



Cyclic Fatigue Durability of Un-coated and EBC Coated 3D SiC/SiC Composites under Thermal Gradient Conditions at 2700°F in Air

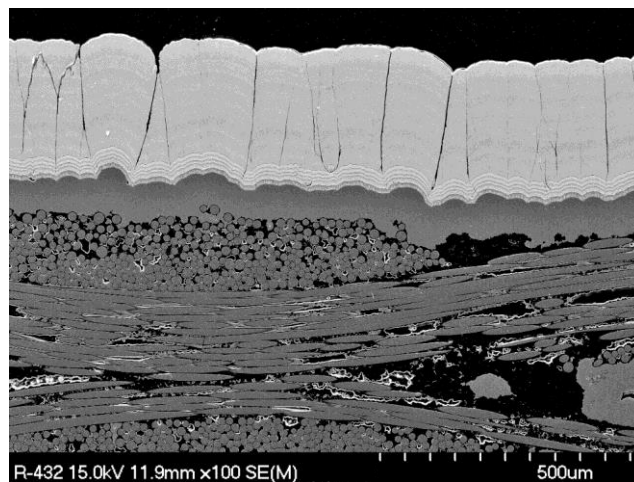
Craig Smith, Bryan Harder, Dongming Zhu
NASA Glenn Research Center, Cleveland, OH

Ramakrishna Bhatt, Sreeramesh Kalluri
Ohio Aerospace Institute, Cleveland, OH

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Material

- SiC/SiC CMC
 - Sylramic-iBN fibers
 - 3D orthogonal weave
 - Hybrid matrix
 - Chemical vapor infiltrated (CVI) SiC
 - Polymer infiltration and pyrolysis (PIP) SiC
- Silicon-Hafnia bond coat
- Rare Earth Silicate EBC deposited by Electron Beam Physical Vapor Deposition (EBPVD)



EBC

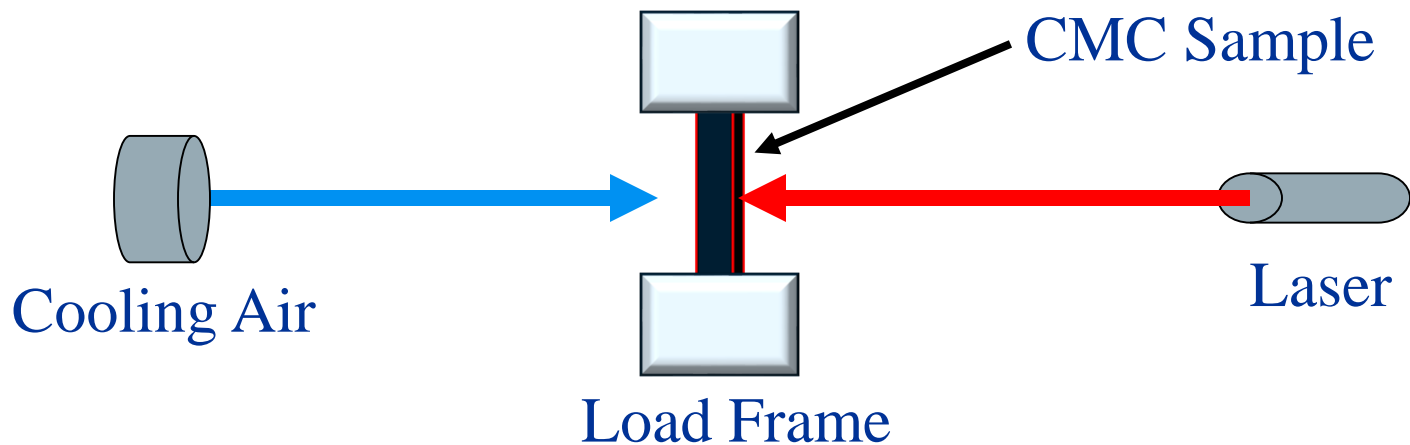
HfO₂-Si Bond Coat

SiC/SiC CMC



Objective

- Explore the durability of CMC/EBC system in air
 - Future tests will be done in steam
- Thermal gradients are representative of the conditions within a cooled CMC component
- What we want to determine
 - What is the failure mechanism?
 - Will the EBC protect from oxygen diffusion?





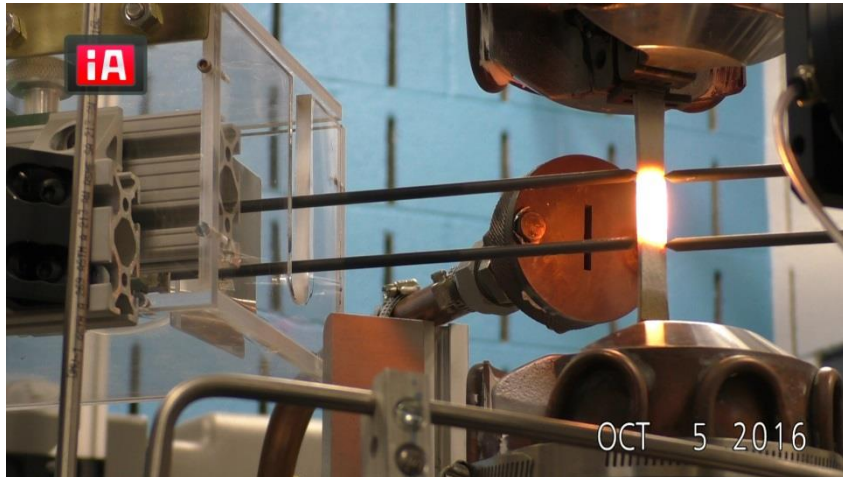
Fatigue Testing of CMCs under Thermal Gradient Conditions

Laser Test Rig

- Laser Heating (4000 W) on Front (0.8 inch spot size)
- Backside Air Cooling
- Surface Temperature Measured with Pyrometers and/or IR Camera
- Surface Temperatures up to 3000 °F (Material Dependent)
- Thermal Fatigue and Combined Thermal Gradient and Axial Fatigue



