FLIGHT SERVICE EVALUATION OF THERMAL BARRIER COATINGS BY PHYSICAL VAPOR DEPOSITION AT 5200 H

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(Received March 3, 1989)

Summary

Thermal barrier coatings (TBC) have the potential to improve the performance of jet engines and have been used in combustors for over 15 years. However, it is only recently that they have been actively used in the harsh turbine environment on nozzle guide vane platforms. It is now intended to use TBCs on turbine vane airfoils and rotating blades where the maximum payoff will be realized. Much work has been done in the last six years towards this goal.

This report will review one such Rolls-Royce program; flight service evaluation of TBCs. It will demonstrate that some TBC systems can survive in the turbine environment for over 16 000 h, but that particulate erosion could be a problem. It will review the service condition of vanes with TBCs applied by physical vapor deposition, and will demonstrate some of the advantages over plasma sprayed coatings such as:

(1) longer thermal cycle lives,
(2) smoother surface finishes,
(3) better surface finish retention,
(4) superior erosion resistance.

1. Introduction

Rolls-Royce has used ceramic thermal barrier coatings (TBCs) in jet engine combustors for many years, and they are used in most of our engines today. TBCs are being used on high pressure turbine (HPT) nozzle guide vane (NGV) platforms in several engines, including the RB211 535-E4 (40 000 lb thrust class engine) that powers the Boeing 757. Much testing of TBCs has been done on turbine rotor blades, and we look forward to using them in regular service in the near future.

TBCs are of prime interest because of their ability to improve gas turbine performance, at a time when potential improvements from alloy modifications and cooling efficiencies are all but exhausted. Thin ceramic coatings can reduce the component metal temperatures by several hundred

0257-8972/89/$3.50

degrees resulting in significant life improvement. This life improvement can be traded off for (a) higher inlet temperatures and increased thrust or for (b) reduced cooling air usage and reduced fuel consumption. The use of a 0.025 cm (0.01 in) of ceramic coating can reduce the mass average temperature at cruise by over 125 °C (200 °F). Or the cooling can be reduced, improving the specific fuel consumption.

2. Review of work to date

2.1. The effect of thermal cycles

One of the major failure modes of TBC systems is the spallation of ceramic topcoat due to thermal cycling. The failures are believed to be caused by stresses induced by coefficient of expansion (α) mismatches and oxidation of the bondcoat. From carousel rig testing [1] we learned several ways to increase the cycle life. For plasma sprayed yttria stabilized zirconia (YSZ), fully stabilized (20% Y_2O_3) zirconia was cubic in phase and had a very short cycle life [1]. But, a partially stabilized system (6 - 8% Y_2O_3) resulted in a tetragonal phase which was very stable. Further improvements were made using high density, oxidation resistant MCrAlY bondcoats, applied by shrouded plasma spray (SPS), vacuum plasma spray (VPS) or physical vapor deposition (PVD). Applying the ceramic by PVD created a strain tolerant columnar structure, resulting in a 6 times improvement in cycle life.

2.2. The effect of oxidation due to time at temperature

Oxidation of the bond coat is a major mode of failure to TBC systems. The amount of oxidation depends on the time spent at high temperatures. It has been shown [2] that spallation occurs when the oxide at the interface reaches a critical thickness of about 4 μm. Time at temperature–cycle data can be very costly to acquire, especially when trying to simulate the engine environment and the interaction with thermal cycles. A flight service evaluation (FSE) program was therefore begun to accumulate this data on several TBC systems [1, 3].

2.3. FSE program

After considerable review, the RB211-22B intermediate pressure turbine (IPT) NGV was chosen as the FSE component (see Fig. 1). Prior work on a bench engine had shown that the IPT NGV platform application was considerably more demanding than the combustion chamber environment.

