

Extreme Oxidative Durability of TBCs on Ti_2AlC MAX Phases

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Motivation and Rationale

Ti_3AlC_2 , Ti_2AlC , Cr_2AlC

- $\alpha\text{-Al}_2\text{O}_3$ formers
- Na_2SO_4 corrosion resistance
- CTE close to YSZ, $\alpha\text{-Al}_2\text{O}_3$
- Damage (Strain ?) tolerance,
nano-laminate shear, machinable
- Thermal shock resistance: $\sim 1400^\circ\text{C}$ quench
- $K_{\text{IC}} \approx 7 \text{ MPa/m}^{1/2}$

Hybrid Concepts (EBC/TBC) Enabled by MAX Phases

Intermediate CTE, Strain Tolerance, YSZ Compatibility

Liner, Seals, Bond Coats (?)

CTE, $10^{-6}/^{\circ}\text{C}$

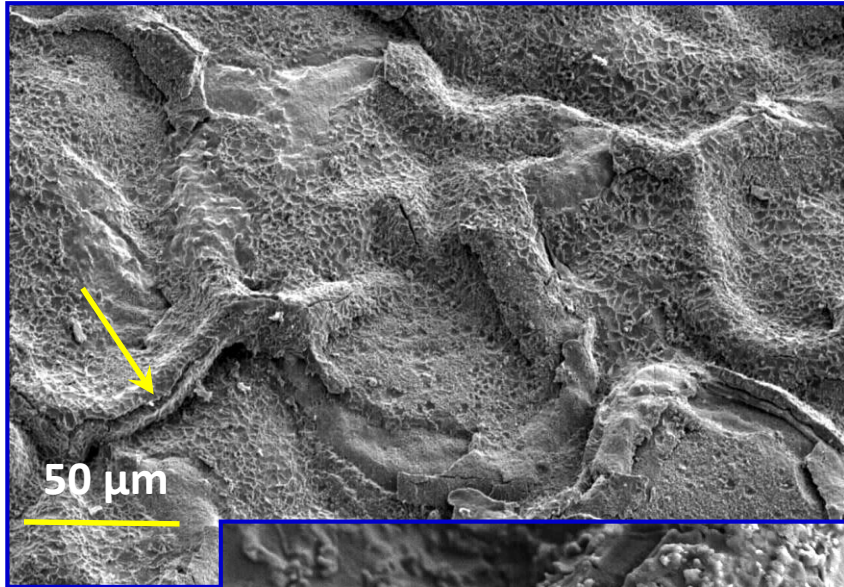
YSZ	12	Top Coat
Al_2O_3	9	Scale
Ti_2AlC	10	Bond Coat, Substrate
Ti_3AlC_2	9	
Cr_2AlC	13	
Rene N5	15	Substrates
SiC CMC	4	
(Mo, Nb, Ti alloys)	10	

← Critical interface

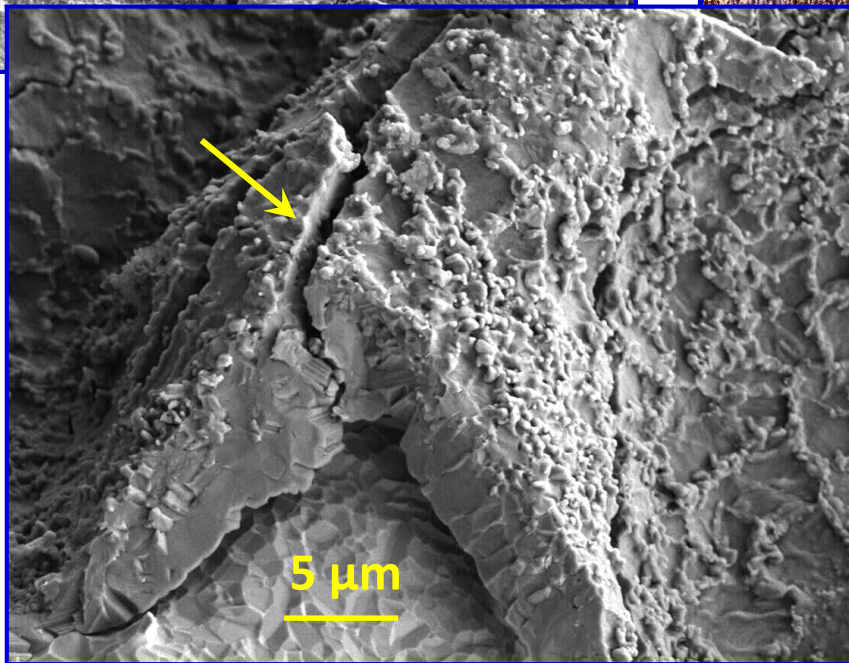
?

Damaged scales: 2000 1-h cycles at 1150°C

Ni(Pt)Al on CMSX-4 (ridges, rumpling, and ratcheting)



Pt-Aluminide Bond Coats

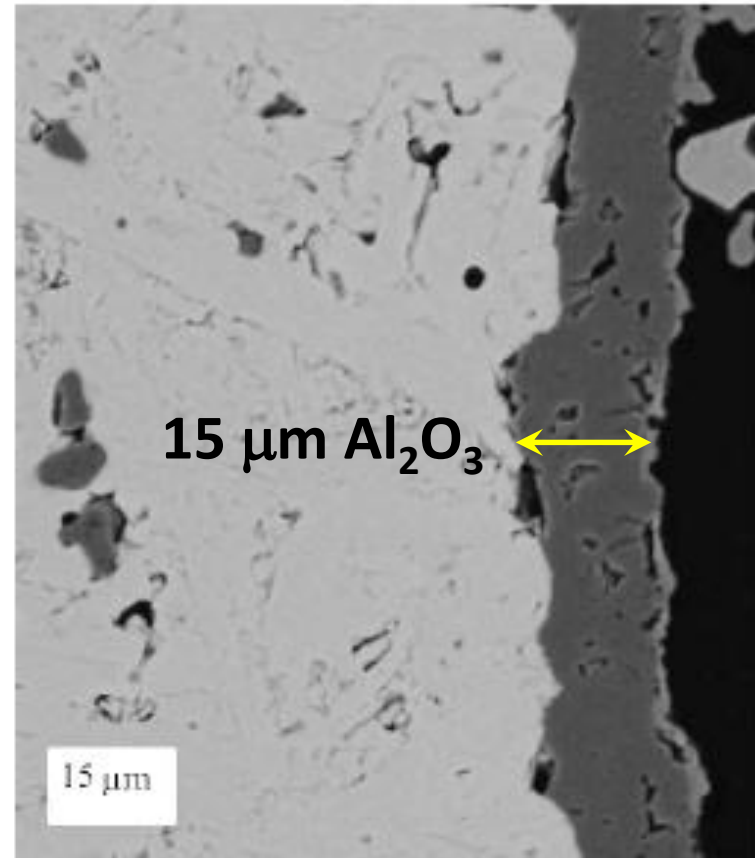


TBC Failure:
300 h at 1150°C
Ni(Pt)Al on N5

Commercial Ti_2AlC 211 MAXthal (Sandvik/Kanthal)

M. Sundberg, G. Malmqvist, A. Magnusson, T. El-Raghy, 2004

8000 cycles to 1350°C!



YSZ TBC Coatings on Al-MAX Phases

S.O.A. Baseline:

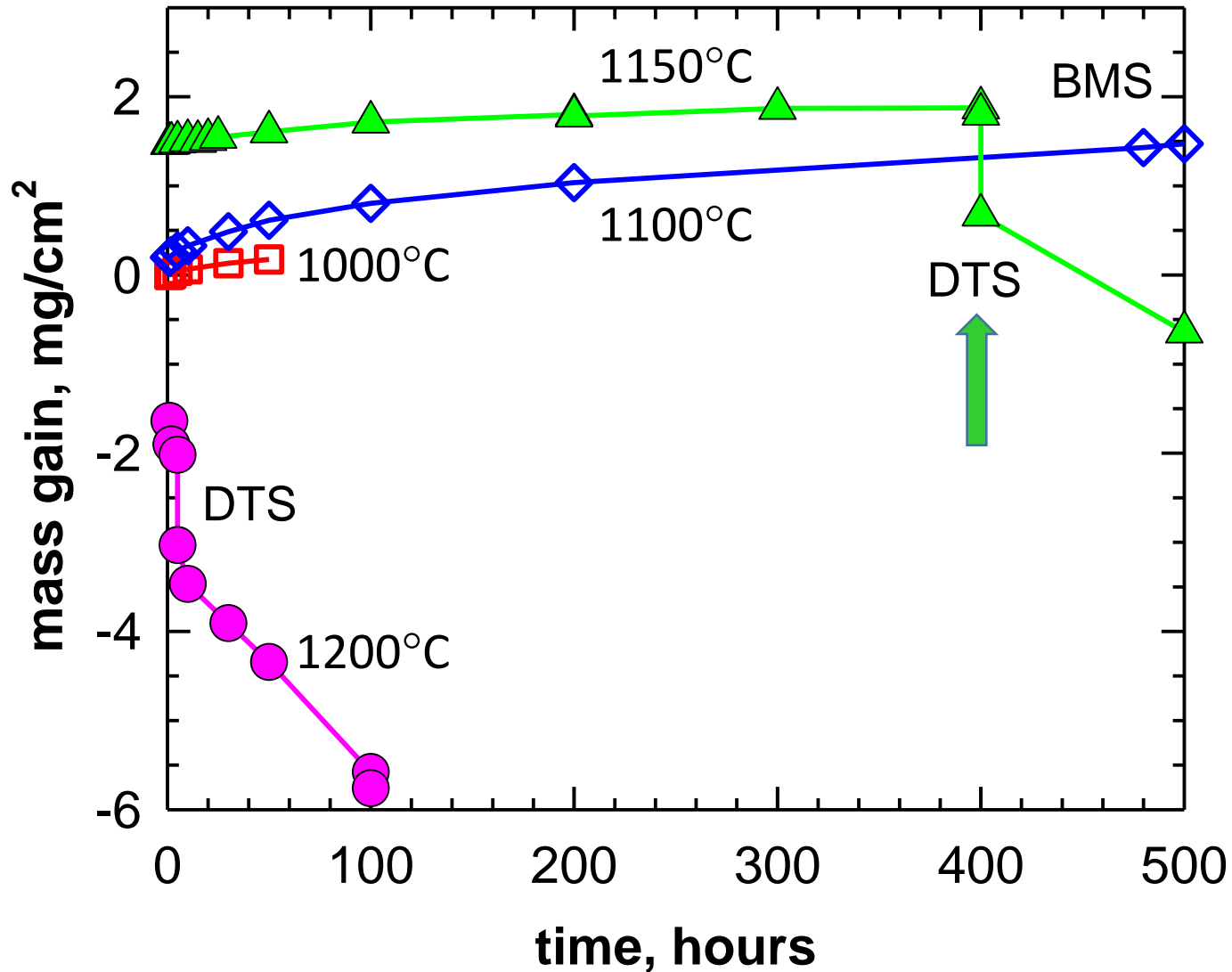
Ni(Pt)Al/YSZ on CMSX-4 at **1150°C**

Less than **1000 h** furnace cycle life

- APS **AND** PS-PVD (~80-100 μm)
- Ti_2AlC (CTE 10); Cr_2AlC (CTE 13); grit blast
- Stepped, interrupted furnace test
 - 1100°, 1150°, 1200°, 1250°, 1300° C
 - 500 h at each temperature

