Property Evaluation and Damage Evolution of Environmental Barrier Coatings and Environmental Barrier Coated SiC/SiC Ceramic Matrix Composite Sub-Elements

Dongming Zhu, Michael Halbig, Martha Jaskowiak, Janet Hurst, Ram Bhatt and Dennis Fox
NASA Glenn Research Center, Cleveland OH

38th Annual Conference on Composites, Materials and Structures
Cocoa Beach, Florida
January 27-30, 2014

Acknowledgements

The work was supported by NASA Fundamental Aeronautics Program Aeronautical Sciences Project.

Authors are grateful to

- Dr. Jim DiCarlo of NASA for many helpful technical discussions
- Ron Phillips and Ralph Pawlik for their assistance in the mechanical tests

Objectives

– Develop advanced, high performance environmental barrier coatings (EBC) and SiC/SiC ceramic matrix composite (CMC) systems relevant to next generation turbine engines

– Develop advanced testing methodologies for long-term durability improvements, emphasizing creep, fatigue and complex environment interactions in simulated operating conditions

- Focus on advanced NASA high heat flux – thermomechanical test rigs for element evaluations
- Evaluate properties or behavior of complex turbine component elements
  - Current CVI, Prepreg, and CVI-MI SiC/SiC systems, commercially purchased

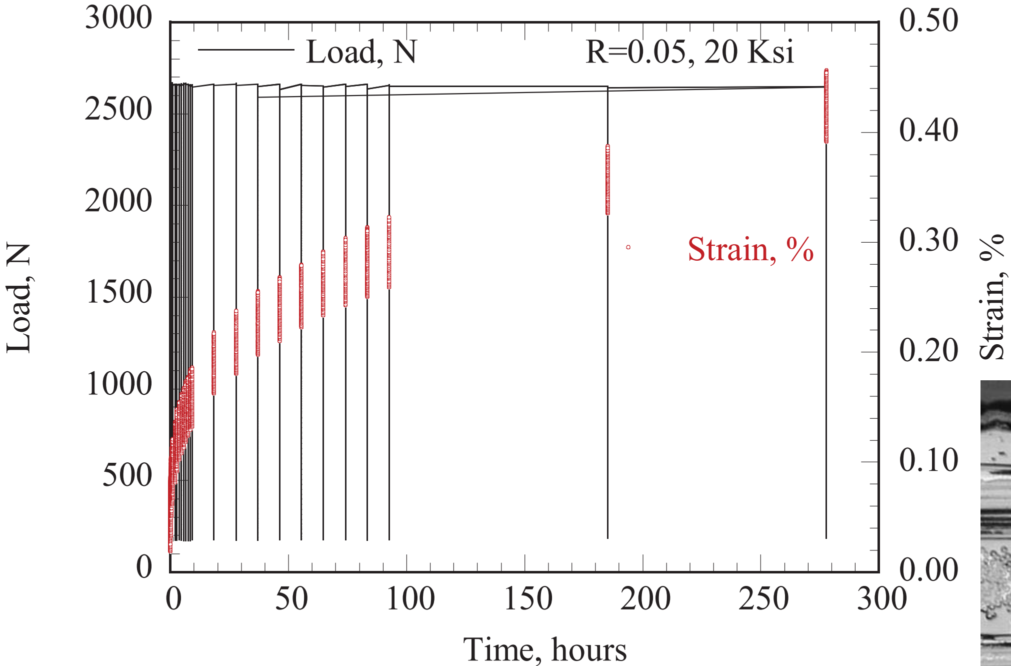
- Help develop testing parameters, establish understand damage evolution and performance database, and advancing environmental barrier coating technologies

Outline

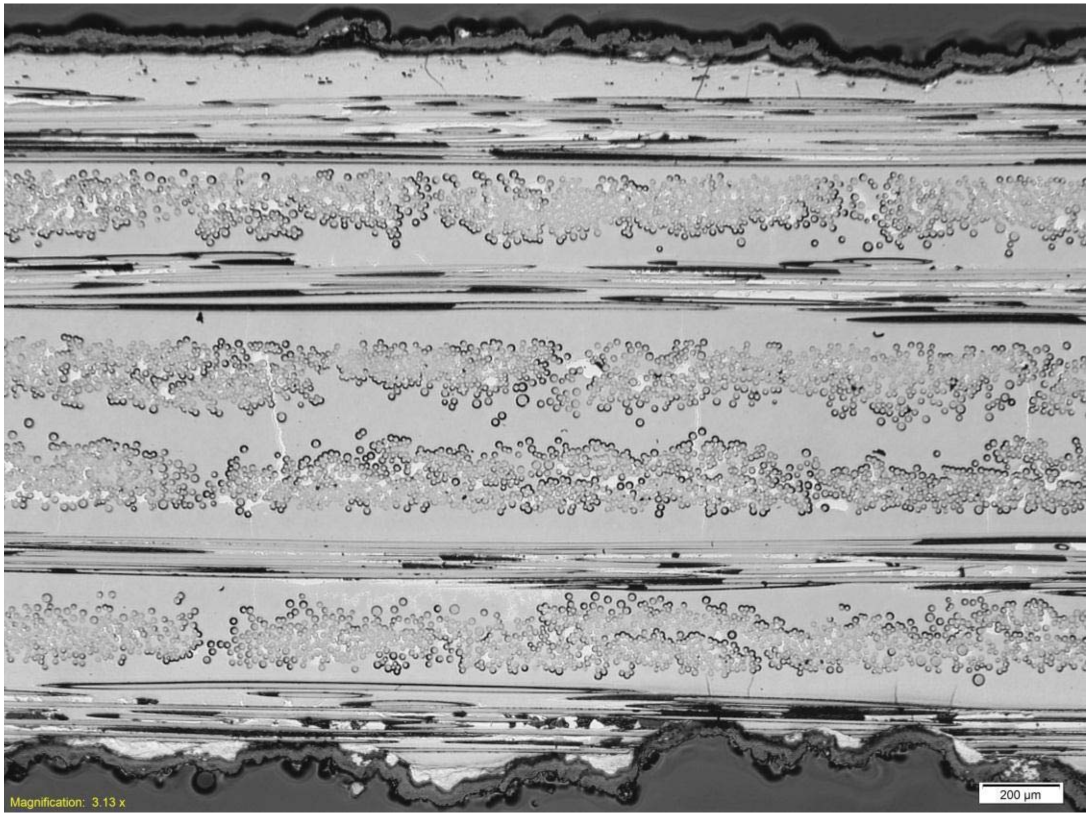
- Creep and fatigue of coated CMCs under thermal gradients
- Thermal conductivity of advanced EBCs based on turbine vane leading edge (LE) elements
- SiC/SiC turbine vane leading edge (LE) and trailing edge (TE) sub-element testing: heat flux durability and mechanical loading
- Summary and Conclusions

EBC – CMC Degradations under Fatigue Loading

– EBC coated 1847-01-007 #5, fatigue cycles tested at 3 Hz frequency, maximum stress 20 Ksi, stress ratio R=0.05 at 2400°F (1316°C)

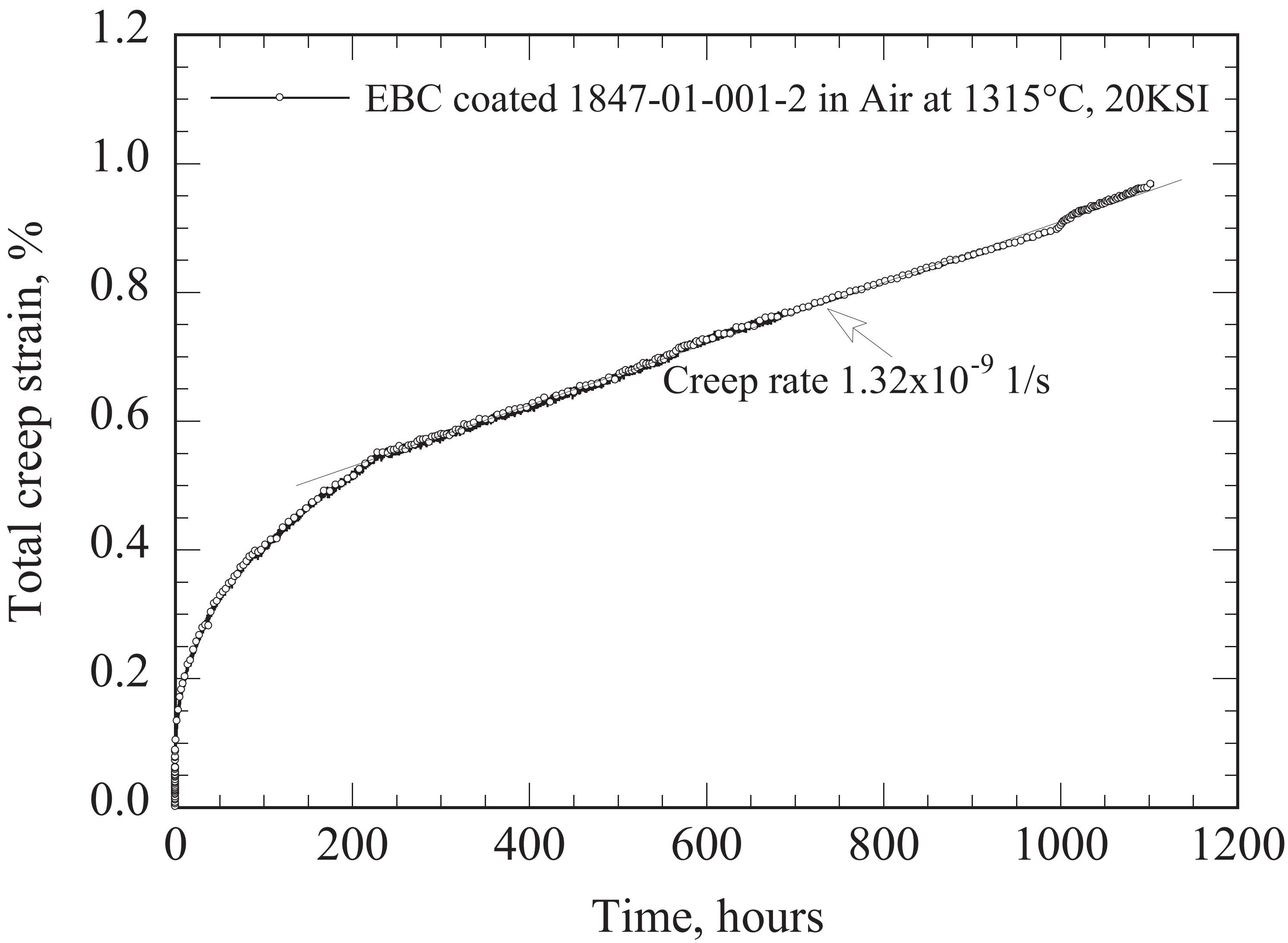


A 20 micrometer thick EBC bond coated Prepreg SiC/SiC CMC after 40 hr, maximum stress 20 Ksi, stress ratio R=0.05 fatigue testing in air



