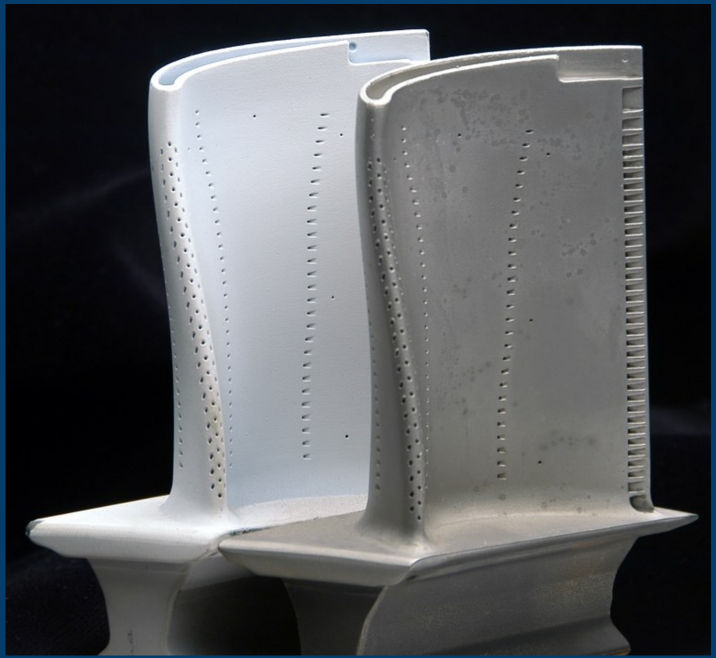
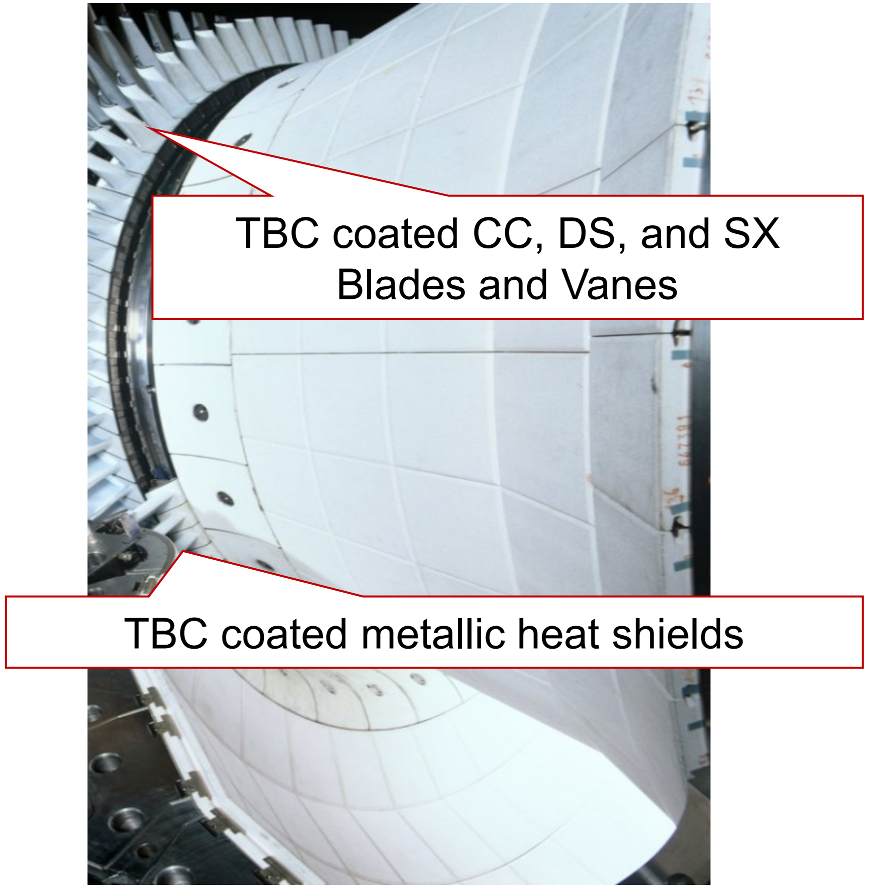
THERMAL BARRIER COATINGS IN GAS TURBINES CURRENT STATE



D.E. MACK

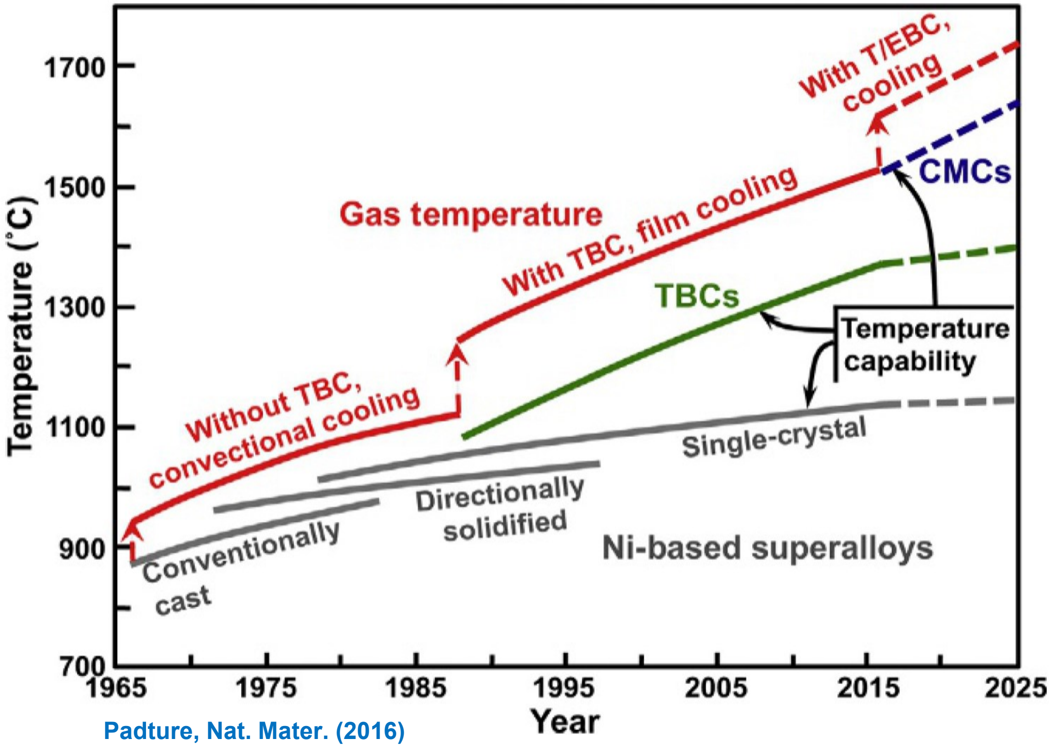
2024-03-21, ETN AGM‘24, LEIDEN, NL

THERMAL BARRIER COATINGS IN GAS TURBINES



Source: Siemens

- Cooling and application of thermal barrier coatings on hot section parts evolve for decades to increase operation temperatures, efficiency, and component life, respectively



Padture, Nat. Mater. (2016)

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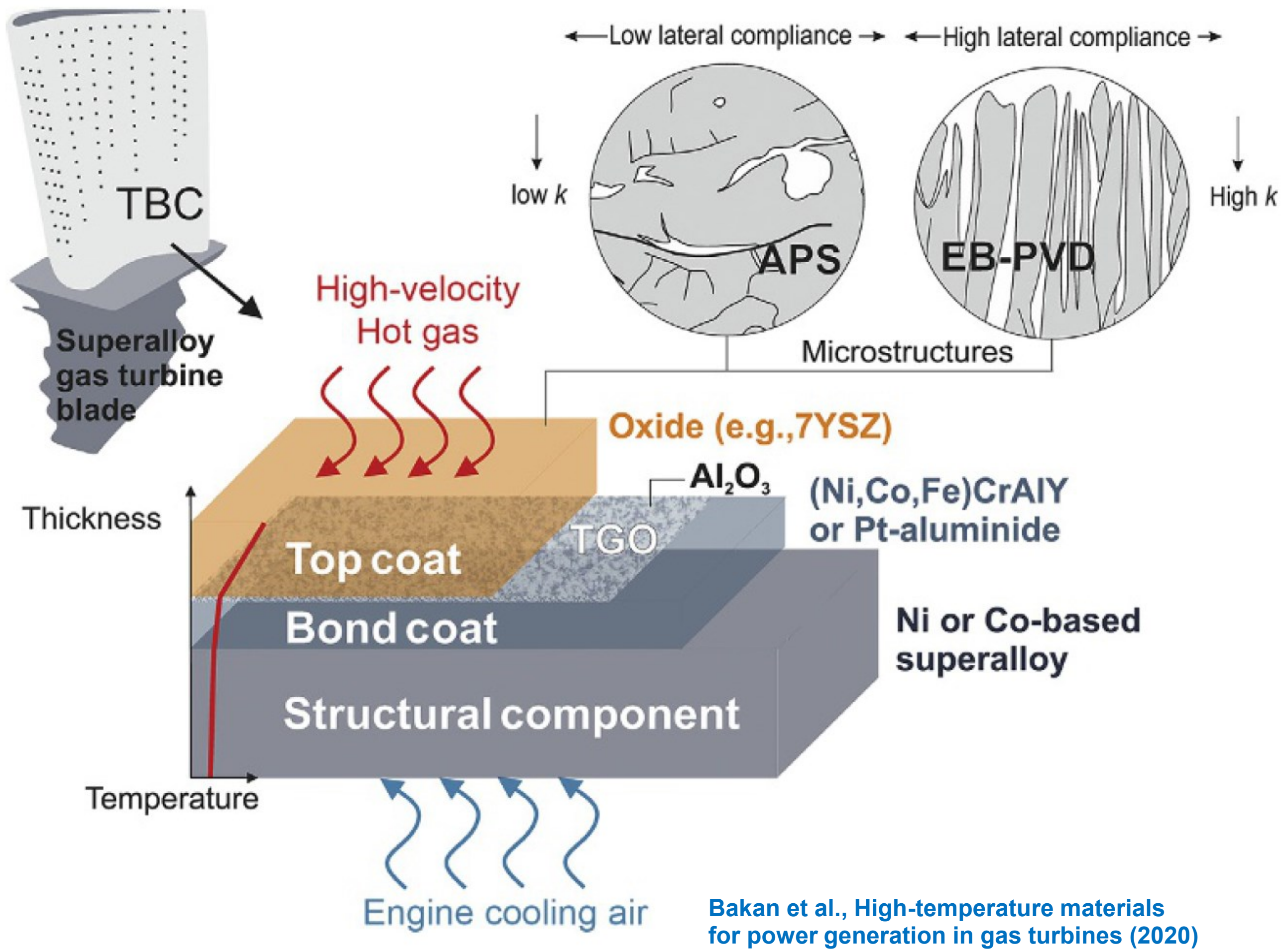
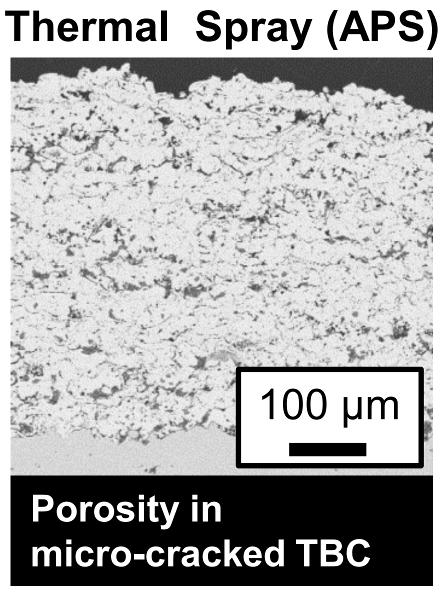
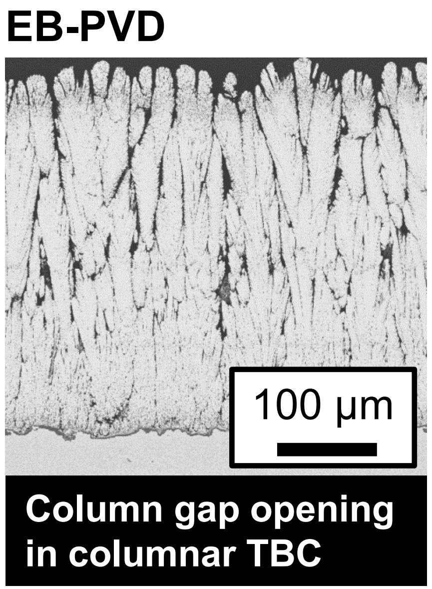
THERMAL BARRIER COATINGS IN GAS TURBINES



