Enabling Additive Manufacturing Technologies for Advanced Aero Propulsion Materials & Components

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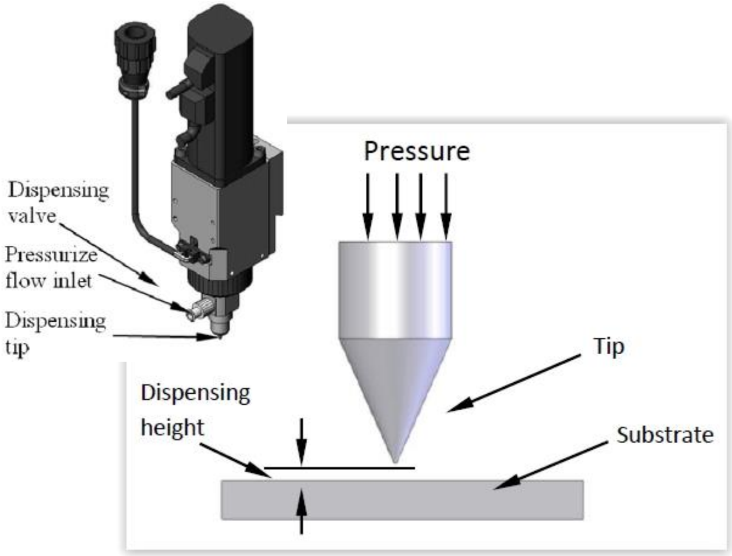
Outline

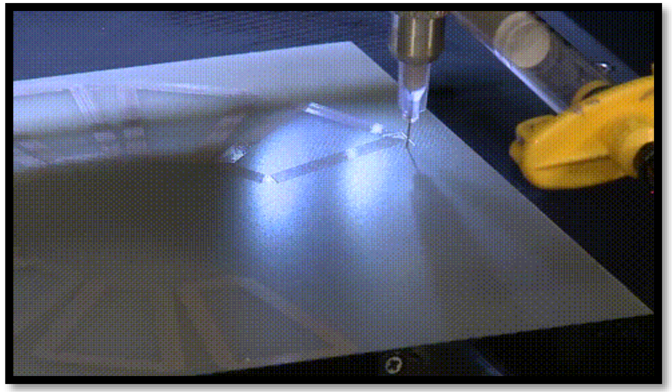
- Background, Applications, and NASA Strategic Thrusts
- AM of CMCs and Polymer Materials for Turbine Engine Applications
  - Laminated Object Manufacturing (OAI) for continuous fiber composites
  - Binder Jet Printing for short fiber composites
  - FDM of polymer-based materials
- AM of Materials and Components for Electric Motors
  - CAMIEM intro: the objectives and approach
  - New component designs for integration into the motor
  - Direct writing of conductors
  - Fabrication and evaluation of a baseline motor
- Summary and next steps

Additive Manufacturing Technologies

Direct Write Printing

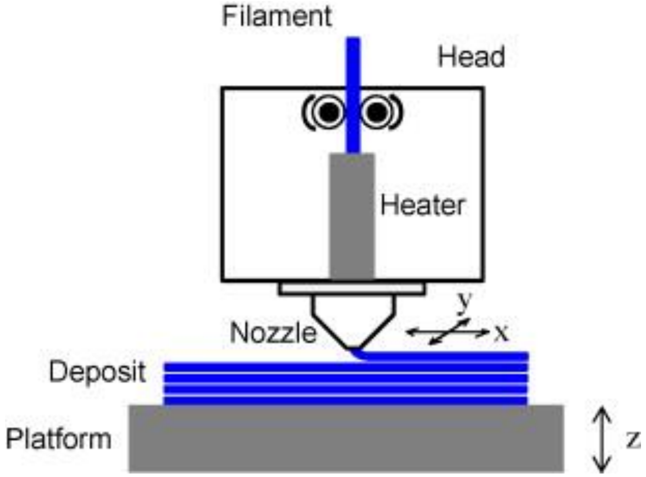
Controlled dispensing of inks, pastes, and slurries.





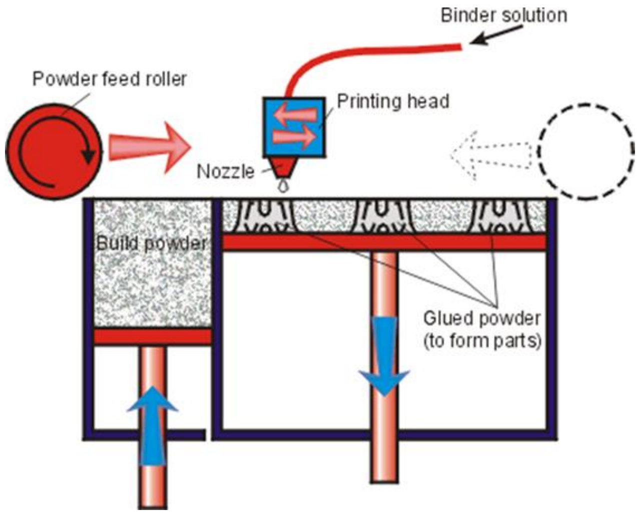
Fused Deposition Modeling

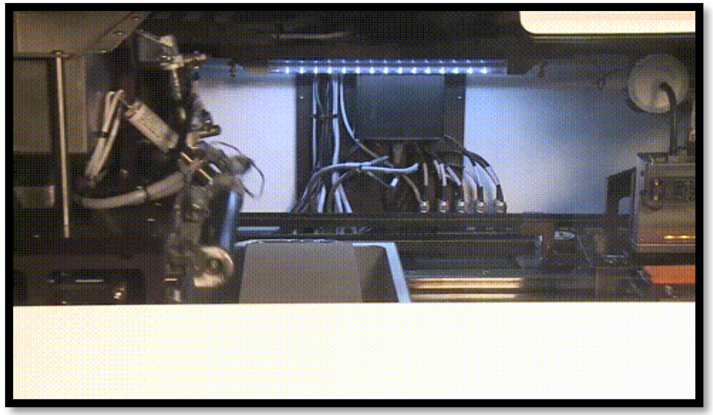
Plastic is heated and supplied through an extrusion nozzle and deposited.



Binder Jetting

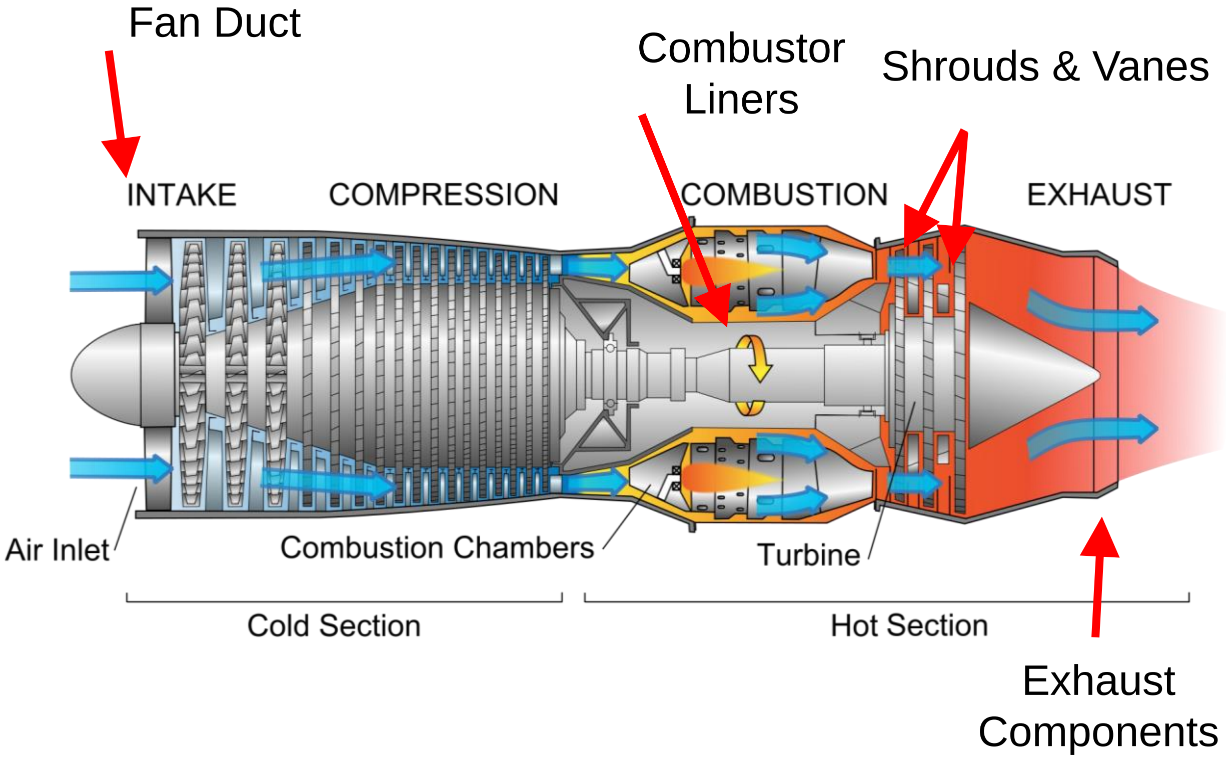
An inkjet-like printing head moves across a bed of powder and deposits a liquid binding material.



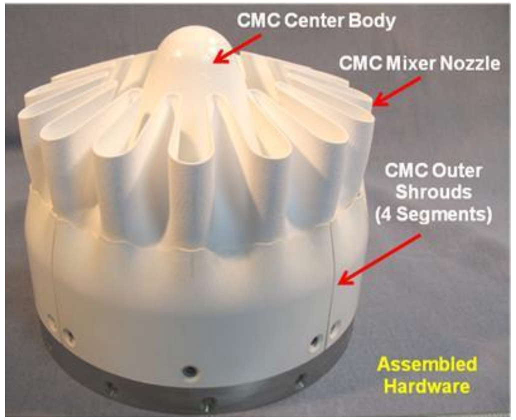


Components for Turbine Engine Applications

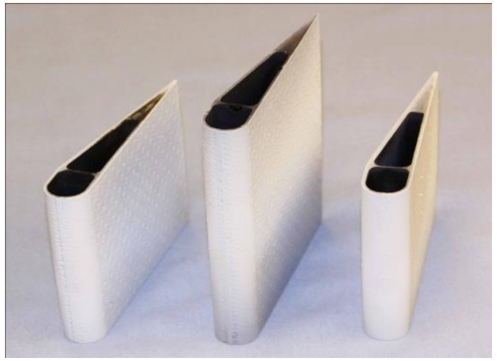
Turbine Engines -
Targeted Components (CMCs and PMCs)



NASA CMC Components from Conventional Fabrication Methods



Oxide/Oxide Mixer Nozzle



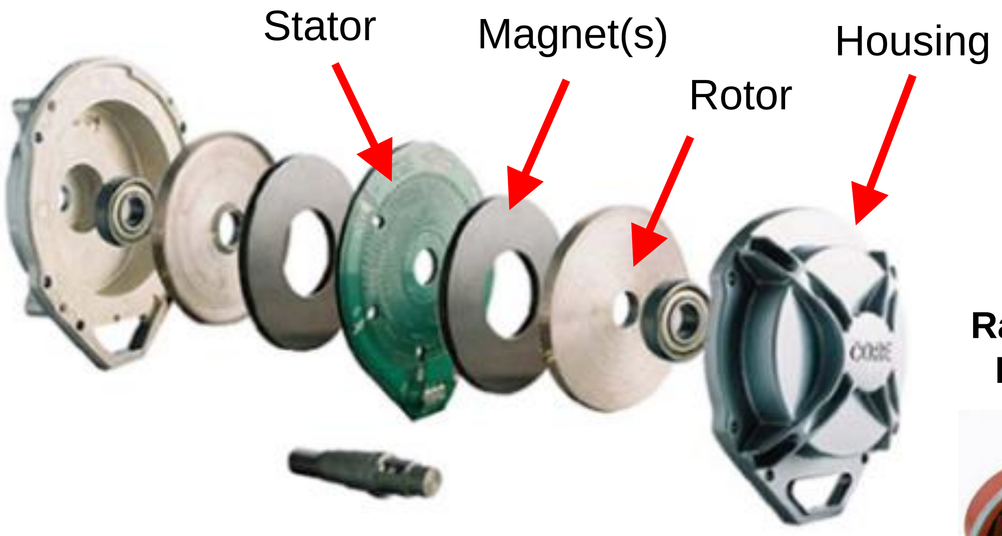
EBC Coated SiC/SiC Vanes

SiC/SiC Combustion Liners: Outer Liner and EBC Coated Inner Liner

Components for Electric Motor Applications

Electric Motors- Targeted Components (structural, functional, and electrical)

