THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
345 E. 47 St., New York, N.Y. 10017

92-GT-203

The Evolution of Thermal Barrier Coatings in Gas Turbine Engine Applications

SUSAN MANNING MEIER and DINESH K. GUPTA

Pratt & Whitney
East Hartford, Connecticut

ABSTRACT

Thermal barrier coatings (TBCs) have been used for almost three decades to extend the life of combustors and augmentors and, more recently, stationary turbine components. Plasma sprayed yttria stabilized zirconia TBC currently is bill-of-material on many commercial jet engine parts. A more durable electron beam-physical vapor deposited (EB-PVD) ceramic coating recently has been developed for more demanding rotating as well as stationary turbine components. This ceramic EB-PVD is bill-of-material on turbine blades and vanes in current high thrust engine models and is being considered for newer developmental engines as well. To take maximum advantage of potential TBC benefits, the thermal effect of the TBC ceramic layer must become an integral element of the hot section component design system. To do this with acceptable reliability requires a suitable analytical life prediction model calibrated to engine experience. The latest efforts in thermal barrier coatings are directed toward correlating such models to measured engine performance.

INTRODUCTION

Commercial gas turbine engines typically use combustor and turbine superalloys which melt in the range of 1230°C to 1315°C. These materials operate in a combustion gas environment typically above 1370°C. To avoid structural failure by melting, creep, oxidation, thermal fatigue, and other mechanisms, the airfoils are made hollow, and compressor discharge air is injected to cool the component. To maximize efficiency, it is desirable to minimize the use of this air for cooling purposes and to use it to perform work in the turbine. This has been traditionally accomplished by designing more effective cooling geometries within the component and by film cooling the surface of the component with drilled cooling holes. As this cooling technology matures, however, the technical community is searching for innovative technologies to further increase efficiency (Duvall and Ruckle, 1982, and Miller and Lowell, 1982).

One method of protecting gas turbine engine components is through the use of thermal barrier coatings. TBC typically is a two layer system (Figure 1) which incorporates a thin layer of ceramic approximately 0.254 mm thick applied to the outer gas path surface of the engine component and an underlying metallic "bond coat" approximately 0.127 mm. The metallic bond coat performs two functions: 1) to provide oxidation resistance and 2) to physically and chemically adhere the ceramic to the underlying superalloy structure.

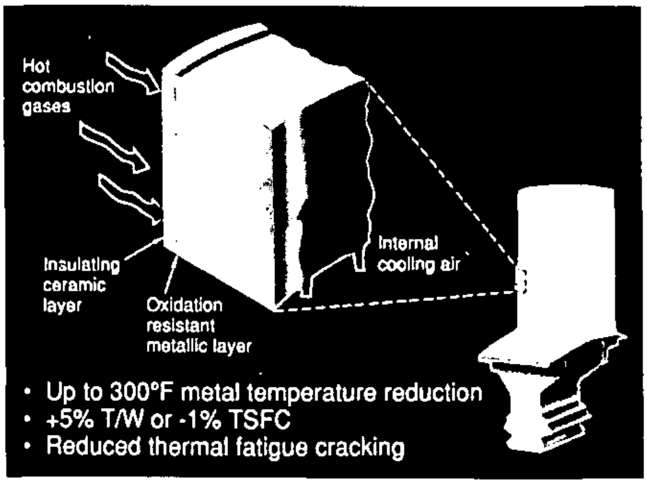


Fig. 1 Thermal Barrier Coating Benefits.

The use of thermal barrier coatings on noncritical turbine components has provided substantial improvements in system performance through increased turbine efficiency, reduction in maintenance requirements, and fuel usage. These insulative coatings can reduce the turbine airfoil temperature by as much as 167°C, thereby improving the component durability by as much as 3 to 4 times and/or specific fuel consumption by more than 1 percent (Miller and Lowell, 1982, and Sheffler and Gupta, 1988).

Presented at the International Gas Turbine and Aeroengine Congress and Exposition
Cologne, Germany June 1-4, 1992
This paper has been accepted for publication in the Transactions of the ASME
Discussion of it will be accepted at ASME Headquarters until September 30, 1992

Ceramic thermal barrier coatings, however, have a tendency to spall upon experiencing thermal cycling from ambient conditions to extremely high operating conditions encountered in the hot section of a gas turbine engine. Improvements have been made to extend coating life and life prediction models have been formulated to permit utilization of thermal barriers in such a way as to attain maximum benefits. This has lead to more widespread use of thermal barrier coatings throughout the gas turbine engine.

PROCESSING APPROACHES

Two major approaches are currently used for deposition of thermal barrier coatings: plasma deposition and electron beam–physical vapor (EB–PVD) deposition. Plasma deposition is essentially an adaptation of the flame spray process. An electric arc in the water cooled plasma gun is used to ionize argon gas, converting it into a plasma (Figure 2). The powder is injected into the flame at the nozzle of the gun, where the ions and electrons of the plasma recombine. The flame heats metal or ceramic powder particles to a semi–plastic state and accelerates them toward the workpiece. Upon impact, the semi–plastic particles deform to produce a complex, interlocking structure which is tightly bonded to the substrate. This plasma sprayed structure (Figure 3) is quite porous and extensively microcracked. The interface between the ceramic and the metal possesses a very complex topology characteristic of the original metallic bond coat surface. This surface includes small, almost free–standing peninsular metal deposits which penetrate relatively deep and are surrounded by ceramic. This feature creates angles and pockets which promote mechanical interlocking between the ceramic and the metal (DeMasi–Marcin, et. al., 1990).

