Advanced Environmental Barrier Coating and SA Tyrannohex SiC Composites Integration for Improved Thermomechanical and Environmental Durability

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NASA's Advanced Environmental Barrier Coating Systems for Ceramic Matrix Composites (CMCs):

Enabling Technology for Next Generation Low Emission, High Efficiency and Light-Weight Propulsion, and Extreme Environment Material Systems

— NASA Environmental Barrier Coatings (EBCs) development objectives

- Help achieve future engine temperature and performance goals with 2700-3000°F EBCs
- Ensure system durability, improving technology readiness– towards prime reliant coatings and CMC systems
- Current emphasis on establishing database, design tools and coating lifing methodologies

Fixed Wing Subsonic and Supersonics Aircraft

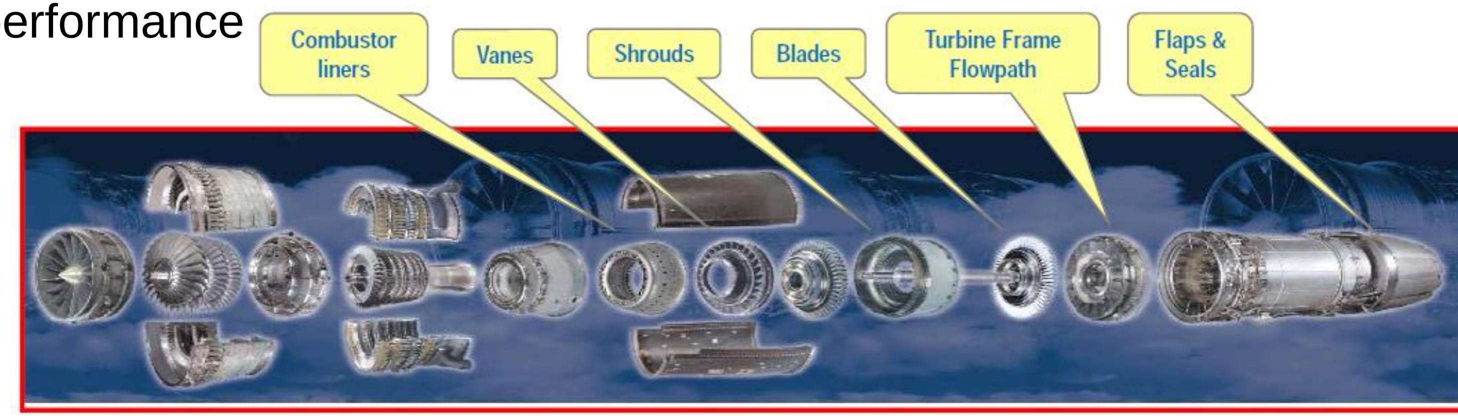
Hybrid Electric Propulsion Aircraft Advanced Propulsion Materials and Multifunctional Materials

NASA Aeronautics Mission Directorate (STMD) Program: High Efficiency Low Emission Propulsion Engines

NASA Space Technology Mission Directorate (STMD) Program: Entry, Descending and Landing: Ultra High Ceramics and Coatings (UHTCC)

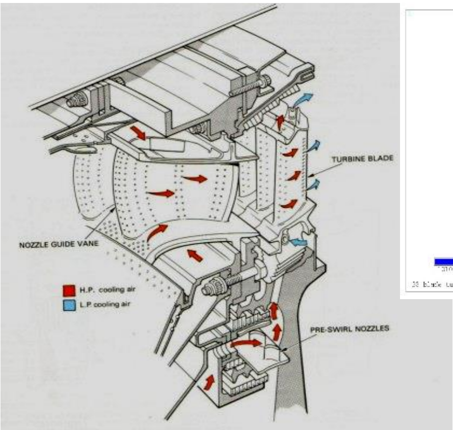
Turbine Engine Components and Engine Integrations

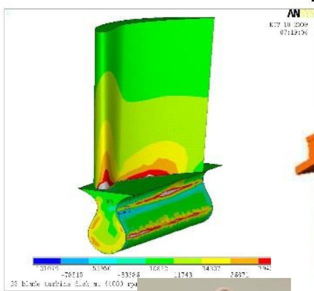
— Advanced light-weight EBC-CMC systems improve turbine engine component temperature capability and reduce cooling requirements, significantly improving engine performance

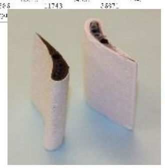


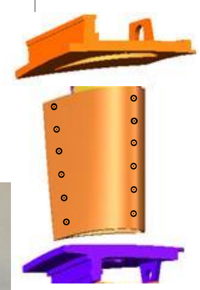
— Explored small blade and vane viability using hybrid 2.5D-3D fiber architecture SiC/SiC CMCs and SA Tyrannohex SiC fiber composites in our programs

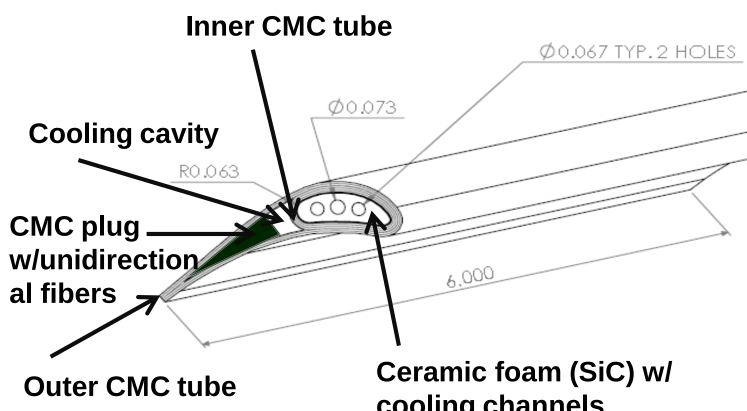
— Thermomechanical load tests, and high heat flux environmental rig tests performed











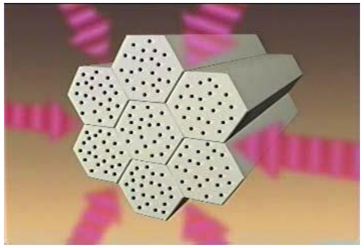
Testing

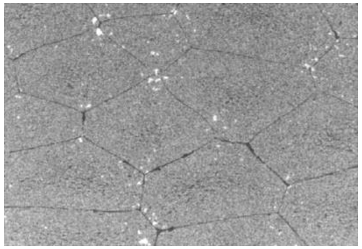
CMC component technologies and Integration, evaluating mixed mode loading capability

Objectives

- Evaluate SA-Tyrannohex SiC composite (Ube, Japan) performance in relatively thick sections
- Evaluate thermomechanical and environmental stability in simulated stress and heat flux environments, relevant to airfoil (turbine blade and vane) applications
    - Determine thermal cyclic stability especially under high thermal gradients and observed failure modes
    - Determine combustion environment recession rates tested at 2500°F (1371°C) under combustion gas velocity up to 200 m/s, 16 atm
    - Compare with other SiC/SiC composites and Si_3N_4 ceramics
    - Evaluate dynamic behavior – vibration damping
- Evaluate environmental barrier coating (EBC) coated Tyrannohex-SA composite durability
    - Long-term flexural fatigue evaluations under high heat flux laser rig at temperatures up to 2700°F
- Summary

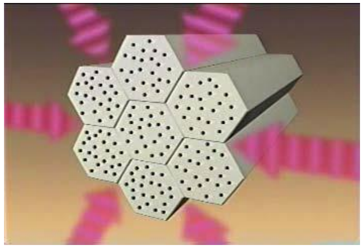
SA-Tyrannohex





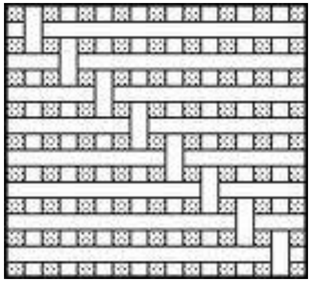
SA-Tyrannohex (SiC Fiber Material)

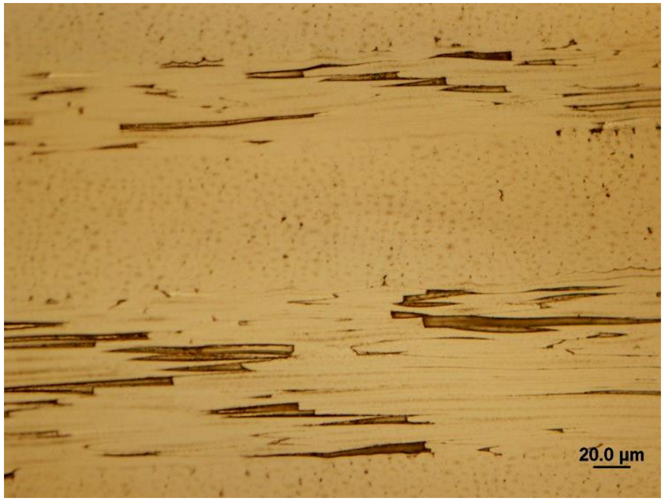
- Two-Direction (8-hearness satin weave of Tyranno fibers), 98% fiber volume fraction (less than 1 % porosity)
- High in-plane and through-thickness thermal conductivity - 36 W/m-K and 24 W/m-K at 1400°C (2552°F)
- Excellent high temperature strengths up to 1500°C or 1600°C (180 MPa to 160 MPa)
- High toughness, particularly compared to monolithics