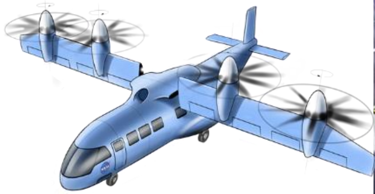
Axial Flux Machine



Radial Flux Machine

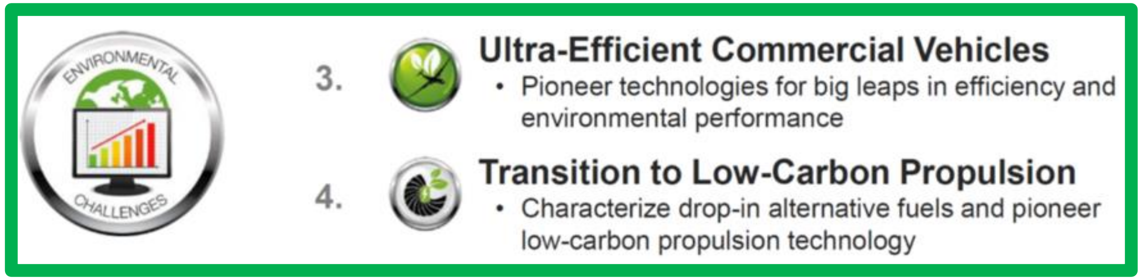
Electrified Aircraft

NASA 15-PAX tiltwing aircraft



Uber Elevate

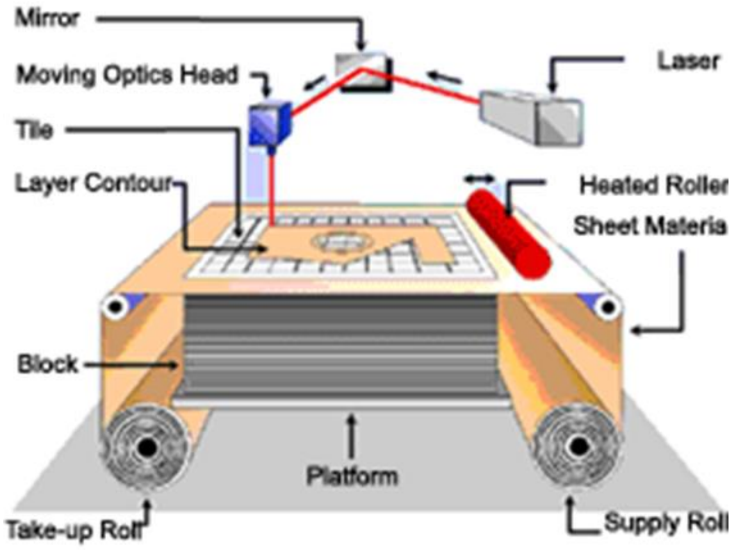
NASA Aeronautics Research Six Strategic Thrusts



3. **Ultra-Efficient Commercial Vehicles**
   - Pioneer technologies for big leaps in efficiency and environmental performance
4. **Transition to Low-Carbon Propulsion**
   - Characterize drop-in alternative fuels and pioneer low-carbon propulsion technology

Achieve and exceed N+2 and N+3 goals for increased efficiencies and reduced emissions.

Laminated Object Manufacturing For Silicon Carbide-Based Composites

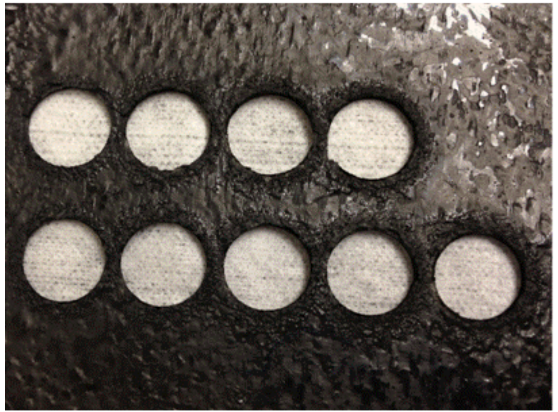


LOM allows for continuous fiber reinforced CMCs.

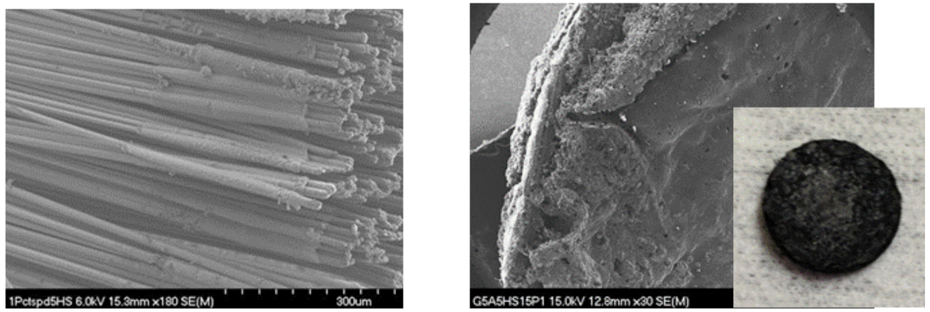
Universal Laser System (Two 60 watt laser heads and a work area of 32”x18”)

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)

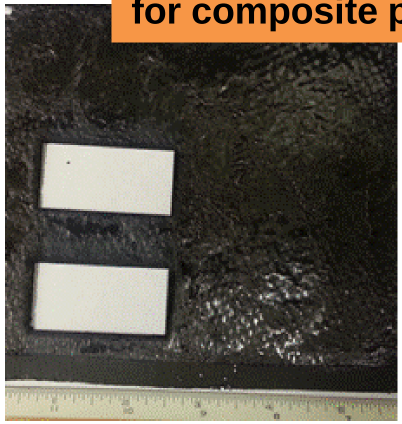


SEM specimens cut with different laser power/speeds



Fabrics and Prepregs cut at different laser powers/speeds

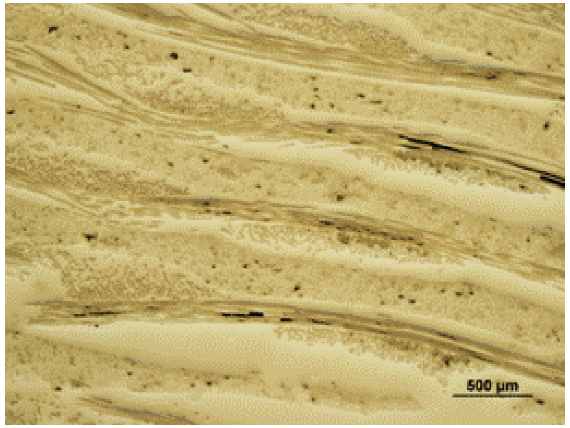
Laser cut prepregs used for composite processing



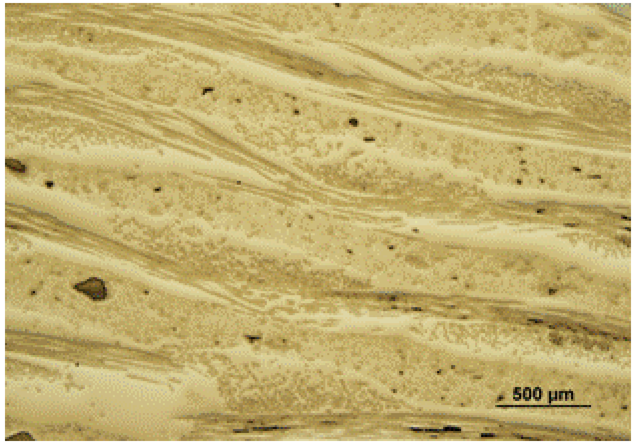
Microstructure of SiC/SiC Composites Fabricated Using Single Step Reaction Forming Process plus Si Infiltration

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

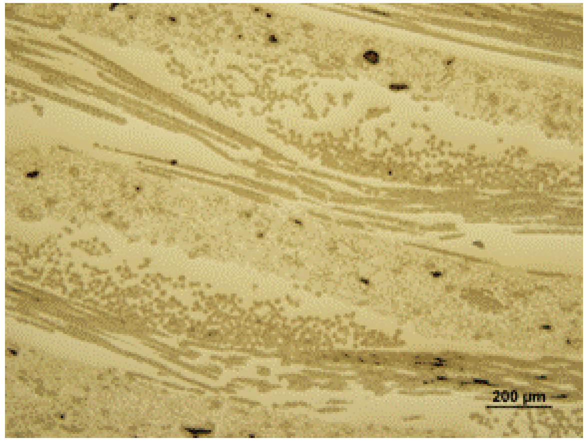
Green Preforms:
8 layers of prepregs; warm pressed @75-85°C



Heat Treatment:
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.



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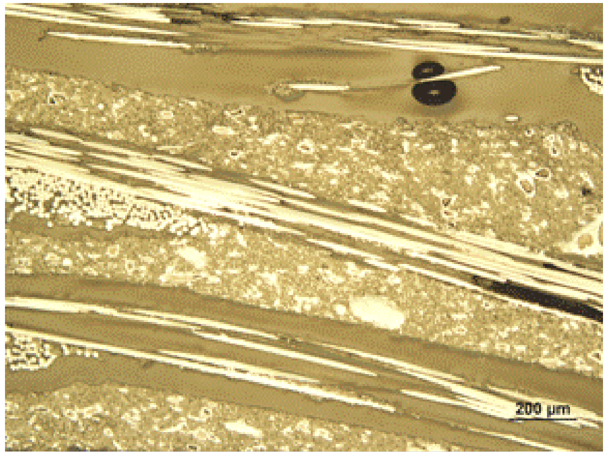

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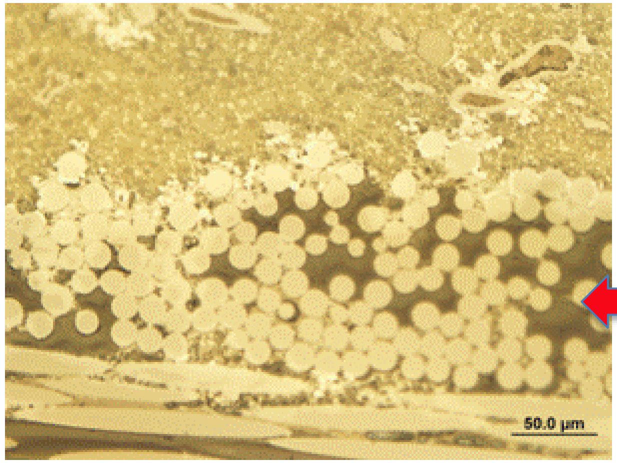
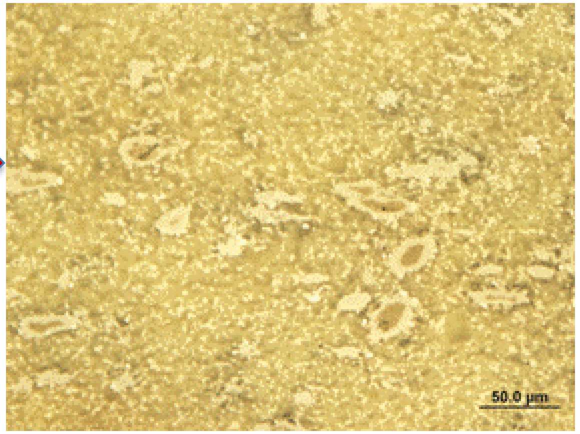


Micrographs show good distribution of SiC and Si phases.

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

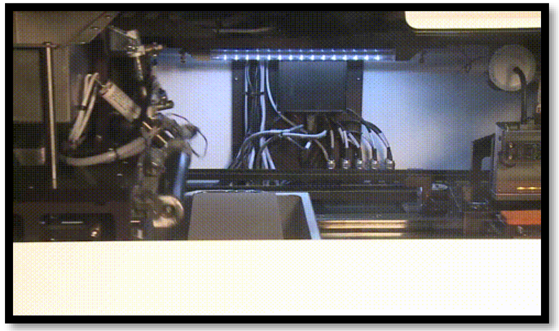


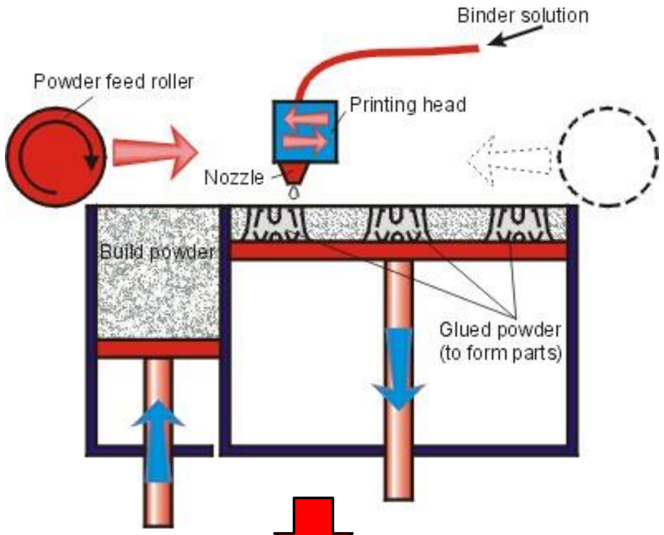
Binder Jet Additive Manufacturing of SiC

ExOne Innovent

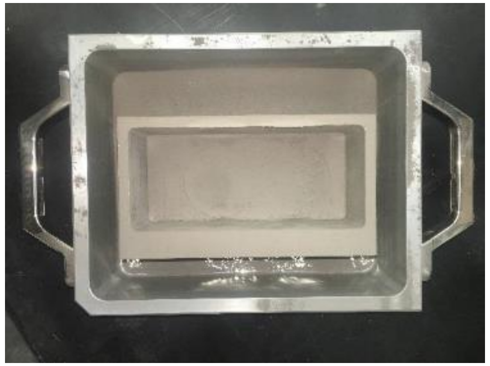
An inkjet printing head moves across a bed of powder and deposits a liquid binding material.

