Table 1. Summary of surface phases for burner rig exposure of bare and YSZ coated Ti_2AlC MAX phase. Rietveld estimates of wt.% phase contents. Test temperature indicates maximum surface temperature of coating in hot zone. (sample from previous furnace tests included for comparison).

				wt.%				
back, uncoated	**location**	**test temperature**	**time**	**Al_2O_3**	**TiO_2**	**Ti_2AlC^+**	**$TiAl_3$ (?)**	**$Fe_2O_3^{++}$**
burner bar	hot zone	926°C	10 m	51	10	38		
burner bar	top end	1300°C	500 h	89	1	9	1.5	
burner bar	hot zone	1300°C	500 h	97	0.1	3	0	
burner bar	grip end	1300°C	500 h	79	0.3	17	3.5	1
front, coated	**location**	**test temperature**	**time**	**t-YSZ**	**t'-YSZ**	**cubic**	**monoclinic**	**$Fe_2O_3^{++}$**
furnace sample	uniform	1100°-1300°C	2500 h			62	21	
burner bar	hot zone	926°C	10 m		68	28	3	
burner bar	top end	1200°C	500 h	34		62		
burner bar	hot zone	1200°C	500 h	31		64		
burner bar	grip end	1200°C	500 h	28		68		
burner bar	top end	1300°C	500 h	12		86	0.5	
burner bar	hot zone	1300°C	500 h	11		86	0.5	
burner bar	grip end	1300°C	500 h		49	32	1.5	16

+ includes other possible MAX stoichiometries

++ includes other possible Fe-oxides

Table 2. Estimates of $YO_{1.5}$ mole % in YSZ phases according to published lattice parameter and c/a ratio calibrations.

					t-YSZ		t'-YSZ		cubic
	sample	location	test temperature	time	*a-LP**	*c/a ratio***	*a-LP**	c/a ratio**	*a-LP**
	furnace	uniform	1100°-1300°C	2500 h					12
	burner bar	hot zone	926°C	17 m			11.6	9.8	
	burner bar	top end	1200°C	500 h	3.7	3.6			16.4
	burner bar	hot zone	1200°C	500 h	3.1	3.7			14.7
	burner bar	grip end	1200°C	500 h	4.8	4.6			16.1
	burner bar	top end	1300°C	500 h	3.2	3.6			15.1
	burner bar	hot zone	1300°C	500 h	1.6	3.0			9.4
	burner bar	grip end	1300°C	500 h			7.0	6.8	10.9

* value based on empirical correlation between mol% YO1.5 and a lattice parameter.

** value based on empirical correlation between mol% YO1.5 and c/a ratio.

See report narrative for discussion of t’ vs. t phases.

Table 3. HP-BRT and Mach 0.3 BRT comparisons. (a) typical burner conditions and (b) relative scale volatility factors ($J_{M0.3}/J_{HPBR}$) according to $v^{1/2}p_{H2O}{}^{n}/p_{tot}{}^{1/2}$.

a)

	v (m/s)	p_{H2O} (atm)	p_{tot} (atm)
Mach 0.3	100	0.1	1
HP-BRT	25	0.6	6

b)

scale	species	n	$(p_{H2O}/p_{H2O})^{n}$	$(p_{tot}/p_{tot})^{1/2}$	$(v/v)^{1/2}$	$J_{Mach\ 0.3}/J_{HPBR}$
TiO_2	$TiO(OH)_2$	1	0.167	0.408	2	**0.816**
Al_2O_3	$Al(OH)_3$	3/2	0.068	0.408	2	**0.333**
SiO_2	$Si(OH)_4$	2	0.028	0.408	2	**0.136**

Table 4. Oxidative Life Summary of YSZ TBC on MAX Phases Compared to Single Crystal Superalloys (SXSA). black (survived); red italic (failed)

(FCT SXSA - Smialek 2015; FCT GZ/YSZ - University West, Mahade, 2019; FCT Kanthal (K) - Smialek, 2016, 2018; FCT Juelich (J) -, Gonzalez-Julian, 2018; BRT Juelich (J) - Gonzalez-Julian 2019); BRT Kanthal (K) – this study

test	TBC	substrate	**1100°**	**1150°**	**1200°**	**1250°**	**1300°**	**1400°**	°C
FCT	PVD	SXSA	*831*	*352*	*158*	*75*	*37*		h
FCT	HVAF*	Hast-X	*580*						
BRT	**HVAF***	**IN-738**						***42***	
FCT	APS	Cr_2AlC-K	500	500	*100*				
FCT	PS-PVD	Cr_2AlC-K	500	500	*100*				
FCT	APS	Cr_2AlC-J	500		500		*268*		
BRT	**HV-APS**	**Cr_2AlC-J**						***62***	
FCT	APS	Ti_2AlC-K	500	500	500	500	*500*		
FCT	PS-PVD	Ti_2AlC-K	500	500	500	500	500		
BRT	**PS-PVD**	**Ti_2AlC-K**			**500**		**500**		

