A STUDY OF ADVANCED MATERIALS FOR GAS TURBINE COATINGS AT ELEVATED TEMPERATURES USING SELECTED MICROSTRUCTURES AND CHARACTERISTIC ENVIROMENTS FOR SYNGAS COMBUSTION

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DOE NETL Research Meeting
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HIGH TEMPERATURE THERMAL BARRIER COATINGS THERMAL & MATERIAL PROPERTIES EVALUTAIONS MODELING

TBCs have excellent potential to improve durability & efficiency of gas turbines by increase of higher Turbine Entry Temperatures (TET)

Critical Need to Understand the Oxidation and Spalling resistance and effects of hot corrosion of Type I and Type II conditions

Superalloy Substrate with Customized Composite Special Microstructured Coatings have been analyzed

YSZ top coat novel microstructured specimens with 2 Processing Regimes

- -Standard APS YSZ Coatings
- -VC APS YSZ Coatings
- -EB-PVD Coatings

Improved Reliability & Performance to 1300 C

Structure Property Correlations Related to Thermal Oxidation and Hot Corrosion

Goals of This Research

•Effects of APS coated Microstructures in Thermal Cycling Oxidation Studies- Role of TGO Growth

•Spalling Resistance studies to 1200 C

•Ongoing Research - Develop advanced materials for harsh environments and high temperatures relevant for power production

•Study of APS and EB-PVD structures – Develop thermal performance of TBCs for selected applications at elevated temperatures

•Thermal Properties -Cycling and Hot Corrosion studies - Current and ongoing studies and results- multilayer structured coatings- thermo-mechanical modeling

Research Tasks/ Activities

(1) Development of APS test samples with novel vertical processing microstructures

-1.1 Customize air plasma spray system for columnar microstructure

Study behavior of these TBC materials.

-1.2 Thermal barrier coating with multi-sectioned microstructure

substrate using NiCrAlY or NiCrCoAlY powder; NiCrCoAlY with 0.25% Hf Bond Coats

-1.3 Thermal barrier coating with alumina based protecting layer

YSZ dense bottom + varying compositions of YSZ and of alumina

Research Tasks/ Activities

(2) Experimental development of industrial grade EBPVD microstructure samples and testing of APS TBC and EBPVD under syngas combustion environment

-2.1 Deposition of APS and Standard EB-PVD YSZ Coatings

-2.2 Hot Corrosion Testing in Sulfur Environment

behavior of samples tested to 100 hrs- Type I and Type II tests

-2.3 Thermal cyclic oxidation testing in dry air and water vapor (moisture) environments-

testing in dry air and up to 1100 C in saturated water vapor (moisture)

Research Tasks/ Activities

(3) Thermo-physical properties experimental characterization

3.1 Characterization Testing Approach

Laser Flashline thermal properties characterization

conductivity measurements and porosity characterizations

3.2 Benchmark Thermo- Physical Properties Characterization of EBPVD and APS Processed TBCs

Properties measurements at elevated temperatures

3.3 Thermo-physical properties characterization of TBC coating with multi-sectioned microstructure and alumina based protective layer

In process

Research Tasks/ Activities

(4) Characterization of effect of microstructures and processing of TBC materials and comparative thermal cycling and spalling studies

4.1 Thermo-Mechanical Behavior and Spalling of Selected TBC Coated Materials

Spalling studies at elevated temperatures

Oxidation and modeling work in progress

4.2 Characterization of Superalloy APS and EBPVD TBC Materials

Thermal properties and porosity characterization and effects

4.3 Analysis of the Effects of Syngas Combustion Deposited Particulates

Research Tasks/ Activities

(5) Development of performance models to predict the life of optimized TBCs under selected test conditions

5.1 Classical Plate theory of Buckling model

study of thermal cycling failure mechanisms in progress

creep of the bond coat and high temperature mechanisms

5.2 Micromechanics and laminated plate theory based method

Thermo-elastic behavior and failure analysisiand structure property correlations and evaluations undergoing currently.

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Research Outcomes for Enhanced Performance

-Development of performance models to predict the life of optimized TBCs under selected test conditions- using Micromechanics and laminated plate theory based method

-Structure property correlations and evaluations undergoing currently.

-Ceramic based YSZ TBCs for higher efficiencies & reliability

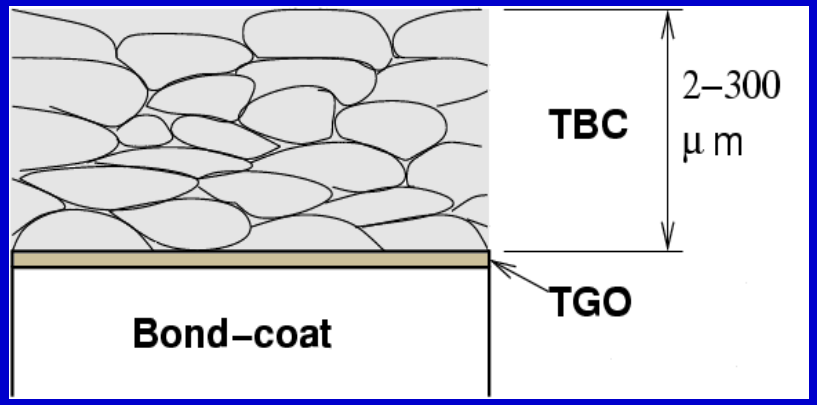
-Higher gas turbine entry temperatures (TET)

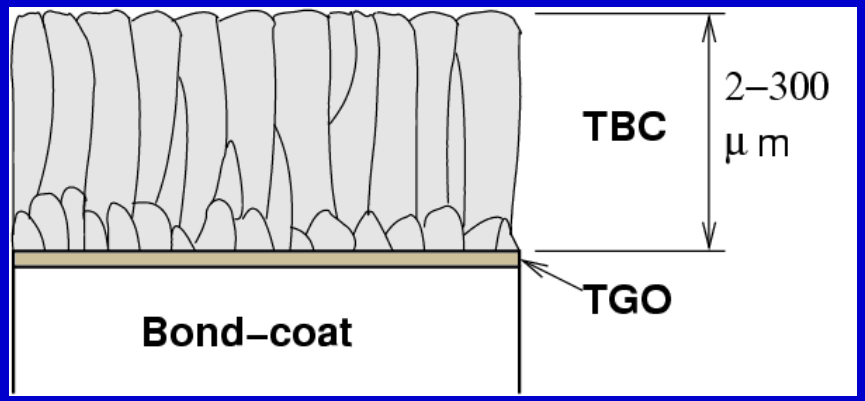
-Blade heat transfer/radiation heat transfer from blade decreased in presence of TBCs

