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PVD TBC Experience on GE Aircraft Engines

A. Maricocchi, A. Bartz, and D. Wortman

The higher performance levels of modern gas turbine engines present significant challenges in the reliability of materials in the turbine. The increased engine temperatures required to achieve the higher performance levels reduce the strength of the materials used in the turbine sections of the engine. Various forms of thermal barrier coatings have been used for many years to increase the reliability of gas turbine engine components. Recent experience with the physical vapor deposition process using ceramic material has demonstrated success in extending the service life of turbine blades and nozzles. Engine test results of turbine components with a 125 μm (0.005 in.) PVD TBC have demonstrated component operating temperatures of 56 to 83 °C (100 to 150 °F) lower than non-PVD TBC components.

Engine testing has also revealed that TBCs are susceptible to high angle particle impact damage. Sand particles and other engine debris impact the TBC surface at the leading edge of airfoils and fracture the PVD columns. As the impacting continues, the TBC erodes in local areas. Analysis of the eroded areas has shown a slight increase in temperature over a fully coated area; however, a significant temperature reduction was realized over an airfoil without TBC.

Keywords microstructure, performance, PVD coatings, TBCs

1. Introduction

THE DRIVE FOR increased aircraft engine thrust and fuel efficiency has resulted in continual increases in hot section temperatures. Several generations of superalloys have been developed over the past 20 years to make these increases in turbine inlet temperature possible. However, the limits of stress rupture, surface protection, and melting point make this increasingly difficult. In addition, the amount of air that can be used for cooling in high-performance engines is limited. The use of thermal barrier coating (TBC) has the potential to extend these advances in aircraft engine development by providing a layer of thermal insulation between the superalloy turbine airfoil and the hot gases (Fig. 1). With the turbine airfoil cooling technology available today, a 250 μm (0.010 in.) thick TBC can reduce the average metal temperature by 111 to 167 °C (200 to 300 °F) (Ref 1). Designing a TBC for full thermal insulating benefit requires high confidence because loss of the TBC could result in rapid component degradation. The payoff in increased engine thrust of fuel efficiency is significant; therefore, much effort is being focused on improvements in the reliability of TBCs. Additional effort is being expended to further the understanding of the behavior of TBCs.

Thermal barrier coatings have been used extensively since the mid 1970s for life extension of combustor and afterburner components. Plasma-sprayed zirconia, with 7% yttria (YSZ) for stabilization of the tetragonal phase, was determined to be most successful for these applications. Very low thermal conductivity, high melting point, inertness, and relatively high coefficient of thermal expansion (CTE) make zirconia ideal as a TBC. Although YSZ has one of the highest CTEs of any high-temperature ceramic, it is still only about 70% of the superalloy substrate. To help accommodate the large compressive stresses that result from cool down of service temperatures, the YSZ must be sprayed to achieve a microstructure that will accommodate these strains. Both porous (Ref 2) and dense vertically cracked (Ref 3) microstructures have been successful in accomplishing this strain tolerance. A plasma-sprayed MCRAlY (where M equals any combination of Co, Ni, or Fe) bond coat is applied prior to the YSZ to promote adherence to the metal substrate.

Roughness of the plasma-sprayed bond coat was found to be essential to the adherence of the plasma-sprayed YSZ because it provided a mechanical bonding of the YSZ to the bond coat (Ref 4). Use of the plasma-spray TBCs was extended to high-pressure turbine nozzles (HPTN) in the late 1980s through the use of low-pressure plasma-sprayed bond coats, which have greater oxidation resistance than atmospheric plasma-sprayed bond coats (Ref 4).

