Edward DeMille Campbell Memorial Lecture
ASM International

Additive Manufacturing

Disrupting Global Supply Chains and Enabling Sustainable Development

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Professor Edward DeMille Campbell

Edward DeMille Campbell (1863-1925)

- Born in Detroit in 1863 and received the degree of Bachelor of Science in Chemistry from University of Michigan in 1886.
- After serving as Chemist in various iron companies, he became an assistant professor of metallurgy at U-M in 1890, where he lost his sight at the age of 28 in an explosion during a laboratory examination of steel.
- For 20 years before his death in 1925, he was head professor of chemistry and metallurgy and director of the Chemical Laboratory at U-M.
- In 1924, Campbell's group pioneered the use of x-ray diffraction in physical metallurgy through their discovery of the tetragonal structure of martensite phase, the basis for super-hard steels.
- He was blind for all but two years of his professional career, yet he contributed 77 papers to the scientific literature.

ASM Edward DeMille Campbell Memorial Lecture Started in 1926

Outline of Presentation

- Background and Introduction
- Manufacturing, Supply Chains, and Sustainability in Global Landscape
- Additive Manufacturing
    - Ceramic Systems
    - Polymer Systems
    - Multi-material Systems
- Technical Challenges and Opportunities
- Summary and Conclusions
- Acknowledgements

Globalization and Sustainable Development

Additive Manufacturing: A Game Changer in Global Supply Chain

Industrial Sectors

- Food, consumer products, pharmaceuticals, and healthcare
- Industrial, energy, infrastructure, and transport

Supply Chain

- Avoids the need to hold spare inventory, reducing warehousing costs, and overstocking
- New production techniques responsive to local needs, flexible production capabilities

Potential Impact

- Transformative products, efficient production to reduce demand for raw materials
- Reduced need for global distribution and supply chains, on-demand flexible production

Layers Have Been Used Differently Through Cultures and Times…

- **Subtractive**
  - Material is successively removed from a solid block until the desired shape is reached (2.5M BC – Hominids)
- **Fabricative**
  - Elements or physical material are combined and joined (6,000 BC – Western Asia)
- **Formative**
  - Mechanical forces and, or heat are applied to material to form it into the desired shape such as bending, casting and molding (3,000 BC – Egyptians)
- **Additive**
  - Material is manipulated so that successive pieces of it combine to make the desired object (1984 –)

National Manufacturing Initiative

Emphasis on Additive Manufacturing Technologies

Major Policy Milestones

Major Initiatives

June 2011

REPORT TO THE PRESIDENT ON ENSURING AMERICAN LEADERSHIP IN ADVANCED MANUFACTURING

Executive Office of the President
President's Council of Advisors on Science and Technology

JUNE 2011

February 2012

A NATIONAL STRATEGIC PLAN FOR ADVANCED MANUFACTURING

Executive Office of the President
National Science and Technology Council

FEBRUARY 2012

July 2012

REPORT TO THE PRESIDENT ON CAPTURING DOMESTIC COMPETITIVE ADVANTAGE IN ADVANCED MANUFACTURING

Executive Office of the President
President's Council of Advisors on Science and Technology

January 2013

NATIONAL NETWORK FOR MANUFACTURING INNOVATION: A PRELIMINARY DESIGN

Executive Office of the President
National Science and Technology Council
Advanced Manufacturing National Program Office

Advanced Manufacturing National Program Office
Innovation in Materials & Manufacturing
TMS 2013, San Antonio, Texas

Frank Gayle, AMNPO, NIST

Potential Benefits of Additive Manufacturing

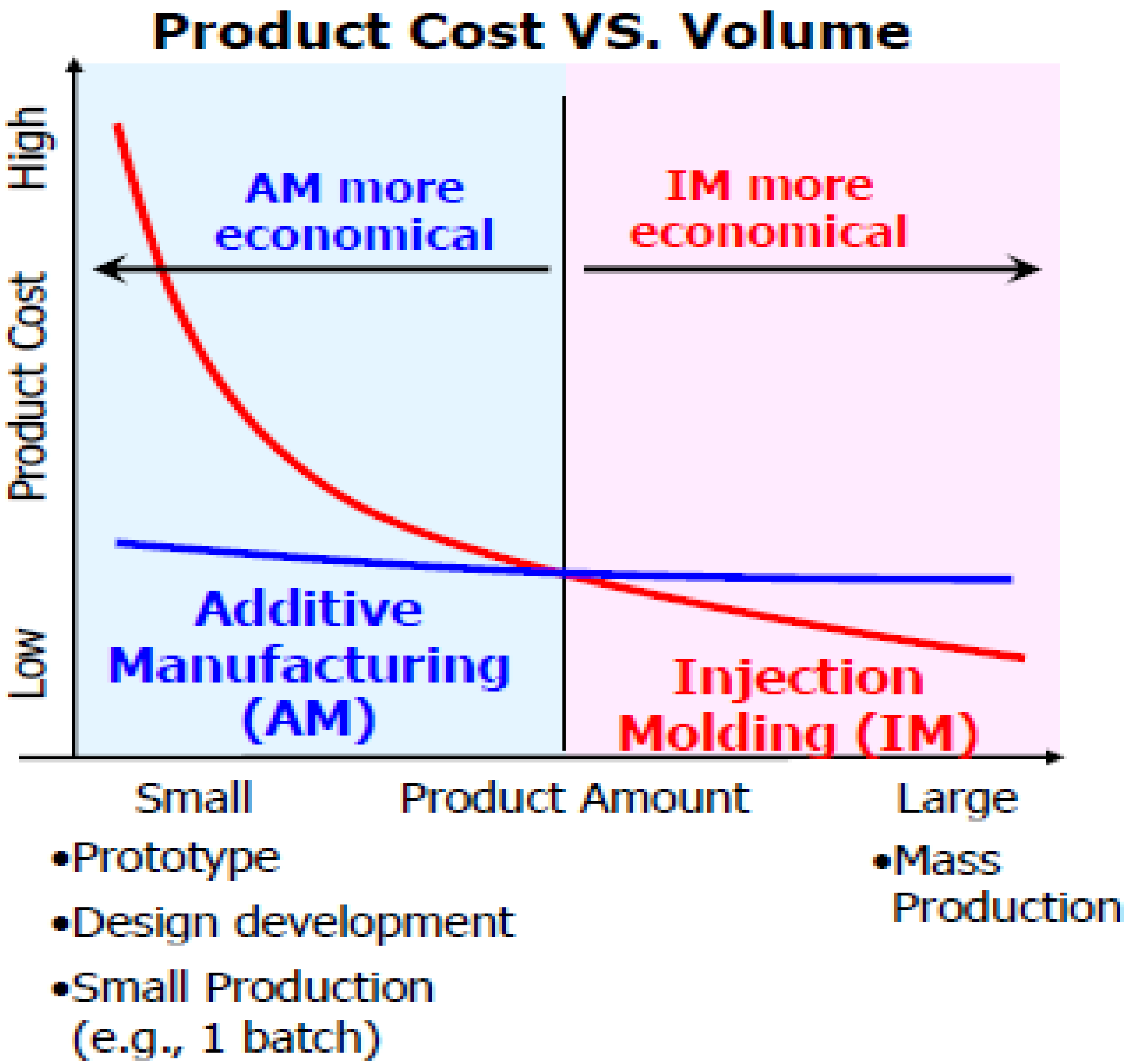
Ease of Fabrication and Manufacturing
- Simplified formation of materials
- Custom-made and complex geometries

Tailorable Composition and Properties
- Hybrid systems
- Multifunctional materials

Lower Cost
- Fewer processing steps
- Short production time

Interdisciplinary Approaches are Needed to Address Complex Additive Manufacturing Challenges

Product Volume and Cost Dictate the Affordability of AM Technologies



Additive Manufacturing of Ceramics/CMCs

Conventional Manufacturing

- Customized parts in small volumes are time consuming and expensive to produce.
- Complex shape fabrication issues: mold design, dimensional tolerances, etc..
- Manufacturing of multifunctional parts is challenging.

Additive Manufacturing

- Small series of ceramic parts can be manufactured rapidly and cost-effectively.
- Specific molds are not required.
- Different designs can be optimized (no major cost of changes)
- Parts with significant geometric complexity.

Material and Process Challenges

- Property and behavior of starting materials
- Sintering and densification challenges
- Process modeling
- Mechanical behavior
- NDE and in-situ damage characterization
- Material and property databases

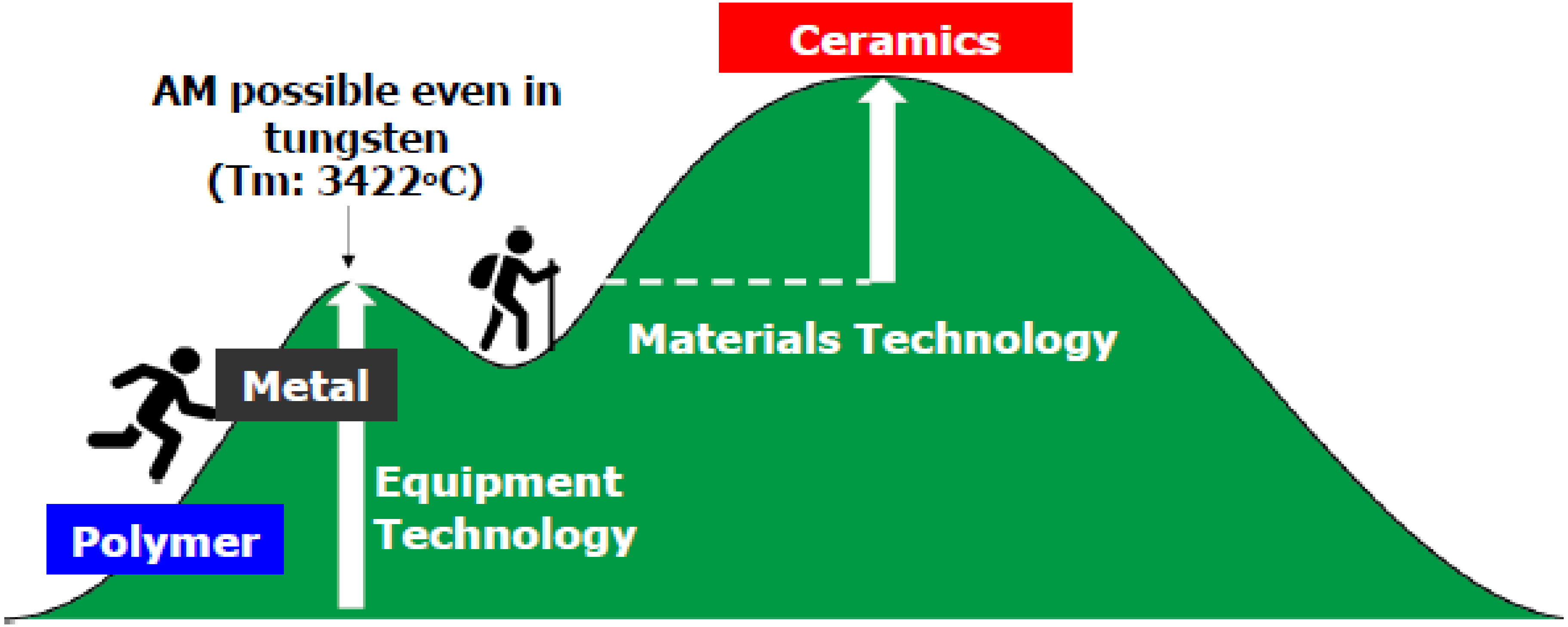
Long term research efforts have now resulted in various applications.

Efforts in this very promising field are now underway.

Materials and processing challenges are quite similar

Technological Challenges in Additive Manufacturing Technologies

Polymer	Metal	Ceramics
Melting/Solidification OK		•Melting/Solidification NG •Sintering Needed



Fiber Reinforced Ceramic Matrix Composites (CMCs)

Current Approaches for Manufacturing of Ceramic Matrix Composites

Preforming and Interface

Hand lay-up and tooling of ceramic fibers or woven shapes

Chemical Vapor Infiltration (CVI) Process

A gas mixture is infiltrated and SiC is deposited into a fiber preform.

- Slow; large objects can take weeks to months.

Polymer Infiltration/ Pyrolysis (PIP) Process

Preceramic polymer infiltration and pyrolysis to create a SiC based matrix.

- Multiple steps to achieve matrix density

Melt Infiltration (MI) Process

Slurry coated prepregs or infiltration of slurry/ resins into a fiber preform.

- Infiltration of liquid silicon to react with carbon to form SiC.

Hybrid Process

Combination of CVI/PIP, CVI/MI, or PIP/MI to create a SiC based matrix.