Powder Blending





De-powdering



Green part

Infiltration

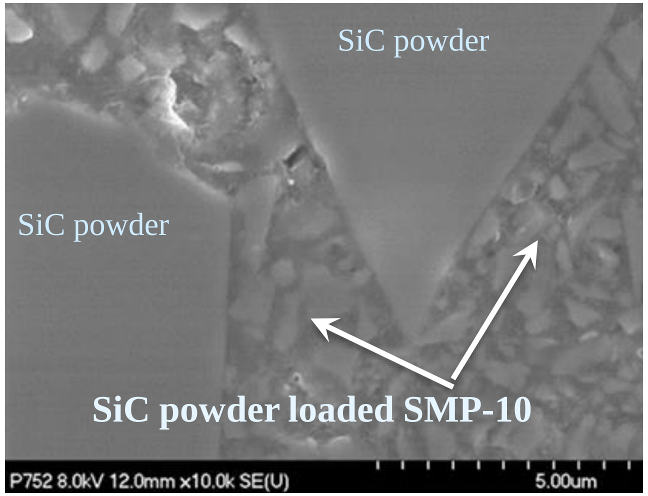
Final Part

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

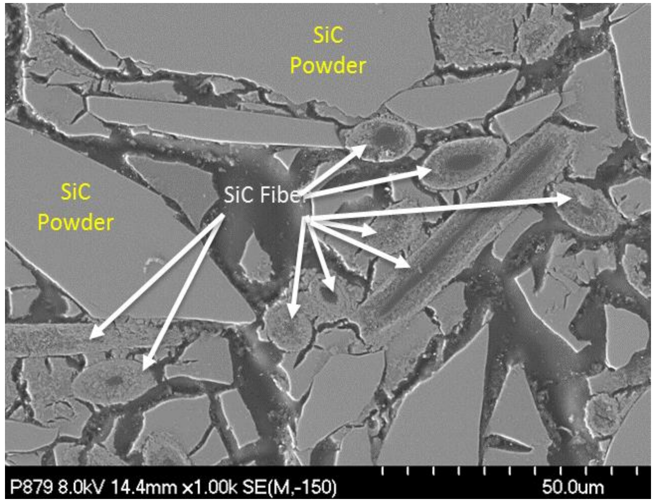
Binder Jetting of SiC Fiber / SiC Matrix Composites

ExOne Innovent

Constituents



~70 µm long and ~7 µm in diameter



Fiber Reinforced Ceramic Matrix Composite

High pressure turbine cooled doublet vane sections.

Approach for Additive Manufacturing of CMCs

Processing

- Constituents
  - SiC powders: Carborex 220, 240, 360, and 600 powders (median grain sizes of 53, 45, 23, and 9 microns respectively). Used solely and in powder blends
  - Infiltrants: SMP-10 (polycarbosilane), SiC powder loaded SMP-10, phenolic (C, Si, SiC powder loaded), pure silicon
  - Fiber reinforcement: Si-TUFF SiC fiber; 7 micron mean diameter x 65-70 micron mean length

Microstructure

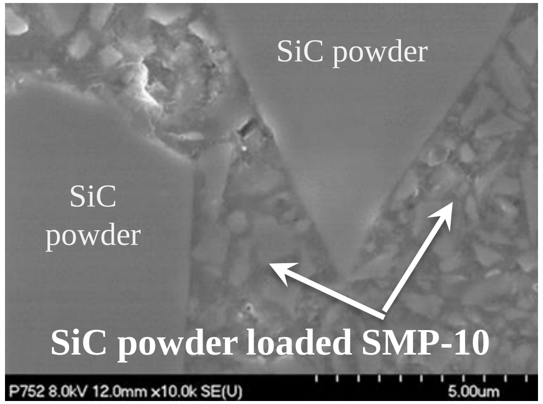
- Optical microscopy
- Scanning electron microscopy

Properties

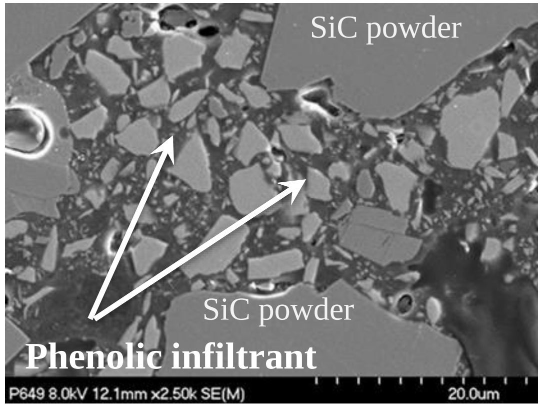
- Material density (as-manufactured and after infiltration steps)
- Mechanical properties: 4-point bend tests

Processing, microstructure, and property correlations provide an iterative process for improving the CMC materials.

Constituents



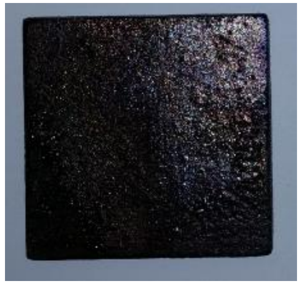
SiC powder loaded SMP-10



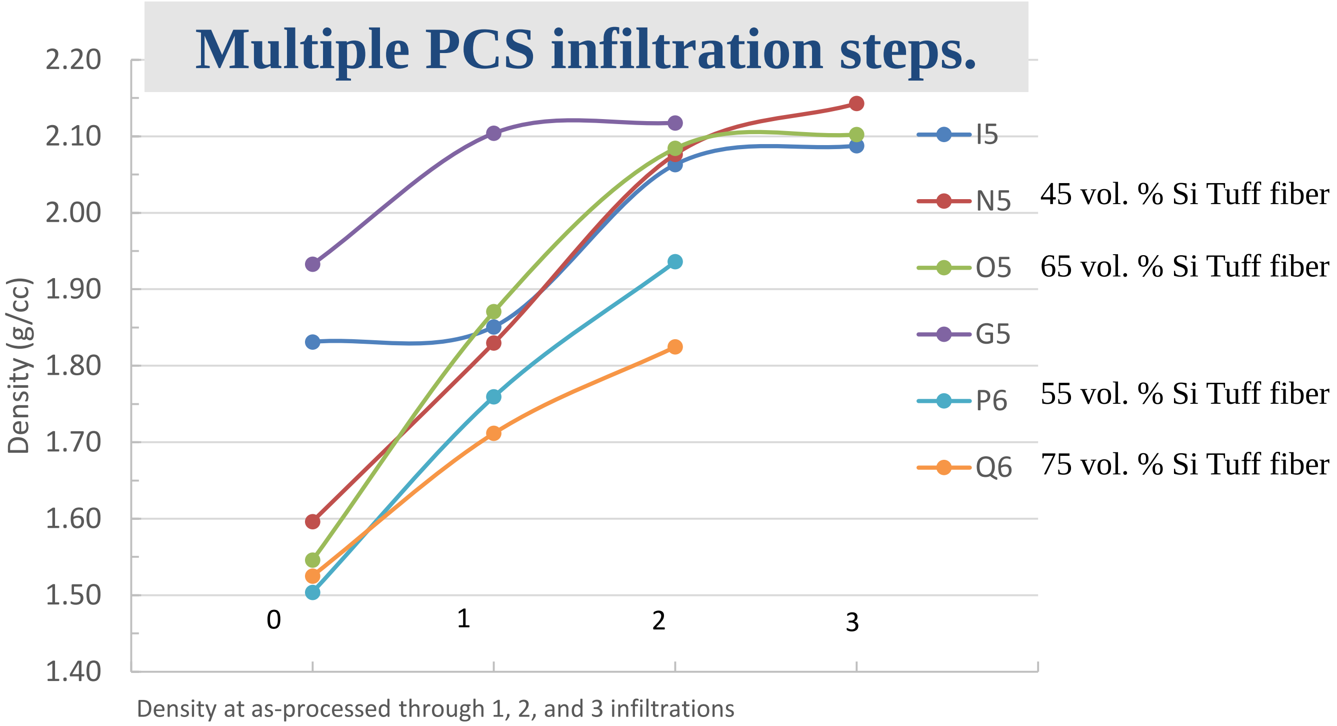
Phenolic infiltrant

Si-TUFF SiC fibers
(Advanced Composite Materials, LLC)

Binder Jetting: Density of SiC Panels



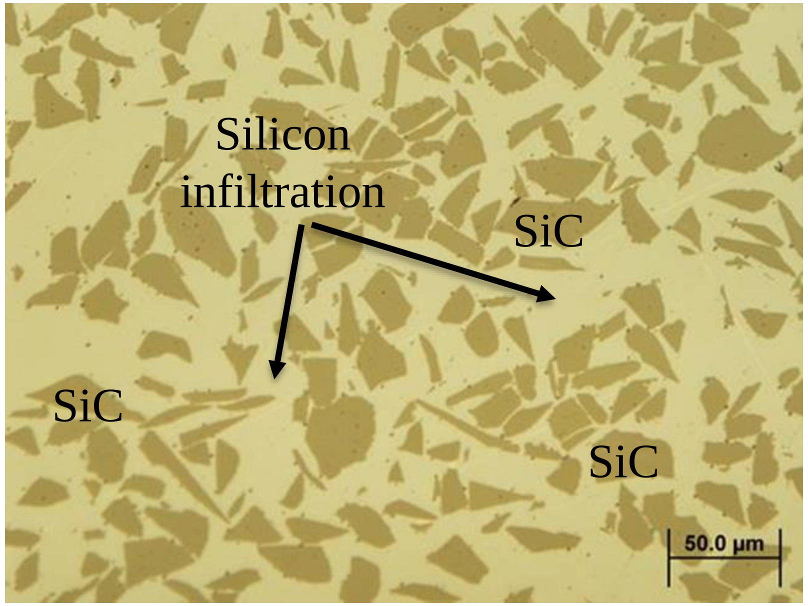
2”x2” CMC coupons



Densities increased by up to 33% from additional PCS infiltration steps and were maintained even at higher SiC fiber loadings of 45, 55, and 65 vol.%.

Polymer approach has a limitation on achievable densities.

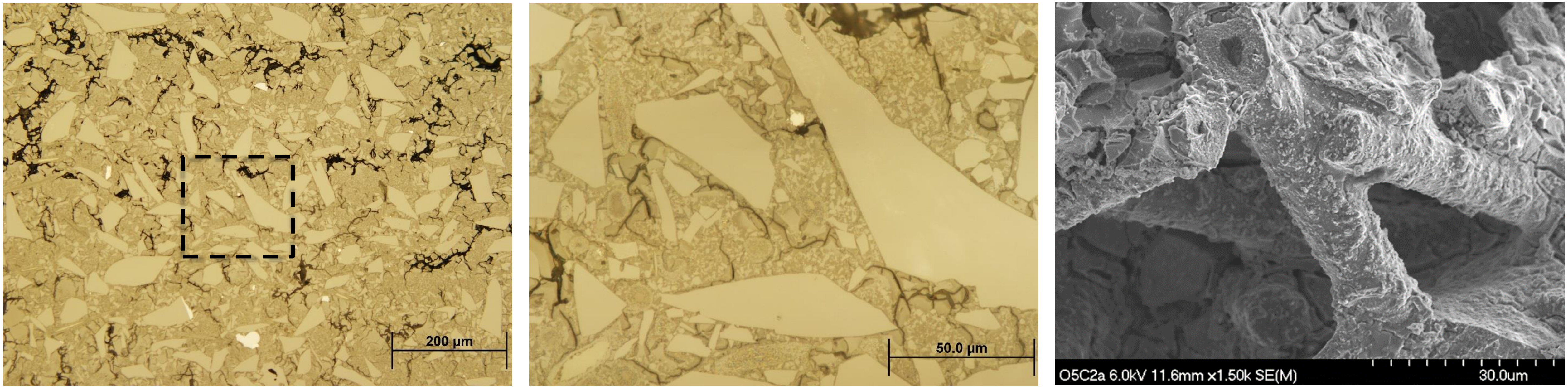
Demonstration of full densification through silicon melt-infiltration.



Melt infiltration methods such, e.g. silicon melt, can achieve near full density.

Binder Jetting: Cross-Section and Fracture Surface from SiC/SiC Sample with 65 vol.% SiC Fiber

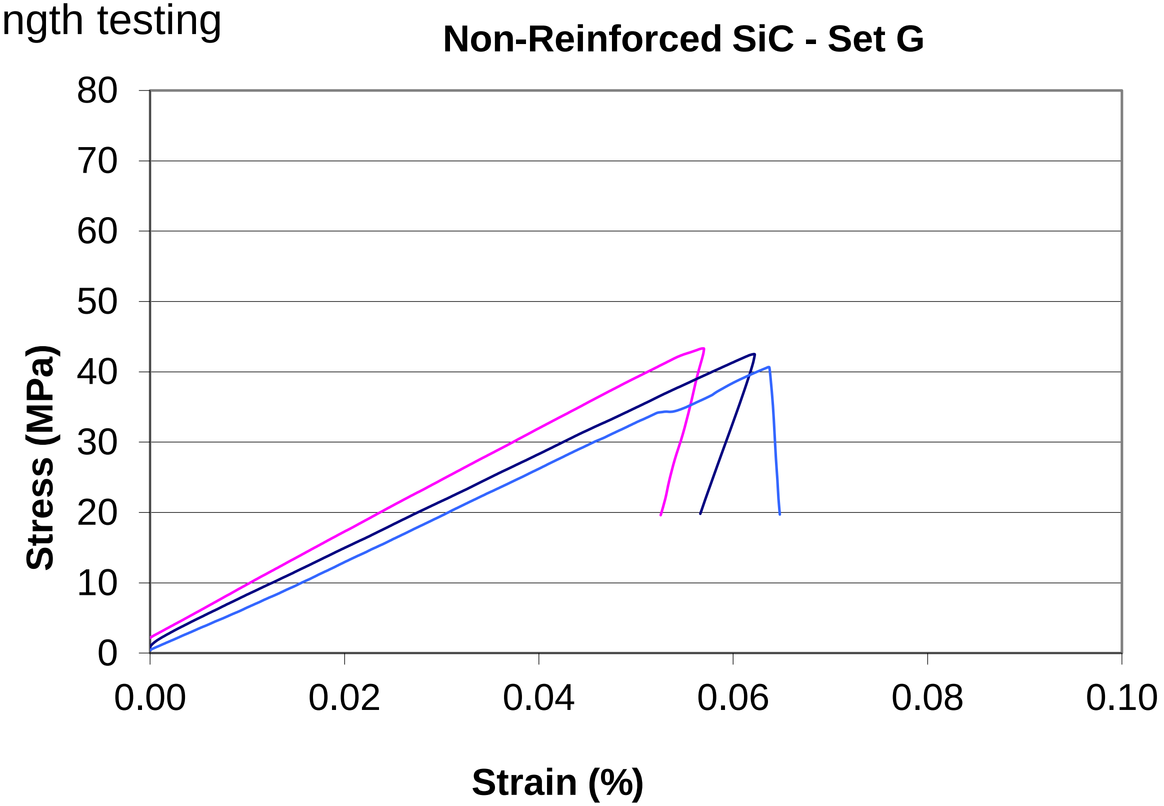
Carborex Powder mix with 65 vol.% Si-Tough SiC fiber, SMP-10 w/800 nano SiC particles vacuum infiltration.

