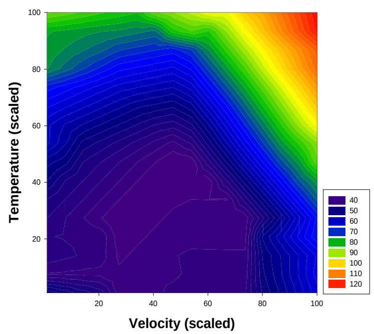
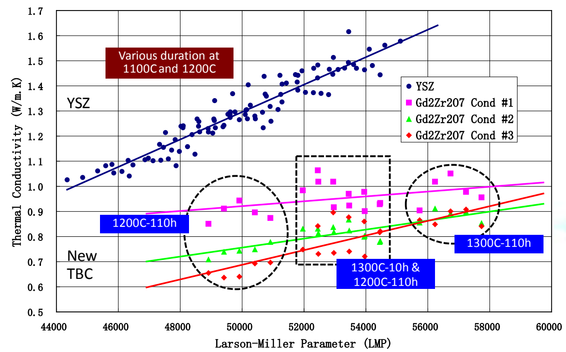
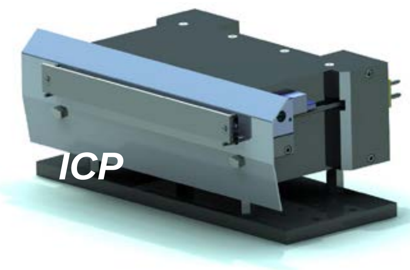
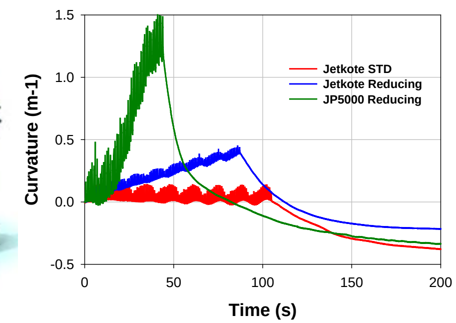
Advanced Thermal Barrier Coatings for Operation in High Hydrogen Content Gas Turbines









Sanjay Sampath, Gopal Dwivedi, Vaishak Vishwanathan

Center for Thermal Spray Research, Stony Brook University

University Turbine Systems Research October 2, 2012

Consortium for Thermal Spray Technology

Consortium is operated by the Center for Thermal Spray Research at Stony Brook University

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DOE NETL UTSR

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Consortium on Thermal Spray Technology

Collaborators: B.Pint, J.A.Haynes ORNL

A.Shyam, E.Lara-Curzio, ORNL

A.Kulkarni, Siemens

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Thermal Barrier Coatings in Hydrogen-Fired IGCC Turbines

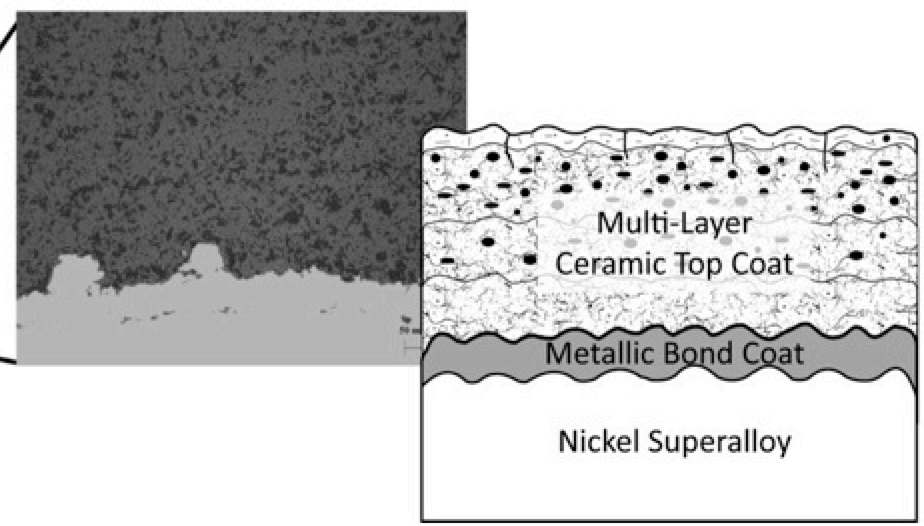
CHALLENGE: *Improved realiability and lifetime of coatings in IGCC gas turbines*

- *Increased mass flow of syngas fuel*
- *Increased heat transfer from water vapor*
- *Impact of water vapor on oxidation*
- *Contaminants*

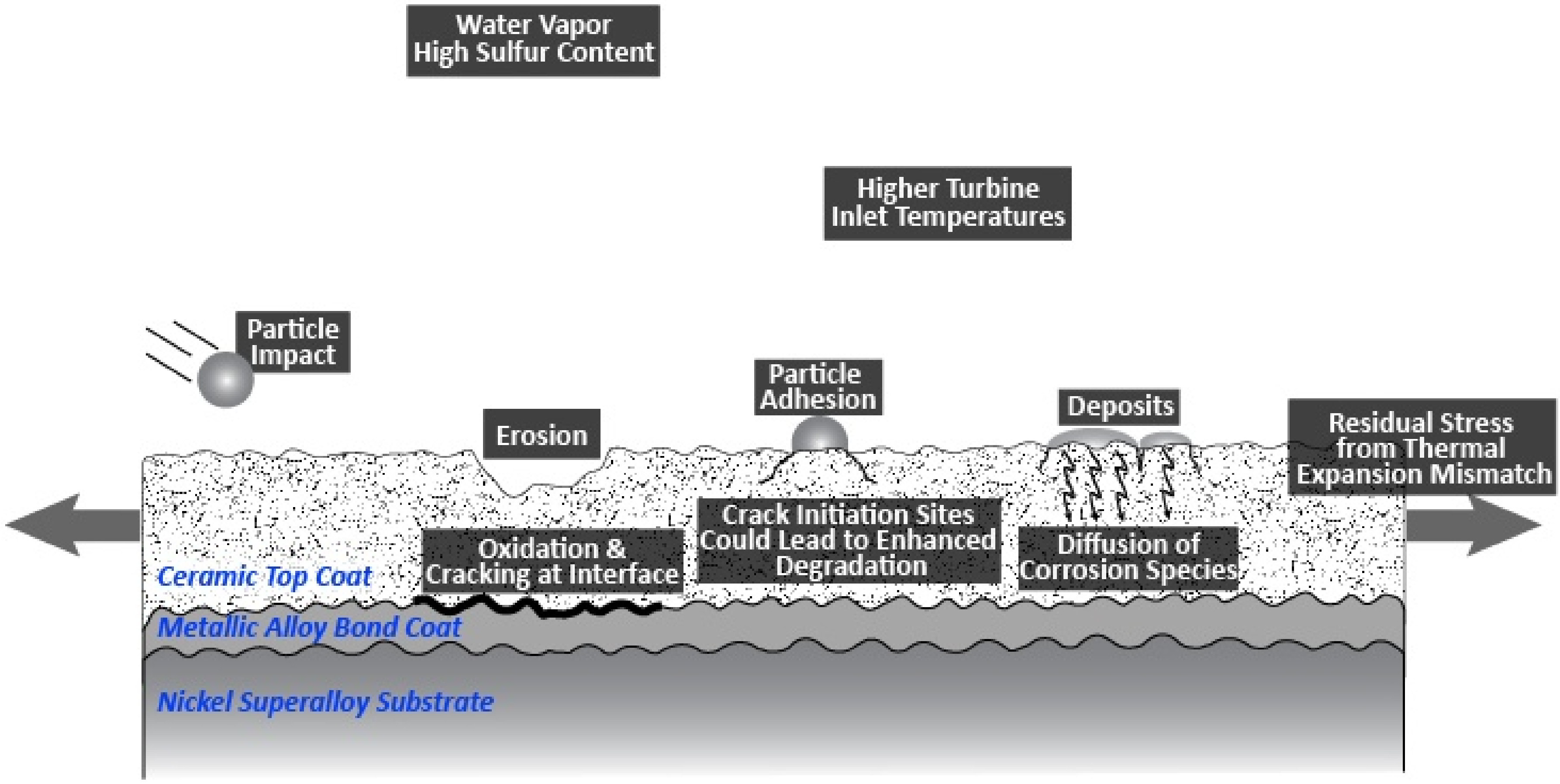
APPROACH: *Tailored and optimized plasma-sprayed thermal/environmental barrier coating*

- *Material requirements and selection*
- *Processing impacts on microstructure and properties*
- *Iterative coating design and testing*
- *Industry feedback and knowledge transfer*

Courtesy of GE



TBC degradation in IGCC is more complex than in natural gas turbines

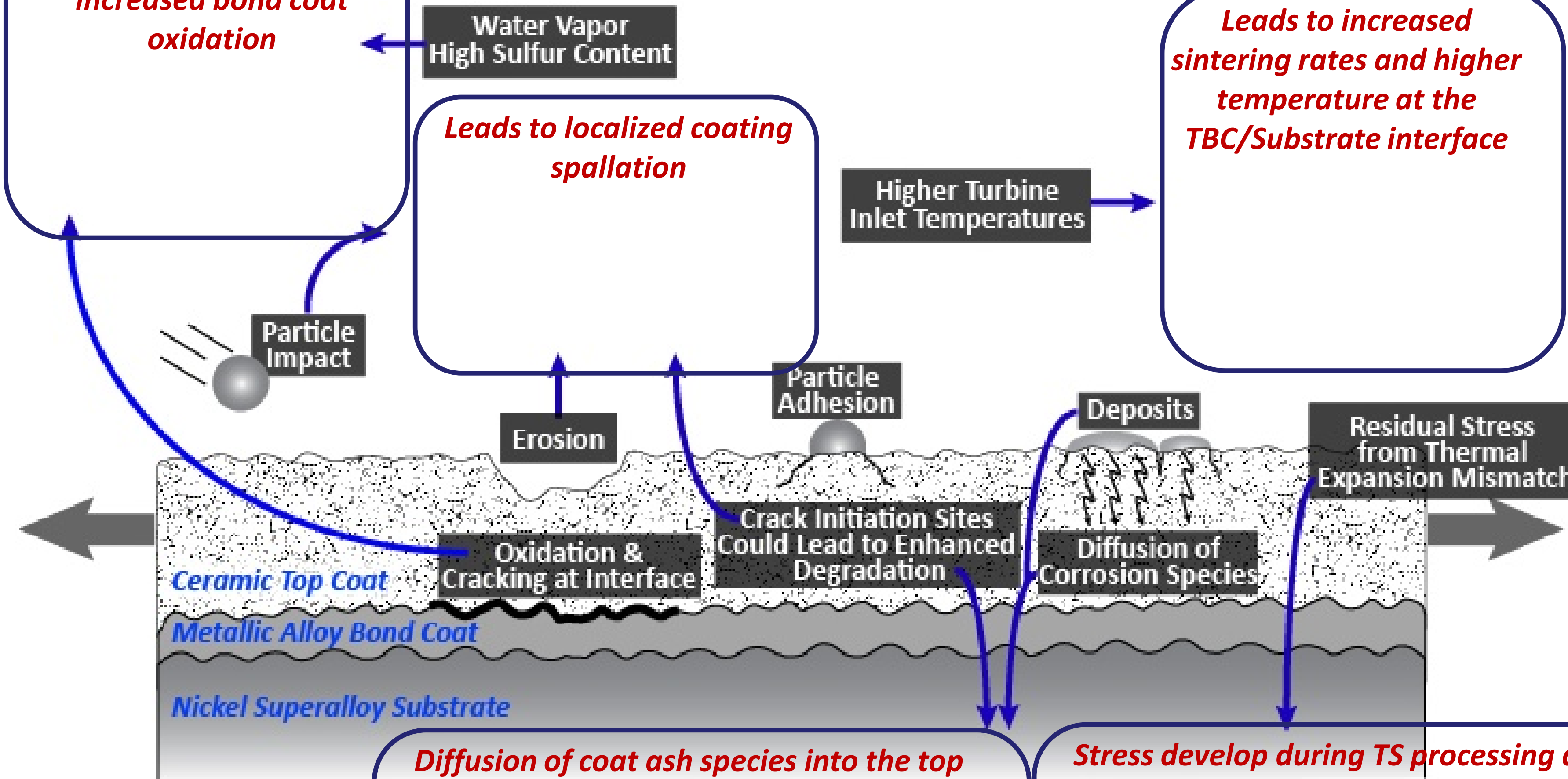


TBC degradation in IGCC is more complex than in natural gas turbines

Can lead to degradation of top coat and also leads to increased bond coat oxidation

Leads to localized coating spallation

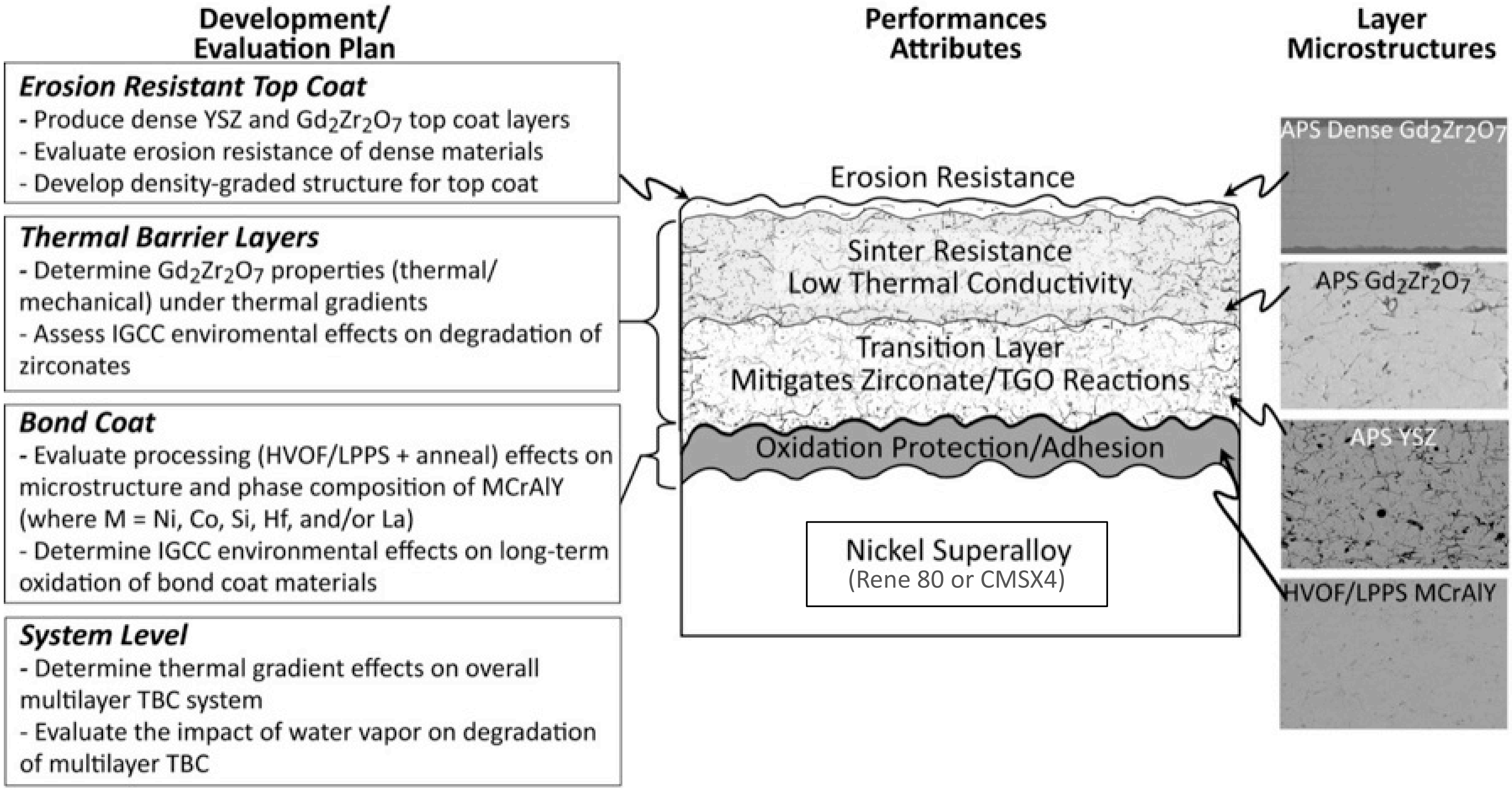
Leads to increased sintering rates and higher temperature at the TBC/Substrate interface



Diffusion of coat ash species into the top coat can lead to local spallation and can increase bond coat oxidation

Stress develop during TS processing and also result from thermal expansion mismatch between the TBC and substrate

Multilayered architecture to combat multifunctional requirements



Plasma spray is naturally suited for such layered manufacturing

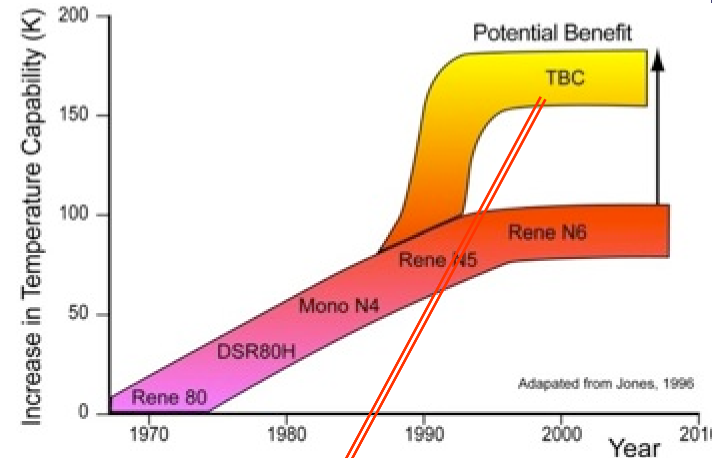
Status of today's TBCs

Plasma spraying is the principle approach for TBC manufacturing

- YSZ by atmospheric plasma spray and variants
- CoNiCrAlY bond coat via LPPS or HVOF

Salient facts:

- 2 M pounds of YSZ was plasma sprayed in 2010
- Multitude to spray cells within OEM and throughout the supply chain all over the world



The TBC system of today was started almost 40 years ago

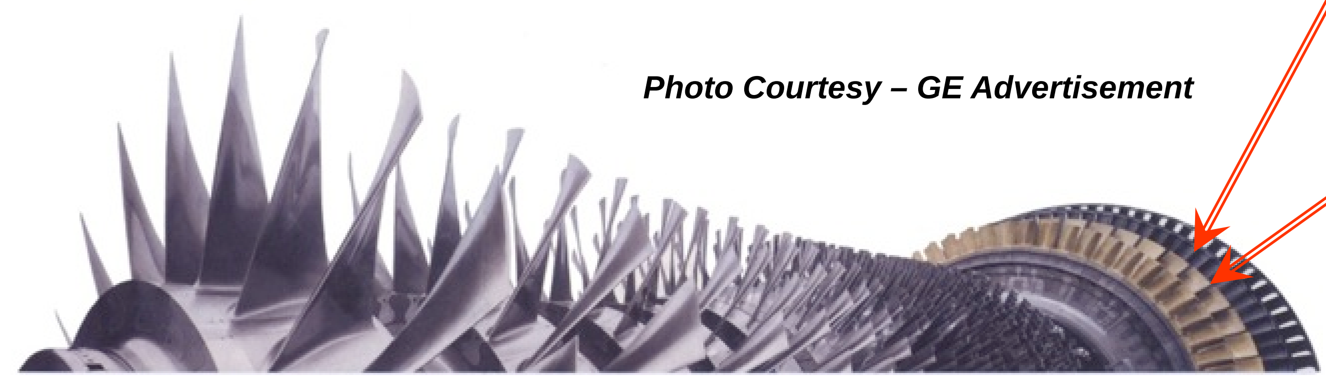
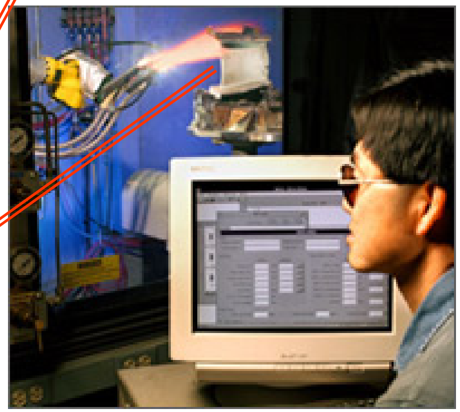
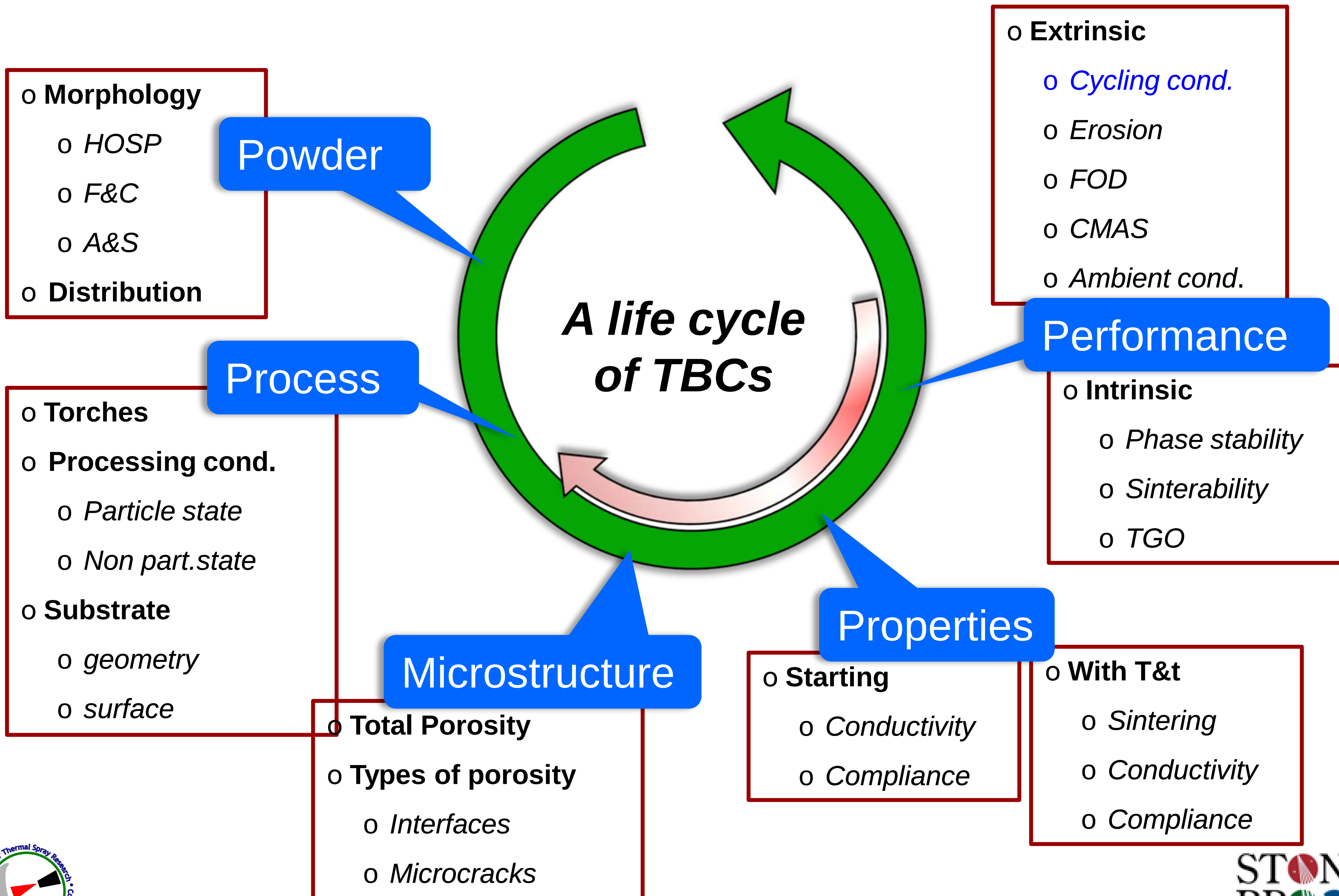


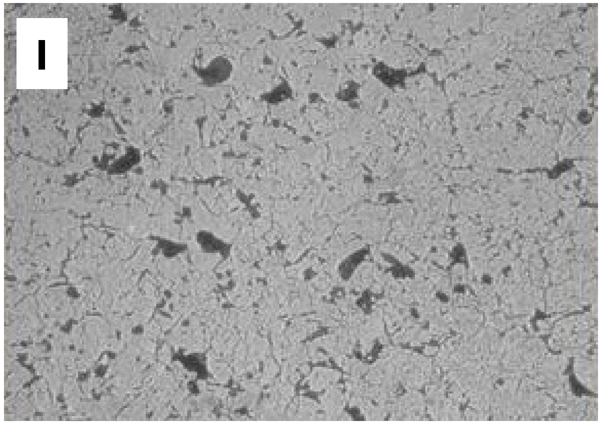
Photo Courtesy – GE Advertisement



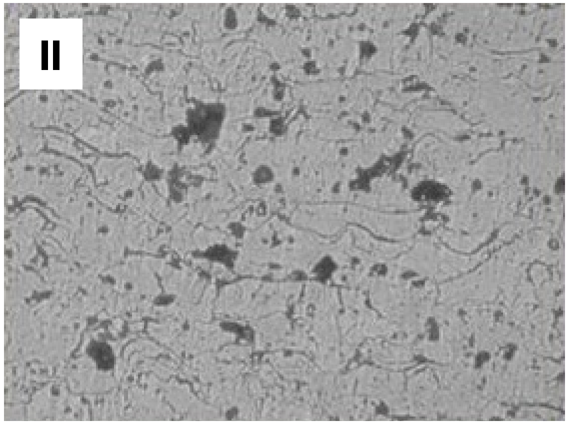
Life cycle of a TBC



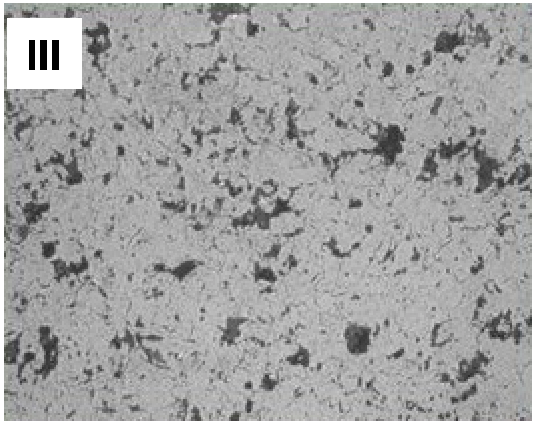
What is the difference in these TBC coatings?



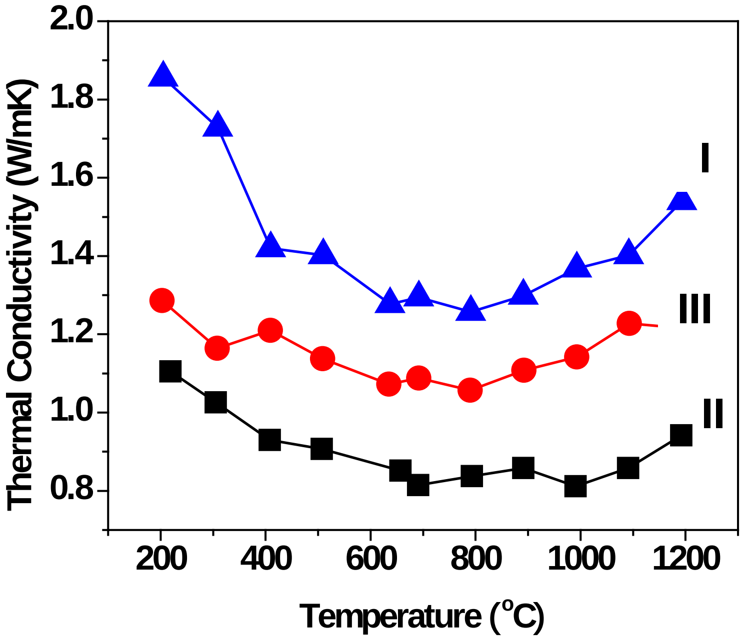
15% Porosity



16% Porosity



20 % Porosity



Understanding, optimizing and controlling microstructure is critical for design, performance and reliability.

