

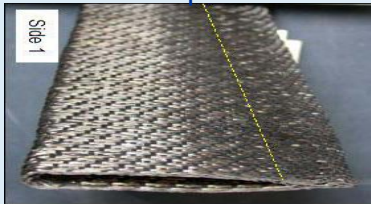
Additive Manufacturing 2.0

Ajay Misra, David Ellis, Chantal Sudbrack,
Robert Carter, Michael C. Halbig,
Mrityunjay Singh, Valerie L. Wiesner,
Joseph E. Grady, William Marshall

Materials and Structures Research and Development

High Temperature Materials

Ceramic Matrix Composite



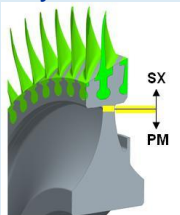
Protective Coatings



Thermal Protection Seal



Hybrid Disk



Lightweight Concepts

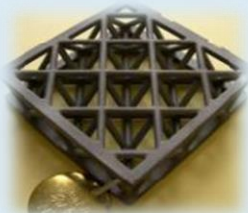
Hybrid Composite Gear



Multifunctional Structures



Lattice Block



Flexible Aerogel



Power System Materials

Materials for High Power Density Electric Motors



SUPERCONDUCTING STATOR WINDINGS



Solid Oxide Fuel Cell Material

Lightweight Power Transmission Cable

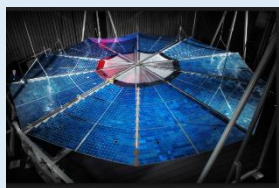


Mechanisms and Drive Systems

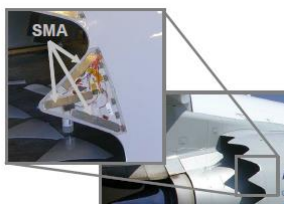
High Efficiency Gear



Deployable Structure



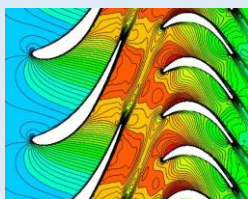
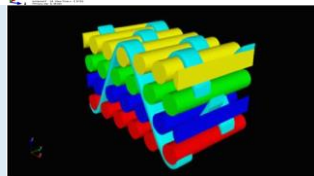
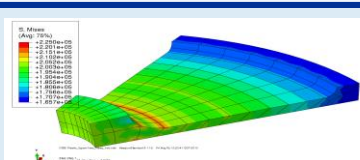
Shape Memory Alloy-Based Actuation



Spring Tire

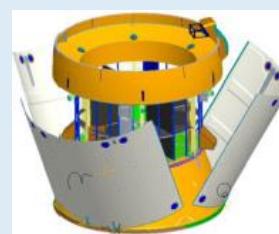


Computational Modeling



Flight Structures

Orion Fairing Jettison



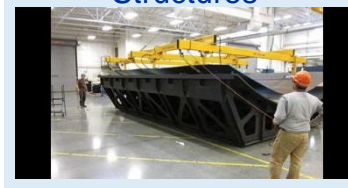
Vibration Testing



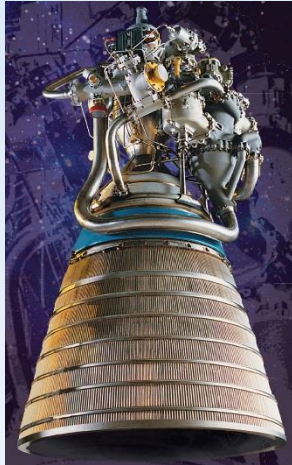
EFT-1



Large Composite Structures



Role of Additive Manufacturing in Aerospace Propulsion and Power



- Reduced complexity
- Faster cycle time
- Complex design features
- New design concepts and material/structural architectures enabled by additive manufacturing



Aircraft Gas Turbine Engine

Large Rocket Propulsion



Solar Electric Propulsion for Space Exploration



Small Propulsion for Cubesat



Hybrid Electric Propulsion for Aircraft

Current GRC Focus in Additive Manufacturing

- Additive manufacturing of space propulsion components
- Testing and characterization related to certification of additively manufactured components
- Location-specific properties in high temperature components enabled by additive manufacturing
- Additive manufacturing of multimaterial/multifunctional systems related to electrical machines and electric propulsion
- Additive manufacturing process for fabrication of continuous fiber reinforced composites
- Understanding and modeling processing-microstructure-property relationship for additive manufactured components



Additive Manufacturing Of Metals At NASA GRC

David Ellis, Chantal Sudbrack, Robert Carter

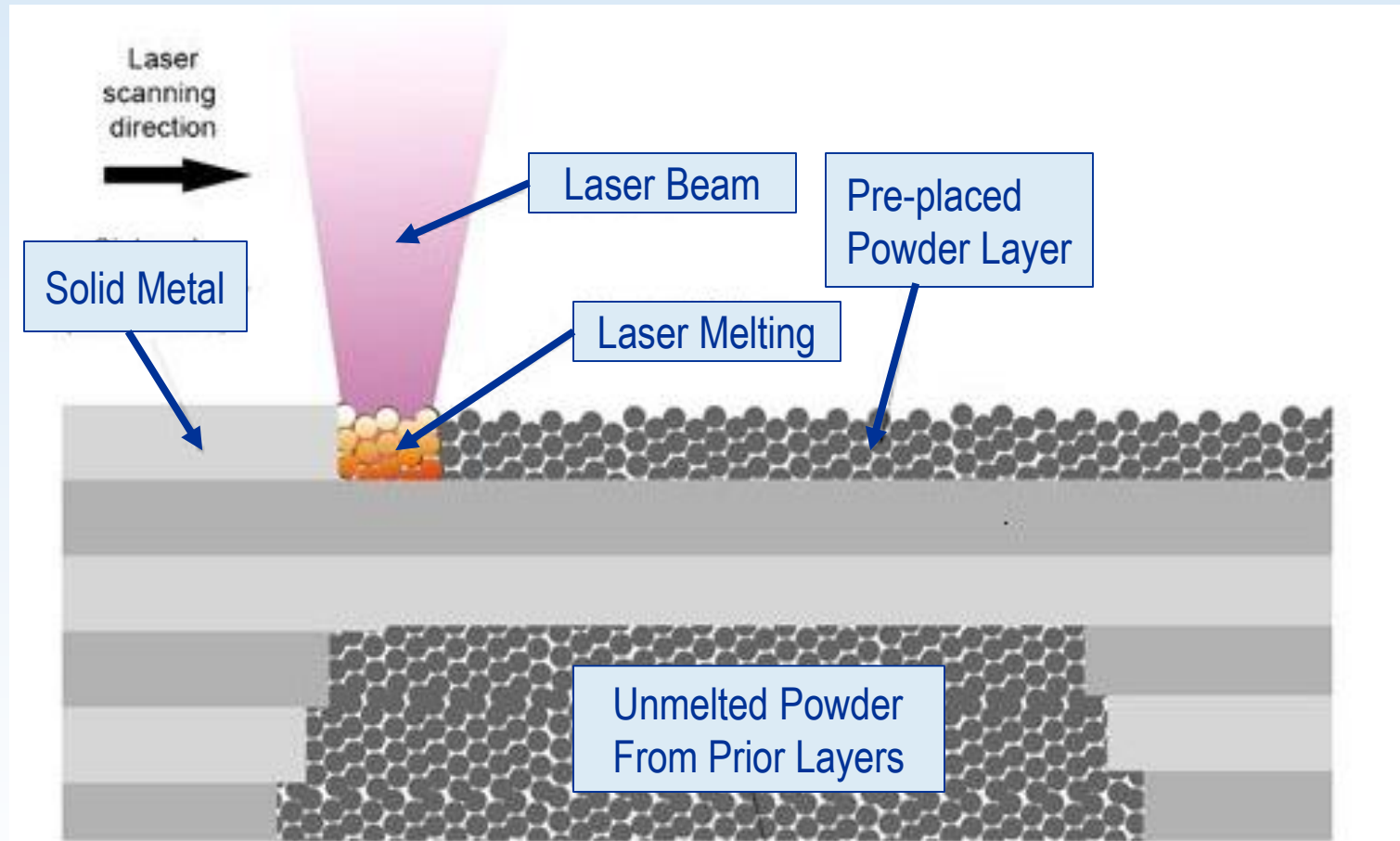
Low Cost Upper Stage Program (LCUSP)

- **GOAL:** Additively manufacture a 30,000 to 40,000 lbf thrust rocket chamber at a lower cost and faster production time than conventional rocket chamber fabrication methods
- Liner is made of GRCop-84, a NASA Glenn Research Center developed Cu-Cr-Nb alloy, and was manufactured using Selective Laser Melting (SLM)
- The jacket is made from IN-625 and was manufactured using Electron Beam Freeform Fabrication (EBF3)

NASA MSFC Concept Laser M2 Machine



Selective Laser Melting (SLM)