- Several steps to make a matrix

Post Processing and Nondestructive Evaluation

Machining (grinding, milling, drilling) → **Joining (brazing and attachments)** → **Coating and Finishing NDE**

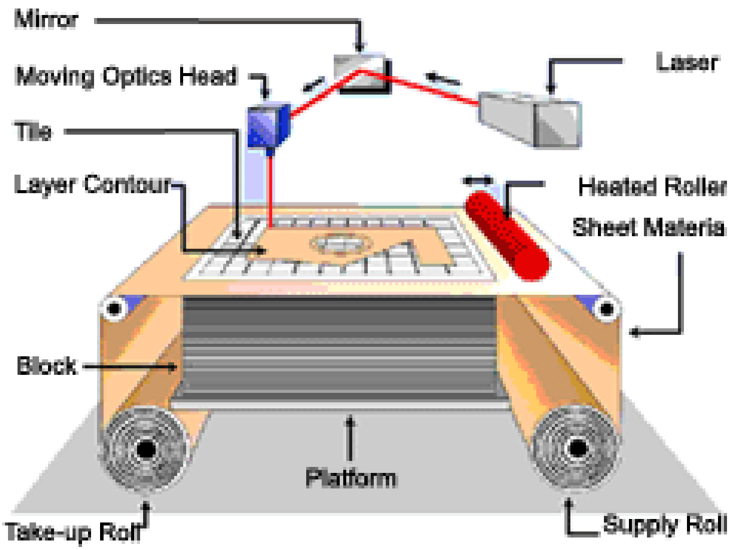
Laminated Object Manufacturing of Ceramic Matrix Composites (NASA LEARN Project: OAI)

- **LOM is a viable option for manufacturing fiber reinforced CMCs with modification to the machine.**
- **Issues with LOM machines manufacturing base.**

Typical Process:

1. CAD design is turned into computer generated cross sections.
2. Layers of adhesive coated materials adhered to substrate with heated roller.
3. Laser cuts cross-section of part.
4. Laser cross hatches non-part area.
5. Platform with completed layer moves down.
6. Fresh sheet moves over and platform moves up. Layers are stacked to form the shape with the desired thickness.

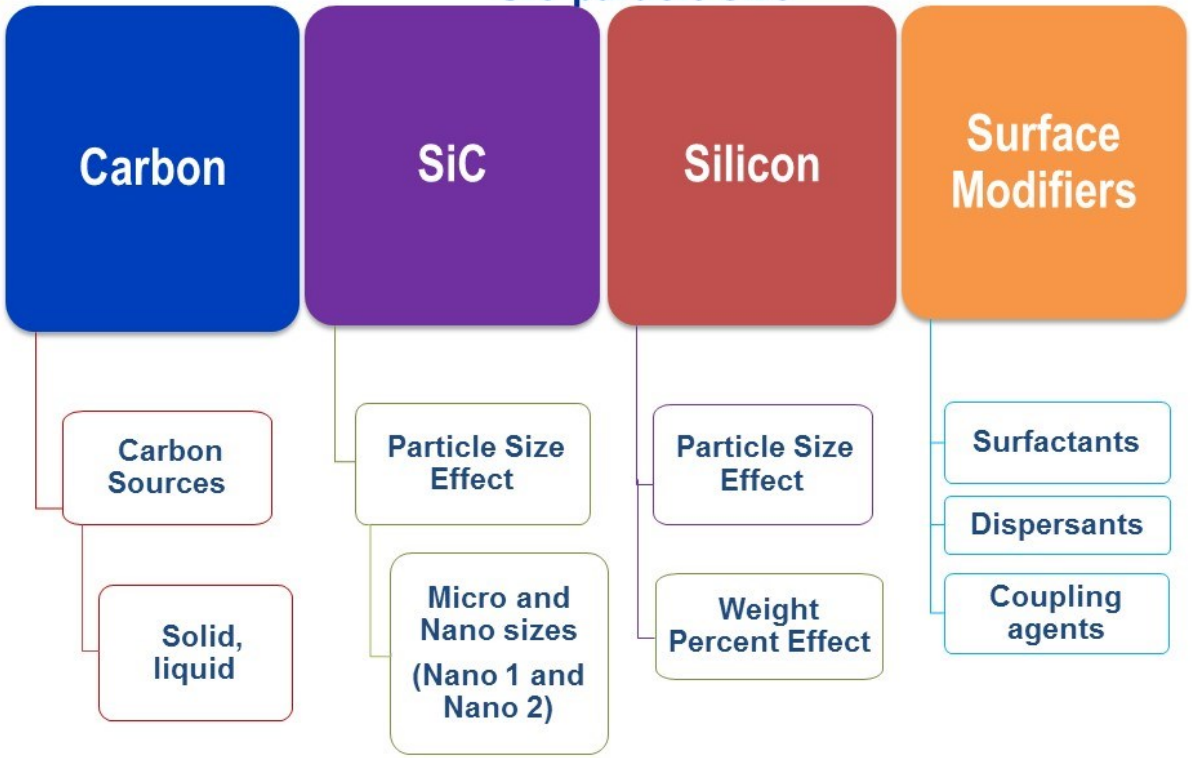
New CMC prepreg material development and characterization is a critical step



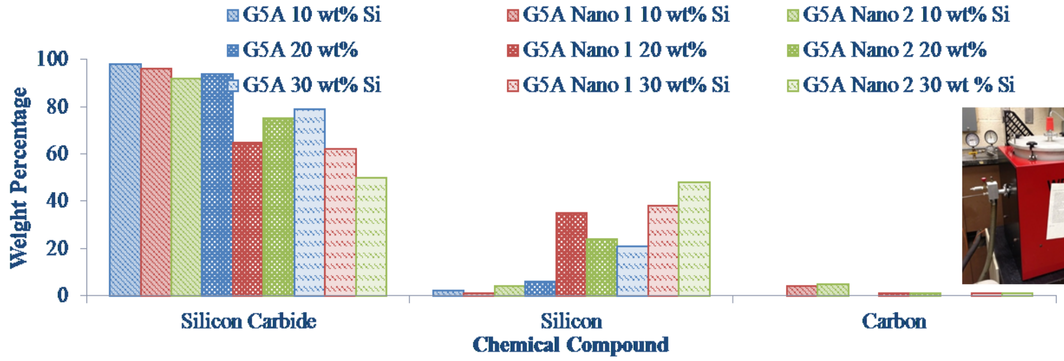
http://www.rpc.msoe.edu

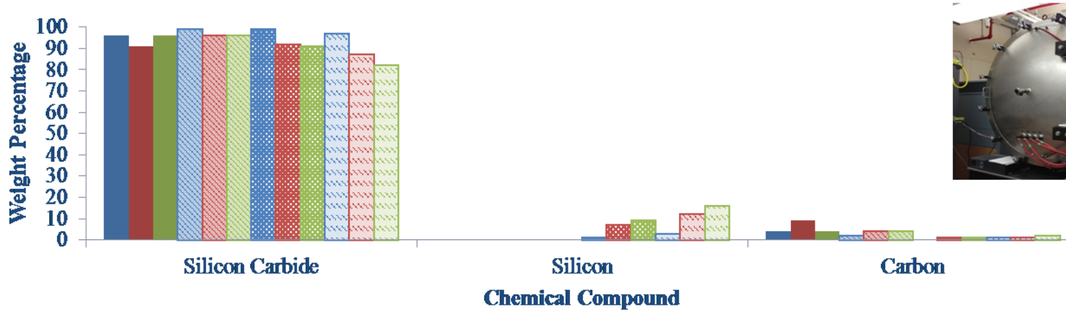
Design of Silicon Carbide Based Material System for Additive Manufacturing

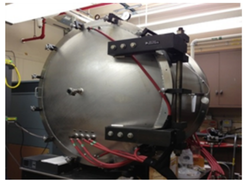
G5A, G5A Nano 1, G5A Nano 2 - in descending order of SiC particle size



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





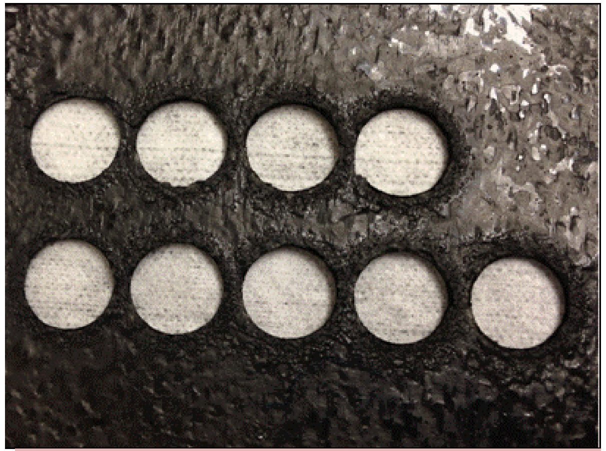


- All compositions after pyrolysis show a high yield of SiC.
- Vaporization of Si occurs in vacuum due to its high vapor pressure.

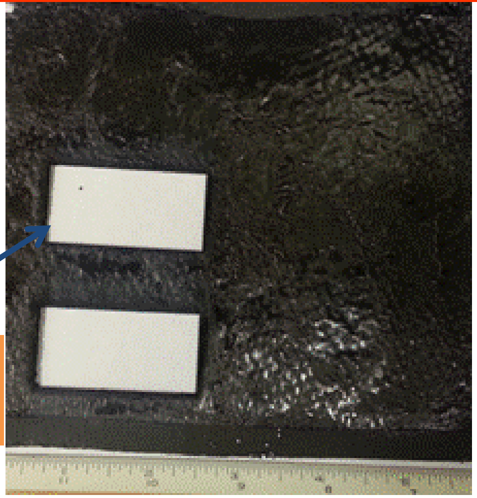
Evaluation of Laser Cutting Parameters for Silicon Carbide Fabrics and Prepregs

Prepregs for Composite Processing
- A number of SiC (Hi-Nicalon S, uncoated) fabrics (~6”x6”) were prepregged.
- These prepregs were used for optimization of laser cutting process.
- Baseline laser cutting data was also generated for different types of SiC fabrics (CG Nicalon, Hi-Nicalon, and Hi-Nicalon S)

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



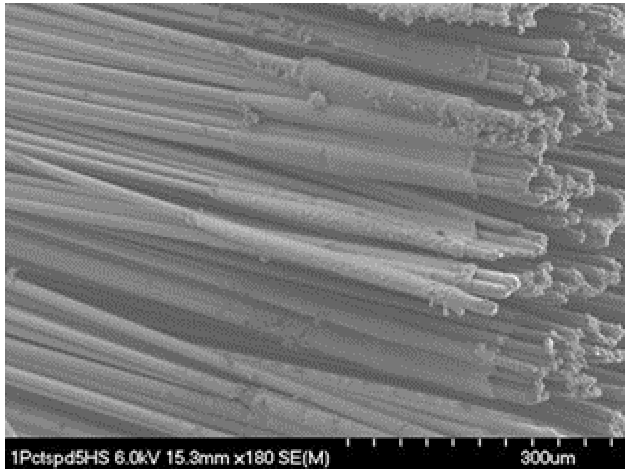
SEM specimens cut with different laser power/speeds



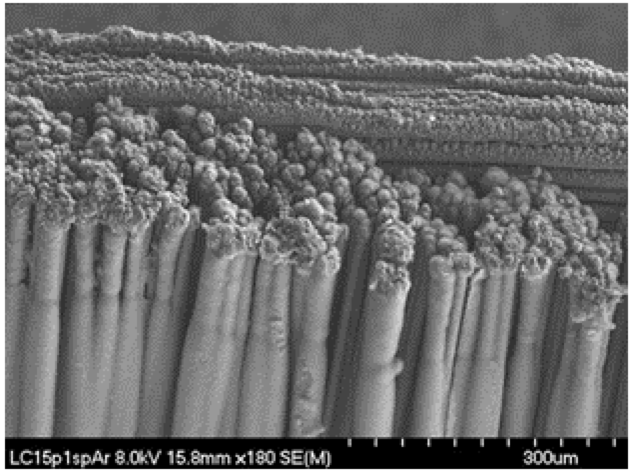
Laser cut prepregs used for composite processing

Investigation of Laser Cutting Parameters (Hi-Nicalon S, 5HS Fabric and Prepreg)