Bakan et al., High-temperature materials for power generation in gas turbines (2020)





- Atmospheric plasma spraying (APS) and electron beam physical vapor deposition (EB-PVD) are most established technologies for ceramic TBCs application

OUTLINE

When discussing the lifing of high temperature coatings for gas turbine blades, let's consider some background on

- failure mechanisms
- impact on lifetime expectation
- deposition processes and microstructures
- the developments in TBC coatings
- (quality aspect during application)

INTRINSIC SOURCES OF TBC DEGRADATION

- Elevated component temperatures

  Oxide growth (TGO) at alloy surfaces/interfaces (typ. Al_2O_3)

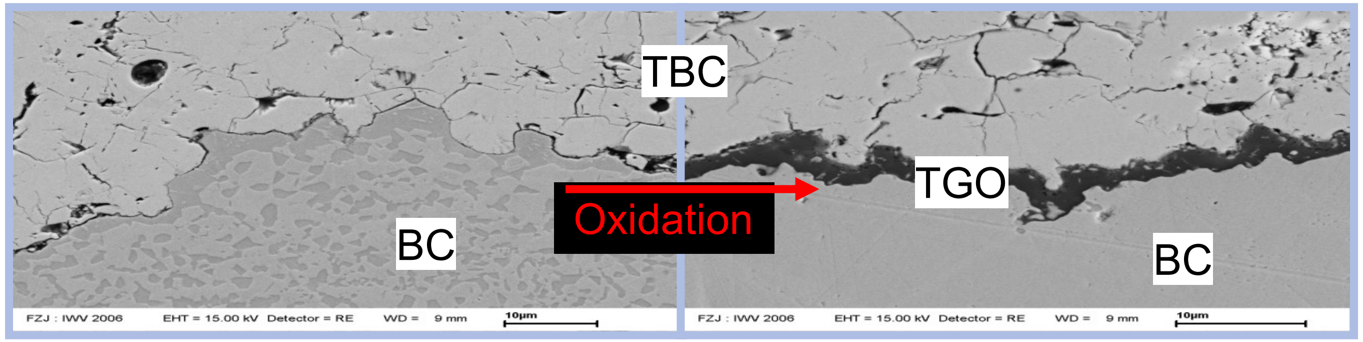
- Extreme surface temperatures

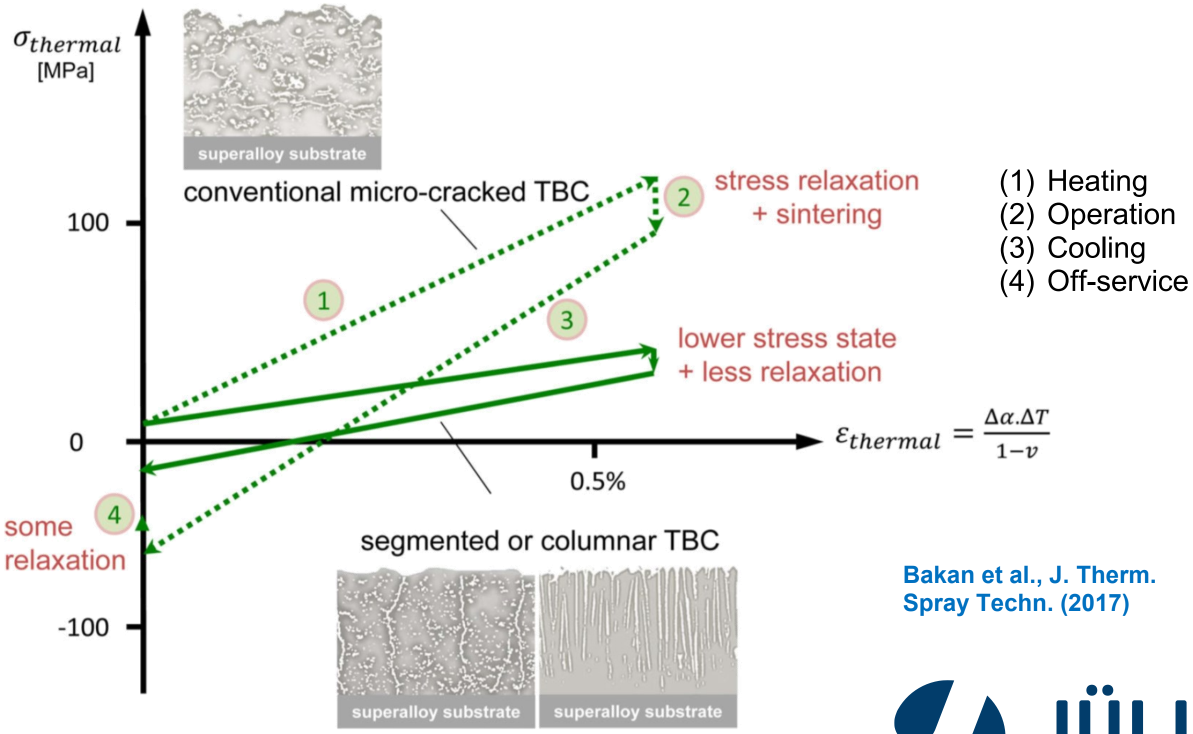
  Sintering and potential phase transformations of the ceramic (Young's modulus, toughness)

- Stresses induced by mismatch of coefficient of thermal expansion

TBC-Layer	$\alpha \approx 11*10^{-6}\ K^{-1}$	(YSZ)
Substrate	$\alpha \approx 16*10^{-6}\ K^{-1}$	(IN738)
TGO	$\alpha \approx 8*10^{-6}\ K^{-1}$	(β-Al_2O_3)

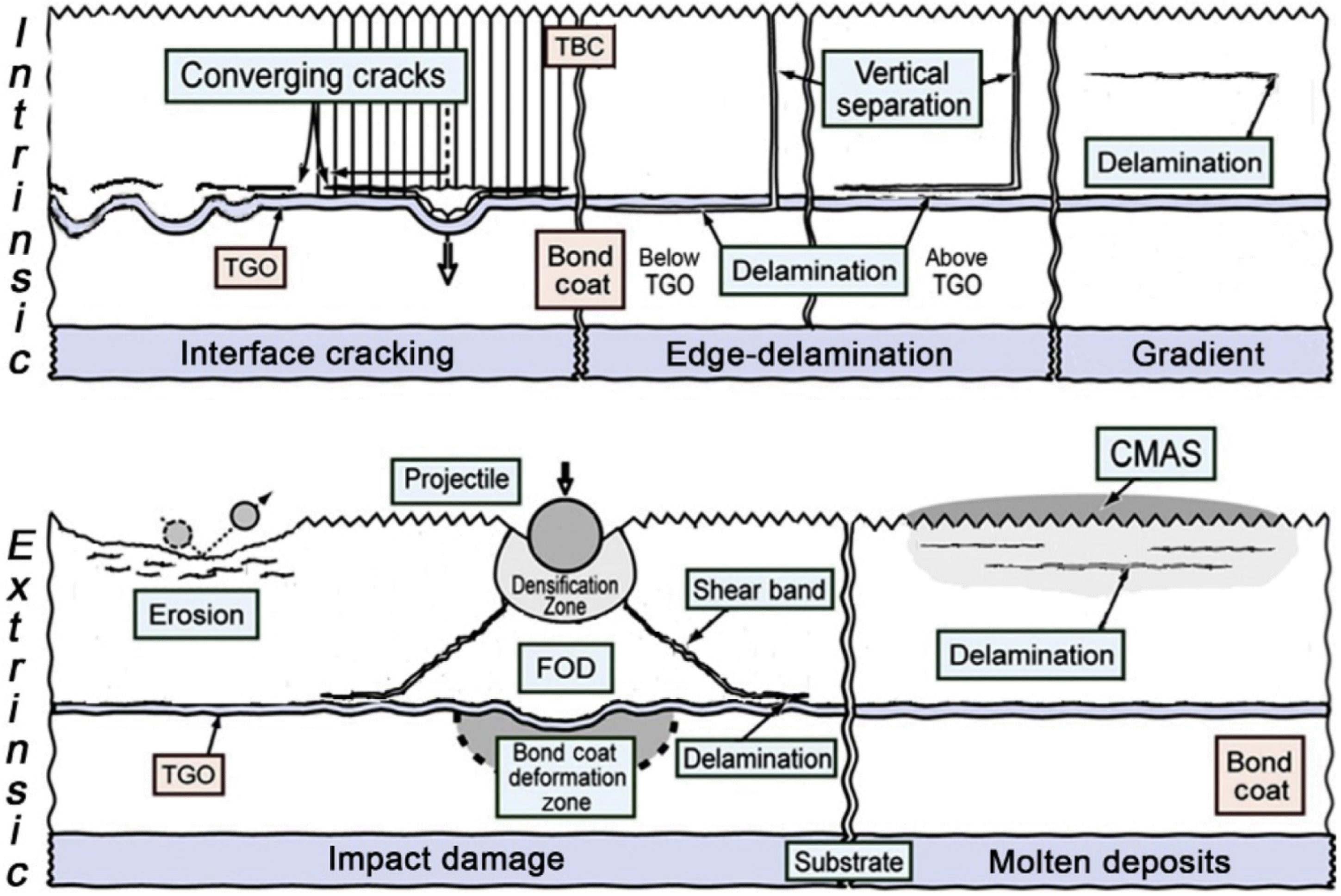
- Maximum stresses during transients (Cooling / Heating), gradient conditions





Bakan et al., J. Therm. Spray Techn. (2017)

COMMON TBC FAILURE MODES



adapted from Evans et al., J. Eur. Ceram. Soc. (2008)

- Strain and stress under cyclic operation are major drivers for evolution and growth of cracks leading to delamination and spallation
- Kinetics is governed by (tempera-ture induced evolution of) intrinsic mechanical properties and thermal shock rate
- Additionally crack density and mechanical properties may be altered by external impact