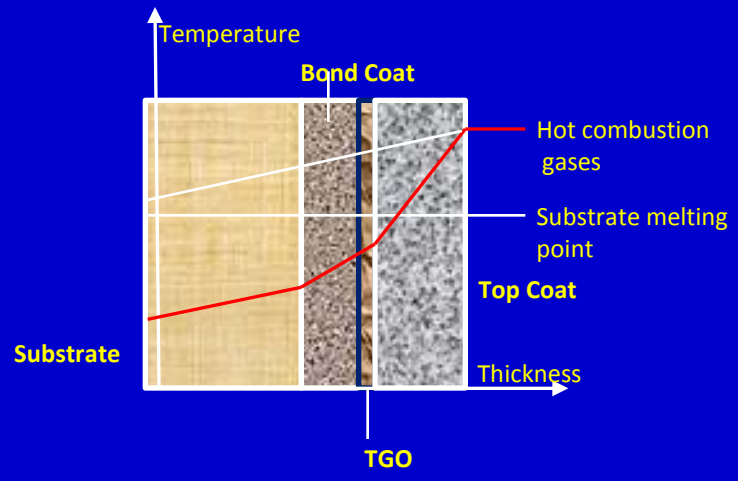
-TBC layer of lower thermal conductivity at elevated temperatures – adherent to Internally cooled gas turbine blades

-Stability of TBCs at elevated temperatures- Std. APS TBCs

-Porous columnar structure using VC APS, and EBPVD;Adherent columnar structure TBC top coat on MCrAlY bond coat and bond coats with 0.25% Hf







- Limit heat transfer through the coating (TBC)

Maximize thermal drop across the thickness of TBC

- Resistance to Wet and Dry oxidation cyclic results
- Hot Corrosion study Type I and Type II results
- Multilayer Graded Components
- Study of YSZ and Alumina
- Long Term Effectiveness at high Temperatures
- Thermal Cycling Resistance

(a) Splat lamellar and (b) vertical columnar APS and EBPVD type microstructured TBCs

Accomplishments To Date

- Composition of research team

Faculty	Research Associates	PhD Grad	MS Grad	Undergrad
SU - 3 PSU - 1 Industry - 1	2	1 (with LSU)	3	1

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Studies and Ongoing Research Topics of SUBR Partnerships, Initiatives and Collaborations

- Multi layer Thermal Characterization of Novel Thermal Barrier Coatings (TBC)
- Thermo-mechanical Analyses and Micro-scale modeling of In-Service Performance Studies of YSZ Thermal Barrier Coating (TBC) ; CTE for Ni alloys 14.0 to 16.0 x 10-6 K-1. YSZ CTE about 9.0 x 10-6 K-1. low k values of YSZ depending on structure, porosity, processing.
- Material Property Characterization of Thermal Barrier Coating Research on advanced smart composite materials
- Collaboration with LSU for customizing plasma spray system for advanced TBC research
- Materials Solutions International , Houston, TX
  - -Plasma processing of TBCs
- Collaboration with Pennsylvania State University on microstructure processing EBPVD coated TBCs

Air Plasma Spray Coatings and Microstructure Property Characterizations

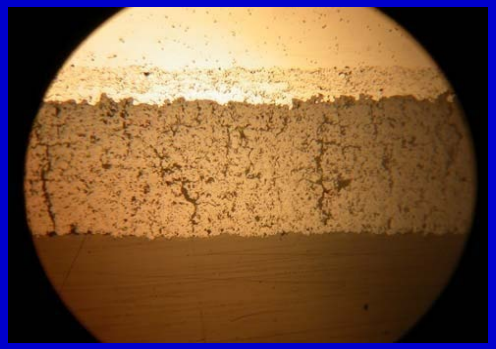

Fig. 1. (a) Bond coat thickness 140 µm;
- Top coat thickness 635 µm VC microstructures
- X100

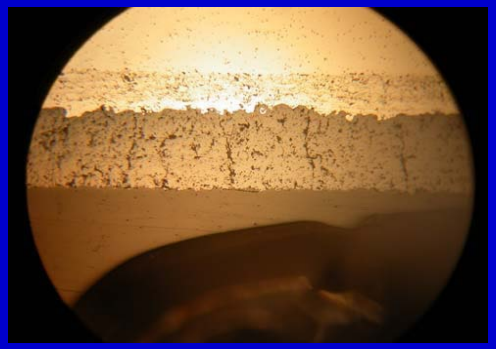

Fig. 1. (b) Bond coat thickness 150 µm;
Top coat thickness 350 µm VC microstructures
X 100

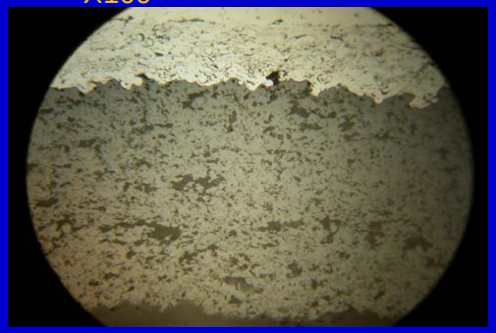

Fig. 2. (a) Bond coat thickness 140 µm;
Top coat thickness 575 µm Standard APS
X 200

