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Thermal Barrier Coating Evaluation Needs

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A 0.025 cm (0.010 in) thick thermal barrier coating (TBC) applied to turbine airfoils in a research gas turbine engine provided component temperature reductions of up to 190°C[1]. These impressive temperature reductions can allow increased engine operating temperatures and reduced component cooling to achieve greater engine performance without sacrificing component durability. The significant benefits of TBCs are well established in aircraft gas turbine engine applications and their use is increasing. TBCs are also under intense development for use in the Low Heat Rejection (LHR) diesel engine currently being developed and are under consideration for use in utility and marine gas turbines. However, to fully utilize the benefits of TBCs it is necessary to accurately characterize coating attributes that affect the insulation and coating durability. The purpose of this paper is to discuss areas in which nondestructive evaluation can make significant contributions to the further development and full utilization of TBCs for aircraft gas turbine engines and low heat rejection diesel engines.

TBC Concept

The Thermal Barrier Coating (TBC) concept involves placing a thermally insulating layer between a cooled metallic component and the hot working gas to reduce heat transfer to the component (Fig. 1). Reduced heat transfer translates to a reduced component steady state temperature, less severe heating and cooling transients and a reduction in the severity of temperature gradients. The insulating material for the majority of applications consists of a ceramic layer. The actual design of a TBC, however, changes significantly with the specific application. TBCs designed for use in aircraft turbine engines and in low heat rejection (LHR) diesel engines will be reviewed here with a view to examining important aspects of TBCs that must be characterized for quality control, in-service inspection and continued research and development purposes.

Evaluation of As-Fabricated TBCs

TBCs for aircraft turbines and LHR diesel engines are quite different due to the differences in environment for the two applications. The state-of-the-art TBC developed for aircraft gas turbine engines incorporates an outer insulating layer (or top coat) of ZrO_2-(6-8)wt%Y_2O_3 (partially stabilized zirconia or "PSZ") 0.013 to 0.038 cm thick and a 0.013 cm thick oxidation resistant inner layer of MCrAlY (also called the bond coat), where the "M" is normally Ni, Co or Ni + Co. The common method of application for both layers is plasma spraying, but electron beam-physical vapor deposition (EB-PVD) of TBCs is gaining popularity, especially for deposition of the PSZ layer[2]. These two methods of deposition produce coatings with significantly different microstructures (Fig. 2).

TBCs developed for LHR diesel engines include a thick partially or fully stabilized zirconia (all zirconia will be referred to as "PSZ" for brevity) layer to provide adequate insulation under the low average heat flux conditions that exist in these engines. Thick PSZ layers tend to