Fabrics

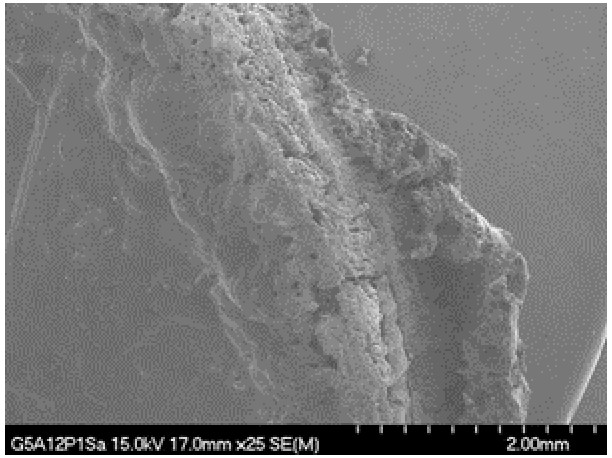


15% Power, 1% Speed, no purge

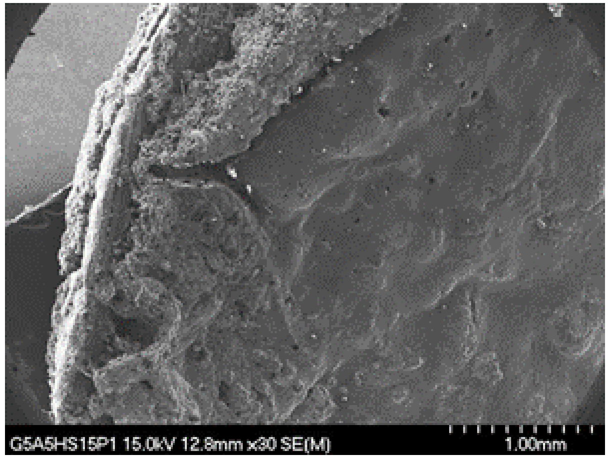


15% Power, 1% Speed, w/Ar Purge

Prepregs



12% Power, 1% Speed, no purge

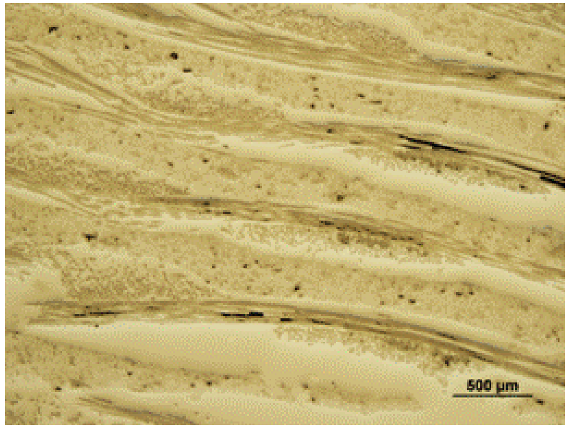


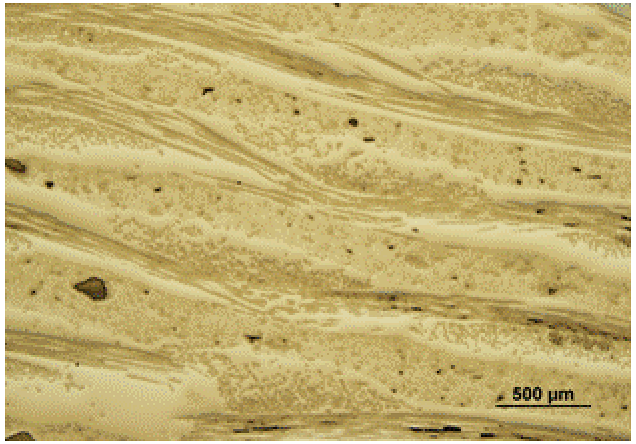
15% Power, 1% Speed, no purge

Microstructure of SiC/SiC Composites Fabricated Using Silicon Infiltration

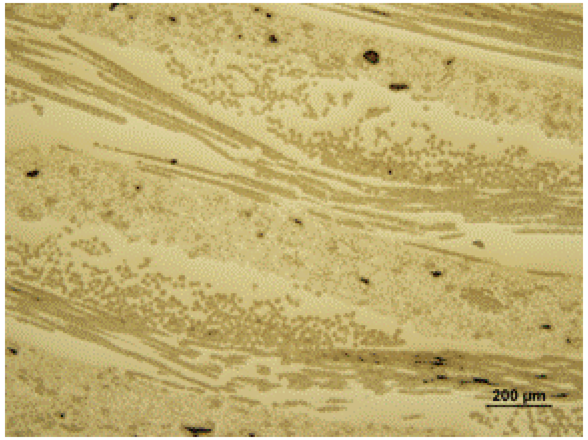
Fibers Used for Prepregs: SiC (Hi-Nicalon S Fibers, 5 HS weave)
Fiber Interface Coating: None
Prepreg Composition: Prepreg 5A Nano 2 + Si

Green Preforms:
8 layers of prepregs; warm pressed @75-85°C





Silicon Infiltration:
1475 C, 30 minutes in vacuum

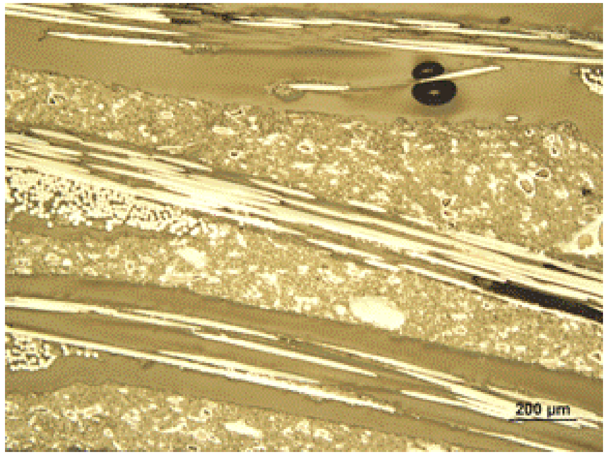


- Dense matrix after silicon infiltration. However, uncoated fibers are damaged due to exothermic Si+C reaction.
- Fiber coatings needed to prevent silicon reaction and provide weak interface for debonding and composite toughness.

Microstructure of SiC/SiC Composites Fabricated Using Single Step Reaction Forming Process

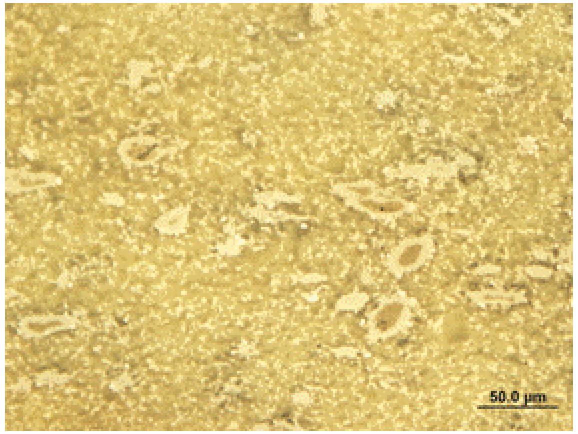
Fibers Used for Prepregs: SiC (Hi-Nicalon S Fibers, 5 HS weave)
Fiber Coating: None
Prepreg Composition: Prepreg 5A Nano 2 + Si

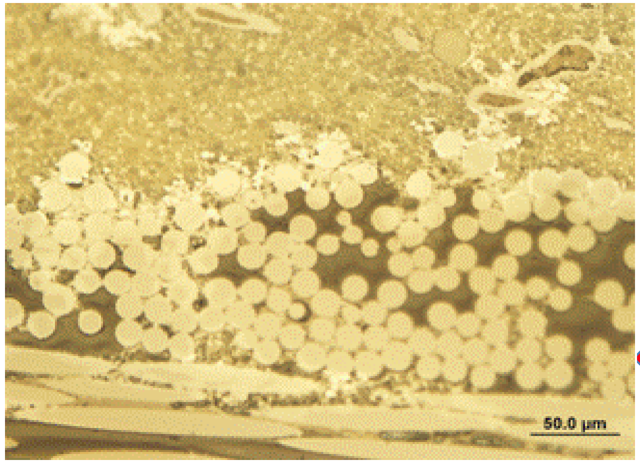
Green Preforms:
8 layers of prepregs; warm pressed @75-85°C



Heat Treatment:
1475°C, 30 minutes in vacuum

Micrographs show good distribution of SiC and Si phases.



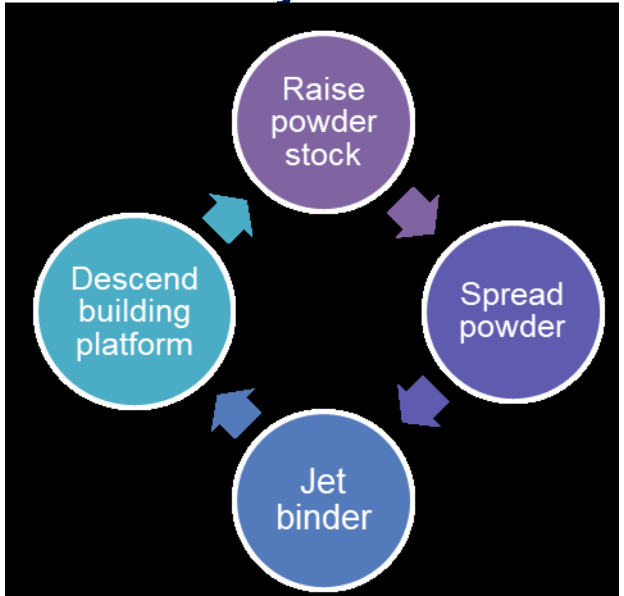


Uncoated SiC fibers show no visible damage due to Si+C exothermic reaction.

Binder Jetting AM Process

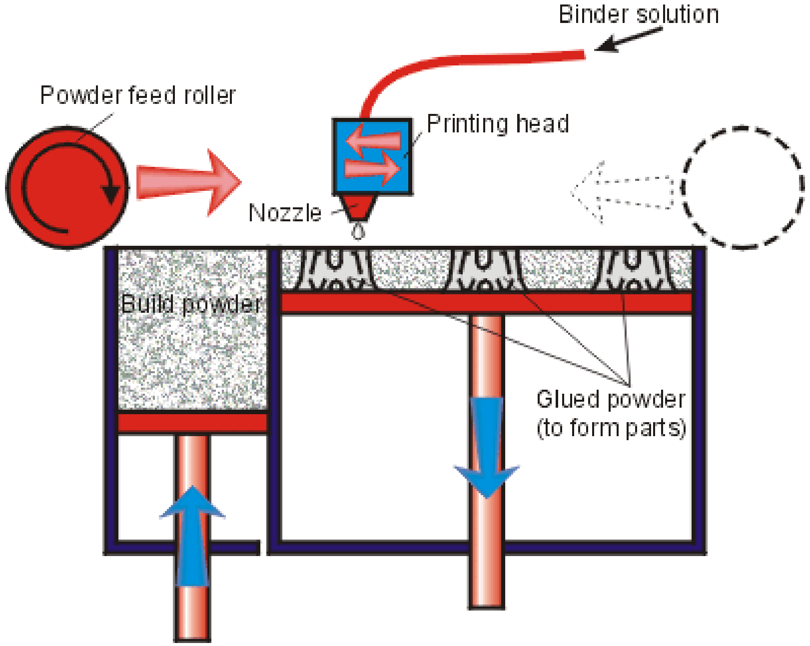
Additive Manufacturing of Ceramics Using Binder Jetting

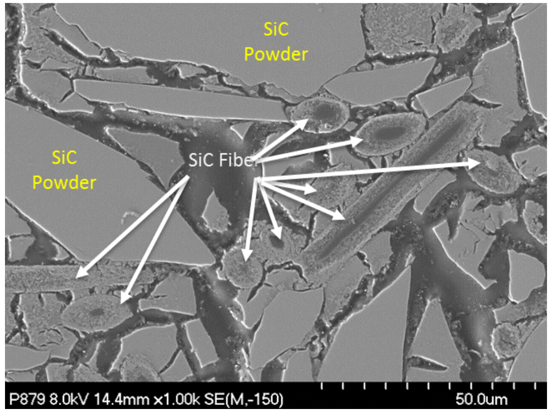
ExOne's Innovent System



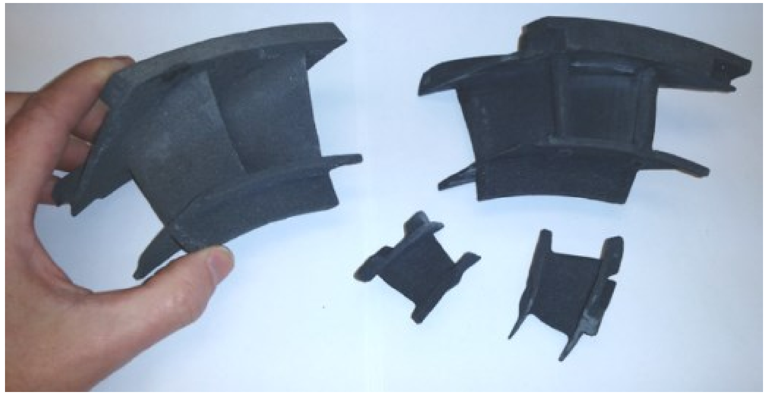
Binder Jetting Process

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.





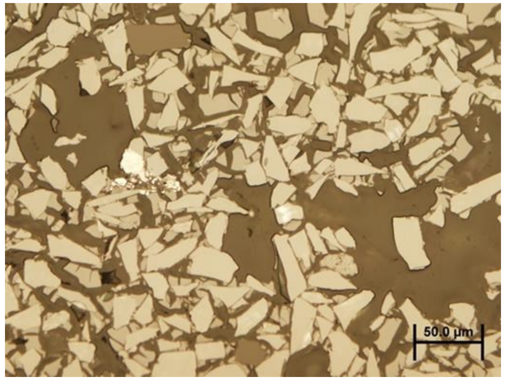
Chopped Fiber Reinforced Ceramic Matrix Composite



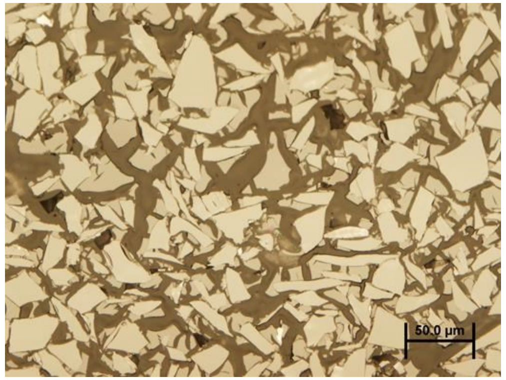
High pressure turbine nozzle segments: cooled doublet vane sections.