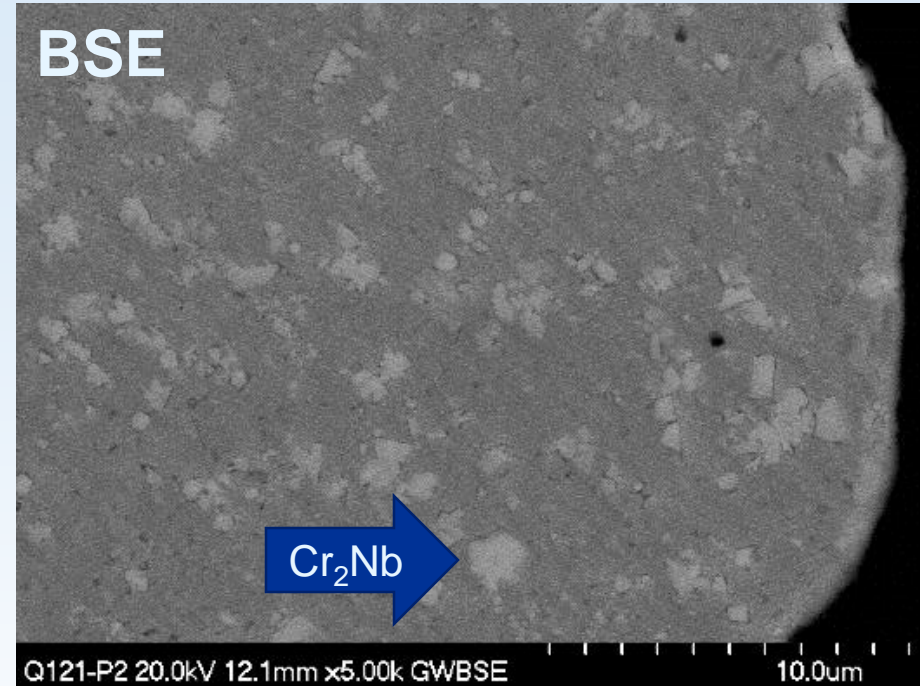
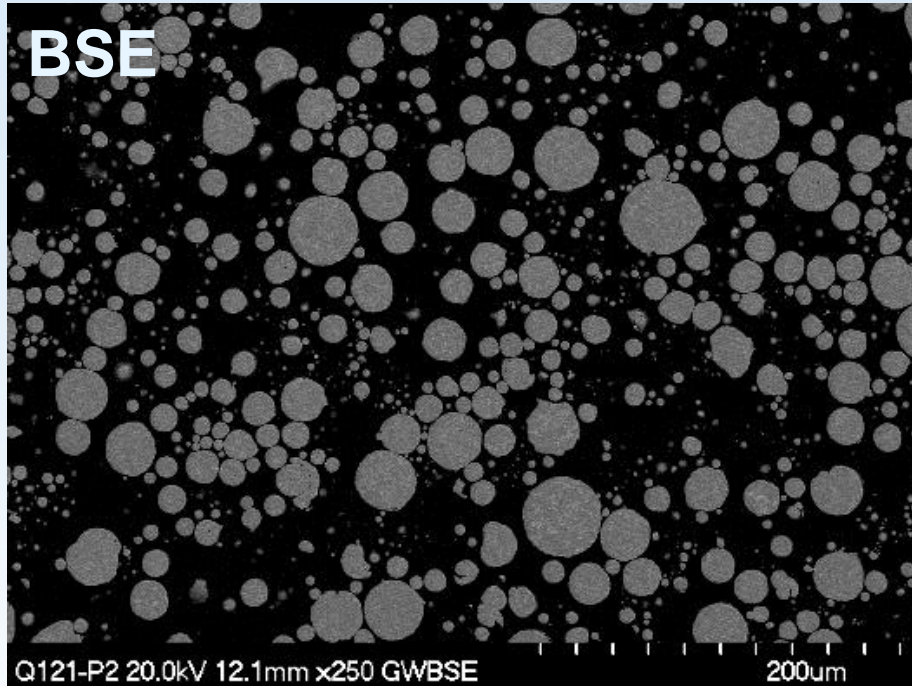


Unlike Selective Laser Sintering (SLS), SLM involves melting and resolidifying the powder

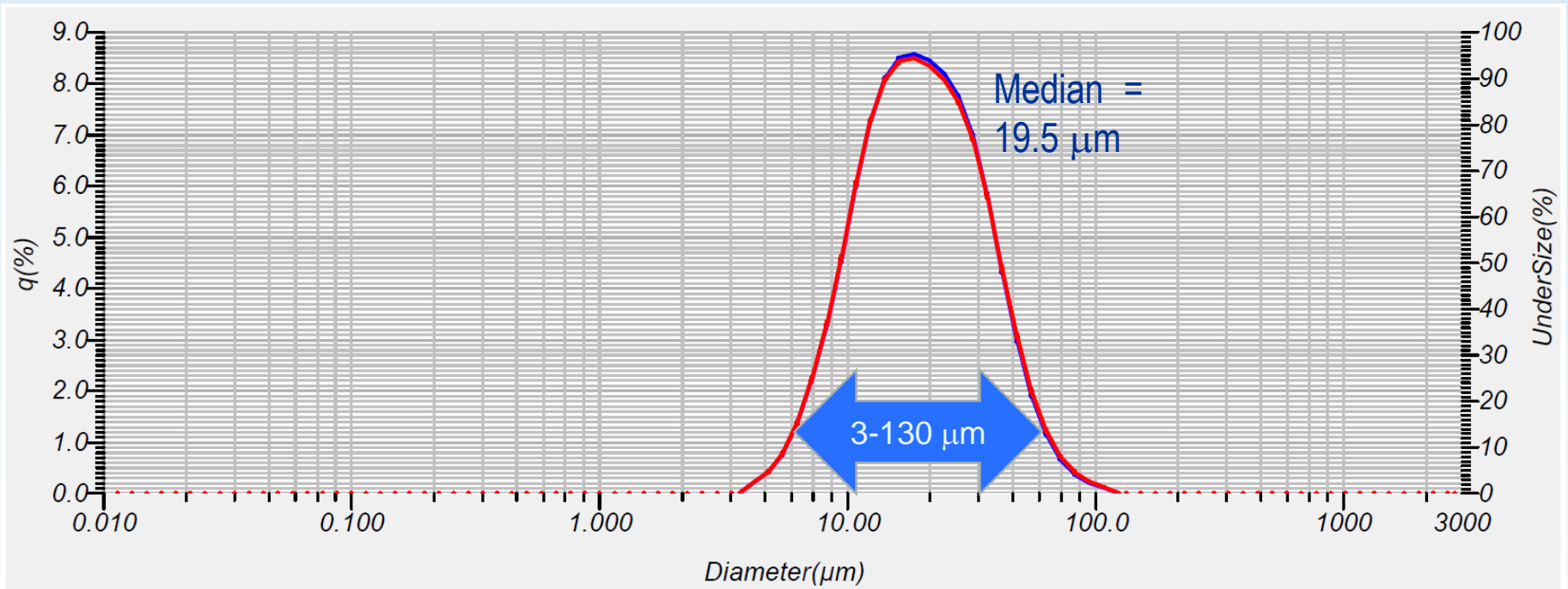
Potential Obstacles To SLM GRCop-84

- High reflectance may limit power that can be put into powder to melt it
 - Copper reflectance is about 0.75 at laser wavelength
- High thermal conductivity may limit maximum temperature that can be attained
- Lower density Cr_2Nb phase used for strengthening may float to surface of melt pool
- Shrinkage porosity may be excessive
 - Copper shrinks about 4% upon solidification
- Surface finish may be too rough
 - A rough surface could be beneficial if it improves heat transfer in the cooling channels