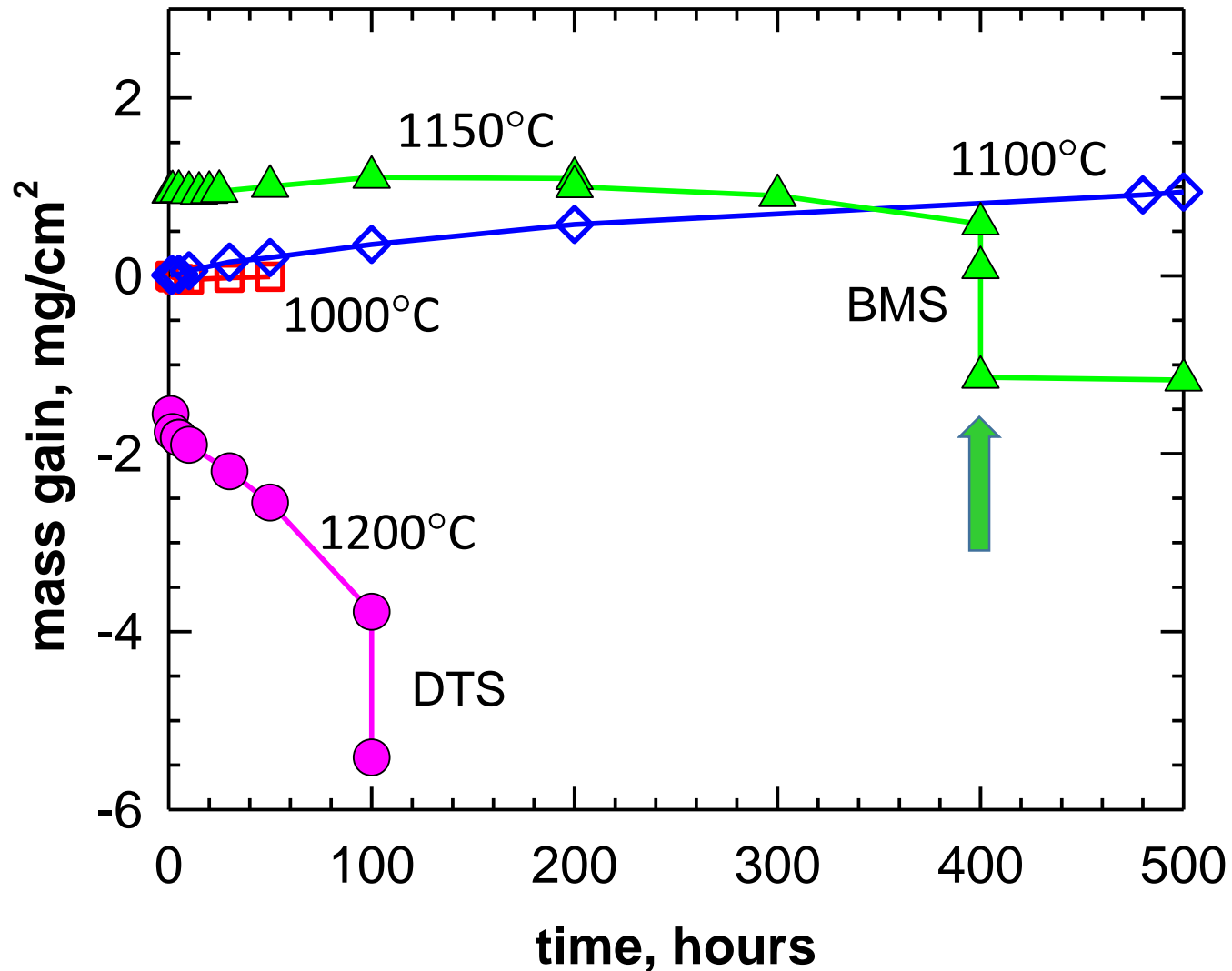
Interrupted Oxidation of APS YSZ on Cr_2AlC

(TBC failure starts at 1150°C)



Interrupted Oxidation of PS-PVD YSZ on Cr₂AlC

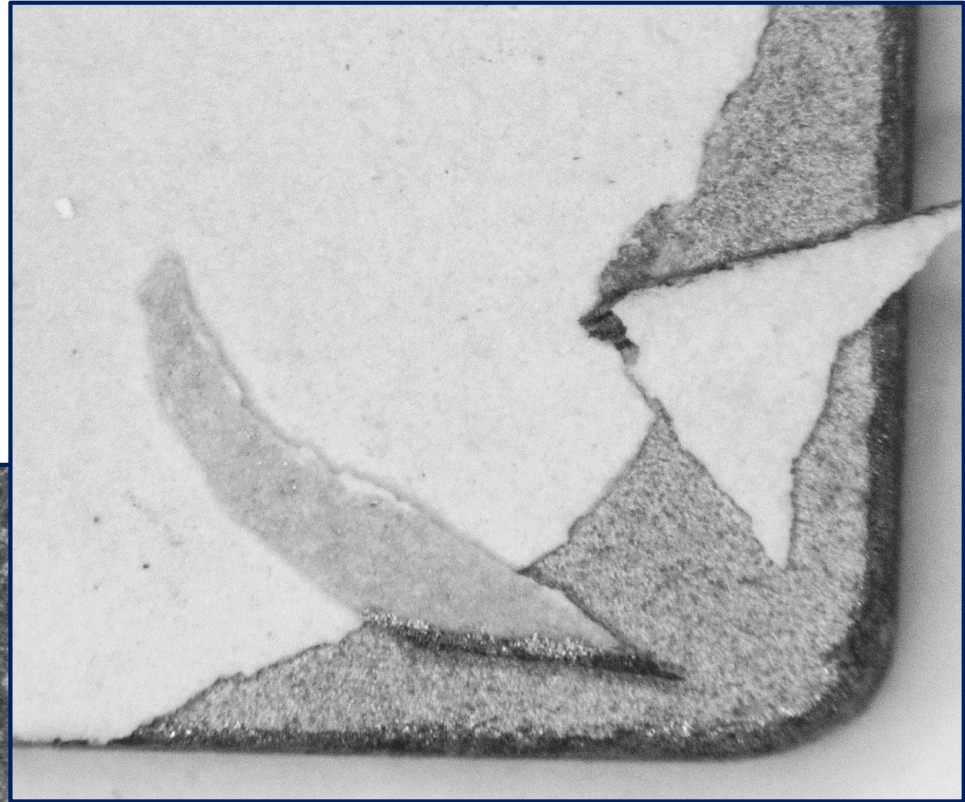
similar spallation behavior



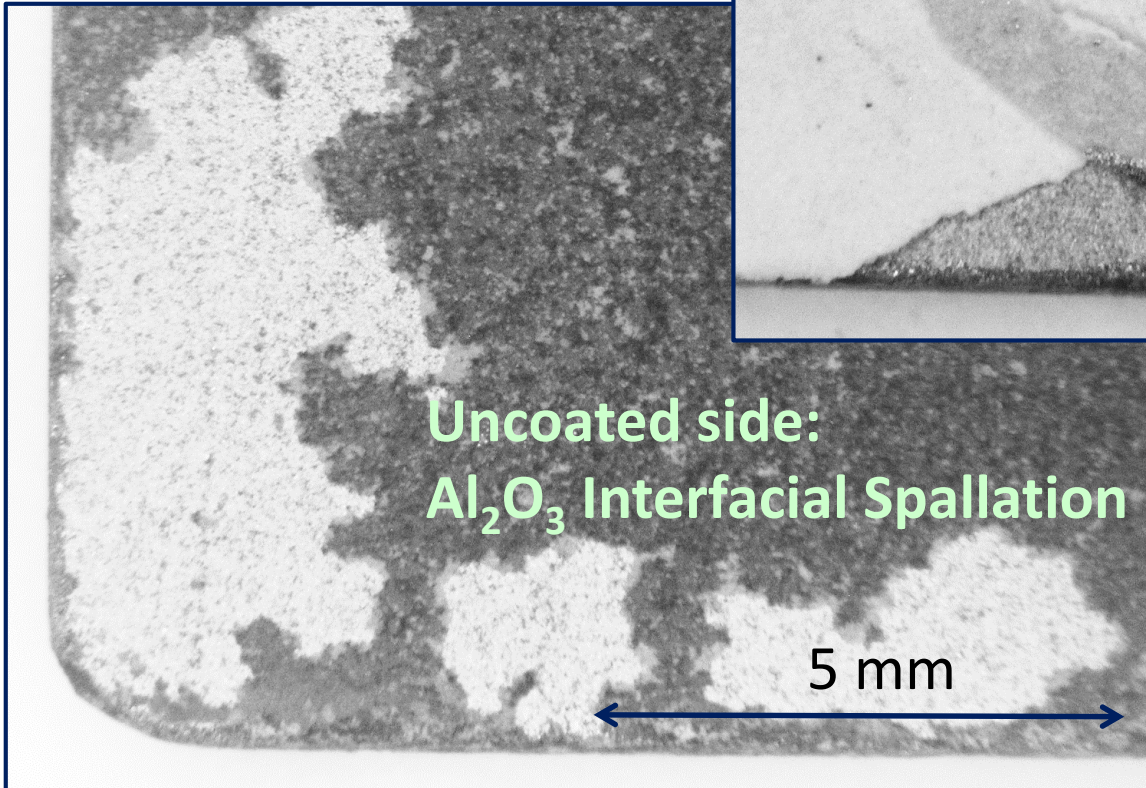
YSZ Coated side:

DTS: Delayed Desktop TBC Spallation

APS YSZ on Cr_2AlC
1150°C, 400 hr



7.5x optical

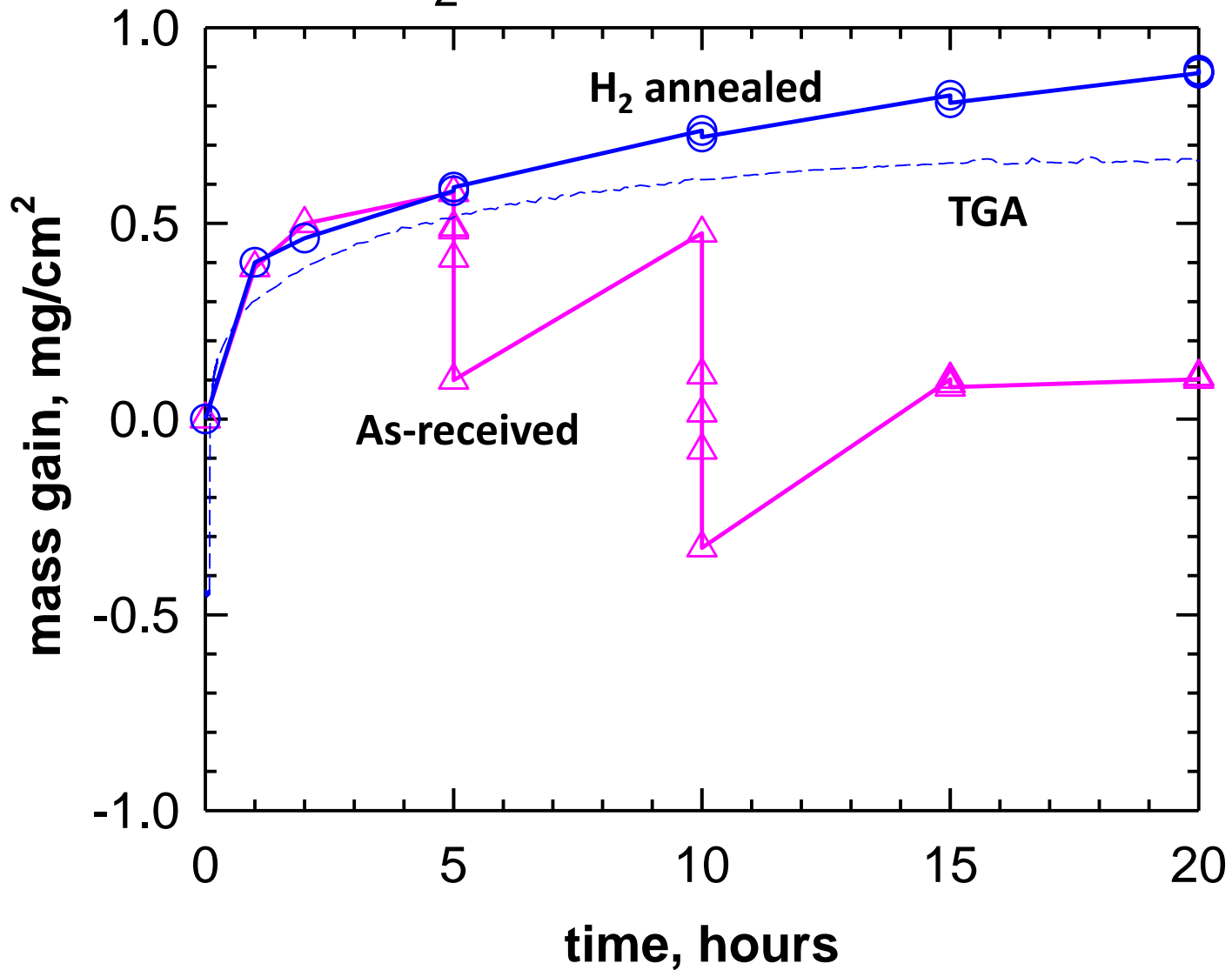


Uncoated side:
 Al_2O_3 Interfacial Spallation

5 mm

1200°C TGA Oxidation of Cr₂AlC

H₂ annealing effects



CTE Matched Ti_2AlC , Al_2O_3 , YSZ

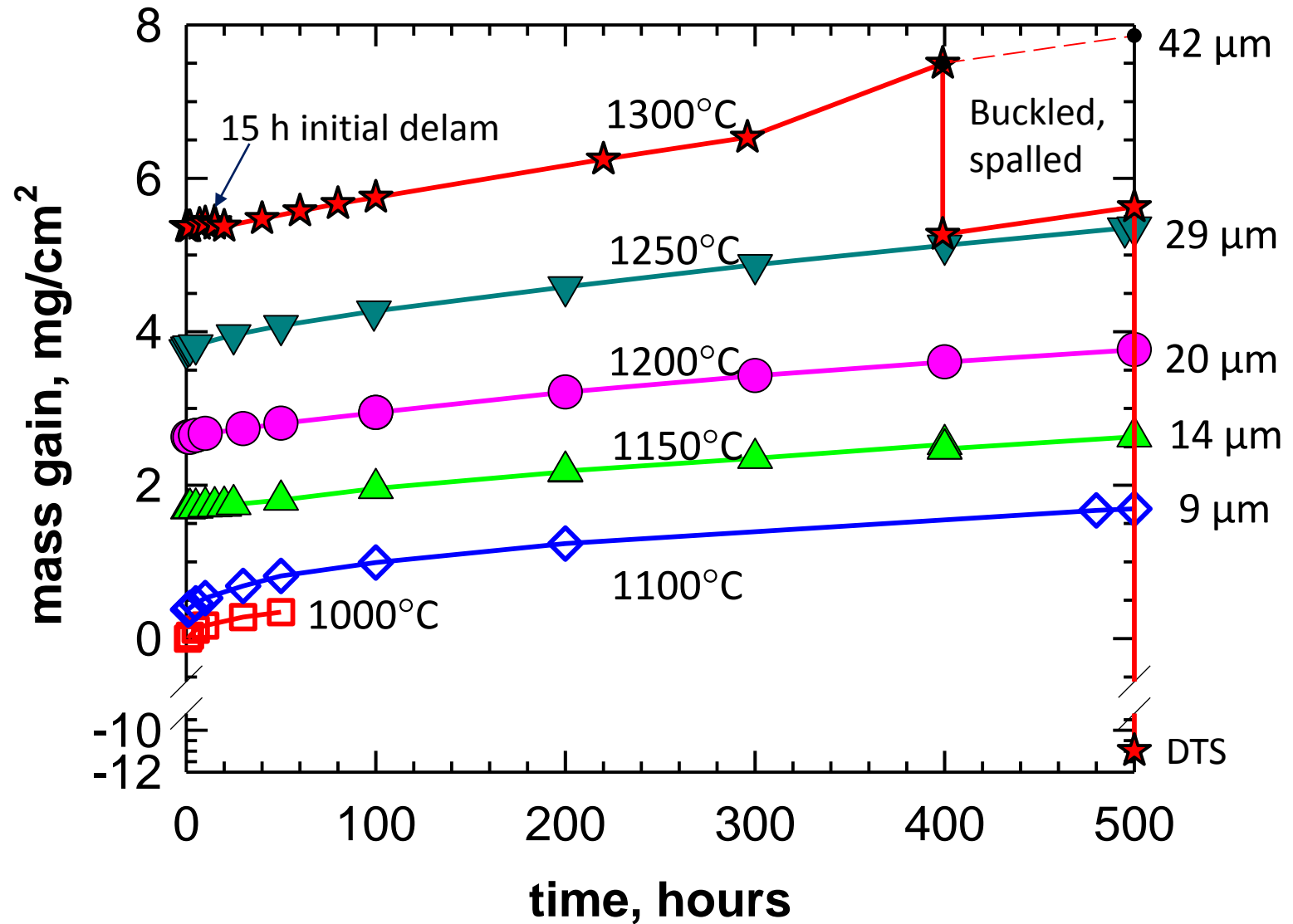
CTE, $10^{-6}/^\circ\text{C}$

YSZ	11.7	Top Coat
Al_2O_3	9	Scale
Ti_2AlC	10.2	Substrate



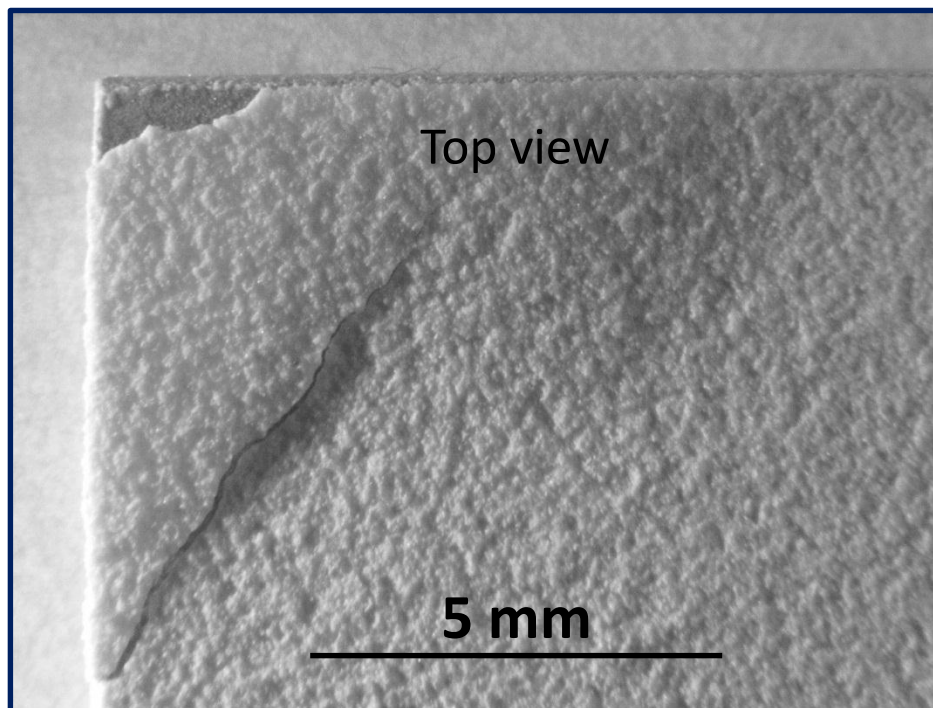
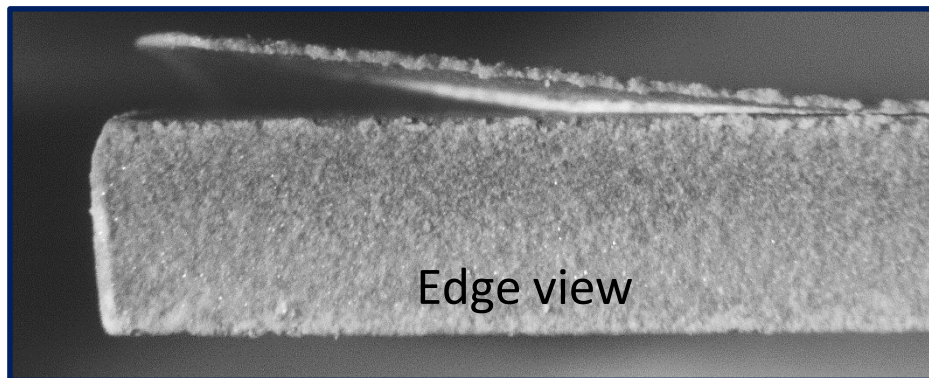
Critical interface