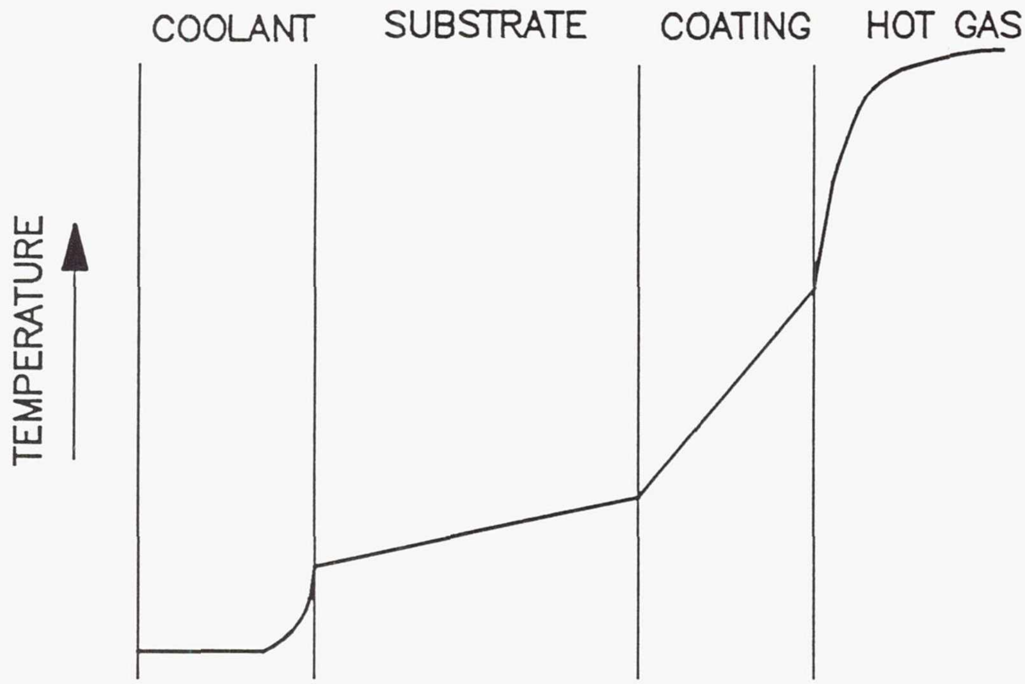


Figure 1. Schematic of the thermal barrier coating concept showing the hot gas heat source, the insulating layer, the component (substrate) and the component coolant.

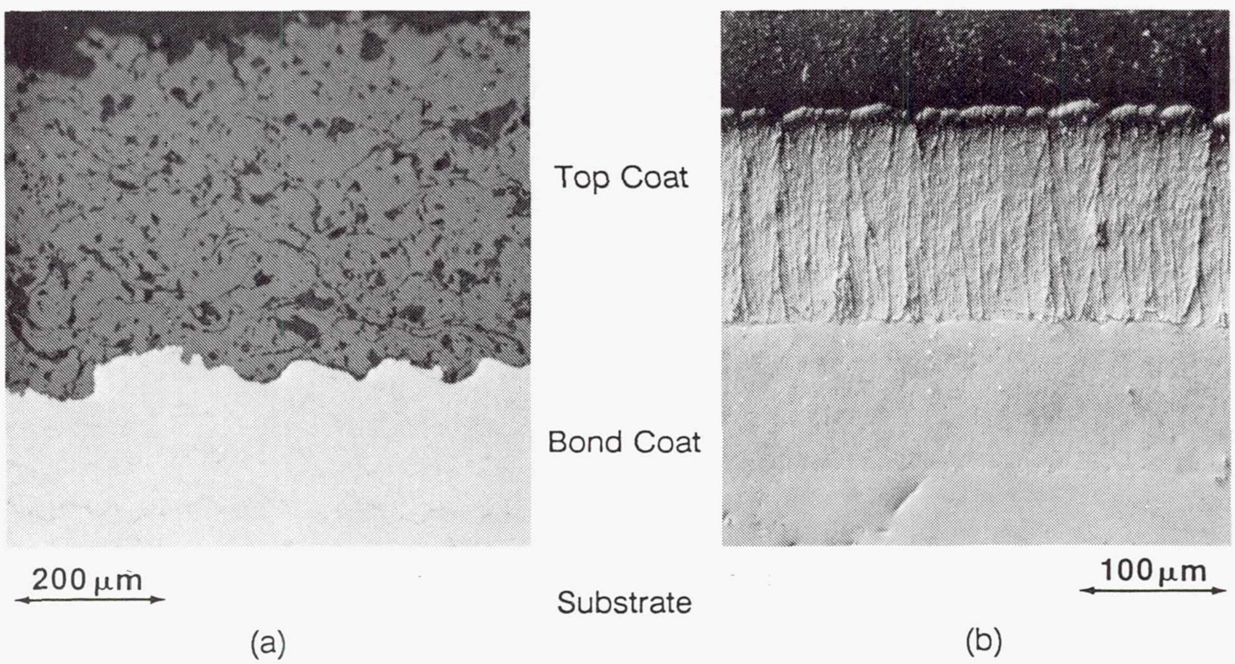


Figure 2. Optical micrographs of (a) a plasma sprayed two layer TBC showing porosity and cracks and (b) an EB-PVD two layer TBC showing a columnar structure. Micrograph (b) was taken using differential interference contrast.

