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

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DOE UTSR Meeting, Oct 22nd, Purdue University

Center for Thermal Spray Research

AT STONY BROOK UNIVERSITY

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Program Manager: Dr. Briggs while

Dwivedi et al., JACerS, DOI: 10.1111/jace.13021

Viswanathan et al., JACerS, DOI: 10.1111/jace.13033

Dwivedi et al., JTST, Under Review

Viswanathan et al., JACerS, Under Review

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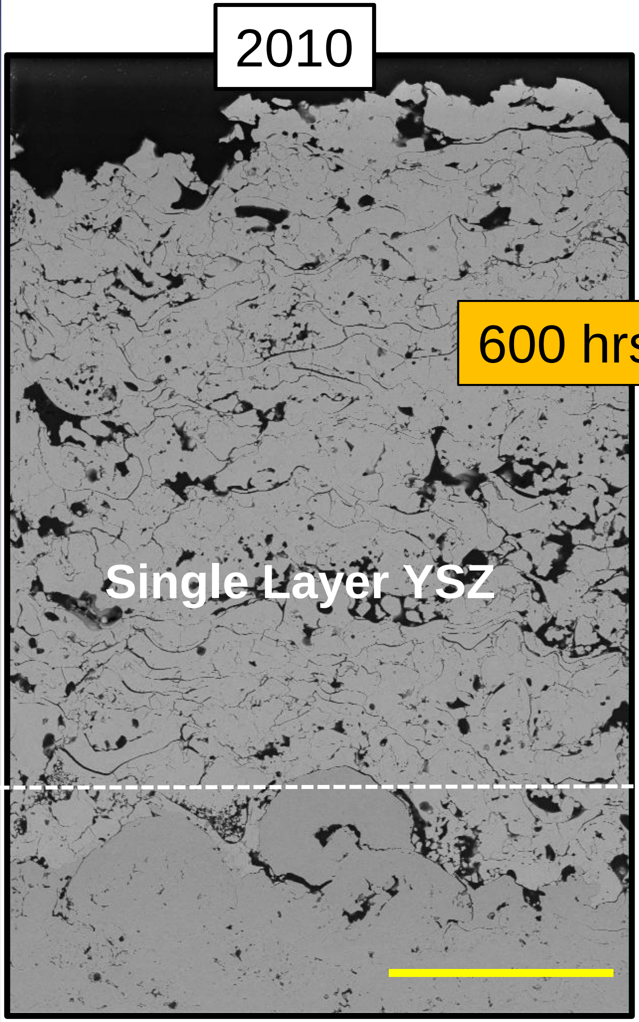
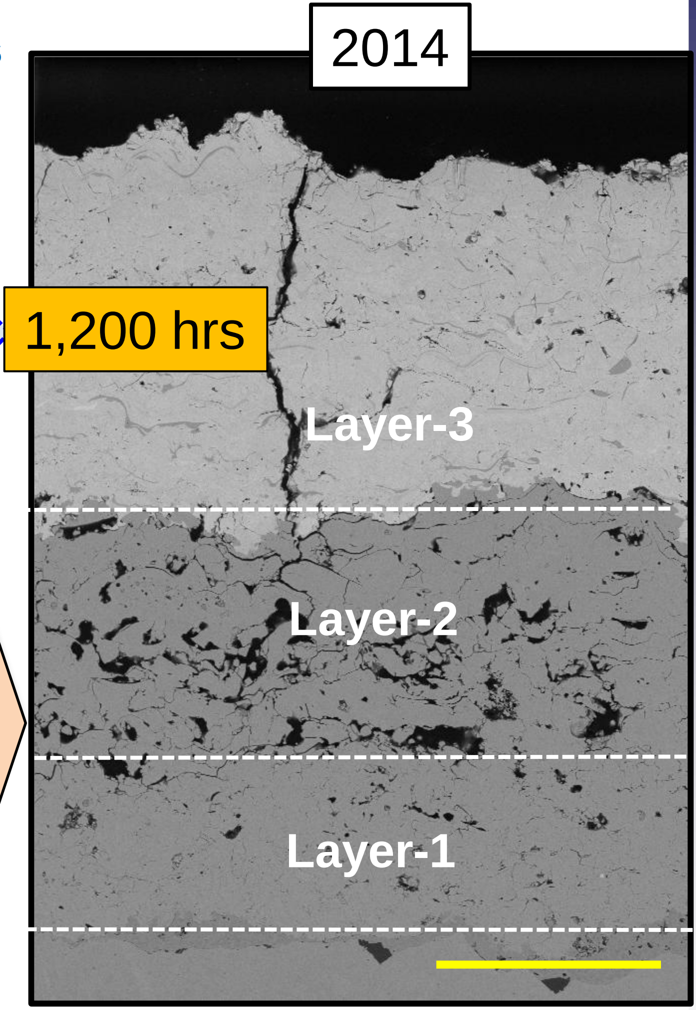
Snapshot of accomplishment under UTSR program



- 50 +coating conditions
- 40+ architectures
- 600+ FCT samples

4 years

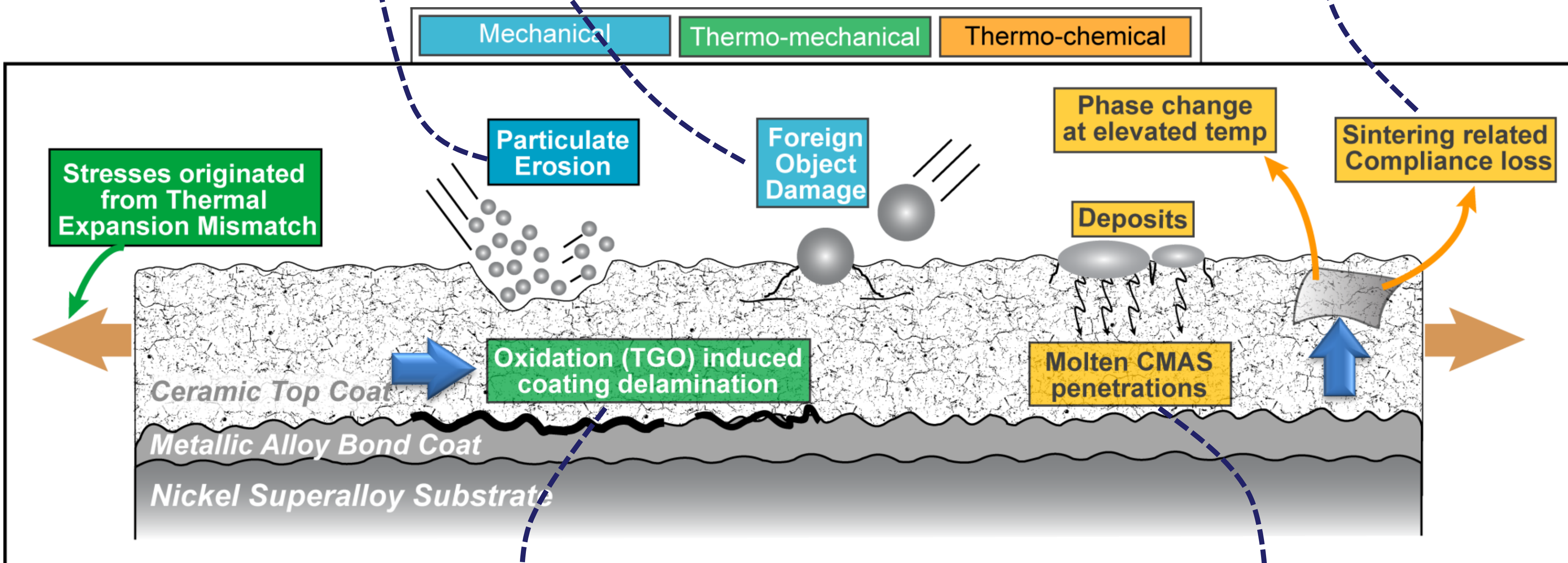


- Adequate erosion resistance
- Significantly higher durability
- CMAS resistance
- Mechanisms and Methodology to incorporate andy new composition

Interplay between TBC durability and “manufactured” coating properties

- Ceramic strength/toughness
- Coating density

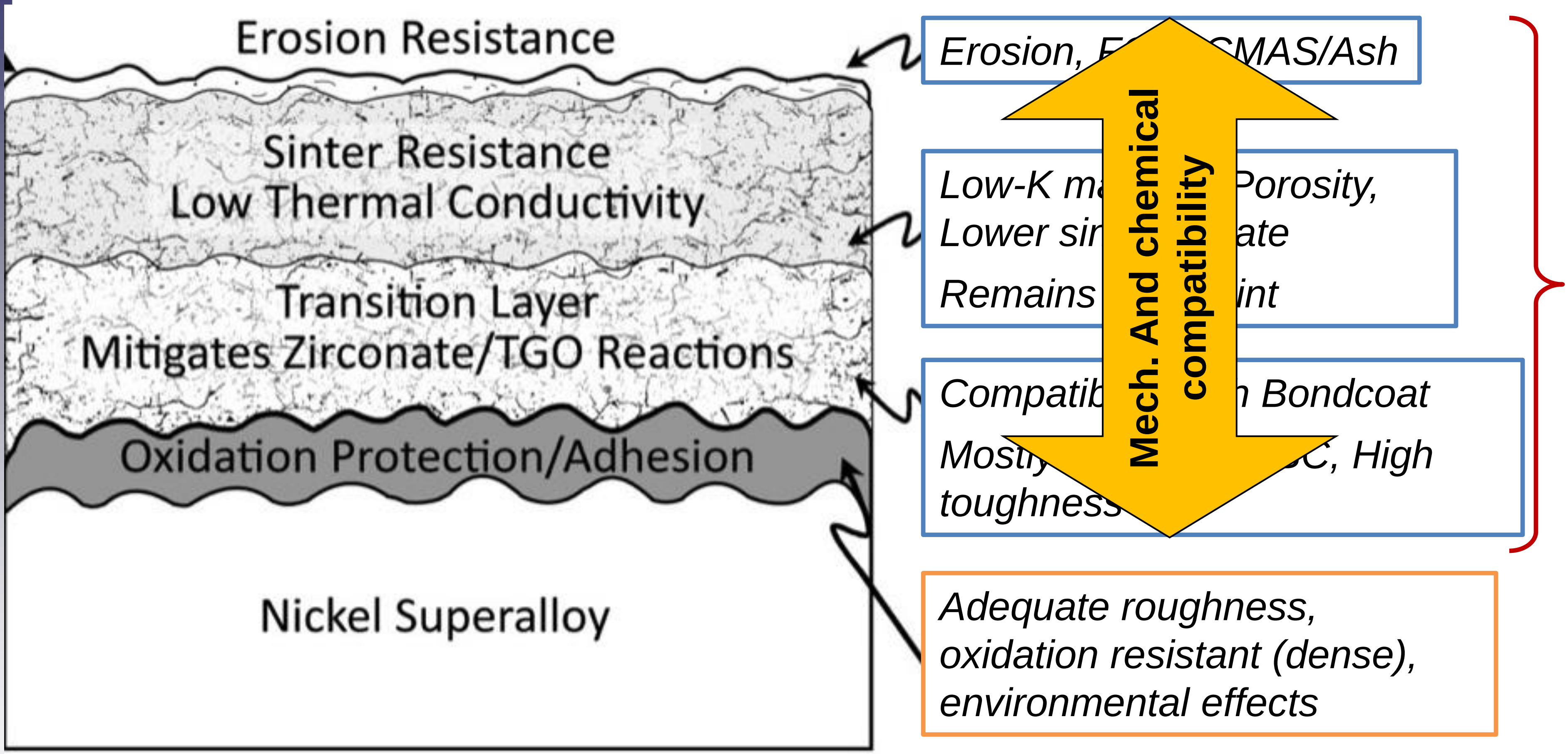
- Ceramic coating compliance and ceramic chemistry
- Coating porosity/cracks



- Bond coat chemistry, Roughness
- Ceramic coating toughness
- Bond coat roughness
- Coating thickness

- Ceramic coating composition
- Pore architecture
- Coating thickness

Multilayered architecture to combat multifunctional requirements



Plasma spray is naturally suited for such layered manufacturing

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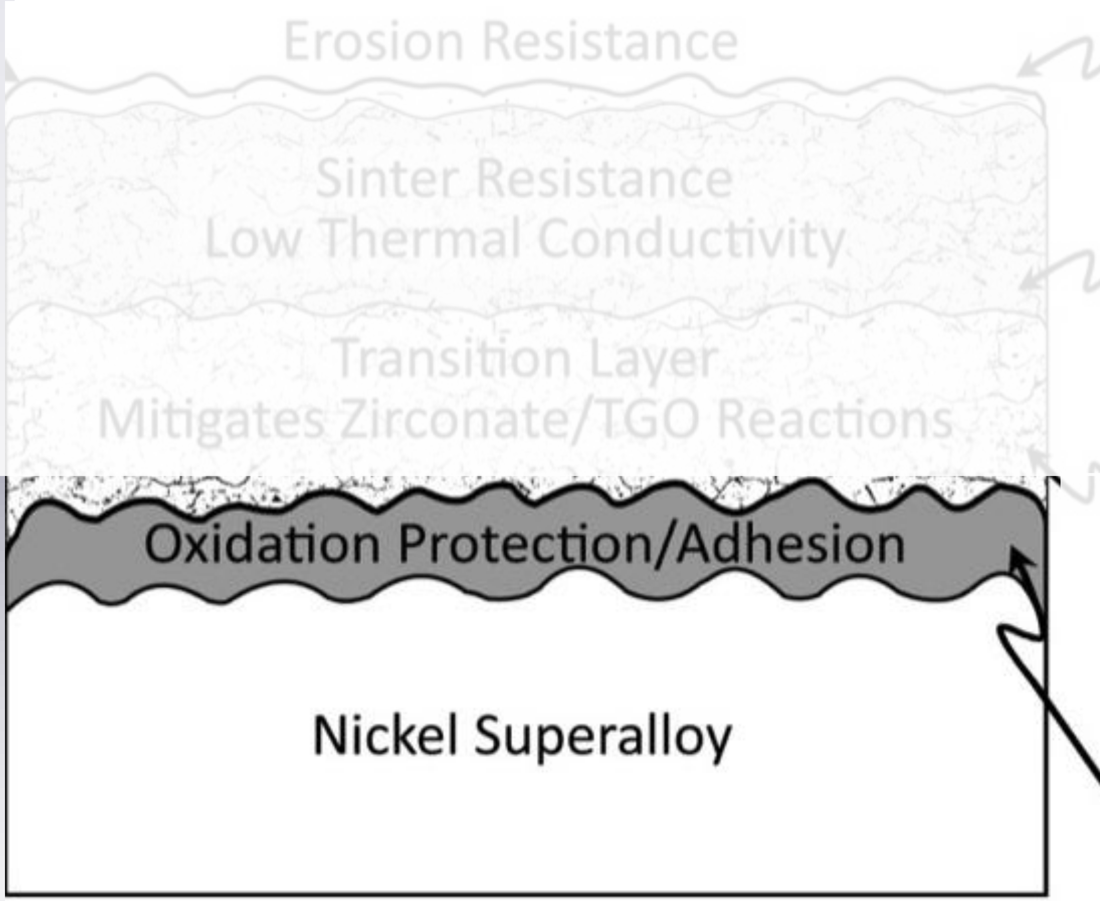
versity

