Materials and Processes for New Propulsion Systems with Reduced Environmental Impact

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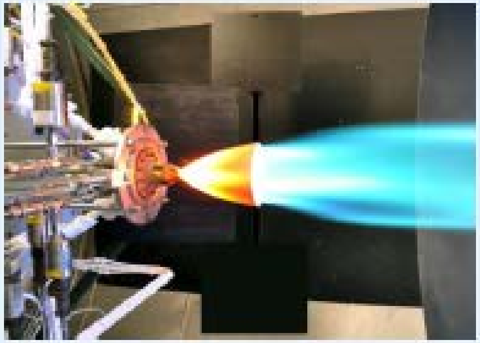
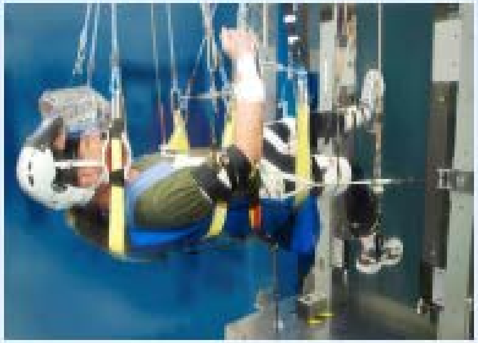
NASA Glenn Core Competencies

Air-Breathing Propulsion



In-Space Propulsion and Cryogenic Fluids Management



Physical Sciences and Biomedical Technologies in Space

Communications Technology and Development

Power, Energy Storage and Conversion

Materials and Structures for Extreme Environments

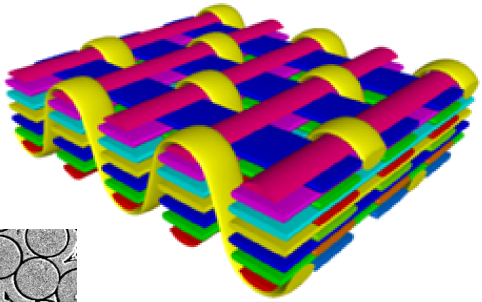
Presentation Topics

- **Ceramic Matrix Composites**
  - CMC development & characterization
  - Environmental Barrier Coatings
- **Polymer Matrix Composites**
  - Toughening for fan blade application
  - Lightweight hybrid Composite/Metal gear
- **Additive Manufacturing Applications**
  - Ceramic Matrix Composites
  - High Power Density Electric Motors

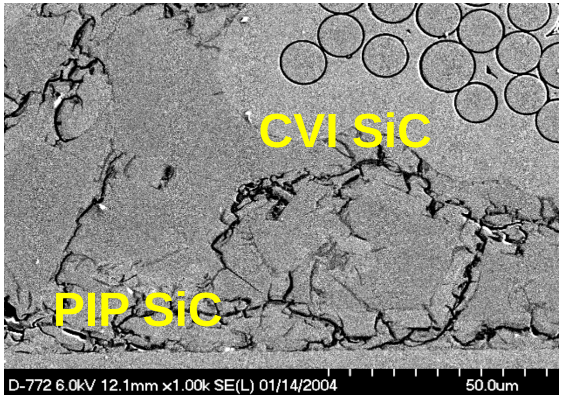
NASA 2700°F CMC combines three technology advancements

- Creep-resistant Sylramic-iBN SiC fiber

- Advanced 3D fiber architecture



- Hybrid CVI-PIP SiC matrix



Creep and fatigue tests demonstrated durability of 3D hybrid-matrix CMC at 2700ºF (1482ºC)

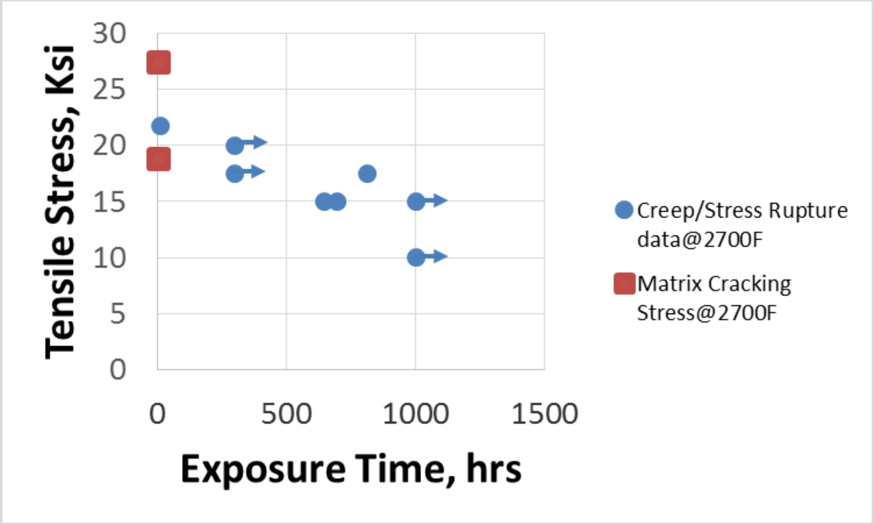
Challenge

Durable 2700°F Ceramic Matrix Composites will reduce cooling air required for turbine engine components, increasing engine efficiency and reducing fuel burn and emissions