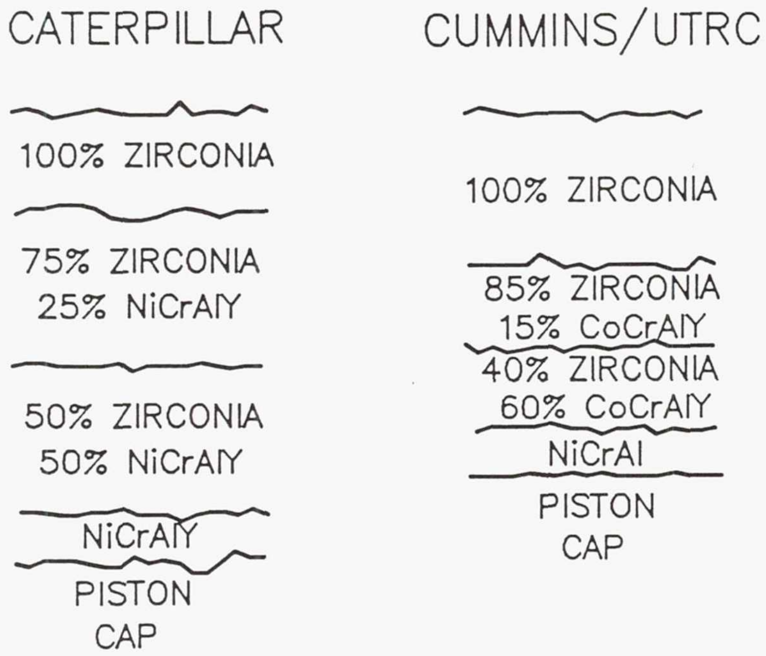
concentrate coefficient of thermal expansion (CTE) mismatch stresses at the top coat/component interface and therefore have poor durability. Improved durability for thick coatings is achieved by "grading" the CTE of the coating through the coating thickness. Grading is accomplished by applying a 100% metallic bond coat layer followed by successive layers of coating with decreasing fractions of bond coat material and increasing fractions of PSZ ceramic. This type of coating achieves a bulk CTE that changes gradually from the substrate to the outer surface. Current generation diesel TBCs achieve reasonable durability with up to four grading layers from the bond coat to the top coat and a total coating thickness of 0.25 cm or greater[3,4] (Fig. 3).

The most important physical features of as-fabricated TBCs both for aircraft turbines and LHR diesels are the thickness, density, microstructure, and residual stresses of the coating layers[5,6]. These features are important to the insulating value of the TBC and critical to the durability of the TBC.

Increased thicknesses of the insulating layer will, of course, increase the insulation of the underlying component. However, stresses concentrated at the PSZ/bond coat interface increase with increasing thickness of the ceramic layer and will reduce the life of the PSZ layer[6,7]. The thicknesses of the graded layers in a diesel TBC are also important to durability[3]. However, coating thickness is often difficult to measure by normal means (micrometers, calipers, etc) due to complex component shapes (Fig. 4). Complex component shapes can also present problems in maintaining uniform coating thickness with the line-of-sight deposition techniques used to fabricate TBCs. Therefore, it is the complex component shapes that most need TBC thickness monitoring. Thus, one critical evaluation need for TBCs is a reliable method for coating thickness measurement for both process control and quality control.

