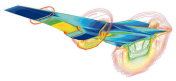

Advanced CMCs, Additive Manufacturing, and Joining/Integration Technologies

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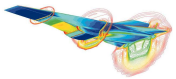
Hypersonic Propulsion Materials and Structures Workshop

NASA Glenn Research Center

May 1-3, 2019



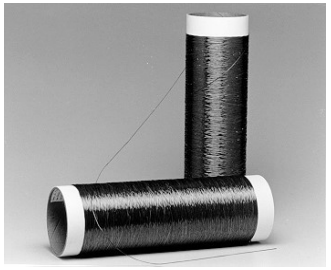
Outline of Presentation

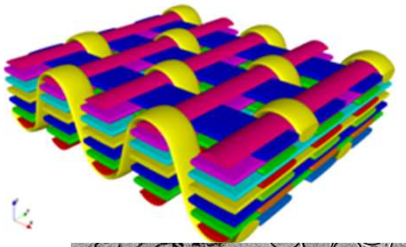
- Overview of CMC Research Capabilities
- Additive Manufacturing Capabilities
  - Laminated Object Manufacturing (LOM)
  - Binder Jetting/3-D Printing/Extrusion
  - Direct Writing of Sensors/Actuators
  - Multi-Materials Additive Manufacturing
- Extensive Expertise in Joining and Integration Technologies
  - Composite-Composite System
  - Composite-Metal Systems
  - Design and Testing
- Robust Refurbishment/Repair Technologies
  - Shuttle RTF Experience
  - Gaskets/Sealants
- Summary and Conclusions

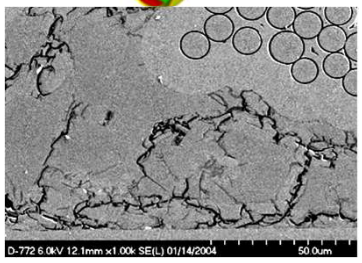
GRC Has Extensive Expertise and Capabilities in High Temperature CMCs

NASA 2700°F CMC combines three technology advancements

- **Creep-resistant Sylramic-iBN fiber**
- **Advanced 3D fiber architecture**
- **Hybrid CVI-PIP SiC matrix**







CMC research includes material development, life prediction and experimental validation

Durable SiC/SiC CMC / EBC System Demonstrated in 2700°F Turbine Environments

Challenge

A durable 2700°F Ceramic Matrix Composite with Environmental Barrier Coating would reduce cooling air required for turbine engine components, increasing engine efficiency and reducing fuel burn and emissions

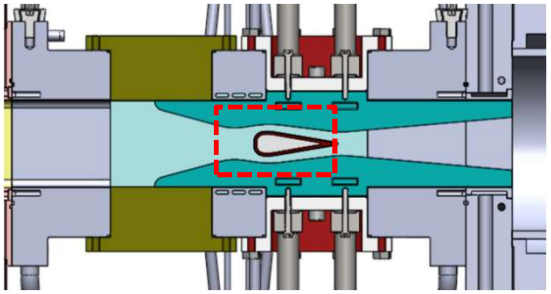
Approach

- Fabricate turbine vane test article from 2700ºF CMC recently developed in TTT
- Coat CMC test article with Environmental Barrier Coating, using two different EBC processing methods
- Evaluate durability of CMC / EBC subelements in a TRL 5 rig test simulating a turbine environment, at temperatures to 2700ºF

Significance

For the first time, a durable CMC/EBC material system was demonstrated at TRL 5 in a 2700ºF turbine environment. Engine implementation could reduce fuel burn 6% in B737-size aircraft