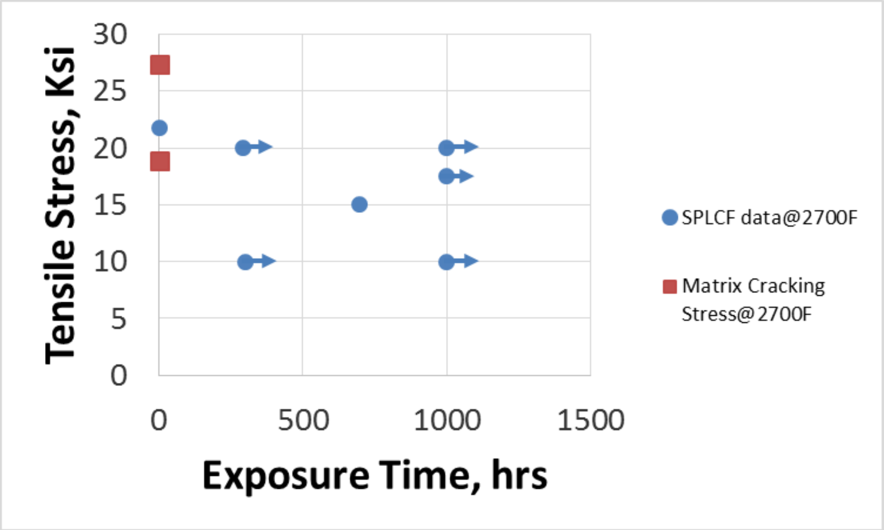
Approach

Characterize mechanical properties and durability of TTT-developed CMC at 2700°F

Creep Rupture



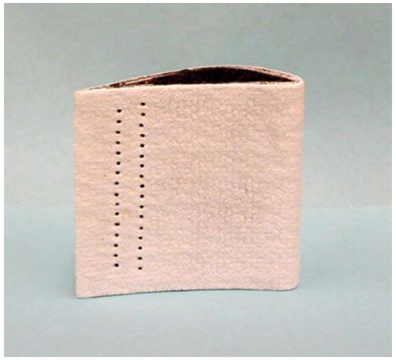
Fatigue (SPLCF)



CMC shows 1000 hours durability at 2700ºF and 20 ksi (138 MPa) in creep and fatigue

Contact: Ramakrishna.T.Bhatt@nasa.gov

Environmental Barrier Coatings are needed

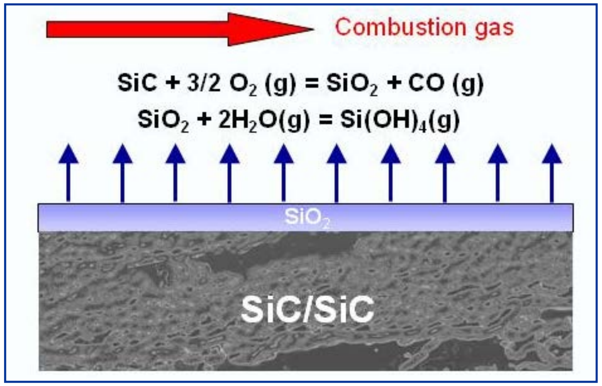


Higher temperature capability

- Mechanical properties (creep rupture, fatigue)
- Oxidation resistance
- Reduced cooling and/or higher turbine inlet temperature

Lightweight

- 1/3 of Ni-based superalloys

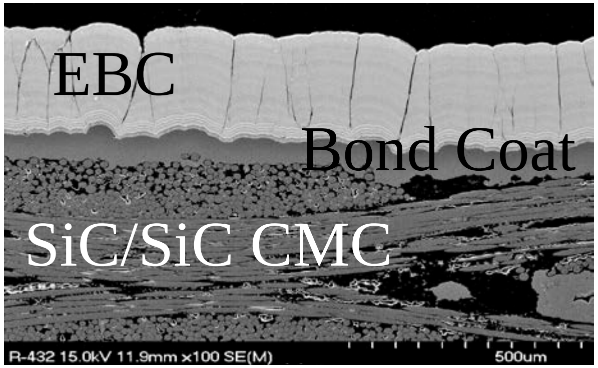


Performance Benefits

- Reduced fuel Consumption
- Higher Thrust
- Reduced Nox and CO emissions

SiC materials limited by water vapor attack

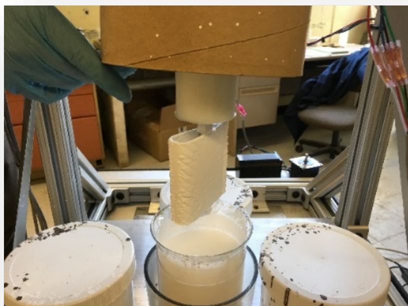
- SiO_2 scale reacts w/ H_2O to form hydroxide species
- Results in severe recession of component



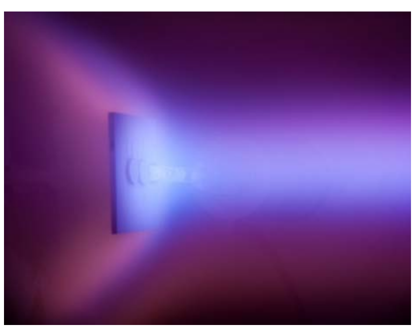
Without EBC, SiC matrix material reacts with H_2O to cause recession and failure of SiC-based CMC

Progress toward a durable 2700ºF CMC / EBC system

PS-PVD & Slurry Coat Process for Turbine Airfoils

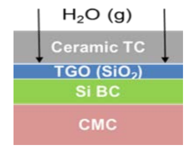


Slurry provides economical, non-line of sight, and chemistry friendliness. PS-PVD is a hybrid process (plasma and/or vapor) that provides variable microstructure along with non-LOS .