* 2-layer $Gd_2Zr_2O_7$/YSZ

K-Kanthal
J – Juelich

black - survived
red -failed

Figure 1

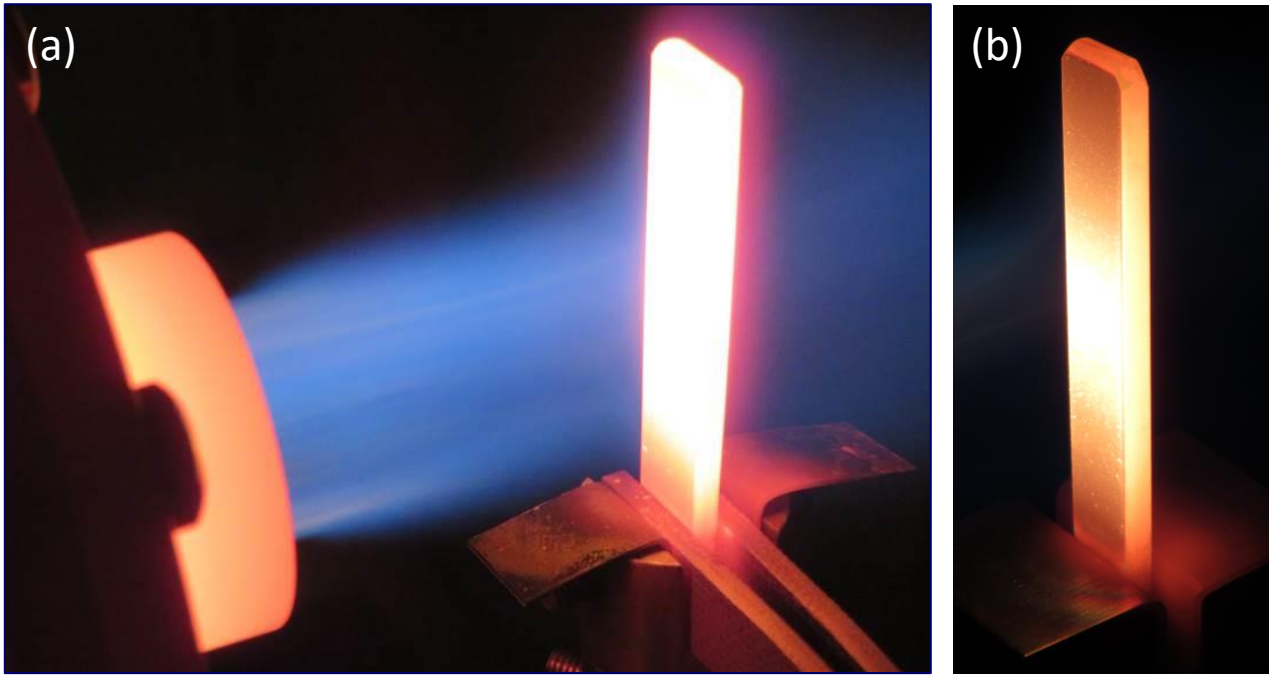

Figure 1. Photographs of burner rig and YSZ coated Ti_2AlC MAX phase sample in operation. a) upper angled view showing flame, sample and mounting base; b) short exposure indicating temperature gradients along sample length.

Figure 2a

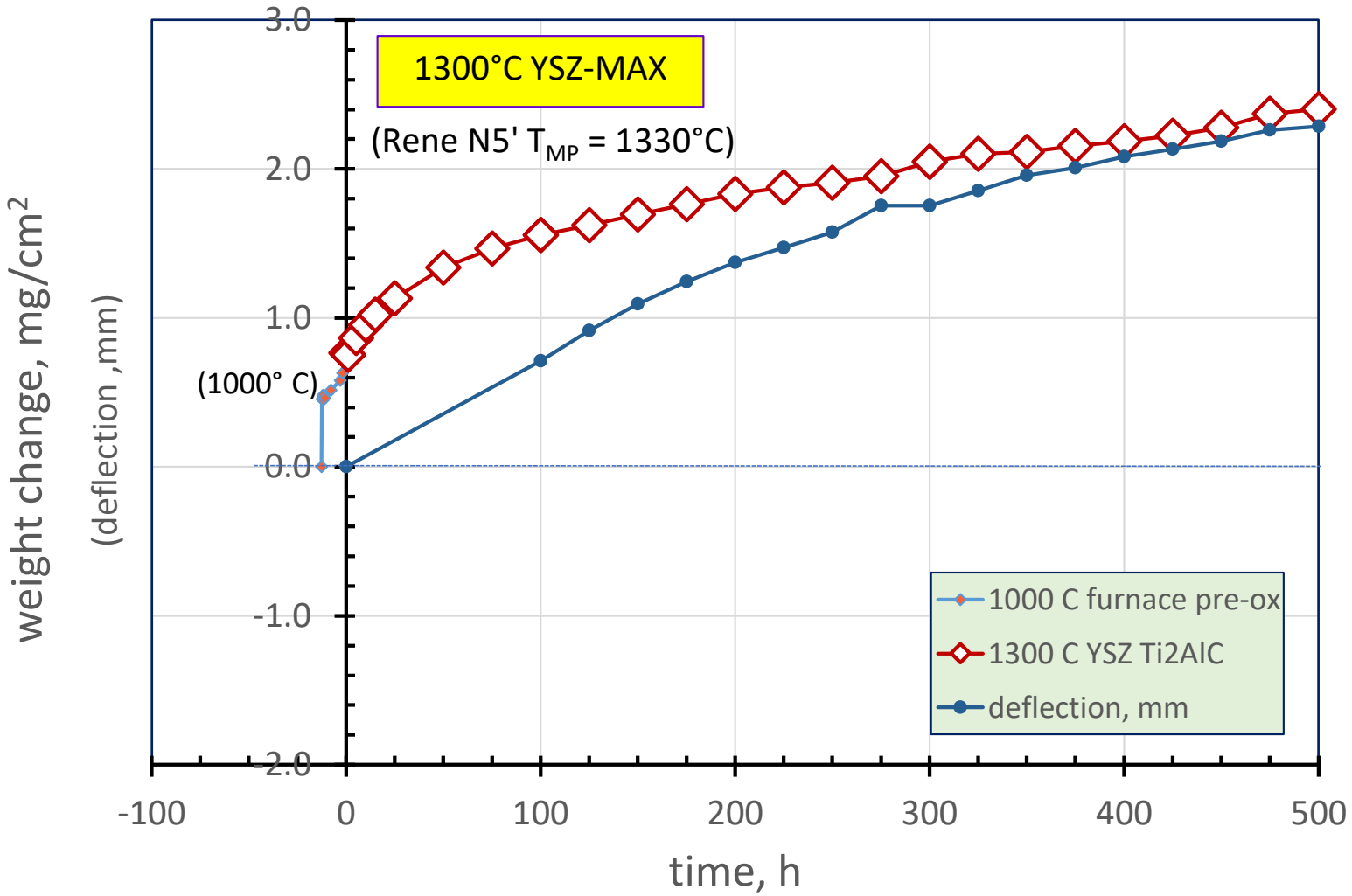

Figure 2. Mach 0.3 1300°C BRT of YSZ TBC on Ti_2AlC. a) Specific weight gain and degree of bending for 500 h Mach 0.3 1300°C BRT. Deflection rate is slightly moderated with time as sample subtended area decreases. b) Cubic oxidation kinetics (without spalling) is suggested by plotting transient corrected weight vs $t^{1/3}$.

Figure 2b.