GRCop-84 Powder Microstructure

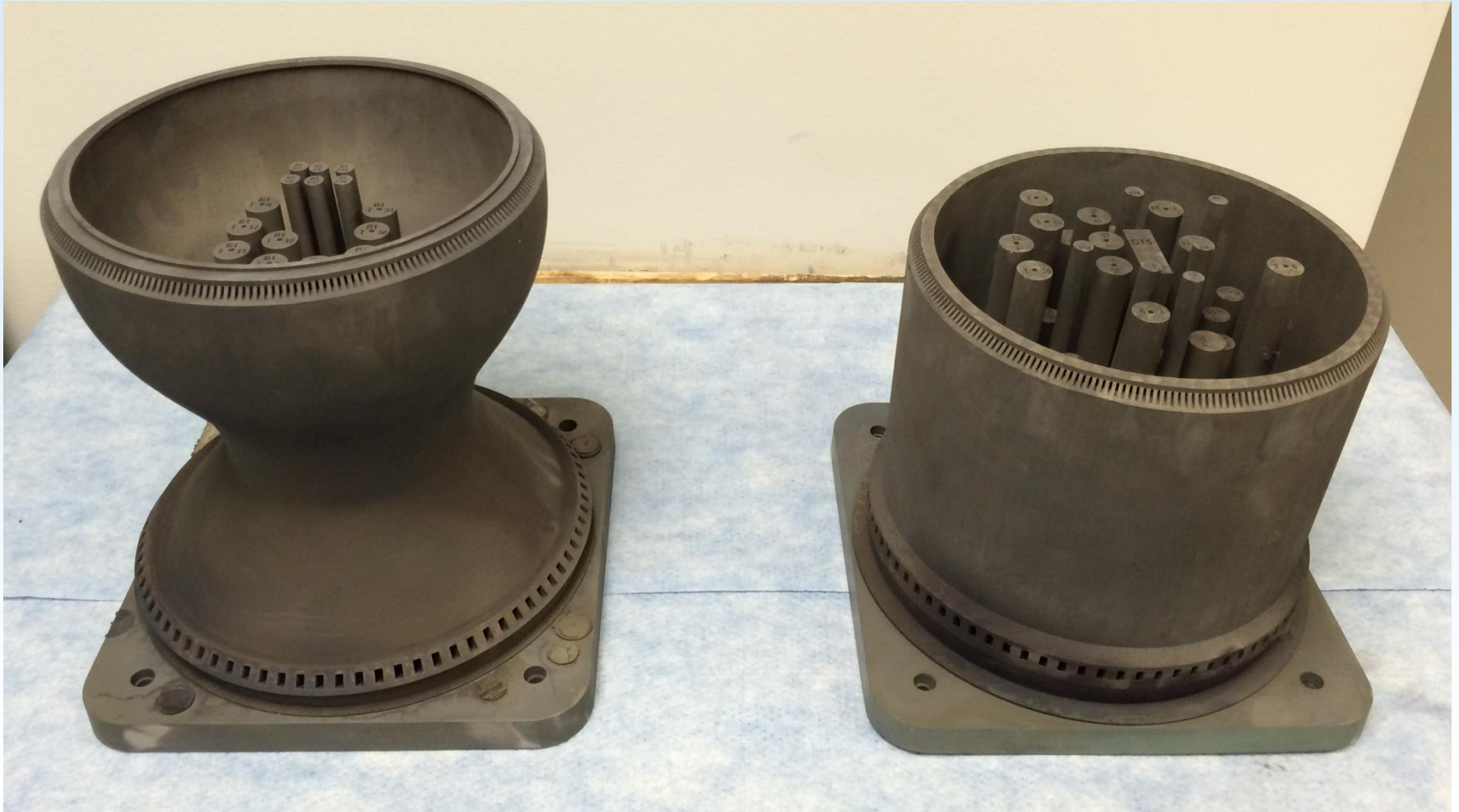


Typical GRCop-84 Powder Size Distribution

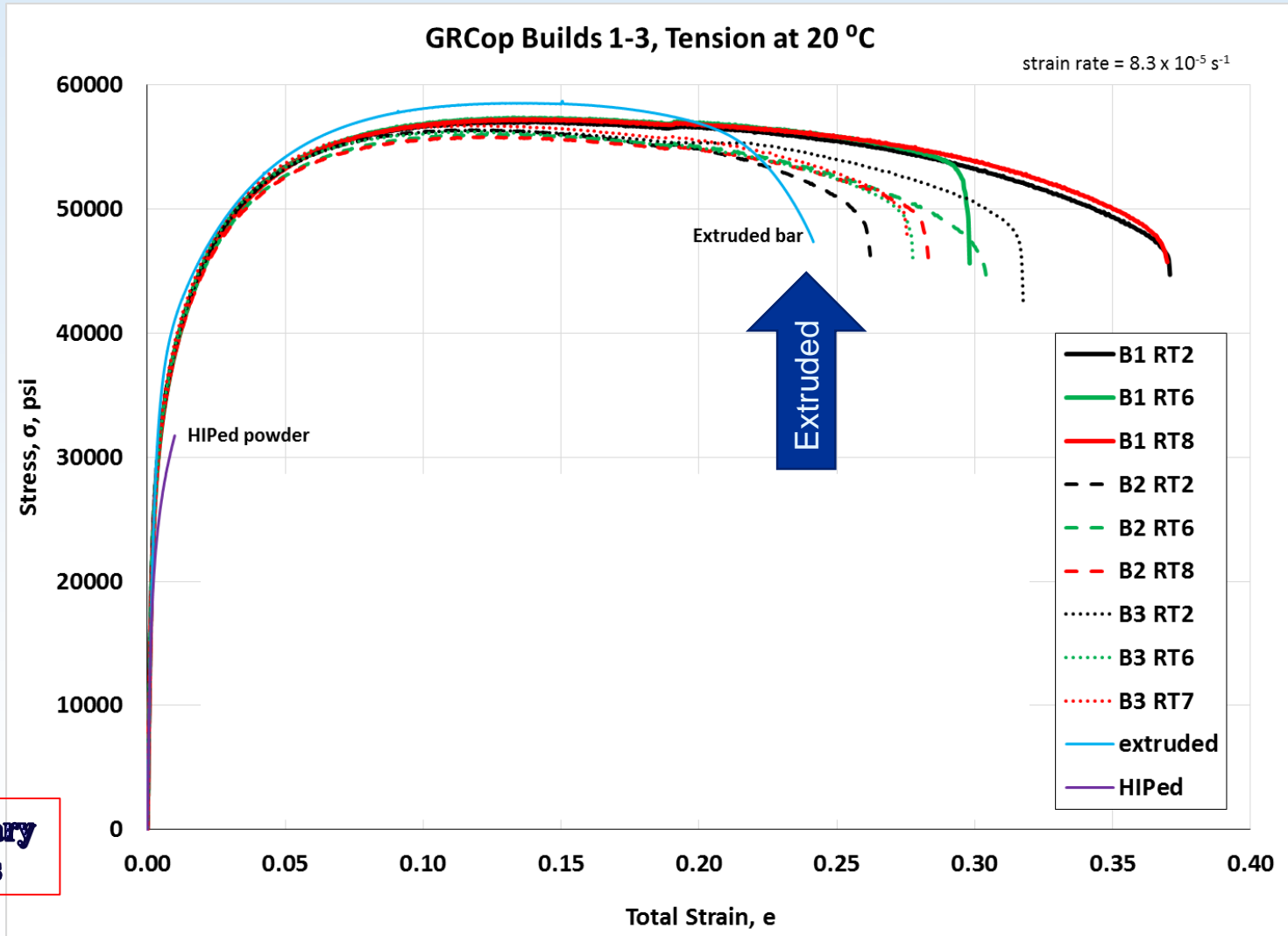


Data Name	Graph Type	Median Size
201502241543055		19.52085(μm)
201502241540054		19.52655(μm)

Liner Sections And Mechanical Test Samples

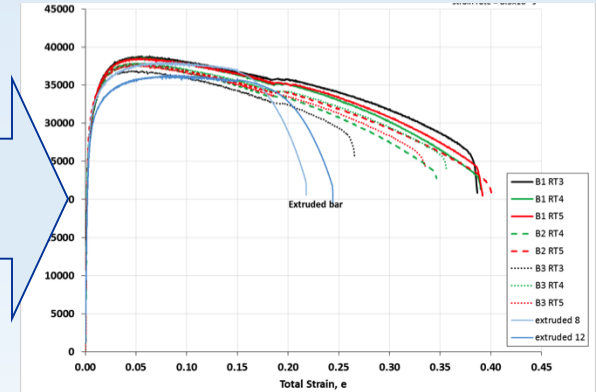
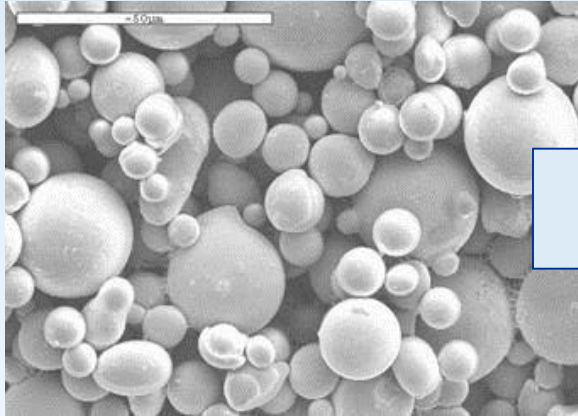


Room Temperature Tensile Strength



Preliminary
Results

Additive Manufacturing Structural Integrity Initiative (AMSII)



AMSII is taking a holistic approach to additive manufacturing from powder to processing to properties

Major Goals:

- Develop feedstock controls and maximum recyclability limits
- Identify powder control and heat treatment metrics for inclusion in standard for RS-25E Engine

Overview Research Plan For AMSII

1. Powder Characterization

- A. Size distribution
- B. Morphology
- C. Rheological properties
- D. Post-use changes / reusability

2. Manufacturing

- A. Powder bed characterization
- B. SLM parameters
- C. Melt pool modeling
- D. HIP parameters
- E. Microstructural modeling

3. Consolidated Properties

- A. Microstructure
- B. Mechanical properties such as tensile, creep and fatigue strengths
- C. Flammability

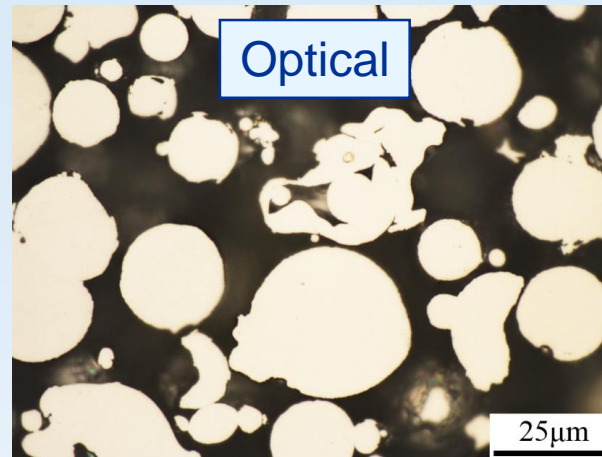
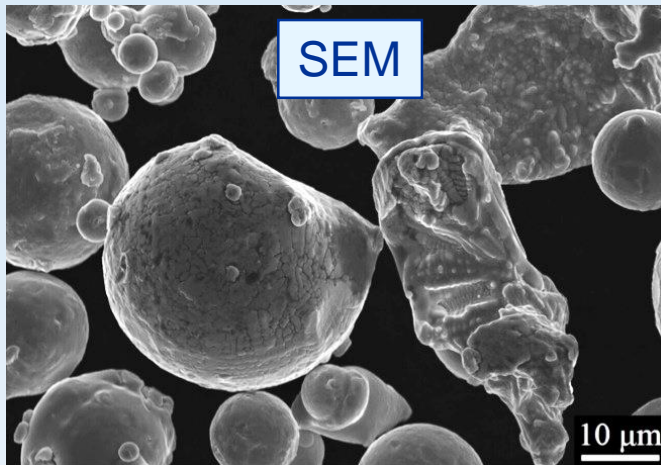
3D Printed Rocket Components Are Already A Reality



