

NASA Technical Memorandum 102408

Thermal Barrier Coatings for Gas Turbine and Diesel Engines

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Prepared for the
Eleventh Workshop on Ceramic Coatings for Wear and Thermal Applications
sponsored by the Canadian University-Industry-Council on Advanced Ceramics
Edmonton, Alberta, Canada, October 16-17, 1989

NASA

(NASA-TM-102408) THERMAL BARRIER COATINGS
FOR GAS TURBINE AND DIESEL ENGINES (NASA)
9 p CSCL 11F

N90-13636

Unclas

G3/26 0243252



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Abstract

The present state of development of thin thermal barrier coatings for aircraft gas turbine engines and thick thermal barrier coatings for truck diesel engines is assessed. Although current thermal barrier coatings are flying in certain gas turbine engines, additional advances will be needed for future engines. Thick thermal barrier coatings for truck diesel engines have advanced to the point where they are being seriously considered for the next generation of engine. Since coatings for truck engines is a young field of inquiry, continued research and development efforts will be required to help bring this technology to commercialization.

Introduction

Thermal barrier coatings (TBCs), applied to airfoils in research gas turbine engines, have reduced component temperatures by as much as 190°C.¹ This large temperature reduction in effect increases the high temperature capabilities of current alloys by an amount that exceeds the advances made by alloy developers in the past two decades. Efficiency improvements are also possible. For example, the cooling air supplied to coated components can be reduced and used instead for propulsion. It is estimated that this would save 10 million gallons of fuel annually in a 250 aircraft fleet.² In diesel engines, thermal barrier coatings on the piston and cylinder head may yield a 3% fuel savings.³ The consequent economic benefits have provided the impetus for TBC research and development efforts in aircraft gas turbine engines and diesel engines. This paper will assess the present state of development of thermal barrier coatings for aircraft gas turbine and truck diesel applications.

Thermal Barrier Coating Concept

Thermal barrier coatings are, typically, an insulating ceramic layer applied to metallic components in a heat engine. The components may be, for example, air cooled turbine blades or oil cooled diesel engine pistons. The low conductivity ceramic coating insulates the underlying air cooled component from the hot gases in the engine. The surface of the ceramic, however, will attain a higher temperature than the surface of an uncoated metallic component. Since the driving force for convective heat transfer from the gas to the component is equal to the gas temperature minus the surface temperature, less heat is transferred to the coated component. Therefore, less coolant is required and the steady state temperature of the underlying metallic component may be lowered. Also heating and cooling transients, temperature gradients, and hot spots in the component will be less severe. For steady-state applications, the coolant is necessary to reduce the component

temperature -- otherwise the component and coating would reach the same temperature. For other applications cooling may not be necessary to achieve certain benefits. For example, components in rocket engines are subjected to extreme thermal transients or extreme thermal gradients for a relatively short period of time. Thermal barrier coatings can moderate these transients and gradients even in an uncooled component.

The desired qualities of a thermal barrier coating system include low thermal conductivity, resistance to thermal degradation (including oxidation resistance for high temperature applications), compatibility with the component (especially a good thermal expansion match), high adhesive strength to the component, cohesive strength at least comparable to the adhesive strength, and in some applications resistance to corrosive contaminants. Few materials can meet these requirements. Of these few, zirconia-yttria has emerged as the leading material for TBCs. Zirconia-yttria exhibits generally good high temperature properties, high thermal expansion, and better toughness than other candidate materials. While zirconia-yttria has many of the required TBC attributes, no single material possesses all of the attributes required of TBCs. Therefore, thermal barrier coatings are normally a coating system incorporating an underlying metallic bond coat. In some lower temperature applications intermediate layers of mixed ceramic and metal are also included.