- Uncoated SiC/SiC Composites
- EBC Coated SiC/SiC Composites



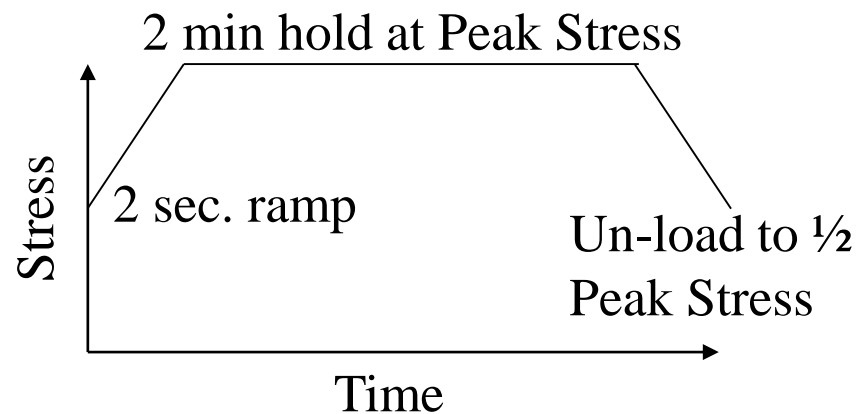
- Servohydraulic , 25 kN Load Cell
- Water-cooled Wedge Grips
- Two 1 in. Gage Length, Water-Cooled Extensometers; 6 in. Long Tensile Specimens
- Frequencies up to 30 Hz
- Load and Stroke Control



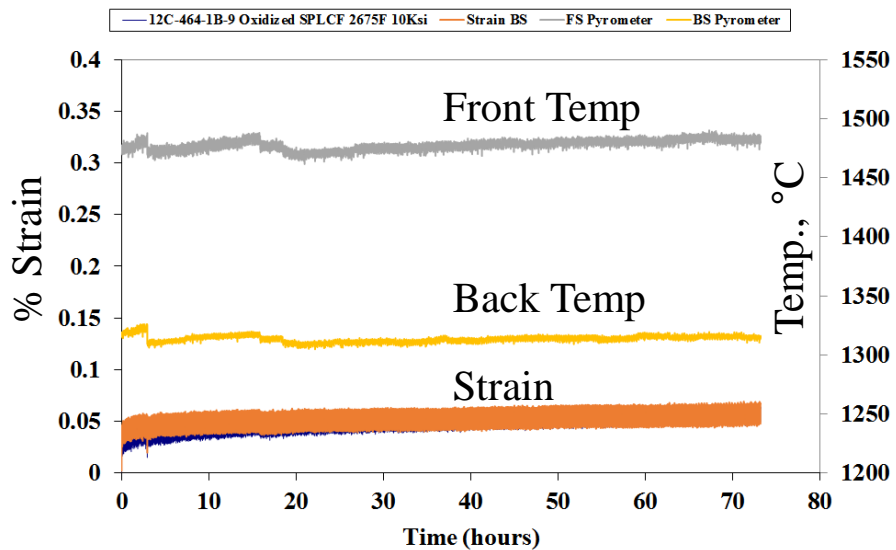
Sustained Peak Low Cycle Fatigue (SPLCF) Results with Through-Thickness Thermal Gradient

As-produced (Un-coated) sample

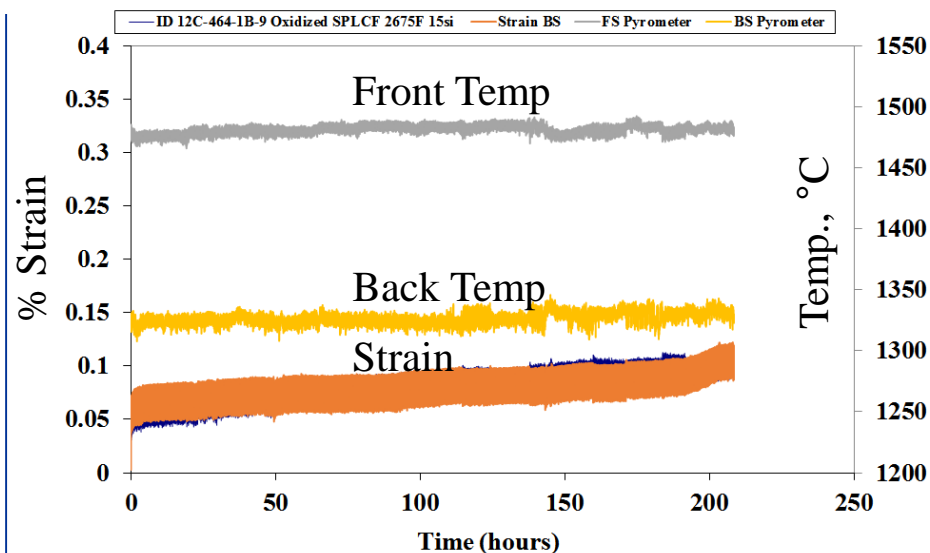
- Front surface temp: 1482°C (2700°F)
- Back surface temp: 1315°C (2400°F)
- 74 hour SPLCF at 69 MPa (10 ksi)
- >220 hour SPLCF at 103 MPa (15 ksi)
- Sample broke after >300 hours total SPLCF



