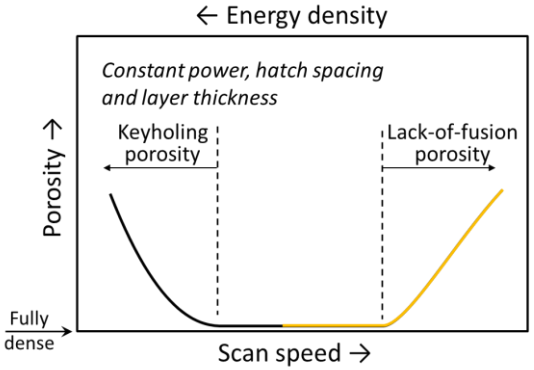


Computational Modeling for Additive Manufacturing: Summary

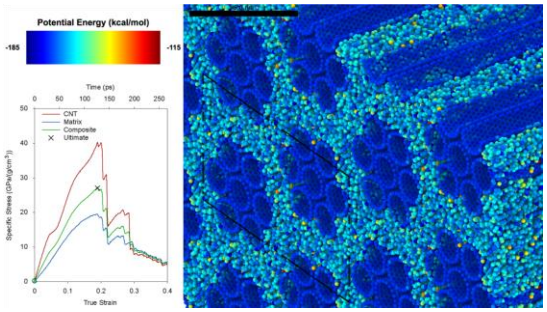
- Certification of AM parts is a current challenge and depends on process and material modeling
  - 39 parts for the RS-25 engine will be produced by AM
  - Process design and defect characterization is critical
- Increasing number of innovative AM methods are being presented, and an exponential growth in complexity leads to a greater dependence on modeling tools
- Component design for AM which exploits the capabilities of the manufacturing process is lacking
- Computational modeling and process design for AM is a growing area of research at Langley
  - Collaboration with D307, D309, D312, D313, D304
  - Four current Early Stage Innovation grants and one STTR phase 2 focused on SLM process and material modeling



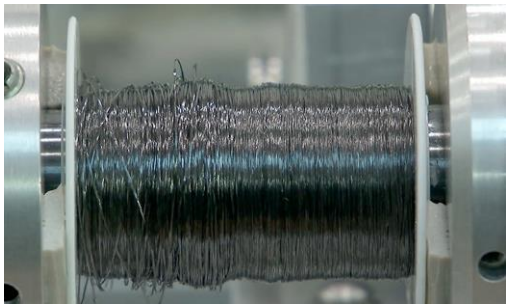
Pogo Z-Baffle made from Selective Laser Melting (SLM)



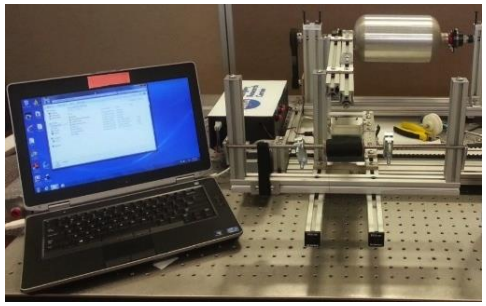
Computationally Guided High Strength Carbon Nanotube Composite Development



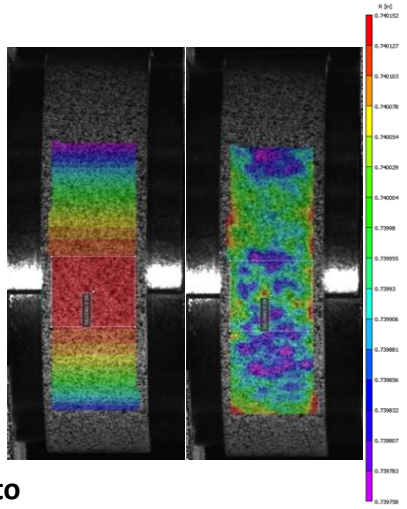
Computational modeling of CNT composite



Collaborate with industry to scale up high strength CNT



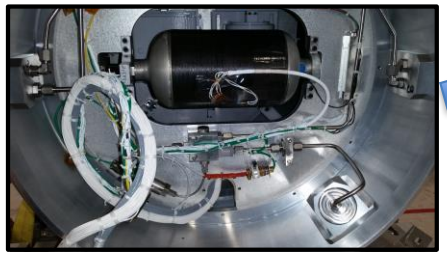
CNT composite process development



CNT composite test method development

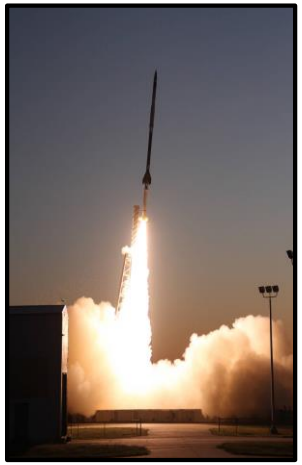


Transfer of CNT processing method to commercial winder at MSFC to manufacture flight test article