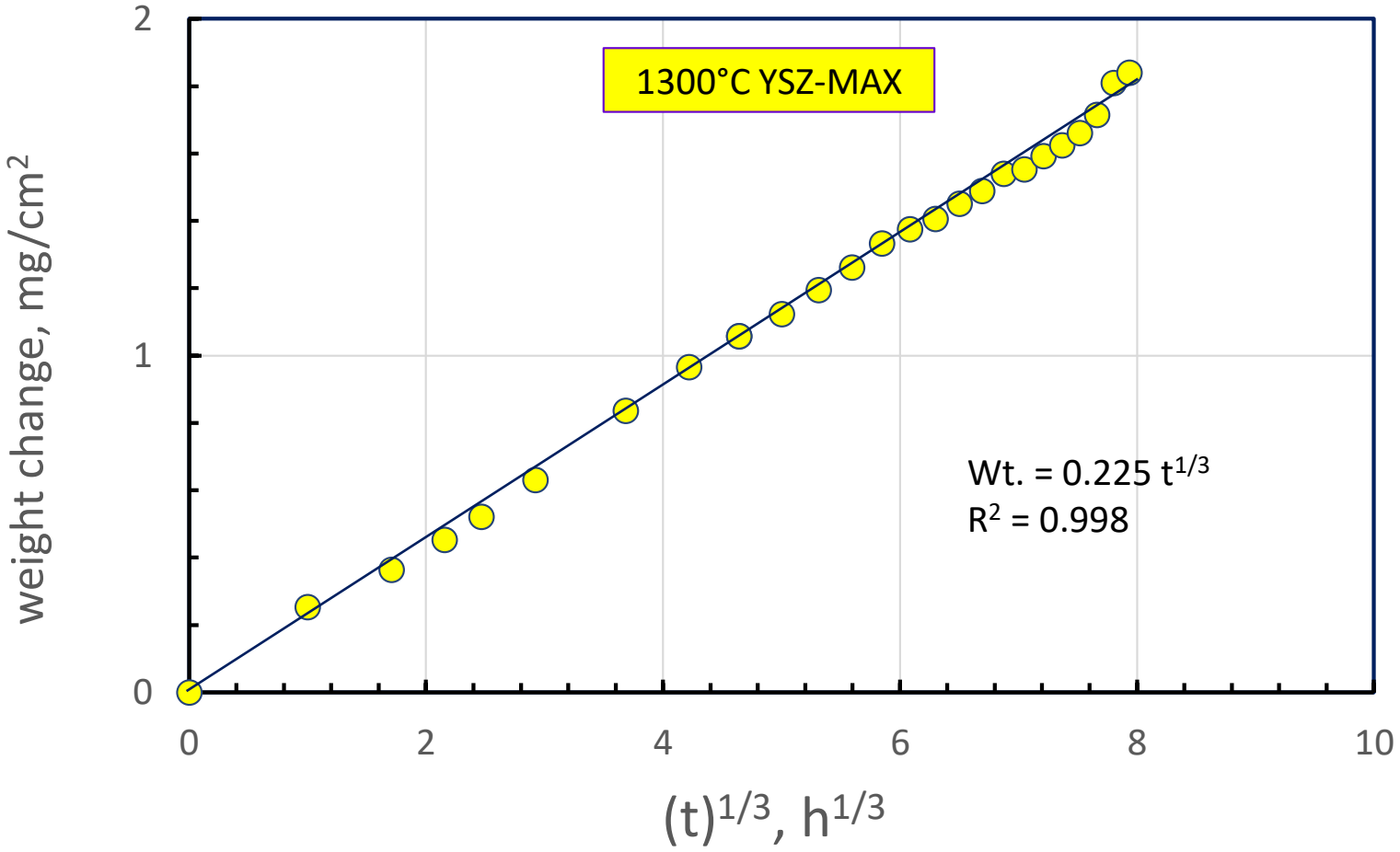

Figure 2. a) Specific weight gain and degree of bending for 500 h Mach 0.3 1300°C BRT. Deflection rate is slightly moderated with time as sample subtended area decreases. b) Cubic oxidation kinetics (without spalling) is suggested by plotting transient corrected weight vs $t^{1/3}$.

Figure 3

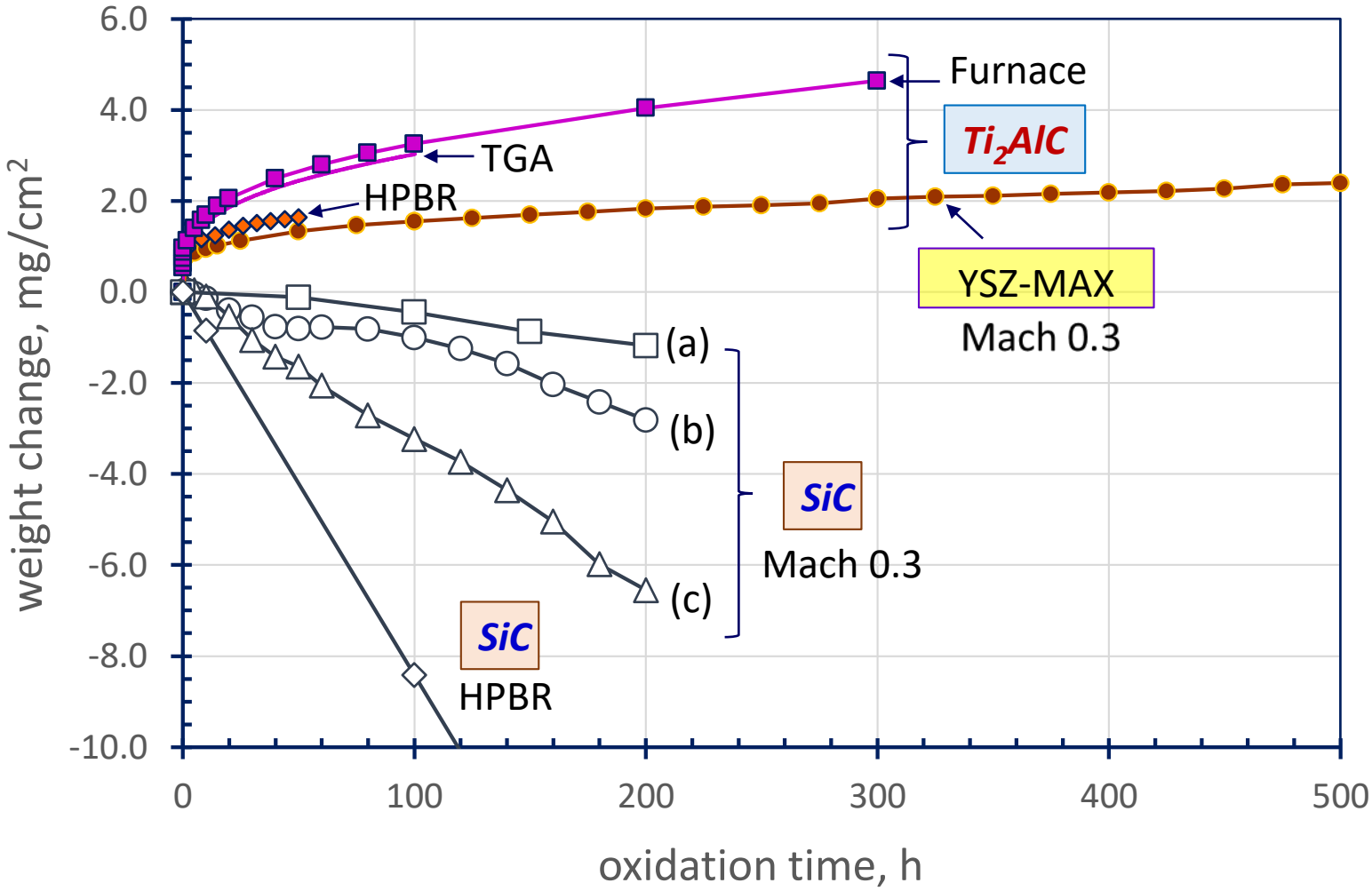

Figure 3. Comparison of YSZ-MAX sample BRT oxidation data with other 1300°C exposures. (HPBR at 6 atm. and 20-25 m/s, TGA dry air, and ambient air furnace tests. Sintered 'Hexoloy' SiC curve (a) Opila, et al., 1316°C, (a,b) pyrometer sighted on leading edge; (c) sighted on face).