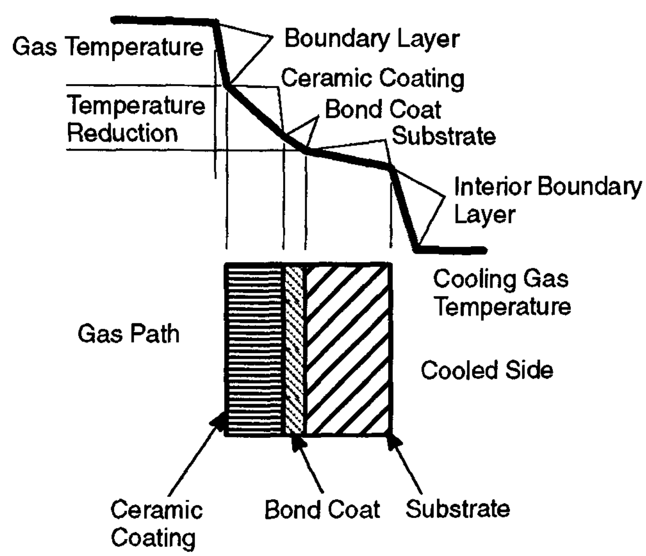

Fig. 1 Schematic of a thermal barrier coating

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2. Physical Vapor Deposited Thermal Barrier Coatings

Physical vapor deposition (PVD) processes such as sputtering will produce highly columnar deposits under certain conditions of evaporation. A strain tolerant microstructure with YSZ produced by sputtering was observed by Bush et al. (Ref 5). Higher deposition rates achievable by electron beam physical vapor deposition make this process economically feasible for deposition of highly strain tolerant TBCs. Figure 2 depicts the features of a PVD TBC. Bond coats are required for adherence and oxidation resistance of the substrate. As opposed to the plasma-sprayed TBC, the PVD TBC relies on a chemical bond between a smooth bond coat, the alumina scale that forms on the bond coat, and the YSZ. The alumina scale between the bond coat and the TBC continues to grow during engine operation. Alumina forming bond coats are successfully used for PVD TBC bonding, and controlling the growth of the alumina scale is