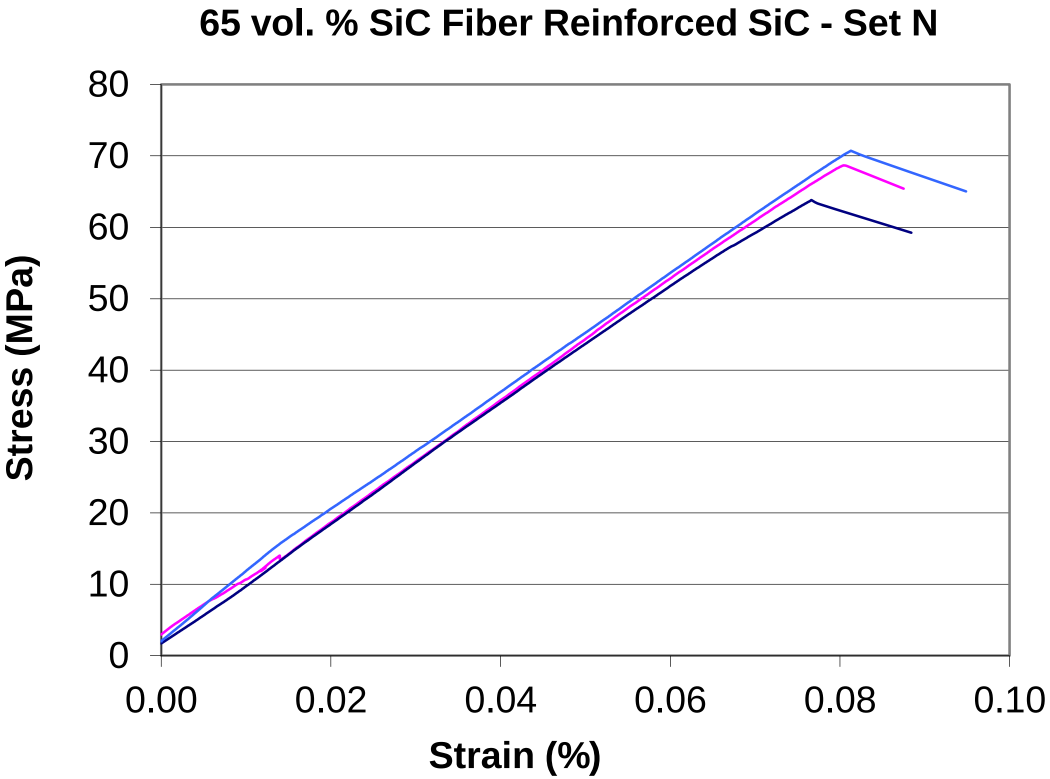


Good densities achieved with high fiber loading.

Binder Jetting: 4 Point Flexure Tests of the Monolithic SiC and CMC materials - at R.T.

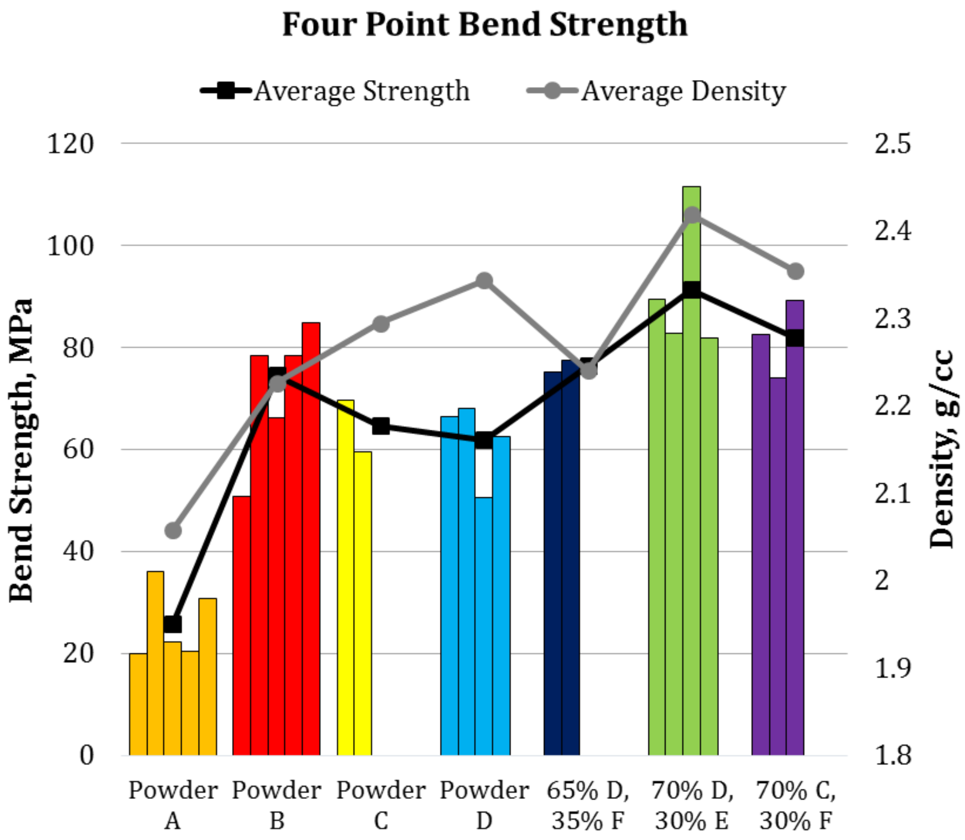
Bend bars for strength testing

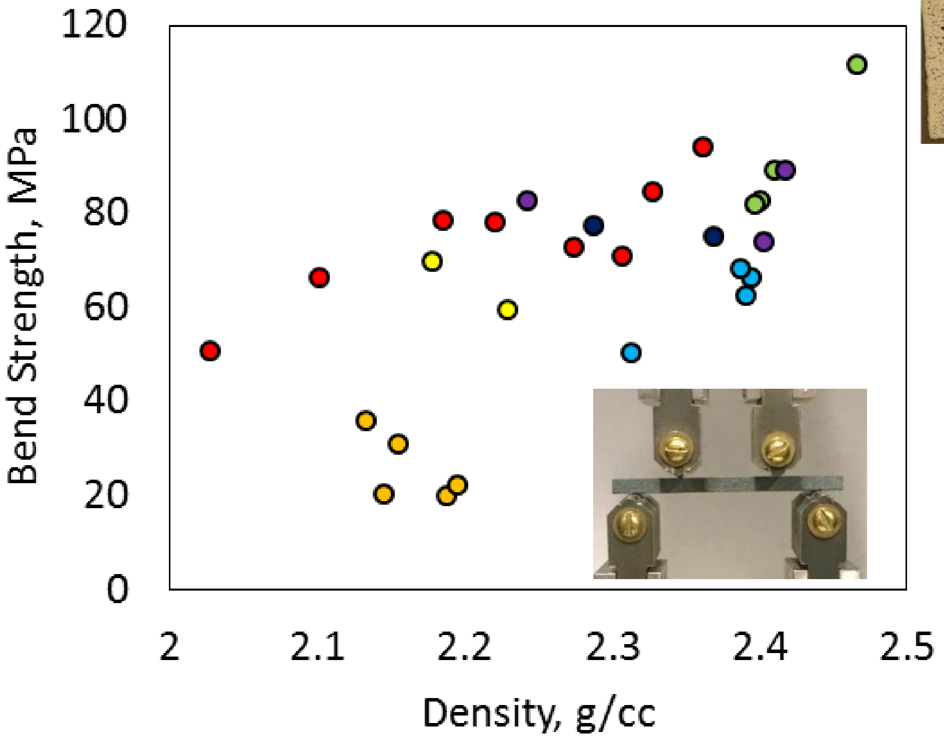


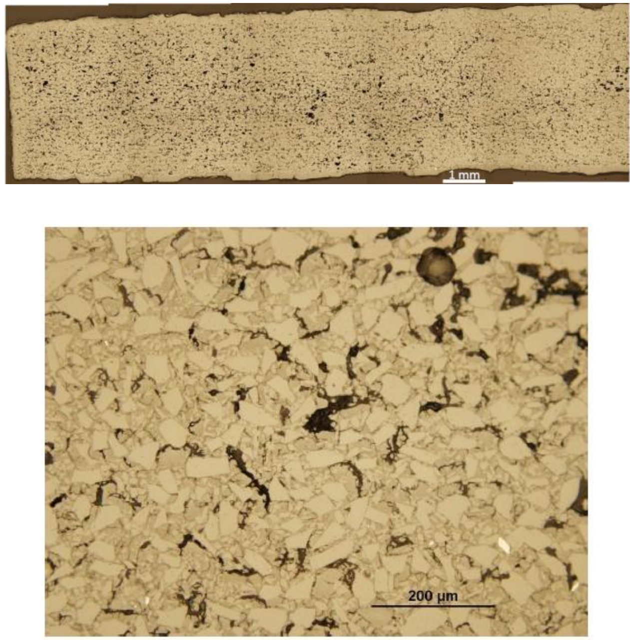


The fiber loaded SiC materials had significantly higher stresses and higher strains to failure.

Recent SiC Binder Jetting Results - Processing and Mechanical Strength Improvements







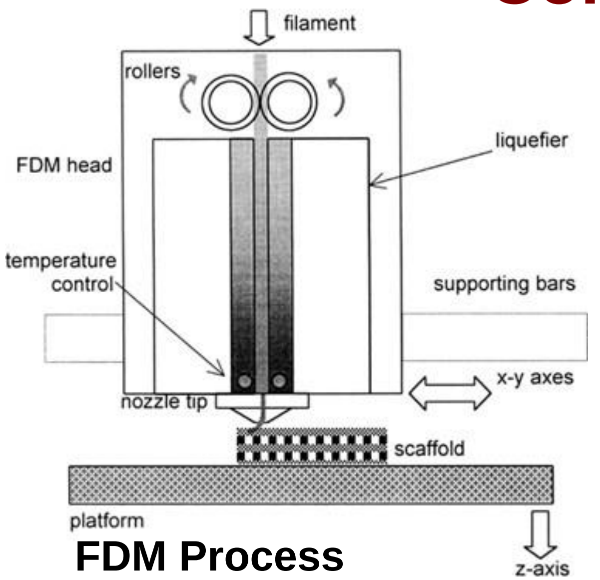
Optical Microscopy of AM SiC after 4 PIP Cycles

- Four point bend tests were conducted on samples after 4 SMP-10 infiltrations
- 50 mm long samples were loaded with a 20 mm loading span and 40 mm support span
- The maximum strength was 111 MPa
- For comparison: Dense CVD SiC and sintered alpha SiC bend strength ranges from 200-450 MPa
- Samples that were tested after 6 infiltrations showed no difference in strength

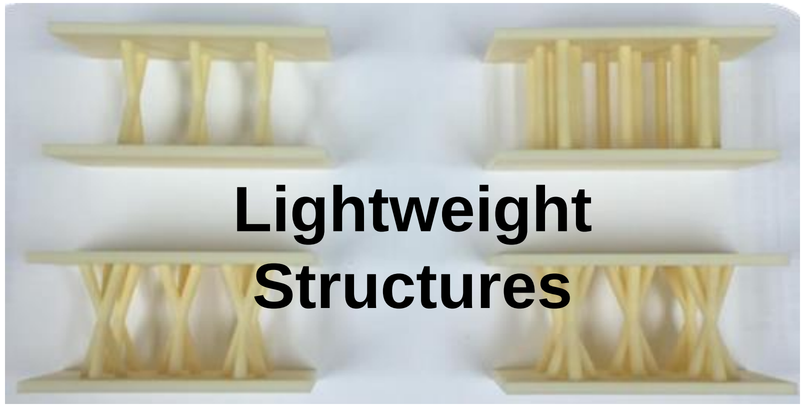
POC:
Craig Smith
NASA GRC

Demonstration of Polymer Components from FDM

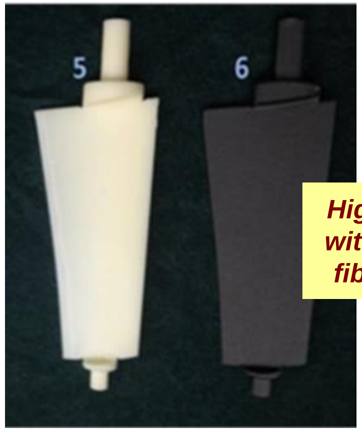
Fortus 400



FDM Process



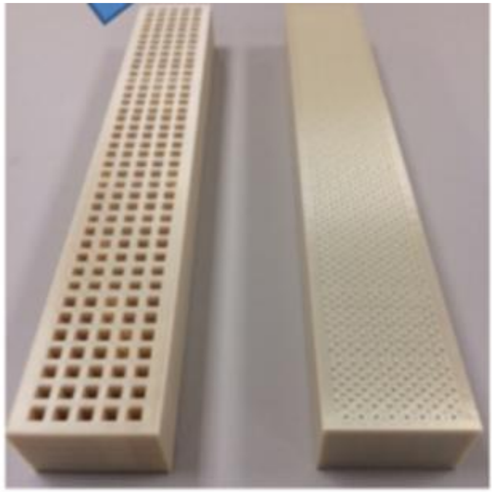
Lightweight Structures



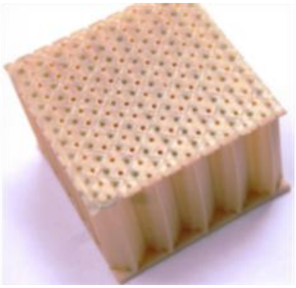
High temp. polymers with chopped carbon fiber reinforcement.