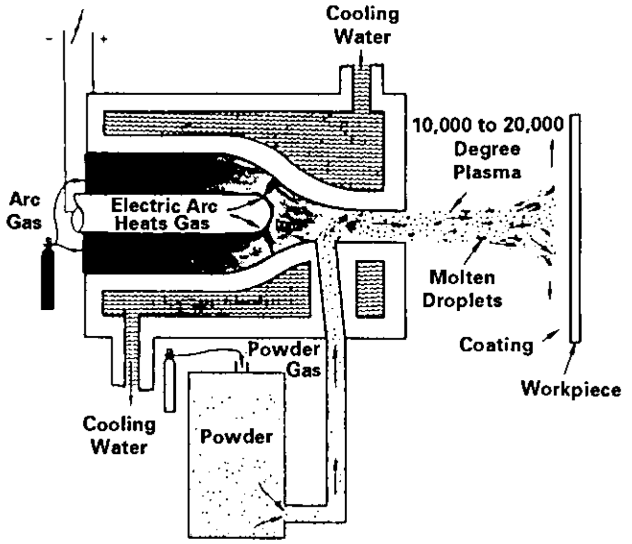


Fig. 2 Plasma Deposited TBC Process Schematic.

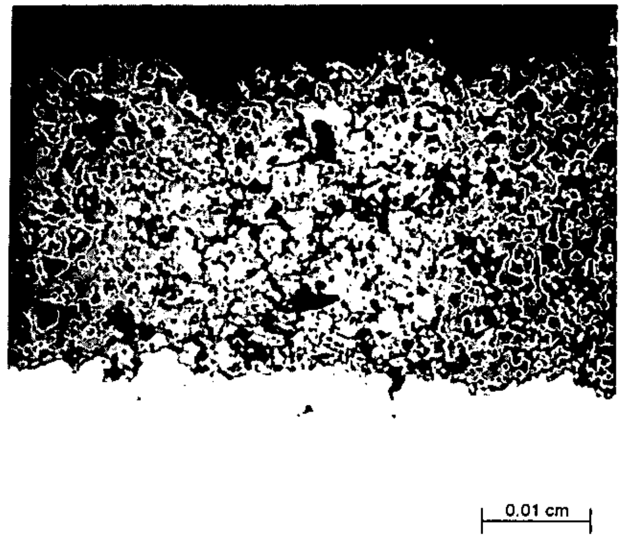


Fig. 3 The Microstructure of Air Plasma Deposited 7 Weight Percent Yttria Partially Stabilized Zirconia.

The EB–PVD ceramic process is a more advanced method of ceramic deposition (Strangman, 1982). In the fabrication of EB–PVD coatings, an electron beam is directed onto the surface of material contained within a crucible (Figure 4). The material in the crucible is heated, melted, and then evaporated to a vapor of atomic proportions. The parts are positioned above the molten material in the crucible to receive the vapor. The EB–PVD ceramic grows in columnar form when processed under the appropriate conditions (Figure 5). In contrast to the mechanical interlocking adhesion mechanism of the plasma sprayed coatings, the EB–PVD coating bonding method is chemical in nature.

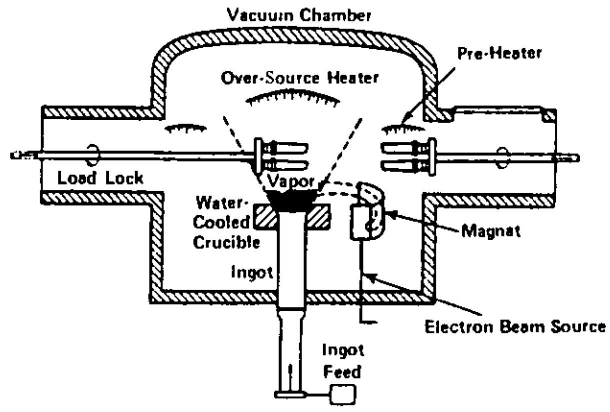


Fig. 4 Electron Beam–Physical Vapor Deposited TBC Process Schematic.

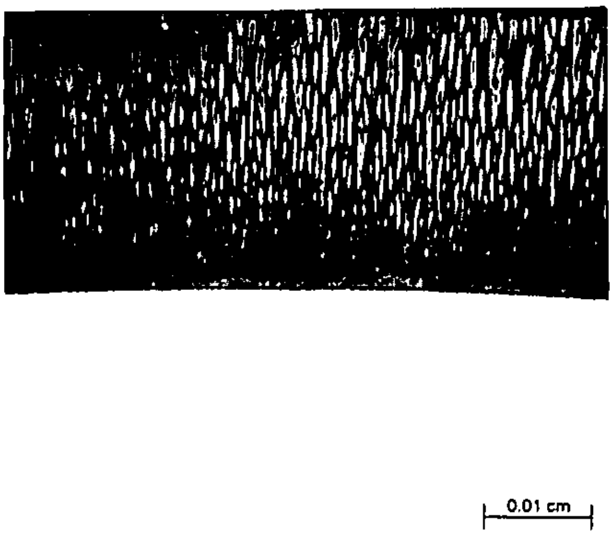


Fig. 5 The Microstructure of an Electron Beam–Physical Vapor Depsoited Ceramic Coating, Showing the Highly Columnar Microstructure Produced by the EB–PVD Process.

In the following sections, evolutionary improvements of the plasma and the EB-PVD deposited coatings will be reviewed and compared, and laboratory and field experience with these coatings will be discussed.

