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TBC Experience in Land-Based Gas Turbines

W.A. Nelson and R.M. Orenstein

This paper summarizes prior and on-going machine evaluations of thermal barrier coatings (TBC) for power generation, that is large industrial gas turbine applications. Rainbow testing of TBCs on turbine nozzles, shrouds, and buckets are described along with a test of combustor liners. General Electric Power Generation has conducted more than 15 machine tests on TBC turbine nozzles with various coatings. TBC performance has been quite good, and additional testing, including TBCs on shrouds and buckets, is continuing. Included is a brief comparison of TBC requirements for power generation and aircraft turbines.

Keywords gas turbine, rainbow tests, thermal barrier coating

1. Introduction

YTTRIA-STABILIZED zirconia (YSZ) ceramic thermal barrier coatings (TBC) on superalloy components are being used successfully in heavy duty gas turbines and aircraft engines. At General Electric Power Generation (GEPG), TBCs applied by air plasma spray (APS) are used in the combustor and turbine sections, at ceramic thickness up to 0.51 mm (0.02 in.). Table 1 summarizes GEPG production experience with TBCs.

A thermal barrier coating is typically comprised of two layers: ceramic oxide top coat and metallic bond coat. The low thermal conductivity ceramic top coat provides thermal insulation, while the bond coat provides a suitable interlayer to improve adherence of the ceramic top coat and environmental protection to the underlying superalloy substrate. GEPG state-of-the-art TBC systems use top coats of 6 to 8 wt% YSZ, while the bond coats are based on Ni(Co)-Cr-Al-Y alloys. Bond coat material development has been successful in improving the high-temperature oxidation resistance and thermal cycle lives of plasma-sprayed TBCs.

In general, the aircraft engine industry has led turbine technology improvements, and these improvements were later adapted in power generation machines. This is also true in the area of TBCs. Experience with TBC usage in aircraft turbine applications is greater than in power generation equipment. While operating conditions in aircraft turbines, especially the peak temperature and number of cycles, are typically more severe than in power generation equipment, the time requirements are much longer in power generation equipment. Table 2 highlights some of the differences between aircraft and power generation requirements for TBCs. The aircraft engine duty cycle is highly cyclic, with only a small percentage of its time at maximum temperature conditions, that is, during takeoff and climb. Conversely, power generation equipment operates under different duty cycles, varying from one cycle per day for peaking power applications to one cycle per year for baseload machines. Coating life, that is, time to refurbish aircraft turbines, is approximately 8000 h; only a small portion, 5 to 15%, of the total coating lifetime of 8000 h is at maximum conditions. In contrast, component life for power generation turbine applications should be 24,000 h, with a majority of all service time at maximum conditions.

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The following time and temperature effects should be considered for power generation use of TBCs: bond coat oxidation, interdiffusion of bond coat and substrate, coating densification, and changes in thermal or mechanical properties of the coating. Accessibility for inspection, repair, and refurbishment is also more difficult for power generation machines than for aircraft engines.

Another significant difference between aircraft and power generation equipment is the component size, as shown in Fig. 1. Component size impacts coating fabrication capabilities. Plasma-spray processing has a significant advantage in being able to accommodate the large-size components found in modern large power generation machines. The large nozzles of power generation machines, especially those with multiple airfoil configuration, could not be accommodated in modern EB-PVD (electron beam physical vapor deposition) coaters. Plasma-spray processing with turbine parts on turntables and robot gun manipulation can more readily accommodate large parts. Each component application of a TBC requires careful review and study to determine whether APS or EB-PVD is most appropriate because there is no clear overall advantage of one process versus the other.

Table 1 GEPG machines employing TBCs for component life extension

Machine	Component	Introduction date
Frame 6B	Combustor	After market only
Frame 7E	Combustor	1982
Frame 7F	Nozzle	1990
Frame 7FA	Combustor	1992
Frame 9E	Combustor	1986
Frame 9F	Combustor	1992

Table 2 Comparison of nominal TBC requirements for aircraft and power generation turbine applications

Requirement	Commercial aircraft	Power generation
Number of cycles	8000	2,400
Total hours	8000	24,000
Hours at peak conditions	300	24,000
Peak surface temperature	>1204 °C (2200 °F)	<1204 °C (2200 °F)
Peak bond coat temperature	1093 °C (2000 °F)	954 °C (1750 °F)
Relative size	1×	5×

The following sections highlight some of the TBC experience at GEPG. In particular, observations from numerous field trials are discussed.

