# Mechanical properties and real-time damage evaluations of environmental barrier coated SiC/SiC CMCs subjected to tensile loading under thermal gradients

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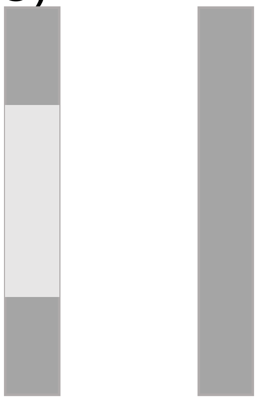
# Introduction

- SiC/SiC ceramic matrix composites (CMCs) require new state-of-the art environmental barrier coatings (EBCs) to withstand increased temperature requirements and high velocity combustion corrosive combustion gasses.
- The present work compares the response of coated and uncoated SiC/SiC CMC substrates subjected to simulated engine environments followed by high temperature mechanical testing to asses retained properties and damage mechanisms
- Our focus is to explore the capabilities of electrical resistance (ER) measurements as an NDE technique for testing of retained properties under combined high heat-flux and mechanical loading conditions.
- Furthermore, Acoustic Emission (AE) measurements and Digital Image Correlation (DIC) were performed to determine material damage onset and accumulation.

# Experimental Materials

- SiC/SiC CMC material (Hyper-Therm HTC; currently Rolls Royce HTC)
  - 8 plies, balanced 5 harness satin 2D woven 0°/90°, SiC/BN/SiC
  - Hi-Nicalon Type-S fiber reinforced
  - Produced by CVI + SiC/Si slurry melt infiltration (SMI)
  - Machined into 6 in. tensile bars
- Environmental Barrier Coating – EBC
  - Deposited via EB-PVD
  - NASA $HfO_2$-Si bond coat
  - NASA $HfO_2$-doped ytterbium-gadolinium di-silicate $(Yb,Gd)_2Si_2O_7$ EBC system



| Specimen | width (mm) | thickness (mm) | $f_0$ |
|---|---|---|---|
| coated | 12.80 | 2.25 | 0.143 |
| uncoated | 12.72 | 2.21 | 0.145 |