69 MPa Peak Stress

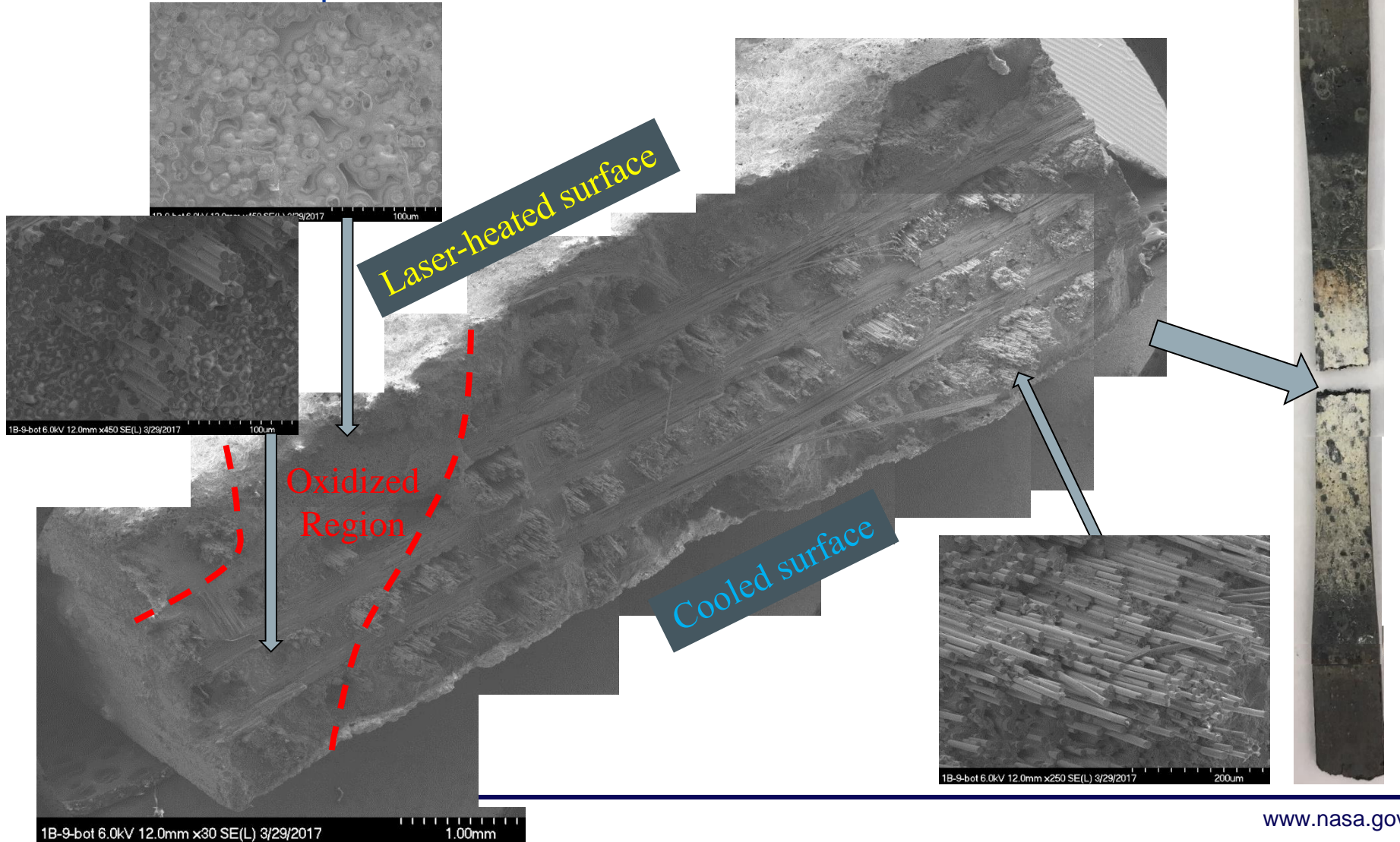


103 MPa Peak Stress



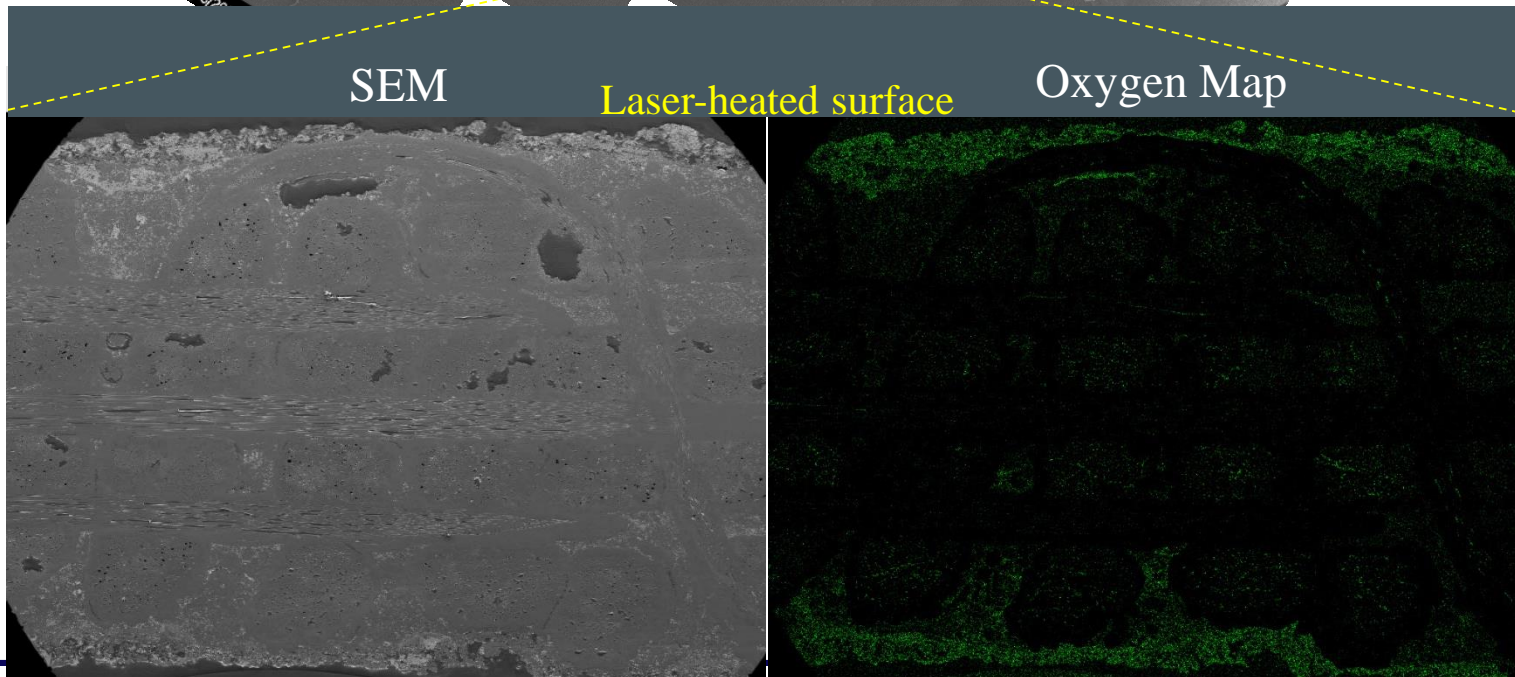
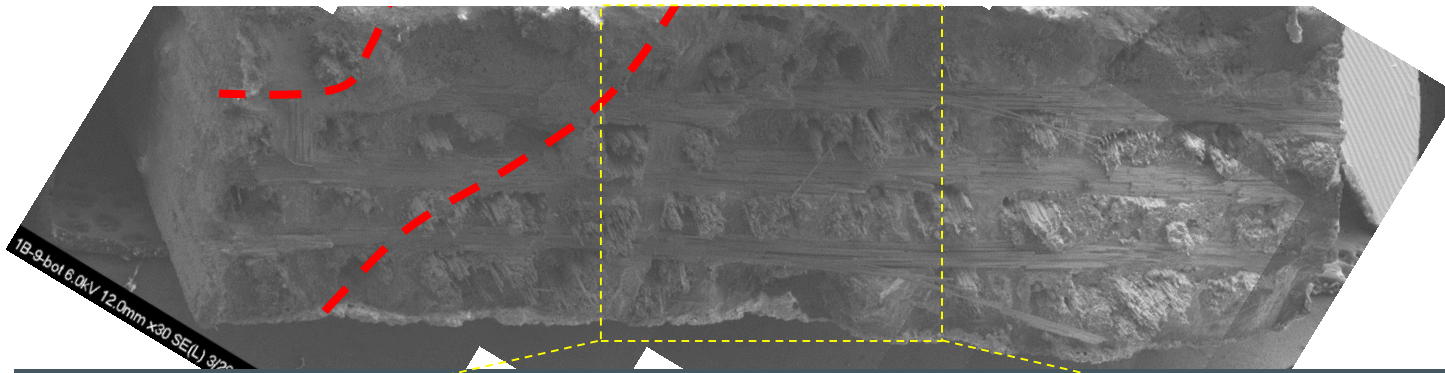
Examination of the Un-coated Sample

- Broke after >300 hours total SPLCF (103 MPa peak)
- The sample broke in the center of the hot zone