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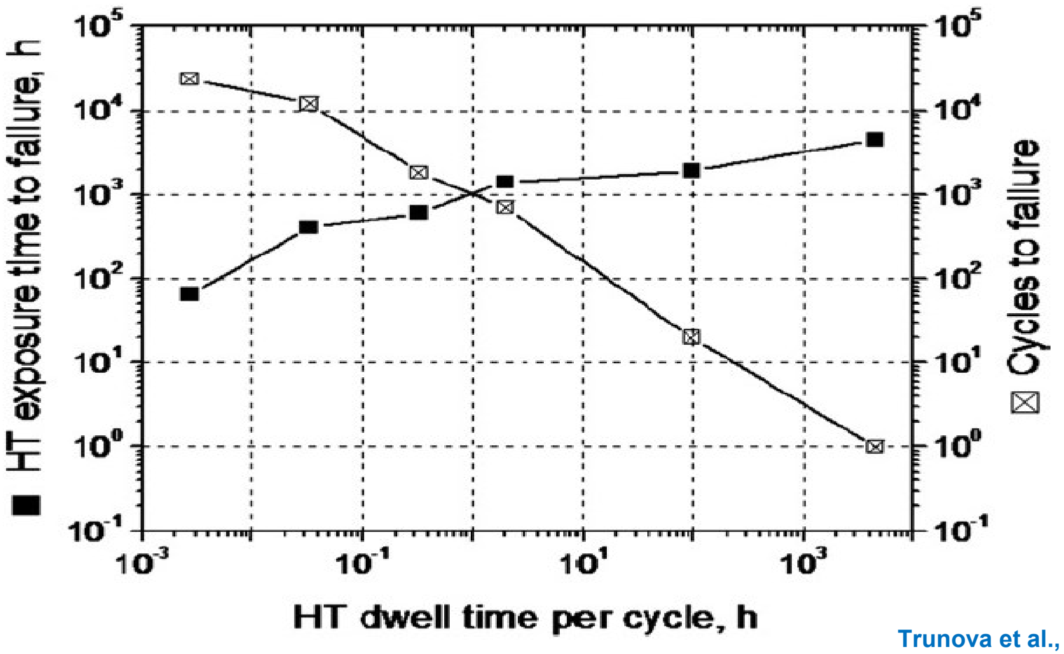
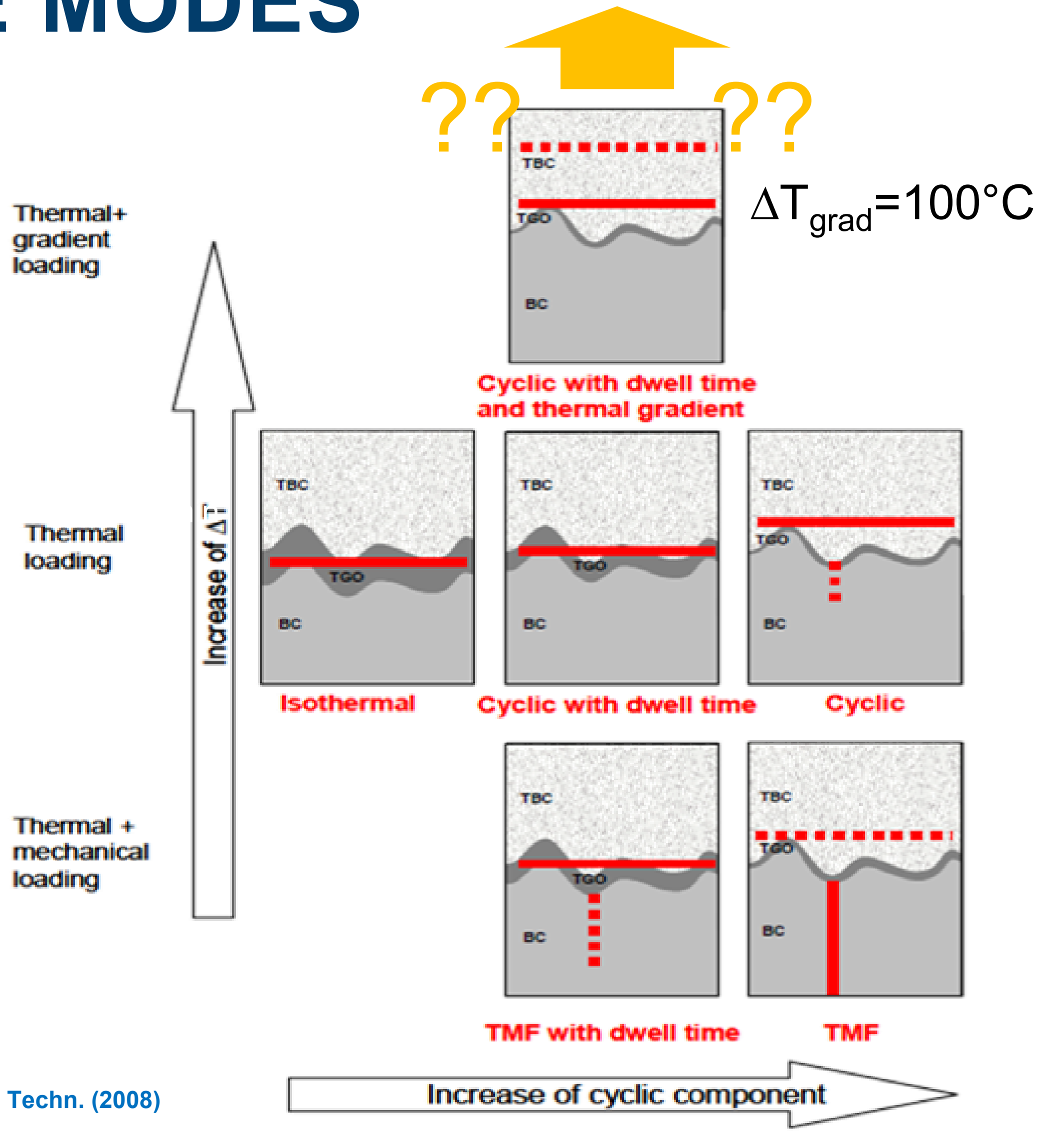
PERFORMANCE AND FAILURE MODES IN CYCLIC OPERATION

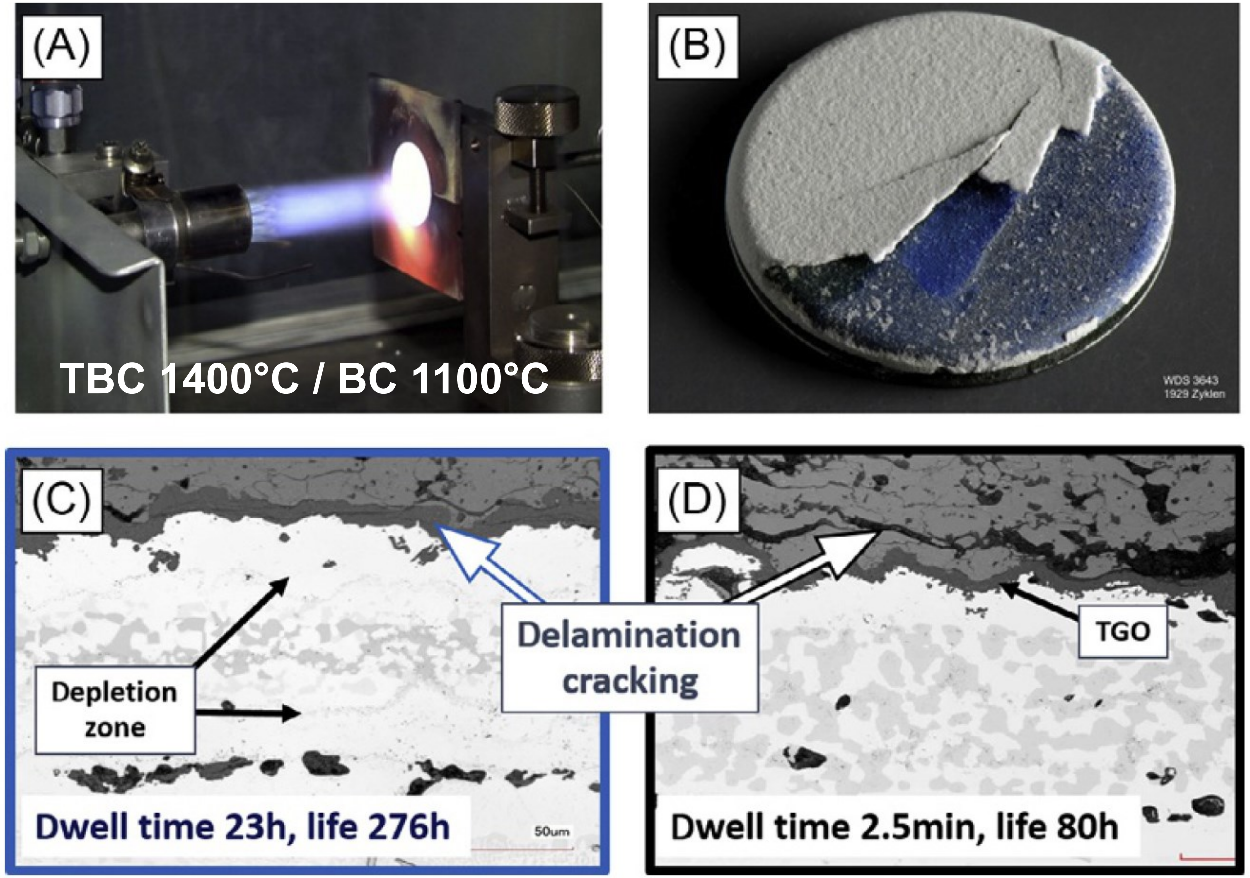
- Failure mode and critical level of intrinsic degradation level dependent on load scenario





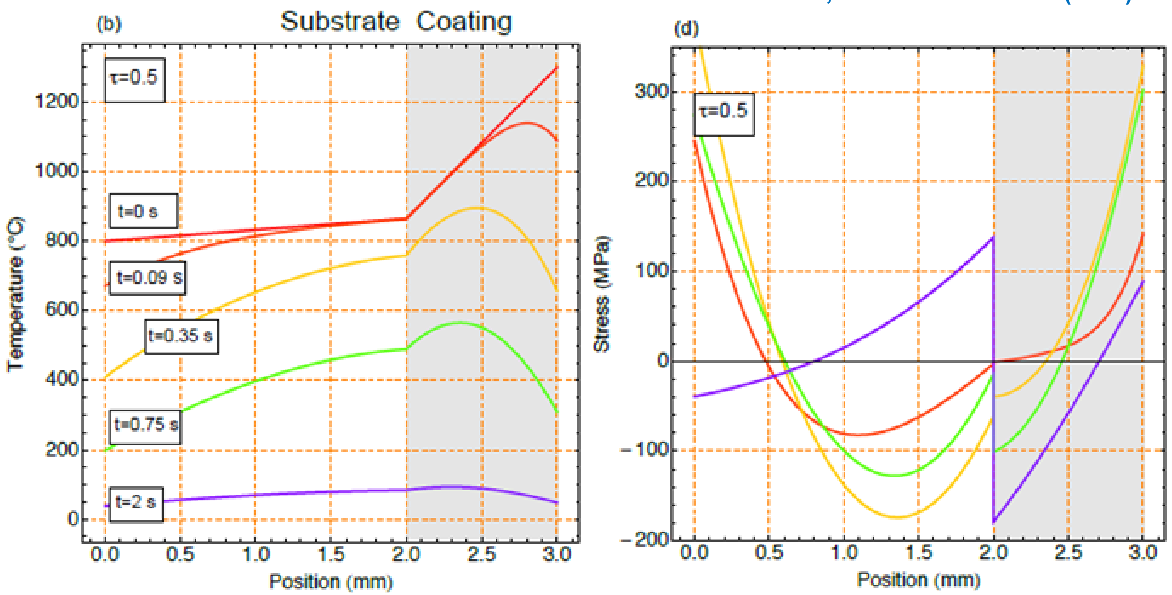
Trunova et al., Surf. Coat. Techn. (2008)

HIGH HEAT FLUX AND TRANSIENT CONDITIONS



Bakan et al., High-temperature materials for power generation in gas turbines (2020)

