NATIONAL ENERGY TECHNOLOGY LABORATORY

– NETL Materials Research –

Materials and Component Development for Advanced Turbine Systems

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UTSR Workshop VII

October 27-29, 2009
Orlando, FL

DOE FE Coal Program

– Goals –

Advanced Power Systems

By 2010 Develop Advanced Coal-Based Power Systems Capable Of 45-50% Efficiency at <$1000/kw

Near Zero Emissions Energy From Coal

By 2015 Demonstrate Future Coal-Based Energy Plants That Offer Near Zero Emissions Including CO_2 with Multi-Product Production (Electricity & H_2)

	Syngas Turbine 2010	Hydrogen-Fired Turbine 2015	Oxy-Fuel Turbine 2010	Oxy-Fuel Turbine 2015
Combustor Exhaust Temp, °C (°F)	~1480+ (~2700+)	~1480+ (~2700+)		
Turbine Inlet Temp, °C (°F)	~1370 (~2500)	~1425 (~2600)	~620 (~1150)	~760 (~1400) (HP) ~1760 (~3200) (IP)
Turbine Exhaust Temp, °C (°F)	~595 (~1100)	~595 (~1100)		
Turbine Inlet Pressure, psig	~265	~300	~450	~1500 (HP) ~625 (IP)
Combustor Exhaust Composition, %	CO_2 (9.27) H_2O (8.5) N_2 (72.8) Ar (0.8) O_2 (8.6)	CO_2 (1.4) H_2O (17.3) N_2 (72.2) Ar (0.9) O_2 (8.2)	H_2O (82) CO_2 (17) O_2 (0.1) N_2 (1.1) Ar (1)	H_2O (75-90) CO_2 (25-10) O_2, N_2, Ar (1.7)

R.A.Dennis, "FE Research Direction – Thermal Barrier Coatings and Health Monitoring Techniques," Workshop on Advanced Coating Materials and Technology for Extreme Environments, Pennsylvania State University, State College, PA, September 12 - 13, 2006

Materials and Component Development for Advanced Turbine Systems

Advanced Materials

- Bond Coat Development
- APS YSZ Development
- Over-Layer Coating Development
- Diffusion Barrier Coating Development
- ODS Alloy Development

Aerothermal Heat Transfer

- Heat Transfer Modeling
- Aerothermal Heat Transfer Test Facilities
- Airfoil Life Prediction Modeling

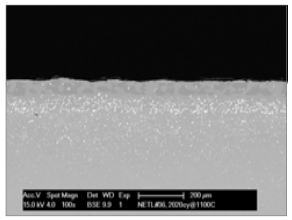
Non-Destructive Evaluation

- Micro-Indentation Stiffness Life Assessment
- Non-Linear Acousto-Ultrasonic Diagnostics Life Assessment

Bond Coat Development

Objectives

- Development of Reduced Cost TBC Bond Coat Systems
  - Modification of a Commercial Air Atomized Spray Coating Technology
  - Achieve Performance of SOTA Systems at 1100°C
  - Integrate Bond Coat/TBC Systems with Higher Temperature Overlay Systems and Internal Diffusion Barrier Coatings (DBC)

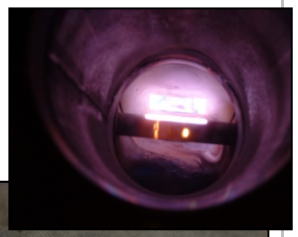


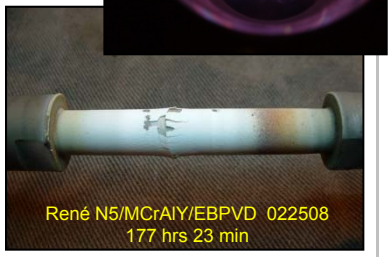
Accomplishments

- Based on Bench-Scale Weight Change as a Function of Cyclic Oxidation at 1100ºC, the NETL-A1D Bond Coat System ~Tripled the Oxidation Life of René N5/Y (850 → 2,120 cycles). Cyclic Oxidation Life for SOTA PtAl Systems on René N5 at 1100ºC is ~1,600 Thermal Cycles, and for Pt-Hf Mod $\gamma + \gamma'$ G2P ~1,100 Thermal Cycles.
  - Relatively Smooth External NETL-A1D Bond Coat Surface Resulted (Absence of Rumpling/Ratcheting)
  - Detrimental Internal Secondary Reaction Zone Was Not Observed
- High Temperature Cyclic Oxidation Performance of the NETL-A1 Bond Coat Was Shown to be Alloy Specific
- Completed ~400 Hrs of Unattended HTTF at WPC which Identified the Enhanced Performance of René N5/PtAl/EBPDV Systems (>185 hrs) over René N5/MCrAlY/ EBPVD Systems (97 hrs)

Current Focus

- Materials Development: CFI, Howmet
  - René N5; Haynes 230
  - Performance Testing
    - Cyclic Oxidation: Bottom Loading Furnace Testing at UPitt (900°C & 1100°C)
    - High Temperature Thermal Flux Testing (HTTF) at Westinghouse Plasma Corporation (WPC)
      - 1100°C
      - 500 rpm
      - Internal Air Cooling