COMBUSTOR COATINGS

Ceramic coating systems have been used for approximately three decades to decrease the severity of oxidation damage and to improve the cracking resistance of combustors and augmentors. The early combustor coatings consisted of an outer ceramic insulative layer of air plasma deposited fully stabilized 22 weight percent MgO stabilized ZrO2 and an inner metallic bond coat of air plasma deposited Ni-Cr or Ni-Al. After thermal exposure, this inner metallic bond coat bonds chemically to the underlying metallic substrate and provides a topologically suitable surface for mechanical bonding with the overlay ceramic. The magnesia stabilized zirconia microstructure shown in Figure 6 has a relatively small amount of porosity, is extensively microcracked, and contains a significant volume fraction of finely distributed free magnesia. It is thought that differential thermal expansion between this free magnesia and the surrounding zirconia matrix assists in the creation and maintenance of the high level of microcrack toughening achieved in this system. The extensive microcracking provides significant toughening and increased tolerance to cyclic thermal strains imposed by repeated heating and cooling (Meier, et al., 1990, and Meier, et al., 1991a).

As the temperatures in the combustor have been increased, the durability of this early combustor coating has become inadequate. The maximum use temperature of the plasma sprayed magnesia stabilized zirconia coating is on the order of 982°C since magnesia stabilized zirconia crystallographically destabilizes above 954°C (Figure 7). By replacing the 22 weight percent magnesia with the 7 weight percent yttria composition used successfully in the turbine section of the engine, the spallation life at temperatures above 982°C has been substantially improved (Stecura, 1979). Figure 8 shows that the thermal spallation life of a seven weight percent yttria partially stabilized zirconia is approximately four times that of the 22 weight percent magnesia fully stabilized zirconia coating at 1094°C (Meier, et al., 1990, and Meier, et al., 1991a).

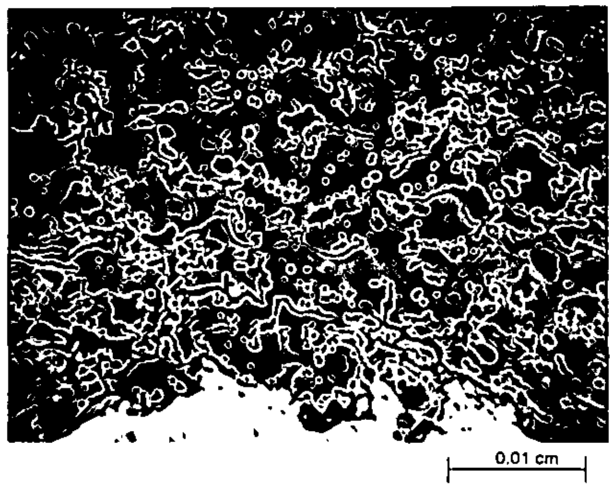


Fig. 6 The Microstructure of Air Plasma Deposited 22 Weight Percent Magnesia Stabilized Zirconia.

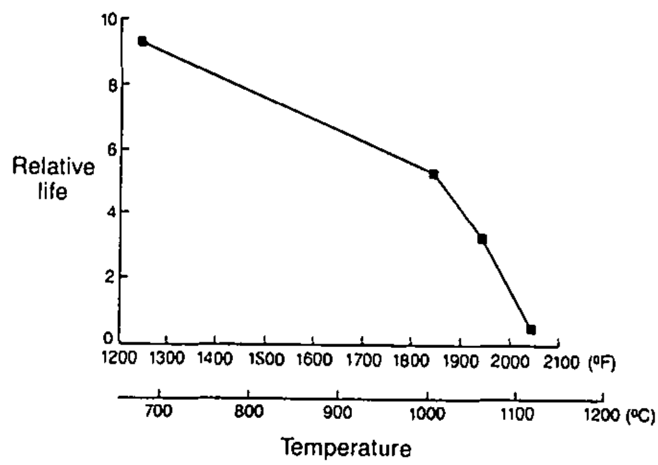


Fig. 7 Influence of Temperature on the Relative Cyclic Thermal Spallation Life of a Magnesia Stabilized Zirconia Thermal Barrier Coating.

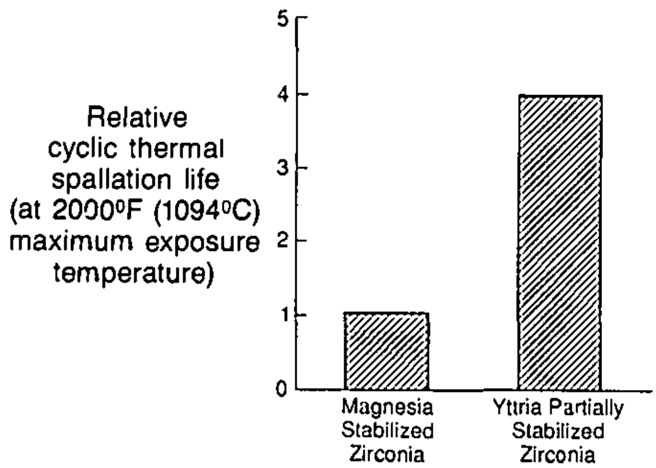


Fig. 8 Relative Cyclic Thermal Spallation Life at a Maximum Exposure Temperature of 1094°C.

