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Thermal Barrier Coatings for Industrial Gas Turbine Applications: An Industrial Note

Z. Mutasim and W. Brentnall

Thermal barrier coatings (TBCs) have been used in high-thrust aircraft engines for many years to provide thermal protection and increase engine efficiencies. TBC life requirements for aircraft engines are typically less than those required for industrial gas turbines. This paper describes current and future applications of TBCs in industrial gas turbine engines. Early testing and applications of TBCs are reviewed. Areas of concern from the engine designer's and materials engineer's perspective are identified and evaluated. This paper focuses on the key factors that are expected to influence utilization of TBCs in advanced industrial gas turbine engines. It is anticipated that reliable, durable, and highly effective coating systems will be produced that will ultimately improve engine efficiency and performance.

Keywords efficiency, industrial gas turbines, thermal barrier coatings, thermal protection

1. Introduction

THERMAL BARRIER COATINGS (TBCs) provide thermal resistance to the external surfaces of turbine components and reduce metal surface temperatures. The expected coating life for high-thrust aircraft engines is on the order of a few thousand hours. For industrial gas turbines (IGTs), where the time between overhaul (TBO) is approximately fivefold that in aircraft engines, coating life becomes critical for the successful application of TBCs. Furthermore, IGT operating cycles are longer than aircraft engine cycles (i.e., a few hundred hours vs. 1 to 15 h), which raises concerns about the long-term stability and adherence of TBCs. The use of TBCs for IGTs will increase if durability and longer service life are successfully demonstrated. The objective of this paper is to provide a perspective on the use of TBCs for IGT applications.

2. TBC Development

TBC development activities over the last 20 years have mainly focused on aircraft engine applications, where the turbine component requirements are high operating temperatures ($T > 2400$ °F), a large number of cycles ($n > 1000$), and relatively short lives ($t < 10{,}000$ h). Aircraft and IGTs differ mainly by the cycling frequencies and TBO. The use of TBCs for IGT applications is strongly influenced by the long-term stability of the TBC system. The dominant failure mode observed for TBC systems in aircraft applications is the spallation of the oxide scale that forms on the surface of the metallic bond coat upon exposure to oxidative environments (Ref 1-4). Spallation is caused by residual, thermal, and mechanical stresses present at the oxide-metal interface. Bond coat material development has increased in the last few years, because it has been determined that TBC system durability is a function of bond coat properties. It has been reported that TBC life could be increased by the use of creep-resistant bond coat compositions and by aluminizing on top of the bond coat (Ref 5).

Early programs for developing advanced ceramic coatings for IGTs (Ref 6) have included field engine data for candidate TBC systems. Various TBC systems applied on turbine blades were run in a 550 h rainbow engine endurance test. The TBC systems included plasma-sprayed calcium silicate, calcium titanate, and yttria-stabilized zirconia ceramic top coats, and various NiCrAlY compositions for the metallic bond coats. The calcium titanate and the yttria-stabilized zirconia systems survived the full test duration but exhibited some coating erosion at the blade leading edges. It was concluded that both systems have potential for IGT applications.

TBCs were applied on utility turbine blades (Ref 7) as part of a field engine study. The effects of TBCs on the lifetimes of turbine components and on the performance of the utility turbine were demonstrated. When the turbine was operated under constant cooling flow, the turbine airfoils heated to 55 °C less than the uncoated turbine airfoils operated under identical conditions. This enhanced performance could translate to ten times the creep rupture life and twice the corrosion life. When the turbine was operated at constant metal temperature and reduced cooling flow, both specific power and efficiency increased, with no change in component lifetime (Ref 7).

For IGT applications, an engine test was conducted (Ref 8) with a TBC system applied using the electron beam physical vapor deposition (EB-PVD) process. Turbine blades and nozzles were coated with EB-PVD yttria-stabilized zirconia and placed in an engine for a 5500 h field test. The TBCs protected the component airfoil surfaces from high-temperature oxidation; however, due to the limitations imposed by the line-of-sight nature of the EB-PVD process, coating thickness was inconsistent between the airfoils of the turbine nozzles. The coating thickness varied from 0.125 mm at the airfoil leading edge to 0.025 mm between the adjacent airfoils due to the shadowing effect (see Fig. 1). As a result, the TBC-coated nozzles did not perform as well as expected for this application.

Another field test was conducted (Ref 9) on EB-PVD thermal barrier coated turbine blades. The engine operated for over 10,000 h using a low-grade liquid fuel in a glass manufacturing environment. It was observed at the termination of the test that the coating experienced hot corrosion attack near the blade base. Although the coating remained mostly intact, there was distress

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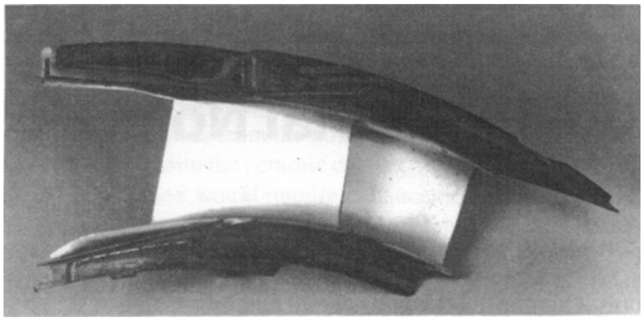