# Experimental Technique: combustion environment exposure

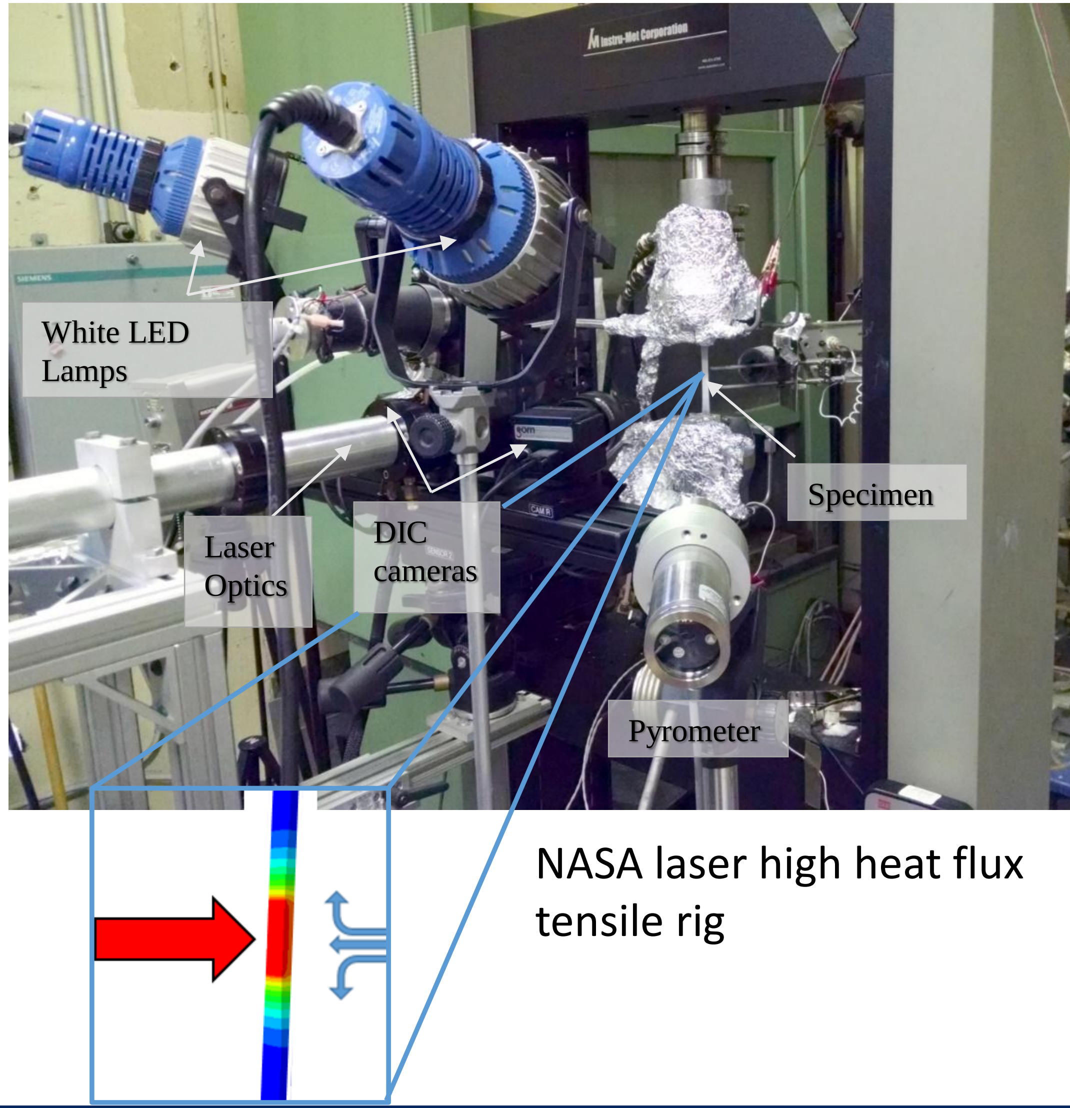
- **NASA High Pressure Burner Rig (HPBR)**
  - Closely simulates aero-turbine engine combustion environments for specimen and component testing
  - Burns jet-fuel and air at user controlled ratios
  - Used to quantify high temperature material oxidation and T/EBC performance over a range of temperatures, pressures and velocities
- Specimens subjected to HPBR exposure at **1316°C for 30 hours** at gas pressures of **10 atm** and combustion gas velocities of and **200 m/s**


HPBR CAPABILITIES

- Jet fuel & air combustion with mass air flow 1.5-2.0 lb/s
- Gas temperature up to 3000°F (1650°C)
- Adjustable testing pressures from 4 to 16 atmospheres
- Gas velocity up to 850 m/s combustion gas velocity in the testing section
- Incorporated advanced air preheater for 800-1200°F cooling air for high temperature film cooling

# Experimental Technique: high temperature tensile testing

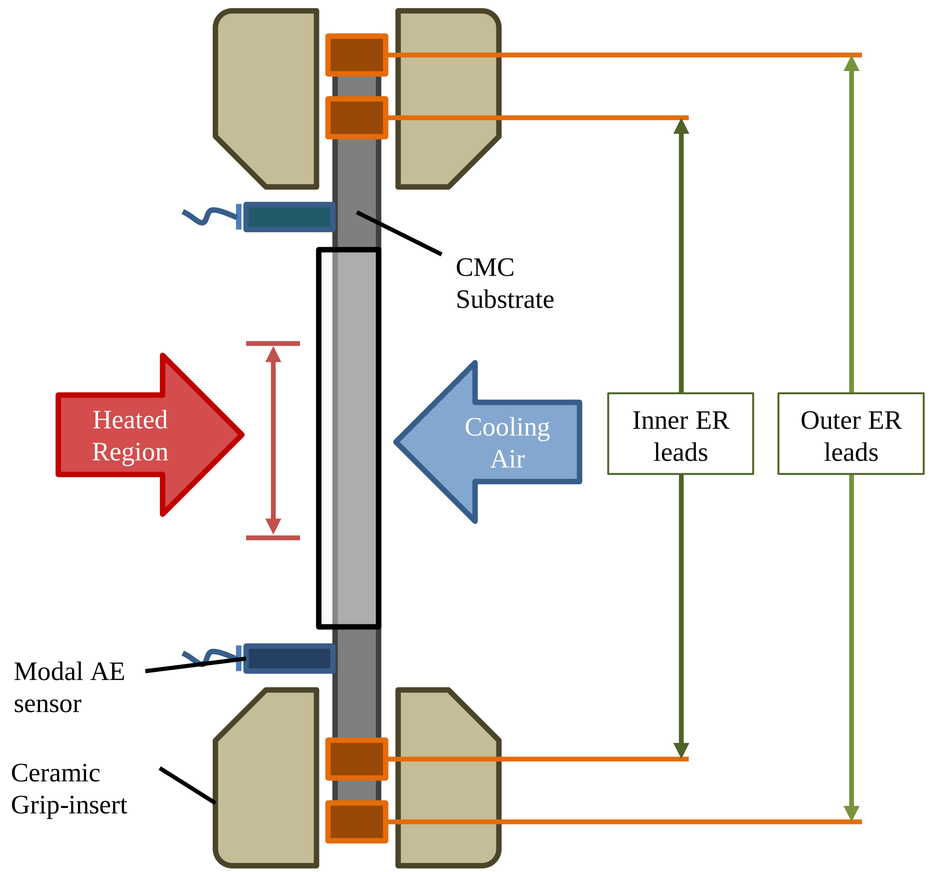
- Specimens are loaded in uni-axial tension rig
- Digital Image Correlation (**DIC**) is used to determine localized strain fields
- Nominal strain measurements are taken using a 25.4 mm extensometer with a ±0.5 mm travel
- **Laser high heat-flux testing**:
  - Face of specimen gage-section heated by a 3.5kW $CO_2$ high heat-flux laser
  - Asymmetrical heating by laser generates thermal gradients (thru thickness and longitudinal)
  - Thermal gradients can be increased by the addition of active back side air-cooling
  - Front and back temperatures of the heated region are monitored by optical pyrometers