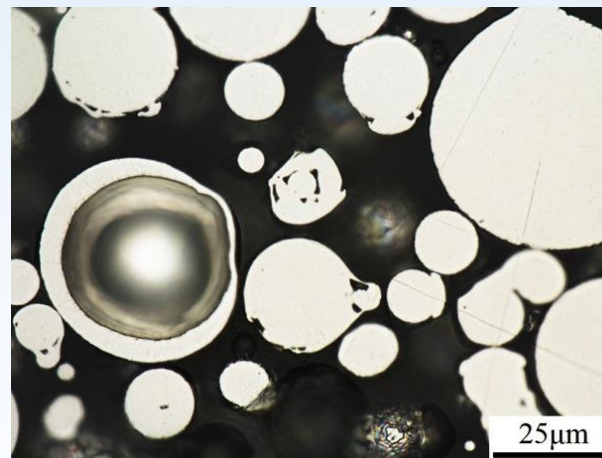
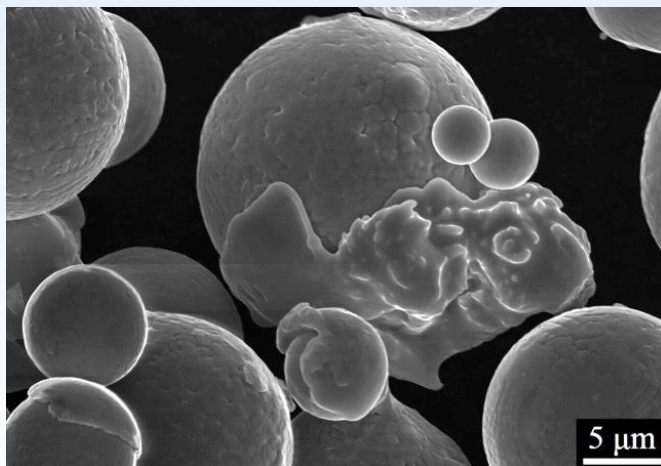
- Fuel Turbopump (FTP) for 30,000 lb_f class rocket engine
 - Suitable for upper stage engine
- 90,000 RPM disk speed
- 45% fewer parts than Space Shuttle Main Engine (SSME) FTP
- Tested under actual service conditions in July 2015 at NASA MSFC

IN-718 Powder Lots 1 and 2

Powder Lot 1



Powder Lot 2



- Differences already observed in commercial powders
 - Lot 1 – More agglomerations, less porosity and inclusions
 - Lot 2 – More spherical, large porosity, many inclusions

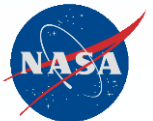
Near Term Work

- Characterize 10 to 12 commercially available IN-718 powders
- Determine the strength and fatigue properties of AM IN-718 as a screening test
- Correlate measured powder properties with mechanical properties to determine primary factors affecting mechanical properties
- Begin modeling microstructural evolution



Additive Manufacturing of Non-Metallics and Multi-materials

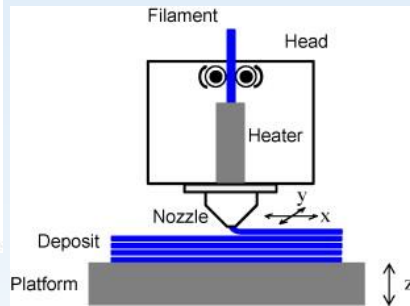
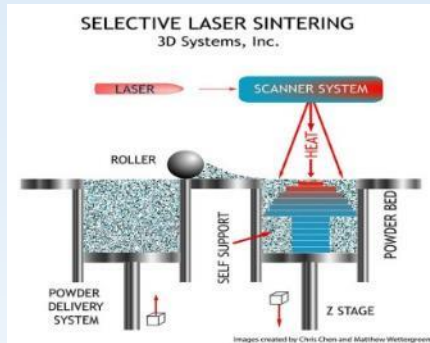
Michael C. Halbig, Mrityunjay Singh,
Valerie L. Wiesner, and Joseph E. Grady



Overview of Additive Manufacturing Technologies

Selective Laser Sintering

High powered laser fuses plastic, metal, or ceramic powders.

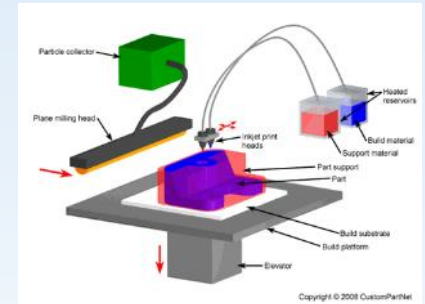
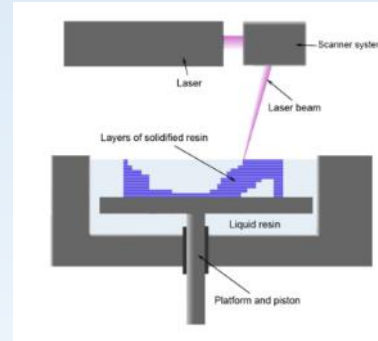


Fused Deposition Modeling

Plastic or metal is heated and supplied through an extrusion nozzle and deposited.

Stereolithography

A beam of ultraviolet light is directed onto a vat filled with a liquid ultraviolet curable photopolymer.



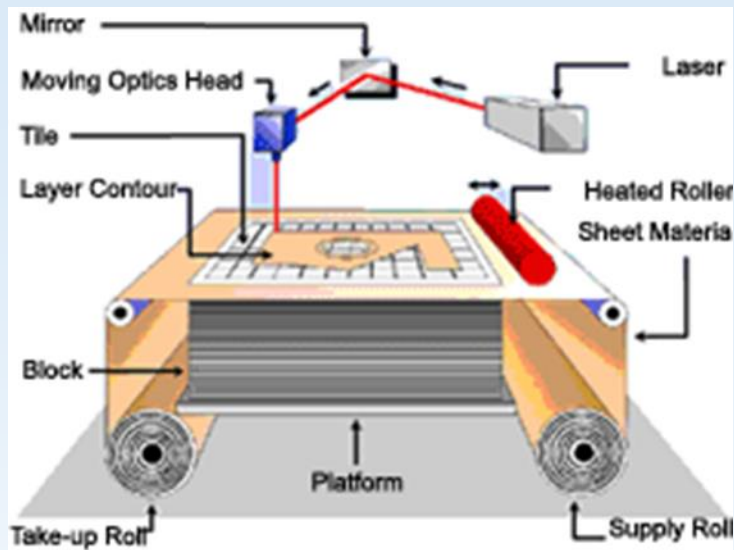
Binder Jet 3D Printing

An inkjet-like printing head moves across a bed of powder and deposits a liquid binding material.

Material choices are limited by the machine's manufacturers
Fabrication of continuous fiber composites is not possible

Objective: Utilize additive manufacturing technologies as alternative processing approaches for fabricating advanced ceramics and CMC components

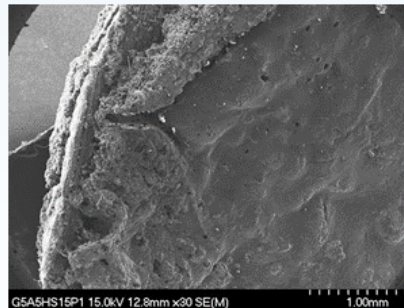
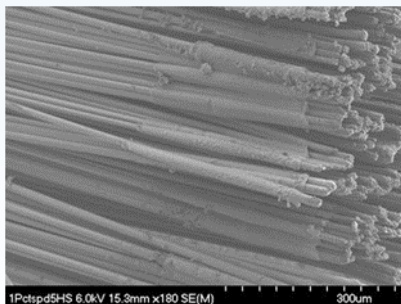
Laminated Objective Manufacturing For Silicon Carbide-Based Composites



LOM allows for continuous fiber reinforced CMCs.