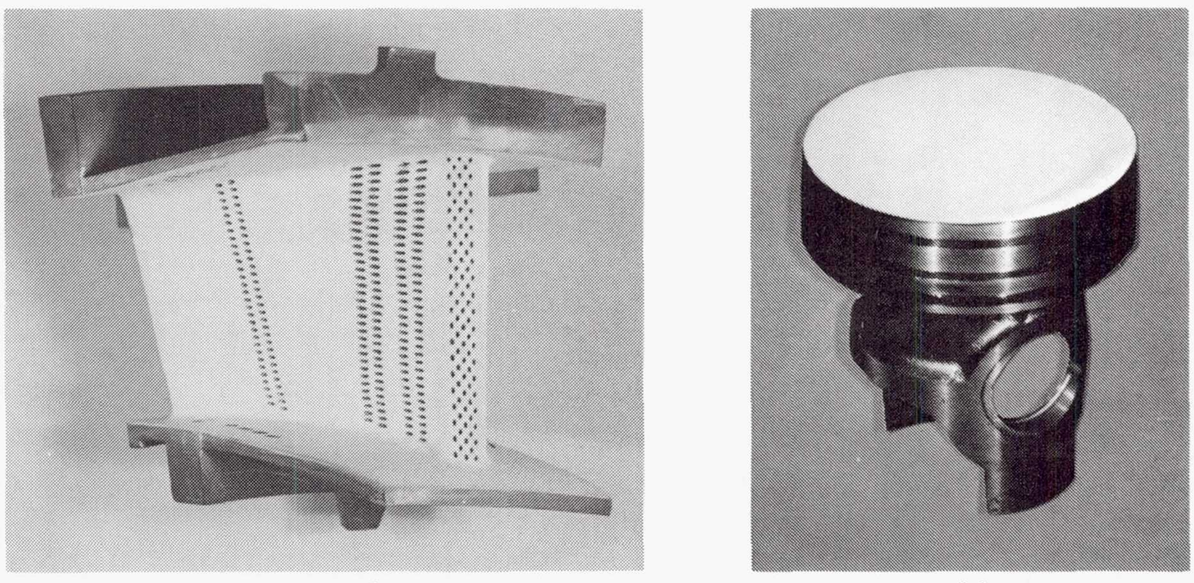
The durability of the top coat for aircraft TBCs is also a function of the thickness of the oxidation resistant bond coat. Bond coats that are too thin are unable to provide oxidation protection to the component for extended periods and will tend to provide shorter than desired PSZ layer life as well[7,8]. Thus, close control of the bond coat thickness is also important to achieving durable TBCs.

The density of a plasma sprayed top coat (as a fraction of the theoretical density) is critical to the life of an aircraft engine TBC[5,7,8] as shown in Figure 5, is suspected to be important to the life of an EB-PVD aircraft TBC and may also be important to diesel engine TBCs[3]. Density variations may occur as a result of process variations or may result from the combination of part shape complexity and the line-of-sight deposition processes that are used. The effect of density on plasma sprayed TBC durability is a result of the strain tolerance gained through porosity and cracking in the top coat[5,8] (Fig. 2). The dependence of TBC life on the amount of porosity is complex in that the ratio of equiaxed pores to flat crack-like pores changes with density. Thus, it is not clear if top coat durability should be a strict function of density or a function of both density and the ratio of the different types of pores. These points have not been addressed due to the lack of adequate means of characterizing the pore content of a TBC. Recent advances in metallographic techniques[9] have made possible metallographic examination of the pore content of coatings and may lead to new information on pore effects on TBC life. Until pore-durability correlations can be made, it is only certain that pore content of a coating is critical to TBC durability. NDE methods that can characterize both density and the pore content of a coating are certain to be useful for both quality control and for research and development.



(a) (b)

Figure 3. Schematics of the four layer graded coating approach to fabricating LHR diesel engine TBCs used by (a) Caterpillar and (b) Cummins/UTRC.



(a) (b)

Figure 4. An aircraft gas turbine engine second stage stator vane (a) and a piston cap (b) are examples of components that can benefit from the use of TBCs.

Density also has an effect on the thermal conductivity of a plasma sprayed top coat material. Pores in the top coat act as air gaps that help to reduce the conductivity of the top coat material[10] (Fig. 6). As for durability, the type of pores that are present have a bearing on the conductivity. Flat pores with the major axis perpendicular to the direction of heat flow are more effective in reducing the conductivity of a PSZ layer than are an equal volume of equiaxed pores[10]. Thus, knowledge of pore types and amounts of pores present in a coating could make it possible to estimate the conductivity of a coating on a production part.

Another area of concern for TBCs is the presence of detrimental residual processing stresses due to the high temperatures at which the coating processes are conducted. Methods to minimize residual stresses in aircraft engine coatings have been widely adopted[2,8] and residual stress management is being investigated as a method to achieve higher durability for LHR diesel TBCs[4]. However, reliable NDE methods to assess the residual stresses in TBCs have not been established. A residual stress measurement technique would be useful in monitoring coating quality, in particular assuring proper temperature control during processing, and would be highly useful for research on controlling residual stresses during processing.