Examination of the Un-coated Sample

- The fracture surface was mounted in epoxy and polished
- Oxygen mapping with EDS revealed little internal oxygen

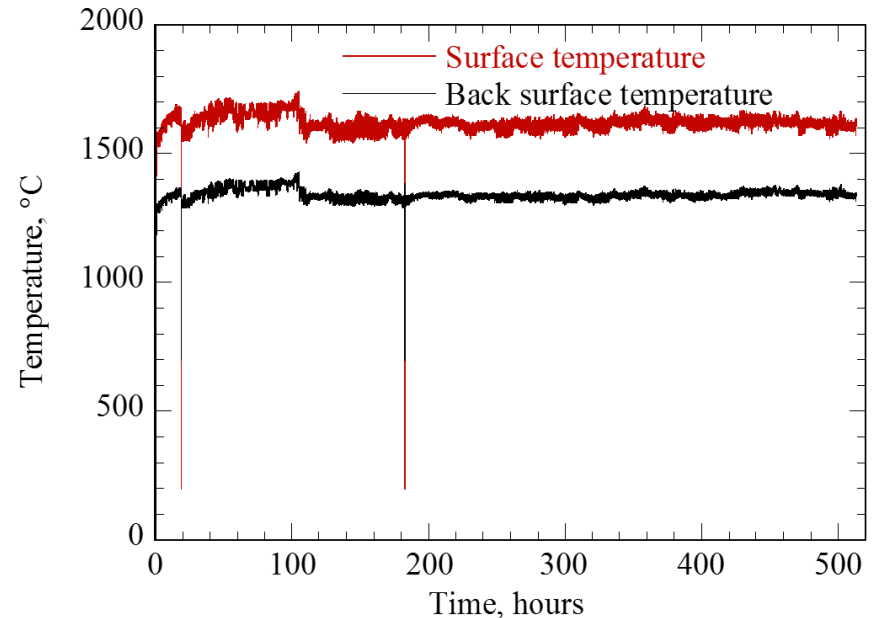
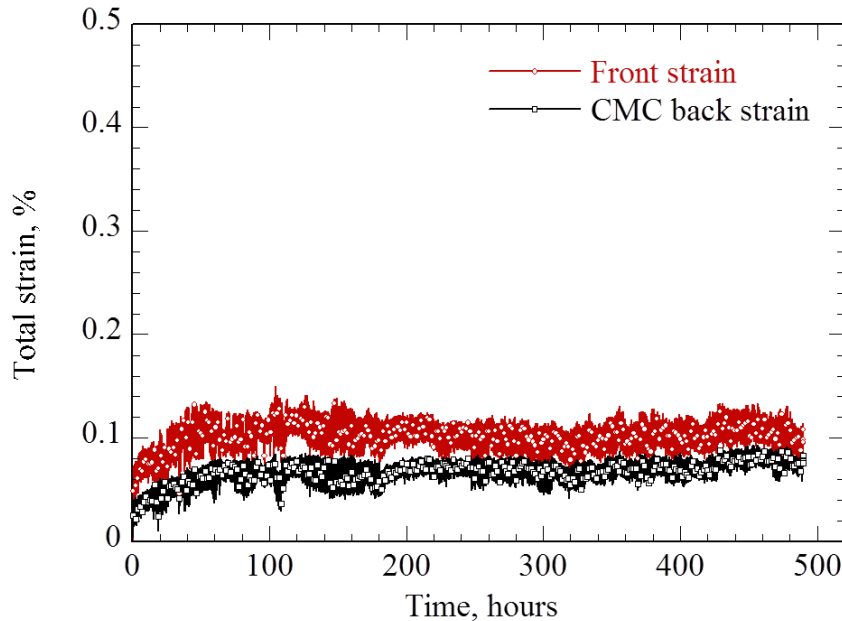
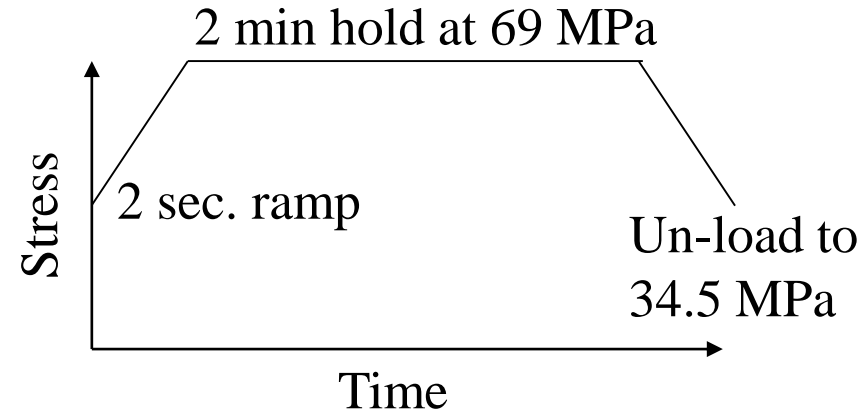