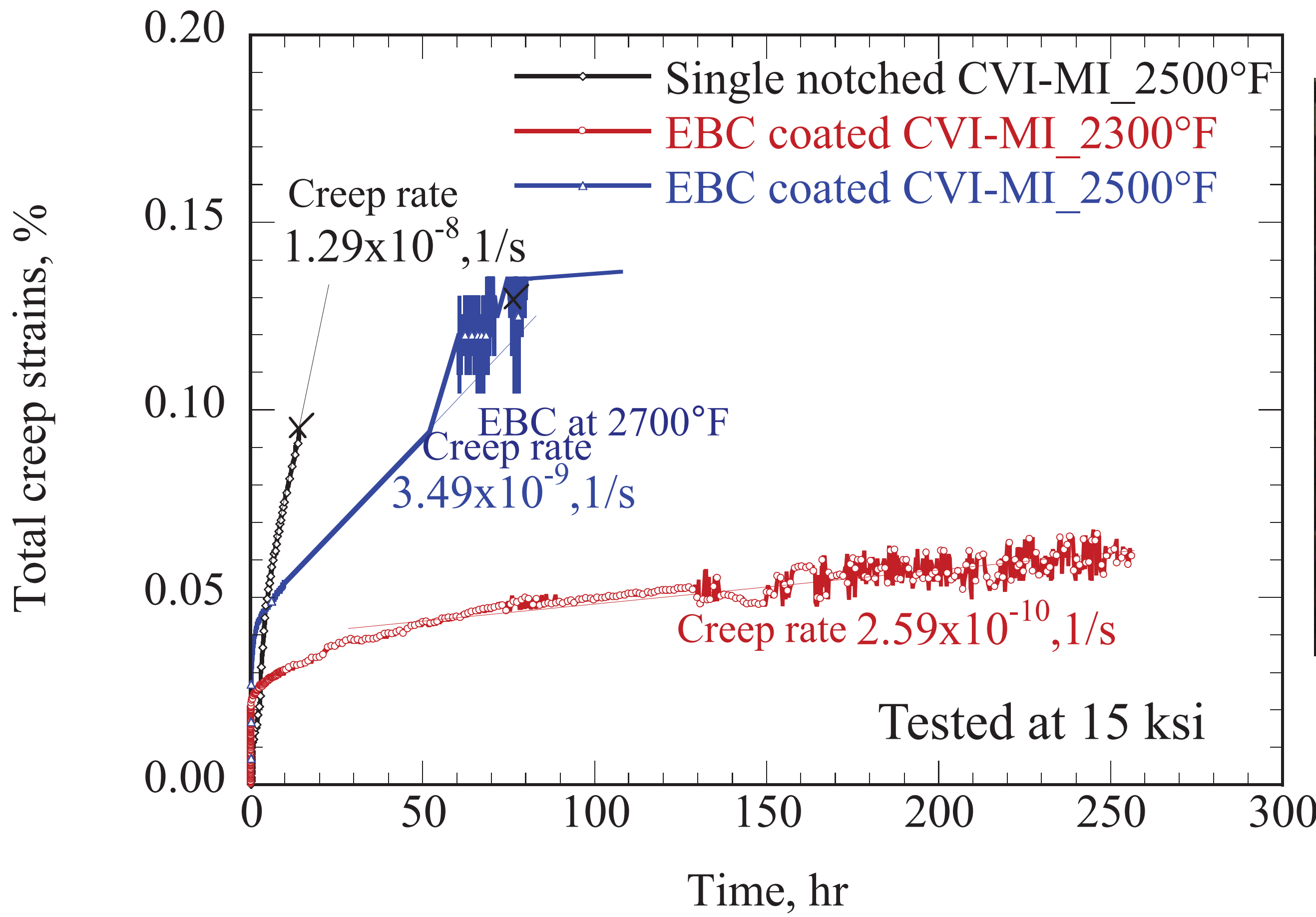
EBC Coated Prepreg SiC/SiC CMC Tested Near 1200hr Creep Life at 2400°F

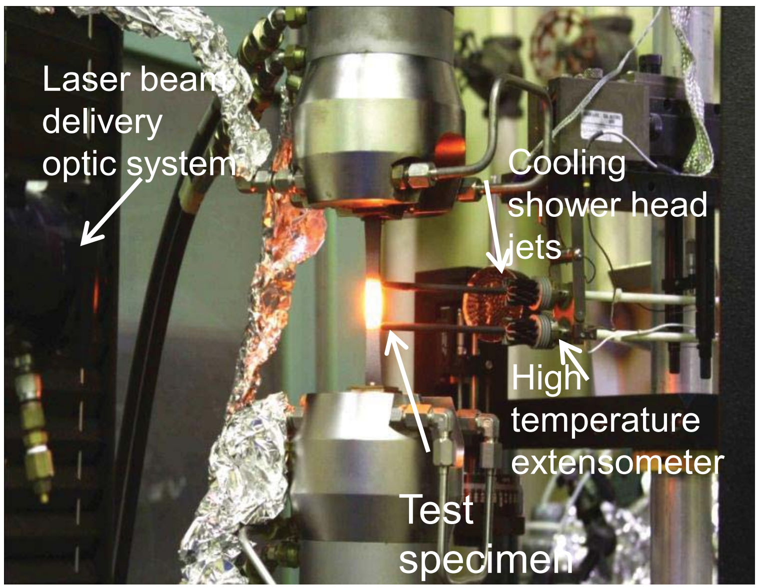
- The EBC coated Prepreg SiC/SiC achieved approximately total 1.0% creep strains at 20 Ksi stress at 2400°F (1316°C)



High Temperature Creep of SiC/SiC and Environmental Barrier Coating Recession in Turbine Environments

- Accelerated degradation observed for an uncoated CVI-MI CMC under a single notched specimen at high temperature (stress concentration factor considered and also verified with strain gauged tests)
- Heat flux and environmental degradation being studied

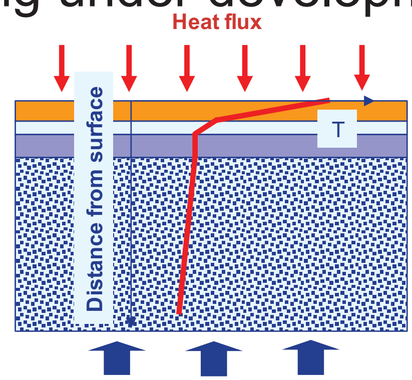




NASA High Heat Flux Tensile Rupture Tests

Laser Heat Flux Rigs for Advanced EBC-CMC Developments

- Turbine level heat flux, environment and load testing capabilities
- Quantitative one dimensional (one-D) steady-state thermal conductivity measurements and durability testing
- Two dimensional (2D) coating and component material degradation real time monitoring under development

