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

GRANT NUMBER:
DE-FG 26-08NT000471

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Introduction

- Advanced TBC considerations-
- YSZ top coat novel microstructured specimens

  processing regimes in consideration
  -Standard APS YSZ Coatings
  -VC APS YSZ Coatings
  -EB-PVD Coatings
- Improved Reliability & Performance to 1300 C
- Structure Property Correlations
- Thermal Modeling & Oxidation Studies
- Hot Corrosion Testing

Goals of This Research

- Effects of APS coated Microstructures and Their Development
- Advanced materials characterization techniques
- 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 Corrosion studies - Current and Ongoing studies and results

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 + 50% of YSZ and 50% 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**
    (currently in progress)
  - **2.3 Thermal cyclic oxidation testing in dry air and water vapor (moisture) environments-**
    Test results under study.

Research Tasks/ Activities

- (3) Thermo-physical properties experimental characterization
  - 3.1 Characterization Testing Approach
    Laser Flashline thermal properties characterization
  - 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 aluminabased protective layer

    In process

Research Tasks/ Activities

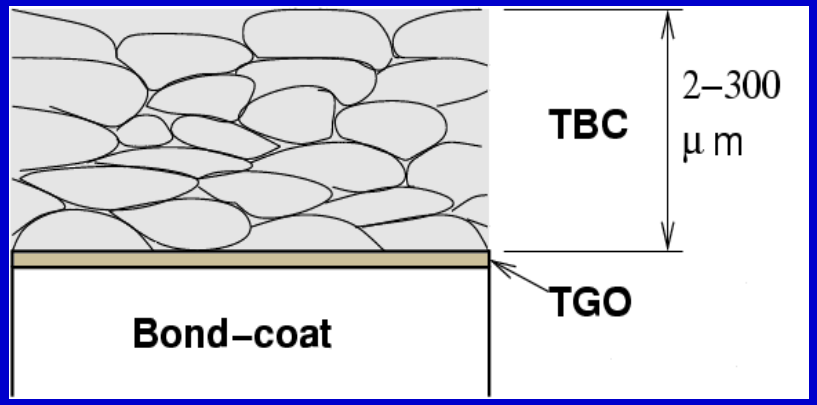
- (4) Characterization of effect of microstructures and processing of TBC materials and comparative thermal cycling and spalling studies
  - 4.1 Thermo-Mechanical Behavior and Spalling of Selected TBC Coated Materials Spalling studies at elevated temperatures
  - 4.2 Characterization of Superalloy APS and EBPVD TBC Materials
  - 4.3 Analysis of the Effects of Syngas Combustion Deposited Particulates

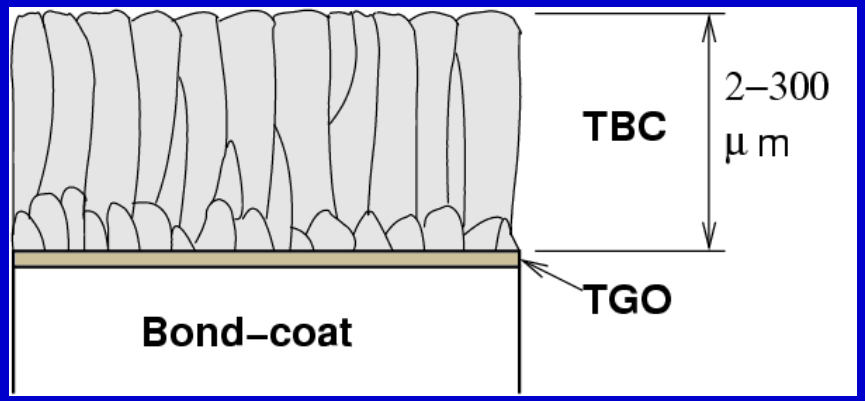
Research Tasks/ Activities

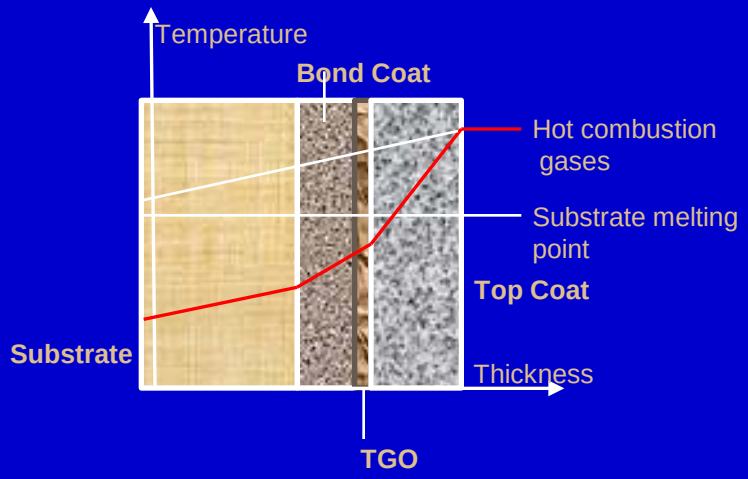
- (5) Development of performance models to predict the life of optimized TBCs under selected test conditions
  - 5.1 Classical Plate theory of Buckling model
  - 5.2 Micromechanics and laminated plate theory based method
  - Structure property correlations and evaluations undergoing currently.

TBC Coatings Studies and Advantages of TBC Applications

- 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
- Porous columnar structure using APS, EBPVD
- Adherent columnar structure TBC top coat on MCrAlY bond coat







- Limit heat transfer through the coating (TBC)
- Maximize the thermal drop across the thickness of TBC
- Resistance to Oxidation Wet and Dry oxidation cyclic results
- Hot Corrosion study to be conducted this year
- 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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Accomplishments To Date

- Drs Patrick Mensah, Ravinder Diwan and Nalini Uppu co-authored a paper which was presented at the ASME Summer Heat Transfer Conference, Jacksonville, Florida, August 10-14, 2008.
- Drs. Ravinder Diwan and Mensah attended the DOE Annual UCR/HBCU & OMI Contractors Review meeting in Pittsburgh, PA, June 10-11, 2008.
- Drs. R. Diwan and P Mensah visited with DOE project collaborator at PSU ARL State College, June 12, 2008.
- Publications:
  - (1) 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.
  - (2) 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.
- **In Progress-**
  - **(1) Ravinder M. Diwan, Patrick F. Mensah and Douglas E. Wolfe"Thermal Oxidation Cycling Studies of APS and EB-PVD Composite TBC Microstructured Coatings", Accepted for ICCE 17, July 2009.**
  - **(2) Patrick F. Mensah, Winston Soboyejo, Ravinder M. Diwan, and Stephen Akwaboa, "Interfacial Kinetics of High Temperature Oxidation in YSZ Thermal Barrier Coatings with NiCoCrAlY Bond Coat" In preparation, for 2009 ASME International Mechanical Engineering Congress and Exposition - presentation and publication.**

