Durability of YSZ Coated Ti_2AlC in 1300°C Mach 0.3 Burner Rig Tests

J. Smialek,[1] M. Cuy,[2] B. Harder,[3] A. Garg,[4] R. Rogers[3]

[1] Distinguished Research Associates, NASA Glenn Research Center
[2] Vantage Partners, LLC
[3] NASA Glenn Research Center
[4] University of Toledo

MST, Portland, OR
Oct 1-4, 2019

Recognition:
Dr. Dongming Zhu, *1962-2018*

Initial acquisition of PS-PVD rig

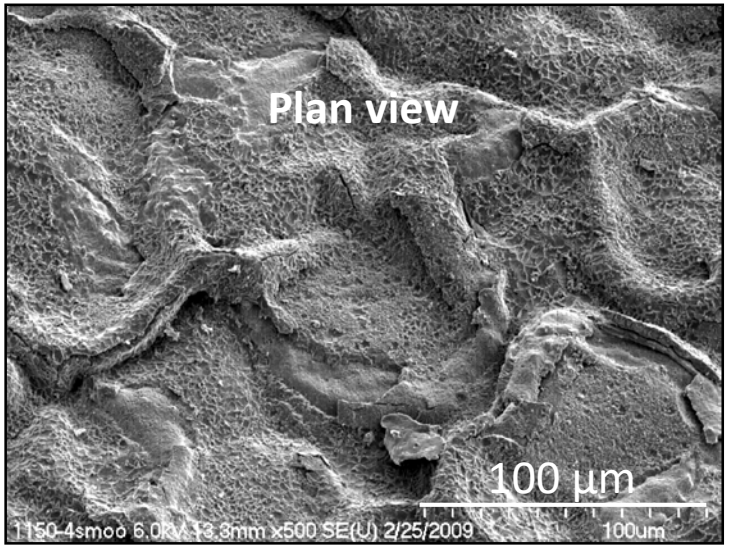
YSZ/MAX thermal gradient calculations

(Decades of intense YSZ TBC research)

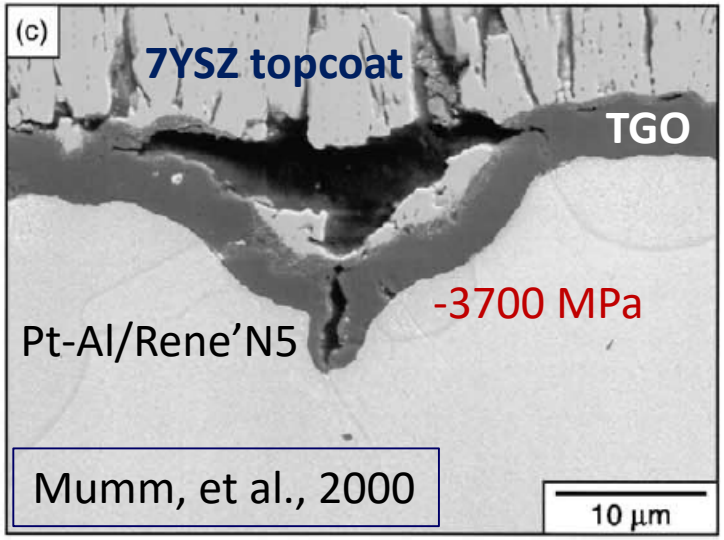
Problem: failure times for TBC on turbine alloys

(7YSZ/Pt-Al/superalloy cyclic furnace oxidation, 2015)

"rumpling, ratcheting, wrinkling"; critical TGO thickness



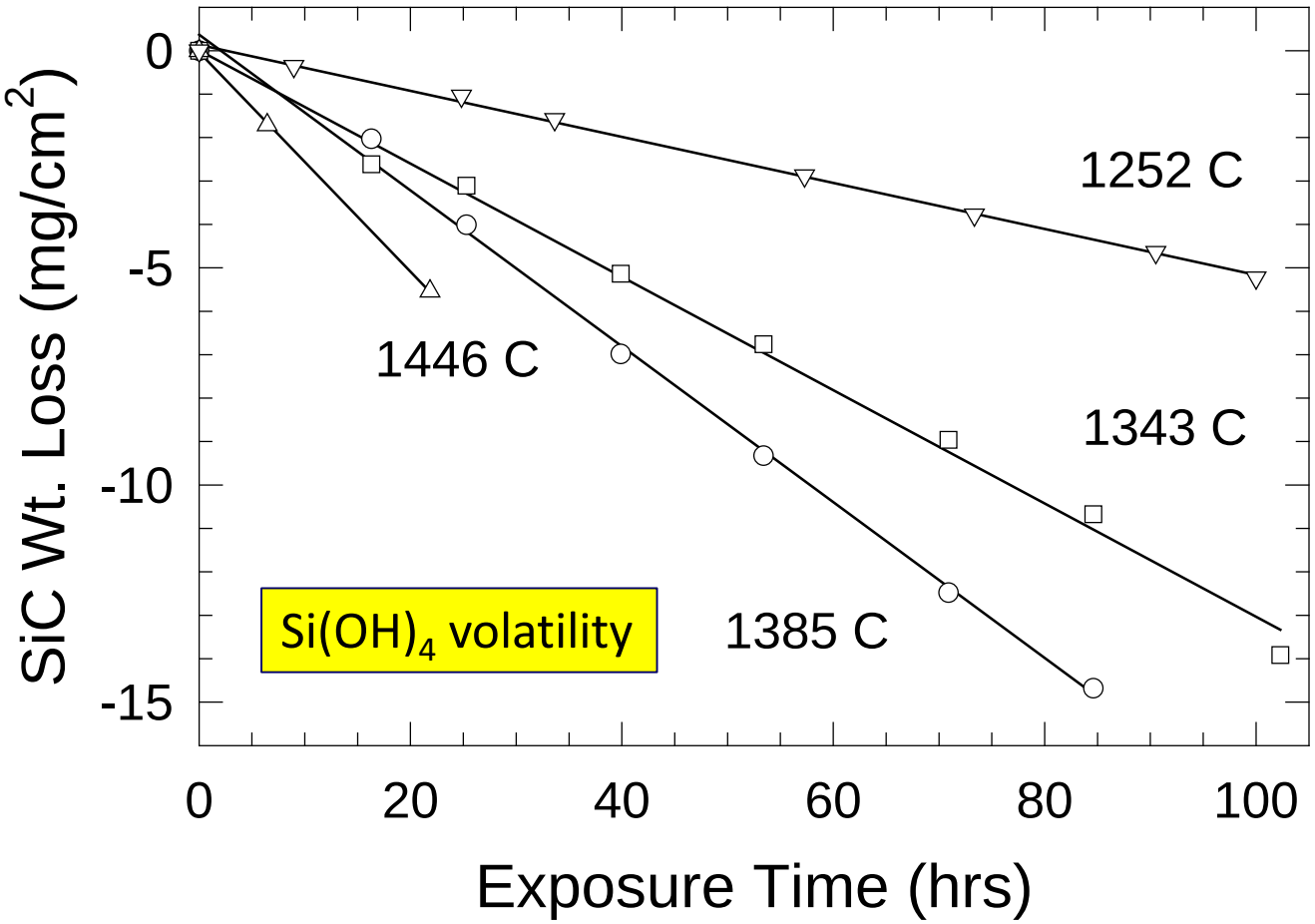
Exposed MDC 150L Pt-aluminide, 1150°C, 2000 h FCT



°C	h	µm
1100	2100	7
1150	700	7
1200	220	7
1250	80	7
1300	**30**	**7**

Linear Weight Loss of SiC in High Pressure Burner Rig

6 atm, 20 m/s (Robinson, Smialek 1999)



Recession Rank of EBC/Oxides in High Temperature H_2O (2005)

EBC	• HfO_2, ZrO_2	**7YSZ**	**best**
	• $2(RE_2O_3)$-$3ZrO_2$	Lu, Y zirconates	↓
	• $3(RE_2O_3)$-$5Al_2O_3$	Yb. Y aluminates, YAG	
	• **RE_2O_3-SiO_2**	**Lu, Yb, Y monosilicates**	
	• **RE_2O_3-$2SiO_2$**	**Lu, Yb, Y disilicates**	
	• $TiAl_2O_5$	titanium aluminate	
	• $Ba(Sr)O$-Al_2O_3-$3SiO_2$	**BSAS**	
Scales	• Al_2O_3	**alumina**	
	• $3Al_2O_3$-$2SiO_2$	mullite	
	• TiO_2	**rutile**	
	• SiO_2	**silica**	↓
	• Cr_2O_3	chromia	**worst**

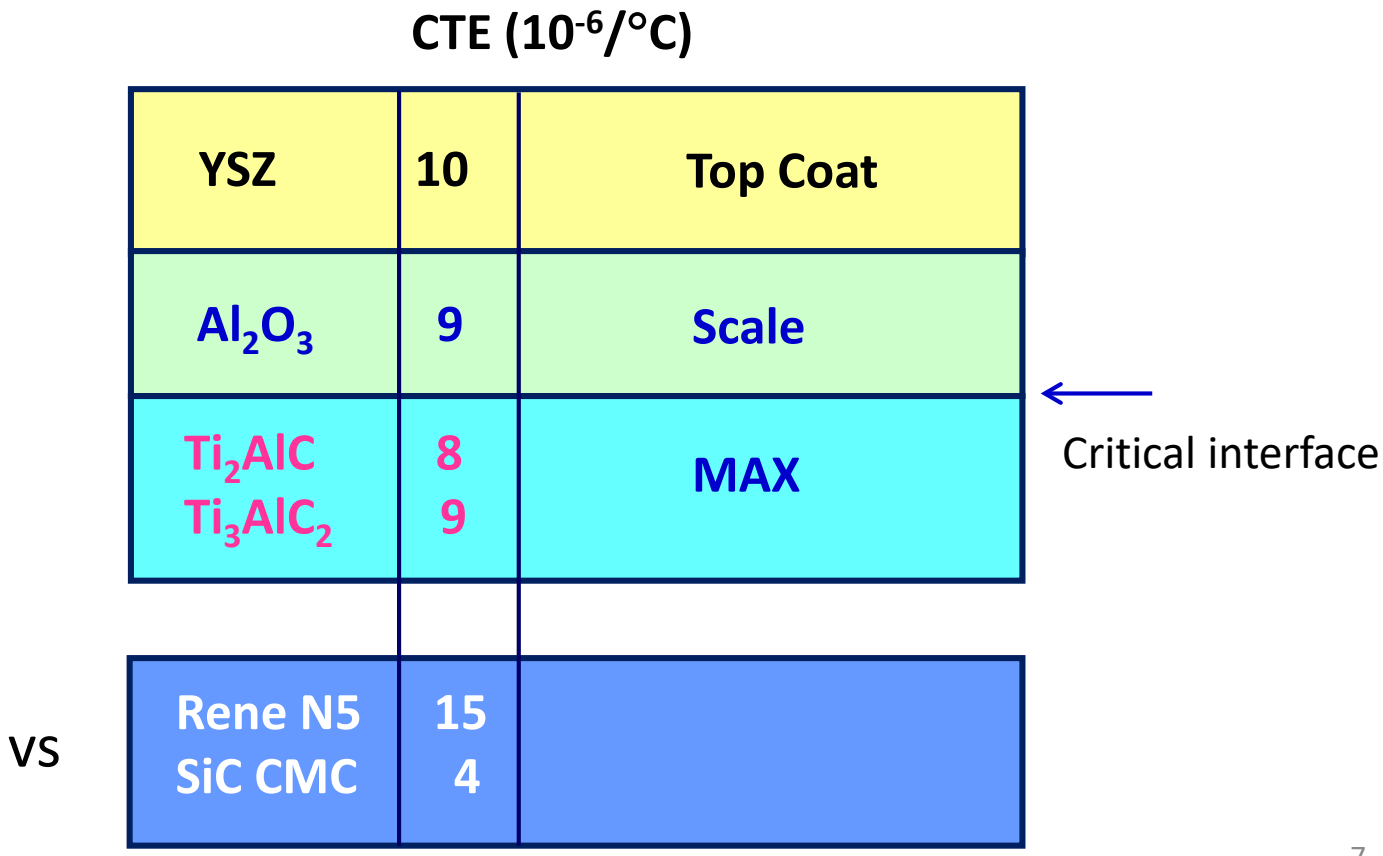
Opila, Jacobson, Lee, Ueno, Ohji, Nakayama, Harada, Yuri, Klemm,……

Why this?