Combustor coating life has not only been improved by ceramic composition alterations but also by modifying the metallic bond coat. Since the operating temperature of the combustor was increased to take advantage of the increased temperature capability of the yttria stabilized zirconia, the underlying bond coat oxidation became a problem. By adopting a more oxidation resistant NiCoCrAlY bond coat composition from the turbine section of the engine, the performance of the combustor has been improved. Pratt & Whitney has designated this seven percent yttria stabilized zirconia plasma sprayed ceramic over air plasma sprayed NiCoCrAlY bond coat PWA 265. The earlier magnesia stabilized system was labeled as PWA 261. An in-house JT9D engine test of PWA 265 and PWA 261 combustor panels clearly demonstrated the durability benefit of the seven percent yttria partially stabilized zirconia as compared to magnesia stabilized zirconia (Figure 9) (Meier, et al., 1990, and Meier, et al., 1991a). Similar favorable results have been achieved with PWA 265 in over three thousand hours and fifteen thousand cycles of commercial engine testing. Also, PWA 265 has accumulated about one hundred thousand cumulative flight hours and seventy thousand cumulative flight cycles of combined fighter and commercial engine field experience with no reported problems. In order to improve component performance and durability as well as to achieve commonality across the product line, Pratt & Whitney has incorporated PWA 265 in all combustor applications.

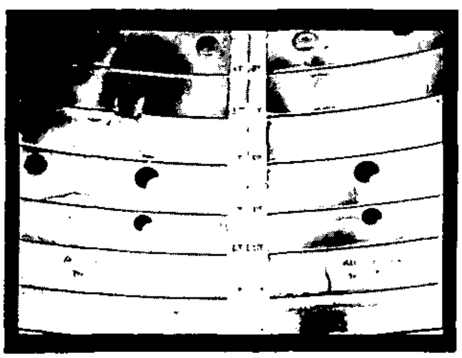


Fig. 9 Engine Operated JT9D Combustor Panels Which Clearly Demonstrate the Durability Benefit of Seven Percent Yttria Partially Stabilized Zirconia (On the Right, Designated PWA 265) as Compared to Magnesia Stabilized Zirconia (On the Left, Designated PWA 261).

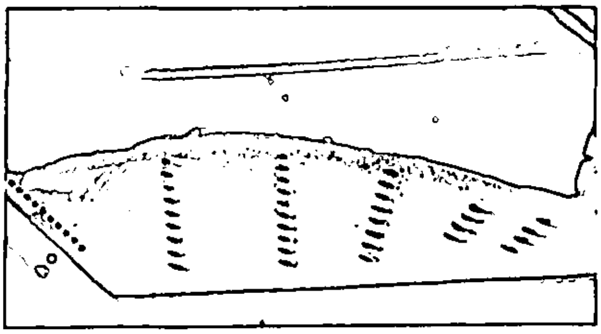
PLASMA SPRAYED TBC LABORATORY AND FIELD EXPERIENCE

Although ceramic coating systems have been used for decades to decrease the severity of oxidation damage and improve the cracking resistance of combustors, it was not until the mid-70's that many important developments were made which led to extension of thermal barrier coating application to the turbine section of the engine (Grisaffe and Levine, 1979, and Ruckle, 1979). One major development was the successful test conducted by NASA-Lewis (Liebert, et al., 1976) on thermal barrier coated turbine blades in a J-75 engine. The results triggered interest in both manufacturers and government agencies and prompted engine advancement in the direction of ceramic coatings for turbine airfoils. Analytical investigations further promoted the use of thermal barrier coatings since they established the large overall engine performance benefits achievable from successful utilization of ceramic thermal barrier coatings on turbine airfoils.

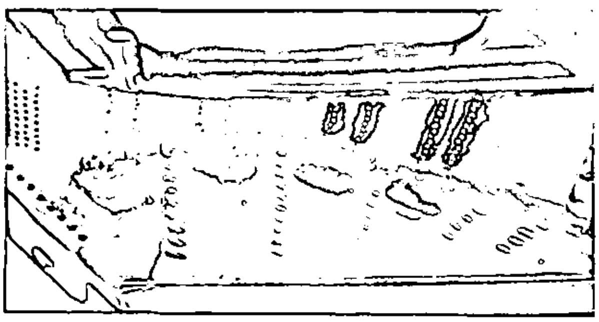
Two factors distinguish plasma sprayed turbine thermal barriers from the combustor coatings. The first is that the ceramic composition is 7 weight percent yttria partially stabilized zirconia which was originally developed for the turbine section and only later retrofitted for the combustor (Miller and Lowell, 1982). The second is the substitution of a more oxidation resistant low pressure plasma sprayed (LPPS) bond coat for the air plasma sprayed bond coat in the combustor. This modification of the bond coat fabrication method improves the performance by as much as 2.5x due to its increased resistance to oxidation damage.

The cyclic thermal spallation life may be improved by altering ceramic compositions, residual stress control, and most importantly, careful control of ceramic microstructure (Duvall, 1977, and Sumner and Ruckle, 1980, and Grot and Martyn, 1981). Progressive improvements have been made to the ceramic microstructure over the past 15 years (Grisaffe and Levine, 1979, and Ruckle, 1979). A relatively dense plasma sprayed ceramic coating portrays a typical brittle ceramic failure and a relatively short cyclic thermal stability life. By incorporating porosity and microcracking to the plasma sprayed ceramic, the ceramic compliance is enhanced and the coatings have greater spalling resistance than high density coatings. The incorporation of a columnar structure further improves the coating durability life, offering improvements as much as 15 times more than the life of plasma sprayed coatings. Plasma sprayed coating process studies have shown that a higher porosity level is usually associated with a coarse particle size (-120 mesh) and finer particle size (-325 mesh) is associated with denser structures. The ceramic composition is an important life critical parameter. As previously mentioned, by substituting yttria for magnesia in the stabilized zirconia combustor coatings, the life of the TBC was increased fourfold at temperatures above 1094°C. Controlling the state of residual stress in the coating is also an important life critical parameter. This can be controlled by careful regulation of the workpiece processing temperature. If the metal substrate is heated too high during coating application, the differential contraction of the substrate on cooling from the process temperature places the ceramic in excessive compression at room temperature, ultimately decreasing the coating durability significantly (Sheffler, et al., 1982).