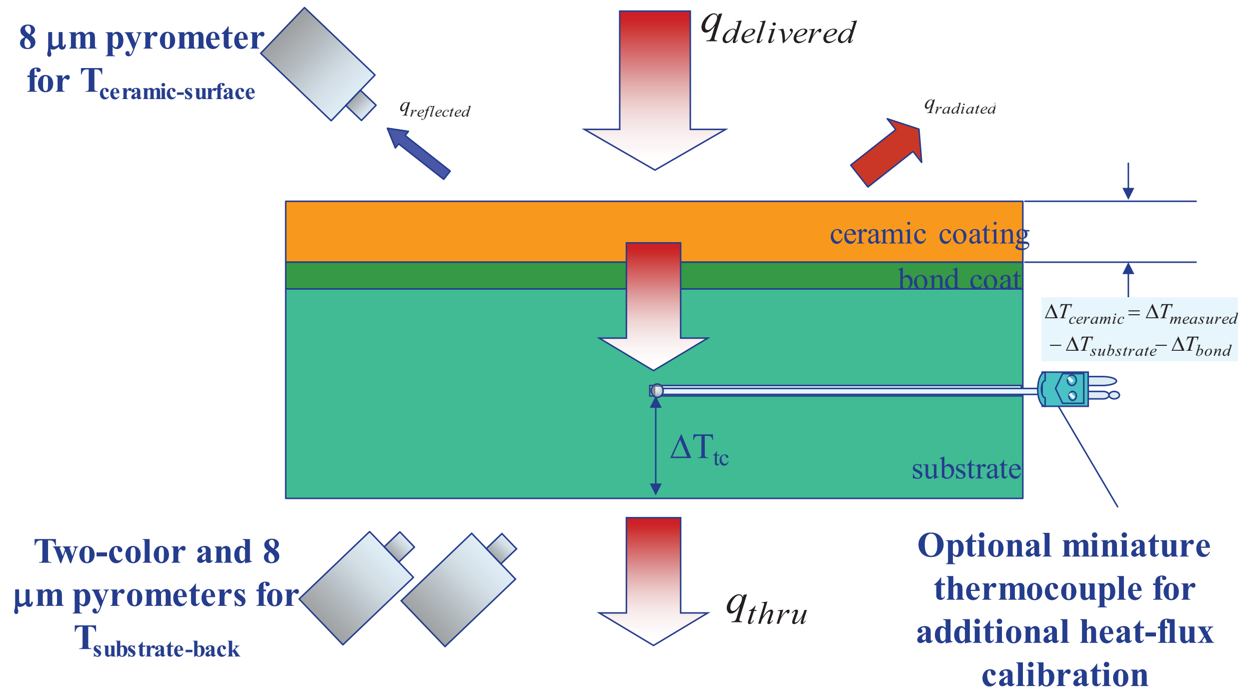


A 3500Kw high power CO_2 laser

$$k_{ceramic}(t) = q_{thru} \cdot l_{ceramic} / \Delta T_{ceramic}(t)$$

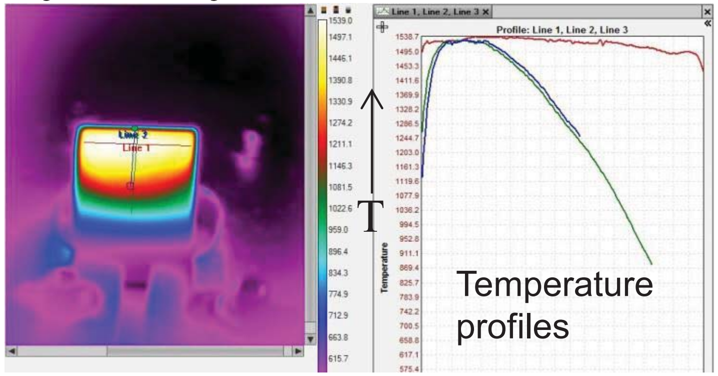
Where

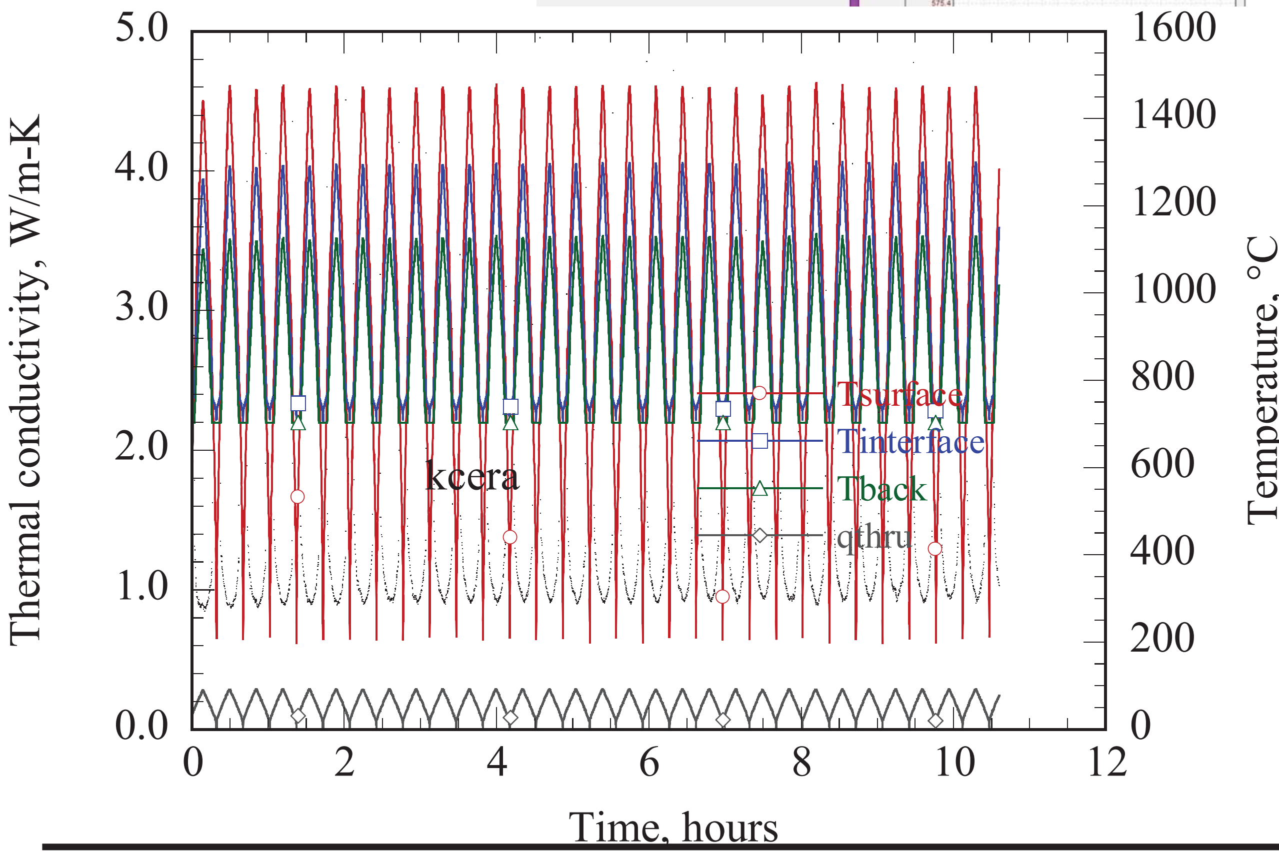
$$q_{thru} = q_{delivered} - q_{reflected} - q_{radiated}$$ and $$\Delta T_{ceramic}(t) = T_{ceramic-surafce} - T_{metal-back} - \int_0^{l_{bond}} \frac{q_{thru} \cdot dl}{k_{bond}(T)} - \int_0^{l_{substrate}} \frac{q_{thru} \cdot dl}{k_{substrate}(T)}$$

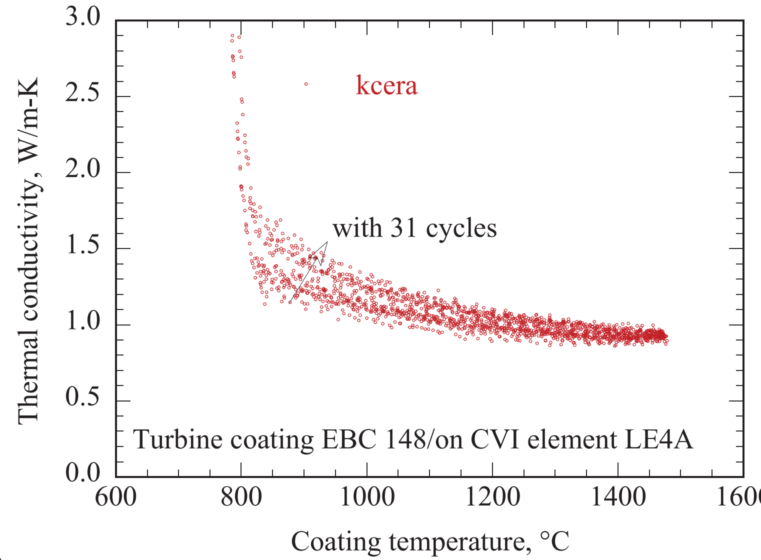


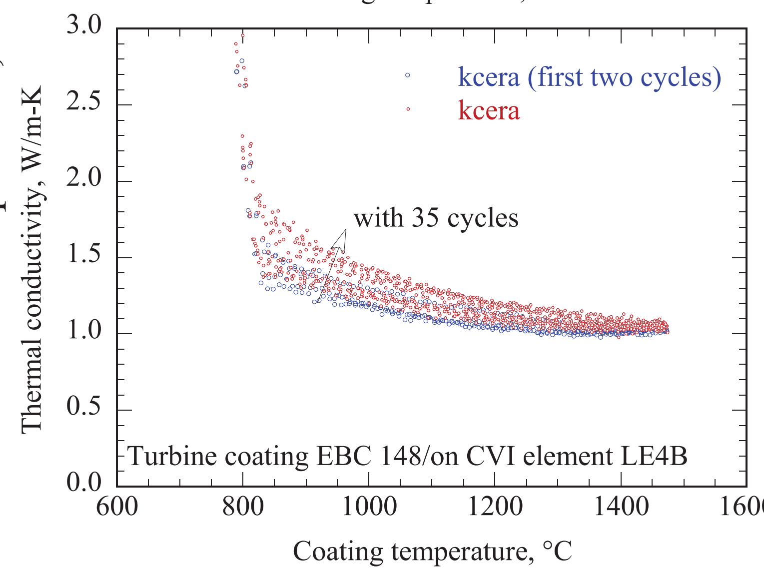
Thermal Conductivity of Environmental Barrier Coating Systems Determined for SiC/SiC CMC Leading Edge (LE) Elements

- Thermal conductivity test cycles of CVI SiC/SiC sub-elements



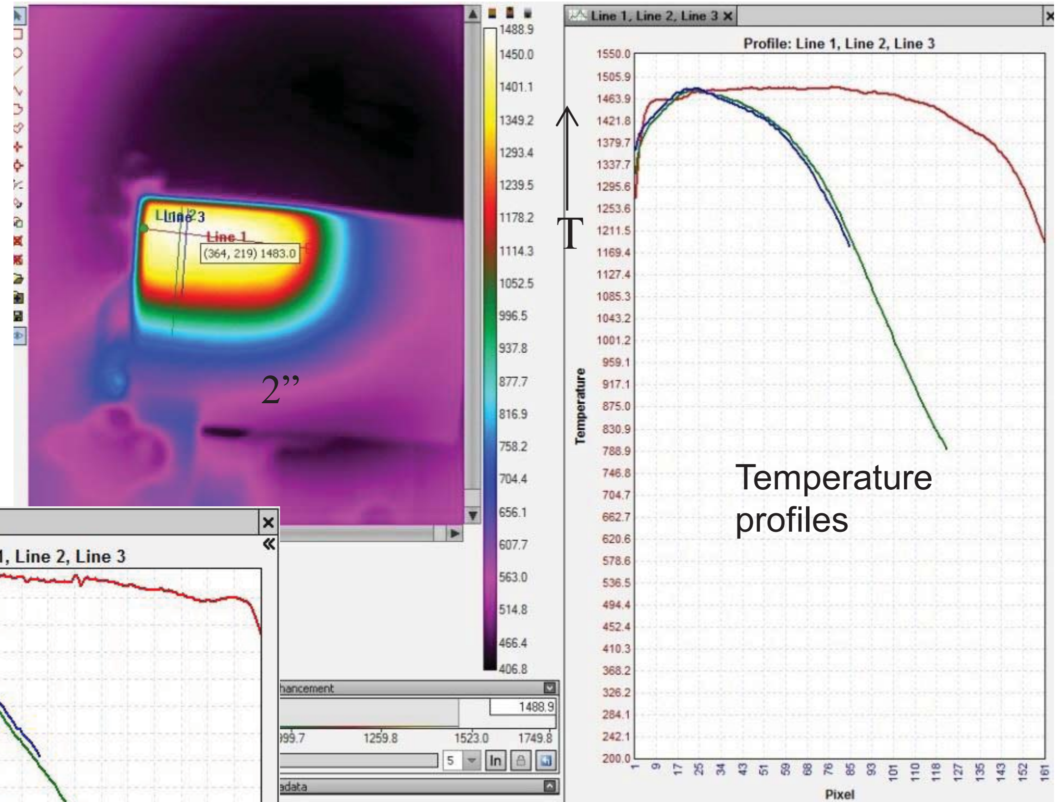


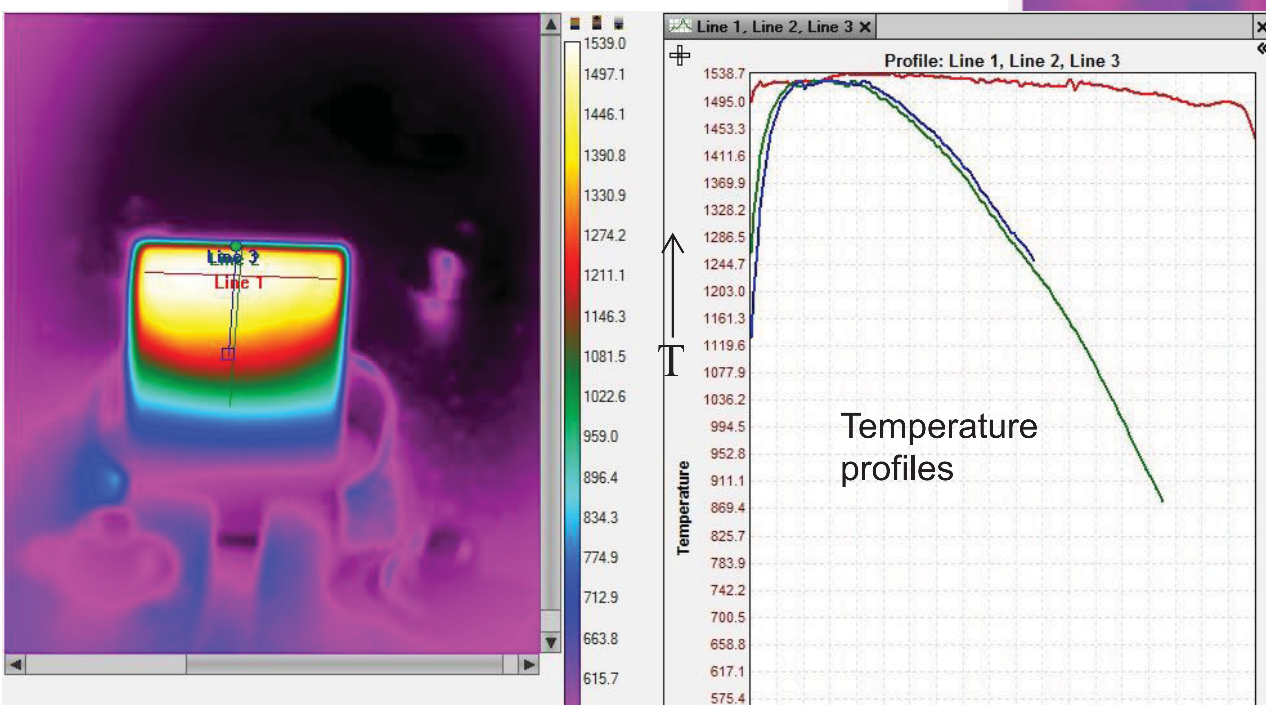




Thermal Conductivity of Environmental Barrier Coating Systems Determined for SiC/SiC CMC Leading Edge (LE) Elements - Continued