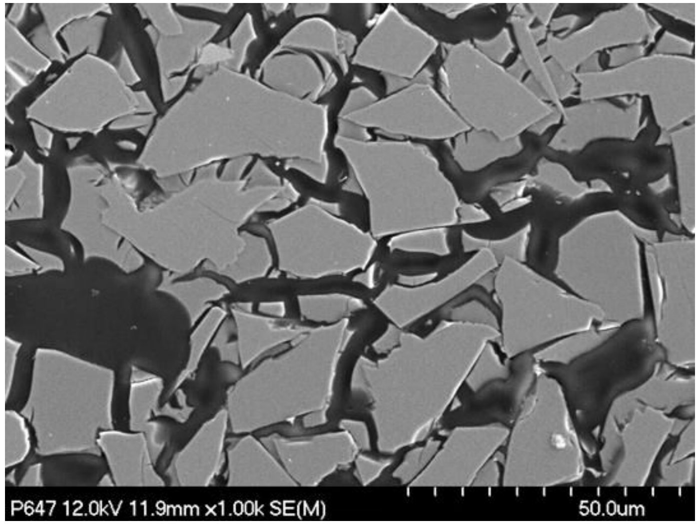
Binder Jet Additive Manufacturing of SiC Ceramics

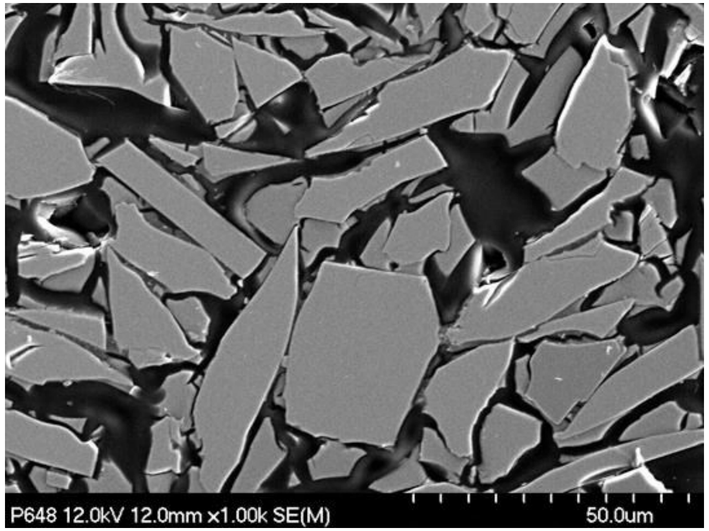
Carborex 240 SiC Powders with SMP-10 Infiltration



Carborex 360 SiC Powders with SMP-10 Infiltration

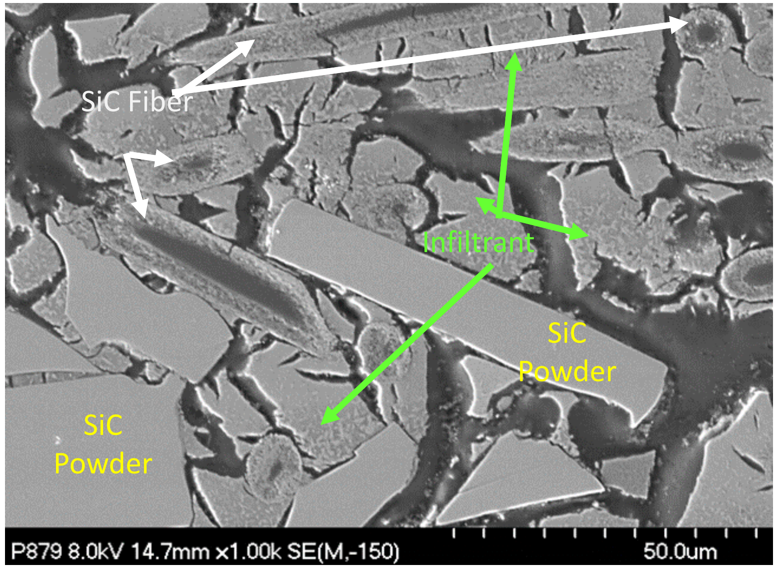


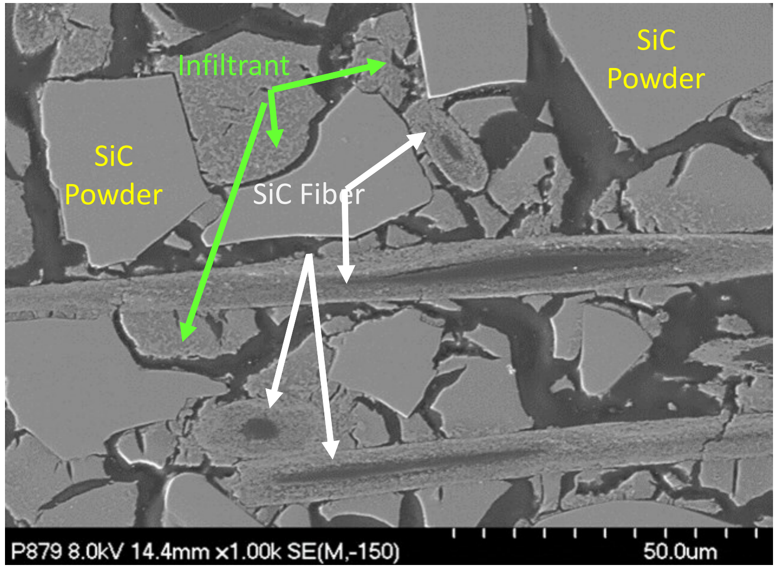


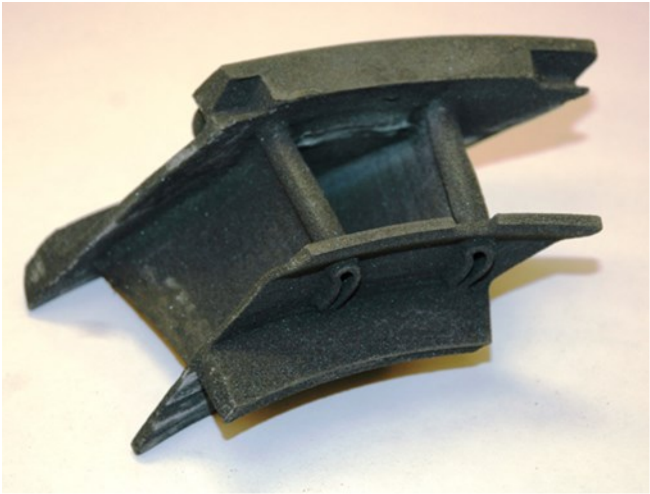


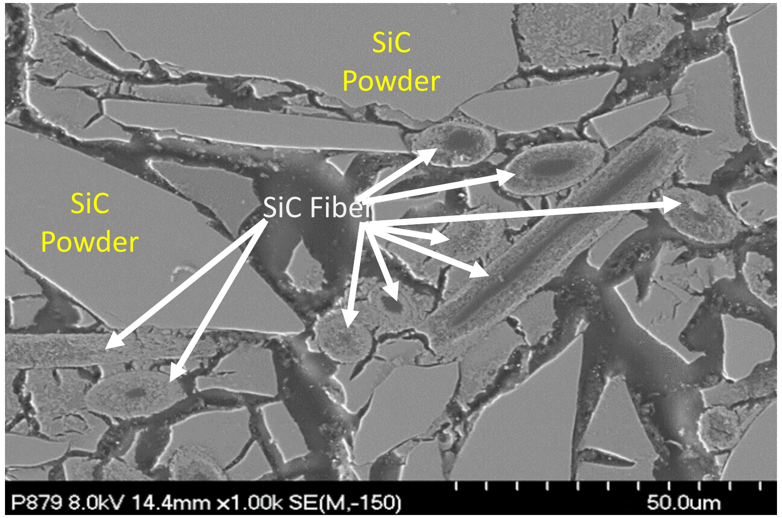
- Initial work was done on M-Flex machine with aqueous binders at rp+m.
- Single infiltration of polymer was carried out to provide some strength in preform/parts.

Binder Jet Additive Manufacturing of Short SiC Fiber Reinforced SiC Composites





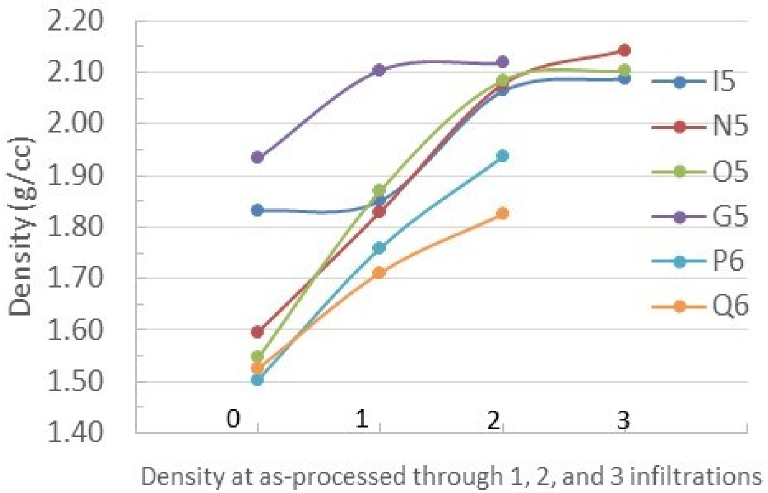




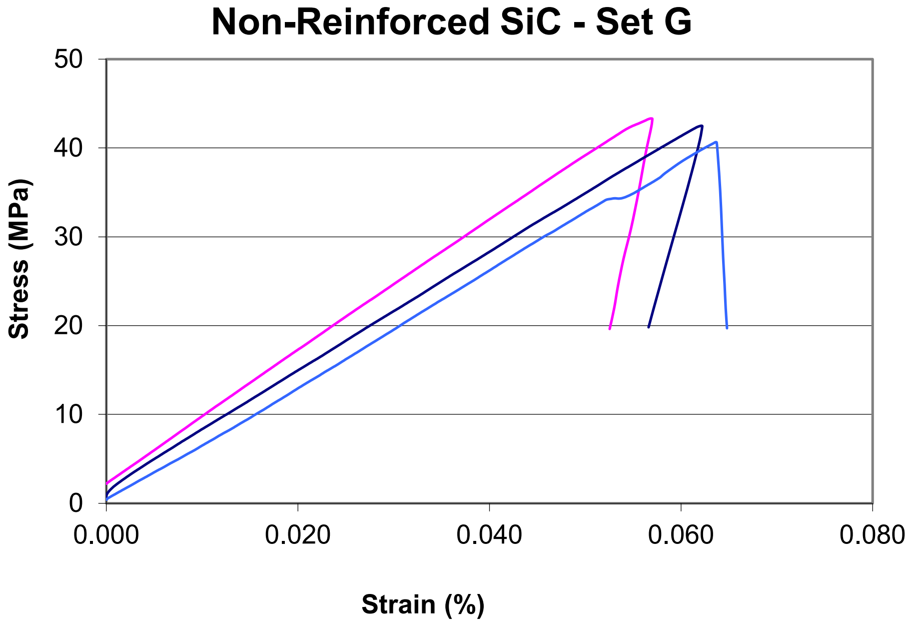
Different views of are shown of a CMC coupon with 35 vol% SiC fiber loading and infiltrant with smaller SiC powders.

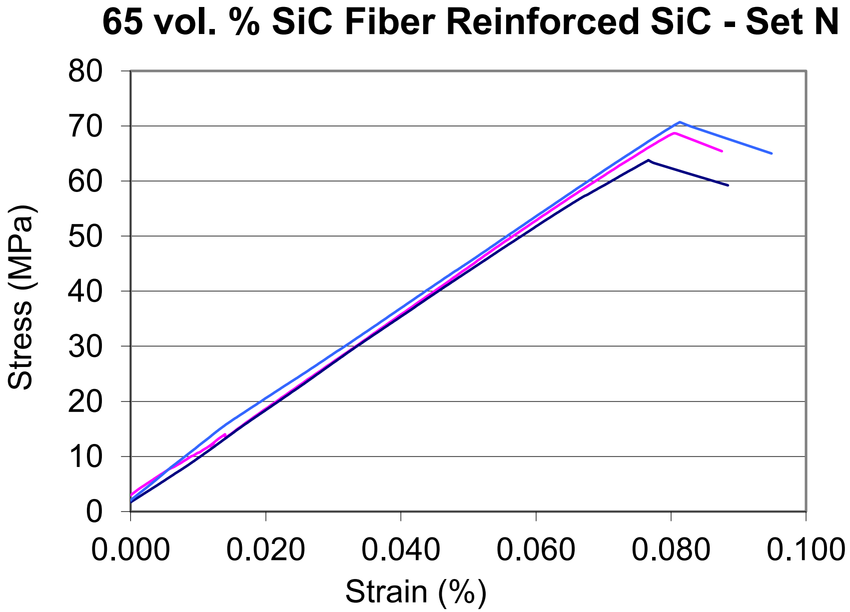
- ***Higher density observed due to powder loaded infiltrant.***
- ***Good distribution and non-preferred orientation of SiC fibers is observed.***

Mechanical Properties of SiC and SF-CMC Materials

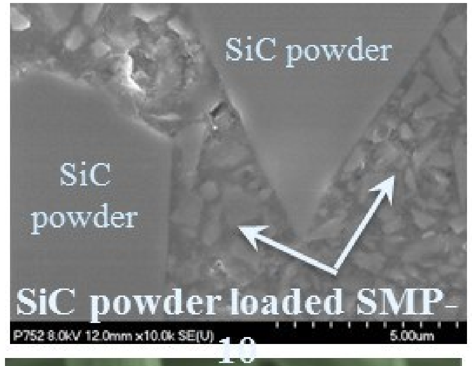


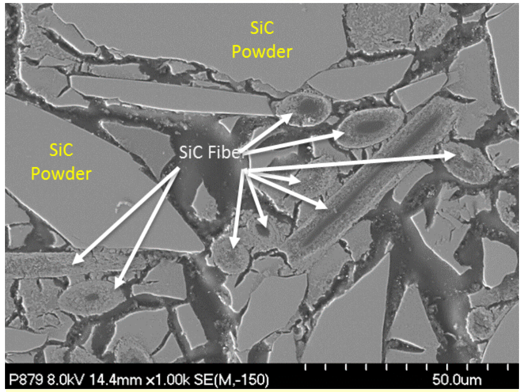
The fiber loaded SiC materials had significantly higher stresses and higher strains to failure.