Interrupted Oxidation of APS YSZ on Ti_2AlC



APS Edge Failure on Ti_2AlC

1300°C, 300 h



Intact APS TBC/ 20 μm scale

1200°C, 500 h

YSZ: Large pores, cracks

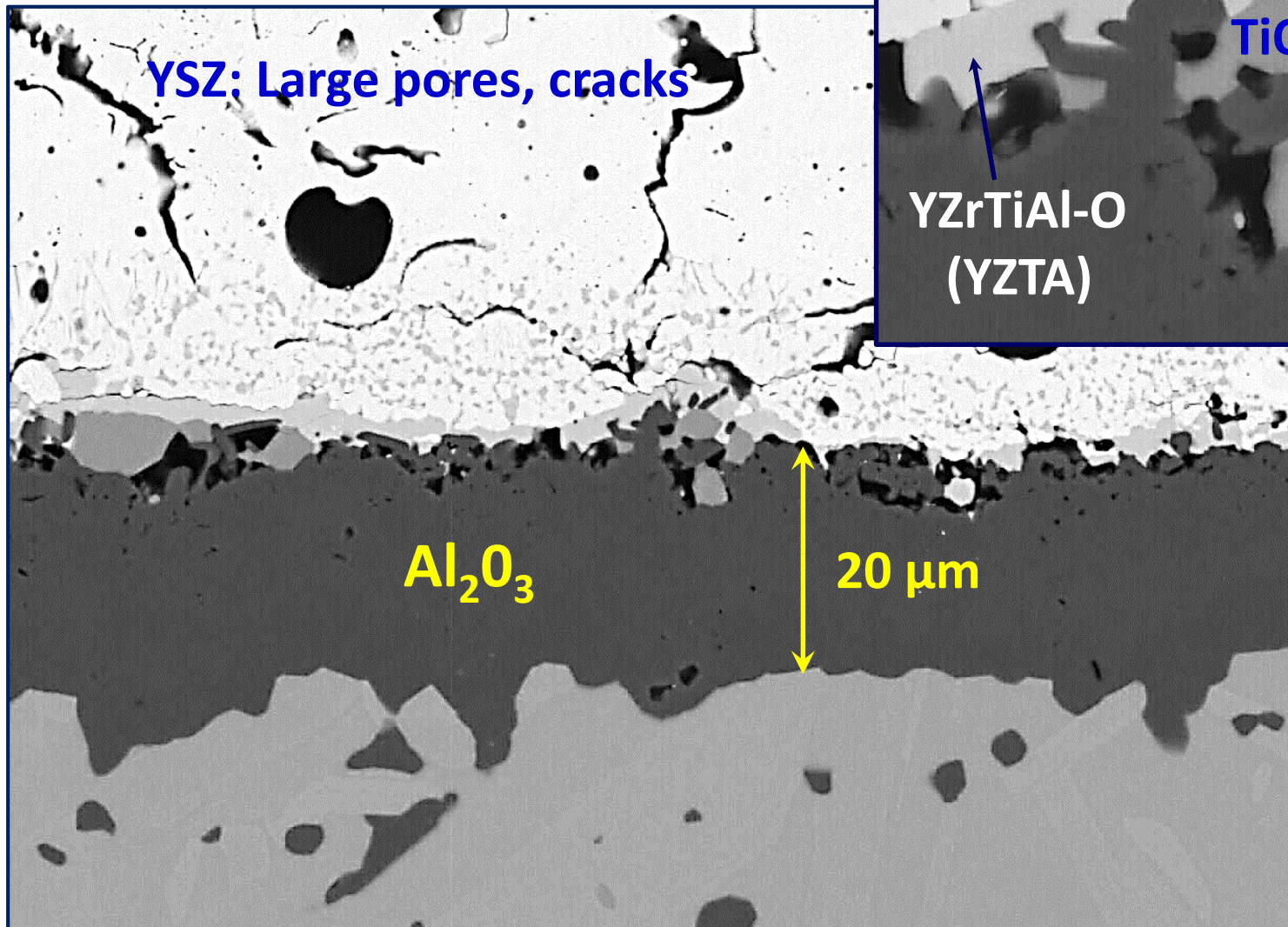
YSZ

TiO₂

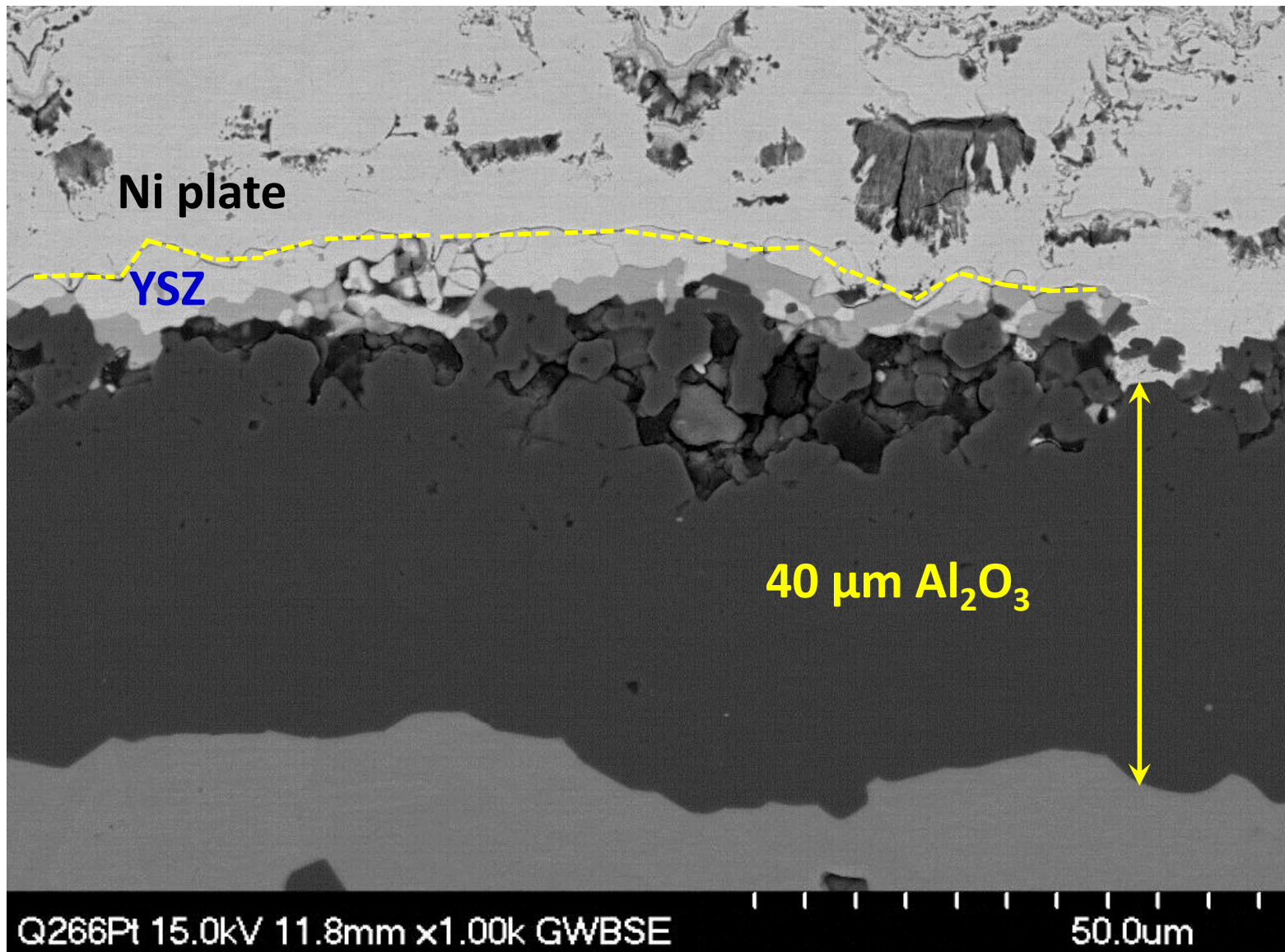
YZrTiAl-O
(YZTA)

Al₂O₃

20 μm

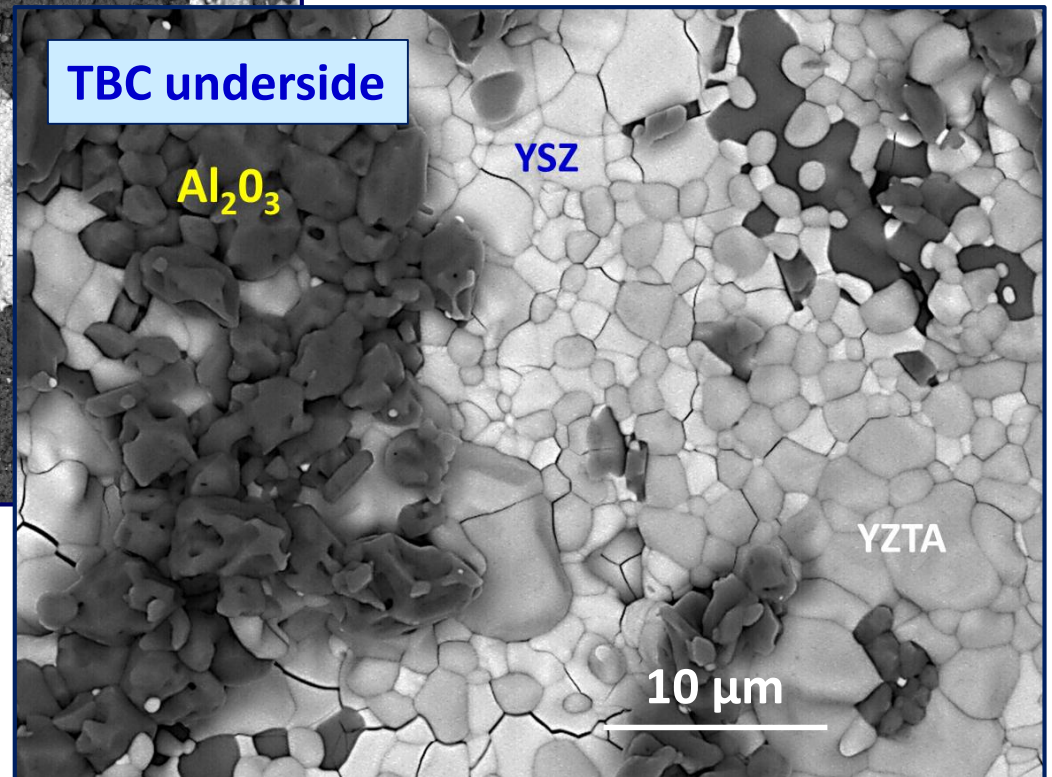
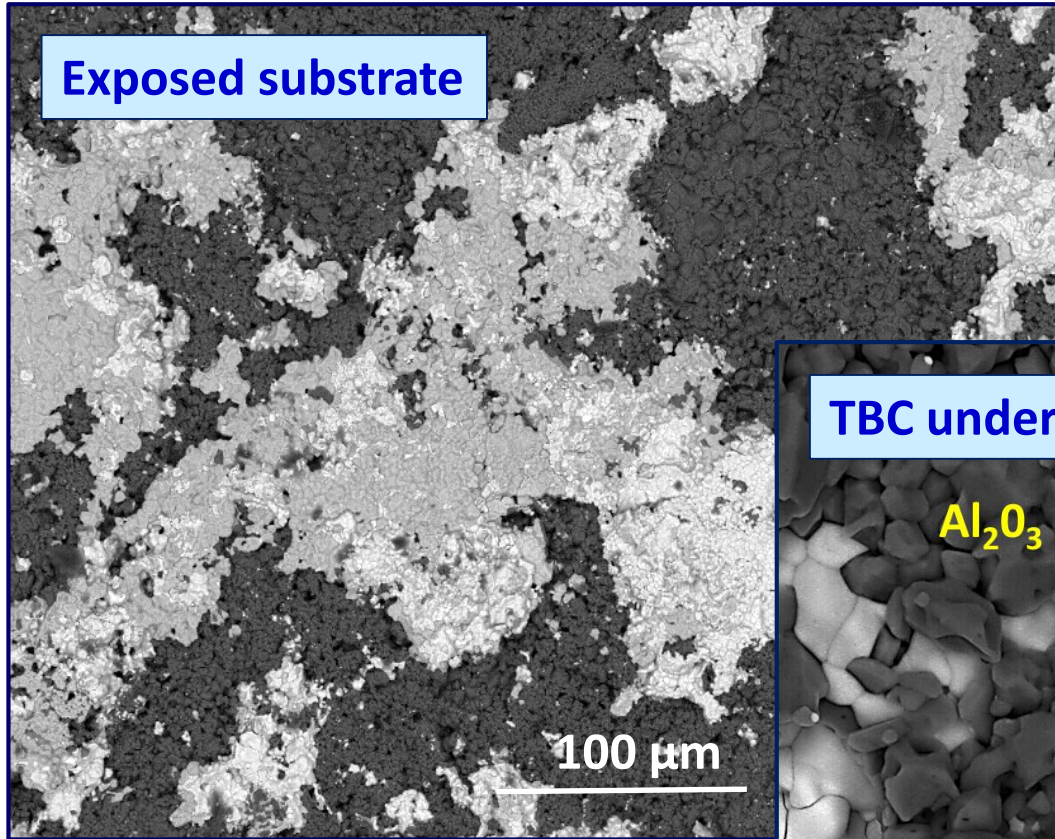


