Additive Manufacturing 2.0

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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
- Lightweight Power Transmission Cable
- Solid Oxide Fuel Cell Material

Mechanisms and Drive Systems
- High Efficiency Gear
- Shape Memory Alloy-Based Actuation
- Deployable Structure
- Spring Tire

Computational Modeling
- Computational Models

Flight Structures
- Orion Fairing Jettison
- EFT-1
- Vibration Testing
- 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

Large Rocket Propulsion

Aircraft Gas Turbine Engine

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
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$_2$Nb 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)

Median = 19.5 µm

3-130 µm
Liner Sections And Mechanical Test Samples
Room Temperature Tensile Strength

GRCop Builds 1-3, Tension at 20 °C

strain rate = 8.3 x 10^{-5} s^{-1}

Preliminary Results

Glenn Research Center at Lewis Field
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 lb₉ 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

- 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.

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

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

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.

Fabrics and Prepregs cut at different laser powers/speeds

Silicon Infiltration:
1475 C, 30 minutes in vacuum
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

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.

ExOne’s M-Flex print machine

In collaboration with rp+m
Constituents

SiC powder

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)

High pressure turbine nozzle segments: cooled doublet vane sections.

First stage nozzle segments.
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

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.
NScrypt Capabilities and Applications

- Ability to host four separate materials and print on curved surfaces.
- Precise control of motion and micro-dispensing pump.
- Direct writing with clean starts and stops.

Highly Conductive Copper Pastes

Additions of graphene and carbon nanotubes

Direct Printing for Multi-Material Systems

Multi-material components

Overlapping direct printed coils

AM for Innovative Electric Motor Designs

Glenn Research Center at Lewis Field
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

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

Copper filled PLA and bismuth filled ABS

Effect of print layer height

[Graphs showing Young's Modulus and Ultimate Strength vs. Layer Height for different materials]
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
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Questions / Discussion