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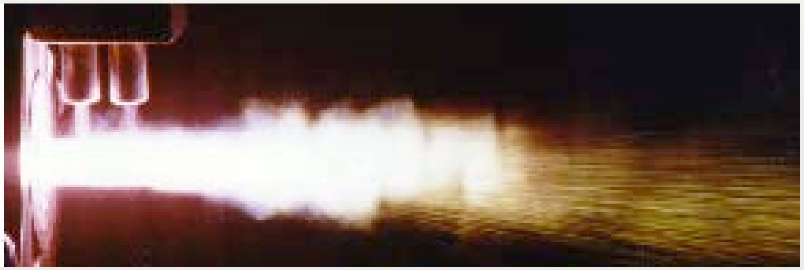
Thermal spray is a complex process

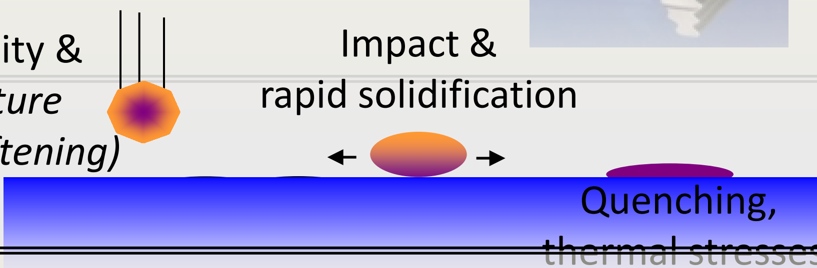
Melting, quenching and consolidation in single process



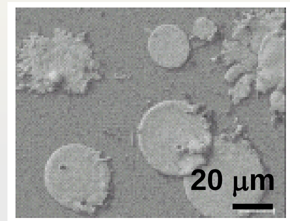
Splat based build-up and state induced properties

High velocity &
temperature
(melting/softening)

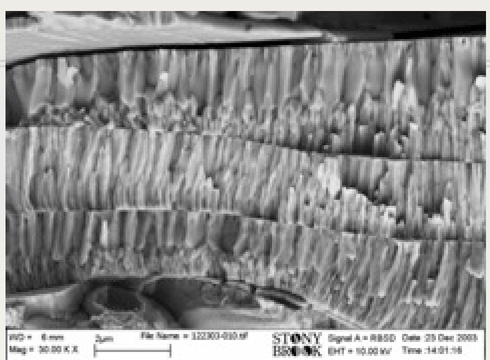
Impact &
rapid solidification

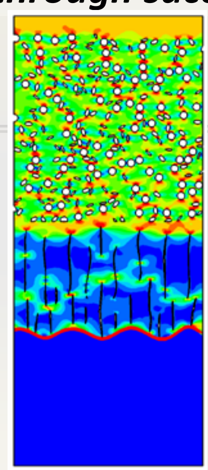


Quenching,
thermal stresses

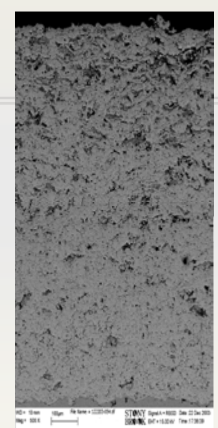


Layered and graded architectures through successive splat quenching



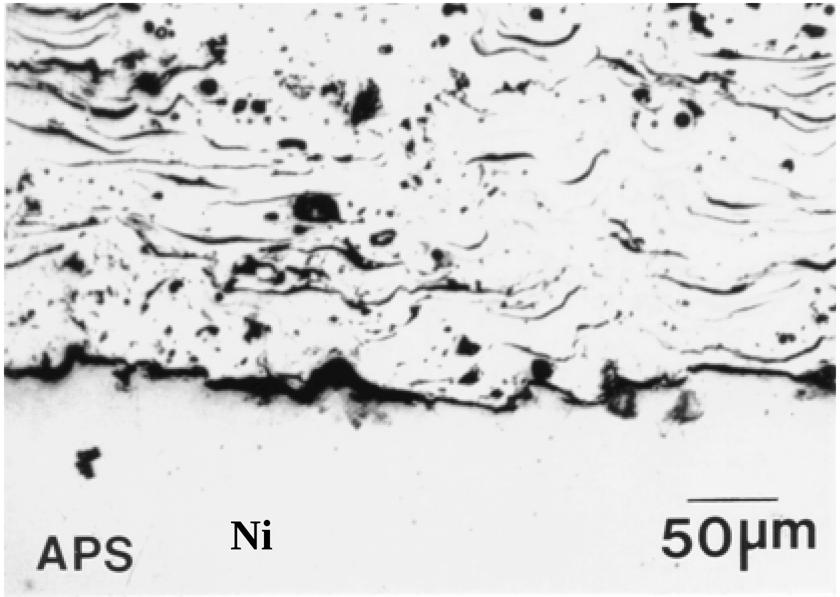


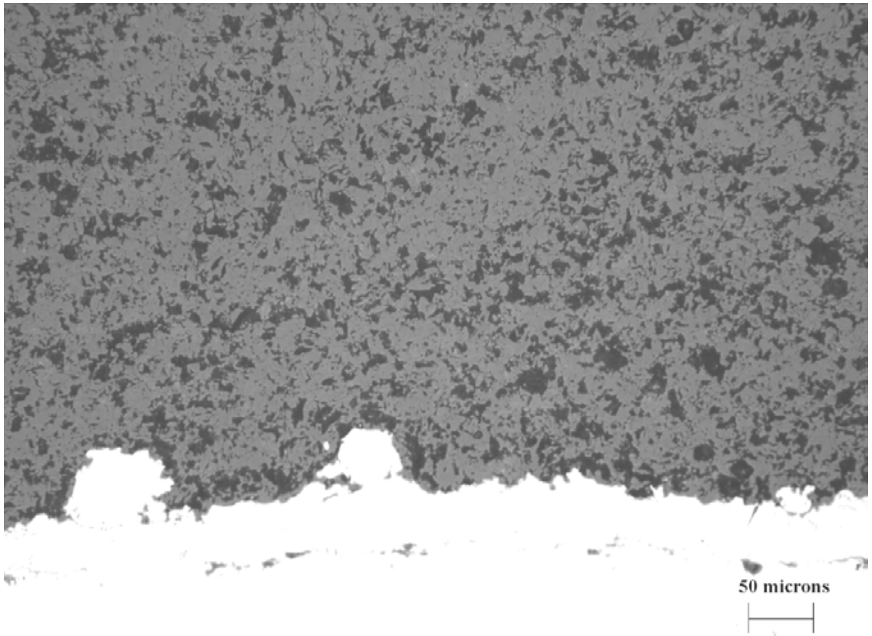
Layered
Thick
Films



Graded
Porosity
In ceramics

Sprayed coatings are complex, layered, high defect density materials





How to design based on the defect architecture ?

How to precisely manufacture coatings with defects ?

What are the relevant and true properties for design ?

How to measure them and How to assess reproducibility ?

What processing protocols do we follow for control ?

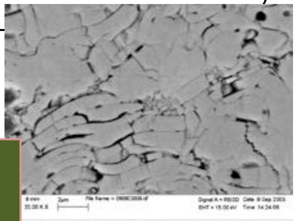
APS TBC fabrication involves numerous variables

- Composition
- Morphology
- Size Distribution

- Plume Orientation
- Plume Spread
- Particle State

- Feed rate
- Raster / Rotation Rate
- Angle of Deposition

- Defect (Cracks & Pores)
- Crystal (Phase & Composition)
- Layering (Splat Characteristics)
- Grain (Size)
- Anisotropy



Feedstock Characteristic

Component Performance

Process Variables

Implications

Extreme variability – local and global

Infant mortality and poor reliability

Difficult to incorporate into life models

- Equipment related (Gun, Gases, Power)
- Particle Injection

- Chemistry
- Adsorbates
- Temperature
- Roughness

Residual Stress,
Stiffness, Elastic Modulus
- Functional
  Electrical / Thermal transport,
  Wear / Erosion / Corrosion Resistance

Multitude of applicators locations

Multitude of spray devices & parameters

Multitude of evaluation Criteria and variants

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Intrinsic

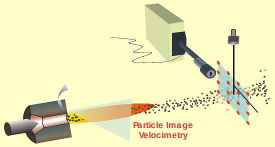
- Engine design variants, operating environment
- Material system and components
- Part geometry
- Location specific performance attributes

Extrinsic

- Feedstock materials (chemistry/morphology/size /homogeneity)
- Coating processing location and equipment attributes (control !)
- Spray Process parameters
- Deposition parameters (robotic manipulation, dep.temp., flux etc.)
- Part handling and management (prep, heating, cleaning)

➡ **Evaluation criteria, specification, semantics !**

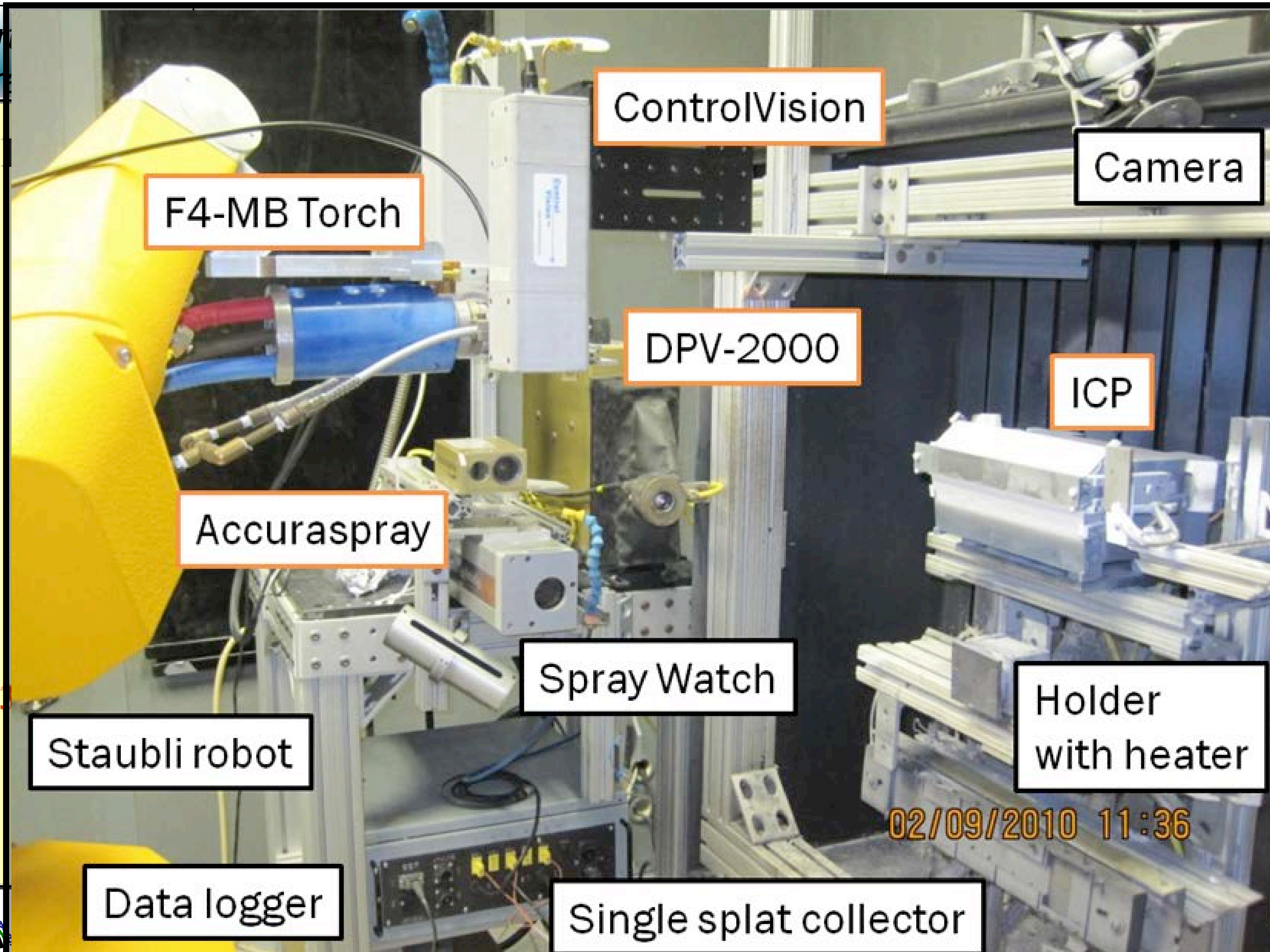
How can modern TS science enhance TBC requirements?



Advances in Process Monitoring and Control

Par
par

N
p



5
10
15
20
25
30
35
40

m)

20 22 24 26 28 30

Elastic Modulus, E (GPa)

Interfaces

ND

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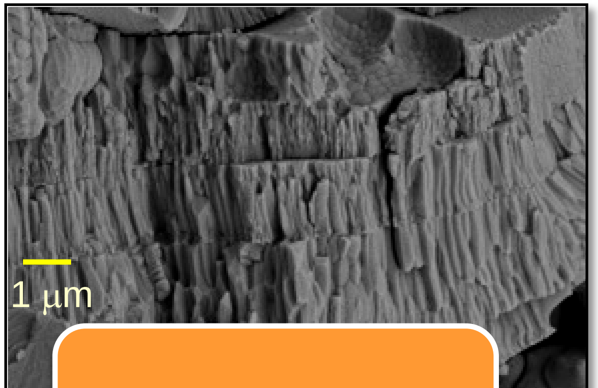
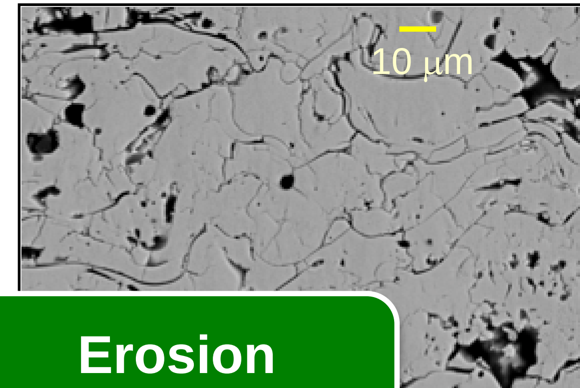
Relevant properties for plasma sprayed thermal barrier coatings





Plasma Sprayed TBCs

Thermal

- Sintering rate
- Thermal conductivity

Mechanical

- Mechanical compliance
- Erosion resistance
- Fracture toughness
- Damping

⇨ All these properties are governed by coating architecture, commonly called as “porosity”

⇨ can be tailored by processing…

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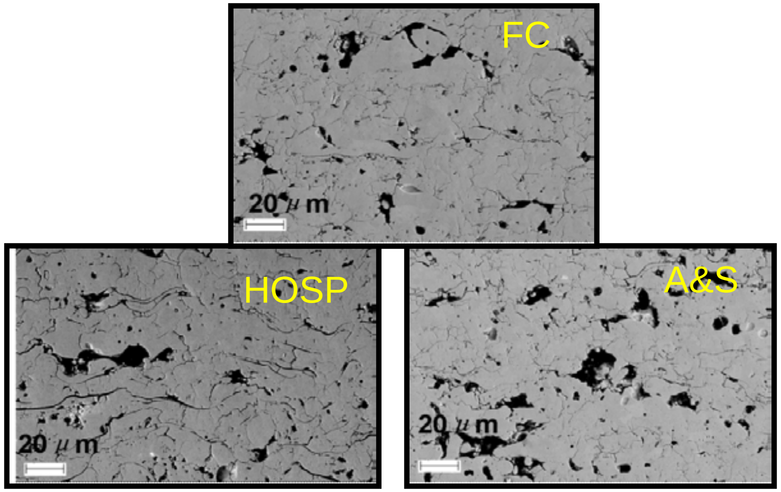
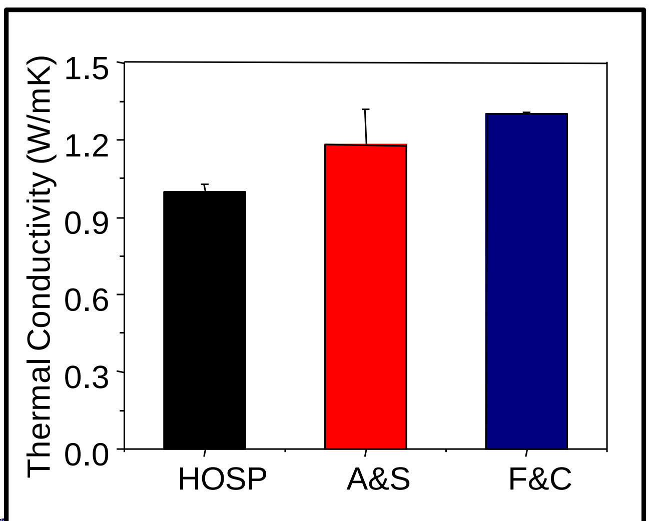
Thermal conductivity





Weiguang Chi, PhD Thesis, Stony Brook University, 2007

Simulation results

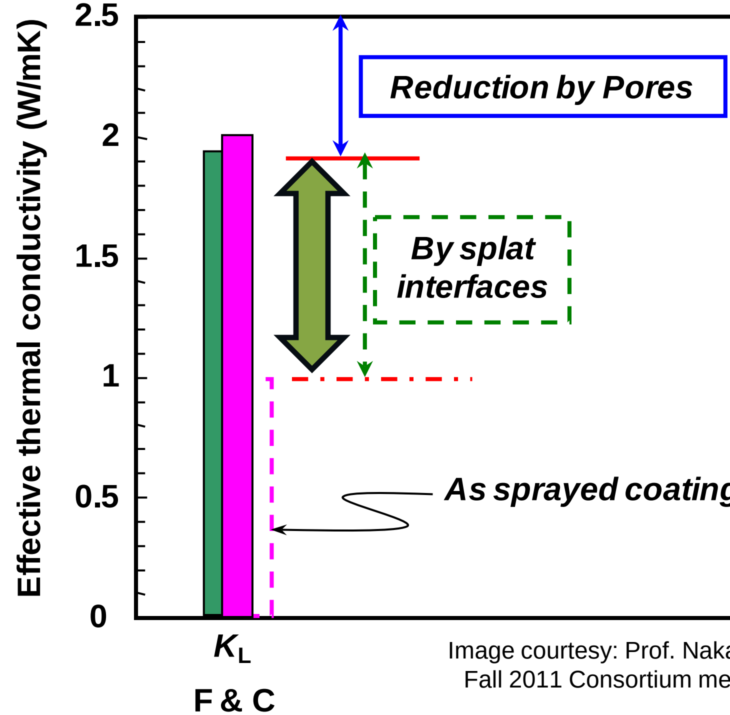
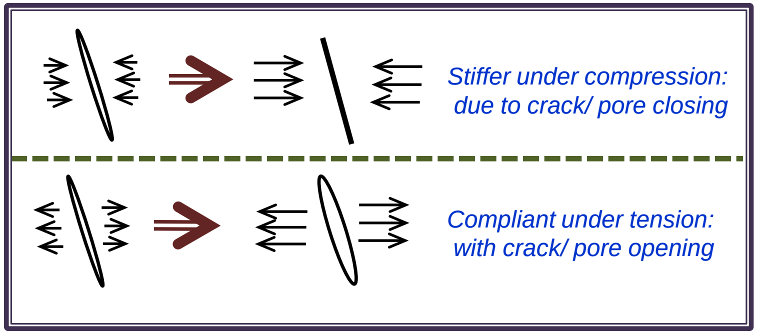
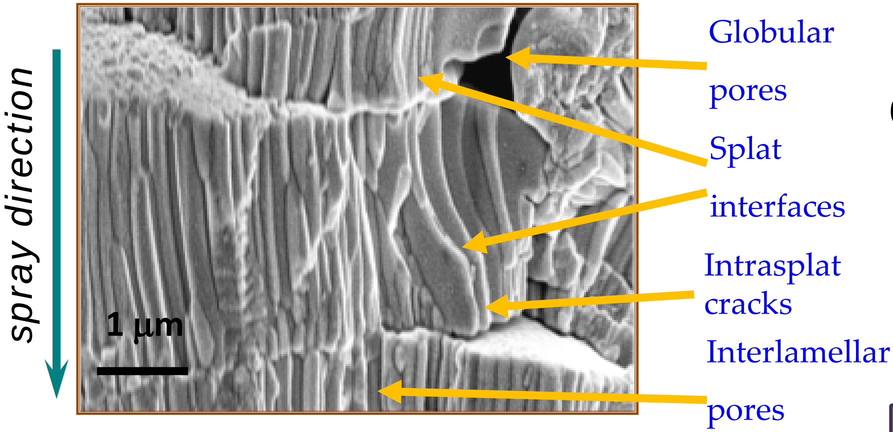


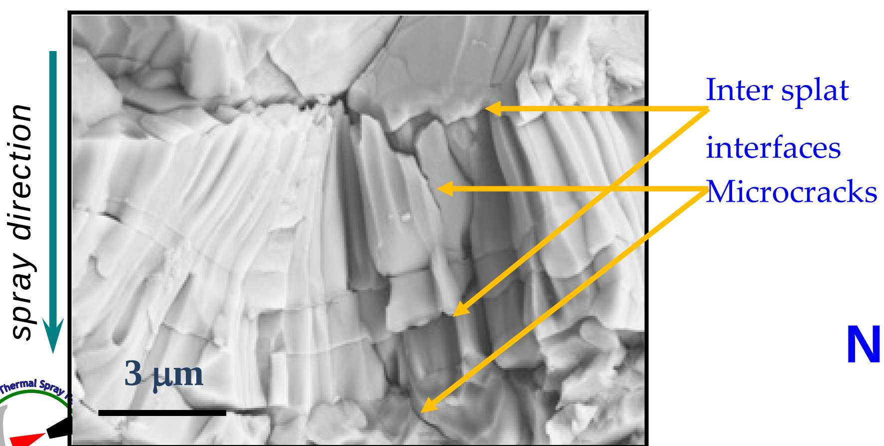
Image courtesy: Prof. Nakamura, Fall 2011 Consortium meeting

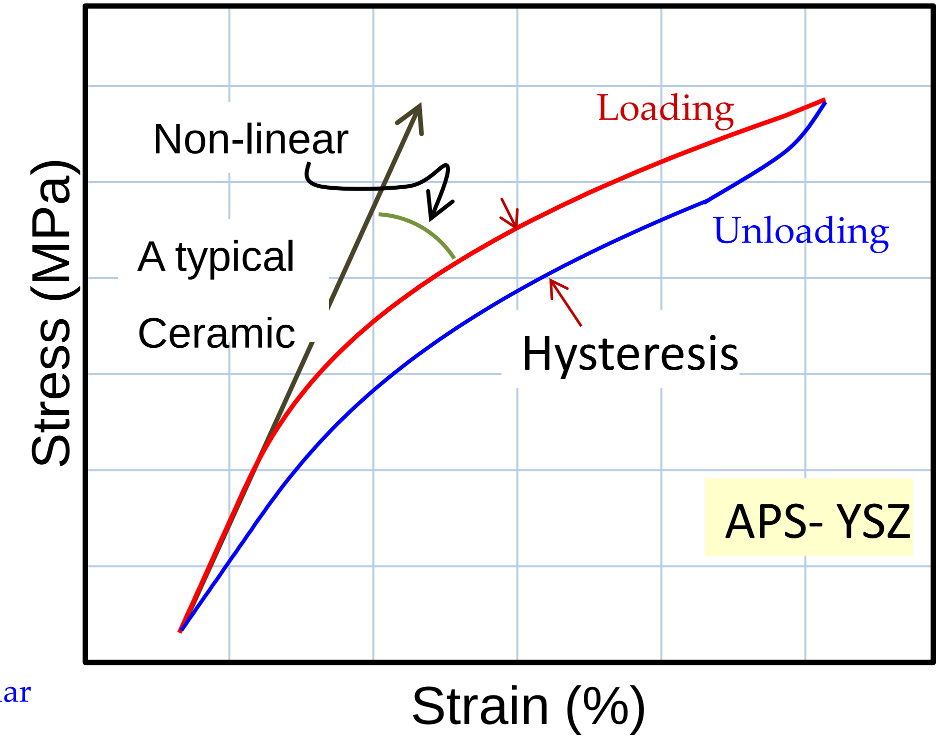
Reduction in thermal conductivity is more prominent by splat interfaces

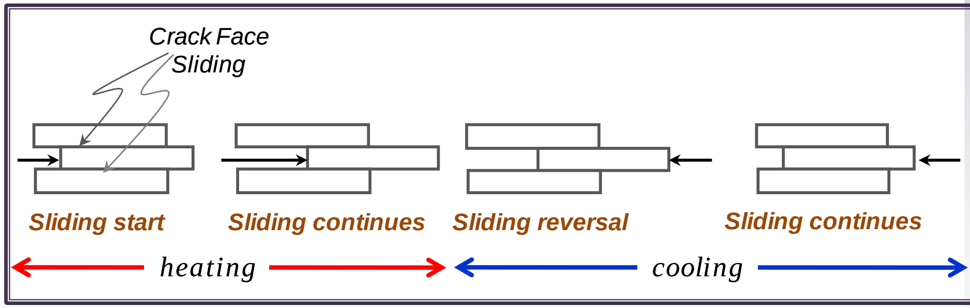
Recent work has demonstrated non-linear elastic effects









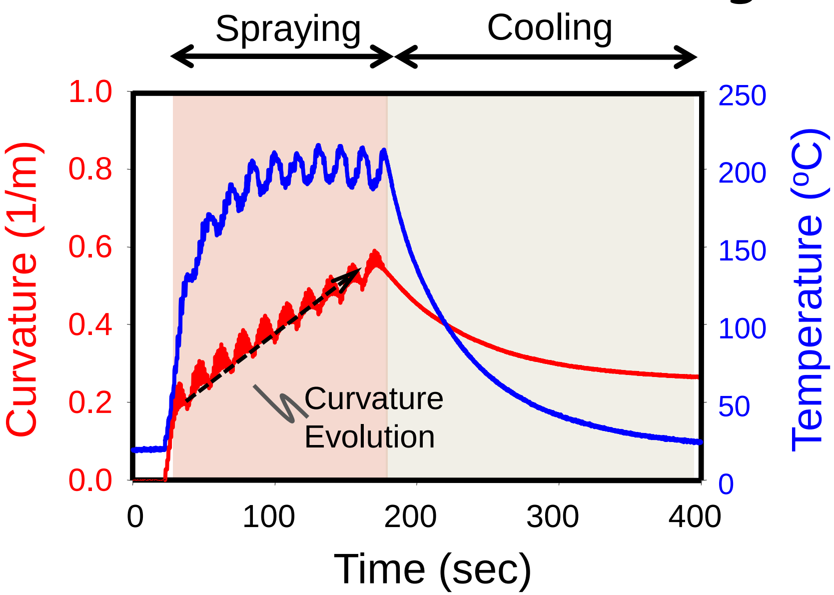


Nonlinearity + Hysteresis:

Anelastic

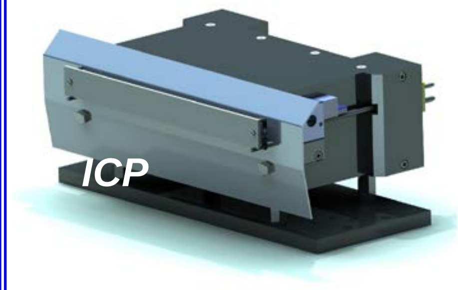
Quantifying compliance for different processing/microstructure

In-situ: Curvature Monitoring

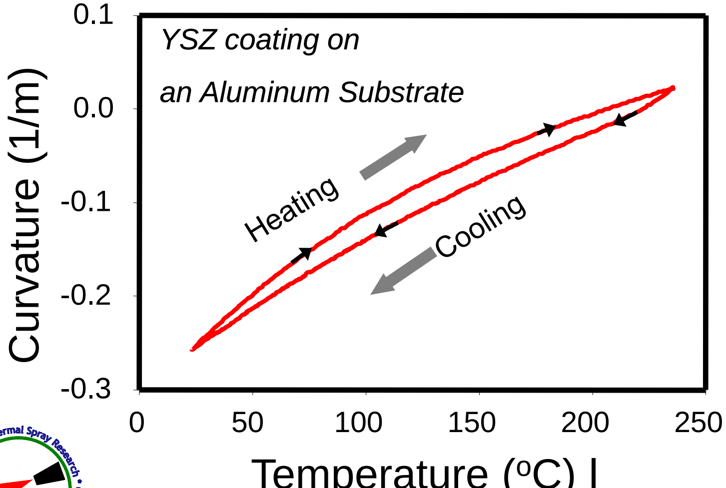


Measurement tells the evolution history of a deposited coating.