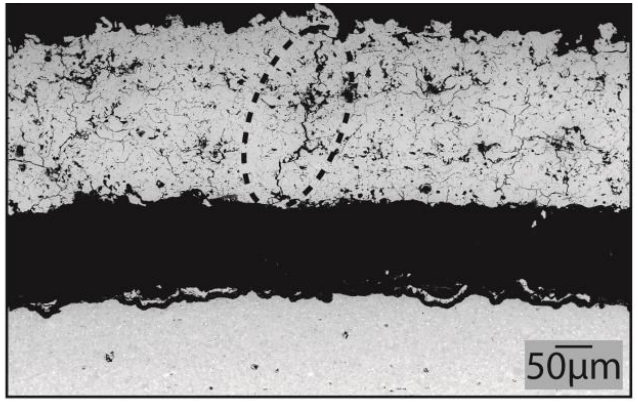
Jackson et al., Int. J. Solid. Struct. (2014)

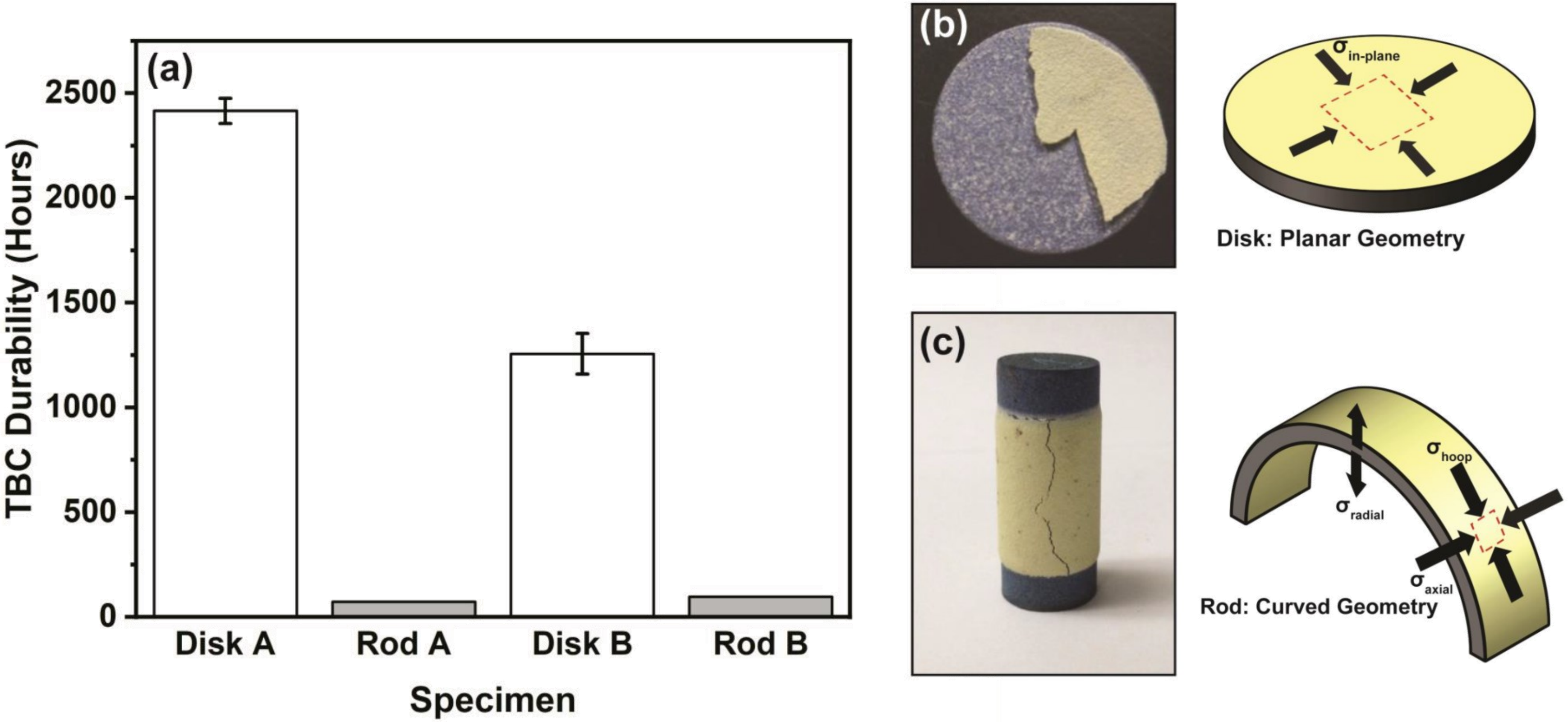


- Shift of delamination cracks into TBC with increased cyclic loading also observed in high heat flux testing (e.g. burner rig)
- In part this can be attributed to (typically) higher transient rates

COMPLEX SHAPES

- Interface curvature (macro & micro) is important to coating delamination
- Complex geometries can foster segmentation



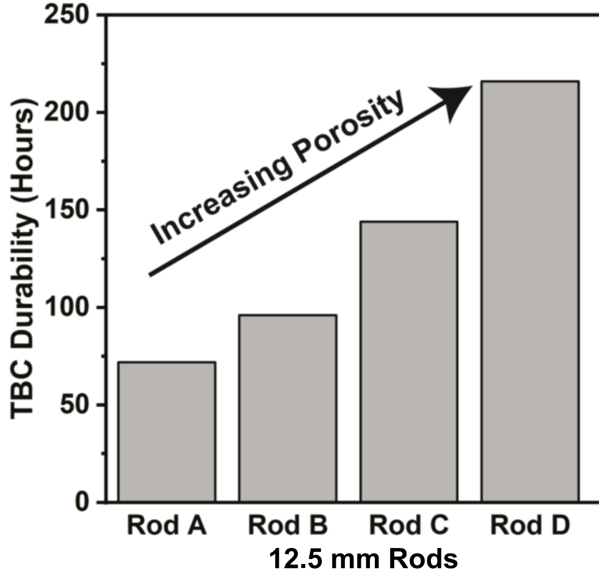


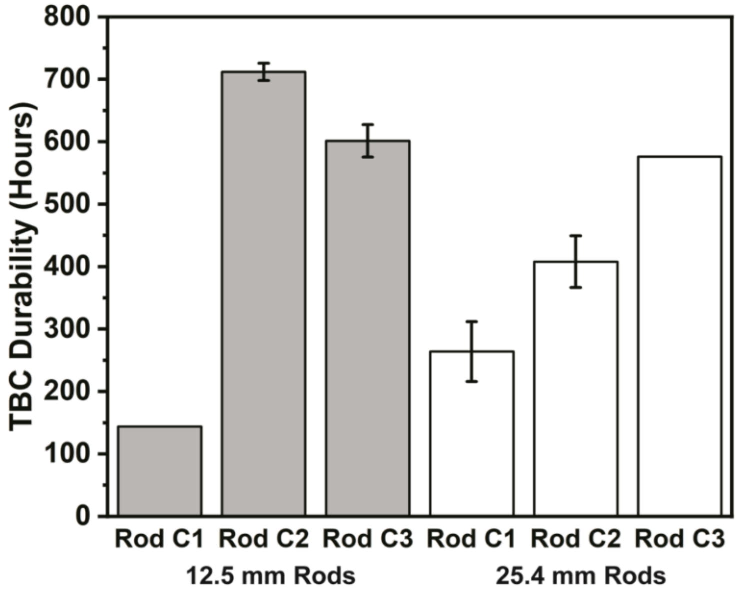
Gildersleeve et al., Surf. Coat. Techn. (2021)

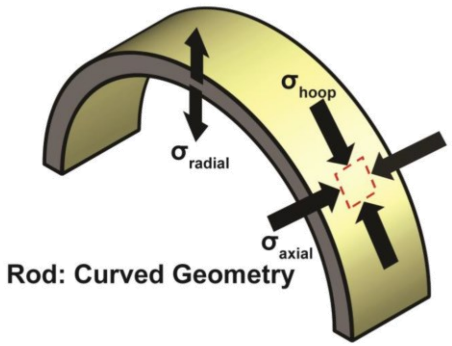
COATING AND INTERFACE TOUGHNESS

- High porosity (low modulus) reduces driving force for interface delamination

- High interface toughness fosters segmentation and mixed mode failure



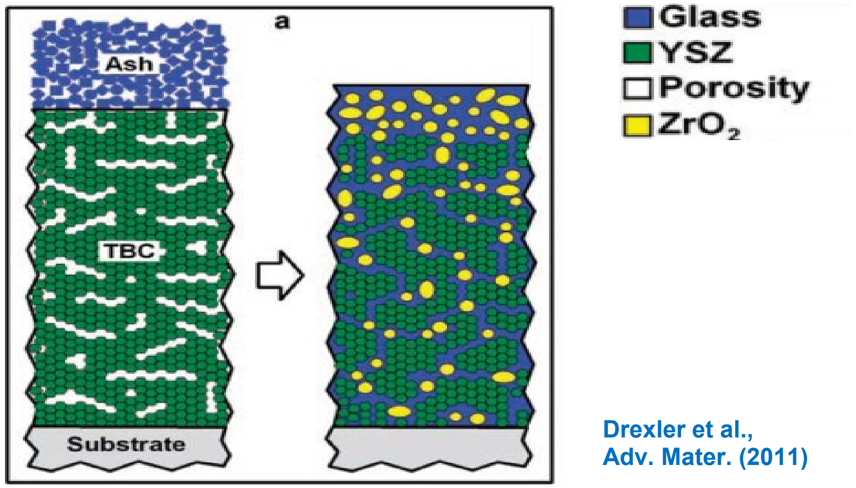




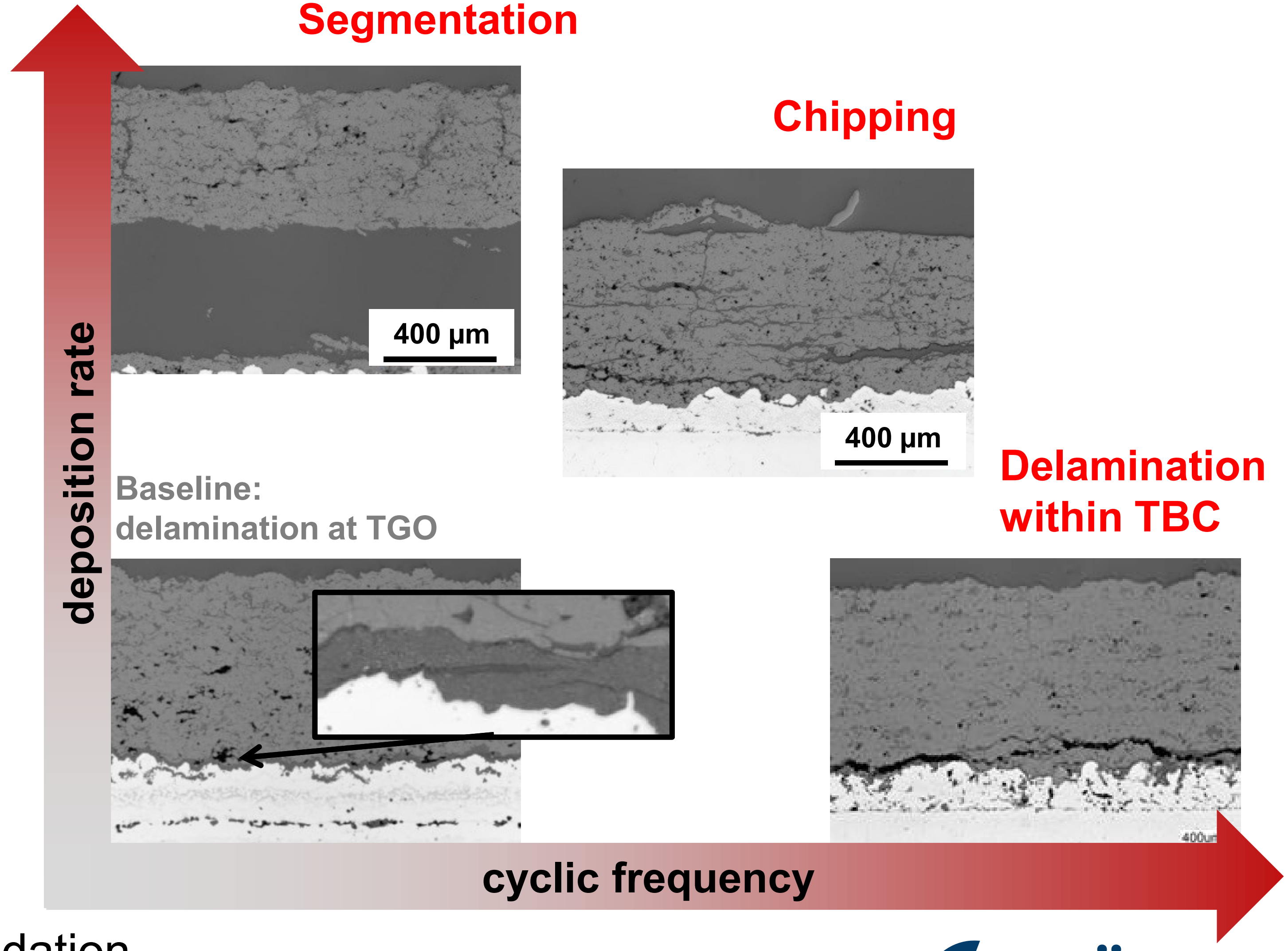
Specimen (bond coat) Rod diameter	C1 (HVOF) 12.5 mm	C1 (HVOF) 25.4 mm	C2 (HVOF+APS) 12.5 mm	C2 (HVOF+APS) 25.4 mm	C3 (VPS) 12.5 mm	C3 (VPS) 25.4 mm
Interface toughness (estimated) [34, 46]	*Low*	*low*	*high*	*high*	*medium*	*medium*
Steady-state radial stress	*large*	*medium*	*large*	*medium*	*large*	*medium*
Initial transient tensile hoop stress	*medium*	*large*	*medium*	*large*	*medium*	*large*
FCT durability (A-F)	***F***	***D***	***A***	***C***	***B***	***B***
Primary failure process	*delamination*	*delamination*	*delamination*	*mixtur*	*delamination*	*vertical crack*