- $M_{n+1}(Al,Si)(C,N)_n$ MAX Phases
  - Stable to ~1400°C
  - Thermal shock resistant
  - Machineable, damage tolerant, basal 'kinking'
  - **Adherent Al_2O_3 scales (e.g., 211 Ti_2AlC, Cr_2AlC)**
- 7YSZ
  - T/EBC
  - No volatility
  - **CTE match**
- Mach 0.3 BRT
  - 100 m/s, 10% H_2O
  - 1500°C capable
  - Automated, cyclic, 100's of hours
  - **Available**

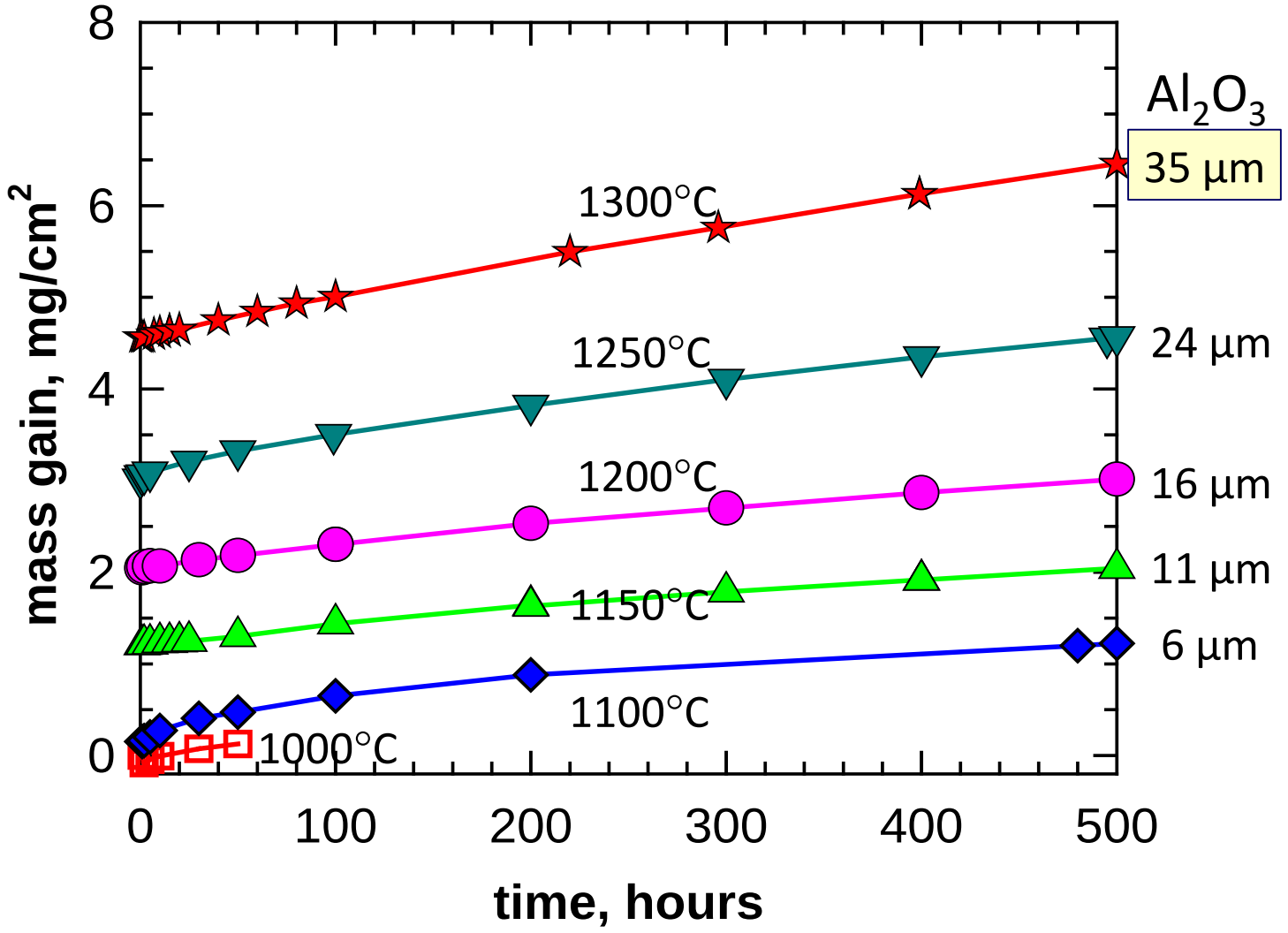
YSZ TBC Enabled by MAX Phases

CTE Matching



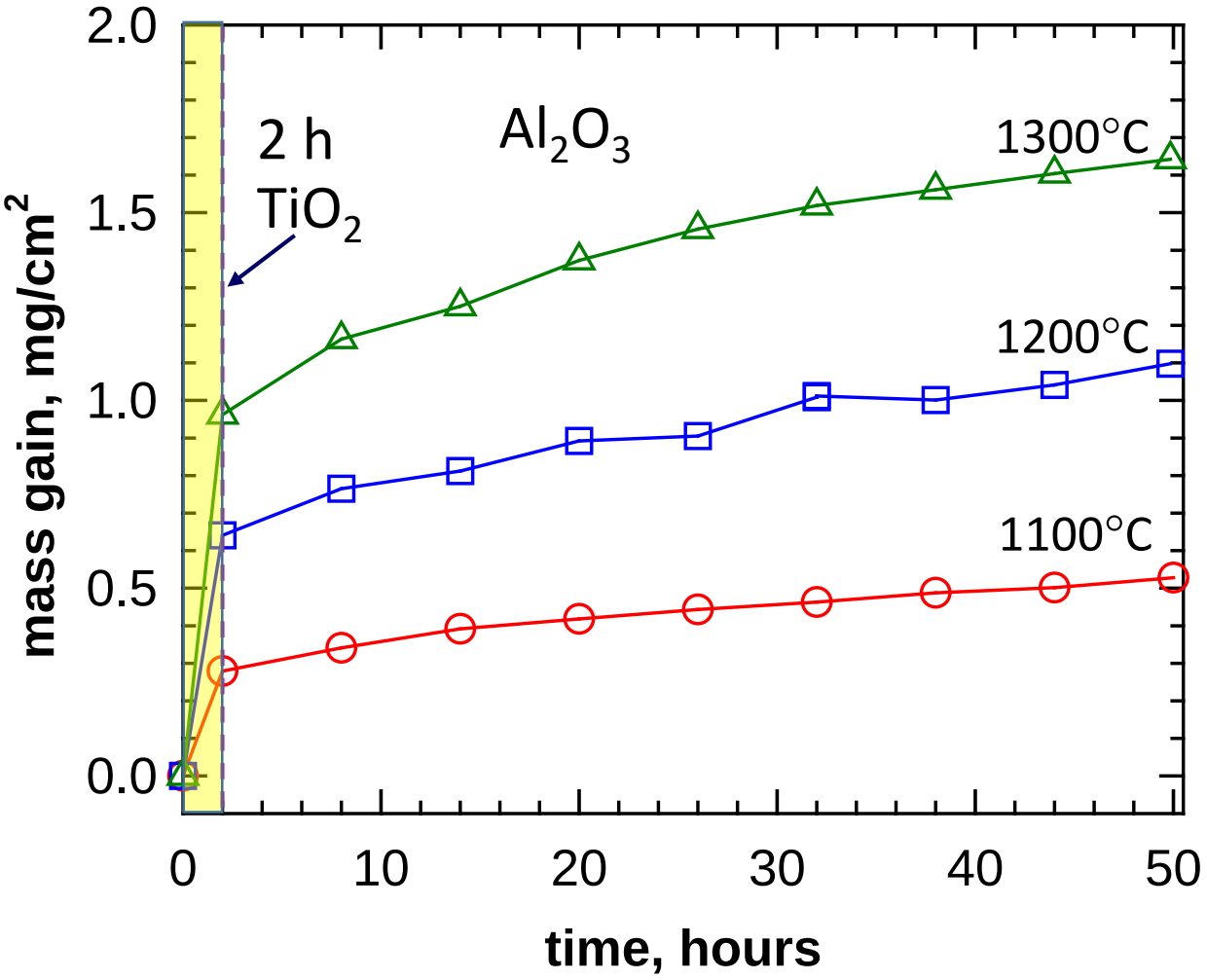
PS-PVD YSZ TBC Survived 2500 hr on Ti_2AlC

Furnace Oxidation; 35 µm TGO (2016)



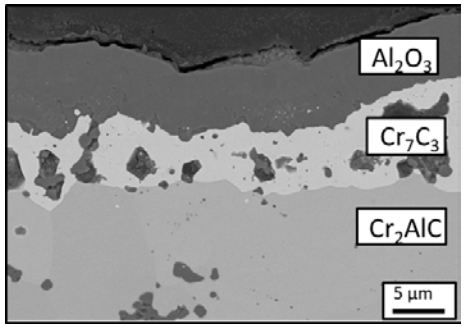
Ti_2AlC Performed Well in High Pressure Burner Rig

6 atm, 25 m/s, 50 h (2016)

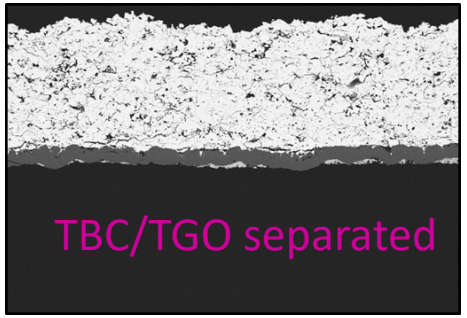


Related Cr_2AlC MAX Phase Work:
Jesus Gonzalez-Julian, et al., *Frztm. Jülich*

- 1200°C Cr_2AlC, Burner Shock Test:
  survived 29 h (500 cycles)
  J. Am. Ceram. Soc., 101 (2018)



- 1300°C YSZ-Cr_2AlC, Furnace Cyclic Test:
  failed 268 h, 40 µm Al_2O_3
  Surf. Coat. Techn., 340 (2018), 17-24

