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Compiled furnace cyclic lives of EB-PVD thermal barrier coatings

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ABSTRACT

Furnace cycling has been widely used to study the failure of EB-PVD thermal barrier coatings. This contribution compiles TBC furnace cyclic lives over a broad literature base to highlight optimum systems and generalized trends not always apparent in one study. Systems included typical bond coats (Pt-modified aluminides, diffused Pt-only γ/γ′, and NiCoCrAlY (±Pt, Hf) overlays) and superalloy substrates (1st, 2nd, 3rd generation single crystals, directionally solidified, or conventionally cast). Pretreatments included controlled low $p(O_2)$ bond coat pre-oxidation and grit blasting (or none). The aggregate lives (~70) suggest a general trend with temperature, ~10-fold decrease for every 100 °C increase. Measured alumina scale thicknesses (~30) were, on average, ~6.1 ± 1.8 μm at failure and independent of temperature for conventional systems. Most failures thus occurred in less time than that predicted to grow 7 μm of alumina scale (as estimated from separate TGA studies of a Pt-modified aluminide coated 2nd generation single crystal superalloy). A tentative activation energy indicated from the broad distribution of failure times was ~280 kJ/mol, while that from homogeneous TGA testing was ~380 kJ/mol, with regression coefficients of $r^2 = 0.57$ and 0.98, respectively.

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1. Introduction

Thermal barrier coatings (TBCs) are widely used in the turbine industry to protect air cooled superalloy airfoils from direct exposure to the full gas temperature of the combustion gas. Yttria stabilized zirconia (YSZ) is commonly deposited by air plasma spray (APS) and electron beam physical vapor deposition (EB-PVD). Aircraft turbines typically employ the latter. Plasma sprayed NiCoCrAlY bond coats are generally necessary for APS TBCs, due to the surface roughness required for mechanical bonding of the top coat. EB-PVD, VPS, detonation gun NiCoCrAlY, and aluminide diffusion bond coats are more typically used for EB-PVD top coats, provided the surface finish of the bond coats is acceptably smooth. More specifically, Pt-modified, β-phase aluminide bond coats are widely reported to provide exceptional oxidation resistance and TBC durability. Pt is known to improve alumina scale adhesion to β-NiAl, as well as to extend the oxidative durability of aluminide coatings. The latter effect stems from higher diffusional stability and ability to form alumina scales, even without aluminizing, as evidenced by the success of commercial low cost and γ/γ′ Pt-only bond coatings [1,2] (Rickerby, Gleeson, and coworkers).

Given the notable engineering success, these systems have become the focus of intense research and sophisticated analyses. This has led to a deeper understanding of failure mechanisms and numerous new approaches to improve durability, as can be surmised from a number of valuable reviews [3–9], as well as the large body of exceptional studies from UCSB [27] (Tolpygo and Clarke), ORNL (Pint, Zhang, Haynes et al.), and others cited below regarding alumina scale growth, Pt-modified aluminizing, bond coat oxidation and TBC failure mechanisms. TBC durability is often evaluated by a furnace cyclic test (FCT), having a strong oxidative component to failure. While self-consistent TBC failure data can be assumed for a given batch of coatings produced by the same process and tested at the same laboratory (albeit with some inherent variability according to a Weibull distribution, as proposed by Strangman) [10], there may be disjunctions arising from different coating or testing facilities. This leads to a degree of uncertainty in evaluating life data obtained for a specific system at a single temperature. In order to assess the performance of coating types as a whole, the failure lives from 30+ published investigations were compiled and categorized by test temperature. It is intended to provide a broader perspective of typical failure times for standard coatings and to highlight any sensitivity to various system or process modifications. Some of these modifications include vacuum or low $p(O_2)$ oxidizing pre-treatments, polished bond coats, or eliminating standard grit blasting or aluminizing. In a secondary emphasis, EB-PVD and VPS NiCoCrAlY bond coat data is included for comparison, often with a variety of process treatments including Hf-doping and Pt plating effects.

This compilation is also intended to contrast superalloy coating behavior with YSZ-coated oxidation resistant bulk substrates, such as doped NiAl(Zr,Hf). Here the effects of interdiffusion and other thermomechanical instabilities between bond coats and substrates are precluded, while scale growth and thermal expansion issues between metals and oxides remain. In that regard, failure lives are compared to oxidative times predicted to obtain scales of a specified ‘critical thickness,’ typically around 5–10 μm [11–13], although other contributing factors must still be present. The original motivation of this compilation

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Table 1
Compiled furnace cycle life of EB-PVD YSZ thermal barrier coatings.
T = test temperature; t = failure time; x_c = estimated/measured scale thickness at failure.