Multilayered architecture to combat multifunctional requirements



Erosion, FOD, CMAS/Ash

Low-K material, Porosity, Lower sintering rate

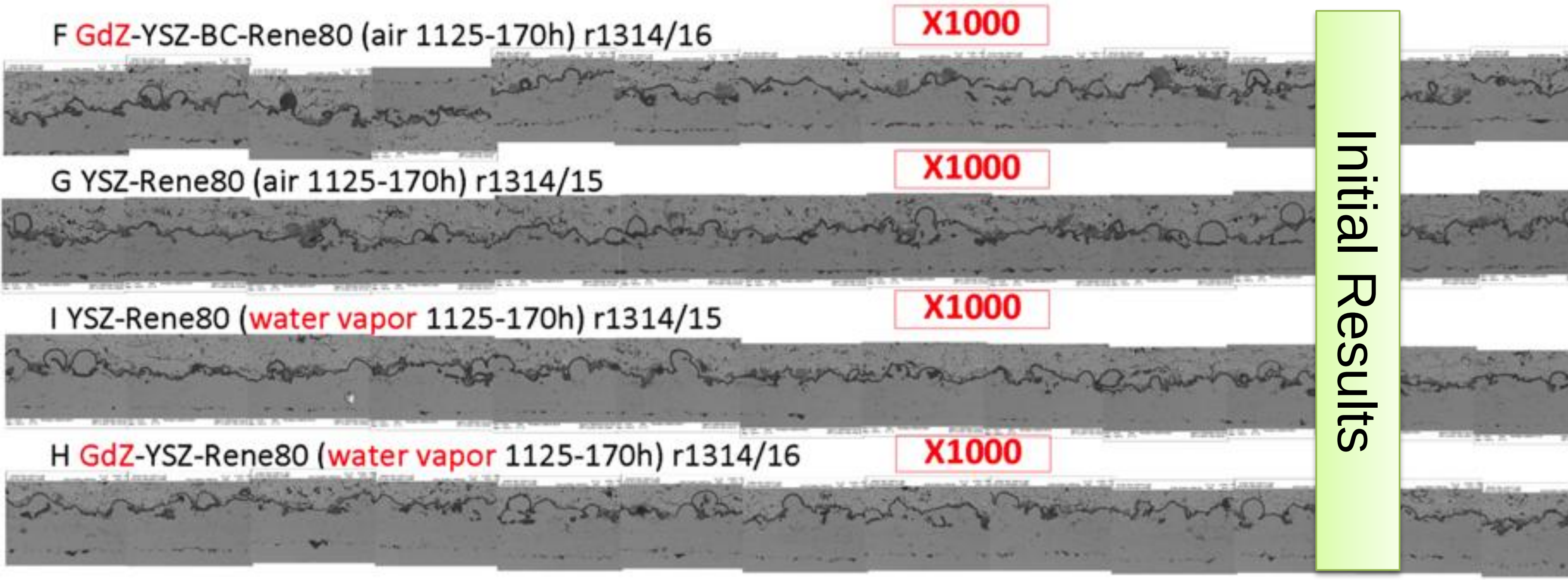
Remains complaint

Compatibility with Bondcoat

Mostly traditional TBC, High toughness

Adequate roughness, oxidation resistant (dense), environmental effects

Impact of water vapor on conv. & new TBC materials

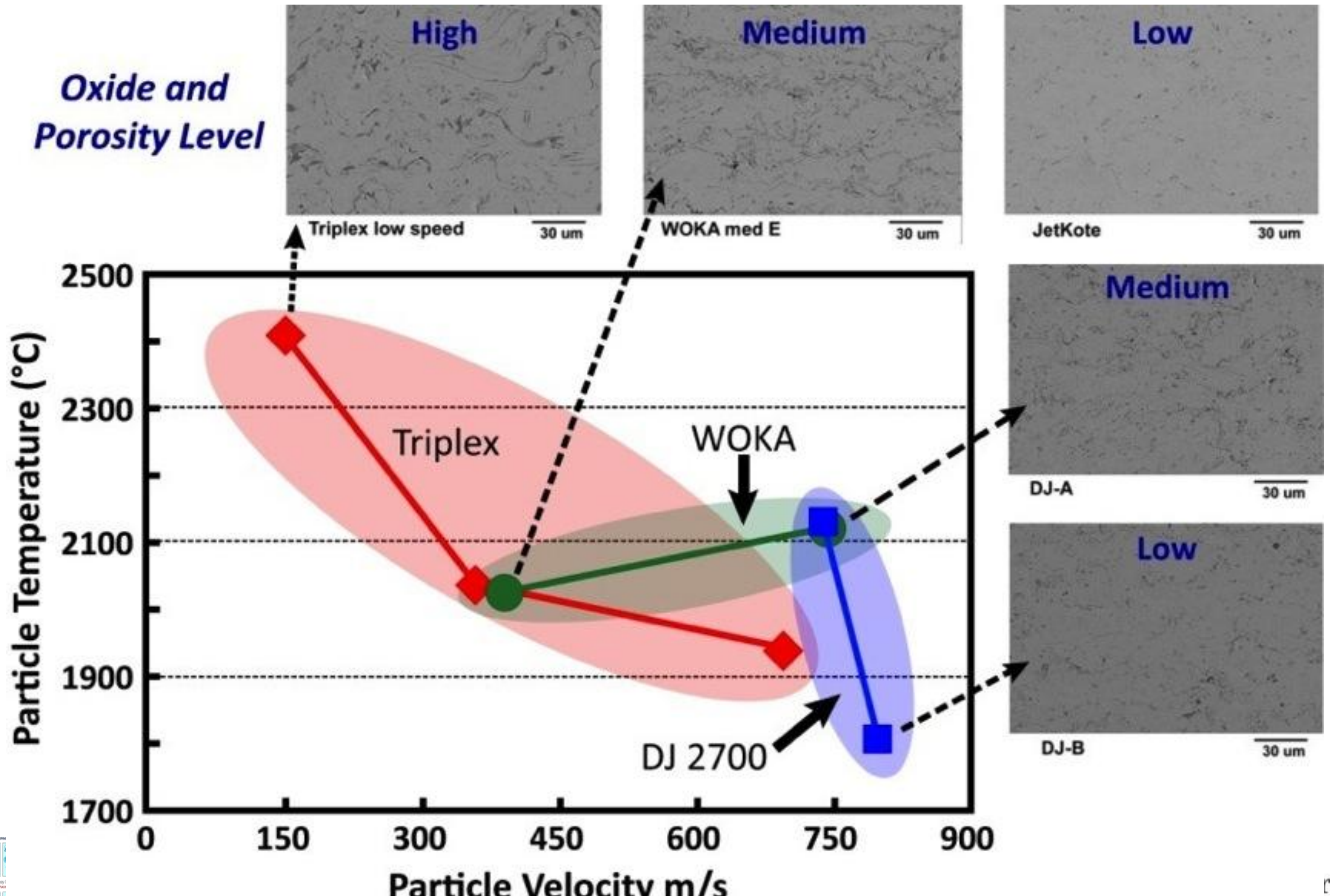


No significant difference found at this temperature, and long term exposures

Collaborative partnership with ORNL- Materials selection

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

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



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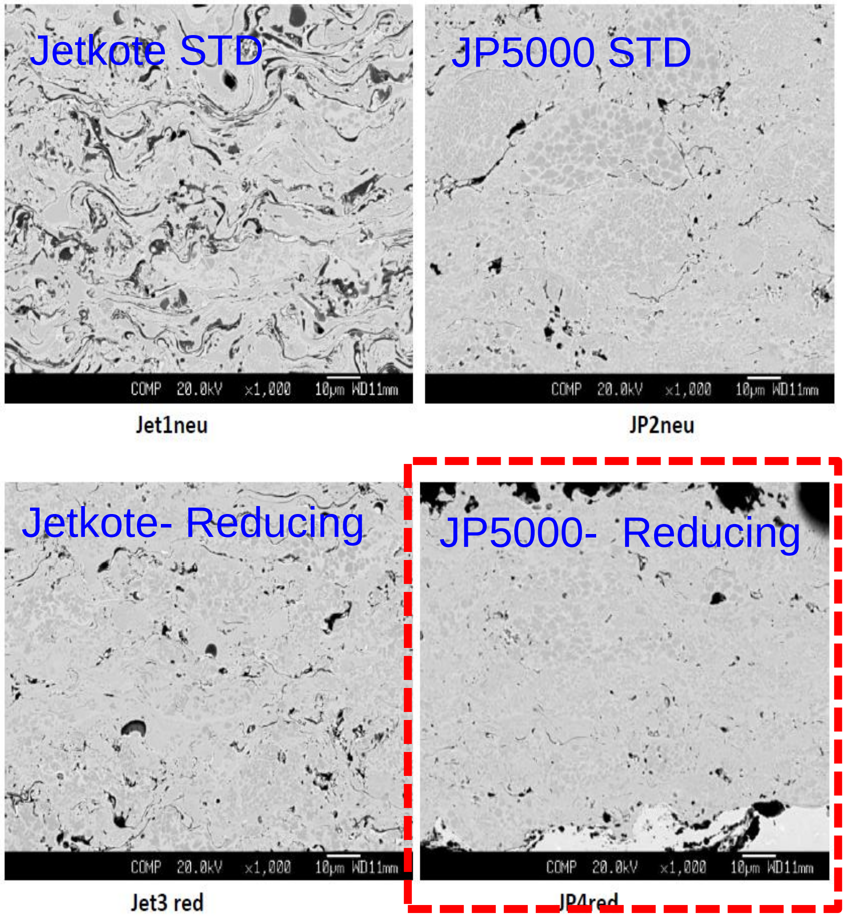
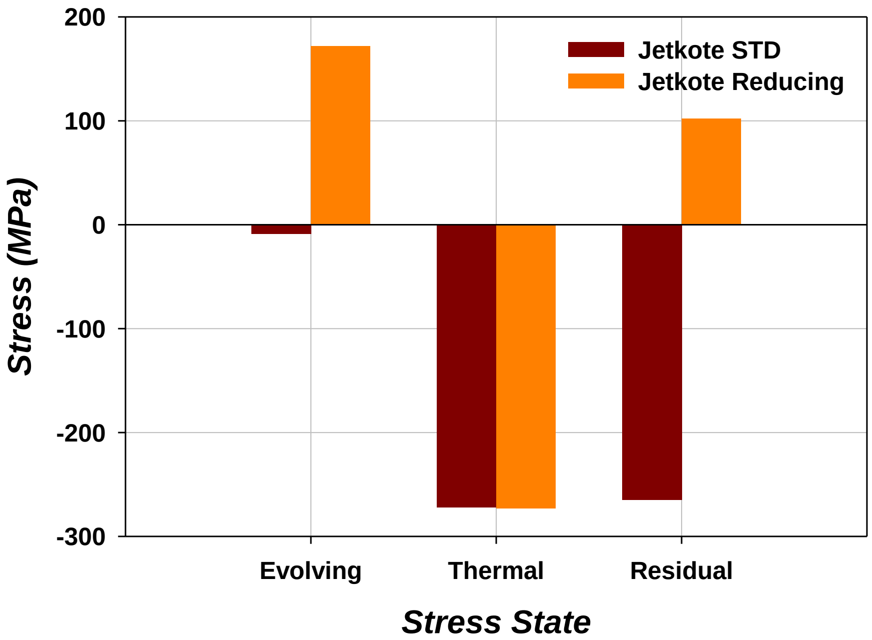
Processing Effects on HVOF Bond Coats

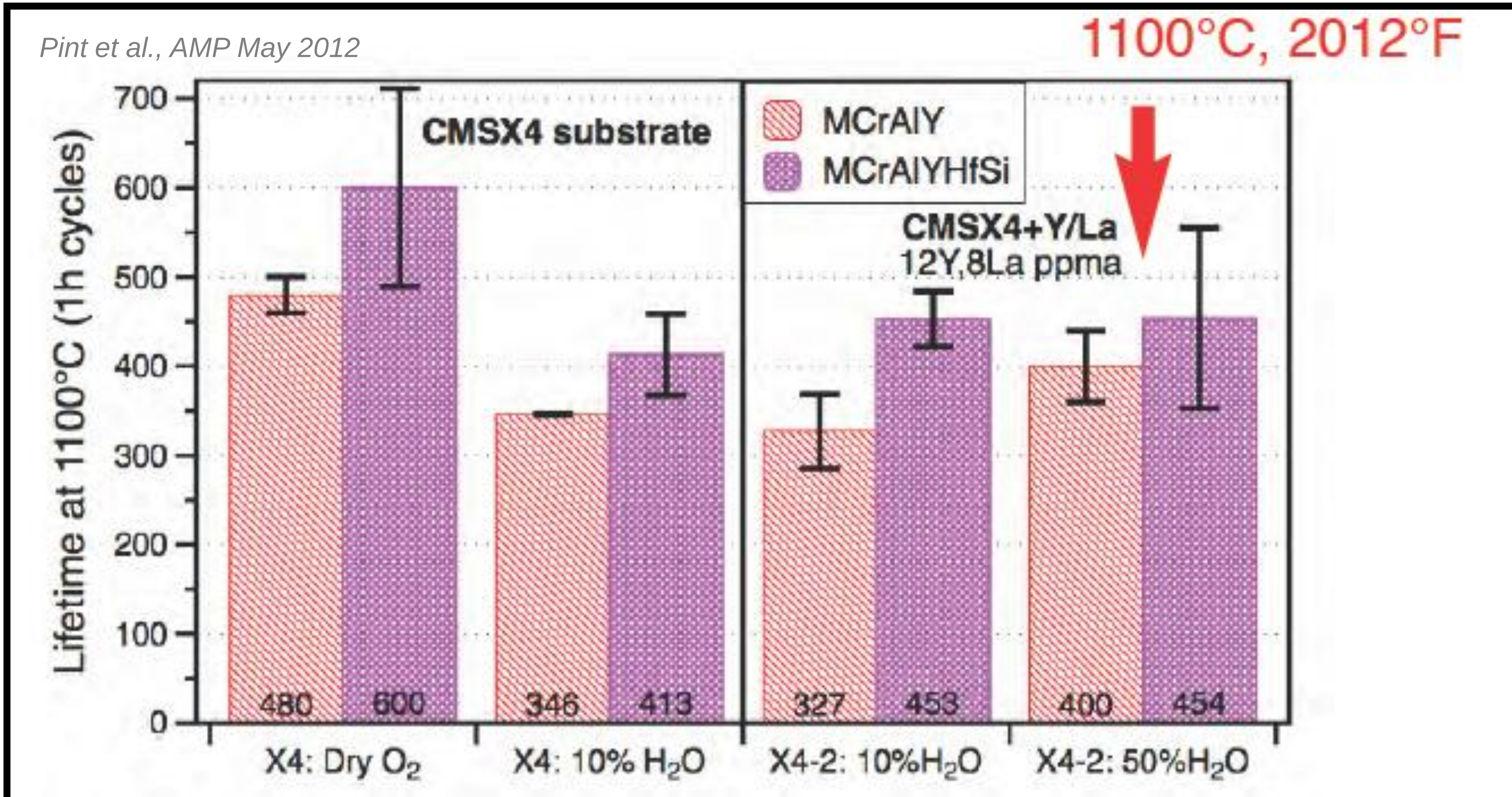




HVOF process type and spray conditions significantly affect deposition stresses and final stress state of the coaitng.

JP5000 chosen due to microstructure and compressive stress state.

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

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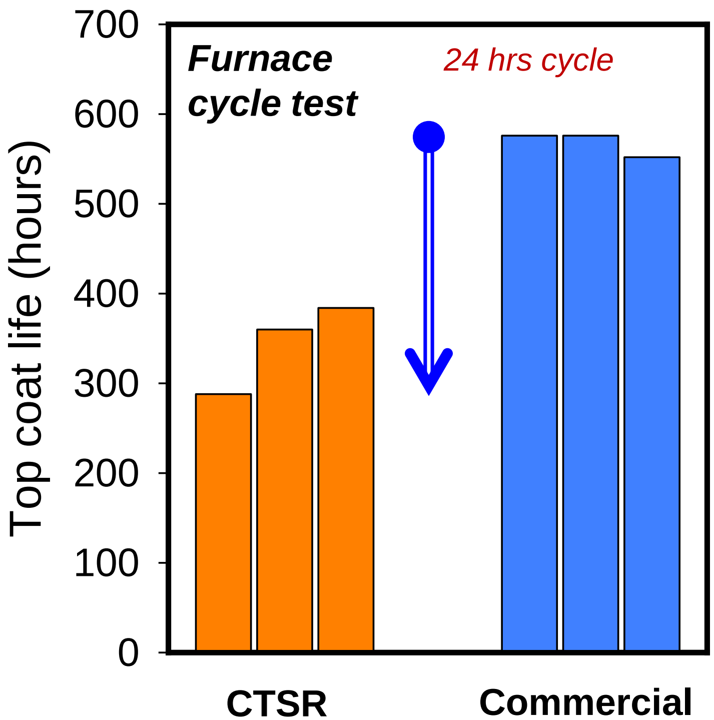
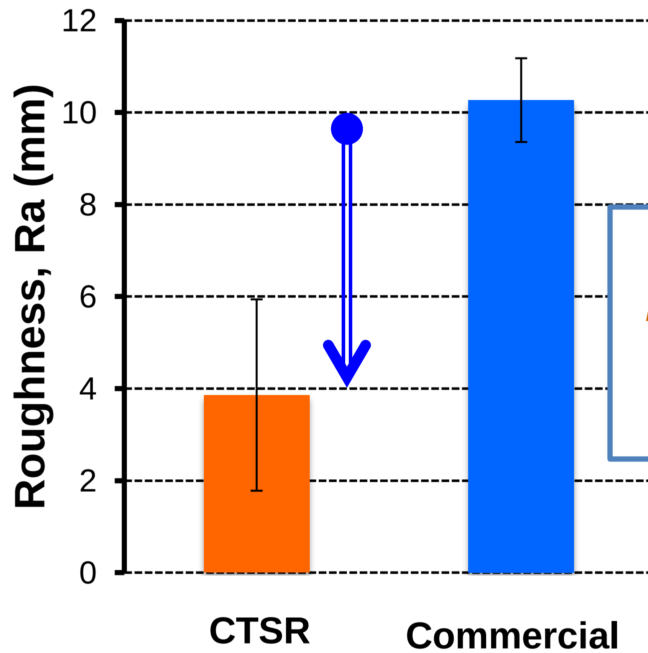
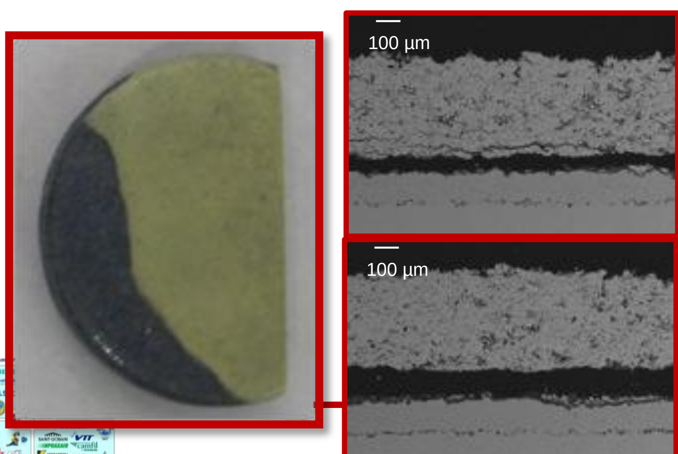
BC roughness effects may overshadow chemical effects?



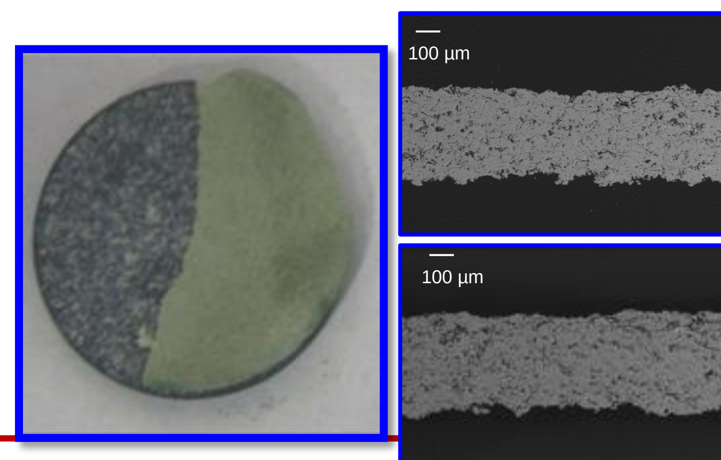
NiCoCrAlYHfSi



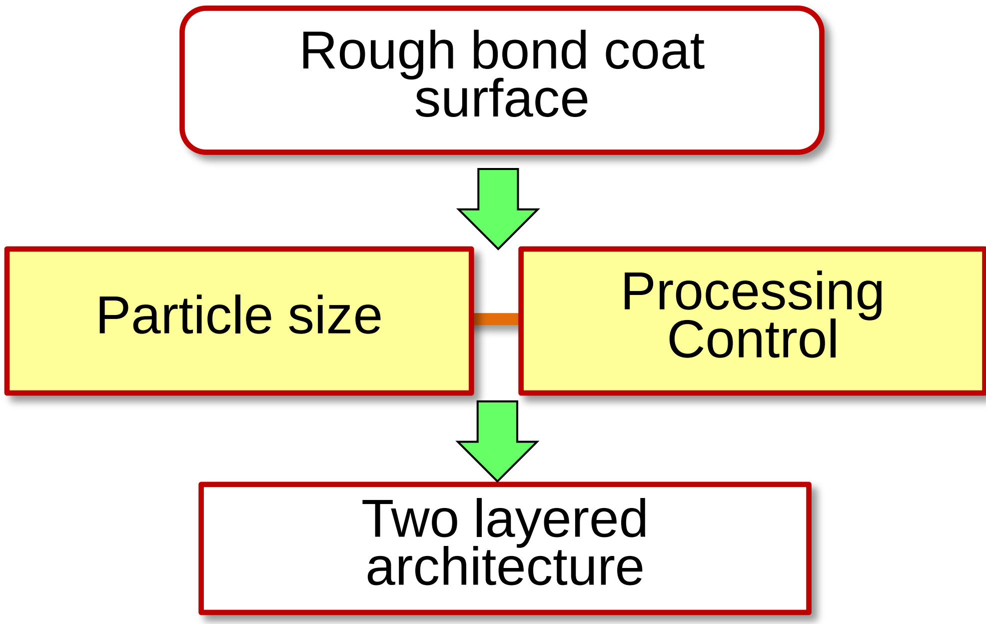
Bondcoat layer require adequate roughness for high TBC life