Integrate flight test article

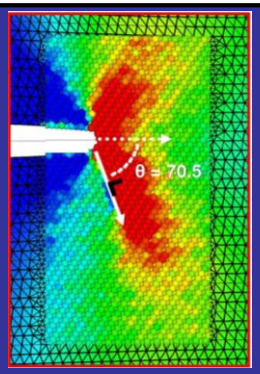




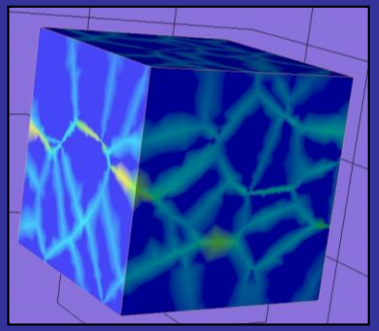
Flight test CNT composite technology

POC: Mia Siochi, emilie.j.siochi@nasa.gov

Computational Materials for Material Performance



Modeling Plasticity at a Crack Tip



Simulation of Crack Growth in a Material Microstructure

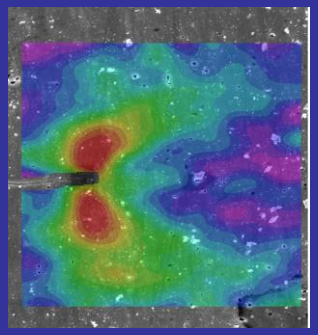
Simulate Operative Physical Processes at Relevant Length Scales

- Simulate critical damage processes
- Develop micro-/nano-structure-based simulations that interrogate damage processes at local length scales and local environments
- Propagate uncertainties across length scale to predict component reliability
- Design materials to extend structural life

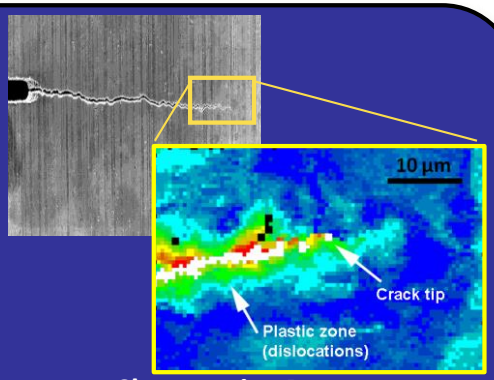
Physics-Based Material Design & Certification Requires Close Integration of Analysis and Experimentation

Characterize the Physics of Damage via Experimental Evaluation

- Develop micro-/nano-structure-based testing & characterization that interrogates damage processes at local length scales and local environments
- Validate damage models and understand operative processes
- Fabricate and evaluate model materials

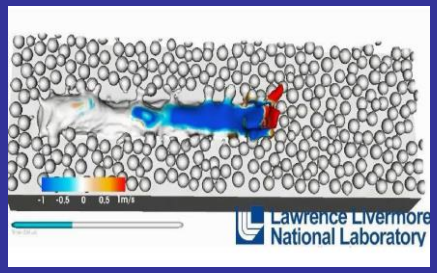


Measure Deformation at Crack Tip

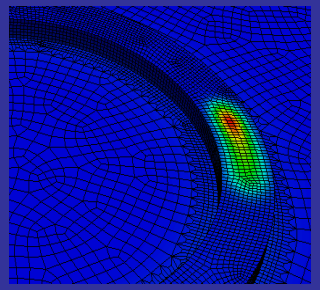


Characterize Damage Evolution

Computational Materials for Material Processing



Simulation of Laser-Powder Bed Interactions



Prediction of Local Heat Distribution

Simulate Fundamental Physics Governing Processing

- Determine role of processing parameters and composition on microstructure
- Simulate physical processes including laser beam absorption in powder bed, heat transfer via conduction and radiation, and fluid flow at the melt pool, particle flow
- Simulate residual stress, distortion, microstructural evolution and precipitate growth

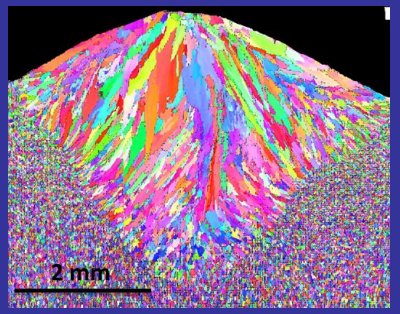
Develop Physically Correct Models Needed to Support Certification of AM Feed Stock and Manufacturing Process

Characterize Material Evolution using Experimental Methods

- Employ heavily-instrumented SLM machine and synchrotron beam lines (APS, CHESS)
- Produce coupon-size specimens using well-controlled parameters
- Understand details of the relationship between processing parameters and resulting microstructure



Selective Laser Melting



Grain Structure from Additive Process