- In-situ, real time 2D or 3D thermal conductivity monitoring being implemented

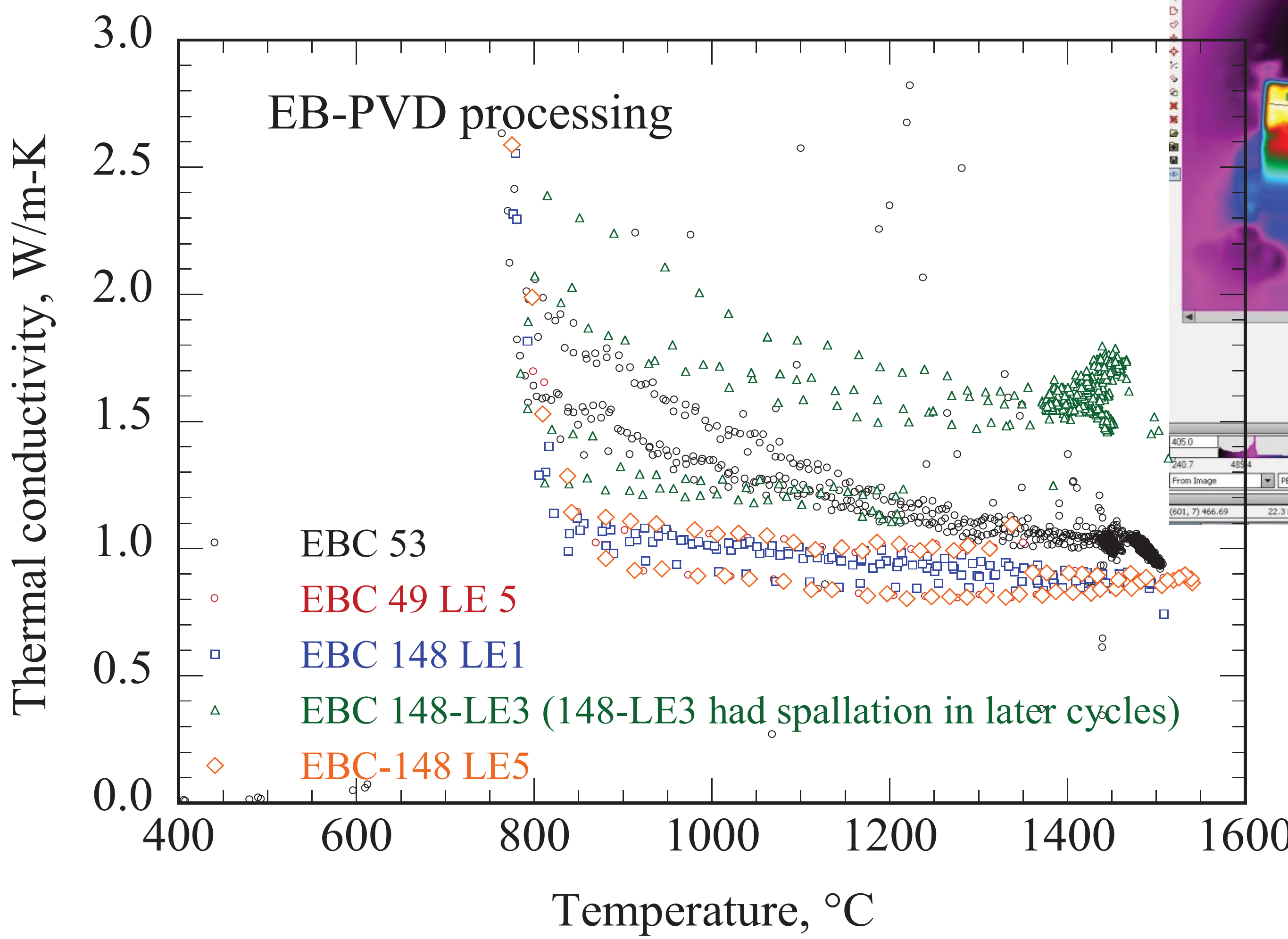


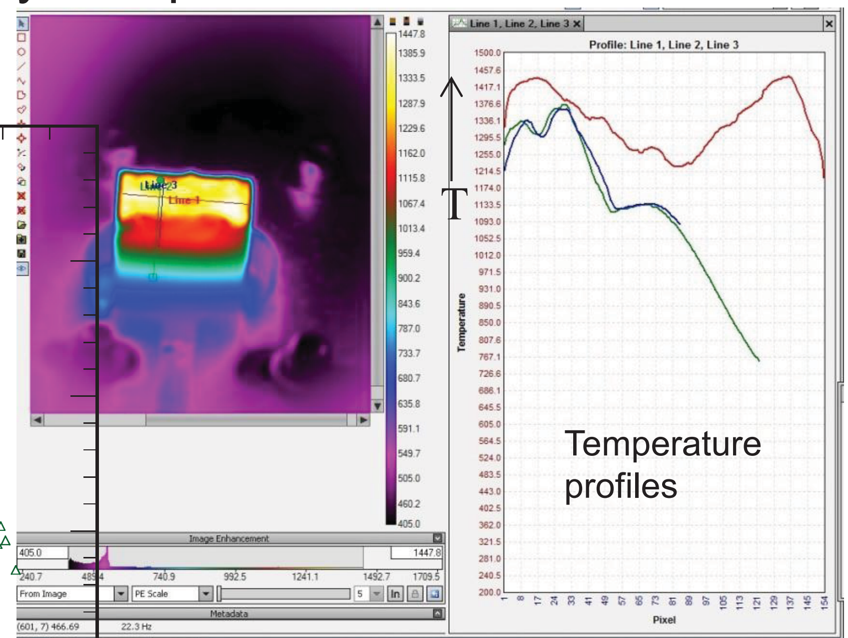


- 1” and 2” specimens in testing
- Heated area 1.25” diameter

Thermal Conductivity of Environmental Barrier Coating Systems Determined for SiC/SiC CMC Leading Edge (LE) Elements - Continued

- Thermal conductivity of turbine EBCs on Prepreg LE subelements determined
- The data used to evaluate processing consistency, composition effect and reliability

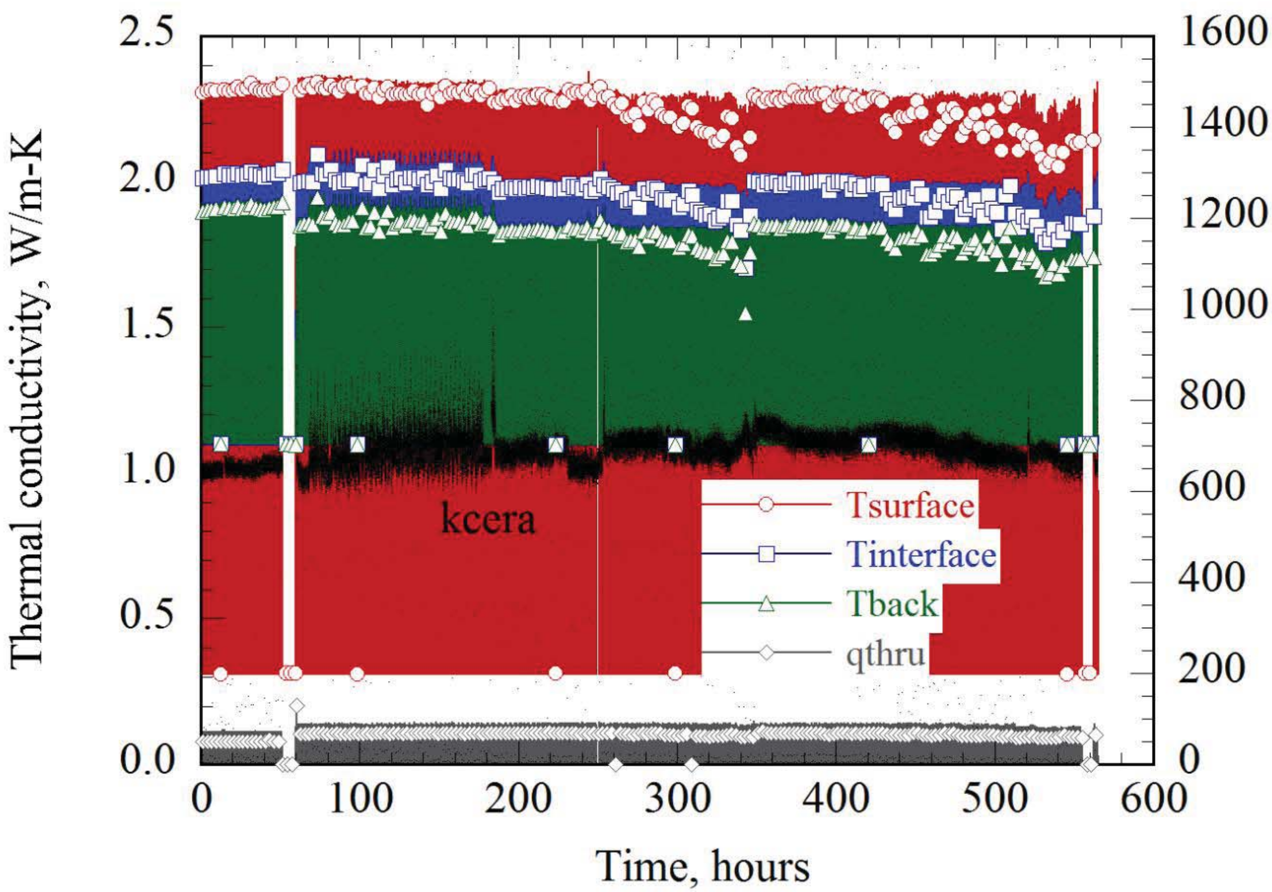


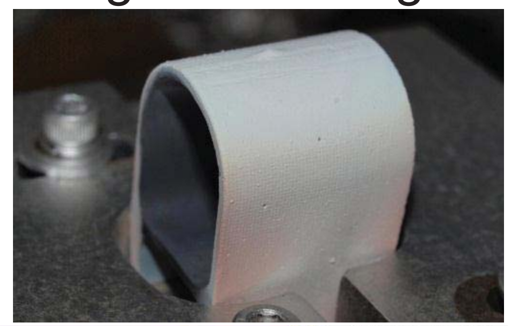


Thermal image of EBC 148-LE3 at 20 cycles

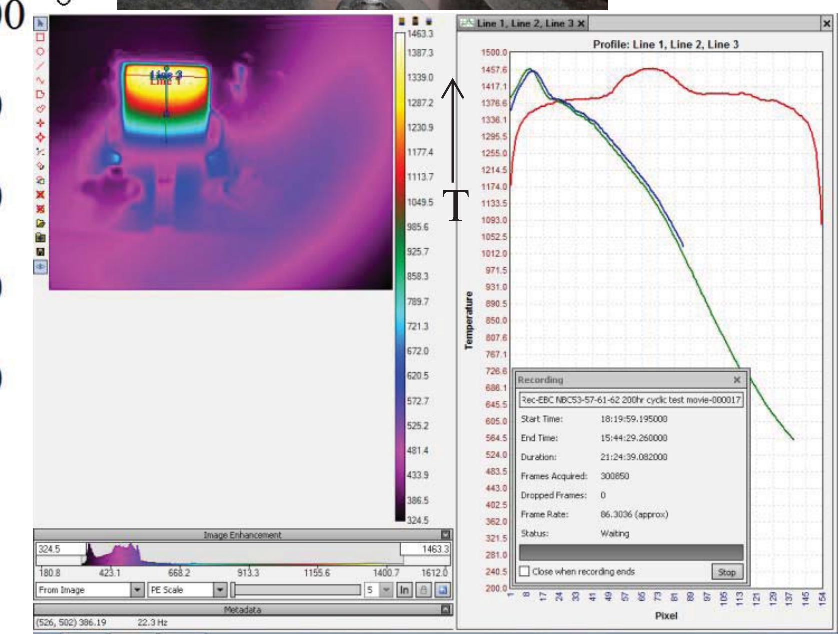
Turbine Environmental Barrier Coating System Long-Term Durability Testing on a Prepreg SiC/SiC Subelement