NASA laser high heat flux tensile rig

# NDE Measurement

- Electrical Resistance (**ER**) measured by four-point probe method
- In order to avoid high temperature exposure during laser heating, **ER** leads for in-situ measurement are attached within the gripped areas
- Acoustic Emission **(AE)** sensors are attached ±40 mm from center



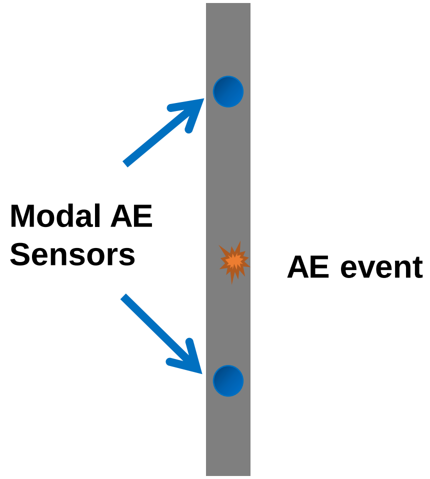

SIDE VIEW

# NDE Principles

## Modal Acoustic Emission Monitoring

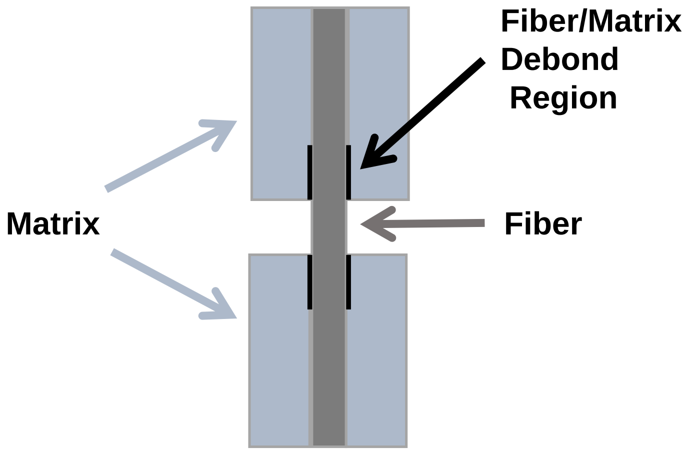
- Fracture energy of solids released as elastic waves which are detected by the use of wide-band sensors in order to quantify stress-dependent cracking initiation and accumulation.
- Location of AE events estimated by the difference in arrival times of AE signals