Each local peak corresponds to a pass (deposition of one layer). The slope of the curvature evolution is referred as "Evolving stress"



Ex-situ: Thermal Cycle of the Coated Specimen

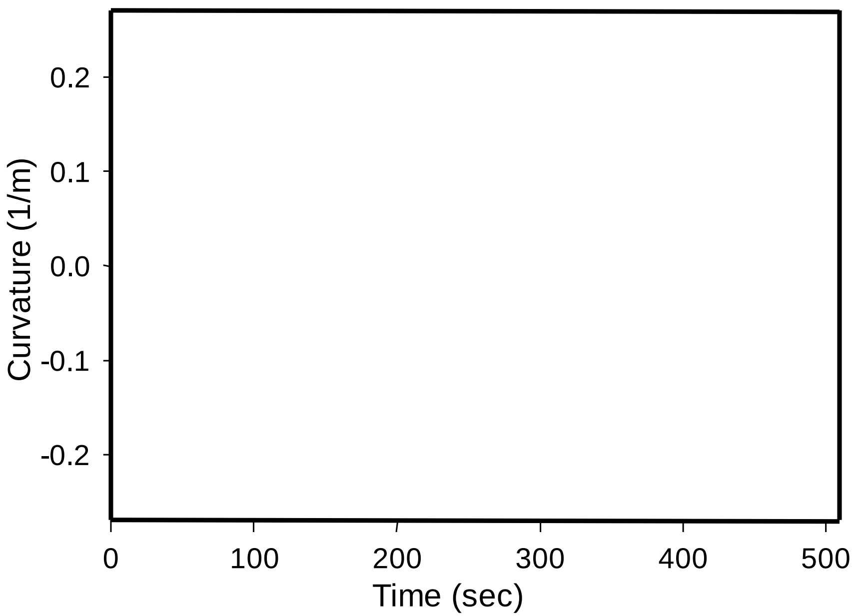


After spraying, the coating (with substrate) is heated inside a furnace. The temperature change induces mismatch strain, and the curvature of coating changes. The continuous recording of one thermal cycle provides an ANELASTIC curv-temp plot, which is then converted to a stress strain curve to quantify the coating compliance.

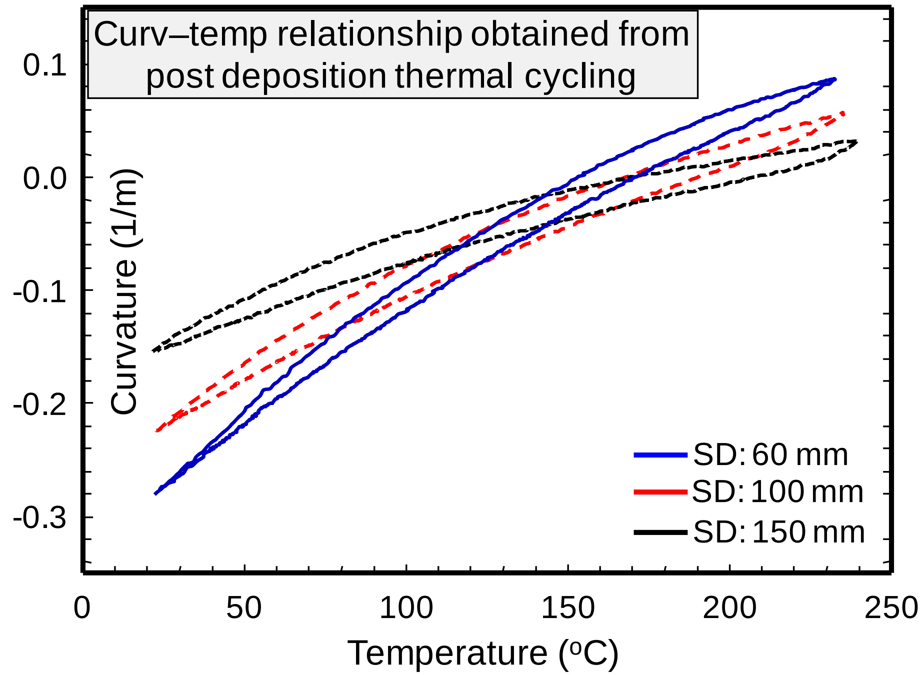
Microstructural Effects on Mechanical Behavior

Case study: three coatings deposited at three different spray distances

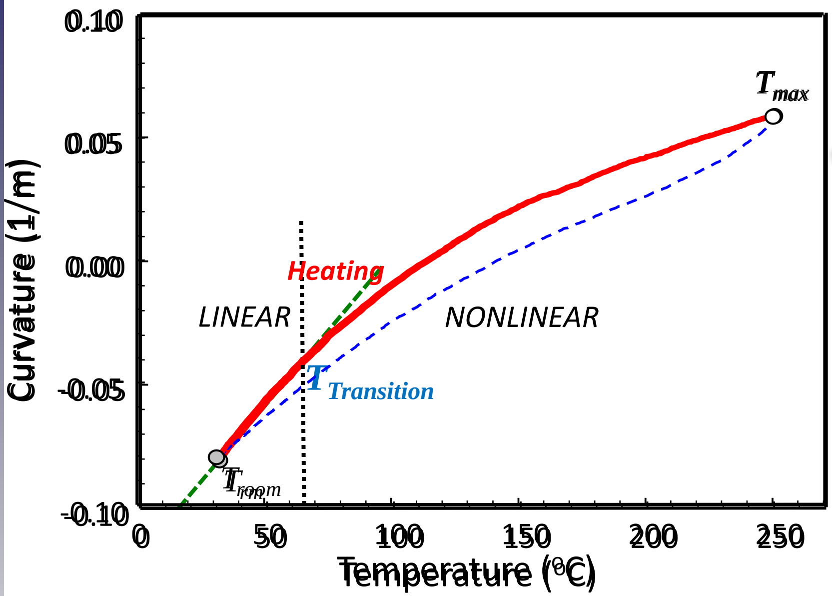
In-situ



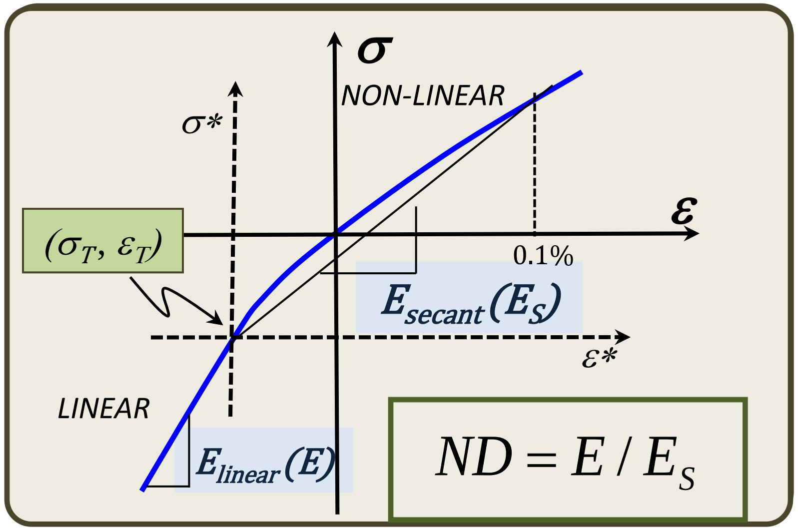
Ex-situ



Identification of compliance parameters



$$\varepsilon = \begin{cases} \dfrac{\sigma}{E} - \dfrac{|\sigma_T|^n}{E\sigma_N^{n-1}} & \text{for} \quad \sigma < \sigma_T \\ \dfrac{\sigma}{E} + \dfrac{(\sigma - \sigma_T)^n - |\sigma_T|^n}{E\sigma_N^{n-1}} & \text{for} \quad \sigma \geq \sigma_T \end{cases}$$



Two non-linear parameters

E

Elastic Modulus

ND

Degree of Non-linearity

The two parameters are unique to a coating.

Early results indicate correlations to FCT life

Non-linear parameters and FCT life

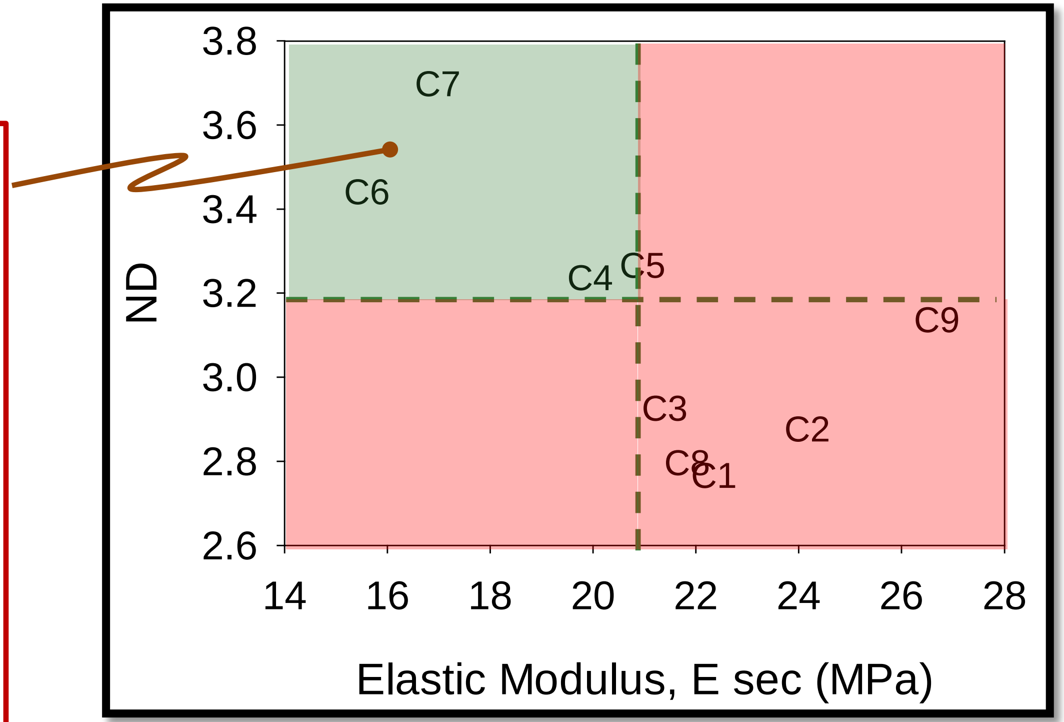
Maximum

Compliance

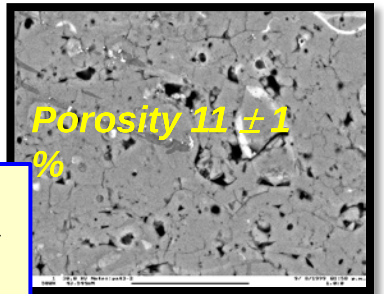
& also

Highest

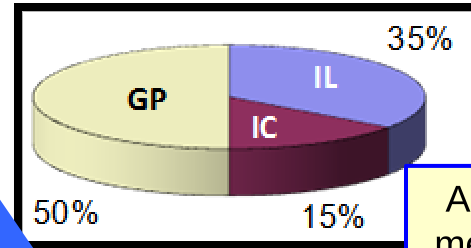
FCT life



It has been a moving target to define properties…

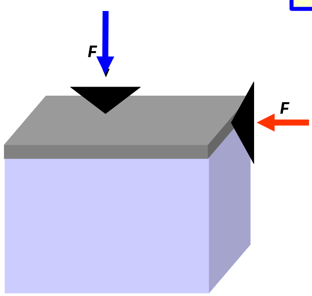


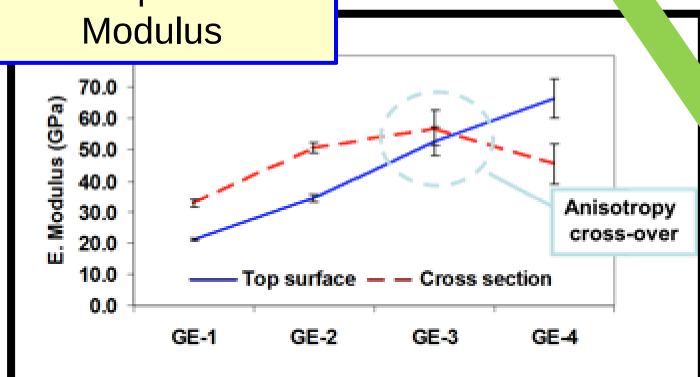
Porosity measurement by image analysis

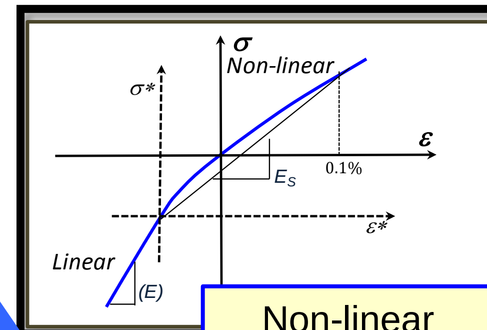


Advances porosity measurement using SANS

Anisotropic Elastic Modulus





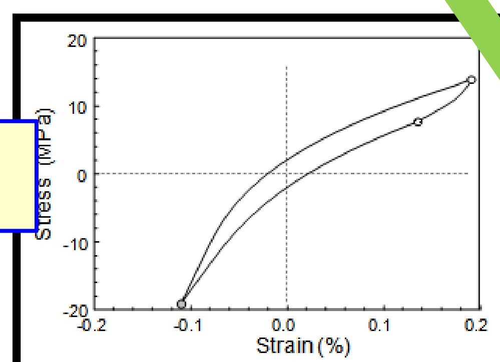


Non-linear elastic

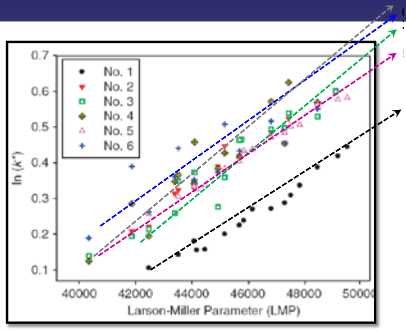
E, ND

Anelastic

E, ND and HD

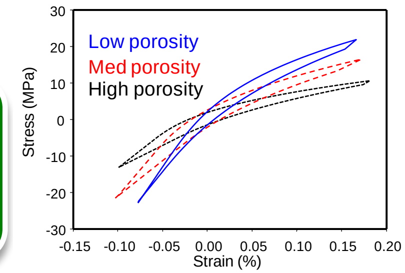


Integration of processing science with properties and performance

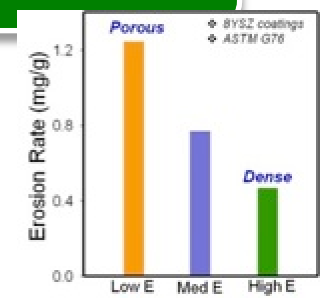


Sintering rate

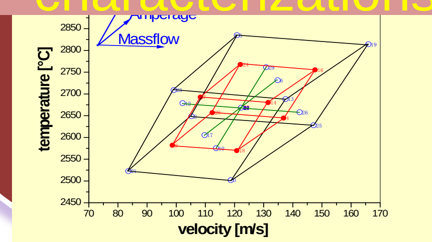
Mechanical compliance



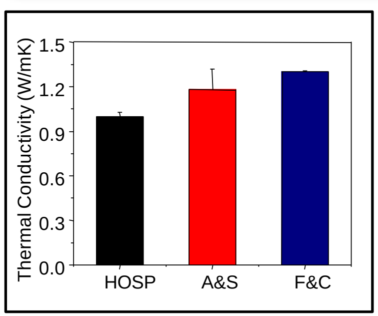
Erosion resistance



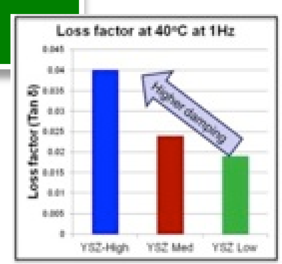
Process maps and advanced coating characterizations



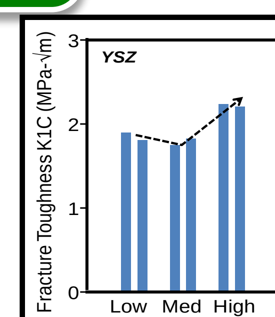
Thermal conductivity



Damping



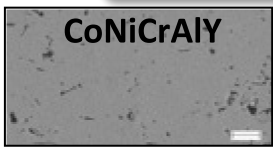
Fracture toughness



Overall UTSR Program Approach

Advanced Thermal Spray TBCs for IGCC Turbine Systems

Bond Coat

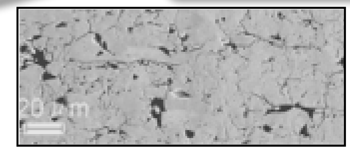


- Materials: MCrAlY
  M = Ni, Co, Si, Hf, La
- Processing Effects on Microstructure (HVOF/LPPS/Anneal)
- Isothermal Exposures in water vapor
- Property Evaluation: Oxidation behavior in high temperature water vapor

System Level

- Rig Testing: Thermal gradient exposure with water vapor
- Isothermal Exposures with ash deposits
- Property Evaluation: Bond coat oxidation, through-thickness residual stress and composition, erosion

Top Coat



- Materials:
  YSZ, $Gd_2Zr_2O_7$, Co-doped
- Processing Effects on Microstructure (APS)
- Isothermal Exposures in water vapor
- Property Evaluation: Thermal conductivity, sintering, compliance, erosion, thermal expansion

UTSR Project Objectives

- Evaluate oxidation characteristics of different types of bond coat materials in water vapor containing atmospheres in order to select the most viable material and processing condition.
- Develop processing strategies and maps for plasma spraying of emerging zirconate materials.
- Optimize engineered coating architectures for the ceramic top coat of the TBC system to simultaneously provide erosion resistance, thermal and environmental protection, low thermal conductivity, sintering resistance and compliance.
- Determine the degradation mechanisms in multilayer TBCs after controlled-atmosphere furnace tests & erosion tests.

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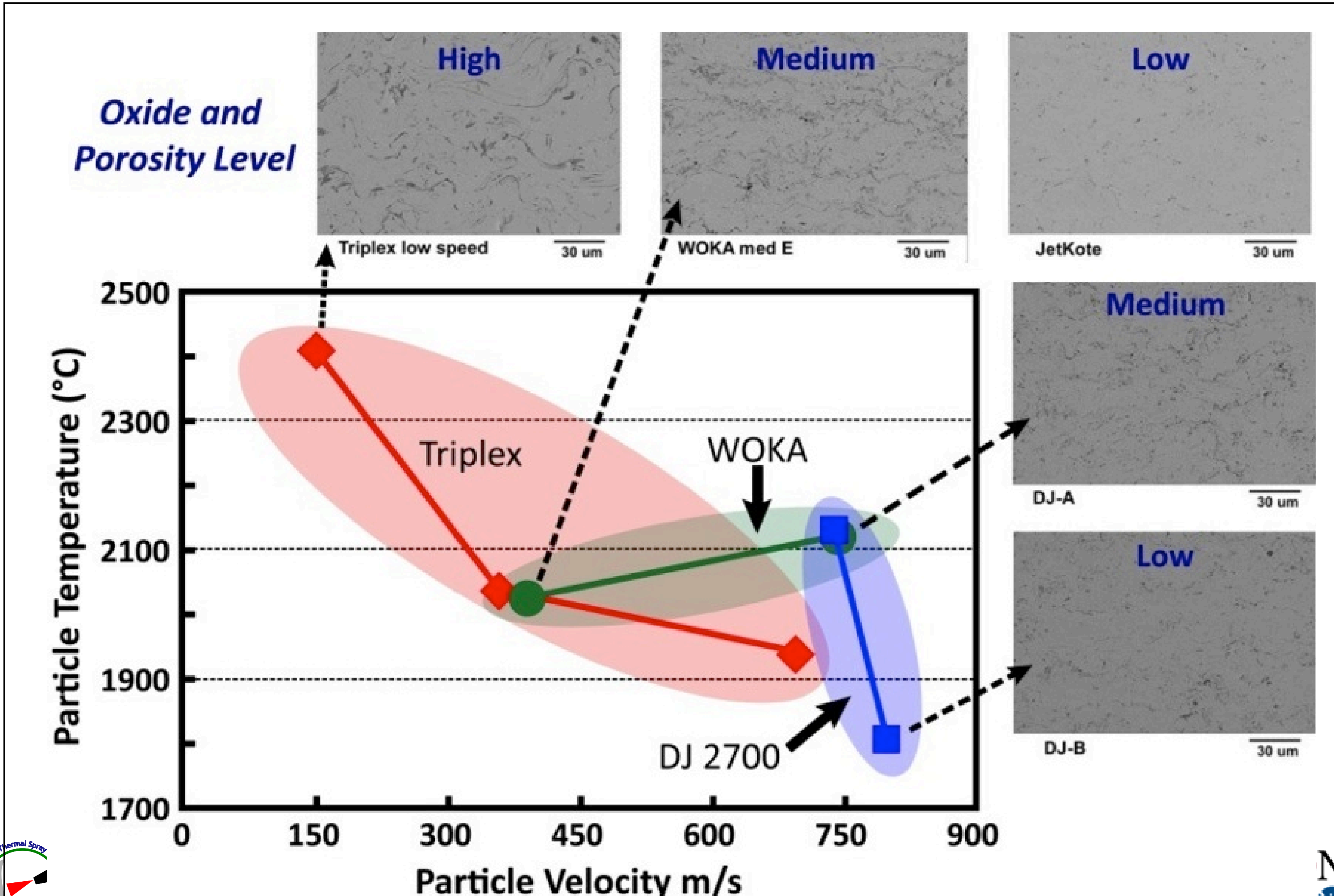
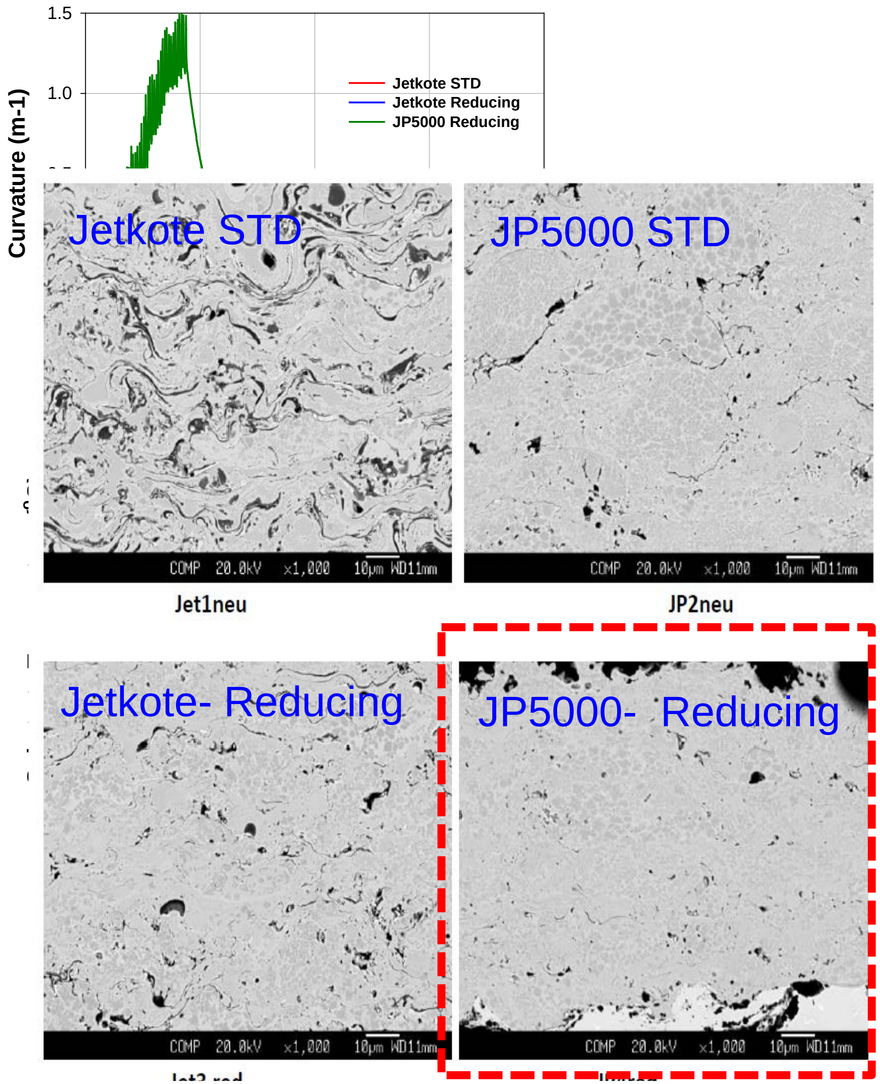
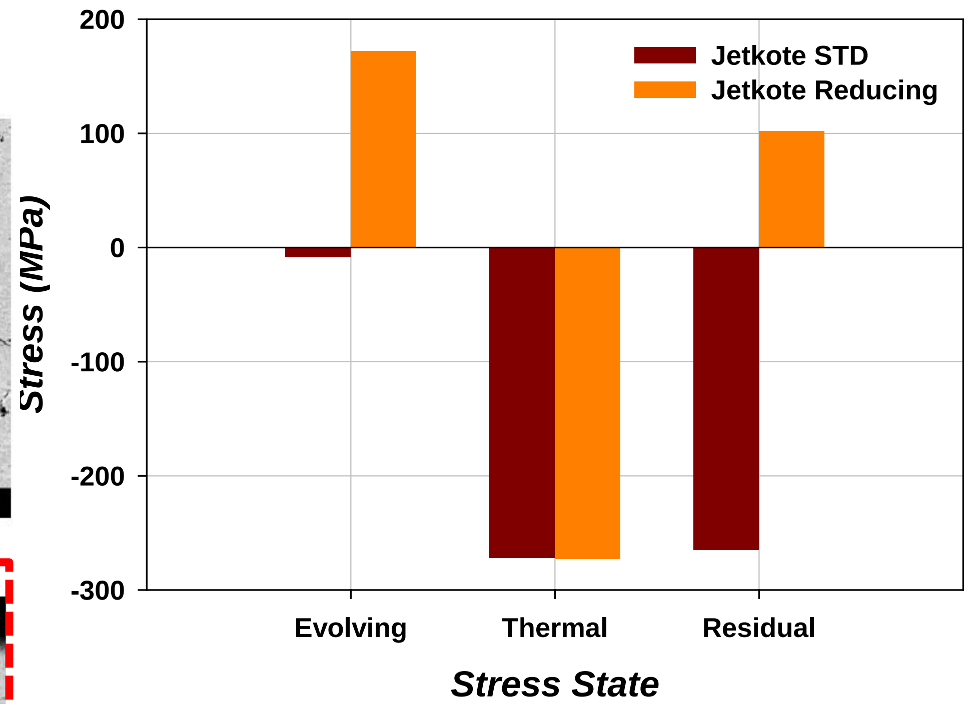
Not all bond coats are the same ! Processing plays a role



Processing Effects on HVOF Bond Coats





HVOF process type and spray conditions significantly affect deposition stresses and final stress state of the coaitng.