- The LE element tested at $T_{EBC\ surface}$ ~2700°F (1482C), $T_{EBC\text{-}CMC}$ interface = 2400-2460°C (1300-1348°C)
- Completed 550, 1 hr cycles
- Coating damage evolution was monitored using during the entire testing
- The coating had only very minor degradation after the long term testing



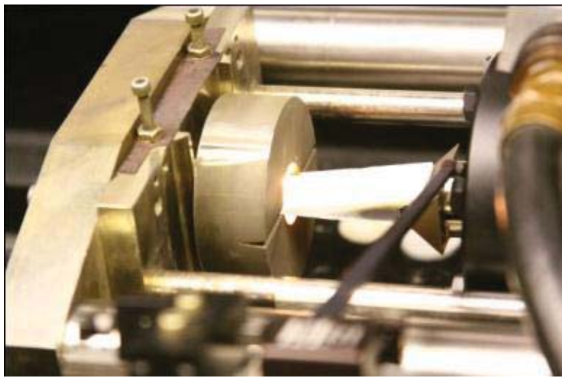


At 550 cycles

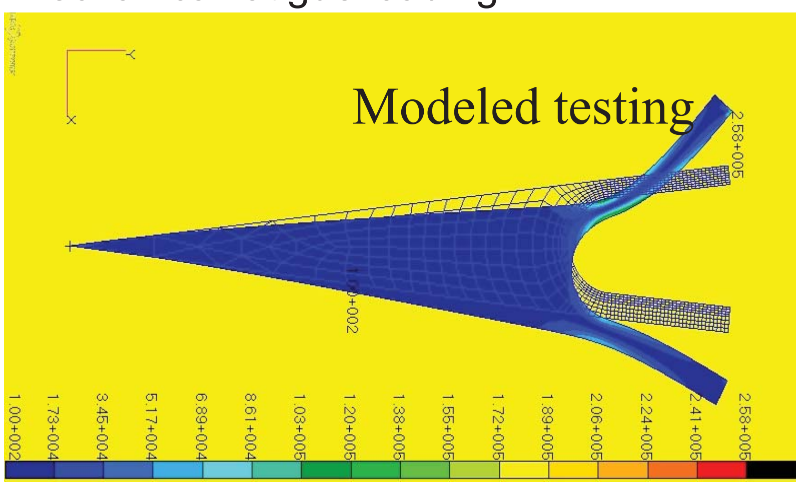


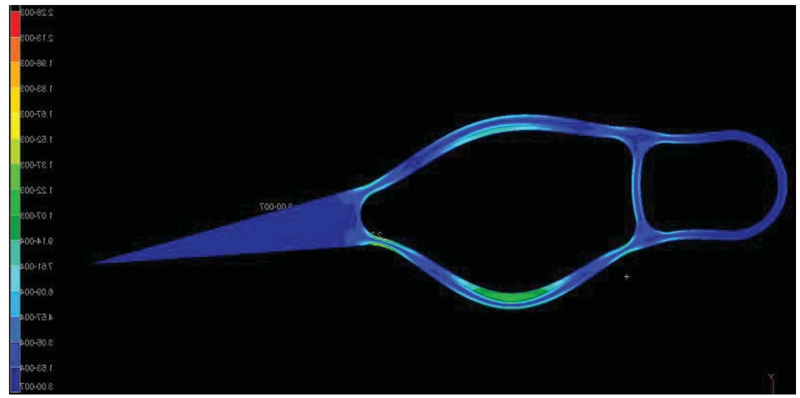
EBC-CMC Turbine Trailing Edge (TE) Fatigue Testing

- Testing approaches developed for EBC-CMC trailing edge thermomechanical testing
- High heat flux capability to simulate required high thermal gradients and more complex temperature distributions in a turbine engine
- Mechanical loading to simulate the high pressure turbine airfoil pressure (ballooning) effects
- EBC-CMC durability being evaluated, planned incorporation of stream jet environments

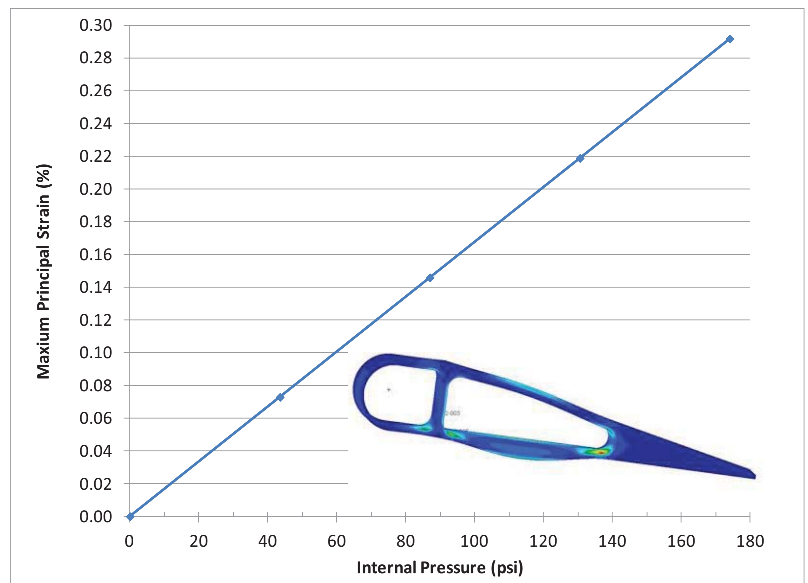


EBC coated Trailing Edge (TE) “wedge” testing in high heat flux and mechanical fatigue loading



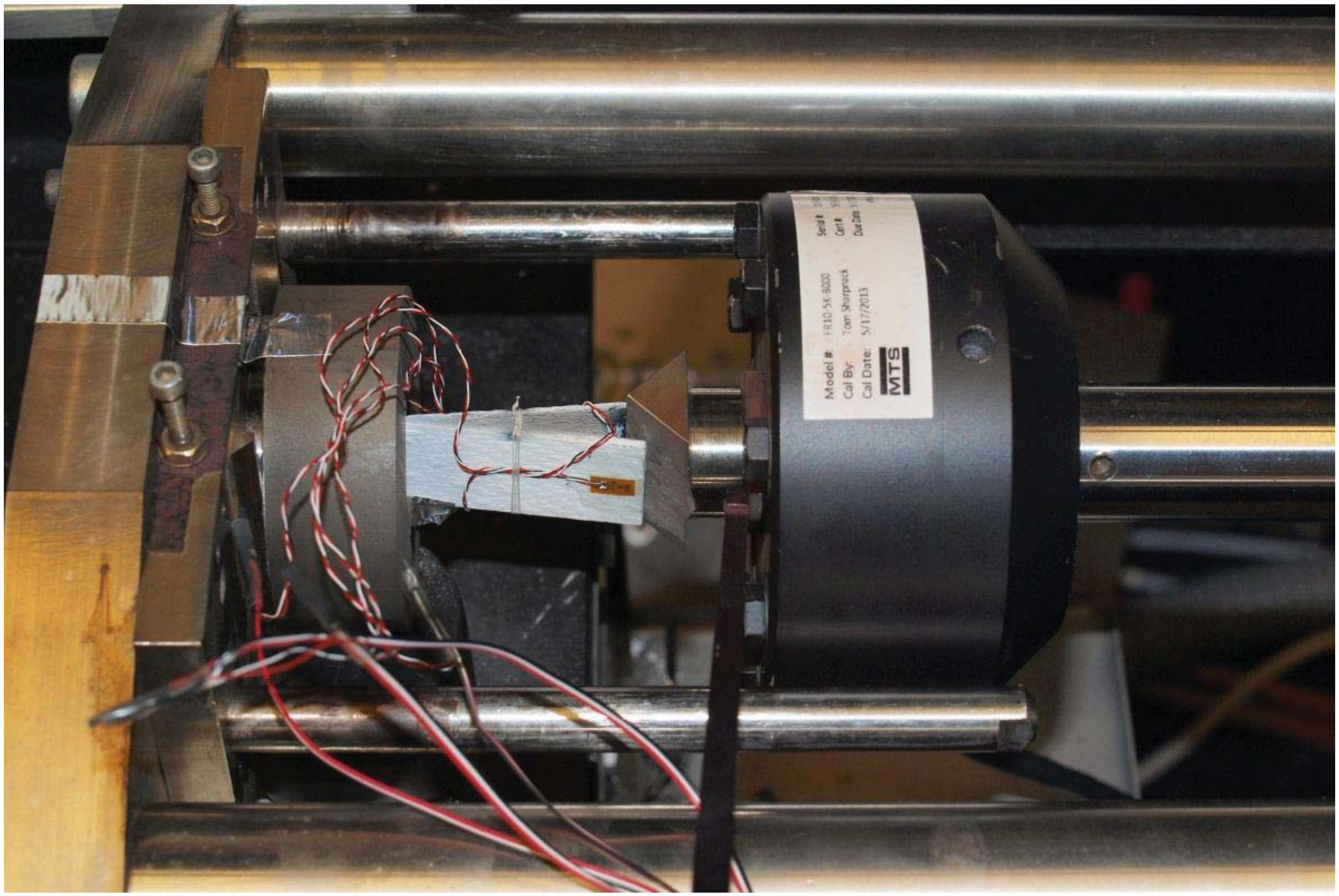


Maximum Principal Strain vs. Airfoil Internal Pressure



EBC-CMC Turbine Trailing Edge (TE) Fatigue Testing - Continued

- Testing approaches developed for EBC-CMC trailing edge thermomechanical testing
- High heat flux capability to simulate required high thermal gradients and more complex temperature distributions in a turbine engine
- Mechanical loading to simulate the high pressure turbine airfoil pressure (ballooning) effects
- EBC-CMC durability being evaluated, with and without stream jet environments