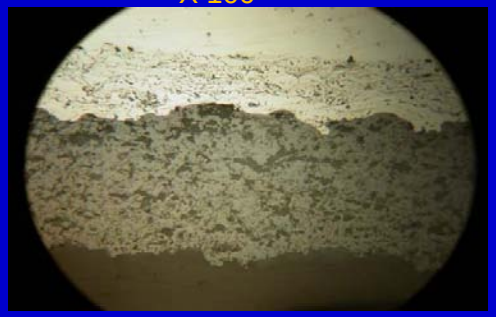

Fig. 2. (b) Bond coat thickness 140 µm;
Top coat thickness 350 µm Standard APS
X 200

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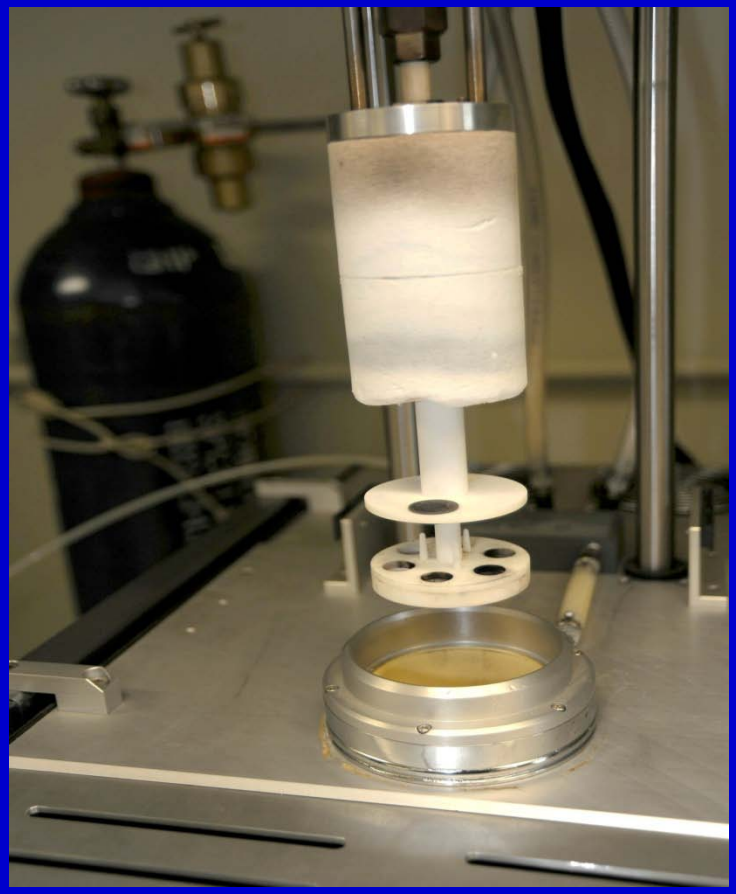
Thermal Properties Measurements
Laser flash system (FL5000)



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TBCs Test Matrix

TABLE 1 APS COATINGS FOR THERMAL PROPERTY CHARACTERIZATIONS

	Substrate	Bond Coat	TBC	No of Samples	Coating Type
1	IN 738	NiCoCrAlY+Hf 120µm	7wt%YSZ 300µm	10 (*)	STD YSZ
2	IN 738	NiCoCrAlY+Hf 120µm		5 (*)	STD YSZ
3	In 738	NiCoCrAlY +Hf 120µm	7wt%YSZ 300µm	10 (*)	VC YSZ
4	IN 738	NiCoCrAlY+Hf 120µm	7wt%YSZ 600µm	10 (*)	STD YSZ
5	IN 738	NiCoCrAlY+Hf 120µm	7wt%YSZ 600µm	10 (*)	VC YSZ
6	IN 738	NiCoCrAlY+Hf 120µm	7wt%YSZ 300µm	10 (*)	STD YSZ dense bottom layer (150 µm) + 50% YSZ & 50% Alumina top layer (150µm)
7	IN 738	NiCoCrAlY+Hf 120µm	7wt%YSZ 300µm	10 (*)	STD YSZ dense bottom layer (150 µm) + 85% YSZ &15% Alumina top layer (150µm)
8	IN 738	NiCoCrAlY+Hf 120µm	7wt%YSZ 300µm	10 (*)	STD YSZ dense bottom layer (150 µm) + 70% YSZ & 30% Alumina top layer (150µm)

The above substrate IN 738 samples are 12.54 mm dia x 3mm disc samples that have been EDM machined and tumbled - to be bond coated and top coated as specified above.

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TABLE 2

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TEST MATRIX FOR EBPVD AND APS COATINGS FOR HOT CORROSION TESTING AT ELEVATED TEMPERATURES- TYPE I AND TYPE II HOT CORROSION TESTING

	Substrate	Bond Coat	TBC	No of Samples	Coating Type
1	IN 738	NiCoCrAlY+Hf 120µm	7wt%YSZ 300µm	31(*)	STD APS YSZ dense bottom layer (150 µm) + 85% YSZ & 15% Alumina top layer (150µm)
2	IN 738	NiCoCrAlY+Hf 120µm	7wt%YSZ 300µm	31 (*)	STD APS VC YSZ dense bottom layer (150 µm) + 70% YSZ &30% Alumina top layer (150µm)
3	IN 738	NiCoCrAlY+Hf 120µm	7wt%YSZ 300µm	31(*)	EBPVD YSZ dense bottom layer (150 µm) + 85% YSZ & 15% Alumina top layer (150µm)
4	IN 738	NiCoCrAlY+Hf 120µm	7wt%YSZ 300µm	31(*)	EBPVD YSZ dense bottom layer (150 µm) + 70% YSZ & 30% Alumina top layer (150µm)