M.C. Halbig, M. Singh, J.E. Grady, et al, NASA Technical Memorandum NASA/TM-2015-218750

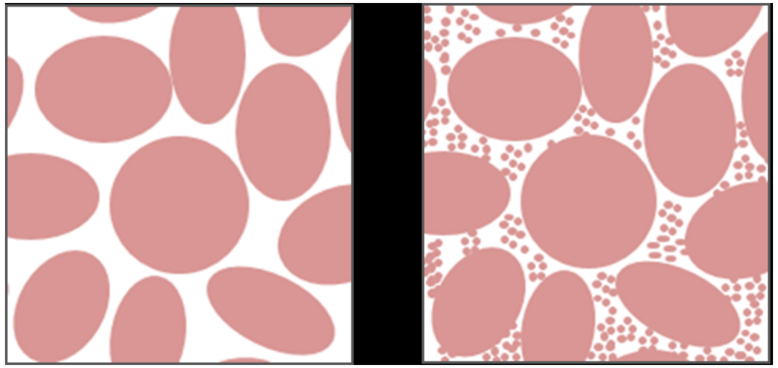




Chopped Fiber Reinforced Ceramic Matrix Composite

Challenges in Binder Jet Additive Manufacturing of Ceramics

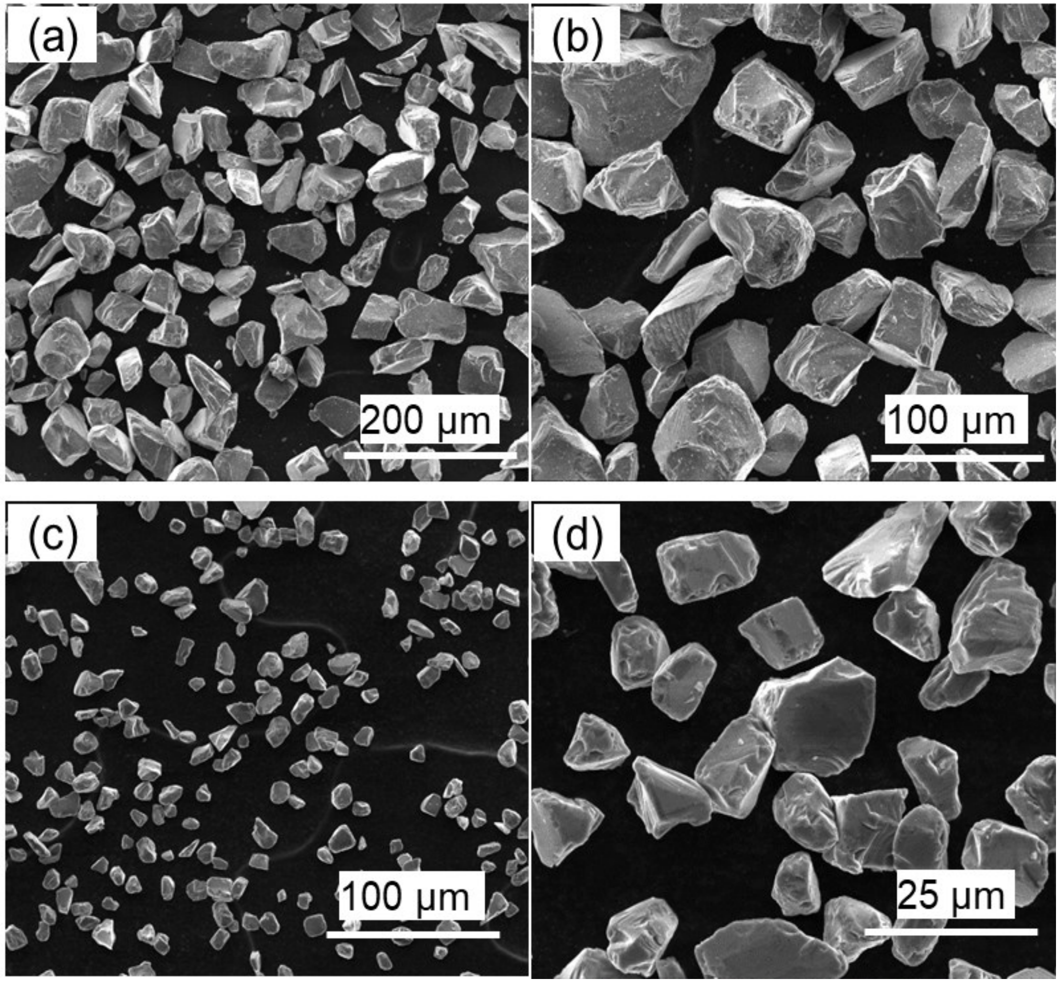
- **Low powder bed packing density**
  - Achieved powder bed densities by dry powder are between 15-50%, much lower than theoretical packing of mono-sized spherical powder (73%).
- **Powder mixing of different-sized powders is an effective method to increase powder bed density and therefore sintered density.**
- **Modeling and analysis of powder packing and verification by experiments is critical for starting powders.**



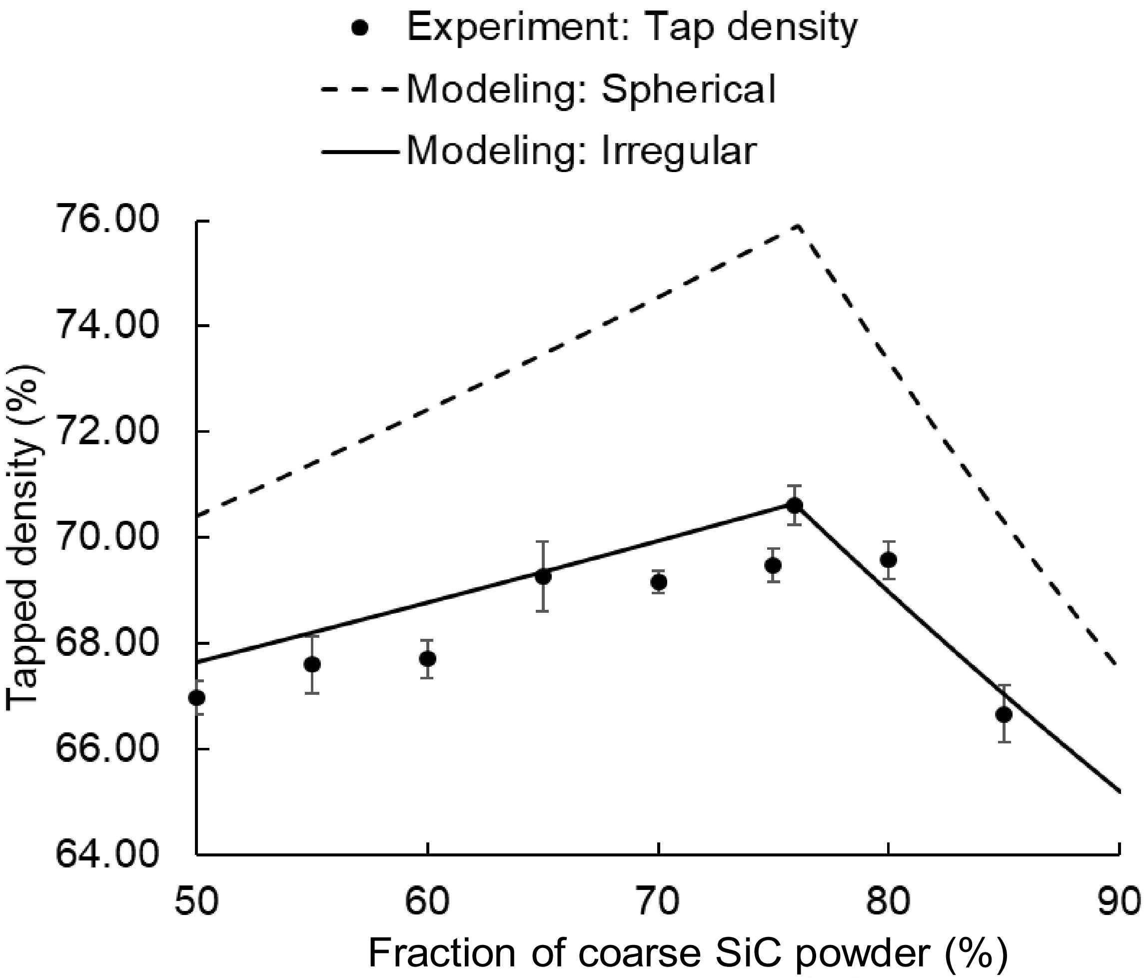
Modeling Methodology:

- Linear packing model
- Packing model for irregular powders (modified interaction functions)

SiC Powder Blend Optimization for Binder Jet Additive Manufacturing



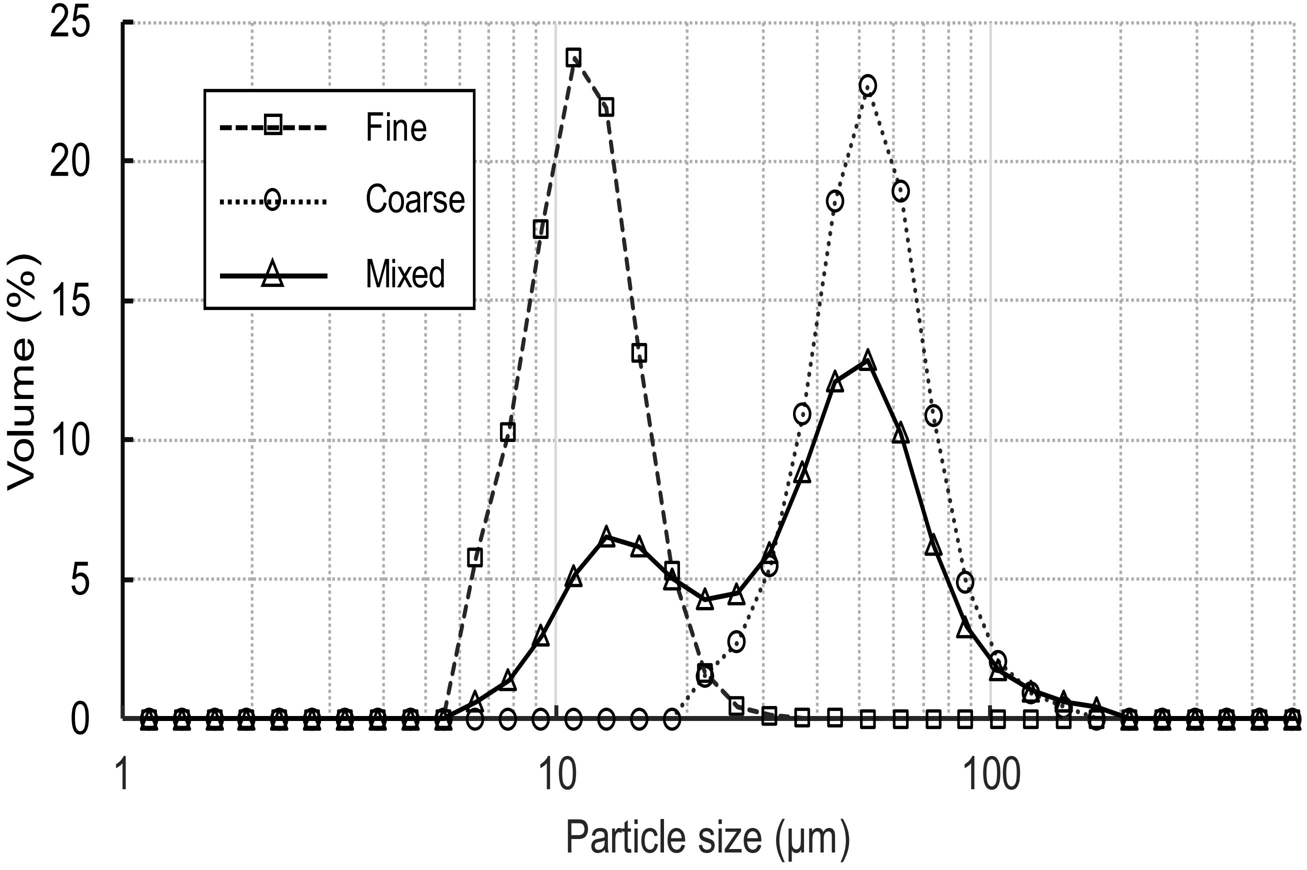
SEM images of the coarse ((a) and (b)) and fine ((c) and (d)) unimodal SiC powders



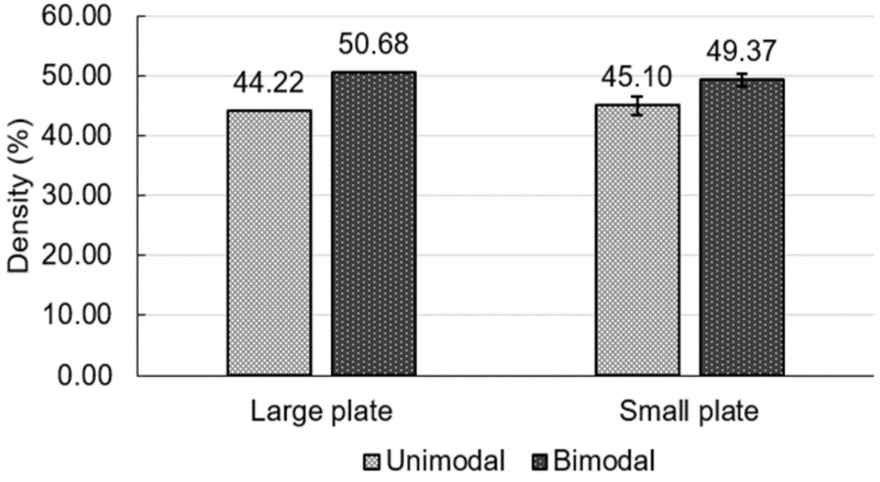
Tap density results from modeling and experimental methods