Forward Efforts

- Demonstrate Repeatability of NETL-A1D 1100°C Cyclic Oxidation Test Performance
- Assess Impact of Co-Doping
- Conduct HTTF Testing of René N5/NETL-A1D/APS YSZ
  - Comparison with MCrAlY Systems
  - Integration with DBC and Overlayers
- Transfer Technology

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K.Murphy, J.Colston, T.Hansen, R.Honick

APS YSZ Development

Objectives

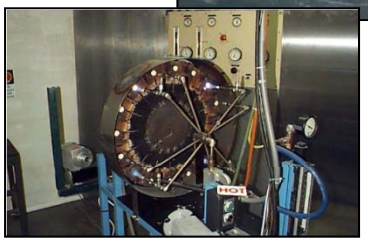
- Improve Adherence, Performance, Viability of Thick APS-YSZ TBCs on Ni-Based Superalloys for Turbine Blades, Vanes, and Combustor Components
- Define Lifetime Behavior of Variable Top Coat TBC Thickness
- Identify Possible Role(s) Base Metal Substrates Have on TBC/Bond Coat Lifetime
- Investigate the Effect of YSZ Purity on Top Coat Microstructure Evolution and Lifetime Behavior
- Identify Failure and Degradation Mechanisms

Accomplishments

- Top Coat Thickness Strongly Influences Lifetime Behavior of TBCs. Thinner Coatings Last Longer Than Thicker Coatings When Other Variables Such As Substrate Selection Are Held Constant.
  - Identified Two Failure Mechanisms Based on APS Coating Thickness
- High Purity Coatings Showed Minimal Sintering and Phase Transformation
- Alloy Selection and Subsequently Alloy CTE Has Substantial Effect on Lifetime and Failure Modes
- For Equivalent Thickness, High Purity-Low Density (HP-LD) APS TBCs Are Projected to Have Superior Performance in Comparison to SOTA EBPVD (1,200 vs 1,000 Thermal Cycles)
- Deposition of a Zircoat (i.e., Dense Vertically Cracked YSZ) Inner Layer (without an Intermediate Step in Deposition Prior to Deposition of the Low Density YSZ) Did Not Produce an Improvement in the Life of the Thin Topcoats, but Did for the Thick Topcoats

Current Focus

- Materials Development: Praxair Surface Technologies – Plasma Sprayed TBCs
  - IN 718; René N5 (GE Aircraft Engines); HA 188
  - Performance Testing
    - Cyclic Oxidation: Bottom Loading Furnace Testing (1100°C)
    - JETS Test Rig (1400°C-450°C)
- Top Coat Thickness
- Substrate Selection
- YSZ Purity



Forward Efforts

- Further Refine TBC Failure Mechanism Addressing the Influence of TBC/Bond Coat Microstructure
- Conduct Combined Sintering & Phase Transformation Kinetic Studies with Microstructural Evaluation & Thermal Conductivity Measurements, Demonstrating the Impact of Impurities
- Demonstrate the Impact of Graded TBC Microstructure for Minimizing Thermal Conductivity and Maximizing Coating Durability

G.Meier, F.Pettit, M.Helminiak, N.Yanar, T.A.Taylor, B.Nagaraj

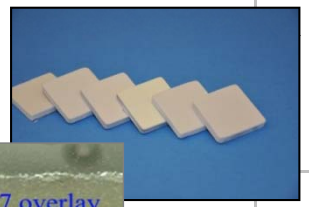
Over-Layer Coating Development

Objectives

- Develop External Coating Overlayers Capable of Providing Thermal Protection at Temperatures to 1600-1700ºC
- Identify Appropriate Rare Earth Zirconate Overlayer Composition(s)
- Define Overlayer Thickness Requirements
- Develop Processing Techniques for Manufacturing Rare Earth Zirconate Overlayers for ASP YSZ TBC Systems
- Conduct Mechanical and Thermal Evaluation of Processed Overlayer/TBC Architectures

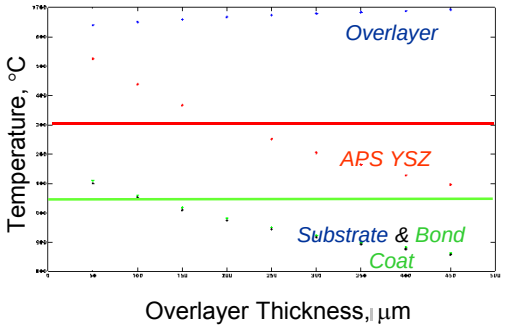
Accomplishments

- $La_2Zr_2O_7$ Was Selected as an Appropriate Overlayer Material Due to Its Low Thermal Conductivity and Mechanical Properties
- For Surface Overlayer Temperatures Reaching 1680ºC, an Overlayer Thickness of ~200 µm Was Estimated to Maintain the Underlying YSZ at Temperatures of ≤ 1300ºC
- When 50-350 µm $La_2Zr_2O_7$ Overlayers Were Manufactured, Cracks Were Not Observed Either before or after Rockwell Hardness Indentation
- After 1100 → 100ºC Thermal Cyclic Oxidation Testing, Mechanical Failure Resulted at the Metal Substrate Interface for Overlayer Thicknesses >100 µm Deposited on 250 µm APS YSZ Due to High Residual Stress Induced during Overlayer Processing