SPLCF Results with Through-Thickness Thermal Gradient

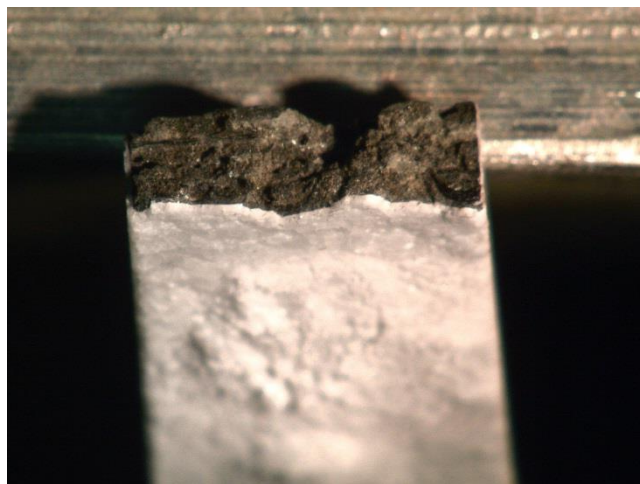
EBPVD Coated sample

- Measured EBC temp: 1620°C (2950°F)
- Measured CMC back side: 1339°C (2442°F)
- EBC/CMC interface: 1506°C (2742°F)
- Max. EBC temp: >1650°C (>3000°F)
- SPLCF at 69 MPa (10 ksi)
- Sample broke at 487 hours



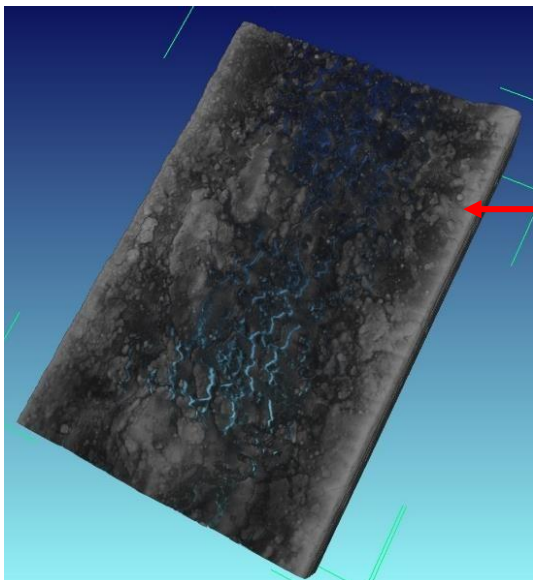
Examination of EBPVD Coated Sample

- Broke after 487 hours SPLCF at 69 MPa
- The sample broke outside the hottest region
- The fracture surface was close to the edge of the hot zone ($\sim 2200^{\circ}\text{F}$)
- The EBC showed pitting/ cracking in the hot zone, below the fracture surface



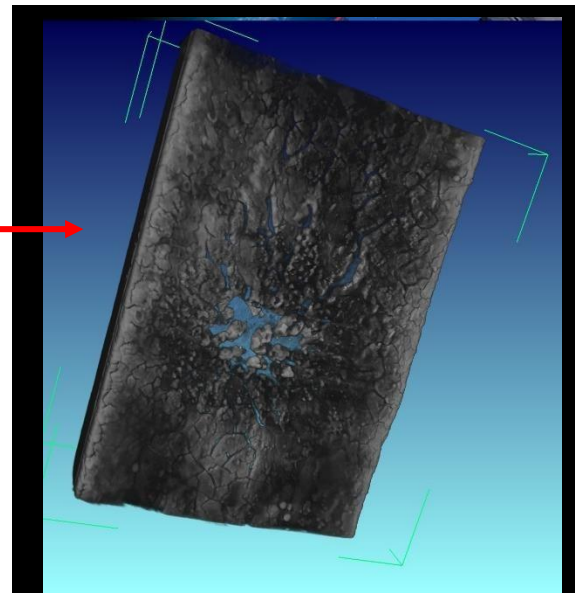
CT Images of EBPVD Coated Sample Before and After Thermal Gradient SPLCF