The coatings in phase I were applied only to the inner diameter pressure side platform area. In phase II, the pressure side airfoil of some vanes were coated as shown by the crosshatching in Fig. 1. The nickel base vane is nominally 20 cm long, 7.6 cm wide and 10 cm tall (8 in × 3 in × 4 in). Eight TBC systems were evaluated (Table 1). The coatings were given designations; A was three-layer magnesium zirconate (MSZ), the standard combustor coating. Coating B was two-layer MSZ, without the cermet (a NiCrAl and

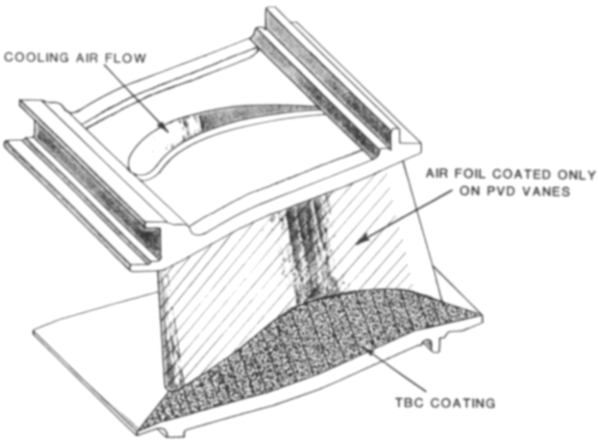

Fig. 1. RB211 IPT NGV showing location of TBCs patches.

MSZ mixture). Coating C used the same NiCrAl bondcoat as A and B, with 6 - 8% YSZ. Coatings A, B, C, G and H were applied by air plasma spray (APS).

Coating E had CoNiCrAlY bondcoat applied by shrouded plasma spray (SPS). Coating F also has a CoNiCrAlY bondcoat applied in a vacuum (VPS) plus a YSZ top coat.

Coatings G, H and I were added in phase II, and therefore have less time on them. Coating G had a CoNiCrAlY bondcoat and YSZ; it had accumulated only 4800 h as of December 1988. Coatings E, F and G should give a direct comparison of the bondcoat performance as applied by three significantly different techniques. Coating H is an APS NiCrAlY and $CaOTiO_2$, which is claimed to be resistant to acid leaching from low grade fuels [4]. It did well in thermal cycle testing. Coating I had a NiCoCrAlY bondcoat plus 8% YSZ, both applied by PVD. (Table 1).

TABLE 1

Coatings used on RB211 IPT NGV FSE

Identification letter	*Bond-coat*	*Ceramic (APS)*	*Bondcoat method*	*On engines*	*Total coated vanes*
A	NiCrAl + C[a]	MSZ	APS	1,2,3,4	24
B	NiCrAl	MSZ	APS	1,2,3a	12
C	NiCrAl	YSZ	APS	1,2,3,4	23
E	CoNiCrAlY	YSZ	SPS	1,2,3,4	23
F	CoNiCrAlY	YSZ	VPS	1b,2,4a	28
G	CoNiCrAlY	YSZ	APS	3a	16
H	NiCrAlY	$CaOTiO_2$	APS	1b,4a	10
I	NiCoCrAlY	YSZ(PVD)	PVD	1b	5
Total					141

[a] Cermet ≡ NiCrAl + MSZ.

TABLE 2

TBC service evaluation status January 1989

Engine build	*Flight time* (h)	*Time of inspection* (h)	*Time on phase II coatings* (h)	*Original vanes*
1	12759	4100, 7500, 10100, 12800	H, I (5200)	9
2	16322	2500, 9800, 16300		15
3	11685	6900, 11700	G (4800)	14[a]
4	8700	5500, 8700	H (3300)	19[a]

[a] These sets removed from FSE.

2.4. Current status of FSE program

The flight status for the four engines as of January 1989 is given in Table 2. Engine build 2 was removed in January 1989, with 16 322 h–8120 cycles, and still had 15 of its original 25 coated vanes. Two reports for this engine have been given earlier, at 2539 h [1] and 9800 h [3]. To get the approximate number of cycles, divide the hours by 2 (Table 2).