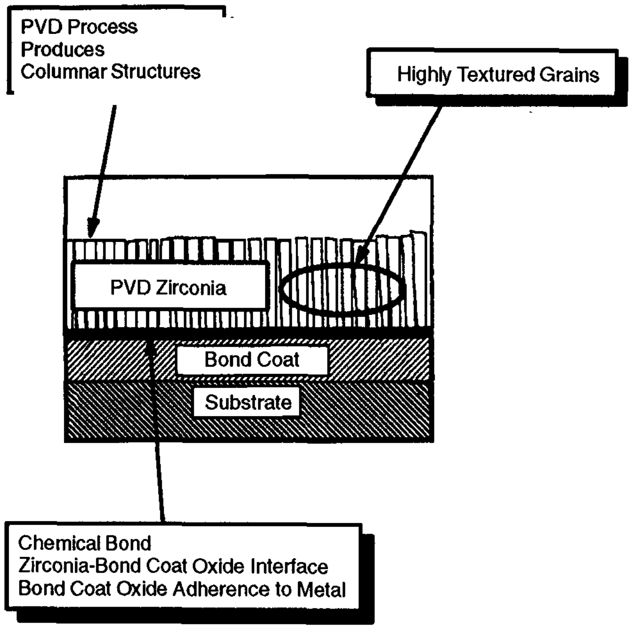

Fig. 2 Typical physical vapor deposited thermal barrier coating

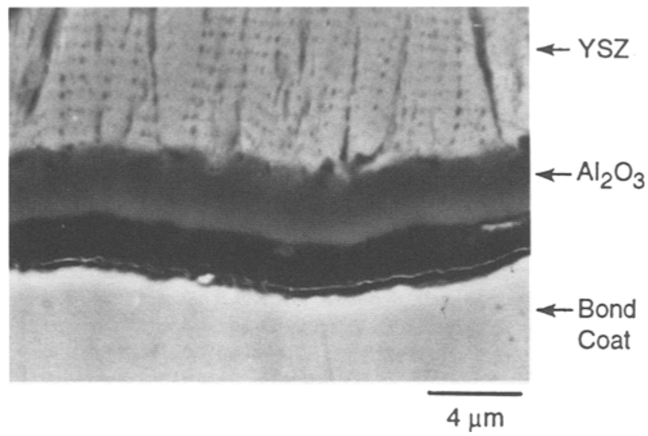

Fig. 3 Micrograph showing separation between Al_2O_3 scale and bond coat

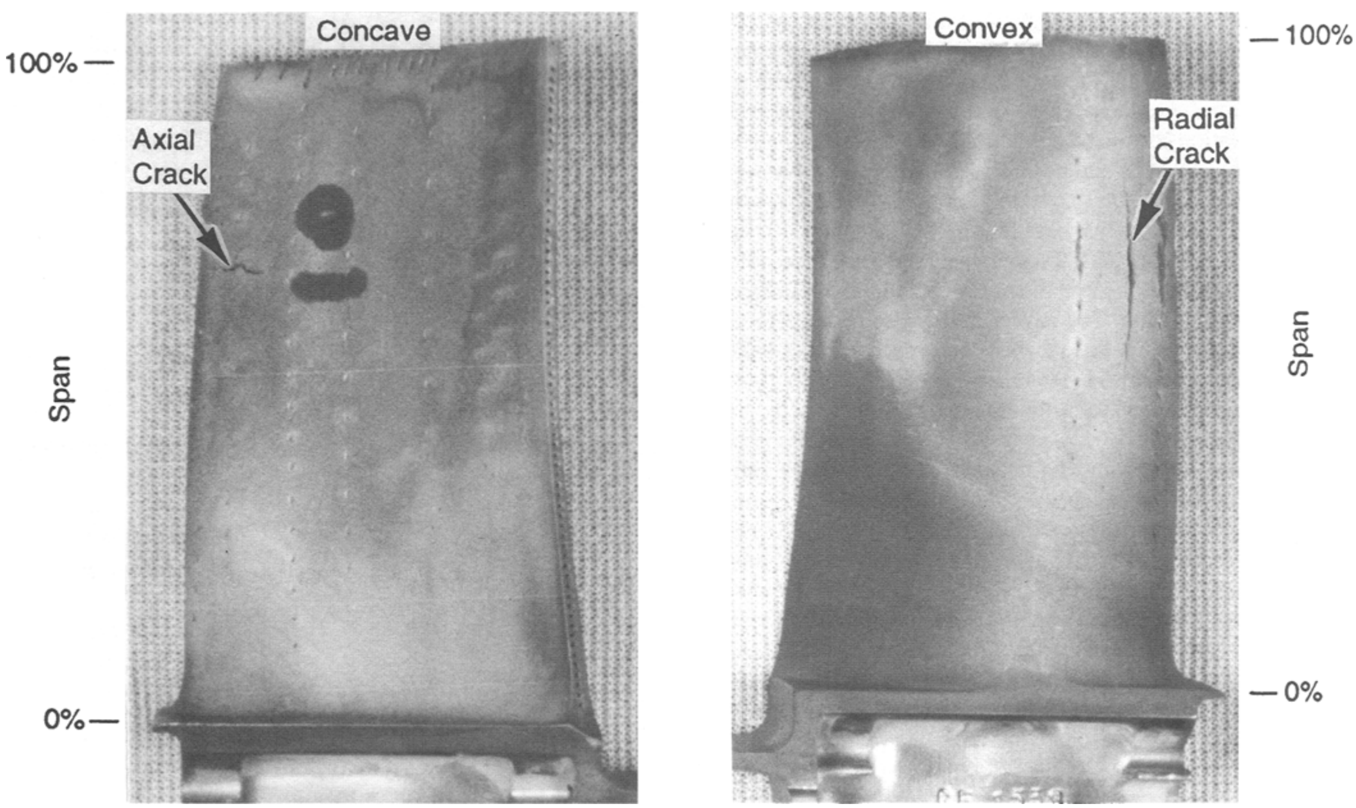

Fig. 4 Stage 1 HPTB without TBC showing axial and radial cracking of the material after 1820 cycles. The airfoil length is 6.4 cm (2.5 in.).

a key feature in increasing the life of these systems. Control of the PVD processing parameters is also important for production of the strain tolerance necessary for reliability.

This paper describes the successful testing of PVD TBC on HPTN and high pressure turbine blades (HPTB) (gamma prime, γ', strengthened nickel-base superalloys) where the TBC significantly extends the life of the components.

3. Application of PVD TBCs to Aerospace Components

The PVD process was used to apply the TBC to several jet engine components to evaluate its effectiveness under operating conditions. High-pressure turbine blades and nozzles were selected because these components reside in the hottest section of the engine and are most susceptible to base material degradation.