Fig. 1 EB-PVD yttria-stabilized zirconia coated nozzle after 5500 h engine test

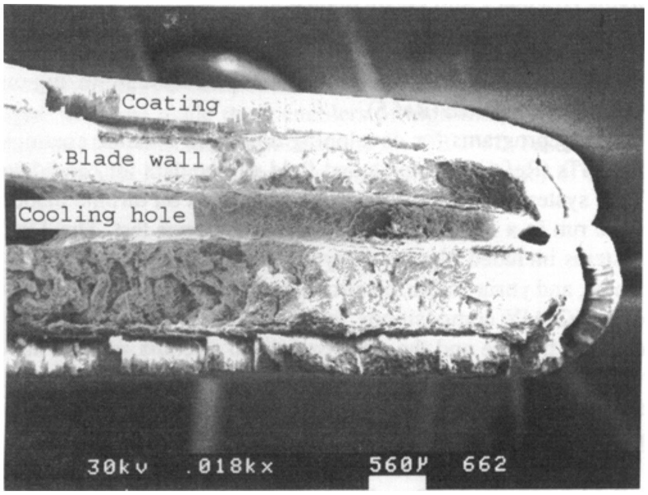

Fig. 3 Scanning electron micrograph of EB-PVD yttria-stabilized zirconia coated blade showing blockage inside cooling hole

and cracks near the blade trailing edge (Fig. 2). The coating distress was attributed to blockage in the trailing edge cooling holes (Fig. 3).

3. Current and Future TBC Applications

The use of TBCs for IGTs is expanding. Currently, TBCs are used on combustors and in other low-risk applications to extend the lives of those components. They are applied to combustion liners in virtually all advanced gas turbines made by General Electric (Ref 10). Some of these components have accumulated over 30,000 h of total life. The application of plasma-sprayed TBCs to hot combustors and turbine vanes is also being conducted on Mitsubishi heavy-duty gas turbines (Ref 11). For medium-size IGT applications (Ref 12), Solar Turbines Inc. applies a NiCrAlY metallic bond coat with a calcium titanate ceramic top coat on fuel injector tips (Fig. 4) and sliding shroud rings. This TBC system has been successfully applied in the field, where it prevented cracking and deformation of the components during service. However, there have been few production applications of TBCs on IGT airfoil components, because these are more complex components and the added processing cost of applying coatings is not economically justifiable.

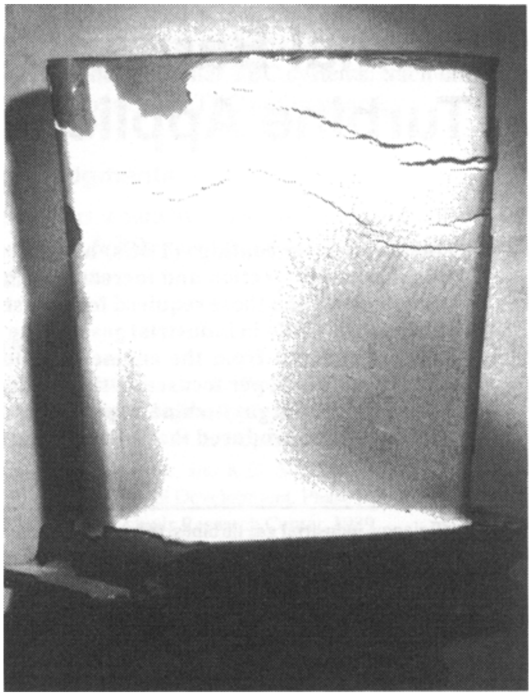

Fig. 2 EB-PVD yttria-stabilized zirconia coated blade showing coating distress and cracking near trailing edge

TBCs are being considered for use on turbine nozzles and blades, where they experience the highest temperature gradients. The advances in EB-PVD processing controls and parts manipulation could facilitate the uniform deposition of TBCs on curved airfoils and between adjacent and partially overlapping airfoils. Furthermore, it is expected that EB-PVD could produce engineered coatings that are capable of withstanding the harsh environment that IGTs are exposed to and that could provide the long-term coating life expected before TBO.

4. Areas of Concern

IGTs are subjected to a more severe environment than aircraft engines, and this raises concerns regarding coating reliability and durability. These concerns are related to the quality of fuels used for IGTs, oxide scale long-term kinetics, and coating life.

4.1 *Quality of Fuels*

Exposure of plasma-sprayed yttria-stabilized zirconia TBCs to combustion environments using clean fuels does little to degrade their properties. However, impurities in the fuel can be very detrimental. This is most likely to occur when lower-grade fuels are used that contain vanadium and sodium. In combination with these impurities, SO_3 gas also adversely affects the performance of these coatings, because thin films of molten salts can be deposited on the surface of the coated components. The principal reason for coating failure in a dirty environment is the localized destabilization of the original tetragonal/cubic structure of the zirconia material, and transformation to the monoclinic phase. This transformation is associated with a 4% volume change and can therefore cause cracking of the coating. EB-PVD allows the phase composition of yttria-stabilized zirconia TBCs to be controlled in combustion environments and inhibits penetration of the corrosive molten salts (Ref 13).