W. Du, M. Singh, D. Singh, Ceramics International, 46, 12 (2020) 19701-19707

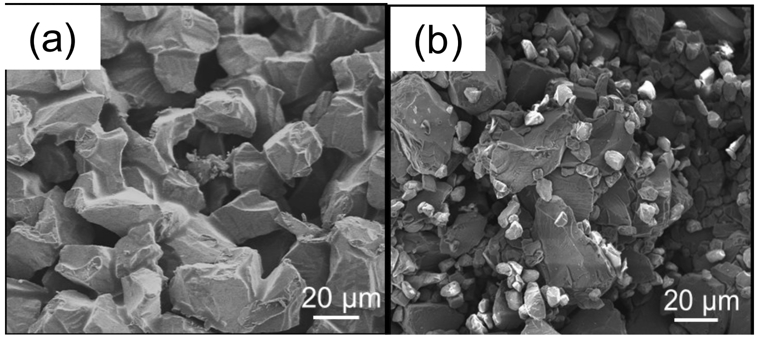
SiC Powder Blend Optimization for Binder Jet Additive Manufacturing



Measured particle size distributions of unimodal and bimodal (75.9 vol.% coarse and 24.1 vol.% fine) powders



Green part densities of large and small plates from unimodal and bimodal powders

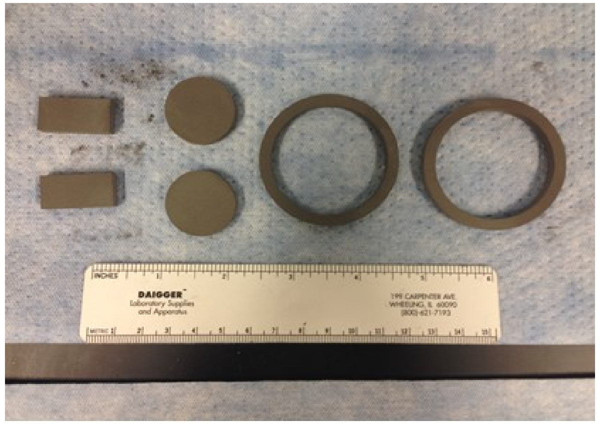


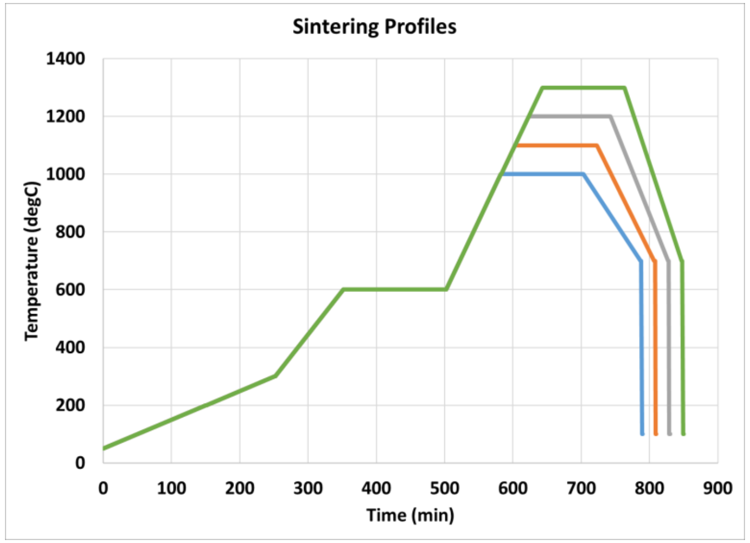
Fracture surfaces of green parts from (a) unimodal and (b) bimodal powders

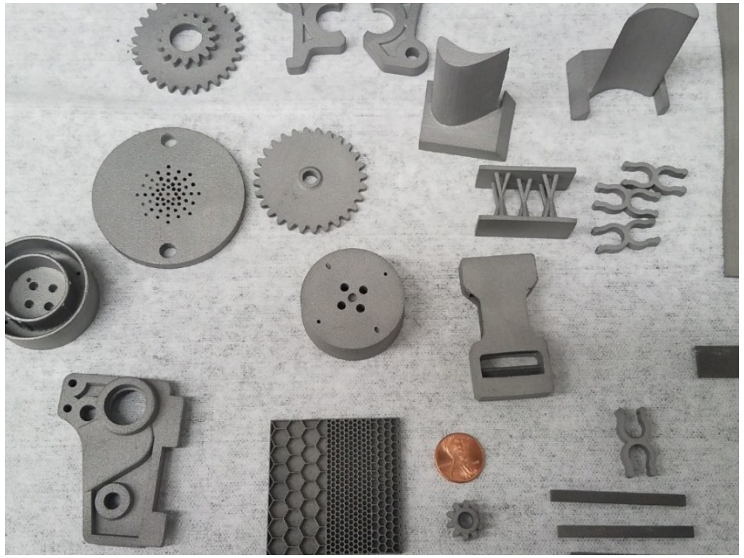
W. Du, M. Singh, D. Singh, Ceramics International, 46, 12 (2020) 19701-19707

Additive Manufacturing of Metallic Components Using Binder Jetting

Iron Based Soft Magnetic Materials

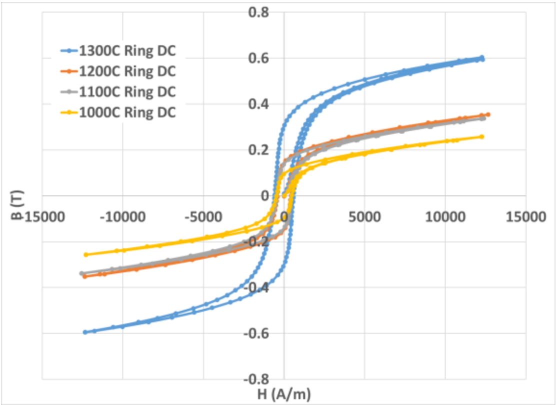


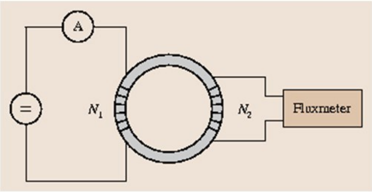


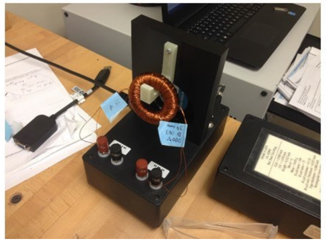


Iron Sample Encapsulation

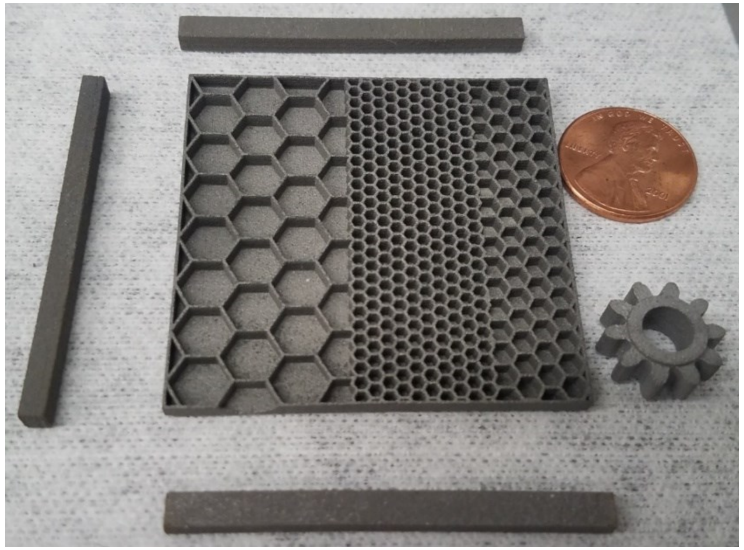
Winding B (flux density) and H (applied field) Coils







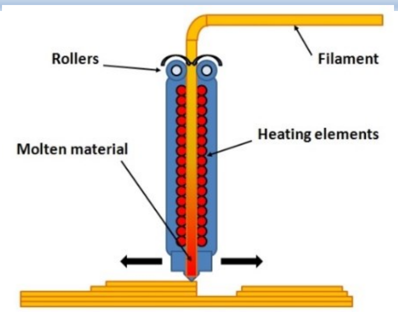
Magnetic Testing Setup



AM is versatile approach to make Soft Magnetic Composite (SMC) materials

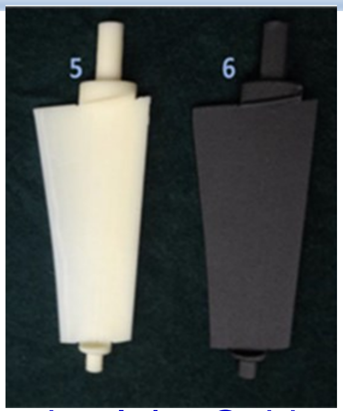
Additive Manufacturing of Polymers and PMCs for Multifunctional Applications

Industrial scale FDM systems (Stratasys)



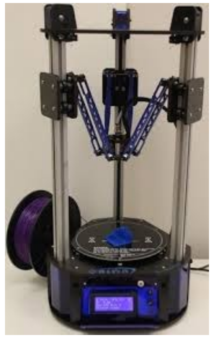
Process Schematic

Engine Panel Access Door

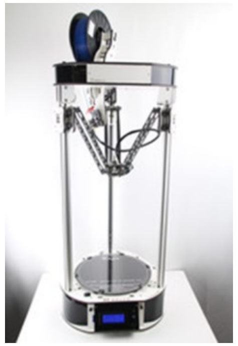


Engine Inlet Guide Vanes from ABS and Ultem 1000

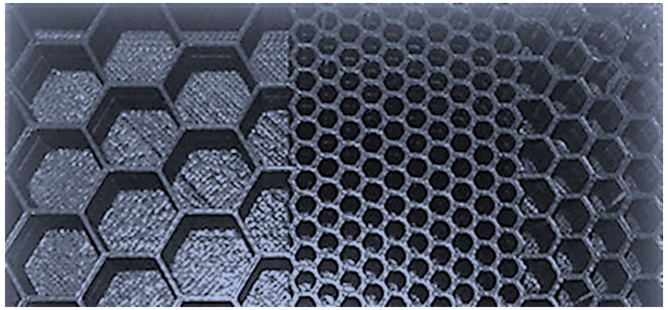
MakerBot Replicator 2X



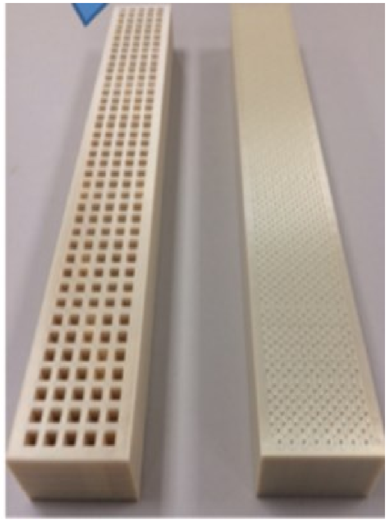
Orion Delta 3D Printer



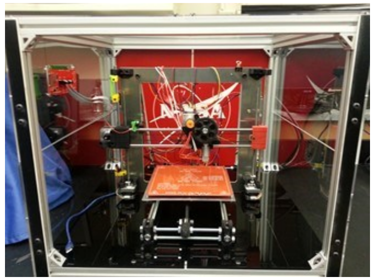
Rostock 3D Printer



Variable Geometry Panels for Acoustic Treatment

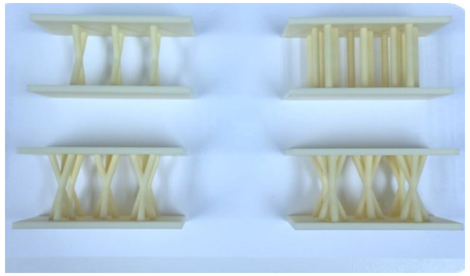


Acoustic Liners



“RepRap is humanity's first general-purpose self-replicating manufacturing machine”.
www.reprap.org

Turbine Blade Shape Demo



Lightweight Structures

3-D Printing of Cellulose Containing Filaments
(Preforms for Conversion to Carbon and Ceramics)

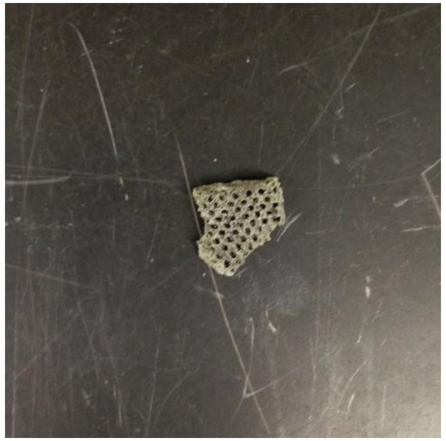
A 3-D printed disc is made using a commercially available wood filament. Printed part is pyrolyzed to serve as a preform.