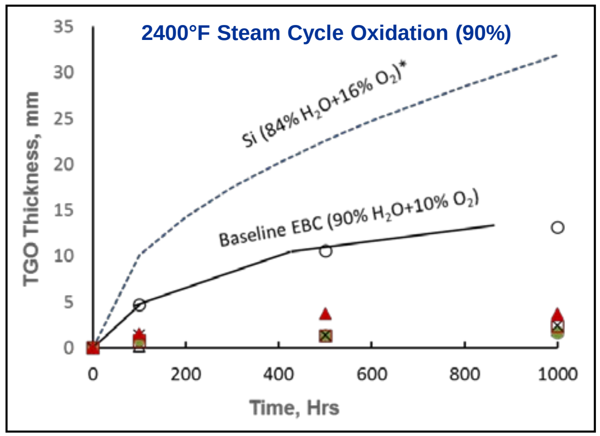


APS $Yb_2Si_2O_7$ EBC Modified for Long Life

- TGO is life-limiting failure mechanism for SOA 2400 F EBC
  - Gen 2 – Si/YbDi
  - H_2O primary Ox
  - TGO from Si BC

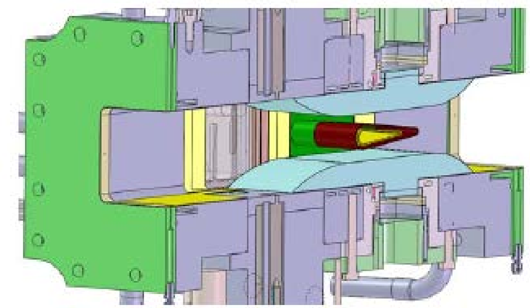


- Al_2O_3/TiO_2 known to reduce diffusivity in SiO_2
- Investigate effect of modifier oxides on TGO growth rates in $Yb_2Si_2O_7$



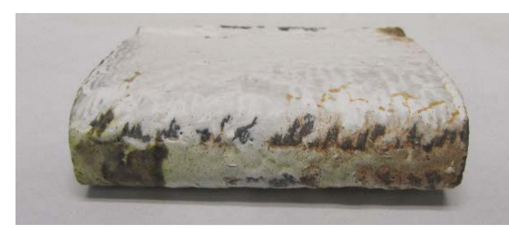
- Modified EBCs reduced TGO by 80%
  - ~20x life to reach TGO t_{fail}
- Hypothesis: modifiers dissolve in SiO_2 TGO, modify structure, decrease Ox
  - Patents & more studies ongoing

Durable CMC / EBC demonstrated in 2700ºF turbine environment



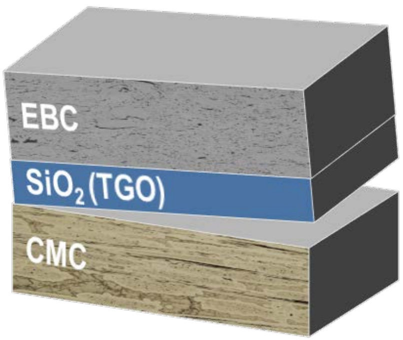
Cooled CMC / EBC Airfoils Evaluated in Turbine Rig Tests

- *Synergy of failure mechanisms*
- *(3) Test Articles, 45 hours total*
- *Compared in-house against commercial EBCs*

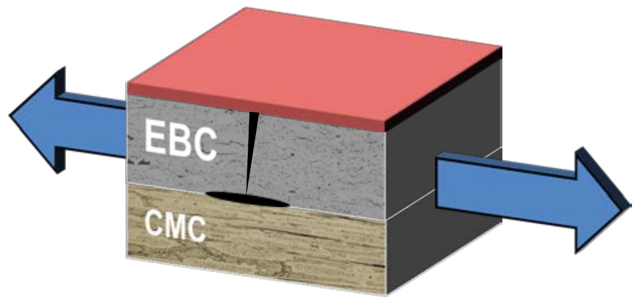


Fundamental Durability Tests Characterize EBC Failure Modes

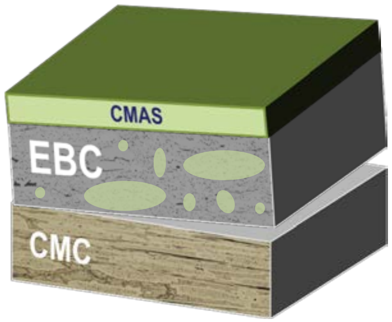
damage mechanisms are incorporated into life prediction models