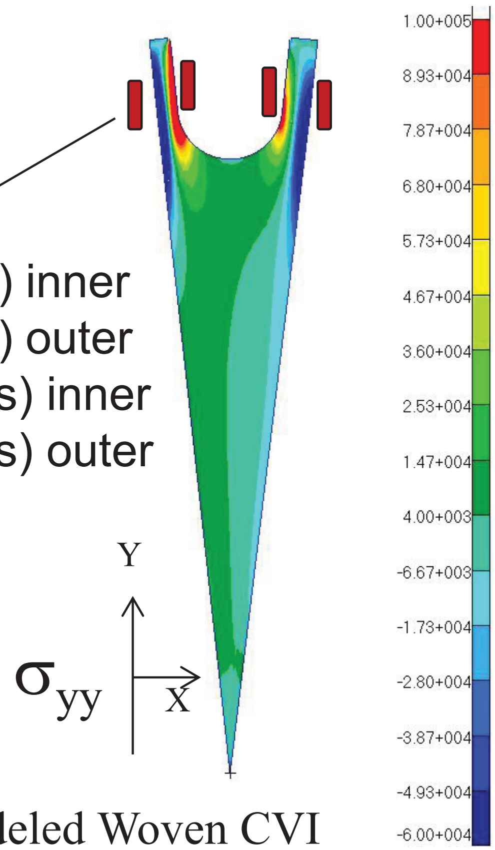


Test setup

Strain Measurements for Uncoated and Coated Airfoil Trailing Edge (TE) Sub-elements

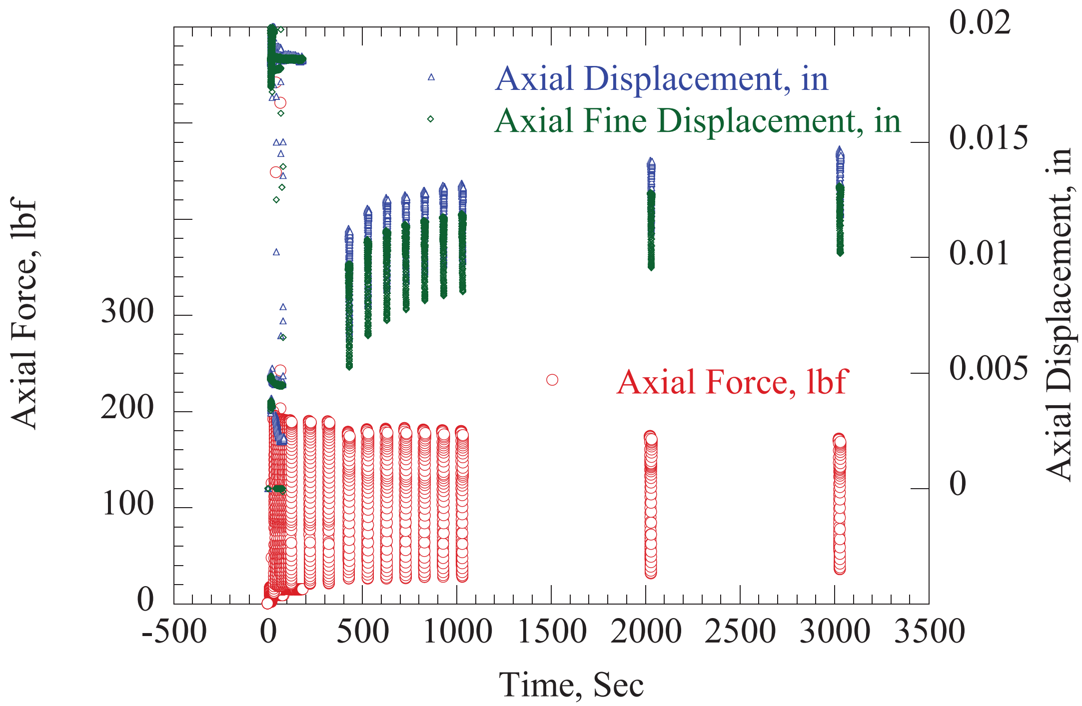
- Strain gauges installed in the high strain thin wall and thick wall areas
- Uncoated elements used for measuring strains near "coating interface areas"
- Coated elements used for measuring the strains near "coating surface areas"
- Data help understand coating design and testing requirements
- Fatigue cycles performed at 200, 300 and 500 lbf loading, 0.1 Hz, stress ratio R=0.05
- Both CVI and Prepreg SiC/SiC CMC elements with EB-PVD EBCs studied

Strain gauges:
Thin wall (6 mils) inner
Thin wall (6 mils) outer
Thick wall (8 mils) inner
Thick wall (8 mils) outer



Modeled Woven CVI

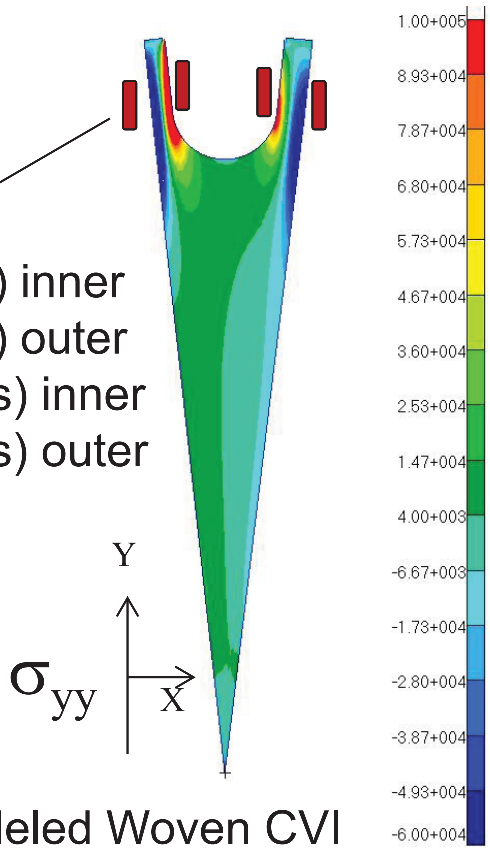
Example of initial testing, showing non recoverable deformation of the element, suggesting some damage accumulation in the element



Strain Measurements for Uncoated and Coated Airfoil Trailing Edge (TE) Sub-elements - Continued

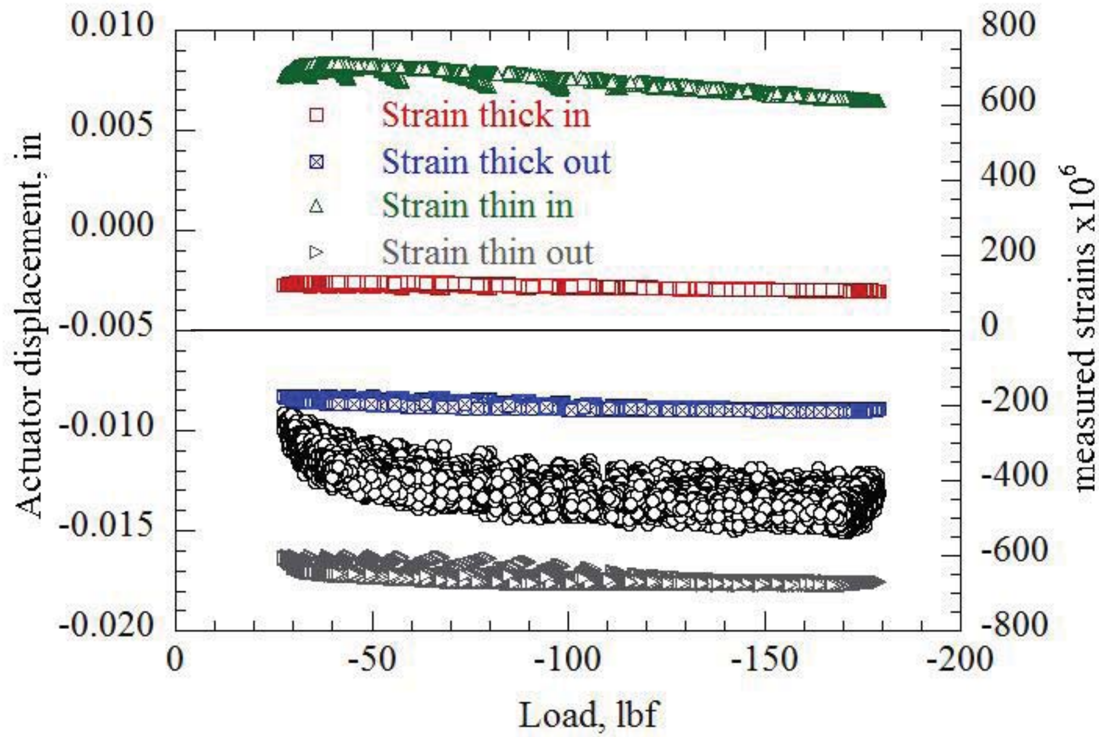
- Strain gauges installed in the high strain thin wall and thick wall areas
- Uncotaed for measuring strains near “coating interface areas”
- Coated for measuring the strains neat “coating surface areas”
- Data help understand coating design and testing requirements
- Fatigue cycles performed at 200, 300 and 500 lbf loading, 0.1 hz, stress ratio initially 0.05
- Both CVI and Prepreg SiC/SiC CMC elements with EB-PVD EBCs studied

Strain gauges:
Thin wall (6 mils) inner
Thin wall (6 mils) outer
Thick wall (8 mils) inner
Thick wall (8 mils) outer