Before Testing

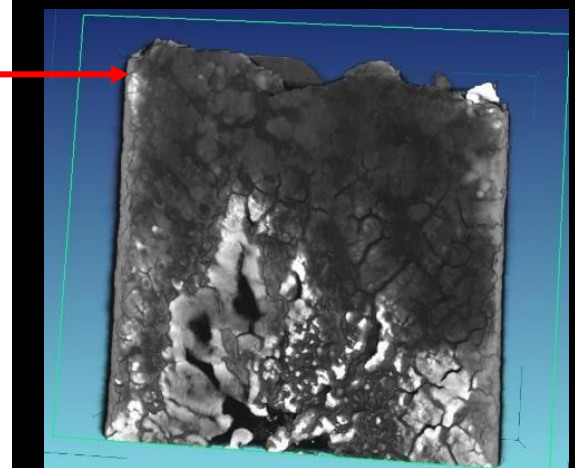


Showing
EBC Only

After Laser SPLCF (69 MPa, 487 hr)



CMC & EBC

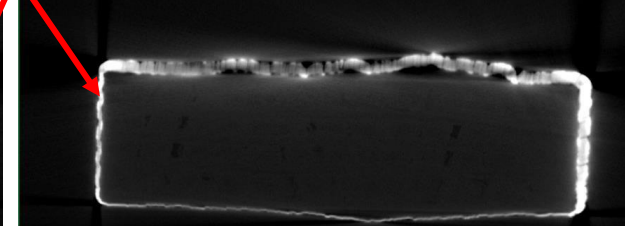
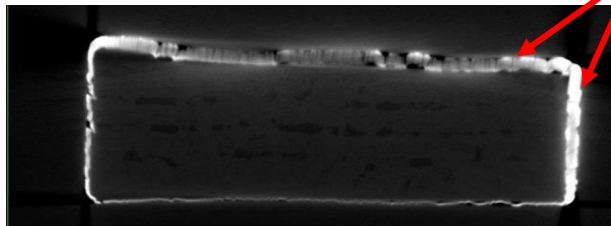
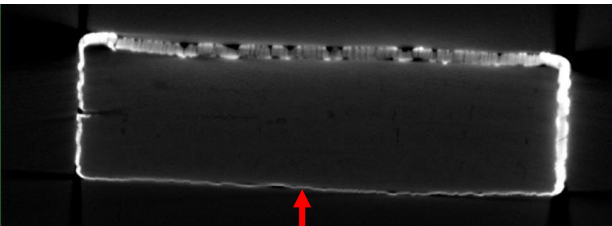


- Prior to testing, the EBC appeared to have thin areas
- After testing, there appeared to be an increase in the size of the thin areas

CT Cross-Section Images of EBPVD Coated Sample Before and After Thermal Gradient SPLCF

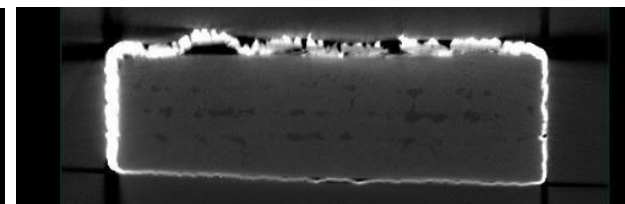
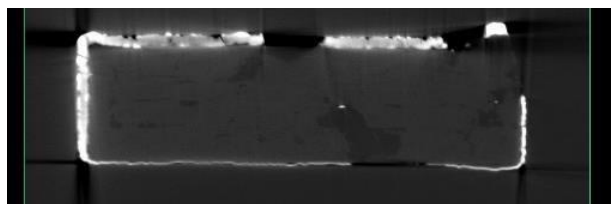
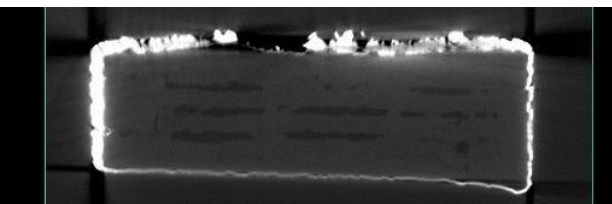
Before Testing