Contact: Ramakrishna.T.Bhatt@nasa.gov



Turbine test rig used by P&W / UTRC

Spall of EB-PVD coating after 7 hours of 2700F cycles

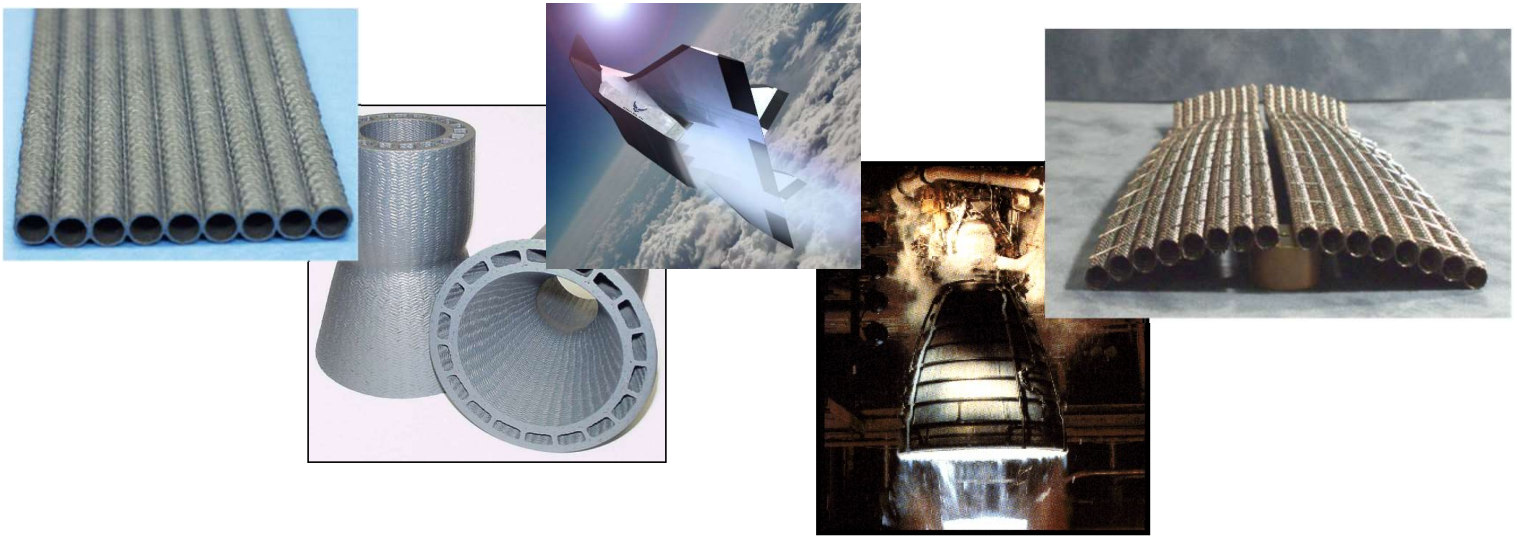
Durable slurry-coated test article after 15 hours at 2500 / 2600 / 2700°F

Key Accomplishment

Demonstrated 15-hour durability for a CMC/EBC system with minimal spallation of the coating under simulated engine operating conditions at temperatures to 2700ºF

Cooled CMC Development at NASA

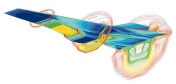
Test capabilities include actively cooled CMC subelements with built-in coolant channels



- **Lighter weight than metallic designs: up to 50% weight reduction**
- **Increased operational margin: enhanced range and/or payload**

Contact: Martha.H.Jaskowiak@nasa.gov

Additive Manufacturing of 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 are 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

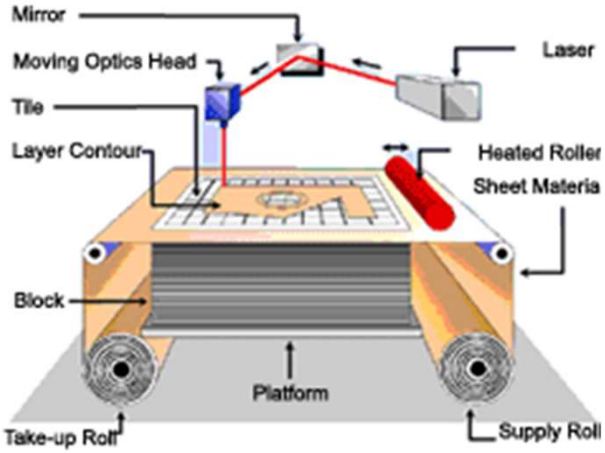
- Property and behavior of starting materials
- Sintering and densification challenges
- Process modeling
- Mechanical behavior
- NDE and in-situ damage characterization
- Material and property databases

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

Laminated Object Manufacturing (LOM) For Silicon Carbide-Based Composites

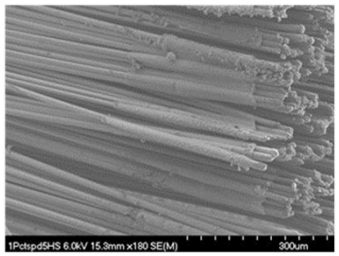


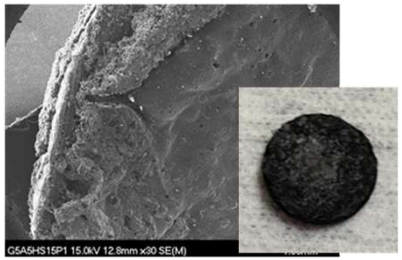
LOM allows for continuous fiber reinforced CMCs.