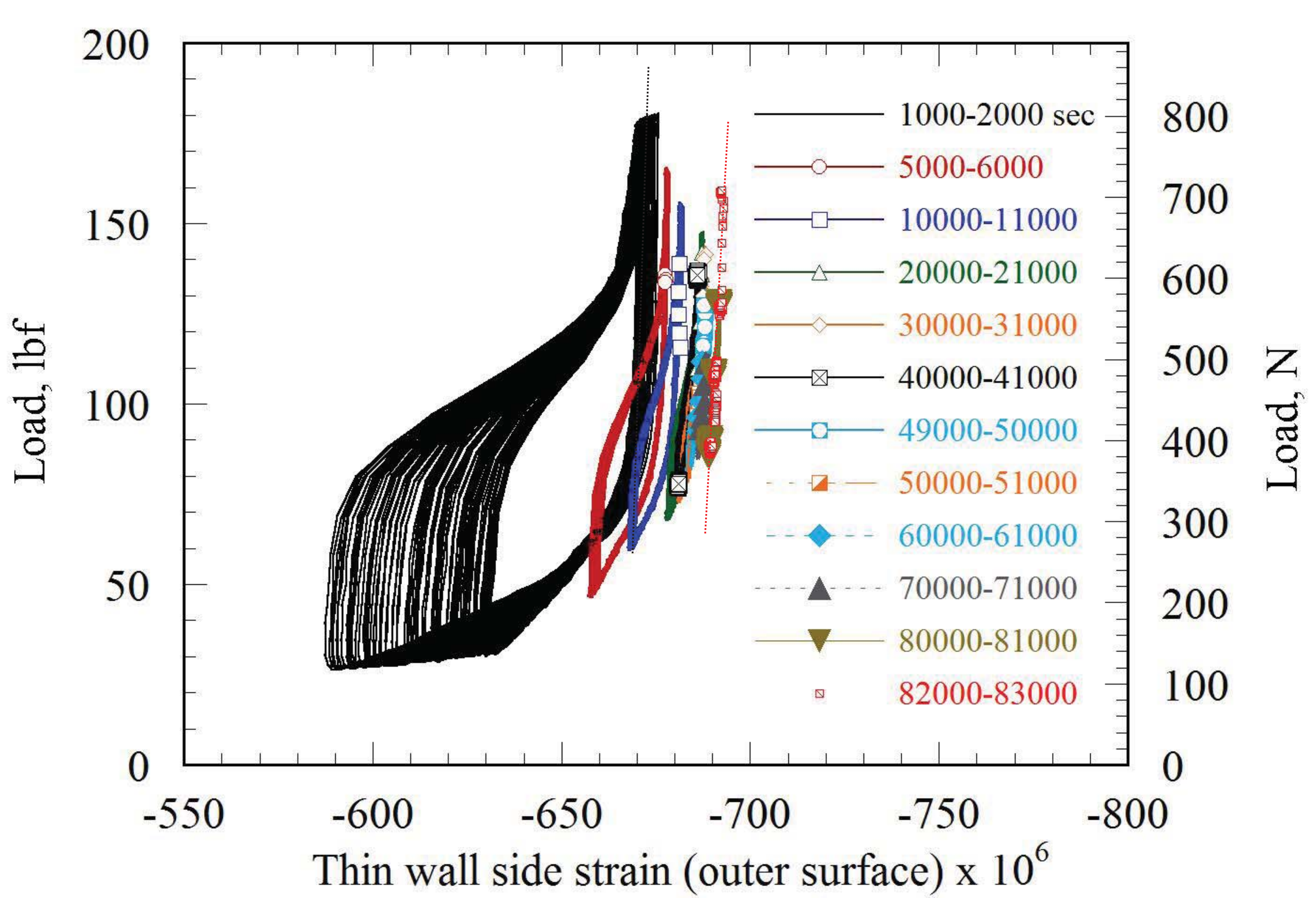
Modeled Woven CVI

The experiments helped the validation of early modeling



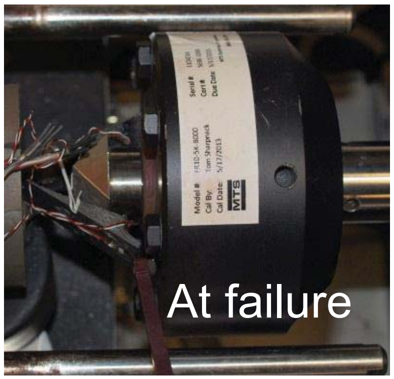
Strain Measurements for a Uncoated Trailing Edge (TE) Sub-elements

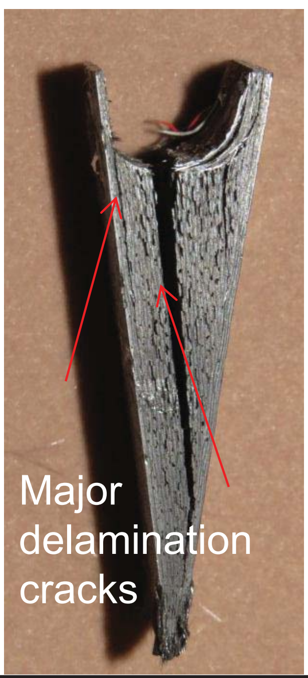
- Strain gauge (thick wall outer) showed the increased strains with fatigue cycles
- Also reduced component stiffness

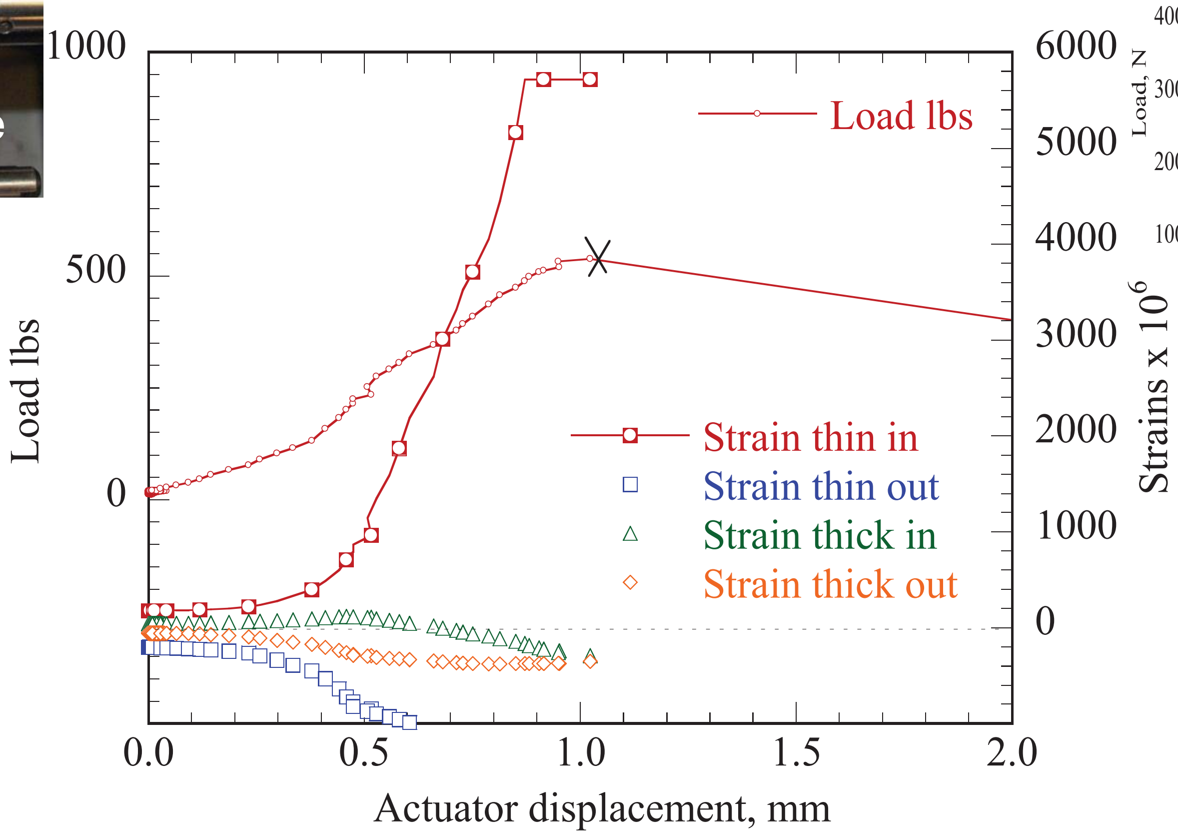


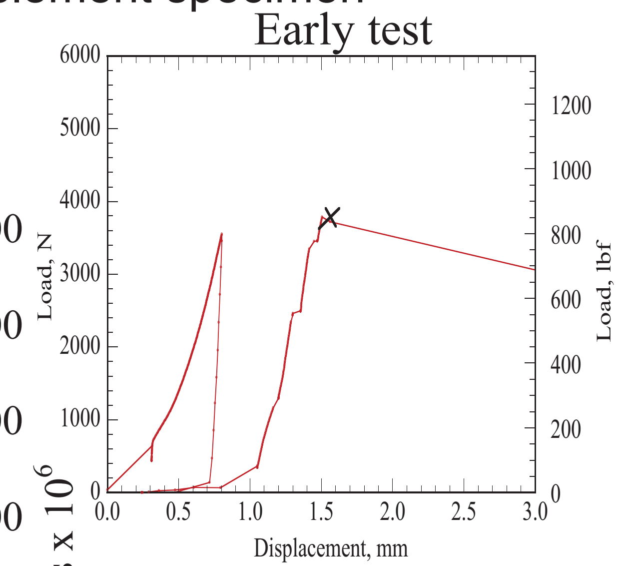
Strength Tests of Trailing Edge (TE) Sub-elements

- Maximum failure strain observed from the gauge at Thin Wall inner location, at ~0.5%
- Failure load at 538 lbf (approximately corresponding to 20 ksi stress at the thin wall inner location)
- The coated element failure load 700 lbf after the progressive fatigue cycles
- Lower than the previous failure load of 800 lbf for an as-received element specimen