Current Focus

- Design Specification Criteria
  - High Melting Point
  - Absence of Phase Transformation between Room Temperature and Process Operating Temperature (to 1700ºC)
  - Low Thermal Conductivity
  - Chemical Inertness
  - Thermal Expansion Compatibility with Underlying TBC
  - Adherence to Underlying TBC
  - Low Sintering Rate of Porous Microstructurre



Forward Efforts

- Address High Temperature Thermal Stability of the $La_2Zr_2O_7$ Overlayer in a Steam-Containing Environment
- Refine the Processing of $La_2Zr_2O_7$ and Alternate Overlayer Architectures
  - Assess Heat Insulating Capabilities and High Temperature Stability and Performance
  - Determine Young's Modulus of the Applied $La_2Zr_2O_7$ Overlayer Via Nano-Indentation

Diffusion Barrier Coating Development

Objectives

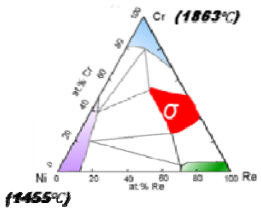
- Develop a Viable and Cost-Effective Processing Route for Deposition of Oxidation Resistant Diffusion Barrier Coating (DBC) Systems to Limit/Mitigate Long-Term Coating/Substrate Interdiffusion at Elevated Process Operating Temperatures
  - Directly Deposit DBC Systems by Plasma Spray Processing, Providing Compositional Flexibility
- Integrate DBC Systems with a Reliable and Durable Al_2O_3-Scale Forming Metallic Coating and, If Necessary, an Outermost Thermal Barrier Coating (TBC)
- Achieve Operational Performance of the DBC Systems during Both Isothermal and Thermal Cycle Exposures at 1100ºC

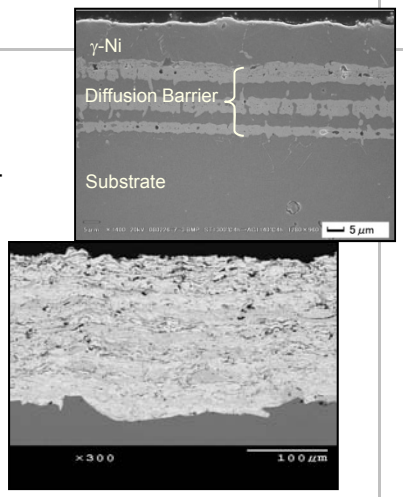
Accomplishments

- The Re-Containing σ-Phase Was Identified to be an Excellent Candidate for DBC Systems
- 40Re-40Cr-20Ni (at%) σ-Phase Powder Was Prepared By Mechanically Milling Constituent Powders Followed by Heat Treating at 1200°C for 6 Hrs
- Intact σ-Coatings Were Deposited onto a Ni-Base Alloy Via Air Plasma Spraying (APS)
- Assessment of the Thermal Stability of the APS σ-Coating Demonstrated Excellent Diffusion Barrier Capabilities (i.e., Minimal Al Diffusion into σ-Diffusion Barrier)
- W-Based σ-Phase Was Also Identified to be an Excellent Candidate for DBC Systems. The Advantage of Using W Instead of Re Is Cost Reduction.

Current Focus

- Application of Cr + Ni + Re-Rich σ-Layer along the Surface of Ni-Based Superalloys and Single Crystal Matrices
- Re-Based Alloy Selected
  - Low Diffusivity
  - Compatibility with Ni-Based Superalloys and Ni-Aluminides





Forward Efforts

- Diffusion Barrier Coating Development
  - Assess and Optimize Oxidation Resistance of Re-Cr-Based DBC Compositions
  - Modify DBCs to Contain a Reactive Element Reservoir (Hf, Y and/or Si)
- Assessment of Al_2O_3-Scale Forming Coatings for DBC Systems
  - Reduce Oxidation Kinetics (k_p) by the Supply of Reactive Elements
  - Verify Thermal Stabilities
- Identify Cost Benefit of DBC with Respect to Life of Commercial and NETL Bond Coat Architectures