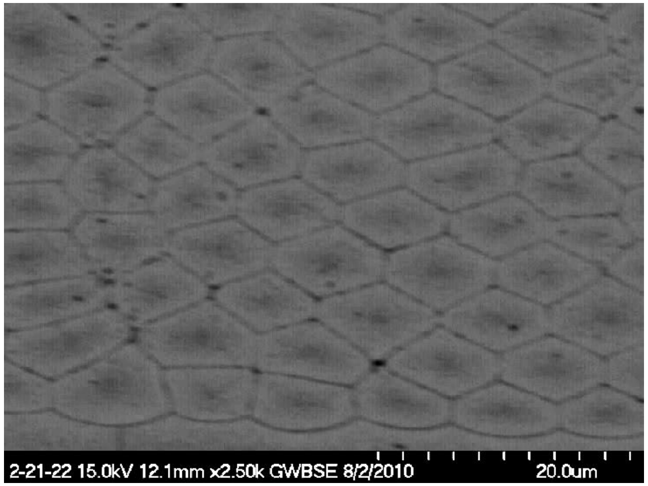
Press and sinter

8 Harness Satin Fiber Tow Weave





Optical Micrograph

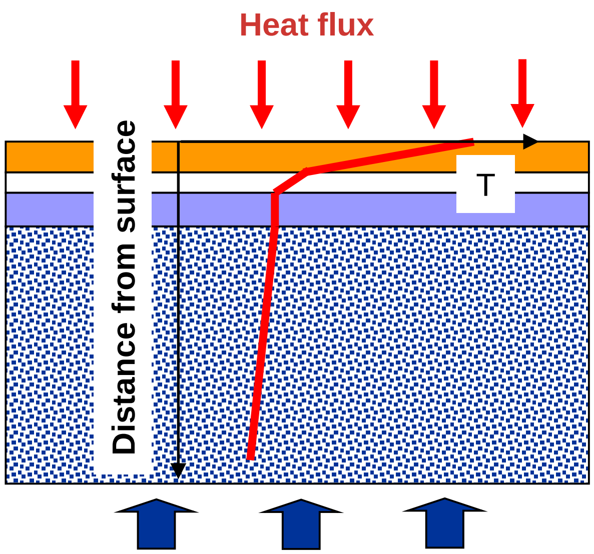


SEM Micrograph

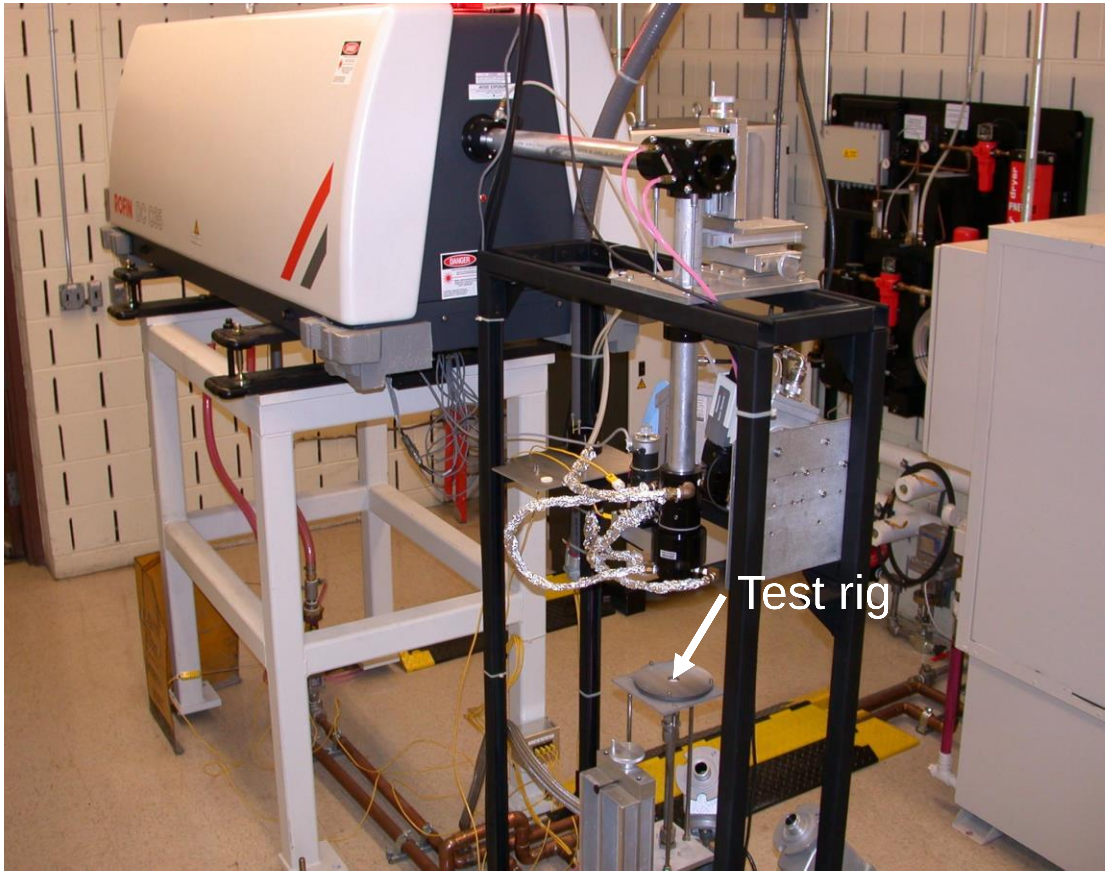
High Heat Flux CO_2 Laser Rig For Thermal Gradient Cycling Stability Evaluations

– High heat flux CO_2 laser rig tested two configurations of SA-Tyrannohex 25x25x10 mm and 25x25x3 mm for thermal gradient and cyclic durability

Turbine: 450°F across 100 microns
Combustor:1250°F across 400 microns



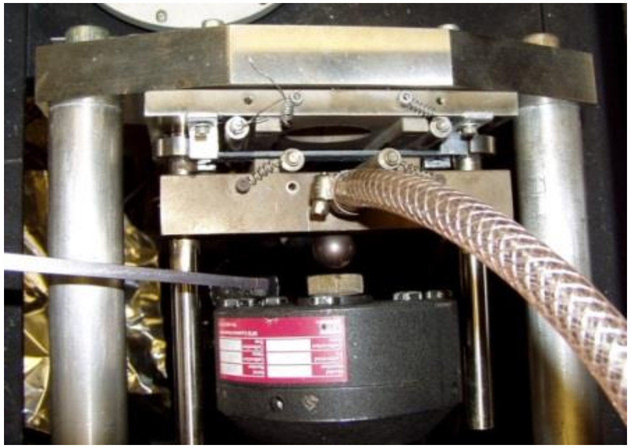
Cooling – high velocity air or air-water mist
Achieved heat transfer coefficient 0.3 W/cm^2-K

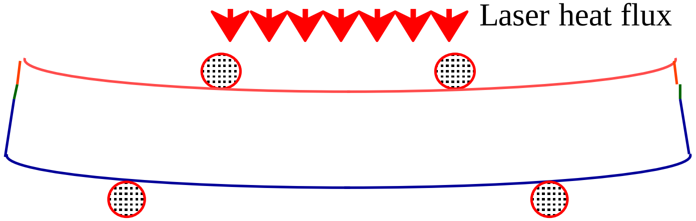


(a) High heat flux cycling test rig

High Heat Flux CO_2 Laser Bend Fatigue Rig For Simulated Thermal Gradient Fatigue Resistance Evaluations

– High heat flux CO_2 laser bend fatigue rig tested SA-Tyrannohex for thermo-mechanical durability: specimen configuration 76x12.7x3 mm

