Additive Manufacturing of Multi-Material Systems for Aerospace Applications

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Outline

- Needs, challenges, and applications
- AM of multi-materials in a single feed-stock
  - Direct writing of low resistance conductors
  - Binder jet printing of SiC fiber / SiC matrix composites
  - FDM of polymer-based materials with functional additions
- Hybrid and two-stage AM toward multi-material components
  - Stators for electric motors
  - Lightweight multi-functional components, e.g. thermal management of battery packs
- Summary and Conclusions

Additive Manufacturing of Multi-Materials

Needs:

- Achieving complex shapes and processing not possible from conventional fabrication methods.
- Components with integrated sub-elements of differing materials and structures.
- Tailored material properties: e.g. microstructure, mechanical, electrical, thermal, and magnetic.

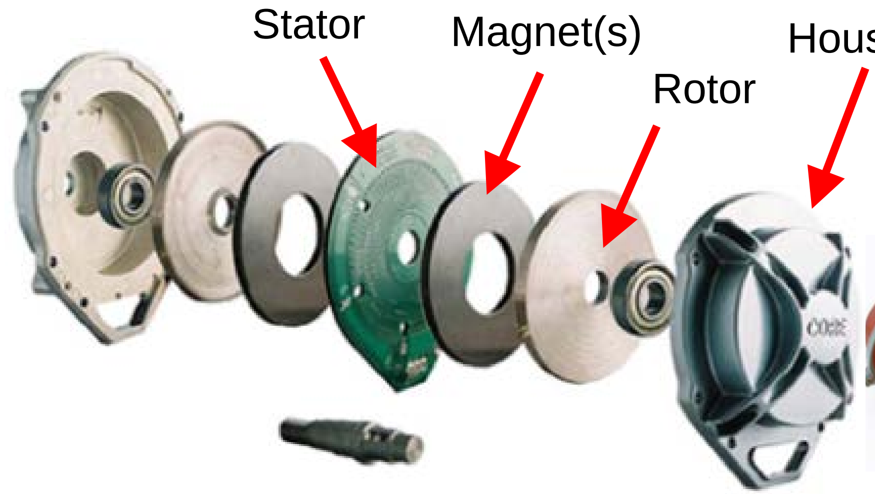
Challenges:

- Additive manufacturing for multi-materials is not as mature as for single materials.
- Optimal utilization of several methods, e.g. single machine AM, multi-machine AM, and hybrid approaches (combinations of AM and conventional).
- Post-processing of multi-materials with differing sintering temperatures and material mismatches and incompatibilities.

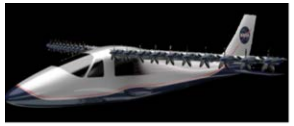
Components for Aerospace Applications

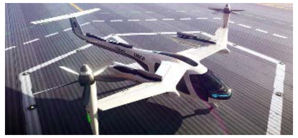
Electric Motors- Targeted Components (structural, functional, and electrical)

Axial Flux Machine



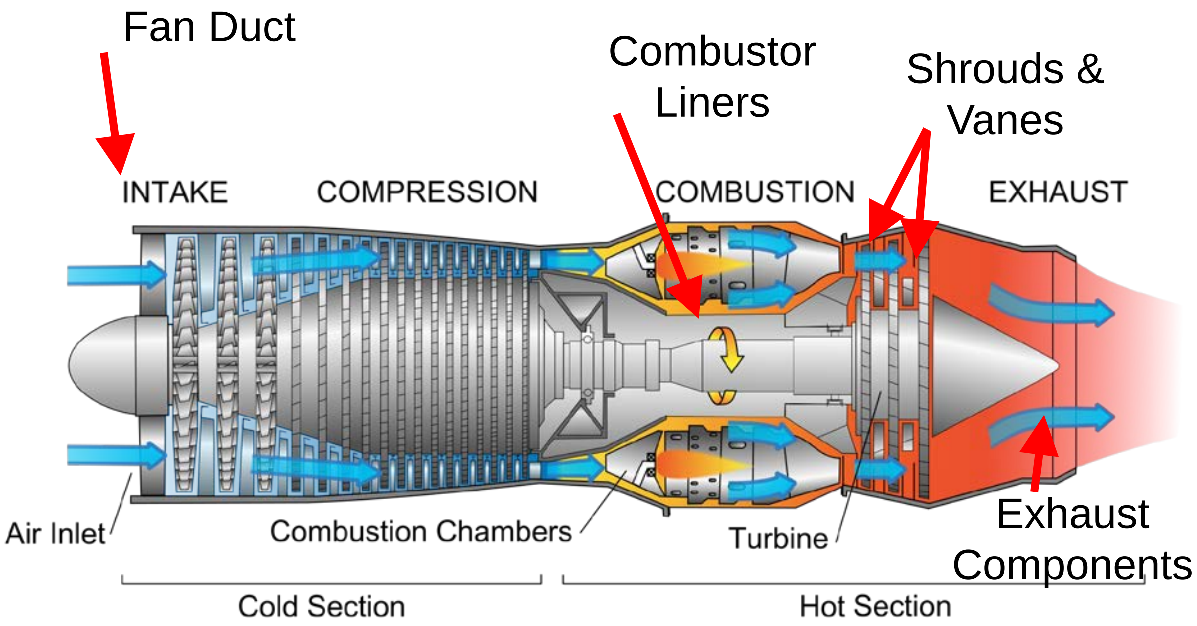
Radial Flux Machine





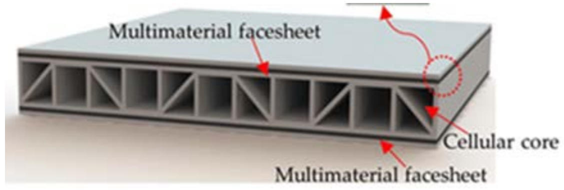
3. **Ultra-Efficient Commercial Vehicles**
   - Pioneer technologies for big leaps in efficiency and environmental performance
4. **Transition to Low-Carbon Propulsion**
   - Characterize drop-in alternative fuels and pioneer low-carbon propulsion technology

Turbine Engines - Targeted Components (CMCs and PMCs)



AM for In-Space and on Terrestrial Planets - Targeted Components (Functional PMCs)

Replacement Part Fabrication

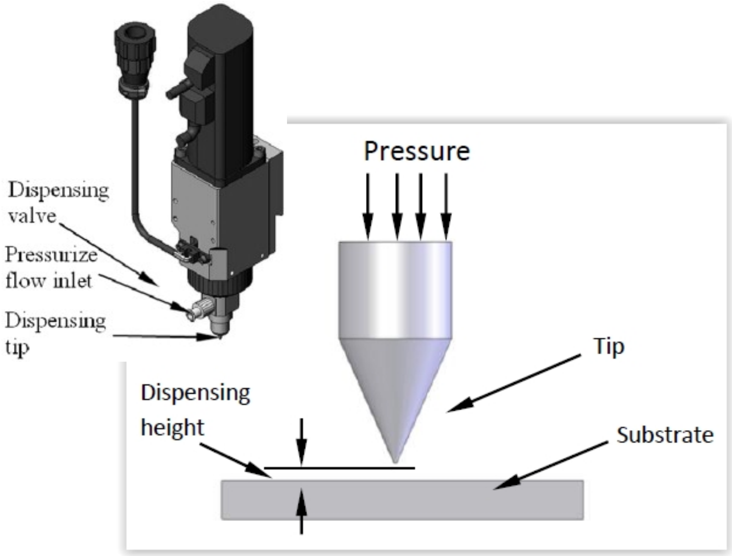


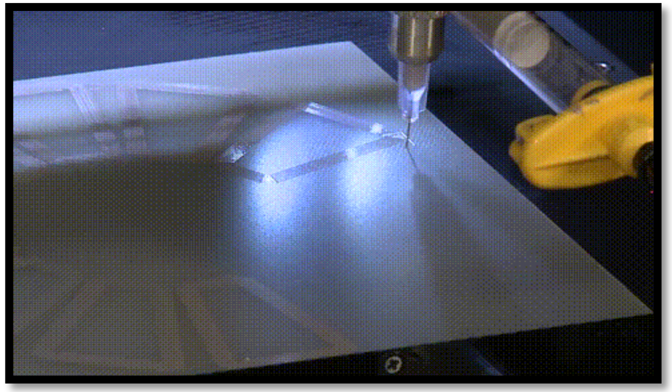
Lightweight Multifunctional Components

Additive Manufacturing Technologies

Direct Write Printing

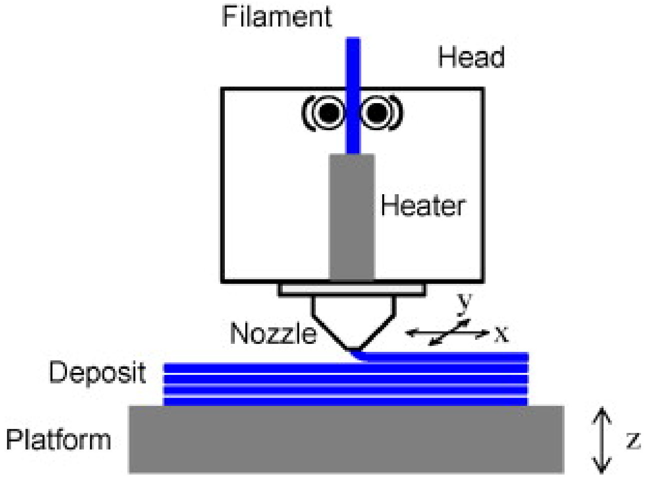
Controlled dispensing of inks, pastes, and slurries.