2. Machine Experience

GEPG frequently uses "rainbow" field tests to assess the capabilities of new materials in actual operating machines. Rainbow refers to the simultaneous testing of a variety of materials or coatings in customers' machines; the term "rainbow" comes from potential differences in the physical appearance of different coatings or materials. Virtually all production gas path materials were evaluated initially in rainbow tests as a prerequisite to actual production introduction. Rainbow test times generally range between 10,000 and 24,000 h. The main purposes of rainbow test programs are to (a) assess the capabilities of new materials in field conditions, (b) restrict any risk with new materials to a few machines rather than to the entire fleet, and (c) provide evidence to customers that a new technology has been proven in the field. Rainbow tests bridge the gap between laboratory tests and production. GEPG has conducted more than 80 rainbow tests since the mid 1950s on numerous alloys and coatings. TBCs have been tested in several turbine machines since 1987.

The earlier TBC rainbow tests evaluated top coat and bond coat compositions, as well as different methods of bond coat application. First stage turbine nozzles of MS6000 or MS7000 machines were coated and tested. The nozzles were doublets; they were comprised of two airfoil sections, which precluded the ability to fully coat the vanes. Typically, only selected portions of the nozzle outer band and airfoil were coated. More than 15 different rainbow tests were conducted with test durations of 6,000 to 45,000 h (Ref 1). Table 3 lists some of the variables investigated. TBC evaluation on turbine nozzles is briefly summarized in Section 3, "Results."

Interest in TBCs has expanded recently, and additional rainbow tests have been initiated with TBCs on combustor liners, turbine shrouds, and buckets on today's higher-firing temperature machines. Information from three recent rainbow tests of particular interest is provided below.

2.1 *Combustor Liners*

A machine set of ten combustor liners, two with each of the five coating systems detailed in Table 4, was installed in an MS7001EA gas turbine fired by natural gas. The entire inner surface of each liner was coated with a TBC. The coating vari-

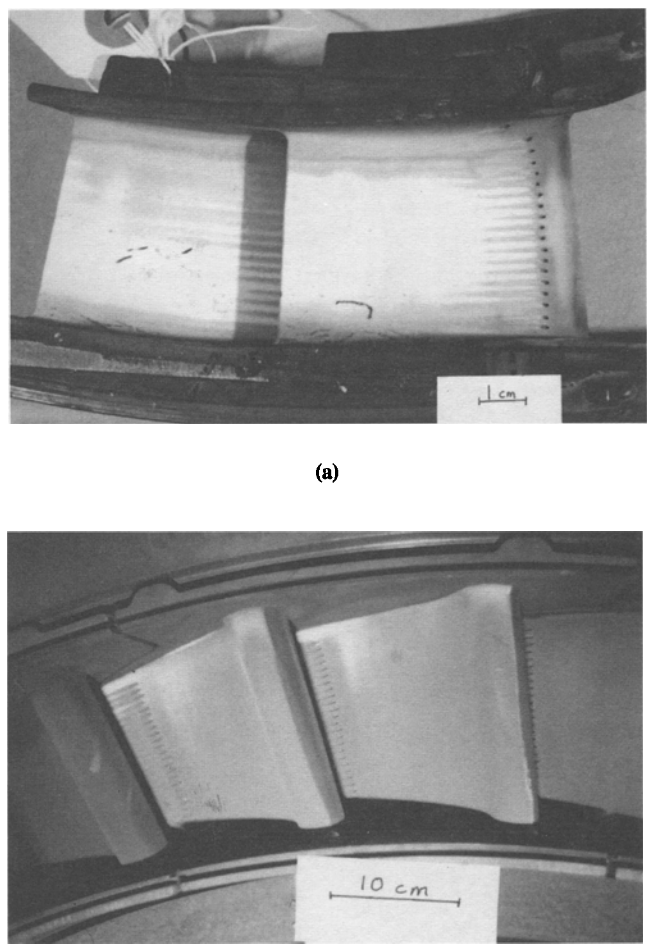
Table 3 TBC coating variables investigated in early nozzle rainbow tests