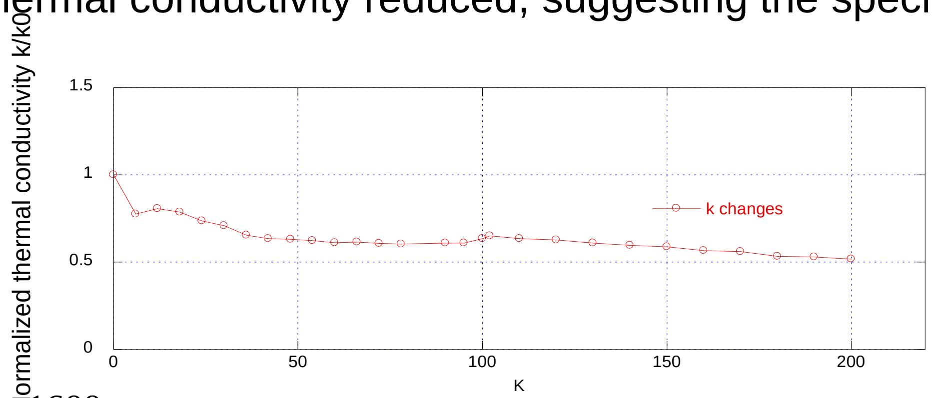


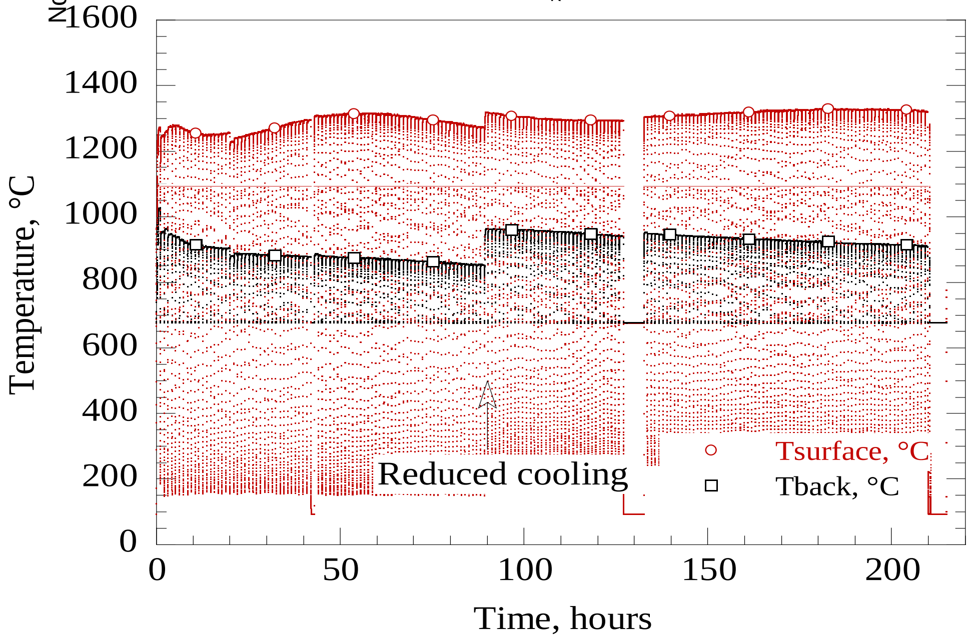


High heat flux flexural fatigue test rig

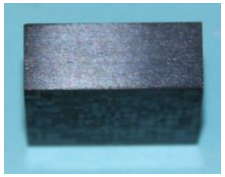
SA Tyrannohex Ceramic Specimen Tested Under Cyclic Heat Flux Thermal Gradients

- SA Tyrannohex specimen (25x25x10 mm) tested under thermal gradient cycling conditions: Tsurface 2300-2400°F (1260-1316°C), Tback 1700-1750°F (927-954°C), 1 hr cyclic in air;
- Thermal conductivity reduced, suggesting the specimen degradation and delamination

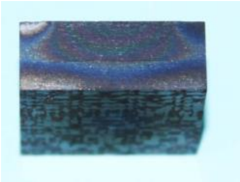




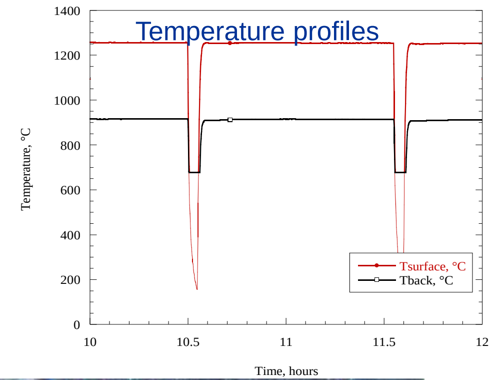
Specimen under testing

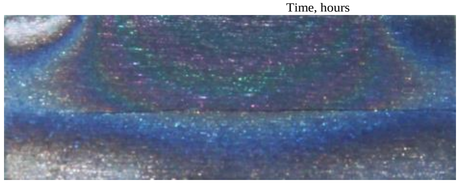


As received specimen-sideview



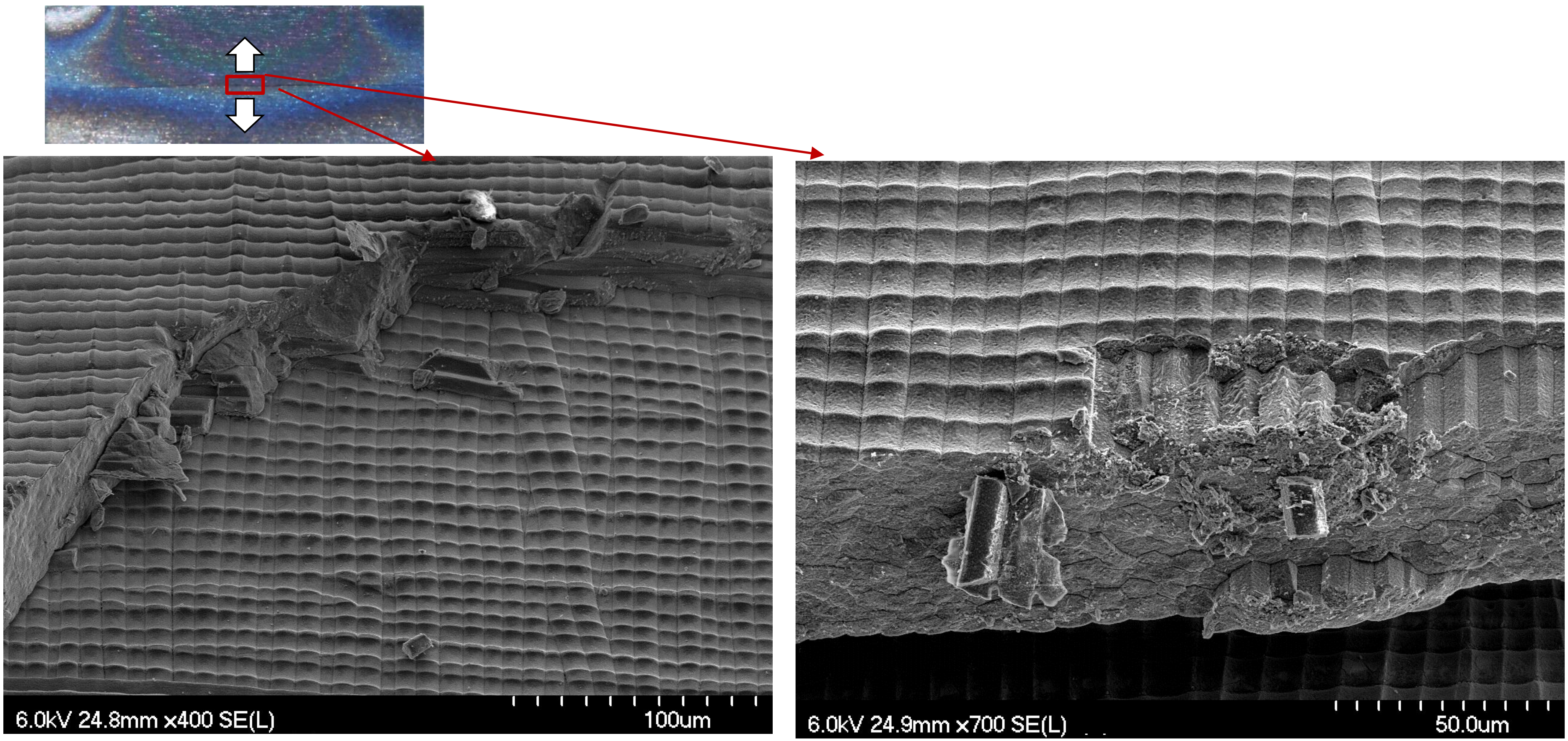
After 195 hr testing specimen - sideview





SA Tyrannohex Ceramic Specimen Tested Under Cyclic Heat Flux Thermal Gradients - Continued

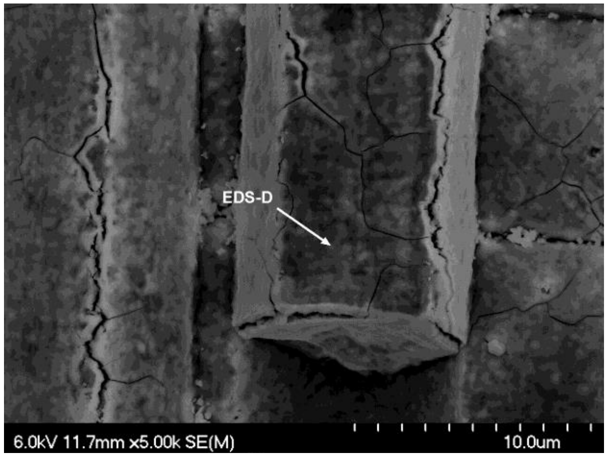
- SEM images of the ceramic specimen delamination areas