One advantage of the PVD TBC is the smooth surface finish that is generated on the surface of a component. The PVD TBC surface as deposited produces a 1.0 to 1.5 μm R_a (40 to 60 μin. R_a) finish, where R_a is surface roughness. Surface finishing to the tips of the columns can also be performed on the PVD TBC to reduce the finish of the surface to 0.5 to 0.75 μm R_a (20 to 30 μin. R_a).

Spallation is a major concern for components treated with the PVD TBC process. This is the loss of coating due to chipping or other operating environmental factors. Spallation can occur when stresses are generated through the coefficient of thermal expansion mismatch between the YSZ ceramic and the metal substrate. Stresses are also generated through the coefficient of thermal expansion mismatch between the substrate and the aluminum oxide that grows on the bond coat surface. Through control of the PVD process parameters, the YSZ can be deposited with a columnar microstructure that accommodates the thermal expansion mismatch without generating compressive stresses in the YSZ on cool down from deposition or operating temperatures. Measurement of residual stress in PVD YSZ shows room-temperature stresses that are less than 10 ksi (68.9 MPa) (Ref 6). Calculation of room-temperature stresses, assuming the deposition temperature as stress free, predicts compressive stresses greater than 100 ksi (689 MPa). Control of the stresses in the thermally grown alumina is more difficult because a dense microstructure is both desired (to slow subsequent oxidation) and naturally formed. With thermally grown alumina, the growth temperature is probably the stress-free temperature. Inward diffusion of oxygen anions may even produce compressive growth stresses at the thermal exposure temperature. Calculation of the room-temperature stresses, due to the coefficient of thermal expansion mismatch with the substrate, predicts a 300 to 400 ksi (2067 to 2756 MPa) compressive stress.

The interfacial strength of the PVD TBC system is greater than 10 ksi (68.9 MPa) in the as-deposited condition as demonstrated by epoxy failures in bond strength tests. After thermal exposure, the bond strength drops below 6 ksi (41.3 MPa), with separation occurring at the alumina bond coat interface. It is believed that the two effects are occurring during thermal exposure. The alumina scale becomes thicker, and therefore, the compressive force (proportional to the thickness of the alumina) increases. The bond strength decreases due to any of several mechanisms (void formation under the alumina, sulfur migra-