Inlet Guide Vanes from ABS and Ultem 1000

Engine Panel Access Door

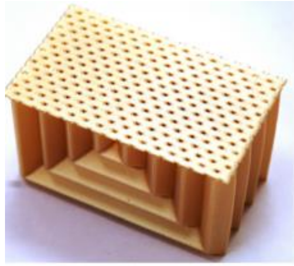


Acoustic Liner Test Articles



Standard Liner

Complex Geometry



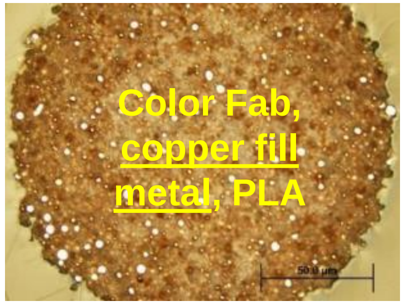
Advanced Liner Design

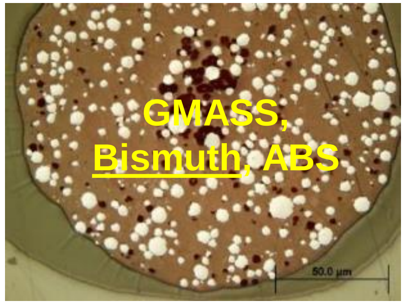
The focus is on unique structures, high temperature capability, and fiber reinforcement.

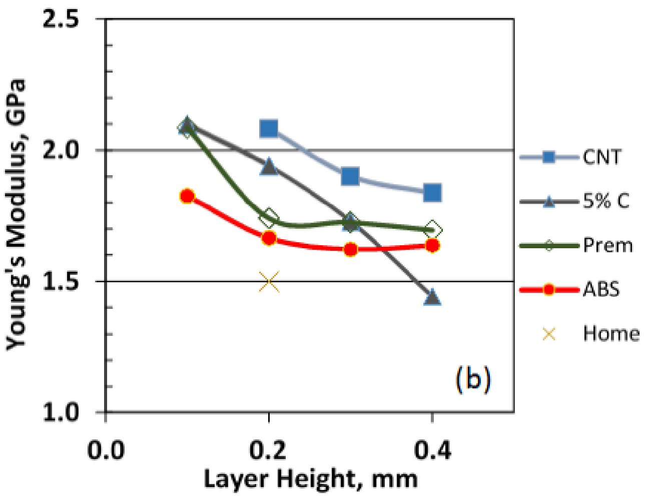
FDM of Composite Filaments for Multi-Functional Applications

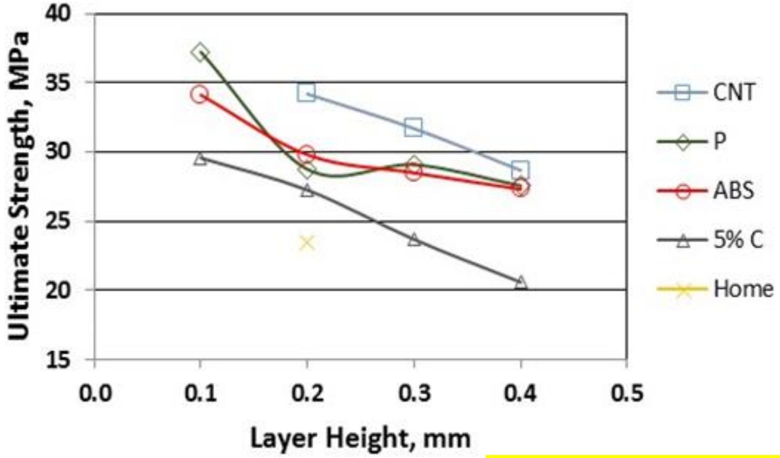
Potential Missions/Benefits:

- **On demand fabrication of as needed functional components in space**
- **Tailored, high strength, lightweight support structures reinforced with CNT**
- **Tailored facesheets for functional properties, i.e. *wear resistance, vibration dampening, radiation shielding, acoustic attenuation, thermal management***

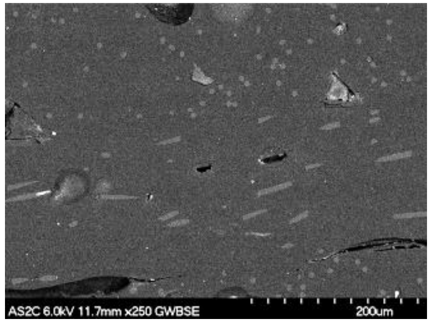




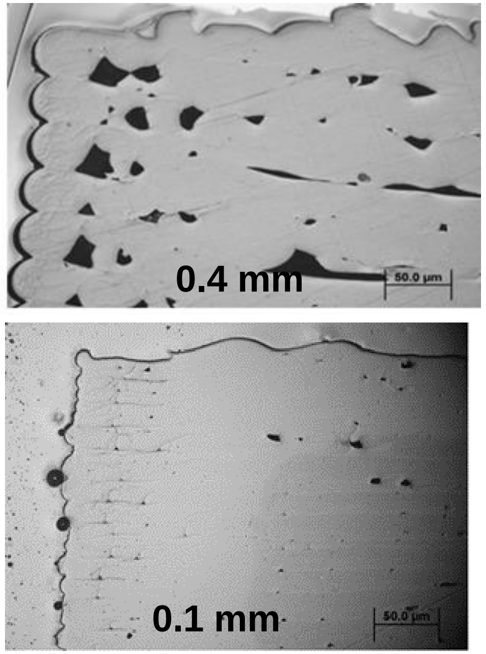




Filaments used: ABS-standard abs, P-premium abs, CNT-w/carbon nanotubes, C-w/chopped carbon, Home-lab extruded filament



C-Fiber Reinforced ABS Filaments

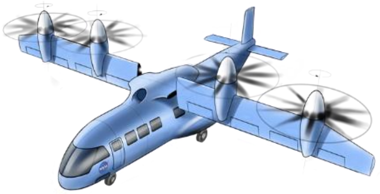


Effect of print layer height

Highest strength and modulus in CNT reinforced coupons versus standard ABS Coupons. Less porosity for lower print heights.

Aircraft Utilizing Electric Motors

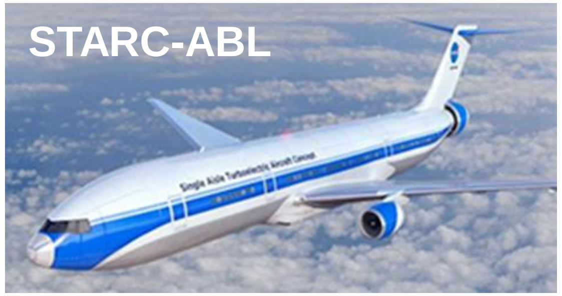
Urban Air Mobility



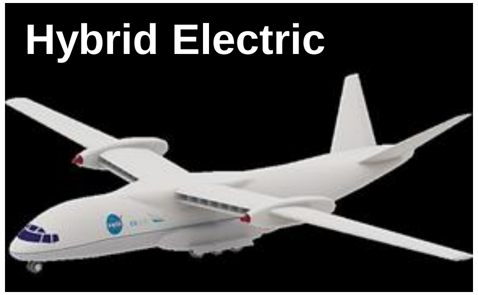
NASA 15-PAX tiltwing aircraft

Uber Elevate

Large Single Isle Transports



STARC-ABL



Hybrid Electric

Greased Lightning GL-10

X-57: Distributed Propulsion

CAMIEM: Compact Additively Manufactured Innovative Electric Motors

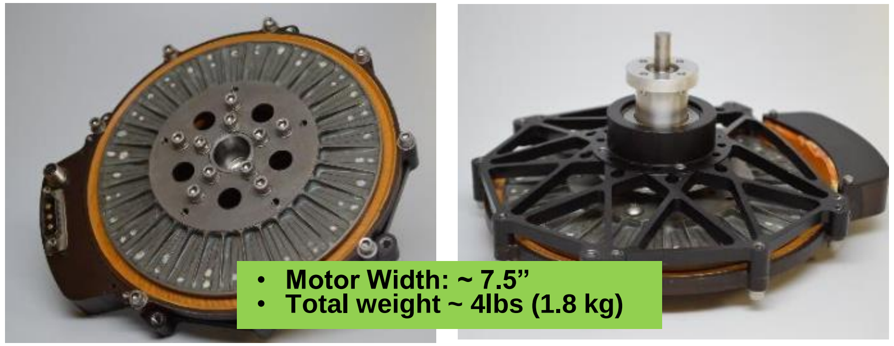
Objective: Utilize additive manufacturing (AM) methods to achieve new motor designs that have significantly higher power densities and/or efficiency.

Mission: efficient, low emission aircraft for Urban Air Mobility.

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



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

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

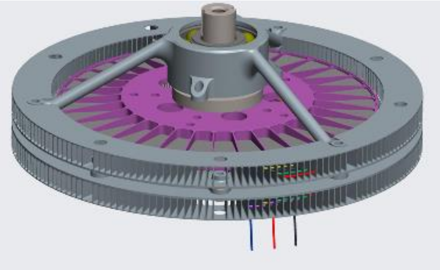
For development of advanced materials, structures, and components.

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

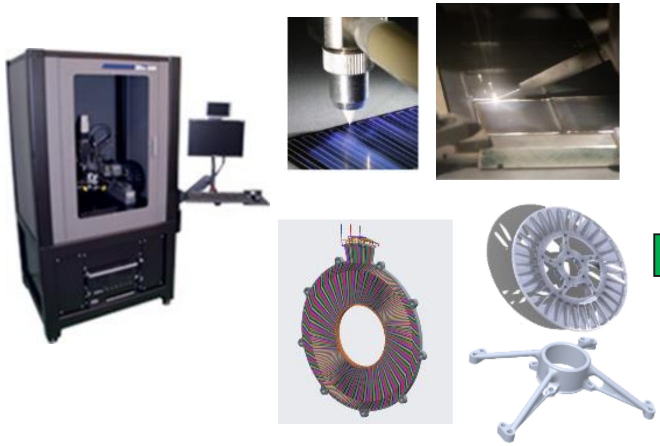
Feasibility Assessment

Baseline Motor

Baseline Motor Testing
for baseline performance

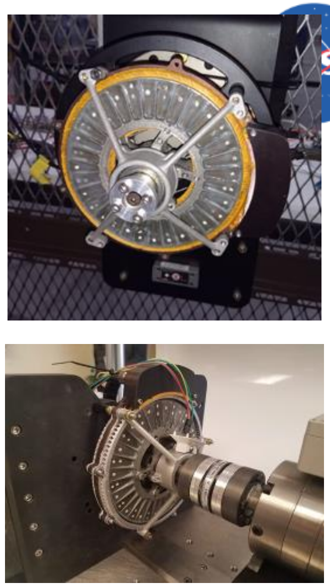


Innovative Motor Design



Additive Manufacturing Processes and Advanced Components

Aircraft Level System Studies



Testing of "New" Motor Configurations to Determine Improved Performance

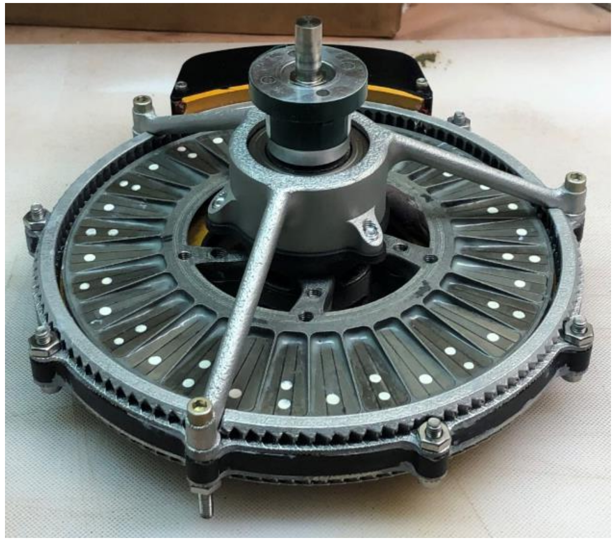
Feasibility Assessed and Benefits Determined