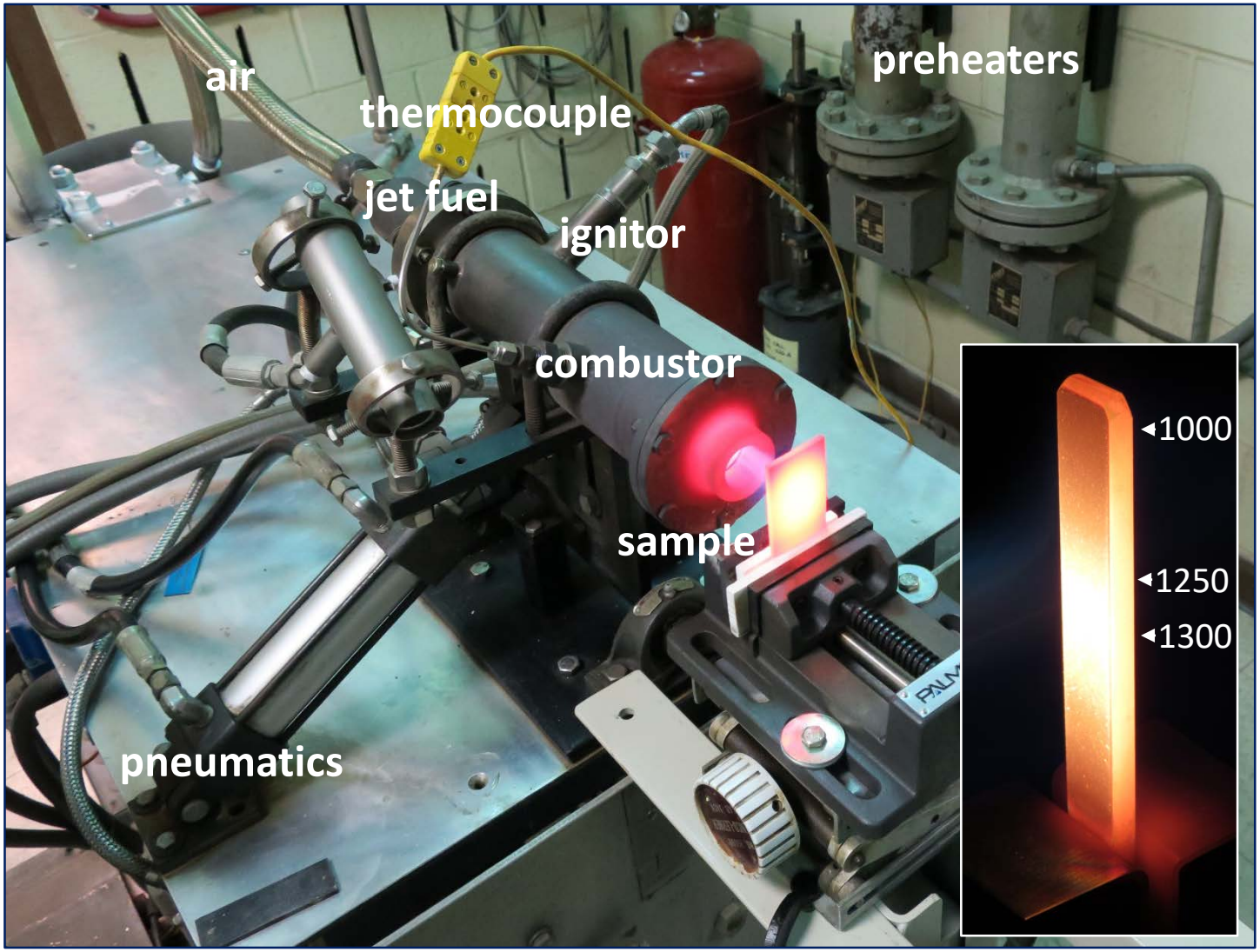


- 1400°C YSZ-Cr_2AlC-IN738, Burner Shock:
  failed 62 h, (745 cycles)
  J. Am. Ceram. Soc., (in press)

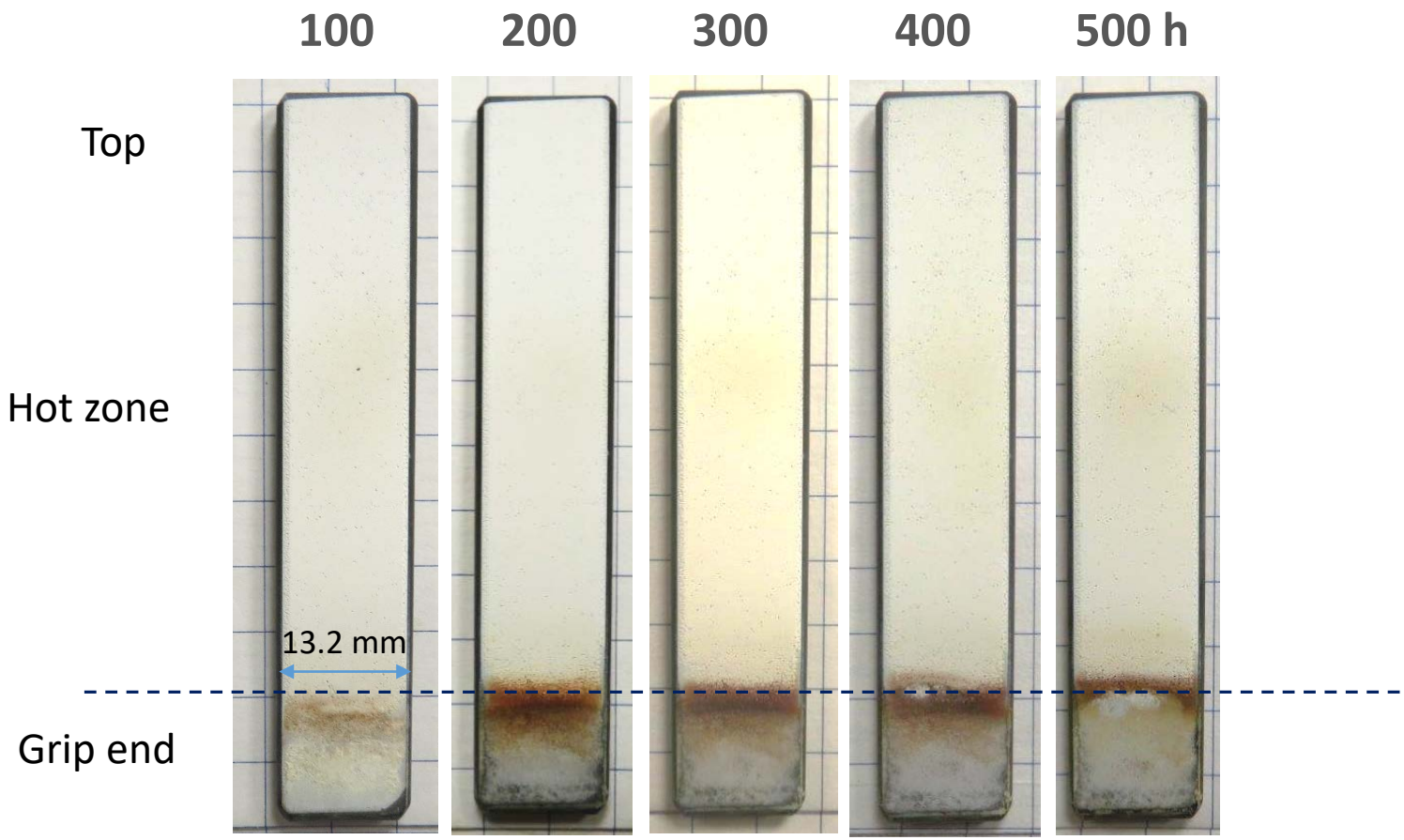
Experimental

- Kanthal (MAXTHAL 211®) Ti_2AlC bar
- EDM slabs, 2400 grit
- PS-PVD 160 µm 7YSZ coating (face side only)
- face-on, atmospheric Mach 0.3 jet fuel burner, 5-h cycles
- 1300°C surface, (~1244°C interface, 1216°C back)
- 2-color pyrometer, weight change, deflection
- SEM, XRD, (FIB-STEM)

NASA GRC Mach 0.3 Burner Rig

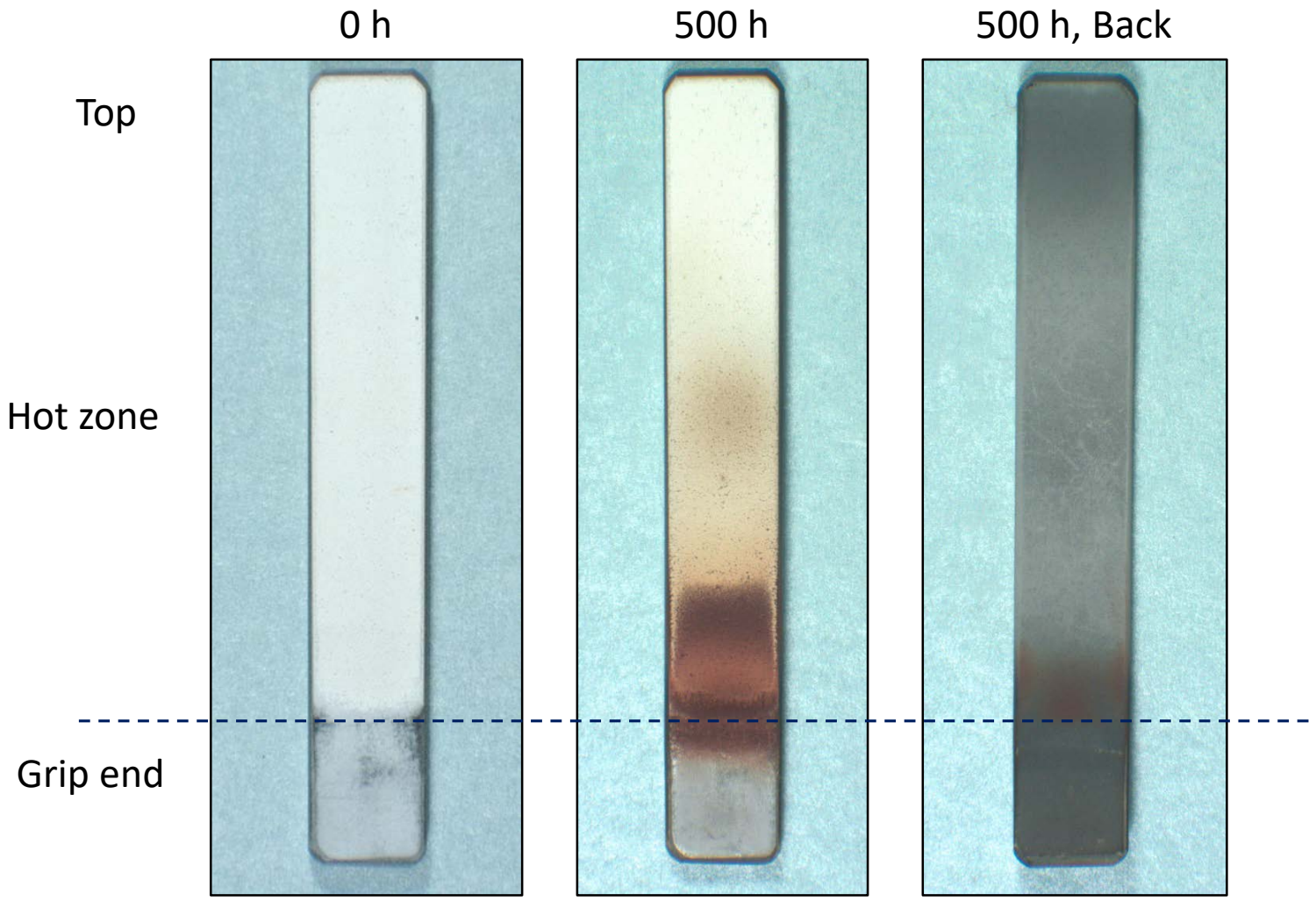


Face-on Burner Oxidation of YSZ-Ti_2AlC Strip
Survived Preliminary 1200°C Mach 0.3 Test