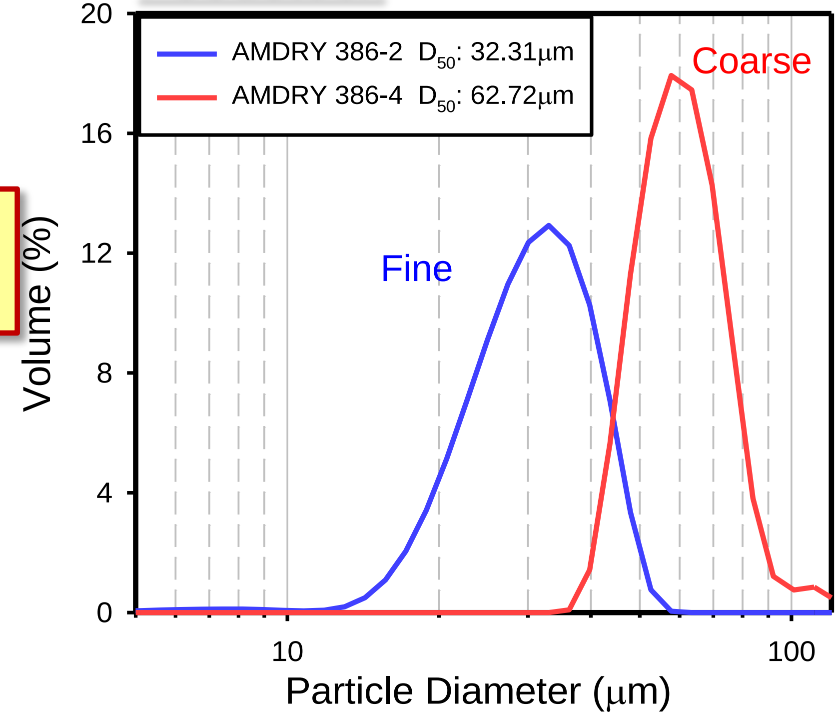
Fracture in TGO



Fracture in topcoat



Feedstock

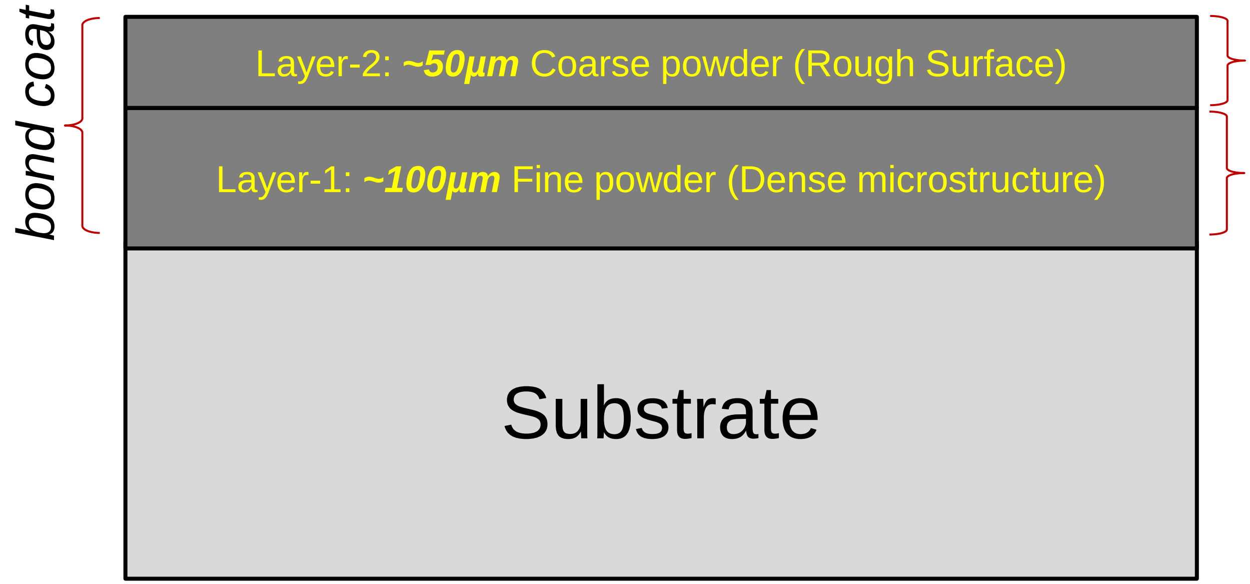


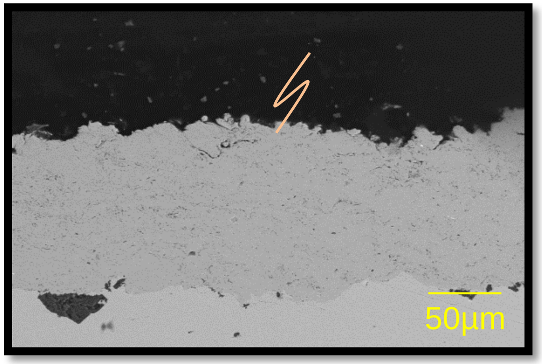
Strategy

- Utilize the *Fine* particle size for *Dense Oxidation Resistant* initial layer
- Utilize the *Coarse* particle size to tailor the topography for high *surface roughness*

Deposition Scheme

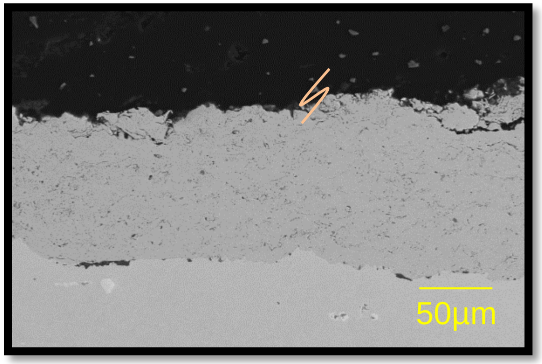
Two layers bond coat deposition





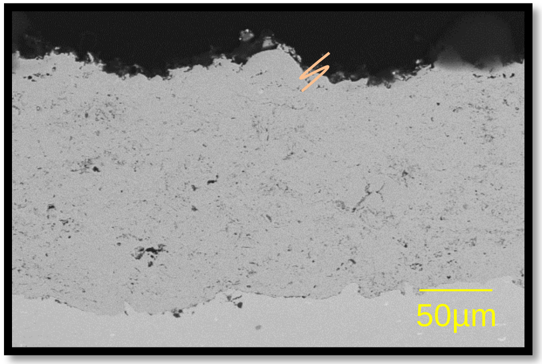
Densest bottom layer

Poor splat cohesion



Denser bottom layer

Poor splat cohesion and some cracking

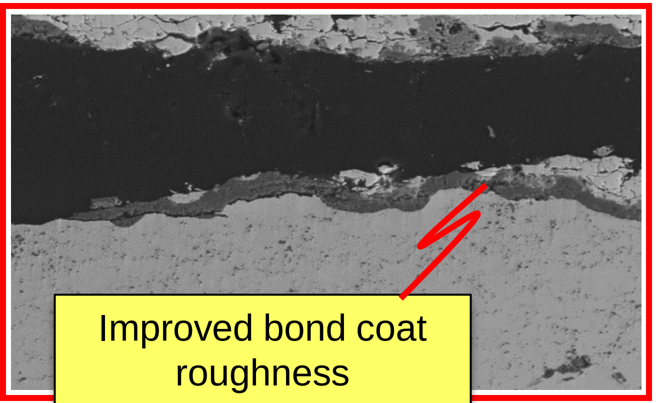


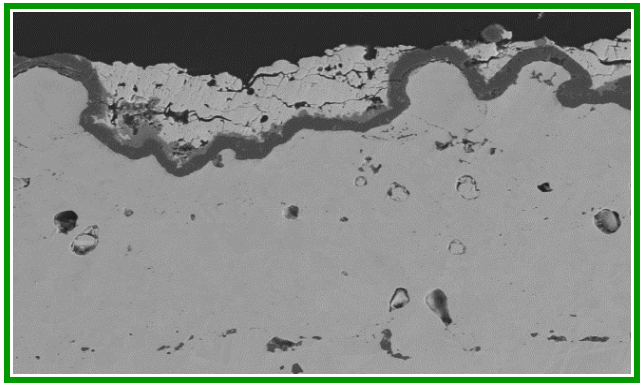
Least dense bottom layer

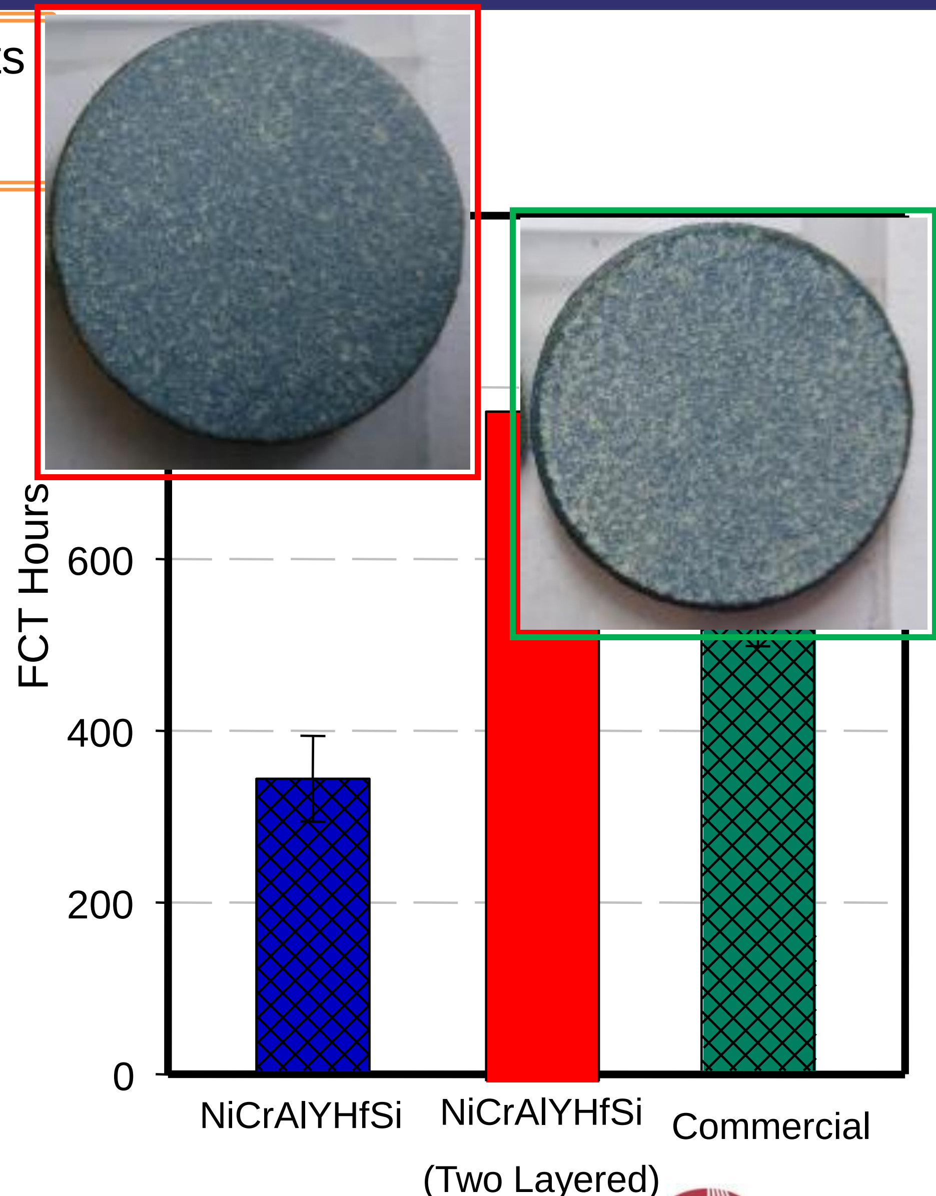
Good particle melting and splat cohesion

Performance of the Two Layered Bond Coat

Similar top coats on 3 different bond coats
FOCUS : Two Layered Bond Coat







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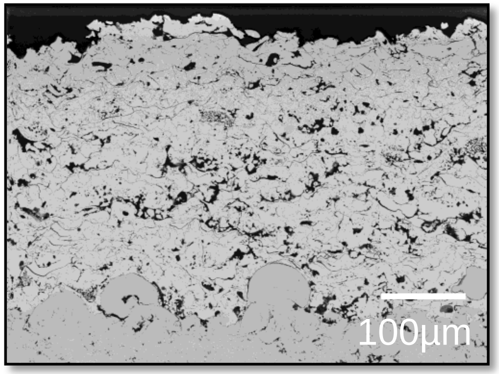
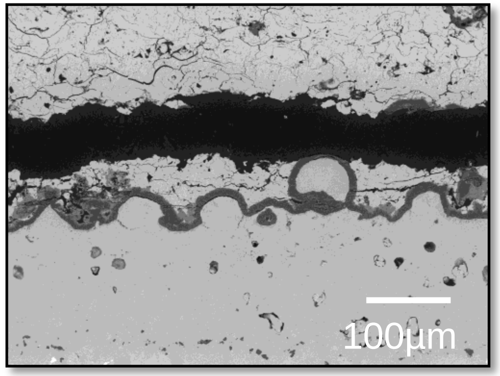
Failure mechanism of TBCs: Occurring at BC-TC interface

As-deposited TBC

Failed (~600 hrs)



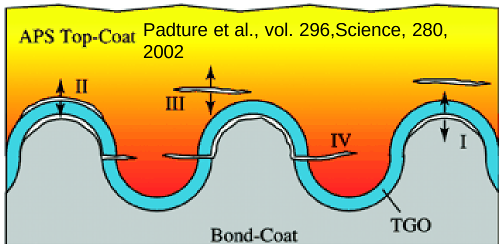


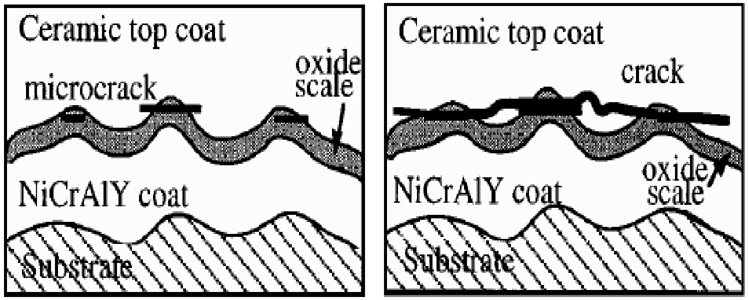
With extending service hours

- **TGO Growth:** Additional Stress build up at the interface. (limited control)
- **Sintering**: loss in compliance => higher stress build up. Higher driving force for crack propagation. Process optimization to design coating with large compliance in as sprayed condition.

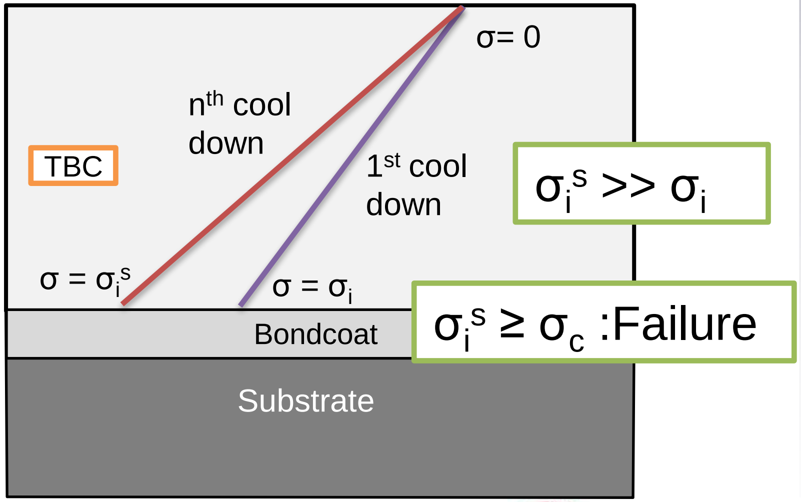
Majority of TBC failure occur at the BC-TC interface. **Parameter of interest is Fracture Toughness.**

Failure Mechanism





Teixeira et al., JTST, 9(2), 2000—191



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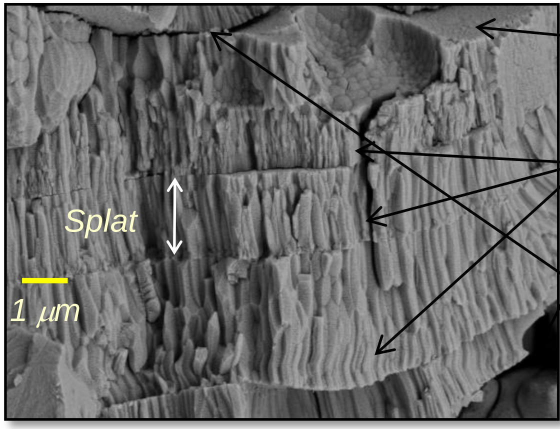
Is the toughness sensitive to microstructure of TBCs?



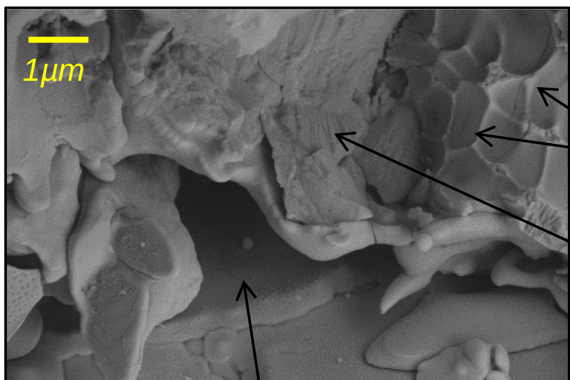
Intrasplat cracks

Intersplat boundaries

Pores or voids

Lamellar pores

Fractured X-section. APS YSZ coating



Splat detachmen

Fracture through splats

Interlamellar pore as a possible crack path

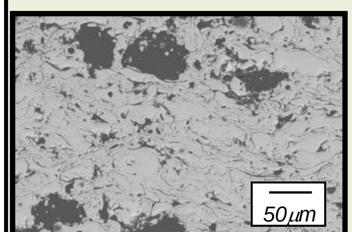
The defect architecture governs Thermal conductivity and Coating compliance

Some defects present more tortuous path to a crack than others.

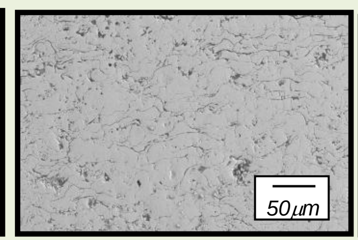
These defects can be controlled via processing.

APS YSZ

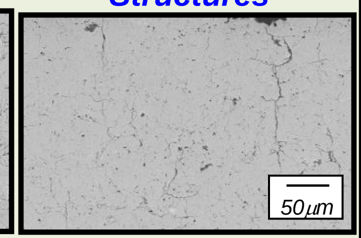
Abradables	**Layered structures**	**Segmented Structures**



Large globular pores



Layered structure with thin splats



Vertical crack with high "local" density

Plasma spray can be utilized to produce significantly different microstructures.

Can we manipulate the effective fracture toughness of these structure?