AM and Hybrid Approaches for Electric Motor Components

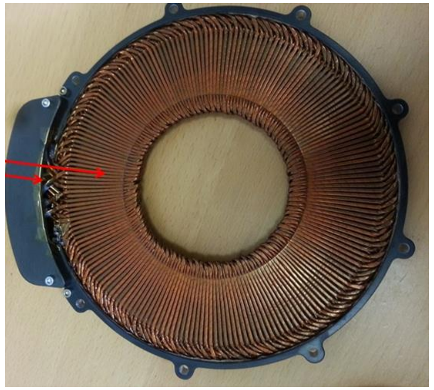
Electric Motors

Components of a Commercial Axial Flux Motor

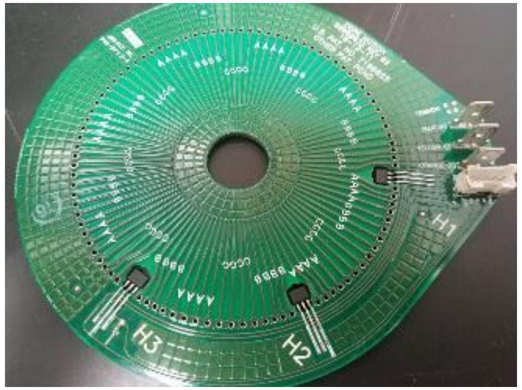
NASA Electric Motor with AM Components



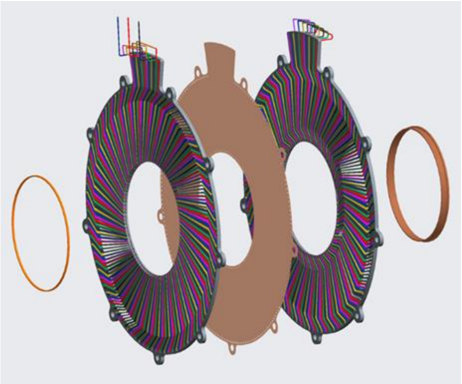
Stators



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

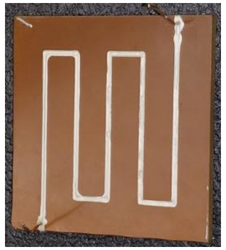
Rotor Constituents:

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

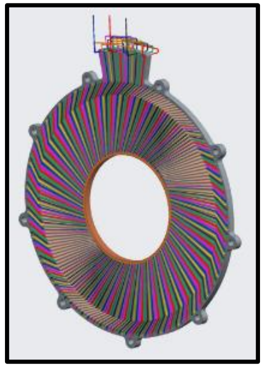
Direct Printed Stators

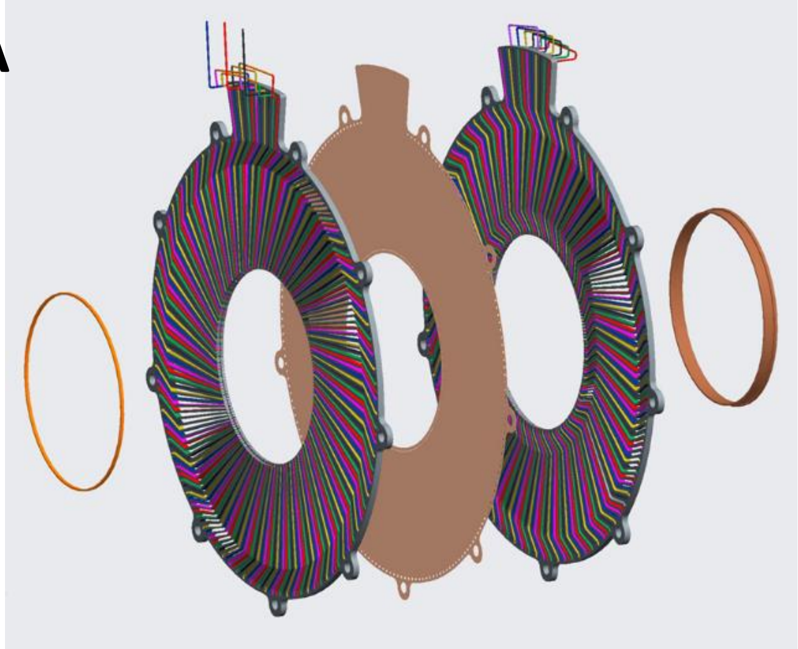
Benefits

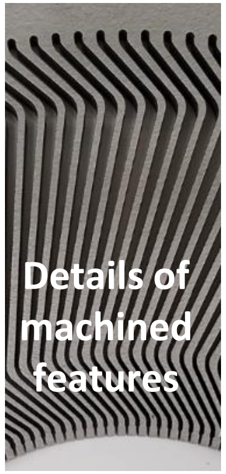
- Higher magnetic flux, torque, and motor constant (K_m).
- Higher temp. capability of >220°C instead of 160°C for baseline stator.
- Direct printed silver coils with high fill.



Concept A





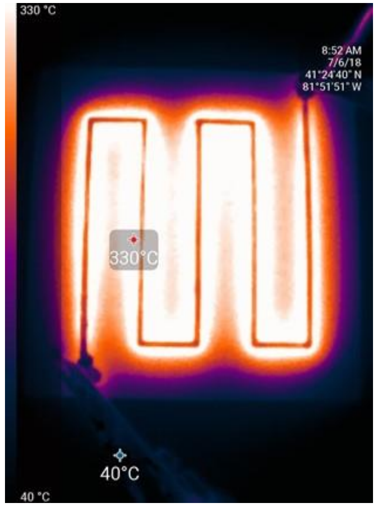


Stator Plate from Cobalt-Iron Alloy

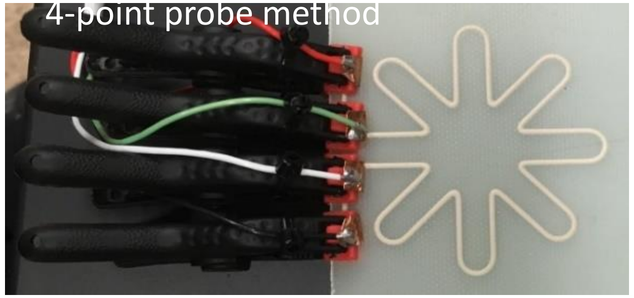
Cirlex Middle Layer

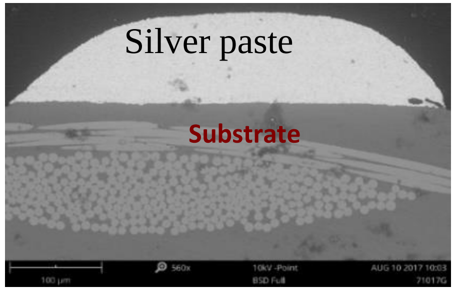
Outer Rings

nScrypt 3Dn-300

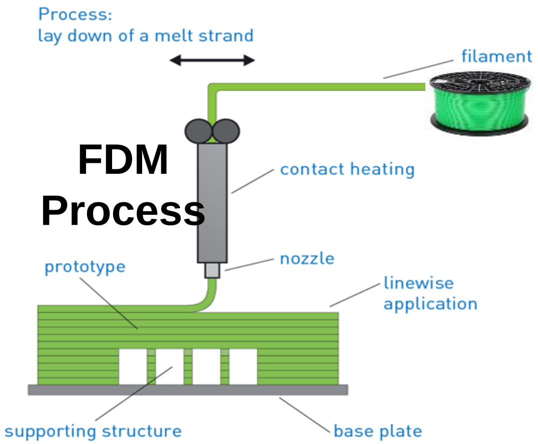


Direct Printed Silver Coils - High Current Test



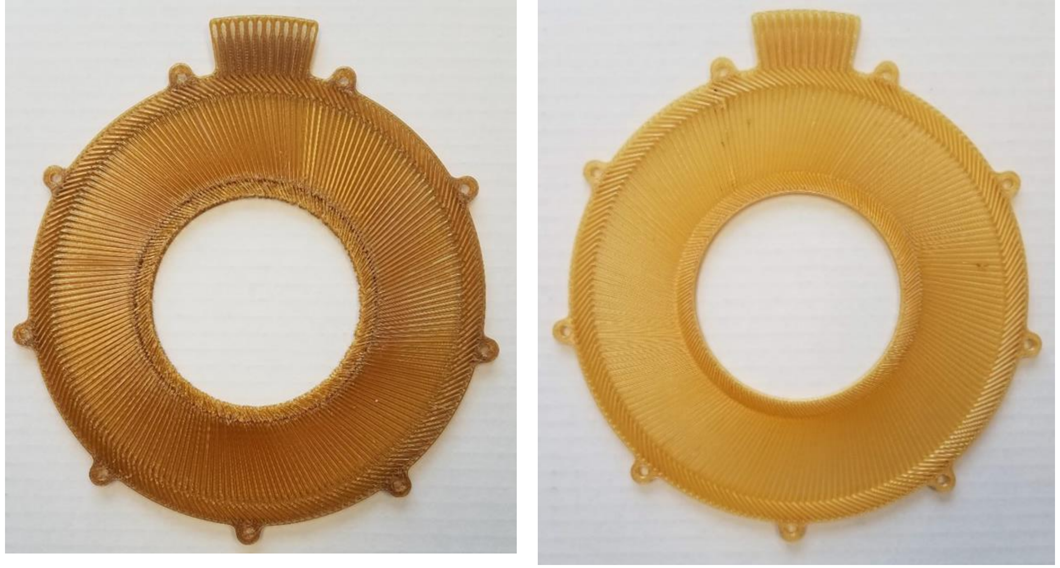


Additively Manufactured Stator Plates



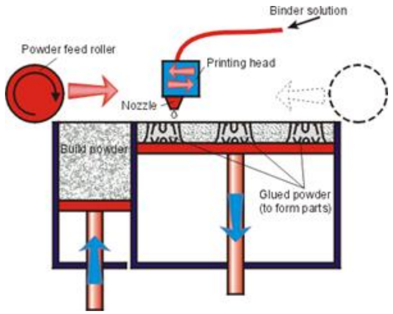
FDM Process

High Temp. Polymer



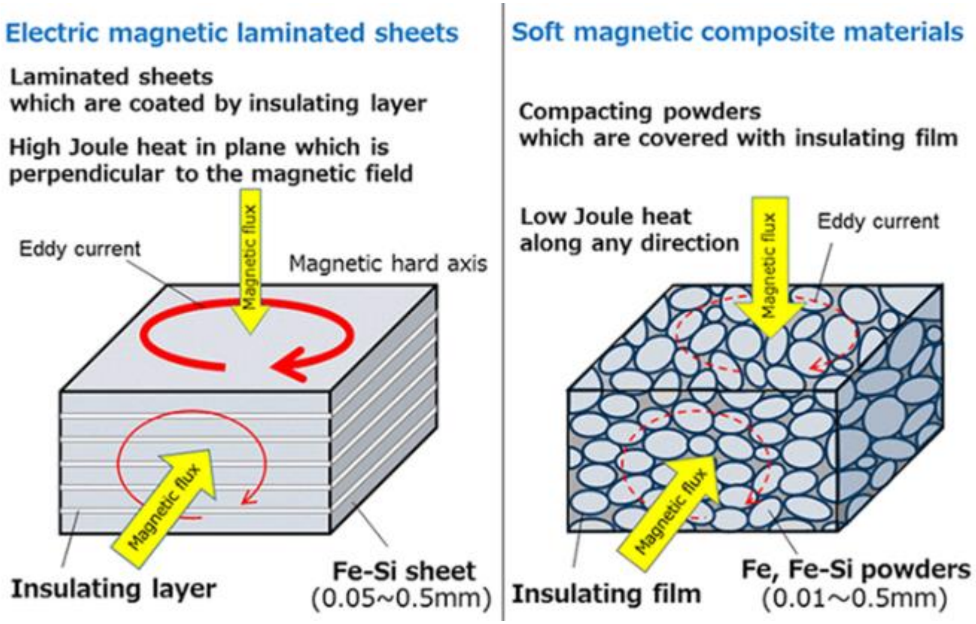
FDM from Extem (Tg of 311°C) (left) and Ultem 1010 (TG of 217°C) (right) FDM filament.

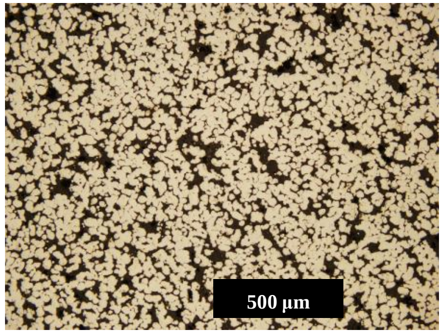
Soft Magnet



Binder Jetting

Stator Plate from Cobalt-Iron Alloy





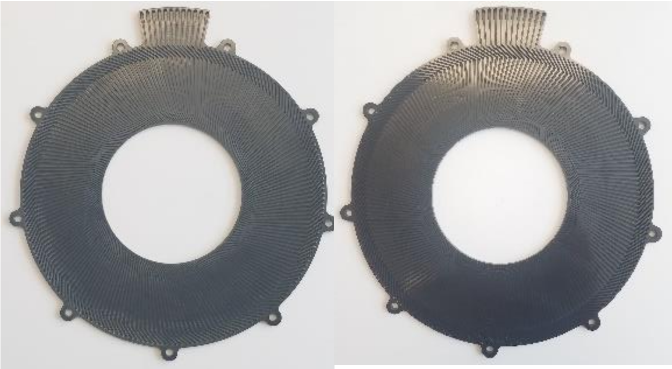
1200°C – 51.3% TD

Low cost and rapidly manufactured sub-components may be possible with further advancements or alternate AM processes.