Gildersleeve et al., Surf. Coat. Techn. (2021)

DEGRADATION BY MOLTEN DEPOSITS (CMAS)



Drexler et al.,
Adv. Mater. (2011)



- Open structure of TBC is vulnerable to attack from molten deposits from dust,sand, volcanic ash, fly ash, or wear debris
- Coating densification and disintegra-tion results in diverse failure modes
- Protective layers may slow down degradation

DEGRADATION IN PRESENCE OF WATER (VAPOR)

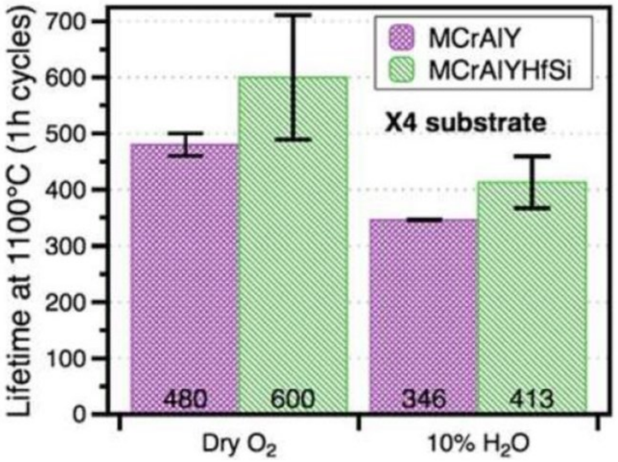
PREPARE FOR H_2 OPERATION

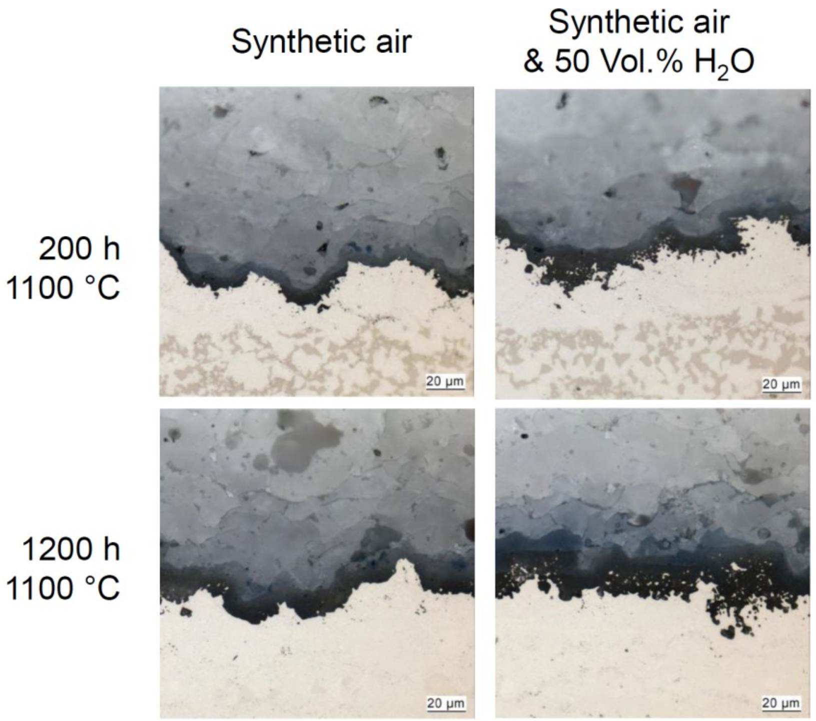
Water (vapor), in some circum-stances, changes

- reaction rates (e.g. TGO formation, sintering)
- interface morphologies
- crack propagation rates

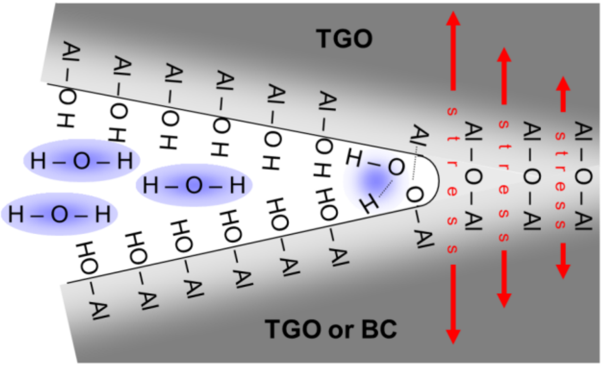
More effects and systems need to be studied in detail and combination ...

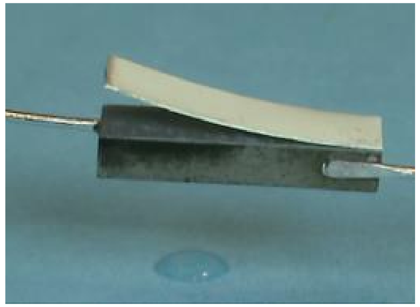
Haynes et al., Surf. Coat. Techn. (2013)





Rudolphi et al., Mat. High Temp. (2009)



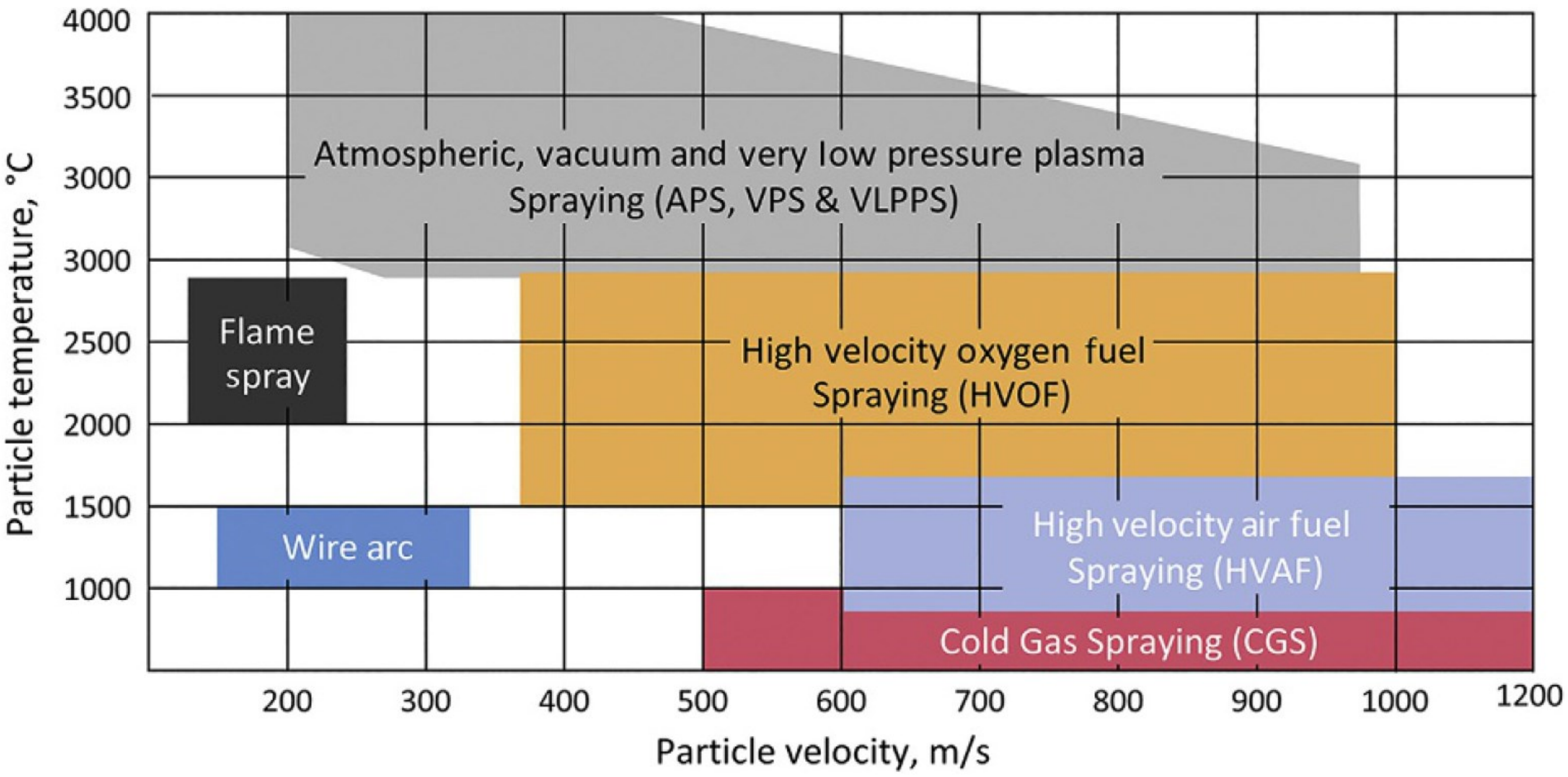


from Wiederhorn et al., Int. J. Fract. Mech. (1968)

THERMAL SPRAY FOR GAS TURBINE APPLICATIONS

- Variety of thermal spray methods used in turbine coating and repair (alloys and ceramic)

- Plasma spraying (APS, VPS, VLPPS) state of the art for high temperature ceramics