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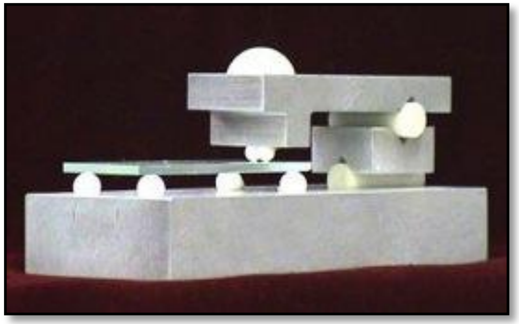
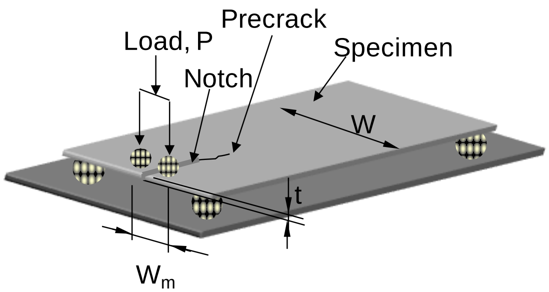
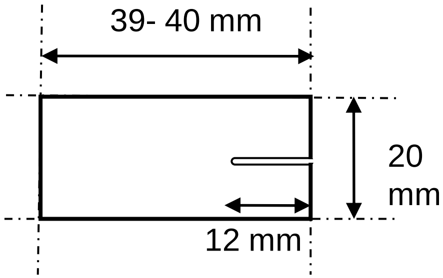
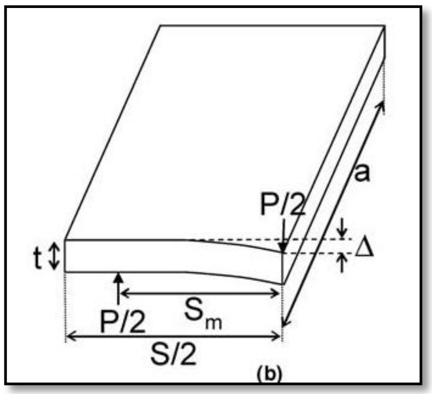
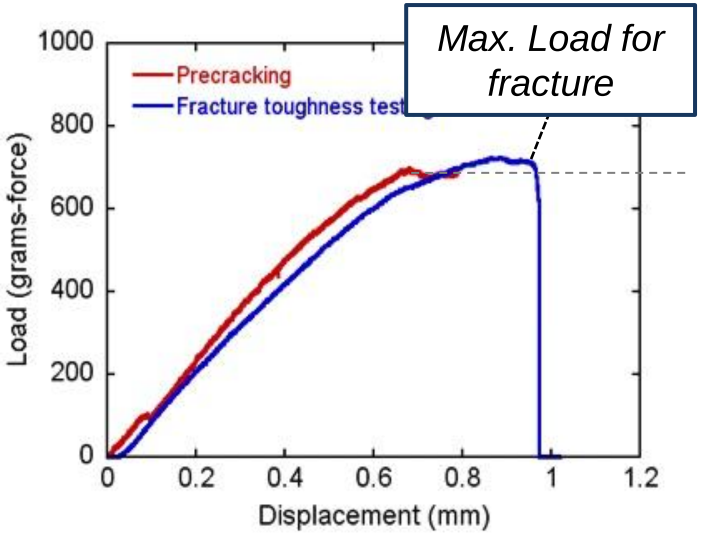
Fracture Toughness: Double Torsion Technique











$$K_{IC} = P_{IC} S_m \left[\frac{3(1+\nu)}{S t^4 \xi} \right]^{1/2}$$

P_{IC} - Maximum load at failure

ν – Poisson's ratio

S - specimen width

S_m - moment arm

t – specimen thickness

...actor

...xp(-πS/2t)

- ✓ 4 poi...
- ✓ *Pre-c...*
- ✓ *Load...*

Advantages:

- ✓ Does not require crack length monitoring
- ✓ Can be performed a low thickness specimen (~600µm).

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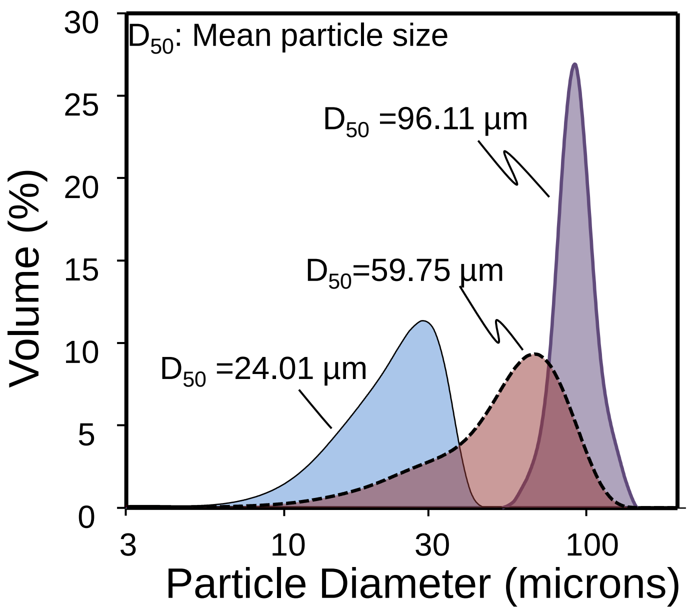
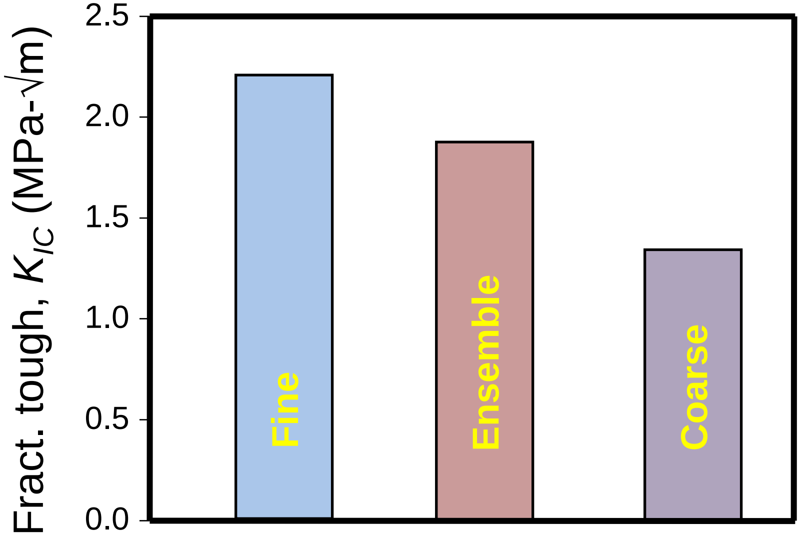
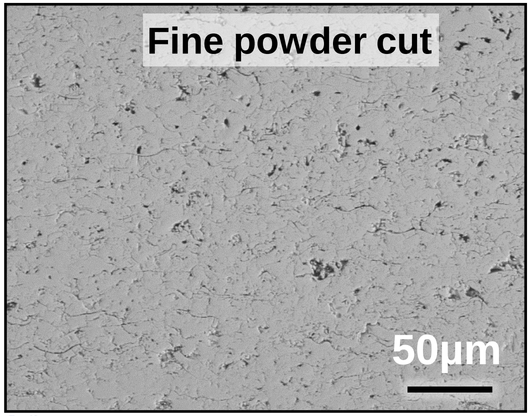
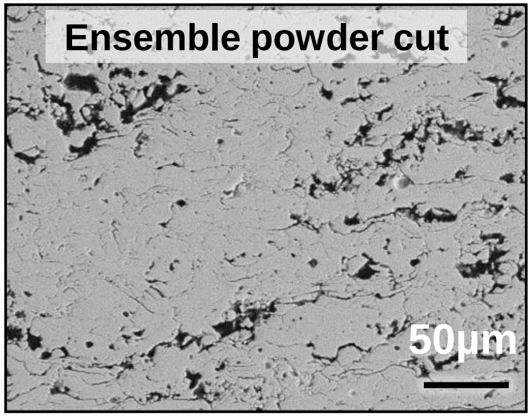
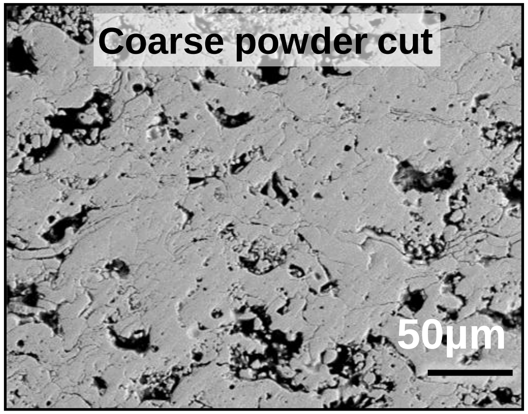
Case Study: Effect of particle size distribution











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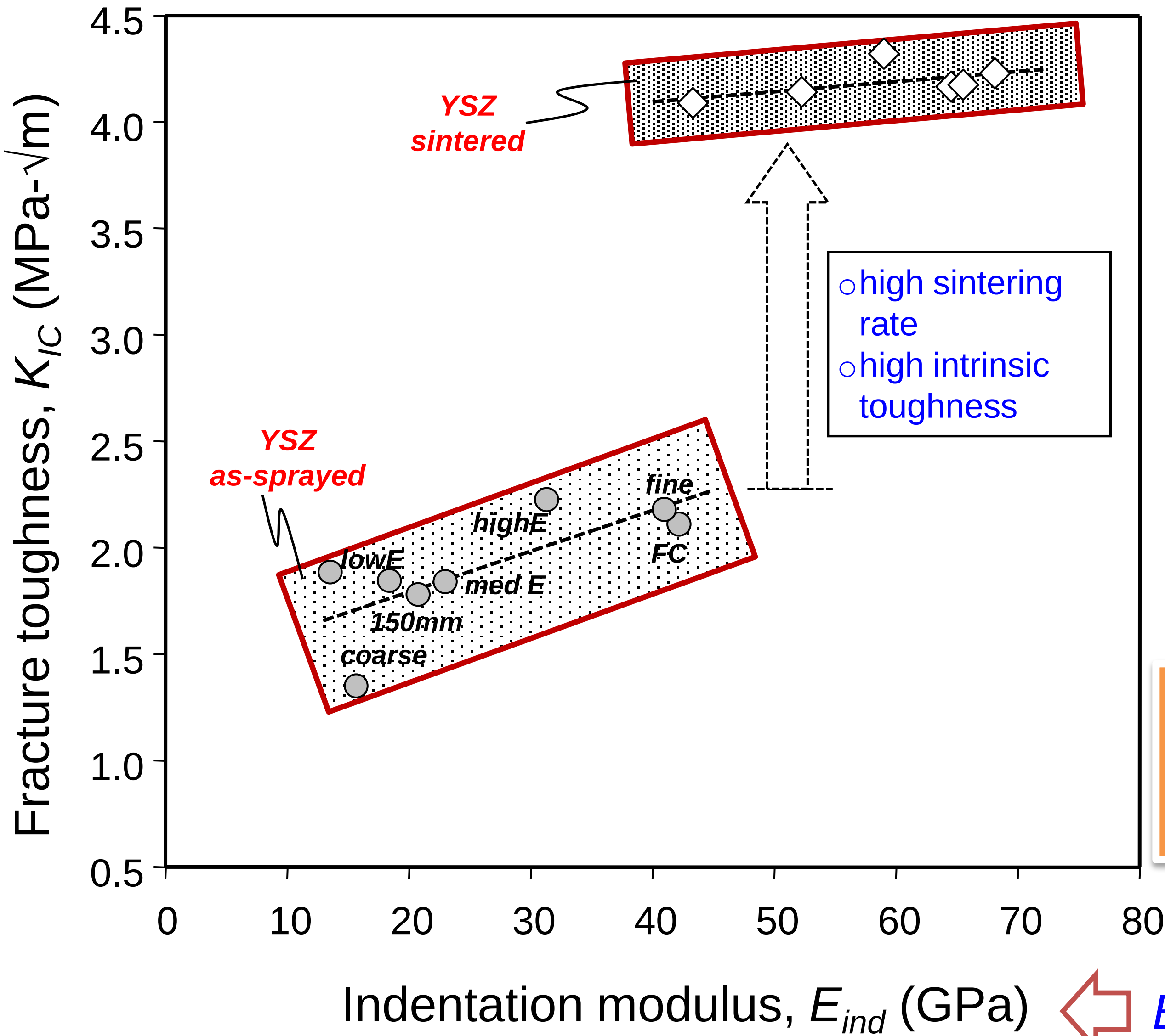
Fracture toughness and modulus relationship



E α 1/porosity

- With sintering or densification of microstructure, fracture toughness increases.
- Toughness is more sensitive towards sintering

Fracture toughness is sensitive to coating microstructure

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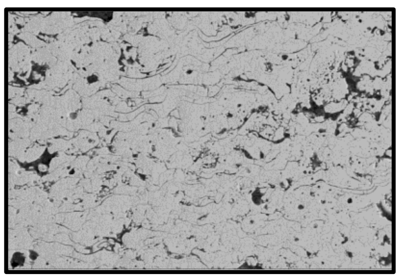
FCT life of various APS YSZ architectures

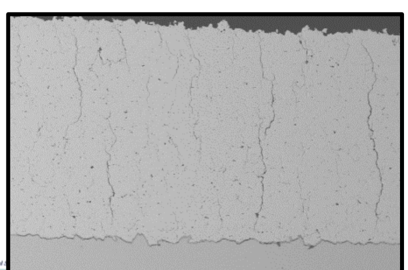
In order to limit the compliance loss

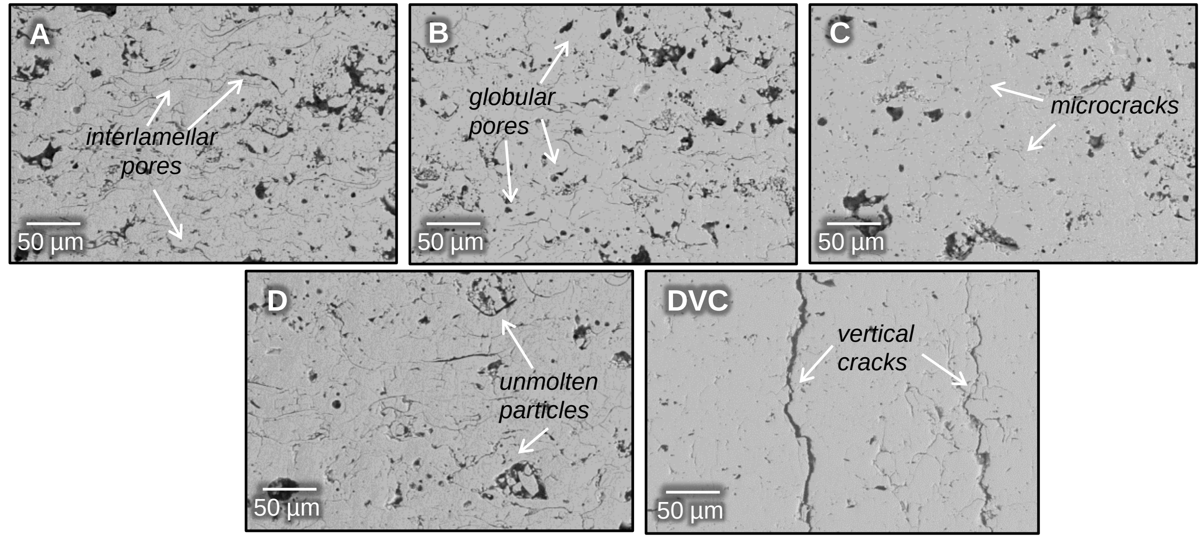
1. Porous coatings

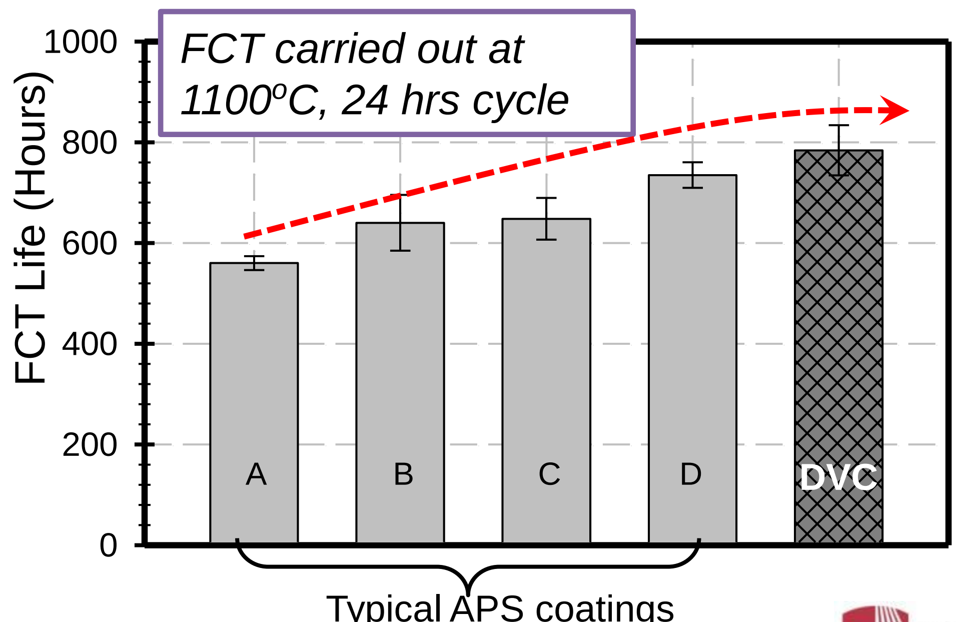
Generally, it has been believed that the porous TBCs last longer.