Figure 4

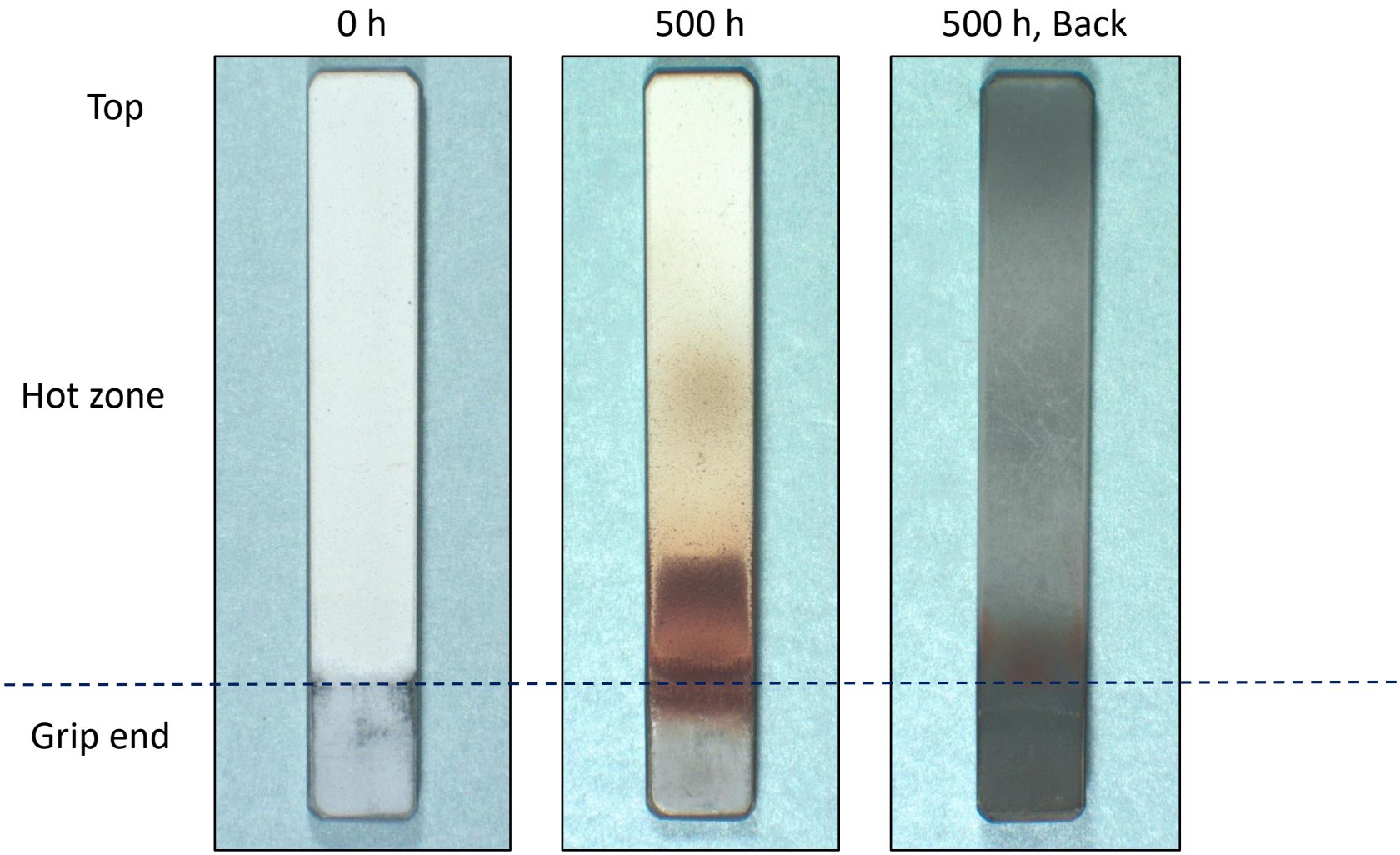

Figure 4. Visual appearance of the YSZ-MAX sample before and after 1300°/500 h BRT. YSZ coating shows rust discoloration due to Fe transfer from Kanthal A1 FeCrAl mounting sheet. (Coating ground off in mounting area to avoid abrasion losses).