Bond coat
APS CoCrAlY
APS NiCrAlY
HVOF NiCrAlY
APS CoNiCrAlY
HVOF CoNiCrAlY
HVOF CoNiCrAlY (higher Al content)

Top coat
20 YSZ
8 YSZ
8 YSZ (less porosity)
CeSZ
Thickness: 0.1, 0.3, and 0.5 mm (5, 12, 20 mils)

Table 4 TBC coating variables in combustor liner rainbow test

Liner No.	Coating supplier	Bond coat	Bond coat thickness mm	Bond coat thickness mils	Top coat thickness mm	Top coat thickness mils
1	A	NiCrAlY	0.1	4	0.33	13
2	A	NiCrAlY	0.3	12	0.48	19
3	B	CoNiCrAlY	0.25	10	0.5	20
4	B	CoNiCrAlY	0.25	10	0.75	30
5	B	CoNiCrAlY	0.25	10	1.08	43
6	A	NiCrAlY	0.1	4	0.33	13
7	A	NiCrAlY	0.25	10	0.6	24
8	B	CoNiCrAlY	0.28	11	0.5	20
9	B	CoNiCrAlY	0.25	10	0.78	31
10	B	CoNiCrAlY	0.23	9	1.13	45



(a)

(b)

Fig. 1 Comparison of relative sizes of TBC coated aircraft and power generation turbine nozzles: (a) aircraft (CFM56) nozzle after 1000 cycles of factory engine test and (b) MS7000 after almost 17,000 h of machine operation ations yielded microstructures ranging from random porosity, as shown in Fig. 2, to a denser, more oriented microstructure such as shown in Fig. 3.

2.2 *Turbine Shrouds*

Fifteen first stage inner shrouds with four APS TBCs were installed in an MS7001FA gas turbine in October 1993. Full shroud cooling was used for this test, which ran for approximately 24,000 h. The shrouds were coated by two different sources. Coating variables included (a) the bond coat composition, NiCrAlY and CoNiCrAlY, (b) bond coat fabrication method, air plasma spray and shrouded arc plasma spray, and (c) top coat density and microstructure. Bond coats were 0.2 to 0.29 mm (8 to 12 mils) thick, while the ceramic topcoats were sprayed to 1.4 mm (55 mils) and ground back to approximately 1 mm (40 mils). Figure 4 shows the shrouds prior to installation.

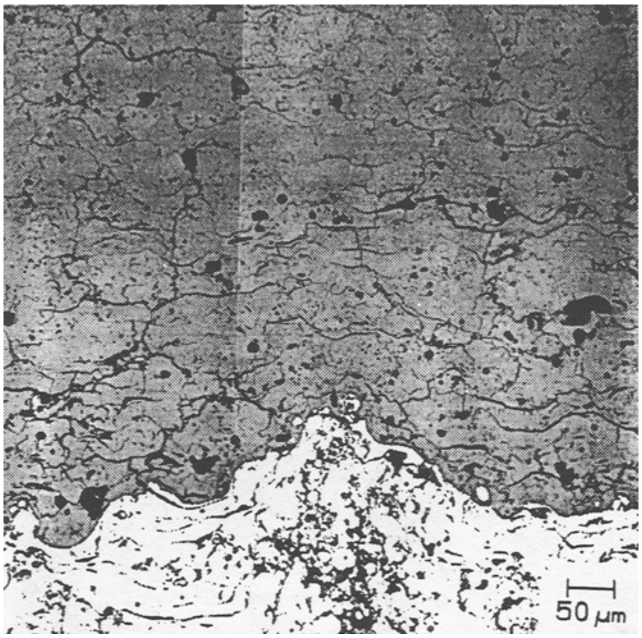


Fig. 2 Photomicrograph of a typical TBC microstructure showing random porosity and microcracking

2.3 *Turbine Buckets*

Seven first stage buckets with APS and EB-PVD TBCs were installed in an MS9001E gas turbine in 1993. These buckets provide a side-to-side comparison of APS and EB-PVD coatings (Fig. 5). The buckets were installed in a peaking machine that will operate less than 2000 h per year but will be cycled frequently to meet short duration power demands. The machine will operate for two to three years prior to removal of the test buckets.