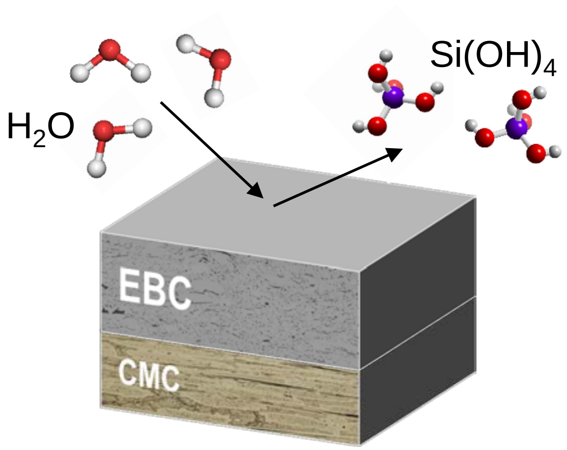
Steam Oxidation



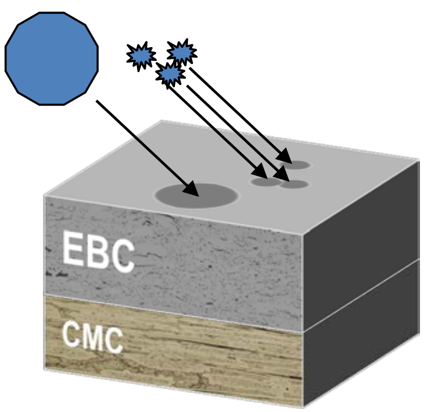
Thermomechanical Durability



CMAS Attack & Infiltration



Hydroxide Formation/Recession

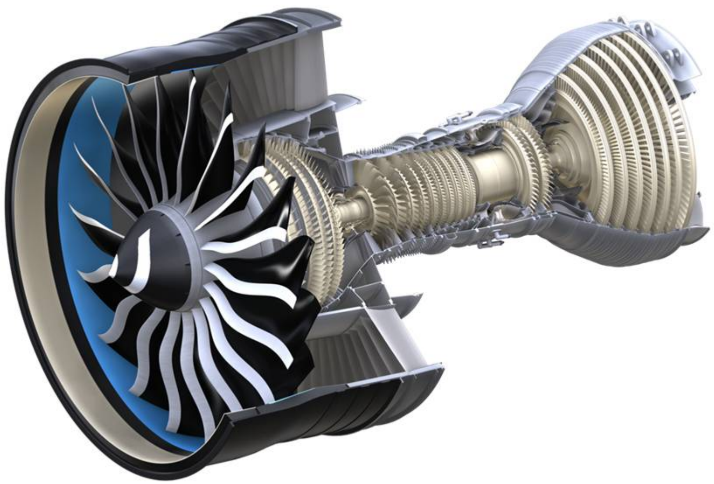


Erosion and FOD

K. N. Lee, "Environmental Barrier Coatings for CMC's"; in *Ceramic Matrix Composites*, Wiley, New York (2015)

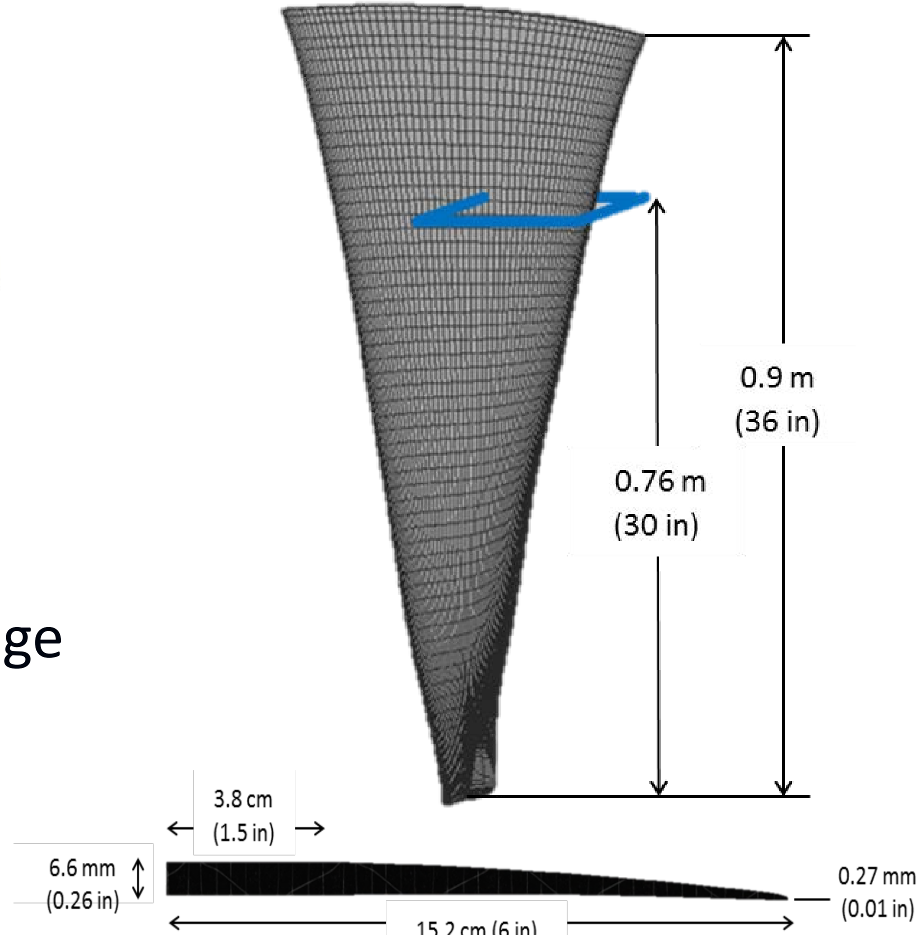
Polymer Matrix Composites:

Fan Blade Application



Challenge: reduce impact damage without sacrificing in-plane properties or manufacturability

Fan Blade Test Article



Tapered cross section

Thermoplastic Veil Interleave

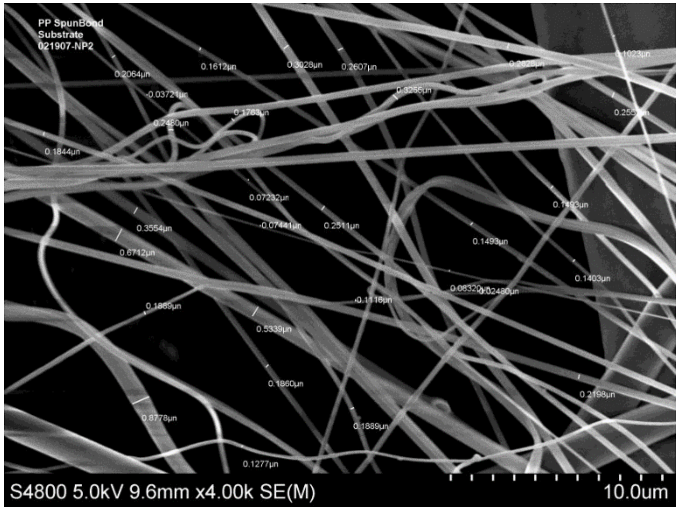
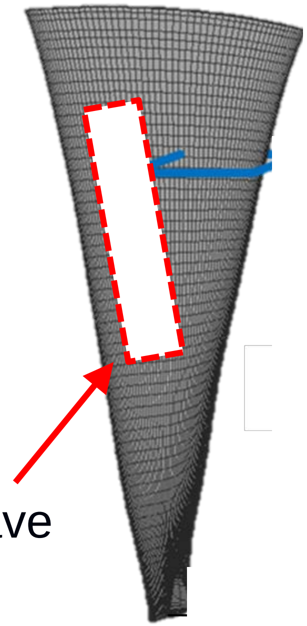


Photo courtesy of
www.hillsinc.net/Fibers



interleave

- Melt-spun thermoplastic polyurethane veil was procured from Hills Inc, of Melbourne, FL.
- Veil areal weight: 15 gsm
- Average diameter on the sub-micron scale. (70 – 150 nm)
- Benefit to veil approach: Reinforcement is placed where it provides the most benefit.

Toughened Fan Blade Has Reduced Impact Damage

Baseline IM7/8551-7 test article leading edge damage after impact

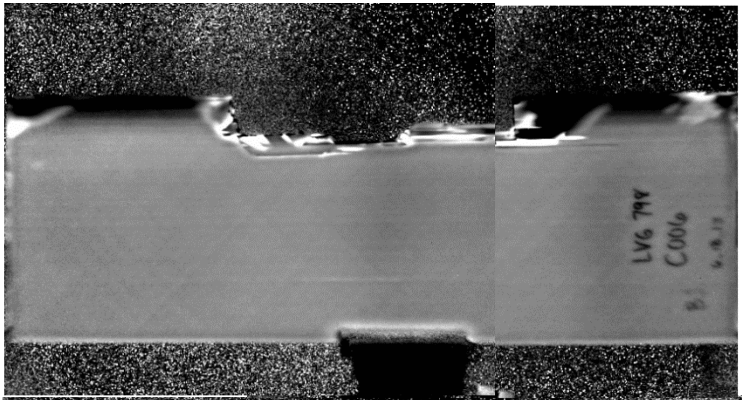
Test article **toughened** with thermoplastic polyurethane veil between plies

Post-impact thermography

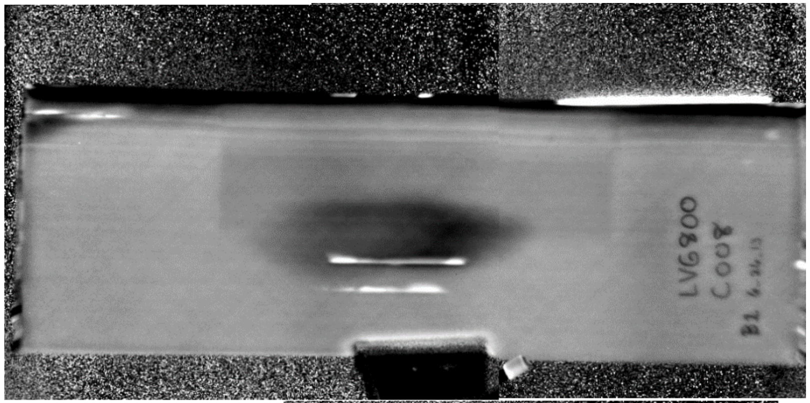
impact location

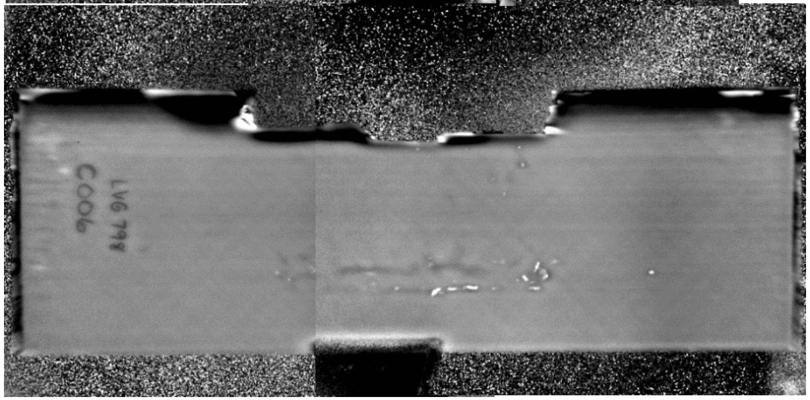
baseline test article (IM7/8551-7)

toughened test article (w/ thermoplastic veil)