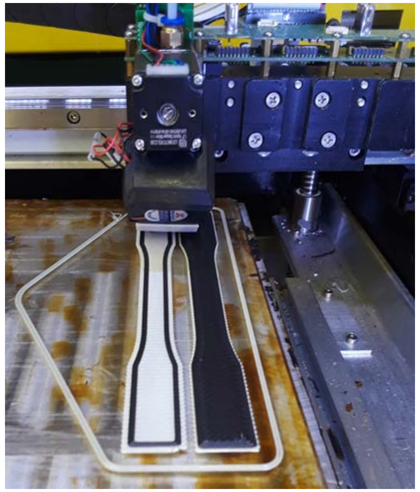




Fused Deposition Modeling

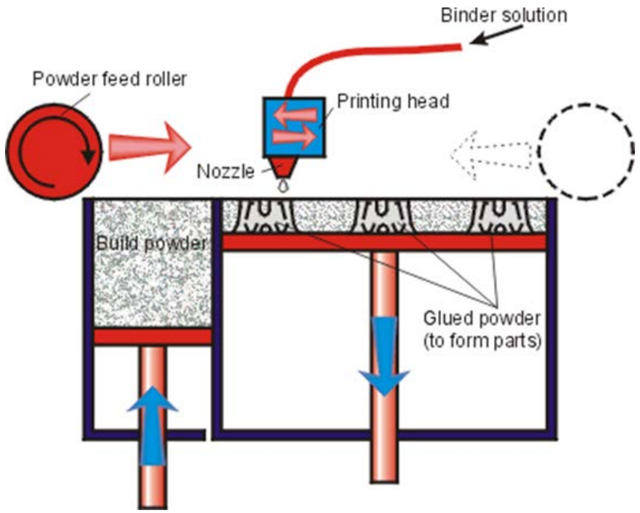
Plastic is heated and supplied through an extrusion nozzle and deposited.

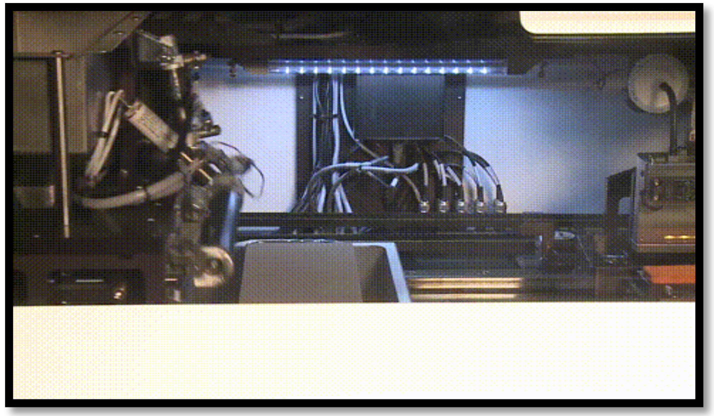




Binder Jetting

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





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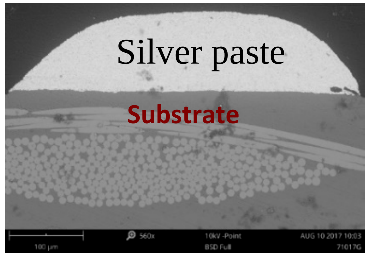
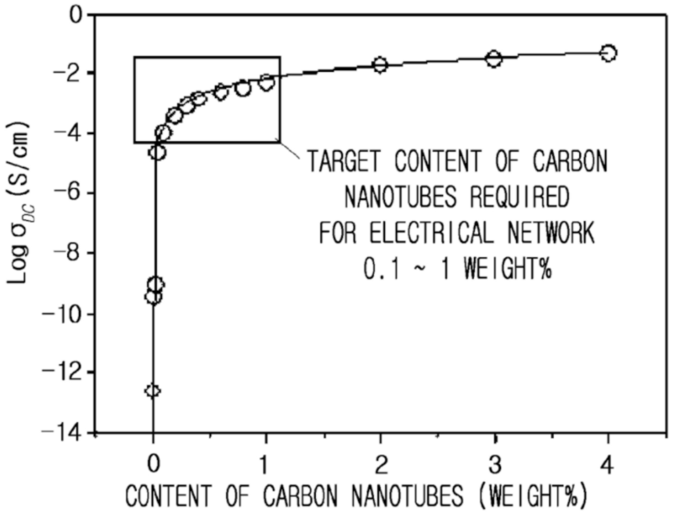
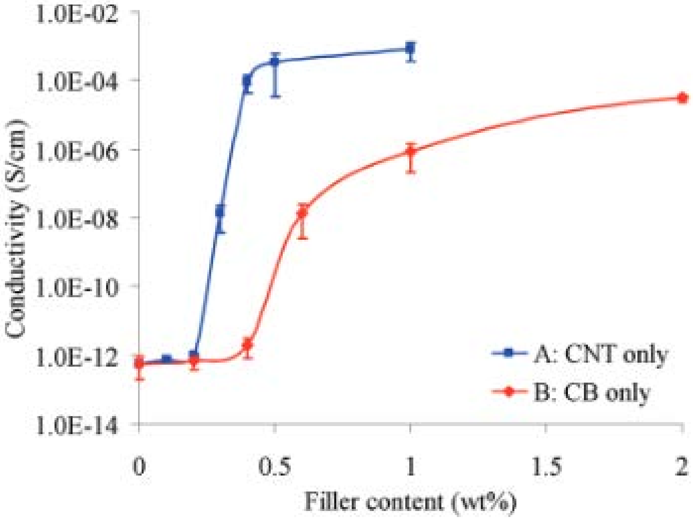
Direct Writing of Low Resistance Conductors

nScrypt 3Dn-300



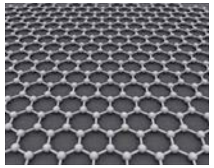


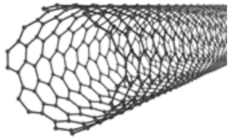
Y. Kim, et al. U.S. Patent 8,481,86, 2013 – Conductive Paste Containing Silver Decorated CNT



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

Additions of Graphene and Carbon Nanostructures





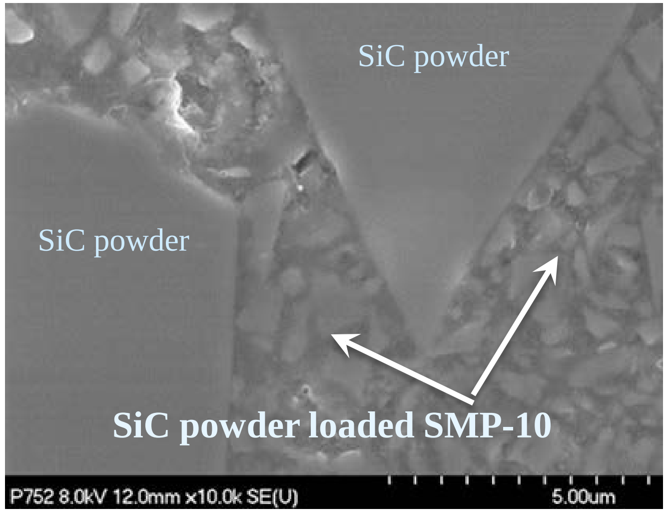
Plain Pastes		
Paste Composition	**Resistivity [Ωm]**	**Conductivity [Ωm]^-1**
Plain CB028	2.82 E-08	3.54 E+07
Plain Heraeus	4.12384E-08	2.42E+07

Most Conductive Composites		
Paste Composition	**Resistivity [Ωm]**	**Conductivity [Ωm]^-1**
CB028 + 0.2 wt% QUATTRO Graphene	8.14798E-08	1.23E+07
Heraeus + 0.04 wt% CNS	8.29725E-08	1.21E+07
CB028 + 0.1 wt% QUATTRO Graphene	1.03586E-07	9.65E+06
CB028 + 0.085 wt% CNS	1.1145E-07	8.97E+06
Heraeus + 0.14 wt% CNS	1.19059E-07	8.40E+06
CB028 + 0.2 wt% MONO Graphene	1.26118E-07	7.93E+06
CB028 + 0.5 wt% MONO Graphene	1.41875E-07	7.05E+06

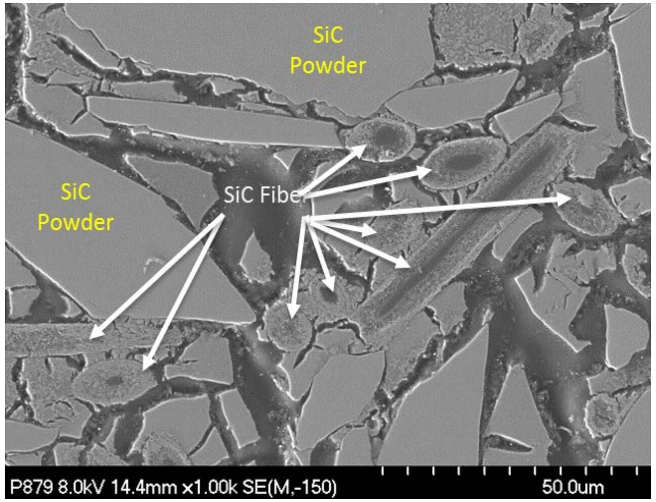
Binder Jetting of SiC Fiber / SiC Matrix Composites