3. Results of plasma sprayed coatings

3.1. MSZ

Coating A lost the most amount of coating (spalling). It was removed from the program at 9800 h with an average area loss of 31% [3]. Twenty data points were used to generate a second order regression analysis curve fit of the data for coating A, which is plotted on semi-log paper in Fig. 2. Bondcoat was missing in the fillet radius of these vanes as early as 2500 h [1].

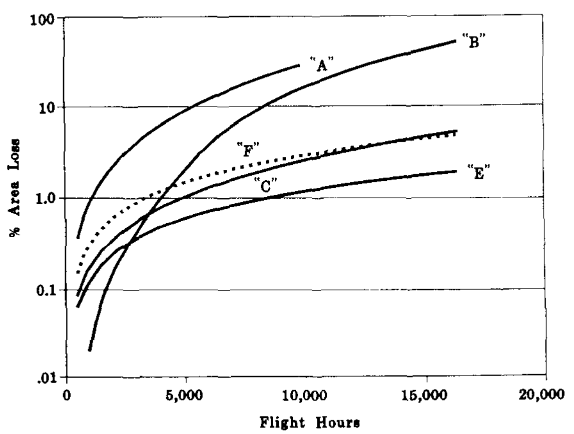

Fig. 2. Loss of ceramic coating (percentage area) on IPT NGVs with time (see Table 1 for coating identification).

Coating B was significantly better than A, but was still not acceptable. The area loss was negligible prior to 3500 h, and only 16% at 10 000 h. By 16 000 h the average loss was close to 50%. Thirty-one points were used to determine the second-order curve as shown in Fig. 2. Bondcoat was missing in the fillet radius at 2500 h [1].

3.2. Yttria partially stabilized zirconia

Coating C had significantly less loss, at 10 000 h the average ceramic loss was less than 3% by area. After 10 000 h the loss accelerated such that two vanes had close to 10% loss by 16 000 h. The second-order curve fit used 32 points of data (see Fig. 2). Figure 3(a) shows a vane at 12 800 h with 8% of ceramic loss. Figure 4(a) shows a similar vane at 16 300 h with 10% of the ceramic coating gone. The NiCrAl bondcoat runs cooler than on A or B because of the lower conductivity of the YSZ ceramic, therefore it oxidizes slower. In the fillet radius where the ceramic is minimal, the bondcoat ran hotter and fell off on some vanes early on [1]. References 1 and 3 have more photographs.

Coating E had minimal ceramic loss, the average was less than 1% by area at 10 000 h. Most of those losses were associated with edge effects in the fillet radius; similar to, but less than that shown in Fig. 3(b), where the E-coated vane had 12 748 h. By 16 300 h the average loss was 1%. The worst vane is shown in Fig. 4(b) with 3% area loss. A linear curve fit was adequate with the 60 points of data used to generate the curve fit as also shown in Fig. 2. The bondcoat on all vanes inspected to date was in excellent condition. The coating losses for F were less consistent, with some vanes having very little loss (less than 0.05%), and others as much as 10% at 16 300 h, the average loss (four vanes) was only 3%. The linear curve fit for F in Fig. 2 is for 20 points of data. The bondcoat was in excellent condition, as seen in Fig. 4(c). Because the losses seem to be confined to one or two vanes in each set and in light of the good results other operators [5, 6] have had, we believe some of the coating losses are process related.