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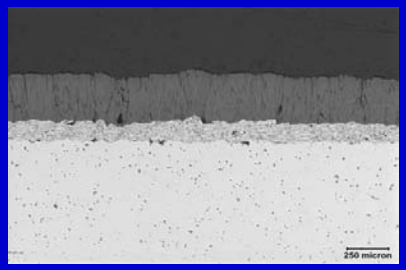
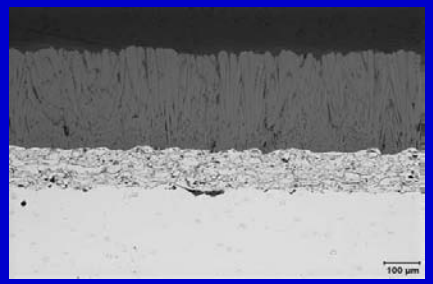
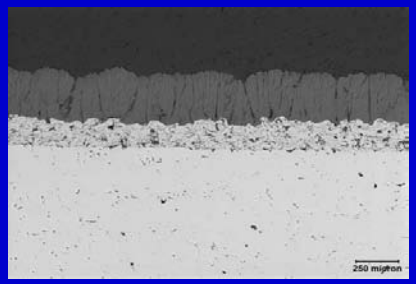
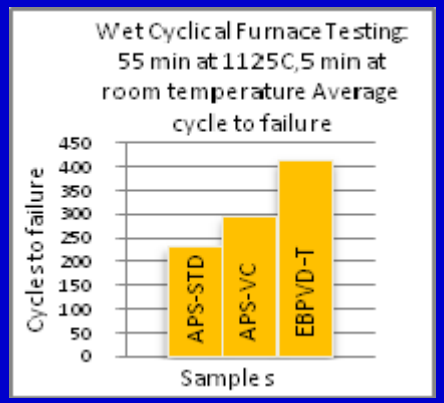
TBC System Components

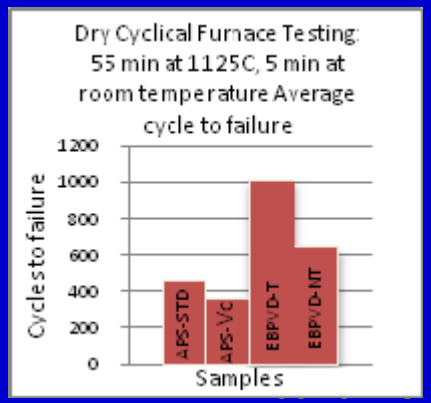
- Superalloy substrate IN 738- A nickel based $Ni_3Al(Ti)$ precipitate strengthened alloy
- composition: Alcoa Howmet Castings of Wachita Falls, Texas.
- Standard and Vertically cracked APS samples were prepared. NiCoCrAlY bond coat with 0.25% Hf. APS with 300 and 600 µm.
- Spalling resistance and thermal cycling at 1250 and 1350 C
- Spalling resistance and thermal cycling Test Results at 1200 C
- Wet and Dry oxidation thermal cycling at 1125 C. 100X (EBPVD Microstructured Coatings)











Outcome:

[1] R. Diwan, O. A. Agu, P. F. Mensah, and D. E. Wolfe, "Thermal Oxidation Cycling Studies of APS and EBPVD Composite TBC Microstructured Coatings", International Conference on Composite Engineering, July 2009, Honolulu, Hawaii, USA

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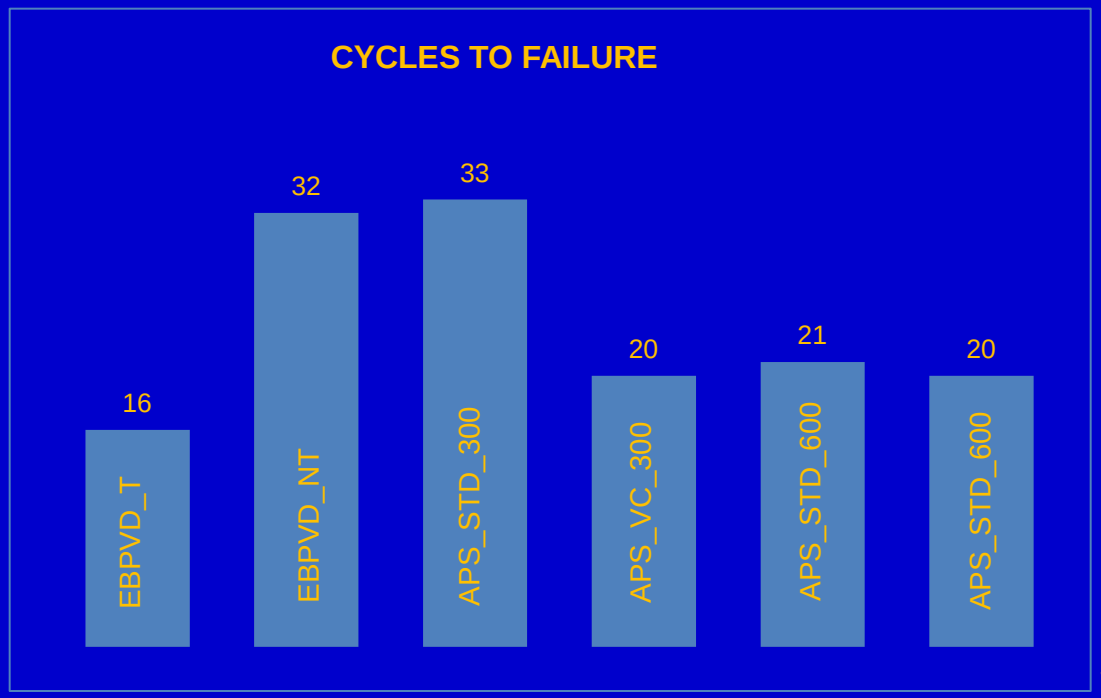
Thermal Cycling Spalling Resistance using 6- hour Thermal cycles at 1200 ºC.