Rainbow testing of prototype components in commercial machines involves several shortcomings compared to factory testing. Rainbow hardware must often be procured with very limited lead time in order to meet machine outage schedules. This may preclude complete development of the coating process and performance of a suitable number of coating trials for TBC optimization on specific hardware. Production implementation may then require additional development and process refinement. Another shortcoming of rainbow testing is that the components may be refurbished and returned to service following the test and thus, become unavailable for detailed post-test evaluations.

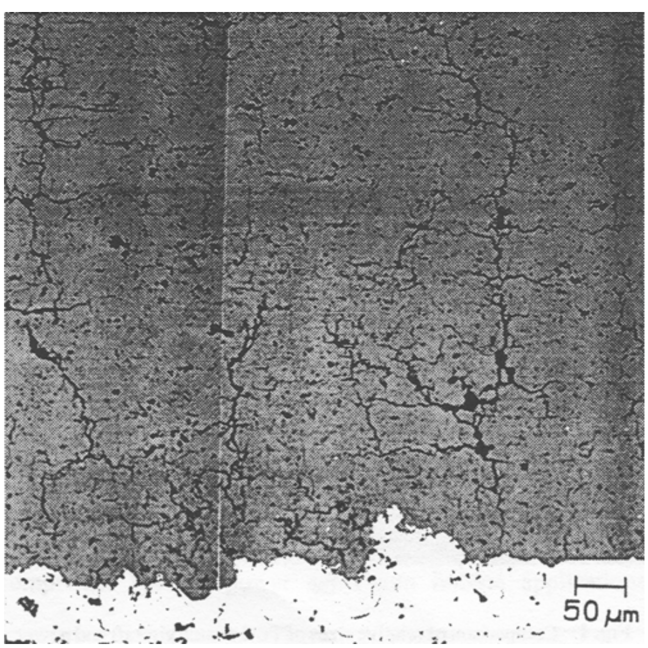


Fig. 3 Photograph of TBC microstructure showing reduced porosity and oriented microcracks

Fig. 4 Photograph of thermal barrier coated MS7001FA shrouds in outer shroud hangar prior to installation into machine

3. Results

3.1 *Nozzle Rainbow Tests*

Nozzle rainbow tests initiated in the late 1980s are now complete. Most conclusions are based upon visual observations rather than metallurgical sectioning and analysis, although loss of the ceramic top coat is easy to see. An MS7000E nozzle after 16,700 h of operation is shown in Fig. 1. Results show that APS TBCs can survive in power generation machines for long time periods. Nozzle degradation at the outer band due to oxidation and/or erosion was reduced by the presence of the TBC. A key result was that the 6 to 8 wt% YSZ top coat outperformed other compositions, and this is consistent with the results of NASA laboratory tests (Ref 2) and aircraft experience. These early tests also showed that APS NiCrAlY is an adequate bond coat; high-velocity oxygen fuel (HVOF) NiCrAlY was also adequate, while CoNiCrAlY was slightly poorer. It was observed that coating source was a factor in performance; similar coatings from different thermal spray processors performed differently. This reinforces the need to ensure adequate development and understanding of the coating processes.

Occasional loss of coatings has been observed in operating machines due to abnormal operating conditions, foreign object damage (FOD), or buildup of deposits. TBC loss was more prevalent at the outer side wall and at nozzle leading edges. TBC loss may also have resulted from accumulation of dust on nozzle surfaces. TBC degradation due to environmental contamination from airborne dust has recently been reported (Ref 3). The overall results from these early nozzle rainbow tests are quite encouraging and give confidence for expanding TBC usage.

3.2 *Combustor Liners*

The five coatings described in Table 4 ran for more than 6000 h at a customer site and provided insight into coating thickness and microstructure effects. This machine used water injection that is used by some utilities for abatement of oxides of nitrogen and for power augmentation. On the test machine, water was introduced from eight nozzles upstream of the fuel nozzle swirl tip. At high flow rates, the water does not completely atomize and vaporize. As a result, high-velocity water droplets impinged directly upon the TBC under some operating conditions.