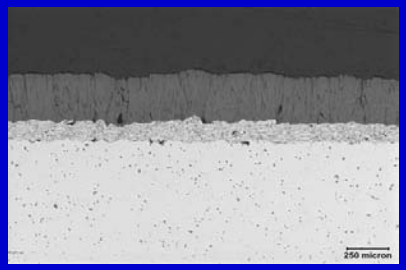
DEVELOPMENT OF APS STD AND VC & EBPVD MICROSTRUCTURES

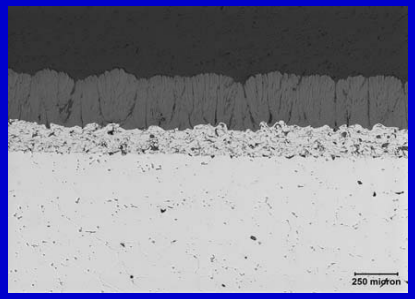
- **Materials Solutions International, Houston, TX**
  - **- Air Plasma Spray processing of TBCs**
  - **-Thermo-mechanical characterization tests and experiments**

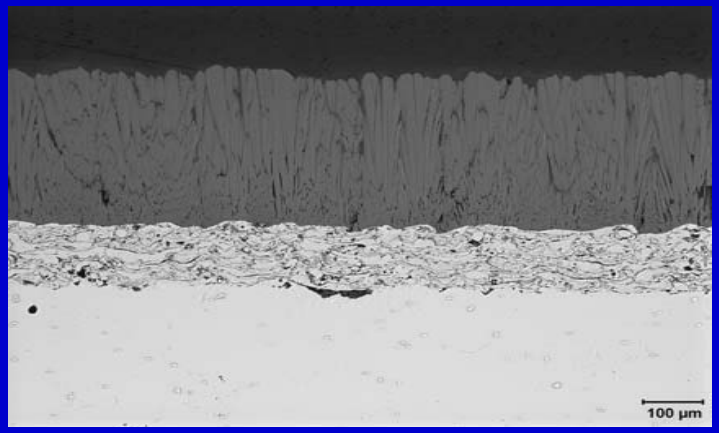
- **SUBR collaboration with Pennsylvania State University- Proposed research for microstructure processing of EBPVD**
  - **– Wet and Dry oxidation of EBPVD and APS STD and VC TBC samples**

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
- Wet and Dry oxidation thermal cycling at 1125 C. 100X (EBPVD Microstructured Coatings)







Air Plasma Spray Coatings and Microstructure Property Characterizations

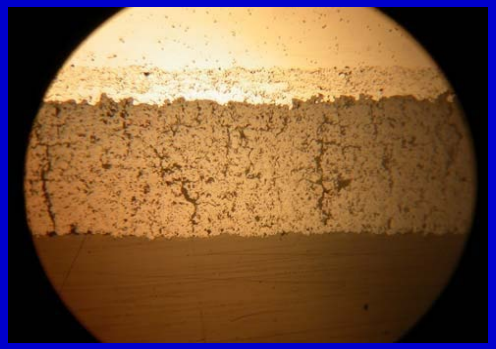


Fig. 1. (a) Bond coat thickness 140 µm;
Top coat thickness 635 µm VC microstructures
X100

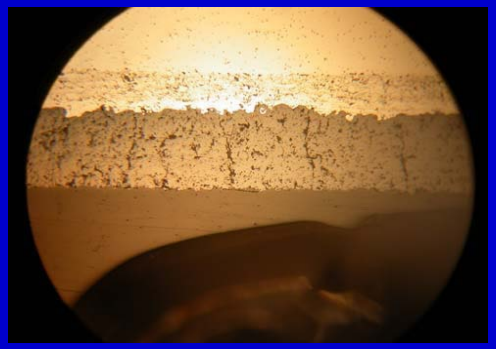


Fig. 1. (b) Bond coat thickness 150 µm;
Top coat thickness 350 µm VC microstructures
X 100

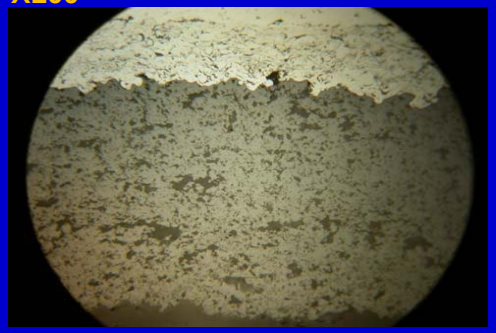


Fig. 2. (a) Bond coat thickness 140 µm;
Top coat thickness 575 µm Standard APS
X 200

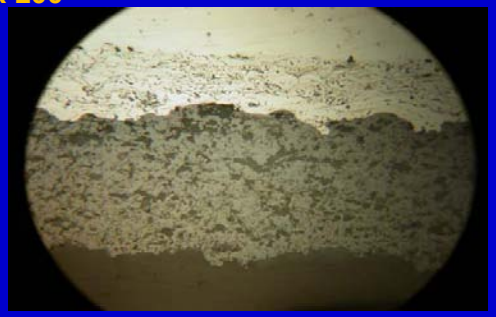


Fig. 2. (b) Bond coat thickness 140 µm;
Top coat thickness 350 µm Standard APS
X 200

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TBCs Test Matrix

APS COATINGS FOE THERMAL PROPERTY CHARACTERIZATIONS

	Substrate	Bond Coat	TBC	No of Samples	Coating Type
1	IN 738	NiCoCrAlY+Hf 120µm	7wt%YSZ 300µm	13 (*)	STD YSZ
2	In 738	NiCoCrAlY +Hf 120µm	7wt%YSZ 300µm	13 (*)	VC YSZ
3	IN 738	NiCoCrAlY+Hf 120µm	7wt%YSZ 600µm	13 (*)	STD YSZ
4	IN 738	NiCoCrAlY+Hf 120µm	7wt%YSZ 600µm	13 (*)	VC YSZ
5	IN 738	NiCoCrAlY+Hf 120µm	7wt%YSZ 300µm	13 (*)	STD YSZ dense bottom layer (150 µm) + 50% YSZ & 50% 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.