3.3. Calcium titanite

Coating H has only accumulated 5200 h, but is holding up very well, with only one out of 10 vanes showing significant loss (1.7%), the average

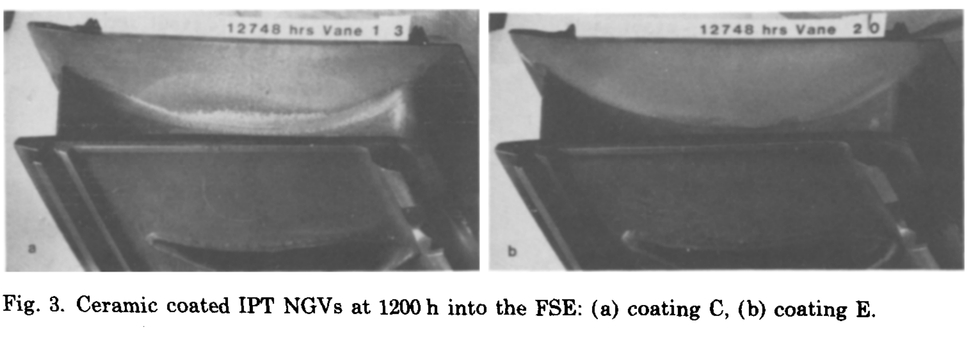

Fig. 3. Ceramic coated IPT NGVs at 1200 h into the FSE: (a) coating C, (b) coating E.

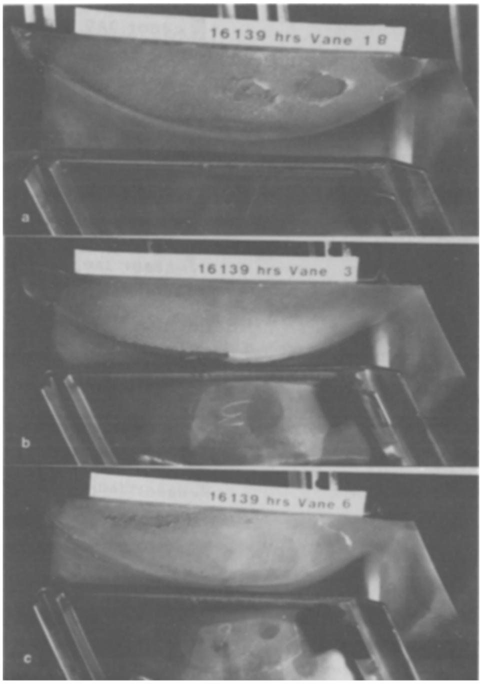

Fig. 4. Ceramic coated IPT NGV at 16 300 h into the FSE: (a) coating C, (b) coating E, (c) coating F.

loss of five vanes at 5200 is less than 0.5%. The curve fit is only for 15 points of data and it is a bit early to come to any conclusions other than it looks very promising.

3.4. Ranking of plasma sprayed coatings

The order of ranking of the TBCs tested is based on the ceramic and bondcoat loss. A - C lost bondcoat on several vanes where not covered by ceramic. Toriz *et al.* [1] has shown the bondcoat loss as early as 2500 h for A and B, and 4100 h for C. This indicates that the bondcoat on C is at or near its oxidation temperature limit when it is on a hot vane. It indicates that C will not be very useful at higher temperatures. The ranking for H is preliminary since it only had 2500 h. The ranking to date (based on ceramic area loss) from this FSE program is as follows.

Coating system	Hours/data points
1. Coating E SPS CoNiCrAlY + YSZ	16300/60
2. Coating F VPS CoNiCrAlY + YSZ	16300/20
3. Coating C APS NiCrAl + YSZ	16300/32
4. Coating H APS NiCrAlY + CaO.TiO_2	5200/15
5. Coating B APS NiCrAl + MSZ	16300/31
6. Coating A APS NiCrAl + Cermet + MSZ	9800/20

Many of the vanes had indications of ceramic erosion near the fillet radius at midchord, where it is thinnest because of geometry constraints. This observation prompted a separate program to understand the erosion behavior of TBCs, as reported earlier [9] and is referred to later in this paper.

4. PVD TBCs

4.1. Benefits of PVD coatings

Our experience to date indicates there are many benefits to PVD coatings. We have found PVD overlays (and bondcoats) to perform very well; they are of similar density and low oxide content as VPS coatings. PVD ceramic coatings have a unique columnar structure which make them very tolerant.