JP5000 chosen due to microstructure and compressive stress state.

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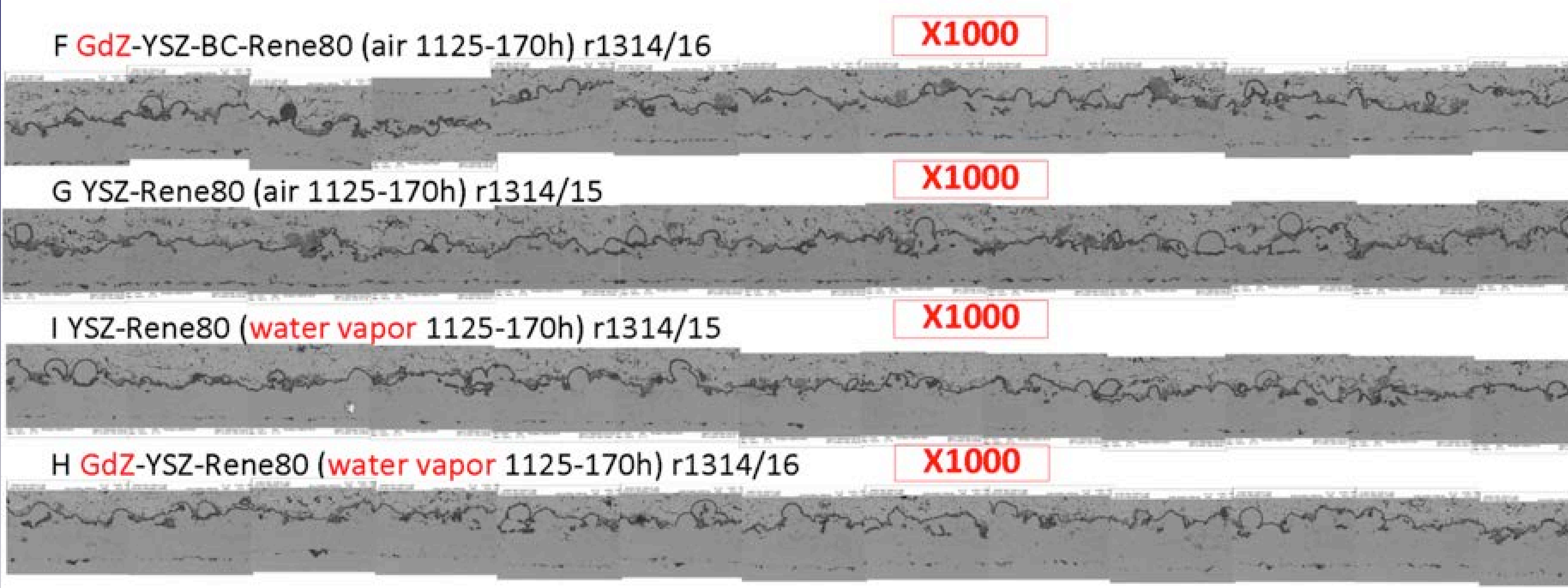
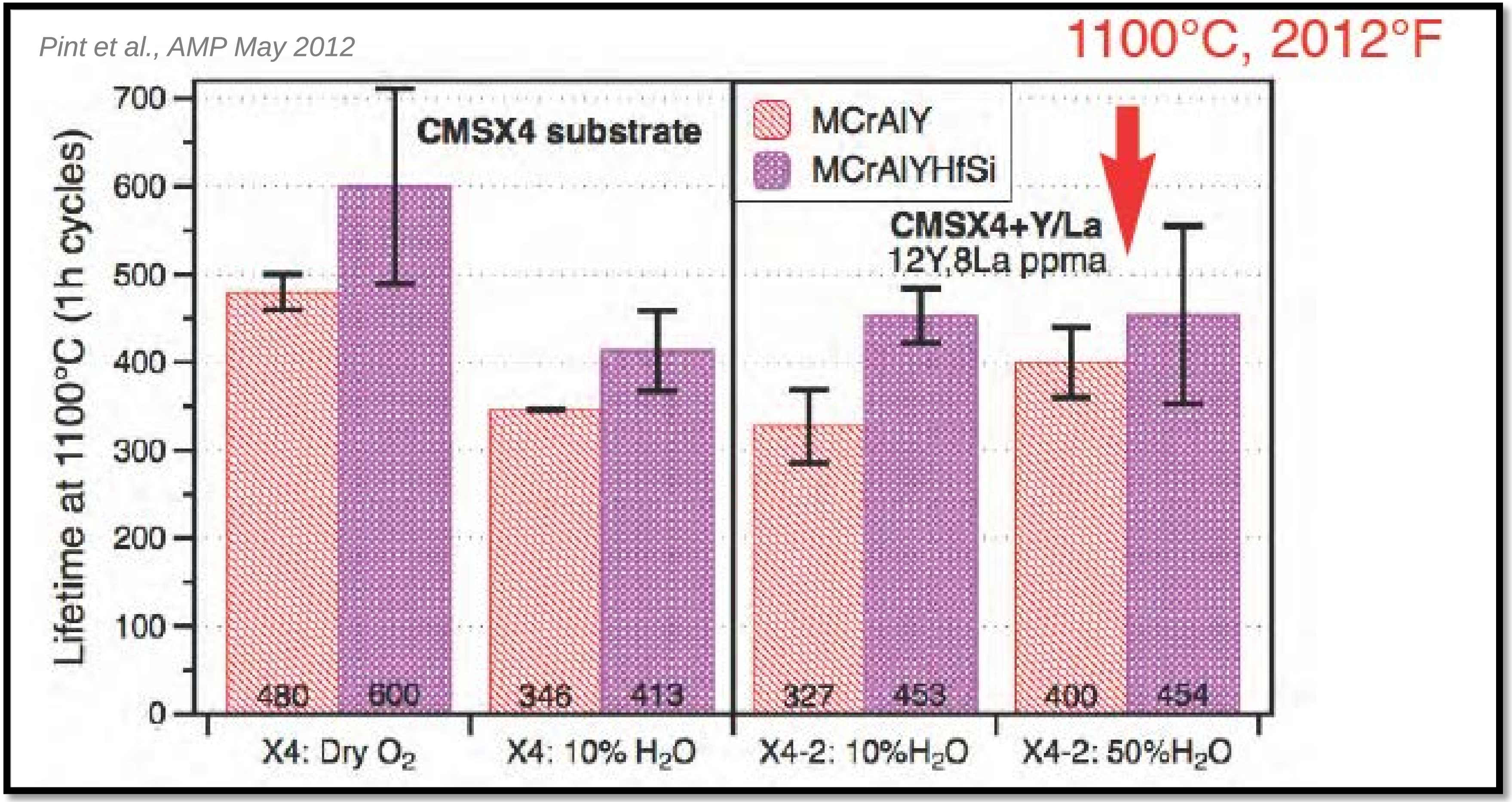


No significant difference found at this temperature

Ongoing collaborative partnership

- HVOF bond coats have been sprayed **(NiCoCrAlY & NiCoCrAlYHfSi)** for ORNL testing
- ORNL is investigating the interactions with several different substrate materials

Down selection of bond coat material



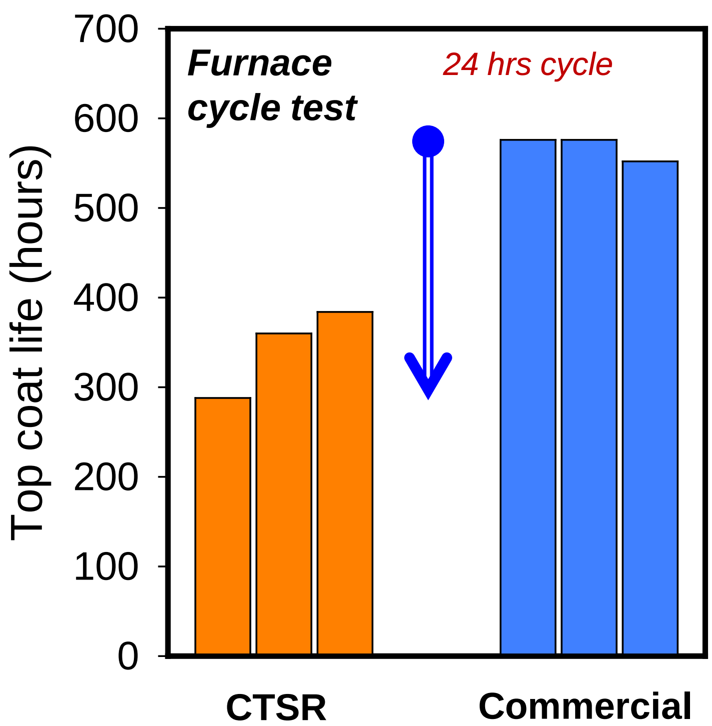
XPT: NiCoCrAlY

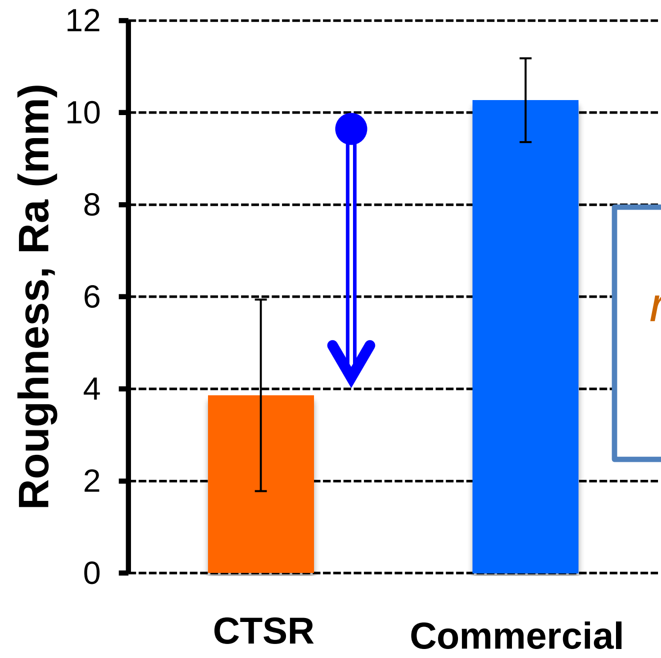
AMDRY: NiCoCrAlY-HfSi

Reactive element bondocat showed higher life under all the conditions

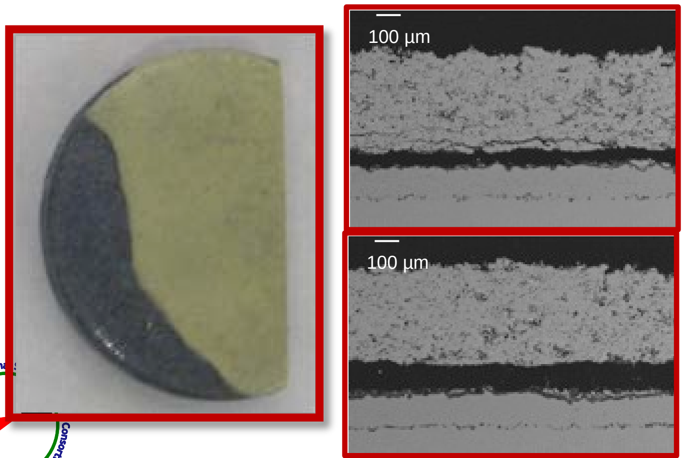
Collaboration with Dr. Bruce Pint and Dr. Allen Haynes at ORNL

Bond coat roughness effects may overshadow chemical effects?

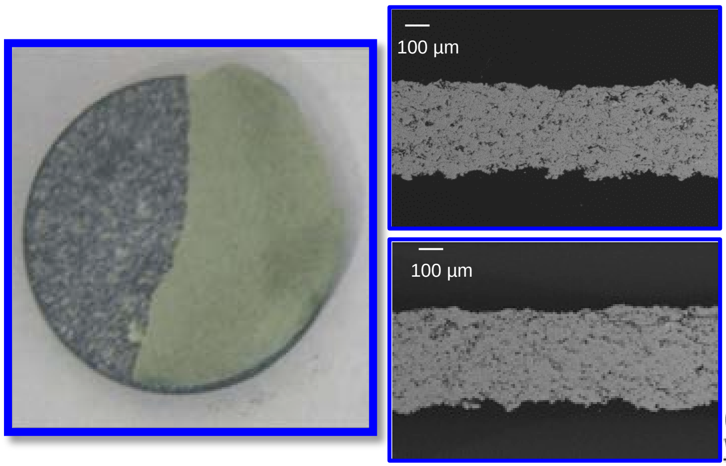




Bondcoat layer require adequate roughness for high TBC life



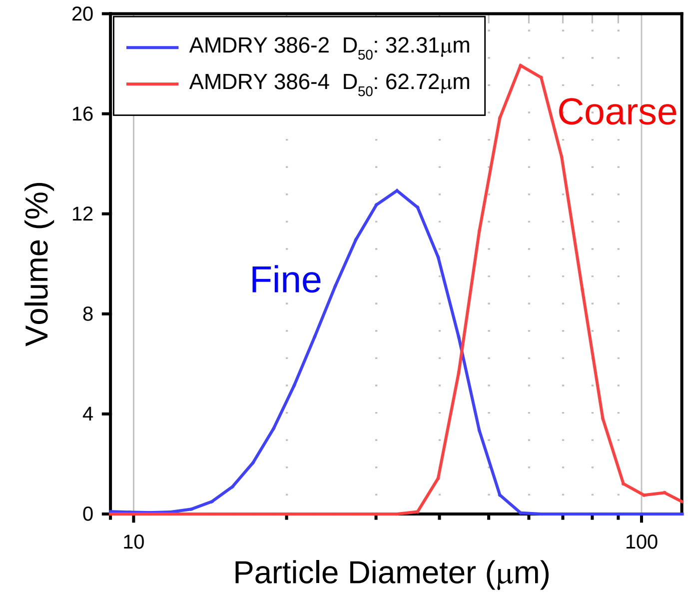
Fracture in TGO



Fracture in topcoat

Approaches for roughness improvement via processing

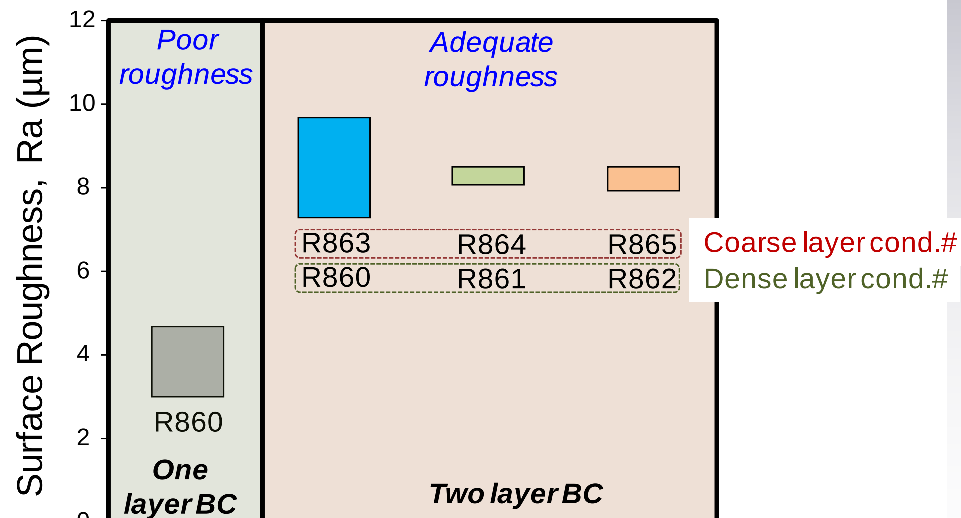
Two layers bond coat deposition



Processing details

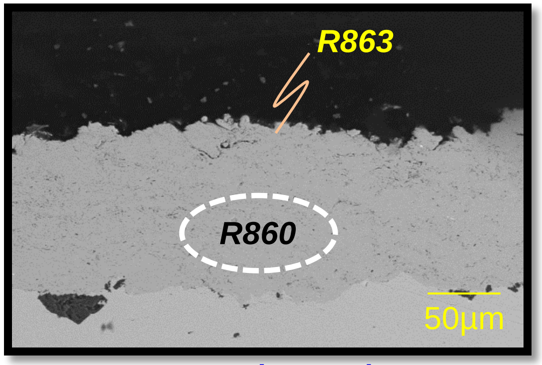
HVOF Torch	**JP5000**		Raster Speed	1 m/sec
Nozzle	8”		Feed Rate	65 g/min
Raster length	627 “		Carrier gas	N_2, 20slpm

Run #	Spray Dist. (inches)	Powder	Condition name	Thick/pass (µm)
860	14	AMDRY 386-2 (Fine)	Cond. # F1	~14
861	16		Cond. # F2	~14
862	16		Cond. # F3	~12
863	18	AMDRY 386-4 (Coarse)	Cond. # C1	~25
864	18		Cond. # C2	~25
865	20		Cond. # C3	~25



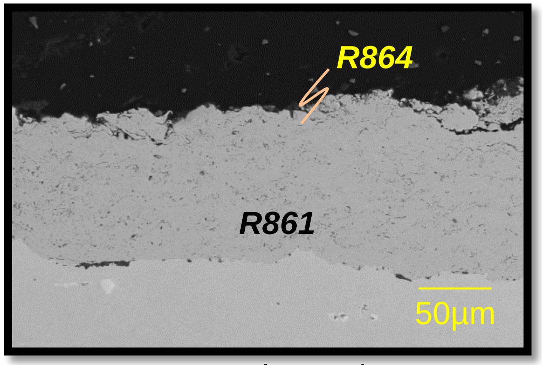
Two layer bond coat: roughness results

Coating #	Spray Run # Fine Powder (AMDRY 386-2)	Spray Run # Coarse Powder (AMDRY 386-2)	Roughness , Ra (µm)
1	R860	R863	7.3 - 9.7
2	R861	R864	8.1 - 8.5
3	R862	R865	7.9 - 8.5



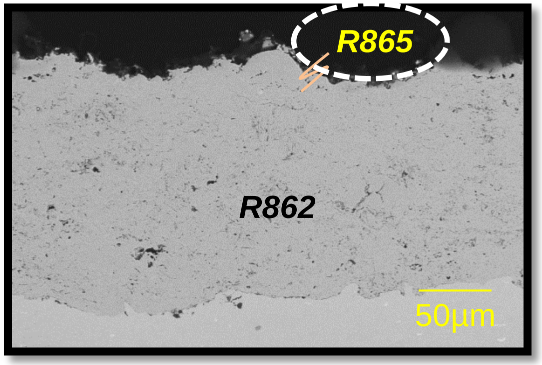
R860: ***Densest bottom layer***

R863: *Poor splat cohesion*



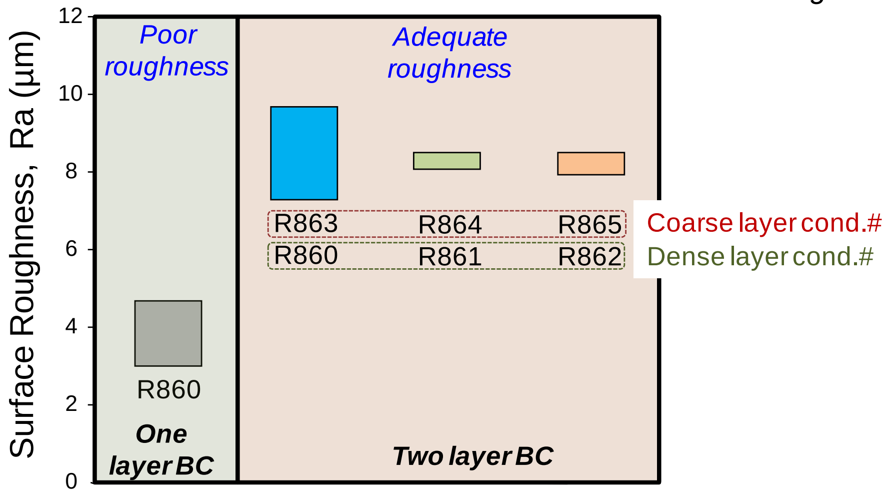
R861: *Denser bottom layer*

R864: *Poor splat cohesion and some cracking*



R862: *least dense bottom layer*

R865: ***good particle melting and splat cohesion***



Selected parameters

- ❑ R860 for dense layer (100µm)
- ❑ R865 for coarse layer (50µm)

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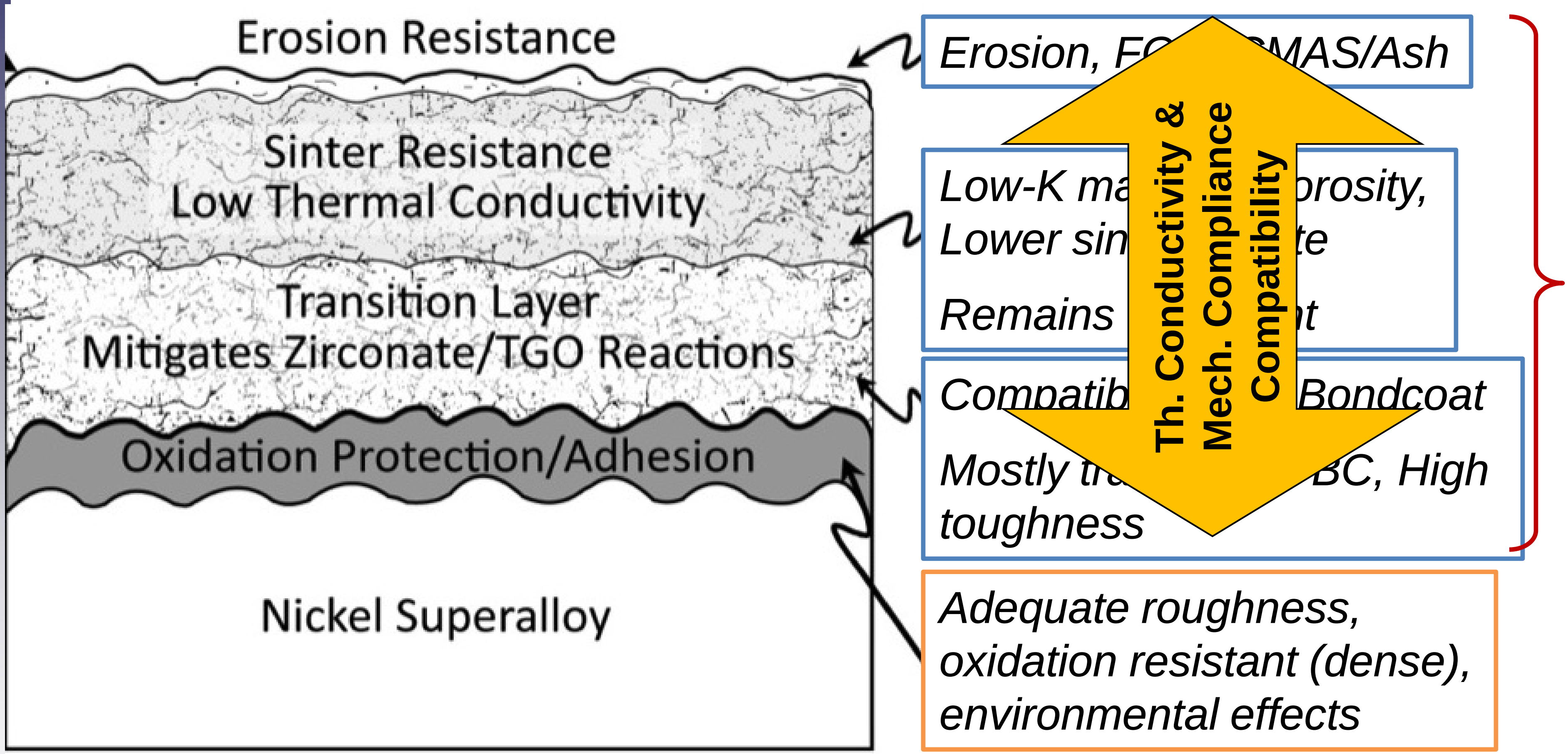
Process development for multilayer top coats is critical



Need for higher operating temperature and severe environments

	Traditional YSZ	New TBC Requirement
Phase Stability	Good < 1200C	Good<1300-1400C
Thermal Expansion	Fair	Challenging
Thermal Conductivity*	Low	Lower
Sintering Resistance*	Fair	Good
Erosion Resistance*	Good	Challenging
Fracture Toughness*	Good	Challenging
Mechanical Compliance	known	To be explored

Materials' intrinsic properties

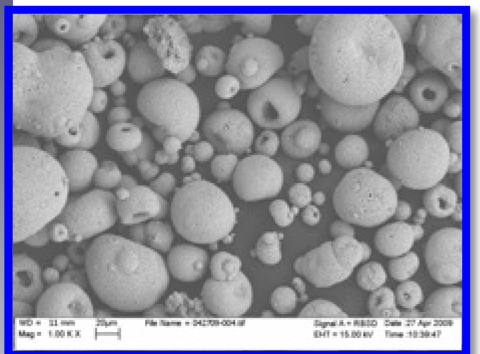
*Can be optimized via processing strategies**

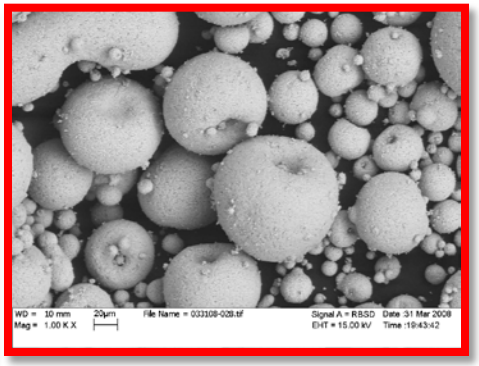
TBC Materials under considerations

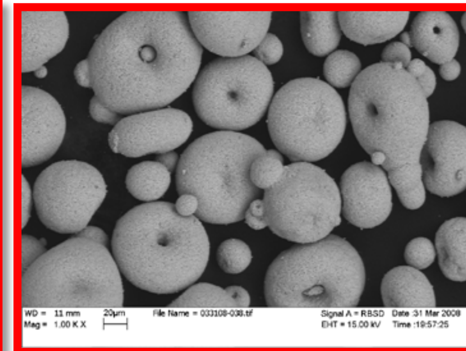
Material	Composition	Advantages	Powder
YSZ	7-8wt% YSZ	Stable below 1200 C, cost effective, properties well-characterized	Various sources, different levels of purity
Zirconate	$La_2Zr_2O_7$	Pyrochlore, low thermal conductivity, phase stability to 1400 C	Julich
Zirconate	$Gd_2Zr_2O_7$	Pyrochlore, low thermal conductivity, phase stability to 1400 C, compatible with YSZ	Saint Gobain, Julich,
Co-doped	1.5mol% Yb_2O_3 1.5mol% Gd_2O_3 2.1mol% Y_2O_3 ZrO_2	t' phase, low thermal conductivity, sintering resistant, compatible with MCrAlY bond coat, high erosion resistance	NASA