Failed APS TBC
1300°C, 500 h

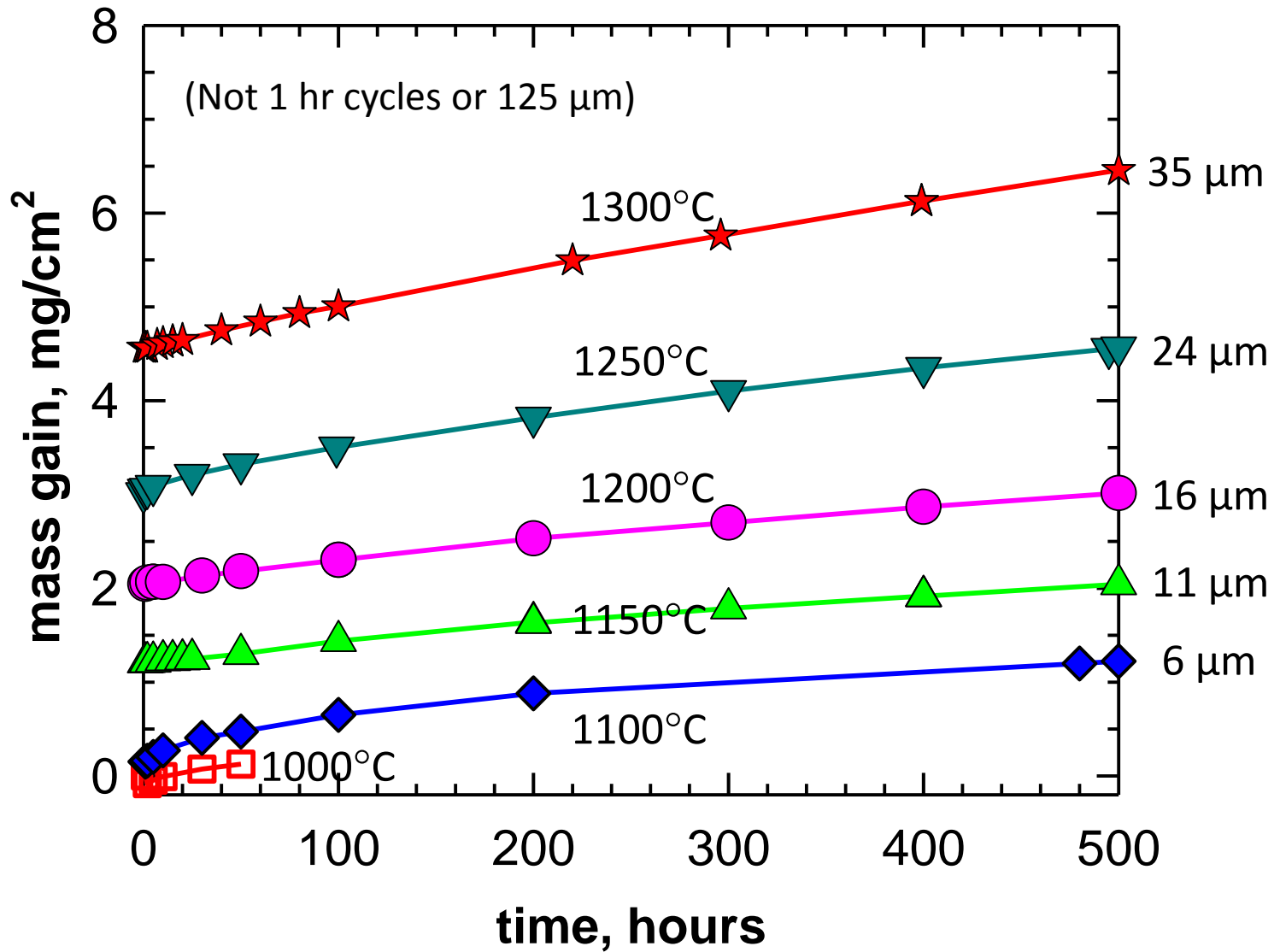


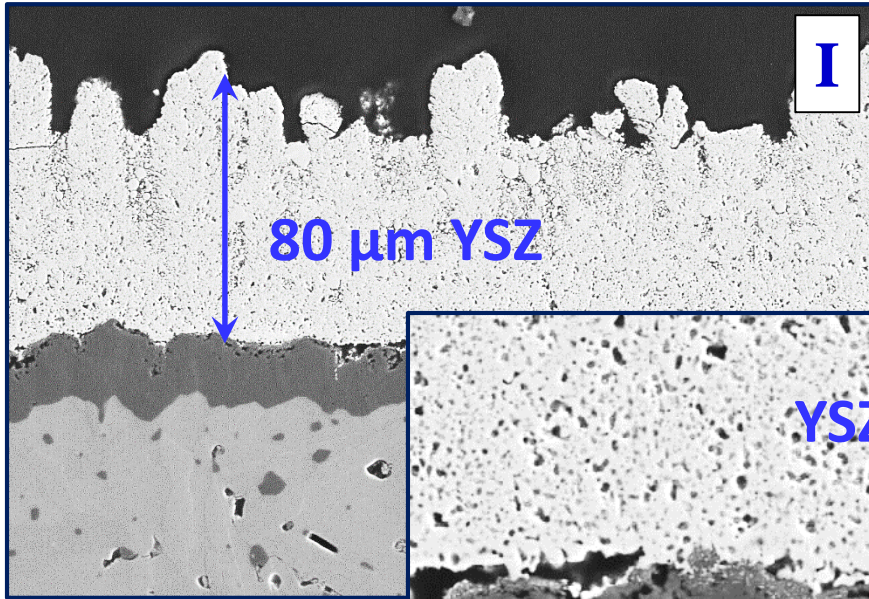
Mixed TBC/TGO Failure

(APS TBC on Ti_2AlC 1300°C, 500 h)

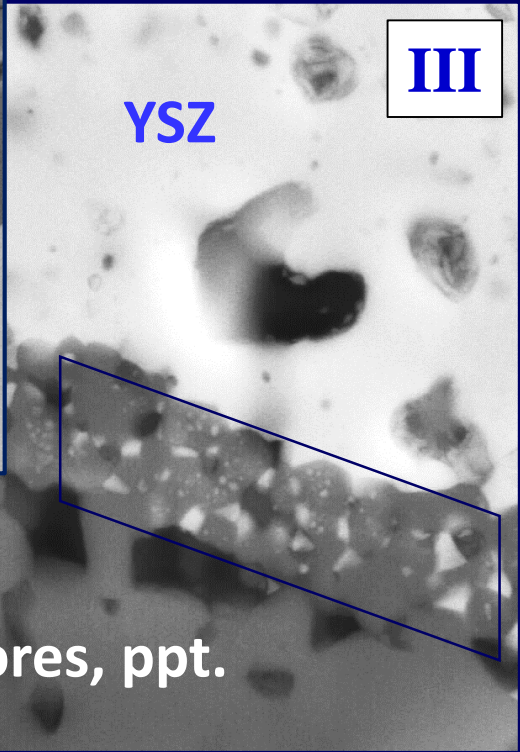
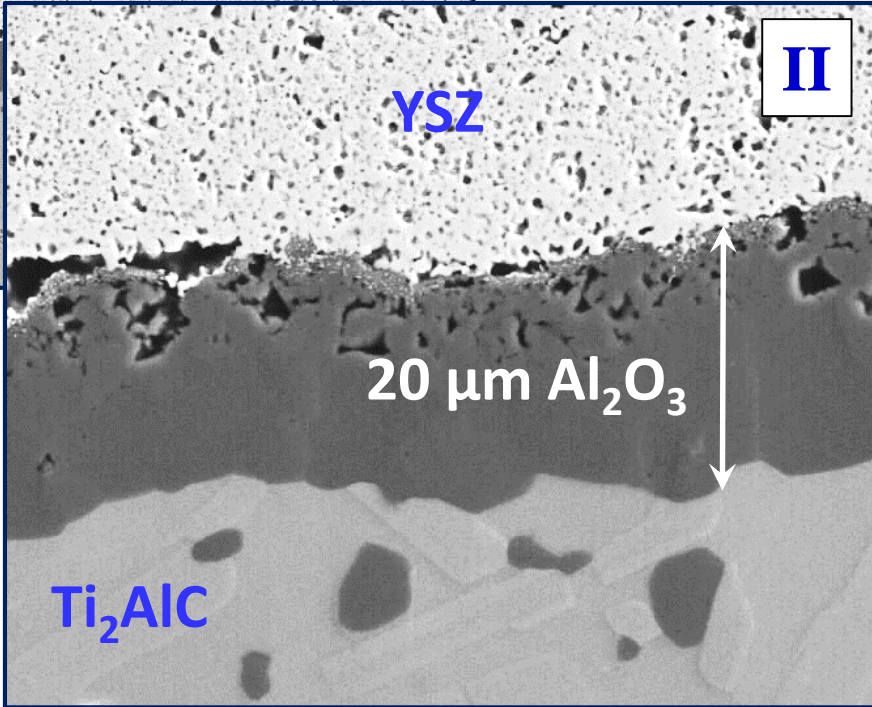