4.1.1. Improved thermal cycle life

In carousel rig cycle testing [7], PVD TBCs out performed all the plasma sprayed coatings including SPS and VPS by 50% or more.

4.1.2. Improved initial surface finish

One of the concerns with the use of TBCs is the loss of aerodynamic performance due to rough surfaces, which can cause laminar-turbulent transition, and increased skin friction. These effects were apparent in numerous cascade, turbine and compressor rig tests involving a range of roughness types [8]. Since APS ceramics are very rough (7.7 μm, 300×10^{-6} in) as sprayed we were reluctant to add them to the airfoils in our FSE program. Even with polishing they were still rougher than desired (3.2 μm, 125×10^{-6} in). However, since PVD ceramics approximately replicate the surface finish of the component applied to, it was added to the pressure side airfoils (2.1 μm, 80×10^{-6} in) of five vanes.

4.1.3. Improved erosion resistance

An erosion test program run at the University of Cincinnati [7, 9] indicated that PVD YSZ was 10 times more erosion resistant than the standard APS YSZ at a 90° impingment angle. Figure 5 shows the relative erosion rates of several ceramic coatings as a function of impingment angle. At low angles of attack, such as on combustors or vane platforms, PVD is only a 2 times improvement over APS YSZ. But the benefit increases with angle, so that coatings applied to flow path airfoils will see life improvements of up to 1000% (at 90°). By looking at the erosion rate at 90° in Fig. 5, one can obtain the erosion ranking for several different TBC materials, more are found in ref. 7.

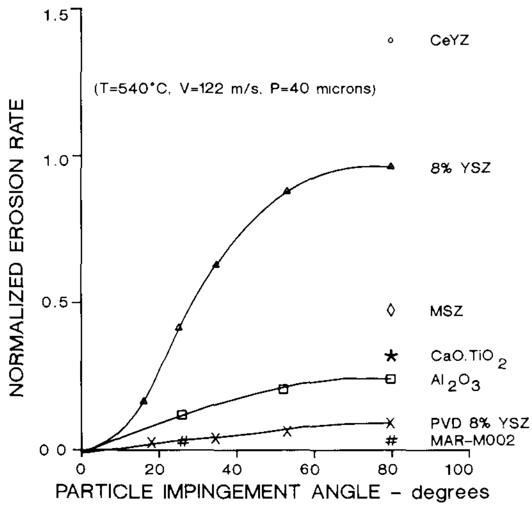

Fig. 5. The effect of impingement angle on the erosion of engine materials. Erosion ranking for six ceramics (five APS) and one metal (substrate) given at 90° impingement angle.

4.1.4. Improved surface finish retention

The erosion test program [7, 9] also showed that PVD TBCs have a better surface finish retention with time than the APS TBCs. The as sprayed YSZ was very rough, it measured over 7.7 μm. Most of the erosion test coupons were polished to about 1 μm (40×10^{-6} in) before testing. The PVD YSZ coupons were 1 μm (40×10^{-6} in) as received. When erosion tested, the polished standard YSZ decayed from 1.2 μm (50×10^{-6} in) to over 7.7 μm (300×10^{-6} in) at a 90° impact angle. At a 20° angle the deterioration was much slower, and probably compares to that of the FSE NGV platforms. The PVD coating did not deteriorate much even after 30 g of particles; as can be seen in Fig. 6.