$$x = \frac{v}{2}\left(t_{bottom} - t_{top}\right)$$



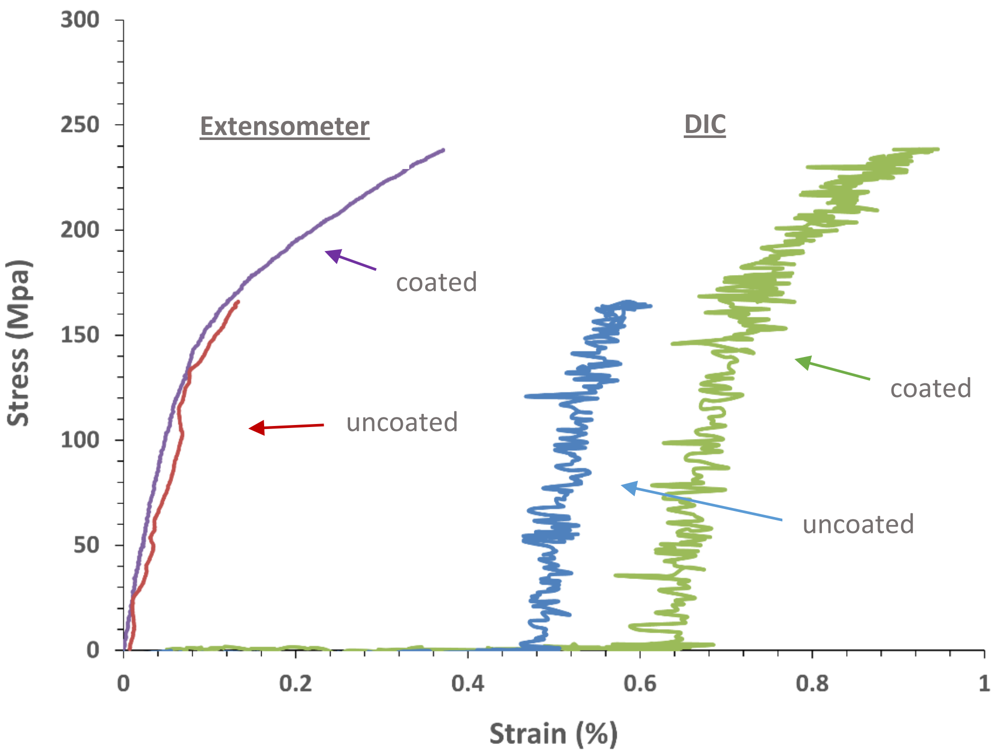

## Electrical Resistance Measurement

- Damage in the form of matrix cracks and associated fiber debonding/sliding increase the overall electrical resistance of the composite specimen
- Matrix cracking of MI SiC/SiC is especially sensitive due to the highly conductive matrix formed from excess silicon deposits left from processing



# Post-HPBR: Retained HT Tensile Properties

- Mechanical behavior of the uncoated specimen indicates severe degradation of composite properties
- Oxidation of CMC in HPBR
  - Recession of SiC (matrix, fibers), Oxidation of BN interphase