Figure 5

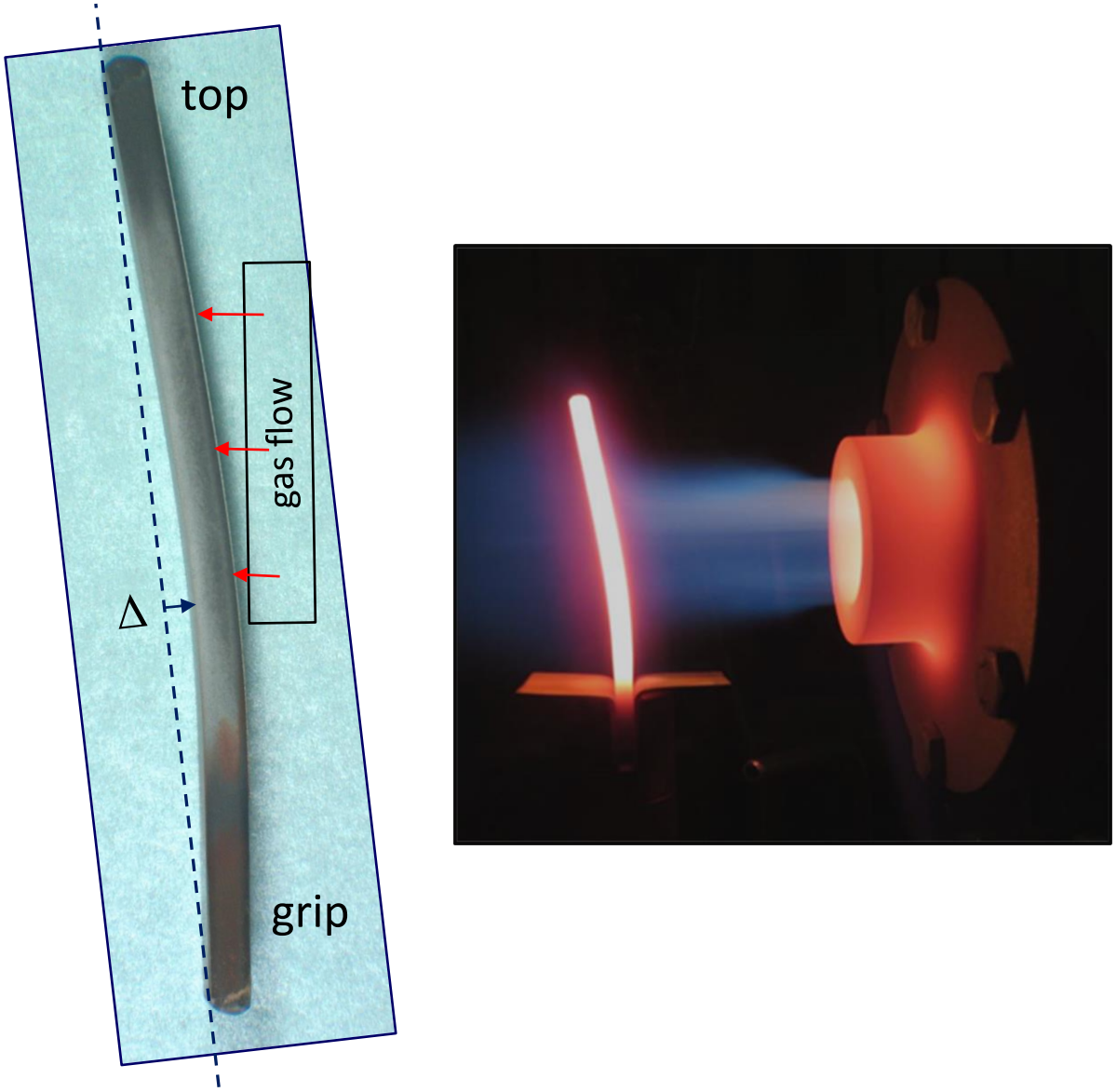

Figure 5. YSZ/Ti_2AlC sample deflection due to creep from face-on, Mach 0.3 BRT flame impingement. (2.3 mm delta over 6.8 cm sample length. Lower ~1.5 cm gripped).

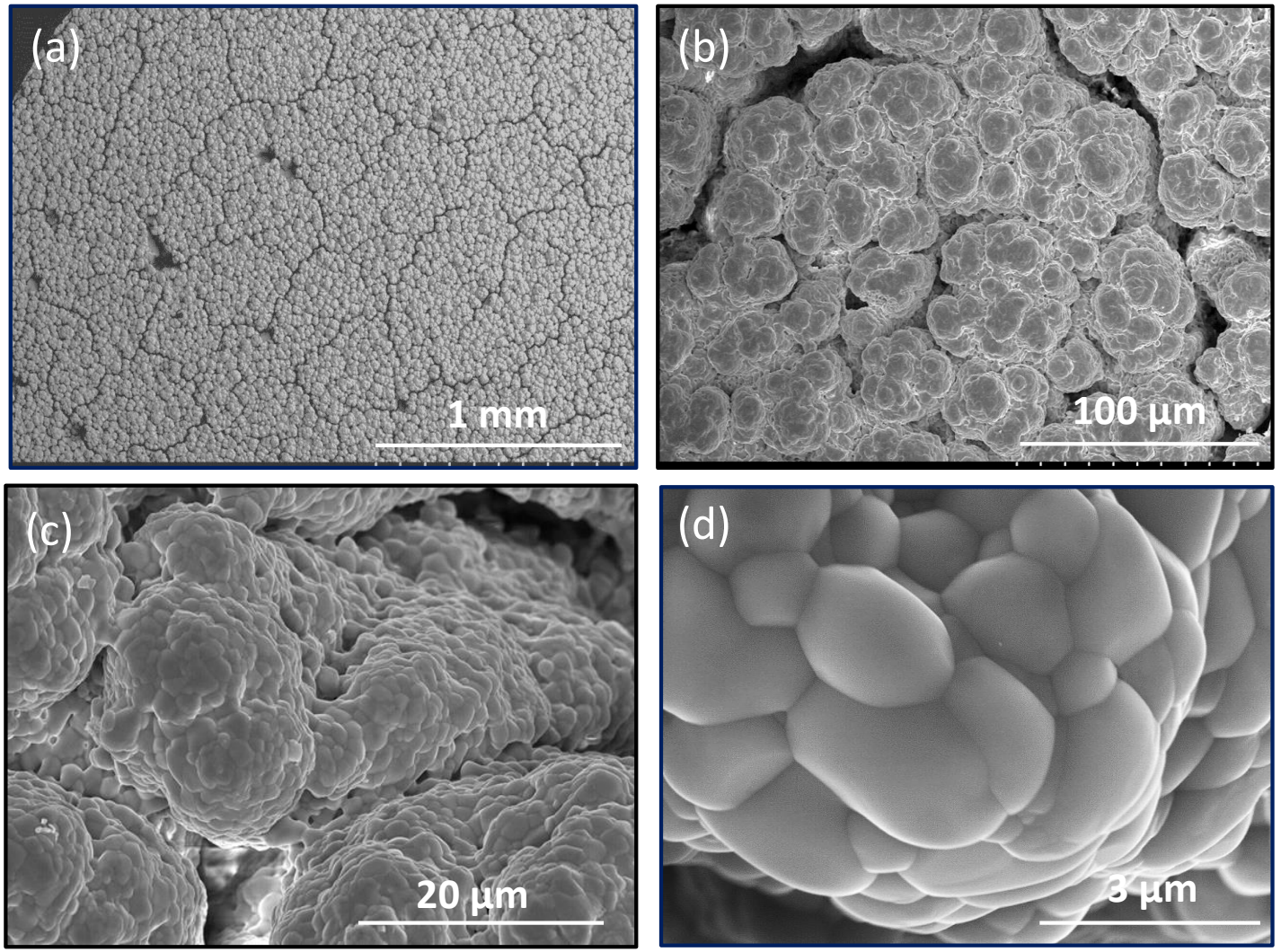

Figure 6. SEM/BSE of YSZ coating surface after 1300°C/500 h BRT, hot zone. a) craze crack pattern; b,c) columnar PS-PVD deposition; d) pristine individual 1-3 µm YSZ grains on column surface.

Figure 7.