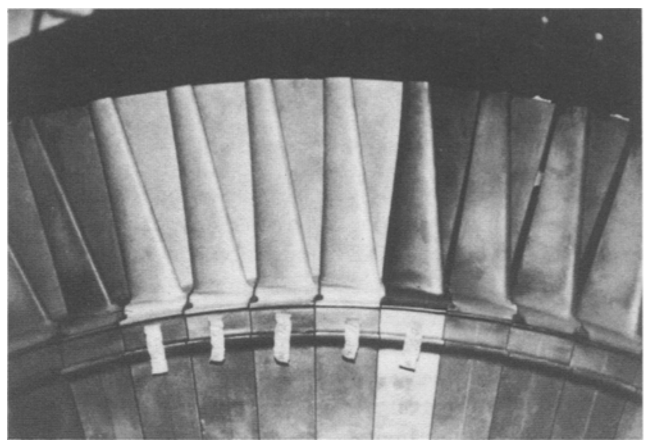
TBC spallation occurred in nine of the ten liners, with significant differences in the size and morphology of the spalled regions (Fig. 6). In all cases, spallation resulted from the impingement of water onto the TBC. The differences in spallation were attributed to differences in TBC microstructure and thickness. The results are summarized as follows: (a) thinner coatings, 0.3 and 0.5 mm (12 and 20 mils) thickness, all showed approximately 77 cm^2 (12 $in.^2$) of coating loss; and (b) thicker coatings, 0.75 and 1.1 mm (30 and 45 mils), had considerably less spalling, approximately 6 cm^2 (1 $in.^2$). Coating loss was less than 20% of the entire surface area of the combustor. Porous coatings tended to fail adjacent to the bond coat/top coat interface, while the denser coatings failed higher within the ceramic layer. The thicker coatings had less porosity and a more oriented microstructure, which is stronger, as evidenced by higher through thickness tensile strengths, and is more strain tolerant due to low in-plane modulus (Ref 4).

3.3 *Turbine Shrouds*

An initial borescope inspection of the shrouds was performed after ~4600 h. All coatings appeared to be performing very well. Four of the fifteen test shrouds showed minor spallation at the shroud edges. Evidence of FOD was noted on some of the adjacent metal shrouds. No rubbing, that is, contact with bucket tips, was observed for these parts. Additional inspections are expected twice per year.

3.4 *Turbine Buckets*

An inspection of this rainbow test was performed at ~1000 h. The EB-PVD coatings tended to show erosive loss at the platform aft of the trailing edge. The EB-PVD microstructure was poorer on the platform due to its orientation during processing and, hence, more likely to erode. The APS coatings showed minor spalls at the platform edges, possibly due to handling or part-to-part contact. One APS bucket was removed from the machine due to distress of the TBC on the airfoil. Analysis is in progress to interpret this result.



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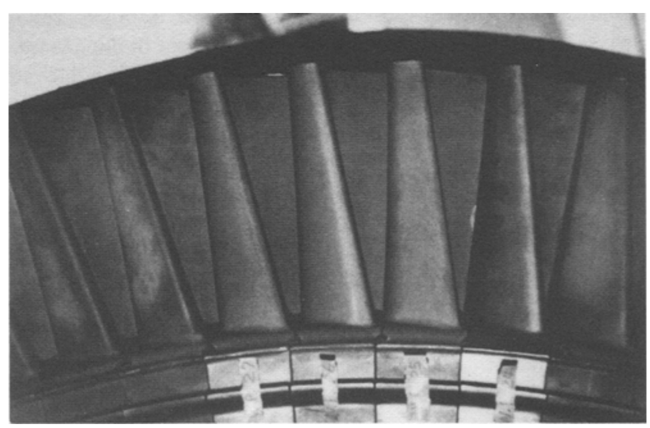
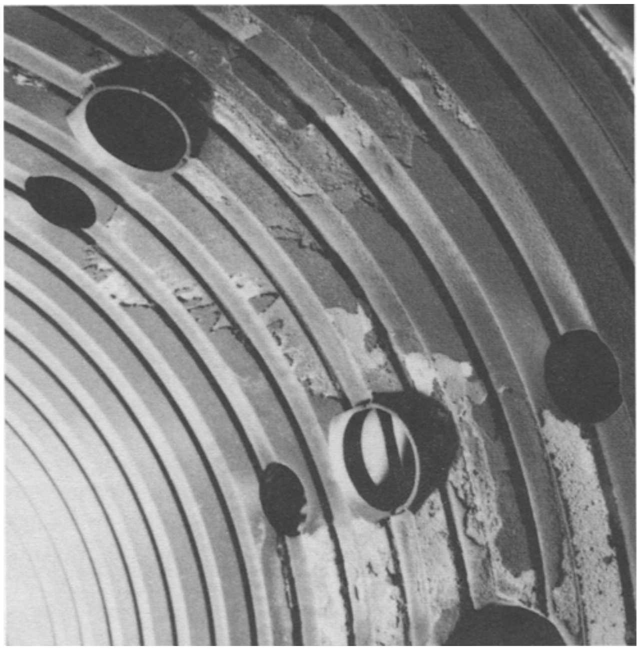