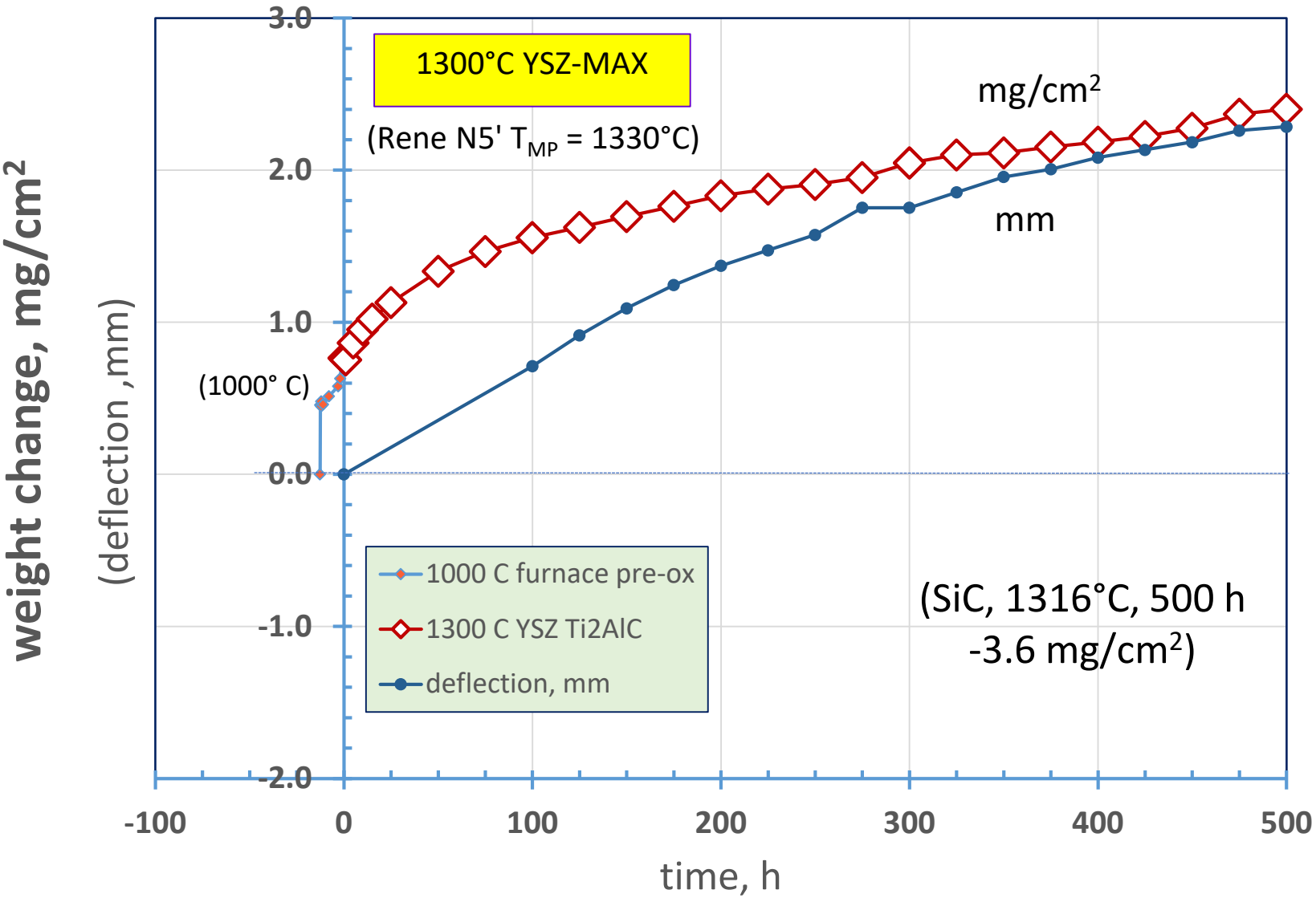


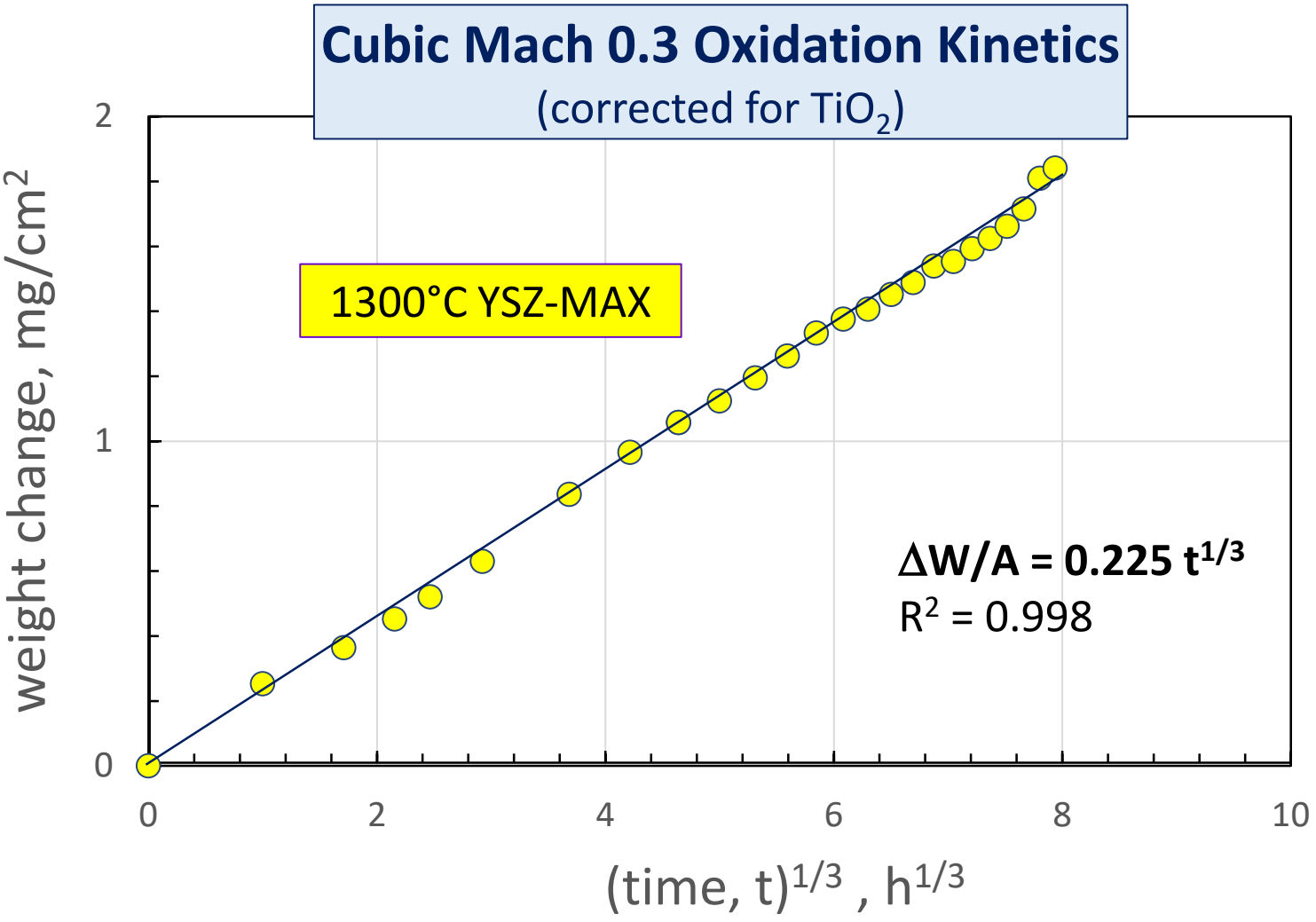
Survived 1300°C Mach 0.3 Test

(Fe_2O_3 staining from metal grips)



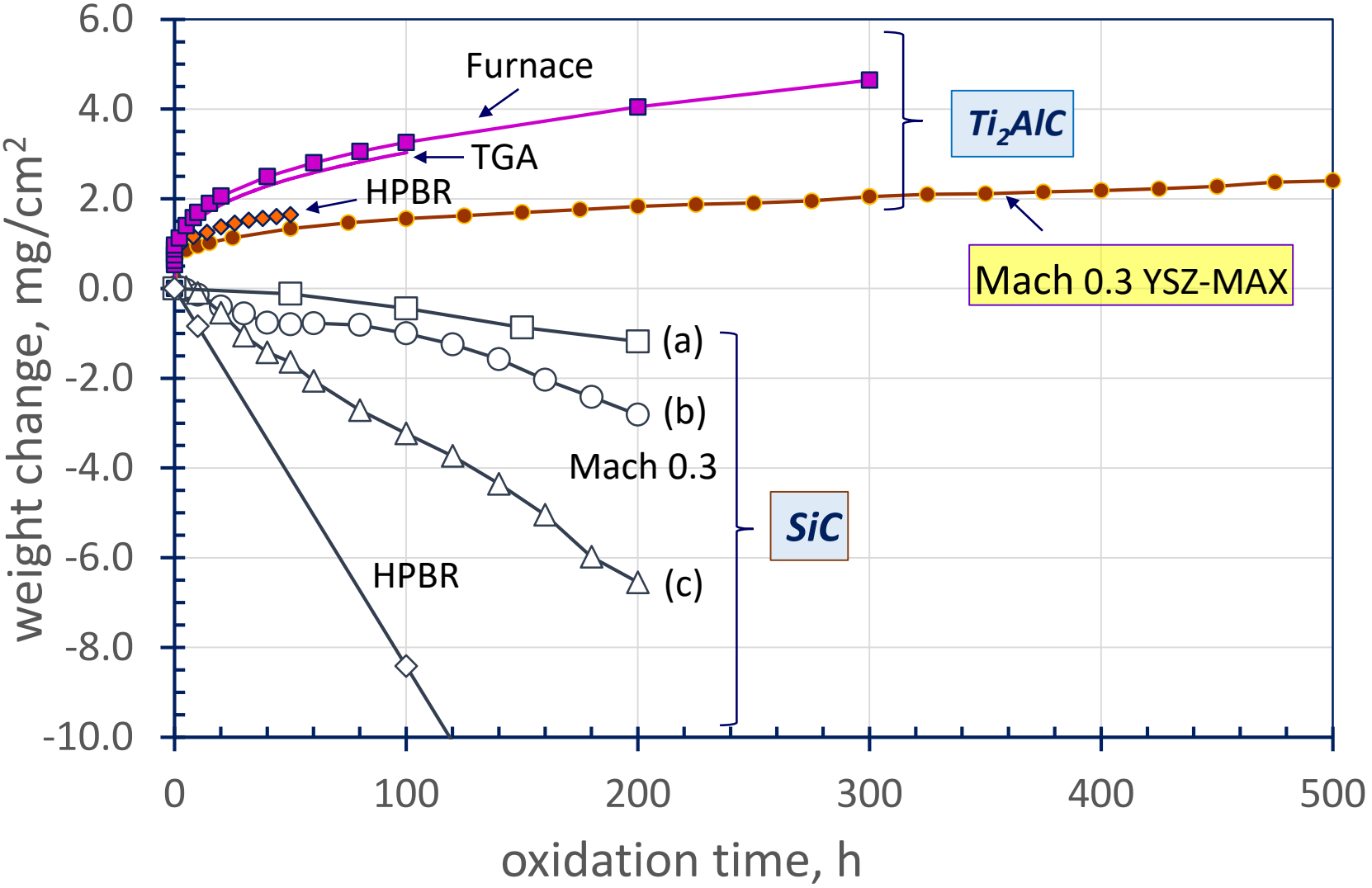
1300°C, 500 h Mach 0.3 BRT Oxidation of YSZ-Ti_2AlC