TBCs Test Matrix

APS COATINGS FOR CORROSION TESTING AT ELEVATED TEMPERATURES

	Substrate	Bond Coat	TBC	No of Samples	Coating Type
1	IN 738	NiCoCrAlY+Hf 120µm	BC only for BPVD	13 (*)	Bond Coat only-for EBPVD
2	In 738	NiCoCrAlY +Hf 120µm	7wt%YSZ 300µm	13 (*)	STD YSZ
3	IN 738	NiCoCrAlY+Hf 120µm	7wt%YSZ 300µm	13 (*)	VC YSZ
4	IN 738	NiCoCrAlY+Hf 120µm	7wt%YSZ 600µm	13 (*)	STD YSZ
5	IN 738	NiCoCrAlY+Hf 120µm	7wt%YSZ 600µm	13 (*)	VC YSZ

The above substrate IN 738 samples are (3/16 inch diameter and 3 inch long pins) samples that have been EDM machined - to be bond coated and top coated as specified above.

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Porosity Measurements using the Poremaster Porosity Results for STD and VC Samples

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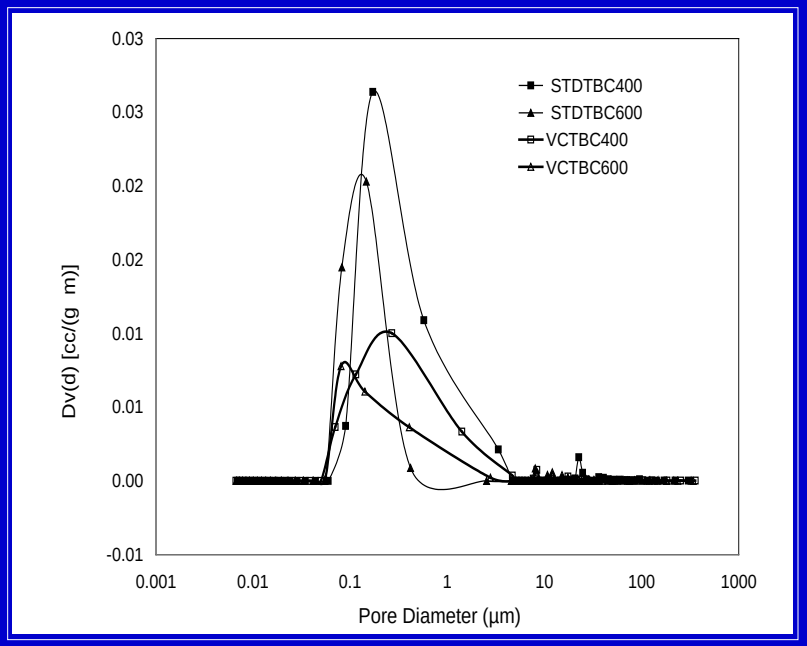
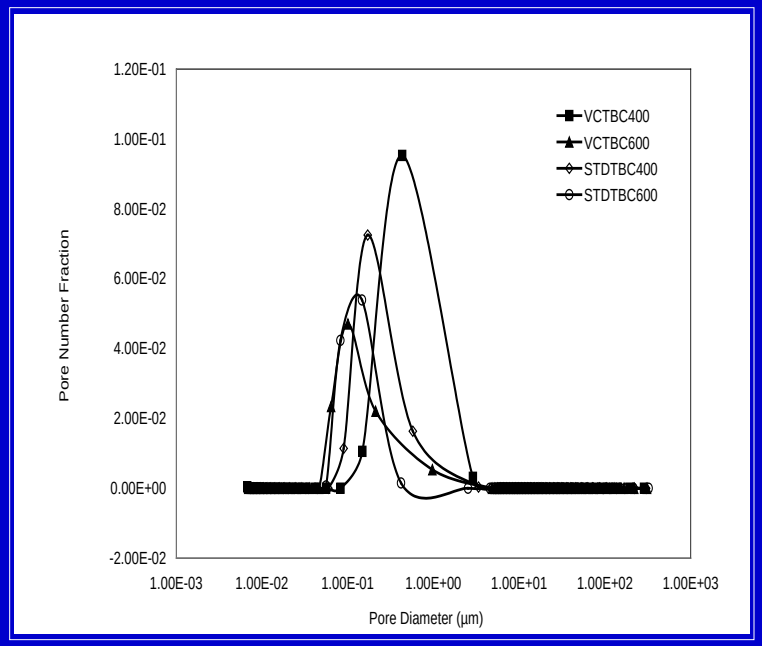
	Porosity Measure (%)	Porosity value using density (%)
STD-TBC400	14	15
STD-TBC600	9	14
VC-TBC400	8	13
VC-TBC600	6	4