One of the first ground based test engines to comparatively test the degrees of durability enhancement provided by this TBC was the JT9D first vane platforms (Figure 10). The plasma sprayed TBC coated vane platforms were operated side by side in the engine. After 1500 endurance test cycles, the coating without the ceramic insulating layer was removed due to burning and cracking damage as seen in Figure 10a. The vane in Figure 10b was subsequently operated an additional 1278 cycles with little damage prior to termination of the test campaign. This comparative engine test clearly showed the durability enhancement supplied by the TBC.



(a)



(b)

Fig. 10 (a) A Thermal Barrier Coated JT9D Vane Platform After 2,778 Endurance Test Cycles. (b) A Metallic Coated Vane Platform from the Same Engine After 1,500 Endurance Test Cycles. The thermal barrier coating clearly reduces burning and thermal fatigue cracking.

This current generation plasma deposited ceramic coating is designated PWA 264. Several million cumulative engine flight hours have been accumulated on turbine vanes in several engines. These engines include the JT9D, the PW2037, the PW4000, and the V2500. The experience has been highly favorable (Figure 11). The high time component has over 18,000 engine flight hours with the coating still in serviceable condition (Meier, et al., 1990, and Meier, et al., 1991a).

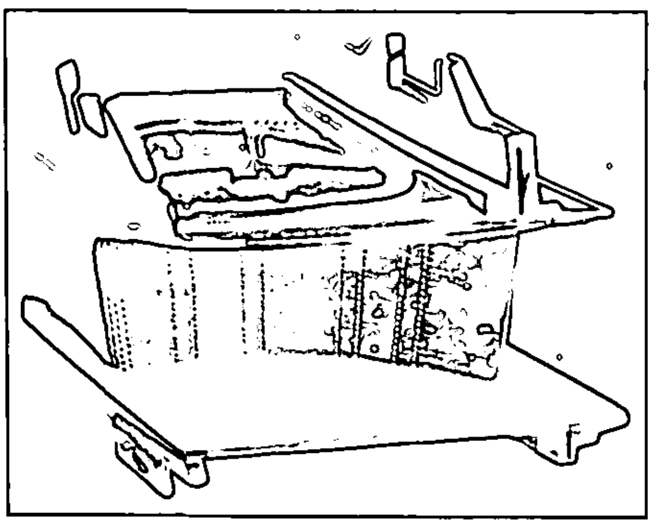


Fig. 11 JT9D-7R4G First Stage Turbine Vane Is In Excellent Condition After 9300 Hours Flight Engine Service.

EB-PVD LABORATORY AND FIELD EXPERIENCE

As discussed previously, the PWA 264 plasma sprayed ceramic coating has demonstrated acceptable life in commercial engines, but as turbine inlet temperatures continue to increase, an improved electron beam-physical vapor deposited (EB-PVD) coating was developed. As shown in Figure 12, the structure produced by this process consists of individual, free-standing ceramic columns, each of which is very tightly bonded to the substrate but essentially free to separate from adjacent columns as the substrate thermally expands relative to the ceramic. Consequently, this structure prevents the build-up of long range stresses. As previously mentioned, the most important element of improvement of ceramic spallation has been through the increased understanding and control of ceramic microstructure. The improvements to ceramic coating durability which have been achieved are summarized in Figure 13 (Duvall, 1977, and Sumner and Ruckle, 1980, and Grot and Martyn, 1981). Whereas relatively dense ceramic fails very quickly, the porous, microcracked plasma-deposited and columnar EB-PVD ceramic structures provide progressively increasing coating durability. The current embodiment of this EB-PVD ceramic TBC concept is designated PWA 266, and it incorporates EB-PVD seven weight percent yttria partially stabilized zirconia over a low pressure chamber sprayed NiCoCrAlY bond coat.

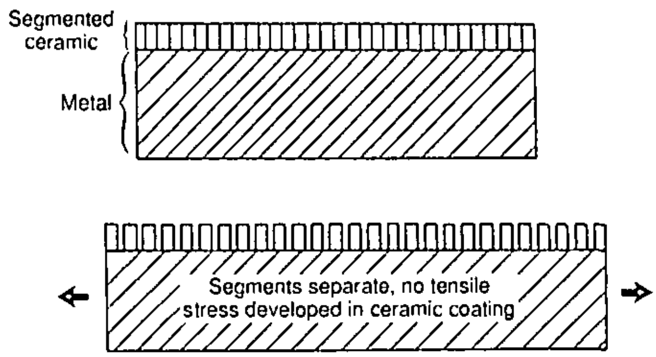


Fig. 12 Illustration of an Idealized Strain Tolerant Ceramic Structure.