ExOne Innovent

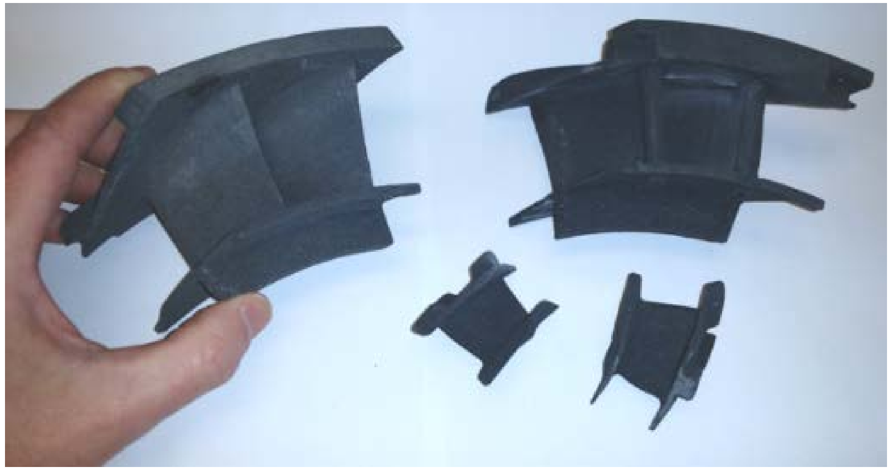
Constituents



~70 μm long and
~7 μm in diameter

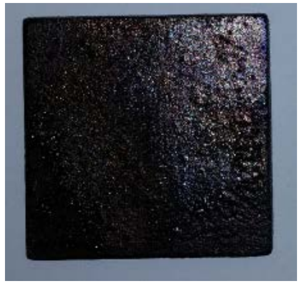


Fiber Reinforced Ceramic Matrix Composite



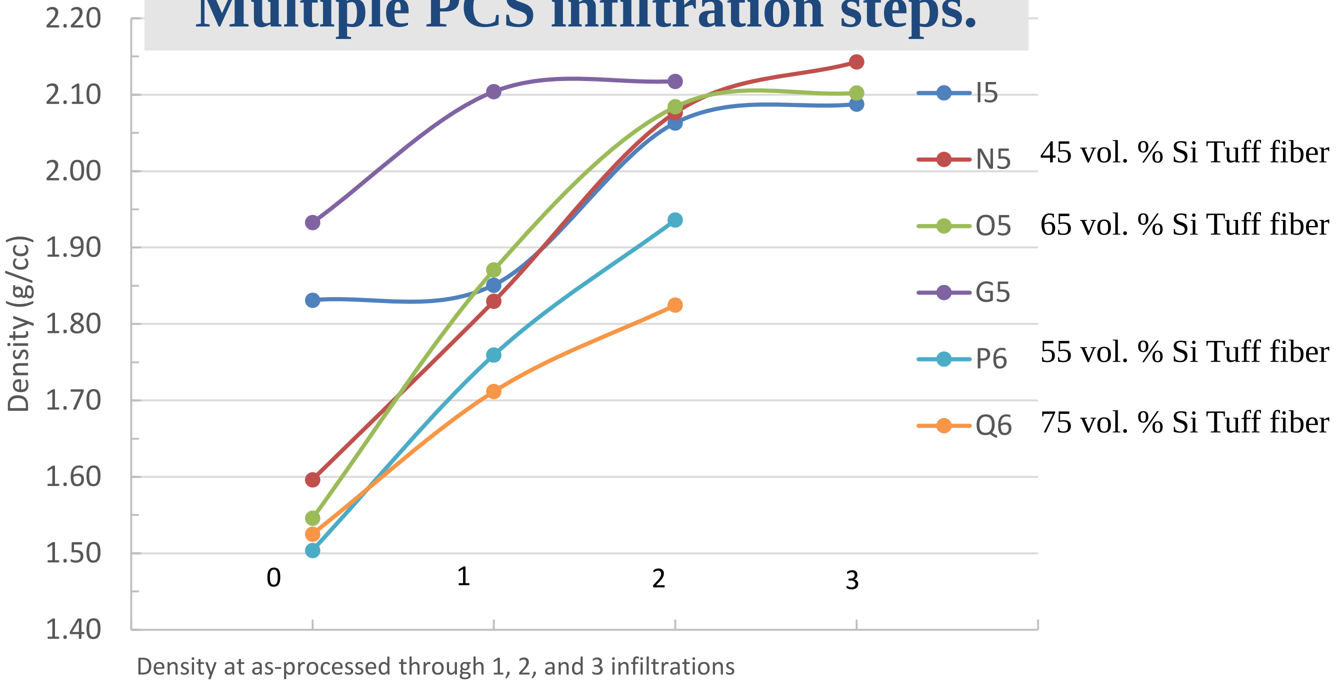
High pressure turbine cooled doublet vane sections.

Binder Jetting: Density of SiC Panels



2"x2" CMC coupons

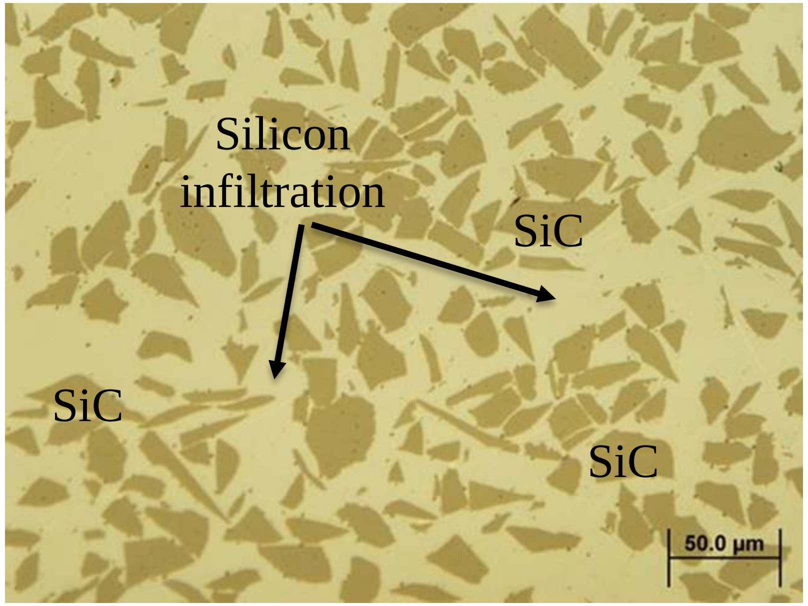
Multiple PCS infiltration steps.



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.

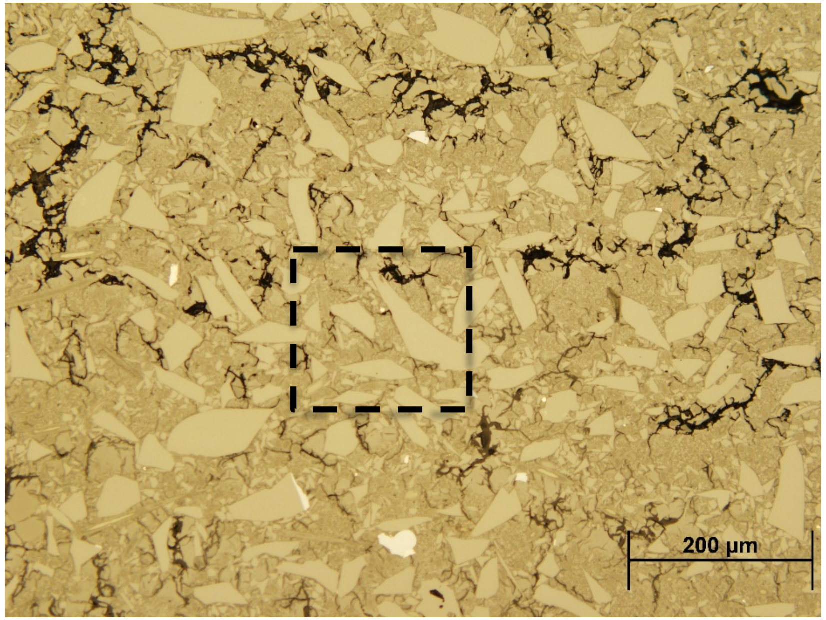
Demonstration of full densification through silicon melt-infiltration.

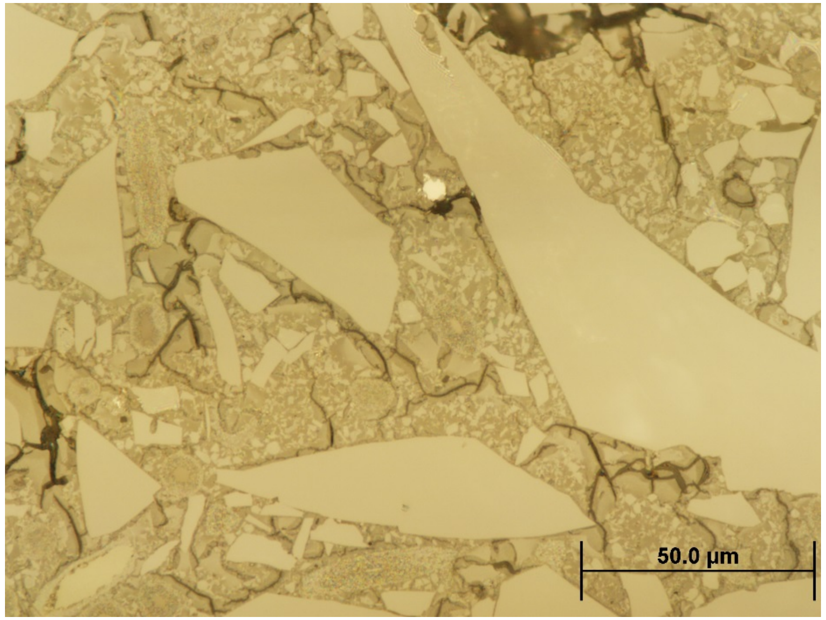


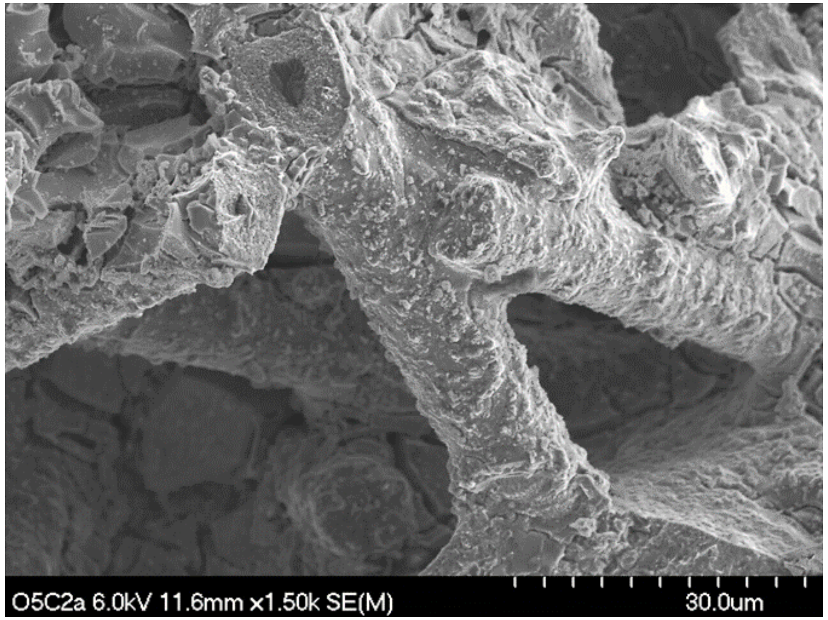
Melt infiltration methods such, e.g. silicon melt, can achieve near full density.

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.