CM Furnace

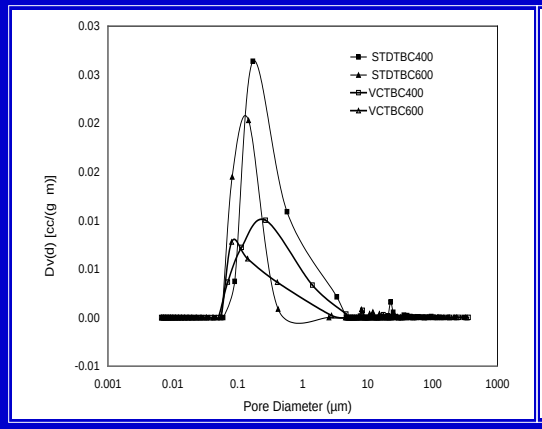
Outcome:

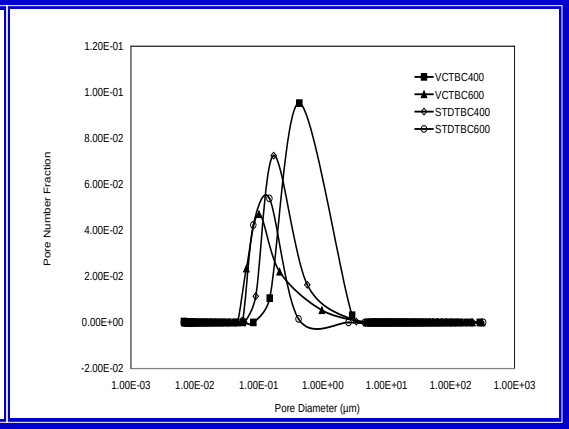
[1] R. Diwan, P. F. Mensah, O. A. Agu and D. E. Wolfe, "Thermal Oxidation Cycling Studies of APS and EBPVD Composite TBC Microstructured Coatings", International Conference on Composite Engineering, July 2009, Honolulu, Hawaii, USA

Porosity Measurements using the Poremaster

Results (STD and VC Samples)

SPCIMEN TESTED	Porosity Measure (%)	Porosity value using density (%)
STD-TBC400	14	15
STD-TBC600	9	14
VC-TBC400	8	13
VC-TBC600	6	4



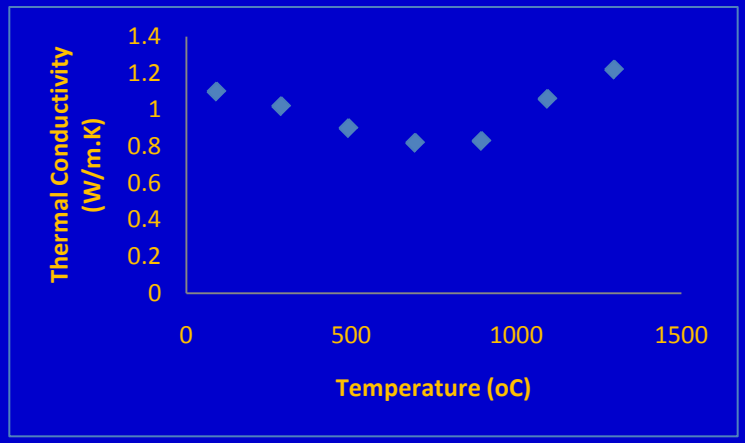


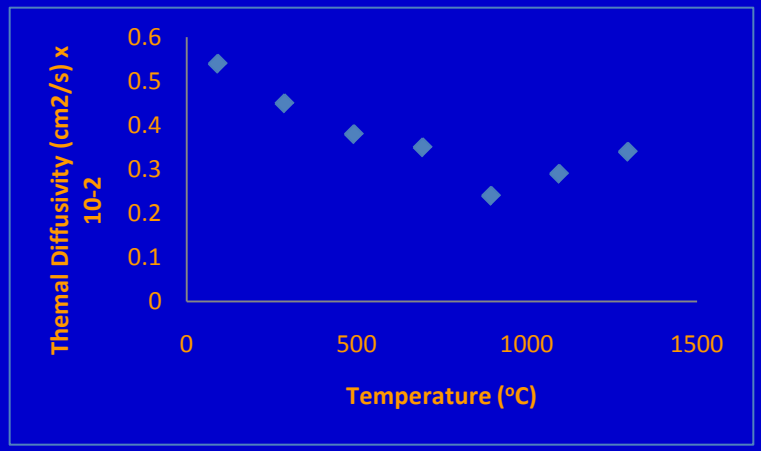
Outcome

[2] M. B. Silva, S. M. Guo, N. Uppu, R. Diwan, P. F. Mensah, " Porosity Effects on thermophysical Properties of Standard and Vertically Cracked Thermal Barrier Coatings", Proceedings of ASME Turbo Expo 2009, June 2009, GT 2009-59826, Orlando, Florida.

[3] M. B. Silva, S. M. Guo. N. Uppu, R. Diwan and P. F. Mensah, "Property Measurements of YSZ - Al2O3 Ceramic Composites", Proceedings of ASME Turbo 2009, June 2009, GT2009-59496, Orlando,Florida.

Thermophysical properties





Laser Flash Equipment (FL 5000)

Outcome

[4] *S. Akwaboa, M. B. Silva, P. F. Mensah, R. Diwan, "Comparison of Cyclic Oxidation Performance of APS and EBPVD Processed TBCs on IN738 with a Bond Coat of NiCoCrAlY Powder with 0.25%Hf.*

[5] *S. Akwaboa, and P. F. Mensah, "A Comparison Study of Heat Transfer Through Electron Beam Vapor Deposition (EBPVD) and Air Plasma Sprayed (APS) Coated Gas Turbine Blades", 14th International Heat Transfer Conference, August 2010, Washington, USA.*