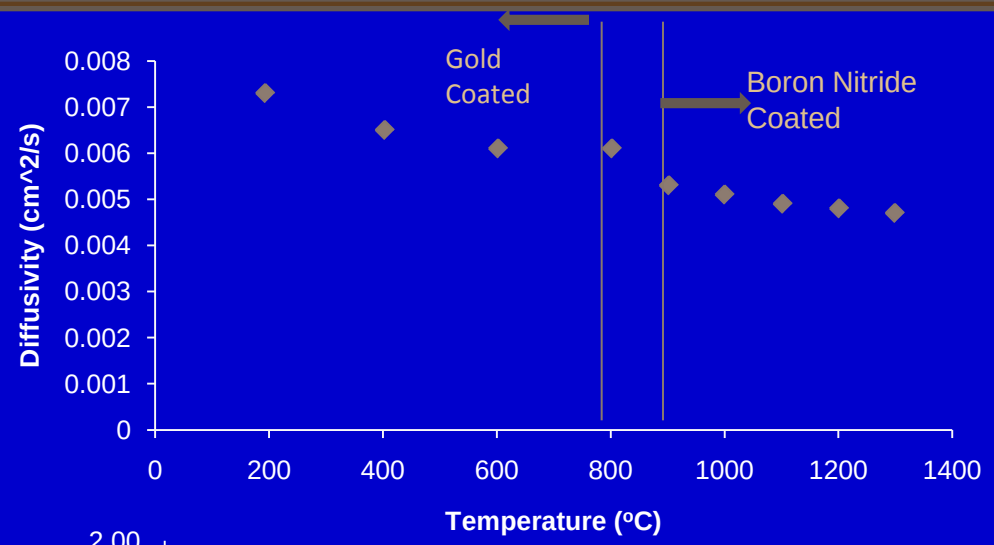


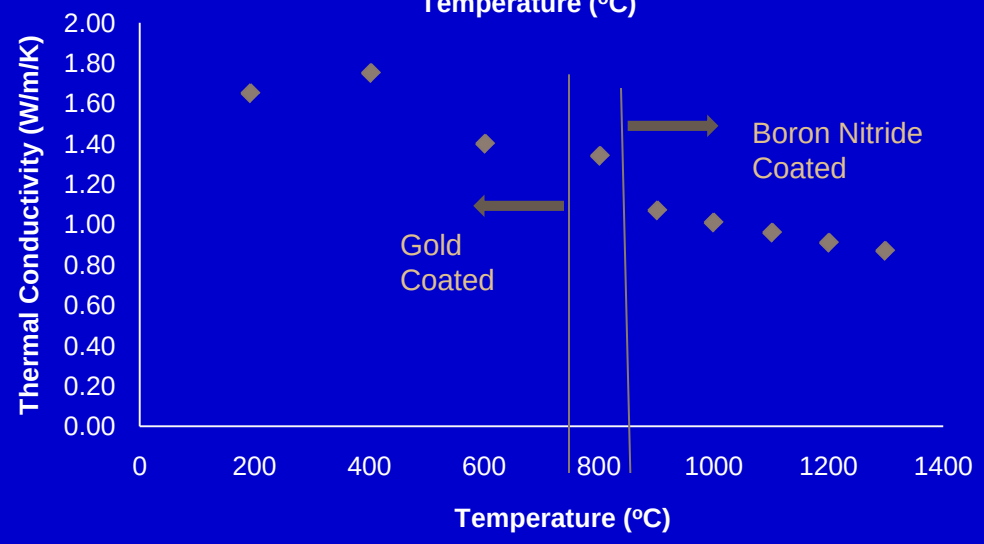
Pore Size Distribution Function of STD and VC TBC Samples



Pore Number Fraction of STD-TBC and VC-TBC Samples

Thermophysical properties APS VC