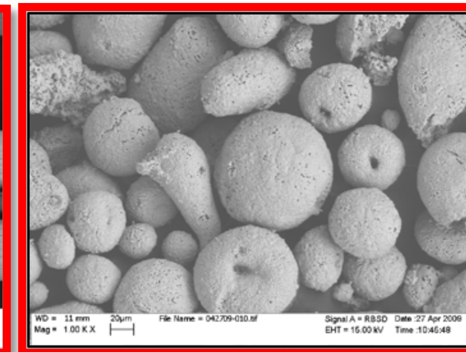
Exploring and processing new materials

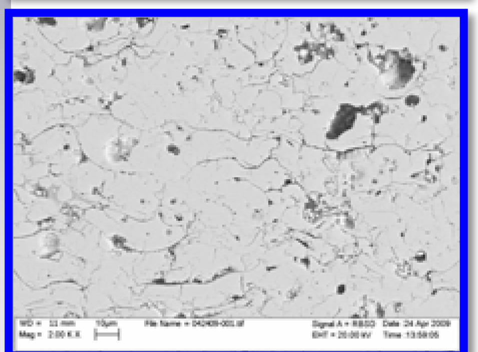
YSZ	$La_2Zr_2O_7$	$Gd_2Zr_2O_7$	Co-doped

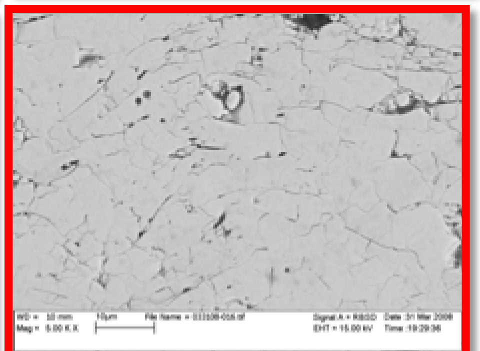


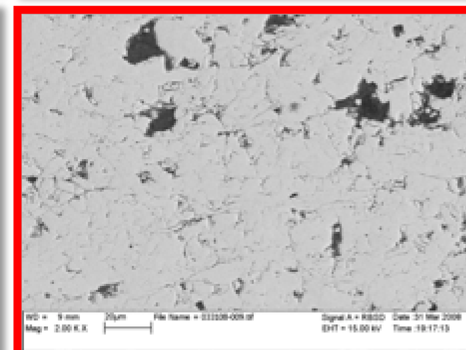


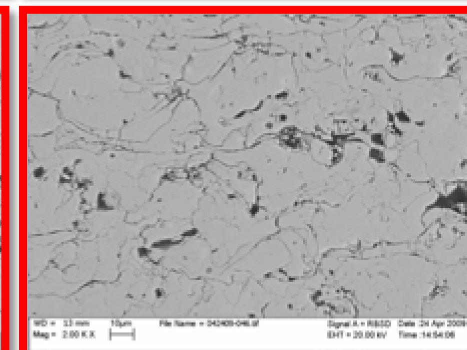












Processing challenges with new materials

General processing challenges

Different melting temperature than YSZ

- ***Optimization of Plasma condition***
- ***Optimization of powder cut***
  - *Different conditions for several layers*

Properties driven processing challenges

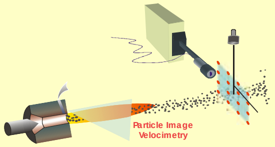
- ***Poor erosion resistant of new materials***
  - *Denser yet sufficient compliance*
- ***Lower fracture toughness than YSZ***
  - *Microstructural optimization*

Cost driven processing challenges

- ***Minimum use of the material***
  - *Traditional or alternative materials*
  - ***Compatibility issue***

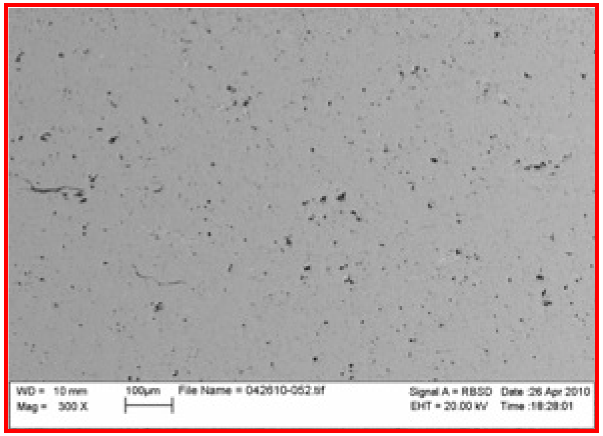
Multi-directional integrated approach to address the challenges

Extend knowledge gained with YSZ to new ceramics

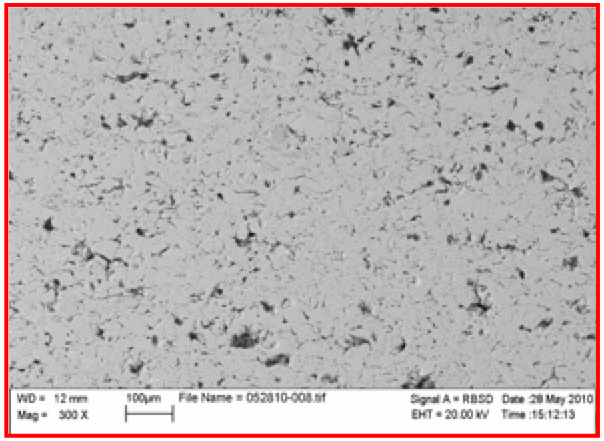


Process enabled tailoring of microstructure & properties

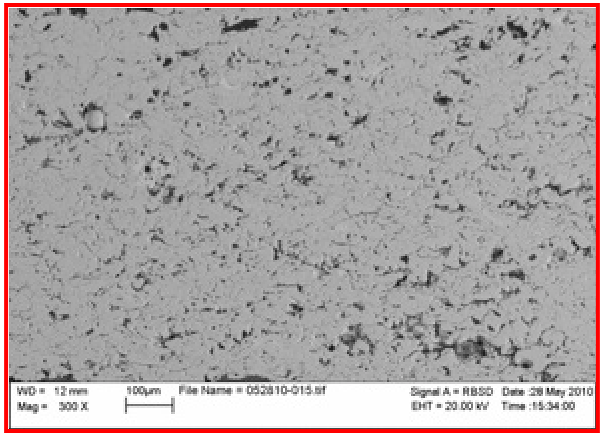
Cond. #1: Porosity 10.7%



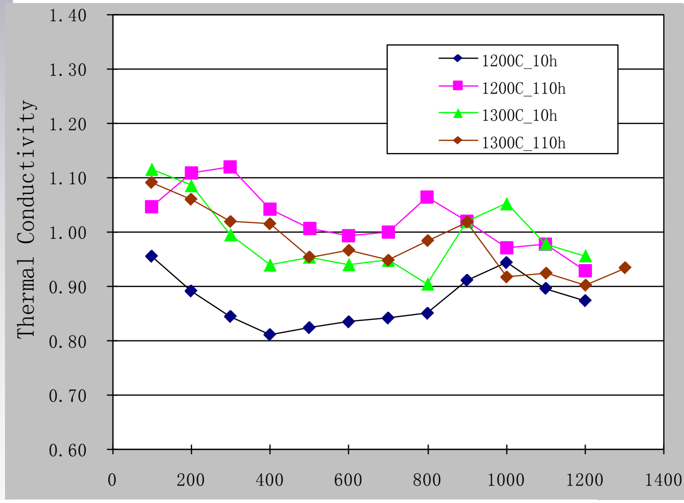
Cond. #2: Porosity 17.8%

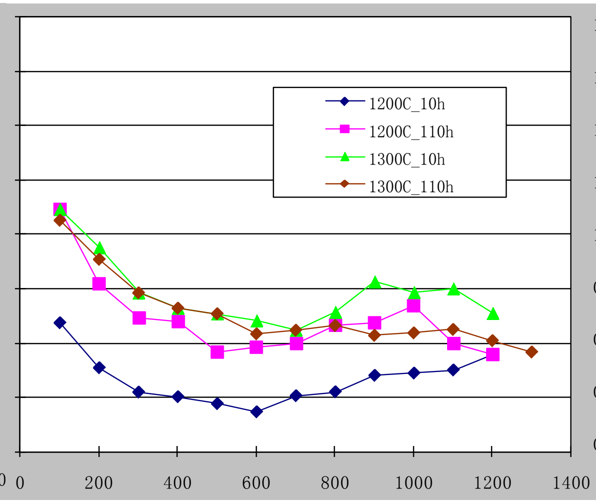


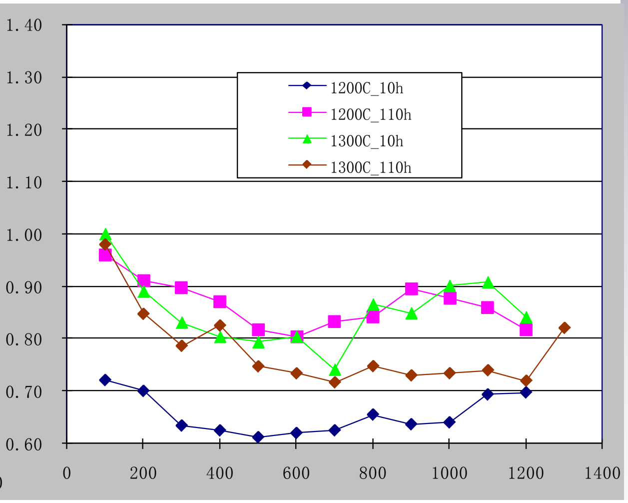
Cond. #3: Porosity 21.4%



$Gd_2Zr_2O_7$

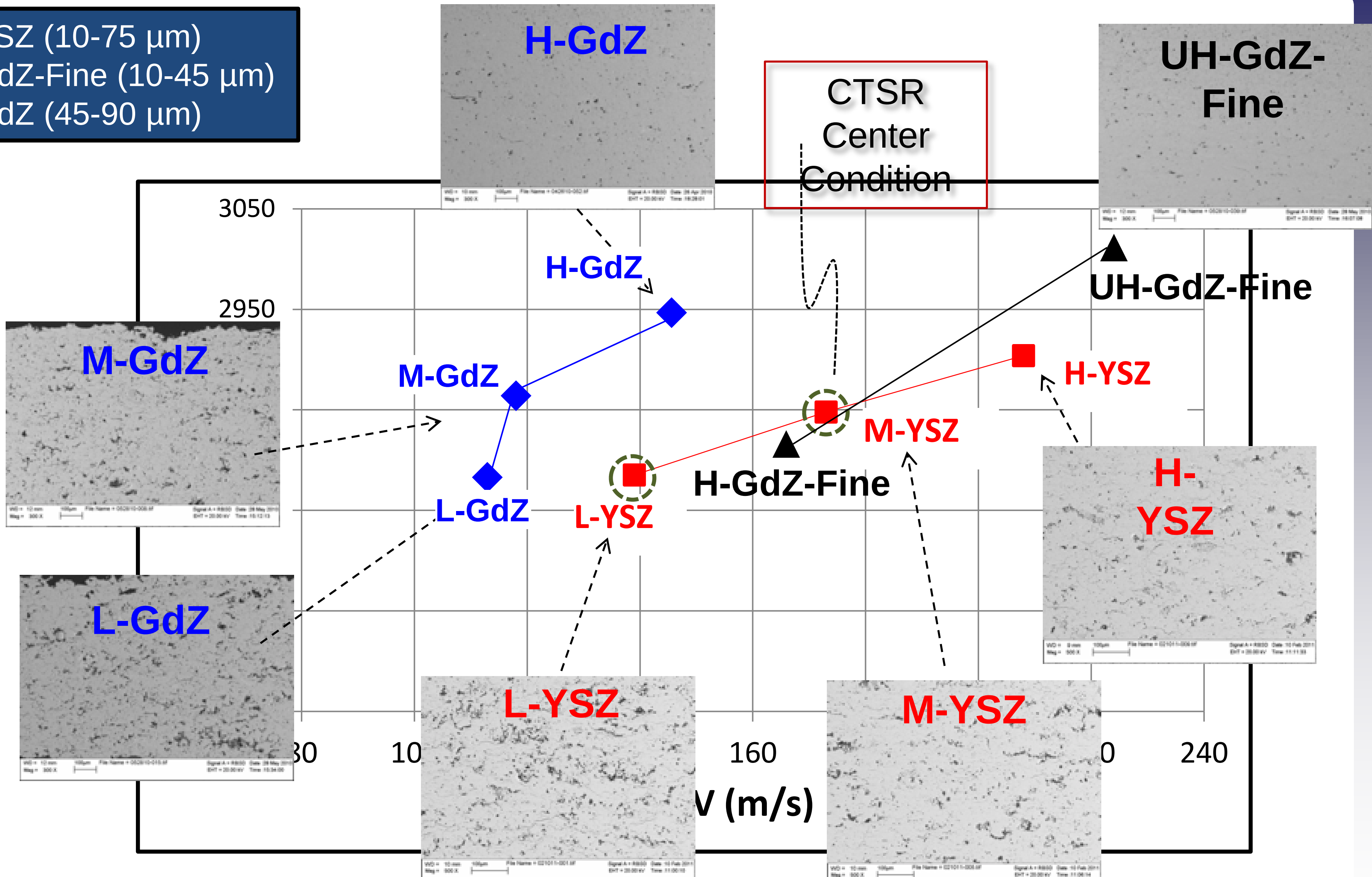




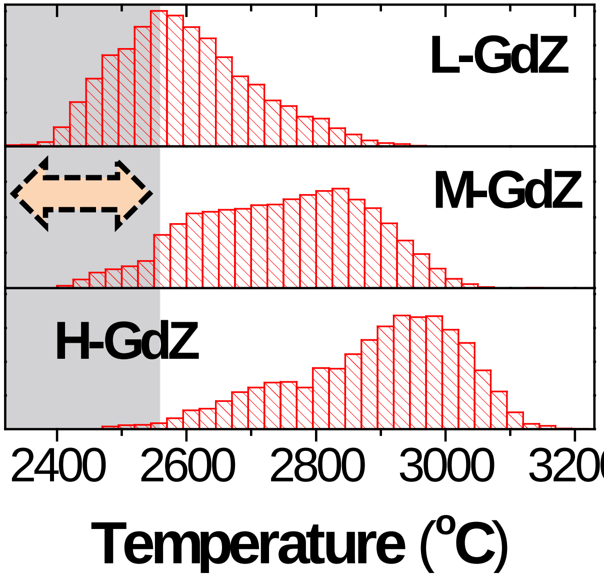


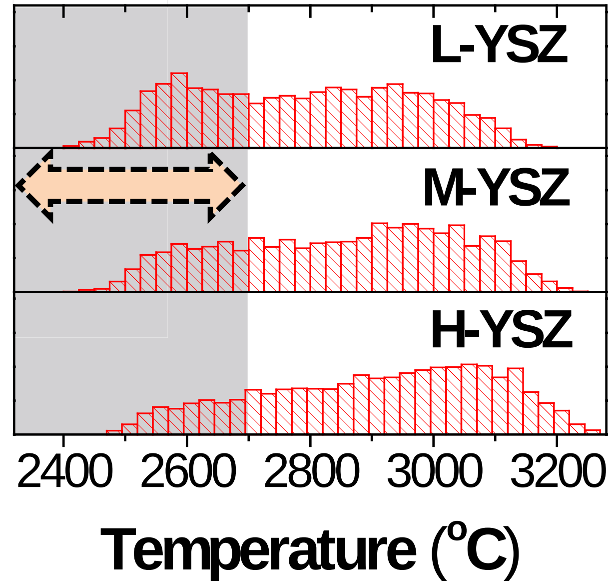
Comparing process space between YSZ and $Gd_2Zr_2O_7$

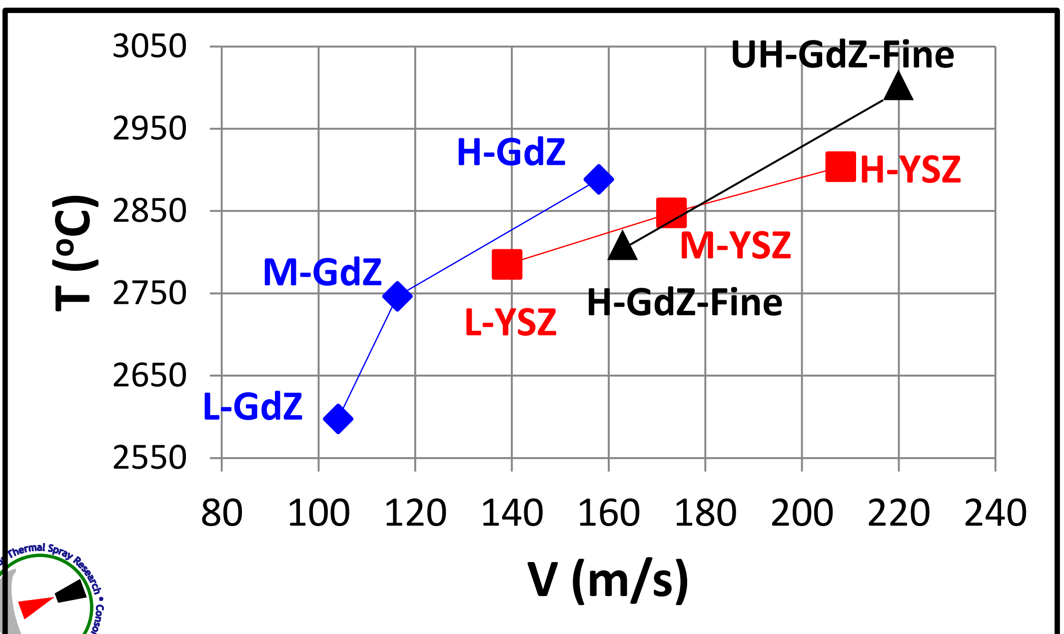
YSZ (10-75 µm)
GdZ-Fine (10-45 µm)
GdZ (45-90 µm)



Process Maps for new materials: case study $Gd_2Zr_2O_7$







- ***Different melting temperatures***
- ***Different powder cut***
- ***Same T-V map??***

Coating Characterization Scheme

Process Map

Coating Deposition

Multidimensional characterization to achieve desired properties

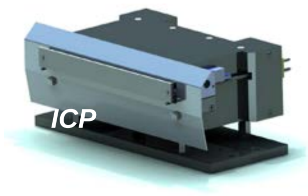
- Evolving Stress
- Coating Modulus
- Non-linearity/Compliance

Advanced

- Thermal Conductivity
- Erosion
- Fracture Toughness

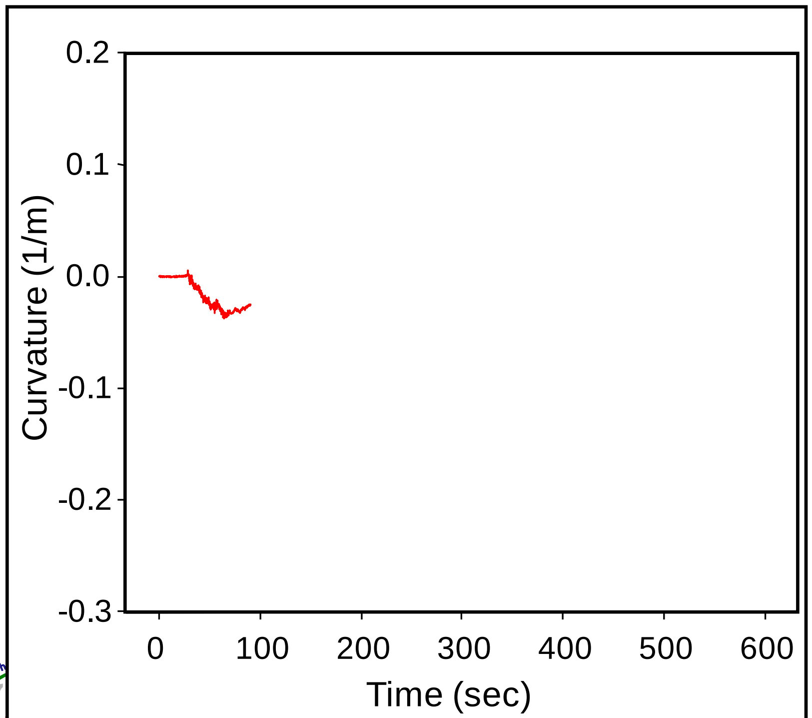
Traditional

ICP: Evolving stress

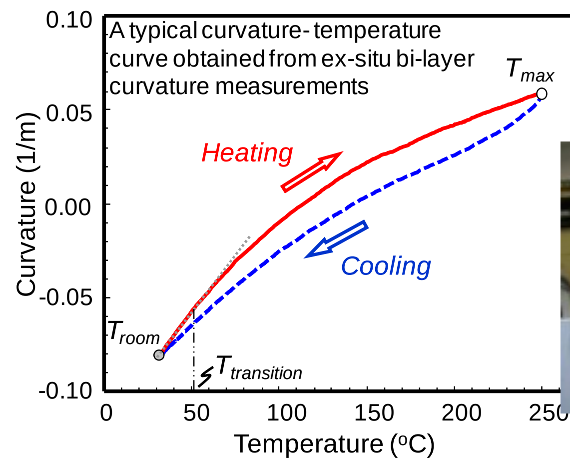


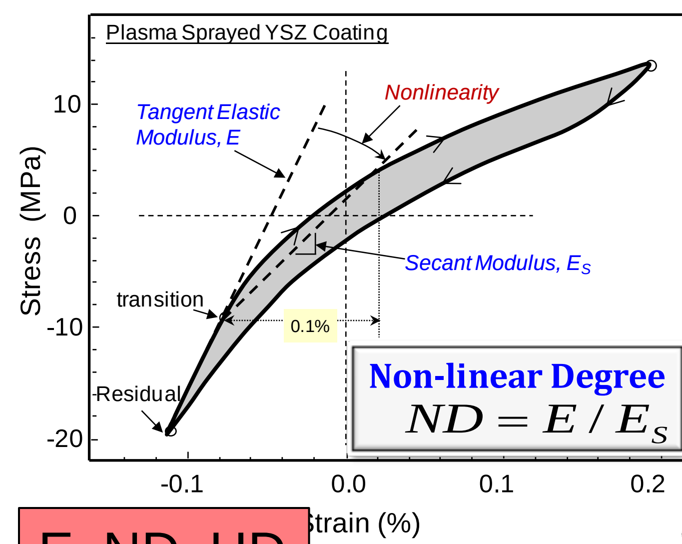
Stoney's formula for Evolving stress

$$\sigma_{Ev} = \frac{E'_S t_S^{\,2}}{6\Delta t_D}\Delta\kappa$$



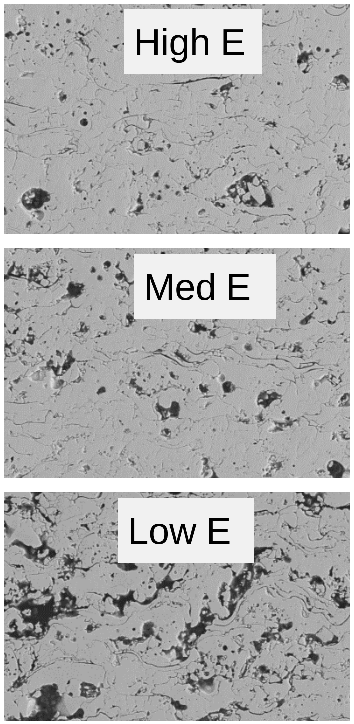
ECP: E, ND and HD

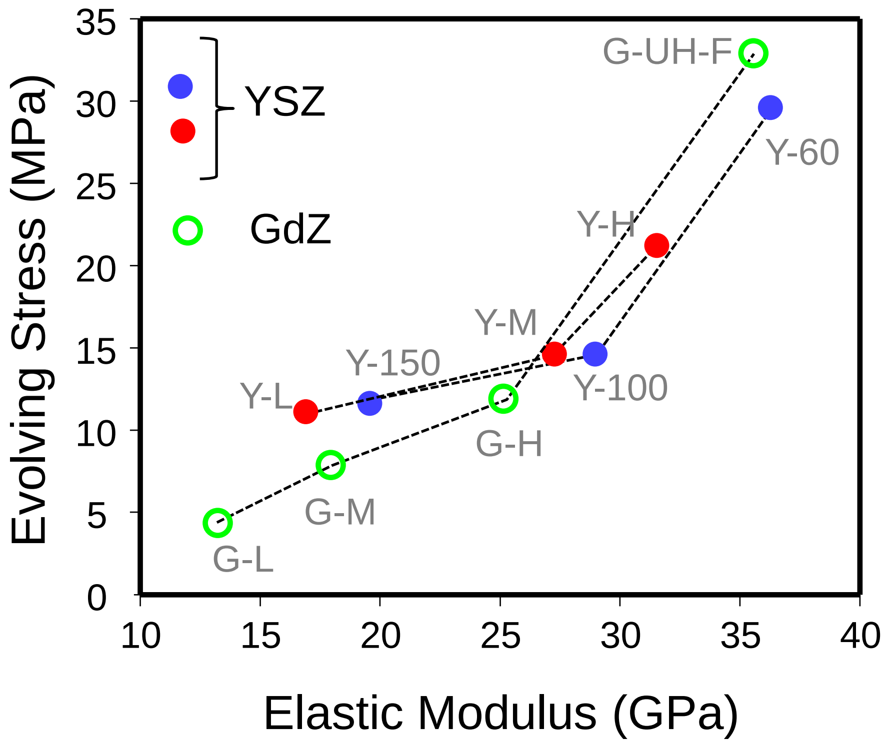


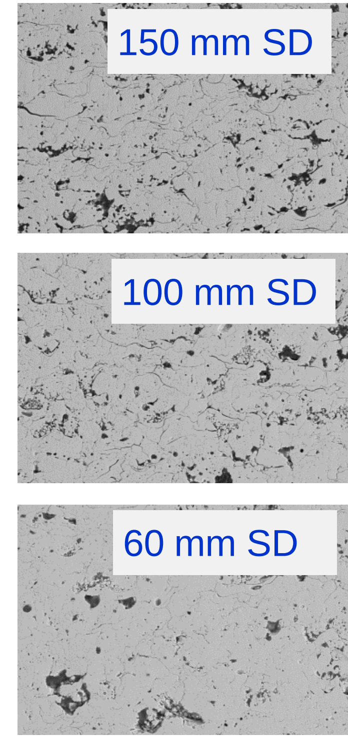


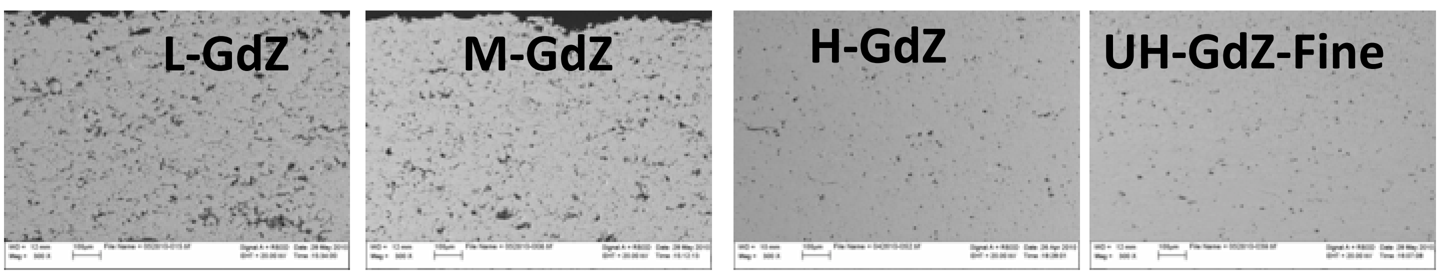
E, ND, HD

Insitu and Exsitu curvature characterization of coating stresses







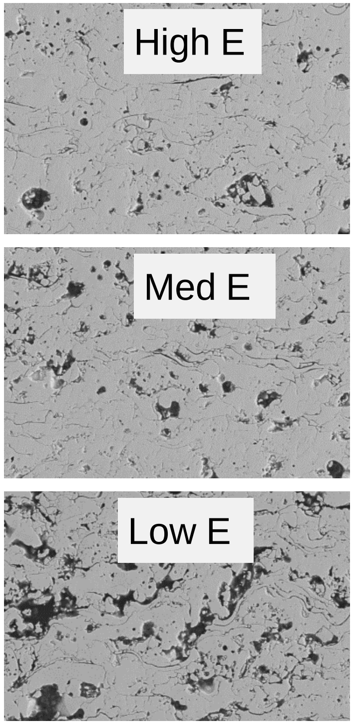


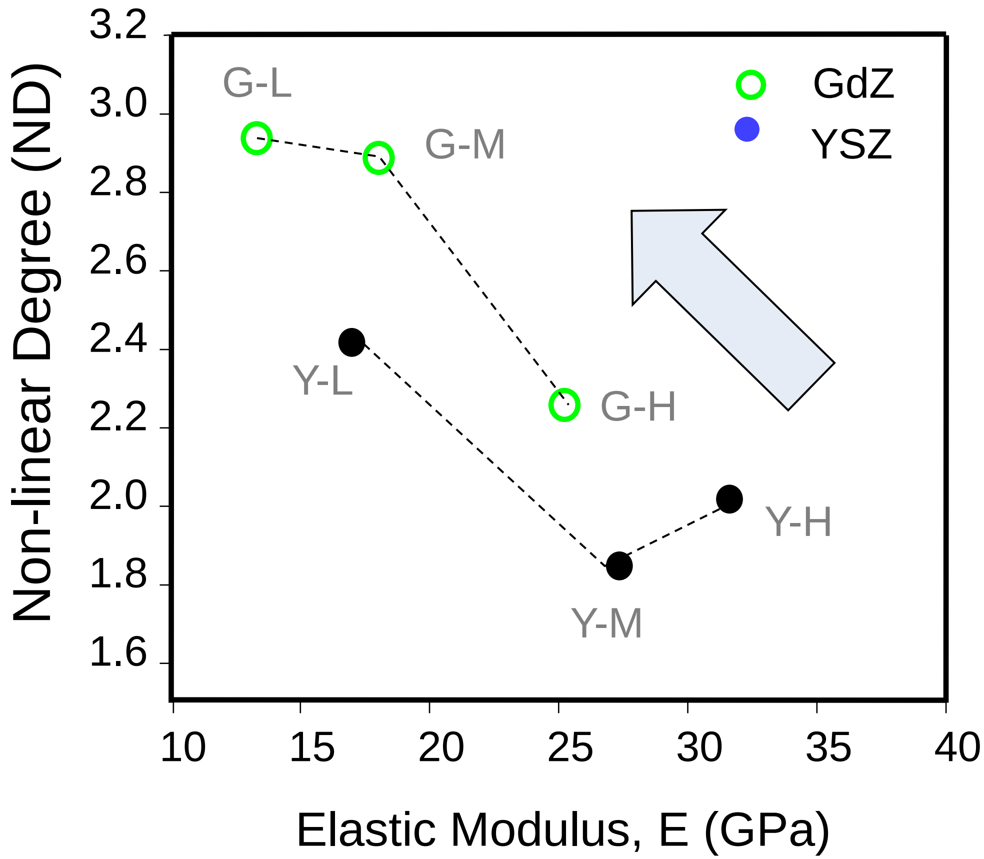
Gd_2ZrO_7 generally shows lower stress evolution than YSZ

Lower toughness ?