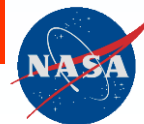
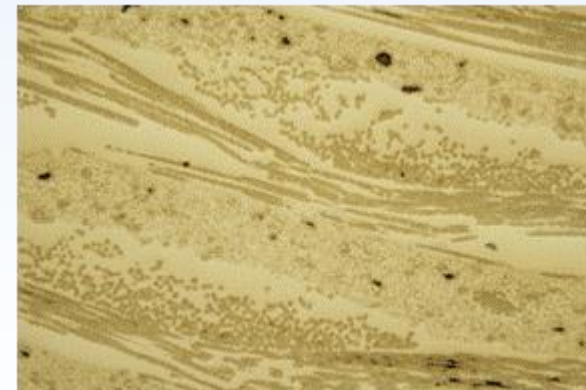


Universal Laser System (Two 60 watt laser heads and a work area of 32"x18")



Fabrics and Prepregs cut at different laser powers/speeds

Silicon Infiltration:
1475 C, 30 minutes in vacuum



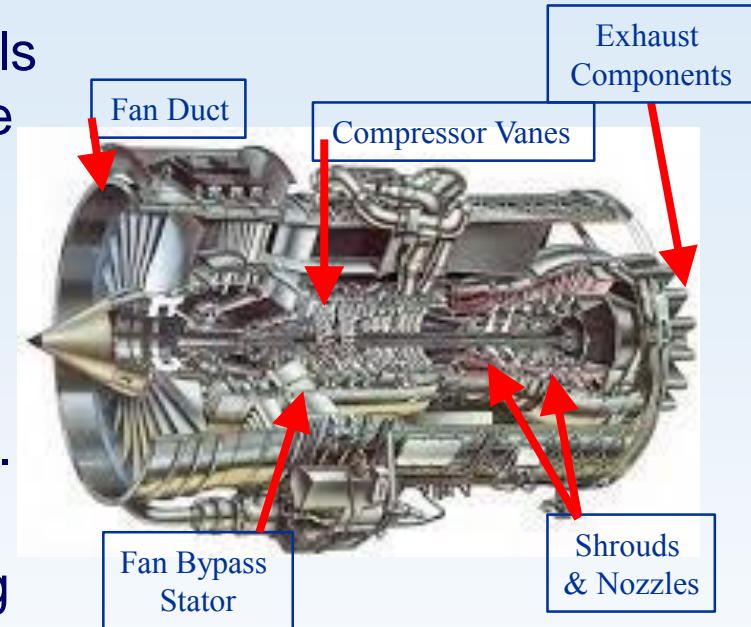
Non-Metallic Turbine Engine Project (NARI)

TEAM: NASA GRC, OAI, Honeywell Aerospace, RP+M, NASA LRC

Project Objective: Conduct the first comprehensive evaluation of emerging materials and manufacturing technologies that will enable non-metallic gas turbine engines.

- Assess the feasibility of using additive manufacturing technologies to fabricate gas turbine engine components from polymer and ceramic matrix composites.
 - Fabricate and test prototype components in engine operating conditions
- Conduct engine system studies to estimate the benefits of a fully non-metallic gas turbine engine design in terms of reduced emissions, fuel burn and cost

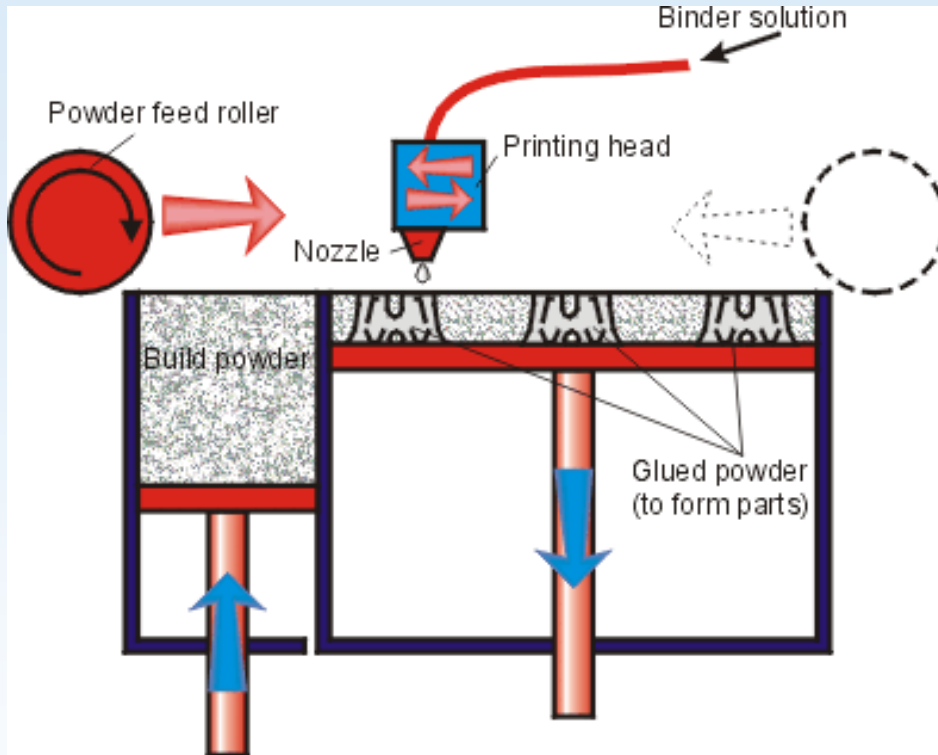
Targeted Components



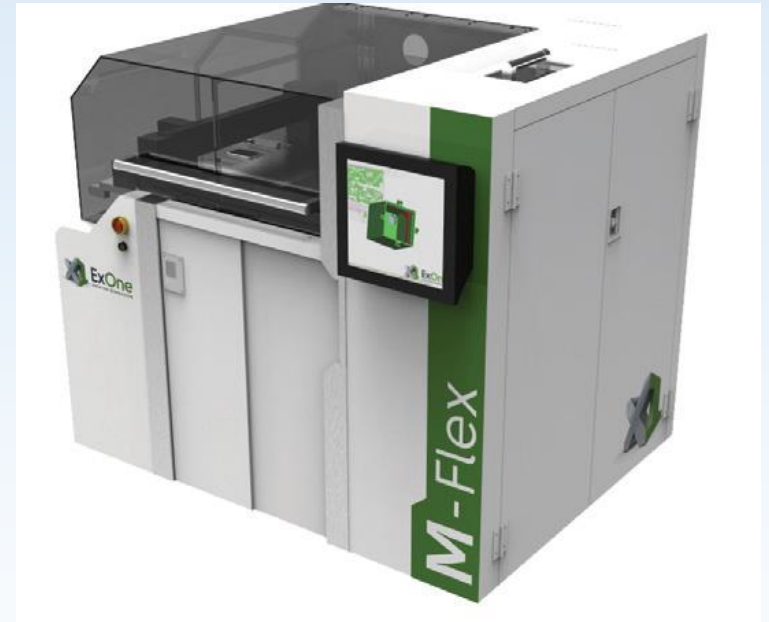
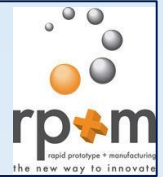
Business Jet size turbofan engine



Additive Manufacturing of Ceramics using the Binder Jet Process



In collaboration
with rp+m

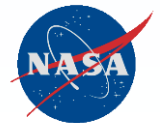


ExOne's M-Flex print machine

Binder Jet printing

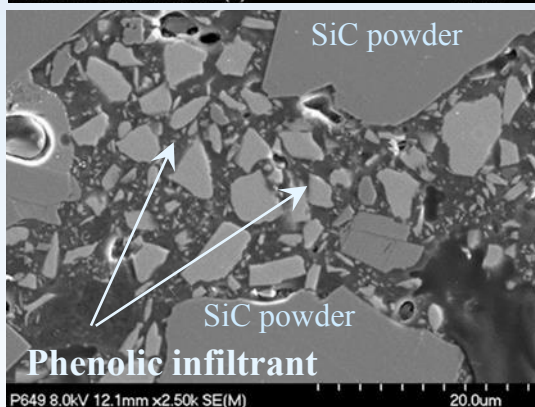
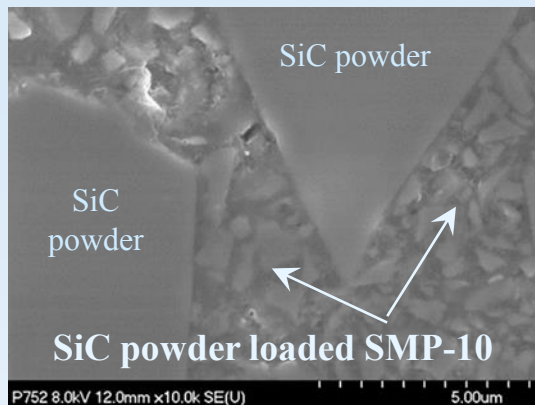
An inkjet-like printing head moves across a bed of powder and deposits a liquid binding material in the shape of the object's cross section

Binder jet printing capability will allow for powder bed processing with tailored binders and chopped fiber reinforcements for advanced ceramics.