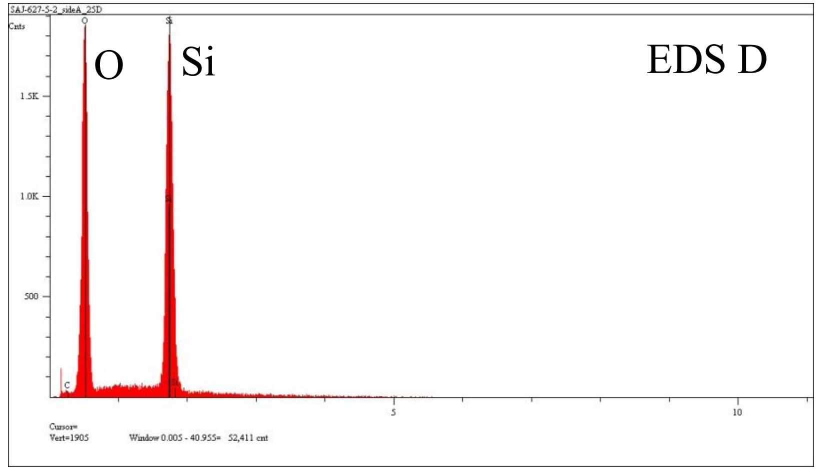


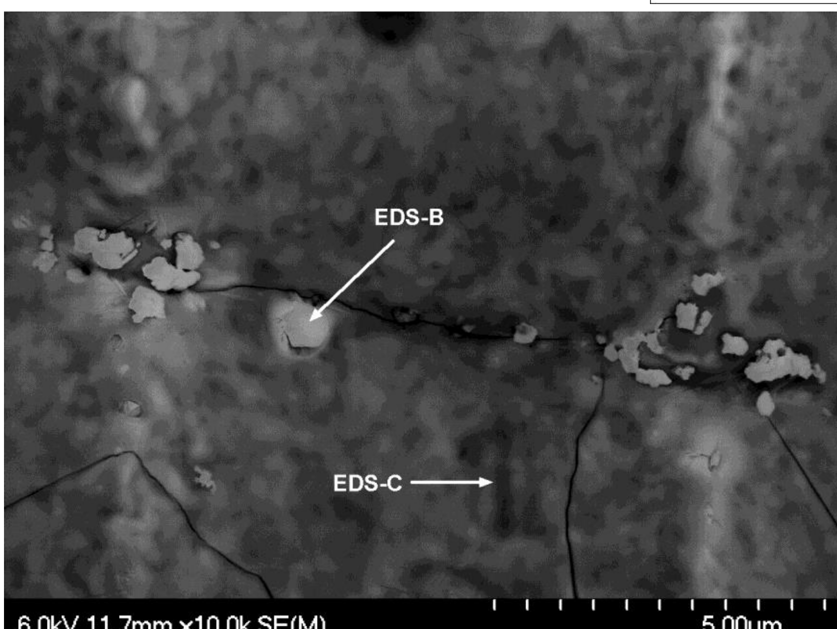
Failed specimen delamination surfaces

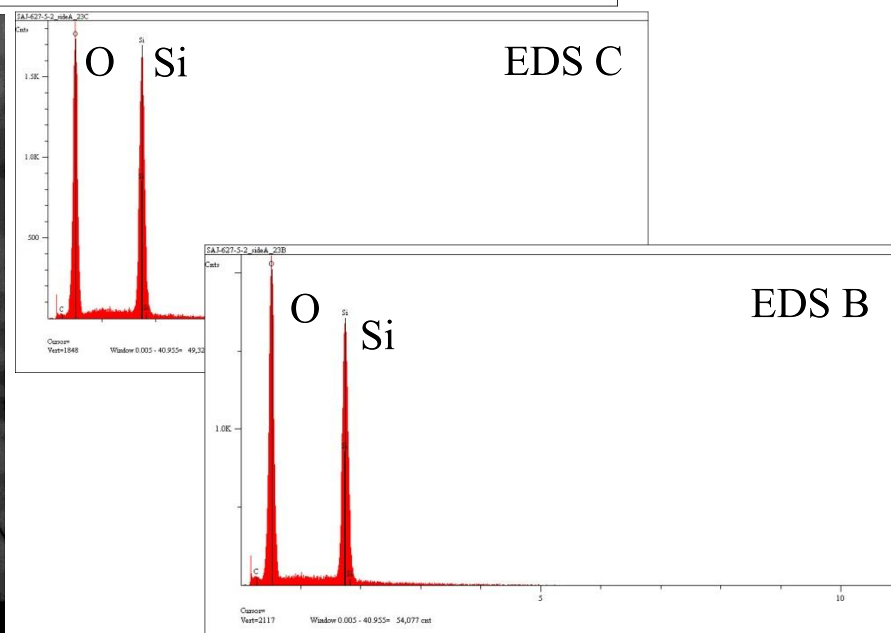
SA Tyrannohex Ceramic Specimen Tested Under Cyclic Heat Flux Thermal Gradients - Continued

- SiO_2 cracking on the fiber surface found also to be detrimental to durability



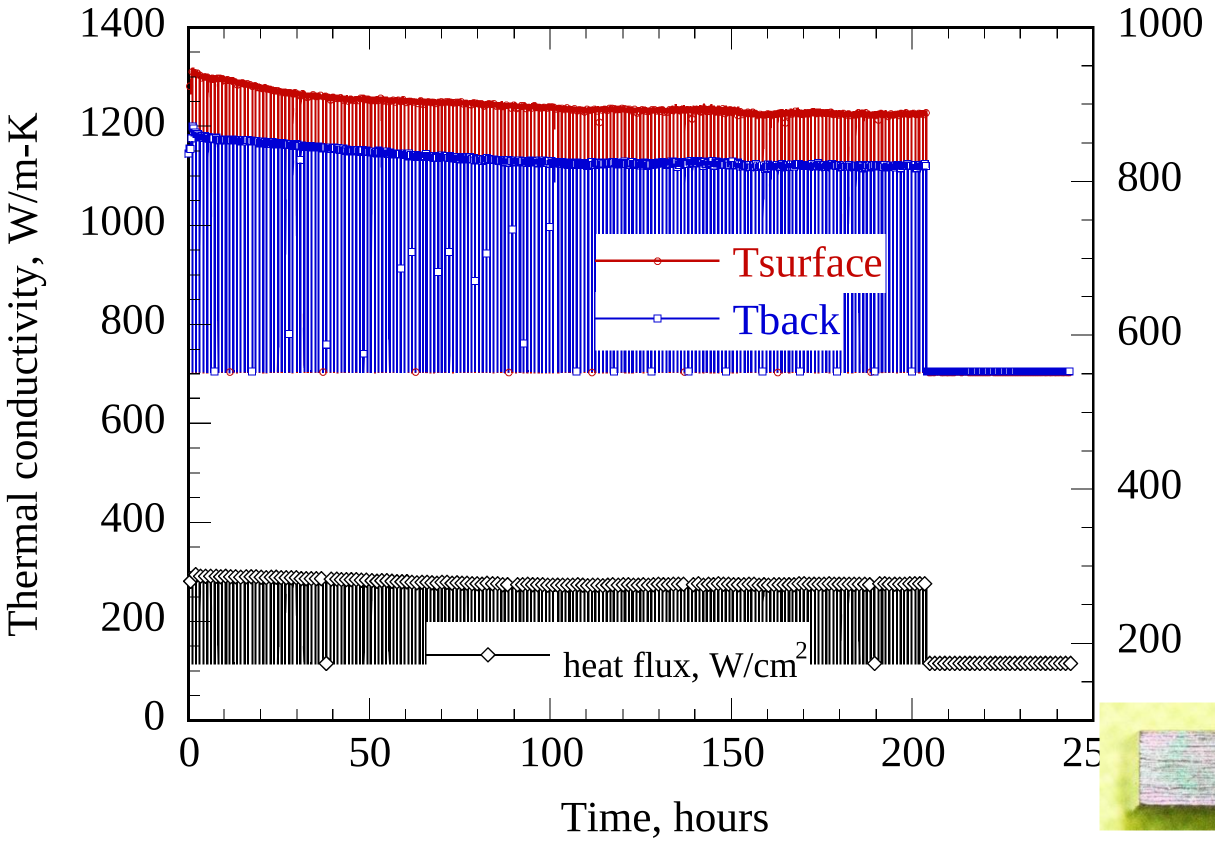






SA Tyrannohex Ceramic Specimen Tested Under Cyclic Heat Flux Thermal Gradients - Continued

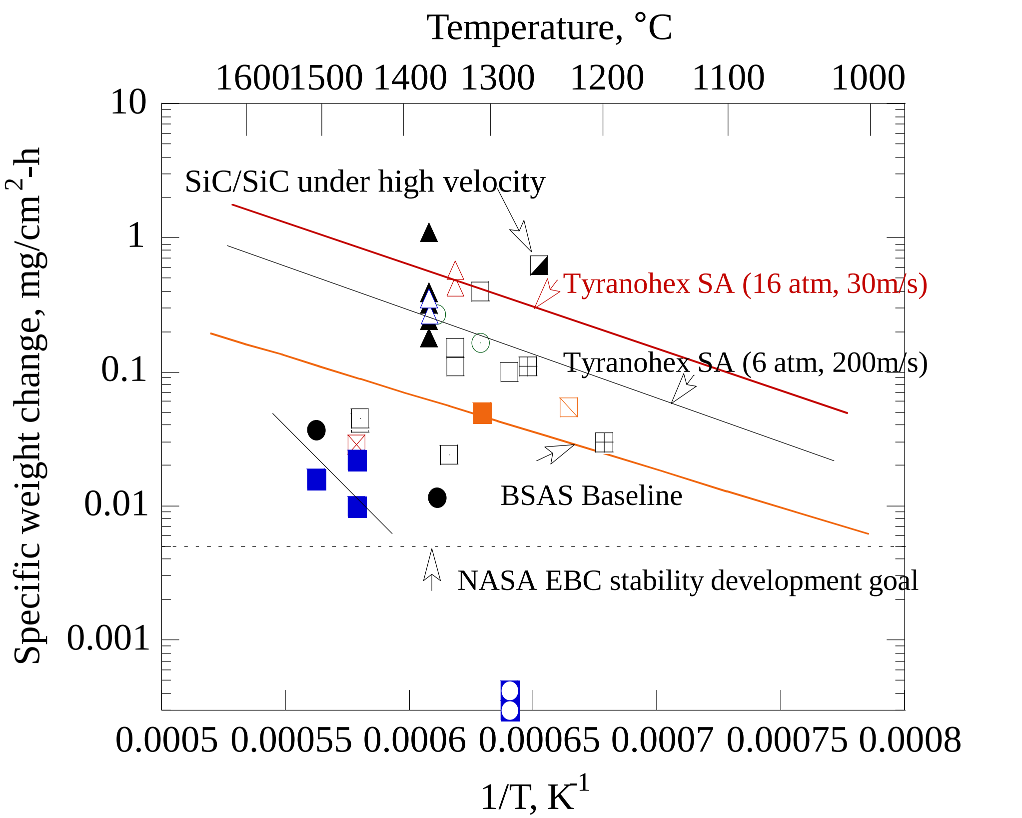
- SA Tyrannohex specimen (25x25x3 mm) tested at under thermal gradient cycling conditions: Tsurface 2300-2400°F (1260-1316°C), Tback 1700-1750°F (900°C), 1 hr cyclic in air, for total 200 cycles
- No major delamination under the thin specimen configuration possibly due to less complex temperature profiles; minor "micro" level delamination cracking and specimen size increase possibly due to oxidation