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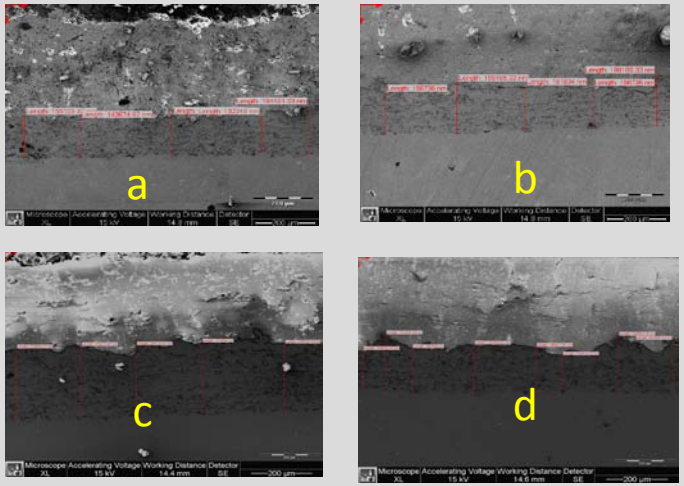
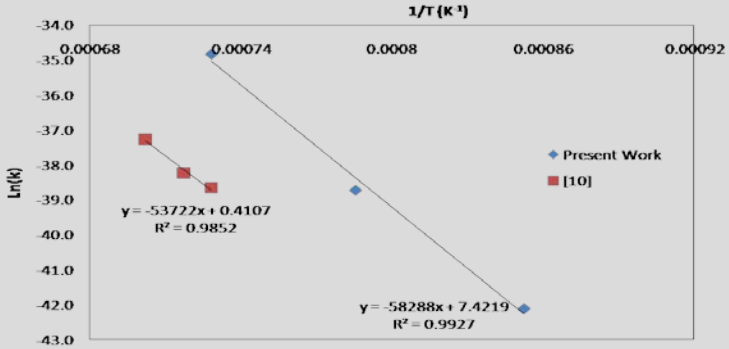
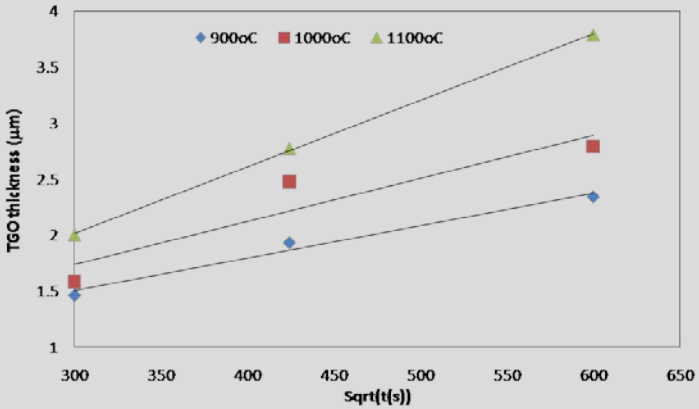
Microstructure of TBC Annealed at 1000 C for (a) 25 Hours (STD); (b) 25 Hours (VC) ;(c) 100 Hours (STD) and (d) 100 Hours (VC)



Plot of Natural Logarithm of Rate Constant against Inverse of Absolute Temperature for APS VC TBC





Outcome

[6] W. Soboyejo, P. F. Mensah, and R. Diwan, "Interfacial Kinetics of High Temperature oxidation in YSZ Thermal barrier Coatings with bond coat of NiCoCrAlY with 0.25% Hf" Proceedings of the ASME 2009 International Mechanical Engineering Congress & Exposition, November 2009, IMECE 2009-11901, Lake Buena Vista, Florida.

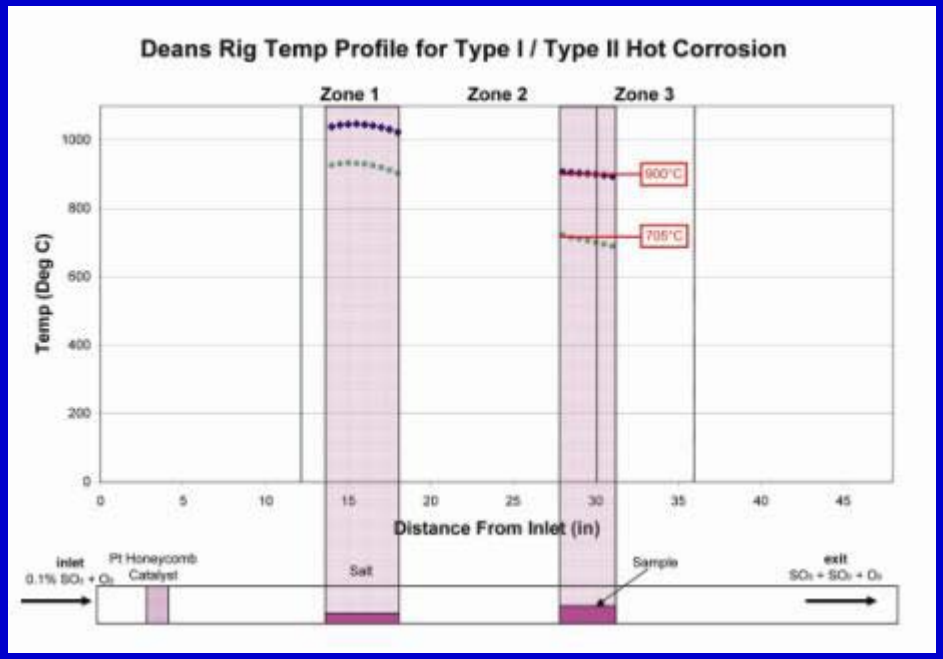
Dean Rig: High Temperature Hot Corrosion Testing Apparatus

System Features and Facility Support

- Process temperatures up to 1100 C
- 18” work zone
- 3 independently temperature controlled zones
- 2.5” sample zone
- Fully enclosed and ventilated process area
- Many different salts available
- Process gas control 10 sccm to 160 sccm
- High purity process gas premixed and available
- Laboratory and metallographical services on site

The Dean’s Rig test simulates high temperature marine turbine environments

- Molten salts combine with sulfurous gases to accelerate material degradation at elevated temperatures (Type I and Type II hot corrosion regimes)
- Dean’s Rig studies are conducted for alloy and protective coating development for a fraction of the time and cost of burner rig tests



Dean Rig: High Temperature Hot Corrosion Testing Apparatus

HOT CORROSION PROCESSES (HTHC)

HIGH TEMPERATURE CORROSION AND DEGRADATION RELATED TO:

ACCELERATED CORROSION EFFECTS OF OXYGEN, CO_2 , SO_2,

FUSED SALTS. SULFATES & CHLORIDES

ACCELERATED CORROSION

BETWEEN 700 – 925 C (1300 – 1700 F)- "HOT CORROSION".

Hot section turbine components can encounter hot corrosion processes:

- Type I (900 C) [> m.pts. Of salts]
- Type II (705 C) [< m. pts. Of salts]

AFFECTED BY HARSH FUEL AND CONTAMINATION AND ELEVATED TEMPERATURES AND MARINE ENVIRONMENTS .