Thermal Barrier Coatings for Aircraft Turbines

The pioneering work and the majority of TBC research and development to date has been paced by aerospace applications. In the 1960's thermal barrier coatings were used on the thrust chamber of the X-15 rocket plane⁴ and on combustor liners⁵ in commercial gas turbine engines. In 1976^{6,7} a coating system was developed that could survive on the turbine blades in a research gas turbine engine. That work led to the current interest in developing TBCs for the turbine section of aircraft gas turbine engines. While rocket engine applications are still important, TBC development has mostly focused on aircraft gas turbine engine applications.

The greatest efficiency benefits of TBCs in an aircraft engine come from their use on the stator vanes and the turbine blades -- the hottest components in the engine. The conditions that must be addressed in developing TBCs for these applications include high temperature oxidizing gases and thermal cycling. The state-of-the-art TBC developed for aircraft engines to achieve both component temperature reductions and component oxidation resistance is a two layer coating system consisting of an inner metallic layer and an outer ceramic layer. An optical micrograph of this coating is shown in Figure 1. The function of the ceramic layer is to provide insulation. The ceramic is typically plasma sprayed ZrO_2 partially stabilized with 6 to 8 weight percent Y_2O_3 . The composition of the zirconia-yttria evolved from extensive experimentation and its selection was based primarily on durability considerations.^{2,7,8} Figure 2 shows an example of the relationship between coating composition and test life as determined in reference 8. The outer ceramic layer that has evolved is typically from 0.13 mm (0.005in.) to 0.38 mm (0.015in.) thick for aircraft engine components.

The inner metallic layer of the TBC, termed the bond coat, is typically a plasma sprayed MCrAlY layer approximately 0.13 mm (0.005in.) thick. The "M" in the MCrAlY is normally nickel or both nickel and cobalt. The bond coat provides oxidation resistance for the substrate and also provides a rough surface to which the top coat layer can adhere. This oxidation resistant layer

is necessary because the top coat provides little or no oxidation resistance for the component which is normally a nickel-base superalloy. These superalloys have relatively poor oxidation resistance since they are designed primarily for high temperature strength and not for environmental resistance. The bond coat layer in Figure 1 is a NiCrAlY alloy plasma sprayed in a vacuum to achieve high density and low included oxide content. Vacuum plasma spraying is commonly used for applying bond coats on components that are subjected to very high temperatures, such as stator vanes and turbine blades. Air plasma spray of bond coats has been found to be sufficient for lower temperature components such as combustors.

A prominent feature of the ceramic top coat shown in Figure 1 is the splat structure that results from the plasma spray process. This structure imparts unusual properties to the ceramic material. As shown schematically in Figure 3, these properties include thermal conductivity of about 1/3 of the fully dense ceramic (and about 1/50 of the metal substrate), high strain tolerance (especially in compression where strains of several per cent have been measured), creep at moderate temperatures (even below 1000 C), and fatigue². As indicated in Figure 4, optimum TBC durability occurs at a porosity level of about 10% .

The useful life of a TBC ends when the ceramic insulating layer separates from the component. While in some cases the ceramic can be removed by erosion, a more typical failure is delamination of sections of the ceramic from the bond coat -- a process called spalling. Spalling is a consequence of cracking in the ceramic layer both near to and at the interface with the metal. The cracking is driven by stresses attributed to oxidation of the bond coat and to cyclic thermal expansion mismatch (thermal fatigue).^{2,9} In fact, under severely oxidizing conditions (typically involving long times at very high temperatures in laboratory furnaces) bond coat oxidation damage can reduce the TBC cyclic life to only one cycle. Therefore, oxidation has been identified as a major factor that affects the durability of a TBC. The current best bond coats, developed through extensive investigation, are MCrAlYs compositions having high chromium (25-35w/o) and low aluminum (6w/o).⁸ These are significantly better in terms of top coat life than are NiCrAlY compositions traditionally used for overlay coatings (15-22w/o chromium and greater than 6w/o aluminum). However, the oxidation resistance of these bond coatings is not as good as that provided by overlay coatings. Therefore additional factors possibly involving bond coat yield strength, modulus, and thermal expansion must affect life. This is an area currently under investigation at NASA-Lewis.