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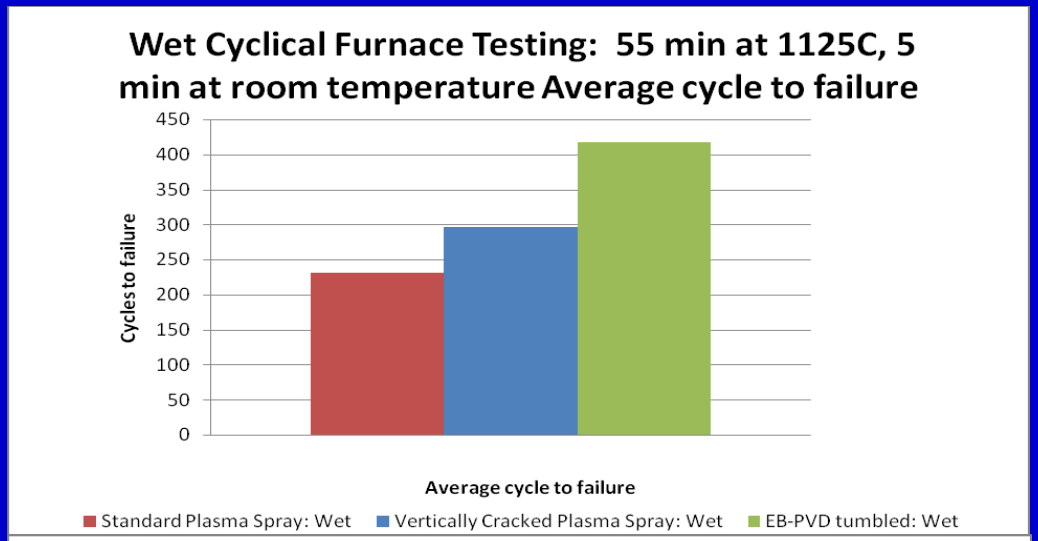
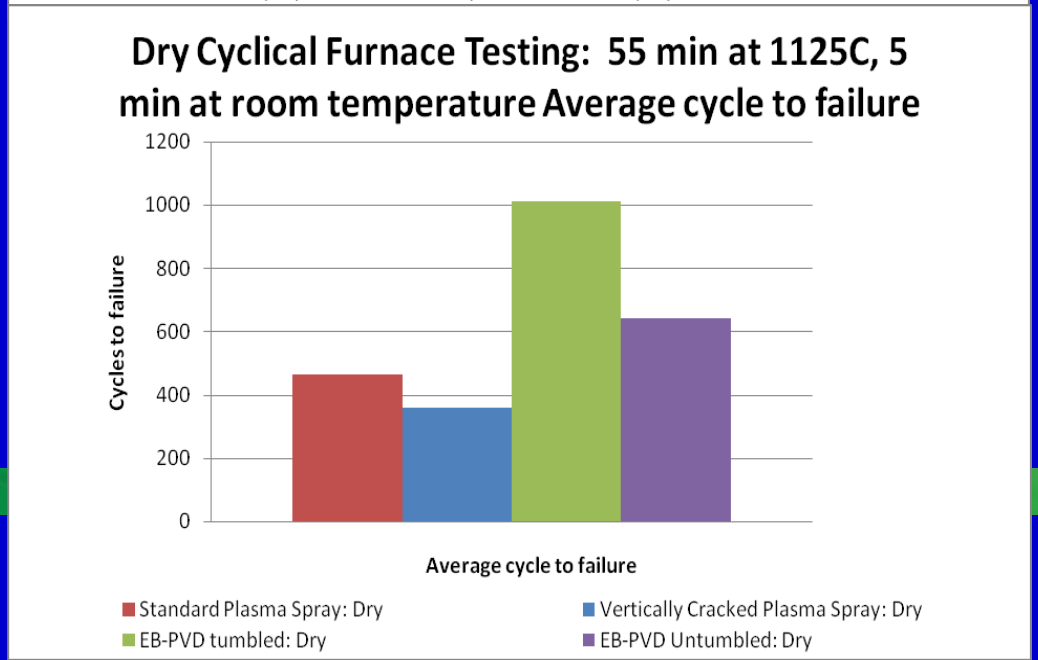
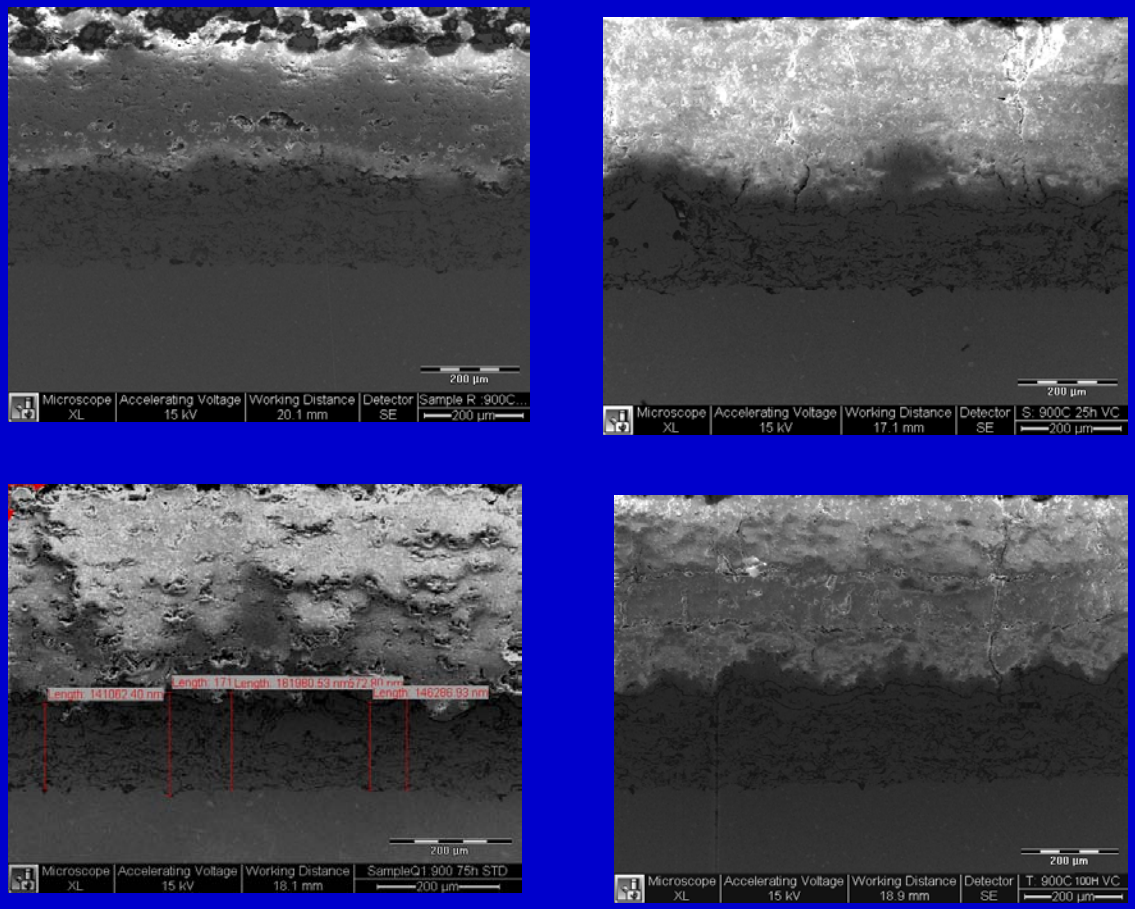
Wet and Dry Cyclic Furnace Testing of TBCs