Processing Steps

3-D printed porous disc → Dip-coated in Polycarbosilane (PCS) solution → Heat treated at 400°C in argon → Dip-coated in PCS solution → Exposed to 1000°C in argon → Pyrolyzed at 1450°C in vacuum

→ 35% wt. Retention →

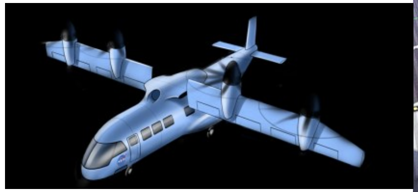
→ 50% wt. Retention →



Additive Manufacturing of Multi-materials

Sustainable Transportation & Infrastructure

Urban Air Mobility



NASA 15-PAX tiltwing aircraft

Uber Elevate

Greased Lightning GL-10

X-57: Distributed Propulsion

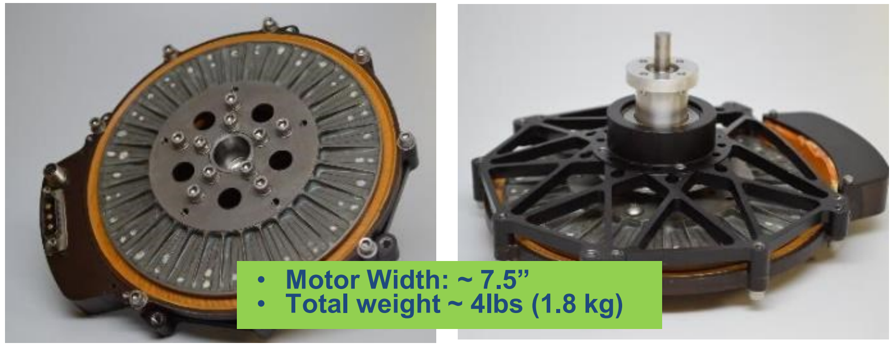
CAMIEM: Compact Additively Manufactured Innovative Electric Motors

Objective: Utilize additive manufacturing (AM) methods to achieve new motor designs that have significantly higher power densities and/or efficiency.

Methods:

- New topologies with compact designs, lightweight structures, innovative cooling, high copper fill, and multi-material systems/components.
- New component designs for the rotors, housing, finned stator cooling ring, direct printed stator, and a wire embed stator.
- Compare new components/new motor against a baseline motor.

CAMIEM Baseline Motor



Already SOA due to compact design, high power density, and halbach array of magnets.

CAMIEM AM Motor Design

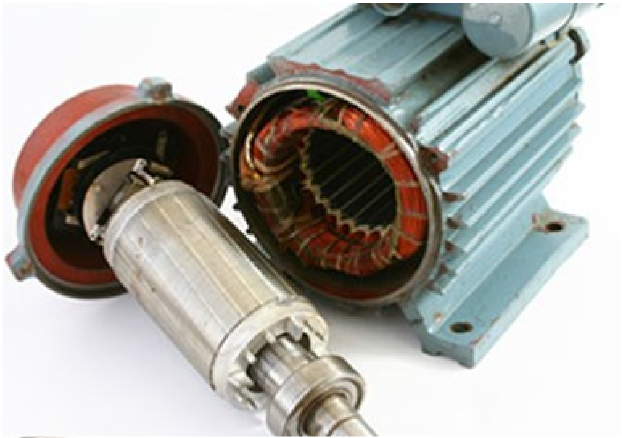
Projecting a 2x increase in Power Density to 10 kW/kg.

GRC Dynamometer

For development of advanced materials, structures, and components.

Compact Additively Manufactured Innovative Electric Motor (CAMIEM) team members:
NASA (GRC, LaRC, ARC), LaunchPoint Technologies and the University of Texas - El Paso

Conventional Manufacturing of Electric Motors



Radial Flux Motor

Axial Flux Motor w/PCB Stator

LP Conventional Axial Flux Stator w/Litz Copper Wire Windings

Baseline LaunchPoint Motor: Views, X-Ray Tomography Scans, and Testing

- Motor Width: ~ 7.5”
- Total weight ~ 4lbs(1.8 kg)

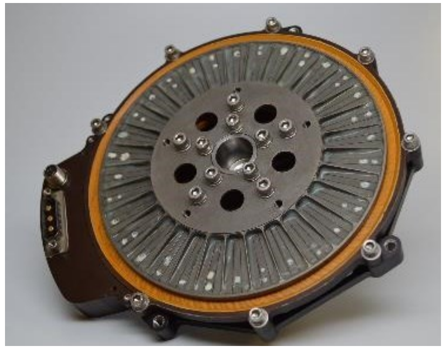
Performance Specs:

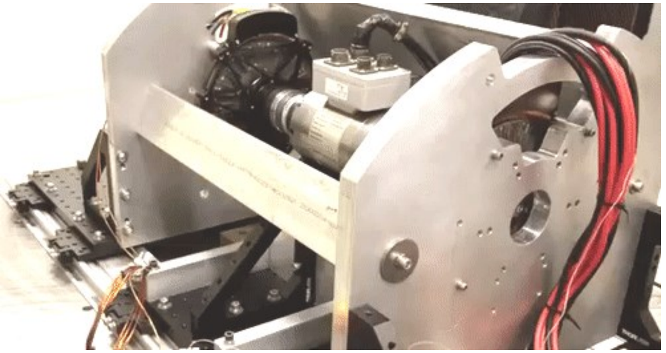
<u>6 kW at 7500 rpm</u>

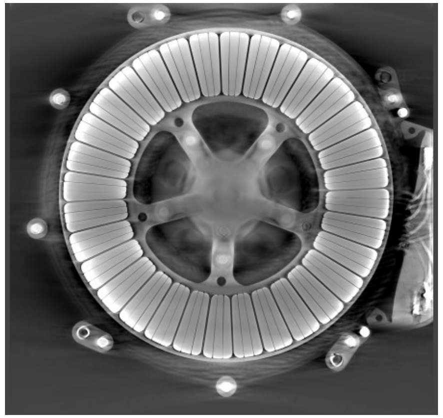
- 95% efficient
- 3.3 kW/kg power density (@ below max. allowable temp.)

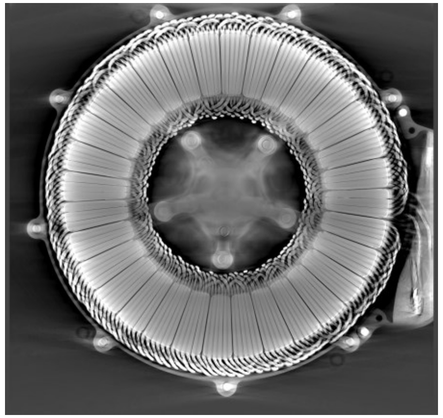
<u>10 kW at 7500 rpm</u>

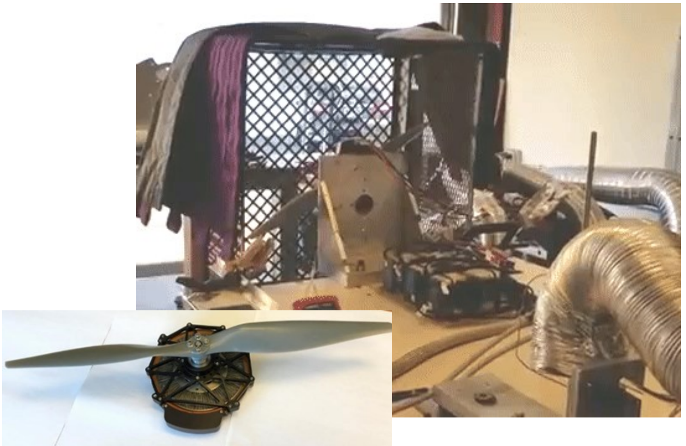
- 5.5 kW/kg power density (@ max. allowable temp.)









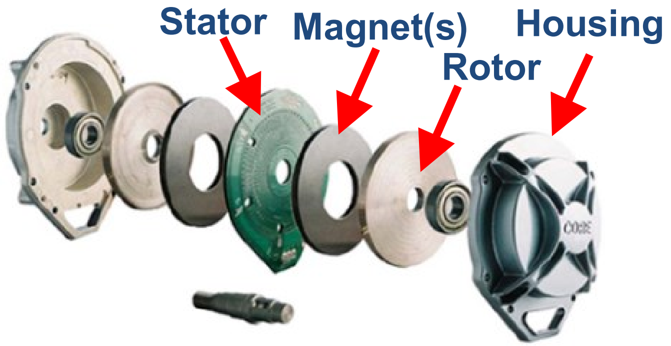


Already SOA due to compact design, high power density, and Halbach array of magnets.

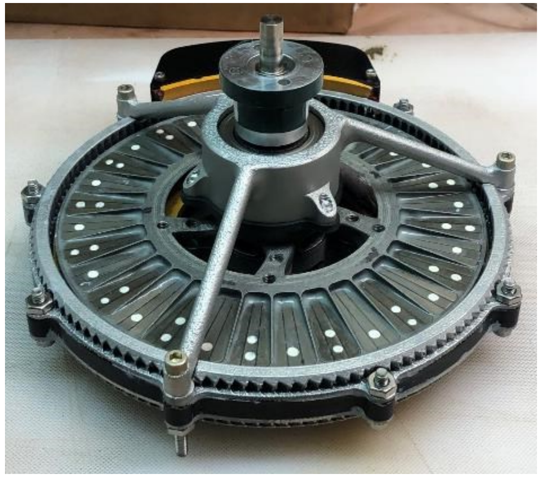
AM and Hybrid Approaches for Electric Motor Components

Electric Motors

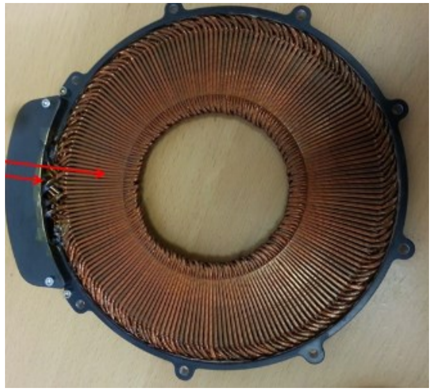
Components of a Commercial Axial Flux Motor



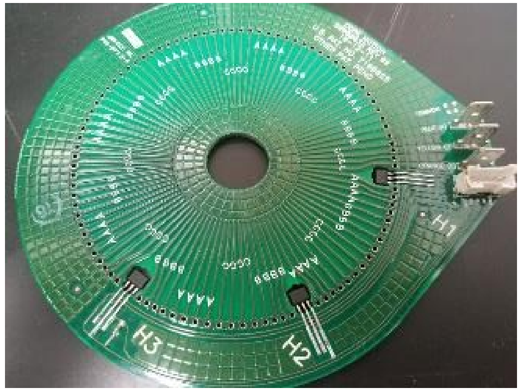
NASA Electric Motor with AM Components



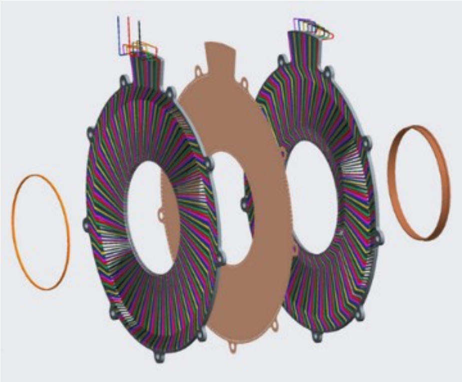
Stators



Litz Wire Coreless Stator



PCB Coreless Stator



Iron Core Stator with Direct Printed Coils

Stator Constituents:

- Conductor: copper, silver.
- Insulators: coatings, dielectrics, epoxy, high temp. polymer.
- Soft magnets (for cores): iron alloys.

Rotors

Additively Manufactured Rotor Plate

Rotor Constituents:

- Permanent magnets.
- High strength structure (typically metallic).