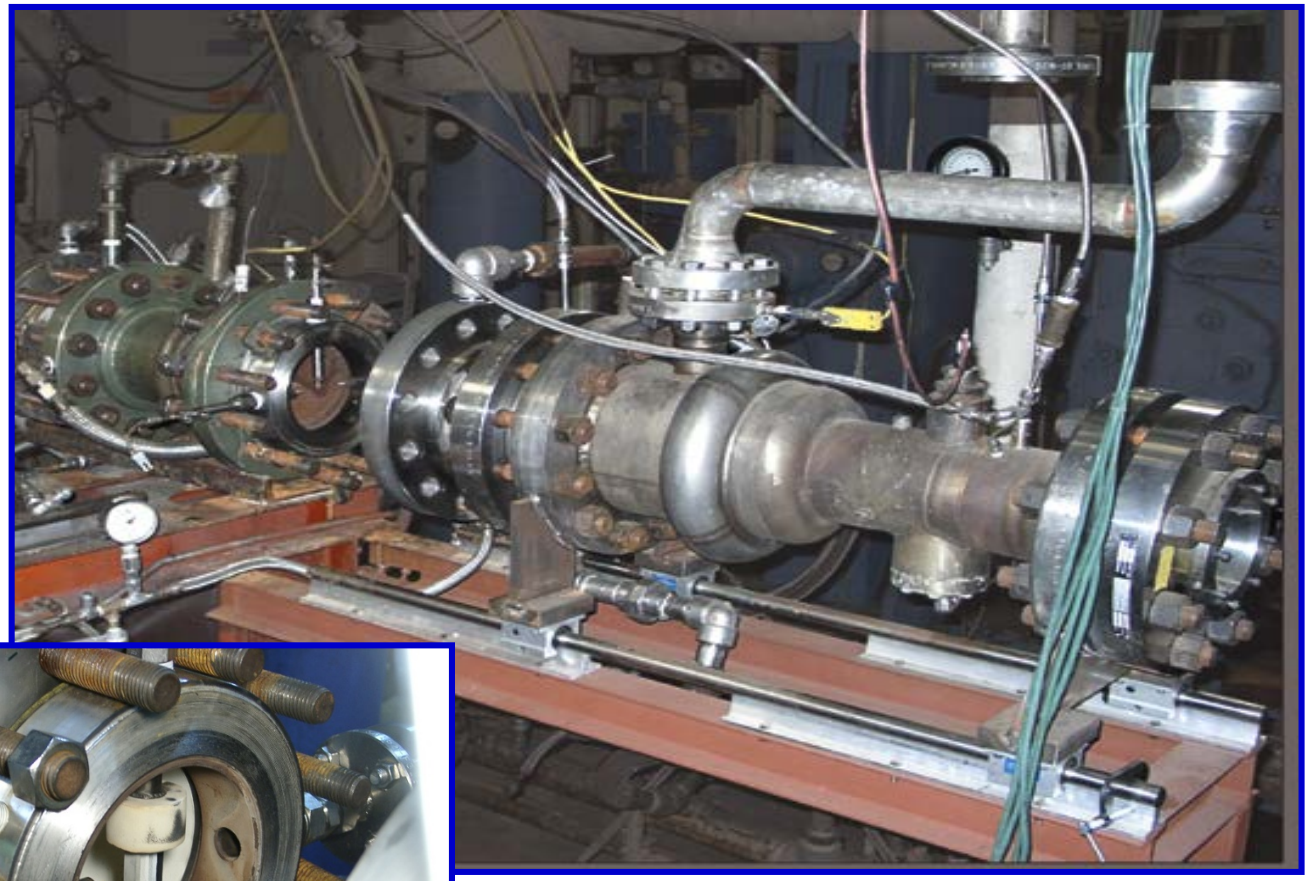

Cubic Mach 0.3 Oxidation Kinetics
(corrected for TiO2)
1300°C YSZ-MAX
ΔW/A = 0.225 t1/3
R2 = 0.998
weight change, mg/cm2
(time, t)1/3 , h1/3
0
1
2
0
2
4
6
8
10

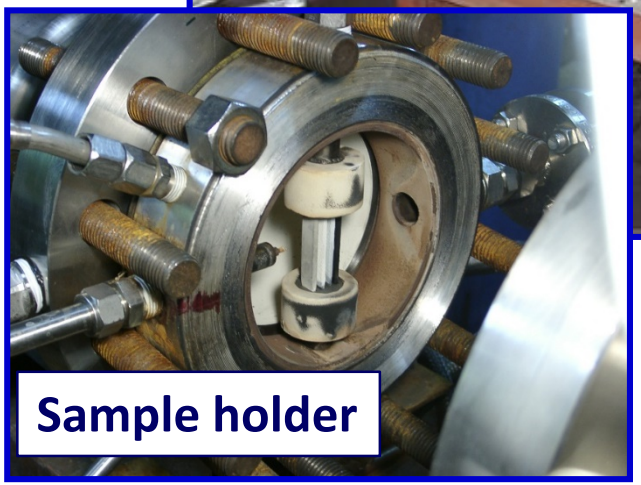
Comparative 1300°C Oxidation of Ti_2AlC

Furnace vs 6 atm, 25 m/s HPBR vs SiC



High Pressure Burner Rig
$H_2O \approx 10\%$





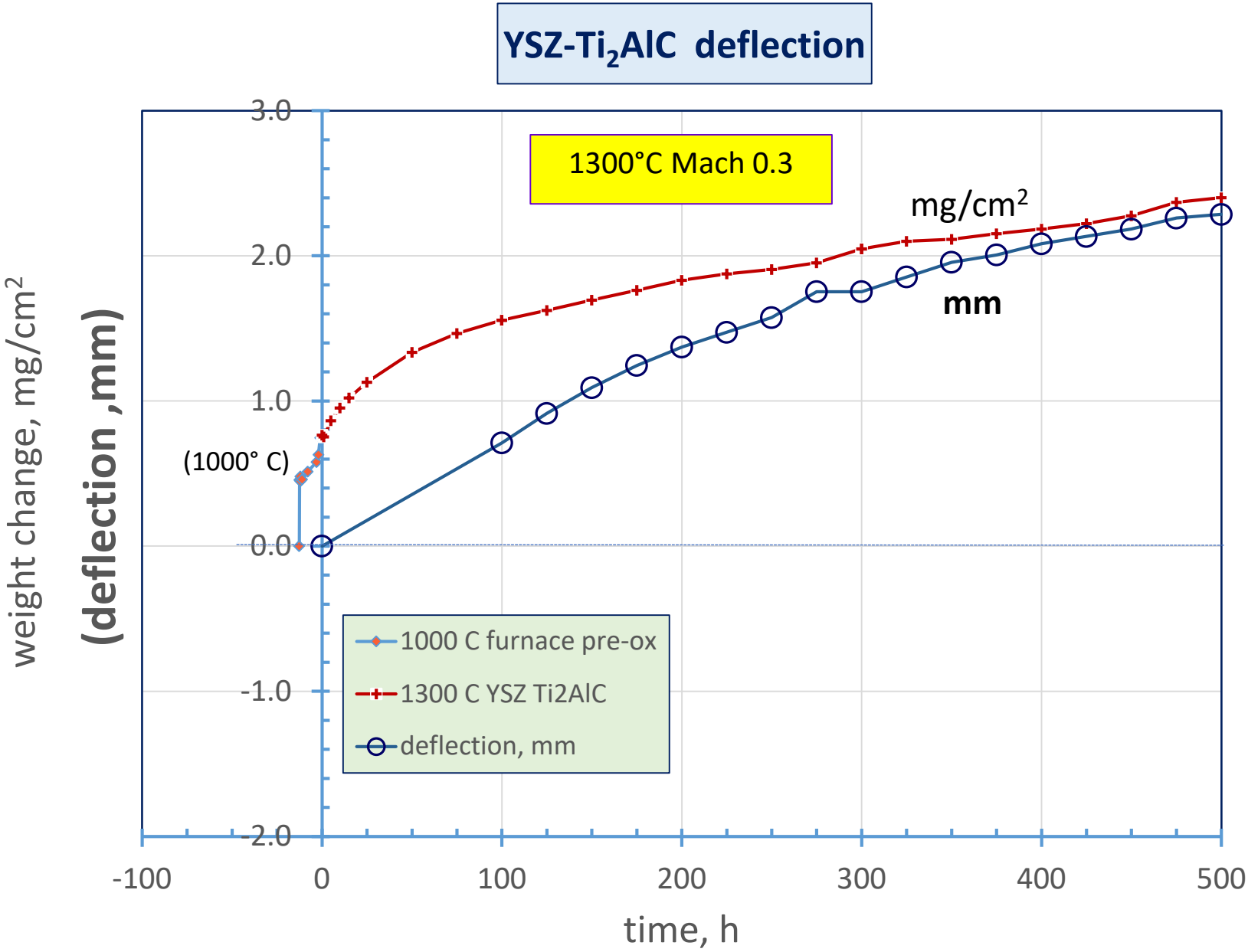
Up to ~1500°C, ~15 atm, ~100 m/s

Relative Severity of H_2O Testing

$v^{1/2} * p_{H2O}{}^{n}/p_{tot}$

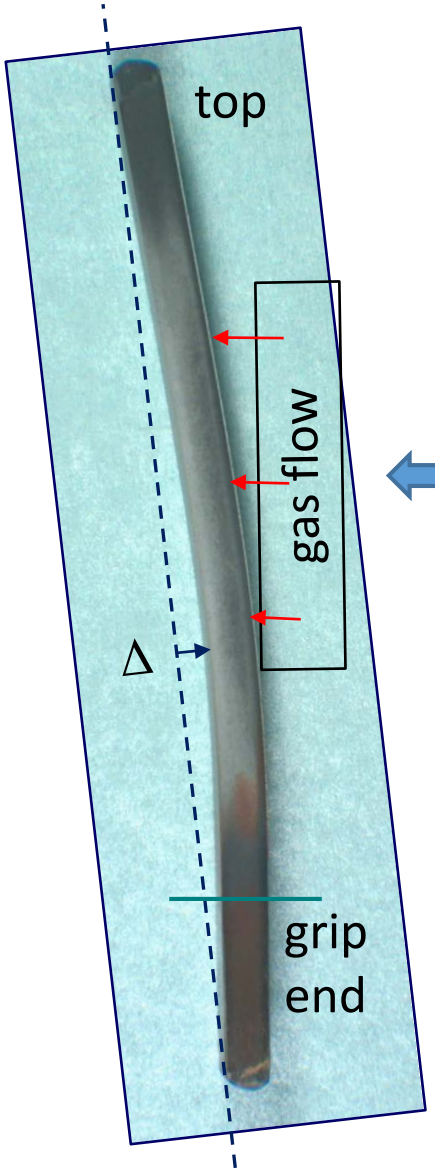
Parametric ranking of $Si(OH)_4$ flux and SiC mass recession in water vapor (n=2)