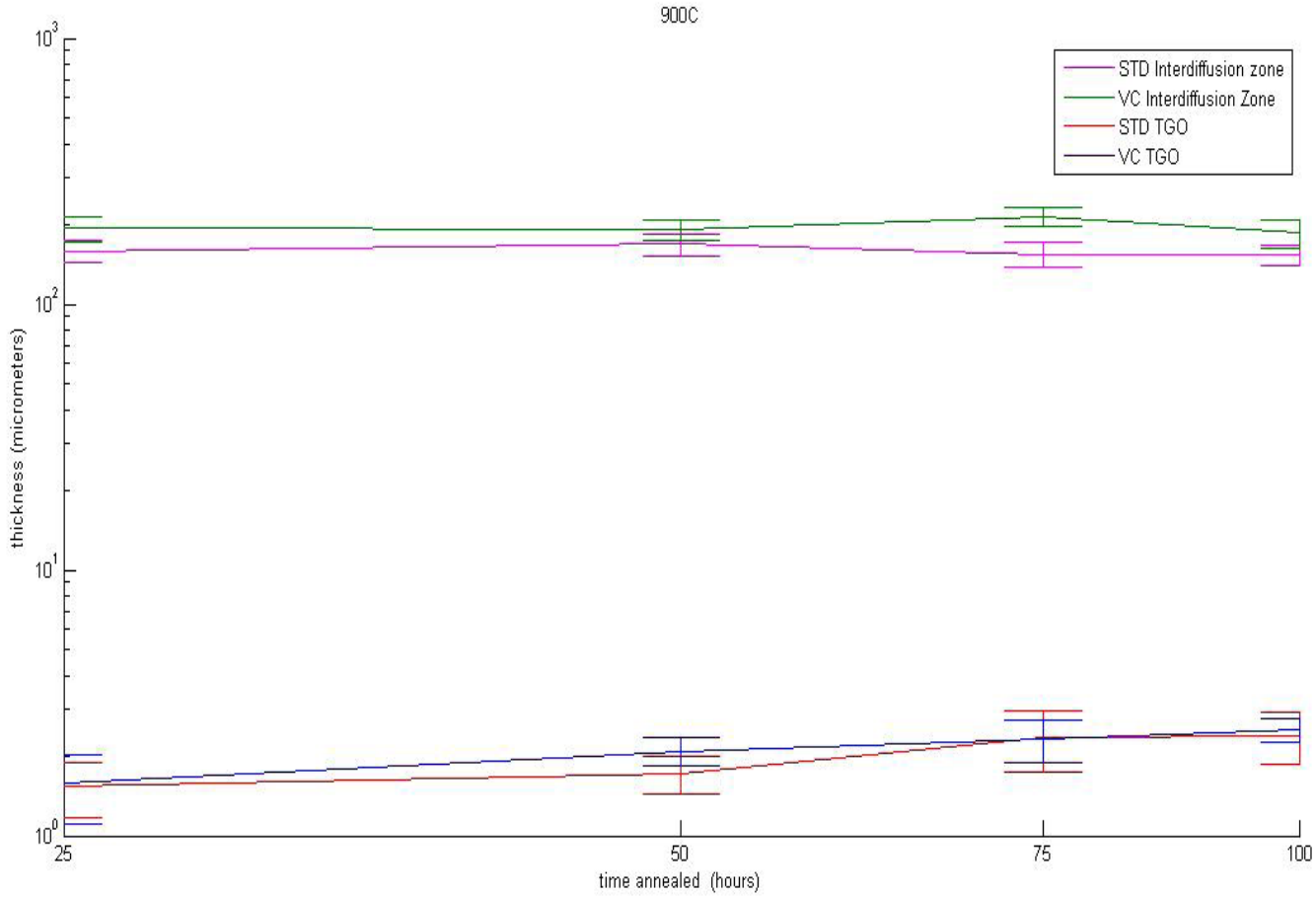


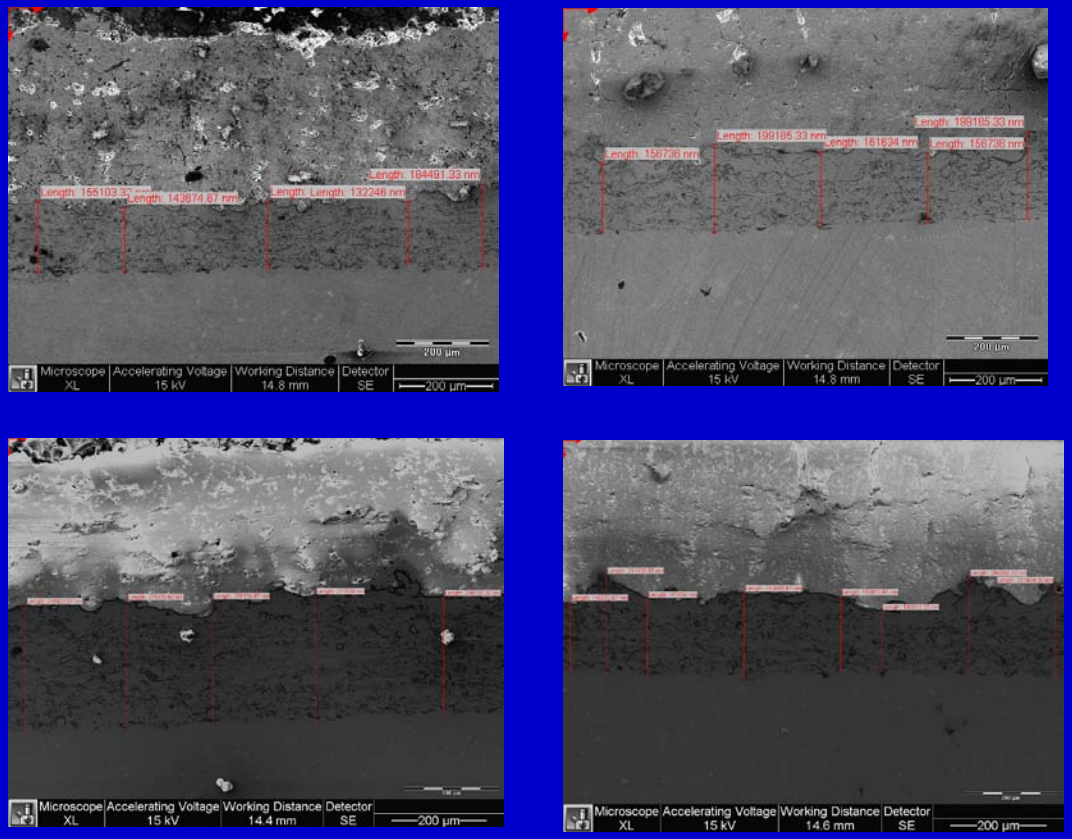
June 9-10, 2009



Microstructure of TBC Annealed at 900 C for: (a) 25 Hours (STD Microstructure); (b) 25 hours (VC Microstructure); (c) 100 Hours (STD Microstructure) and (d) 100 Hours (VC Microstructure)

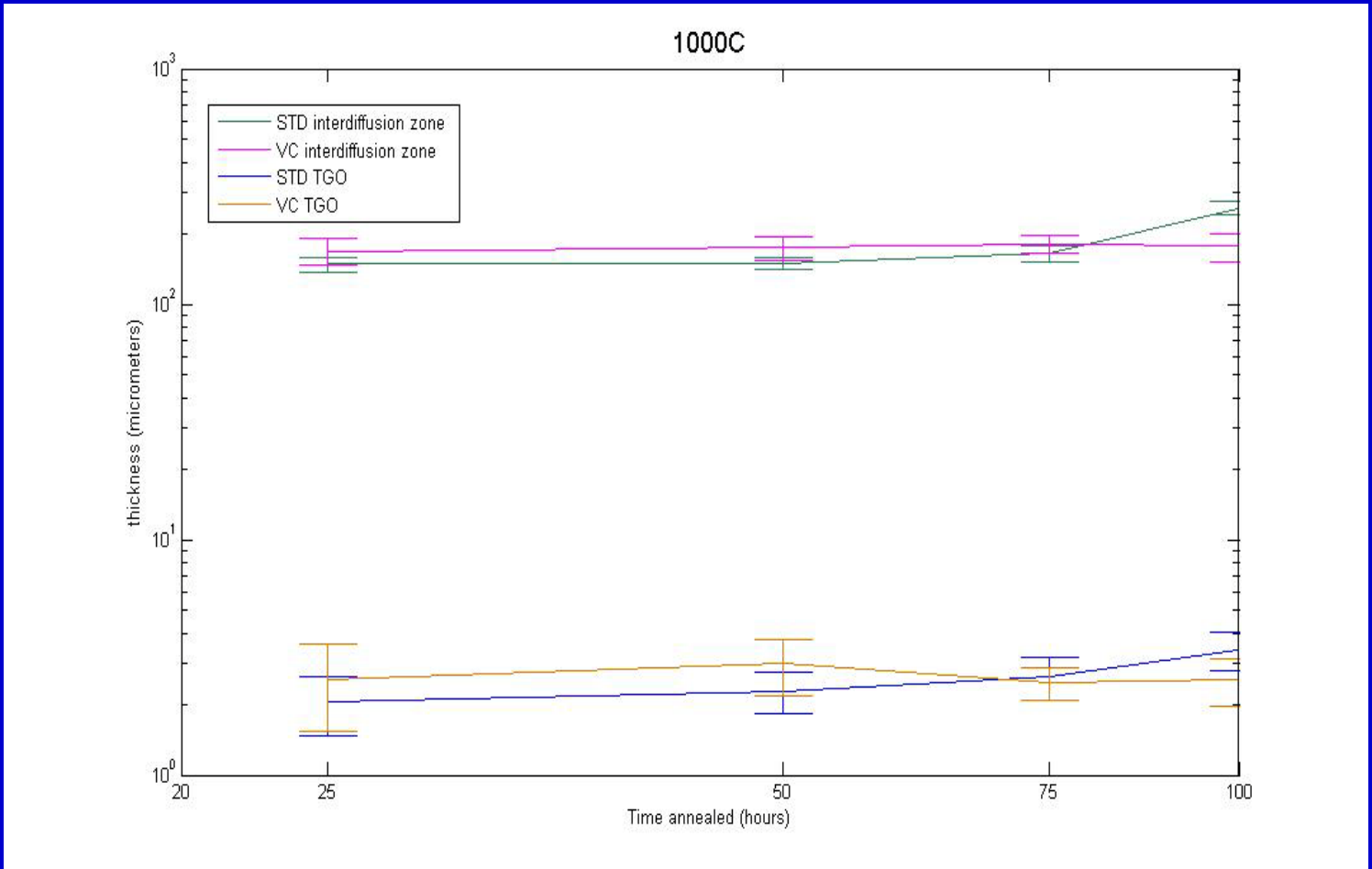
Dependence of TGO and Bond Coat Thickness of TBC Annealed at 900 C