2. DVCs







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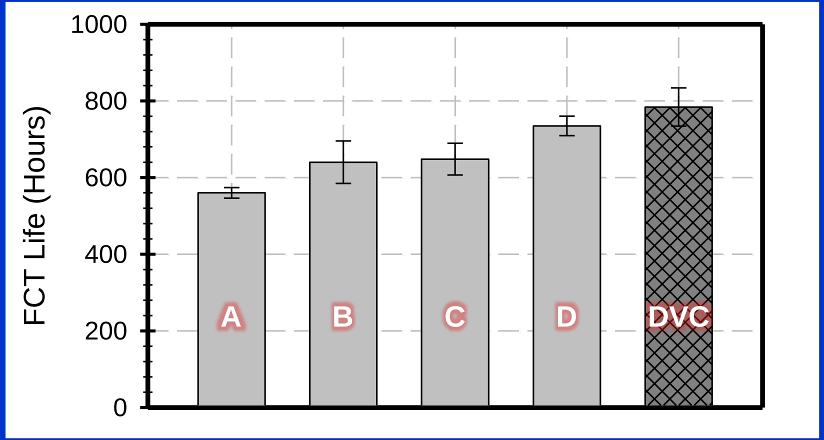
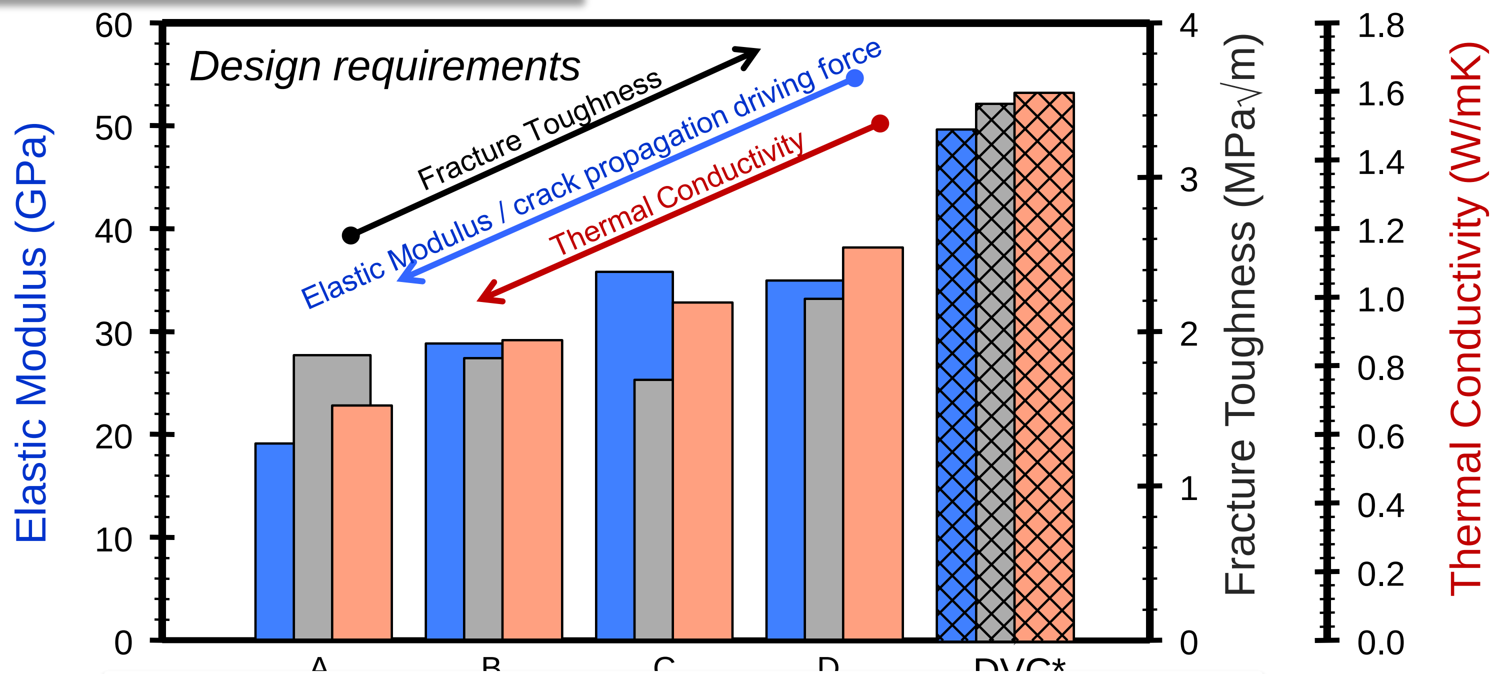
Multiple requirements from a thermal barrier coating



Design requirements

1. *High* toughness : Improved Cyclic Life
2. *Low* modulus : Less driving force to failure
3. *Low* thermal conductivity : Low substrate temperature



Need a strategic approach towards coating design for multi-functionality

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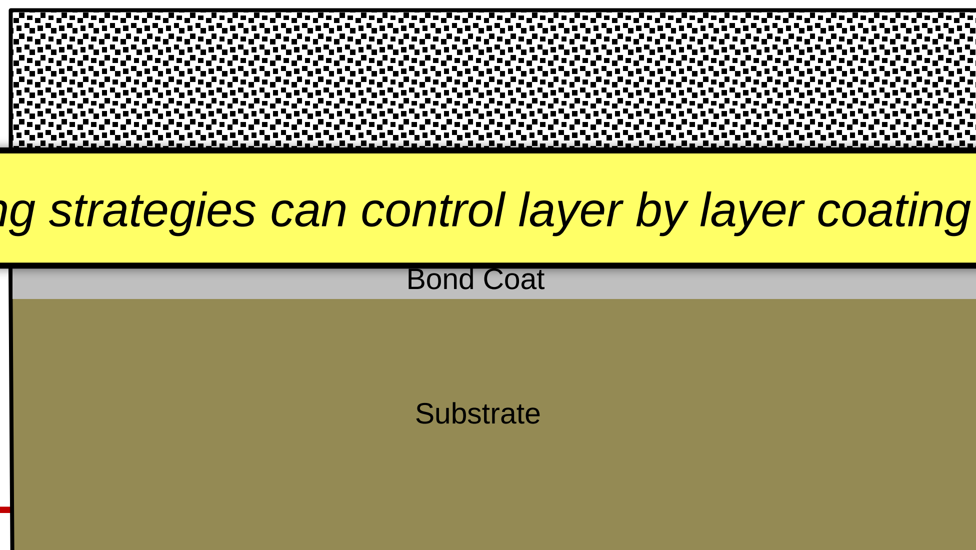
Multiple requirements from a thermal barrier coating

Primary Requirement

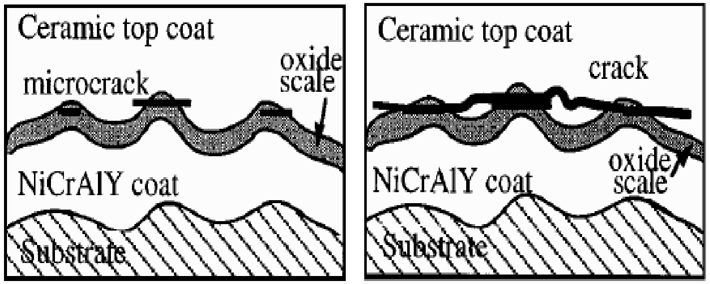
Compliance	Durability	Thermal Performance
↓	↓	↓
Elastic Modulus	*Fracture Toughness*	*Thermal Conductivity*

Function of coating microstructure

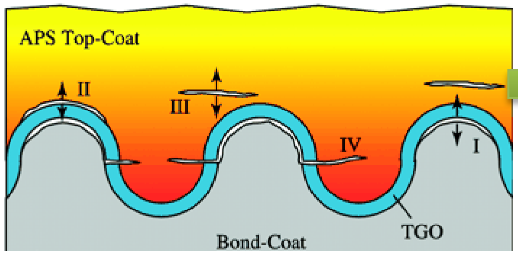


Processing strategies can control layer by layer coating properties

Focus on need for high toughness ceramic at failure location

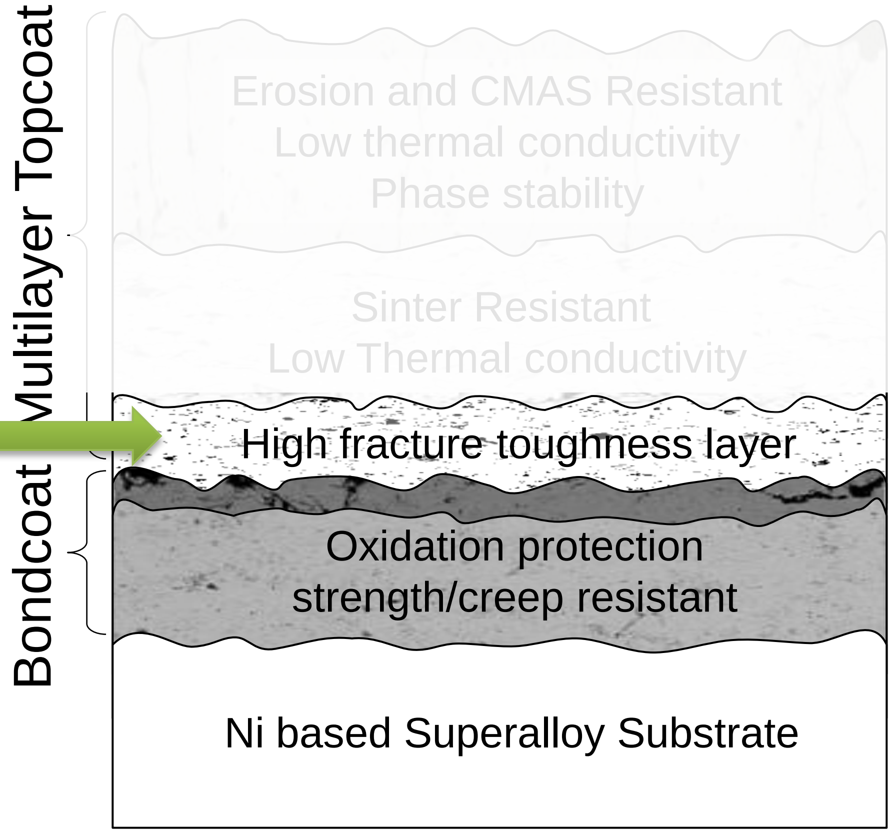


Teixeira et al., JTST, 9(2), 2000—191



Padture et al., vol. 296,Science, 280, 2002

$\sigma_i^s \geq \sigma_c$:Failure



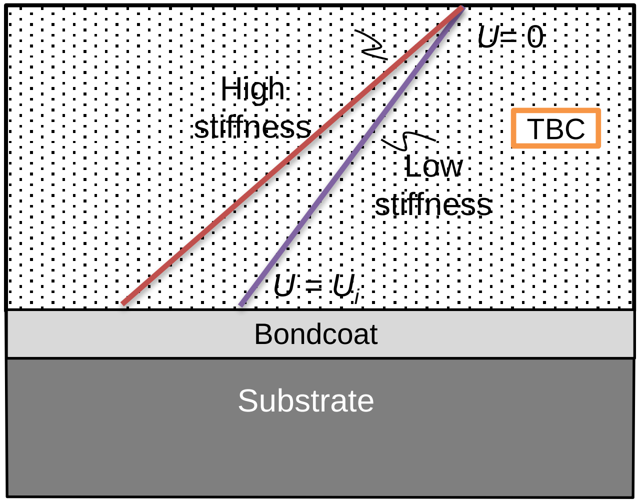
Elastic Energy approach to optimize coating architecture

Approach: Higher toughness with denser coatings…

Total Elastic Energy available for interfacial crack propagation

$$U_{isothermal} = \frac{(1+\nu)}{2(1-\nu_c)}(\Delta\alpha_c \Delta T_{sub})^2 (E_c h_c)$$

Levi et al., MRS Bulletin, 2012



For constant h_c

$U_{interface}$ α E (modulus)

Failure occurs when

$U_{interface} \geq Gc$

$E^{Dense} > E^{Porous}$

$U_i^{Dense} > U_i^{Porous}$

Elastic Energy approach to optimize coating architecture

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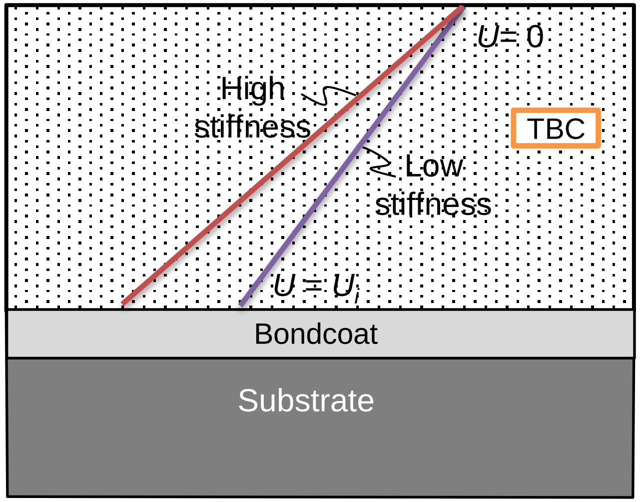


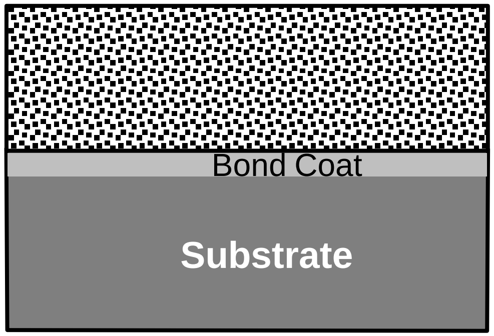
For multilayer coatings

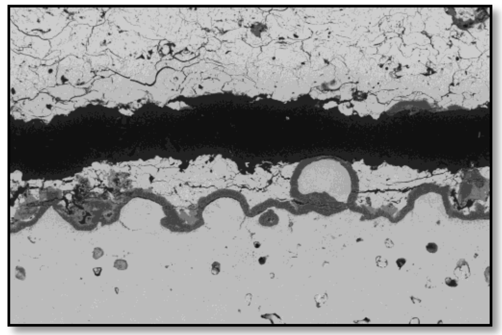
$$U_{isothermal} = \frac{(1+\nu)}{2(1-\nu_c)}(\Delta\alpha_c \Delta T_{sub})^2 \left(E_{c1}h_{c1} + E_{c2}h_{c2} + E_{c3}h_{c3} \ldots\right)$$

Derived from Levi et al., MRS Bulletin, 2012

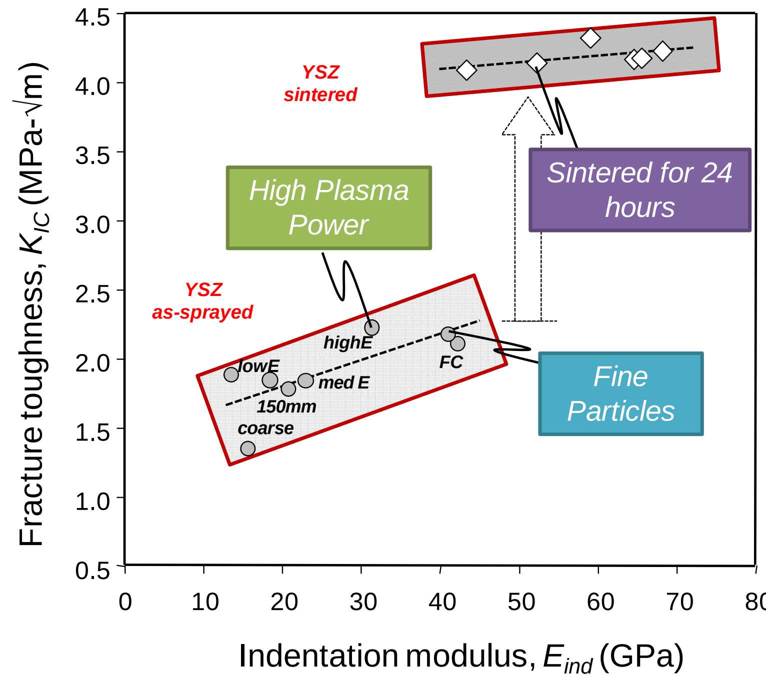
Revised TBC Architecture: Strategic approach for multi-functionality

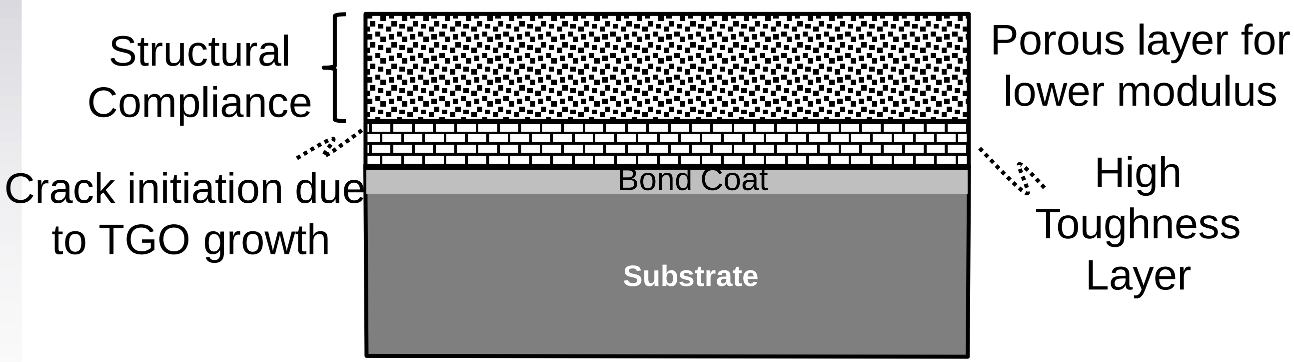
Typical APS TBC



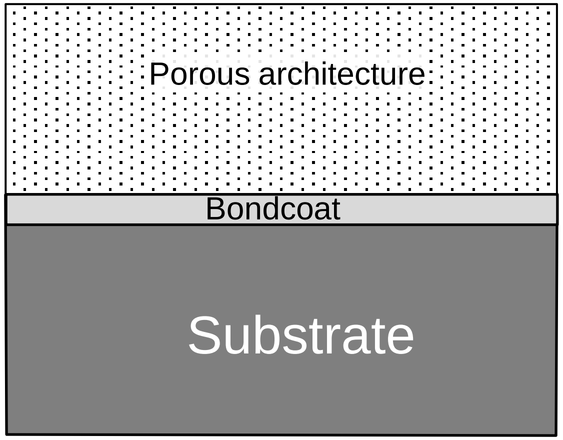


Functionally Optimized TBC with high fracture toughness interface layer



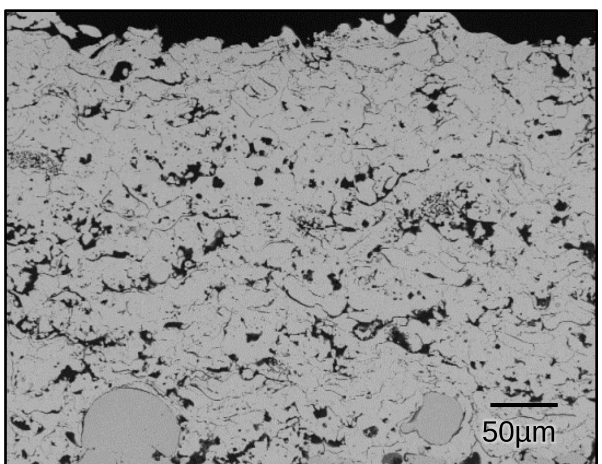


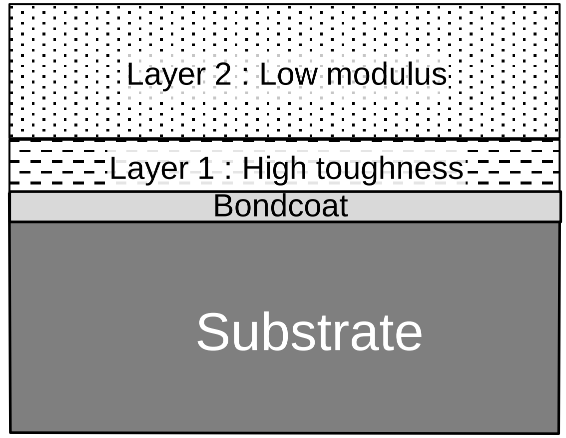
Revised TBC Architecture



Conventional TBC

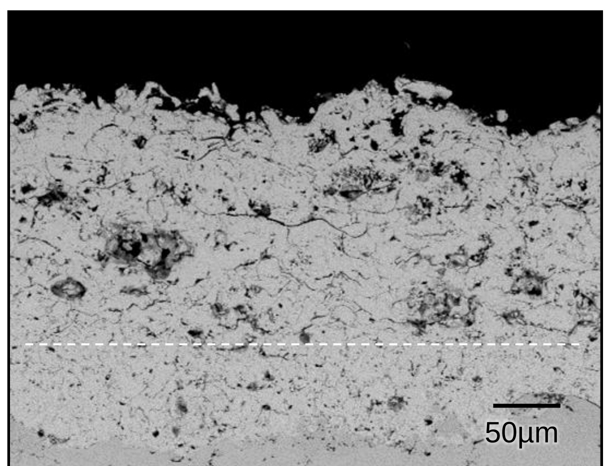
Porous single layer

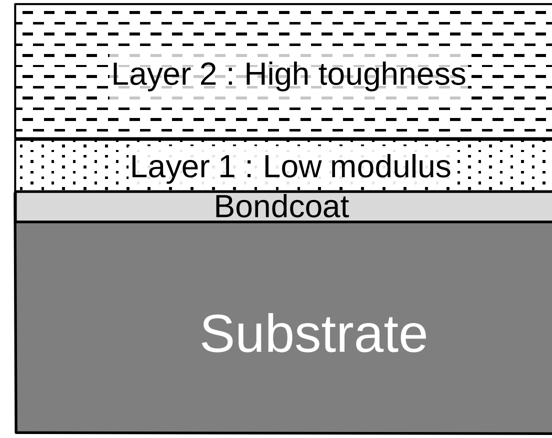




Optimal bi-layered TBC

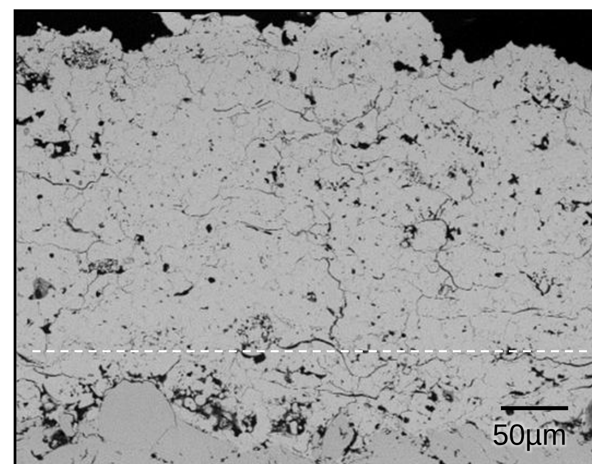
Bi-layer with tough near-interface layer