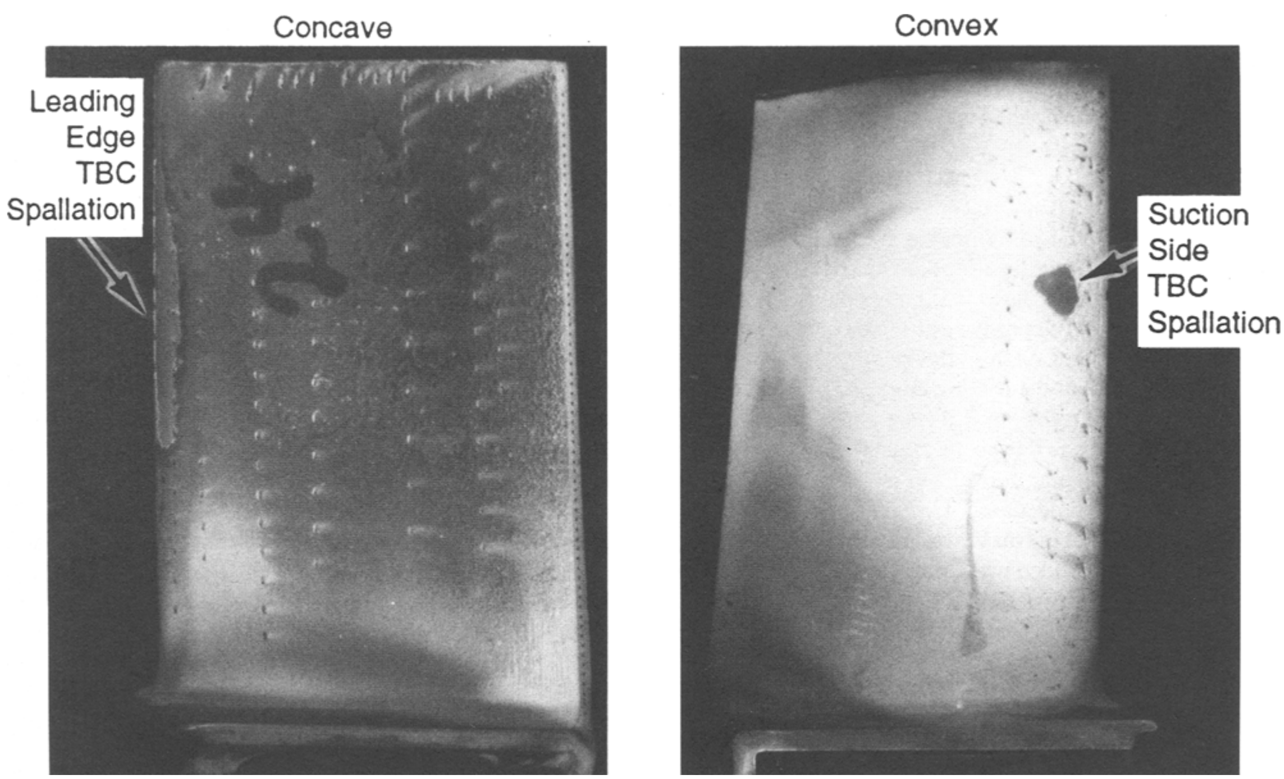

Fig. 5 Stage 1 HPTB with TBC showing leading-edge and suction-side TBC spallation after 1820 cycles. The airfoil length is 6.4 cm (2.5 in.).

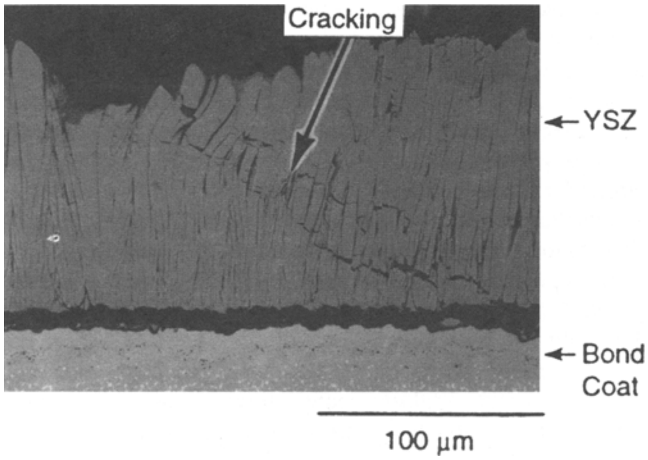

Fig. 6 Micrograph of the TBC cracking due to particle impact damage

tion to the scale metal interface, or thermal cycle induced cracking in the scale). The tensile bond test cannot differentiate between these two effects. However, the result is clear; exposure to elevated temperature eventually leads to compressive loads that produce buckling at the interface between the alumina scale and the bond coat and subsequent spallation of the TBC (Fig. 3).

4. Engine Turbine Blade Testing of PVD TBCs

The PVD TBC has been tested on the stage 1 HPTB of a high bypass engine. The test was conducted for 1820 endurance engine cycles, where one cycle simulates the takeoff, climb, cruise, and thrust reverse. The TBC was deposited over the entire airfoil surface to a thickness of 125 μm (0.005 in.).

The test included both coated and uncoated blades to accurately evaluate the impact of the PVD TBC. Figure 4 shows post-test photographs of one of the test blades without the PVD TBC. The blade contained an axial crack at the 55% span and a radial crack on the suction side from the 40% to the 80% span. The blade failed due to rupture of the base material.

Figure 5 shows a TBC coated blade after the engine test; it shows no spallation on the concave airfoil and no spallation on the convex airfoil after the leading edge region. However, there is some TBC spallation at the leading-edge and on the suction-side leading edge. Both of these spalls are attributed to impact damage or erosion damage from debris coming through the turbine. This blade did not have any cracks and can be reserviced using a strip and recoat procedure.

Closer examination of the blade was performed to determine how the PVD TBC responded when impacted by debris. Figure 6 shows the microstructure of the TBC near the spalled regions. The engine debris impacted the ceramic at the surface, cracking the columns. The cracks propagated to the interface and eventually spalled the ceramic.