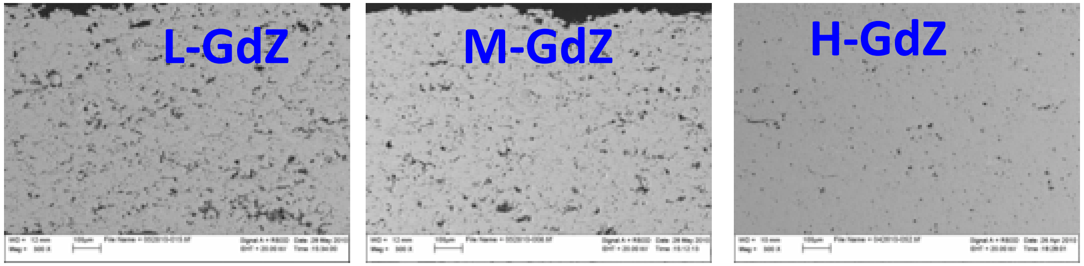
Poorer splat-splat bond ?

Comparison of non-linear elastic properties for range of process conditions





A systematic shift in Gd_2ZrO_7 from YSZ for the given set of parameters



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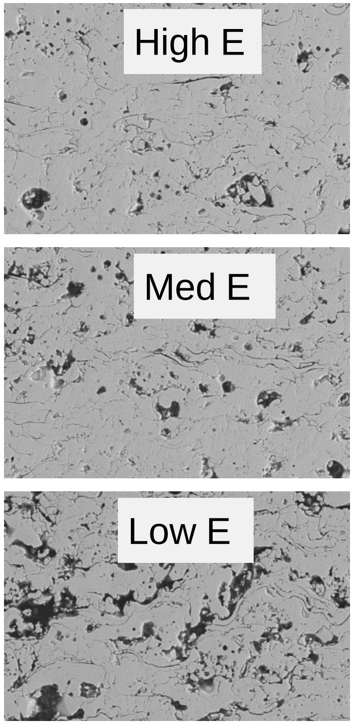
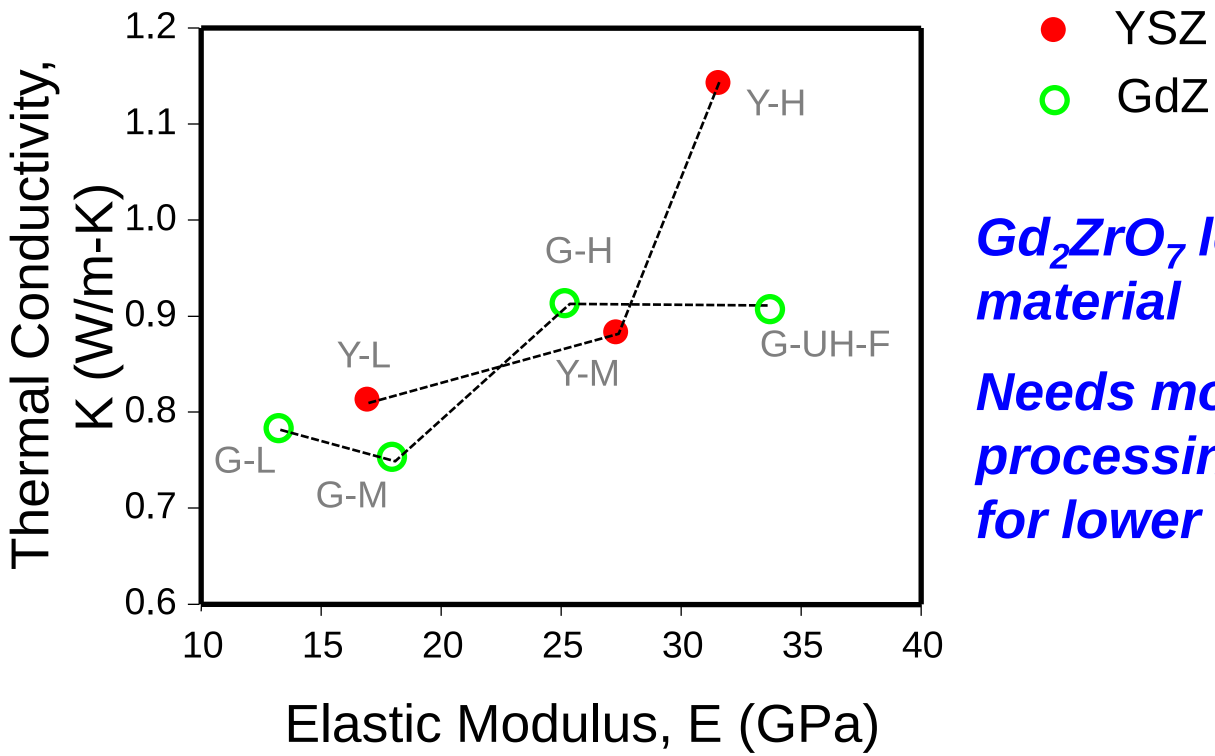
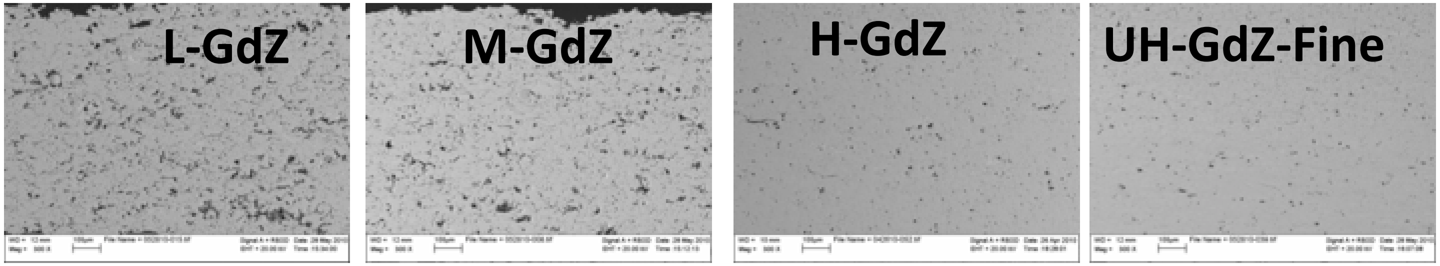
Correlation between thermal and mechanical properties



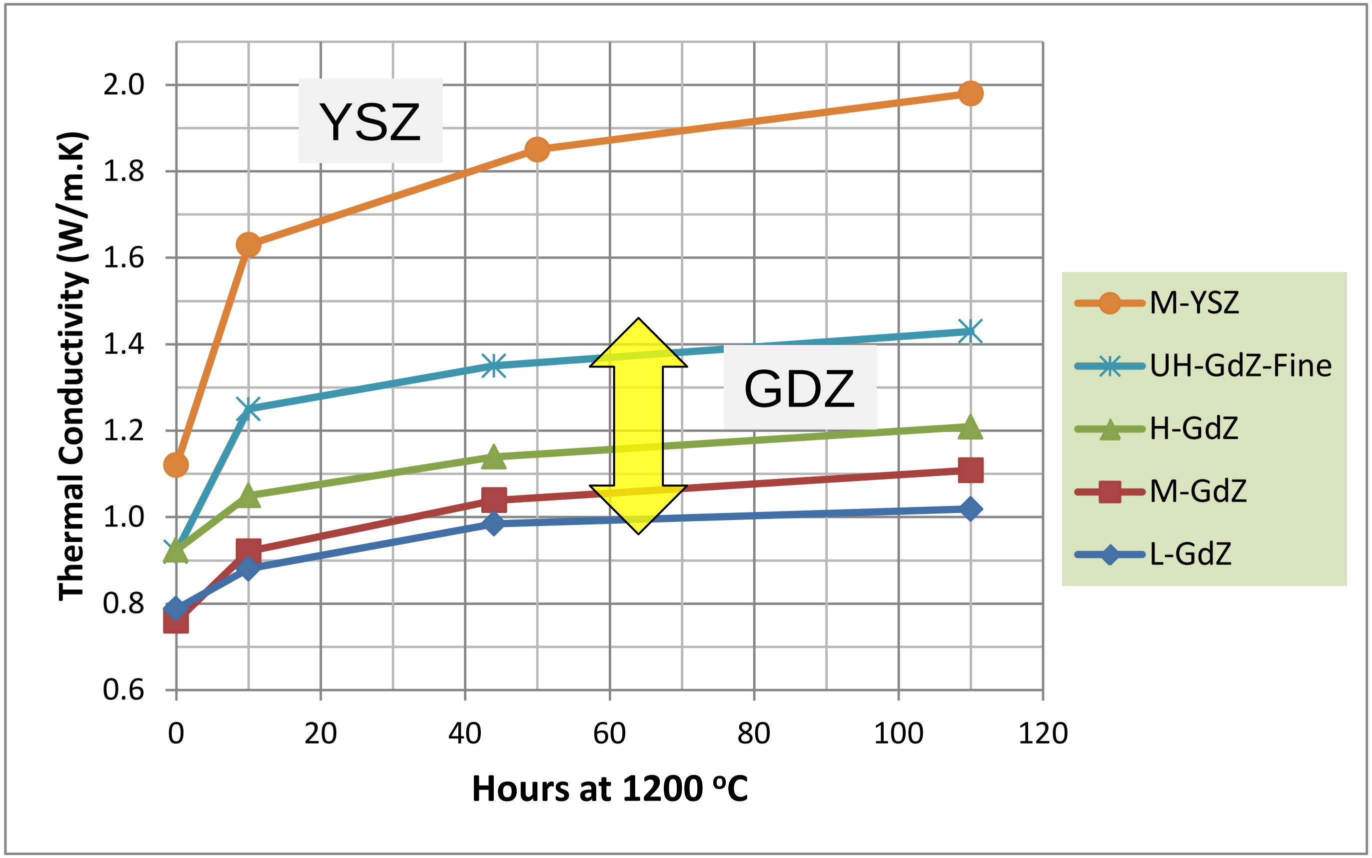


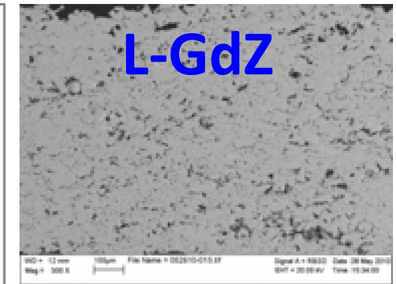
Gd_2ZrO_7 low K material

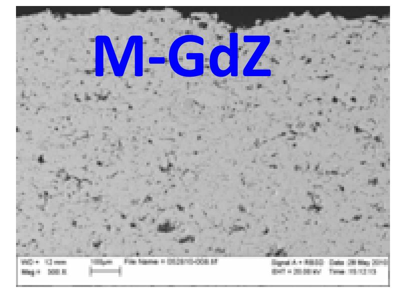
Needs more processing control for lower K

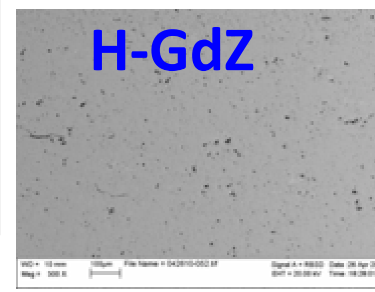


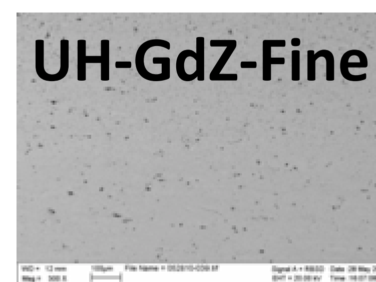
GdZ is significantly more sinter resistant and related to starting microstructure









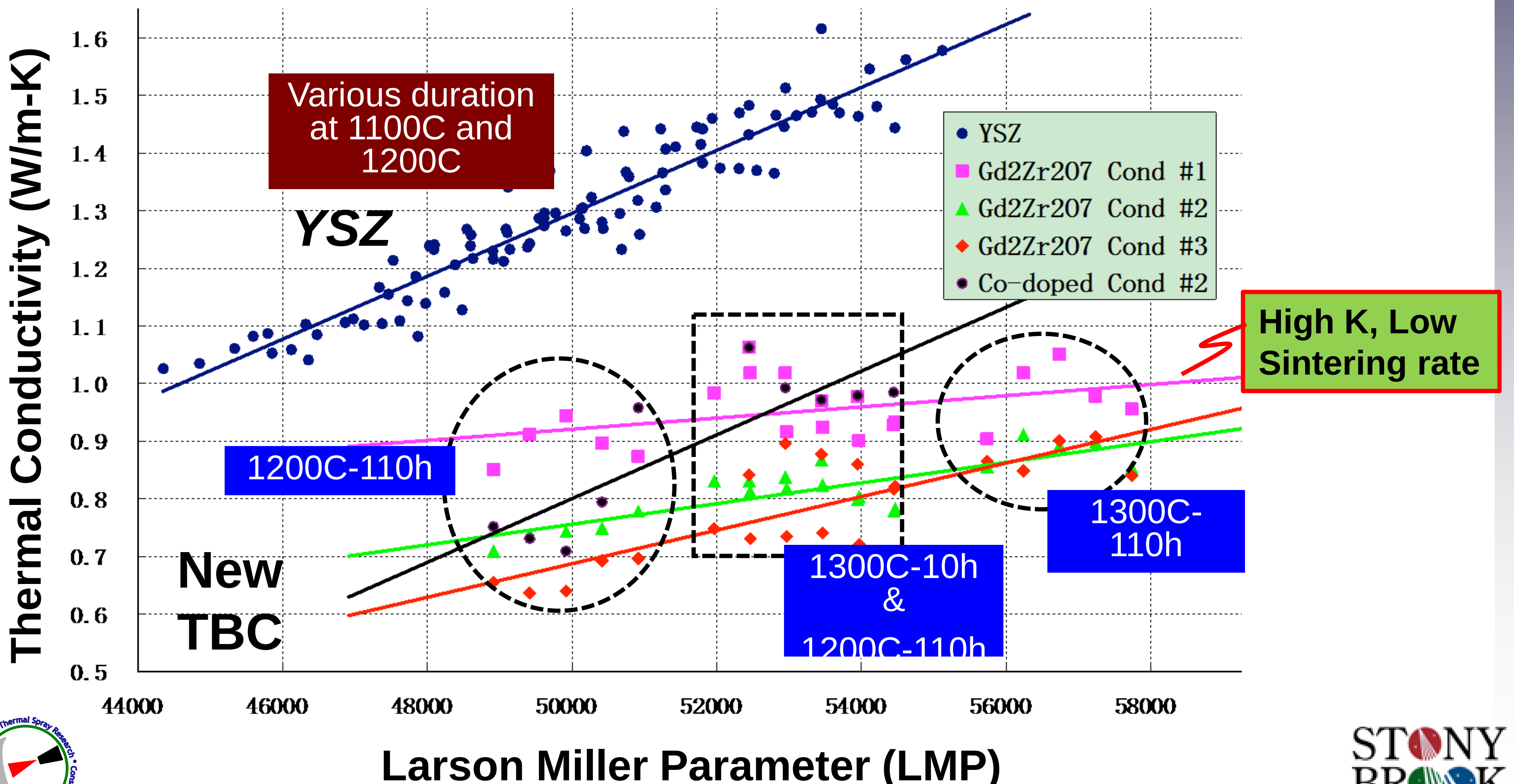


- ❑ GDZ: Showed Low-K
- ❑ The sintering rate can be controlled via processing
- ❑ Important for multilayer TBC development

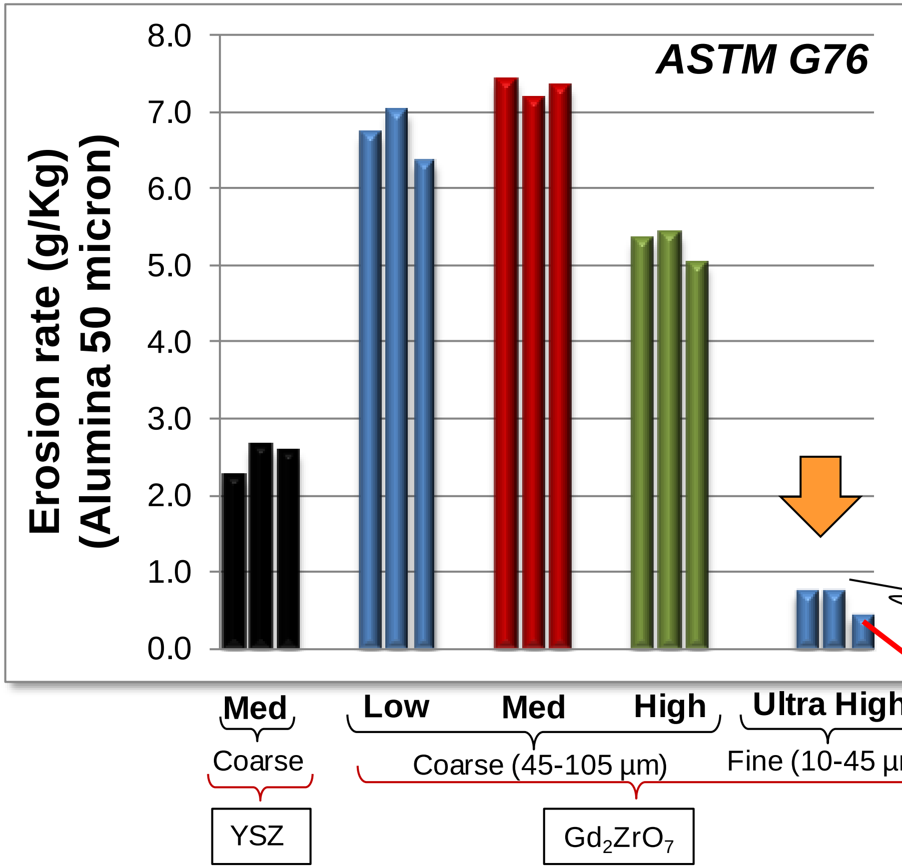
Sintering behavior of new materials

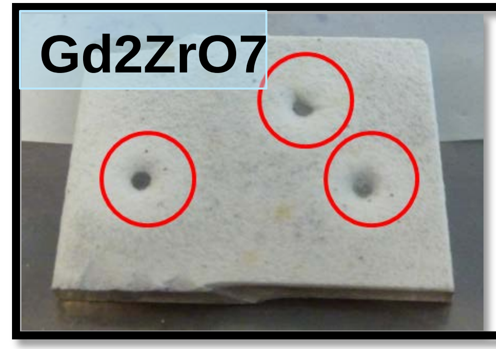
Larson Miller Parameter (LMP): *Temp and Time for thermal exposure*

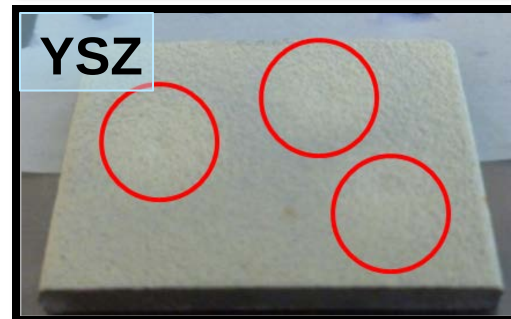
- LMP = T(ln t + C)
- $k^* = k/k_{as}$
- $\ln(k^*) = b_0 + b_1\mathbf{LMP}$



Erosion performance of new material (Gd_2ZrO_7)

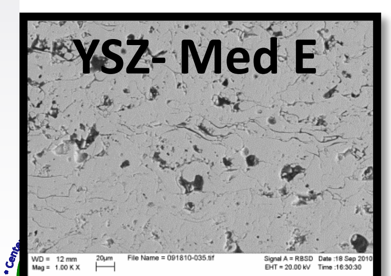


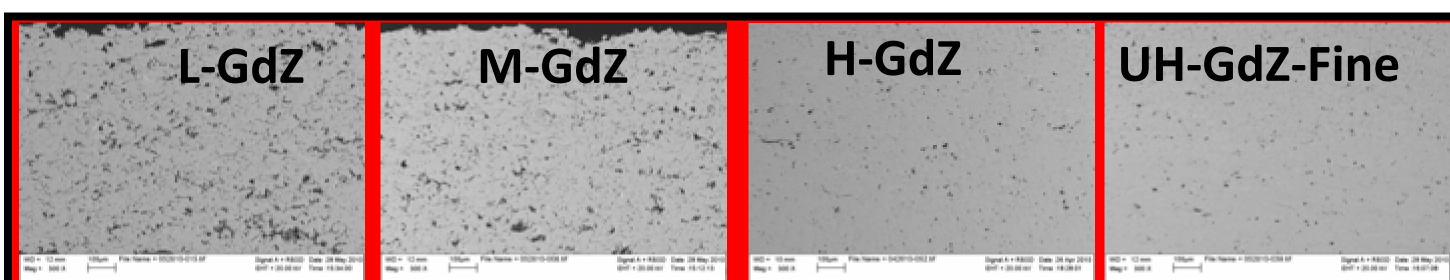




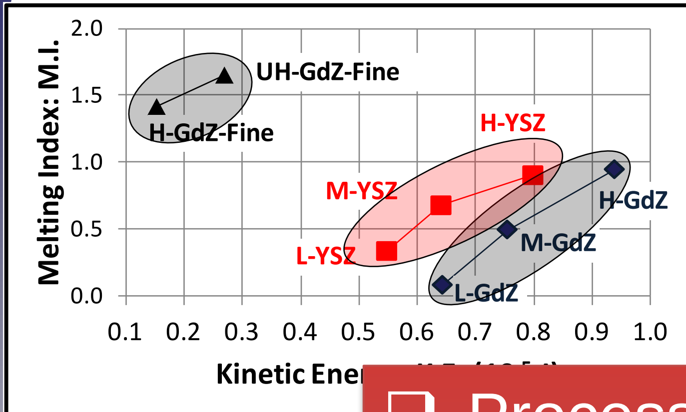
Pros: Excellent erosion resistant

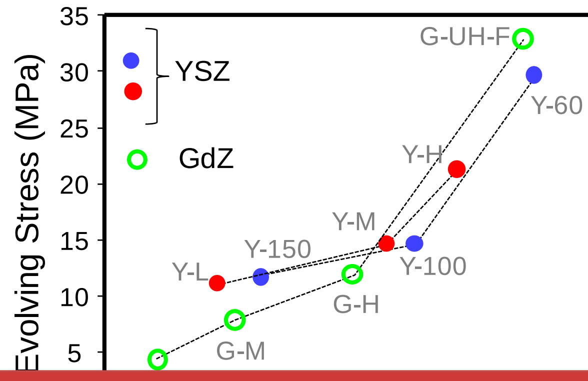
Issue: Poor Compliant

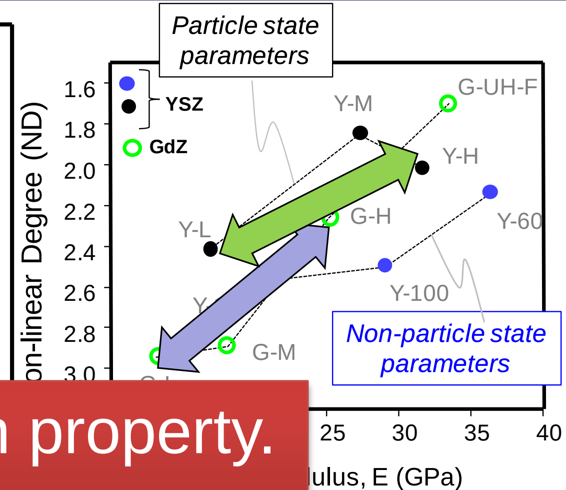




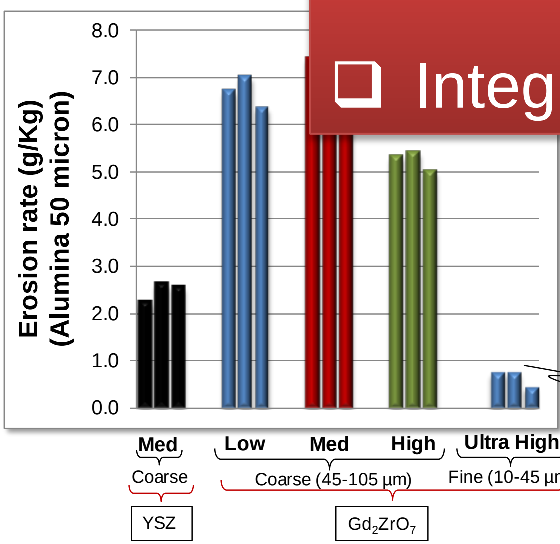
Process monitoring and other observations for Gd_2ZrO_7

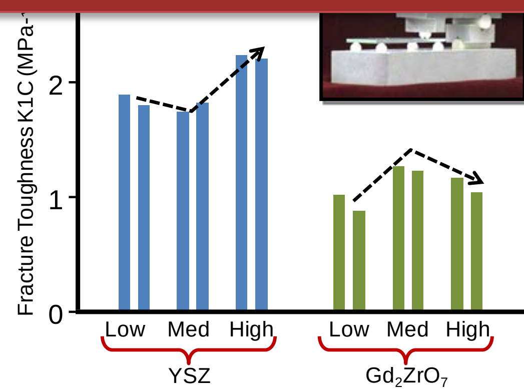


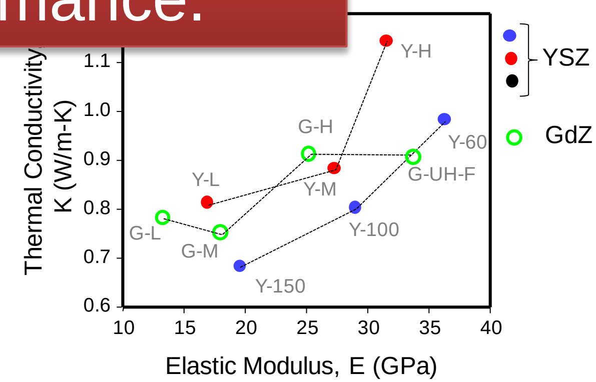


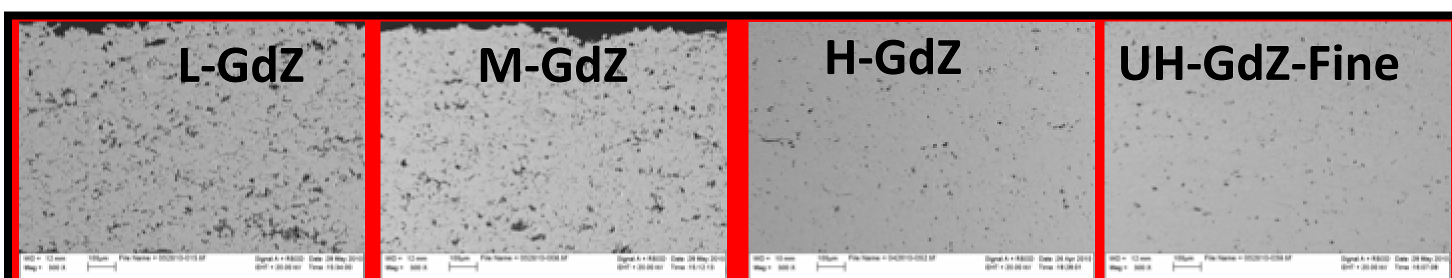


- ❑ Process optimization for each property.
- ❑ Integration for overall performance.