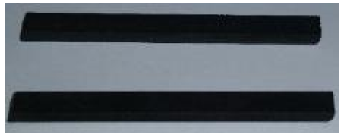






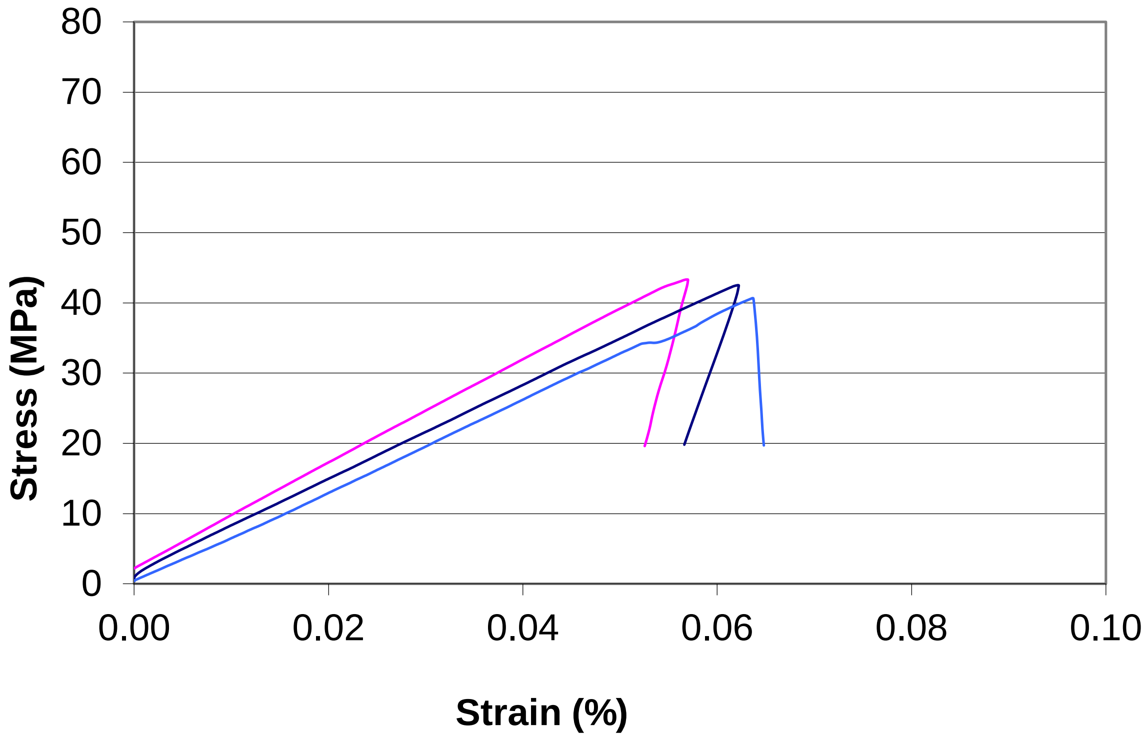
Good densities achieved with high fiber loading.

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

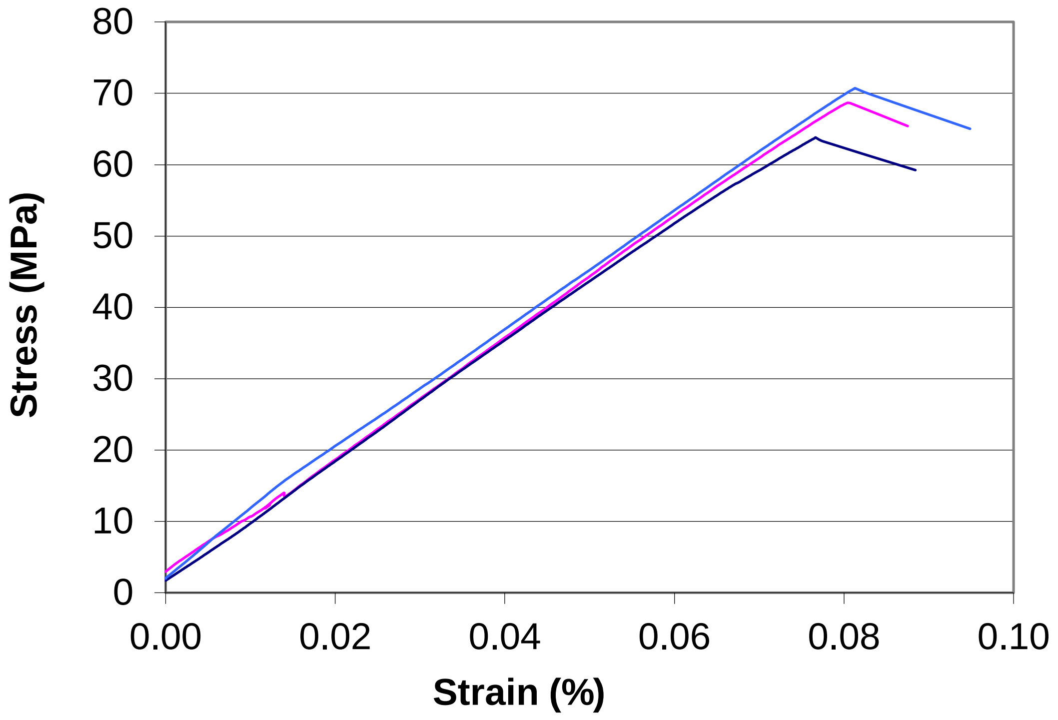


Bend bars for strength testing

Non-Reinforced SiC - Set G



65 vol. % SiC Fiber Reinforced SiC - Set N

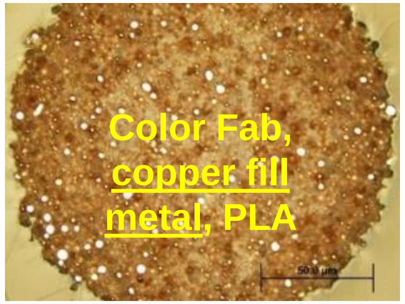


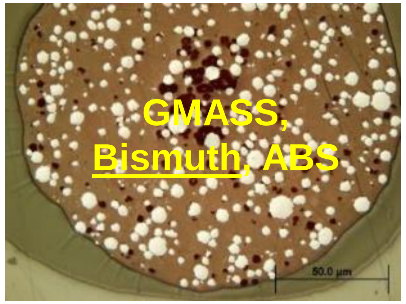
The fiber loaded SiC materials had significantly higher stresses and higher strains to failure.

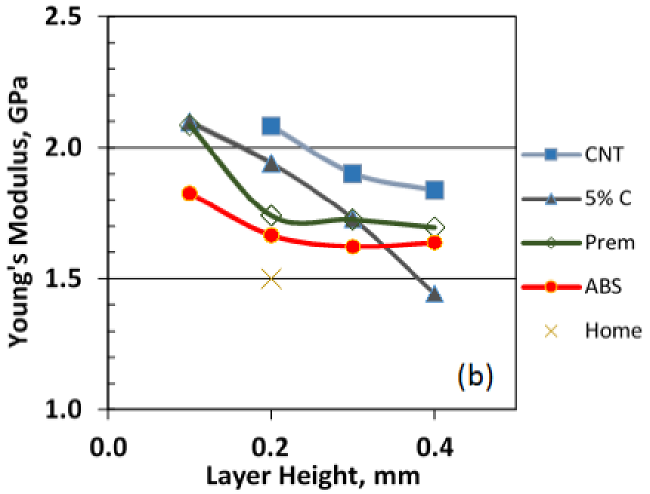
FDM of Composite Filaments for Multi-Functional Applications

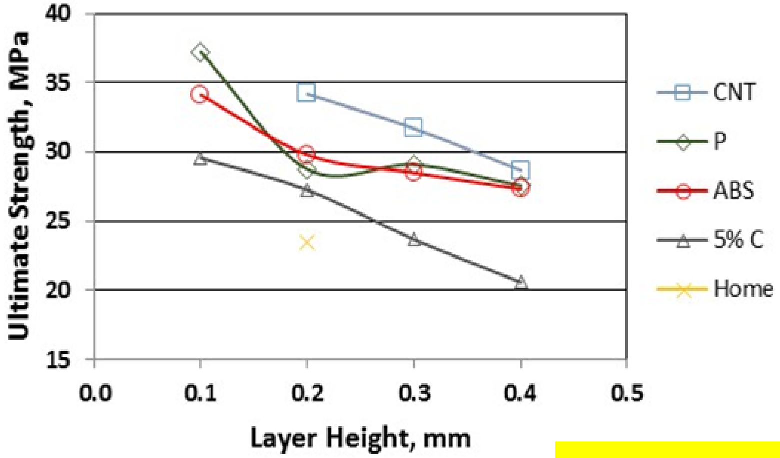
Potential Missions/Benefits:

- **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***

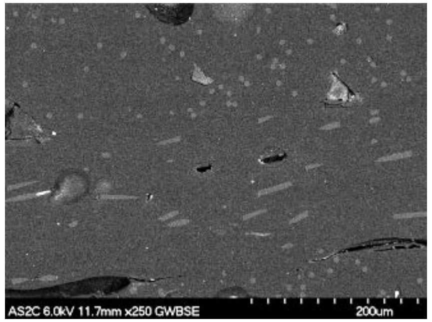




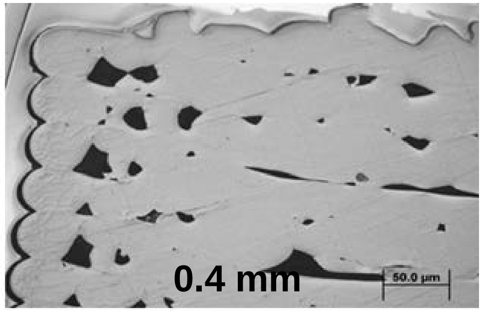


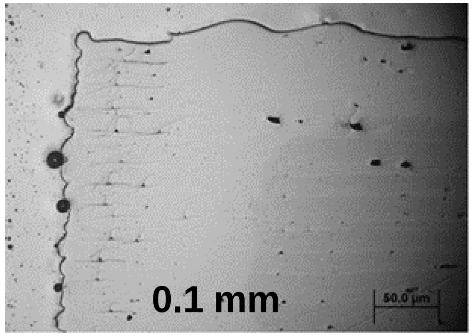


Filaments used: ABS-standard abs, P-premium abs, CNT-w/carbon nanotubes, C-w/chopped carbon, Home-lab extruded filament