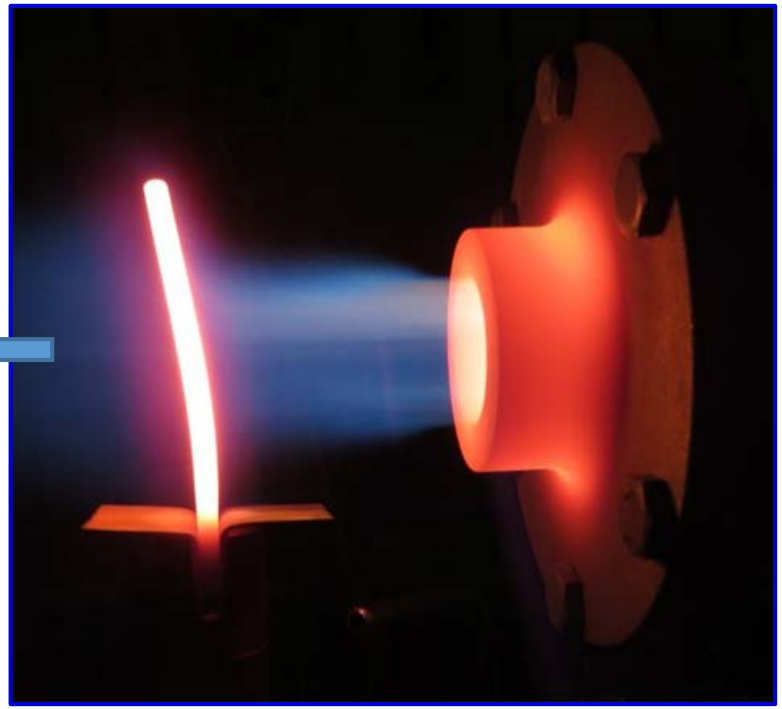
laboratory	rig	gas	P_{total}	$\%H_2O$	$P(H_2O)$	v	$J(Si(OH)_4)$ factor	dia.	mass loss
			atm		atm	m/s	relative	mm	relative
UVa (Opila)	steam jet	steam	1	1.00	1	175	13.23	**1.00**	1	**1**
NASA	NG-O_2	CH_4	1	0.58	0.58	110	3.51	0.27	25	**172**
Fraunhofer (Klemm)	HPBR	CH_4	5	0.18	0.9	50	2.56	0.19	25	**125**
NASA	CE9	jet fuel	30	0.05	1.5	30	2.25	0.17	25	**110**
EPRI-Yokosuka (Yuri)	HPBR	CH_4	4	0.11	0.44	150	1.19	0.09	25	**58**
NASA	HPBR	jet fuel	6	0.10	0.6	30	0.80	0.06	25	**39**
Jülich (Vassen)	BRT	CH_4	1	0.5	0.5	5	0.56	0.04	25	**5**
NASA	M0.3	jet fuel	1	0.10	0.1	100	0.10	0.01	25	**27**


YSZ-Ti2AlC deflection
1300°C Mach 0.3
mg/cm2
mm
(1000° C)
3.0
2.0
1.0
0.0
-1.0
-2.0
-100
0
100
200
300
400
500
time, h
weight change, mg/cm2
(deflection ,mm)
1000 C furnace pre-ox
1300 C YSZ Ti2AlC
deflection, mm

Deflection from face-on, Mach 0.3 flame impingement

(Lower ~1.5 cm gripped).

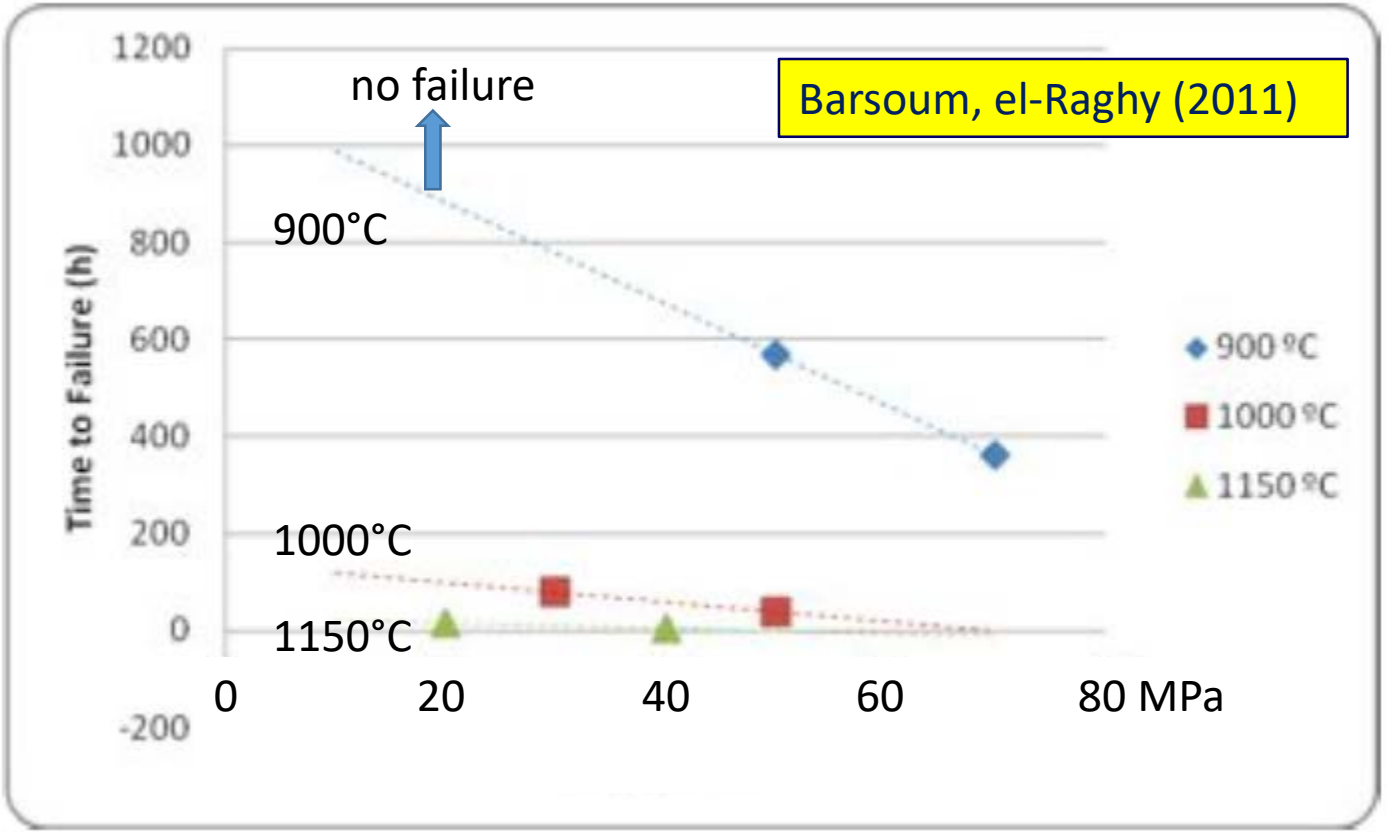




2.3 mm deflection Δ, 500 h
(6.8 cm total length)