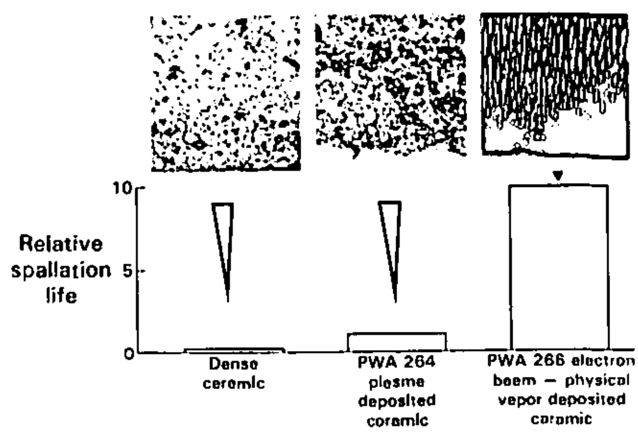
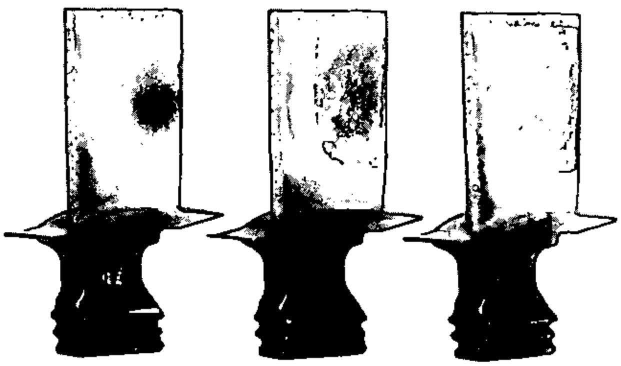


Fig. 13 The Improvement in Relative Spallation Life Provided by Modification of the Ceramic Microstructure. (a) Dense Ceramic. (b) Plasma Deposited Ceramic. (c) EB-PVD Ceramic.

The earliest engine demonstration of the EB-PVD ceramic durability benefit was achieved in flight service testing of this coating side-by-side with PWA 264 plasma sprayed ceramic and non-ceramic coated JT9D first turbine blades. As shown in Figure 14, both the non-ceramic and the PWA 264 plasma ceramic coated blade exhibited significant damage. The PWA 266 EB-PVD ceramic, on the other hand, was in good condition (Meier, et al., 1990, and Meier, et al., 1991a).



(a) (b) (c)

Fig. 14 The Relative Durability of (a) Metallic Coating, (b) Plasma Deposited Ceramic, and (c) EB-PVD Ceramic as Demonstrated in JT9D Flight Service. While the other samples show damage, the EB-PVD ceramic coated turbine blade exhibits discoloration due to engine deposits.

Demonstration of the EB-PVD ceramic thermal benefit has been obtained in successful ground based experimental engine testing on the PW2000 first turbine blade (Figure 15) (Meier, et al., 1991a). Earlier attempts to incorporate plasma sprayed ceramic were unsuccessful due to the cyclic thermal spallation. This test not only demonstrated the durability against spallation in high strain, high heat flux environments, but it also allowed assessment of the thermal benefit by post-test metallographic evaluation. Base metal temperatures of adjacent ceramic and non-ceramic coated blades showed the blade with 5 mils of ceramic operated up to 139°C cooler in the hot spot, thereby demonstrating a very substantial thermal benefit (Figure 16) (Meier, et al., 1990, and Meier, et al., 1991a).

Additional confirmation of the EB-PVD ceramic durability benefit has been obtained in field testing on JT9D second vanes. Without TBC, this vane can suffer significant thermal distress. Flight service evaluation has demonstrated that PWA 266 can reduce the thermal distress dramatically (Figure 17). Based on this demonstration, PWA 266 EB-PVD ceramic was incorporated as bill-of-material on this part in mid-1989 (Meier, et al., 1990, and Meier, et al., 1991a).

Further substantiation of the EB-PVD ceramic durability benefits was demonstrated in field testing on the JT9D-7R4 first stage high turbine blades. Figure 18 shows a blade before engine operation and after nearly 4000 hours of hot operation. This engine test provided dramatic evidence of the durability of the ceramic and was incorporated as bill-of-material on this part in 1990.

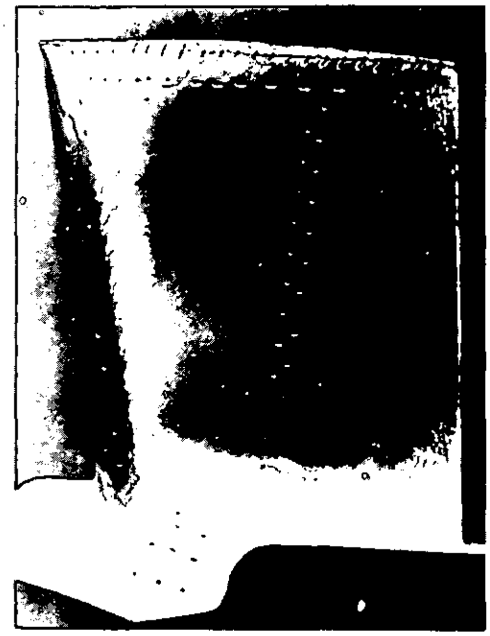


Fig. 15 An EB-PVD Ceramic Coated PW2000 First Stage Turbine Blade Exposed in a 150 Hour Endurance Test. Color variations and especially the mottled appearance near the tip of the trailing edge, are the result of engine deposits.