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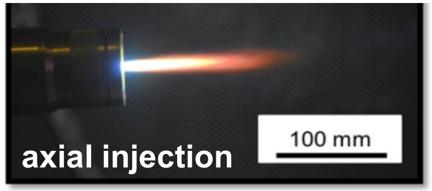
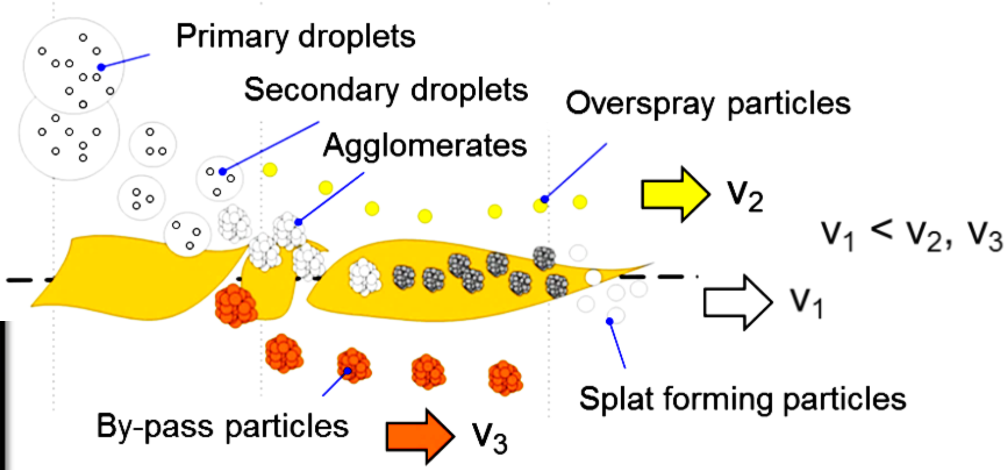
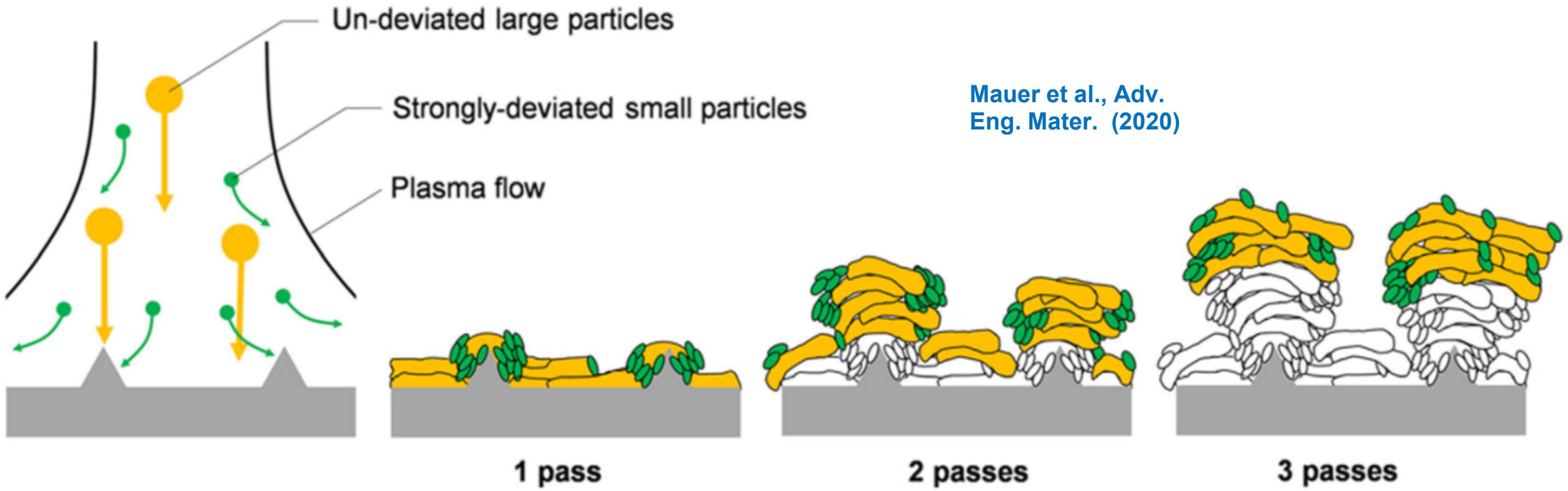
SUSPENSION PLASMA SPRAYING (SPS)



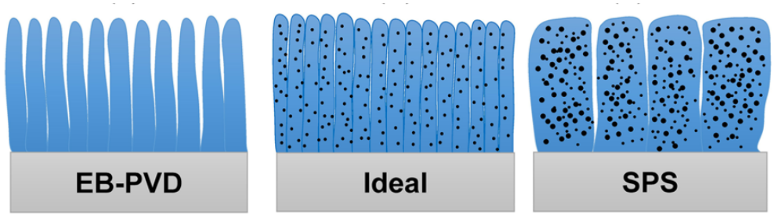


Siegert PhD (2006)



Mauer et al., Adv. Eng. Mater. (2020)

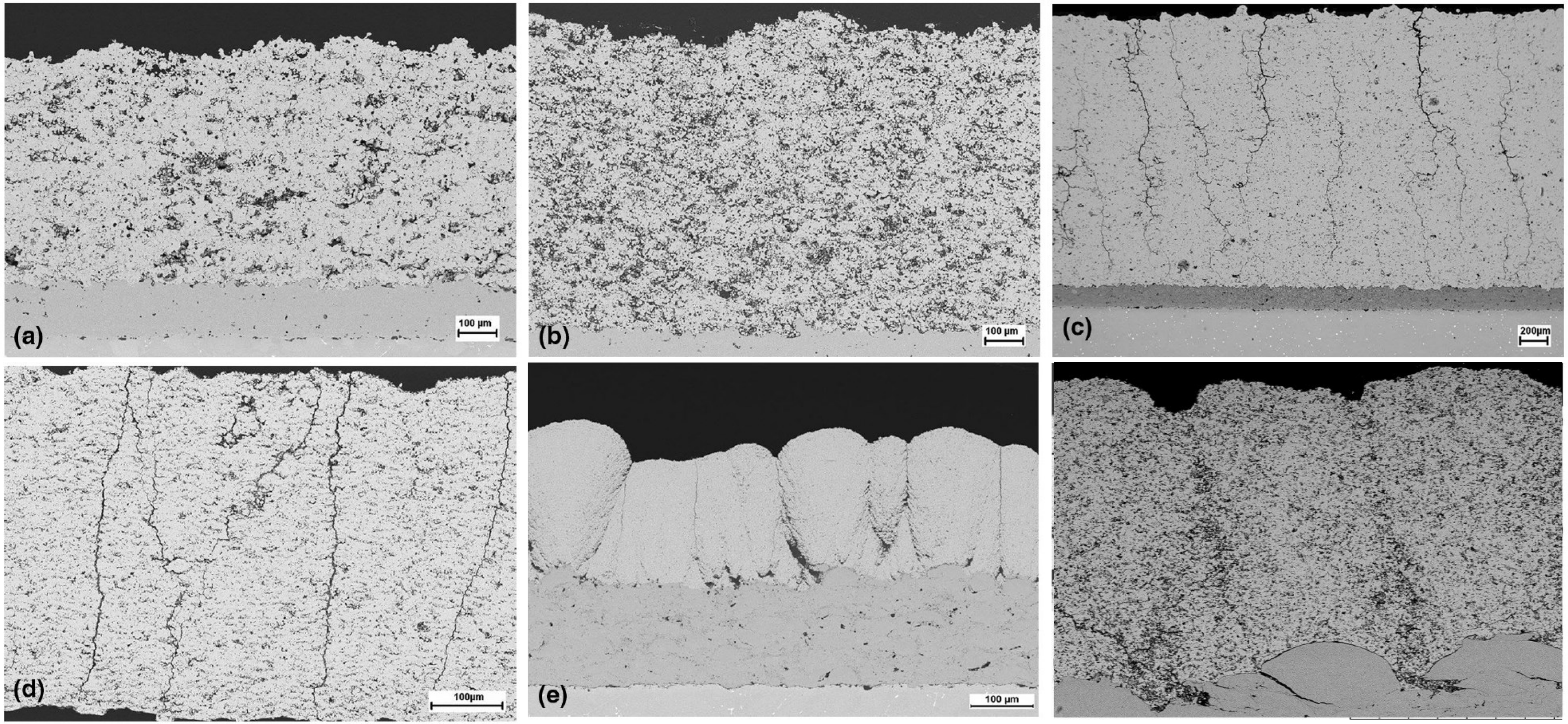
- Plasma spraying with liquid feedstocks (suspension or precursor)
- Unique potential for micro-porous and columnar micro-structures from (sub)micron sized droplets



Kumar et al., J. Therm. Spray Techn. (2021)

MICROSTRUCTURE VARIABILITY IN THERMAL SPRAY

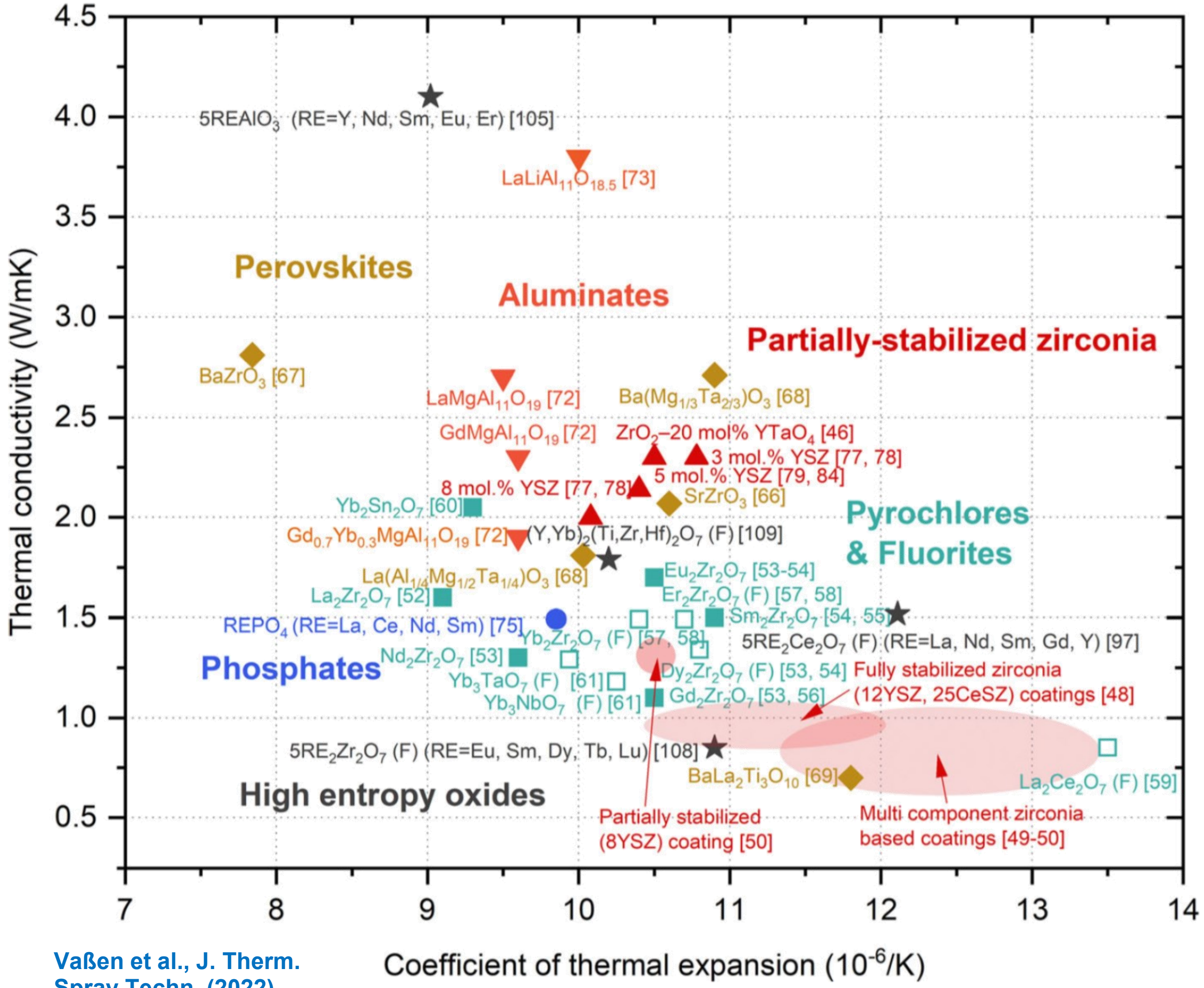
conventional APS (medium porosity level) | highly porous APS | thick segmented APS