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

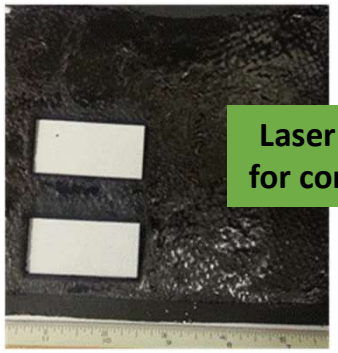
Prepregs for Composite Processing

- 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)

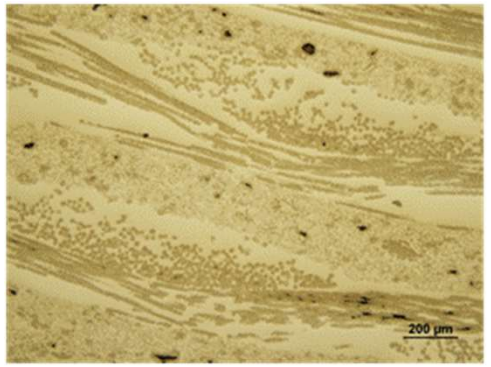




Fabrics and Prepregs cut at different laser powers/speeds

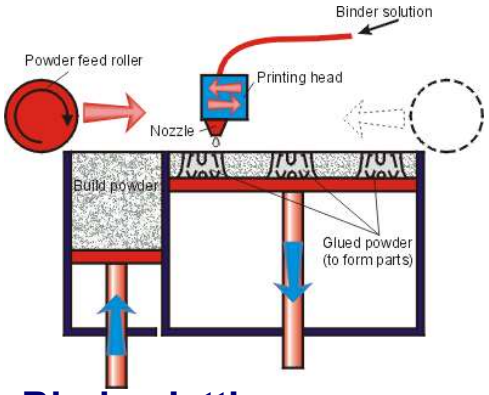


Laser cut prepregs used for composite processing



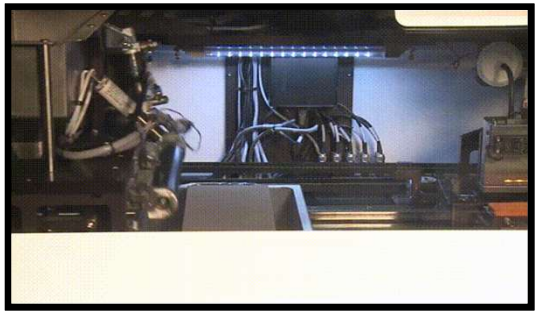
Silicon Infiltration:
1475°C, 30 minutes in vacuum

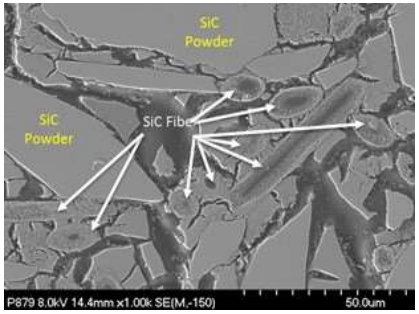
Additive Manufacturing of Ceramics Using Binder Jetting



Binder Jetting process

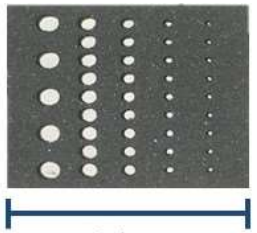
ExOne's Innovent System





Chopped Fiber Reinforced Ceramic Matrix Composite

High pressure turbine nozzle segments: cooled doublet vane sections.