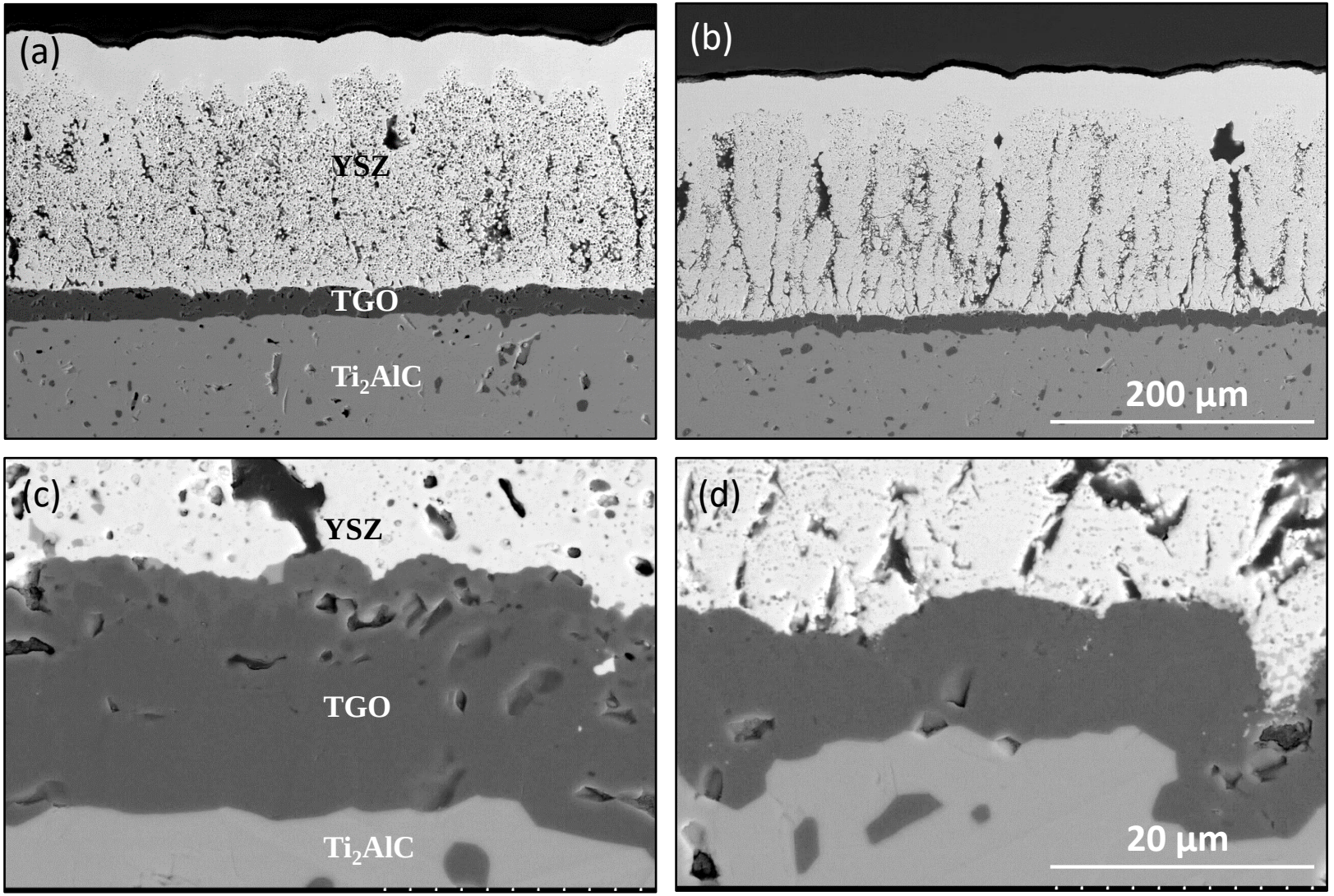

Figure 7. SEM/BSE images of the coating cross-section after 500 h BRT at 1300°C . (Ni plated) YSZ/TGO/Ti_2AlC matrix: a, c, at the hot zone; b, d, at the grip end. Clean interfacial structures; 22.2/20.7 µm and 12.4 µm alumina scale thickness, respectively.

Figure 8

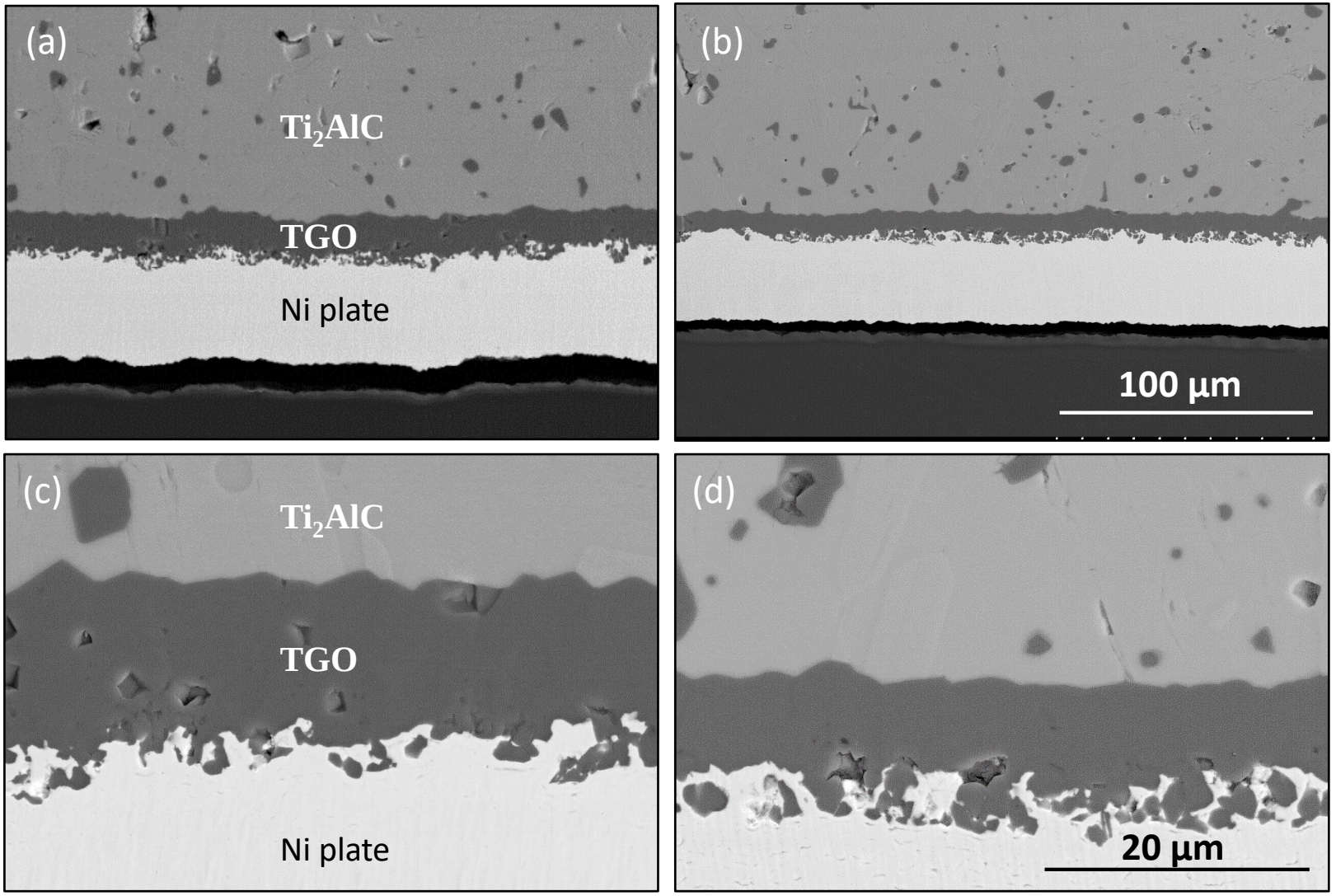

Figure 8. SEM/BSE images of the uncoated backside cross-section after 500 h BRT. (Ni Plated) TGO/Ti_2AlC matrix: a, c, at the hot zone; b, d, at the grip end. Clean interfacial structures with moisture attack of external scale; 12.8/13.8 µm and 9.0 µm alumina scale thickness, respectively.