Bond coat	Substrate	T, °C	t, h	x_c, µm	Hot time/cycle	Study	
a) No bond coat and Pt–Al bond coats							
None	NiAl(Zr)	1150	3800	14.6	1-h	Pint	2000
None	NiAl(Zr)	1200	1700[a]	11.0	2-h	Pint	2000
None	NiAl(Hf,GaTi)	1175	>1770		45 min	Rigney	2000
None	Rene′N5	1100	2096		45 min	Yanar	2011
NiAl(5Cr–0.5Hf)	Rene′N5	1163	600		45 min	Hazel	2008
Pt–Al opt.	Rene′N5	1100	1530		45 min	Yanar	2011
Pt–Al SOA	Rene′N5	1100	839		45 min	Yanar	2011
Pt–Al SOA	Rene′N5	1200	96		45 min	Yanar	2011
Pt–Al	Rene′N5	1150	650	4.5	1-h	Pint	1998
Pt–Al	Rene′N5	1200	212	5.6	2-h	Pint	1998
Pt–Al	Rene′N5	1150	907	7.6	1-h	Pint	2015
Pt–Al	Rene′N5	1163	173		45 min	Hazel	2008
Pt–Al	Rene′N5	1150	260	2.6	1-h	Smialek	2008
Pt–Al	Rene′N5	1100	974		1-h	Kim	2002
Pt–Al	Rene′N5	1200	107		1-h	Kim	2002
Pt–Al	Rene′N5	1163	234		45 min	Jackson	2014
Pt–Al	Rene′N5	1163	271		1-h	Zhu	2012
Pt–Al	Rene′N5	1163	225		45 min	Zhu	2004
Pt–Al	Rene′N5[b]	1163	280		45 min	Zhu	2004
Pt–Al	Rene′N5[b]	1163	333		1-h	Zhu	2012
Pt–Al	Rene′N5[b]	1150	300	2.9	1-h	Smialek	2008
Pt–Al	CMSX-4	1100	1046	8.6	45 min	Sridharan	2005
Pt–Al	CMSX-4	1121	514	6.9	45 min	Sridharan	2005
Pt–Al	CMSX-4	1121	514	9.8	24 h	Sridharan	2005
Pt–Al	CMSX-4	1150	280	8.1	45 min	Sridharan	2005
Pt–Al	CMSX-4	1100	622	4.6	40 min	Wen	2006
Pt–Al	CMSX-4	1121	307	5.3	40 min	Wen	2006
Pt–Al	CMSX-4	1151	118	4.9	40 min	Wen	2006
Pt–Al	CMSX-4	1121	450	~6	40 min	Xie	2003
Pt–Al[c]	CMSX-4	1121	640	~6	40 min	Xie	2003
Pt–Al	CMSX-4	1100	365	5.9	45 min	Baufeld	2006
Pt–Al vac[c]	CMSX-4	1100	668	8.4	45 min	Baufeld	2006
Pt–Al H2/Ar[c]	CMSX-4	1100	1041	6.9	45 min	Baufeld	2006
Pt–Al (1)	CMSX-4	1100	406		50 min	Schulz	2008
Pt–Al (1)	CMSX-4	1150	278		50 min	Schulz	2008
Pt–Al (1) H_2/Ar	CMSX-4	1100	1157		50 min	Schulz	2008
Pt–Al (2)	CMSX-4	1100	800		50 min	Schulz	2008
Pt–Al (2)	CMSX-4	1150	420		50 min	Schulz	2008
Pt–Al	CMSX-4	1100	545	5.9	1-h	Sohn	2015
Pt–Al	Gen 2	1150	550	6.1	1-h	Tolpygo	2001
Pt–Al[c]	Gen 2	1150	730	6.1	1-h	Tolpygo	2001
Pt–Al	Gen 2	1150	190		1-h	Tolpygo	2005
Pt–Al	Gen 2	1150	750		1-h	Tolpygo	2005
Pt–Al pre-ox	Gen 2	1150	790		1-h	Tolpygo	2005
Pt–Al pre-ox	Gen 2	1150	2870	>5	1-h	Tolpygo	2005
Pt–Al	CMSX-10	1093	650		100 h	Kimmel	2000
Pt–Al	CMSX-10	1038	>3400		100 h	Kimmel	2000
Pt–Al high	PWA 1484	1135	435		1-h	Wu	2008
Pt–Al low	PWA 1484	1135	322		1-h	Wu	2008
Pt–Al	Rene′142	1100	817		45 min	Lau	2013
Pt–Al (1)	Rene′142	1100	823		50 min	Schulz	2013
Pt–Al (1)	IN100	1100	181		50 min	Schulz	2008
Pt–Al (1) H_2/Ar	IN100	1100	600		50 min	Schulz	2008
Pt–Al (2)	IN100	1100	509		50 min	Schulz	2008
Pt–Al (2)	IN100	1150	150		50 min	Schulz	2008
Pt–Al	IN100	1100	615		50 min	Lau	2013
Pt–Al	AM1	1100	1055		1-h	St.-Ramond	2004
S–Pt_2Al_3	AM1	1100	1086		1-h	St.-Ramond	2004
S–$PtAl_2$	AM1	1100	624		1-h	St.-Ramond	2004
S–PtAl	AM1	1100	589		1-h	St.-Ramond	2004
b) Pt-only bond coats							
Pt opt.	Rene′N5	1100	3536		45 min	Yanar	2011
Pt pre-ox	Rene′N5	1100	435		45 min	Yanar	2011
Pt	Rene′N5	1150	1447	9.1	1-h	Pint	2015
Pt	CMSX-4	1150	400		24 h	Tawancy	2008
Pt	CMSX-4	1135	390	5.9	1-h	Wu	2008
Pt	PWA 1484	1135	1000	>9	1-h	Wu	2008
Pt	2Co Gen3	1150	351		1-h	Wu	2008
Pt	2Co Gen3	1170	382		1-h	Wu	2008
Pt	2Co Gen3	1190	205		1-h	Wu	2008
Pt	2Co Gen3	1210	108		1-h	Wu	2008
Pt	2Co Gen3	1230	61		1-h	Wu	2008