C-Fiber Reinforced ABS Filaments





Effect of print layer height

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

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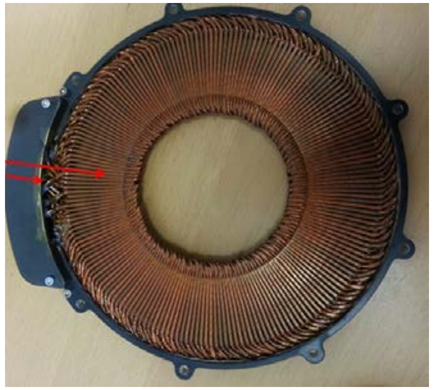
AM and Hybrid Approaches for Electric Motor Components

Electric Motors

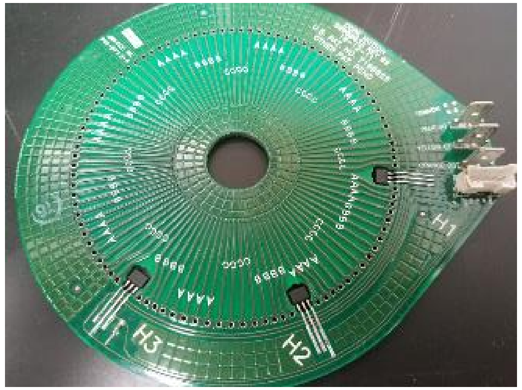
Components of a Commercial Axial Flux Motor

NASA Electric Motor with AM Components

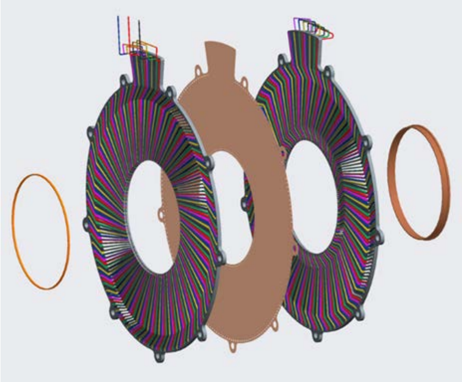
Stators



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

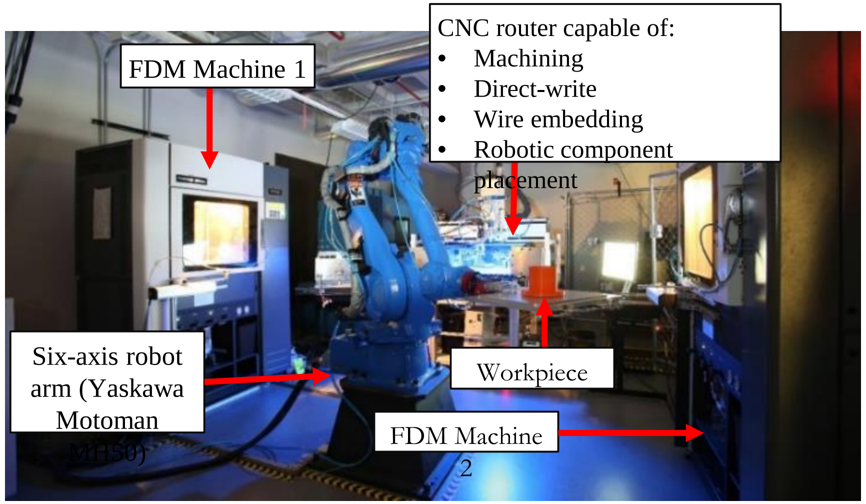
Additively Manufactured Rotor Plate

Rotor Constituents:

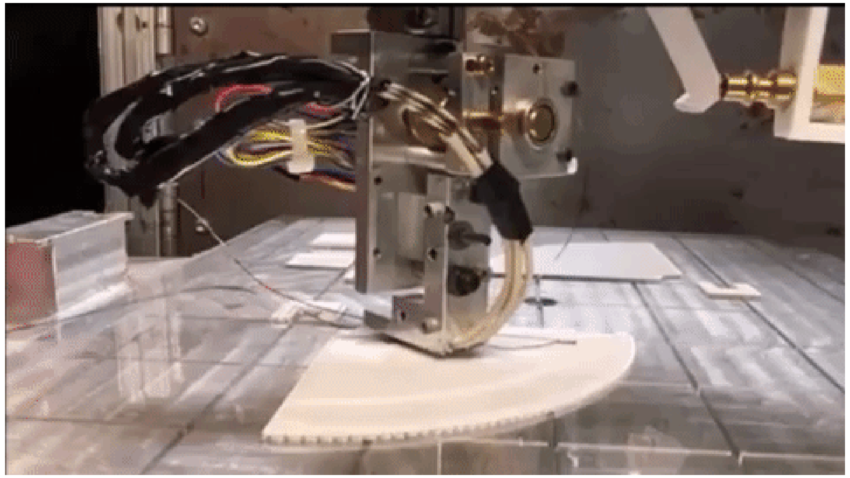
- Permanent magnets.
- High strength structure (typically metallic).

Wire Embedded Stator: U. of Texas El Paso (NASA CAMIEM)

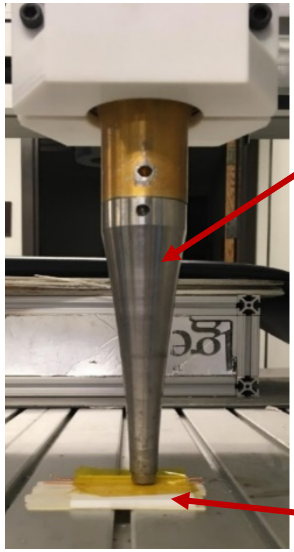
Conventional stator by LaunchPoint Technologies



Multi3D System



Cartridge heated embedding demonstration



Ultrasonic embedding horn

20 kHz Ultrasonic system

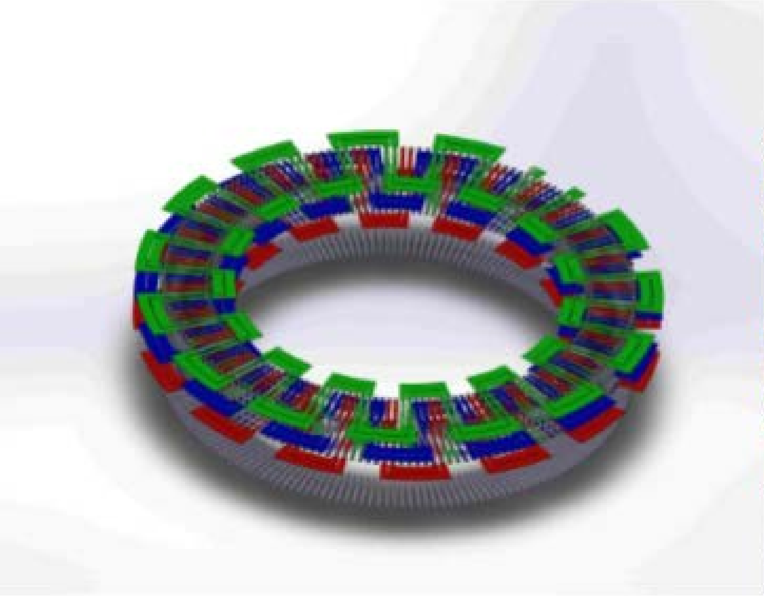
PC substrate

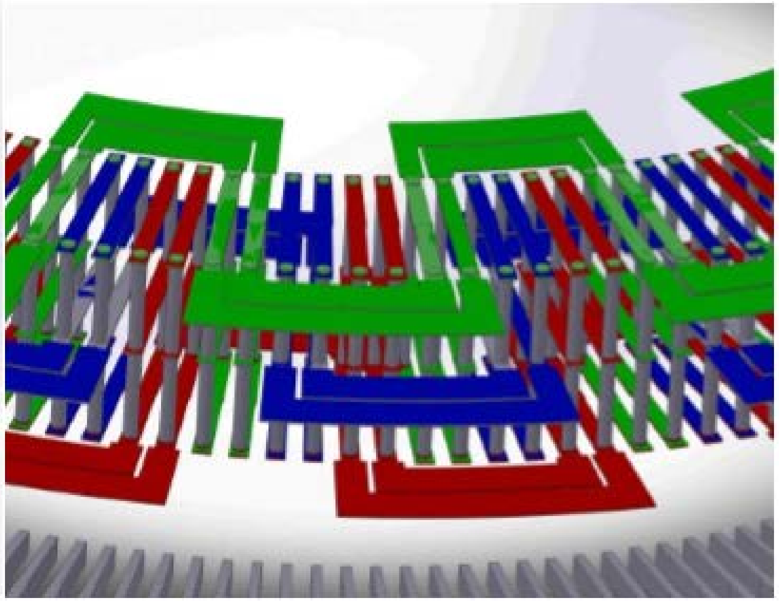
Pressing process needed to further densify the stator

Final stator

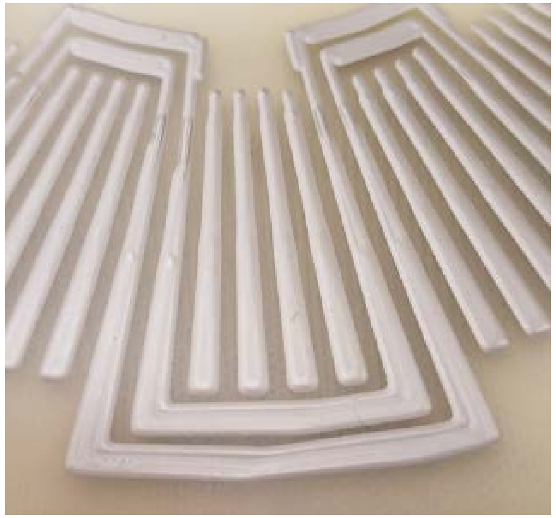
- **Challenges with feeding wire through ultrasonic horn of required 14 AWG wire.**
- **Challenges with overprinting polycarbonate onto embedded wire.**