POSSIBLE PROCESS REACTIONS-

$2\,NaCl + SO_2 + O_2 = Na_2SO_4 + Cl_2$

$4\,NaCl + 2SO_2 + 2H_2O + O_2 = 2Na_2SO_4 + 4HCl$

FOR YSZ TBCs

$Y_2O_3 + 3Na_2SO_4 = Y_2(SO_4)_3 + 3Na_2O$

$3\,SO_2 + ½\,O_2 = 3SO_3$

$3Na_2O + 3\,SO_3 = 3\,Na_2SO_4$

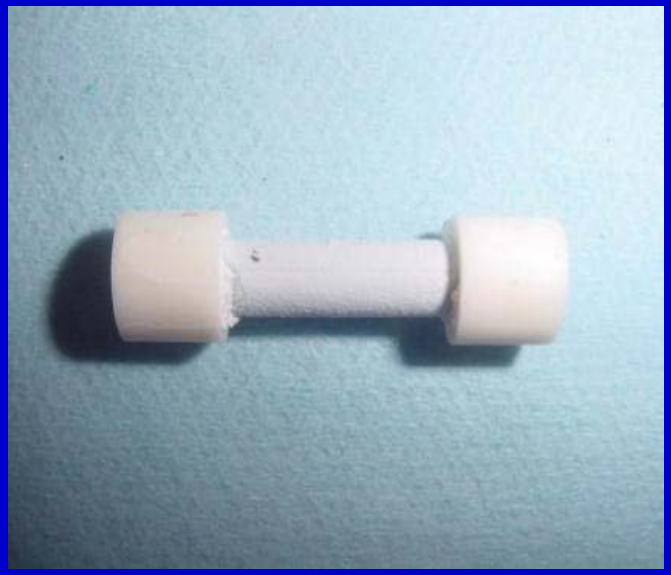
TESTING UNDER ENCLOSED CONTROLLED CONDITIONS

Table Summarizing Hot Corrosion testing under Type I (900C) and Type II (705C) Results

	Substrate	Bond Coat	TBC	Coating Type	Type I Hot Corrosion	Type II Hot Corrosion
1	IN 738	NiCoCrAlY+Hf 120µm	7wt%YSZ 300µm	STD YSZ	4	4
2	In 738	NiCoCrAlY +Hf 120µm	7wt%YSZ 300µm	VC YSZ	5	3
3	IN 738	NiCoCrAlY+Hf 120µm	7wt%YSZ 600µm	STD YSZ	2	2
4	IN 738	NiCoCrAlY+Hf 120µm	7wt%YSZ 600µm	VC YSZ	3	5
5	IN 738	NiCoCrAlY+Hf 120µm	7wt%YSZ 300µm	EB-PVD	1	1

Ranking system: 1 = Best, 5 = Worst

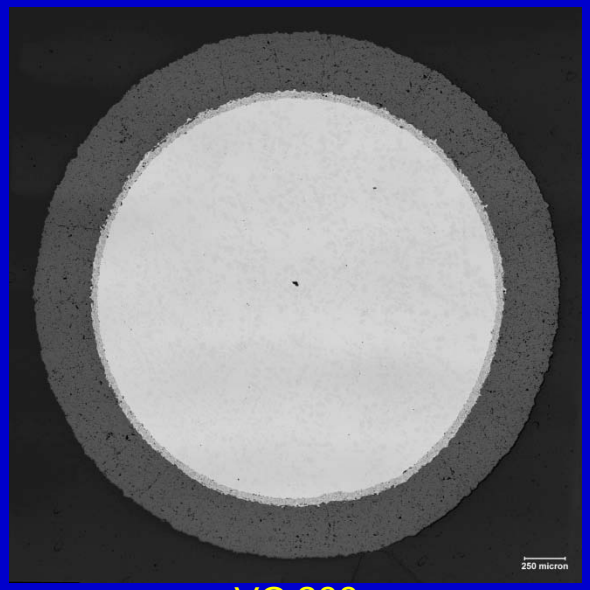
EB-PVD 300 (Sample A-2) images showing 2 different views of sample EB-PVD 300 after 100 hr low temperature (Type II: 705C) hot corrosion test has finished.



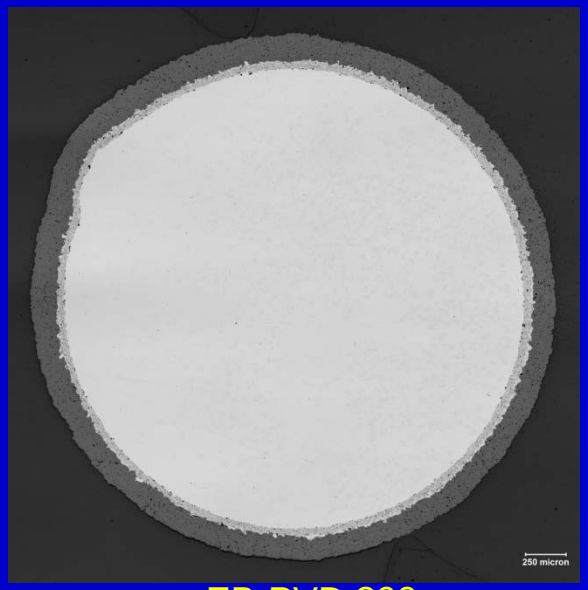
VC 300 (Sample B-2) images showing 2 different views of sample VC 300 after 100 hr low temperature (Type II: 705C) hot corrosion test has finished.