In-Service Evaluation of TBCs

The above discussion concentrated on the as-fabricated features that are of importance to the durability and insulating ability of a TBC. The most pertinent features of in-service evaluation of coatings are those that indicate degradation or imminent failure of the coating. Coating degradation and failure for aircraft turbine engines and diesel engines are distinctly different. Failure of aircraft engine TBCs is generally by delamination of the insulating PSZ top coat from the bond coat, a process called spalling. The delamination process is clearly due to progressive crack growth and link-up within the PSZ for plasma sprayed coatings[8] and is thought to be a process of sudden (rather than progressive) cracking through the Al_2O_3 layer for EB-PVD coatings. While the process of cracking in a plasma sprayed coating is progressive, the actual spalling event is often catastrophic. This is a result of the crack growth occurring at the top coat/bond coat interface and remaining essentially invisible until spalling actually occurs. For this reason, NDE detection of delamination cracks is particularly attractive for plasma sprayed TBCs. Such a technique could be used at regular inspection intervals to determine how much delamination has occurred and if the coating is nearing the end of its useful life. Some work has already been conducted in this critical area[11].

Spalling for EB-PVD coatings is thought to be sudden, without the progressive cracking that occurs in plasma sprayed coatings. However, there is a tendency for the coating to spall in much smaller sections than do plasma sprayed coatings and, therefore, a single spalling event for an EB-PVD coating is not likely to be as detrimental to the component life as a spalling event for a plasma sprayed coating. An EB-PVD coating will become more likely to spall in a large section if the independent columns that provide strain tolerance (Fig. 2) become bonded together by sintering. In this case, periodic density checks of EB-PVD coatings may signal the occurrence of sintering that could lead to premature coating failure.

Other in-service inspection possibilities for aircraft TBCs include density examination of plasma sprayed coatings to look for increases or decreases in density that may indicate potential premature failure. The growth of an oxide between the top coat and the bond coat is detrimental to the life of both types of coating and an examination technique that could

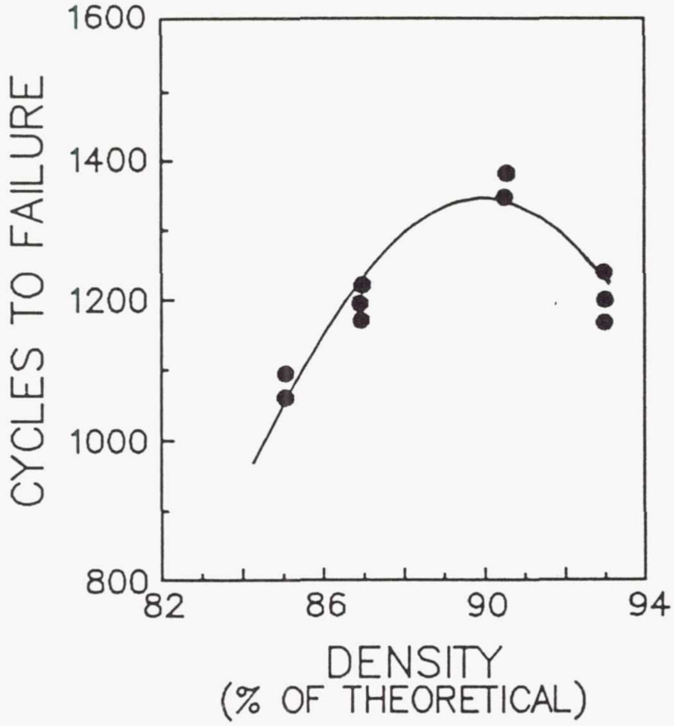


Figure 5. Cyclic life of an aircraft engine two layer TBC as a function of the density of the top coat[7]. The density is expressed as a percentage of the theoretical density.