The percent volume of γ' precipitant in the alloy was measured through microstructure analysis. This measurement was then compared to the solubility curve (percent precipitate versus temperature) of the alloy to estimate the highest operating temperature at that specific location on the blade. These examinations were taken at the mid-wall location between the blade surface and the internal cavity of the blade. Results indicate that the blade with the TBC ran at a temperature 56 to 83 °C (100 to 150 °F) lower than the blade without the TBC.

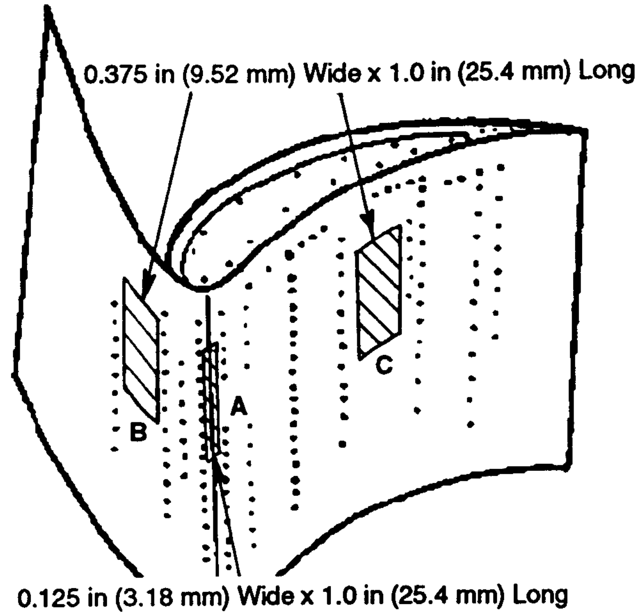

Fig. 7 Schematic of blade airfoil showing location of intentionally missing TBC

For the next engine test, blades were prepared with the TBC intentionally missing from certain areas of the blade. The TBC was applied to the entire airfoil, then locally grit blasted to remove the TBC (Fig. 7). The three locations of the blade with missing TBC are (a) the nose of the blade between the 50 to 80% span (location A), (b) the suction-side leading edge between the 50 to 80% span (location B), and (c) the pressure side at the mid chord between the 50 to 80% span (location C). The blades were tested for 2000 engine endurance cycles along with blades that contained a full TBC and blades without a TBC.

Figure 8 shows the blades after the engine test. The intentionally grit-blasted areas did not grow in size after 2000 engine cycles, and no distress was observed. The blades were then metallographically examined to determine the maximum metal operating temperatures through γ' analysis. In location A, along the leading-edge nose, no temperature reduction was observed between the blade with the intentionally spalled TBC and the blade that did not have TBC. In location B, the temperature reduction on the intentionally spalled TBC blade was minimal, and in location C, the temperature reduction was estimated to be 24 °C (75 °F) at the mid-wall location for the intentionally spalled TBC. At the surface of locations B and C, the temperature reduction is estimated to be 38 °C (100 °F) for the spalled TBC blade when compared to the blade without TBC.

5. Engine Nozzle Testing of PVD TBCs

Tests of the PVD TBC were also performed on the HPTN of a high bypass engine. The test was conducted for 750 endurance engine cycles, where one cycle simulates takeoff, climb, cruise,