Interrupted Oxidation of PS-PVD YSZ on Ti_2AlC

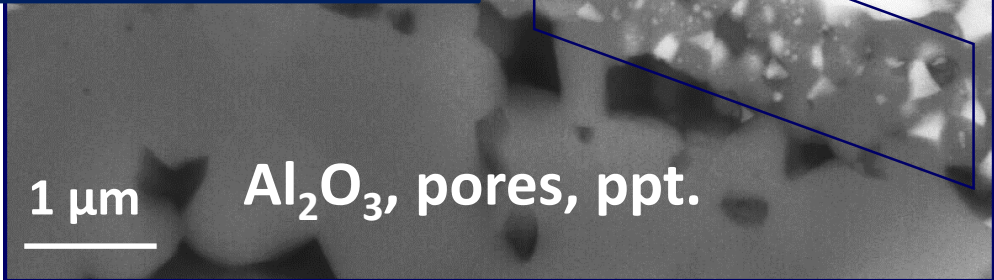




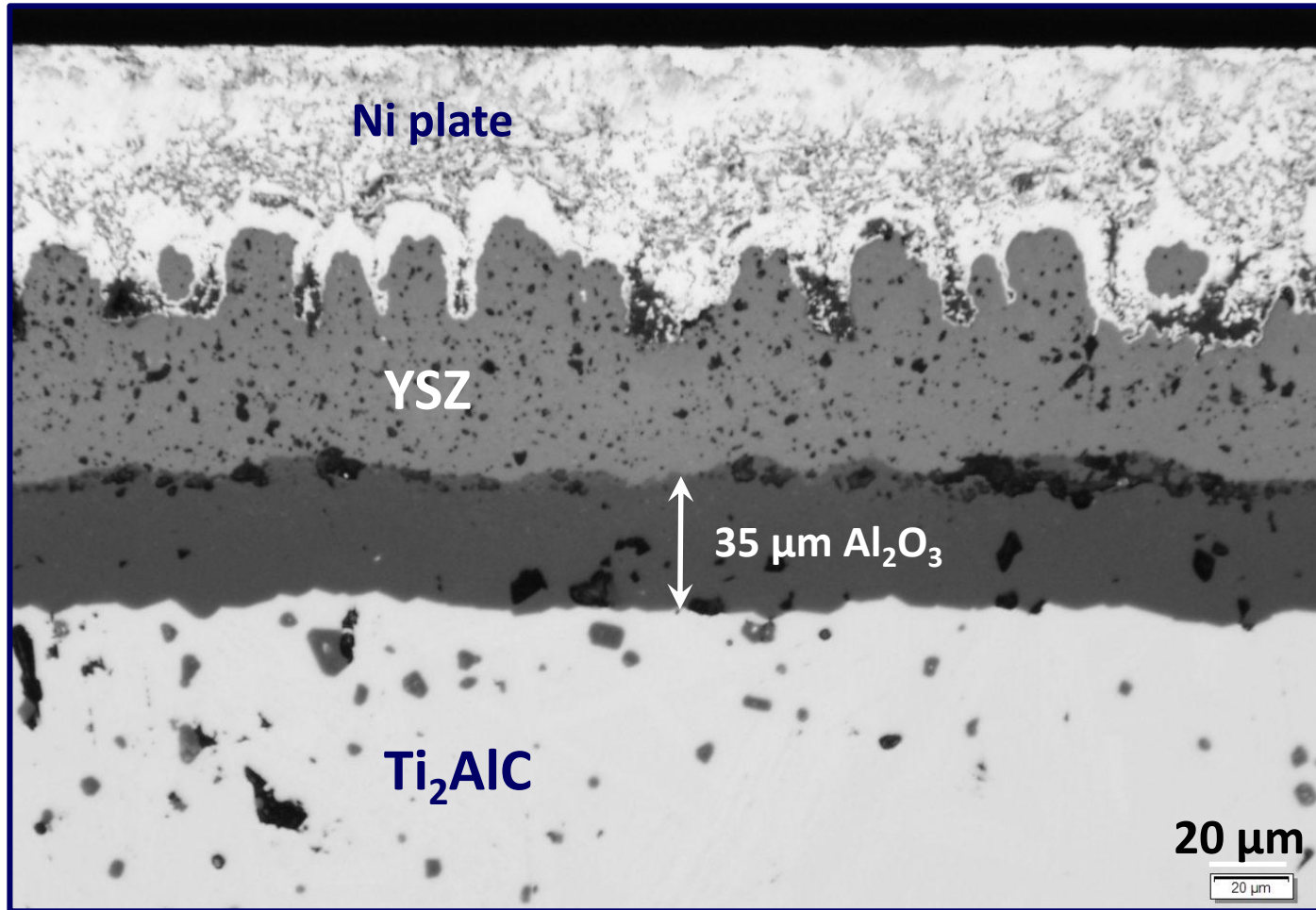
Intact PS-PVD TBC
(Ti_2AlC , **1200°C**, 500 h)
SEM/BSE



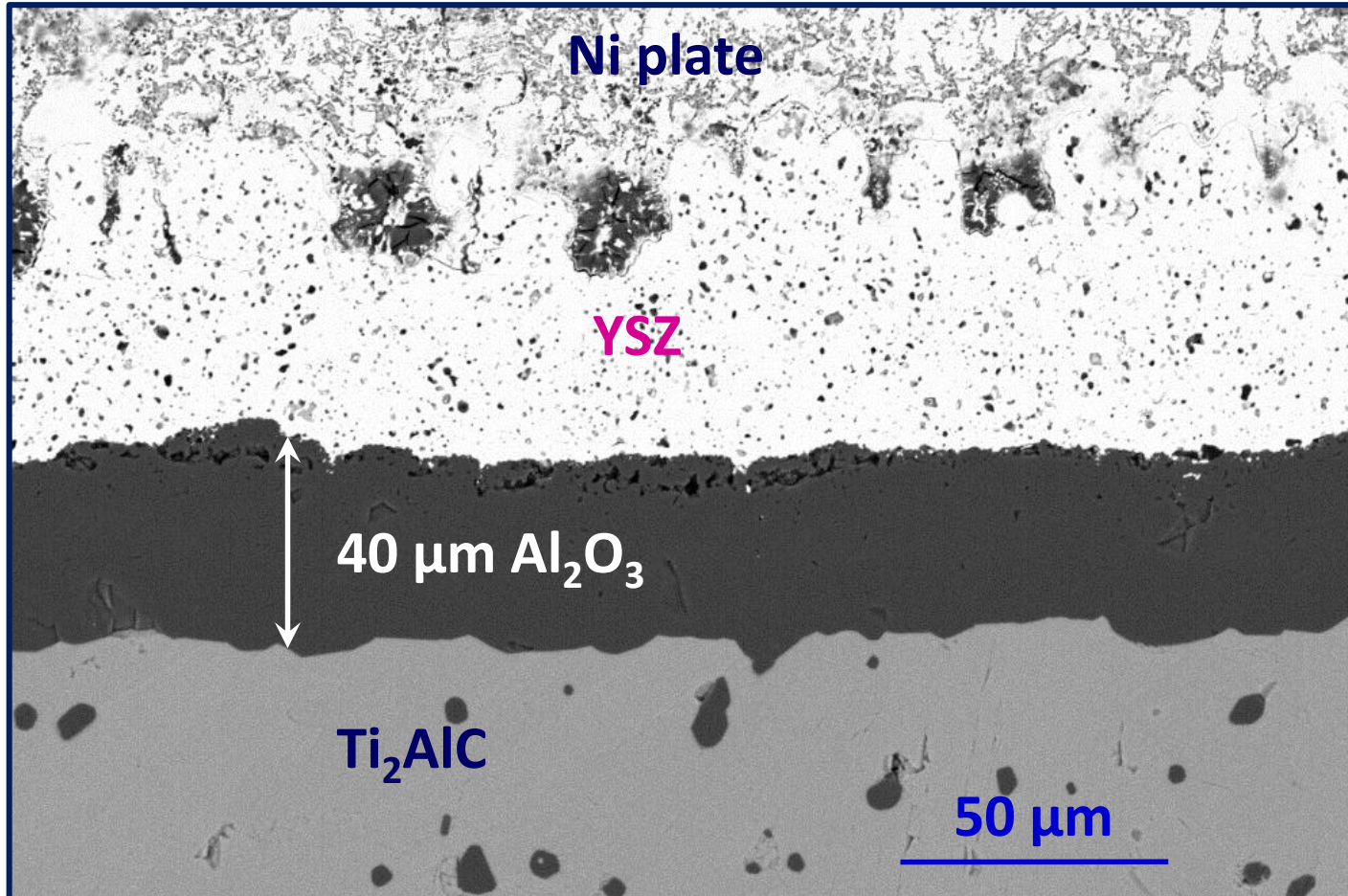
Pseudo-columnar,
dispersed porosity,
no splat boundaries



Intact PS-PVD TBC
(Ti_2AlC , **1300°C**, 500 h)
optical



Intact PS-PVD TBC
(Ti_2AlC , **1300°C**, 500 h)
SEM/BSE



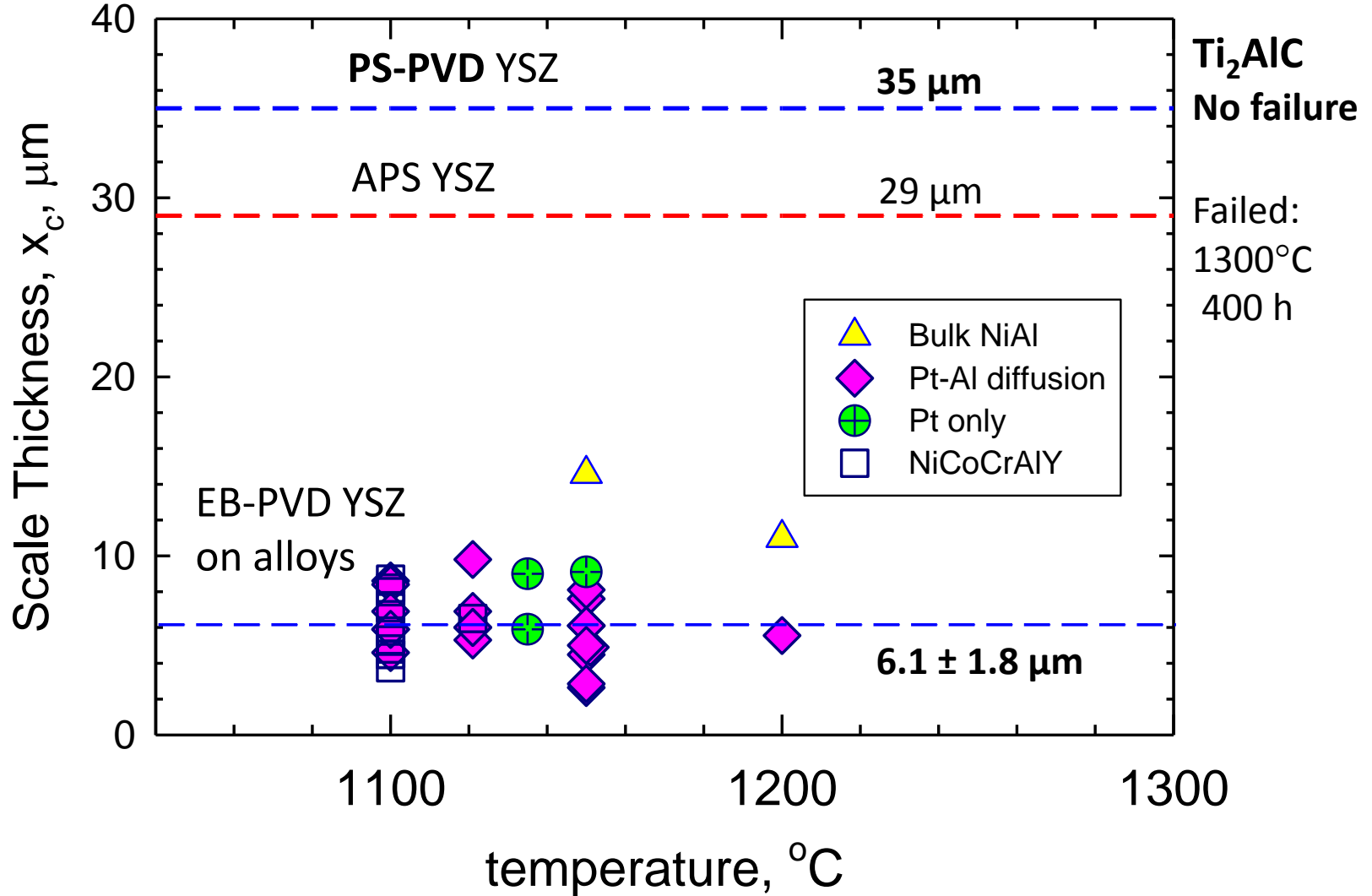
TBC Life Comparisons:

- Bond Coats/Superalloy (cyclic)
- Ti_2AlC substrates (stepped T, intermittent)

- Compiled literature EB-PVD life, TGO vs T
- “Critical TGO thickness” $\approx 7 \mu\text{m}$
- TGA Life projections:
 - Pt-Al/CMSX4 (life time t_c for $7 \mu\text{m}$)
 - Ti_2AlC (time t_c for $35 \mu\text{m}$)
 - Compare life t_c vs T

TGO Thickness Compared to Literature:

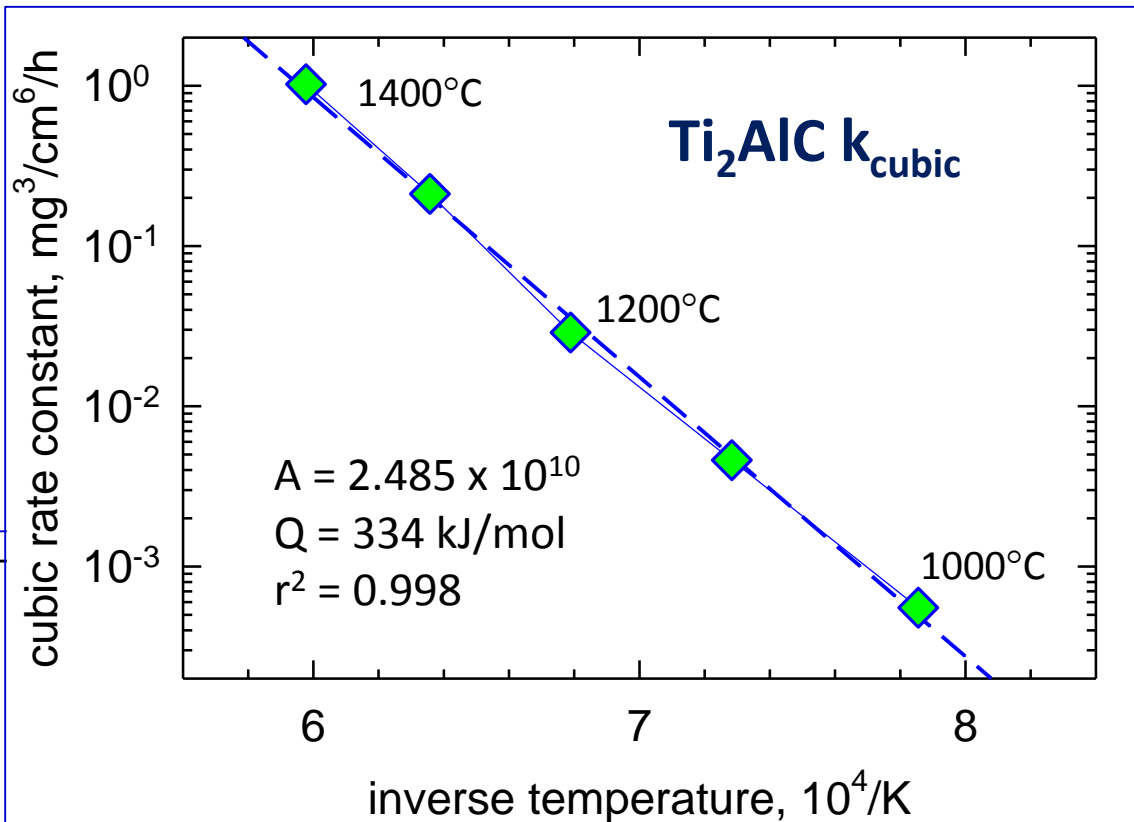
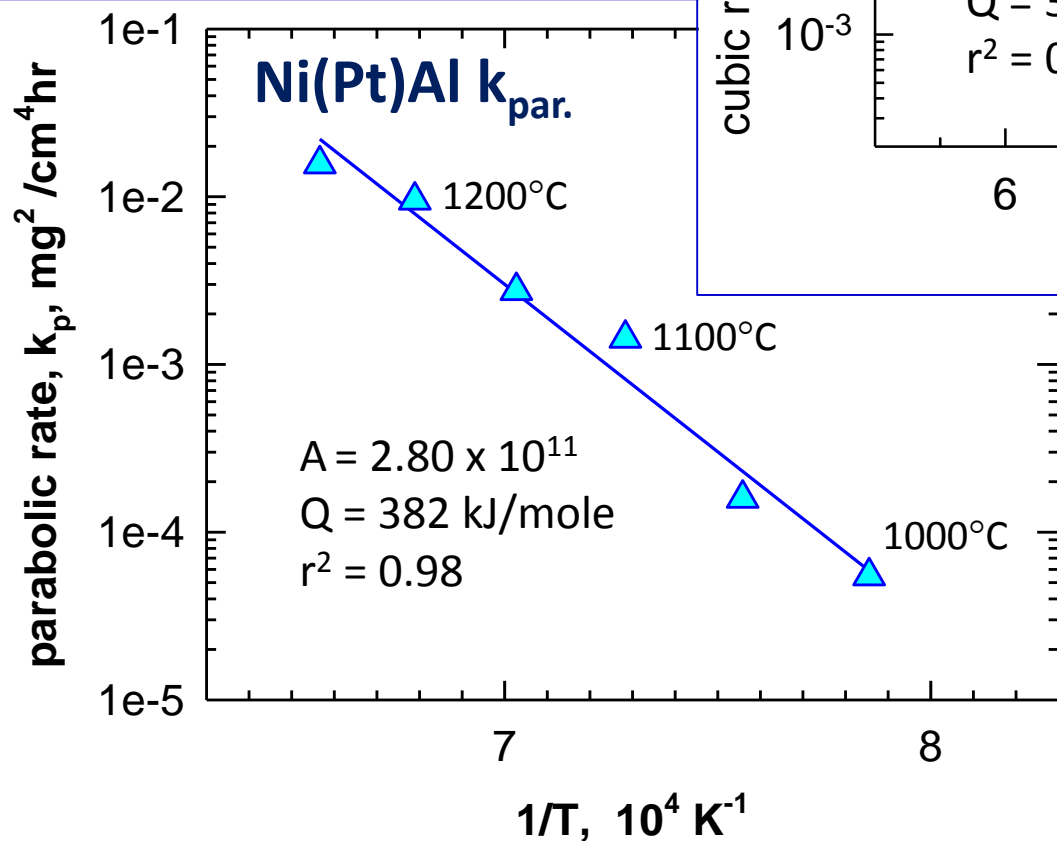
Alumina Scale Thickness at TBC Failure



Al₂O₃ TGA Kinetics:

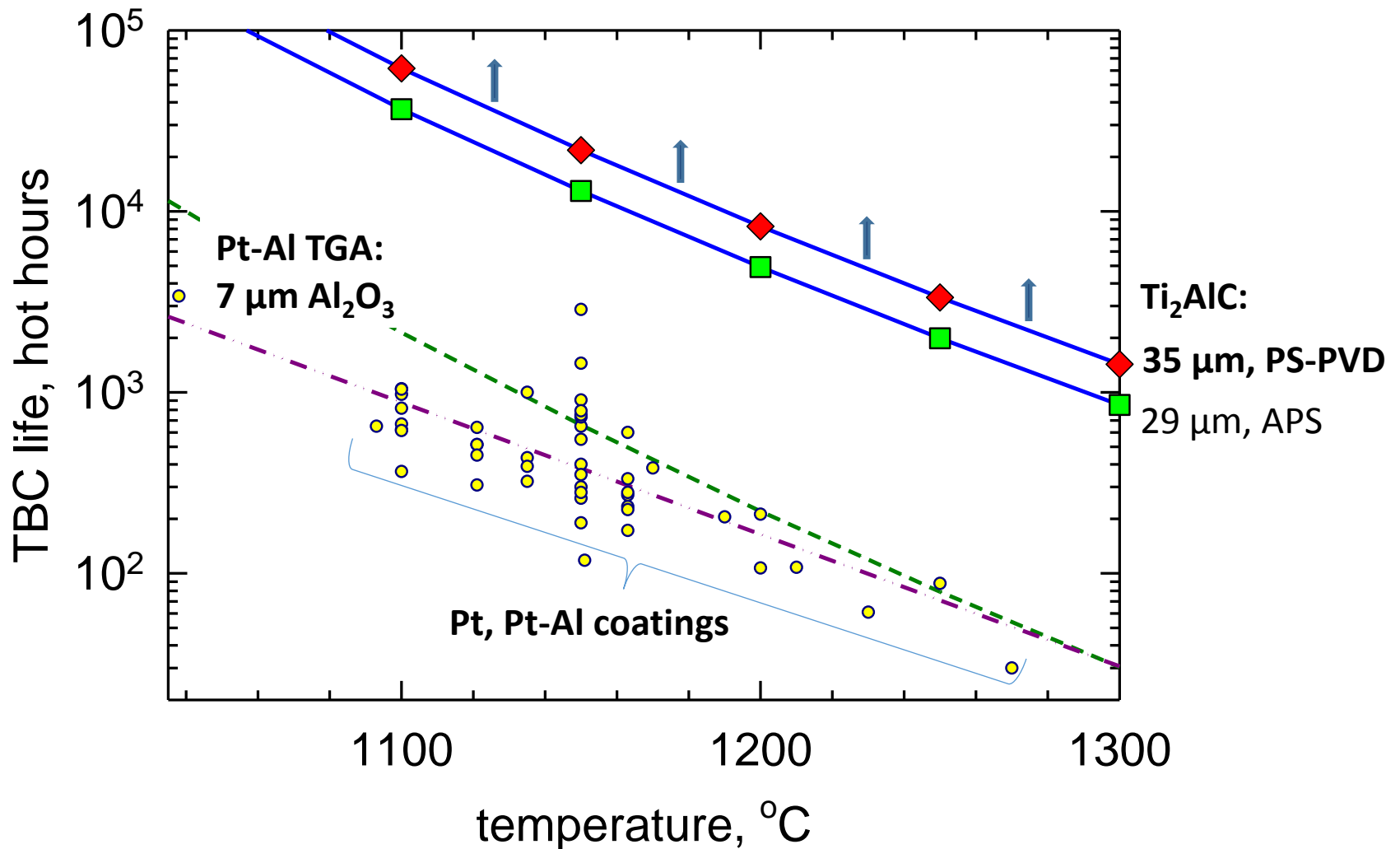
→ x vs t, T

parabolic Ni(Pt)Al

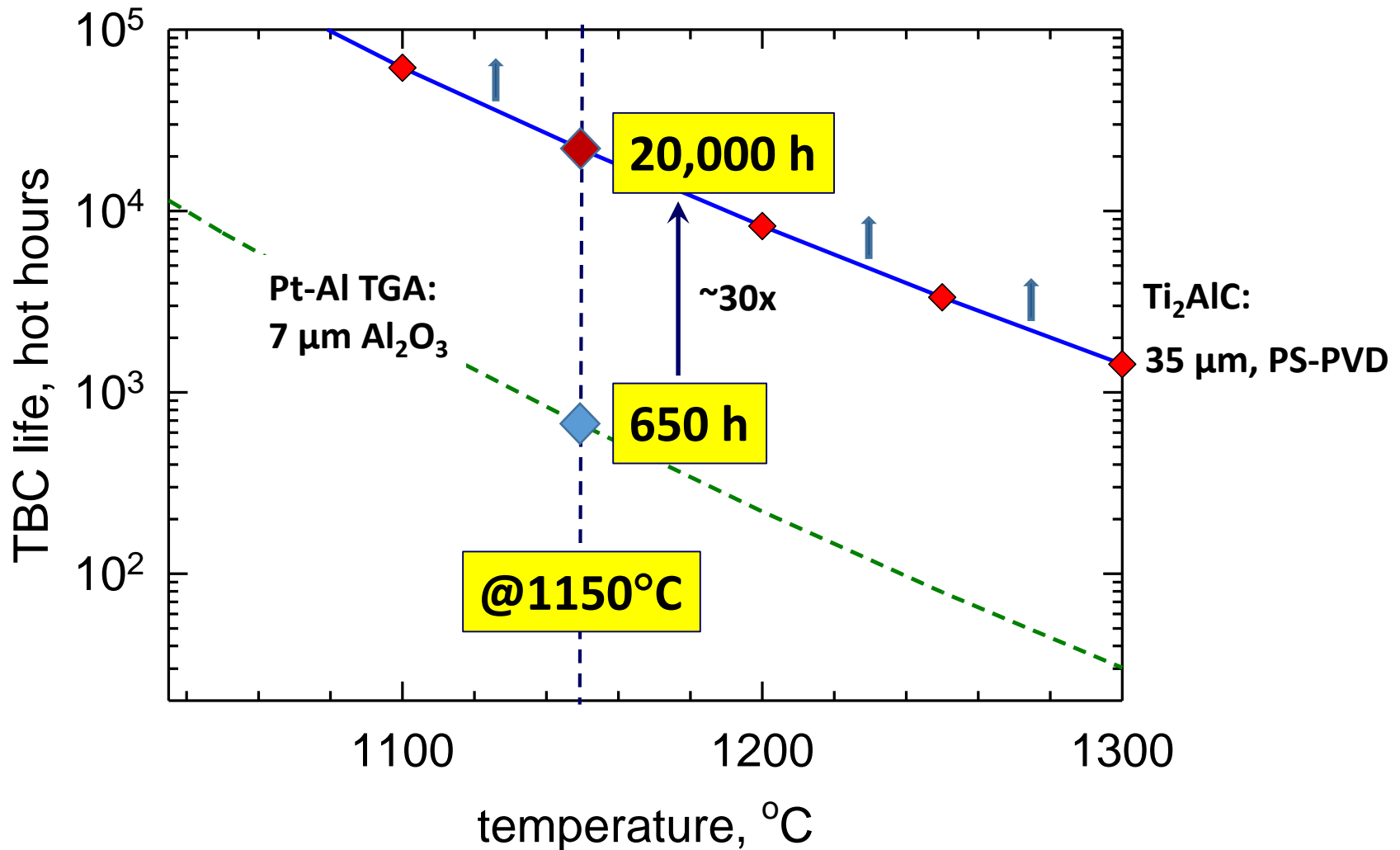


cubic Ti₂AlC

EB-PVD TBC FCT Life on Alumina-Forming Systems

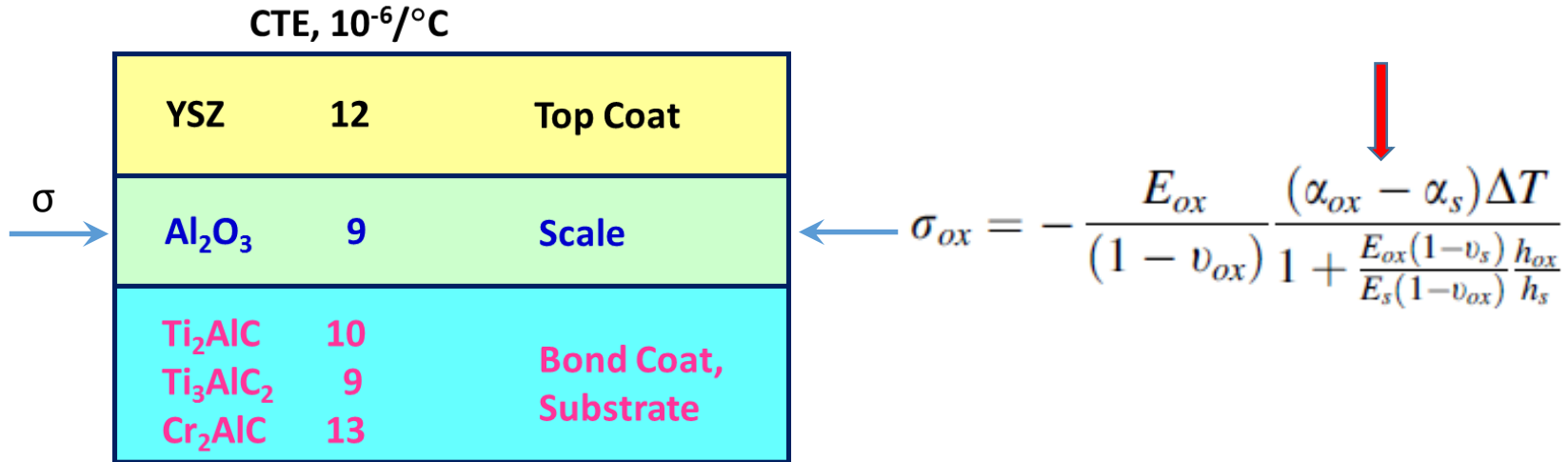


EB-PVD TBC FCT Life on Alumina-Forming Systems



Thermal Stress Balance of Forces

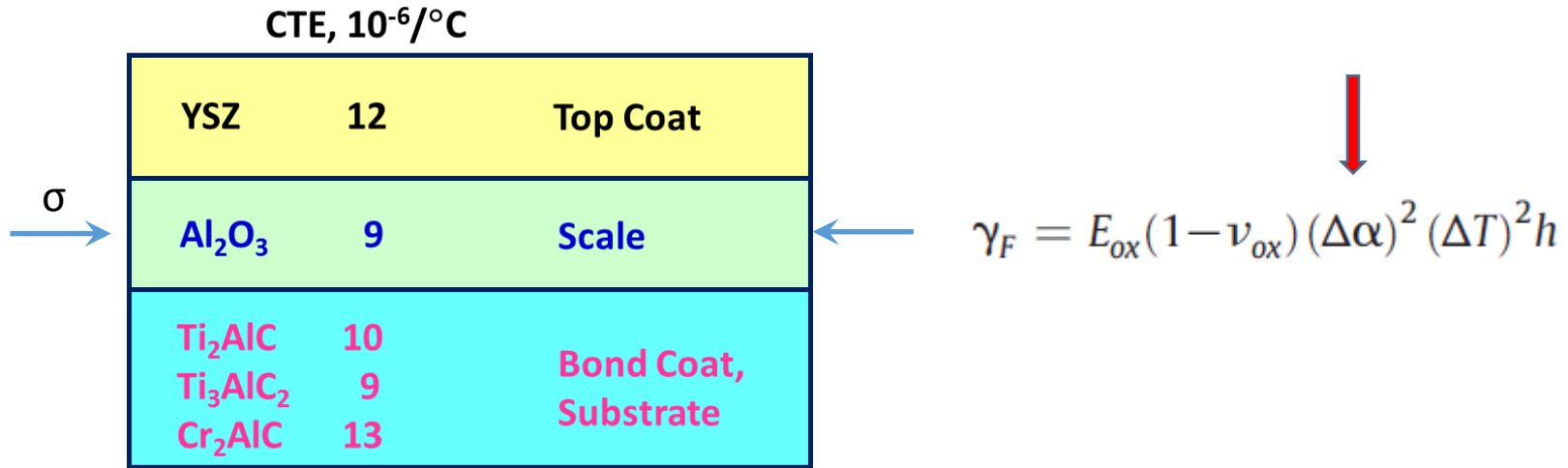
(1200°C, 20 μm scale, 2 mm substrates)



(CTE, 10 ⁻⁶ /K)	stress, GPa	stress, GPa
substrate	σ Al₂O₃ (9.3)	σ YSZ (11.7)
Ti ₂ AlC (10.2)	-0.52 Comp.	0.06
Cr ₂ AlC (13.1)	-2.06 Comp.	-0.04
Rene'N5 (16)	-3.71 Comp.	-0.14

Strain Energy Failure Criterion

A.G. Evans, H.E. Evans (2001, 2011)



(CTE, 10⁻⁶/K)

substrate	x, μ (Al ₂ O ₃)	T (°C)	Γ (J/m ²)
Ti ₂ AlC (10.2)	35	1300	14
Cr ₂ AlC (13.1)	5	1150	28
Rene'N5 (16)	10	1150	175

Oxidative Durability of TBCs on MAX Phases

Summary

- YSZ survived 1300°C on Ti₂AlC
- Ti₂AlC substrates, scale adhesion surpass Cr₂AlC
- PS-PVD superior to APS

- 35 μm Al₂O₃ for Ti₂AlC vs 7 μm for Ni(Pt)Al
- 30x life equivalence @ 1150°C (20,000 h)
- CTE ⇒ stress ~1/7 metal system
⇒ strain energy 1/12 metal at failure