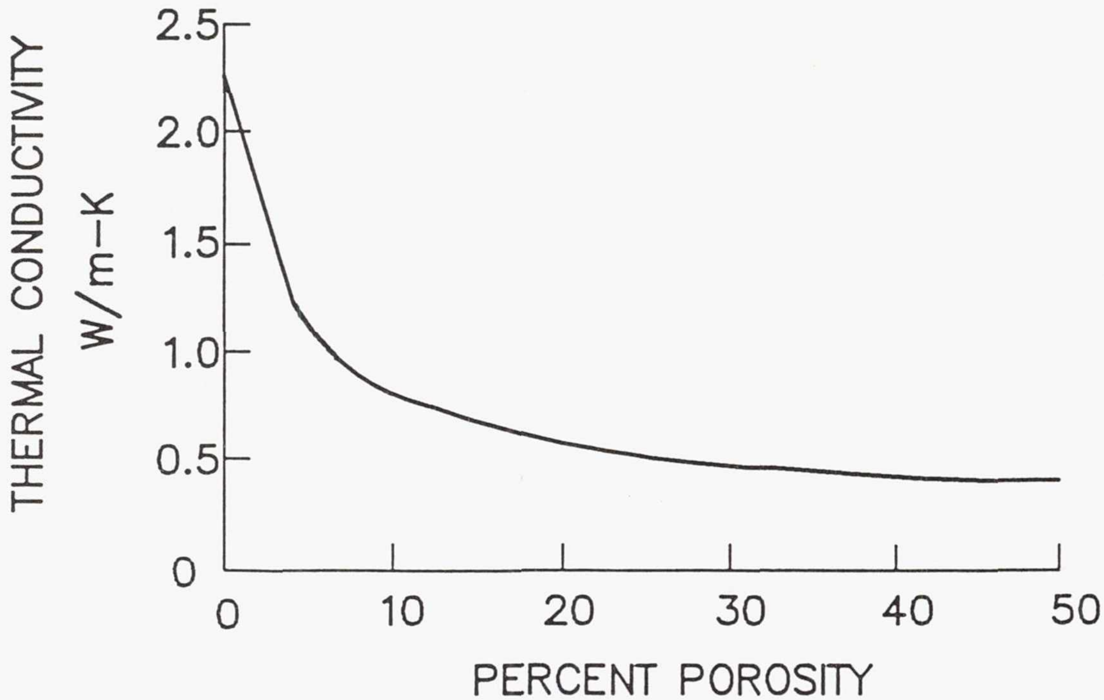


Figure 6. Variation in the conductivity (inverse of insulating ability) of a PSZ layer as a function of PSZ porosity content[10].

determine oxide thicknesses below the PSZ on in-service parts may be helpful in determining the remaining life of a part. Finally, both types of coating are subject to erosion due to their strain tolerant structures and severe operation environments. Thus, monitoring of in-service coating thickness will be essential in future, higher operating temperature aircraft turbines in which the insulation provided by a TBC is critical to the short term life of the engine.

In-service inspection requirements for LHR diesel engine TBCs are expected to be somewhat different than for gas turbines. The dominant mode of in-service coating failure is yet to be identified for LHR TBCs but a few degradation mechanisms have been identified. Shallow spalling, which is spalling of chips of PSZ that are a small fraction of the coating thickness, has been observed for diesel coatings and is attributed to high cycle thermal fatigue[3]. Shallow spalling could damage the insulating capability of the coating by reducing the coating thickness. Delamination of TBCs, similar to that in aircraft engines, has also been observed and could lead to spalling of significant fractions of the coating thickness. Both shallow spalling and delamination may be amenable to detection during regular service intervals for diesel engines.

CONCLUSIONS

Thermal barrier coatings offer the potential to significantly increase heat engine efficiency or performance by allowing increased operation temperatures while maintaining component durability. However, TBC durability and insulating ability are highly dependent on thickness, density, microstructure and residual stresses. Therefore, establishment of coating evaluation techniques that can handle the complexities of TBCs is critical to the continuing development and use of TBCs for high performance heat engines.

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16. Abstract

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