ODS Alloy Development

Objectives

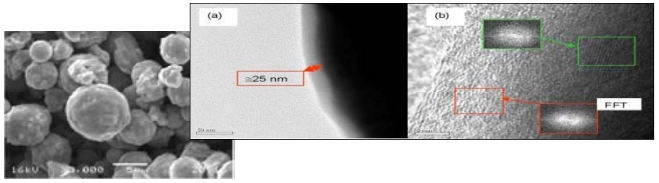
- Investigate Alloying Effects on Dispersion Stability and Oxidation Resistance of ODS Alloys Utilizing a High Throughput Powder Mixing Technique to Produce ODS Powders with Reduced Manufacturing Cost
- Develop Suitable Processing Conditions to Achieve a Homogeneous ODS Powder Mixture Comparable to That Achieved by Mechanical Alloying
- Evaluate Applicability of ODS Coatings on Superalloy Substrates Using Cold Spray Technique with Processed ODS Powders
- Assess ODS Alloy Mechanical Behavior Using Micro-Indentation

Accomplishments

- Demonstrated via TEM That the MCB Process Forms a Uniform ~25 nm Y_2O_3 Layer along the Surface of Particles throughout the Ni-Cr Powder Matrix
- A Combined MCB and Ball-Milling ODS Powder Mixing Procedure Was Developed
  - Results Indicate Similar ODS Powder Microstructural Characteristics as Compared to Commercial ODS Powders
  - Ball-Milling Time is Significantly Reduced (~15 Hrs) with Smaller Size ODS Powder Mixture
- Using Cold Spray Techniques and the MCB-ODS Powders, Haynes 230 and René N5 Coupons Were Successfully Coated to Thicknesses of 0.8 to 1.5 mm

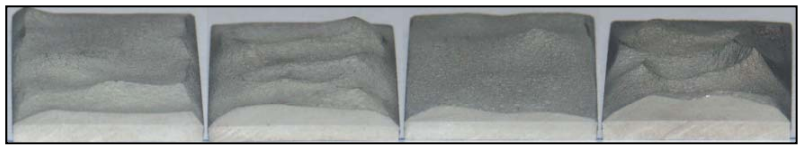
Current Focus

- Hosokawa Mechano-Chemical Bonding (MCB) Process
- Establish Suitable Processing Conditions to Achieve Homogenized ODS Powder Mixtures Comparable to Mechanical Alloying
  - Cr-Al-Y_2O_3-(W)-Ni Powders
- ODS Coating Development
  - Utilization of Cold Spray Techniques
  - IN625, Haynes 230 & René N5 Substrates



Forward Efforts

- Continue ODS Powder Optimization Processing (Combined MCB and Ball-Milling)
- Continue Development of ODS Coatings on Superalloys Using Cold Spray Techniques. Optimize Surface Heat Treatment.
- Establish ODS Alloy Mechanical Behavior Using Micro-Indentation (RT → 1200ºC)



B.S.Kang, K.Ogawa, L.Ma, N.Wu, G.Smith, M.A.Alvin

Micro-Indentation Testing

Objectives

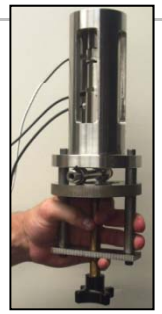
- Develop Load-Based, Multiple Loading/Partial Unloading Micro-Indentation Technique for Determining Mechanical Property Degradation and Debonding/ Spallation of TBC Systems
- Develop Portable Test Unit for Evaluating Curved and Flat TBC Coupon Geometries
- Demonstrate Feasibility of Technique/Equipment on As-Manufactured and Bench-Scale Tested Commercial and NETL BC/TBC Systems
- Develop High Temperature Micro-Indentation System for Determining Material Mechanical Properties (i.e., Young's Modulus, Creep, Hardness, etc.) at Temperatures up to 1200ºC. Validate Determined Material Properties.

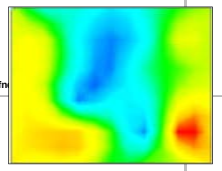
Accomplishments

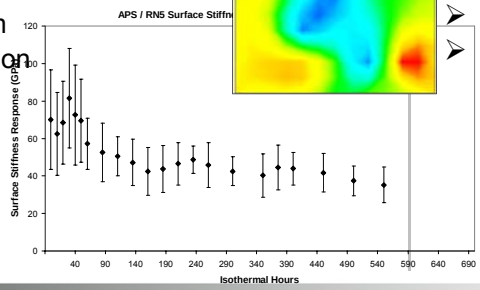
- Developed Table-Top and Portable Handheld Micro-Indentation Units, and High Temperature System
  - Validated Accuracy of These Systems in Terms of Reported Literature Data. Room Temperature Young's Modulus : ~200–210 GPa for Haynes 230 ; ~130–150 GPa for René N5
- SEM Characterization of Indented Region Indicated No Additional YSZ Cracking or Degradation
- Developed Stiffness Contour Profiles for TBC-Coated René N5 and Haynes 230 Coupons
  - Within the Initial 20 Thermal Cycles at 1100°C, Surface Stiffness Was Reduced by ~2.8% for APS/MCrAlY, and ~15.1% for EBPVD/MCrAlY Systems
- Successfully Predicted TBC Spallation Regions on Four 1100ºC - Exposed René N5/MCrAlY/APS YSZ TBC Coupons
- Demonstrated Technique Feasibility on an OEM TBC-Coated First-Stage Blade