PCB Stator Concepts

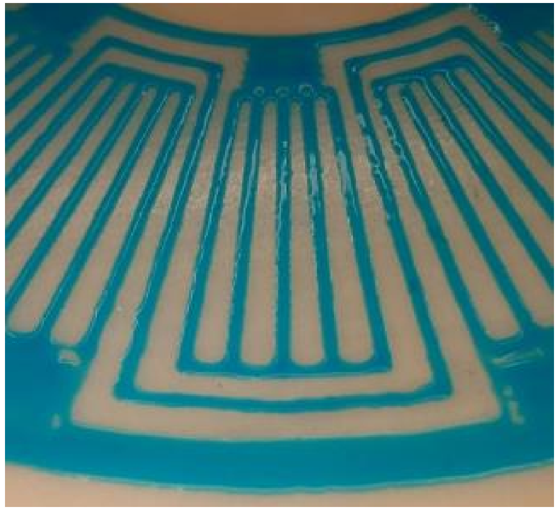




Direct Printed Silver Conductor Layer



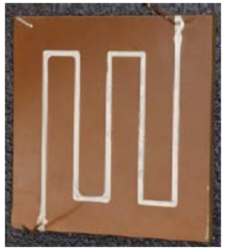
Direct Printed Dielectric Layer



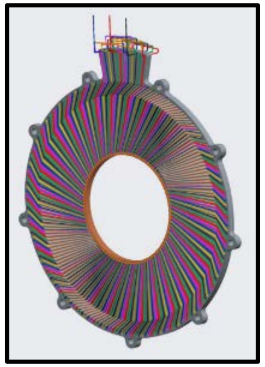
Direct Printed Stator - Concepts A and B

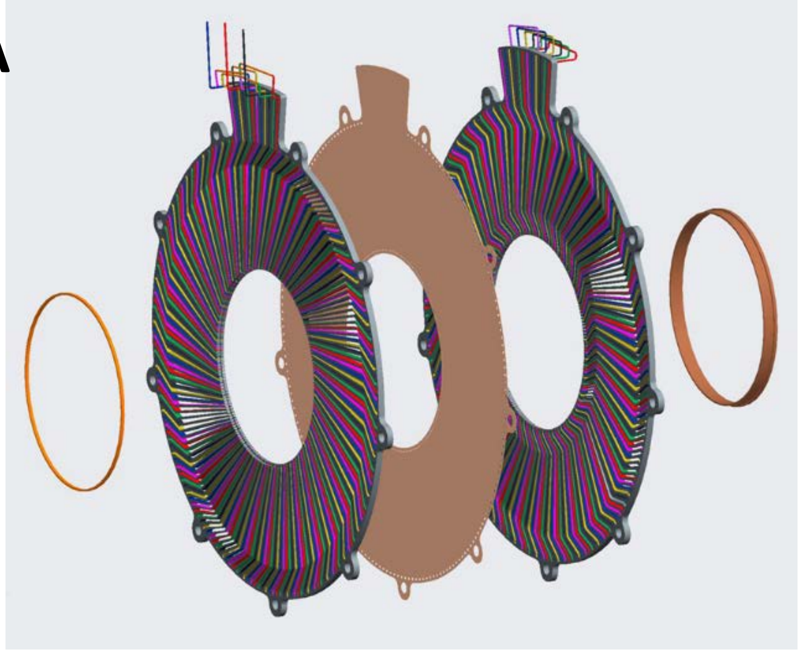
Benefits

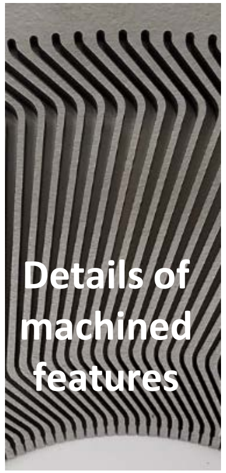
- Higher magnetic flux, torque, and motor constant (K_m).
- Higher temp. capability of >220°C instead of 160°C for baseline stator.
- Direct printed silver coils with high fill.



Concept A







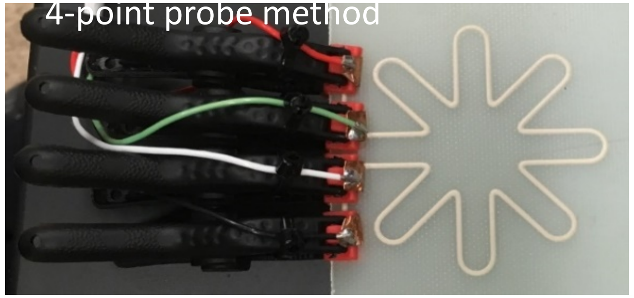
Stator Plate from Cobalt-Iron Alloy

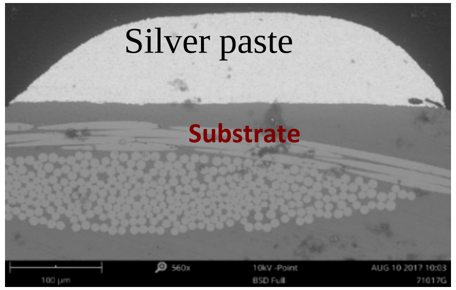
Cirlex Middle Layer

Outer Rings

nScrypt 3Dn-300

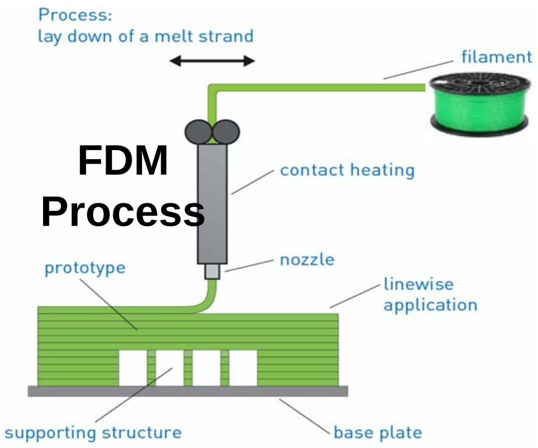
Direct Printed Silver Coils - High Current Test





Additively Manufactured Stator Plates

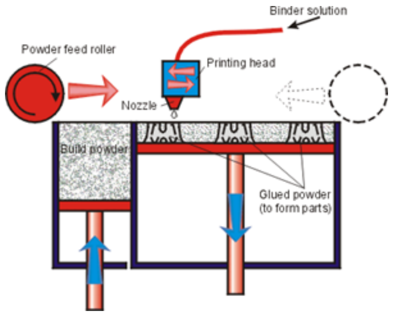
FDM Process



High Temp. Polymer

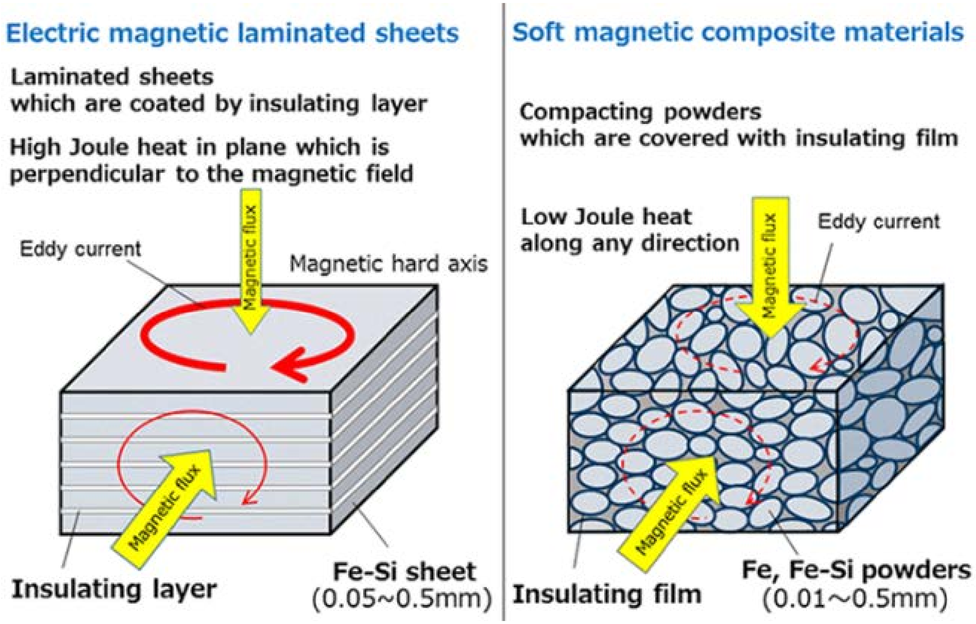
FDM from Extem (Tg of 311°C) (left) and Ultem 1010 (TG of 217°C) (right) FDM filament.

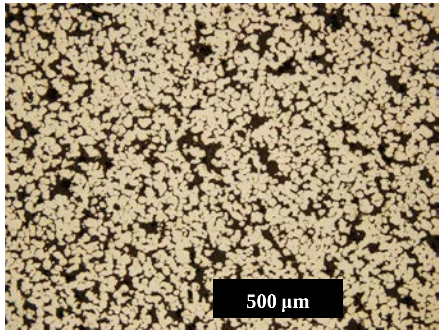
Soft Magnet



Binder Jetting

Stator Plate from Cobalt-Iron Alloy

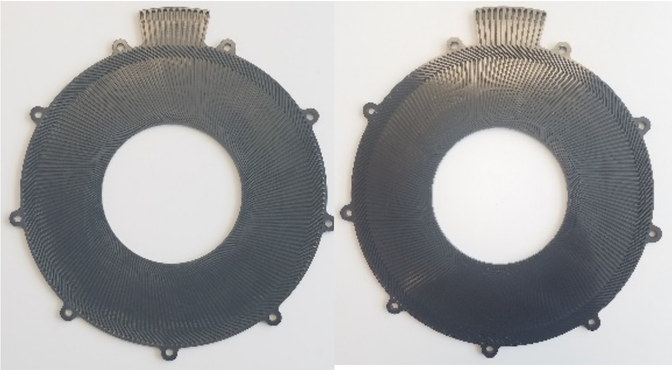
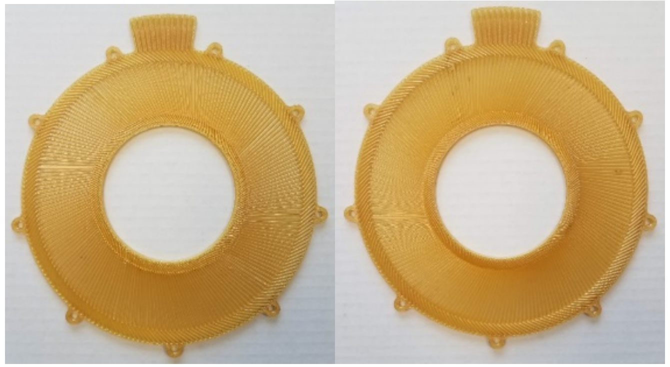