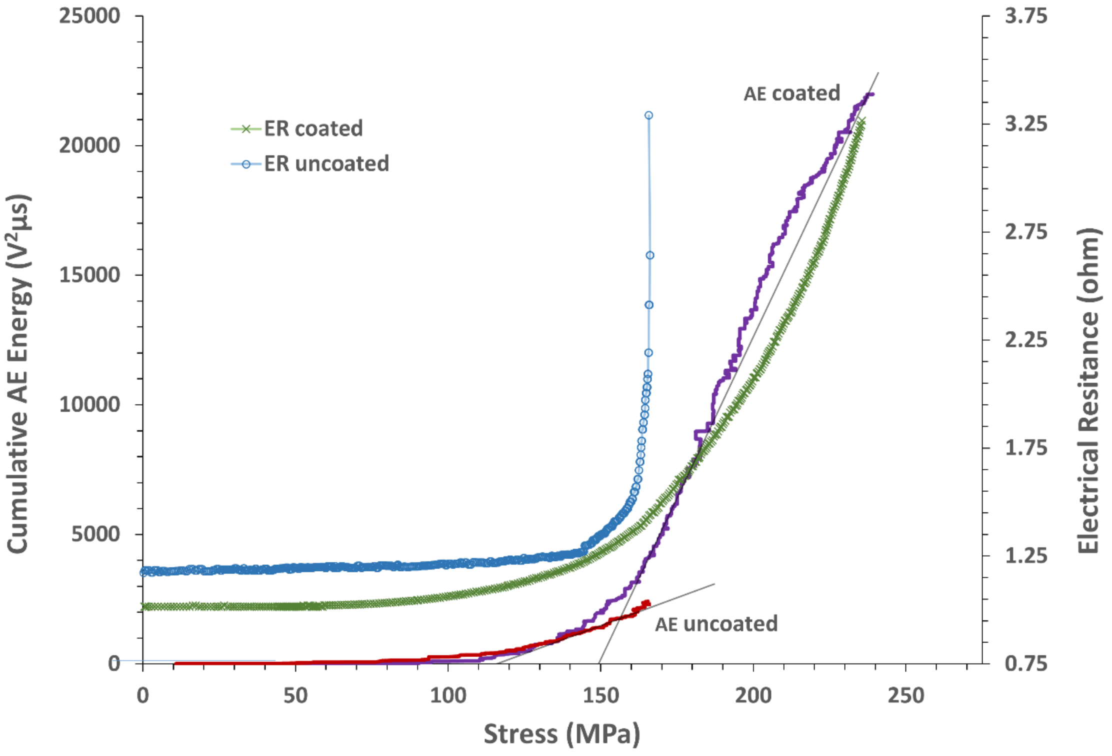



| Specimen | Surface Temp. (°C) | Back Temp. (°C) |
|---|---|---|
| coated | 1230 | 1070 |
| uncoated | 1200 | 1010 |

| Specimen | E (GPa) Extensometer | E (GPa) DIC | $\sigma_{UTS}$ (MPa) | $\varepsilon_{fail}$ (%) |
|---|---|---|---|---|
| coated | 241 | 266 | 238 | 0.371 |
| uncoated | 146 | 221 | 166 | 0.134 |

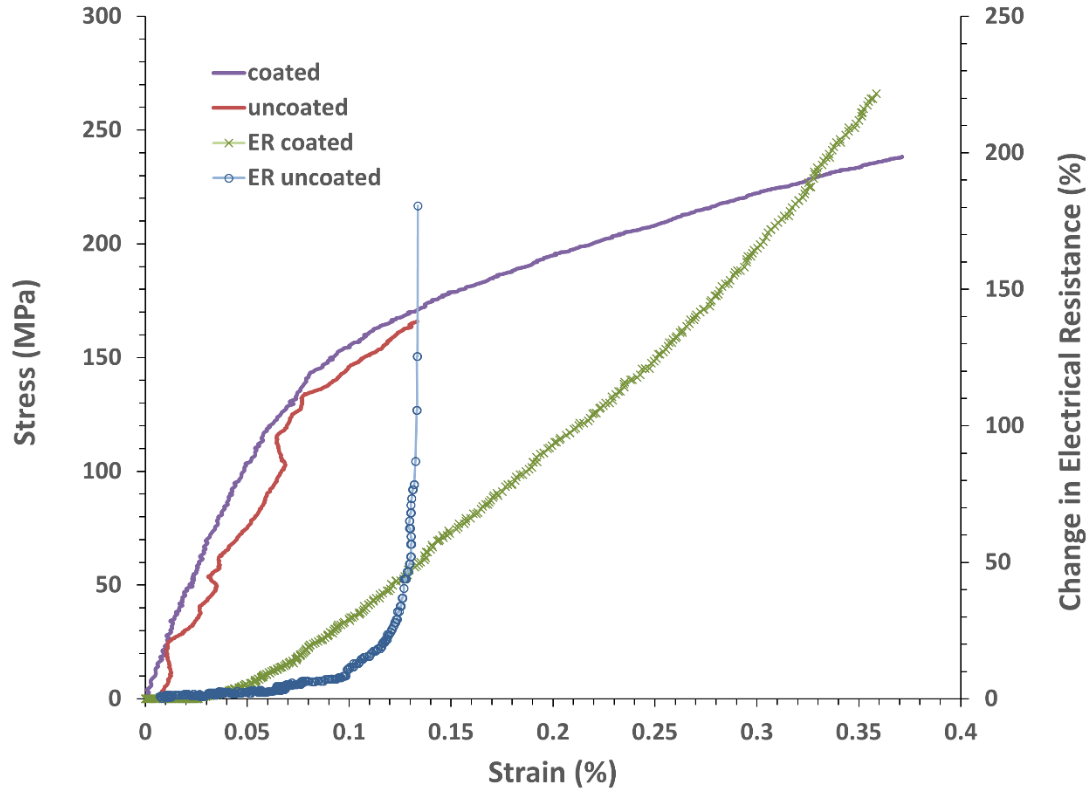
# HT Tensile Test: ER and AE Comparison

- Accumulation of AE energy indicative of stress-dependent cracking behavior
  - Bridged vs. unbridged matrix cracking
- Small ER increase prior to AE onset (approx. 115 MPa and 150 MPa respectively)
- Drastically different ER behavior in increased stress region