Tested specimen (cross-sectional view)

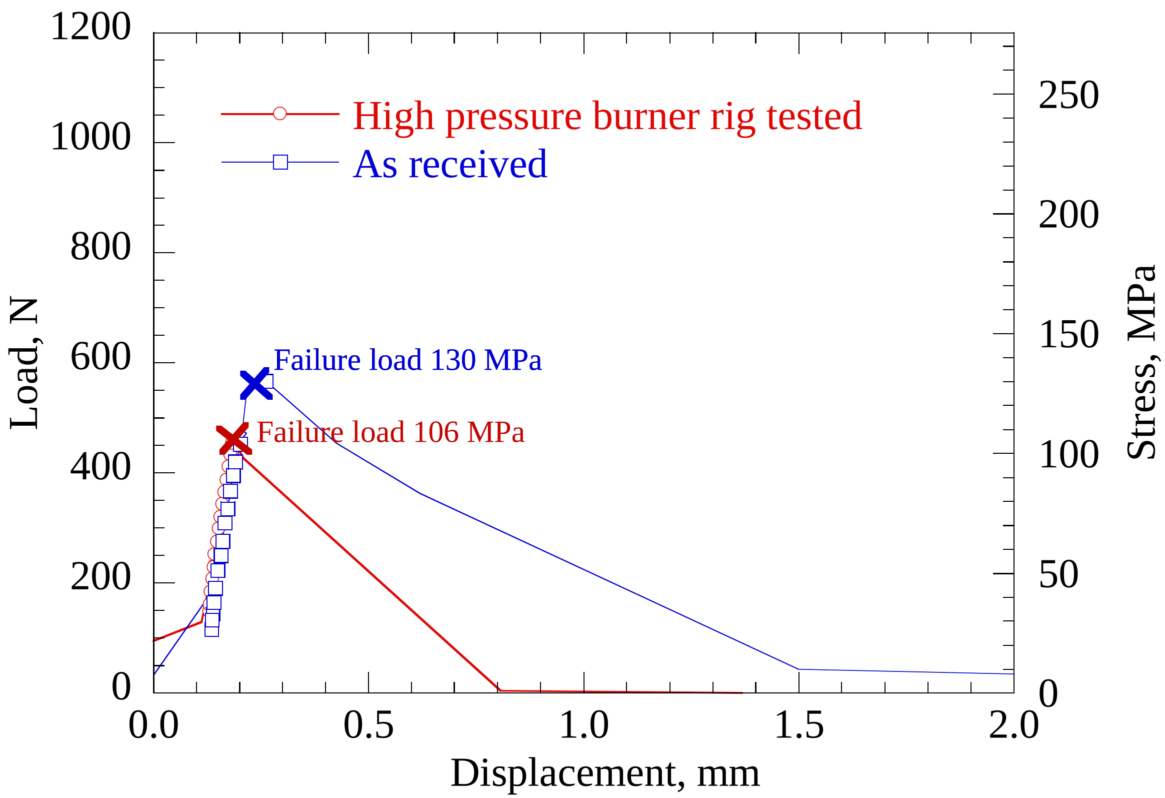
SA Tyrannohex SiC Ceramic Composites Recession Rates Tested at Various Simulated Combustion Rig Conditions

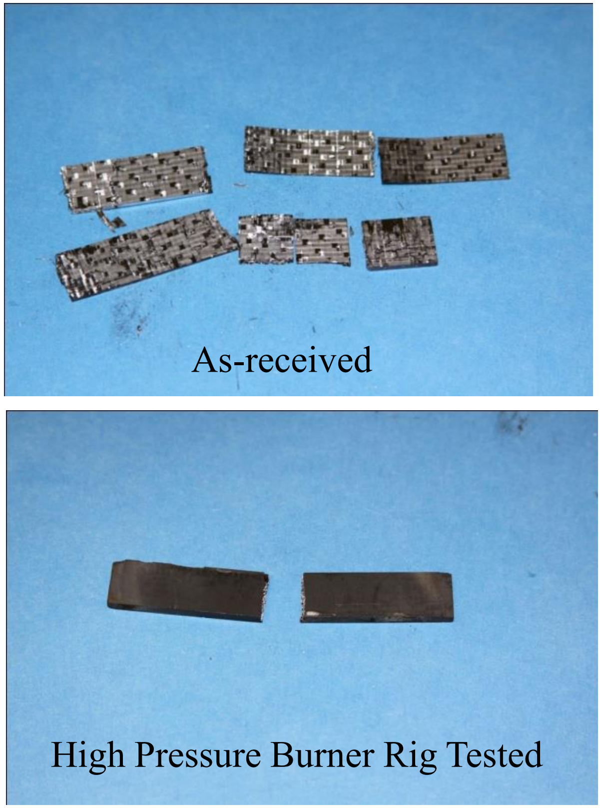
- Recession rates of SA Tyraonnohex SiC composite tested at 1340 – 1371°C (2445-2500°F) all at 200 m/s gas velocity in a High Pressure Burner Rig
- The ceramic stability is in-line with other silicon-based materials
- Unlabeled comparison specimen test conditions are standard condition, 6 atm 30 m/s



Uncoated SA Tyrannohex Composite Flexural Strengths

- Some as-processed specimens seemed to have low interlayer/interlaminar strengths in the flexural test configuration at room temperature (RT) tests
- Flexural test strength tests of High Pressure Burner Rig Tested at 2500°F (1371°C) for 20 hours shoed reduced strength after testing
- *Generally lows strengths for the uncoated specimens at the RT tests*





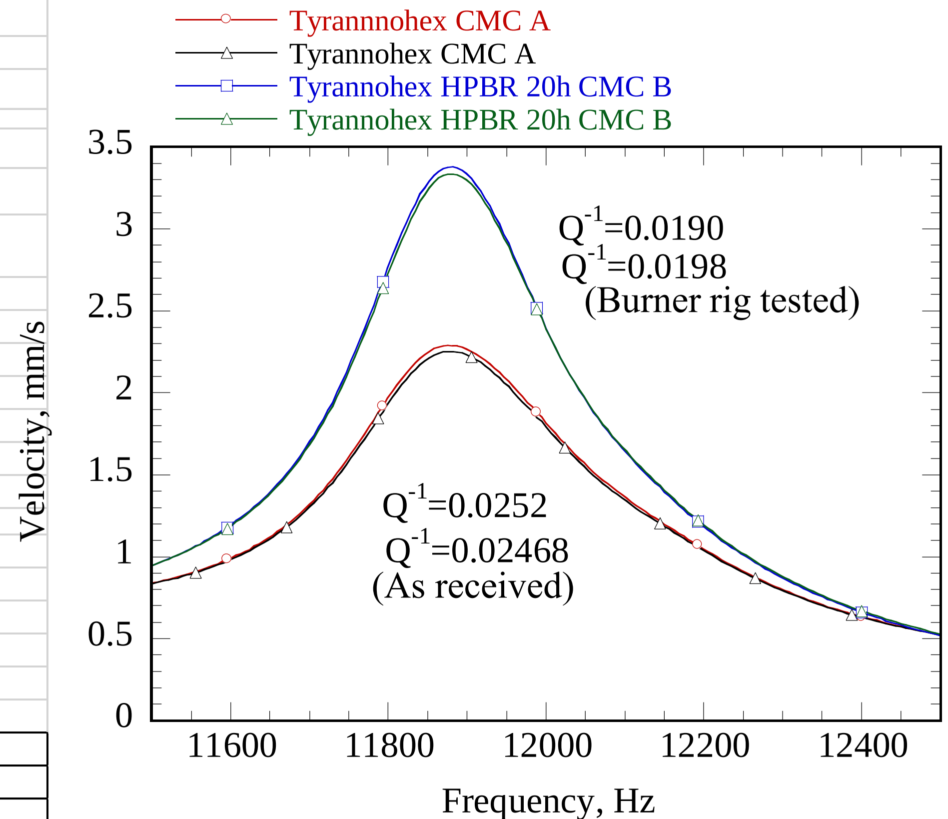
Examples of Tyrannohex composites failure after testing