1200°C – 51.3% TD

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

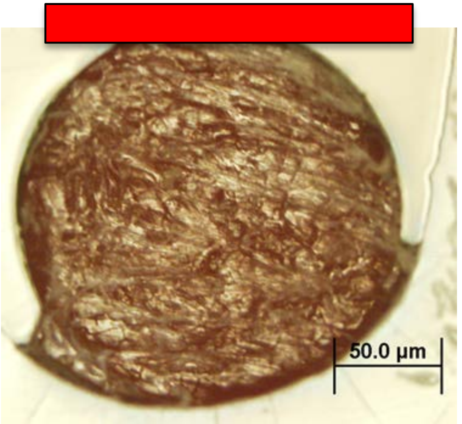
Comparison of Methods to Obtain Outside Fabrication for Channeled Plates for Stators

	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)

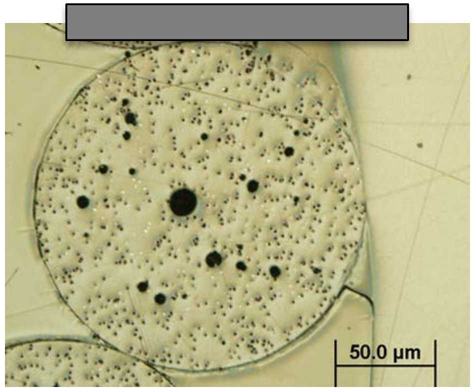
Currently relying on machined stator plates.

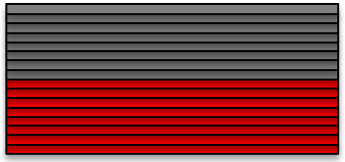
FDM of Multi-Material Test Coupons for Lightweight Multi-Functional Applications

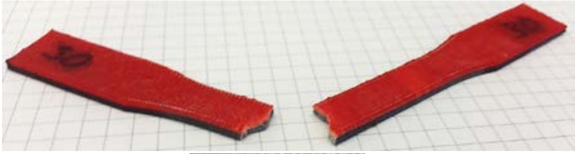
Premium ABS (P-ABS)

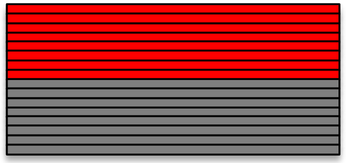


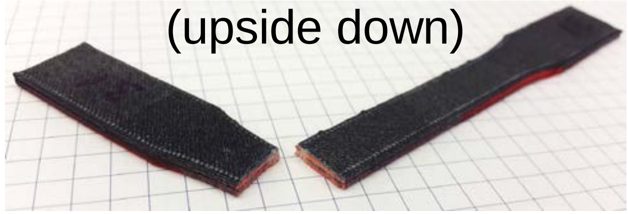
5% Carbon Fiber by weight ABS (CF-ABS)

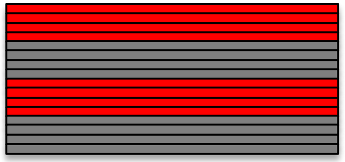


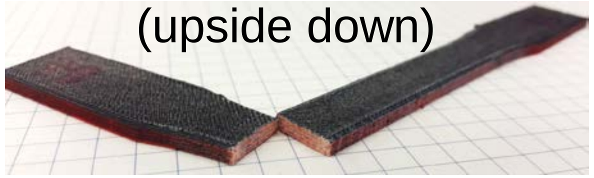












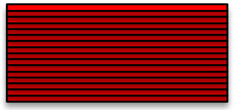
System A
- Half P-ABS
- Half CF-ABS
- P-ABS bottom

System B
- Half P-ABS
- Half CF-ABS
- CF-ABS bottom

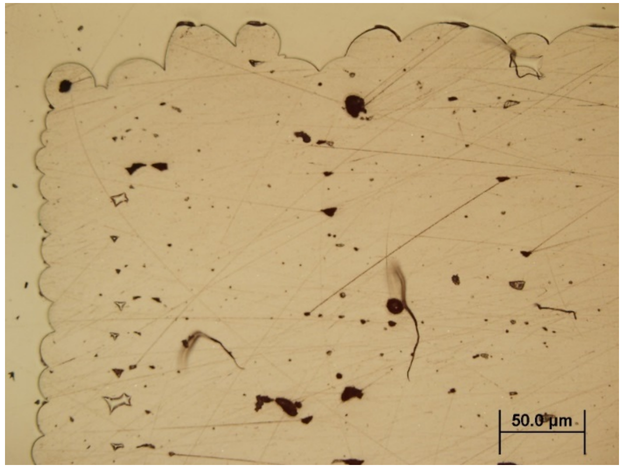
System C
- 4 alternating layers of P-ABS and CF-ABS
- CF-ABS bottom

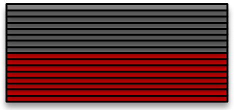
System D
- 8 alternating layers of P-ABS and CF-ABS
- CF-ABS bottom