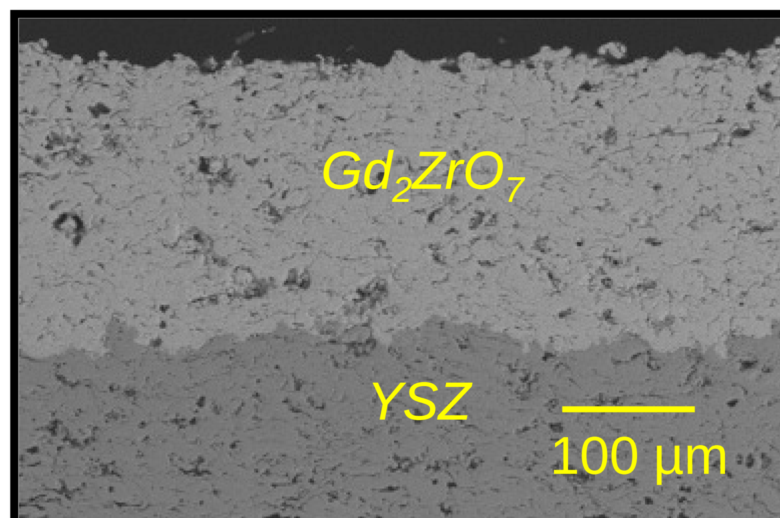


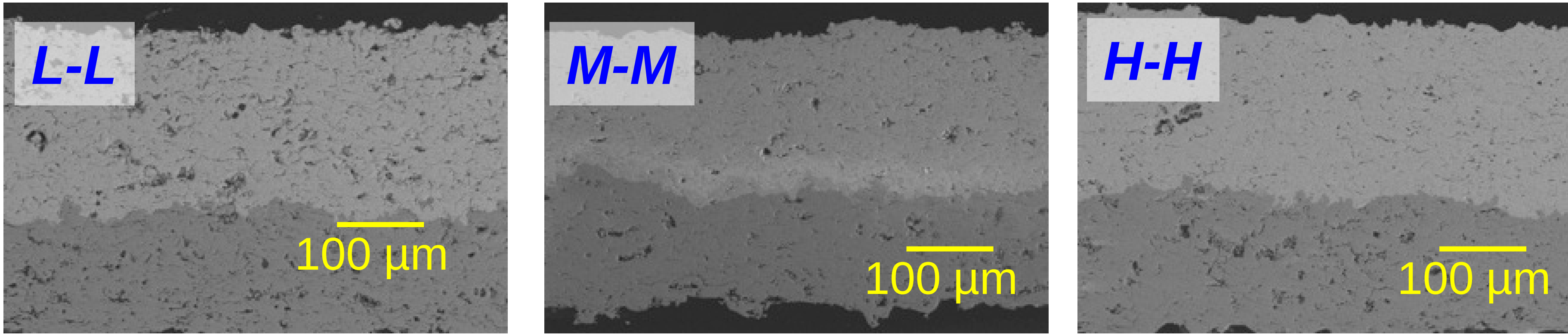
- Evaluate oxidation characteristics of different types of bond coat materials in water vapor containing atmospheres in order to select the most viable material and processing condition.
- Develop processing strategies and maps for plasma spraying of emerging zirconate materials.
- Optimize engineered coating architectures for the ceramic top coat of the TBC system to simultaneously provide erosion resistance, thermal and environmental protection, low thermal conductivity, sintering resistance and compliance.
- Determine the degradation mechanisms in multilayer TBCs after controlled-atmosphere furnace tests & erosion tests.

Understanding for individual layer

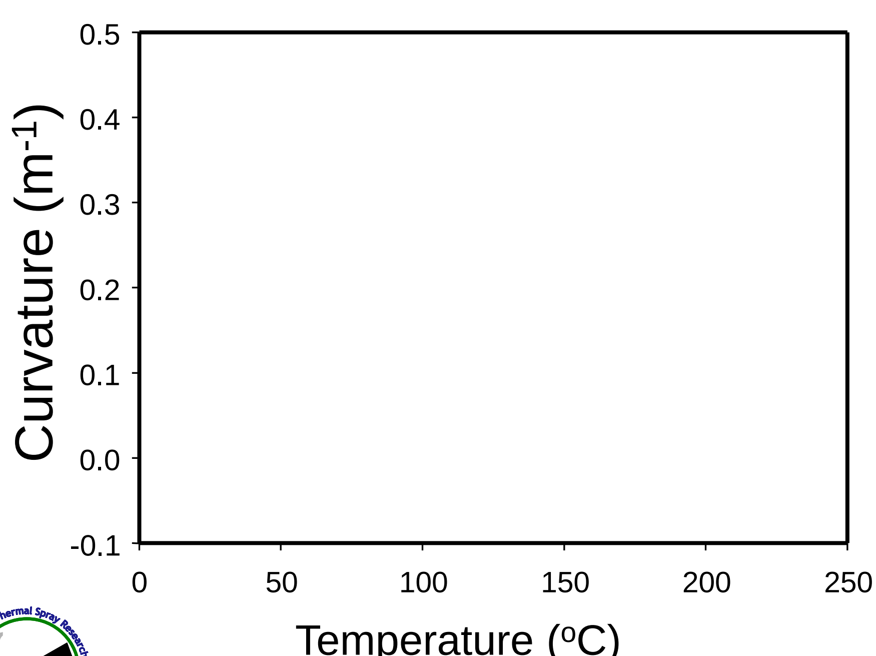
Step to multilayer coatings

Step-1: Bi-layer

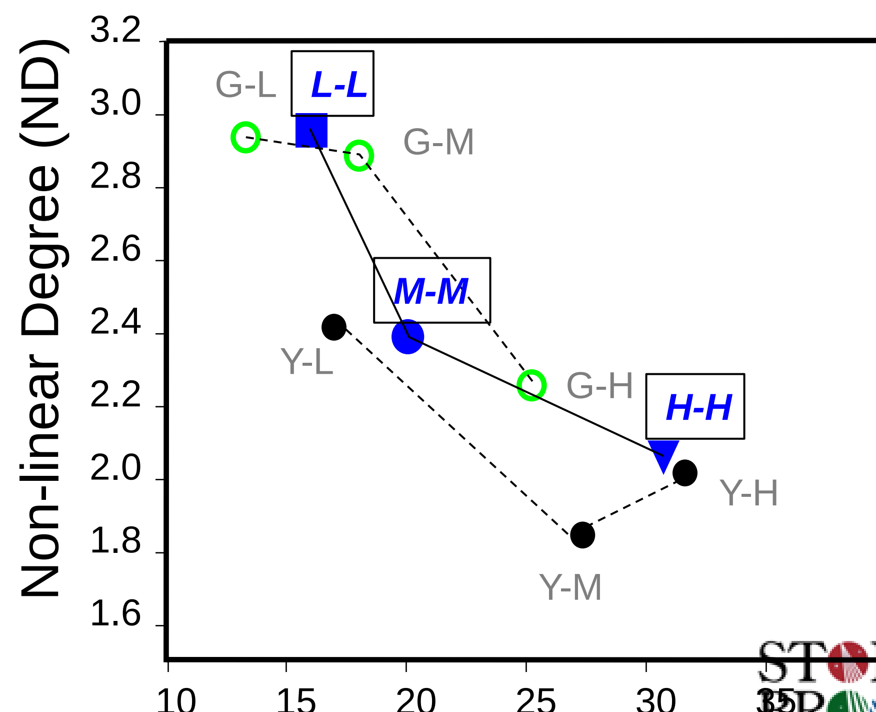




L-L
100 µm
M-M
100 µm
H-H
100 µm

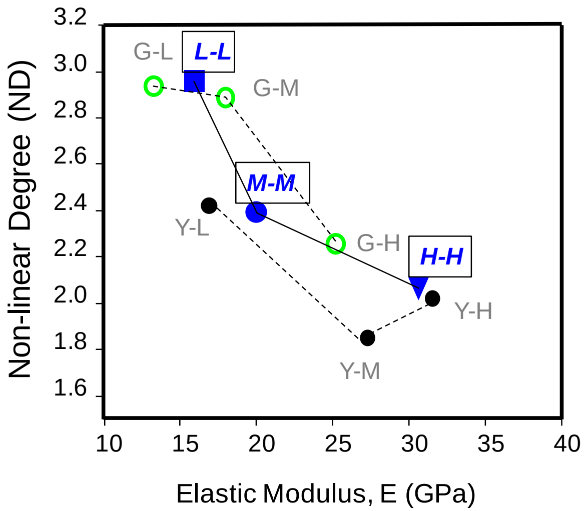


Curvature (m^{-1})
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
0
50
100
150
200
250
Temperature (^{o}C)



Non-linear Degree (ND)
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
G-L
L-L
G-M
M-M
Y-L
G-H
H-H
Y-H
Y-M
10
15
20
25
30
35
40

FCT results of bi-layer top coats



L-L

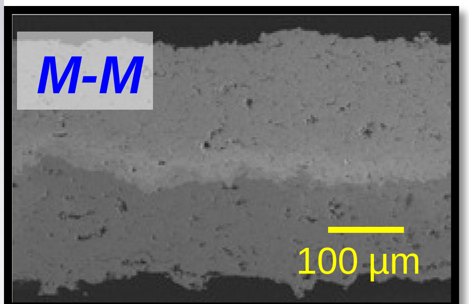
Spallation in GDZ layer Only

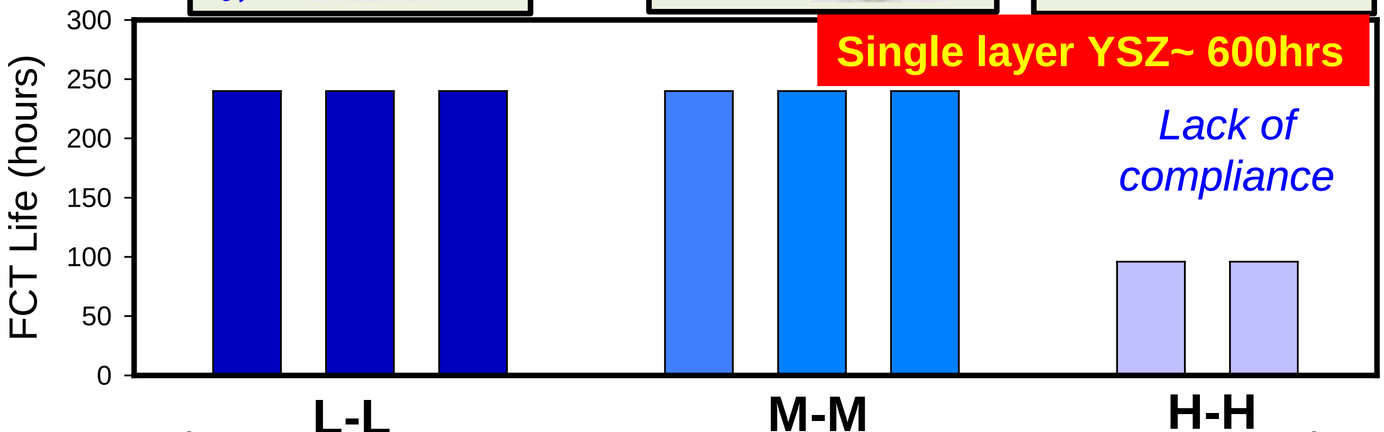
M-M

Spallation at GDZ-YSZ interface

H-H

Spallation at GDZ-YSZ interface. Major edge delaminations

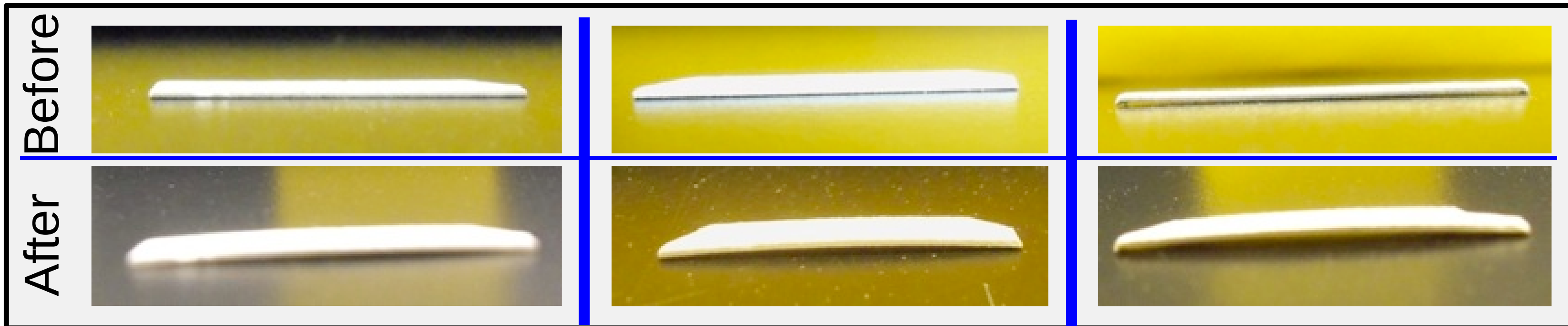


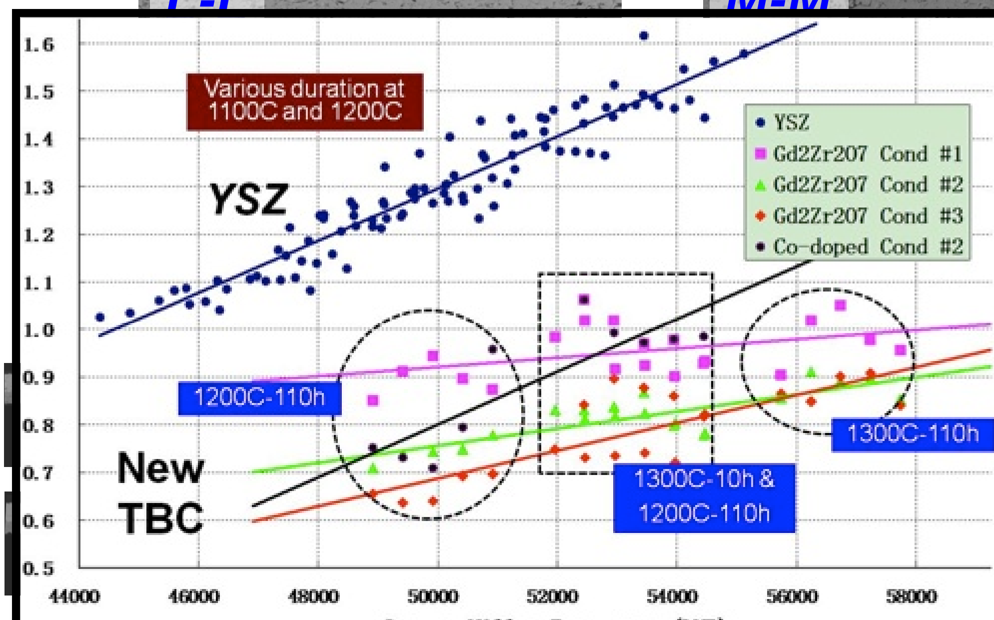


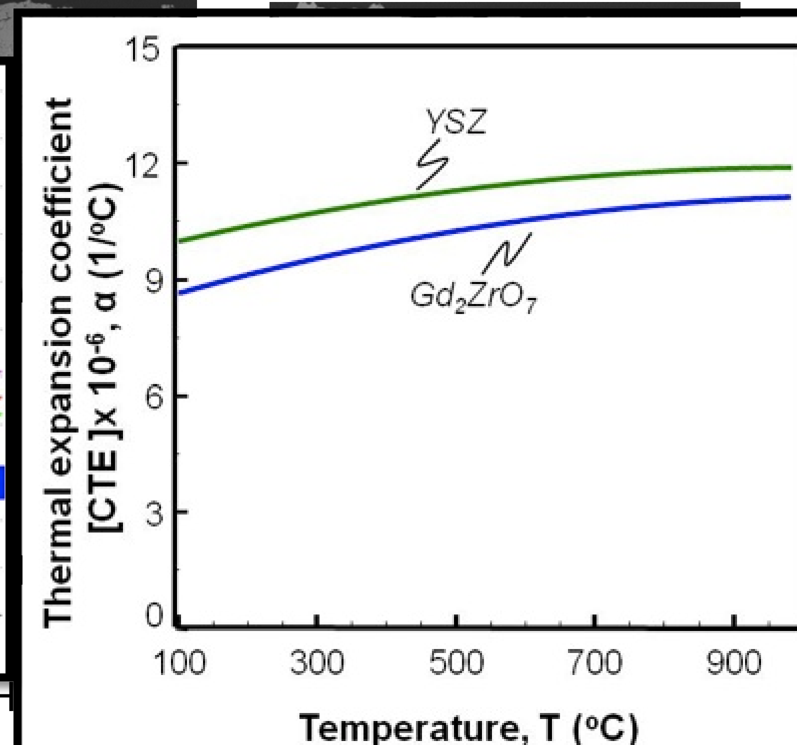
Gd_2ZrO_7/YSZ double layer

Sintering compatibility of bi-layers

Isothermal exposure at 1200°C for 24 hours

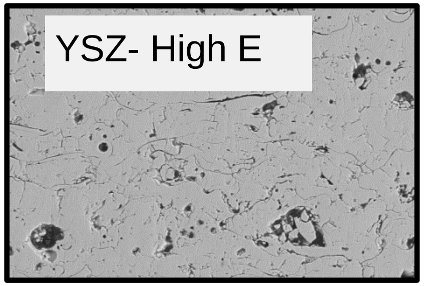


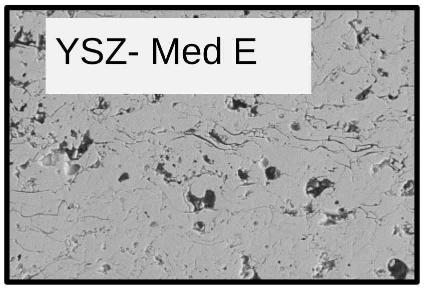


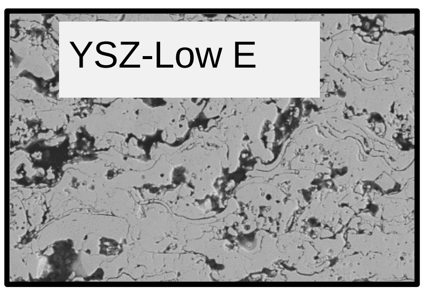


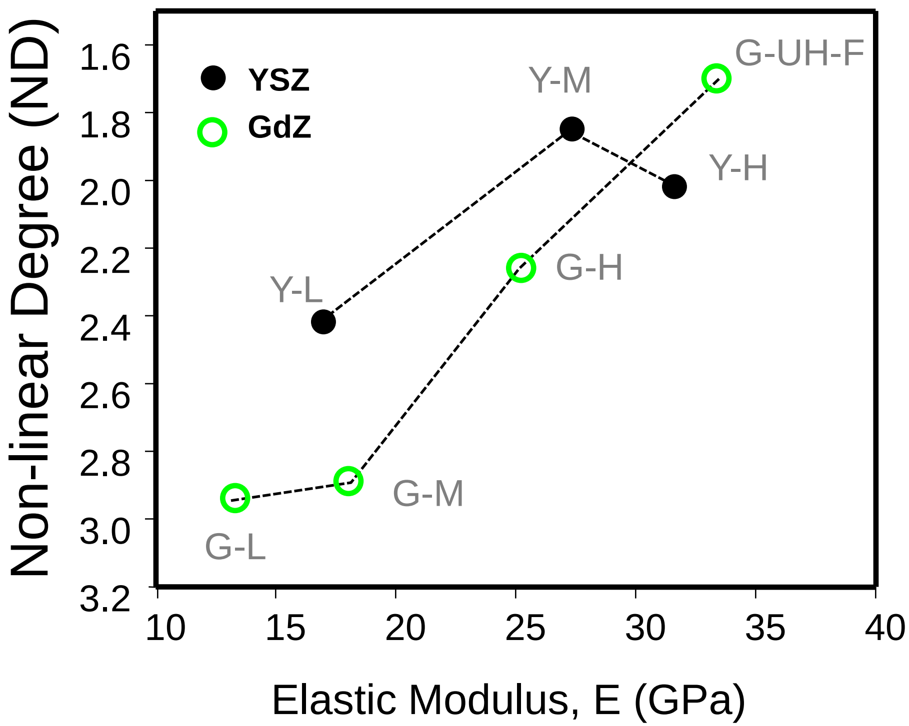
H-H

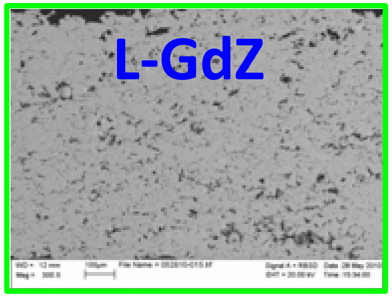
Matching compliance of GdZ with that of YSZ