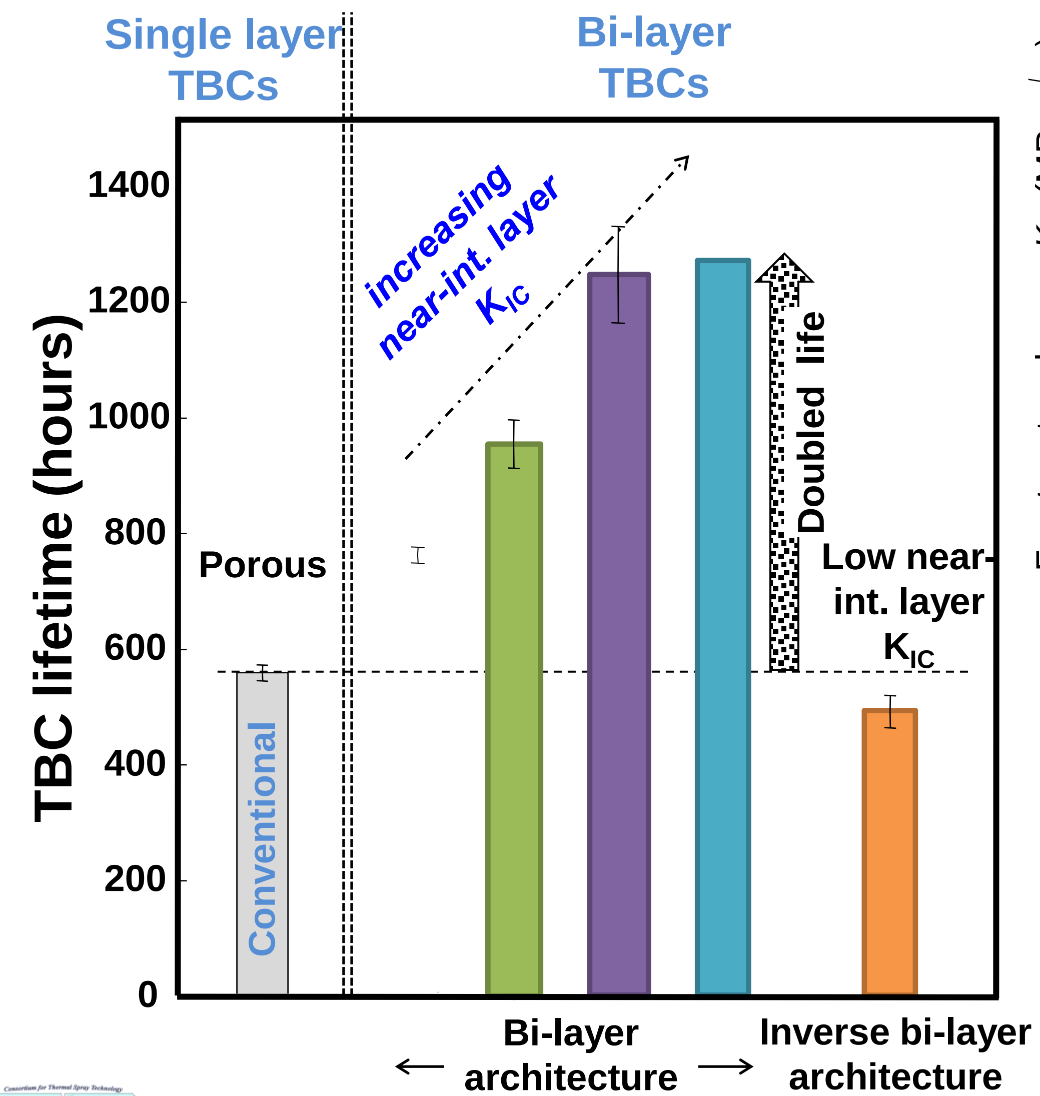


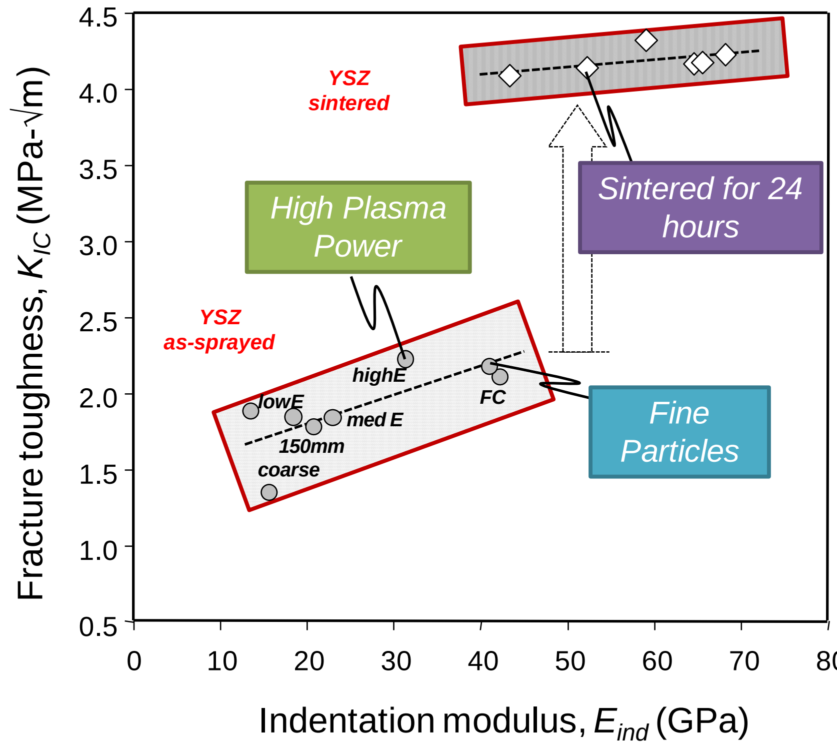
Inverse bi-layered TBC

Bi-layer with inverse architecture



FCT durability of revised TBC Architecture





Consistent improvement in TBC life for bi-layer coatings

With high toughness interface layer

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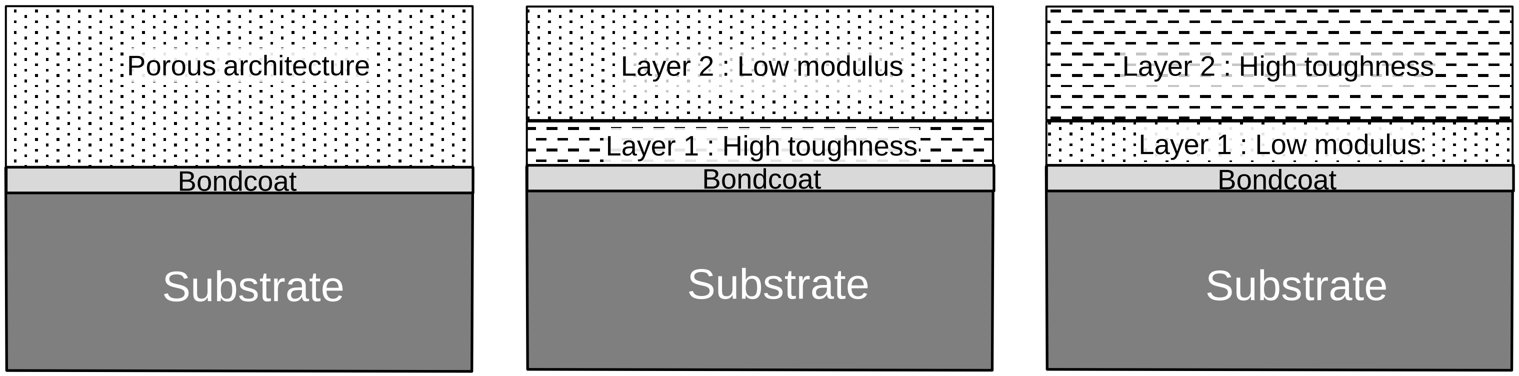
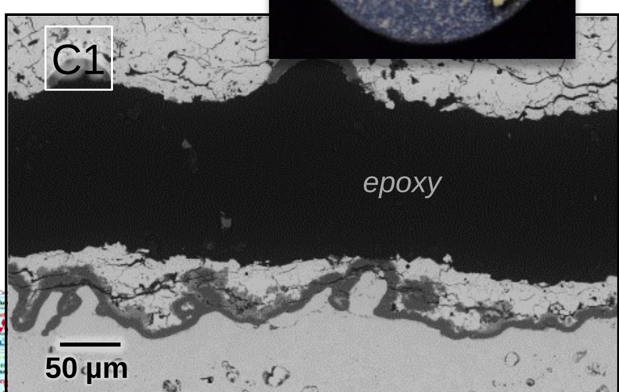
The failure location for all the architectures remains the same



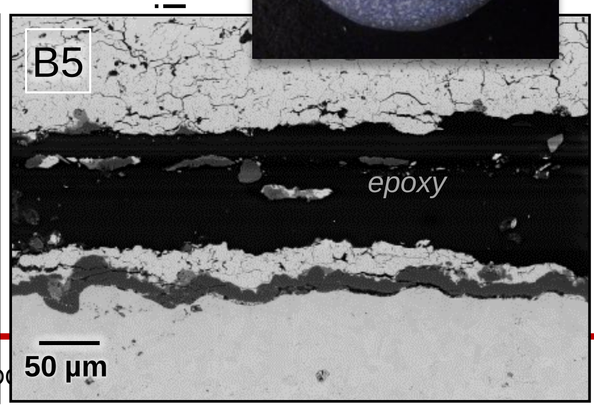
Conventional TBC | **Optimal bi-layered TBC** | **Inverse bi-layered TBC**

Failed Specimens

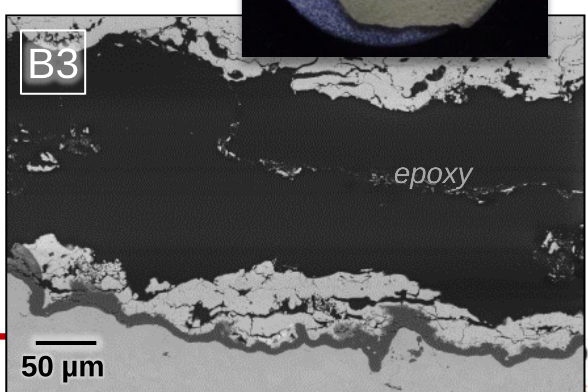
Conventional porous single layer



bi-layer with dense near-interface layer

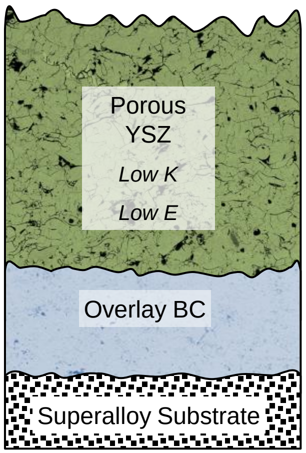


bi-layer with inverse architecture

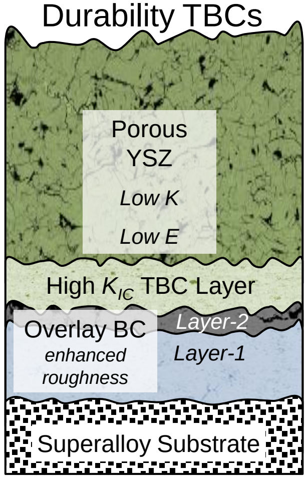


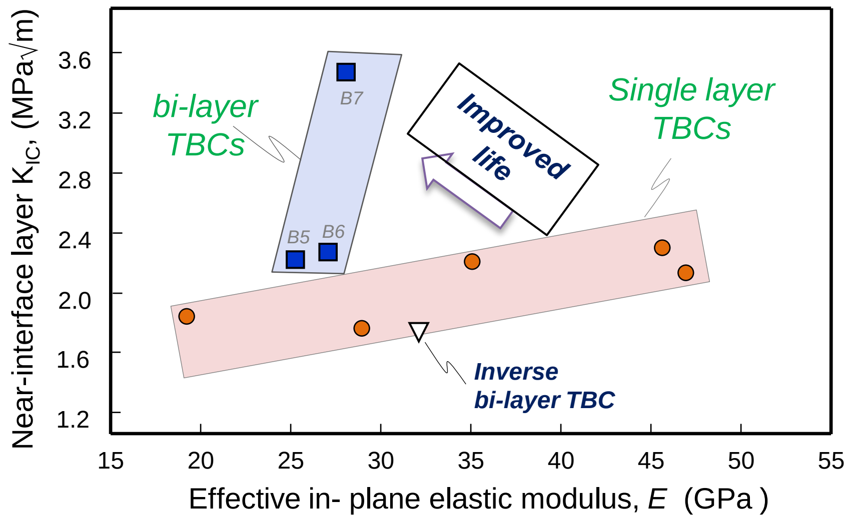
Process optimization strategies

Conventional TBCs

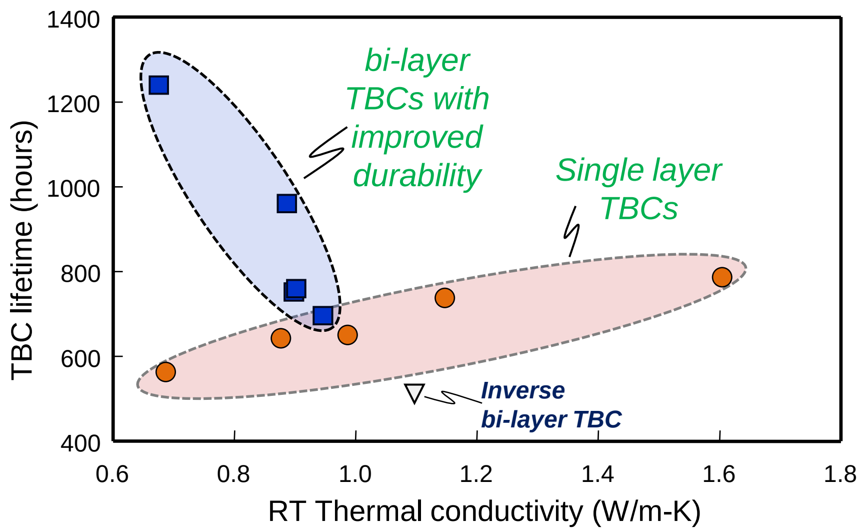


Enhanced Durability TBCs





Property based design map for coatings with enhanced durability



Simultaneous optimization of coating durability and functionality

Materials need for higher operating temp. 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**

Candidates for top coat composition under consideration

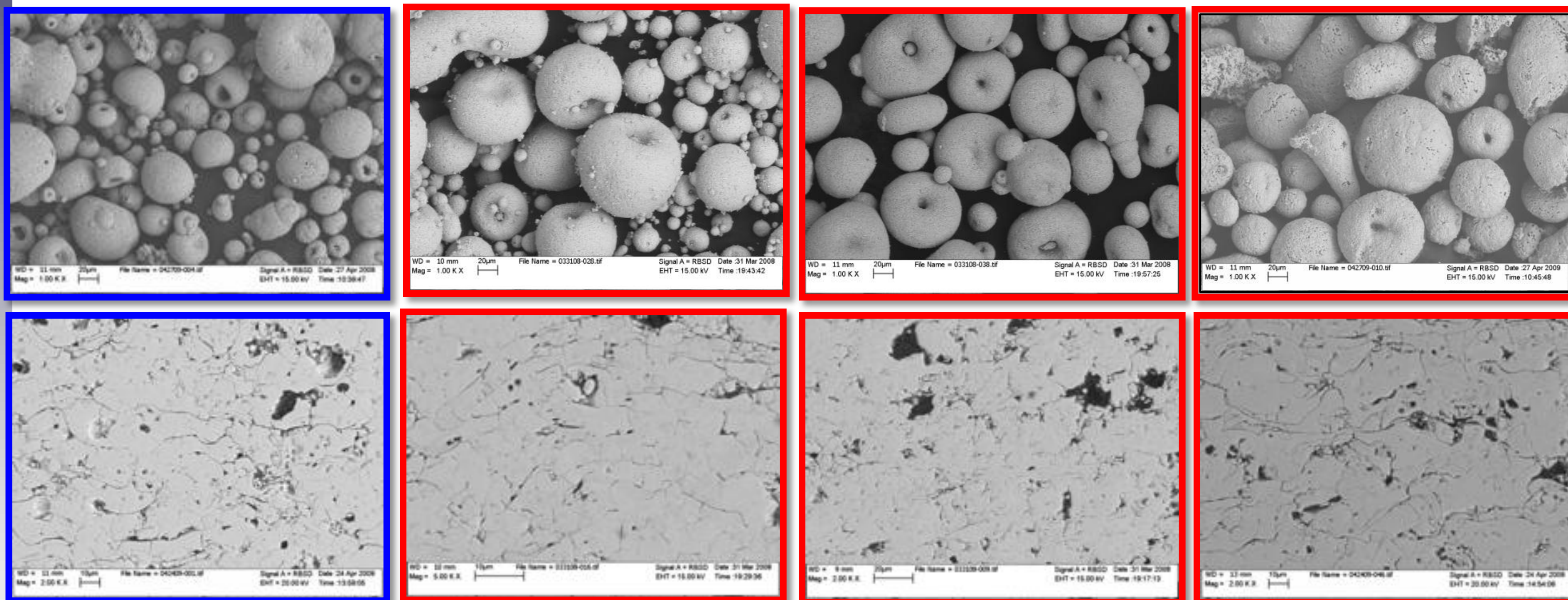
TBC Materials under considerations

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
YSZ-Al-Ti	*YSZ+20mol%Al +5mol%Ti*	*CMAS resistant*	*Ohio State Univ*