Fast Fracture Due to Tensile Creep, MAXTHAL® 211

Courtesy of Lew Schmidt: NAVAIR SBIR N68335-10-C-0197

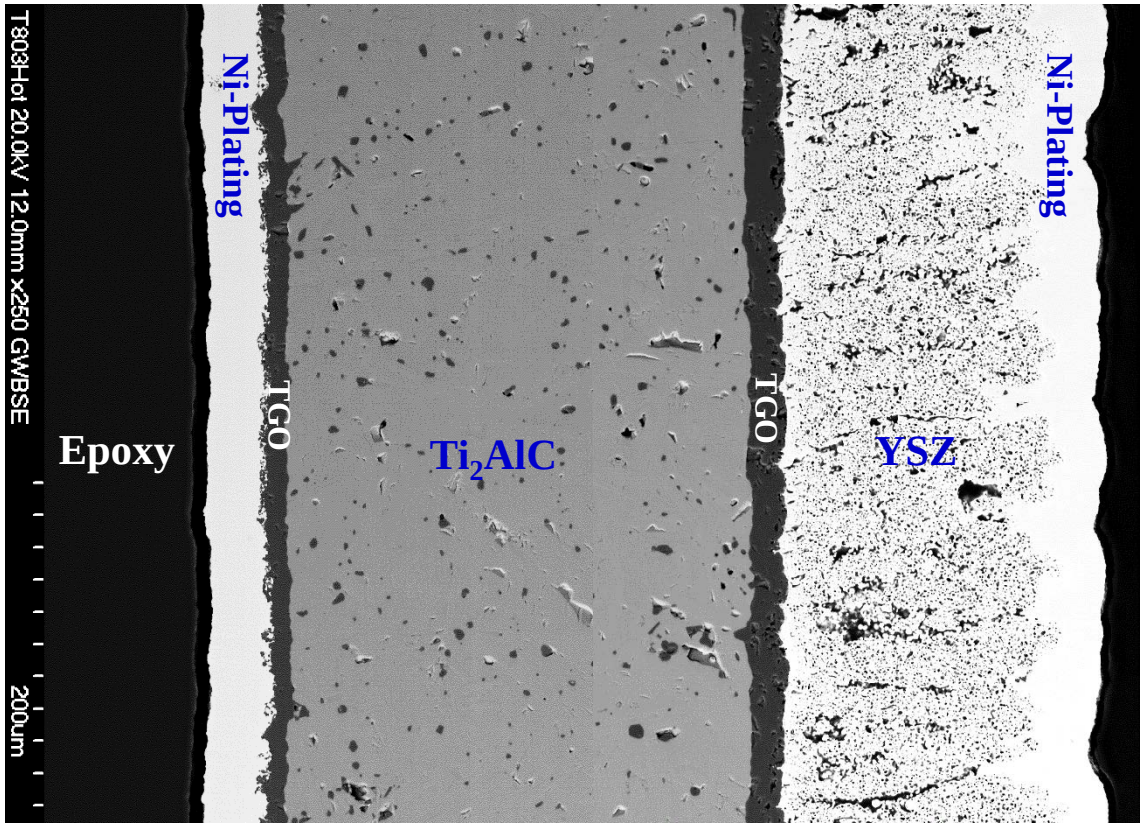


Entire Cross-Section at Hot Zone

YSZ Face/Al_2O_3/Ti_2AlC /Al_2O_3/Uncoated Backside

Uncoated backside

YSZ-coated face

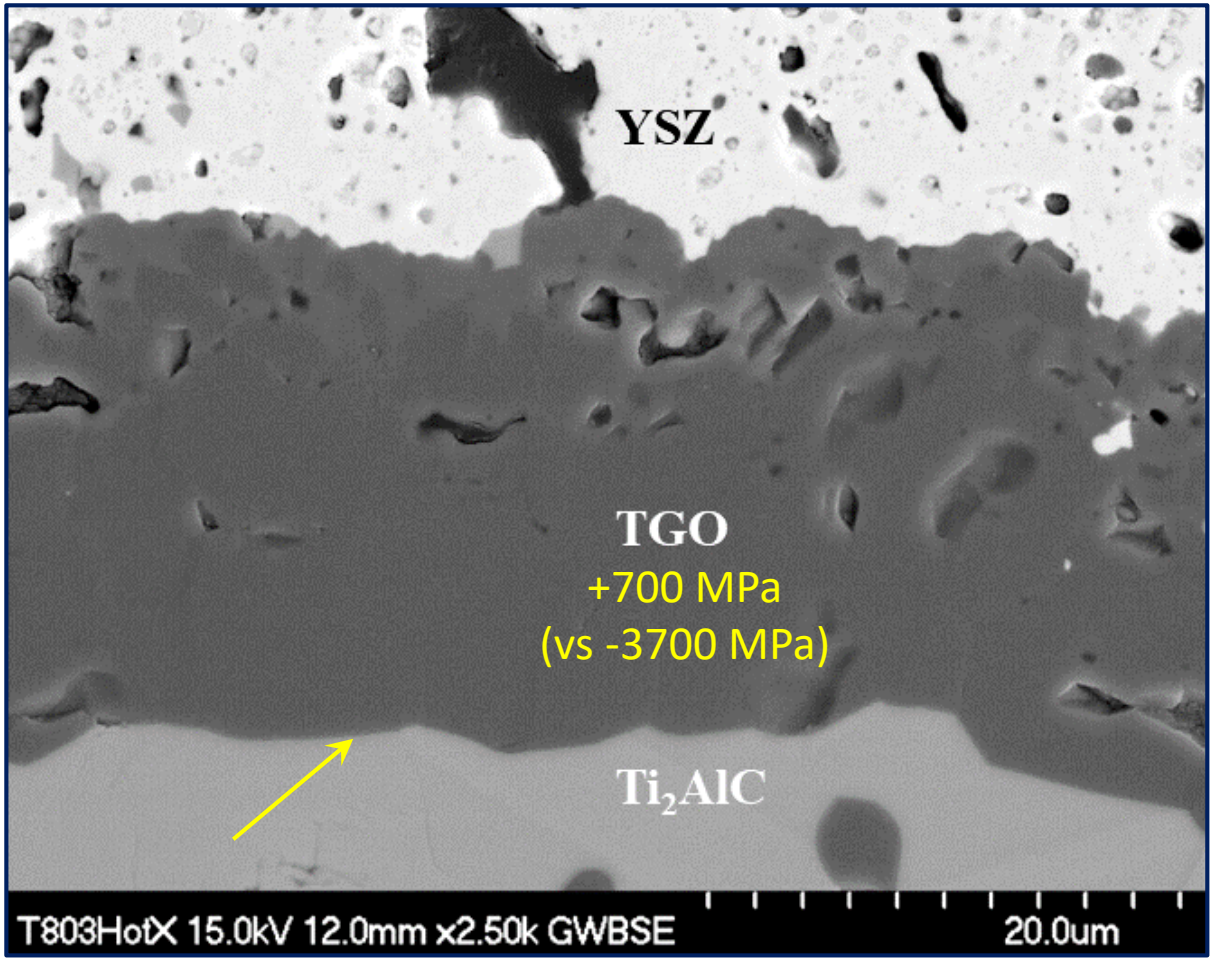


flame

200 µm

Intact 23 µm Al_2O_3 Scale

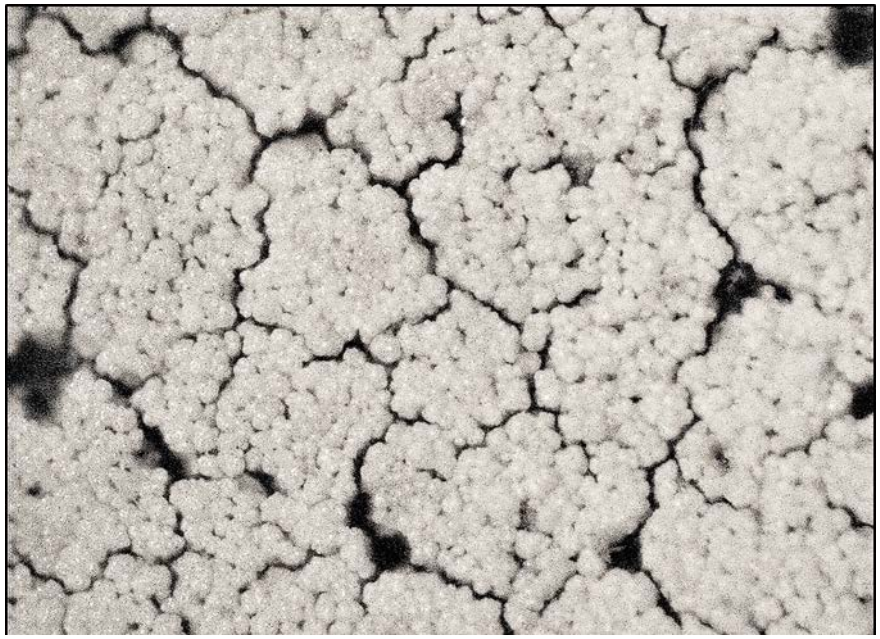
YSZ/Ti_2AlC Face, 1300°C, 500 h Mach 0.3 BRT



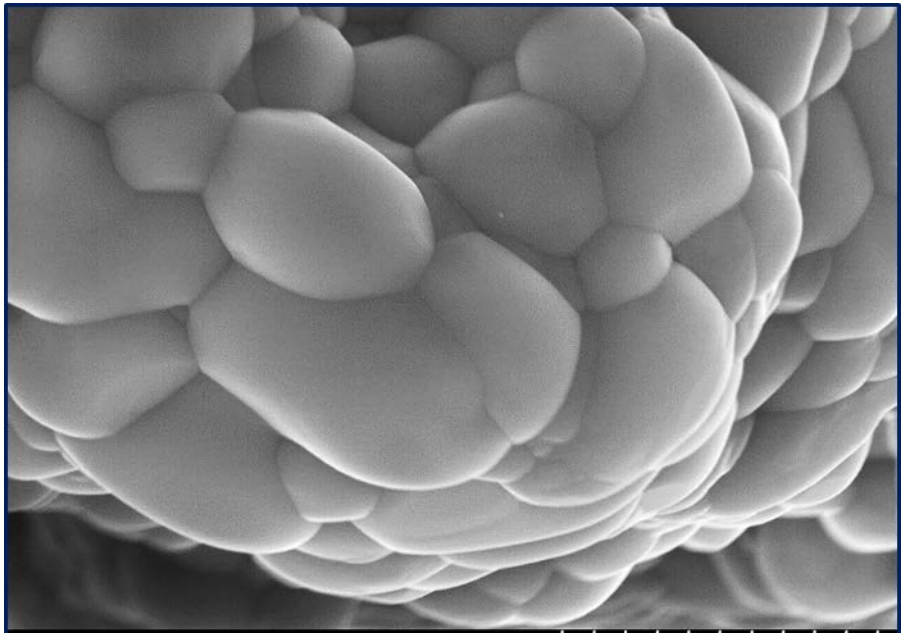
YSZ Surface (500 h, Mach 0.3, 1300°C BRT)

Craze cracking and smooth grain surfaces. Hot zone.

No $ZrO(OH)_2$?



1 mm

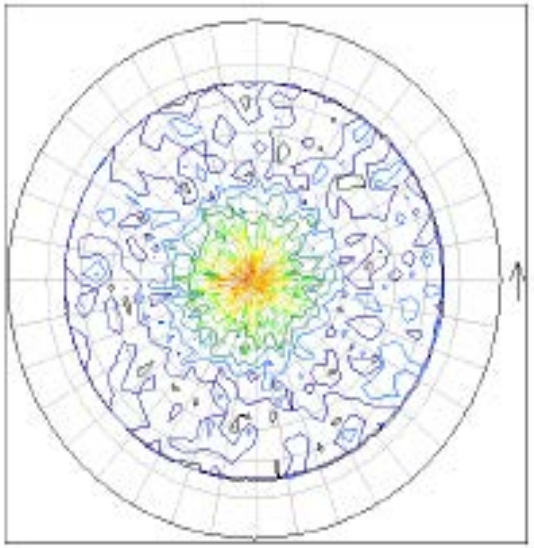


3 µm

XRD Summary

Backside Ti_2AlC	α-Al_2O_3	(TiO_2 rutile, trace)
YSZ TBC face	t, t′, cubic	(monoclinic, trace. Also Raman, TEM)

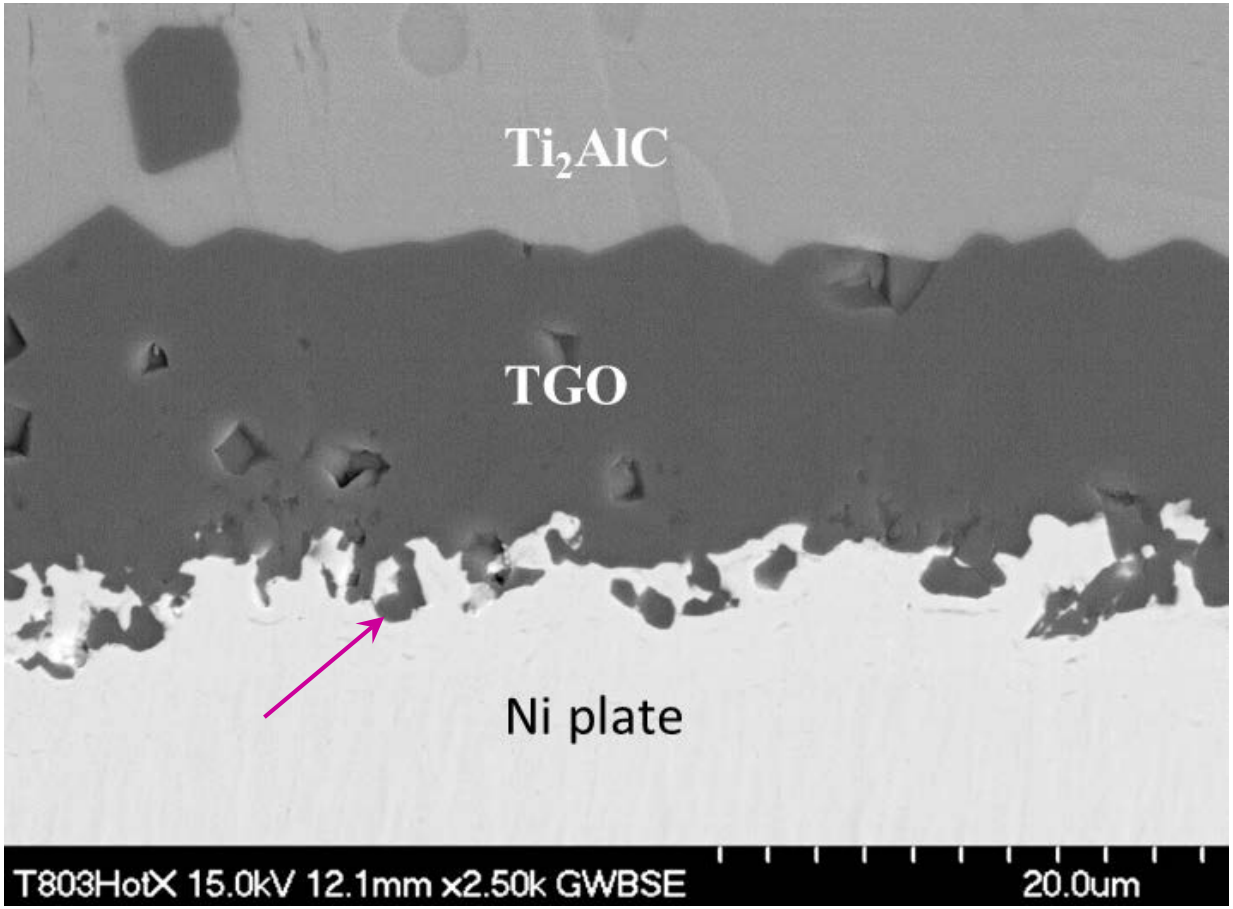
Oriented PS-PVD growth columns as-deposited:



YSZ $(111)_C$ pole figure

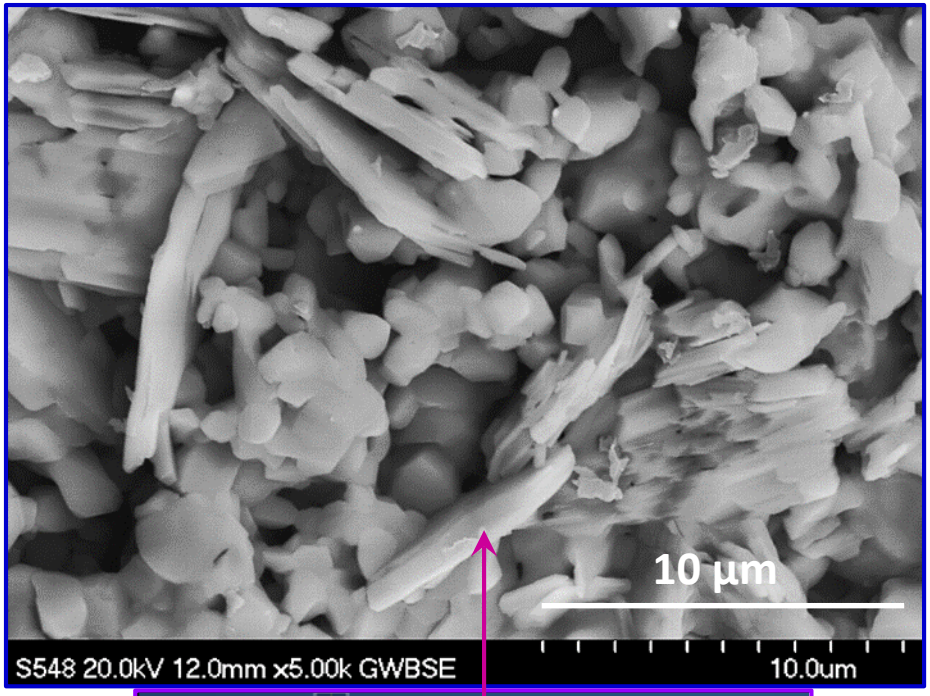
Attacked 15 µm Al_2O_3 Scale

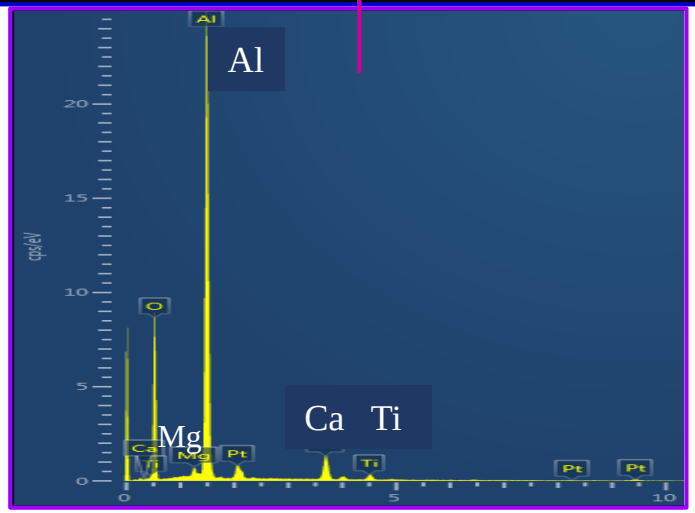
Bare Ti_2AlC Backside, 1216°C, 500 h Mach 0.3 BRT



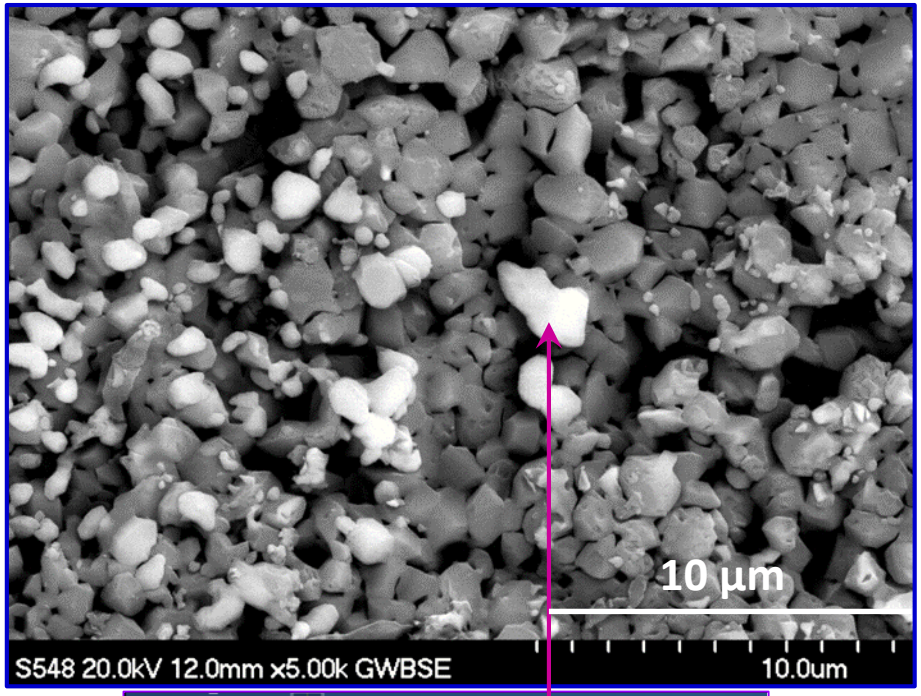
Open Scale Structure, Uncoated Backside

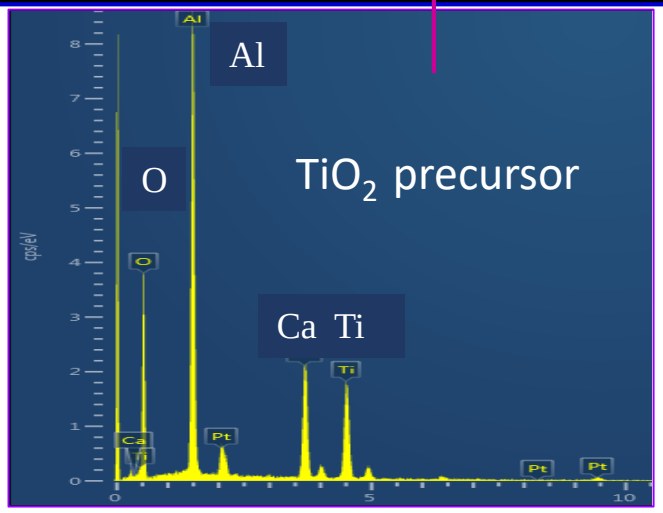
hot zone



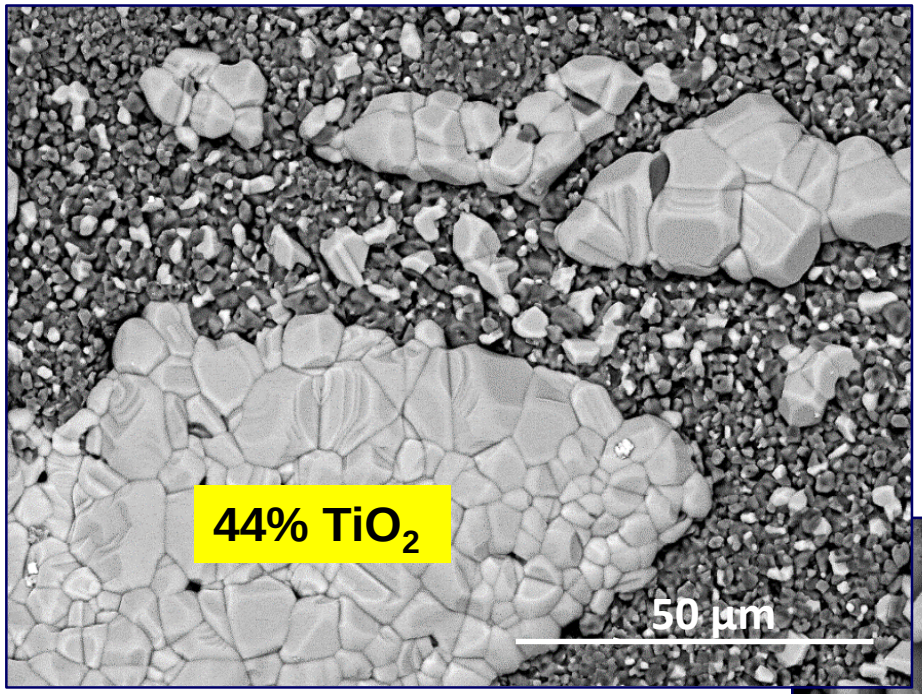


cool grip end



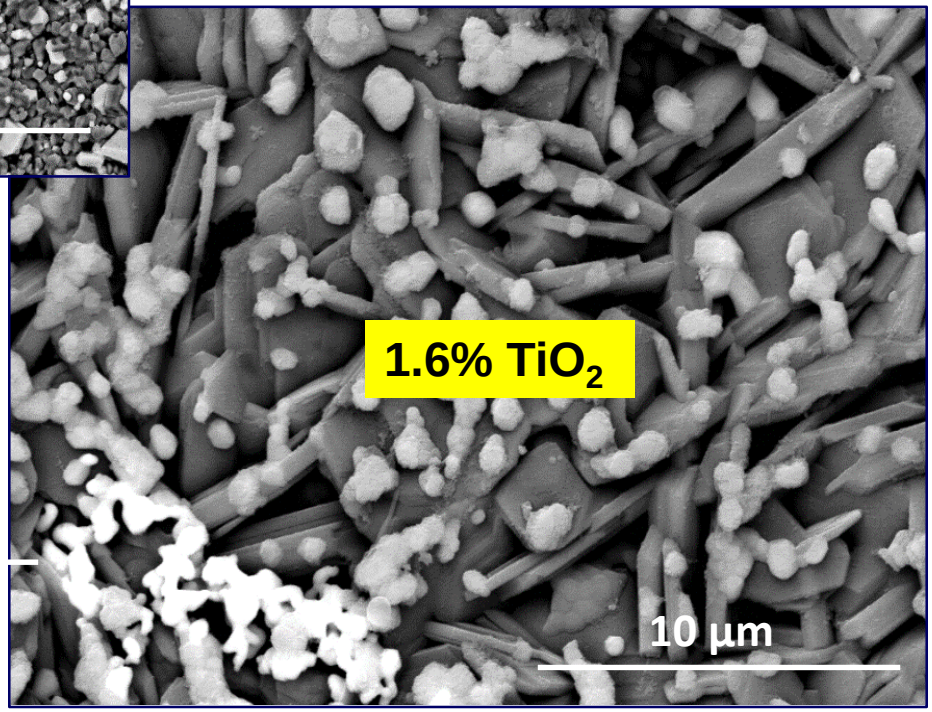


1200°C HPBR Exposures: TiO_2 Removed from Al_2O_3



TGA, 100 h

6 atm, HPBR, 25 m/s, 50 h



Relative Severity of H_2O Testing

$v^{1/2} * p_{H2O}{}^{n}/p_{tot}$

Parametric ranking of $Si(OH)_4$ flux and SiC mass recession in water vapor (n=2)

laboratory	rig	$J(Si(OH)_4)$ relative	dia. mm	mass loss relative
UVa (Opila)	steam jet	**1.00**	1	**1**
NASA	NG-O_2	**0.27**	25	**172**
Fraunhofer (Klemm)	HPBR	**0.19**	25	**125**
NASA	CE9	**0.17**	25	**110**
EPRI-Yokosuka (Yuri)	HPBR	**0.09**	25	**58**
NASA	HPBR	**0.06**	25	**39**
Jülich (Vassen)	BRT	**0.04**	25	**5**
NASA	M0.3	**0.01**	25	**27**

Highlights

Mach 0.3 Burner Rig Test of YSZ Coated Ti_2AlC MAX Phase

- TBC survived 500 h at 1300°C (Possible record)
- YSZ untouched by water vapor
- Well-behaved, cubic, +2.4 mg/cm^2 weight gain (Al_2O_3 TGO: 23 µm face; 15 µm back)
- Intact Al_2O_3/Ti_2AlC interface, again
- Slight TiO_2/Al_2O_3 scale volatility (backside)
- Ti_2AlC creep, but no fracture

Consult and Support

Nate Jacobson
Dan Scheiman
Wayne Jennings
J. Gonzalez-Julian

Dennis Fox
Joy Buehler
Craig Robinson
J. Cormier