Figure 9

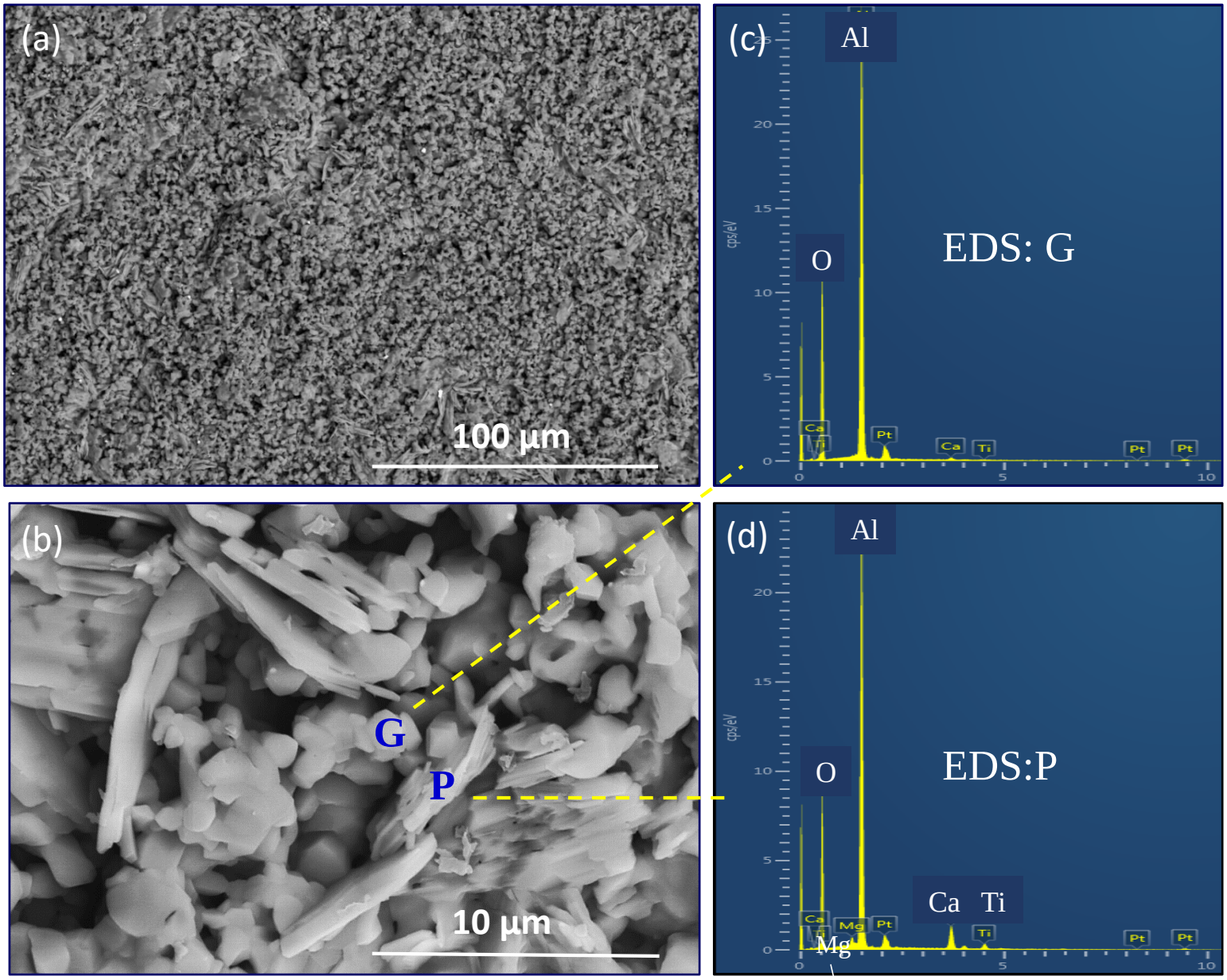

Figure 9. SEM/BSE images of uncoated Ti_2AlC backside surface at the hot zone after BRT. a) textured open scale structure; b) higher magnification showing individual laminar ~1 x 5 µm platelets (P); corresponding EDS spectra showing: c) high Al, O peaks for granular particles (G); and d) small Mg, Ca, Ti peaks corresponding to platelets (P).