segmented SPS | columnar SPS | highly porous SPS

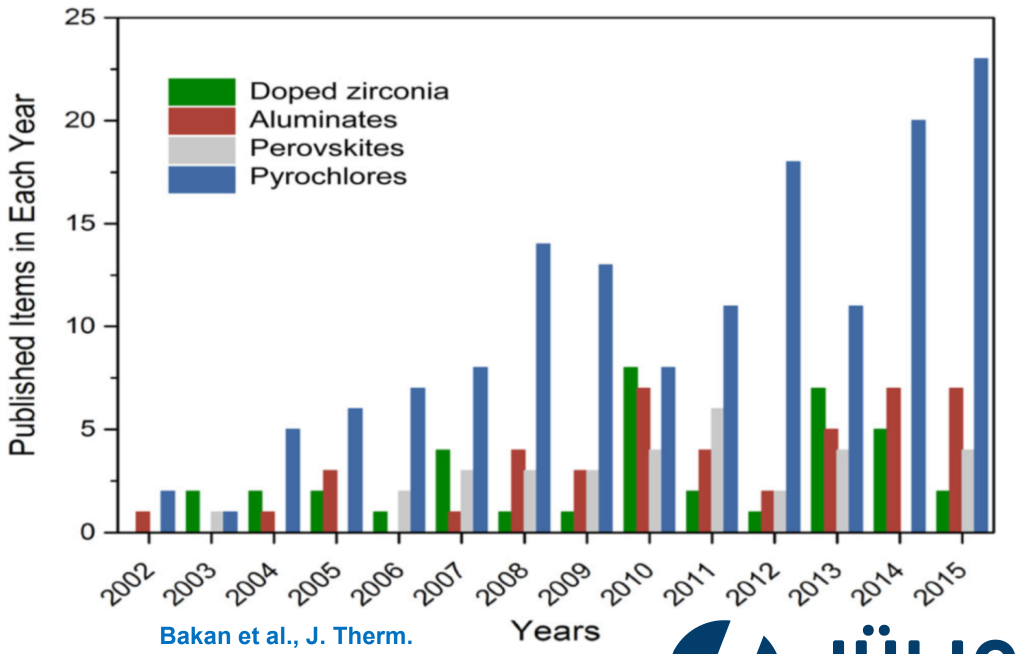
Vaßen et al., J. Therm. Spray Techn. (2022)

ALTERNATIVE TBC MATERIALS



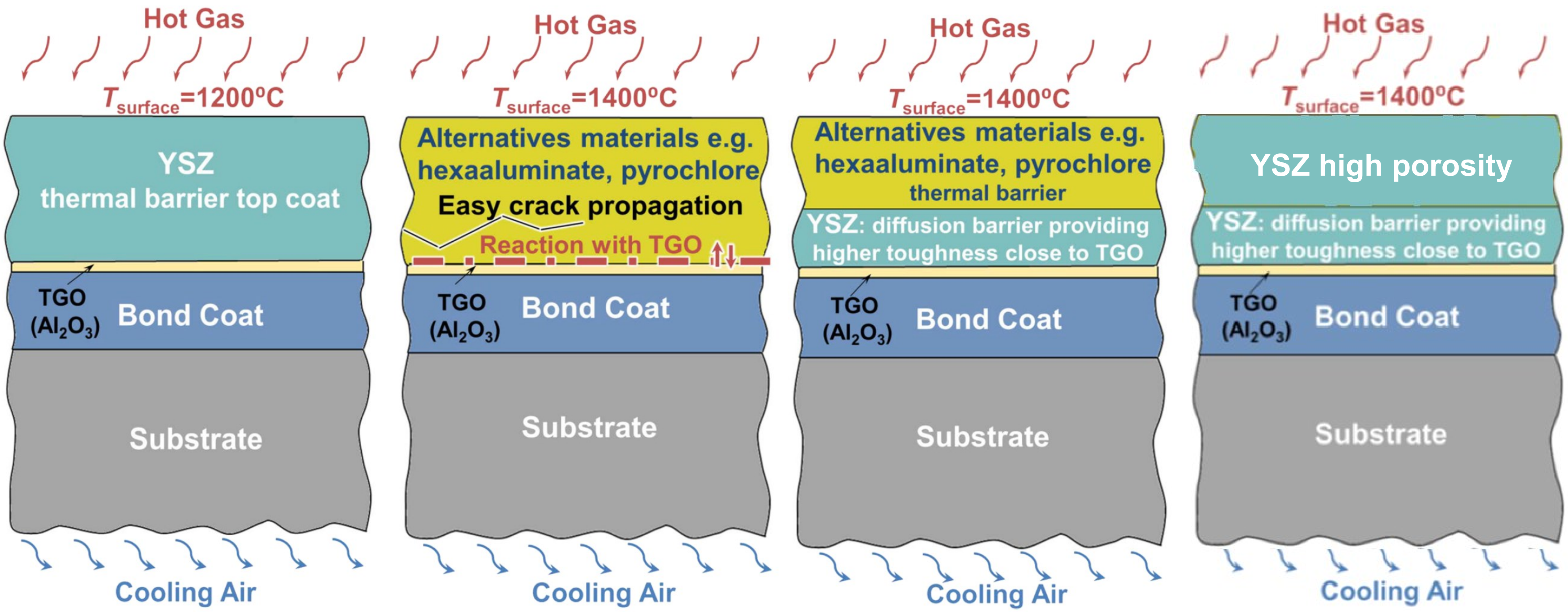
Vaßen et al., J. Therm. Spray Techn. (2022)

- Continuous search for materials with improved temperature stability to replace YSZ
- None offers superior mechanical properties



Bakan et al., J. Therm. Spray Techn. (2017)

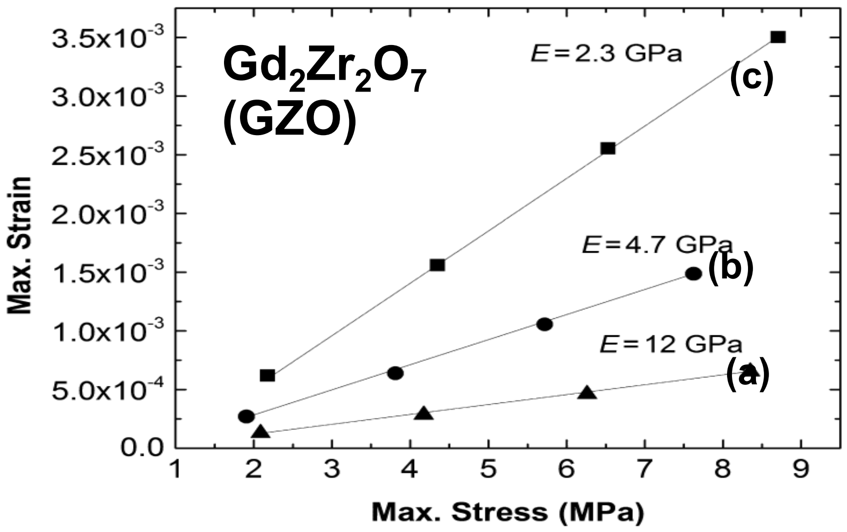
MULTILAYER CONCEPTS FOR INCREASED TEMPERATURE

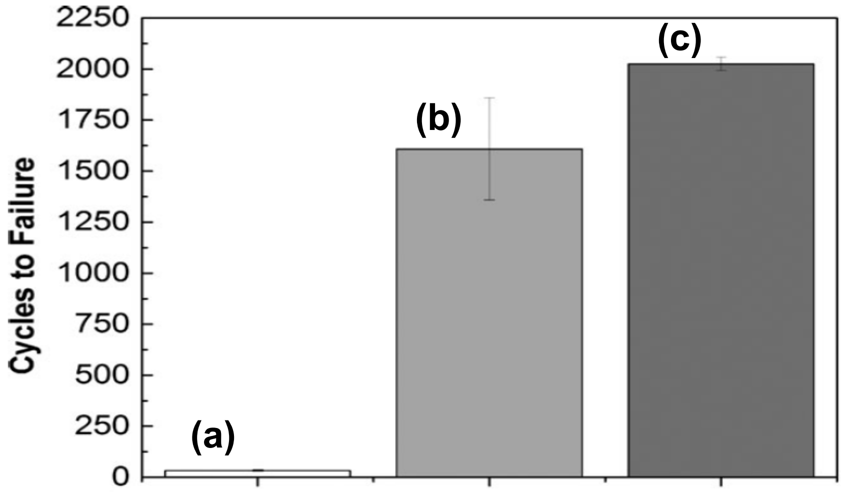


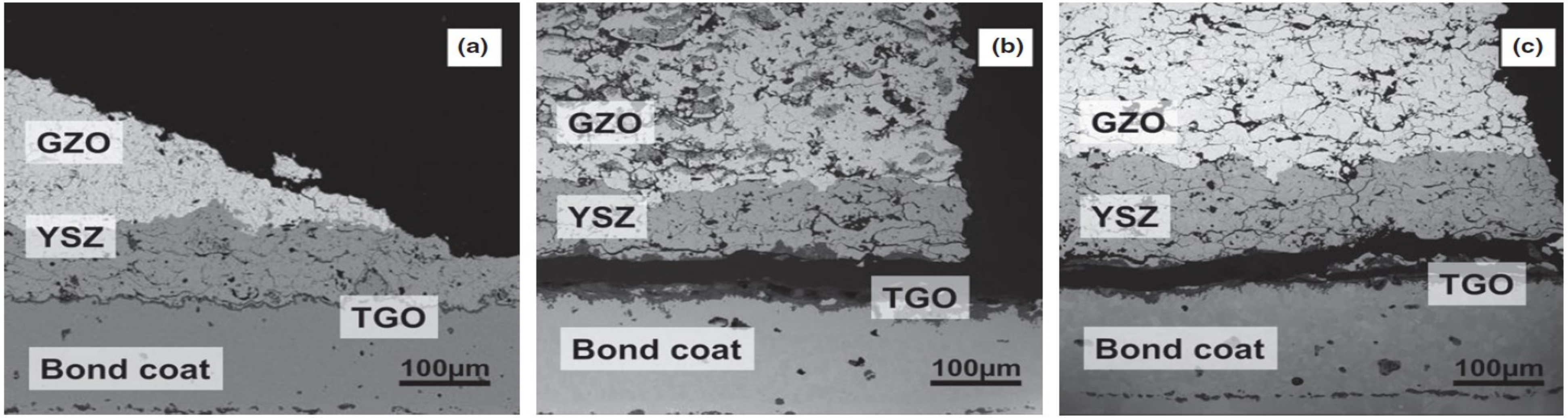
Bakan et al., J. Therm. Spray Techn. (2017)

PYROCHLORE DOUBLE-LAYER TBC

Low intrinsic fracture toughness of pyrochlore (here GZO) counter-balanced by reduced Young‘s modulus