4.2 *Oxide Scale*

Another area of concern related to IGT applications is the long-term stability of the thin oxide scale formed at the bond coat/ceramic coat interface during service, even when using clean fuels. Many reports (Ref 1-4) have indicated that TBC failure occurred at the oxide scale. With long-term exposures and fewer cycles, the oxide scale will grow at different rates than those experienced in aircraft engines. A better understanding of the oxide scale growth kinetics is therefore necessary for the design of more reliable TBCs.

4.3 *Coating Life*

TBC life is the limiting factor for the reliability of the TBC-coated component. Analytical models that describe the mechanical stress distribution and heat transfer of coated components are essential for component design. Models that can accurately describe TBC system life during specified service conditions are important to designers in defining component lives. Development of life prediction models are necessary to understand the TBC system behavior and be able to estimate time before coating failure. Life prediction modeling incorporates analysis of materials properties, component stress, and heat transfer, nondestructive techniques for detecting impending coating failures, and an accurate definition of failure modes. With better understanding of these parameters, the use of TBCs on IGT components will become less uncertain and therefore more attractive.

5. Conclusions

The use of TBCs on IGT components has the potential to provide many benefits. First and foremost, TBCs act as thermal insulators, thereby reducing the heat transmitted to the component from the hot gas flux. The heat flux is dissipated through radiation back into the hot gas path and through conduction across the coating and base metal, where the excess heat is absorbed by the back side cooling air. The temperature gradient across the coating allows for higher operating temperatures without distortion or degradation of the base metal. Second, TBCs provide thermal shock protection to turbine components during cold starts. The application of TBCs on turbine blades and nozzles could allow for higher turbine inlet temperatures, reduction in air cooling, and therefore increased volume of the working fluid in the turbine section, which could translate to greater total efficiency.

The expected benefits of TBCs to IGTs are very realistic. Solar Turbines Inc. conducted thermal analysis (Ref 14) on its existing airfoil designs coated with a nominal TBC system and using literature-available heat transfer properties. A three-dimensional thermal analysis estimated the heat flux and temperature distribution around the airfoil with and without a TBC. With a TBC, preliminary calculations showed that the temperature distribution drops by approximately 65 °C at the leading and trailing edges and by 38 °C near the airfoil platform. These temperature reductions were achieved without any optimization of the airfoil cooling schemes or optimization of TBC properties. The model also indicated that the temperature reduction at the metallic surface is a function of coating thickness, and it was estimated that internal cooling requirements may be decreased by as much as 30 to 50%, resulting in an increase in overall thermal efficiency.

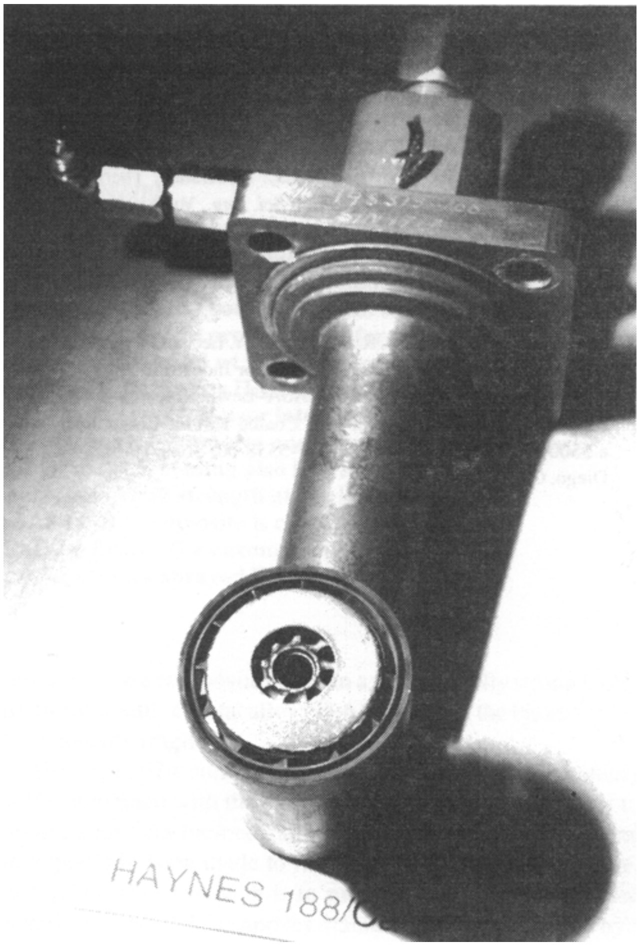

Fig. 4 Fuel injector tip coated with plasma-sprayed calcium titanate coating

For advanced IGTs, it is recognized that the use of TBCs will reduce maximum temperatures and thermal stresses on the components, allow for higher turbine inlet temperature, and reduce the extent of back-side air cooling. Together, all of these positive factors translate to an increase in total engine efficiency. The use of TBCs for IGTs will increase dramatically if durability and longer service life are successfully demonstrated.

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