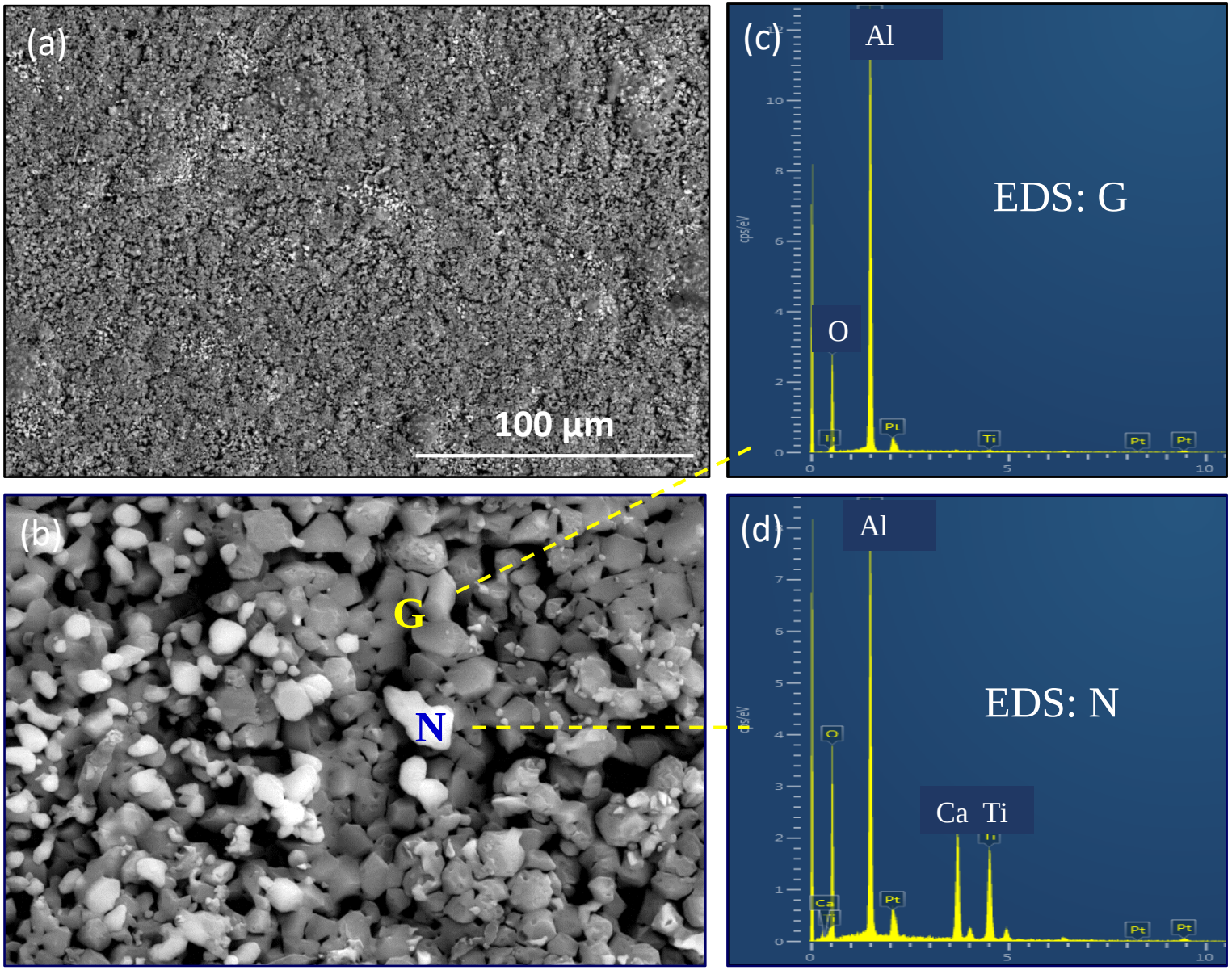

Figure 10. SEM/BSE images of uncoated Ti_2AlC backside surface at the lower grip end after BRT. a) finely peppered nodules dispersed on textured dense scale structure; b) higher magnification showing individual equiaxed ~1 µm grains (G) and bright nodules (N); corresponding EDS spectra showing c) high Al, O intensity for granular particles (G); and d) additional Ca, Ti peaks corresponding to bright nodules (N).

Figure 11

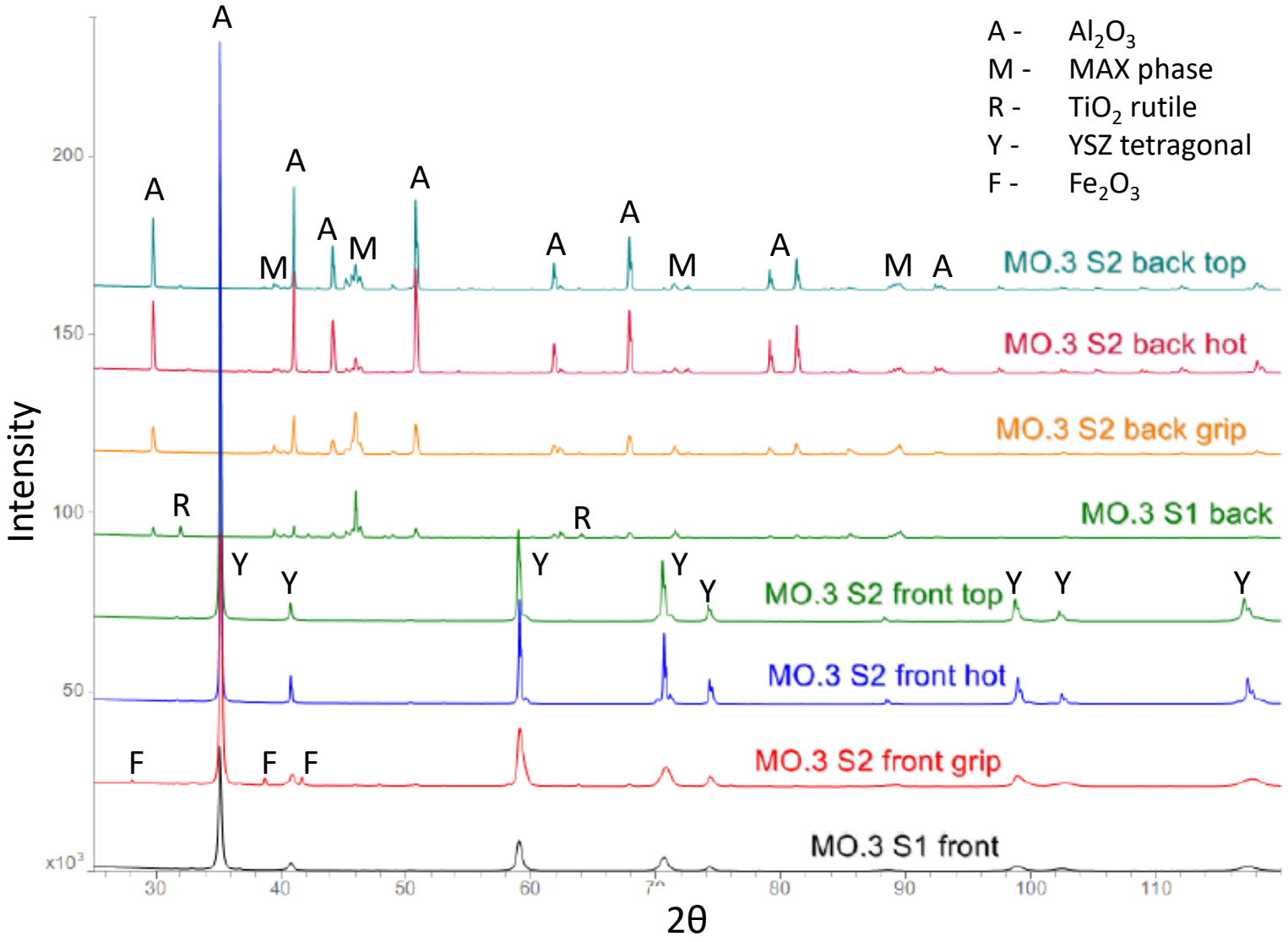

Figure 11. XRD scans for uncoated (back) and YSZ coated (front) sides for the Ti_2AlC burner sample tested at 926°C for 10 m (S1) or at 1300°C for 500 h (S2). Top end, hot zone, and grip end positions. Primary peaks for (A) α-Al_2O_3, (R)TiO_2 rutile, (M) Ti_2AlC MAX phase, (Y) cubic/tetragonal YSZ, and (F) Fe_2O_3 hematite.

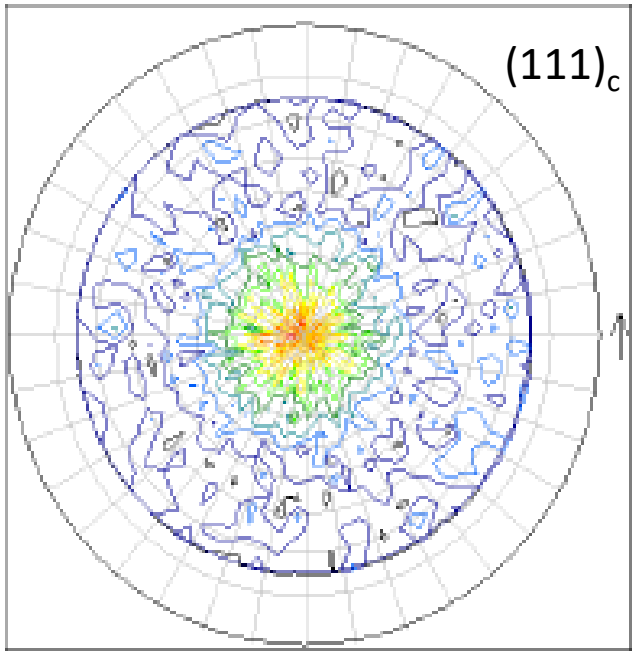

Figure 12. Pole figure from YSZ columns showing primarily $(111)_{cubic}$ fiber texture (926°C/10 m exposure). B-G-Y-R color scale corresponds to 200-450 relative intensity range.