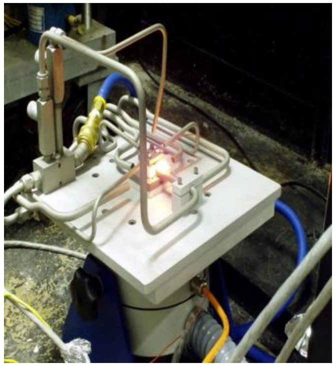
Vibration Damping of Tyranno SiC Composites

– Tested at both high temperature (1900°F) and room temperature using 3”x0.5”x0.125” beam specimen configuration; second bending frequency ~12000 Hz

Beam Length	**2**	**in**
Beam Width	**0.5**	**in**
Beam Thickness	**0.125**	**in**
Density	**0.112**	**lb/in^3**
Young's Modulus	**4.49E+07**	**psi**
Mass Density	0.000289855	lb-s^2/in^4
Mass per unit length	1.81E-05	lb-s^2/in^2
Area moment of inertia	8.13802E-05	in^4
EI	3.66E+03	lb-in^2
a	14206.35449	
K1	1.875	
K2	4.694	
K3	7.855	
K4	10.996	
K5	14.137	
ω1	12486.05	rad/s
ω2	78254.41	rad/s
ω3	219136.66	rad/s
ω4	429429.74	rad/s
ω5	709801.92	rad/s
f1	1987.2	**Hz**
f2	12454.6	**Hz**
f3	34876.7	**Hz**
f4	68345.9	**Hz**
f5	112968.5	**Hz**

Modal calculations

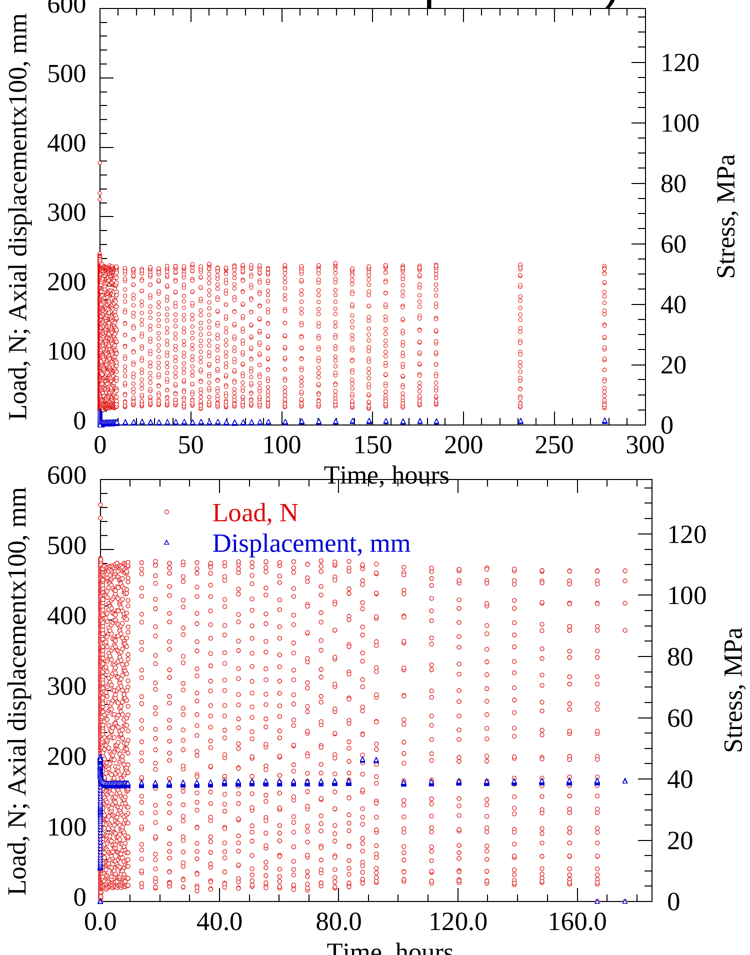




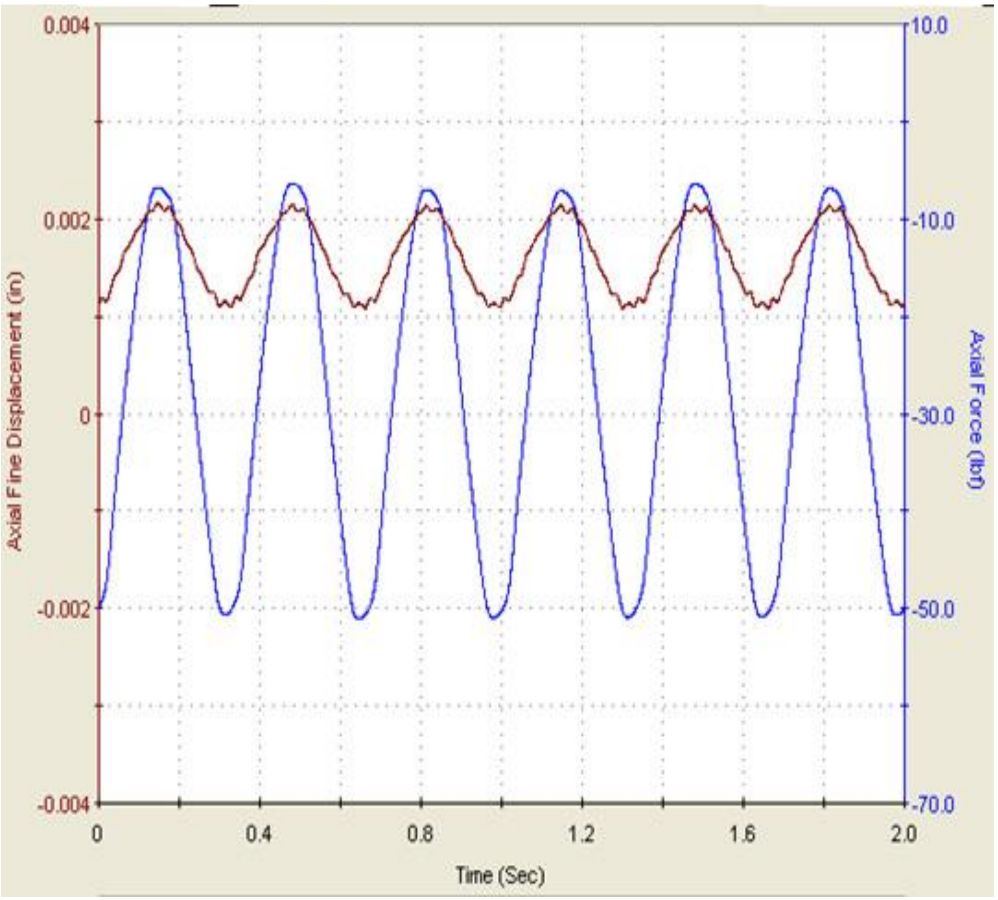
Second mode bending at RT: burner rig tested specimens showed stiffer behavior from the room temperature tests

High Temperature Long-Term Thermomechanical Fatigue Testing of SA Tyrannohex SiC Composites with Advanced 2700°EBCs

– Step load increases for testing up to 103.5 MPa (15 Ksi); with fatigue frequency 3 Hz and stress ratio R=0.05, tested at 2700°F (1482°C; less than 100°F ΔT across the 0.125” thick specimen)