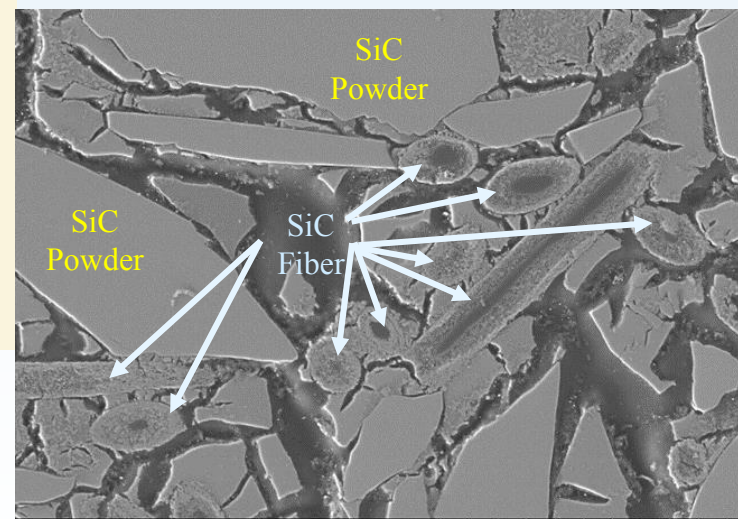
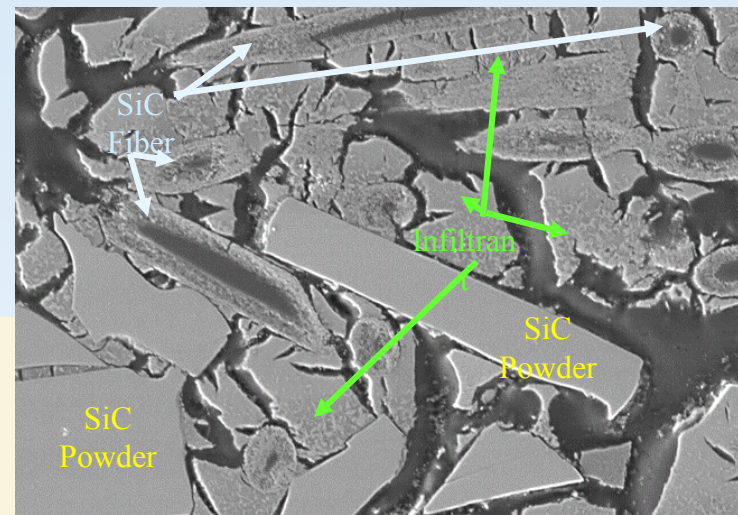
Fabrication and Microstructure of SiC Fiber Reinforced CMCs

Constituents

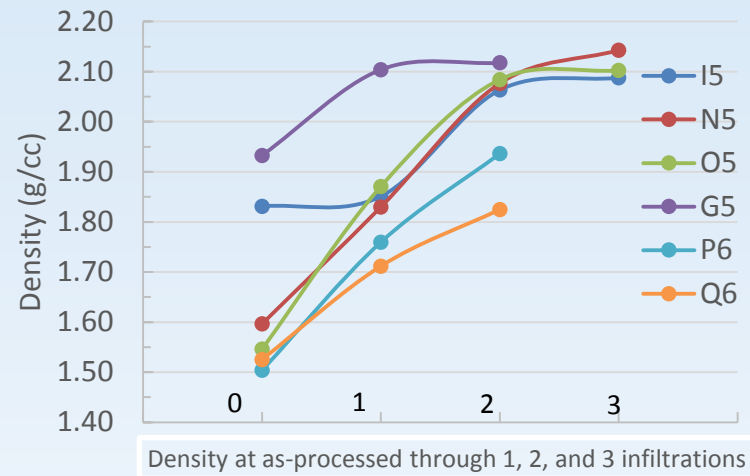


CMC coupon with 35 vol% SiC fiber loading and infiltrant with smaller SiC powders.

- *Higher density observed due to powder loaded infiltrant*
- *Good distribution and non-preferred orientation of SiC fibers is observed.*

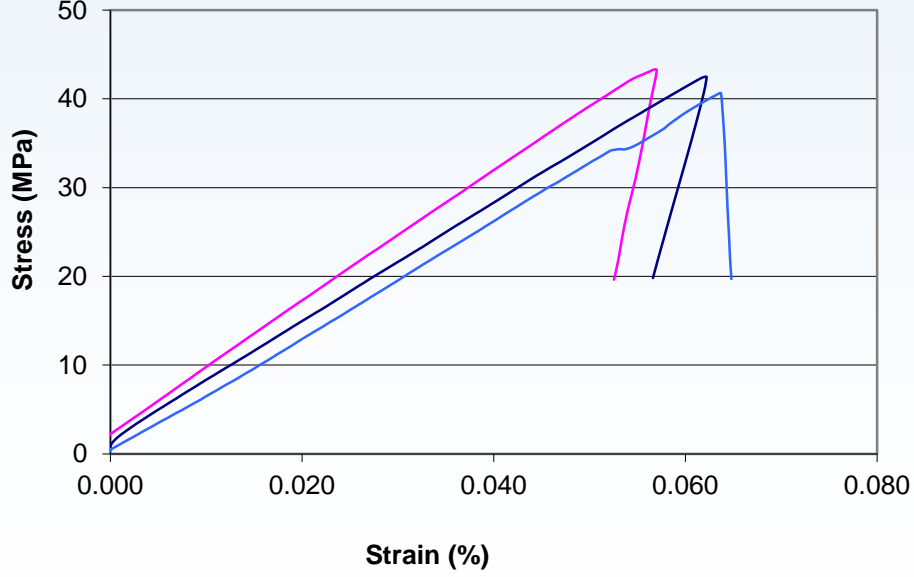


4 Point Flexure Tests of the Monolithic SiC and CMC materials - at room temperature and 1200°C

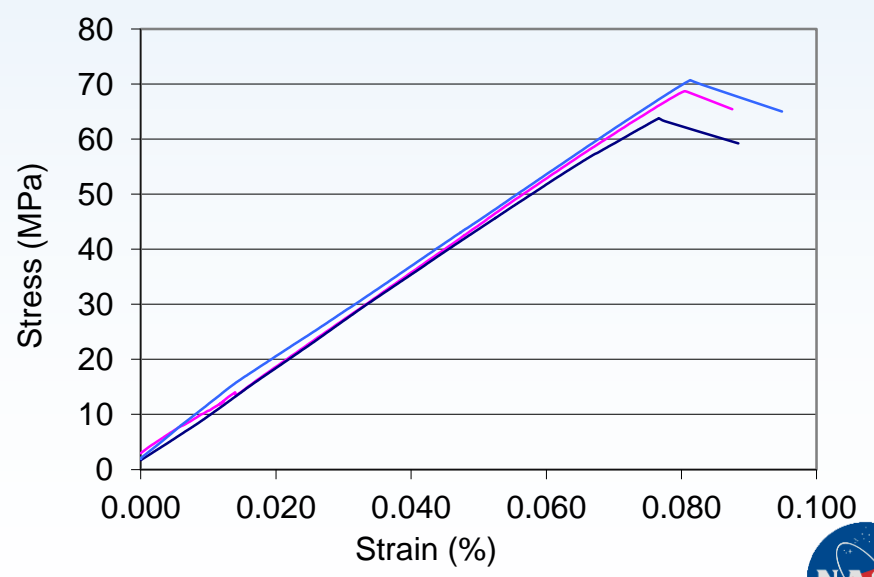


The fiber loaded SiC materials had significantly higher stresses and higher strains to failure.

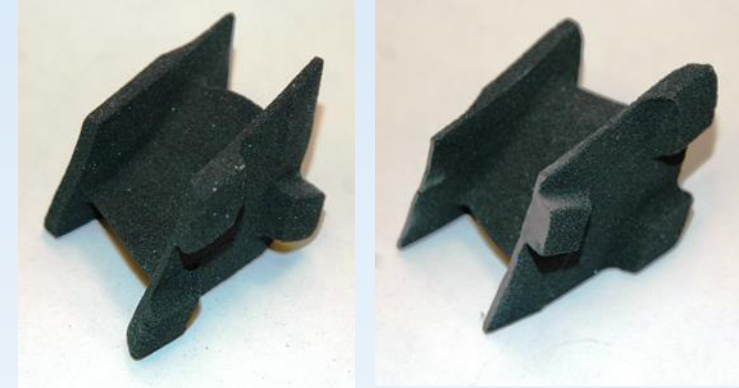
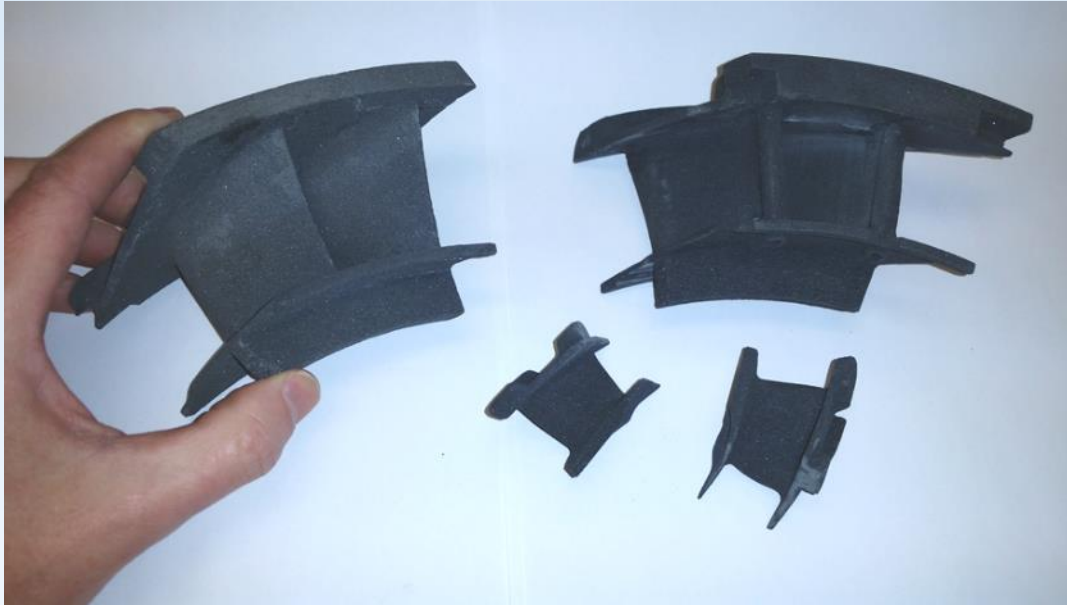
Non-Reinforced SiC - Set G



65 vol. % SiC Fiber Reinforced SiC - Set N



Demonstration of the Additive Manufacturing of Turbine Engine CMC Components (20 vol.% SiC Fiber)



First stage nozzle segments.