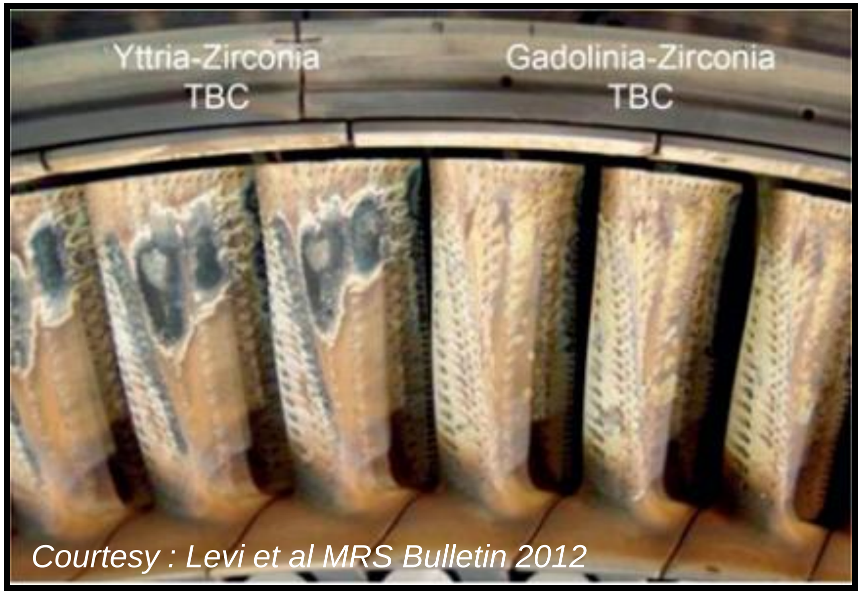
Stony Brook University

Exploring and processing new materials

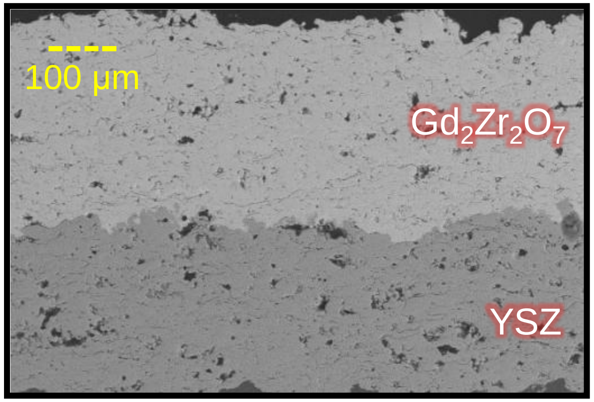
YSZ | $La_2Zr_2O_7$ | $Gd_2Zr_2O_7$ | Cluster-doped



Transitioning to low K TBC: $Gd_2Z_2O_7$ pyrochlores



Courtesy : Levi et al MRS Bulletin 2012

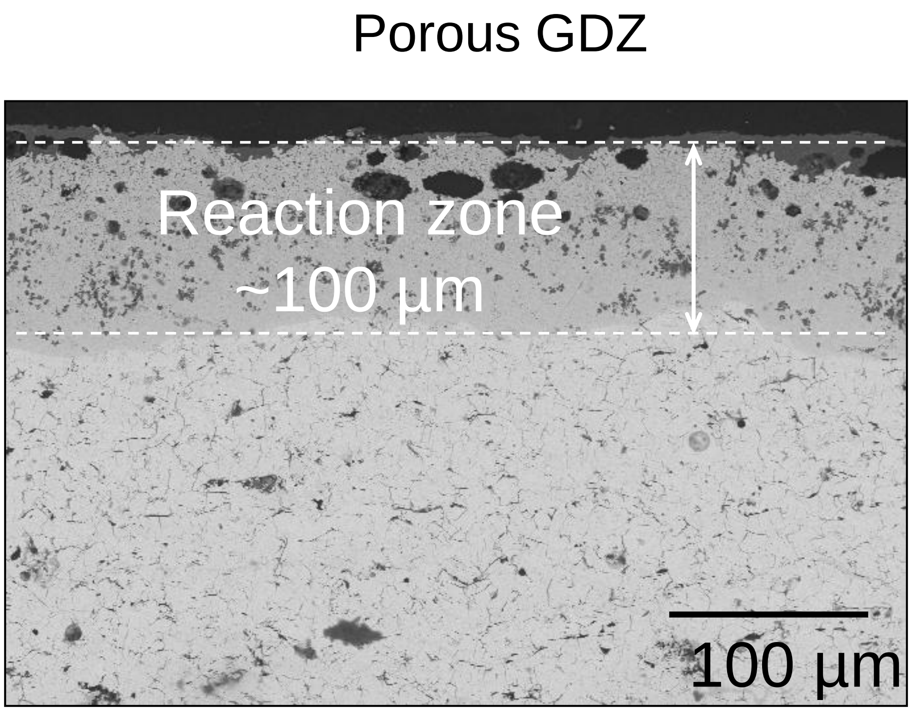


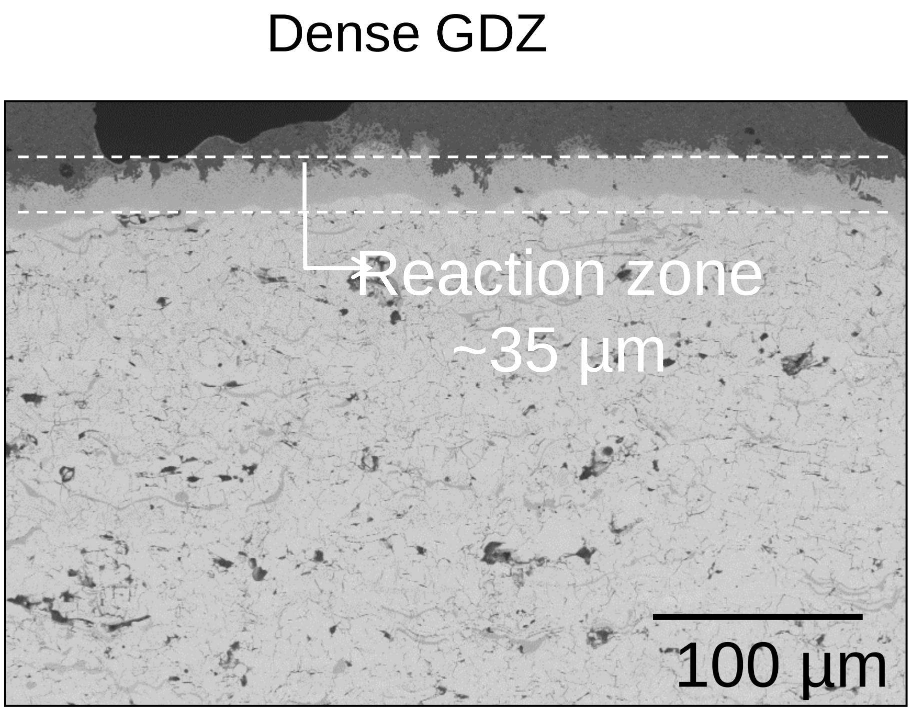
Challenges:

1. CMAS mitigation
2. High erosion/FOD resistance
3. Compatibility with YSZ

All have significant dependency on processing

Coating microstructure for enhanced CMAS resistance





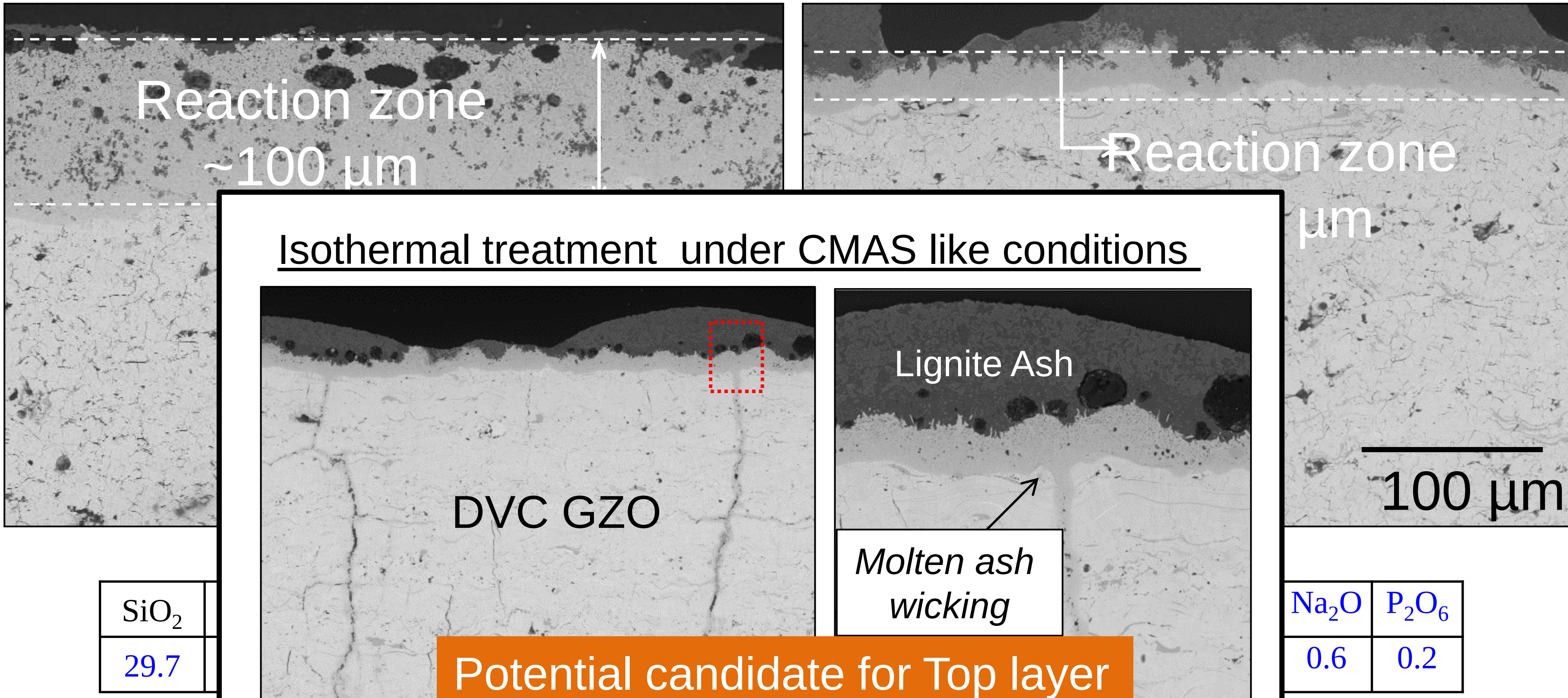
SiO_2	CaO	FeO	Al_2O_3	Cr_2O_3	MgO	SO_3	TiO_2	SrO	MnO	K_2O	Na_2O	P_2O_6
29.7	25.4	14.8	14.7	5.1	3.6	1.8	1.1	1.0	0.9	0.8	0.6	0.2

Courtesy: Prof. Nitin Padture

- **Dense GDZ seems to offer lesser Lignite ash penetration depth.**
- **It also offer benefits in terms of erosion resistance.**
- **However, it has high modulus, which will increase the overall strain energy**

Coating microstructure for enhanced CMAS resistance

Porous GDZ | Dense GDZ



Potential candidate for Top layer

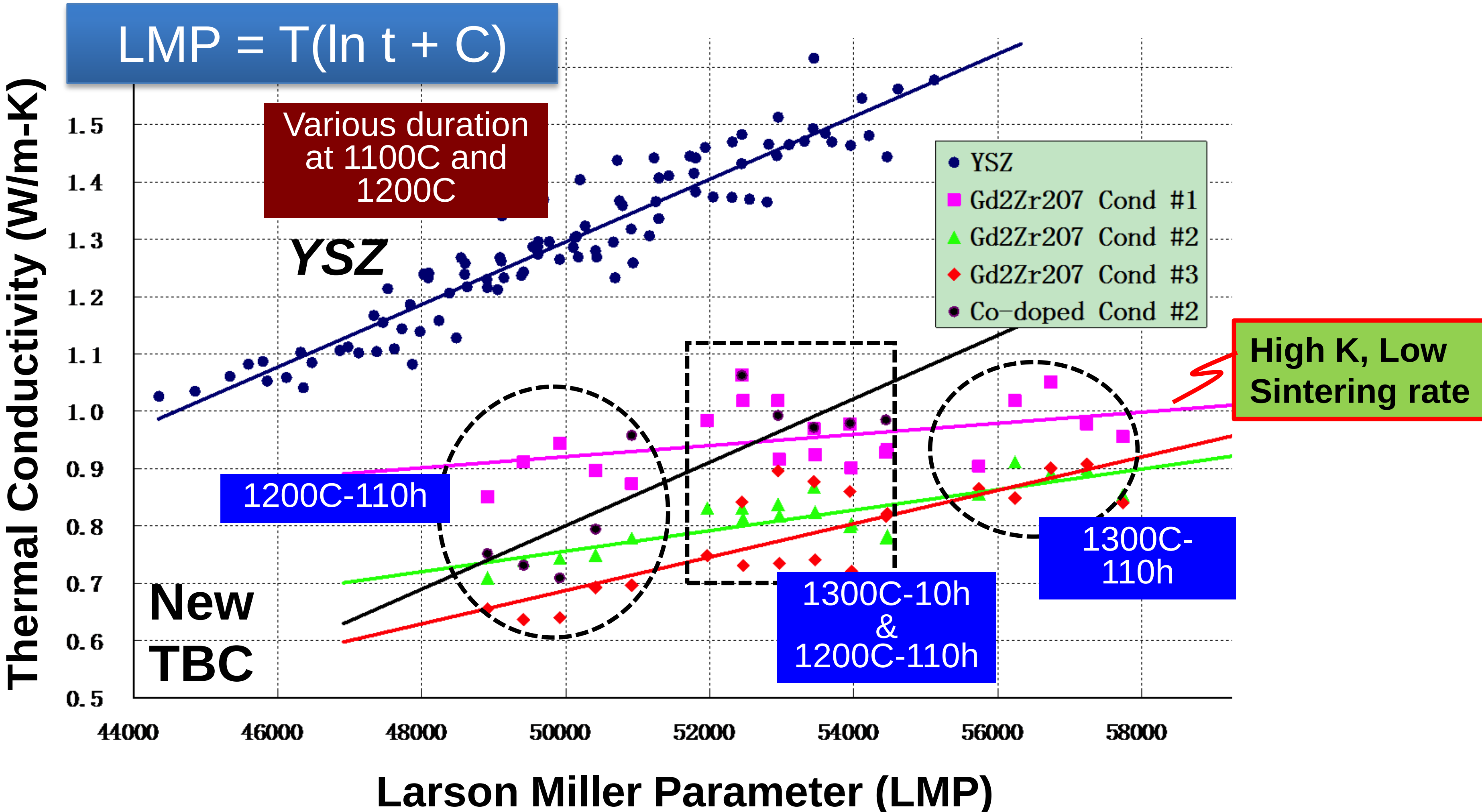
SiO_2	...	Na_2O	P_2O_6
29.7	...	0.6	0.2

Courtesy: Prof. Nitin Padture

- **Dense GDZ seems to offer lesser Lignite ash penetration depth.**
- **It also offer benefits in terms of erosion resistance.**
- **However, it has high modulus, which will increase the overall strain energy**

Sintering behavior of new materials: Challenges

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



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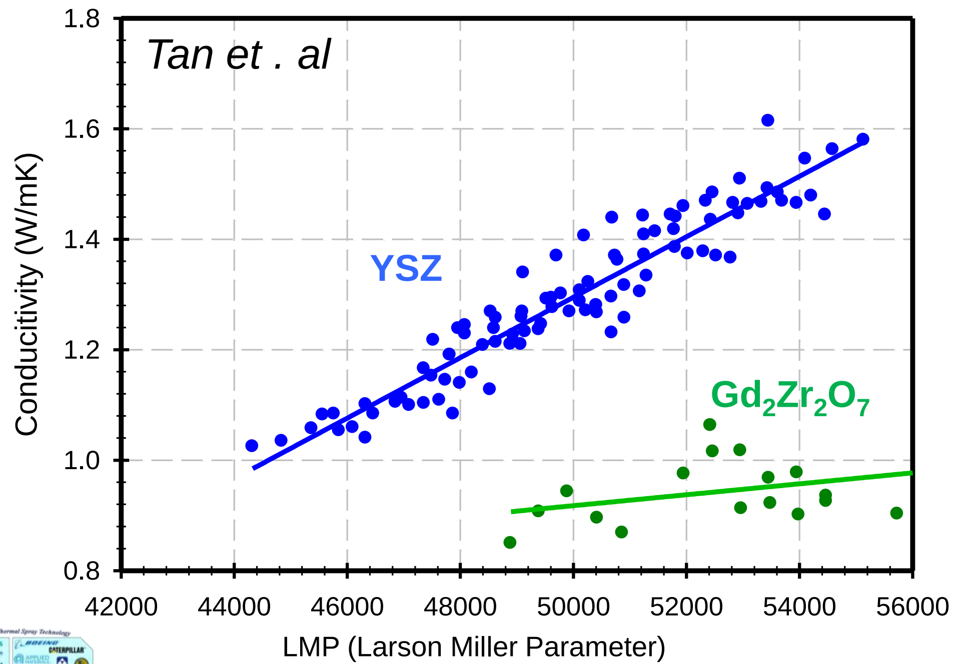
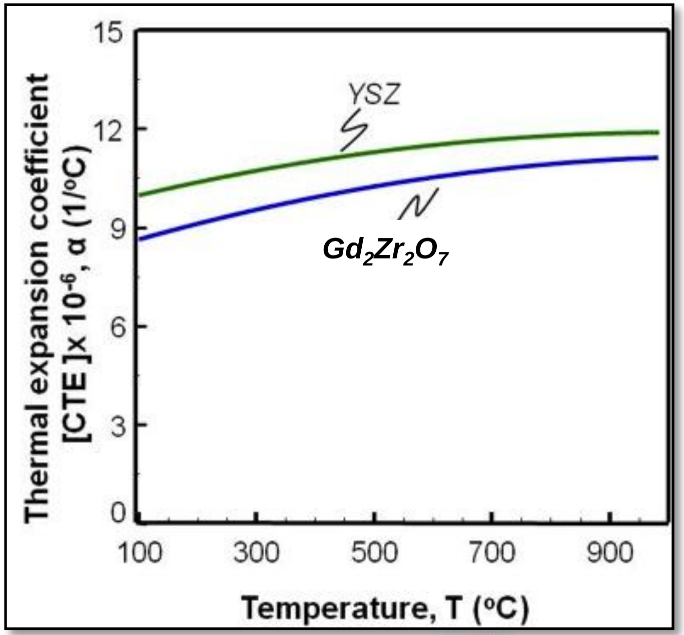
Big difference in sintering rates require microstructural modifications