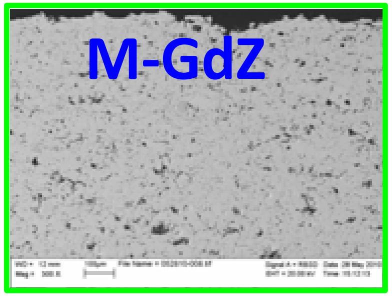


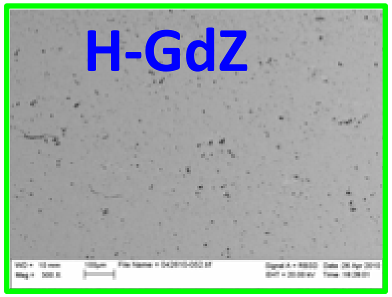




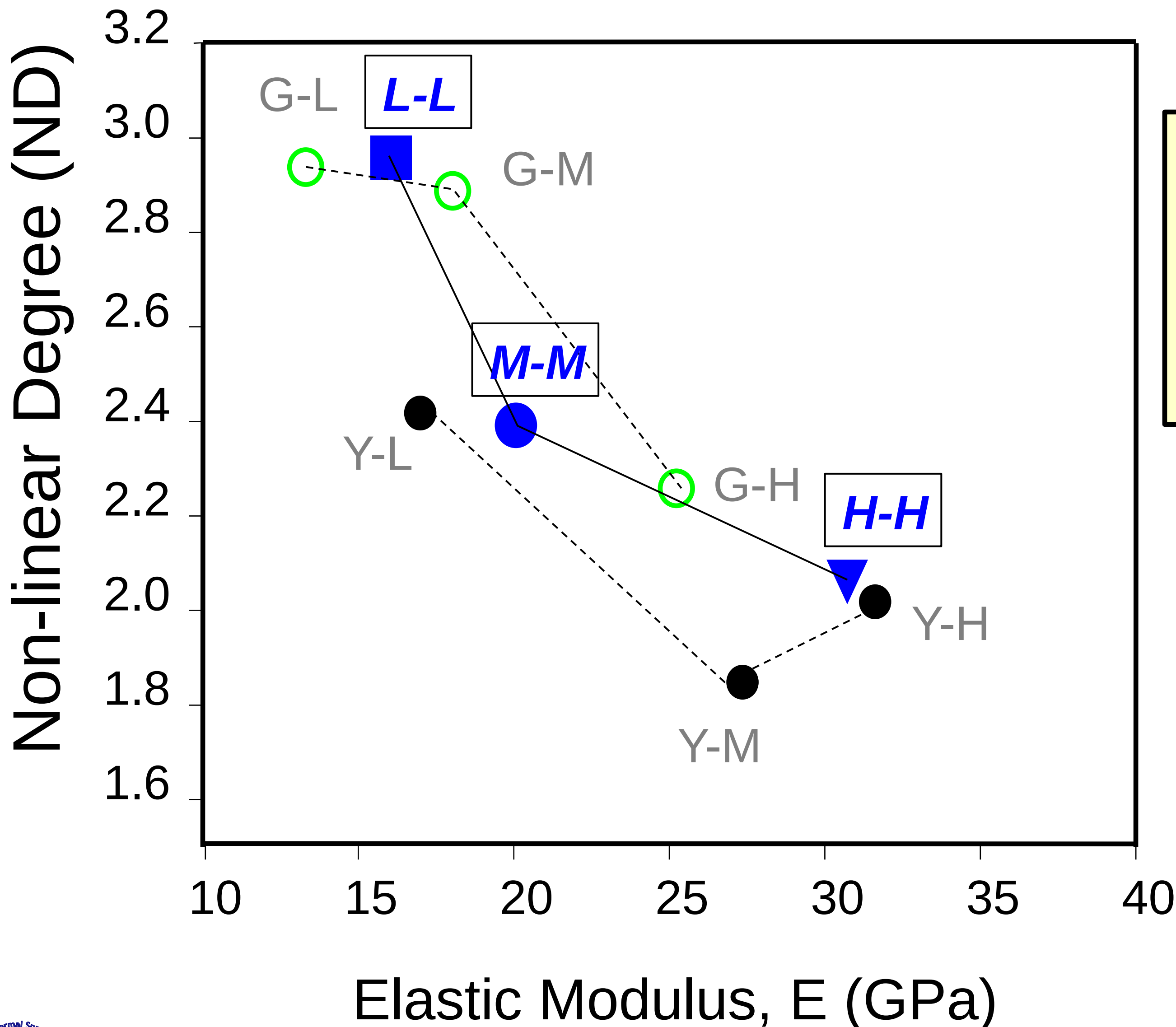


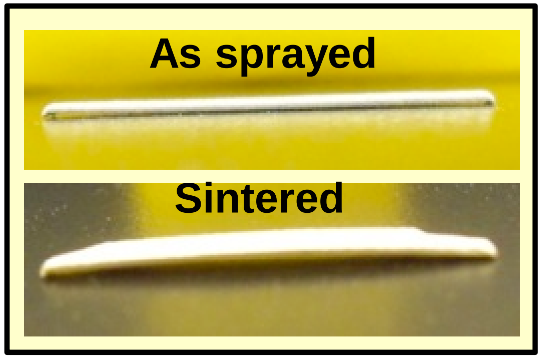






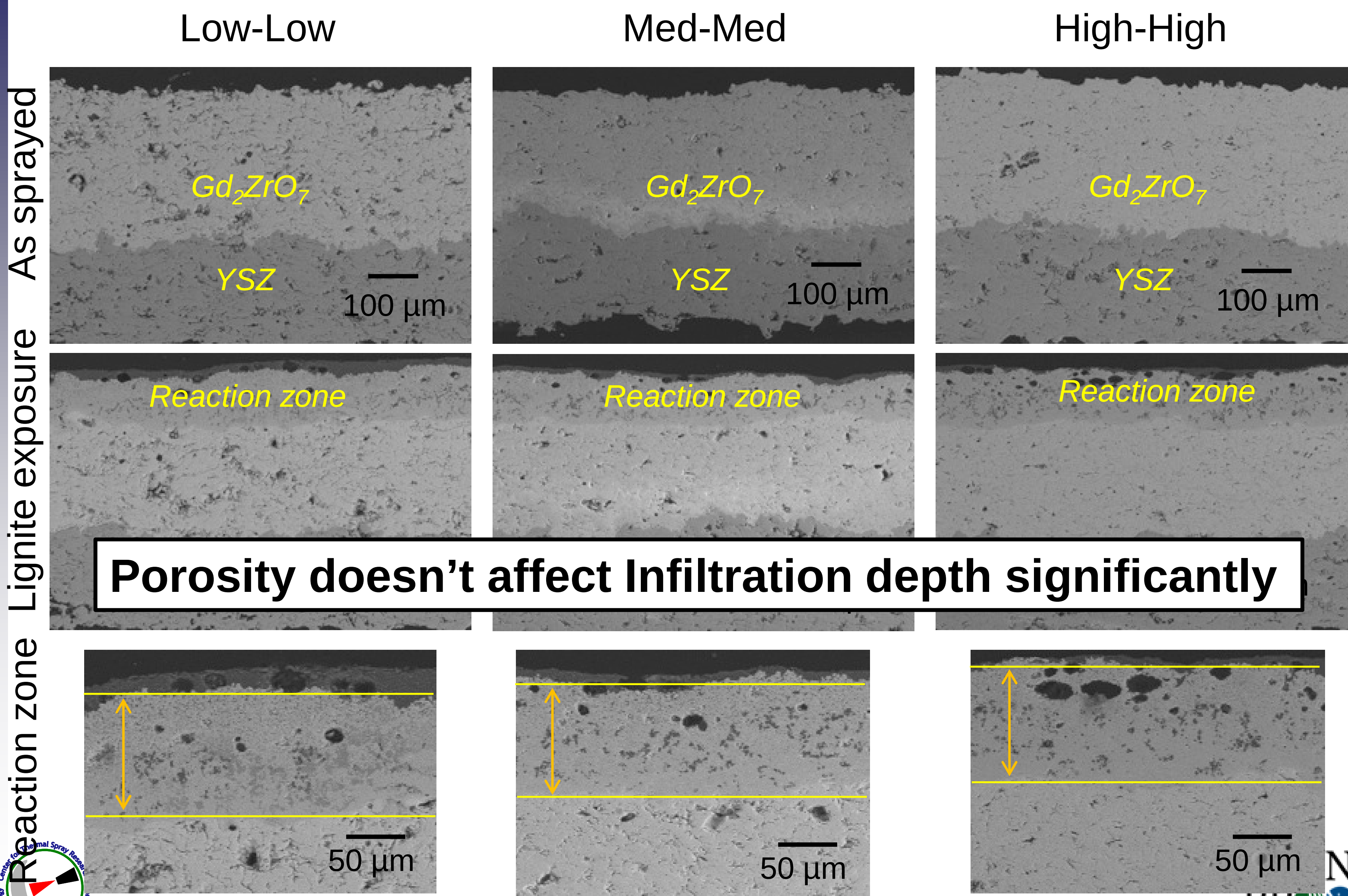
Sintering compatibility of bi-layers via processing





Work in progress

Lignite ash exposure @ 1200C for 24 hours

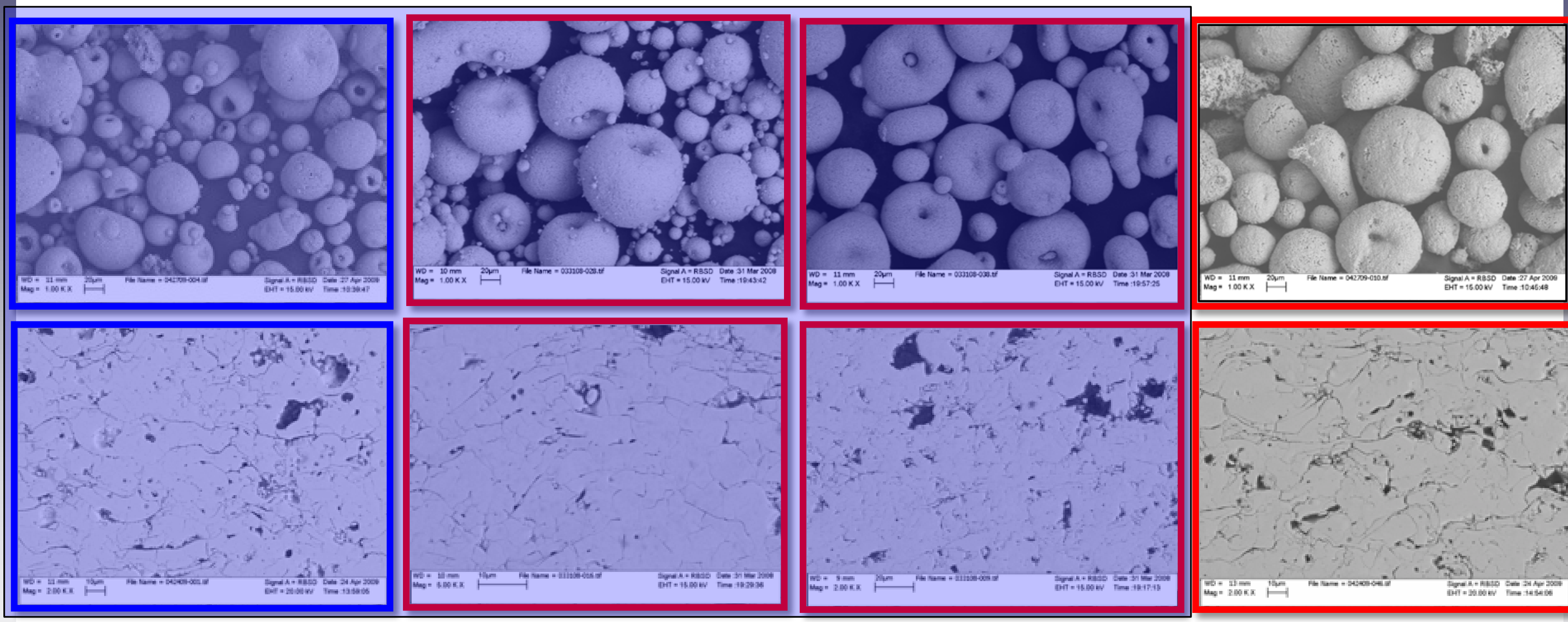


Porosity doesn't affect Infiltration depth significantly

Simulated Lignite ash was provided by Prof. Nitin Padture, Brown University

IGCC Turbine Coating Properties: Material Effects

YSZ | $La_2Zr_2O_7$ | $Gd_2Zr_2O_7$ | Co-doped



NASA Co-doped materials

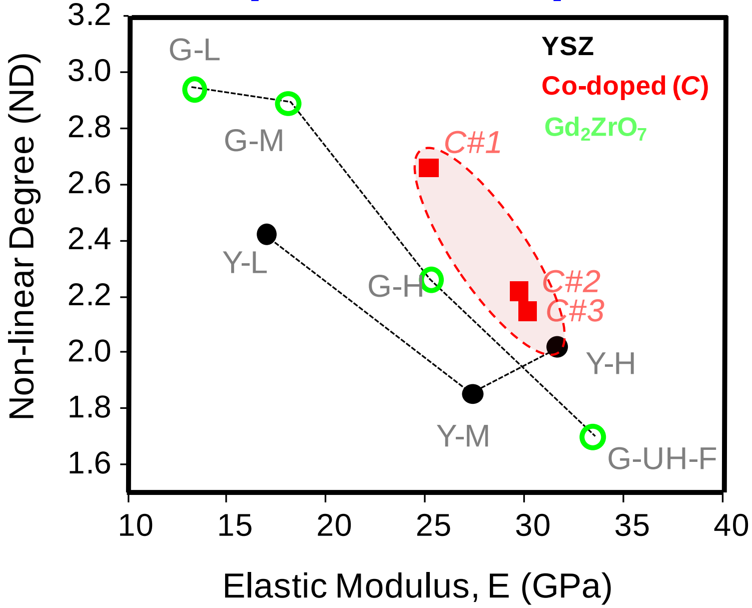
NASA Co-doped materials for topcoat

Comp. 1	1.5mol% Yb_2O_3 1.5mol% Gd_2O_3 2.1mol% Y_2O_3 Balance ZrO_2	❑low K ❑sintering resistant ❑compatible with MCrAlY BC ❑high erosion resistance	**t' phase**
Comp. 2	1.2mol% Yb_2O_3 1.2mol% Gd_2O_3 1.7mol% Y_2O_3 Balance ZrO_2		
Comp. 3	1.9mol% Yb_2O_3 2.0mol% Gd_2O_3 6.0mol% Y_2O_3 Balance ZrO_2		**Lower K cubic**
Comp. 4	3.0mol% Yb_2O_3 3.0mol% Gd_2O_3 3.0mol% Y_2O_3 Balance ZrO_2		

Material courtesy: Dongming Zhu, NASA Glenn

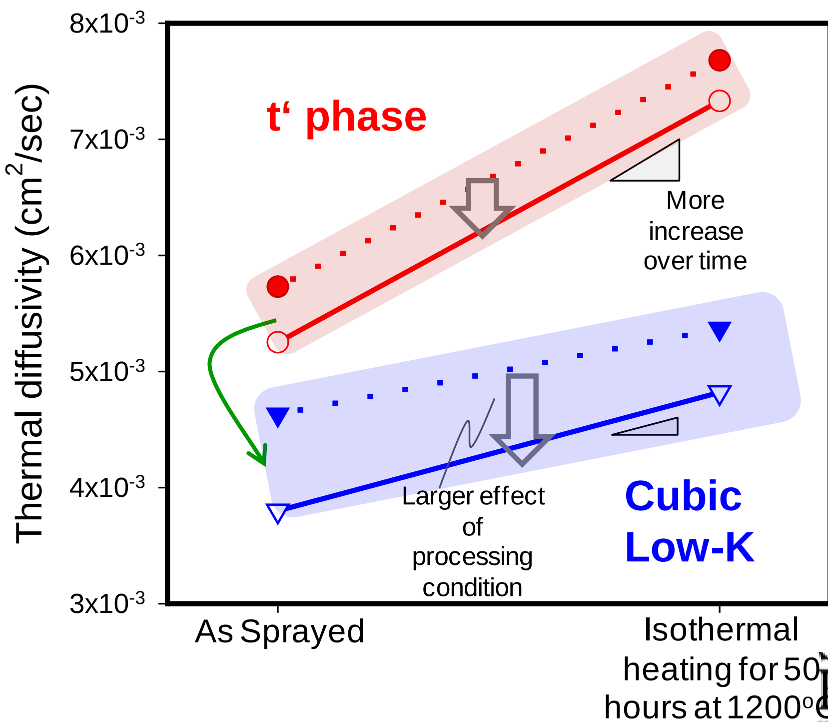
Knowledge application to Co-doped materials

Non-linear parameter space



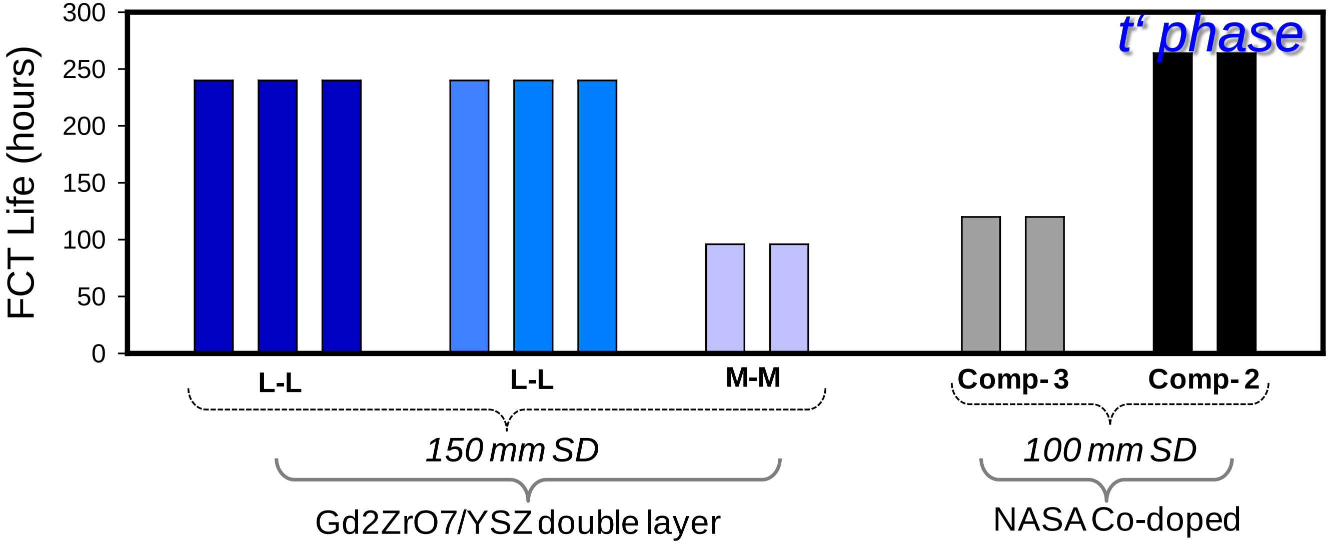
G-L	Gd_2ZrO_7 Low Cond
G-M	Gd_2ZrO_7 Medium Cond
G-H	Gd_2ZrO_7 High Cond
G-UH-F	Gd_2ZrO_7 Ultra High Cond (Fine powder)
Y-L	YSZ Low Cond
Y-M	YSZ Med Cond
Y-H	YSZ High Cond
C#1	Co-doped # 1 Med Cond
C#2	Co-doped # 2 Med Cond
C#3	Co-doped # 3 Med Cond

Thermal properties



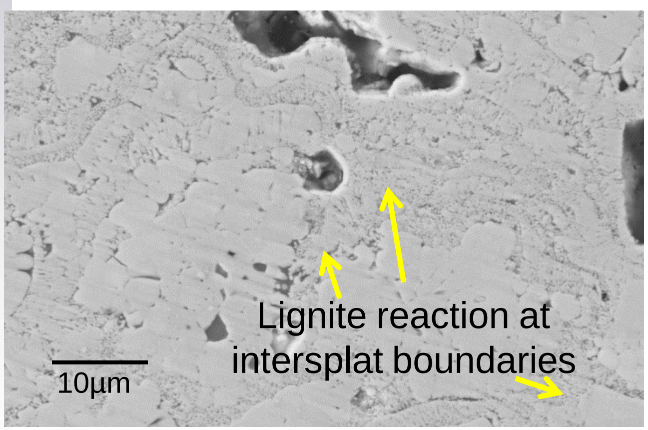
Isothermal exposure: System level

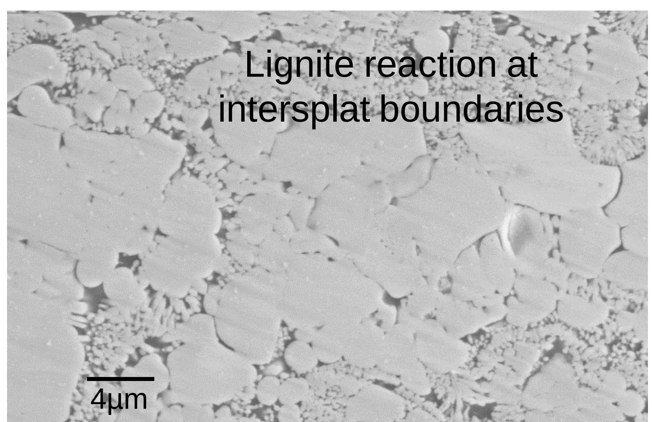
Single layer YSZ~ 600hrs



- ✓ *Limited FCT life*
- ✓ *further process optimization*

Lignite exposure at 1200°C





- ➢ *Poor performance against lignite ash*
- ➢ ***Can not be used as top layer***

Co-doped powder#2 and 3: Reaction with Lignite at high temperature

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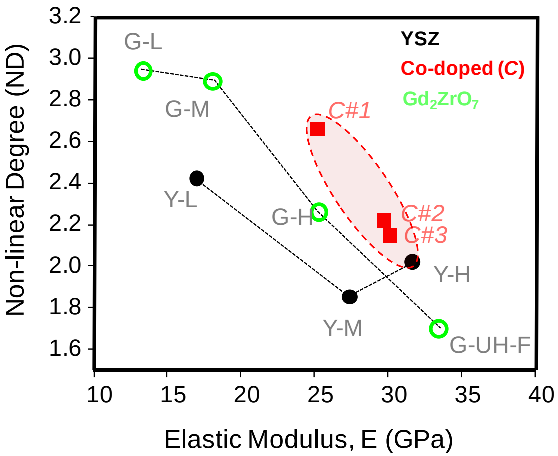
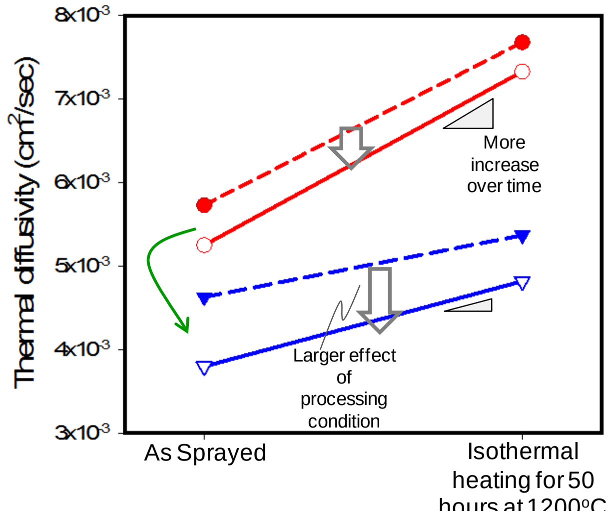
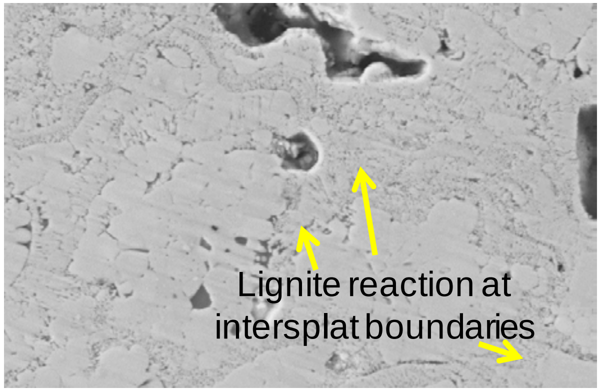
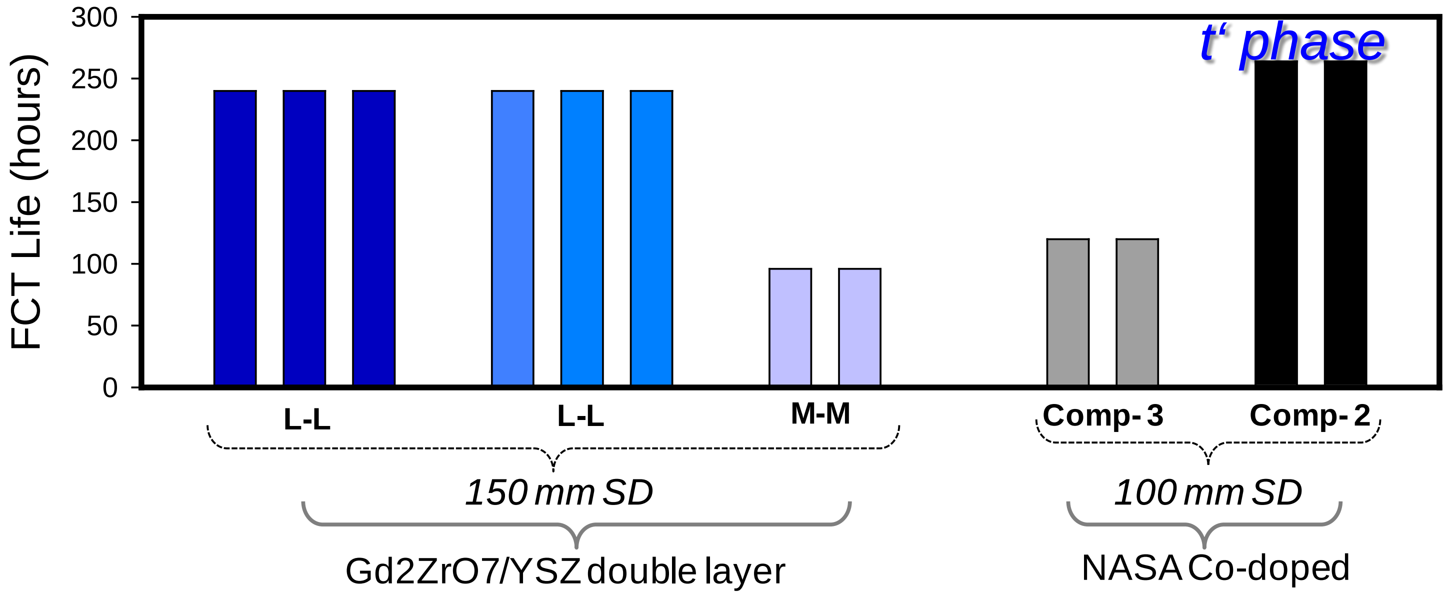
Co-doped powder: summary









❑ Promises and Challenges.

Task update summary

Task Discription	% Progress	Status	Comment
1. Project Management and Planning			
1.1 Revise and Maintain Project Management Plan	100	Completed	
1.2 Quarterly Assessment and Reporting	100	Completed	
1.3 Annual Meetings	100	Completed	
1.4 Final Report	0	On schedule	
2. Bond Coat Processing and Evaluation			
2.1 Bond Coat Processing and Microstructural Evaluation	90	Completed	Additional characterization
2.2 Determination of Bond Coat Oxidation Behavior in High Temperature Water Vapor	60	Completed/revisiti	Working with ORNL
2.3 Final Selection of Bond Coat Material for System-Level Coating	90	Completed/revisiti	Collaboration with ORNL
MILESTONE: Determination of bond coat oxidation behavior in controlled atmospheres	60	Completed/revisiti	Working with ORNL + Setup developed at CTSR
MILESTONE: Down-selection of optimum bond coat material and processing for multilayer coating	80	Completed/revisiti	In progress, working with ORNL
3. Thermal Barrier Processing and Evaluation			
3.1 Process Optimization of Zirconates Using Diagnostics and In Situ Property Sensing	100	Completed	Additional process conditions are being considered
3.2 Evaluate Sintering Behavior of Bilayer TBC	100	Completed	More work is being done
3.3 Determine Thermal Conductivity Changes Due to Thermal Gradient Exposure	50	Behind Schedule	Burner rig test setup is completed
3.4 Determine Coefficient of Thermal Expansion for Gd2Zr2O7	100	Completed	More measuremnets will be conducted
3.5 Erosion Testing of Dense Top Coat	100	Completed	
MILESTONE: Process maps will be completed relating processing conditions to properties for plasma sprayed Gd2Zr2O7	100	Completed	
MILESTONE: Development of gradient thermal conductivity model for plasma sprayed Gd2Zr2O7	80	Completed	Application of the model for various layers is being considered
MILESTONE: Development of erosion-resistant Gd2Zr2O7 top layer for TBC	100	Completed	Additional processing conditions are being explored
4. System-Level Evaluation of Multifunctional Coating			
4.1 Production of Multilayer TBC	50	On schedule	
4.2 Rig Testing	10	On schedule	Burner rig test setup is completed
4.3 System-Level Oxidation and Hot Corrosion Testing	30	On schedule	FCT test setup is completed and started
4.4 Residual Stress and Composition Evolution in Multilayer Coatings	30	On schedule	
4.5 Additional Ex Situ Characterization of Multilayer Coatings	35	On schedule	
MILESTONE: System-level determination of oxidation and hot corrosion behavior of multilayer TBC	20	On schedule	FCT and Burner rig setup
MILESTONE: Determination of residual stress state and compositional evolution in multilayer coatings exposed to high temperature water vapor atmospheres	NA	On schedule	
MILESTONE: Determination of thermal and mechanical properties in multilayer TBCs after high temperature, controlled atmosphere exposures	NA	On schedule	

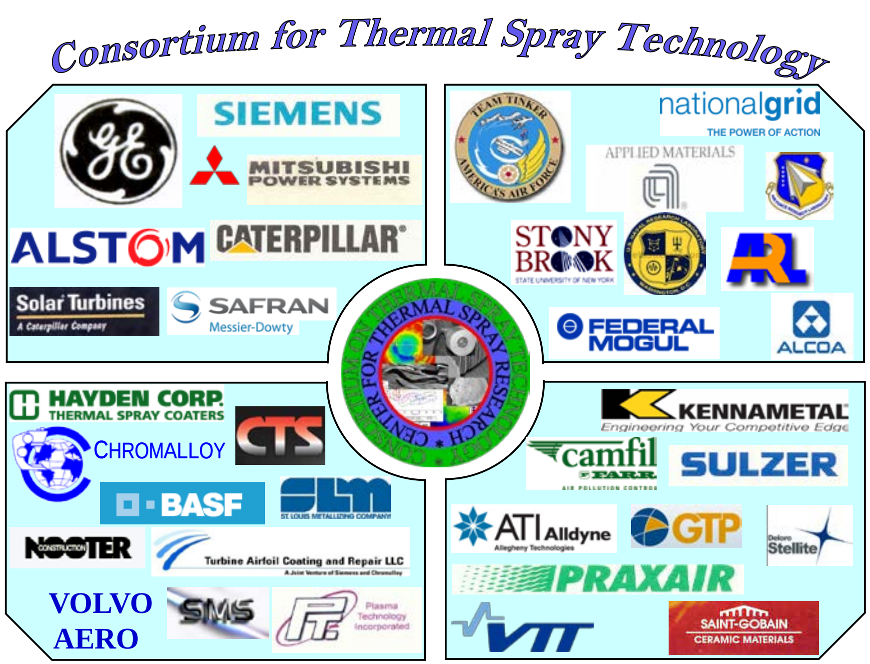
Collaboration Efforts: Industrial Partnerships

SAINT-GOBAIN CERAMIC MATERIALS — Working with them regarding $Gd_2Zr_2O_7$ commercial thermal spray powder development

SIEMENS — Anand Kulkarni of Siemens for Substrate and FCT testing

Oak Ridge National Laboratory — Bruce Pint/Allan Haynes ORNL

A.Shyam, E.Lara-Curzio ORNL HTML



Consortium is operated by the Center for Thermal Spray Research at Stony Brook University

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