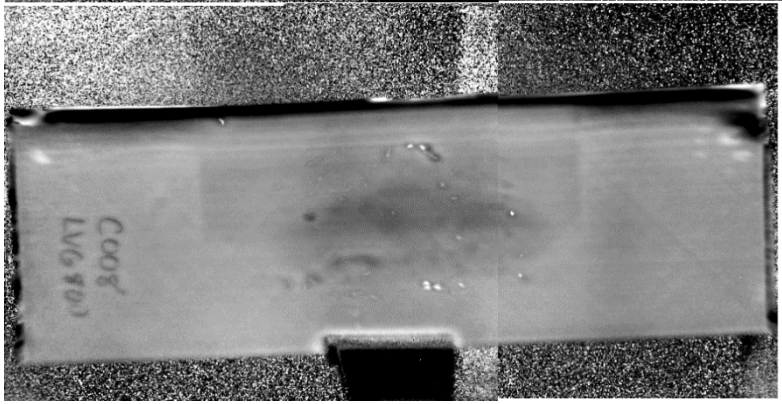


bottom side



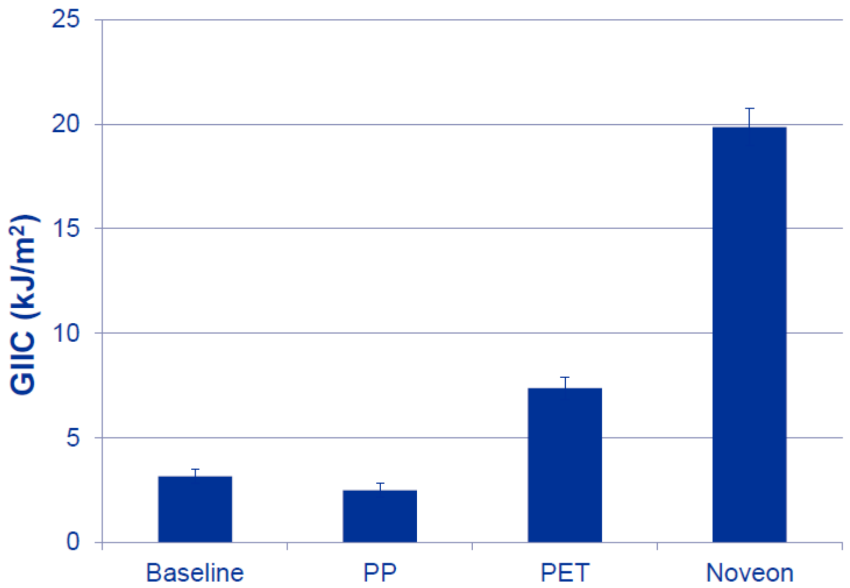


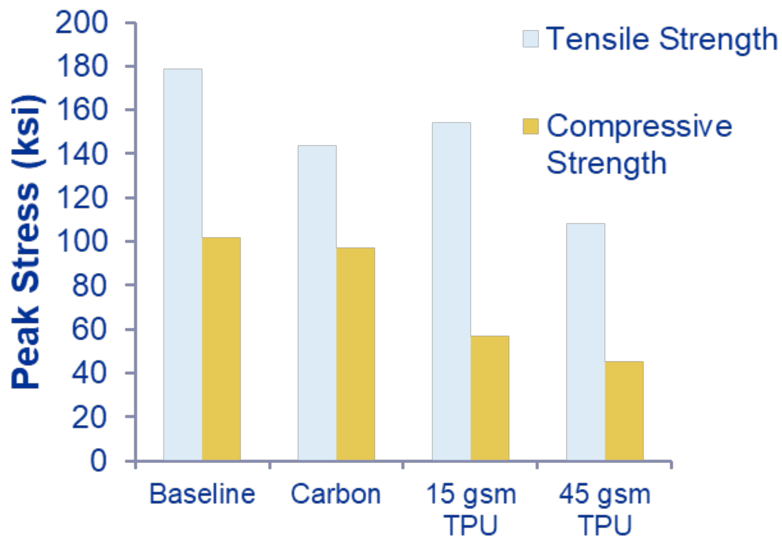
top side



Thermoplastic veil interleave distributes impact energy more effectively in toughened composite (right side)