Now to correlate this with the FSE program. Vanes coated with A, B, C and F (Table 1) were polished. Their roughness increased with flight time, as shown in Table 3. None of the E-coated vanes were polished and they stayed at about 7.7 μm up to 12 800 h. From Table 3 we see that it took 9800 h to deteriorate from a 2.8 to 5.1 μm finish at low angles of attack. In Fig. 6 this decay takes approximately 25 g; so we have the rough relationship that 25 g in wind tunnel testing is roughly equal to 10 000 FSE h. Using this relationship, by 8000 h (20 g) the leading edge of an airfoil (at 90°) would have a surface finish of about 7.7 μm. Its surface finish would be 5.1 μm (200×10^{-6} in) in only 1000 h. The PVD YSZ however, will still have a good surface finish 1.5 μm (60×10^{-6} in) at 13 000 h (32 g). The FSE experience data band is overlayed on Fig. 6. Airfoil measurements further indicate that the PVD coating has a better surface finish (130×10^{-6} in) than the bare metal (185×10^{-6} in) at 5200 h (see Table 3).

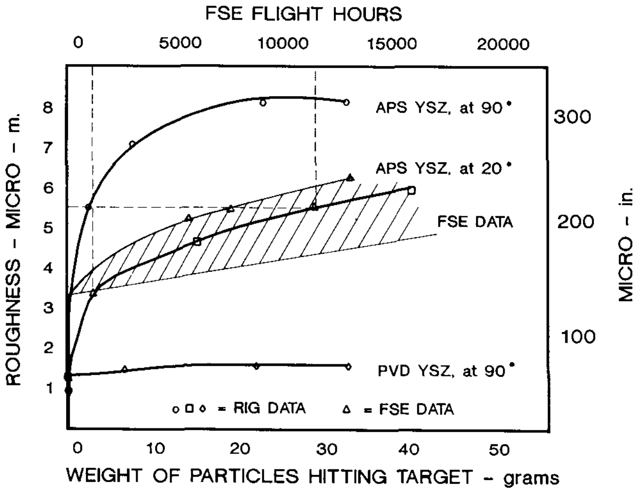

Fig. 6. Ceramics surface roughness variations with erosion–time from rig testing correlated to surface finishes experienced in the FSE program.

TABLE 3

FSE NGV surface roughness (in µm (× 10^{-6} in)) with time

Coating	*Time* (h)					
	0	5500	6900	7400	9800	12800
Platform pressure side						
A	2.8 (110)			4.3	3.5	
B	2.8 (110)		3.3	4.3	5.1	7.7 (300)
C	2.8 (110)	4.8		5.1	5.1	5.8 (230)
E	7.7 (300)		7.4		7.7	7.4 (290)
F	2.8 (110)	3.4			3.8	
I	2.0 (80)	2.3				
Airfoil pressure side trailing edge						
I	2.5 (100)	3.3				
None	2.5 (100)	4.7		5.1		6.2 (245)

4.2. Phase II FSE results

In phase II of the FSE program five vanes were PVD coated and put into engine build 1b (second rebuild at 7500 h). Both the NiCoCrAlY bondcoat and the 8% YSZ coating were applied by electron beam physical vapor deposition (PVD) by Chromalloy R&T Coating Systems, Orangeburg, NY. The bondcoat was 76 - 127 µm (0.003 - 0.005 in) thick and the ceramic was 20 - 25 µm (0.008 - 0.0010 in) thick. The coating was also applied to the pressure side airfoils. The coating tapered off to within 1.27 cm (0.5 in) of the trailing edge, it wrapped around the leading edge by 1.27 cm (0.5 in) (see Fig. 1).

4.2.1. The 2500 h inspection

The vanes were inspected at 2500 h when the engine came in for a shop visit, a detailed inspection was not possible as the module containing the IPT vanes was not taken apart at that time. A photograph of a vane prior to service is given in ref. 7. This IPT vane set appeared to have suffered considerably more erosion than any engine inspected to date, even uncoated vanes had visual signs of metal removal on the leading edge (LE) airfoil. Erosion was evident on all of the PVD vanes, but more so on three that had distinct lines outlining the eroded areas, none were eroded through to the bondcoat. Erosion to the platform coating was not noticeable. Two vanes had spalling on the LE, which may have been initiated by small dings which occurred in shipping, one vane (number 2) is shown in Fig. 7. Two vanes had minor spalling on the platforms. The IPT castings are fairly rough, especially on the platforms, and may have reduced the adhesion quality of the PVD coating which performs better on a smooth surface. Some edge chipping was seen, but most of it occurred prior to installation. The coating on the pressure side of all five airfoils was in excellent condition. No mud flat cracking or crazing was evident. The surface finish appeared to be as installed, except on the eroded LEs. The parts did not come out of the engine, so the surface finish was not measured. Table 4 summarizes the area losses.