Free standing bi-layer coatings
Isothermal exposure at 1200ºC for 24 hours





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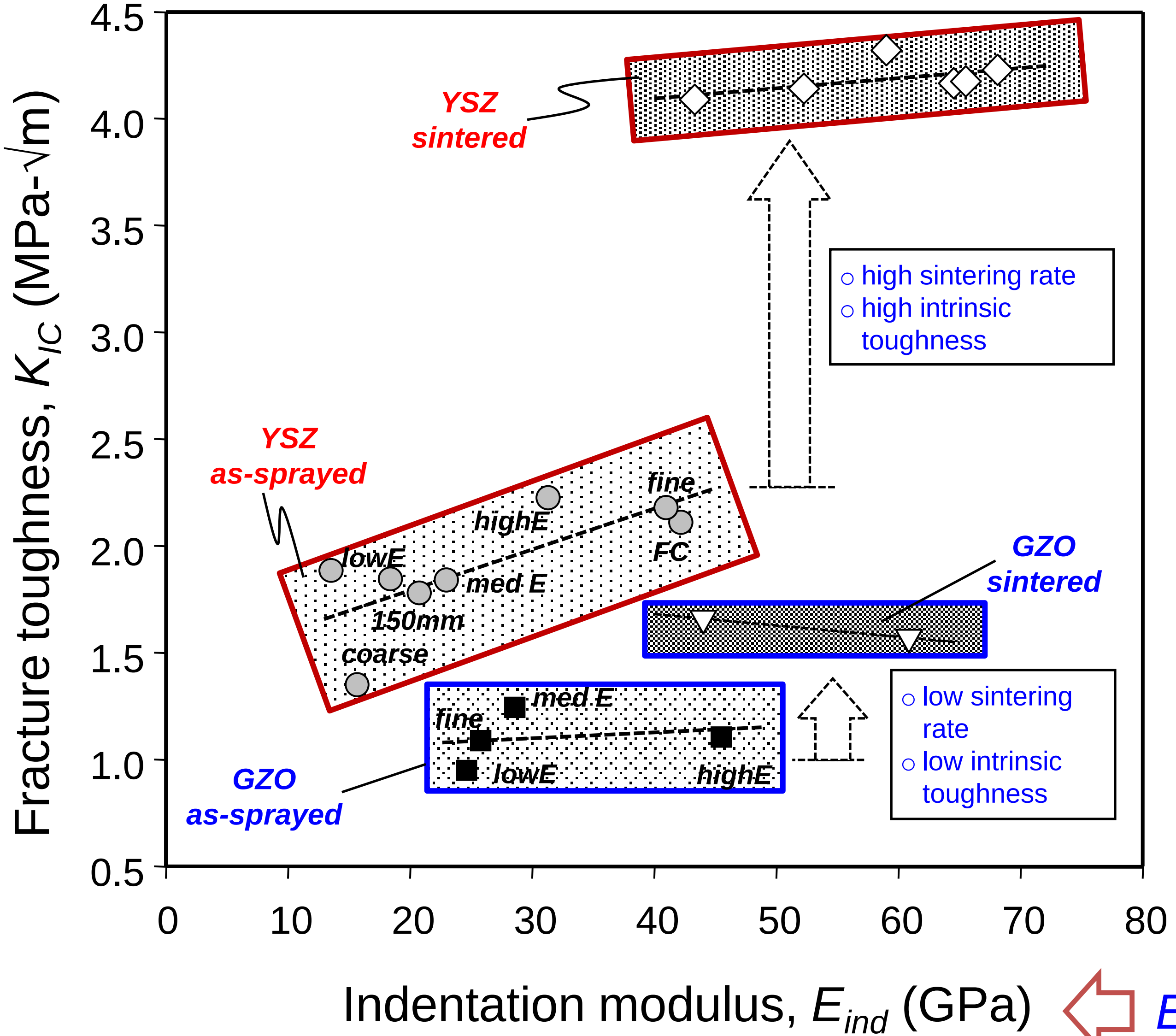
Toughness is an issues with Cubic pyrochlore, GDZ



E α 1/porosity

- YSZ more sensitive to processing than GDZ
- Equivalent sintering affects YSZ fracture toughness more than GDZ

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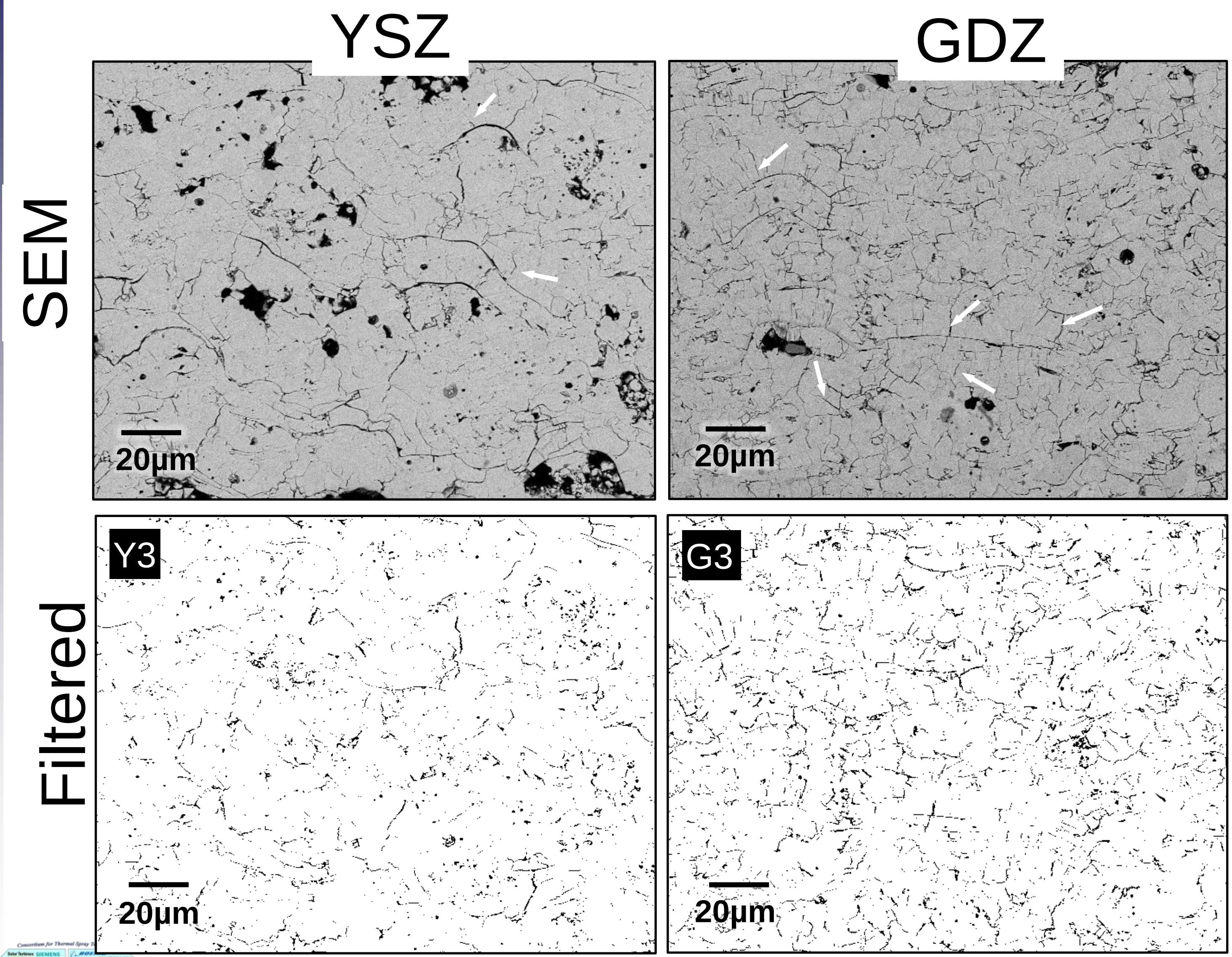
Larger microcracking in GDZ due to low toughness



Introduces processing challenges

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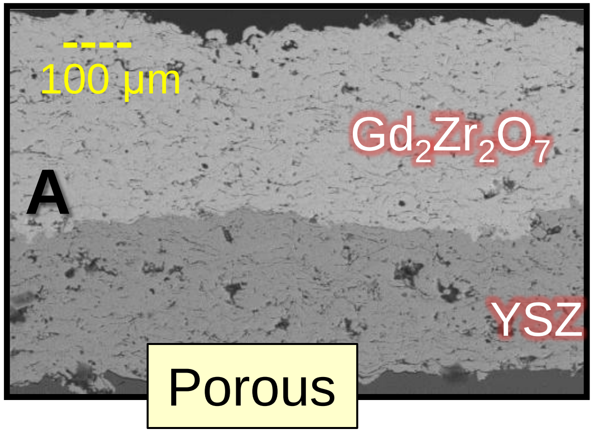
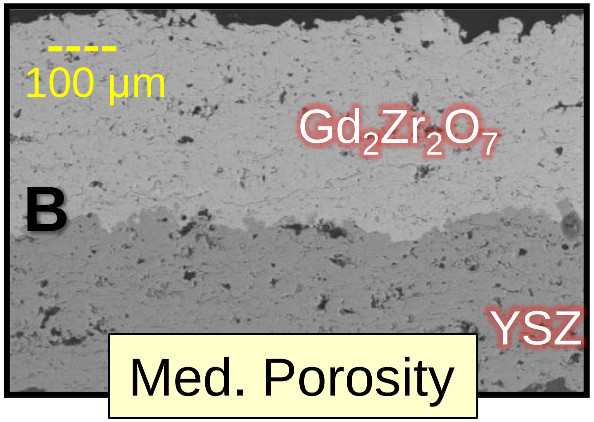
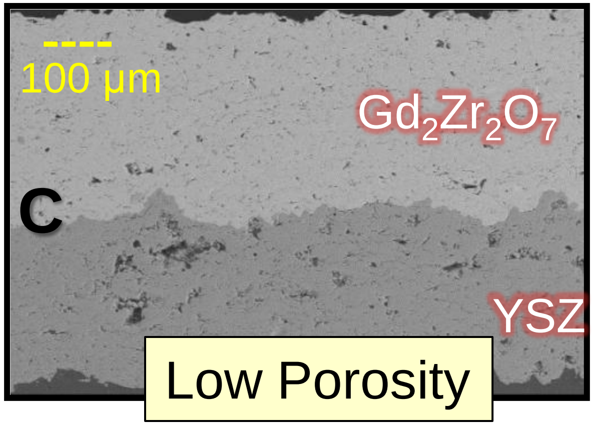
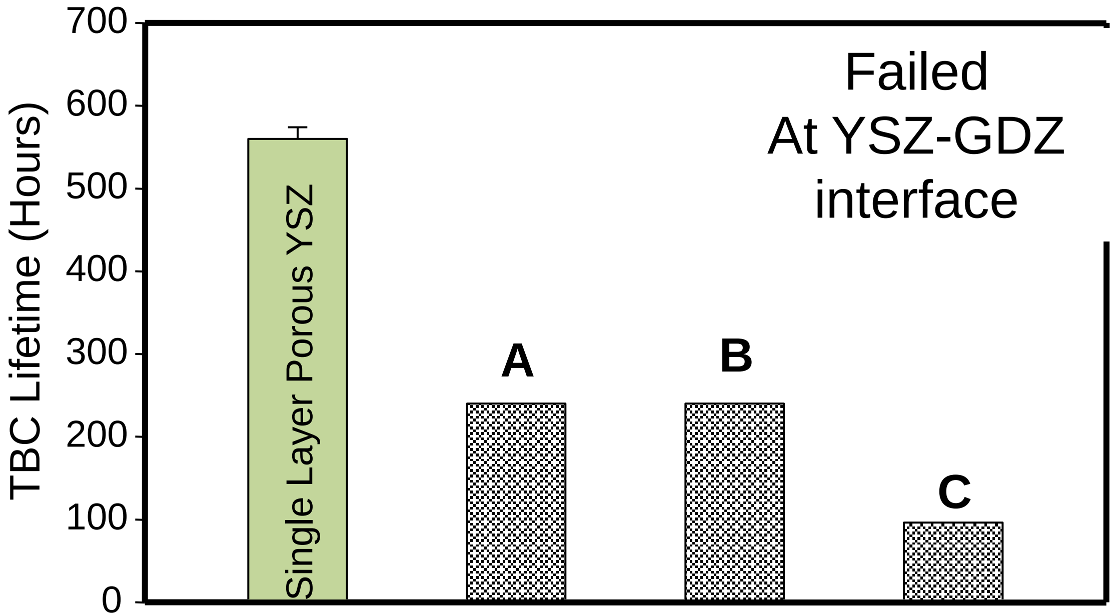
FCT durability of bi-layered YSZ and $Gd_2Zr_2O_7$ coatings

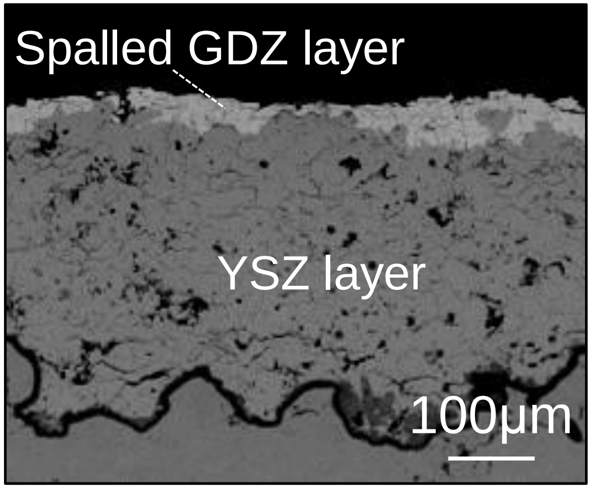








Failed microstructure (C)



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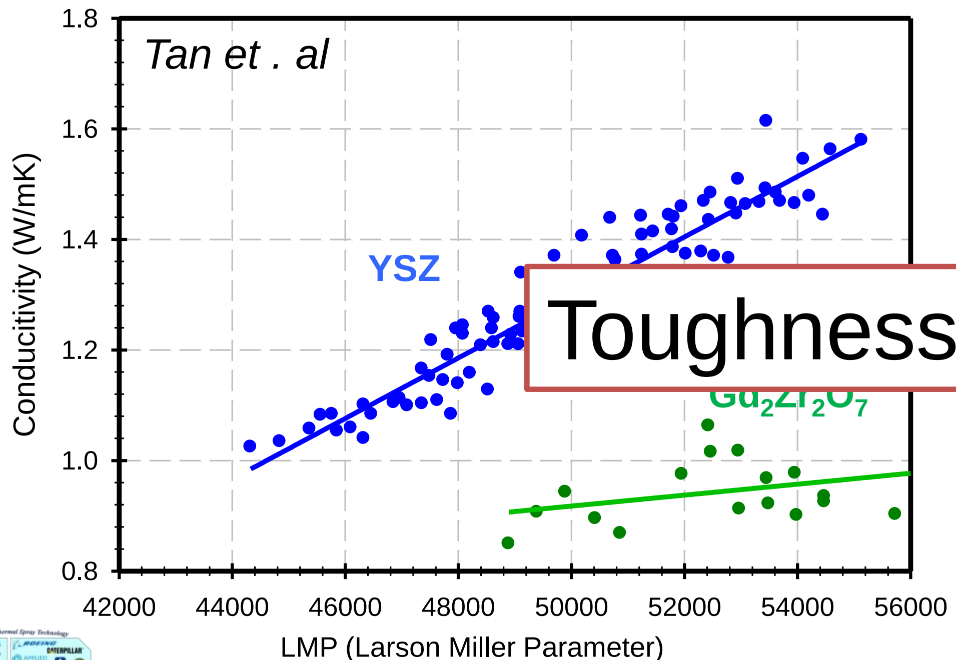
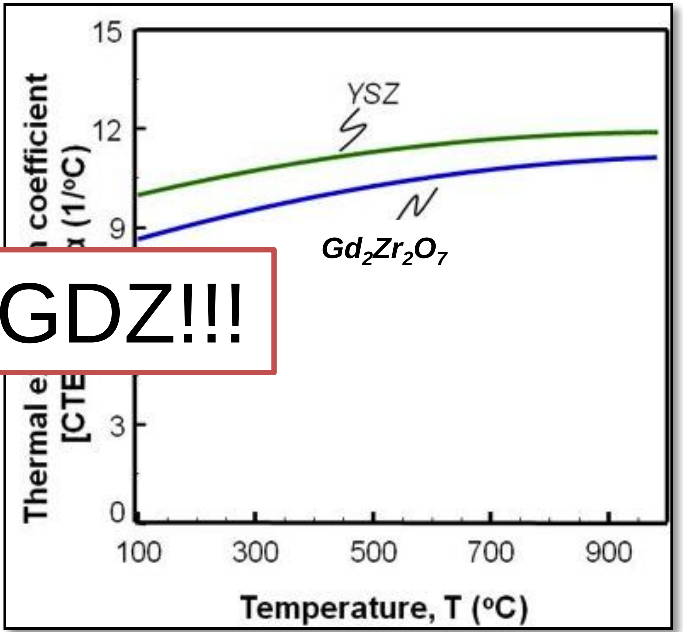
Big difference in sintering rates require microstructural modifications

Free standing bi-layer coatings
Isothermal exposure at 1200°C for 24 hours



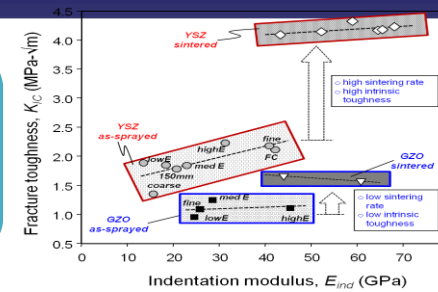


Toughness of GDZ!!!

Systematic progress over past four years

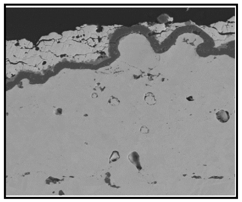
Y1

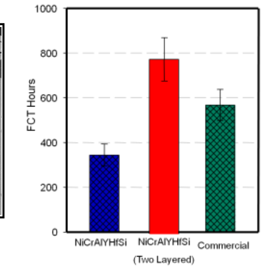
- YSZ and GDZ process property relationships
  - **Process Map development**
  - ***Toughness, Lignite ash penetration depth, erosion***



Y2

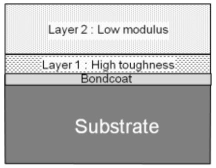
- Rough bond coat process optimization with 40% increase in FCT life
  - **Two layer dense BC layer**



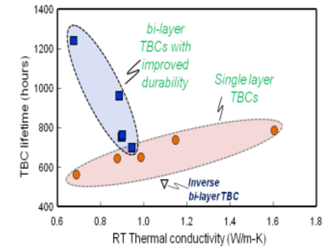


Y3

- bi-layer YSZ coating with two fold increase in FCT life, and maintaining low *K*
  - **High toughness interface layer, Elastic energy model**



Optimal bi-layered TBC



Y4

- Multilayer YSZ-GDZ coating system
  - **enhanced life, Lignite ash penetration minimization, erosion resistance**

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Extension and evaluation of multilayer YSZ-GDZ coatings

CTSR

Further reduction in the cost- Bondcoat processing, other TBC materials

GE Aviation

Different FCT cycling time

Praxair

Gradient Jet-test

CTSR

Burner rig testing with CMAS attach

CTSR

UTSR Program

Siemens

FCT

CTSR

TBC overhaul: reclaimed substrates

CTSR

Deposition and testing on an actual component

ORNL

Various cycling time and substrate material

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Gratefully acknowledged

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

Prof. Nitin Padture

Dr. Briggs While, Program Manager

Prof. Toshio Nakamura, Stony Brook University

Dr. Curtis Johnson, Rtd. GE GRC

Prof. John Hutchinson, Harvard university