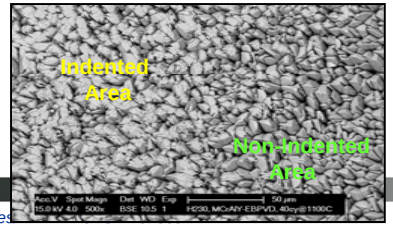
Current Focus

- Multi-Partial Unloading Indentation
  - PZT Actuator Accuracy: 4 nm
  - Loading Accuracy: 0.05N
  - Indenter Size: 1/16 in
  - Loading Range: 60-200 N
  - Contact Diameter:180-280 μm
  - Estimated Maximum Indentation Depth: 15-20μm









Forward Efforts

- Production Validation: Identify Stiffness Response of a Second Production Lot of René N5/MCrAlY/APS YSZ Coupons during Exposure to 1100°C Isothermal and Cyclic Oxidation Conditions
  - Correlate Stiffness Response with Microstructural Changes within the TBC Architecture
- Demonstrate Response for René N5/MCrAlY/EBPVD System
- Refine Micro-Indentation Testing Capabilities on Full Blade Architectures
  - Initiate Development of Automated Characterization for Rapid Assessment of Turbine Components

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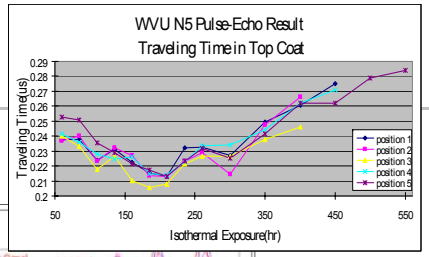
Non-Linear Acousto-Ultrasonic Diagnostics

Objectives

- Develop Acousto-Ultrasonic Diagnostic Techniques for Early Failure Detection of Commercial MCrAlY/EBPVD and MCrAlY/APS Systems as a Function of Extended Thermal Cycling and Static Oxidation Exposure at 1100ºC
- Explore Finite Element Analysis (FEA) Simulation of Nonlinear Acoustic Effects to Project Detection of Delamination and Change of TBC Material Properties
- Explore Acousto-Ultrasonic Capability for NDE of Industrial Components Coated with Thermal Barrier Coatings

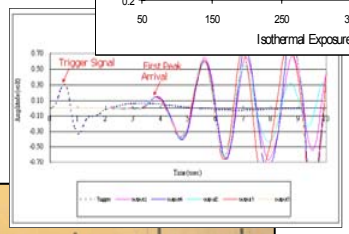
Accomplishments

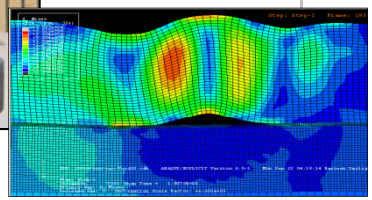
- Acousto-Ultrasonic Techniques Successfully Provided Early Warning of TBC Delamination for 1100ºC Exposed Coupons
- FEA Simulation of Ultrasonic Wave Propagation Correlated Well with Experimental Measurements and Was Used to Estimate Coating and Substrate Material Properties
  - FEA Showed Nonlinear Effects Related to Delamination between TGO and YSZ
- Demonstrated Feasibility of the Acousto-Ultrasonic Technique on an OEM TBC-Coated First-Stage Blade



Current Focus

- Configuration: Miniature Piezoelectric Sensors; Gel Contact; Laser Vibrometer and Spectrum Analyzer
- FEA Abaqus Wave Propagation Simulations





Forward Efforts

- Validate NDE Analyses Using a Second Production Lot of René N5/MCrAlY/APS YSZ Coupons during Exposure to 1100°C Isothermal and Cyclic Oxidation Conditions
- Modify Surface Wave Measurement Equipment to Reduce Sensor Contact Area to Improve Accuracy of Top Coat Thickness Measurements and Material Property Predications
- Address Non-Contact (Laser) Acousto-Ultrasonic Diagnostics

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Airfoil Life Prediction Modeling

Objectives

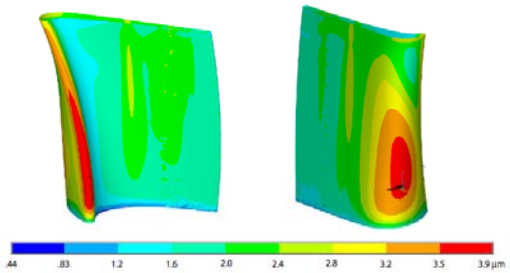
- Develop 3D Damage Mechanics-Based Models for Hydrogen-Fired and Oxy-Fuel Airfoil Life Prediction
  - Implement Models within a Commercial Finite Element Analysis Code
  - Determine Evolution of Stress and Creep Damage within a Generic Airfoil
  - Assess Need for External Film Cooling
  - Determine Evolution of Fatigue Damage for a Variety of Cyclic Loading Scenarios
  - Assess Importance of Creep/Fatigue Interaction
  - Predict Airfoil Life
- Conduct Isothermal, Uniaxial Constant-Load, Thermal-Mechanical Testing to Validate Damage Mechanics Variables Pertaining to Both Substrate and TBC
- Develop Damage Mechanics Models for Fatigue Crack Initiation and Growth, and Assess the Impact on TBC Structural Integrity