Comparison of Methods to Obtain Outside Fabrication for Channeled Plates for Stators

Concept A - Stator Plates from Cobalt-Iron Alloy

Concept B - Stator Plates from Cirlex



Concept B - Stator Plates from Ultem1010

Fabrication Method	Machine/EDM	Machine/Mill	3D Print/FDM
Fabrication Time	4+ months	3 months	1 week (92.3% reduction)
Fabrication Costs	$21,400	$19, 870	$1,000
Material Costs	$600	$330	$0 (included in fab.)
Total Costs	$22,000	$20,200	$1,000 (95.0% reduction)

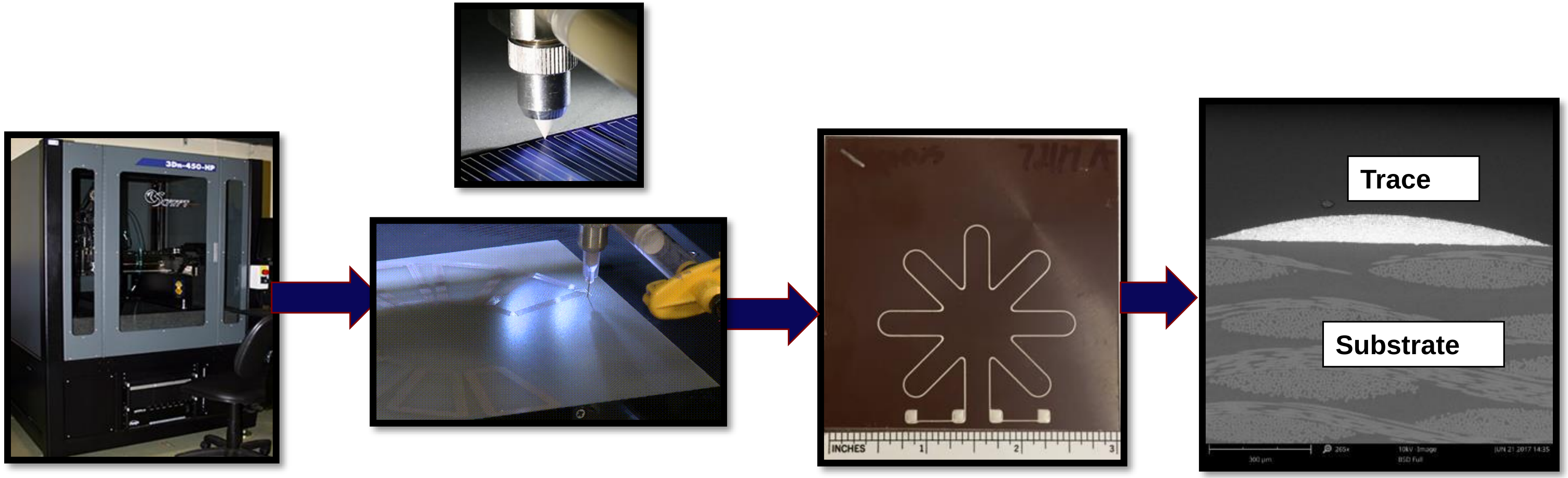
Currently relying on machined stator plates.

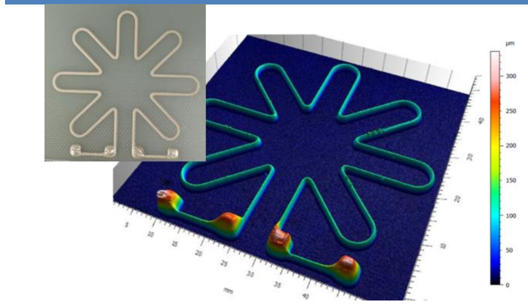
Direct Printing for Innovative Stator Designs for Electric Motors

Samples were printed on the nScrypt 3Dn-300.

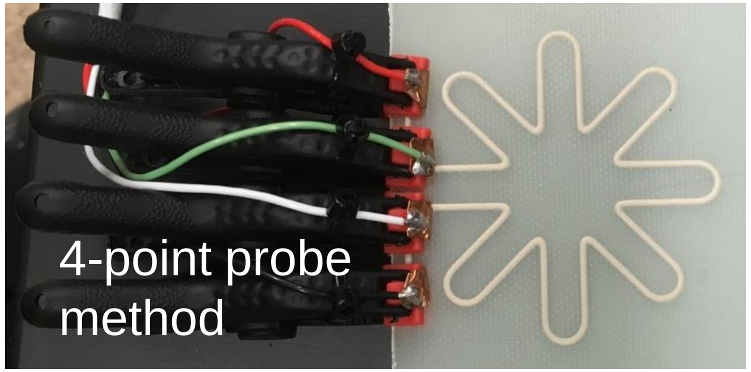
Crucial Parameters:

- Print Speed
- Dispensing Pressure
- Nozzle Diameter
- Print Offset
- Valve Opening



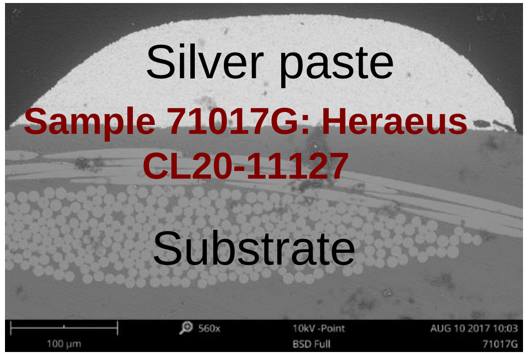


Thin Surface and Imbedded Thick 4-Pt Probe Windings



Evaluation of Silver Pastes

PLAIN PASTE				
Paste Composition	**Lowest Resistivity Obtained [Ωm]**	**Conductivity [Ωm]^-1**	**Max Temp (*C)**	**Vendor Resistivity**
CL-11190 (Heraeus)	2.06×10^{-8}	4.86×10^{7}	300	N/A
CB028 (DuPont)	2.82×10^{-8}	3.54×10^{7}	175	7 – 10 (mΩ/sq/mil)
CL20-11127 (Heraeus)	3.6×10^{-8}	2.78×10^{7}	300	N/A
CB100 (DuPont)	5.23×10^{-8}	1.91×10^{7}	175	>7.5×10^{-8} Ωm
Ag-PM100 (Applied Nanotech)	9.13×10^{-8}	1.10×10^{7}	300	>5×10^{-8} Ωm
Kapton (DuPont)	2.11×10^{-7}	4.74×10^{6}	225	<5 (mΩ/sq/mil)

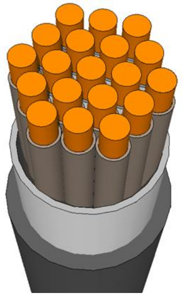


Conductivity of bulk metals [Ωm]^-1:

-Silver: 6.3×10^{7}

-Copper: 6.0×10^{7}

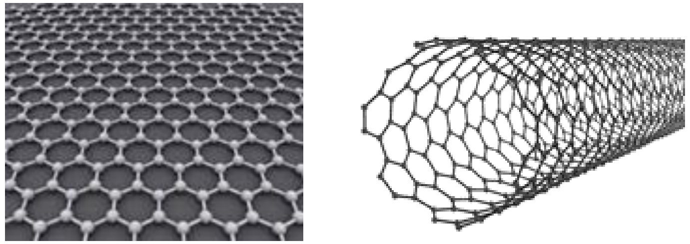
Printed conductors will have a higher effective conductivity than the Litz wire conductors.

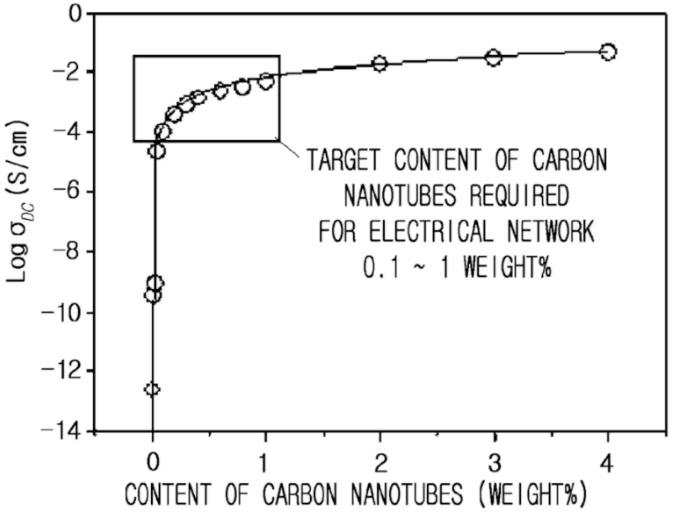


Litz Wire ~60% fill and less in stator windings

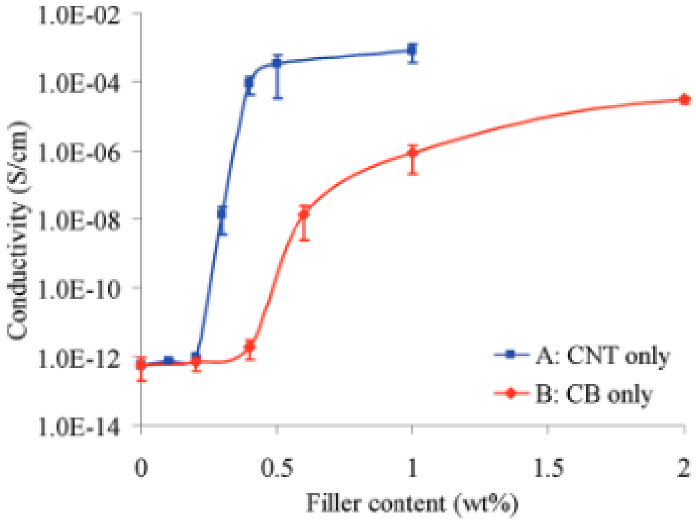
Pastes Additions for Higher Electrical Conductivity

Additions of Graphene and Carbon Nanostructures





Y. Kim, et al. U.S. Patent 8,481,86, 2013 – Conductive Paste Containing Silver Decorated CNT



Peng-Cheng Ma, “Enhanced Electrical Conductivity of Nanocomposites Containing Hybrid Fillers of Carbon Nanotubes and Carbon Black.”

Plain Pastes		
Paste Composition	**Resistivity [Ωm]**	**Conductivity [Ωm]^-1**
Plain CB028	2.82 E-08	3.54 E+07
Plain Heraeus	4.124E-08	2.42E+07

Most Conductive Composites		
Paste Composition	**Resistivity [Ωm]**	**Conductivity [Ωm]^-1**
CB028 + 0.2 wt% QUATTRO Graphene	8.148E-08	1.23E+07
Heraeus + 0.04 wt% CNS	8.297E-08	1.21E+07
CB028 + 0.1 wt% QUATTRO Graphene	1.036E-07	9.65E+06
CB028 + 0.085 wt% CNS	1.114E-07	8.97E+06
Heraeus + 0.14 wt% CNS	1.191E-07	8.40E+06
CB028 + 0.2 wt% MONO Graphene	1.261E-07	7.93E+06
CB028 + 0.5 wt% MONO Graphene	1.419E-07	7.05E+06

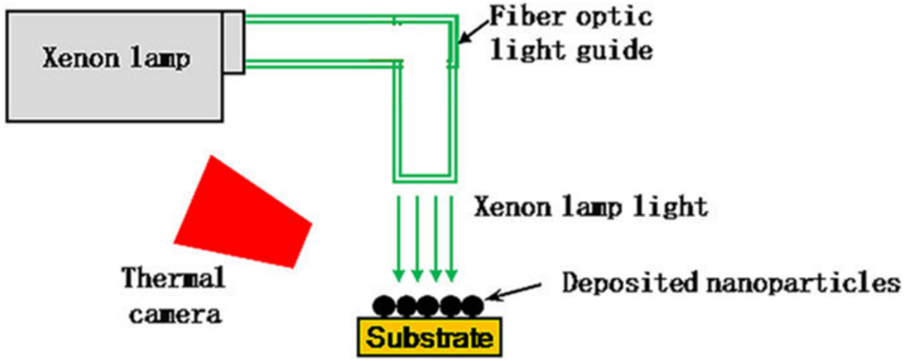
Advanced Sintering Processes for Higher Electrical Conductivity

Photonic Sintering

Investigating the use for photonic sintering for printed silver inks.