The success of porous and microcracked plasma sprayed TBCs has led to the development of electron beam-physical vapor deposition (EB-PVD) techniques for fabricating TBCs.^{2,5} These EB-PVD coatings have a columnar structure that is thought to be extremely compliant in the direction parallel to the interface. Therefore, they are expected to exhibit thermal fatigue resistance superior to plasma sprayed coatings. However, higher thermal conductivities and greater permeability to oxygen and molten salts are negative consequence of the columnar structure. Early EB-PVD thermal barrier coatings suffered from "infant mortality". Current research has solved those problems and is likely to result in the use of EB-PVD coatings in the near future.²

Thermal Barrier Coatings for Low Heat Rejection Truck Diesel Engines

The next generation of truck diesel engines will operate at much higher temperatures than current engines. The water cooling system will be

eliminated, peak and mean cylinder pressures will be increased, and in-cylinder insulation will help to keep heat energy in the exhaust gas for recovery by turbocharging and turbocompounding. This engine, known as the low heat rejection (LHR) diesel engine, is expected to be more efficient, more reliable, and more powerful per liter of displacement. The current goal for the LHR engine is a 30% improvement in fuel economy over 1982 levels. About 1/10 of that improvement will come directly from the in-cylinder insulation. Thermal barrier coatings are expected to be part of the insulation package in the LHR engine. The coating systems that are presently under development for insulating the pistons and possibly other components are thick (approximately 2.5 mm) and use intermediate layers of metal and ceramic to alleviate thermal expansion differences.^{3,10} These coatings are adapted from the plasma sprayed ceramic abradable seals that were developed for aircraft gas turbine applications.¹¹ A schematic of a thick thermal barrier coating is shown in figure 5.

The environment encountered by thick thermal barrier coatings on diesel engine components differs significantly from the environment encountered by thin thermal barrier coatings on gas turbine airfoils. In the aircraft turbine engine, maximum temperatures occur during take off and climb. Lower temperatures are encountered in the steady-state cruise portion of the mission. In the diesel engine maximum temperatures occur many times per second (e.g. 24 times per second at 2600 RPM). Peak gas temperatures, pressures, and heat transfer values associated with ignition actually exceed the maximum values encountered in the gas turbine engine. On the other hand, mean values of these parameters in the diesel engine are much lower than in the gas turbine engine. As a result, materials temperatures are much lower in the diesel engine. The lower temperatures permit the use of graded coatings but the 24 or so explosions per second may fatigue the outer surface of the coating. Coating development for diesel engines is a relatively young field and most of the research to date has been applied. As a result, there is no general agreement on the detailed mechanisms of coating degradation and failure. On the other hand the applied work has led to reference engine designs which incorporate thermal barrier coatings.

Technical and Economic Considerations

The potential economic advantages of thermal barrier coatings for gas turbine airfoils cannot be disputed. As discussed earlier, the benefits involve increased temperature capabilities and significant improvements to engine efficiency and performance. These improvements plus the relatively low cost combine to make them very attractive. While cost benefits are not in dispute, the potential durability of the TBCs under the more extreme operating conditions needed for future engines is a cause for concern. That is, even though current TBCs are flying in commercial engines and are meeting the 10,000 hour endurance goals, TBCs may not be adequate for future engine designs. Therefore, much more work is required in the areas of process quality control, optimization, and new coating system development.

For diesel TBCs there are both costs and durability questions. The costs of applying thick TBCs to the piston and cylinder head could add about \$1000 to the cost of the engine. Payback would occur through the increased fuel economy, through a higher horsepower rating (which would increase the value and therefore selling price of the engine), and through improved component life. A recent cost analysis performed under DOE/NASA supported contracts has predicted a favorable return-on-investment for an LHR engine with TBCs on the

pistons. Therefore the main questions with diesel engine TBCs, as with aircraft engine TBCs, involve durability. As with aircraft TBCs the answer must involve more research and development.