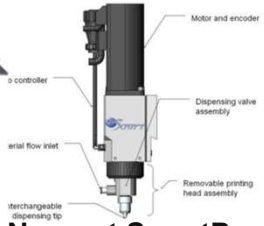


AM SiC with 500 µm diameter holes

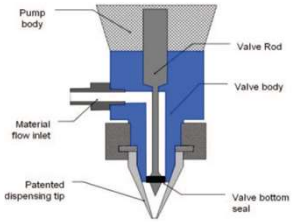
AM SiC with 1.5 mm channels

Direct Writing Technologies for Sensors/Embedded Systems

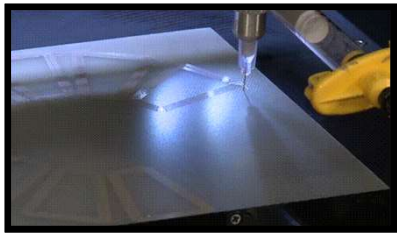
NScrypt Direct Write Printer

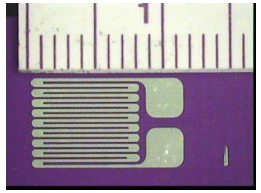


Nscrypt SmartPump



SmartPump Valve Assembly

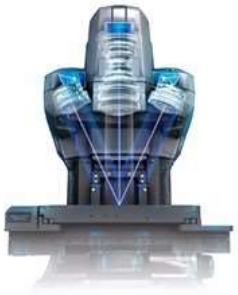




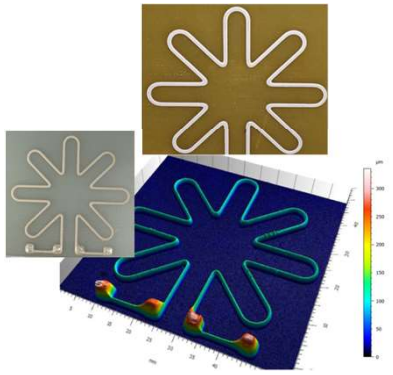
Printed strain gages.

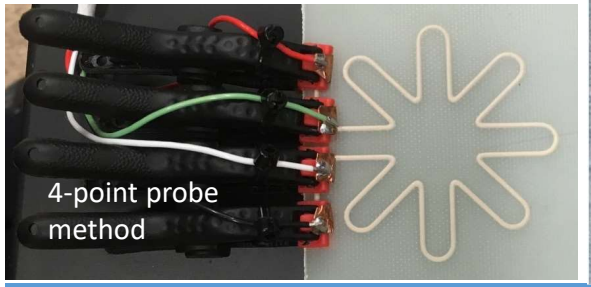
NScrypt Capabilities and Benefits

- 300x300x150mm Gantry XYZ Platform
- SmartPump with 100 Picoliter Volumetric Control
- Ability to host up to four separate materials.
- Print on curved surfaces and 3D structures.
- Precise motion control and micro-dispensing of materials.
- Direct writing with clean starts and stops (no contact or masks as for screen printing).
- Ability to print a wide variety of ceramic pastes (structural and functional), electronic pastes, adhesives, solders, bio-materials.



Keyence VR 3200 Profilometer

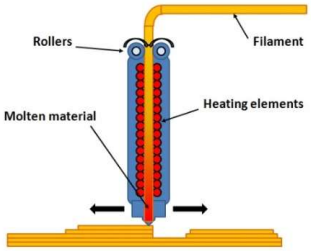




Thin Surface and Imbedded Thick 4-Pt Probe Windings

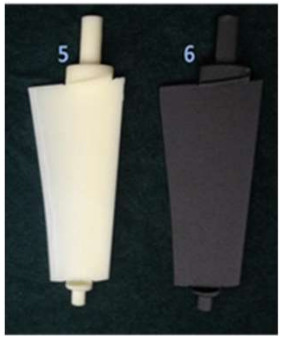
Additive Manufacturing of Polymers and PMCs for Multifunctional Applications

Industrial scale FDM systems (Stratasys)