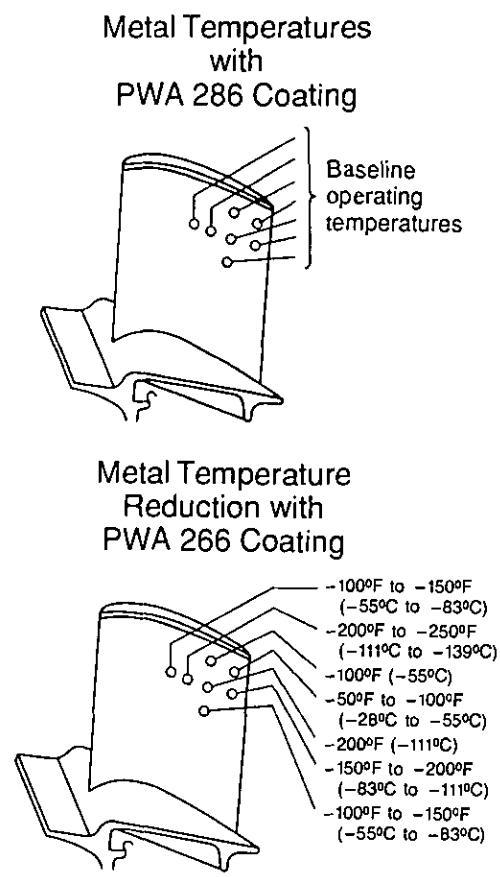


Fig. 16 PW2000 Engine Demonstration of PWA 266 EB-PVD Ceramic Durability and Temperature Reduction Benefits.

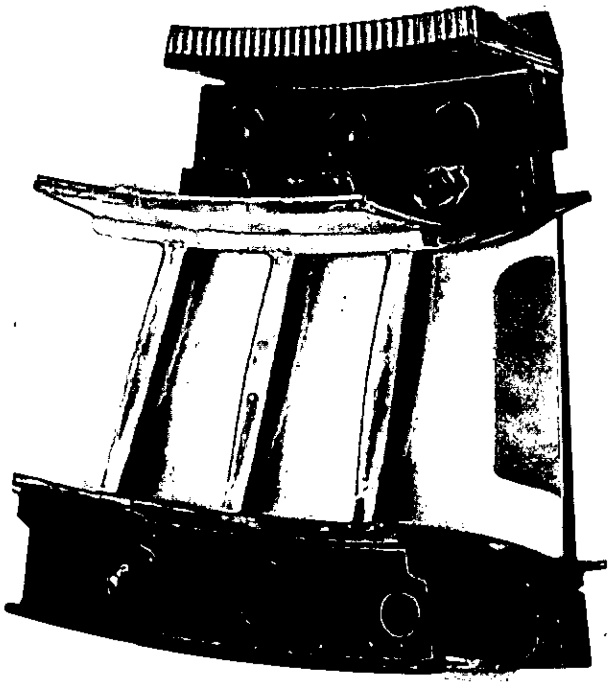
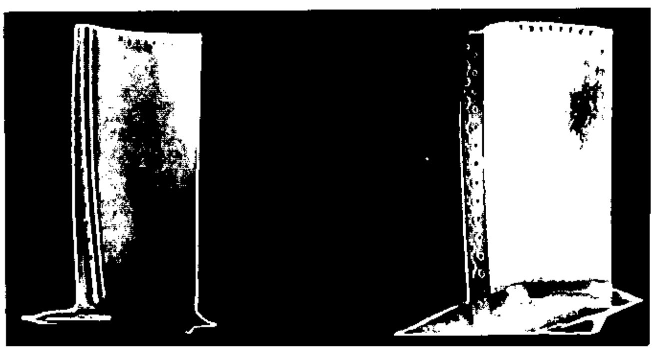


Fig. 17 A JT9D-7Q Second Stage Turbine Vane After 4,200 Hours of Field Service, Which Is Known to Cause Significant Degradation of Uncoated Vanes. This vane was coated with EB-PVD ceramic.



(a) (b)

Fig. 18 A JT9D First Stage Turbine Blade (a) Before Engine Exposure and (b) After 3085 Hours of Field Service.

Ground based experimental engine testing on the PW4000 first turbine blade (Figure 19) has shown significant increases in component durability. No appreciable reduction of cooling airflow was evident after deposition of the EB-PVD ceramic coating. This is in contrast to an essentially 100 percent closure of the cooling holes when plasma sprayed ceramic is applied.

The EB-PVD ceramic TBC offers numerous advantages in addition to minimal reduction of flow. Aerodynamically, the most important benefit is the smooth surface finish. This is achieved because the EB-PVD ceramic structure duplicates the surface finish of the substrate on which it is applied. In contrast, plasma sprayed TBC's require a mechanical surface finishing after deposition. In terms of processing, the EB-PVD process provides a more reproducible coating by the control of process parameters as opposed to the plasma sprayed process.

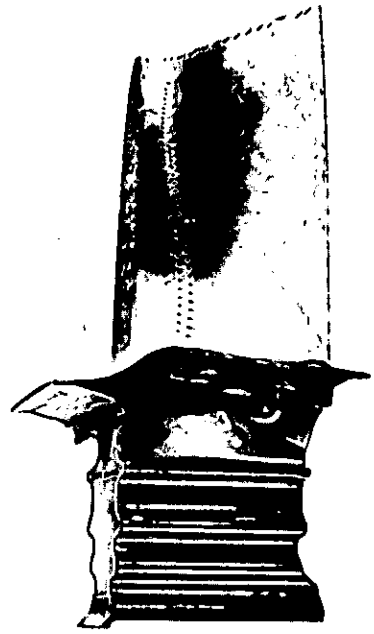


Fig. 19 A PW4000 First Stage Turbine Blade After Ground Based Engine Testing Shows Improved Durability.