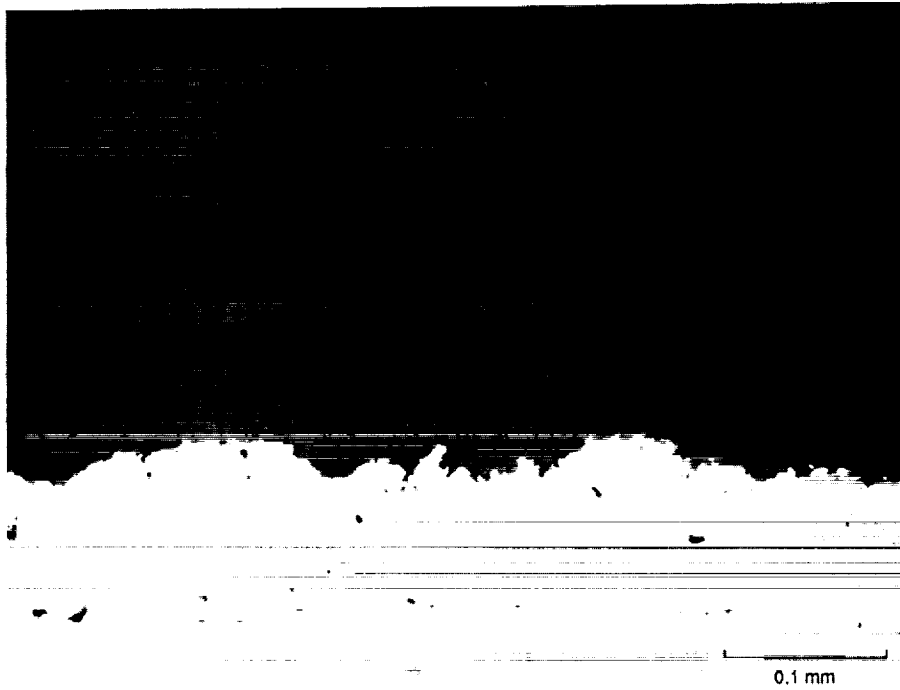
Conclusions

Significant increases in heat engine efficiency and performance as well as increased durability can be achieved through the use of thermal barrier coatings on critical heat engine components. The resulting economic benefits have provided the driving force for research and development aimed at using TBCs in gas turbine engines and in low heat rejection diesel engines. This development work has resulted in use of TBCs on the stator vanes of commercial aircraft turbine engines and promises to establish TBCs as a cost effective means of increasing the efficiency of diesel engines in the near future.

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ORIGINAL PAGE
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ZrO₂-(6 TO 8 PERCENT)-Y₂O₃
AIR PLASMA SPRAYED
POROUS AND MICROCRACKED

MCrAlY BOND COAT
LOW PRESSURE PLASMA SPRAYED
HIGH DENSITY

SUPERALLOY SUBSTRATE

Figure 1. - Micrograph of the cross section of a typical aircraft thermal barrier coating.

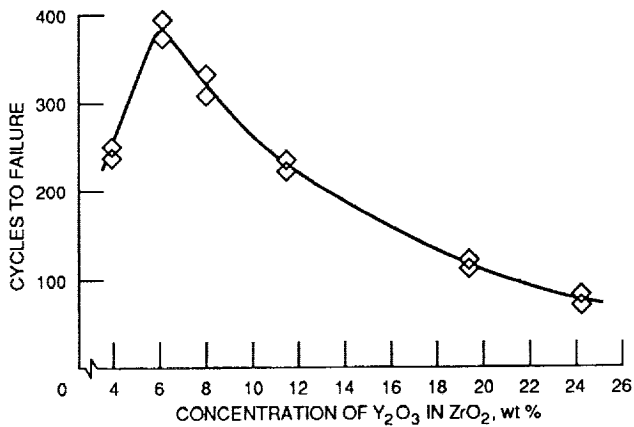


Figure 2. - Relationship between level of yttria in zirconia and test life.