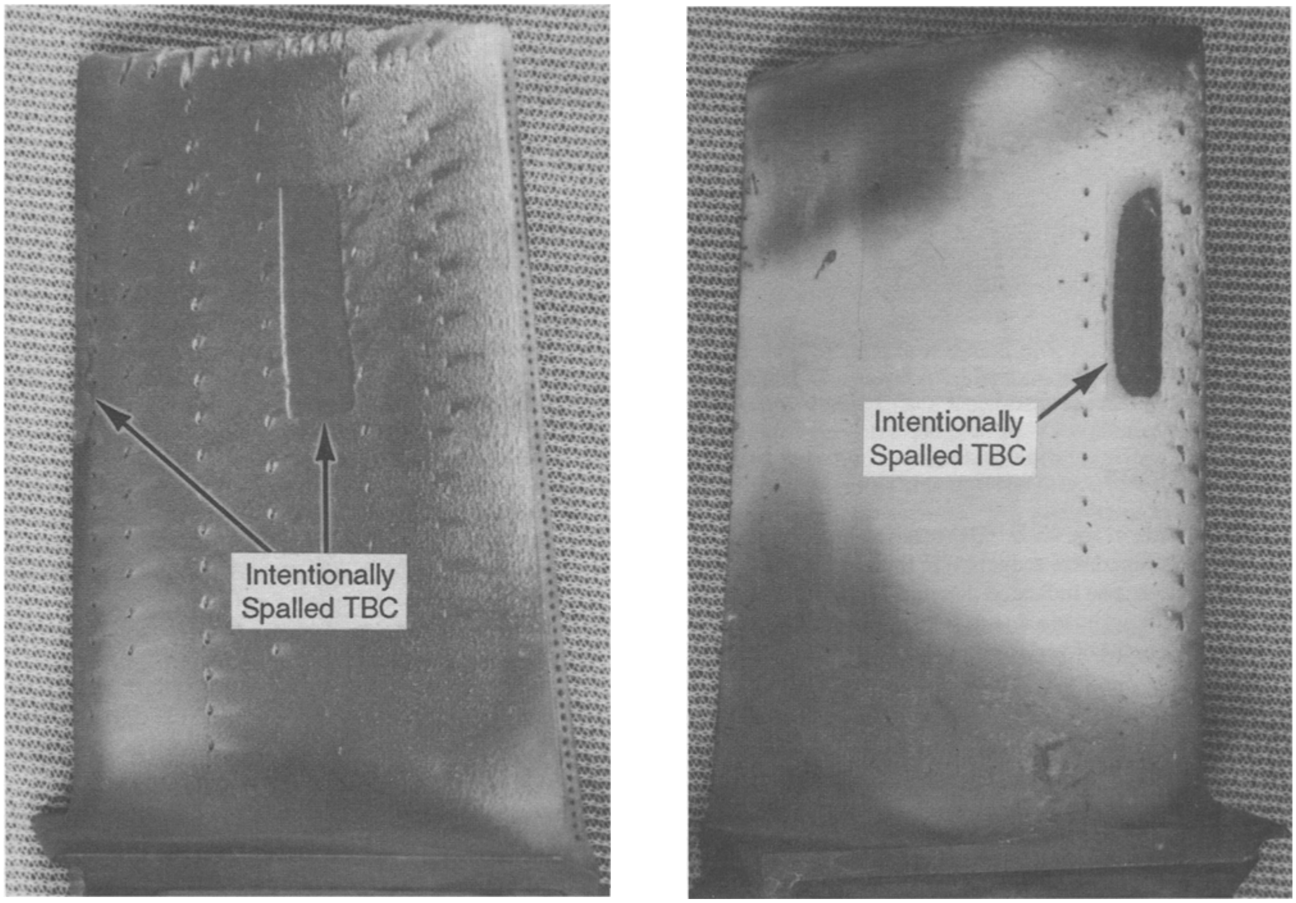

Fig. 8 Stage 1 HPTB showing the areas of intentionally spalled TBC after 2000 cycles. The airfoil length is 6.4 cm (2.5 in.).

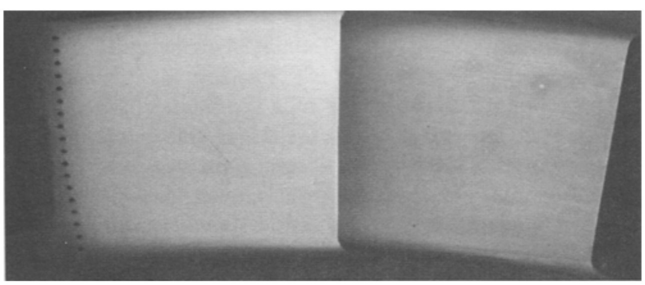

Fig. 9 HPTN with a PVD TBC prior to engine testing

and thrust reverse. The engine was operated at or above standard "red line" conditions, resulting in an engine test that exceeded normal operating parameters. The TBC was deposited on the airfoil surface to a thickness of 125 μm (0.005 in.).

The TBC was only applied to the suction side of the nozzle as shown in Fig. 9. The PVD TBC has an application advantage in that it provides a smooth transition from the noncoated region to the coated region. This eliminates aerodynamic effects with turbulence that would be caused if the process created a step between the TBC and non-TBC regions. Turbulence created when the boundary layer air crosses a step in the coating will reduce the cooling effectiveness of the air, which then increases the material temperature.