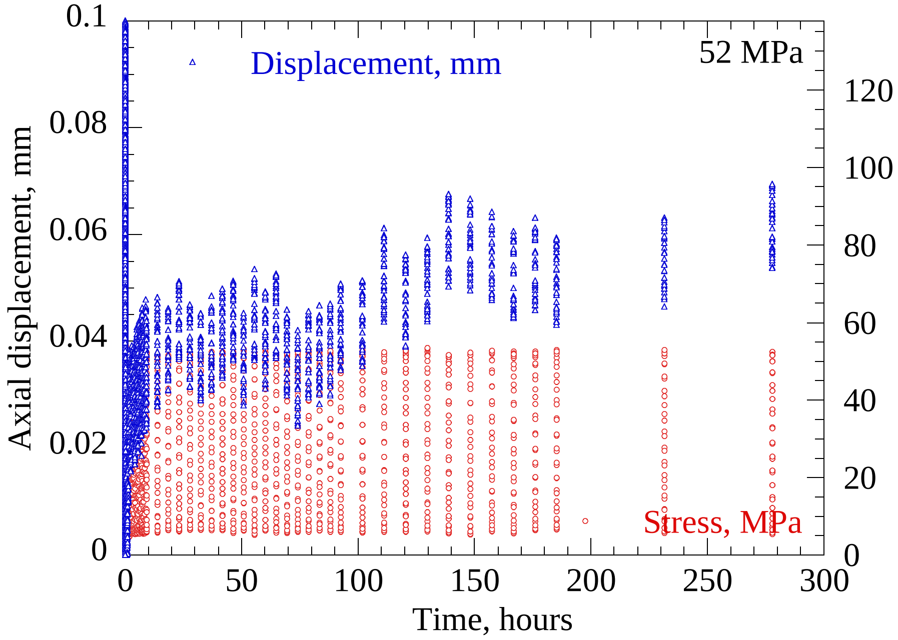
Test load and displacement amplitudes

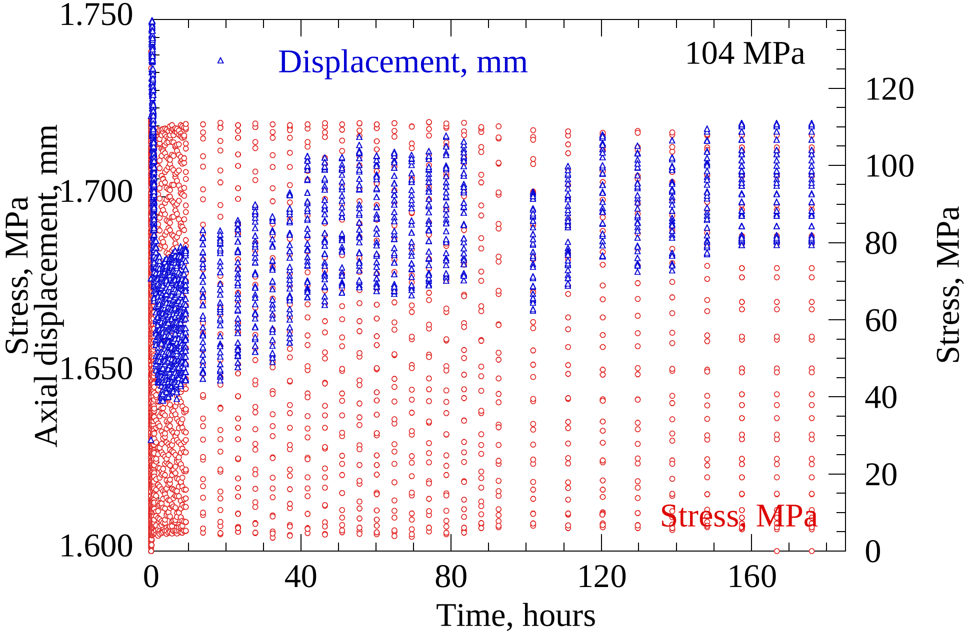


Wave form, 3 Hz fatigue cycles

High Temperature Long-Term Thermomechanical Fatigue Testing of SA Tyrannohex SiC Composites with Advanced 2700°F EBCs - Continued

- The fatigue cycles at load conditions of 52 MPa (tested 3 million cycles) and 104 MPa (tested 2 million cycles)
- Measured total creep strains 0.035% at the 52 MPa and 0.06% at 104 MPa, respectively, derived from the displacements

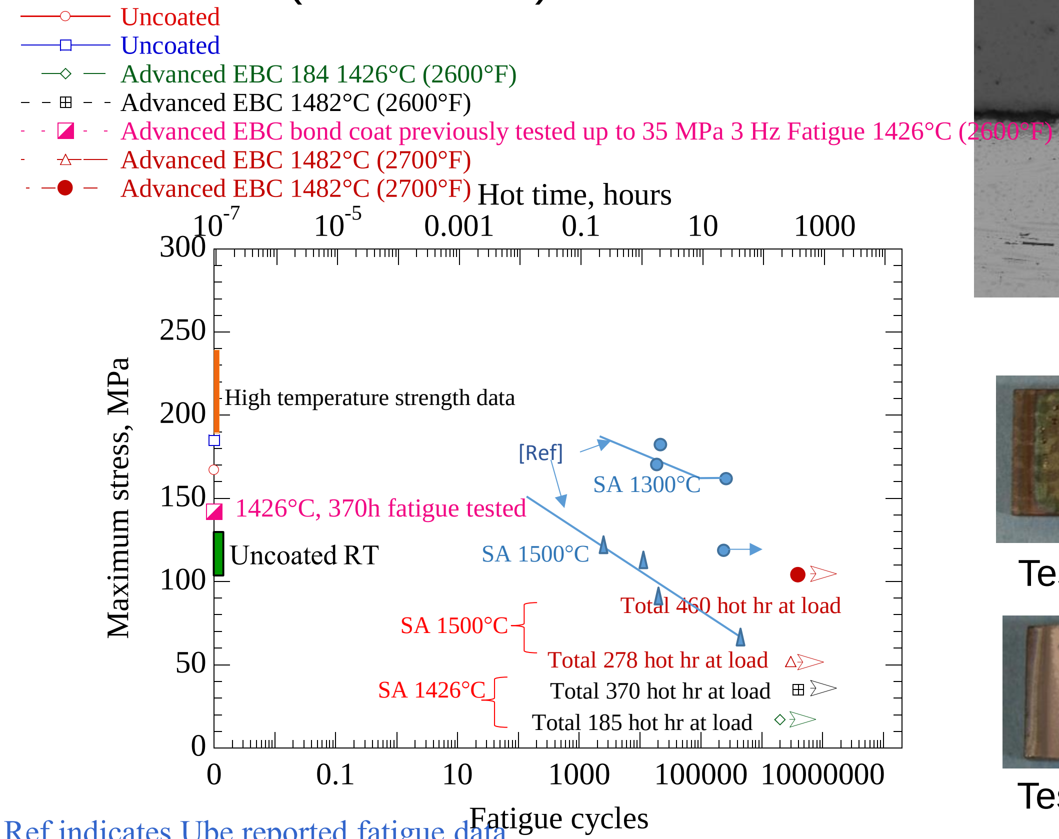




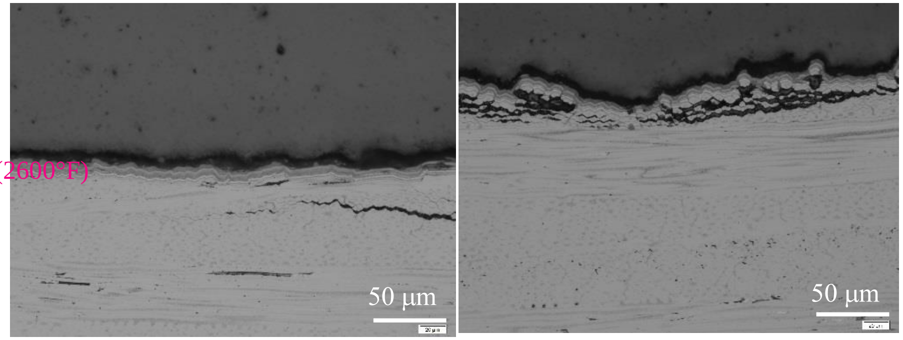
Displacement and Stress amplitudes of the test specimens under 52 MPa and 104 MPa

High Temperature Long-Term Thermomechanical Fatigue Behavior of Advanced 2700°F EBC Coated SA Tyrannohex Materials

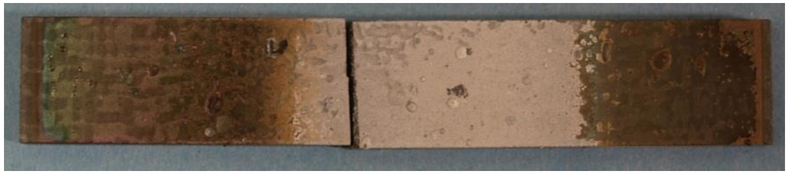
- Advanced turbine Rare Earth-Silicon (O) environmental barrier coatings developed suitable for the SA Tyrannohex composites
- The coating showed excellent performance, improved over uncoated systems
- Long-term fatigue lives (near 500 hr) achieved at 1482°C (2700°F) under loading at 15Ksi (103.5 MPa)



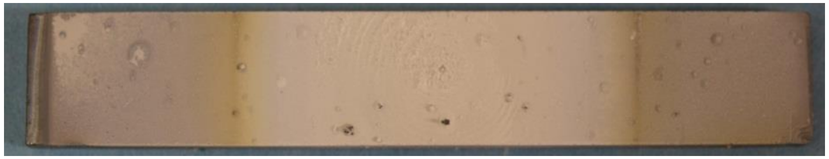
Ref indicates Ube reported fatigue data



~ 500h tested Fatigue tested



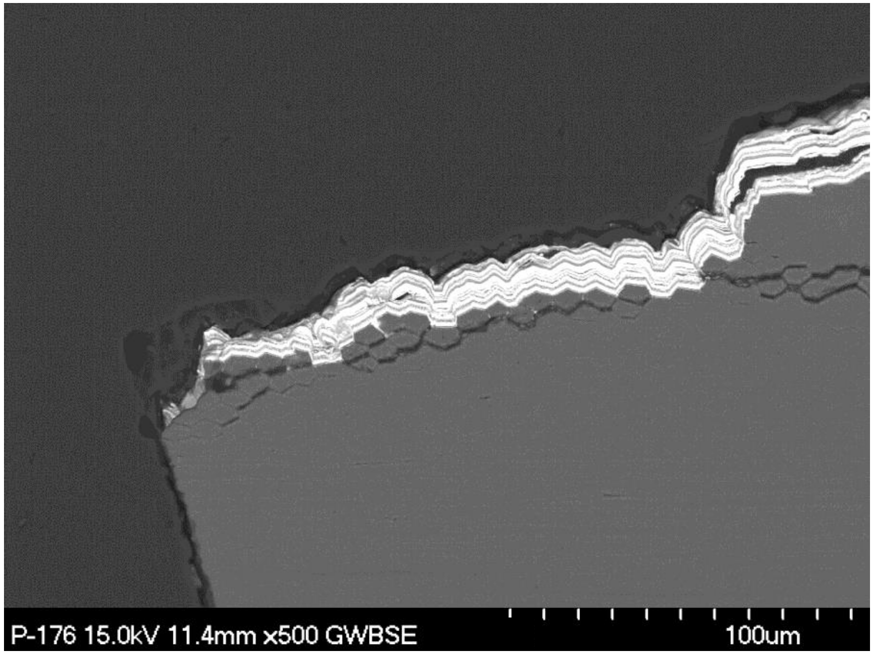
Tested, SA Tyrannohex with EBC bond coat only