High pressure turbine nozzle segments: cooled doublet vane sections.

Additive Manufacturing of Ceramics using 3-D Printing Technologies

Objective: To develop and characterize feed materials for 3-D printing of silicon carbide (SiC)-based ceramics.

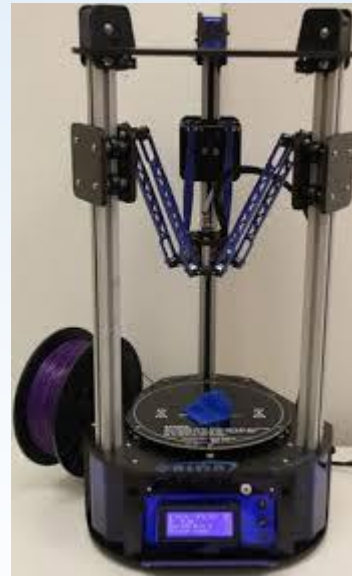


3-D Printing Efforts

- Powder Loaded Filament - direct printing of ceramic parts
- Wood Containing Filament - provide preforms for densification
- Slurry Dispensing of Pastes - evaluate pastes for full conversion to dense SiC



MakerBot Replicator 2X



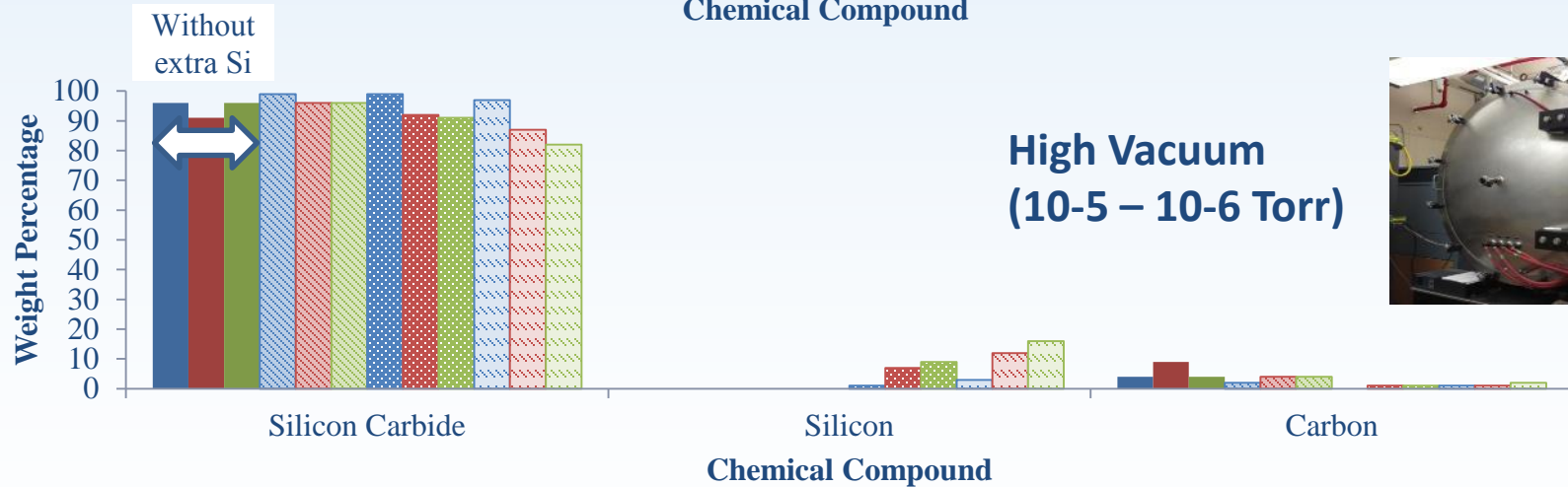
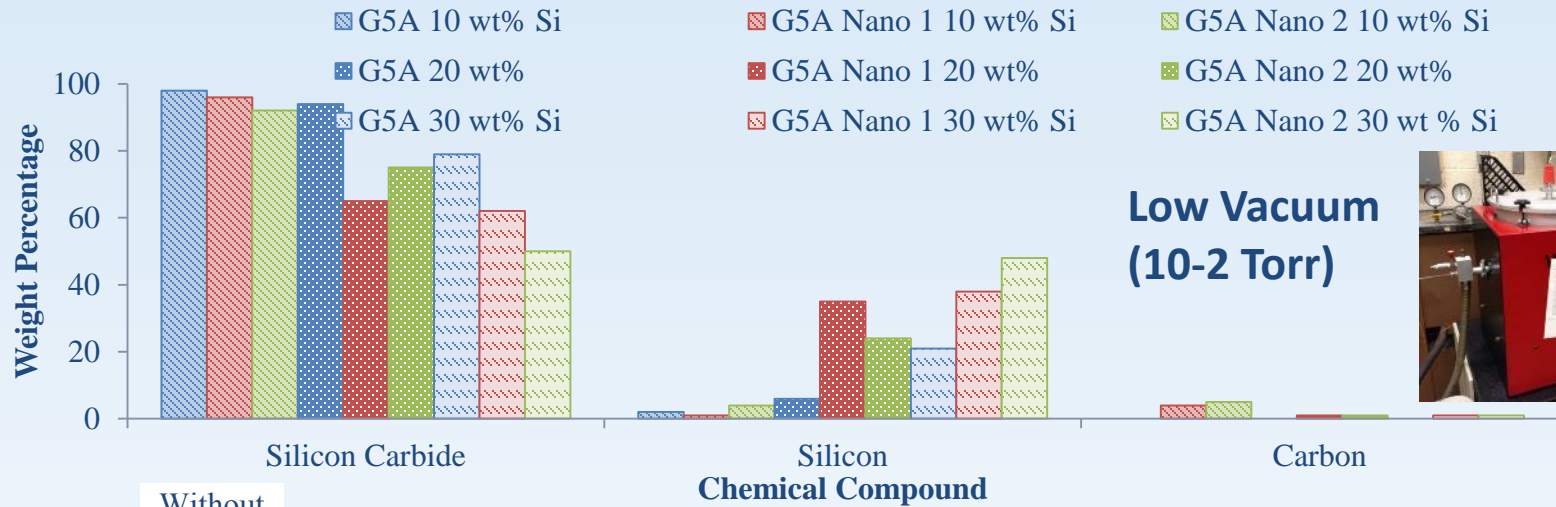
Orion Delta 3D Printer



Rostock 3D Printer

***These printers can print polymers with specific filaments
Ability to fabricate ceramics is being investigated***

Chemical Composition of Heat-treated Pastes at 1450°C (from X-Ray Diffraction Analysis)



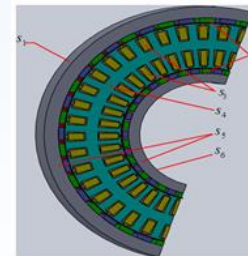
- All compositions after pyrolysis show a high yield of SiC.
- Vaporization of Si occurs in vacuum due to its high vapor pressure

NScript Capabilities and Applications

- Ability to host four separate materials and print on curved surfaces.
- Precise control of motion and micro-dispensing pump.
- Variety of print materials: ceramic pastes, electronic pastes, adhesives, solders, bio-materials, plastics.
- Direct writing with clean starts and stops



Direct Printing for Multi-Material Systems



Multi-material components

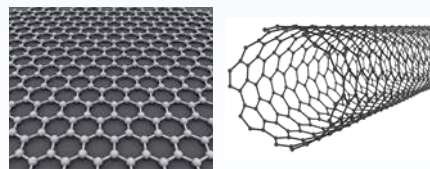


Overlapping direct printed coils.



AM for Innovative Electric Motor Designs

Highly Conductive Copper Pastes



Additions of graphene and carbon nanotubes

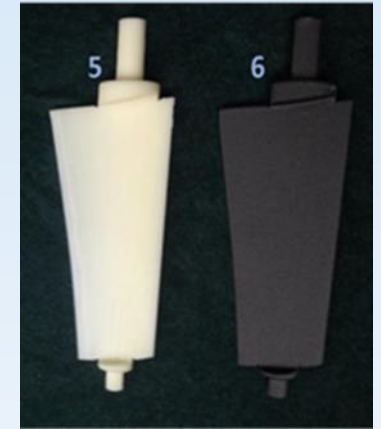
3-D Printing Capability of Various Components Demonstrated in Polymers at NASA GRC