TBC LIFE PREDICTION MODELING

Achievement of the maximum TBC benefit potential will require incorporation of the TBC thermal effect as an integral element of initial component design. This will in turn require development of a TBC design system and supporting TBC life prediction methodology. This latter requirement was pursued under NASA sponsorship (Marcin, et al., 1989, and Meier, et al., 1991b).

Modeling of TBC life requires a good understanding of coating failure modes. Thermal barrier coatings fail by spallation of the insulative ceramic layer after prolonged exposure to thermal cycling in the engine. Examination of failed components coated with plasma sprayed ceramic indicates that spallation occurs as a result of cracking in the ceramic layer parallel and adjacent to the very rough metal-ceramic interface, although not coincident with this interface (Figure 20) (DeMasi-Marcin, et al., 1990).

Phenomological evidence indicates that the plasma sprayed ceramic cyclic life is strongly influenced both by the severity of cyclic strain in the ceramic phase and by the amount of bond coat oxide which results from cyclic thermal exposure in the gas turbine engine. While no direct evidence of oxide induced ceramic crack initiation was found, the phenomological evidence for the strong influence of oxidizing (and only oxidizing) thermal exposure was overwhelming. The interactive life model developed for plasma sprayed ceramic was designed to account for both the oxidative and mechanical forms of TBC degradation (Marcin, et al., 1989).

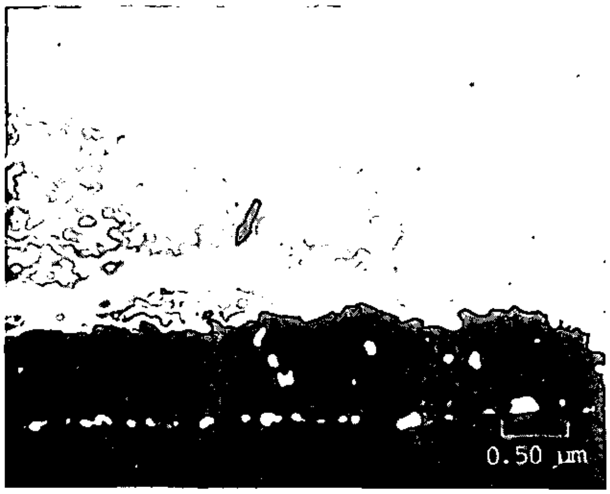


Fig. 20 Plasma Sprayed Ceramic TBC Fails from Cracking within the Ceramic Layer.

Engine failure of EB-PVD ceramic occurs by cracking associated with the thermally grown oxide layer that forms at the interface between the insulative zirconia ceramic and the underlying metallic bond coat (Figure 21). While this layer is predominantly aluminum oxide, it also may incorporate oxides of other bond coat or substrate metals such as nickel, cobalt, chromium, etc. (Meier, et al., 1990, and Meier, et al., 1991b).

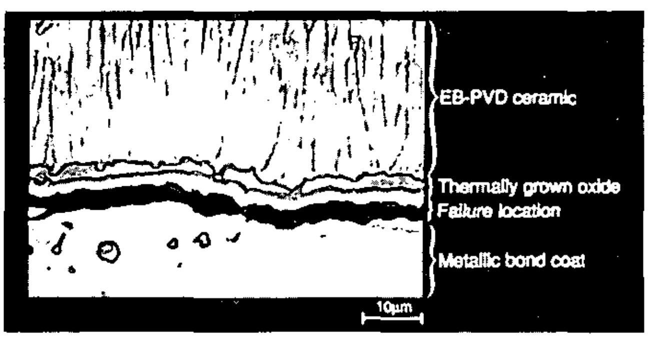


Fig. 21 Ceramic EB-PVD TBC Fails from Cracking at the Thermally Grown Oxide/Bond Coat Layer.

Past experience with plasma sprayed TBC indicated that inelastic deformation of the ceramic was a critical life parameter. However, nonlinear analysis of the EB-PVD ceramic behavior during thermal cycling indicated that the EB-PVD ceramic remained elastic. For that reason and because spallation failure of the EB-PVD TBC system is caused by cracking at the thermally grown oxide/metallic bond coat interface, life modeling efforts for the EB-PVD coating have used TGO elastic strains instead of EB-PVD ceramic strains (Meier, et al., 1991b).

Laboratory generated EB-PVD thermal barrier coating cyclic thermal test results have been used to define a fatigue life model to correlate the TBC spallation lives (Meier, et al., 1991b). The fatigue model includes the combined effects of cyclic thermal loading and oxide scale growth due to elevated temperatures during test. The model is the same as that used in the evaluation of plasma sprayed thermal barrier coatings except the mechanical damage parameter in the EB-PVD model is the thermoelastic stress within the actual oxide layer, where spallation fracture occurs.

SUMMARY

The thermal insulation benefit provided by plasma deposited zirconia thermal barrier coatings (TBC) extends the durability of gas turbine engine combustors. Improvements to the underlying metallic bond coat, the ceramic composition, and the ceramic microstructure have lead to the use of TBCs in the turbine section of the engine. More recent optimization of the composition and processing for increased durability electron beam-physical vapor deposited zirconia has allowed TBCs to be successfully utilized in the most demanding stationary and rotating components. Production of JT9D vanes and blades with EB-PVD ceramic has commenced in mid-1989. Performance of this coating in the field has been highly favorable and has lead to more widespread use in developmental situations.

Up to the present time, TBCs have been used to extend the life of existing or derivative component designs. The development of a TBC design system is allowing achievement of the maximum TBC benefits to be achieved in the engine as the TBC thermal effect becomes an integral part of the component design.

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