50x

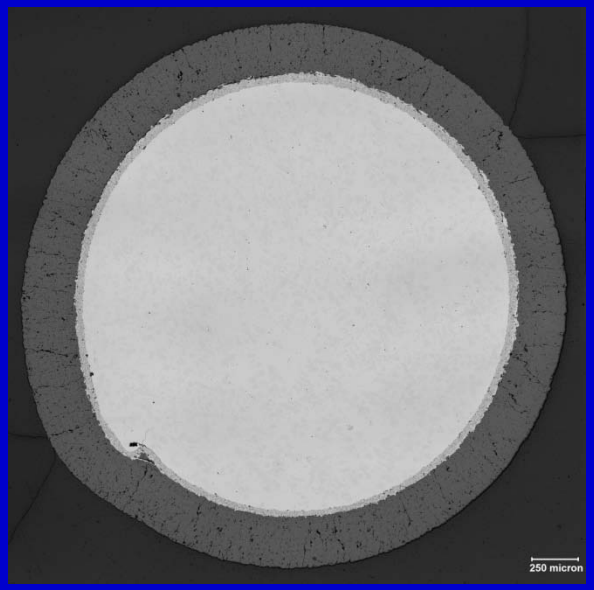
STD 600



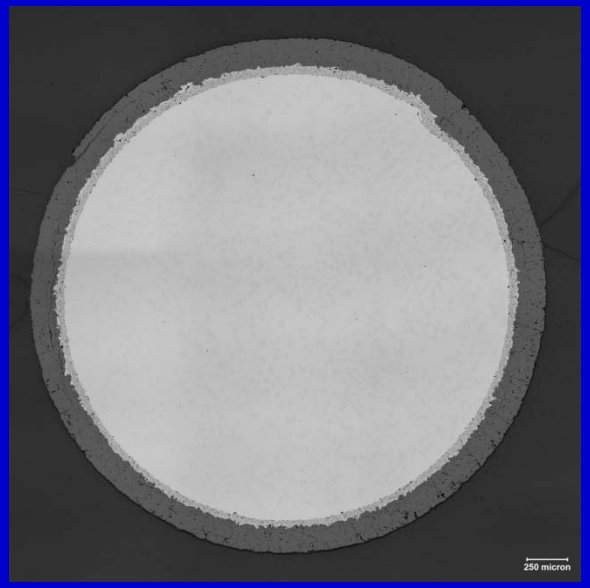
STD 300



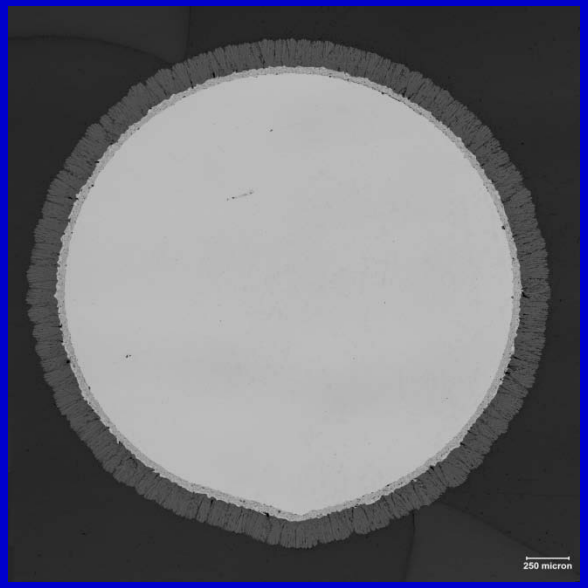
VC 600



VC 300



EB-PVD 300



Optical microscope composite images showing coating before hot corrosion testing using the Deans Rig apparatus.

STD 600 (Sample E-2) images showing 2 different views of sample STD 600 after 100 hr high temperature (Type I: 900C) hot corrosion test has finished.

STD 600 sample images showing 2 different views of sample after 100 hr low temperature (Type II: 705C) hot corrosion test has finished.

RESEARCH OUTCOMES

CONFERENCE PRESENTATIONS:

•RaviOxidation and Microstructural Effects of TBCs in Spalling Resistance", New Advances in IGT Coatings, Panel session, Ander M. Diwan, "Thermal SME Research Symposium, Houston, TX, September 14- 17, 2009.

•Ravinder M. Diwan, "High Temperature Oxidation and Hot Corrosion Studies of APS and EBPVD advanced Thermal Barrier Coatings Materials," 5th international African Materials Research Society Conference in Abuja, Nigeria, December 14th - 18th, 2009.

•Patrick Mensah "Simulation of nonlinear 2 D Steady State Thermal Stress in vertically Cracked Air Plasma Coated gas turbine Blades", 5th international African Materials Research Society Conference in Abuja, Nigeria, December 14th - 18th, 2009.

RESEARCH PUBLICATIONS:

•Monica B. Silva, S.M. Guo, Nalini Uppu, Ravinder Diwan and Patrick F. Mensah, " Thermal Property Measurements of YSZ-Al_2O_3 Ceramic Composites", Proceedings of ASME IGTI conference, GT2009-59496, Orlando, FL June 2009.

•Monica B. Silva, S.M. Guo, Nalini Uppu, Ravinder Diwan and Patrick F. Mensah, "Porosity Effects on Thermo-physical Properties of Standard and Vertically Cracked Thermal Barrier Coating Samples", Proceedings of ASME IGTI conference, GT2009-59826, Orlando, FL June 2009.

•Stephen Akwaboa, Patrick Mensah, Monica. B. Silva, Ravinder Diwan, Douglas E. Wolfe, and S. M Guo, "Thermal Properties and Porosity Comparison of APS and EBPVD TBCs Deposited on MCrAlY Hf Bond Coated IN738", IMECE 2009-11901, ASME IMECE, November 13-19, 2009, Lake Buena Vista, Florida.

•W. Soboyejo, P. Mensah, and R. Diwan, "Interfacial Kinetics of High Temperature Oxidation in YSZ Thermal barrier Coatings with NiCoCrAlY Bond Coat," ASME IMECE2009-11556, November 13-19, 2009, Lake Buena Vista, Florida.

•Ravinder M. Diwan, Patrick F. Mensah, Ogad A. Agu and Douglas E. Wolfe, "Thermal Oxidation Cycling Studies of APS and EB-PVD Composite TBC Microstructured Coatings", ICCE/Nanoengineering Conference, July 26-31, 2009.

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•As a result of this research and collaboration with Clean Power Energy Research Consortium (CPERC) we are currently doing further work in the area of clean power and energy research.

•This has also resulted in continuing collaboration with LSU materials Group and in funding from NASA EPSCoR in research work on novel TBC materials.