Engine Panel Access Door



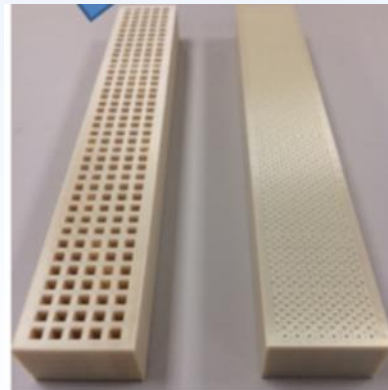
Lightweight Structures



Engine Inlet Guide Vanes from ABS and Ultem 1000



Variable Geometry Panels for Acoustic Treatment



Acoustic Liner Test Articles

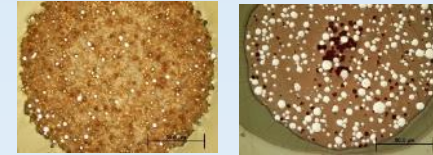


Turbine Blade Shape Demo

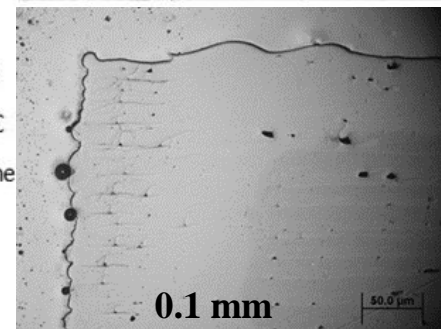
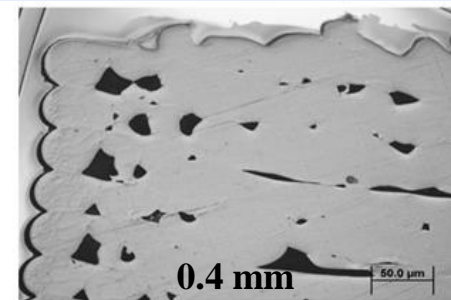
Additive Manufacturing of Polymer Composites for Multifunctional Applications

Potential Missions/Benefits:

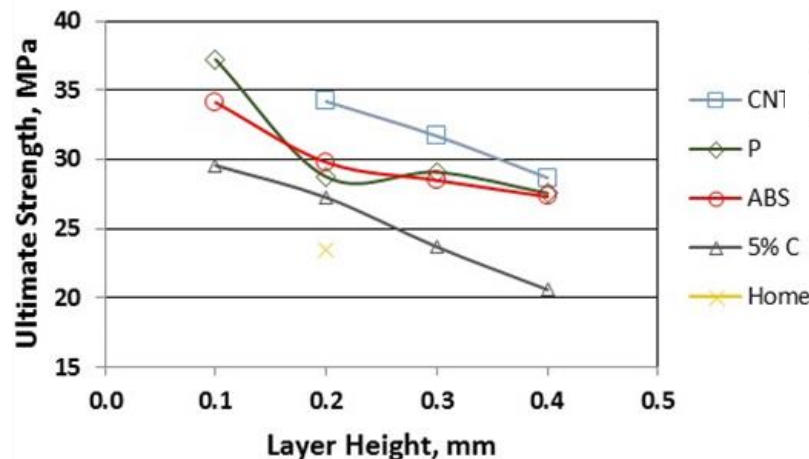
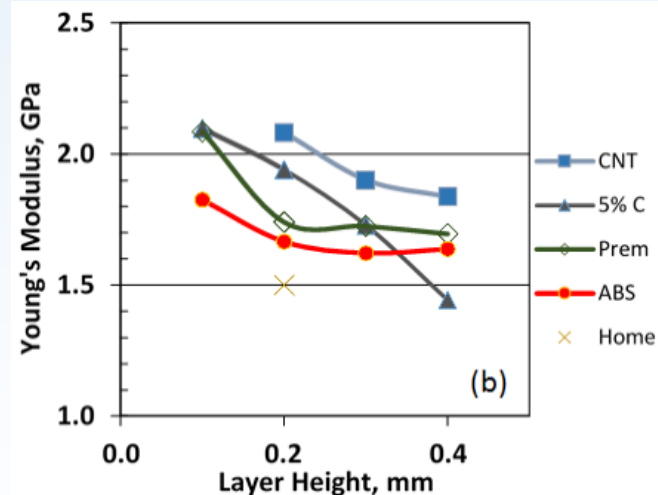
- Tailored, high strength, lightweight support structures
- Tailored facesheets for functional properties, i.e. *wear resistance, vibration dampening, radiation shielding, acoustic attenuation, and thermal management*



Copper filled PLA and bismuth filled ABS



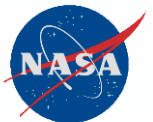
Effect of print layer height



Highest strength and modulus in CNT reinforced coupons
 Pure ABS Coupons – less porosity for lower print heights

Summary/Conclusions

- Additive manufacturing can offer significant advantages in fabricating preforms, ceramics and CMCs.
- They will have to be selectively applied to “traditional” components but can also enable new applications.
- Good progress in binder jet printing and LOM for fiber reinforced SiC-based ceramics.
- AM and 3-D printing of ceramics has the potential to be game changing.
- New opportunities for multi-functional plastic components and multi-material systems.





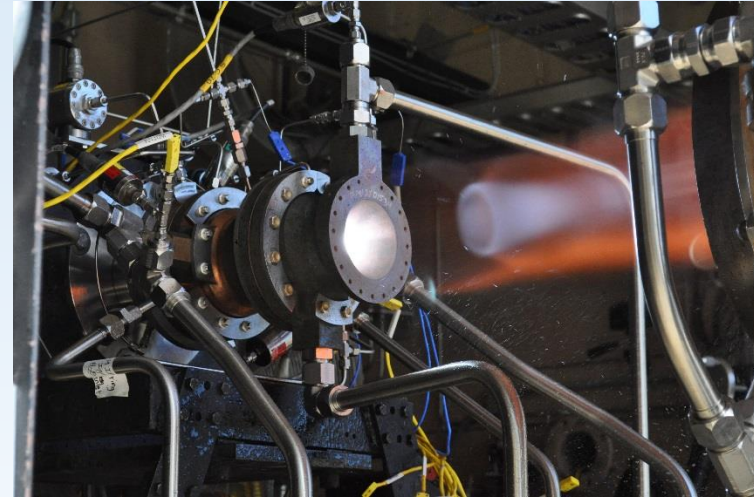
Materials Testing Capabilities

NASA GRC Rocket Engine Test Stands for
Realistic Extreme Pressure and Temperature
Environments

Dr. William Marshall

3-D Printed Rocket Engine Parts Withstand Hot-Fire Tests

- NASA and Aerojet Rocketdyne conducted 19 hot-fire tests on four additively manufactured rocket injector and thrust chamber assembly configurations
 - Used copper alloy additive manufacturing (AM) technology
 - Explored various mixture ratios and injector operability points and were deemed fully successful against the planned test program
 - **The work is a major milestone in the development and certification of different materials used in this manufacturing process**



Significance:

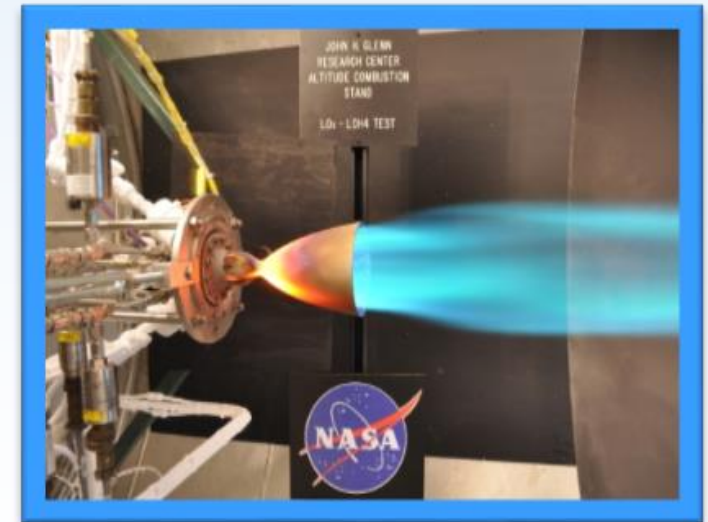
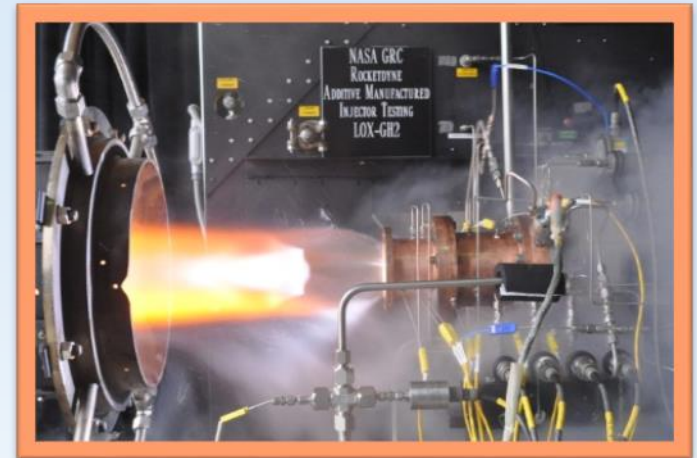
- First ever hot fire test of an AM copper component
- Potential for improved engine performance and significant cost savings
- **Enables verification of AM component functional requirements, validates AM design tools and paves the way for full scale infusion**

“The successful hot fire test of subscale engine components provides confidence in the additive manufacturing process and paves the way for full scale development”
– Tyler Hickman, NASA

NASA GRC

Chemical Propulsion Research Complex

- NASA GRC has several rocket engine test stands to provide a realistic hot-engine environment for testing additively manufactured materials at extreme temperatures and pressures
 - Include sea-level and altitude (100,000 ft.) capable test stands
 - Thrust levels up to 2000 lbf (8.8 kN), Chamber pressures up to 1000 psia (6.9 MPa).
 - Hydrogen, methane, hydrocarbon fuels, and oxygen propellants capability
- For more information:
<http://facilities.grc.nasa.gov/rcl/index.html>
or contact Lori Arnett
(216.433.2947 or lori.arnett@nasa.gov)



Questions / Discussion