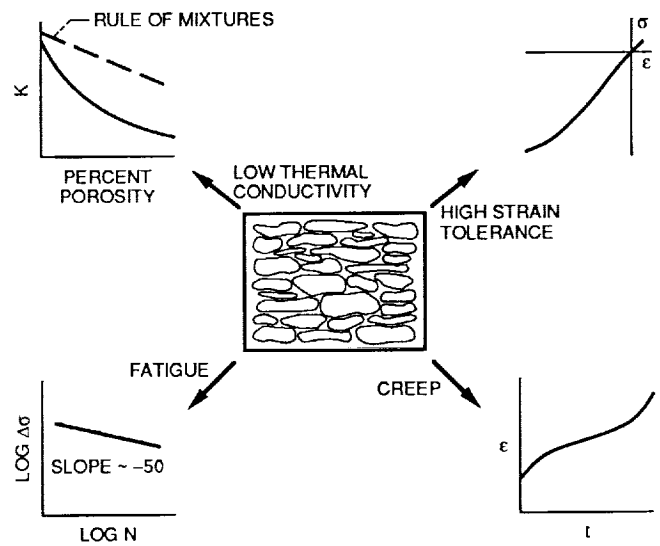


Figure 3. - Schematic representation of thermomechanical properties resulting from coating splat structure.

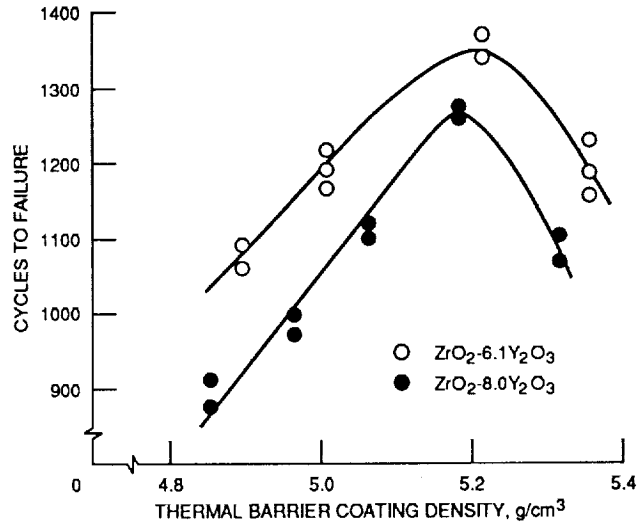


Figure 4. - Relationship between ceramic layer density and test life.

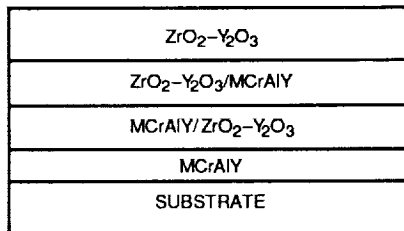


Figure 5. - Schematic of a four layer thick thermal barrier coating for diesel engine application.



Report Documentation Page

1. Report No. NASA TM-102408	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle Thermal Barrier Coatings for Gas Turbine and Diesel Engines		5. Report Date	
		6. Performing Organization Code	
7. Author(s) Robert A. Miller, William J. Brindley, and M. Murray Bailey		8. Performing Organization Report No. E-5160	
		10. Work Unit No. 505-63-1A	
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191		11. Contract or Grant No.	
		13. Type of Report and Period Covered Technical Memorandum	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546-0001		14. Sponsoring Agency Code	
15. Supplementary Notes Prepared for the Eleventh Workshop on Ceramic Coatings for Wear and Thermal Application sponsored by the Canadian University-Industry-Council on Advanced Ceramics, Edmonton, Alberta, Canada, October 16-17, 1989.			
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17. Key Words (Suggested by Author(s)) Coatings Zirconia yttria Gas turbine engines Diesel engines		18. Distribution Statement Unclassified-Unlimited Subject Category 26	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No of pages 8	22. Price* A02