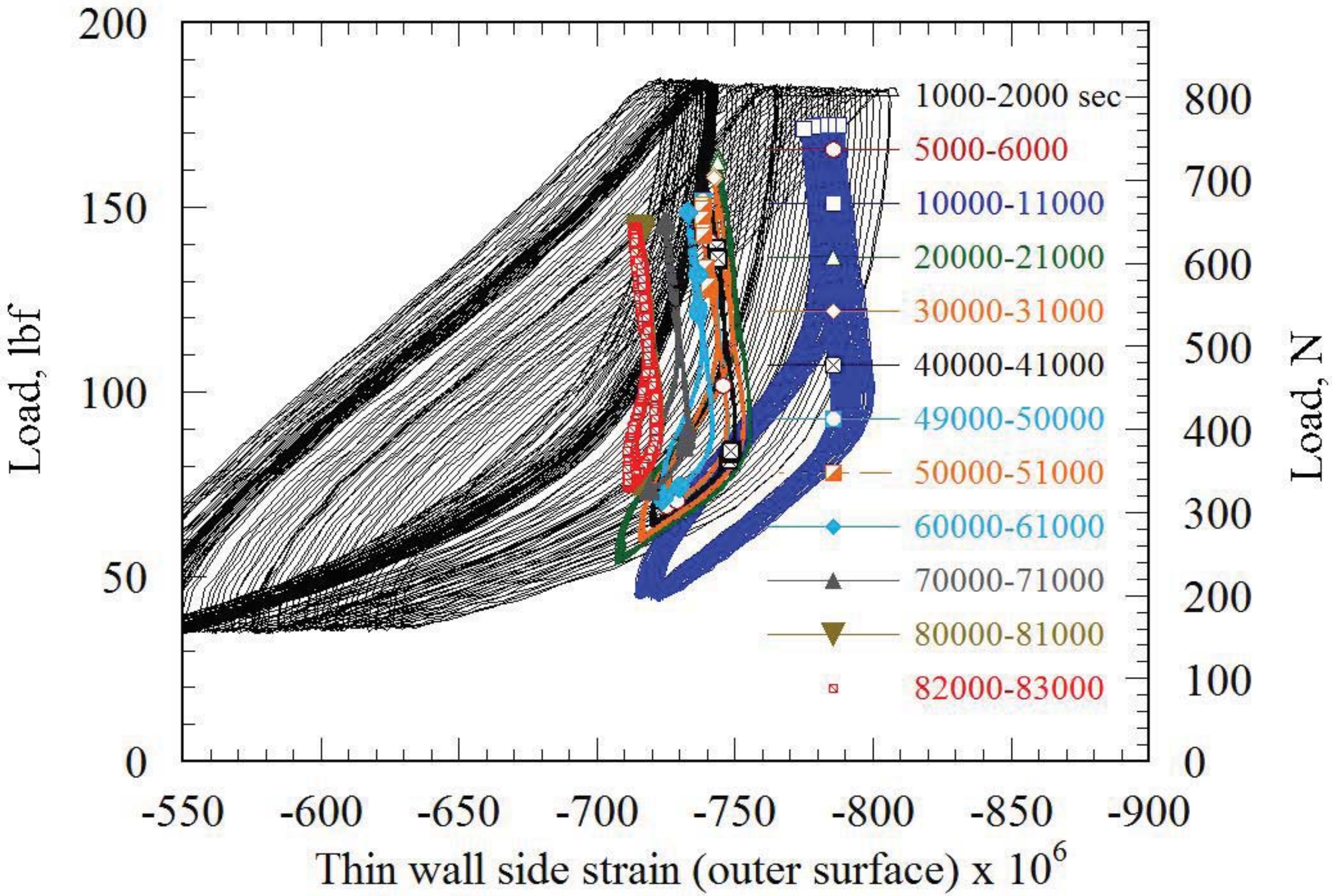






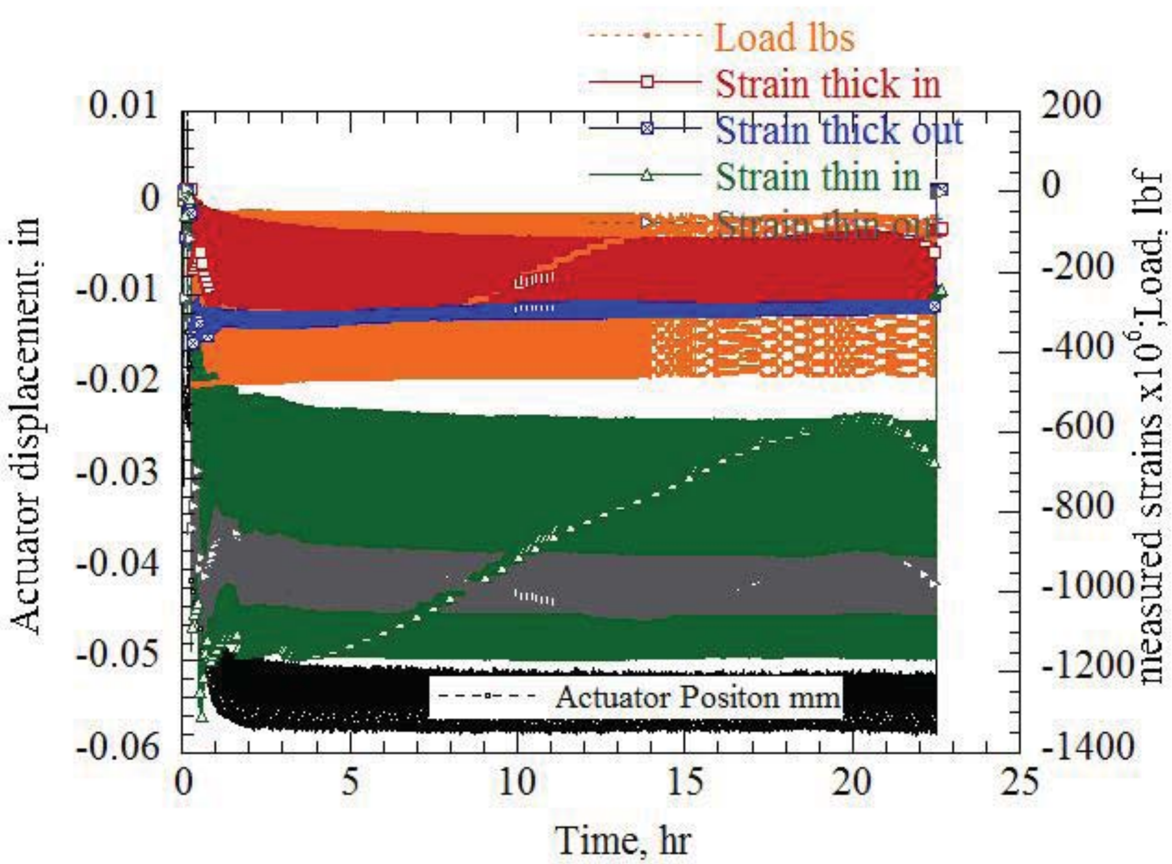
Strain Measurements for Coated Airfoil Trailing Edge (TE) Sub-elements

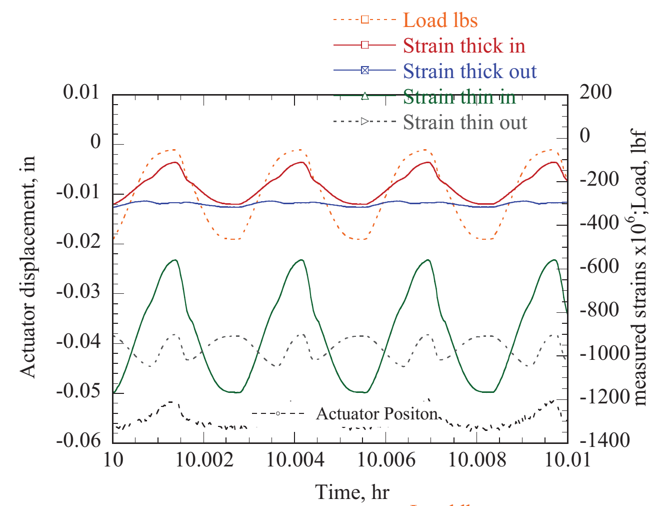
- Higher surface strains measured for the coated specimen
- Out of phase Load (stress) – Strain behavior in fatigue cycles

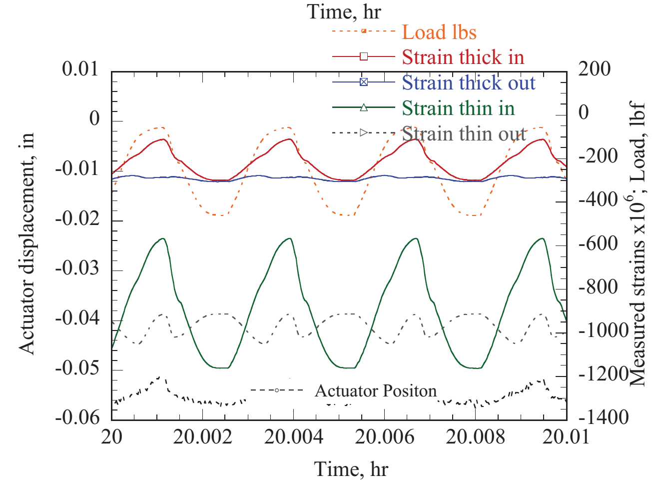


Strain Measurements for Coated Airfoil Trailing Edge Sub-elements at High Loads

- Higher strains measured at 500 lbf load amplitude for the coated specimens
- Possibly changed neutral axes of the deflections of the CMC thin and thick walls
- Observed damped EBC surface strains (“Strain thin out” and “Strain thick out”) as compared CMC side strain gauges
- Observed gradually changed out of phase strain cycles on the EBC coated sides
- The results showed complex coating cycling behavior

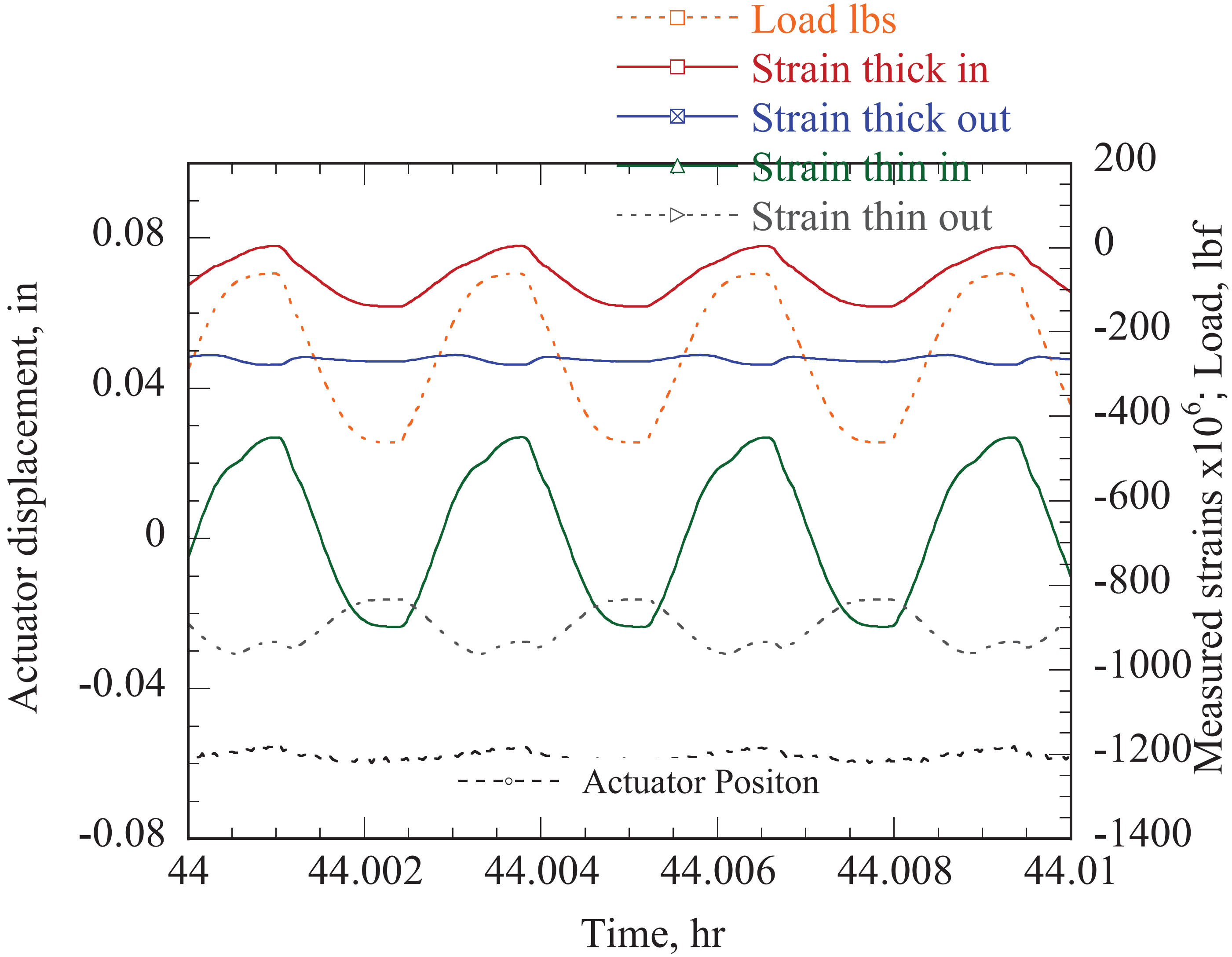






Strain Measurements for Coated Airfoil Trailing Edge Sub-elements at High Loads - Continued

- The results showed complex coating cycling behavior
- Fully reversed, out of phase coating surface strain cycles



Summary and Conclusions

- Creep and fatigue data are continued to be obtained for robust turbine coating systems, in particular under thermal gradients
  - 2700°F turbine environmental barrier coatings being developed and tested in various conditions
  - Thermal conductivity data determined for selected coating systems on the SiC/SiC CMC sub-elements
  - Thermal gradient durability of element coatings demonstrated, coating damage in-situ monitoring viable during testing
  - Advanced turbine trailing edge testing approaches developed, validating modeling
  - Combined environmental, heat flux and fatigue loading durability testing in progress