- Rapid post processing of conductive patterns
- Few second to minute processing times without damaging/heating the substrate

Photonic Sintering for high through-put



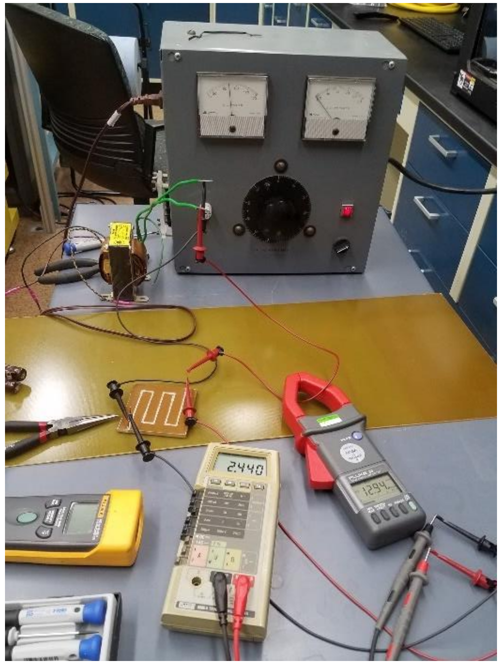
Heraeus CL20-11127 Thermally Cured on Fiberglass (195°C/1hr due to substrate limitations)		
Sample Name	**Resistance [Ωm]**	**Conductivity [Ωm]^-1**
71017G	4.37×10^{-8}	2.29×10^{7}
71017H	5.75×10^{-8}	1.74×10^{7}
Heraeus CL20-11127 Thermally Cured on Vespel (300°C/1hr)		
72117A	4.12×10^{-8}	2.42×10^{7}
Heraeus CL20-11127 Photonically Cured		
71017A	4.89×10^{-8}	2.05×10^{7}
71017B	4.55×10^{-8}	2.20×10^{7}
71017C	6.04×10^{-8}	1.65×10^{7}
DuPont CB028 Thermally Cured on Fiberglass (150°C/1hr)		
032917-6	2.82×10^{-8}	3.54×10^{7}

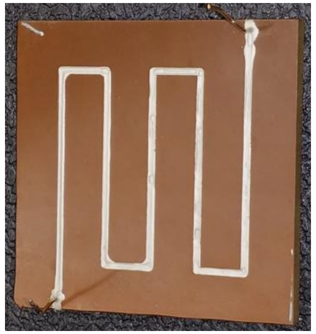
Resistivity greatly improved from 8 ohm in green state to 1.8 ohm after photonic sintering.

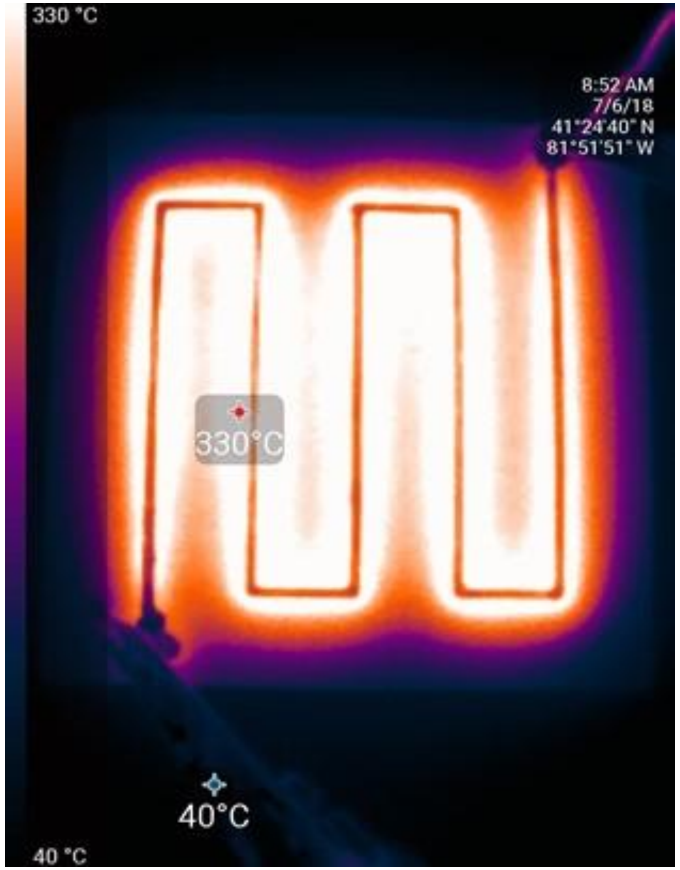
Potential, further optimization by investigating offset distance, kV setting, pulses, duration and nano-sized silver particles.

Thermal/Oven Curing

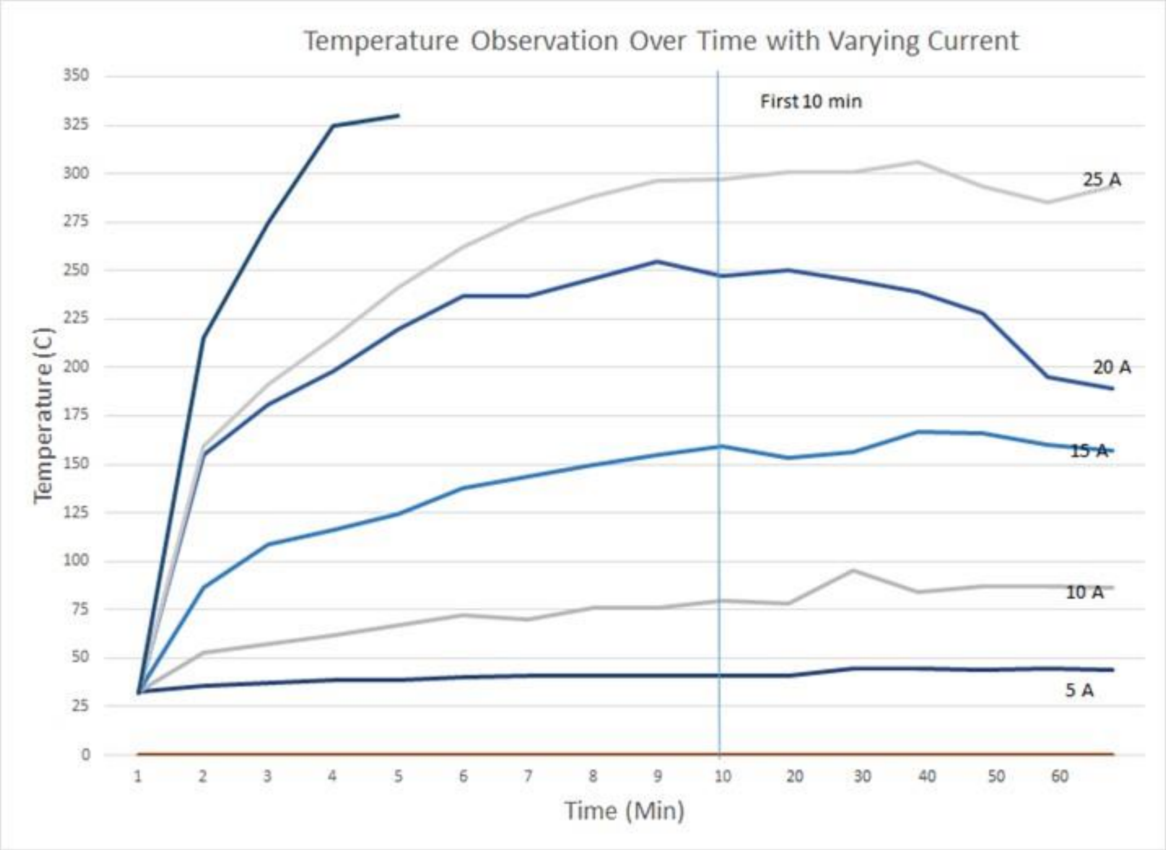
Direct Printed Silver Coils - High Current Test







Temperature capability far exceeds that of the baseline motor which is 180°C.



Temperature decreases with extended heat potentially due to self sintering and decreasing resistance within the paste traces.

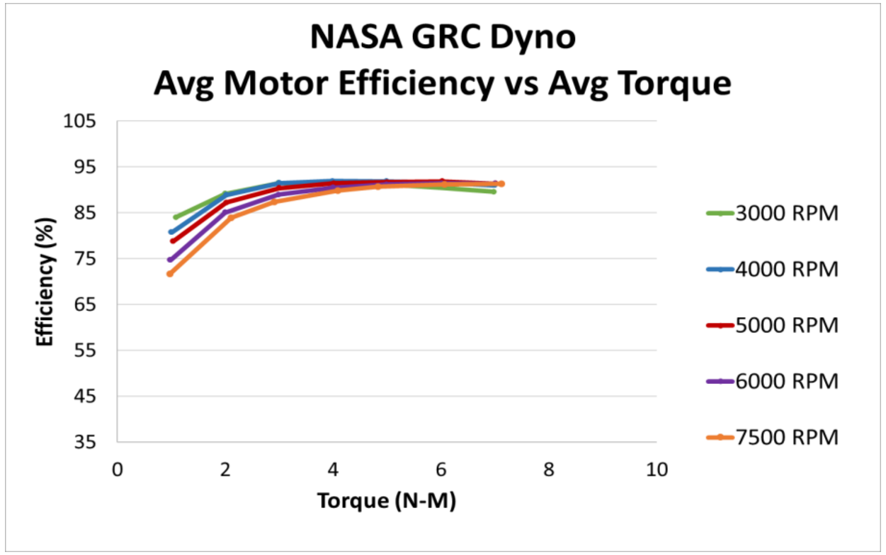
Testing of Motor Configurations

AFRC prop motor testing:

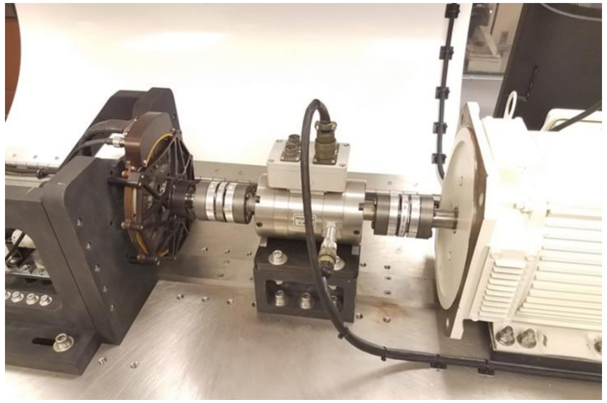
- Baseline motor
- Motor Version 1: Structural LaRC parts - rotors and housing

GRC motor testing in a dynamometer:

- Baseline motor
- Motor Version 2: Structural LaRC parts - rotors, housing, finned cooling ring



Prop Test Stand



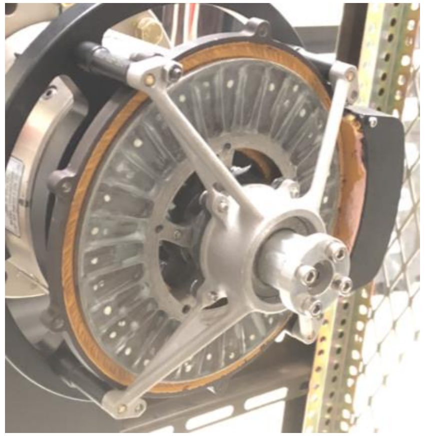
Dynamometer

Baseline Motor

Mass = 1968 g

V1. Motor

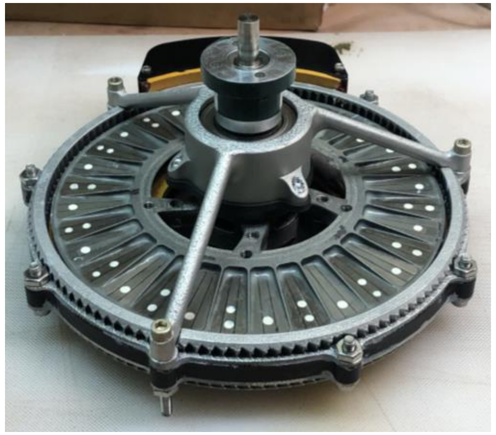
Mass = 1833 g (7% less mass)



V2. Motor

Mass = 1870 g (5% less mass)

Total heat sink mass = 92 g



Summary and Conclusions

Summary

- Good progress is being made in applying additive manufacturing methods to the fabrication of components for turbine engine and electric motors.
- LOM offers continuous fiber reinforced CMCs while the binder jet method offers short fiber reinforced SiC-based ceramics.
- AM offers the potential for electric motors with much higher efficiencies and power densities.
- Additive manufacturing technologies were demonstrated to be capable of enabling new innovative direct printed stator designs for electric motors.
- New electric motor component designs will offer performance gains through such improvements as lighter weights, higher coil packing, higher coil electrically conductive, higher temperature operation, and higher magnetic flux.

The CAMIEM Team and Acknowledgements

Support provided by the Convergent Aeronautics Solutions Project within the ARMD Transformative Aeronautics Concepts Program.

Organization	Name	Role
Glenn Research Center	Michael Halbig (POC)	PI and GRC POC
	Mrityunjay "Jay" Singh	Additive manufacturing
	Valerie Wiesner	
	Greg Piper / Daniel Gorican	AM /Direct printing
	Derek Quade	Dynamometer
	Steven Geng	Motors and magnets
	Chip Redding	Design
	Chun-Hua “Kathy" Chuang	Insulator materials
	Peter Kascak	Electric Motors
	Jeff Chin	System benefits
LaunchPoint Technologies	Michael Ricci (POC)	Baseline & innovative motor designs
	Brian Clark	
	Dave Paden	

Organization	Name	Role
Armstrong Flight Research Center	Ethan Niemen (POC)	AFRC POC and ground testing
	Otto Schnarr III	Electric propulsion ground testing
	Kirsten Fogg	
	Patricia Martinez	
Langley Research Center	Samuel Hocker (POC)	Additive manufacturing
	Christopher Stelter	
	Russell “Buzz” Wincheski	NDE
	Stephen Hales	Materials evaluation
	John Newman	Computational materials
University of Texas El Paso	Jose Coronel (POC)	Stator winding and cooling efficiency
	David Espalin	
	Ryan Wicker	

Also Summer Interns at GRC (Anton Salem and Hunter Leonard) and LaRC.