4.2.2. The 5200 h inspection

More recently the engine was removed again and this time the module was taken apart, the PVD coated vanes having 5188 h and 2629 cycles flight experience. There was no further evidence of erosion; however, there was spalling on all the LE coated vanes. The LE spalling was typically 0.38 cm × 3.8 cm along the vertical LE of the vane. Vane number 3 is shown in Fig. 8. The average area loss at the LE is 0.64 cm^2. The platform loss increased only slightly to 1.5% by area. The area summary loss is given in Table 4. The pressure side airfoils were still in excellent condition. No mud flat cracking or crazing was seen (Table 4).

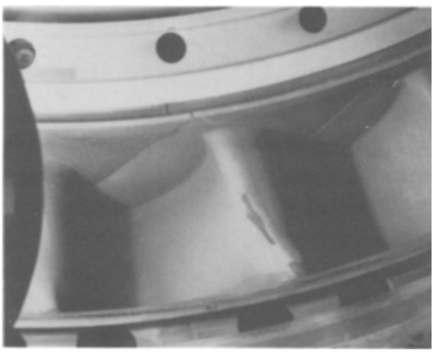

Fig. 7. Condition of PVD YSZ coated IPT vane at 2500 h into the FSE program.

TABLE 4

IPT PVD vane area loss at 2500 and 5200 h

Platform area loss (%)[a]			*Airfoil area loss*			
Vane	2500 h	5200 h	2500 h		5200 h	
			cm^2	in^2	cm^2	in^2
1	0.5	0.9	0	0	2.1	0.32
2	0	1.1	1.3	0.20	2.2	0.34
3	0	0.5	0	0	1.0	0.15
4	2.1	2.1	0	0	2.6	0.40
5	2.5	2.9	0.3	0.05	0.3	0.05
Average	1.0	1.5	0.3	0.05	1.6	0.25

[a] Platform area is 53 cm^2 (8.2 in^2).

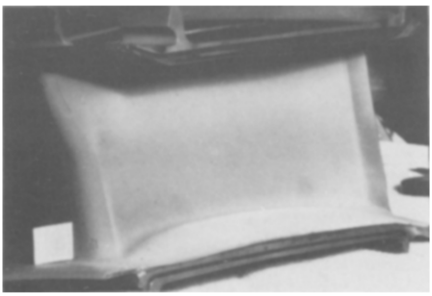

Fig. 8. Condition of PVD YSZ coated IPT vane at 5200 h into FSE program.

5. Conclusions

We have demonstrated in this program that TBCs on turbine components can survive for up to 16 000 h in the harsh turbine environment and should therefore be used in earnest.

We have identified the benefits of PVD TBCs, namely they have a superior thermal cycle life, better initial surface finish, better surface finish retention than either APS TBCs, or the bare nickel base alloy, and are more erosion resistant than APS TBCs.

Erosion of TBCs is a potential problem that will have to be dealt with on airfoils or where high angles of impingment occur. Here PVD YSZ or APS erosion resistant top coats can be used with low conductivity ceramic underneath.

$CaOTiO_2$ has done well in thermal cycling and in the FSE program and may be required for industrial, military or mid-eastern operations, where acid leaching is a problem.

It is thought that advanced TBC systems using high density bondcoats such as those produced by SPS, VPS and PVD, and 6 - 8% YSZ ceramics, will be required for future turbine airfoil applications. This is especially true on rotating airfoils.

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