# HT Tensile Test: ER change with plastic deformation

- Little change in with elastic strain, followed by increased rate with plastic strain
- High strain sensitivity
  - ~200% ER change to failure
- ER response indicative of nature of damage accumulation
  - Coated v. uncoated

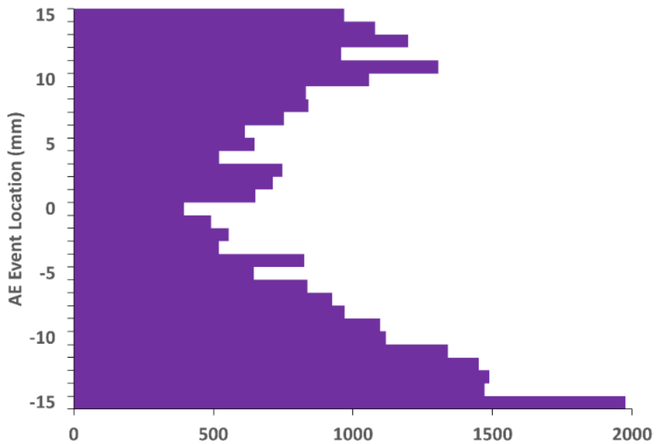



Post HPBR exposure

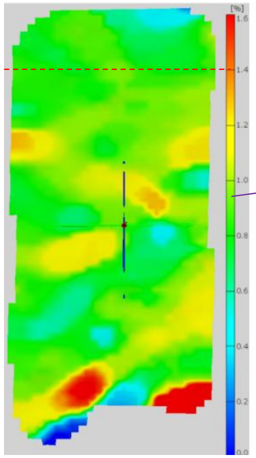
| Specimen | Electrical Resistance (ohm) | |
|---|---|---|
| | Room temp. | Test temp. |
| coated | 0.61985 | 1.0150 |
| uncoated | 0.73418 | 1.1726 |

# AE waveform analysis: energy distribution

- Energy distribution of AE events recorded in specimen gage section with corresponding DIC strain mapping at failure stress