EBC covers three sides



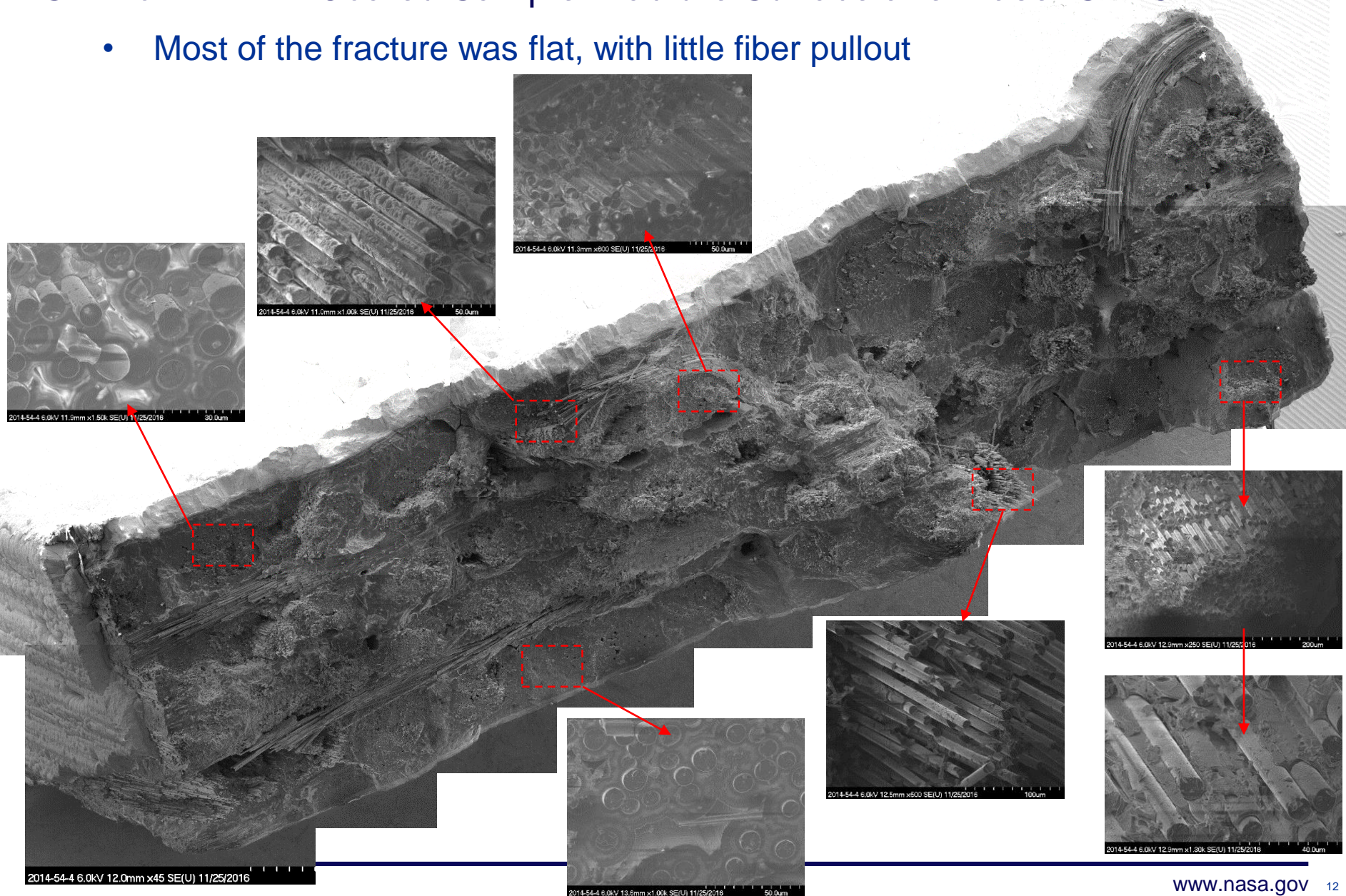
Bond coat covers all sides

After Laser SPLCF (69 MPa, 487 hr)



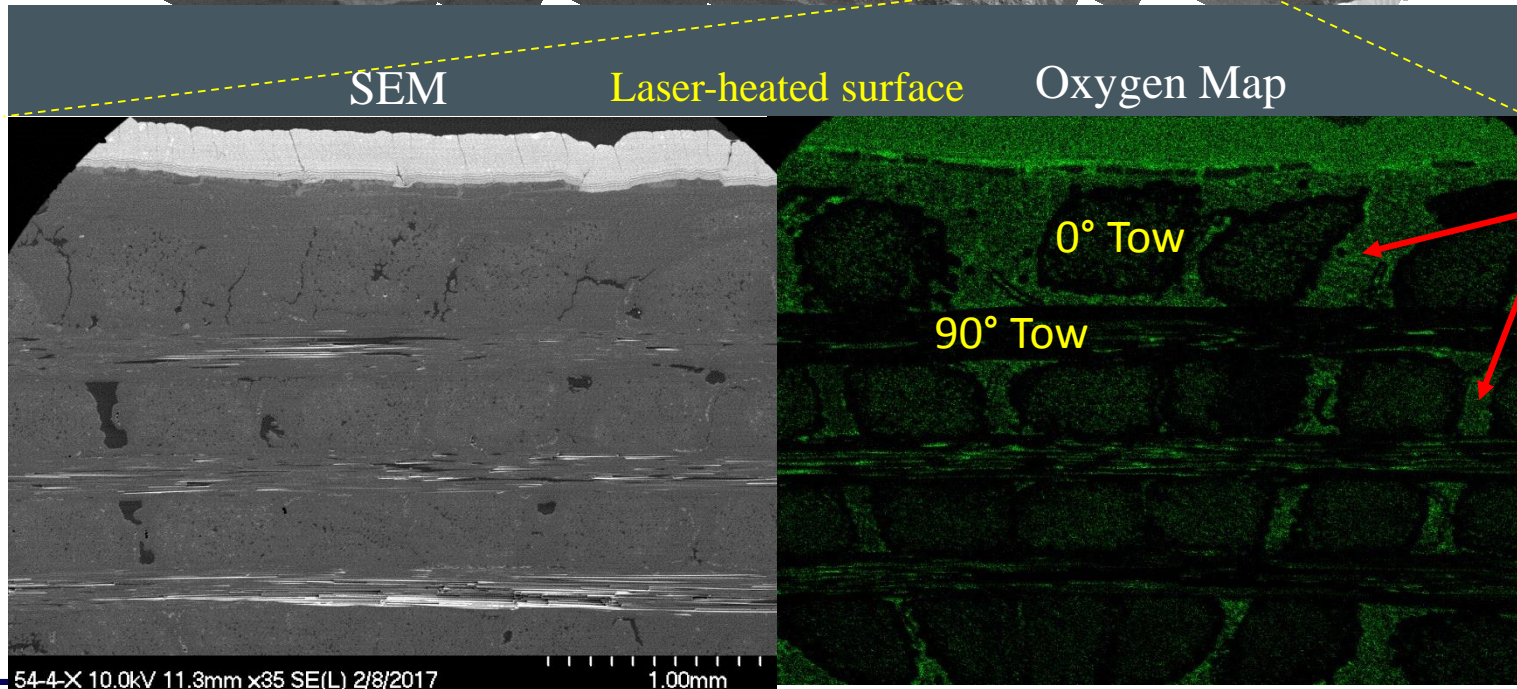
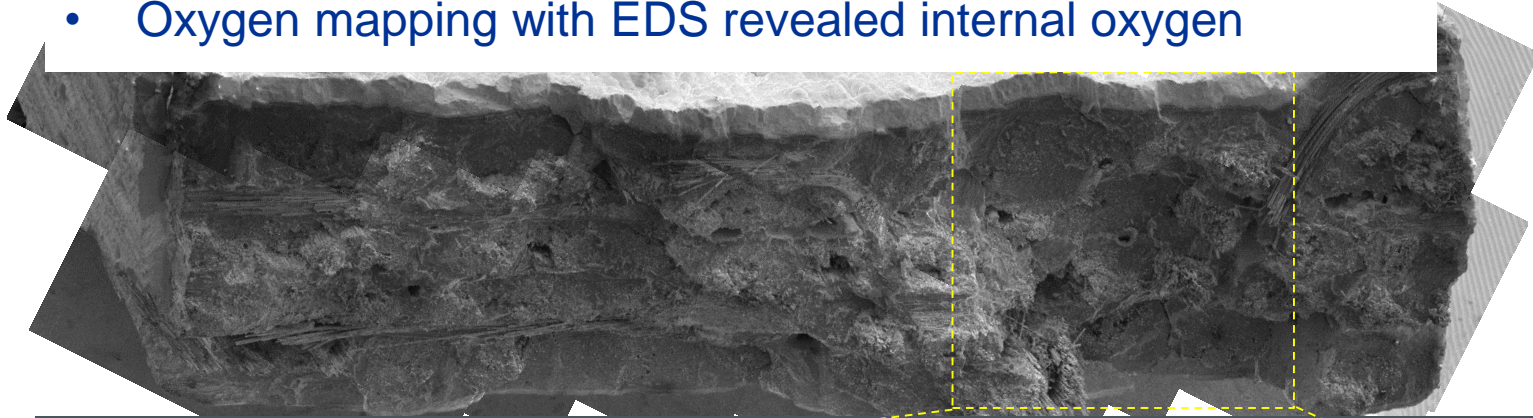
SEM of EBPVD Coated Sample Fracture Surface after Laser SPLCF