High Conductivity Silver Inks and Pastes for Direct Write Printing

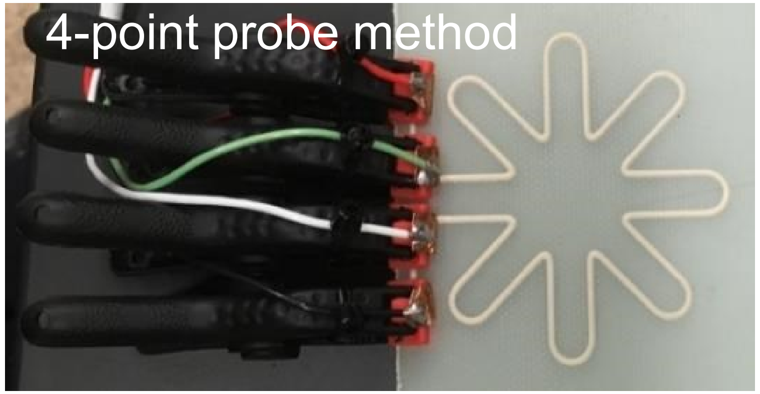
- **Silver has higher conductivity σ (lower resistivity ρ) value compared to copper**
  - **Copper $\rho = 1.68 \times 10^{-8}\ \Omega m$**
  - **Silver $\rho = 1.59 \times 10^{-8}\ \Omega m$**
- **Higher temperature stability**
  - **Copper oxide formation**
- **Variety of industrial applications**
  - **Photovoltaic industry**

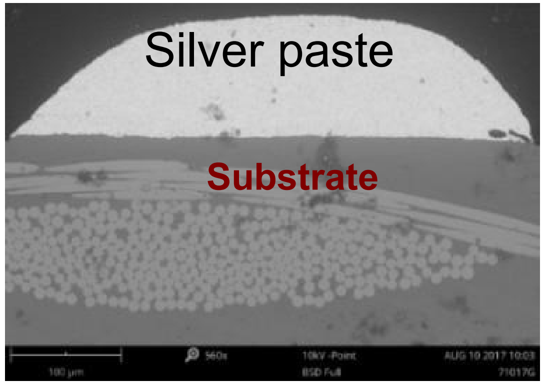
Silver Ink/Pastes Investigated
Applied Nanotech Ag-PM100
DuPont Silver CB028
DuPont Silver CB100
EMS Silver CI-1031-7
Heraeus CL20-11127
Kapton Silver KA801

➢ **Investigate thermal stability of inks/pastes**

Silver Paste Selection and Printing Optimization

nScrypt 3Dn-300

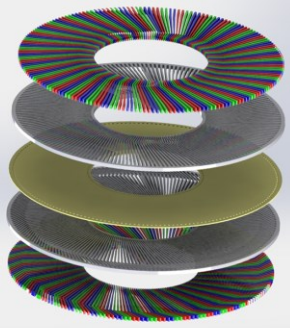


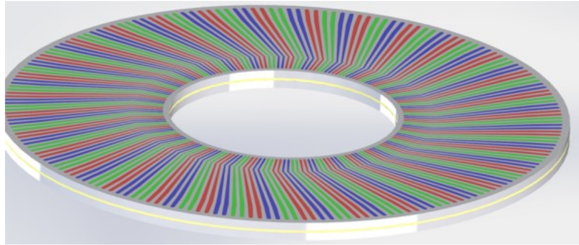


PASTE			
Paste Composition	Conductivity [Ωm]^-1	Max Temp (*C)	Vendor Resistivity
CL-11190(Heraeus)	4.86×10^7	300	N/A
CB028 (DuPont)	3.54×10^7	175	7 – 10 (mΩ/sq/mil)
CL20-1127(Heraeus)	2.78×10^7	300	N/A
CB100 (DuPont)	1.91×10^7	175	>7.5 x 10^{-8} Ωm
Ag-PM100 (Applied Nanotech)	1.10×10^7	300	>5 x 10^{-8} Ωm
Kapton (DuPont)	4.74×10^6	225	<5 (mΩ/sq/mil)

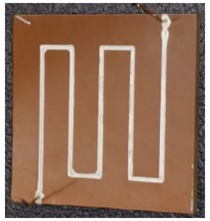
Down-selected the silver paste with highest electrical conductivity and temperature capability.

New Components and Performance Benefits

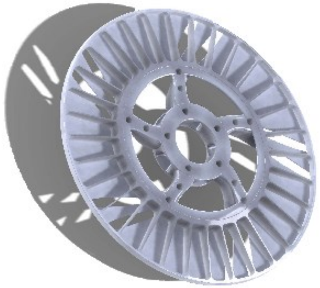


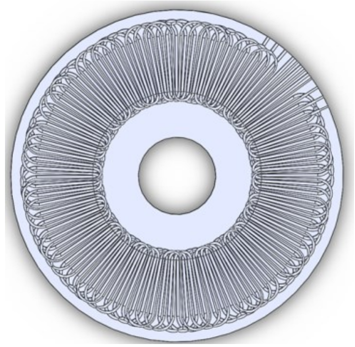


Direct printed stator with higher temperature capability, improved cooling, high conductor packing, and iron for higher torque.

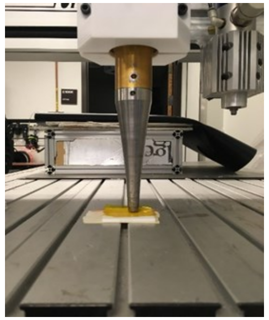


Benefits from structural optimization, mass reduction, and innovative cooling from housing, rotors, and stator ring components.





Automated windings through copper wire embedding for benefits in time and labor.



Comparison for Baseline and CAMIEM Concepts A and B

Baseline and predicted CAMIEM motor performance metrics

- These predictions are for CAMIEM motors with all of the final components designs for the structural parts (rotors, housing, finned cooling ring, and shaft) and concept A and B stators.

Baseline

	Baseline Motor	CAMIEM Concept A	CAMIEM Concept B
Maximum Power	8325 W	13310 W	16300 W
Maximum Torque	10.6 N*m	16.9 N*m	20.8 N*m
Mass	2.04 kg	2.50 kg	2.32 kg
Specific Power	4.0 kW/kg	5.3 kW/kg	7.0 kW/kg

The baseline and predicted CAMIEM motor performance metrics predict an increase in maximum power (x1.96), maximum torque (x1.96), and power density (x1.75).

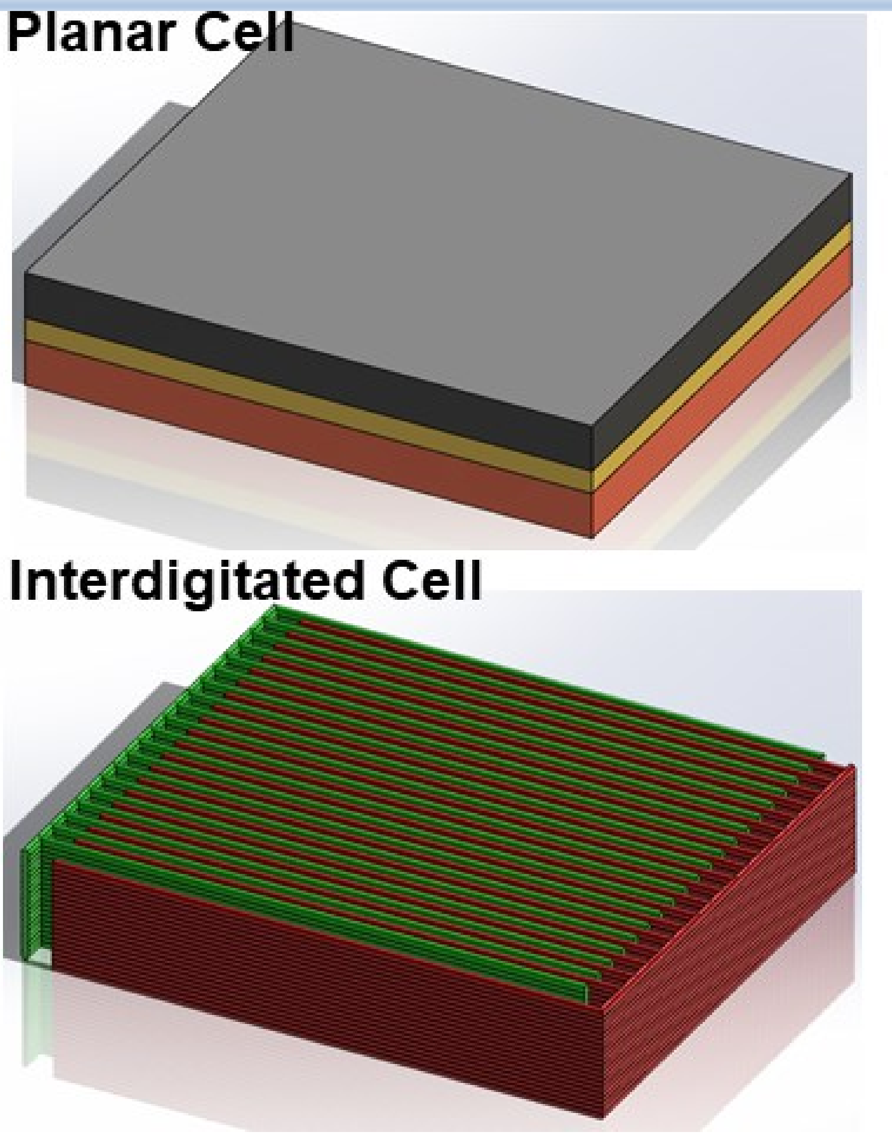
Additive Manufacturing of High-Power Density Batteries

Current Situation/Status:

- **Conventional lithium battery electrode materials have relatively slow diffusion speeds of lithium ions, resulting in low rate and power density of batteries.**
- **Fabrication of thicker electrodes is a common method for enhancing the energy density and areal capacitance. However, this increases overall mass and can also significantly raise electrode electrical impedance, resulting in reductions of power density and rate capability.**
- **Compared to planar battery cells, battery electrodes with 3-dimensional porous structures can yield greater electrochemical reaction surface area, shorter ionic diffusion pathways and lower resistance during the ion-transport process, which can significantly enhance the power and energy density of batteries while efficiently using the limited space in a compact battery.**

Challenges

- **Validated electrochemical models of 3D printed batteries don't currently exist. Without these models, the benefits / limitations of these battery architectures in electrified aircraft applications will be unknown. OEMs need these models for next-generation batteries.**
- **During cycling of solid-state batteries, >80% electrode volumetric expansion and contraction can cause cracking and delamination at the interface.**
- **Advanced manufacturing methods are needed to achieve the complex electrode structures with high surface areas and tailored porosity.**
- **Most current collector materials can't withstand ceramic electrodes sintering temperatures.**

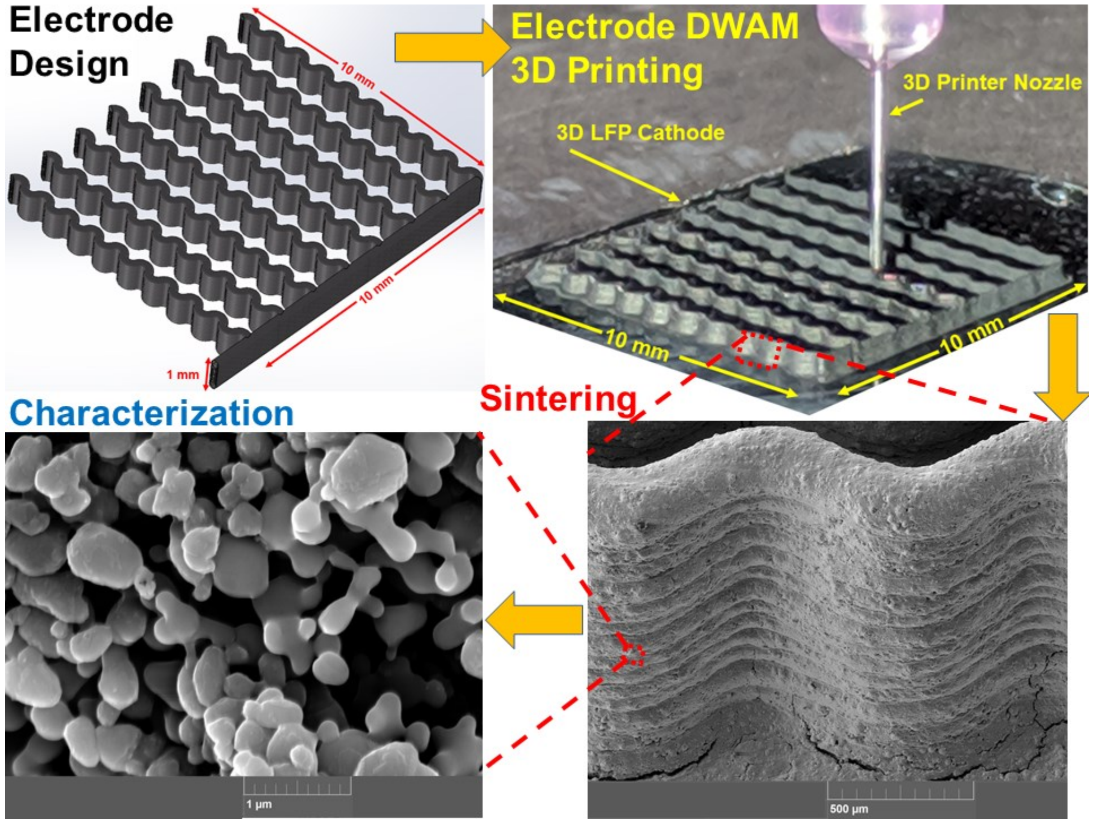


1D and 3D Batteries

Additive Manufacturing of High-Power Density Batteries

Focus Areas / Solution Paths

- Electrochemical modeling-guided design of three-dimensional (3D) battery electrodes structures is being leveraged to additively manufacture (AM) batteries with increased electrolyte/electrode interfacial area to maximize battery power and energy densities, volumetric capacity, and mechanical stability.
- COMSOL electrochemical model will be used to examine various design parameters (such as current collector position, electrode thickness, porosity and conductivity) to guide, inform and optimize the final battery electrodes design.
- Optimization of electrode ink composition, processing conditions, sintering temperature and environment by tape casting and sintering thin film electrodes followed by testing its electrochemical performance in coin cell.
- Addition of Super P carbon black electrically conductive particles which can reduce the electrical impedance of the electrode and enhances the battery power and energy densities and rate capability.
- Fabrication of high surface area/power density 3D interdigitated electrodes and current collectors via 3D direct write additive manufacturing.



Design, 3D printing, sintering and characterization of interdigitated lithium iron phosphate cathode (LFP) with curved lines and layers and engineered nano-porosity.

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Summary and 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.
- Additive Manufacturing of lightweight and multifunctional polymer composites can provide wide ranging properties.
- Multi-material printing approach could provide new opportunities to explore and expand the design envelope.
- AM technologies are potentially game changing by disrupting global supply chains and enabling sustainable development.

Acknowledgements

- Michael C. Halbig, Dr. Craig E. Smith, Dr. Amjad Almansour, and Dr. Jon Salem from NASA GRC and many other colleagues from other NASA centers.
- Dr. Dileep Singh and W. Du from Argonne National Laboratory, Chicago.
- Prof. Surojit Gupta, University of North Dakota and his students.
- Dan Gorican, Dan Scheiman, and other staff members at GRC.
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