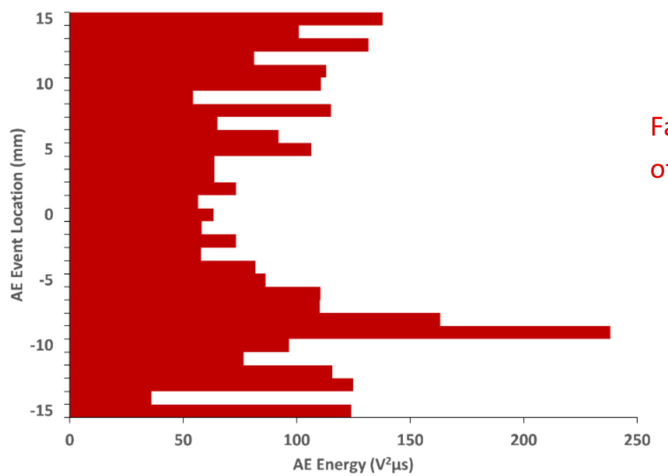



Failure Plane

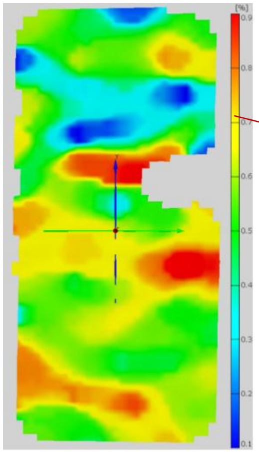


COATED

Nominal thermomechanical strain: 0.96%




Failed below area of DIC interest

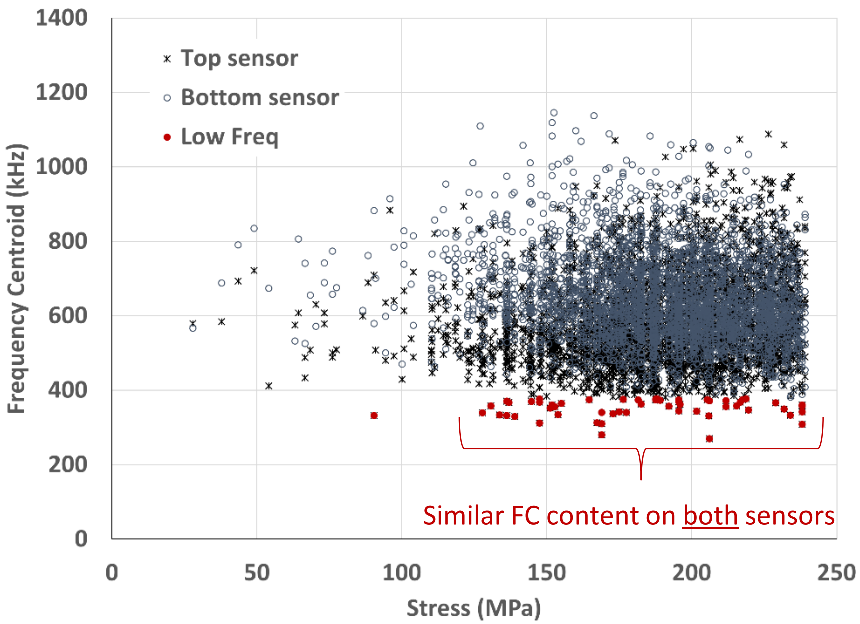


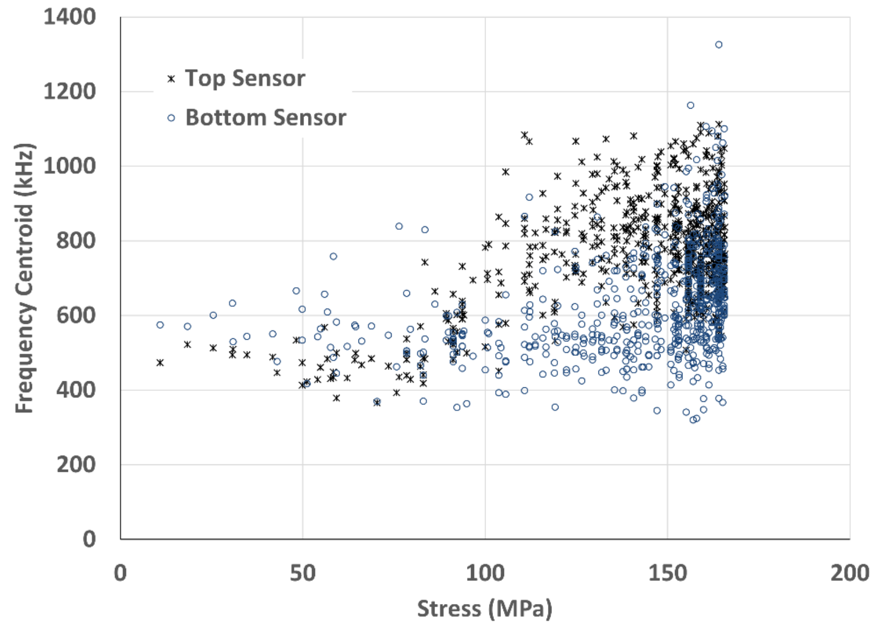
UNCOATED

Nominal thermomechanical strain: 0.71%

# AE waveform analysis: frequency content

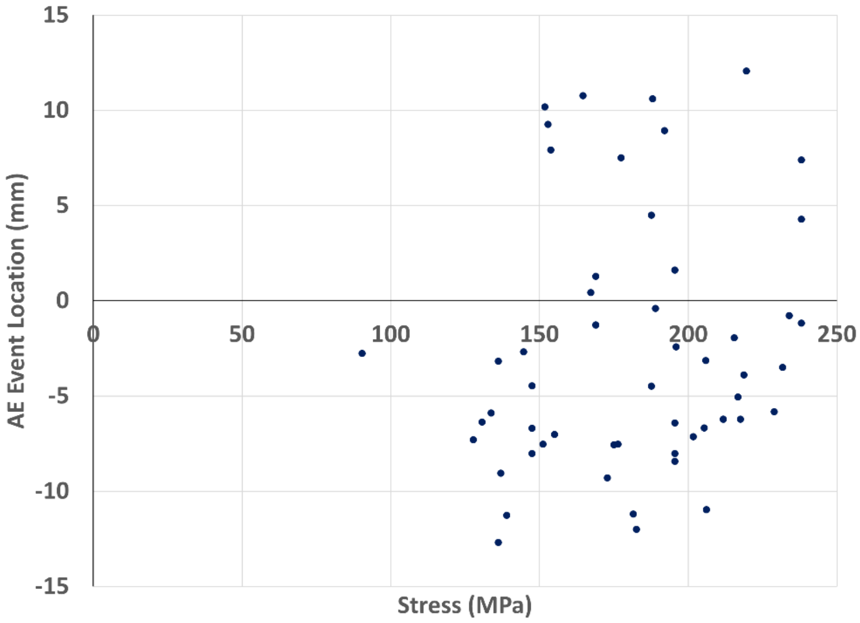
- Frequency centroid was calculated for each waveform captured by top and bottom sensors for each AE event
- The FC of damage events in similar MI SiC/SiC laminates has been shown to be in the range of 600 kHz – 1200 kHz [Maillet and Morscher, Mech Syst. Signal Processing 2015]
- Coated sample exhibited a dense, low freq. (<375 Hz) cluster beginning ~125MPa
  - Highlighted in red

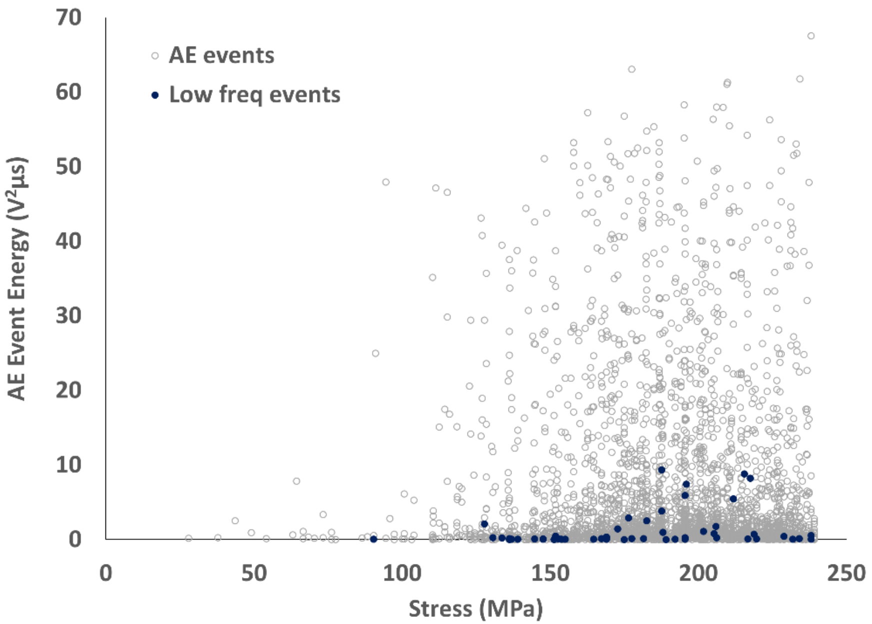


# AE waveform analysis: low freq. events in coated sample

- Closer investigation of the low frequency cluster seen in the coated sample shows that are spatially dispersed throughout the gage.
- These low FC events also exhibit similar low energy content.



# Conclusions

- Decrease in retained tensile properties post HPBR exposure clearly shows degradation of uncoated specimen, and in turn the increased performance benefit of the NASA EBC system
- ER measurement shown to be an effective tool for **in-situ damage monitoring** of MI SiC/SiC CMCs <u>under high-temperature thermal gradients</u>
  - Damage onset indicated by steep ER increase in both cases
  - Increases in ER response show high sensitivity (100's of % increase to failure)
- AE energy distribution in good agreement with DIC strain mapping in terms of damage location and distribution
- AE waveform analysis revealed some differences in frequency content and energy between the coated and uncoated samples
  - While further study is required, there is evidence that AE analysis can be used to differentiate EBC from CMC damage events

# Acknowledgements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- Questions?