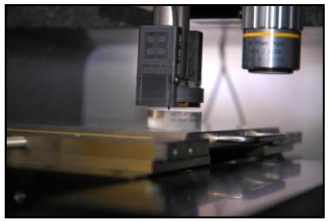
Accomplishments

- Creep and Fatigue Damage Models Were Integrated into Finite Element Analysis (FEA) Package (ANSYS)
  - Includes Effect of Stress Relaxation
  - Centrifugal Load (Coating Mass): 3,600 rpm with a Base Radius of 0.6 m
  - Aerothermal Loading for Hydrogen-Fired and Oxy-Fuel Applications from Separate Investigation
  - With and without Film Cooling
  - Internal Cooling Temperature of 527ºC with Heat Transfer Coefficients from 1,000–3,000 W/m²K
  - Coating: 250 µm YSZ; 10 µm TGO; 125 µm Bond Coat
- Predicted Extent of Compact TGO Growth, Inward Growth, and Phase Depletion
- Current Model Predictions
  - Hydrogen-Fired: After 1,000 Hrs, Limited Creep Damage Projected along Pressure Surface of Middle Rib; After 4,000 Hrs, Extensive Creep Damage along Pressure Surface of Middle Rib, with Damage along Suction Surface near Trailing Edge
  - Oxy-Fuel: Extensive Creep Damage after 10 Hrs, Indicating Need for External Film Cooling; Minimal Creep Damage after 800 Hrs with Film Cooling
  - Creep Damage Dominates Fatigue Damage; Effects of Creep/Fatigue Interaction are Negligible

Current Focus

- ProEngineer, ANSYS, MatLab; Serpentine (Reference NASA E^3) and Skin-Cooled Architectures
- Initial Model Validation Efforts: Bench-Scale Isothermal Testing Using René N5/MCrAlY/APS TBC at 900-1100°C with Applied Uniaxial Compressive Stress (3,000 Hrs Max Exposure)





Forward Efforts

- Further Develop Model to Incorporate TBC Layer Damage Mechanisms to Predict TBC Failure
  - Utilize Continuum Micromechanics & Fracture Mechanics to Predict Initiation & Growth of Cracks in TBC Layers
  - Construct Relation for TBC Damage Evolution
  - Incorporate into Life Prediction Model
- Complete Experimental Stress Characterization of Effect of Substrate Deformation on TBC Systems
- Model Validation with OEM Interaction

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Airfoil Heat Transfer Modeling

Objectives

- Develop 2D & 3D Computer Simulations Identifying Temperature and Heat Transfer Distributions over Generic Airfoil Configurations
- Assess the Impact Various Cooling Configurations on Temperature, Stress, Strain Characteristics under Varying Load Conditions
- Evaluate Aerothermal Effects of Various Working Fluid Compositions: Air (N_2), H_2O, H_2O/CO_2
- Identify Optimal Cooling Configurations and Guidelines to Lower Temperature Magnitude, and Minimize the Temperature Gradient and Associated Stress

Accomplishments

- Gas with Higher Steam Content Leads to Higher Heat Transfer Coefficient
  - Oxyfuel is ~40% Higher Than Hydrogen-Fired or Syngas
- Internal Cooling Heat Transfer Coefficient Significantly Affects Substrate Metal Temperature. For Hydrogen-Fired Turbines:
  - 3X Increase in Internal Heat Transfer Coefficient Decreases Metal Surface Temperature by ~150-200°C
  - Higher Temperature Gradient through the Metal
- P,T Distribution for Hydrogen-Fired and Oxy-Fuel Airfoil Exhibit Similar Trends to Those Under Convection Dominated Flow
- Skin Cooling Reduces Metal Surface Temperature by ~50-100°C
- Increasing TBC Thickness to ~550μm for Skin-Cooled Airfoils, Reduces Temperature by ~50-70°C
- If Complete TBC Spallation Occurs, a Surface Metal Temperature Increase of ~200-250°C Is Projected

Current Focus

- Hydrogen-Fired, Oxy-Fuel, and Syngas TIT Conditions
- FEA Modeling Using FLUENT & ANSYS
- Serpentine (Reference NASA E^3) & Skin Cooled Architectures
- Matrix Parameters:
  - Substrate: CMSX-4
  - 250 μm Topcoat
  - 10 μm TGO
  - 100 μm Bond Coat
- Coolant: Steam &/or CO_2
- Film Cooling