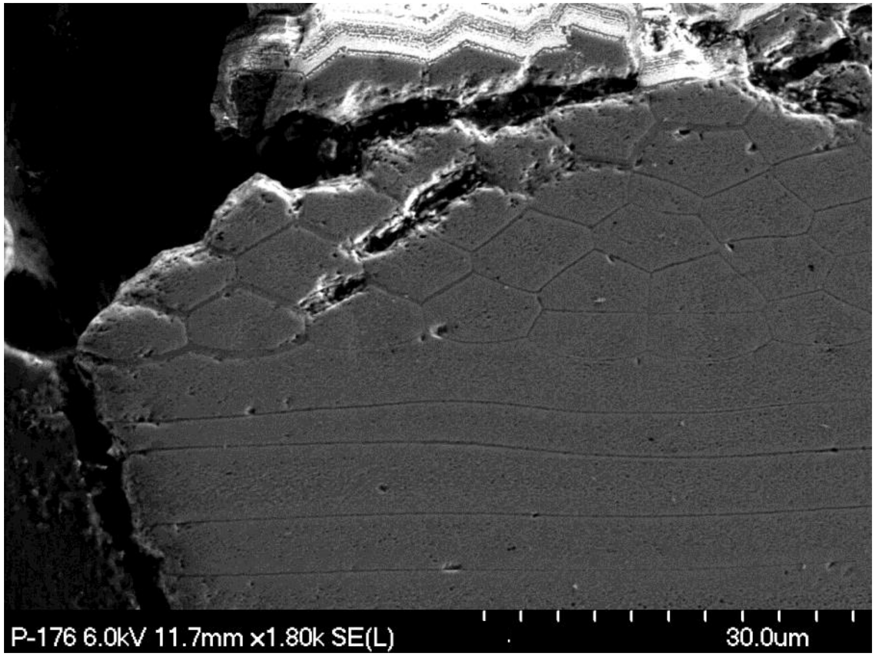


Tested, SA Tyrannohex with EBCs

High Temperature Long-Term Thermomechanical Fatigue Behavior of Advanced 2700°F EBC Coated SA Tyrannohex Composites - Continued

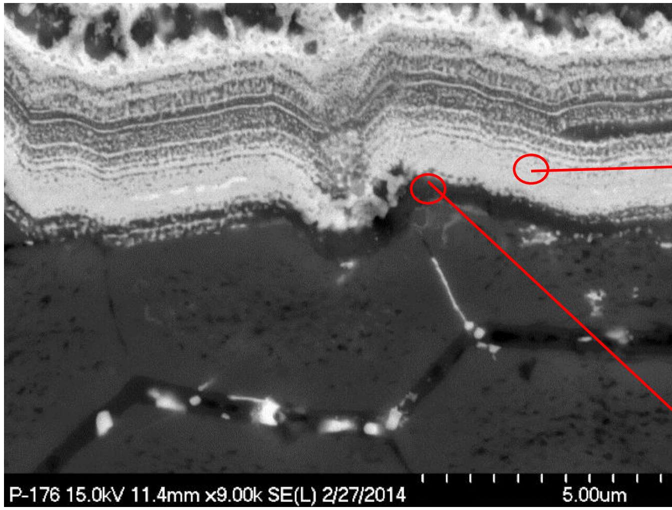
- Strong coating - fiber bonding observed after the fatigue – fracture testing

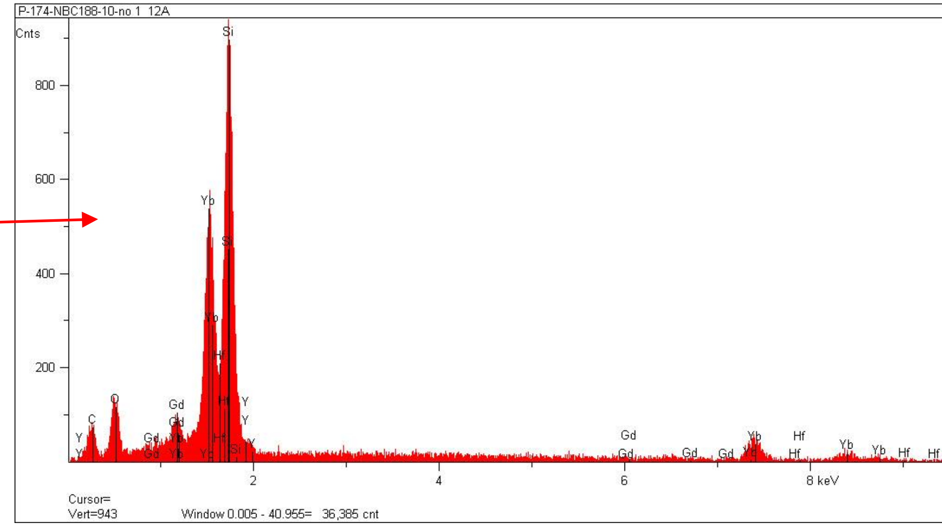


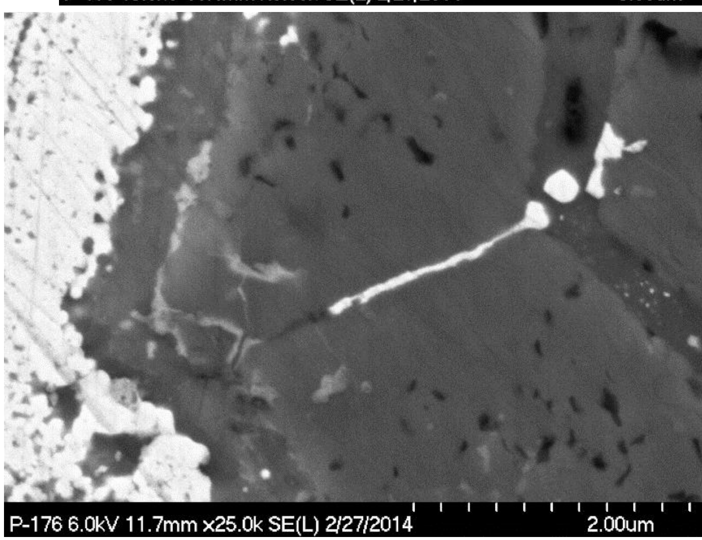


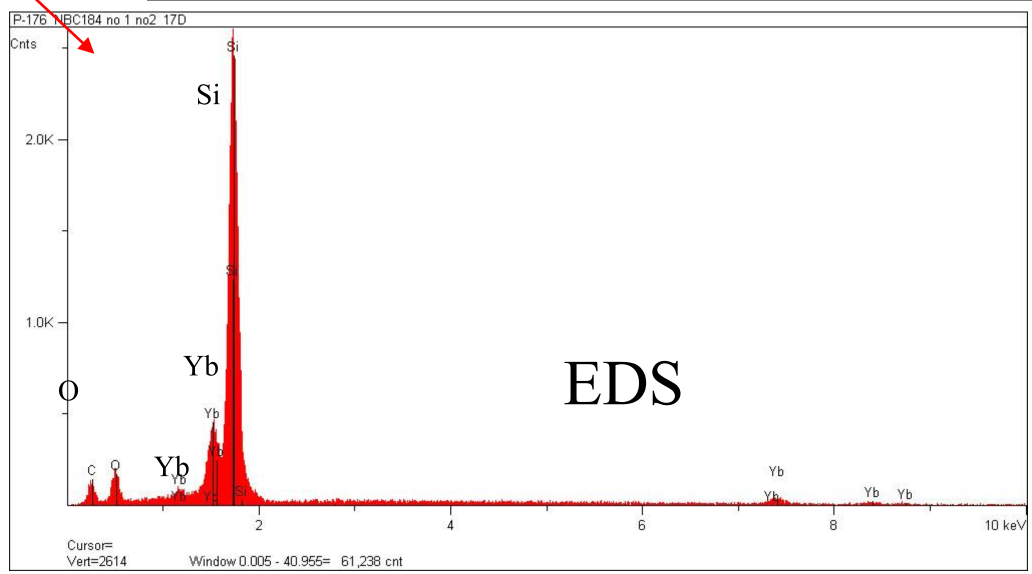
The Flexural Fatigue Tested Environmental Barrier Coating System - Continued

- Ytterbium (RE)-Si (O) based bond coats on fibers help improve fiber bonding, self-healing the composite fatigue cracking









~500 hr, 2600-2700°F fatigue tested

Summary

- Environmental stability and thermal gradient cyclic durability performance of SA Tyrannohex composites investigated under very harsh simulated combustion and heat flux thermo-mechanical conditions

- The material showed good combustion environment resistance at 2500° F; the recession rates are generally expected in line with major advanced MI SiC/SiC or Si_3N_4 systems, but the composite material is capable of the higher testing temperatures

- SA Tyrannohex tends to delaminate in the as-processed condition, possibly due to processing variations; some heat treatment may help improve the composite internal closed-pack hexagonal columnar substructure adhesion. A thinner 3 mm thick specimen showed good high thermal gradient cyclic resistance

- Advanced turbine environmental barrier coated SA Tyrannohex composite systems showed excellent long-term durability performance in the environment fatigue tests up to 104 MPa (15 Ksi) and at 1482° C (2700° F) in air. Rig environmental tests were also performed among the hybrid airfoil systems, the analysis are also in progress.

Acknowledgement

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