(b)

Fig. 5 Photograph of (a) APS and (b) EB-PVD thermal barrier coated MS90001E buckets installed in rotor prior to installation into machine. The airfoil is approximately 24 cm high.



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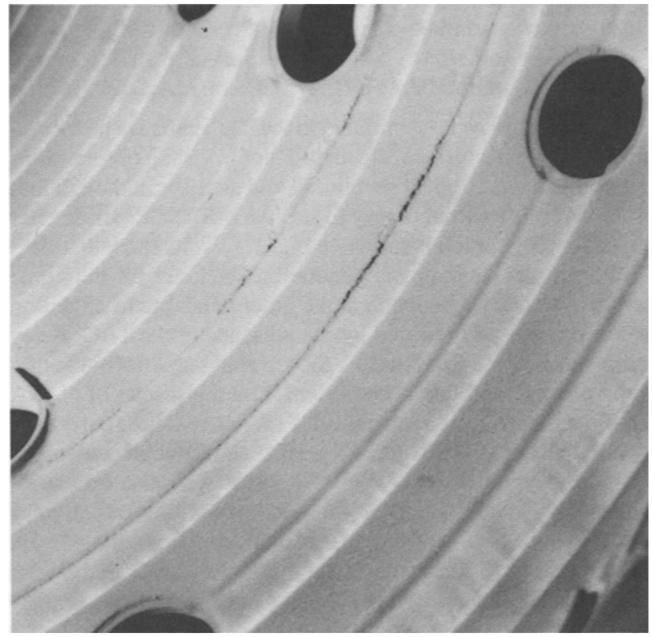

(b)

Fig. 6 Photographs of TBC coated combustion liners after more than 6000 h in MS7001E machine. (a) 0.5 mm (20 mils) thick porous coating and (b) 1.1 mm (45 mils) thick dense coating. The dilution holes are approximately 3 cm in diameter.

4. Summary

The earlier rainbow tests, which evaluated top coat compositions, resulted in confirmation of the superiority of YSZ and, especially, the 6 to 8 wt% YSZ composition. On-going tests are more focused on the TBC process and property variations. The prevalent failure modes seen thus far in the various rainbow tests are spalling, erosion, FOD, and buildup of deposits. Additional post-test analysis is required to investigate bond coat oxidation and other time/temperature dependent changes to the system. Water injection, at very high levels, has been detrimental to TBC coatings in combustor applications.

Despite the experience gained from operating ceramic-coated components in current generation gas turbines, much more remains to be learned about TBC behavior in the gas turbine hot section. The full advantage of TBCs can be achieved only when the reliability of the coating approaches that of the superalloy component substrate. Rainbow test programs will serve to improve confidence in TBCs, but these tests must be supported by an improved understanding of TBC thermomechanical behavior and process variability. Ultimately, the linkage of process, properties, and performance relationships to component design rules and guidelines must be achieved.

Acknowledgments

The efforts of Allan Foster to initiate and track the early nozzle rainbow tests and of Eric Brambani to conduct the combustor rainbow testing of TBCs were instrumental to this activity.

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