Forward Efforts

- External Cooling
  - Shape-Hole Film Cooling
  - Pulse (Unsteady) Film Cooling
- Conjugate Heat Transfer Analysis
  - Combined Internal & External Thermal Modeling
- Structural & Coating Damage
- Complement/Integrate with Ames Aerothermal Effort
- Additional Consideration
  - Transpiration or Effusion Cooling
  - Internal Cooling – Modeling & Experimental Efforts
    - Surface Heat Transfer Enhancement
    - Advanced Internal Cooling Configurations

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Aerothermal Test Facilities

– Atmospheric Unit –

Objectives

- Demonstrate Double Wall Internal Cooling Concepts to Improve Heat Transfer Using Pin-Fin Vortex Generators with Cooling Air
- Investigate Effects of 90 Degree Jet Inlet on Internal Cooling with Staggered Pin-Fin Arrays
  - Address Effect of Side Blockages
- Investigate Heat Transfer Characteristics in Tip Turning Region with Various Pin-Fin Arrangements
  - Address Effect of Pin-Fin Placement to Side and Tip Endwalls
- Acquire Detailed Distribution of Local Heat Transfer Coefficient on Both Pin-Fins and Endwalls
- Develop Simulation Approach to Predict Heat Transfer within Internal Cooling Channels

Accomplishments

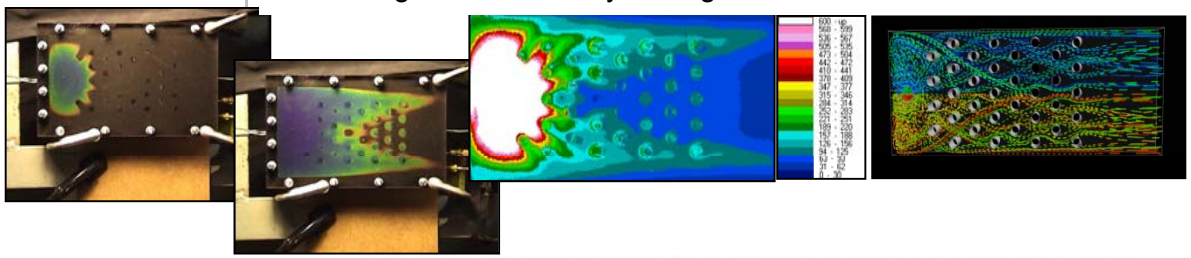
- Test Unit Designed and Constructed
- Jet Impingement from 90-degree Inlet Demonstrated an Increase in the Overall Average Heat Transfer Coefficient throughout the Entire Cooling Passage
- Channels with Blockages Have Up to 29% Higher Performance Factor Than Those without Blockages
- Simulations Predict Heat Transfer Distribution and Flow Patterns, but Are ~48% Lower Than Experimental Results
- Pin-Fins at Tip Turn Regions Alter Flow Field and Enhance Heat Transfer in These Regions

Current Focus

- Double Wall Cooling Geometry
  - 90-degree Coolant Jet Inlet
  - Staggered Pin Fin Array Arrangements on Top and Bottom Channels
  - Variable Pin Fin Height
  - Side Blockage
  - Reynolds Number Ranging from 13,000 to 28,000
- Serpentine Configuration
  - Heat Transfer Enhancement at Tip Turn Regions
- Transient Liquid Crystal Thermography; Video Recording; Data Regression

Forward Efforts

- Continue Conduct of Heat Transfer Testing
  - Assess Pin-Rib Hybrid Geometry and Novel Pin-Element Shapes for Enhanced Cooling Performance
  - Experimental Tasks to be Conducted in Conjunction with Tom Shih's CFD Simulation Capabilities
- Address Film Cooling Improvements with Shaped Hole Configurations & Array Arrangements



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Aerothermal Test Facilities

– Atmospheric Steam/CO_2 Unit –

Objectives

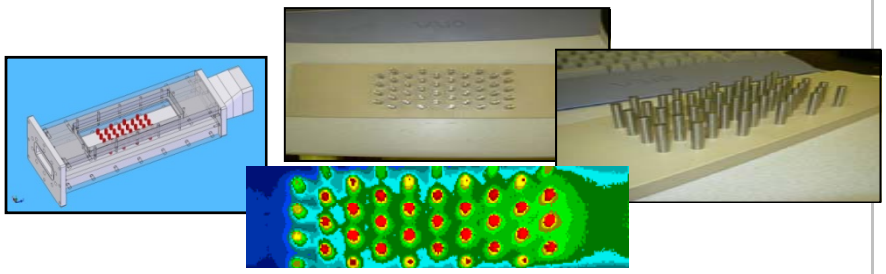
- Develop Test Facility to Explore Novel Concepts and Technology for Enhanced Internal Cooling with Superheated Steam and/or CO_2 with High Aspect Ratio Enhancement Features (i.e., Vortex Generators)
- Develop Flow and Heat Transfer Correlations for Air and Steam Cooling
- Explore Advanced Cooling Concepts, Characterizing Effects of Partial Pin-Height on Pin-Fin Array Heat Transfer
- Explore Flow Field Using FLUENT and Compare Numerical Results with Experimental Data
- Address Material Degradation near Flow-Solid Interface and Effects on Cooling Performance