Microstructures of FDM of Multi-Material Test Coupons

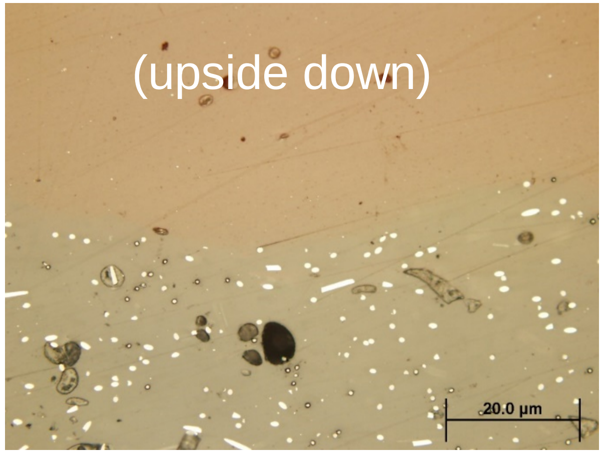


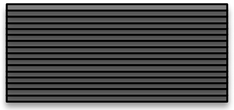
P-ABS



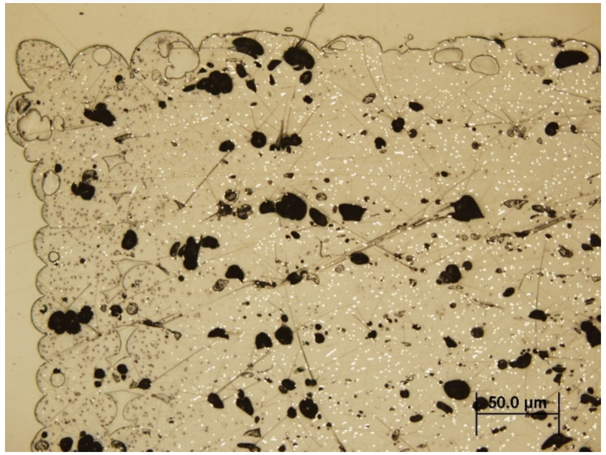


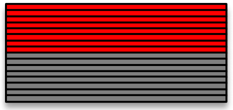
System A



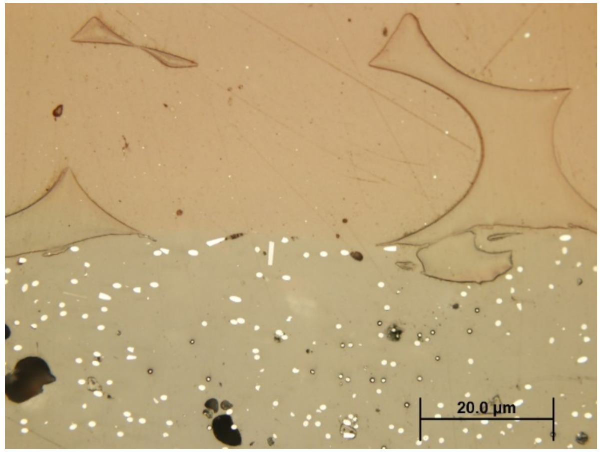


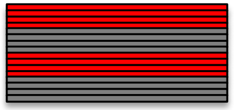
CF-ABS



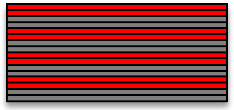


System B

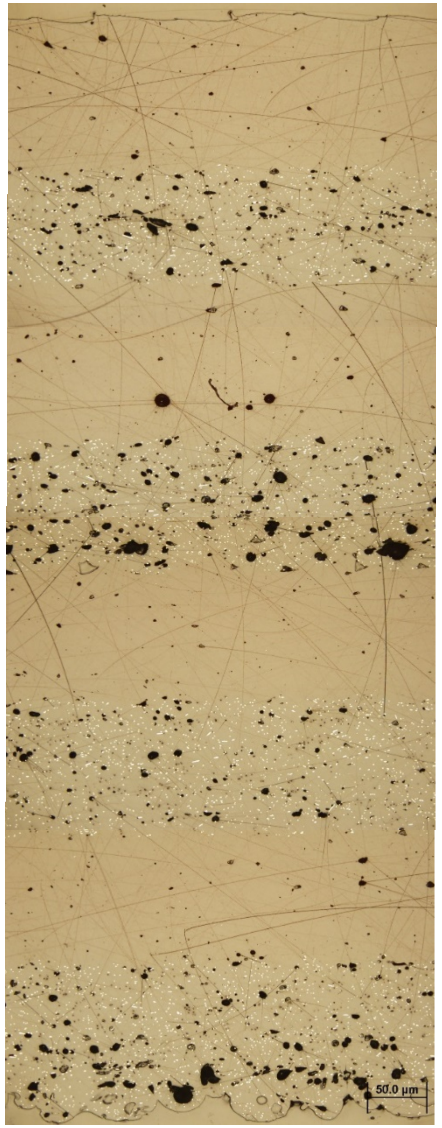


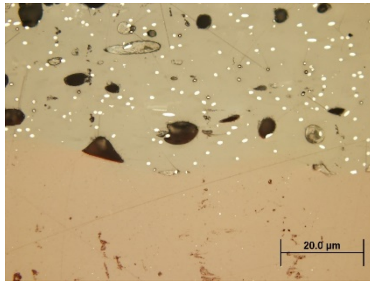


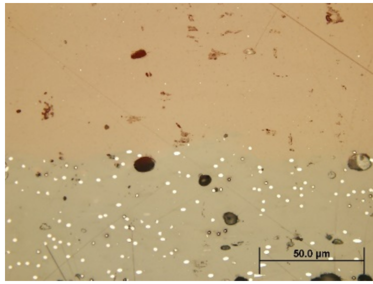
System C

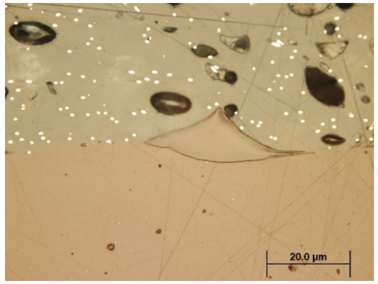


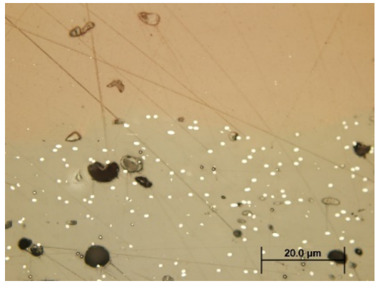
System D





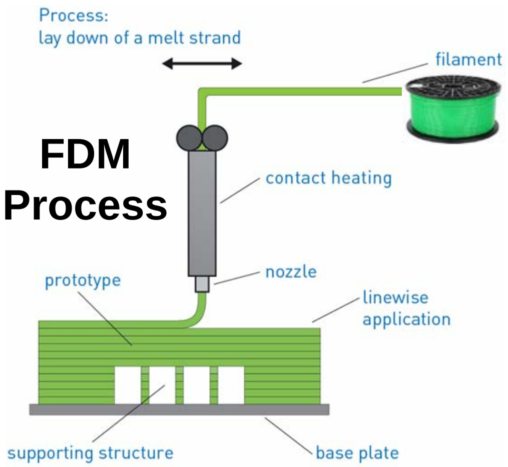






Multi-Material Tensile Testing

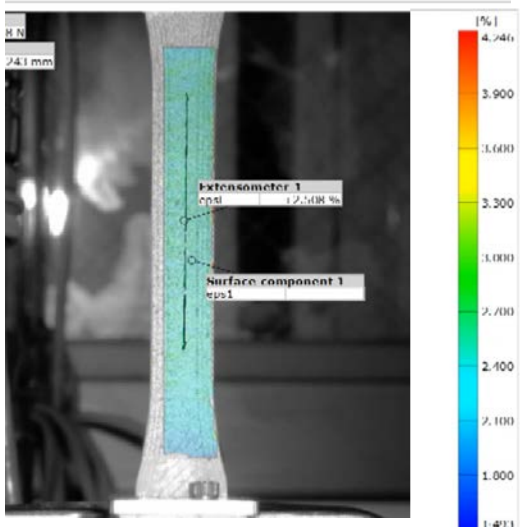
FDM Process



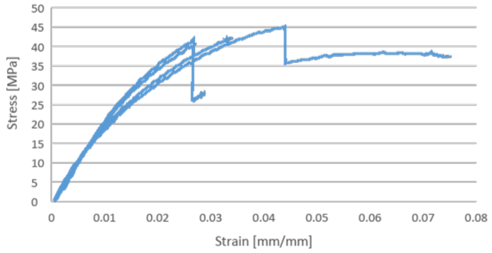
Hyrel Hydra 645

Multi-material print

Tensile Testing

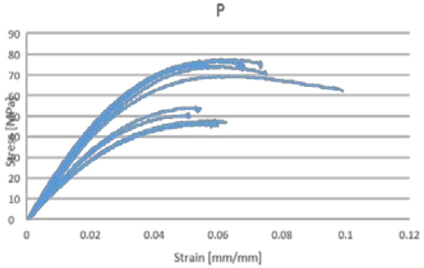


(DIC)

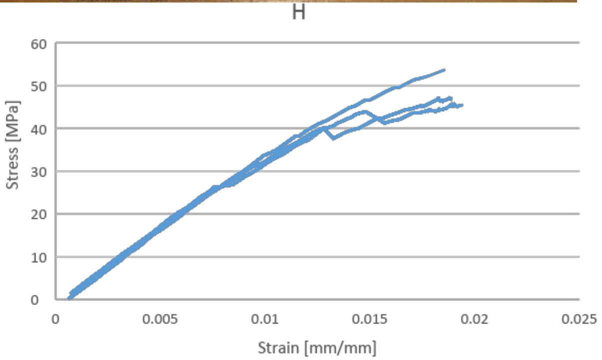


Single and Multi-Material Tensile Testing

SABIC 9085



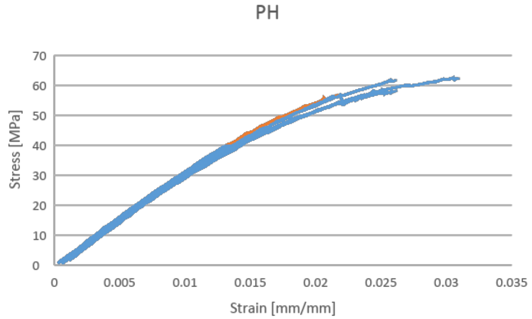
3DXTech Ultem 9085 CF



1=3DXTech Ultem 9085 CF
2=SABIC ULTEM AM9085F

SABIC 9085 + 3DXTech 9085 CF

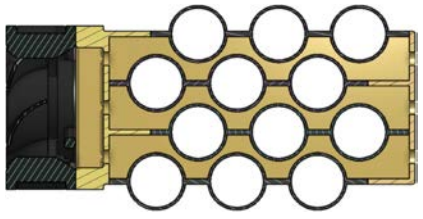
122122
121212
121212
122122
111222
111222



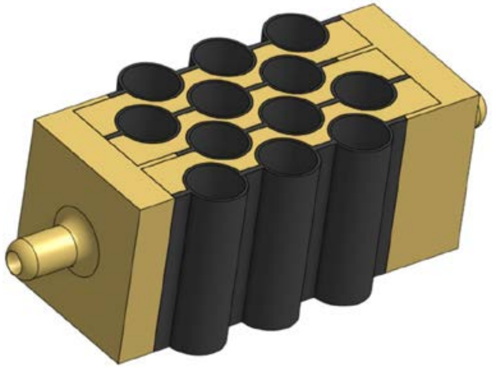
Material	Letter	Max Load [N]	Avg Load [N]	Max Ult [Mpa]	Avg Ult [Mpa]	Max Mod	Avg Mod	Avg STF
3DXTech Ultem 9085 CF	H	1992.1	1893.4	53.7	50.5	3380.5	3204.2	1.8974
SABIC ULTEM AM9085F	P	3163.6	2988.7	77.5	74.5	2395.3	2261.5	7.5265
SABIC 9085+3DXTech 9085 CF	PH	2679.0	2480.6	62.4	59.1	3082.6	3005.3	2.5691

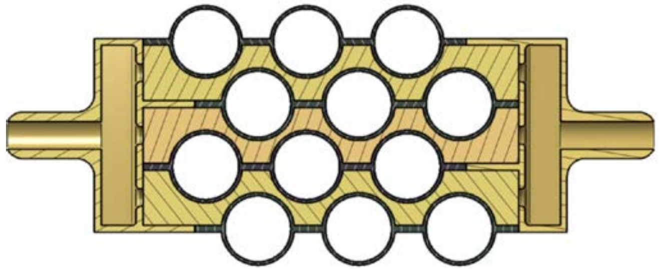
Multi-Material Heat Exchanger Designs

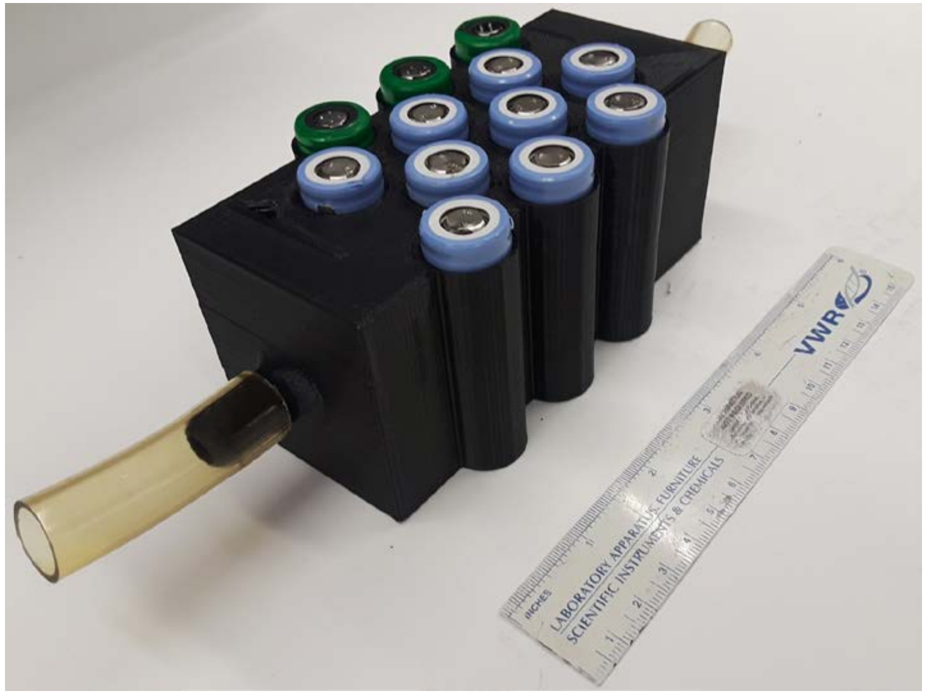
Forced Air Cooled



Liquid Cooled







Single Material Battery Case Demostrations

Conclusions

- Additive manufacturing enables advanced materials, structures, and components.
- AM of multi-materials in a single feed-stock allows for optimized properties and functionality, e.g. electrical conductivity, thermal conductivity, strength, etc.
- Achieving multi-material components requires hybrid and two-stage AM approaches.

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