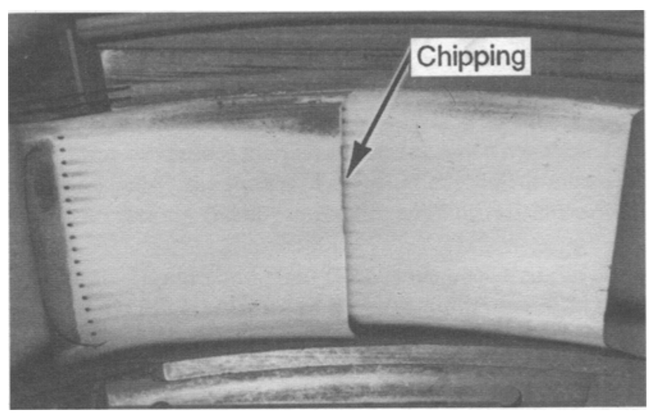

Fig. 10 HPTN with a PVD TBC after 750 cycles of engine testing

Figure 10 shows the TBC HPT nozzle following the engine test. The TBC remained intact with no spallation. The minor chipping at the trailing edge was caused by assembly. Figure 11 shows a HPTN that did not have a TBC. The extreme conditions of the test resulted in massive thermal fatigue cracks on the suction side of the nozzle, which extended through the wall of the base alloy. There were no thermal fatigue cracks extending through the walls of the nozzle with the TBC, but there was some cracking in the environmental bond coating.

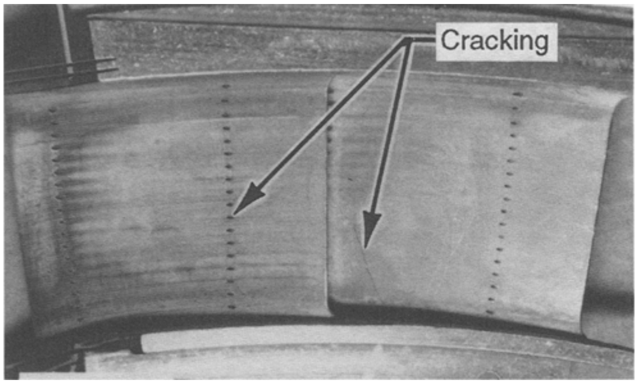

Fig. 11 HPTN without TBC after 750 cycles of testing showing thermal fatigue cracking in the airfoil material

6. Conclusions

The engine tests of the PVD TBC resulted in a 38 to 66 °C (100 to 150 °F) temperature reduction in the stage 1 HPTB and the HPTN. The tests also indicated that the PVD TBC is susceptible to leading-edge damage due to impact from particles running through the engine or various other engine debris. The PVD TBC has been introduced for stage 1 HPTB. Additionally, over 10,000 cycles of engine testing have been accumulated on nozzles with the TBC. The TBC for nozzles was introduced in the early 1990s.

References

1. S.M. Meier and D.K. Gupta, "The Evolution of Thermal Barrier Coatings in Gas Turbine Engine Applications," 92-GT-203, ASME Conf. Publication
2. J.T. DeMasi, K.D. Scheffler, and S. Bose, Mechanisms of Degradation and Failure in a Plasma-Deposited Thermal Barrier Coating, *J. Eng. Gas Turbines Power,* Vol 112, Oct 1990, p 521-526
3. G. Johner and K.K. Schweitzer, Flame Rig Testing of Thermal Barrier Coatings and Correlation with Engine Results, *J. Vac. Sci. Technol.,* Nov/Dec 1985, p 2516-2524
4. D.J. Wortman, B.A. Nagaraj, and E.C. Duderstadt, Thermal Barrier Coatings for Gas Turbine Use, *Mater. Sci. Eng.,* Vol A121, 1989, p 443-440
5. R. Bush, J. Patten, and J. Fairbanks, High Rate Sputter Depositions of Protective Coatings on Marine Gas Turbine Hot-Section Superalloys, MCIC 75-27, *Proceedings 1974 Gas Turbine Materials in the Marine Environment Conference* (Castine, Maine), Metals and Ceramics Information Centers, July 1974
6. C. Johnson, GE Corporate Research and Development, unpublished work