Accomplishments

- Test Unit Designed and Constructed
- Verified Analysis Approach and Testing Procedure Using a Smooth Test Plate. Results Were Compared against Well-Known Dittus-Boelter Correlations.
- Conducted Experiments with Pin-Fins Using Transient Infrared Thermal Imaging Technique for Heat Transfer Characterization
  - Tests Were Conducted at Re_{Dh} =15,000 – 30,000
  - Experiments Were Repeated with Hot Air
- Superheated Steam Has Significant Contribution on Heat Transfer Enhancement; 10-15% Higher as Compared to Hot Air
- Completed 7 Pin-Fin Tests at Re_{Dh}=10,000-25,000
  - Presence of Pin-to-Endwall Spacing Promotes Wall-Flow Interactions, Generates Additional Separated Shear Layers, Augments Heat Transfer
  - C/D=1 (Staggered) Exhibits the Highest Heat Transfer Enhancement
  - Pressure Loss Seems to Increase with C/D

Current Focus

- Removable Test Plate
  - Single Aluminum Pin Fin Array
  - Variable H/D Full Channel Height Pin Fins
- Superheated Steam (~300°C) As Coolant
- Optical ZnSe Window; IR Camera



Re_{Dh}=30,000 (Steam)

Forward Efforts

- Perform Flow and Heat Transfer Studies around Pin-Fin Elements for Internal Cooling Enhancement
- Investigate Heat Transfer and Friction Characteristics of Rib-Pin Combined Internal Cooling Configurations
- Quantify Differences in Heat Transfer and Friction Correlations between Steam and Air
- Assess Effects of Using Steam, CO_2 and Their Effects as Injectants for Film Cooling
- Develop Experimental Capabilities for Combined Internal and External Cooling Studies

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Aerothermal Test Facilities

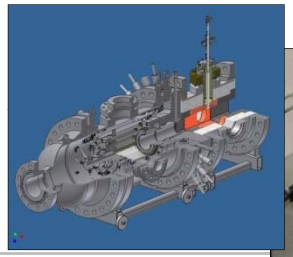
– High Temperature, Pressurized Module –

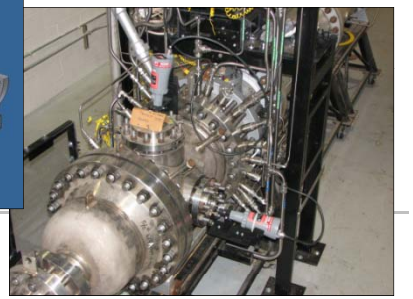
Objectives

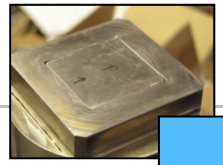
- Develop High Temperature, Pressurized Test Facility to Experimentally Address Potential Aerothermal Cooling Improvements for Hydrogen-Fired and Oxy-Fueled Turbines Where Maximum Targeted Inlet Temperatures Are 1425°C and 1760°C, Respectively
- Assess Heat Transfer; Micro-Scale Cooling Hole Fabrication Including Stress Reduction & High Yield Manufacturability; Optimize Film Hole/Slot Configurations; Proper Coolant Selection & Flow Distribution

Accomplishments

- Completed Design & Construction of the Experimental Test Module. Initiated Shakedown Phase.
- New 1-in Cooling Line with Initial Flow Rate up to 8000 scfh Installed
- Rebuilt Compressor for 700 psi Air Compression
- Machining of Test Coupons

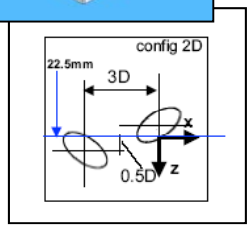






Current Focus

- Haynes 230 Coupons (2”x2”x0.25”)
  - Film Cooling Hole Diameter: 3/32”
  - Surface & Back-Side Thermocouples
  - TBC: MCrAlY/APS YSZ
- Test Parameters
  - 1000°C; 5 atm
  - Gas Flow: $N_2/H_2O/O_2/CO_2$
  - Back-Side Air Impingement Cooling
  - Blowing Ratio: 0.5-2.0
- Optical Temperature Measurements
- 7 Test Campaigns
  - Flat Plate; Cylindrical Holes; Cylindrical Holes in Trench; Double Jet Film Cooling; Anti-Vortex Film Cooling Hole (NASA), or Alternate Geometries
  - With/without TBCs



Forward Efforts

- Measure Film Cooling Effectiveness, η, under Realistic Turbine Operating Conditions
- Assess Film Cooling Performance on Various Hole Configurations, with and without TBCs. Address Surface Roughness Effects on Film Cooling
- Quantify Realistic Effects of Coolant Density and Other Material Properties on Film Cooling Performance through Comparison of Room Temperature Data
- Establish Capabilities for Controlling Free-Stream Turbulence, Both Intensity and Scale under High Temperature and High Pressure Conditions
- Explore Measurement Approach for Conjugate Heat Transfer with Combined Internal /External Cooling Modules

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