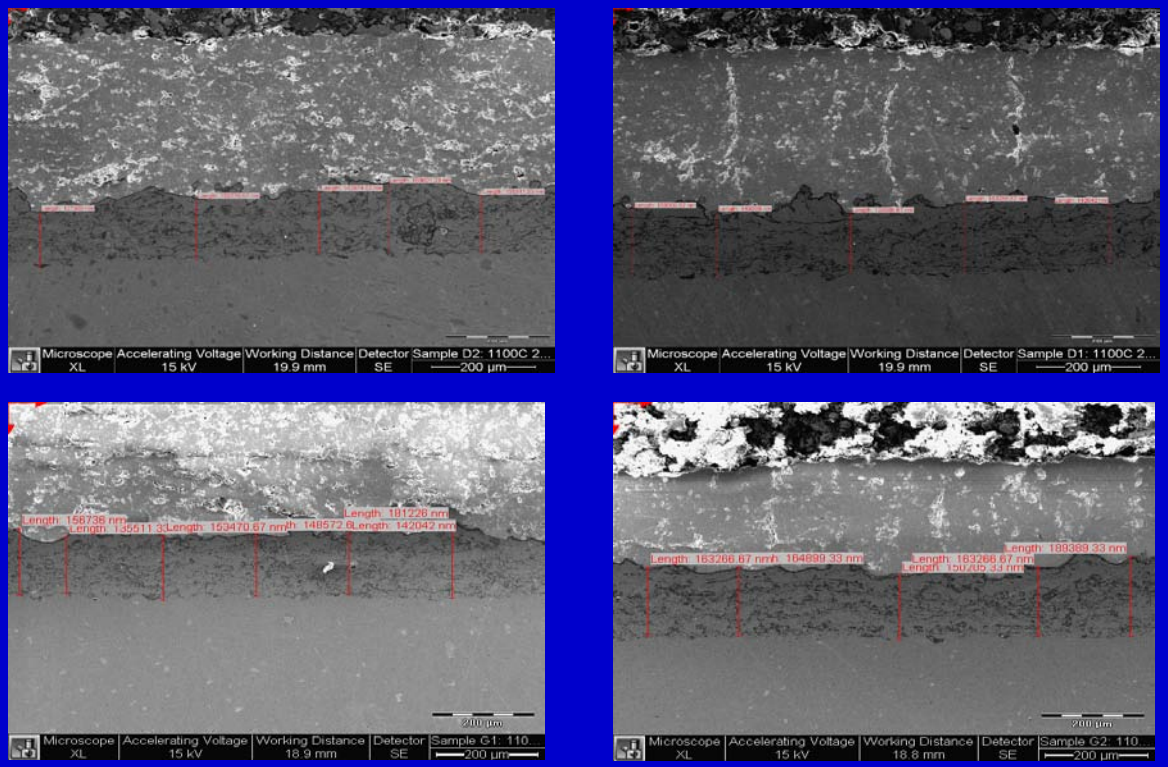




Microstructure of TBC Annealed at 1000 C for: (a) 25 Hours (STD Microstructure); (b) 25 hours (VC Microstructure); (c) 100 Hours (STD Microstructure) and (d) 100 Hours (VC Microstructure)

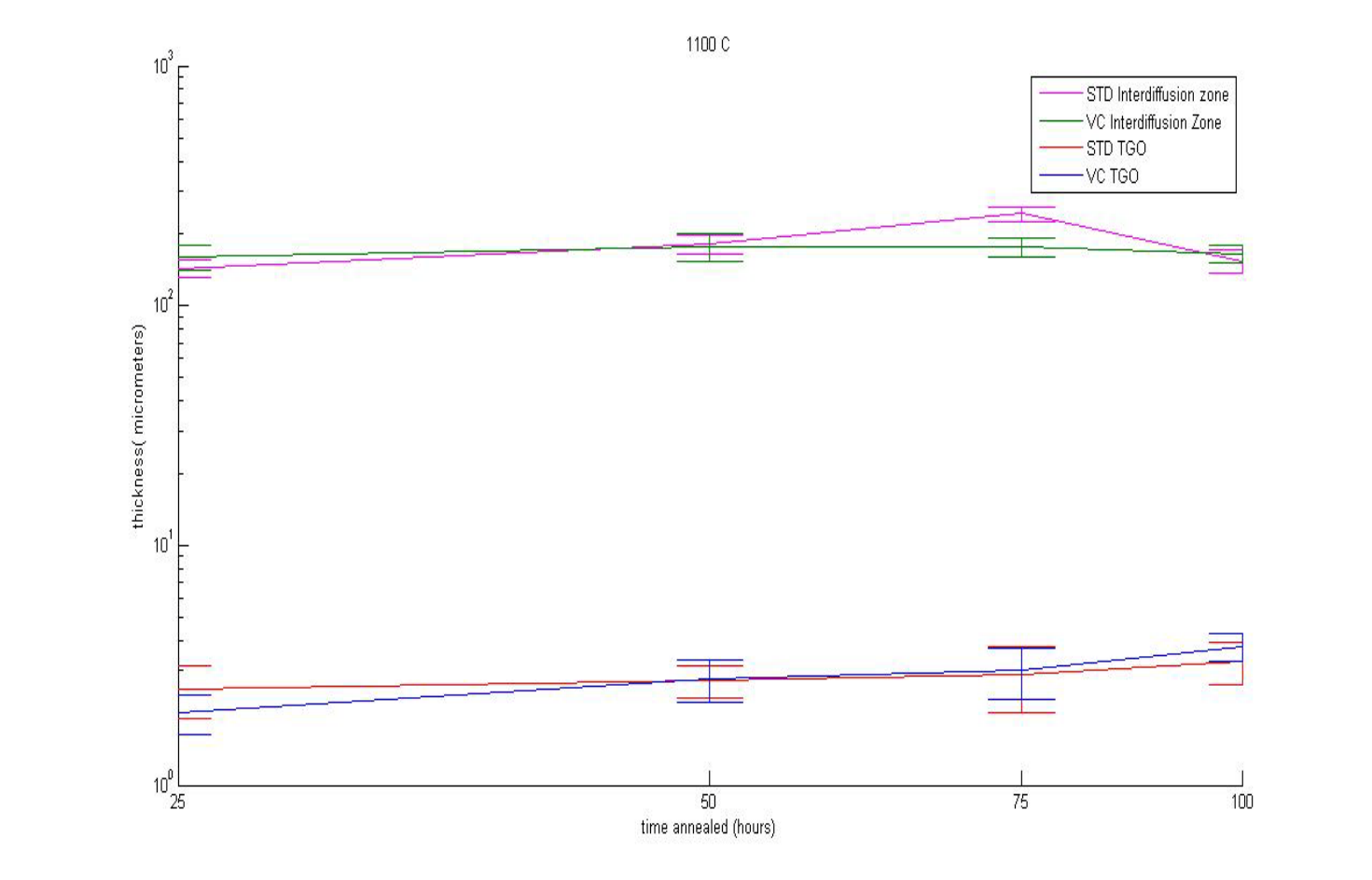
Dependence of TGO and Bond Coat Thickness of TBC Annealed at 1000 C