Toughness vs. strength tradeoff

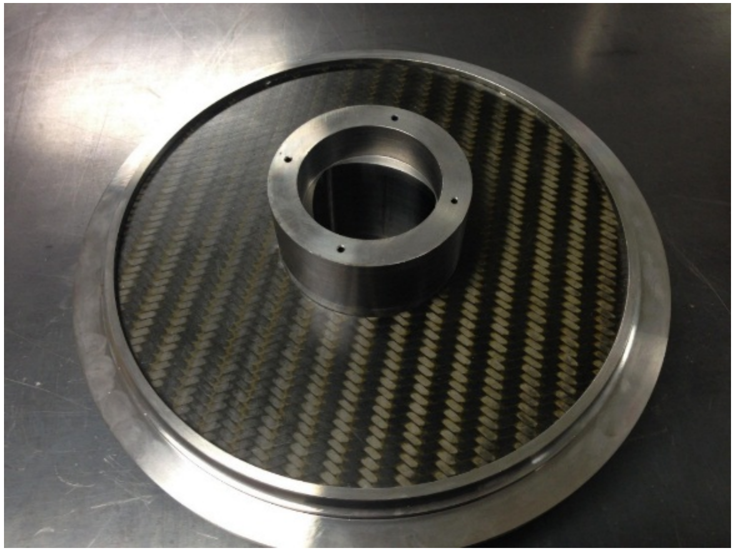




Noveon TPU interleave resulted in a 7- fold increase in Mode II fracture toughness.

Tension and Compression Data shows a drop of in-plane performance with increasing areal weight of veil

Hybrid Composite-Steel Gear for Rotorcraft



Objective: Replace steel web helicopter gear with composite to reduce weight and noise due to vibration.

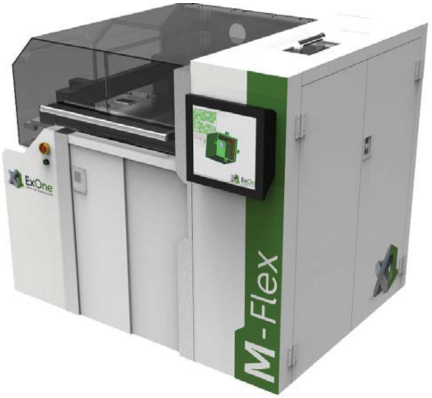
Challenge: Hybridization of dissimilar materials without sacrificing performance

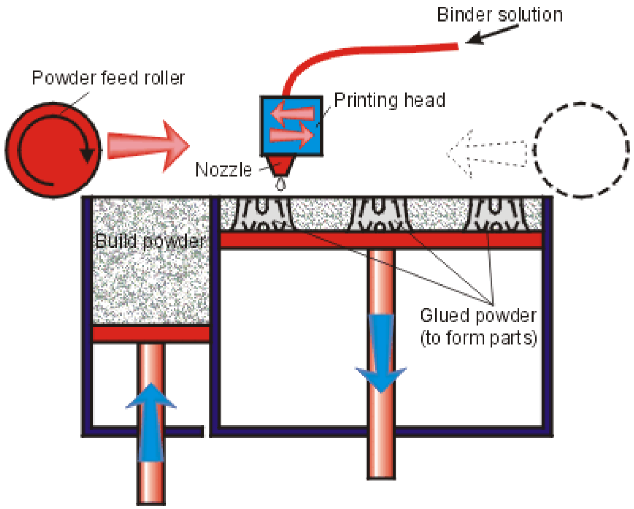
“hybrid” gear
(15% weight reduction)

Challenges:

- *Processing considerations at the flange in particular- low void, low wrinkling.*
- *Ensure high quality laminates in complex architectures*
- *Reduce processing time and cost while maintaining aerospace grade performance.*

Additive Manufacturing: GRC Composites Research



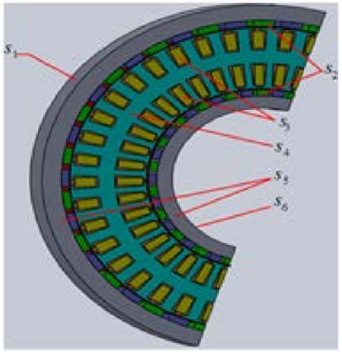


ExOne M-Flex Binder Jet machine:

Powder bed process with *tailored binders* and *chopped fibers* for CMC fabrication

n-Scrypt direct printing machine:

- Multi-material systems
- Ceramic pastes, electronic pastes, adhesives, solders, plastics