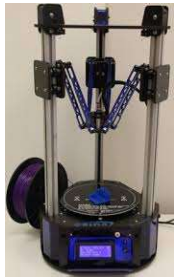
Process Schematic

Engine Panel Access Door



Engine Inlet Guide Vanes from ABS and Ultem 1000

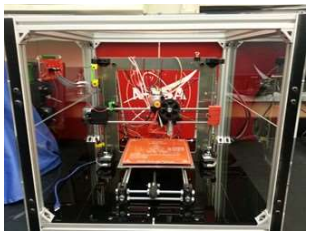
MakerBot Replicator 2X



Orion Delta 3D Printer

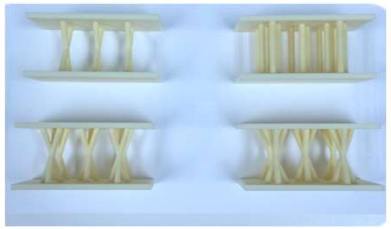
Rostock 3D Printer

Variable Geometry Panels for Acoustic Treatment

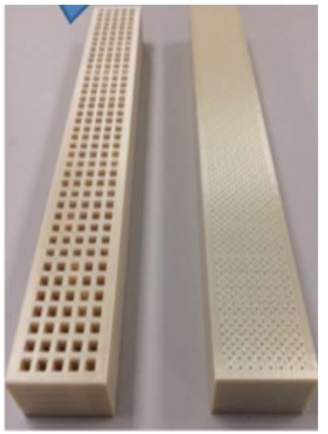


"RepRap is humanity's first general-purpose self-replicating manufacturing machine". www.reprap.org

Turbine Blade Shape Demo



Lightweight Structures



Acoustic Liners

ARCJoinT: Joining of Ceramic Components Using Affordable, Robust Ceramic Joining Technology (ARCJoinT)

Apply Carbonaceous Mixture to Joint Areas

Cure at 110-120°C for 10 to 20 minutes

↓

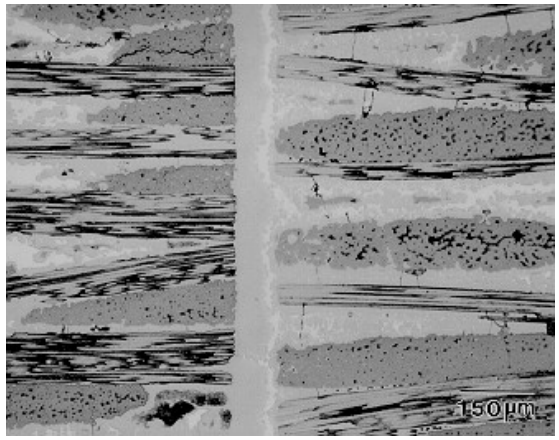
Apply Silicon or Silicon-Alloy (paste, tape, or slurry)

Heat at 1250-1425°C for 10 to 15 minutes

↓

Affordable and Robust Ceramic Joints with Tailorable Properties

1999 R&D 100 Award
2000 NorTech Innovation Award



Joined MI C/SiC Composite

Advantages

- Joint interlayer properties are compatible with parent materials.
- Processing temperature around 1200-1450°C.
- No external pressure or high temperature tooling is required.
- Localized heating sources can be utilized.
- Adaptable to in-field installation, service, and repair.

Very good quality, high strength bonds are obtained.

Integration of Metals to Ceramics and Composites Using Metallic Interlayers

Active Metal Brazing
Soldering

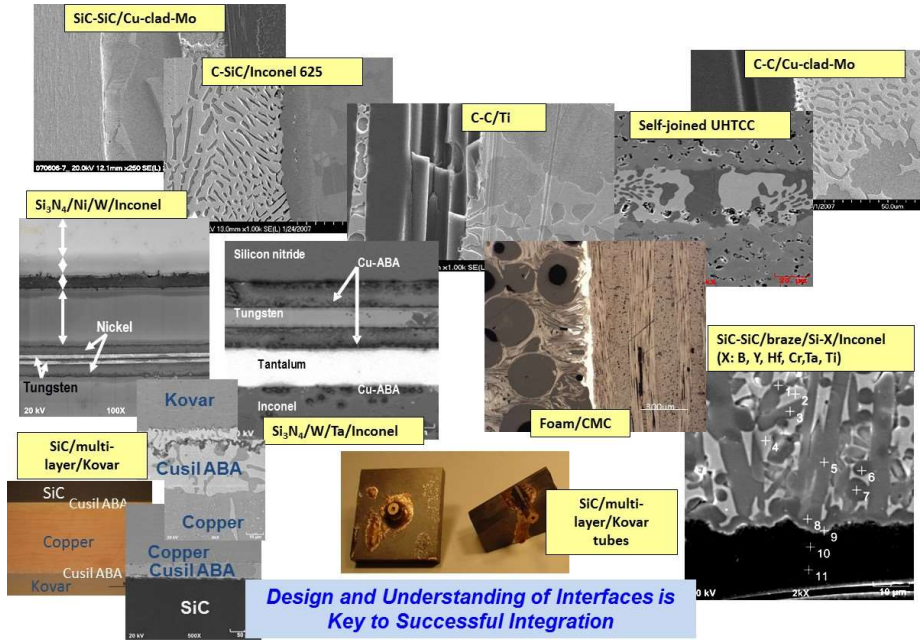
Metallic Systems
- Titanium
- Inconel and Other Ni-Base Superalloys
- Kovar, Cu-Clad Mo,
- Stainless Steels, W