- Most of the fracture was flat, with little fiber pullout



SEM of EBPVD Coated Sample Fracture Surface after Laser SPLCF

- The fracture surface was mounted in epoxy and polished
- Oxygen mapping with EDS revealed internal oxygen



Cooled surface

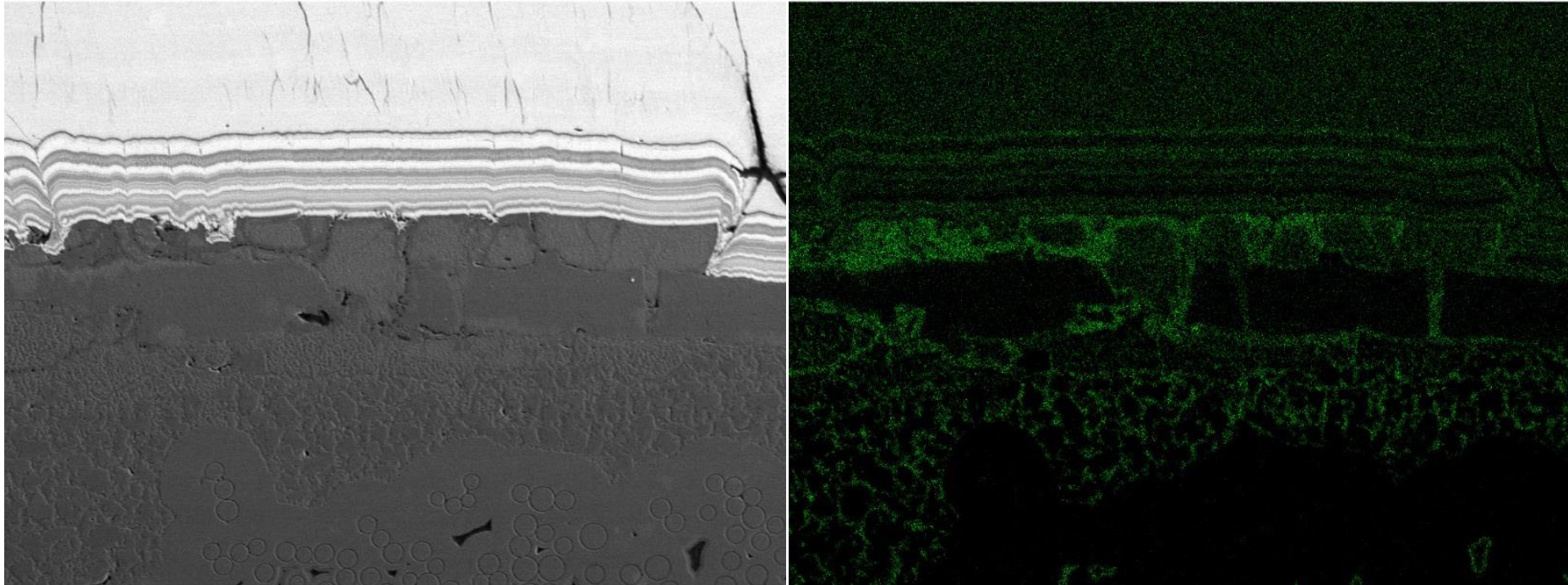
SEM of EBPVD Coated Sample Fracture Surface after Laser SPLCF

- There does not appear to be a thermally grown oxide layer beneath the coating

SEM

Laser-heated surface

Oxygen Map





Conclusions

- Thermal gradient tests are relevant for cooled CMCs
- Interpretation of the data is complicated
- Un-coated sample lasted >300 hours in SPLCF
 - Combination of 69 and 103 MPa peak stresses
 - 1482°C front side temp
 - 1315°C back side temp
 - Only a small part of the fracture surface was oxidized
- EBC coated sample lasted 487 hours in SPLCF
 - 69 MPa peak stress
 - 1506°C CMC front side temp
 - 1339°C back side temp
 - CT images indicate that the coatings had local thin spots after the test
 - Thermally grown oxide did not appear beneath the coating
 - Further testing in steam is needed to evaluate the CMC/EBC system