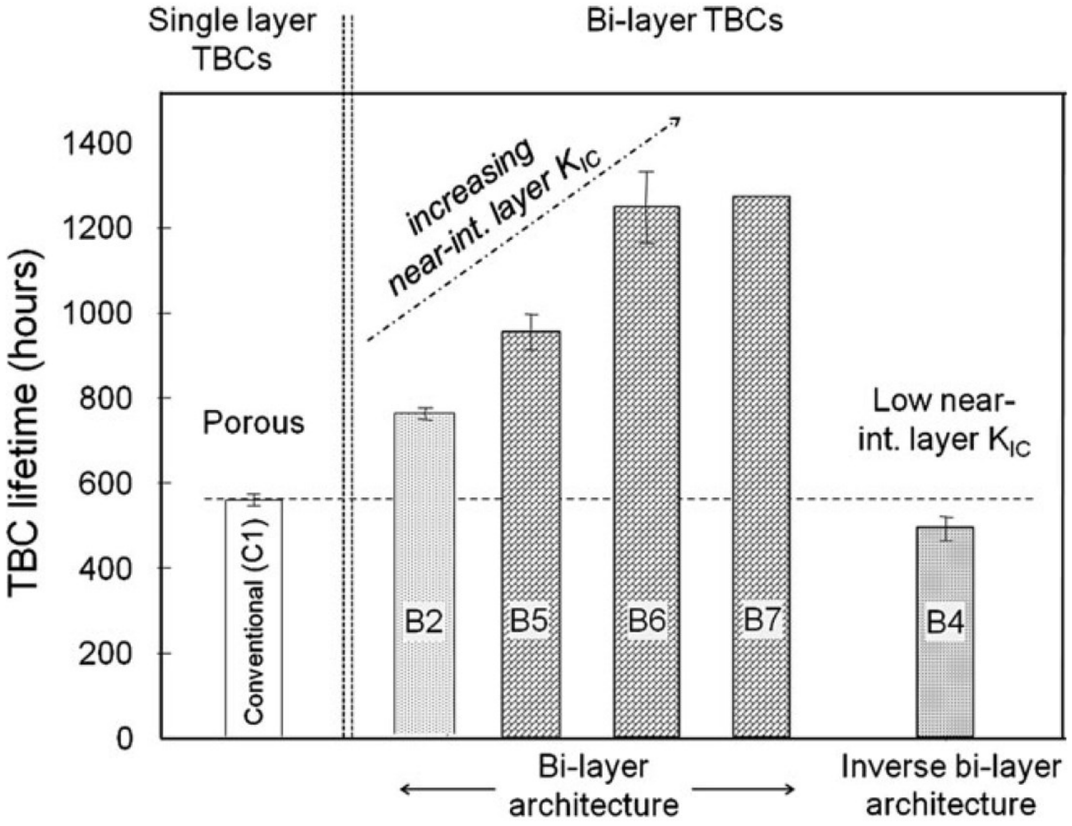




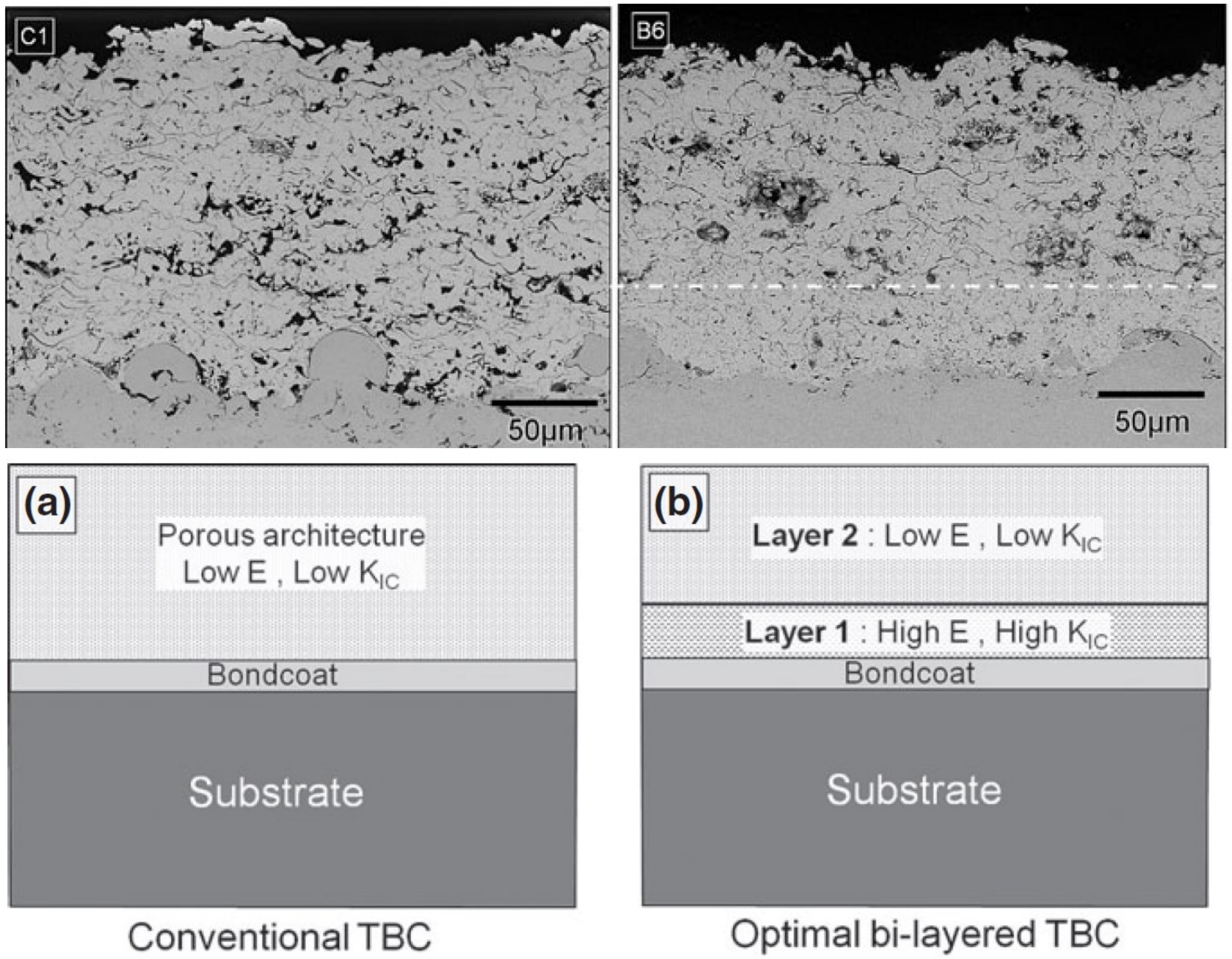


Bakan et al., J. Therm. Spray Techn. (2017)

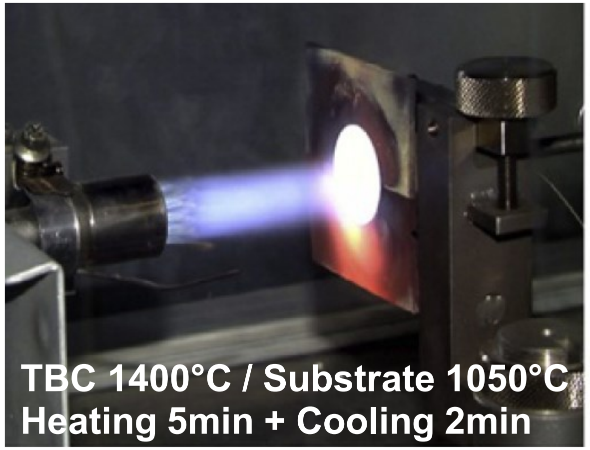
YSZ „DOUBLE LAYER“ TBC



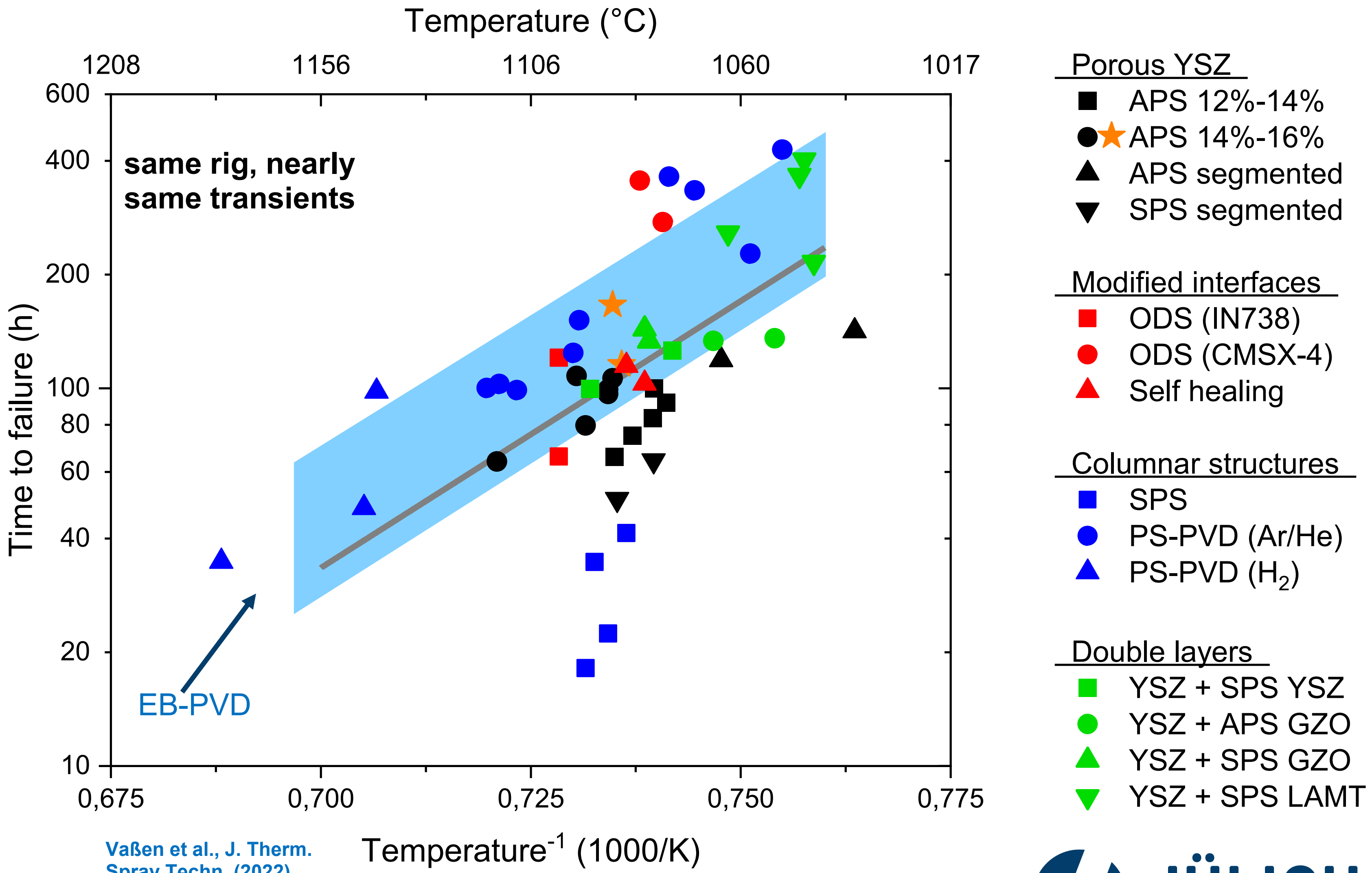
Viswanathan et al., J. Am. Ceram. Soc. (2014)



BURNER RIG LIFE OF VARIOUS TBC STRUCTURES



- Arrhenius behaviour suggest TGO as driver
- Columnar and segmented spray coatings not optimized
- Multi-layer based on YSZ most reliable approach for increased temperatures



Vaßen et al., J. Therm. Spray Techn. (2022)

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