Ceramics/Composite
- SiC, Si3N4
- YSZ, Alumina
- UHTCs and UHTCMCs
- C/C Composites
- C/SiC, SiC/SiC

Interlayer Systems
- Active Metal Brazes (Ag, Cu, and Pd based)
- Metallic Glass Ribbons
- Solders (Zinc based)

Technical Issues
- **Melting range / behavior**
- **Wetting characteristics**
- **Atmosphere compatibility**
- **Compositional compatibility**
- **Cost & availability**

Interfacial Microstructure of Integrated Ceramic-Ceramic and Ceramic-Metal Systems

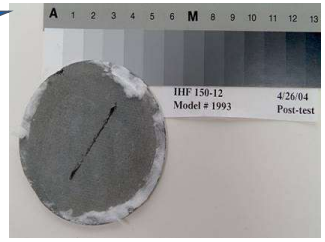


Glenn Refractory Adhesive for Bonding and Exterior Repair (GRABER)- *Space Shuttle RTF Program*

Arc Jet Testing Front View

Arc Jet Testing Side View

Post Test- Front Side



Post Test- Back Side

Multiuse Capability/Versatility of GRABER

- Repair of cracks, gouges, small holes, and missing surface coatings
- Edge sealant/adhesive for Plug concept
- Gap filler for T-seals and other areas
- Sealing the edges, gaps, attachment areas for flexible ceramic/metallic wrap concepts for large area damage repair
- Prepregs made with various ceramic fabrics are useful for various high temperature applications in aerospace and ground based systems.

- **Analogue RCC Plug Sealed with GRABER 5A Crack Sealant**
- **Survived the ArcJet Testing at JSC**

- **2005 R&D 100 Award**
- **Northern Ohio Live Magazine- Awards of Achievement, S&T Category- Runner Up**

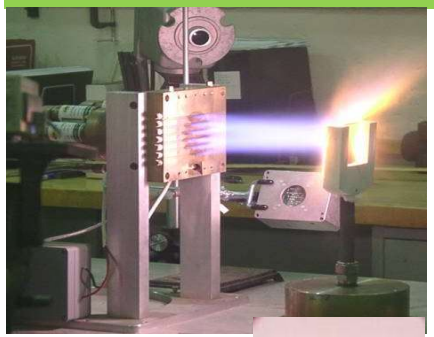
Flexible Gaskets for Hypersonic Applications

GRC 11 Gaskets made from RTV foam

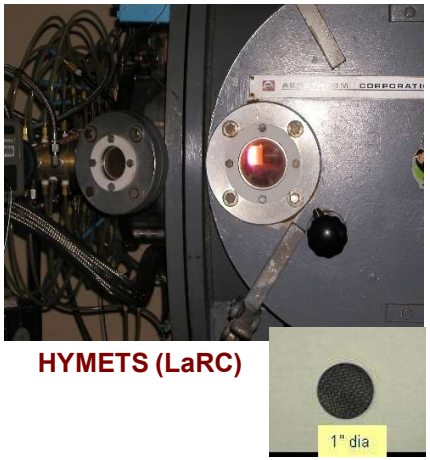
GRC 16 Gaskets made from Ablative polymer

GRC 17 Gaskets made from silicone based RTV polymer

These gaskets have shown excellent plasma performance in various facilities under re-entry and hypersonic conditions.