Multi-material stator for high power density electric motor

The first CMC turbine engine components by additive manufacturing

high pressure turbine nozzle segments

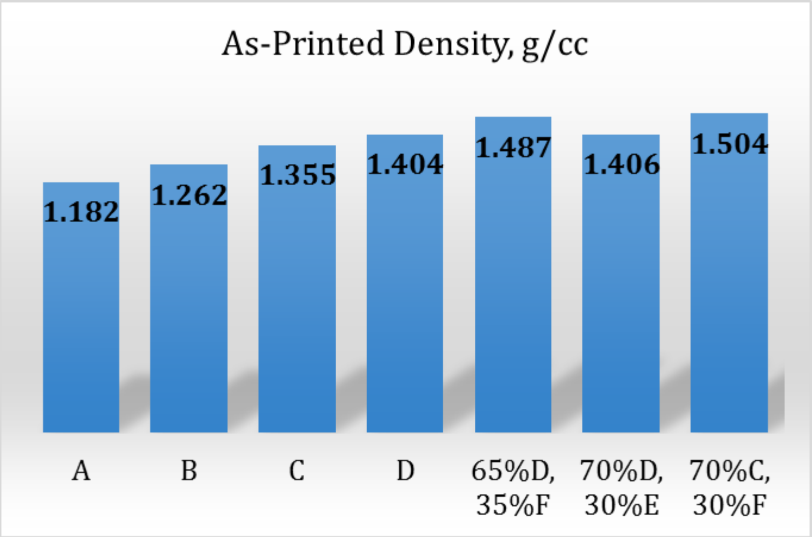
first stage nozzle segments

cooled doublet nozzle sections

contact: michael.c.halbig @nasa.gov

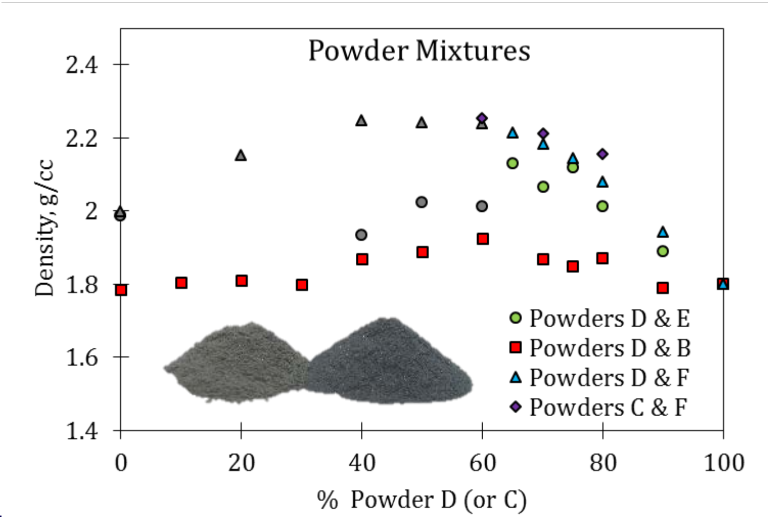
SiC/SiC CMCs have 20% chopped SiC fiber

Densification of Binder Jet Fabricated SiC

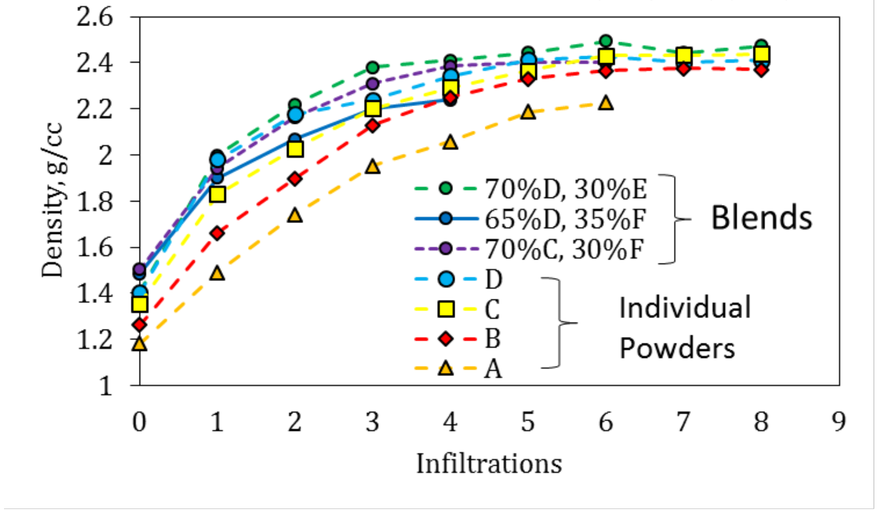


Binder Jet Machine

Density of Green Printed SiC



PIP Densification



Contact: Craig.E.Smith@nasa.gov

Additive Manufacturing for Electric Motor Fabrication

Objective: Use additive manufacturing methods to fabricate electric motors with higher efficiency and power density

Approach:

- Use Direct Printing and Electron Beam Freeform processes to build lightweight and compact rotor, stator & motor housings for advanced motors
- Measure improvements in motor efficiency and power density compared to baseline SOA motor

Urban Air Mobility Application

Baseline Motor:
7.5-inch diam and 4 lbs

Advanced Motor Design with AM components

AM motor design enables a 2x increase in power density (8 kW/kg)

LAUNCHPOINT TECHNOLOGIES

UTEP

Contact: Michael.C.Halbig@nasa.gov

Motor components optimized for power density using Additive Manufacturing methods

**Baseline motor:
power density = 4 kW/kg**

reduced weight of structural housing 67%

optimized fabrication process for wire-embedded stator

integrated airfoil-shaped cooling fins into motor housing

power density doubled to 8 kW/kg using Additive Mfg methods to fabricate motor components

Summary

NASA Glenn Research Center has recently demonstrated a range of new high temperature and lightweight materials technologies to enable reduced emissions and fuel burn in aircraft engines, including:

- Ceramic Matrix Composites and Environmental Barrier Coatings for 2700^{o}F turbine operation, reducing the need for cooling air and increasing engine efficiency
- A toughened Polymer Matrix Composite that significantly reduces impact damage in fan and nacelle structures
- A hybrid composite/steel gear concept that reduces gear weight by 15%, demonstrating feasibility of multi-speed drive systems for power transmission in rotorcraft
- New Additive Manufacturing processes to fabricate components that double the SOA power density (to 10 kW/kg) of UAV electric motors