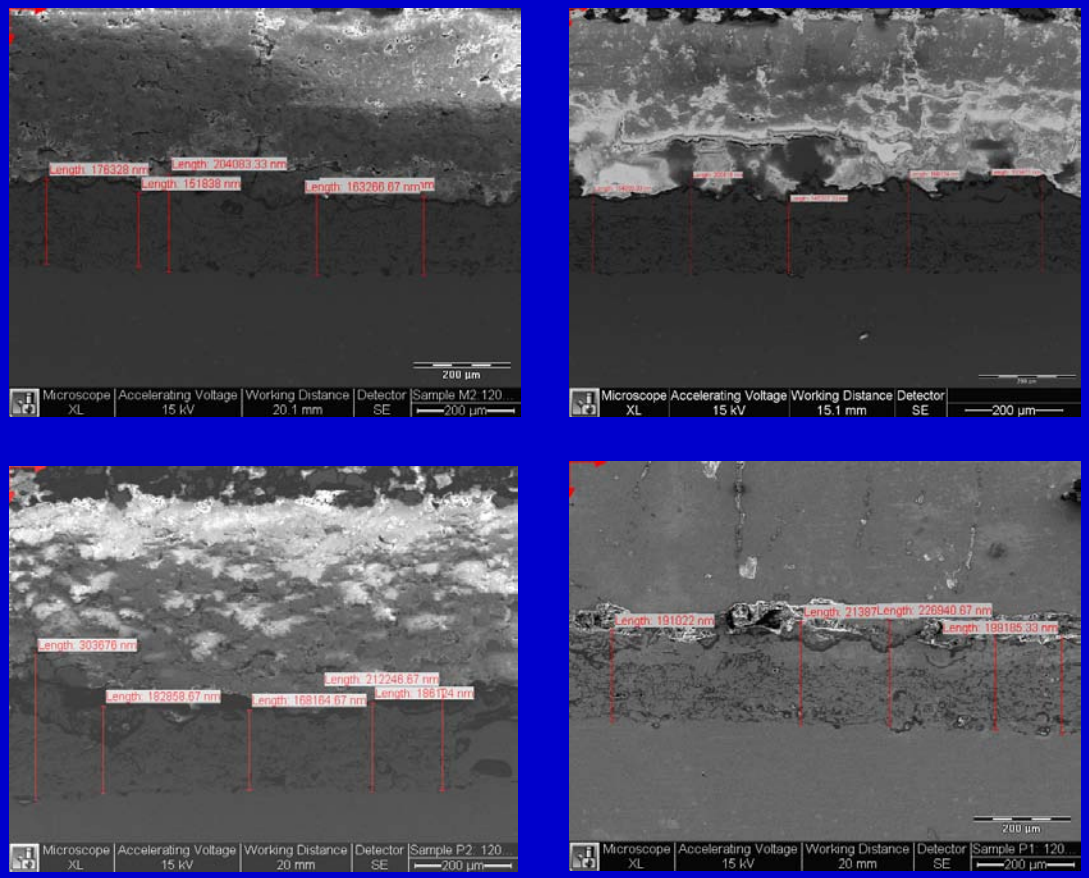




Microstructure of TBC Annealed at 1100 C for: (a) 25 Hours (STD Microstructure); (b) 25 hours (VC Microstructure); (c) 100 Hours (STD Microstructure) and (d) 100 Hours (VC Microstructure)

Dependence of TGO and Bond Coat Thickness of TBC Annealed at 1100 C





Microstructure of TBC Annealed at 1200 C for: (a) 25 Hours (STD Microstructure); (b) 25 hours (VC Microstructure); (c) 100 Hours (STD Microstructure) and (d) 100 Hours (VC Microstructure)

Ongoing Research Activities

-TBC with multi-sectioned microstructure and using alumina based protecting layer

-Thermal Oxidation to study interfacial kinetics of TGO behavior

-Hot Corrosion Testing – In progress

-Physical Properties Measurements of Free Standing YSZ Discs (including thermal properties and porosity measurements and behavior modeling)

-Thermo-Mechanical Characterization of Novel YSZ TBC –with MSI Houston TX and PSU

-Characterization of Effect s of Microstructure & Processing

-Thermo-Mechanical Behavior & Spalling studies and Characterizations

Current Research Summary

- Wet and Dry oxidation studies of TBCs have been carried out
- Thermal properties and porosity is being related to thermal characteristics of standard, VC and EB-PVD microstructures
- Two research papers have been accepted for publication in Proceedings of ASME Turbo Expo 2009
- Two papers are under preparation and have been accepted for presentation and publication in ICCE and ASME Conferences in 2009
- Further studies will continue as per the proposed grant proposal.
- Research has strengthened our capacity building in TBC research and development of our AMRL research laboratory at SUBR
- Three graduate students and one undergraduate student have been working on this project and one Ph.D. student at LSU in collaboration
- A new research associate has joined the project from January 2009
- Research collaboration with LSU, PSU and our industrial partner MSI

Acknowledgements

- This research has been funded by DOE DE-FG 26-08NT000471.
  - We appreciate the financial support of this research work from DOE NETL and in particular the Project Officer Dr. Richard Dunst and Award Administrator Ms. Mary Beth Jackline-Pearse for their support.

- Further collaboration and support of our partners is acknowledged of ARL Pennsylvania State University and Materials Solutions International, TX.

- 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.