QARE Testing at GRC



HYMETS (LaRC)

ArcJet Testing at ARC and LCAT

Of course .....We have also worked on UHTCs

Journal of the European Ceramic Society 22 (2002) 2757-2767
www.elsevier.com/locate/jeurceramsoc

Evaluation of ultra-high temperature ceramics for aeropropulsion use

Stanley R. Levine[a,*], Elizabeth J. Opila[b], Michael C. Halbig[c], James D. Kiser[a], Mrityunjay Singh[d], Jonathan A. Salem[a]

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[b]*Cleveland State University, Cleveland, OH 44135, USA*
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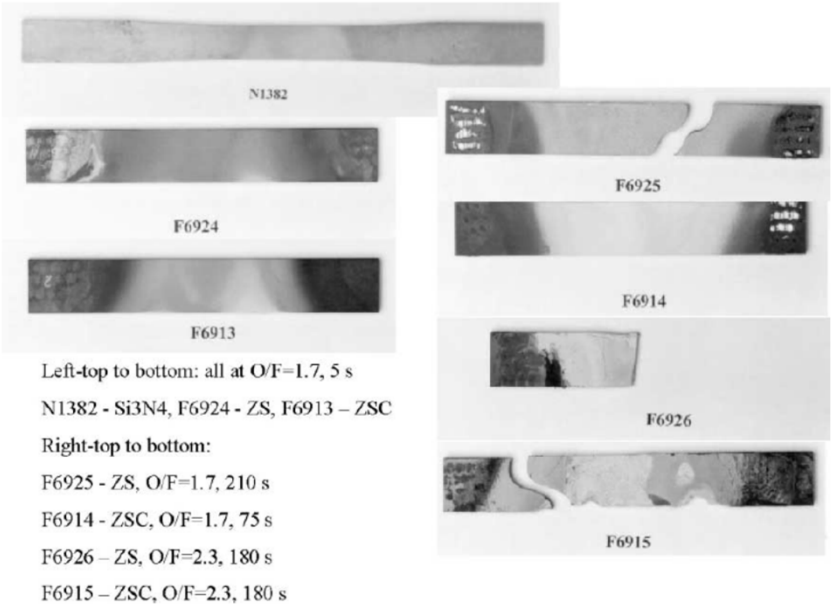
[d]*QSS Group Inc., USA*

Received 20 October 2001; received in revised from 20 January 2002; accepted 20 February 2002

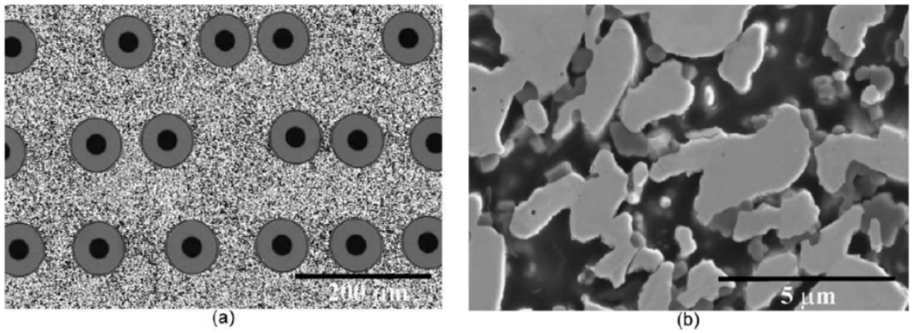
https://www.sciencedirect.com/

The 2002 paper was among the 25 most downloaded papers in 2011 from Elsevier's Sciverse ScienceDirect and currently has ~673 citations (Google Scholar).

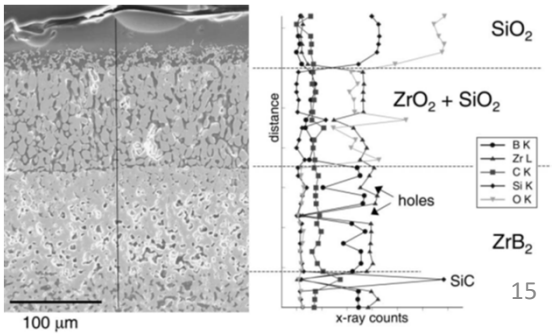


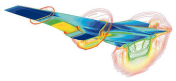
Photographs of specimens tested in thermal shock.

Microstructure of polished sections of ZrB2 plus 20 v/o SiC plus SCS-9a fibers composite showing (a) representative fiber distribution and (b) matrix porosity.



SEM micrograph and XEDS line scan of ZS after oxidation in air at 1627 °C for 10 10-min cycles.





Summary

- GRC has extensive experience in development and implementation of CMCs in various aerospace systems.
- 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.
- Joining and Integration technologies, gaskets and sealants, as well as repair and refurbishment are also keys for Hypersonic applications.